A THEORY OF DEFAULT REASONING

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ABSTRACT

We propose a theory of default reasoning satisfying a list of natural postulates. These postulates imply that knowledge bases containing defaults should be understood not as sets of formulas (rules and facts) but as collections of partially ordered theories. As a result of this shift of perspective we obtain a rather natural theory of default reasoning in which priorities in interpretation of predicates are the source of nonmonotonicity in reasoning. We also prove that our theory shares a number of desirable properties (completeness, soundness etc.) with the theory of normal defaults of R. Reiter.

We limit our discussion to *logical* properties of the proposed system and prove some theorems about it. Modal operators or second order formulas do not appear in our formalization. Instead, we augment the usual, two-part logical structures consisting of a *metalevel* and an *object level,* with a third level - *a referential level.* The referential level is a partially ordered collection of defaults; it contains a more permanent part of a knowledge base. Current situations are described on the object level. The metalevel is a place for rules that can eliminate some of the models permitted by the object level and the referential level.

1. Introduction: postulates for a theory of default reasoning

We begin by introducing and justifying a list of five postulates we believe a theory of default reasoning should satisfy.

THE POSTULATES :

(D1) A theory of default reasoning should take into account the fact that predicates have different interpretations in different situations. The number of such interpretations is potentially infinite, but not all of them are equally plausible.

(D2) The structure of defaults should be compatible with a hierarchical organization of a knowledge base. In particular, it should admit inheritance of properties and exception handling.

(D3) The structure of defaults should allow existence of coarse and subtle versions of the same problem; the passage from coarse to subtle versions should be possible by effectively computable rules.

(D4) The theory should distinguish between local and global consistency of a knowledge base. This means it should postulate a structure of defaults such that an inconsistency does not imply any formula.

(D5) Interpretations of data should be effectively computable.

These postulates are natural. We argue briefly for D1-D4, and then discuss effective computability (D5).

We take an interpretation (or a meaning) of a fact to be a set of its logical consequences in a certain context. Since we want to investigate *logical* properties of default reasoning, we naturally assume a context to be given as a collection of formulae (i.e. a theory). Then D1 should be assumed since defaults, which are supposed to express what is normal in a given situation, are not all equally plausible. (Cf. also the arguments of D.Marr, 1977; and Reiter,1980 p.130).

D2: A hierarchical organization and inheritance of properties make knowledge representation systems more efficient. It is also recognized that any general rule must have exceptions. Since standard logic does not provide means of expressing exceptions efficiently, nonmonotonic mechanisms have been proposed to deal with this problem.

D.Marr (1977, and 1982 pp.335 - 361) argued for D3. We believe that the coarse and subtle versions of the same problem should depend not only on syntactic or efficiency considerations like number of resolution steps or depth of search, but also on semantic properties, like plausibility or importance. That is, a coarse version should have less facts than a subtle one, but it should have important facts.

Effective computability

A minimal *formal* assumption assuring effective computability of default conclusions is

A Principle of Finitism : *All considered theories have finite models.*

This is *not* a radical postulate, because

(a) it is possible to base a semantics of a large fragment of natural language on finite Herbrand models, (cf. Kamp, 1981).

(b) Ehrenfeucht *et al.* (1972) prove that if a first order sentence is classically consistent, then it has a *-model whose domain is finite. Also, the theory FIN of Mycielski (1981) is strong enough to develop mathematical analysis, yet each finite part of it has finite models.
(c) P.N. Johnson-Laird's (1980,1983) mental models are finite structures.

Finiteness of the universes makes the default provability decidable. Intractability of classical implication means that finding an interpretation of a fact cannot depend on the all facts and all defaults. Hence further restrictions on default theories are needed if we want to have a practicable theory of reasoning. We believe that two ideas may prove useful: the "vivid representations" of Levesque (1986), and the restrictions on expressive power of the language in which defaults and object theories are formulated, (cf. Levesque, 1984; Levesque and Brachman ,1985 ; Frisch ,1985 ; Patel-Schneider,1985).

Current theories of default reasoning

The nonmonotonicity of default reasoning is usually captured by extending the set of inference rules of classical logic. This is true for the standard formalizations of default reasoning : the nonmonotonic logic of J.Doyle and D.McDermott(1980), (cf. also McDermott, 1982) , the logic of default reasoning of R.Reiter (1980), and the circumscription of J.McCarthy (1980,1986). To different degrees postulates D1, and D2 are satisfied in all these systems. Circumscription, for instance, makes it possible to represent exceptions by declaring them abnormal; minimizing abnormality has the effect of saying "the general rule is correct, except for these special cases". Touretzky (1984) argues that the default logic of Reiter cannot handle exceptions in a proper way. Etherington (1987) argues in the other direction.

Effective computability (D5) could be adressed in these systems by restricting the classes of formulae dealt with, e.g. to universal, function-free sentences. It would be difficult however to express in any of these systems the fact that one default is more plausible than another one (D1) . Similarly, we do not see any natural extensions of these systems which would allow distinction between local and global inconsistency (postulate D4). Neither do we see how semantic distinctions between coarse and subtle versions (D3) could be incorporated into them.

In effect, we conclude that there is no clear way of extending the discussed default logics to satisfy D1 - D5 .

2. *Partial orderings as models of default theories*

We plan now to derive a model theoretical structure of defaults from the postulates D1 - D5 . We do this explicitly in a series of observations and conclusions. The conclusions make D1 - D5 more precise. We don't maintain however that they are the only ones possible to draw.

The arguments for D4 (cf. Levesque, 1984) imply that a large knowledge base cannot be considered as a collection of facts and rules. An intuitively appealing alternative is then to treat large bodies of knowledge as collections of *theories* . Each theory should be consistent, but they may contradict each other.

Conclusion 1. Knowledge bases are collections of theories.

In other words, instead of $KB \subset Sent$ we have $KB \subset \mathcal{P}(Sent)$; KB means 'a knowledge base' , $Sent$ stands for all sentences in a given formal language, $\mathcal{P}$ is the standard powerset operator . After this change a knowledge base KB may be only locally consistent, i.e. all its elements (the subtheories) are consistent, and it doesn't have to be consistent as a whole. But the difficulty is now in deciding when a theory should apply to a situation. Moreover we need a definition of derivability, i.e. of the meaning of $\mathrm{KB} \vdash \psi$. But we know already that such a provability relation must be nonmonotonic.

Let's make an analysis of defaults then. Whatever they are, (by D1) they are not equally plausible. But, if a default d1 is more plausible than d2 then d2 is not as plausible as d1. Also, plausibility is transitive. Thus

Conclusion 2. A plausibility relation on defaults is a partial ordering.

We argued that knowledge bases should be considered sets of theories. But a description of a situation is a theory. This difference in set theoretical types is one of logical reasons to separate the *level of object theory* from the *level of reference,* which is a collection of theories that constitute a more permanent part of an agent's body of knowledge. Then the only place for defaults can be on the referential level. Notice that defaults should not be a part of a metalevel, since the metalevel formalizes knowledge about knowledge - autoepistemic knowledge, for instance. Defaults work not because they are *about* what is known, but because predicates expressing knowledge about a current situation actually *refer* to them as to a background information and use them to eliminate *logically* possible but implausible interpretations (cf. Doyle, 1985).

Conclusion 3. There exists a separate logical level - the referential level - which contains a relatively permanent part of knowledge in the form of a partially ordered collection of theories. Defaults constitute this level.

We are now in a position to give a technical definition of defaults. The function of a default is to provide additional, but often only conjectural information. We express this function by assuming that, for a formula ψ , a default is a theory T_ψ , which can be added to a logical description of a current situation whenever ψ appears. This is expressed as $\psi \rightarrow T_\psi$. From this and Conclusions 1 - 3 we get:

DEFINITION. A *referential level* (or - a *referential model*) **R** is a structure

$$\mathbf{R} = \{ (\psi, <_\psi) : \psi \in \textit{Formulae} \}$$

where, for each ψ, $<_\psi$ is a partially ordered (by a relation of plausibility) collection of defaults (i.e. of $\psi \rightarrow T_\psi$'s) for ψ. We assume also that all sentences have the least preferred *empty interpretation* $\emptyset$.

We also suppose that interpretations are additionally ranked according to the canonical partial ordering on subformulas. This provides a natural method of dealing with exceptions, like in the case of finding an interpretation of $\alpha \,\&\, \rho \,\&\, \beta$ with R containing $(\alpha \rightarrow \gamma)$, $(\alpha \,\&\, \beta \rightarrow \neg\gamma)$, where $\neg\gamma$ would be preferred to γ - if both are consistent, and both defaults are equally preferred.

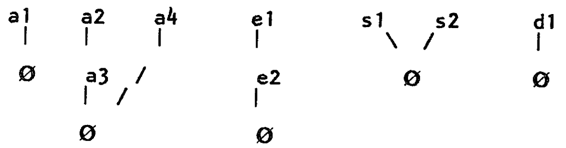
EXAMPLE

The following set of theories may be a part of a referential level **R** . It is easily seen that **R** is only *locally* consistent. We will use this example later to explain the notions of a default proof and a default model.

$$\psi \rightarrow T_\psi$$

$adult(x) \rightarrow employed(x) \,\&\, married(x)$	(a1)
$adult(x) \,\&\, \neg employed(x) \rightarrow dropout(x)$	(a2)
$adult(x) \,\&\, \neg employed(x) \rightarrow student(x)$	(a3)
$adult(x) \,\&\, \neg employed(x) \rightarrow \neg has(x,car)$	(a4)
$employed(x) \rightarrow adult(x) \,\&\, has(x,car)$	(e1)
$employed(x) \rightarrow taxpayer(x)$	(e2)
$dropout(x) \rightarrow \neg student(x)$	(d1)
$student(x) \rightarrow \neg employed(x) \,\&\, \&\, adult(x) \,\&\, \neg married(x) \,\&\, \neg dropout(x)$	(s1)
$student(x) \rightarrow employed(x) \,\&\, \&\, married(x) \,\&\, \neg dropout(x)$	(s2)

The partial ordering is given by the figure below ; one should also remember that we have supposed that special cases are preferred to general rules.



3. Models and proofs

In this section we continue the development of a theory of default reasoning that satisfies postulates D1 - D5. We define the notion of a model (extension), and proof procedures for deciding whether a formula is a consequence of a system of defaults.

We have already discussed the structure and ontology of defaults. In effect we have decided to augment the usual, two-part logical structures consisting of a *metalevel* and an *object level*, with a third level - a *referential level*. The referential level is a collection of defaults. Thus instead of formal structures of the form (**M** , **T** , $\vdash_M$) , where **M** is a metarule (e.g. **M** = "formula circumscription"), **T** is an object theory to which **M** is applicable, (some "simple abnormality theory" - for instance) , and $\vdash_M$ is a provability relation that possibly extends classical provability by using the rule **M**, we propose to analyze the quadruples (**M** , **T** , **R** , $\vdash_{R+M}$) , where **R** is a referential level, and $\vdash_{R+M}$ uses **R**, and possibly **M**.

We follow the exposition of Reiter (1980) since there are some similar features in both systems, and from now on, we will abbreviate his logic as RDL .

To define a semantics of default models we need some logical notions :

DEFINITION.

- A *theory* is a finite conjunction (or - equivalently - a finite set) of formulae.
- A *deductive closure* operator is a function $Th : \mathcal{P}(Sent) \longrightarrow \mathcal{P}(Sent)$
  (a) $T \subset Th(T)$, for any T
  (b) $Th(Th(T)) = Th(T)$
  (c) $Th(T)$ is finite, for finite T.
- A theory T is *consistent* if there is no formula ϕ such that both ϕ and $\neg\phi$ belong to $Th(T)$.

We do not require $Th(T)$ to be closed under *modus ponens* and substitution instances of tautologies. This allows us to consider deductive closures with respect to nonstandard logics, (cf. Levesque,1984; Frisch,1985; Patel-Schneider,1985). Moreover, since we are interested only in theories which have finite models, the deductive closure of a first order theory can be identified with ground disjunctions which are provable in this theory; and up to subsumption there are only finitely many of these.

DEFINITION. Let T be an object theory, R a set of partially ordered defaults. A consistent theory M is an *extension* of T if

1. $T \subset M$
2. If $\psi \in M$, $r \in R$, $r = (\psi, <_\psi)$, and $\psi \rightarrow T_\psi$ is a most preferred, consistent with M element of $<_\psi$, then $\psi \rightarrow T_\psi \in M$.

   (In other words, if a most preferred piece of information about a formula ψ is consistent with M , then it must have been already assumed.)
3. M is deductively closed.

(This assumption isn't really necessary, but it allows us to eliminate complicated, and interesting, situations in which some default information cannot be used because of a method of representing facts in T or R.)

4. No subtheory of M satisfies 1 - 3 .

It is easily seen that the definition is similar to this one of Reiter, except that in our case defaults have to be chosen according to the partial orderings. Also, a default is not applied if it leads to an inconsistency. This allows us to obtain as a direct consequence of the definition :

PROPOSITION 3.1. (**Soundness**) *Any consistent object theory has an extension.*

Proof procedure and basic logical results

We present now a construction of partial models $PM_i(T)$ of an object theory T which, as we prove, converge to a default model (a set of extensions) DM(T) . The method of constructing the models PM_i and DM is similar to this of RDL, except that the partial orderings on associated theories are taken into account. This new structure changes the mechanism of default reasoning.

DEFINITION. A *partial model* of a formula consisting of a sequence of subformulas (possibly one element) is a conjunction of their most preferable interpretations. It must be however consistent.

More formally, let ϕ be a formula and ψ_i, $1 \leq i \leq m$, its subformulas. For each i, let $<_i$ be a partially ordered collection of theories of ψ_i : $<_i = (\{ \psi_i \to T^i_0, \psi_i \to T^i_1, ..., \psi_i \to T^i_{n_i} \}, <_i)$. Let

$$\Pi(\phi) = \prod_{i \leq m} <_i$$
$$= \{ f : f(i) = \psi_i \to T^i_l \text{ , where } i \leq m \text{ and } l \leq n_i \} ,$$

$$\tilde{\Pi}(\phi) = \{ f \in \Pi(\phi) : \bigwedge_{i \leq m} f(i) \text{ is consistent with } \phi \} .$$

Let $<$ be the partial order induced on $\tilde{\Pi}(\phi)$ by the orderings of associated defaults and the canonical ordering of subformulas. We define then the *partial models* $PM(\phi)$ of a formula ϕ as the most likely theories of ϕ given by $(\tilde{\Pi}(\phi), <)$:

$$PM(\phi) = \{ \phi \,\&\, \Phi : \Phi = \bigwedge_{i \leq m} f(i) \text{ and } f \text{ is a minimal element of } (\tilde{\Pi}(\phi), <) \}.$$

The partial models pick up from the referential level the most obvious, or - perhaps - most important, information about ϕ . This immediate information may be insufficient to decide the truth of the formulae of ϕ . For instance, if $\phi = bird(Tweety)$, and

$$PM(\phi) = \{bird(x) \to has(x,wings) \} \cup \{ \phi \} ,$$

but only $PM (PM (\phi))$ contains the formula $has(x,wings) \to flies(x)$, then iteration of the PM operation is needed to decide whether Tweety flies.

DEFINITION. Let $t, t_1, ..., t_k$ be theories. Then

$$PM_1(t) = PM(t)$$
$$PM(\{ t_1, ..., t_k \}) = PM(t_1) \cup ... \cup PM(t_k)$$
$$PM_{n+1}(t) = PM(\{ Th(m) : m \in PM_n(t) \})$$
$$PM_\infty(t) = \bigcup \{PM_n(t) : n < \infty \} .$$

$PM_\infty(t)$ is a set of many models that interpret t . It will be infinite even if all the $PM_n(t)$ are one element sets. Clearly, we are interested in those elements of $PM_\infty(t)$ which contain maximum of information.

DEFINITION. We define the *default models* of t

$DM(t) = \{m \in PM_\infty(t) : m \text{ is maximal under } \subset \}$.

It is easy to check that

PROPOSITION 3.2. *DM(t) is a collection of least fixpoints of PM.*

We are now in a position to define two notions of provability : a weak provability corresponding to provability in RDL, and strong provability, which is more like the classical one.

The notion of a *default proof* of a formula α from T and R is defined similarly to Reiter(1980). The difference is that the set of prerequisites of D is defined for most preferred sets of defaults D ,only. Also we require that all available information be used. Notice that, under the definition below, given $(\phi \to \alpha) <_\phi (\phi \to \beta)$, with α preferred as a default for ϕ, β doesn't have a default proof unless α is inconsistent with default consequences of the object theory.

DEFINITION. (weak provability)

$T \;{}^{*}\!\vdash_R\; \phi$ iff there exists a sequence $m_0, ..., m_{k-1}$ and a sequence $D_0, ..., D_k$ such that

1. $\phi \in Th(T \cup D_k)$
2. $D_0 \subset T$, $m_0 \in PM(T)$
3. $D_{i+1} \subset m_i$, $m_{i+1} \in PM(m_i)$

Results parallel to these of RDL can be proven. The proofs extend Reiter's techniques by taking into account our new definitions.

We use $\models$ to denote the classical satisfaction in Hintikka or Herbrand models. Then $m \models \phi$ iff $\phi \in m$, when m is deductively closed.

PROPOSITION 3.3 *(completeness of weak provability)*

$T \; {}^{*}\!\vdash_{R} \; \phi$ *iff* *there exists* $m \in DM(T)$ *such that* $m \models \phi$.

THEOREM 3.4. (cf. Theorem 2.1. of RDL).

Let E *be a set of sentences.* *Let* $E_0 = T$,

$E_{i+1} = Th(E_i) \cup \bigcup \{ \omega : (\alpha, \omega) \in \mathbf{R} ,\ \omega$ is the most preferred element of $<_\alpha$, $\alpha \in E_i$, and ω is consistent with E $\}$.

Then, E *is an extension of* T *iff* E *is the union of* E_i*'s* .

THEOREM 3.5.

E *is an extension of* T *iff* E *is one of default models* $DM(T)$ *of* T.

As a corollary to Theorem 3.5. we obtain :

THEOREM 3.6. *(default completeness)*

All facts in an extension are weakly provable.

The class of provable formulas, as defined above or in RDL, corresponds to a set of beliefs an agent may entertain about a situation T given defaults R . These beliefs may be inconsistent. But it is possible to define a stronger notion of provability, according to which no two inconsistent formulae are provable. Since all our models are finite and there are only finitely many of them for finite R's , we can express the strong provability as follows:

DEFINITION. (strong provability)

$T \vdash_{R} \phi$ iff there exists a k such that for *any* sequence $m_0 , \ldots , m_{k-1}$, where $m_0 \in \mathrm{PM}(T)$ and $m_{i+1} \in \mathrm{PM}(m_i)$, there exists a sequence $D_0 , \ldots , D_k$ such that $D_0 \subset T$, $D_{i+1} \subset m_i$, and $\phi \in Th(T \cup D_k)$.

PROPOSITION 3.7 *(completeness of strong provability)*

$T \vdash_{R} \phi$ *iff* ϕ *is true in all models* $m \in DM(T)$.

Changed preferences , nonmonotonicity and metarules

We need also a definition of provability with metarules.

DEFINITION. We define

$T \vdash_{R+M} \phi$ iff $m \vdash_{M} \phi$, for all models $m \in DM(T)$.

I.e. ϕ is provable from R and T under the metarule M, if M applied to any default model yields ϕ .

We have defined the basic notions of our theory. We explain them now using the example from Section 2. We show how changed preferences modify default theories and are a source of nonmonotonicity in our formalization of default reasoning. We will also see that the strong and the weak provability differ. Finally, we say a few words about the metalevel.

EXAMPLE (continued)

Consider the following two object theories:

U. *adult(John) & ¬employed(John)* (u)

S. *student(John).* (s)

Their partial models are described below [1] :

$\mathrm{PM}(U) = \{ U_1 , U_2 \}$, where $U_1 = \{u, a2, e1\}$, and $U_2 = \{u, a4, e1\}$.

$\mathrm{PM}(U_1) = \{U_1^1, U_1^2\}$, where $U_1^1 = U_1 \cup \{d1\}$, and $U_1^2 = U_1 \cup \{d1, a4\}$.

$\mathrm{PM}(U_2) = \{U_2, U_2^1\}$, where $U_2^1 = U_2 \cup \{a2\}$.

$\mathrm{PM}(U_2^1) = \{U_3\}$, where $U_3 = U_2^1 \cup \{d1\} = U_1^2$.

$\mathrm{PM}_4(U) = \{ U_1^1 \cup \{s1\}, U_1^2 \cup \{s1\}, U_1^1 \cup \{s2\}, U_1^2 \cup \{s2\}, U_2 \}$.

Also $\mathrm{PM}_4(U) = \mathrm{PM}_k(U)$, *for* $k \geq 4$.

$DM(U) = \{ \{u, a2, e1, d1, a4, s1\} , \{u, a2, e1, d1, a4, s2\}\}$.

$DM(S) = \{\{s1, d1, a3, a4, e1, s\} , \{s2, d1, a1, e1, s\}\}$.

The following facts hold (assuming the standard Th) :

$S \vdash_{R}$ *has(John, car) & employed(John)* $\vee$ $\vee$ *¬has(John, car) & ¬employed(John)*.

$S \; {}^{*}\!\vdash_{R}$ *has(John, car)* and

$S \; {}^{*}\!\vdash_{R}$ *¬has(John, car)* .

It is possible to think of S as information complementing U. In this case:

$DM(U + S) = \{\{s, s1, a3, e1, a4, u, d1\}\}$

$U + S \vdash_{R}$ *¬has(John, car) & ¬dropout(John)*

and $U \vdash_{R}$ *dropout(John)* , while

$U + S \vdash_{R}$ *¬dropout(John)* .

We observe then the **nonmonotonic change of the theory :** a theory (U + S) does not prove all theorems of its subtheory (U) , although the same set of preferences serves as a referential model. As expected, metarules like the generalized CWA (Minker, 1982) allow us to prove stronger results than a combination of an object theory with a referential level alone : it is *not* true that $S \vdash_{R}$ *¬has(John,car)* , but we have $(CWA, S, R) \vdash_{R+M}$ *¬has(John,car)* .

[1] Assuming that the theories (a1) ... (s2) constitute the whole referential level.

4. Conclusions and summary

We have shown that it is possible to develop a natural theory of default reasoning based on the separation of the referential level from the object level and the metalevel; in this theory defaults are logical theories partially ordered by a relation of plausibility. We've demonstrated how priorities in interpretation of predicates on the level of reference can be the source of nonmonotonicity in reasoning. We've also proven that our theory shares a number of desirable properties with the theory of normal defaults. But additionally it satisfies the five postulates D1-D5. Namely, in our approach, consistency of a knowledge base is checked quite often but only with respect to a small part of it; a knowledge base may contain incompatible information (global inconsistency), but contradictions shall not appear in the same default model (local consistency). Exception handling is particularly easy - an exception is just another theory; adding an exception means adding a new theory to the referential level. The differences between coarse (PM) and subtle (DM) versions of a problem are semantically justifiable: one can expect that - due to the ordering of defaults - important information will appear in the very first iterations of PM. Moreover, existence of different theories of the same situation supports the principle of finitism.

The existence of a referential level is a very natural postulate. Collections of relational databases can be "vivid" referential levels for knowledge based systems; natural language in the form of (on-line) dictionaries, grammars, etc. can be taken as the referential level for commonsense reasoning (Zadrożny,1987). The "ubiquity of preference rule systems" (Jackendoff , 1983; Rock, 1983) also gives psychological plausibility to the proposed model.

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