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Reasoning with Levels of Modalities in BDI Logic

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Abstract. Modelling real world problems using rational agents has been heavily investigated over the past two decades. BDI (Beliefs, Desires, and Intentions) Logic has been widely used to represent and reason about rational agency. However, in the real world, we often have to deal with different levels of confidence in the beliefs we hold, desires we have, and intentions that we commit to. This paper proposes the basis of a framework that extends BDI Logic to take into account qualitative levels of the mentalistic notions of beliefs, desires, and intentions. We also describe a set of axioms and properties of the extended logic.

Keywords: BDI Agents, Modal Logic, Nonmonotonic Logic, Belief Revision.

1. Introduction

Agent Technology is now well recognised, in the field of information and communication technologies, for modelling complex real world problems [6]. BDI Logic is one of the most widely studied formal languages that provides theoretical foundations for rational agents. This logic originated from the early work of Bratman [3], and was chiefly developed by Rao and Georgeff [10]. BDI Logic is used for several current agent languages and architectures, such as AgentSpeak [9], JASON [2], and JACK [4]. The main goal of agent frameworks is to model human-like reasoning by capturing the mentalistic notions of belief, desire, and intention. In the real world, these notions can not be simply evaluated in terms of true or false. We argue that, like humans, the agent must have an ability to reason with different levels of mentalistic notions. These levels of agents' attitudes reflect the degree of its confidence about its beliefs, desires, and intentions and thereby allow more versatility in modelling situations. As a simple example, let us introduce the personal assistant software of an academic (Helen). Part of the duties of this assistant software involves arranging Helen's academic schedule. The system receives email notifications of seminars, meetings, etc, and using its database of Helen's beliefs, desires, and intentions, it allocates a schedule for Helen. There may be several seminars, meetings, or combinations of these occurring at the same time that Helen desires to attend. Unfortunately, with standard BDI, the system is unable to decide which to

schedule, at least not without a machine learning process to “teach” the system further differentiation. We propose a framework to integrate grading or levels of the BDI mentalistic notions and therefore give that differentiation and more versatility.

There have been many attempts to grade such mentalistic notions as belief, usually into different types of belief as in [14]. Some introduce actual levels of belief as in [13]. The most interesting work is that of Casali *et al* in [5] which extends the earlier work of Parsons & Giorgini [8]. Like the framework in this paper, Casali introduces levels in all the mentalistic notions of BDI, as well as, using numeric, possibilistic type functions in its semantics. However, the similarity ends there. Casali’s framework uses multi-contexts with a different semantics for each of the mentalistic notions, though a common underlying multi-valued Lukasiewicz logic is used. This tends to make it overly complex, unwieldy and somewhat counter-intuitive. While there are nominally three modalities, they are more akin to possibility functions. Desires tend to be combined arbitrarily with no defined method for calculating the result.

The framework of our paper uses a common syntax and underlying logic for each of the mentalistic notions. The framework is extended loosely from the multi-modal BDI logic of [10] with each grading or level being a separate modality. It also introduces *doxastic ignorance*, an effective absence of real belief, and an example methodology defining dependencies of desires and their calculation. While the framework can have n levels of each of the mentalistic notions, we suggest five basic levels of each notion for ease of presentation and understanding, with two of the levels being able to be expanded into more levels if required. In section 2 we present the basic syntax of the framework, the modal levels and axioms and properties as they pertain to belief, and the framework extended to desires and intentions. The paper is concluded in section 3.

2. Basic Framework Syntax

The alphabet of this framework is the union of the following pairwise disjoint sets of symbols: a non-empty countable set \mathcal{P} of atomic propositions; a non-empty countable set \mathcal{A} , of atomic actions; the set $\{\wedge, \vee, \rightarrow, \neg\}$ of connectives; the set of brackets $\{(\, [, \,), \,]\}$; and a set of modalities $\{\text{BA}, \text{BU}, \text{BI}, \text{BW}, \text{BD}, \text{DA}, \text{DU}, \text{DI}, \text{DW}, \text{DD}, \text{IA}, \text{IU}, \text{II}, \text{IW}, \text{ID}\}$, described in Sections 2.1 and 2.2. The syntax of the language is as follows:

$$\varphi ::= p \mid (\neg\varphi) \mid (\varphi_1 \wedge \varphi_2) \mid (\varphi_1 \vee \varphi_2) \mid (\varphi_1 \rightarrow \varphi_2) ;$$

where $\varphi \in \mathcal{L}$ (\mathcal{L} is the set of all formulae of the alphabet), and $p \in \mathcal{P}$.

2.1 Levels of Belief

As stated in the introduction, in realistic situations agents may have shades of belief. We note that in the nonmonotonic logic, Defeasible Logic [1, 7], situations may be believed to be *usually* true, (e.g. any random given bird is usually able to fly), or *usually not* true (weakly believed).

Definition 1: The five belief levels are defined as follows:

$BA\phi$ means that ϕ is Believed Absolutely and is the strongest level of belief (e.g. ϕ is “the sun will rise tomorrow”).

$BU\phi$ means that ϕ is Believed Usually true (e.g. ϕ is “the bus will be on time”) and this level can be divided ($BU_{.8}\phi$ and $BU_{.7}\psi$ means ϕ is more strongly believed than ψ). For example, an agent’s belief that a random bird can fly may be greater than the belief that the bus will be on time at the bus stop, but both beliefs are “usual” beliefs.

$BI\phi$ means that ϕ is not believed or disbelieved (e.g. ϕ is “the weather will be fine on Xmas day next year”). It is labelled as *Doxastic Ignorance* and is actually an absence of definite belief. *Doxastic Ignorance* is a term we introduce to denote something that is essentially neither believed, nor disbelieved and is similar to the logic presented in [12], but differs in that *Doxastic Ignorance* pertains to belief.

$BW\phi$ means that ϕ is usually not believed, only Believed Weakly, i.e. might be true (e.g. ϕ is “used car salesmen tell the truth”). This is the mirror opposite of BU and can similarly be divided into more levels if necessary.

$BD\phi$ means that ϕ is absolutely Disbelieved, i.e. believed false with the strongest level of belief, and is mirror of BA (e.g. ϕ is “a comet will hit my house tonight”).

Doxastic possibility (P) is the \diamond (diamond) to belief’s \square (box) ($P\phi \equiv \neg B\neg\phi$).

There is a natural affinity between the BA level and the BD level ($BA \neg\phi$ is the same as $BD \phi$) as well as between BU and the BW . This suggests the ability to cut the five levels down to three basic levels. However, with three levels the direction of belief strength priority between levels could alter depending upon the inclusion of a negated formula. Therefore, five levels are retained here to simplify the reasoning.

Belief Axioms and Properties

In this section we present the major belief axioms, and properties that follow from those axioms. Axiom numbering is prefixed by the letter “A” and properties by the letter “P”. Let ϕ and ψ be any formulae in \mathcal{L} .

$$\text{For each } \phi \text{ in } \mathcal{L}, BA\phi \vee BU\phi \vee BI\phi \vee BW\phi \vee BD\phi. \quad (A1)$$

$$\text{If } \Phi, \Psi \in \{A, U, I, W, D\} \text{ and } \Phi \neq \Psi, \text{ then } B\Phi\phi \rightarrow \neg B\Psi\phi. \quad (A2)$$

$$\text{If } \Phi \in \{A, U, I, W, D\} \text{ and } \phi \equiv \psi, \text{ then } B\Phi\phi \equiv B\Phi\psi. \quad (A3)$$

$$BA\phi \equiv BD\neg\phi. \quad (A4)$$

$$BD\phi \equiv BA\neg\phi. \quad (P1)$$

$$BU\phi \equiv BW\neg\phi. \quad (A5)$$

$$BW\phi \equiv BU\neg\phi. \quad (P2)$$

$$BI\phi \equiv BI\neg\phi. \quad (A6)$$

$$B\Phi\phi \rightarrow \neg BI\phi \wedge \neg BI\neg\phi \text{ (where } \Phi \in \{A, U, W, D\}). \quad (P3)$$

$$BI\phi \equiv \neg BA\phi \wedge \neg BA\neg\phi \wedge \neg BU\phi \wedge \neg BU\neg\phi. \quad (P4)$$

$$BI\phi \equiv \neg BA\phi \wedge \neg BD\phi \wedge \neg BU\phi \wedge \neg BW\phi . \quad (P5)$$

Definition 2: $P\Phi\phi \equiv \neg B\Phi\neg\phi$ and so $B\Phi\phi \equiv \neg P\Phi\neg\phi$ [where $\Phi \in \{A, U, I, W, D\}$].

$$BI\phi \equiv \neg PI\phi . \quad (P6)$$

(P6) follows (A6) and $BI\neg\phi \equiv \neg PI\neg\neg\phi \equiv \neg PI\phi$. Bearing in mind the relationship between the belief levels, let us look at the five doxastic possibility levels.

$$PA\phi \equiv \neg BA\neg\phi \equiv \neg BD\phi \equiv (BA\phi \vee BU\phi \vee BI\phi \vee BW\phi) . \quad (P7)$$

$$PU\phi \equiv \neg BU\neg\phi \equiv \neg BW\phi \equiv (BA\phi \vee BU\phi \vee BI\phi \vee BD\phi) . \quad (P8)$$

$$PI\phi \equiv \neg BI\neg\phi \equiv \neg BI\phi \equiv (BA\phi \vee BU\phi \vee BW\phi \vee BD\phi) . \quad (P9)$$

$$PW\phi \equiv \neg BW\neg\phi \equiv \neg BU\phi \equiv (BA\phi \vee BI\phi \vee BW\phi \vee BD\phi) . \quad (P10)$$

$$PD\phi \equiv \neg BD\neg\phi \equiv \neg BA\phi \equiv (BU\phi \vee BI\phi \vee BW\phi \vee BD\phi) . \quad (P11)$$

KD45 Axioms

In multi-modal BDI logic, and doxastic logic, their axioms include the axiom system **KD45**. We now look at how closely **KD45** hold for our levels of belief.

It has been shown elsewhere, [11], that the strict **K** axiom does not hold over modality gradings. An example of the **K** axiom applied to the **BD** level of belief ($BD(\phi \rightarrow \psi) \rightarrow (BD\phi \rightarrow BD\psi)$) is that if we strongly disbelieve the rule *if the sun is shining then it is raining*, then it follows that if we disbelieve *the sun is shining*, this implies that we disbelieve that *it is raining*. This is plainly nonsense and the other levels (except for **BA**) have this problem to varying degrees. However, an altered **K** axiom of the form of (A7) makes much more sense.

$$B\Phi(\phi \rightarrow \psi) \rightarrow (BA\phi \rightarrow B\Phi\psi), \text{ (where } \Phi \in \{A, U, I, W, D\}\text{)}. \quad (A7)$$

By convention, (A7) can also be rewritten as $BA\phi \wedge B\Phi(\phi \rightarrow \psi) \rightarrow B\Phi\psi$. This is similar to Modus Ponens. So if we believe $\phi \rightarrow \psi$ at the Φ level and we strongly believe ϕ , then (A7) allows us to derive ψ at the Φ level.

$$B\Phi\phi \rightarrow P\Phi\phi \text{ (where } \Phi \in \{A, U, W, D\}\text{)}. \quad (A8)$$

The axiom **D** (serial), can be applied to all levels except **BI** (A8). For example, using (P8), $BU\phi \rightarrow PU\phi$ is equivalent to $BU\phi \rightarrow (BA\phi \vee BU\phi \vee BI\phi \vee BD\phi)$. $BU\phi$ is included on both sides of the implication arrow and this is then a tautology. A problem with the **BI** level with **D** is that using (P9), $PI\phi \equiv \neg BI\phi$, so $BI\phi \rightarrow PI\phi$ is converted to $BI\phi \rightarrow \neg BI\phi$. This is obviously not what we want. However, it must be remembered that doxastic ignorance is not actual belief, but an effective absence of belief. Therefore **D** holds for all the levels of actual belief.

Normally, the axioms **4** (transitivity) and **5** (Euclidean) are used for introspection. To demonstrate the problem with transitivity for these belief levels, observe that $BD\phi \rightarrow BD\neg BD\phi$ means if ϕ is disbelieved, then that disbelief is disbelieved. By converting through (P1), we get $BA\neg\phi \rightarrow BA\neg\neg BA\neg\phi$, or, $BA\psi \rightarrow BA\neg\neg BA\psi$. This is definitely not the axiom of transitivity, nor positive introspection. The Euclidean axiom **5** has similar problems. Using (P11), we can convert $PD\phi \rightarrow BD\neg PD\phi$ to

$(BU\phi \vee BI\phi \vee BW\phi \vee BD\phi) \rightarrow BD (BU\phi \vee BI\phi \vee BW\phi \vee BD\phi)$. So, if the disjunction of formulae on the left of the statement is true, then this implies that we disbelieve that same disjunction of formulae. This is not what we want and is not true negative introspection. However, we present altered versions of 4 (resp. 5) that allow introspection (similar to ‘arbitrary’ introspection defined in [13]). By locking the first (resp. only) belief level on the right side of the axioms to absolute belief, we get true positive (resp. negative) introspection, which is what we are really seeking here.

$$B\Phi\phi \rightarrow BA B\Phi\phi \quad (\text{where } \Phi \in \{A, U, I, W, D\}). \quad (\text{A9})$$

$$P\Phi\phi \rightarrow BA P\Phi\phi \quad (\text{where } \Phi \in \{A, U, I, W, D\}). \quad (\text{A10})$$

2.2 Levels of Goals

Desires and Intentions can be described as weak goals and strong goals respectively (i.e. desire + commitment = intention) and an agent can conceivably have varying degrees of strength of these. The desire to live/survive is stronger than the desire to go to work, which in turn is stronger than the desire to be robbed. Having levels of desire gives an agent more versatility in representing a wider range of situations.

The framework of levels introduced for beliefs can be extended to desires and also intentions. Essentially, each goal level will have a similar meaning to similar levels of belief. While beliefs are usually held about current states in a world, goals are always held about future states. The difference between goal types is that a given desire, among several desires, becomes an intention if it is committed to by the agent. A rational agent may have conflicting desires, but not conflicting intentions.

Due to space limitations, we have omitted the definition of desire and intention levels, but they essentially mirror the levels presented for belief. Briefly, $DA\phi$ denotes ϕ is absolutely desired, $DU\phi$ means ϕ is desired, less than DA , $DI\phi$ applies if neither ϕ nor $\neg\phi$ is desired (*goal indifference*), $DW\phi$ denotes ϕ is only weakly desired, and $DD\phi$ means ϕ is *not* desired, or $DA\neg\phi$. As with BU and BW , DU and DW may be subdivided if required.

So, after deliberation, an agent commits to a particular desire, thereby creating an intention of the same level as the relevant desire (e.g. $DU\phi + \textit{commitment} \rightarrow IU\phi$). The desire and intention axioms and properties are essentially the same as in belief. Naturally there are no goal equivalents to the introspection axioms (A9) and (A10).

3. Conclusion and Future Work

The framework undertaken in this paper provides a foundation for a layered BDI architecture. This essentially enables a rational agent to capture commonsense reasoning. We believe that representing and reasoning with levels of mentalistic attitudes significantly enhances an agent’s ability to perform human-like practical reasoning in complex domains. The proposed framework has the prospect of being simpler and more intuitive than other BDI frameworks, including that of Casali. Intended future work includes extending the syntax to include plans, strictly defining

a multi-modal BDI semantics partially based on [10], and introducing this basic framework into an existing BDI agent platform, most likely the AgentSpeak(L) platform, JASON. Naturally this will necessitate dropping any strictly modal aspects, but the logic, as stated, should be able to be easily adapted to JASON. We thank the Smart Internet Cooperative Research Centre (SITCRC) for their funding of this work.

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