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Memory Management with Explicit Time in Resource-Bounded Agents

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The primary objective of my research project is the formal treatment (in Computational Logic) of memory issues in Intelligent Software Agents. Memory is a basic component of every reasoning process, and vice versa interaction between the agent and the environment can play an important role in creating memory and can affect future behavior. Most methods to design agent memorization mechanisms have been inspired by models of human memory (cf. e.g., (Pearson and Logie 2003)) developed in cognitive science. Atkinson and Shiffrin in (Atkinson and Shiffrin 1968) proposed a model of human memory which consists of two distinct memory stores, the short term memory (or *working memory*), where explicit beliefs are stored, and the long term memory which stores the *background knowledge*.

In reference to memory management, the most important cognitive architecture which has a model of memory is SOAR, which was defined by Laird, Newell and Rosenbloom in (Laird, Newell, and Rosenbloom 1987). In recent work (Balbiani, Duque, and Lorini 2016), Balbiani, Fernández-Duque and Lorini proposed a (partial) formalization of SOAR architecture in modal logic, reasoning on a particular type of agents: *resource-bounded* agents. They proposed a new logic called DLEK (Dynamic Logic of Explicit Beliefs and Knowledge) which helps in clarifying how a non-omniscient resource-bounded agent can form new beliefs either through perception or through inference from existing knowledge and beliefs. In this logic there are mental operations either of perceptive type or of inferential type, having effects on the epistemic states of the resource-bounded agent. In fact, DLEK is a logic that consists of a static component and of a dynamic one.

However DLEK does not explicitly consider temporal aspects, as rules and beliefs are seen as time-independent. The starting point of my research project is the extension of (Balbiani, Duque, and Lorini 2016) introducing timed beliefs and timed background rules by means of Metric Temporal Logic. Specifically:

- the formalization of short-term memory by associating to each perception the temporal instant of arrival;
- the introduction in the general rules of long-term memory of the time intervals within which the rules are valid and/or certain inferences can legally be enforced;
- the formalization of the possibility that a memory update, specified by rules in the long-term memory, might remove/restructure previous beliefs. This is different from simple "forgetting", which consists in removing single beliefs either arbitrarily, or after a certain time; the objective it to make beliefs defeasible, which is useful to many purposes among which for representing the effects of actions.

Perceptions (future beliefs) are in fact in our view inherently timed, and so are the conclusions that can be drawn from them. For instance, if one buys today a ticket for a trip then (s)he knows that (s)he can go to that trip on the date and time indicated on the ticket; if one gets a bill to pay, then one usually has to pay within a certain date; if the present temperature is low then a heavy jacket is needed in order to go out now, etc. Also, similar perceptions can be repeated: e.g., to choose a jacket one should refer to the last measurement of temperature, ignoring previous ones.

I introduce TDLEK starting from DLEK and its non-dynamic version LEK. In this setting, a time interval $I \subseteq (0, \infty)$ is an interval of natural numbers with the upper extreme in $\mathbb{N}$, as $[t_1, t_2]$, (t_1, t_2), or mixed $(t_1, t_2]$, $[t_1, t_2)$ where however in the open cases the upper bound could be ∞ (in any case, we have $t_1 \leq t_2$). The extension to the LEK language ($\mathcal{L}_{LEK}$) presented in (Balbiani, Duque, and Lorini 2016) to the TLEK language ($\mathcal{L}_{TLEK}$) by adding timed formulas, indicated by Φ_I where I, I_1, I_2 are intervals, is defined as follows (t being a natural number):

$$\begin{aligned}\Phi_I \quad := \; & p \mid p_t \mid p_I \mid \neg\Phi_{I_1} \mid \Phi_{I_1} \vee \Phi_{I_2} \mid \\ & \Phi_{I_1} \wedge \Phi_{I_2} \mid \Box_I \Phi_{I_1} \mid B_i \Phi_I \mid K_i \Box_I \Phi_{I_1}\end{aligned}$$

where the other boolean constructions $\top$, $\bot$, $\rightarrow$, $\leftrightarrow$ are defined from $\neg$ and $\wedge$ in the standard way. Assuming a countable set of atomic propositions $Atm = \{p, q, \ldots\}$, p_t is atom p annotated with "time-stamp" t, where t is a time instant in the underlying linear model of time. By p_I with $I = [t_m, t_n]$, $0 \leq m \leq n$ we mean $p_{t_m} \wedge p_{t_{m+1}} \wedge \ldots \wedge p_{t_n}$. Plain atom p can be seen as equivalent to $p_{\hat{I}}$ with $\hat{I} = [0, \infty)$. A formula Φ_t is entirely composed of atoms of this form. Operator B_i is intended to denote belief and operator K_i to denote knowledge, both referred to agent i. $\Box_{I_1} \Phi_{I_2}$ applies the MTL Interval "always" operator to a timed formula, where it is required $I_2 \subseteq I_1$. Both I_1 and I_2 can be $[0, \infty)$.

There are many syntactic features/restrictions for timed formulas like Φ_{I_1} *OP* Ψ_{I_2}, where OP can be $\vee$, $\wedge$, $\rightarrow$, $\leftrightarrow$ and $\Phi_I = \phi_{I_2}$ *OP* ϕI_2 (there are restriction for I, $I_1 \ldots$ that for lack of space I cannot detail here). Expressions of the form $K_i \Box_{I_1} \varphi_{I_2}$, where in particular φ_{I_2} can be an implication, represent knowledge in the long-term memory wherever applicability of such knowledge is time-dependent. The role of the $\Box$ operator becomes apparent when the interval extremes are defined by means of expressions over time instants; such correlations indicate that a certain implication makes sense only within a certain interval.

Interaction between long-term and short-term memory and thus derivation of new beliefs is not automatic, rather is performed by an agent whenever deemed necessary. This by means of invocation of an explicit, we might say "conscious", mental operator. Preliminarily, I need an abuse of notation: given $I_1 = [t_1, t_2]$ and $I_2 = [t_3, t_4]$ I write $I_1 \leq I_2$ meaning that $t_1 \leq t_3$, i.e., I_1 is "before" I_2 with a possible non-empty intersection (there can be $t_2 = t_4 = \infty$).

The language of Temporalized DLEK ($\mathcal{L}_{TDLEK}$) is obtained by augmenting $\mathcal{L}_{TLEK}$ with the expression $[\alpha]\, \psi_{I_1}$ where ψ_{I_1} is a timed formula, which reads "ψ holds in I_1, after the mental operation (or mental action) α is publicly performed by all agents". The mental operations that we consider are:

- $+\varphi_{I_1}$: the mental operation that forms a new belief from a perception φ_{I_1};
- $\cap(\varphi_{I_1}, \psi_{I_2})$: an agent, believing both φ_{I_1} and ψ_{I_2}, starts believing their conjunction $\varphi_{I_1} \wedge \psi_{I_2}$.
- $\vdash (\varphi_{I_1}, \psi_{I_2})$ with $I_1 \leq I_2$: an agent, believing that φ is true in I_1, and having in its long-term memory that φ_{I_3} implies ψ_{I_4}, where $I_1 \subseteq I_3$, $I_2 \subseteq I_4$ and $I_3 \leq I_4$, starts believing that ψ is true in I_2; we assume ψ_{I_2} to be positive;
- $\vdash (\varphi_{I_1}, \neg\psi_{I_2})$ with $I_2 \leqslant I_1$: an agent i has ψ_{I_2} as one of its beliefs, and perceives φ in I_1 and has φ_{I_1} implies $\neg\psi_{I_2}$ in its background knowledge, agent i updates her beliefs.

I extend the semantic accordingly. In TDLEK, we have $V : W \rightarrow 2^{Atmt}$ where $Atmt$ is the set of atoms. For a world w, let t_1 the minimum time-stamp of atom $p_{t_1} \in V(w)$, and let t_2 be the maximum (we can have also $t_2 = \infty$). Then, we can designate w as w_I where $I = [t_1, t_2]$; we can designate by w_{I_1} with $I_1 \subseteq I$ the "subworld" of w corresponding to atoms with time-stamp t belonging to I_1 in the valuation. We can refer to $V_t(w)$ as the set of atoms in $V(w)$ with time-stamp t. Through previous consideration and some restrictions, which would require a more detailed explanation, I properly extend the definition of a *LEK Model*. Truth conditions for TDLEK formulas are defined inductively, where the difference from (Balbiani, Duque, and Lorini 2016) consists in: (i) the entailment of timed atoms (timed formulas follow in consequences), (ii) considering the $\Box_{I_1}$ operator on timed formulas, (iii) introducing extended definitions for mental operations. I extend the axiomatization, theorems, lemmas and complexity results which appear in (Balbiani, Duque, and Lorini 2016) as well. For future developments I include to study how to (at least partly) overcome the approach with limited resources which is taken as starting point.

Below I illustrate the new logic *TDLEK* by means of a small example.The following example is about enrollment at the university; let us take as range $[1, 366]$ representing the days of a solar year (366 because there could be a leap year). In the background knowledge we have the following rules, where the specific days of the year refer to the Italian regulations:

$K_s(\Box_{[181,304]}(\textit{high-school-exam}_{t_0} \longrightarrow (\textit{university-enrollment}_{[t_0+1,304]})))$: if student s passes the high school final exam at time t_0, from the next day (s)he may start thinking about enrolling at a university;

$K_s(\Box_{[182,334]}(\textit{university-enrollment}_{[182,304]} \wedge \textit{registration}_{[213,304]} \longrightarrow \textit{pay-fee}_{[214,334]})))$: if student s knows (s)he can enroll at a university and asks for registration, from the next state (s)he can pay the fees;

$K_s(\Box_{[214,365]}(\textit{paid-fee}_{[214,304]} \wedge \textit{pay-fee}_{[214,334]}) \longrightarrow \textit{registrated}_{[214,365]})$: if student s knows that (s)he can pay the fees and (s)he has paid them then (s)he can be considered as registered.

$K_s(\Box full\text{-}time\text{-}work_{[t_p,\infty)} \rightarrow \neg\, \textit{university-enrollment}_{[t_p,\infty)})$: if s finds a full time job, (s)he quits university.

If student s has passed the final exam, say, on July 3rd, (s)he starts believing $B_i(\textit{high-school-exam}_{184})$, that could be added to her/his working memory. Thanks to the first rules (s)he starts believing $B_i(\textit{university-enrollment}_{[185,304]})$. Now if s finds a full time job at time 280 (s)he starts believing $B_i(\textit{full-time-work}_{280})$ and thanks to the last rule and update operation, the belief $B_i(\textit{university-enrollment}_{[185,304]})$ can be replaced by $B_i(\textit{university-enrollment}_{[185,279]})$.

In summary, I aim to introduce explicit time and time intervals into a logic for representing agents' short-term and long-term memory and the interaction of the two in a resource-bounded setting. The proposed extension adds significant power in terms of practical expressiveness as it allows an agent to perform timed inferences and so to be able to interact with the environment in a timely way.

References

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