Dynamics and Automaticity of Context: A Cognitive Modeling Approach

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Abstract. AI and psychological approaches to context are contrasted and the dynamic and automatic nature of the continuous context change in human cognition is emphasized. A dynamic theory of context is presented which defines context as the dynamic state of human mind. It describes the interaction between memory, perception, and reasoning in forming context as well as how they are influenced by context. A general cognitive architecture, DUAL, is presented that implements the mechanisms of context formation and accounts for the context-sensitivity of human cognition. A model of human problem solving, AMBR, has been built upon the DUAL architecture and the simulation experiments performed with it produce data that are coherent with experimental data on human problem solving.

1. AI Approaches to Modeling Context: The Box Metaphor

Two world tour travelers who flew in a balloon landed in a small village and they wanted to know where they arrived. One of them asked the first person who came by:

“Could you, please, tell us where have we landed?”.
“On the earth.” the stranger replied and went further.
“This one must be a mathematician” commented the second traveler.
“How do you know that?” asked the first one.
“Well, he gave an absolutely correct and useless answer!”

AI systems need to give more useful answers than the mathematician[1] in the anecdote, therefore they have to provide not only correct but also relevant solutions to the problems in a specific context. Thus after leaving the toy worlds AI researchers faced

1 Having my first degree in mathematics this joke applies to me as well.

the need to deal with the problem of context.[2] There are numerous reasons why context is important for an intelligent system and among them are the following:

- *AI systems need to provide correct solutions.* The problem here is that a particular system is designed for use in a typical context and therefore many assumptions behind the facts and rules in the domain are not explicated. Thus if context changes these facts and rules become no more valid and the system produces an incorrect response [13, 31]. One possible solution is to explicate all assumptions and always check whether these assumptions hold in a particular situation before using the corresponding facts or rules, however, this is not possible since the number of such assumptions is infinite. Another solution proposed by McCarthy is to keep the assumptions implicit, but to relate each fact or rule to a specific context where these assumptions hold [32], i.e. instead of stating that a particular proposition p is universally true, to state that it is true in a specific context c.
- *AI systems need to provide relevant solutions.* This means that they should not generate solutions which could work in principle (or in another possible world), but such that work here and now. Contexts might be useful for solving this problem by relating each operator or rule to a specific context allowing it to be applied only in this context.
- *AI systems need successful natural language communication.* The problem is that the meaning of words and phrases changes from one context to another.
- *AI systems need to act and communicate at the right level of granularity or right level of description.* Imagine a commentary of a soccer game which goes like this: “The ball flies with a speed of 62.3 km/h in a direction which is 36.4 degrees to the north of the side line. The ball hits the solid plane of the boot of Asparuhov under an angle of 47 degrees and gets an acceleration of 15 m/s^2 ...”. This commentary is correct and to some extent relevant, but is made at an inadequate level of description. Contexts might be associated with a specific level of description of a domain.
- *AI systems need to act in an efficient way*. If the system has extensive knowledge it is inappropriate to search the entire knowledge base every time a fact or rule is needed – this would make it highly inefficient. Thus contexts have been used to play the role of smaller domains where the search is restricted.

AI researchers introduced the concept of context in order to make their systems more flexible and at the same time more efficient [25]. While context information was initially included in the domain rules making them more and more specific and complex [10], later on AI moved towards explicit representation of context. In most cases the “box metaphor” is used, i.e. context is considered as a box. “Each box has its own laws and draws a sort of boundary between what is *in* and what is *out*” [13]. The boxes are labeled and the reasoning system should always keep track of the box it is in. Boxes can be embedded in other boxes. Thus McCarthy [32] uses the labels of

[2] Even in the block world context-sensitive behavior can be demonstrated: by changing the goals of the intelligent system different reactions to the same external stimulation will be obtained. However, context is restricted to the goals of the system in this case.

the boxes as logical constants and designed a logical calculus that requires the box we are in to be always specified. There are special rules for entering and leaving a box. Giunchiglia and his colleagues [5, 12, 13] introduce another approach where the box is described by a separate logical theory (separate language, axioms, rules of inference) and again there are bridge rules which make it possible to travel from one box to another. Turner [42] uses a frame-like representation of the boxes and provides mechanisms for recognizing the context we should be using in a particular moment; for example, certain events trigger demons that change the box. Abu-Hakima and Brezillon [1] use a vector of variable-values which characterizes the box. Öztürk and Aamodt [34] represent a set of context features in each episode in a case-based reasoning model and describe how each particular type of task selects relevant episodes based on the prespecified relevant features.

In summary the AI approach to contextual reasoning may be characterized as navigation between and within the context-boxes (Figure 1). Crucial issues are how to represent the individual boxes, how to recognize that we have to change the box and how to choose a new box. In most cases the boxes are predefined, e.g. the logical theory or the frame representation describing the box should be defined in advance by the user or programmer. The issue of how to construct a new context on the fly is not addressed. The main issue being addressed is when and how the reasoner decides to change the context – either because the goal has been changed or because an external event has happened which should trigger a new context.

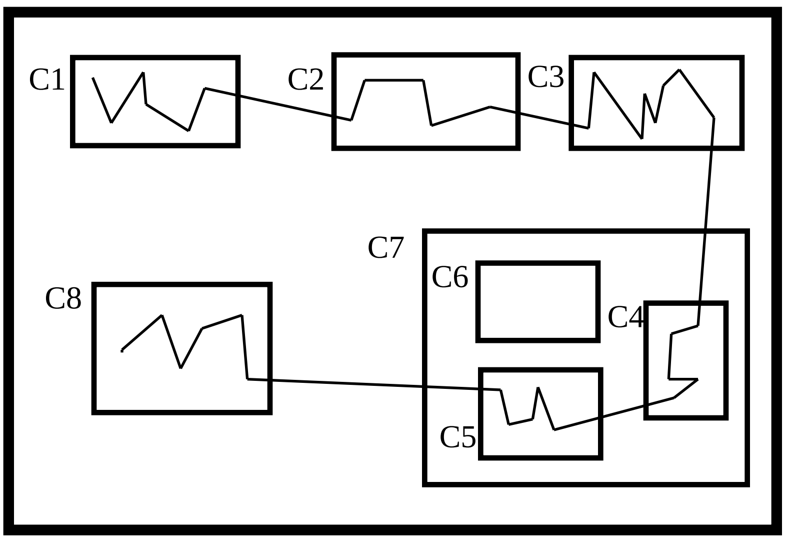

Fig. 1. Contextual reasoning as navigation between and within context-boxes (spaces). All boxes are labeled and can be referred to.

2. Psychological Approaches to Studying Context: Dynamics and Automaticity of Context Change

When psychologists study context effects they do not even think of changing the goals or beliefs of the subject, or the task or instruction to see whether a different perspective imposed on the subject would influence human reasoning. All this seems so obvious that nobody has studied it experimentally. Psychologist went further studying much more subtle influences – those that occur automatically but have no obvious explanation at the knowledge level – the level of human goals and beliefs.

Analyzing the automaticity of cognitive processes Bargh [3] has defined four different and more or less independent aspects that have to be studied: intentionality, controllability, awareness, and efficiency. *Intentionality* is related to the presence or lack of control on the start-up of the process by the individual. While problem solving is typically an intentional process since it starts when we decide to do so, categorization and evaluation are typically unintentional ones since these processes occur automatically when a stimulus is noticed and do not require a deliberate goal or intention. *Controllability* is related to the ability of the individual to stop a cognitive process once started or at least to override its influence if so desired. Examples of uncontrollable cognitive processes would be some strong visual illusions which occur even if one knows they are illusions. *Efficiency* refers to the extent to which the cognitive process requires attentional resources, i.e. its results would depend on the amount of attention paid to it. With respect to *awareness* a cognitive process may be automatic at several different levels. A person may not be aware of the presence of the stimulus event and still be influenced by it as in subliminal perception. A person may be aware of the stimulus but not be aware of the way it has been interpreted. Finally, a person may be aware of the interpretation of the stimulus but not aware of the way it influences his or her further behavior.

The results obtained in numerous experiments have shown that context effects can be produced without subjects' intention and awareness. For example, having cookies in the waiting room may influence subjects to produce a higher number of positively colored life experiences than in a controlled group [15]; a brief incidental touch by a waitress when returning change increases the size of the tip she receives [6]; even subliminal presentation (as short as 5 ms) of facial expressions can have an effect on a following target stimulus evaluation [33].

Psychologists have shown context effects on virtually all cognitive processes. Thus, for example, context effects on perception have been demonstrated by Gestalt psychologists in various forms: different interpretations of ambiguous figures; visual illusions depending on the background elements or on the presence of other stimuli. In language comprehension context effects can be exemplified by lexical, syntax, semantic, inference, thematic and other types of context effects [41]. In memory studies various effects of context have been demonstrated – context-dependence of recall and even recognition, memory illusions in false recognition, context-based interference, priming effects, etc. [7, 27]. In problem solving various forms of context effects have been shown: functional fixedness [9, 30], set effects [29], lack of transfer from previous problem solving experience [11], priming effects [17, 38], effects of incidental elements of the environment [26, 30]. In decision-making various context effects have been shown: framing effects – the effects of alternative descriptions, e.g. percentage dead or saved; effects of alternative methods of elicitation; and effects of added alternatives [39]. Barsalou [4] demonstrated context effects on concept characterization.

Two concrete examples of context effects on problem solving will be discussed. Kokinov [17] demonstrated that when the target problem was preceded by different priming problems subjects may solve it in different ways. Since the solution of the priming problem was known to the subjects in advance the only effect that its presentation had on the subjects was making certain concepts, facts, or rules more accessible. This turned out to be crucial for the problem solving process that followed. Moreover, the dynamics of the process has been studied and the results show that this priming effect decreases exponentially with the course of time and disappears within less than 20 minutes. Kokinov and his colleagues [24, 26] have demonstrated that a picture that is incidentally on the same page as the target problem can also influence the way the problem is being solved. Moreover, when prompted to use the picture subjects were less successful in solving the target problem than in the control condition, while when they seemingly ignored the picture they were still influenced by it and had a better performance than in the controlled condition.

The conclusion from this short review of the psychological studies of context effects is that context has often an unconscious and unintended influence on people's behavior and that this happens continuously and is triggered by all sorts of incidental elements of the environment but also by the previous memory states. On the other hand, this influence has its own internal dynamics and decreases and disappears in a short period of time. It seems very important that the previous memory state produces context effects since this maintains the continuity of the cognitive processes and prevents human thought from continuously running in leaps. It also ensures efficiency since it restricts the set of all possible interpretations, inferences, searches, etc. to the set of relevant ones. On the other hand, context effects produced by the perceptual processes are also important since they ensure that the cognitive system will be flexible and adaptive to changes in the environment.

The effects described in this section cannot be explained by postulating pre-existing and static contexts (boxes) and intentional decisions to switch between these contexts taken by the individuals. These effects require context to be considered as a continuously changing (evolving) state of the cognitive system which is not completely under its control. The fact that changes in context can take place automatically and without subject's intention and awareness is very important. If changes in context were taking place only under conscious human control, this would have raised a number of issues. For example, reasoning about contexts must also be context-sensitive and we would run into an endless meta-meta-meta-... explanation. This mechanism would also be very ineffective since the space of possible contexts is unlimited and the limited reasoning resources would have to be distributed among all these levels of reasoning about contexts.

3. Dynamic Theory of Context: A Cognitive Modeling Approach

Kokinov [21] introduced the following operational definition of context which is in accordance with the above psychological studies. *Context is the set of all entities that influence human (or system's) behavior on a particular occasion, i.e. the set of all elements that produce context effects.*

Although in most psychological experiments the manipulated elements are part of the physical or social environment within which the subject's behavior is tested [7, 8, 37], these elements cannot directly influence human behavior unless perceived and corresponding internal representations built. Thus in this paper *the term context refers to a set of internal or mental representations and operations* rather than a set of environmental elements. In other words *context refers to the current 'state of the mind' of the cognitive system* rather than the state of the universe. Similar views are shared by a number of researchers in AI, psychology, linguistics, and philosophy [13, 16, 28, 40]. Others consider context as the state of the universe or the environment.

Various mental representations or operations can have different degrees of influence on a cognitive process. This is determined by the degree to which they participate in or are used by the cognitive process: from not being used at all to being central for the processing. Thus, usually, the goal is much more important for the problem solving process than the representation of an incidental object in the problem solver's environment, but the latter can still play a role in processing as shown in the previous section. That is why if we define context as the set of important or relevant mental representations/operations (the ones that pay a role in processing) it cannot be considered as a set with clear-cut boundaries. It would be better to consider it as a fuzzy set with graded membership corresponding to the graded importance or relevance of the elements. How this graded relevance is computed is discussed later on.

The mental representations involved in the current context are being formed by the interaction between at least three processes: *perception* of the environment that builds new representations and activates old ones; *accessing and reconstructing memory* traces that reactivates or builds representations of old experiences; and *reasoning* that constructs representations of generated goals, inferred facts, induced rules, etc. It is also assumed that context in turn influences perception, memory, and reasoning processes (Figure 2).

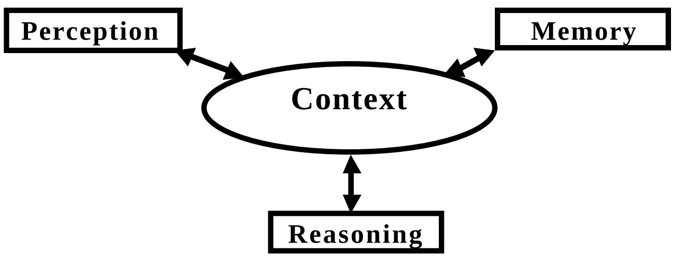

Fig. 2. Interaction of processes forming context and being influenced by it.

The representations built by the reasoning mechanism (e.g. goals, subgoals, and facts established by the inferential mechanism) form what we call *reasoning induced context*. Representations built by the perceptual mechanisms form what we call *perception induced context*. Finally, representations built by the memory processes form what we call *memory induced context*.

The interaction between reasoning, perception, and memory allows for a more efficient processing. Thus from all possible inferences that the reasoning mechanisms can construct only those which are somehow related to the representations produced by the perceptual and memory mechanisms should be actually constructed. Likewise, only those memory elements should be retrieved which are related to the currently reasoned and perceived elements. Finally, perception-built representations which are supported by related memory and reasoned elements should be stronger. All this would be possible only if the three processes are continuously running in parallel and interacting with each other. This would require a highly parallel cognitive architecture.

One way to describe how context influences cognitive processes is to assume that it assigns priorities to all mental representations and operations in a way that facilitates the usage of the more relevant elements and discourages the usage of the less relevant ones. How could the system know the relevance of a particular element prior to even trying to use it? Efficient processing requires that the system uses some relevance measure which will be cheap and will be based on its past experience. The measure that the dynamic theory of context uses is called *associative relevance.* It is defined by the *degree of connectivity* of the element in question with all other elements of the current context. The judgment of the degree of connectivity reflects the frequency of joint usage in past experience. Associative relevance is by definition graded because it is clear that all elements are somehow related to each other, so it is the degree of connectivity that matters. It is also important that this measure is a cheap one, i.e. its computation does not require a lot of resources, otherwise it would be pointless to use it as a heuristics. It is also important that relevance is computed relatively independently of the reasoning process itself, automatically (without intention and awareness) and continuously in parallel to the reasoning process itself. In this way the relevance computation can guide the reasoning porcess in one or another direction. On the other hand the reasoning process should also influence the computation of relevance, e.g. if a new goal is formed the relevance should change automatically.

Thus summarizing the main principles underlying the dynamic theory of context we can state that:

- context refers to the state of the mind and not to the environment;
- context corresponds to the specific distribution of priorities over all mental representations and operations in a given moment;
- priorities are measured by the associative relevance of mental elements;
- associative relevance is graded and is computed automatically and in parallel to the reasoning process;
- context is dynamic and the set of priority elements has no clear-cut boundaries.

Thus, *context is considered as the dynamic fuzzy set of all associatively relevant memory elements (mental representations or operations) at a particular instant of time.*

4. Context-Sensitive Cognitive Architecture DUAL

The cognitive archtecture DUAL[3] is one specific implementation of the Dynamic Theory of Context. It provides general structures and mechanisms for building context-sensitive models of cognitive processes [19, 20, 22, 36]. The DUAL approach rests on emergent and dynamic computations and representations. Context-sensitivity is explained in terms of dynamic re-organization of the cognitive system which continuously adapts to the changing situation. This approach allows for higher flexibility and efficiency compared to a system based on fixed computations and representations [25].

A system built on the DUAL cognitive architecture consists of a large number of relatively simple micro-agents whose collective behavior produces the global behavior of the system. Each micro-agent is a simple and specialized computational device which represents only a small piece of declarative and procedural knowledge. Thus the global computations in DUAL emerge from the local interactions between the agents and the representations in DUAL are distributed or decentralized over a set of agents.

Each micro-agent is a hybrid (symbolic/connectionist) processing device. Its symbolic component takes part in the emergent global symbolic computation processes and in the emergent representations, while its connectionist component takes part in a emergent global process of spreading activation which computes the associative relevance of the knowledge represented by its symbolic component. The speed at which its symbolic component is running depends on the activation level computed by its connectionist component [18, 19, 20, 36]. In this way the mental operation performed by the symbolic processor of the agent has a dynamically assigned priority. The current context-sensitive representation of a concept or episode emerges from the distribution of activation over the set of agents that represent various aspects of it.

The population of all micro-agents forms the Long-Term Memory of a DUAL system. The agents are connected into a network reflecting the typical patterns of interaction between them, each agent communicating directly with its local neighbors only. However, the agents can establish new links dynamically and thus change (temporary) the topology of the network. The agents that are active at a particular instant of time form the Working Memory (WM) of the system. Some of them are permanent and are part of the LTM. Others are temporary — constructed recently by other agents and belonging to the WM only. The latter usually disappear after a certain period of time but some can become permanent and join the LTM.

Knowledge is represented in DUAL by the symbolic components of the agents. The frame-like symbolic structures used for representation are dynamic and distributed over a coalition of agents. The slots are part of the same agent but the corresponding fillers are represented by other agents. The relations to the fillers are represented by links between the agents each link having a semantic interpretation (like co-reference, is-a, instance-of, etc.). The actual representation used in a particular moment will

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[3] An extended description of DUAL, including the source code in LISP, is available on-line at http://www.andrew.cmu.edu/~apetrov/dual.

depend on the activation levels of all agents in the coalition and thus it will depend on the context. Episodes are represented in an even more decentralized way since there is no single agent with a list of pointers to all the aspects of the episode. The aspects of the episode which will be retrieved or constructed completely depends on the context.

Context is represented in DUAL by the distribution of activation over all micro-agents in the system, i.e. by the state of the WM of the system at a particular instant of time. This representation fulfills all the principles of the dynamic theory of context as outlined in the previous section:

- the state of the WM is in fact a complete description of the “state of the mind” of a cognitive system;
- the activation level determines the speed of processing and therefore assigns the priorities;
- the activation level of the WM elements corresponds to the calculated associative relevance of the corresponding piece of knowledge since this activation level reflects their connectivity with all other WM elements;
- the degree of membership to the WM is graded since it is measured by the activation levels which are real numbers in the segment [0,1);
- the activation level is computed automatically, continuously and in parallel to all symbolic processes, including the reasoning process;
- the WM is dynamic as the set of its elements and the degrees of their membership change continuously.

In summary, context has a dynamic and distributed representation in DUAL: the distribution of activation over the set of all memory elements (the set of all agents). In other words the context is reflected by the specific group of agents performing the computations and representing various aspects of the situation in that moment. In this way the system re-organizes itself and adapts to the particular situation.

Thus context is implicitly represented by the distribution of activation over the set of all memory elements. Each pattern of activation represents a specific context. This does not exclude having additional explicit meta-context representations. The mental state of the cognitive system can be self-observed and part of it (which is consciously accessible) can be explicitly represented in a local structure and referred to on a later occasion. However, this is always a partial representation of the actual mental state.

The particular state of WM is computed by a connectionist mechanism of spreading activation which emerges from the local computations performed by the connectionists components of all agents. These computations are performed continuously and in parallel to all the symbolic processing done by the symbolic components of the agents. All the links in the network are used for spreading activation. This includes both the semantic and the associative links between the agents.

There are two agents which are considered as permanent sources of activation: the *GOAL* agent and the *INPUT* agent. They continuously emit activation and pass it over to their neighbors connected by weighted links to them. The agents directly related to the *GOAL* agent represent the particular goals that the system is currently pursuing and are called *goal* agents. On the other hand, the agents directly related to the *INPUT* agent represent objects (or their properties and relations) currently being perceived by the system and are called *input* agents.

The particular state of WM reached on a particular occasion and computed by the above mechanism depends on the particular list of *goal* and *input* agents as well as on the initial state of WM which is the distribution of activation computed in the previous context. It is important to stress that there is a decay process which decreases the activation of each individual node (agent) with time, however, its decay rate is relatively slow which enables the previous state to influence the new one.

Context is changed continuously by the connectionist mechanism in parallel to the reasoning process emerging from the symbolic computations. Thus context changes can influence the reasoning process. The changes in the context are not a result of the reasoning process although the reasoning process can influence the context changes by manipulating the *goal* agents.

The dynamics of the connectionist computation produces continuous changes in the context. However, more radical changes occur as a result of changes in the lists of *goal* and the *input* agents, i.e. in the sources of activation. This is performed by the processes of reasoning and perception, respectively. Both the reasoning and the perception processes are emergent from the collective behavior of many agents.

Perception plays a crucial role in context changes. Most of the well known context effects in psychology are about how the changes in the outside world (the environment) influence human behavior, i.e. about the influence of perception induced context. This is modeled in the following way. The perception process produces temporary agents corresponding to elements of the environment and connects them to the *INPUT* agent. Currently DUAL has quite simple perceptual abilities. The system receives both a formal description of the problem and its textual description as input and the formal description becomes a *goal* agent while the system produces *input* nodes for each word in the textual description. In this way the representations of the words (which are different from the representations of the concepts) form the perception induced context and the effects of different wordings on the problem solving can be modeled. The perception of objects from the environment is simulated by directly implanting an *input* agent in WM. Currently the architecture is being extended in order to equip it with more elaborate perceptual abilities. It should be able to construct the internal representation of the problem by itself starting from an image of the scene: in our case a text-processing situation. For this reason the architecture is extended with a visual buffer.

Goal agents are the other source of changes. These agents are produced and linked to the *GOAL* agent by the reasoning process or are old *goal* agents which are currently activated. This is the way in which the reasoning process can influence the process of changing the context.

DUAL is a specific version of a Society of Mind architecture and in that respect is similar to CopyCat and TableTop architectures developed by Hofstadter and his group [14]. Anderson's ACT-* architecture [2] is also related, but is much more centralized and goal-driven.

5. Context-Sensitive Problem Solving with AMBR

A computer model of human problem solving, AMBR[4], has been developed which simulates deductive and analogical reasoning and demonstrates some of the context effects shown in psychological experiments [18, 23]. Problem solving in AMBR is an emergent process. It emerges from the collective performance of many agents most of which are domain specific such as *water* agent, *heating* agent, *tea-pot* agent, etc.

The general idea of context-sensitivity of problem solving in AMBR is the following. Contexts may differ in their perceived and/or their memorized parts. The perception induced context is established by activating from outside some agents corresponding to words in the problem description as well as some agents corresponding to objects in the environment (e.g. stone) simulating their perception. The memory induced context is established by the initial distribution of activation as a residue of a previously solved problem. These different activation patterns result in different sets of agents contributing to the problem solving process as well as different distribution of their performance speeds. As a result different bases for analogy are found or different constraint satisfaction networks are built up and different correspondences between the same base and target are established. In other words in one particular context the system fails to solve the problem, in another one its solves it successfully, and in a third one it solves it in a different way.

The simulation results have replicated the experimental data about the dynamics of the memory induced context influence on problem solving demonstrating the same pattern of decreasing priming effect [18]. Moreover, these simulation results have predicted the influence of the perception induced context on the specific way the problem is being solved [18] and these predictions have been confirmed in successive psychological experiments [24, 26]. Recently new predictions have been made about the existence of mapping influence on retrieval and order effects [35] which have yet to be psychologically tested.

6. Conclusions

A dynamic theory of context has been proposed which considers context as the set of all entities that influence human behavior on a particular occasion. As a consequence context is thought of as the dynamic fuzzy set of all associatively relevant memory elements (mental representations or mental operations) at a particular instant of time.

In the cognitive architecture DUAL the memory elements are called agents and they have variable availability determined by their activation level. Problem solving is modeled by an emergent computation produced by the collective behavior of the agents (the AMBR model). Context influences problem solving by changing the availability of the agents. In this way different sets of agents take part in the computation in

[4] An extended description of AMBR, including its source code in LISP, is available on-line at: http://www.andrew.cmu.edu/~apetrov/dual/ambr

different contexts. They run at different speed depending on their estimated relevance. It is clear that these mechanisms produce different outcomes in different situations even if the goals of the system are fixed. Moreover, context changes dynamically because of the inherent dynamics both of the memory induced context (decreasing its influence with the course of time) and of the perception induced context (continuously changing the perceived elements of the environment).

The simulation experiments on priming and context effects performed with DUAL and AMBR have replicated successfully psychological data and have predicted results which later on have been confirmed experimentally.

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