Marker-Augmented Robot-Environment Interaction

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Abstract

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There has been an increasing interest in developing computational theories of autonomous robots. However previous work has dwelled on intelligent modifications to internal computational structures of robots, ignoring modifications to external environments. Our work is the first to formalize the modification of an environment by externalizing internal state. We argue that externalizing internal state by addition of markers increases communication through the world and that stronger markers have a higher potential to externalize internal state. We also show that markers can be used to maintain task fulfilling capability of a robot constant even when stimuli are specialized or effects of actions are made weaker. We argue that markers can be useful in composing more complex reactive behavior and show how such markers can be synthesized. Our results apply to all kinds of autonomous agents (robots as well as softbots) that are intended to use minimal internal representations.

1 Introduction

The paradigms of autonomous robotic intelligence are moving towards a more distributed architecture. We focus on the behavior-based robots that are typically reactive (though some may have a meta-level reasoner or a monitor) and treat the world as an external memory from which knowledge can be retrieved by perception. Encouraging results have been obtained using the behavior-based approach, like behavior-based box pushing [8], reactive robots for fetching and delivering objects in an outdoor environment [1], a reactive serpentine robot that navigates complex pipe structures to inspect them [4] and the robot that reacts to bumps and slips while maintaining body posture [13].

Early research on robots assumed environment to be completely static, predictable and avoided sensory processes, e.g. the robot Shakey [9]. The building and maintenance of and reasoning with global internal representations was considered to be responsible for the failure of this approach in more complex and dynamic environments. Ideas of Brooks[2] lead researchers to build robots without global representations and hierarchy. Robots in such systems communicate though the world by making changes to it that other robots can perceive (humans do this very often, by leaving notes or home memos in voice mail that serve the purpose and do not contain any names or addresses used in direct communication).

Since some such robots exhibited problems like deadlocks and myopic behaviors, hybrid architectures with deliberative components to fix these began to be explored. In this transition, the potential of reactivity went unexamined. Making a system more reactive essentially means transforming internal state into external state that can be extracted through perception. Some internal states have to be updated whenever external world changes and externalizing these states eliminates such updates, since the most recent information is available in the world itself. Hence there are reasons for robots to be more reactive. It appears that externalization of state is common in several biological systems. O'Keefe[5] claims that in symmetrically shaped mazes, cues outside the maze itself form an important source of input to an animal's spatial representation and if animals are prevented from perceiving these distant cues, the animals' goal seeking capability is highly adversely affected. One may worry that by externalizing internal state, we are pushing the complexity of building and updating internal world models into the complexity of sensing. However minor modifications to external environments that have an appropriate semantics and can be efficiently sensed, can drastically reduce the perceptual computations.

The previous literature ignores the intelligent use of space in synthesizing more complex reactive behavior, rather it concentrates on designing internal computational structure of a robot more intelligently. It is common to introduce markers to externalize internal states to enhance the robot-environment interaction, e.g. the mobile robot competitions. The rocks in the event of finding life on Mars [11] were painted black to aid in visual recognition and the danger zones were indicated by spreading black paper on part of the floor. The doors of the lander were painted blue and orange. The life forms consisted of balls and cubes of bright colors. The squiggle balls and tennis balls in the "clean up the tennis court" event were painted black [6]. The vision system that was trained to recognize the yellow tennis balls and pink squiggle balls proved to be very reliable during the competition, benefitting from the color cues provided by the objects [12]. In this event, the gate was marked by two cyan markers that were taped to the ground in front of the gate. The goal area in the event of cleaning up the tennis court was marked with a blue square [10].

But this kind of environmental modification has not been formally incorporated into the architectures of autonomous agency. As a result, the introduction of markers has been viewed more as a low level fix rather than as a paradigm that deserves a separate investigation. Our work bridges this gap by formalizing the externalization of internal states and evaluating its impact on a robot's capabilities. We provide semantics for markers and show how they can be compared. We discuss the advantages of introducing markers and mechanisms for synthesizing them.

This paper is organized as follows. We formalize reactive agency, the marker-augmented environments, provide semantics for markers and define metrics to compare different markers (section 2). We investigate the role of markers in recovering the task fulfilling capabilities of a robot (section 3). We provide results on the synthesis of such markers and show how they make the construction of a more complex reactive behavior possible (section 4). Our conclusions are presented in section 5.

2 A Model of Reactive Agency

Here we develop a formal model of reactive agency and state externalization and use it in sections 3,4 to prove our results on the properties of markers and their synthesis.

• **Behavior** - A behavior β_i is modeled as a 2 tuple $< s_i, c_i >$ and defined as a mapping from stimulus s_i to consequence c_i. Note that though this representation of behaviors is same as the $< pre-conditions, effects >$ representation of state transforming operators in the planning literature, the execution criteria for behaviors and operators are different. The behavior of an autonomous robot is generally executed once the stimulus is true, while an operator is executed only if its pre-conditions are true and the operator is relevant to the goal that the planner is trying to achieve. Purely behavior-based autonomous robots do not have an explicit representation of goals.

• **Behavior space** - It is the set of all behaviors of a robot. It is denoted by B and $\mid B \mid$ is size of the behavior space.

• **Stimulus** - It is assumed that stimuli of all behaviors are expressed in a purely conjunctive form (with an exception of the *local externalization* that we discuss in the semantics of markers in this section). It is assumed that each literal in a stimulus may correspond to a number of sensor readings, i.e. sensor readings are processed to extract meaning out of them and there may be a literal to which this meaning is mapped. For example, if readings of 10 sonars are all less than a certain limit, it may indicate presence of a wall or a big obstacle. Not every distinct set of sensor readings corresponds to different stimulus. If there are p sensors, each of which can have m distinct readings, we do not consider them to be m^p distinct stimuli, since all these readings can be mapped to fewer predicates. Universal truths which are required for execution of a behavior are not listed in its stimulus, since such list can be arbitrarily long. The universe is a conjunction of predicates denoted by U. Hence when we say that a stimulus is s_i, we mean that it is $(s_i \wedge X)$, where $(U \Rightarrow X)$, X being a part of the universe, e.g. to pick up a can, it is necessary for a robot to have a gripper in a good condition (not mechanically damaged), but this is not listed in stimulus of the behavior *pick_up_can*. The stimulus s_i is defined to be at least as strong as stimulus s_x if $(s_i \Rightarrow s_x)$. It is stronger if $(s_i \Rightarrow s_x)$ is a tautology and s_x does not subsume s_i.

• **Consequence** - It is assumed that consequences of all behaviors are expressed in a purely conjunctive form. A consequence c_i is defined to at least as strong as consequence c_j if $(c_i \Rightarrow c_j)$.

• **Behavior chain** - Complex behavior occurs because a number of primitive behaviors (like β_i) operate sequentially and/or concurrently. Here we focus on the temporal sequencing mechanism that gives rise to a complex behavior. A behavior chain C is a temporal sequence of behaviors, $\{\beta_{i_1} : \beta_{i_2} : \beta_{i_3} : ... : \beta_{i_k}\}$, where $\beta_{i_m} : \beta_{i_{m+1}}$ is used to denote that these two behaviors are contiguous and occur immediately next to each other in time, with the former behavior preceding the latter. Such a chain is said to be composable from the behavior space B if behaviors in the chain are elements of B. This is denoted by $C \lhd B$. This sequential model of complex behavior is very widely used in ethological analysis [3]. We use the behavior chains to model complex task fulfilling functionality since the primary paradigm for solving most of the problems in artificial intelligence is to construct a sequence of actions that can be executed from the current state to reach the goal. Our work [7] shows how the analysis in this paper can be extended to handle concurrent behaviors by considering seven temporal relationships between two behaviors.

$\beta_i \in C_j$ denotes that the behavior β_i is a member of the chain C_j. In the chaining mechanism, the action of an earlier behavior changes the situation in such a way that the newly changed part of the situation in conjunction with the the universe U implies stimulus of the next behavior in the chain (however the universe is not explicitly listed in the logical formulae here). For example, consider the chain $\{\beta_1 : \beta_3 : \beta_7\}$. Here we may have $c_1 = (a \wedge c)$ and $s_3 = (a \wedge c \wedge z)$. $(c_1 \Rightarrow s_3)$ if $(U \Rightarrow z)$. z is not explicitly listed in c_1.

The length of a chain C_i is defined as the number of behaviors in the chain and is denoted by l_{C_i}. $C_i(j)$ denotes jth behavior element of chain C_i. A chain C_i precedes chain C_j (denoted by $C_i \prec C_j$) if all behaviors in C_i precede all behaviors in C_j ($\prec$ denotes the temporal precedence relation). A chain C_i immediately precedes chain C_j (denoted by $C_i : C_j$) if $(C_i \prec C_j) \wedge (\{C_i(l_{C_i}) : C_j(1)\})$. If a chain C_i immediately precedes the chain C_j, the chains are said to be concatenated, and the longer chain resulting from the concatenation is denoted by $[C_i : C_j]$. Behavior chains are responsible for fulfilling tasks (defined in the discussion on *task space* in this section).

• **Consequence of a chain** - The consequence of a behavior chain

$\{\beta_{i_1} : \beta_{i_2} : \beta_{i_3} : \ldots : \beta_{i_k}\}$, where $1 \leq i_m \leq \mid B \mid$, and $1 \leq m \leq k$ is defined as the difference

$$(\wedge_{p=1}^{k} c_{i_p} - \wedge_{q=1}^{s} x_q)$$

computed by dropping literals in the latter conjunction from the former, such that $\forall x_q(\exists t_1, t_2((\beta_{i_{t_1}} \prec \beta_{i_{t_2}}) \wedge (c_{i_{t_1}} \Rightarrow x_q)$
$\wedge (c_{i_{t_2}} \Rightarrow \neg x_q) \wedge \neg\exists t_3((\beta_{i_{t_2}} \prec \beta_{i_{t_3}}) \wedge (c_{i_{t_3}} \Rightarrow x_q))))$, where $1 \leq t_1 < t_2 < t_3 \leq k$. This means that the consequence of a chain is a conjunction of consequences of its members with the literals that are made false by consequences of behaviors occurring later and never made true after that point in time, dropped from it.

• **Stimulus of a chain** - The stimulus of the behavior chain $\{\beta_{i_1} : \beta_{i_2} : \beta_{i_3} : \ldots : \beta_{i_k}\}$ is s_{i_1}, stimulus of the first behavior in the chain.

• **Power of a chain** - Ideally, one would like a behavior chain to execute under a wider range of situations (and thus have a weaker stimulus, for this to happen) and result in a consequence that is as strong as possible. A stronger consequence of a chain is likely to imply stimuli of many other chains, resulting in a highly useful and complex behavior. Hence we define the power of a behavior chain in terms of the strengths of its stimulus and consequence. The stimulus and consequence of a behavior chain C_i are denoted by s_{C_i} and c_{C_i} respectively. The power is a relative metric. A behavior chain C_i is at least as powerful as the behavior chain C_j if and only if $(s_{C_j} \Rightarrow s_{C_i}) \wedge (c_{C_i} \Rightarrow c_{C_j})$.

• **Degree of reactivity** - We are interested in reactivity along spatial dimension, the amount of internal state rather than the response time. Let the set of predicates occurring in stimulus s_i of a behavior β_i be S_i. Let the set of those predicates from S_i whose truth value is decided by the robot based on external information gathered by sensors be S_{ir}. The degree of reactivity of the behavior is said to increase if S_{ir} is modified to S'_{ir} such that $S_{ir} \subset S'_{ir}, S'_{ir} \subseteq S_i$. The degree of reactivity of β_i is denoted by r_i and it is less than 1 if $S_{ir} \subset S_i$. It is unity if $S_{ir} = S_i$. The definition of degree of reactivity is independent of the time required to sense or deliberate to determine truth of predicates and is concerned only with spatial dimension corresponding to the internal storage space. However since lower amount of internal state is generally correlated with lower reasoning and thus lower internal computation, we do expect faster responses from a robot when states are externalized, when markers can be sensed faster.

• **Task space** - A task is defined as a transition from an initial state of the world to a new state, achieved through a temporal chain of behaviors. We are interested in defining a measure of the number of tasks that are potentially fulfillable. These correspond to all possible temporal chains of behaviors. Thus the chain $\{\beta_1 : \beta_2 : \beta_3\}$ fulfills a task that is different from $\{\beta_1 : \beta_2\}$. The set of all possible temporal chains of behaviors from B is defined as the greatest potential task space, denoted by $\tau_G(B)$.

• **Marker** - A marker is a percept denoted by M_i and is described by a pure conjunction of its features. For example, a colored cube kept on a flat surface can serve as a marker and be described as $\exists x(cube(x) \wedge color(x, red))$. We focus on the logical description of a marker rather than its physical realization in real world, e.g. the logical description $(sphere(x) \wedge green(x))$ of a marker can be implemented using spheres of different radii, with different shades of green color, but we limit ourselves to the logical description.

The term marker is used in this paper to refer to ((a) objects introduced in an environment or (b) new features added to current objects in an environment or (c) those features of current objects that were not used before but used later), with the intention of externalizing internal state (we consider these as the three primary mechanisms of externalizing internal state), e.g. if a robot is supposed to collect all dishes and keep them in sink, except those on a table, one way to design this behavior is to store absolute location of center of the table in the form of internal state and design *pick_up* behavior of the robot not to pick up dishes within some radius around that location. However one can put a blue cube at center of the table and replace the absolute location in the stimulus of the behavior by presence of the blue cube that can be sensed by vision. The blue cube is a marker.

We assume that the markers are semantically equivalent (denoted by $\equiv$) to the internal state that they externalize. In the example above, the blue cube and the location of table are semantically equivalent because both of them represent the area from which dishes are not to be picked up. Note that the semantics of a marker is different from its logical description. When a marker is used to externalize internal state, one can either place the marker on every object in the environment that satisfies the description of the internal state (is an instance of the condition in the internal state) or on fewer objects. We refer to this latter case as *local externalization*. For example if there are multiple tables such that no dish on any of those is to be moved to the sink, one can either keep a blue cube on each of them (global externalization) or only on some of them (local externalization). When a marker is introduced to externalize the internal state of a behavior, the stimulus of the behavior must be adapted to this change. Consider a behavior β_2 and a marker M_3 such that $s_2 = (p_1 \wedge p_2 \wedge p_3)$ and $M_3 \equiv (p_1 \wedge p_2)$. In case of local externalization, we can modify s_2 to $(p_1 \wedge p_2 \wedge p_3) \vee (M_3 \wedge p_3)$ (thus changing the purely conjunctive nature of s_2) and in case of global externalization, we can modify s_2 to $(M_3 \wedge p_3)$. $M_3 \equiv (p_1 \wedge p_2)$ does not necessarily mean that an object that satisfies $p_1 \wedge p_2$ will necessarily have the marker M_3 on it. However the reverse is true - an object with the marker M_3 on it will satisfy $(p_1 \wedge p_2)$, assuming that the externalization is *fair* in the sense that markers are not put on irrelevant objects. We assume fair externalization in this paper.

A marker is recognized based on its logical description rather than its semantics. Thus if a stimulus s_i is $(M_q \wedge p_1 \wedge p_4)$, p_1, p_4 being predicates, s_i will be true if the logical description of M_q and p_1, p_4 are true. We assume that a robot's motor actions do not destroy any marker. If the logical description of a marker M_i is same as the purely conjunctive formula f_j, $M_i \equiv f_j$ always holds. We assume that if $M_i \equiv f_1$ and $M_j \equiv f_2$, then $(M_i \wedge M_j) \equiv (f_1 \wedge f_2)$, f_1 and f_2 being purely conjunctive formulae. $M_i \Rightarrow f_1$ holds when either (i) both $M_i \equiv f'$ and $f' \Rightarrow f_1$ hold, f_1, f' being purely conjunctive formulae or (ii) the logical description of M_i subsumes f_1.

Markers can also be used to specialize stimuli of behaviors. A stimulus s_i is more specialized than s_j if s_i is stronger. A stimulus may be specialized to avoid triggering of a behavior on unwanted occasions, e.g. if an agent (softbot) has the behavior of forwarding all mails received at the office e-mail address to home e-mail address and if user X does not want to get all those messages at home, X can specialize the stimulus of *forward_mail* behavior to forward only those e-mails that have certain keywords in their titles. A marker M_i can be used to specialize stimulus s_j by modifying it to $(s_j \wedge p)$ where $(M_i \equiv p)$. Though it is not necessary to have a marker for stimulus specialization and thus the literal p may be an internal state, it is useful to introduce markers to enhance reactivity.

A marker M_i is at least as *strong* as a marker M_j if $(M_i \Rightarrow M_j)$. $M_i \Rightarrow M_j$ holds only when there exist purely conjunctive formulae p_i and p_j such that $M_i \equiv p_i$ and $M_j \equiv p_j$ and $p_i \Rightarrow p_j$ and the logical implication relation $M_i \Rightarrow M_j$ also holds between the logical descriptions of the markers. Thus the marker M_i is stronger than the marker M_j if both the logical description and semantics of M_i are respectively stronger than the logical description and semantics of M_j. We assume that if the logical description is stronger, the semantics will be stronger as well and vice versa. This maintains consistency between the relations between the logical descriptions of the markers and the relations between their semantics.

We next give semantics for four other types of logical relationships that involve markers.

a. Consider the relation $(M_i \wedge f_j) \Rightarrow M_j$. **(i)** This holds if $M_i \equiv f_q$, $M_j \equiv f_s$, f_q and f_s being purely conjunctive formulae and $(f_q \wedge f_j) \Rightarrow f_s$ also holds. The logical relation $(M_i \wedge f_j) \Rightarrow M_j$ should not be interpreted to mean that any object that satisfies f_j and has the marker M_i on it will necessarily have the marker M_j on it. The relation $(M_i \wedge f_j) \Rightarrow M_j$ can be used however to avoid redundant introduction of markers. For example, if an object that satisfies f_j has the marker M_i on it, putting the marker M_j on the object is redundant. **(ii)** The relation $(M_i \wedge f_j) \Rightarrow M_j$ also holds when both M_i and M_j are the logical descriptions of the markers. In this case, an object that satisfies f_j and has the marker M_i on it also has the marker M_j on it.

b. Consider the relation $f_i \Rightarrow M_j$. **(i)** This relation holds if $M_j \equiv f_q$, f_q being a purely conjunctive formula and $f_i \Rightarrow f_q$ also holds. Note that $f_i \Rightarrow M_j$ should not be interpreted to mean that an object that satisfies f_i

also has the marker M_j on it. The relation $f_i \Rightarrow M_j$ however can be used to identify the state externalization possibilities. **(ii)** $f_i \Rightarrow M_j$ also holds when M_j is the logical description of the marker. In this case any object that satisfies f_i also has the marker M_j on it.

c. Consider the relation $(M_i \wedge f_j) \Rightarrow (M_j \wedge f_q)$. **(i)** This holds if $M_i \equiv f_s, M_j \equiv f_t$, f_s, f_t being in purely conjunctive form and $(f_s \wedge f_j) \Rightarrow (f_t \wedge f_q)$ also holds. $(M_i \wedge f_j) \Rightarrow (M_j \wedge f_q)$ does not mean that every object that has the marker M_i on it and satisfies f_j will also have the marker M_j on it. The relation can be used to prevent redundant introduction of markers. For example, if $(M_i \wedge f_j) \Rightarrow (M_j \wedge f_q)$, then it is redundant to put marker M_j on an object that satisfies f_j and has the marker M_i on it. **(ii)** $(M_i \wedge f_j) \Rightarrow (M_j \wedge f_q)$ also holds when both M_i and M_j are logical descriptions of the markers. In this case any object that satisfies f_j and has the marker on M_i on it, also has the marker M_j on it.

d. Consider the relation $(M_i \wedge f_j) \Rightarrow f_q$. **(i)** This holds if $M_i \equiv f_s$, f_s being a purely conjunctive formula and $(f_s \wedge f_j) \Rightarrow f_q$ also holds. The relation $(M_i \wedge f_j) \Rightarrow f_q$ can be used to avoid the redundant introduction of markers. For example, it is redundant to put the marker $M_s, M_s \equiv f_q$ on an object that satisfies f_j and has the marker M_i on it. **(ii)** $(M_i \wedge f_j) \Rightarrow f_q$ also holds when M_i is the logical description of the marker.

A set of markers becomes *stronger* as more markers are added to it and/or existing markers from that set are replaced by *stronger* ones. The term "stronger" is used to capture the notion of subsumption. The strength of a marker captures the extent to which one can exploit the marker in externalizing state. The strength of a marker is a measure of its stimulus specialization potential too. $S_1 >_t S_2$ denotes that the marker set S_1 is **stronger** than the marker set S_2. $S_1 >_s S_2$ denotes that the marker set S_1 has a higher **stimulus specialization potential** than the marker set S_2. A marker set is **redundant** if there exist some markers $M_{i_1}, M_{i_2}...M_{i_n}, M_k$ in that set such that $((M_{i_1} \wedge M_{i_2} \wedge ... \wedge M_{i_n}) = M_k)$, where $M_{i_j}, j \in [1, n], M_k$ are all either the logical descriptions of the markers or they are all their semantics. A marker M_i is more **efficient** than a marker M_j if the time required to recognize M_i is less than the time required to recognize M_j.

• **Environment -** $E \leadsto E'$ denotes that the environment E' is obtained from the environment E by adding one or more markers to E and/or replacing existing markers by *stronger* ones. We also refer to this process as augmenting the environment with markers.

• **Marker power** - It is the potential of a marker to increase the degree of reactivity of a behavior, also termed as the externalization potential of the marker. The power of a marker M_i, depends on the size of the set of predicates p from internal state in stimuli such that $(M_i \Rightarrow p) \wedge (s_j \Rightarrow p) \wedge \neg(p \in S_{jr})$, where $j \in [1, \mid B \mid]$. In words, it depends on the literals in stimuli of behaviors of a robot that are implied by the marker and whose truth can be determined based on external information provided by the marker. If a marker M is stronger than marker M', then M is at least as **powerful** as M'. The power of a set of markers either stays constant or increases, when new markers are added to the set, or existing markers are replaced by stronger markers. $S_1 >_p S_2$ denotes that the marker set S_1 more powerful than the set S_2 (and hence S_1 is obtained from the set S_2 by adding more markers and/or replacing the existing markers by stronger ones). Note that the notions of power, strength and stimulus specialization potential of markers capture different properties, though they are related.

3 Properties of Markers

We state below without proof, certain properties of the sets of markers and marker-augmented environments.

Lemma 1. If $S_1 >_p S_2$ and $S_2 >_p S_3$, then $S_1 >_p S_3$.
Lemma 2. If $S_1 >_s S_2$ and $S_2 >_s S_3$, then $S_1 >_s S_3$.
Lemma 3. If $E_1 \leadsto E_2$ and $E_2 \leadsto E_3$, then $E_1 \leadsto E_3$.
Lemma 4. If $S_1 >_t S_2$ then $S_1 >_s S_2$.
Lemma 5. A marker used to specialize a stimulus s_i also increases degree of reactivity r_i of behavior β_i if $r_i < 1$.

We now examine the role of markers in recovering certain properties of a behavior space that may be lost or degraded due to certain modifications to the behavior structure.

Theorem 1. When consequences of behaviors in B are generalized or stimuli of behaviors in B are specialized, to modify the behavior space B to B', introduction of m markers maintains $\tau_G(B) = \tau_G(B')$, $m > 0$.

Proof - The behavior spaces B and B' are identical with the only difference that either the stimulus or the consequence of β_i is different. β_i in B' has either a stronger stimulus or a weaker consequence, compared with the $\beta_i \in B$. We consider two cases. **Case 1.** A consequence c_i is generalized to c'_i, so that we have $(c_i \Rightarrow c'_i)$, c_i being stronger, s_i being the same. If there is a behavior β_j whose stimulus is not triggered (made true) by new consequence of β_i (but was triggered by the old consequence c_i), a reduction in the number of temporal chains composable occurs. As per the definition of the greatest potential task space in sec.2, $\mid \tau_G(B) \mid > \mid \tau_G(B') \mid$. The chains broken can be joined again by adding a marker M_k such that $((c'_i \wedge M_k) \Rightarrow s_j)$. This process can be repeated for all such chains broken due to generalization of consequences, to have $\tau_G(B) = \tau_G(B')$.

Case 2. Let a stimulus s_i be specialized to s'_i by adding a literal p to s_i, p being internal state, c_i being the same. Let us assume that the original stimulus was implied by the consequence of c_j of some behavior β_j and the specialized stimulus can no longer be. This prevents the formation of temporal chains containing $\beta_j : \beta_i$, reducing the greatest potential task space. The chains broken can be joined by adding a marker M_k such that $((c_j \wedge M_k) \Rightarrow s'_i)$. This process can be repeated for all such chains broken due to specialization of stimuli, to have $\tau_G(B) = \tau_G(B')$. Hence the proof. (The procedure in Lemma 6 can be used to compute the marker M_k.) □

4 Synthesis of Markers

In this section, we provide results on synthesizing markers for making the formation of longer behavior chains possible. This composition of chains is different from the generation of plans because plans are generated by an explicit selection and sequencing of actions and we compose longer behavior chains by concatenating them through the external world, by adding markers to it. In Theorem 1, we considered repairing the damage to an existing behavior chain to restore the performance. In Lemma 6, we consider joining two existing chains to enhance the performance. However the basic idea in both the proofs is the same - the computation of a marker that joins the chains. The result f_i of this computation can either be interpreted as the logical description f_i of the marker M_j to be added or one can add a marker with some other logical description as long as the semantics of the marker and the semantics of the result of computation are the same $(M_j \equiv f_i)$. It should be noted that global externalization should be carried out when chains are to be joined with markers.

Lemma 6. There exists a procedure to find a marker that can join C_1 and C_2, s_{C_2} being purely conjunctive.

Proof - Let $C_1 = \{\beta_{i_1} : \beta_{i_2} : ... : \beta_{i_k}\}, k \geq 1$ and $C_2 = \{\beta_{j_1} : \beta_{j_2} : ... : \beta_{j_m}\}, m \geq 1$ be two behavior chains to be joined to form chain $C' = \{\beta_{i_1} : \beta_{i_2} : ... : \beta_{i_k} : \beta_{j_1} : \beta_{j_2} : ... \beta_{j_m}\}$ (so that $l_{C'} = l_{C_1} + l_{C_2}$). Let $A = \{a_i\}$ be the set of all predicates a_i in s_{j_1} such that $(c_{C_1} \wedge U)$ does not subsume a_i, U being the universe (A is essentially the set of literals from $(s_{C_2} - c_{C_1})$). If a marker M is introduced such that $\forall a_i((a_i \in A) \Rightarrow (M \Rightarrow a_i))$, we have $((c_{C_1} \wedge U \wedge M) \Rightarrow s_{j_1})$, joining the chains. Hence the proof. □

Theorem 2. Joining chain C_1 with chain C_3 requires at the most as strong a marker as that required to join the chain C_2 with the chain C_3, if the chain C_1 is more powerful than the chain C_2, s_{C_3} being purely conjunctive.

Proof - The result follows from the fact that $(s_{C_3} - c_{C_2}) \Rightarrow (s_{C_3} - c_{C_1})$. To compose the chains $[C_1 : C_3]$ and $[C_2 : C_3]$ we need markers M_x, M_y respectively, such that $M_x \Rightarrow (s_{C_3} - c_{C_1})$, $M_y \Rightarrow (s_{C_3} - c_{C_2})$. Since the chain C_1 is more powerful than the chain C_2, $(c_{C_1} \Rightarrow c_{C_2})$. Hence $(M_y \Rightarrow M_x)$. Hence the proof. □.

In [7] we show how a robot can generate plans in presence of markers and how the markers can be automatically introduced and removed.

5 Conclusion

Current autonomous robots that are highly reactive are not significantly intelligent and the robots that are significantly intelligent are not sufficiently reactive. The previous research has dwelled on intelligent modifications to internal computational structures of robots, ignoring the modifications to external environments (which can preserve both intelligence and reactivity). We bridged this gap by formalizing the externalization of internal state. We provided semantics for markers that facilitate this state transfer. We provided metrics for comparing markers based on various properties. We showed a number of advantages of using markers, like more flexibility in specializing stimuli, emergence of more complex reactive behavior and recovery from degraded task-fulfilling capability arising from certain modifications to behavior structure.

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