Focusing Reasoning Through Emotional Mechanisms

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Abstract. In concrete environments, where uncertainty and dynamism are pervasive and time and resources are limited, reasoning and decision-making processes raise important problems related both to adaptive ability and to the computational complexity of the underlying cognitive mechanisms. In this paper we propose that a symbiotic integration between emotion and cognition is a key aspect to address these problems. To concretize this view we present an agent model where emotion and cognition are modeled as two integrated aspects of intelligent behavior and where affective-emotional mechanisms are used to support adaptability and to focus the reasoning and deliberation mechanisms to cope with their computational complexity.

1 INTRODUCTION

Relevant theoretical and experimental work (e.g. [1, 2]) has demonstrated the fundamental role that emotion plays in reasoning and decision-making. For example, experimental results reported by Damásio [1] indicate that a selective reduction of emotion is at least as prejudicial for rationality as excessive emotion, and Gray et al. [3] reported neural evidence for a strong highly constrained form of emotion-cognition interaction, with loss of functional specialization, indicating that emotion and higher cognition can be truly integrated. On the other hand, the importance of emotional phenomena in learning and adaptive behavior is also well documented (e.g. [2]). This evidence of an encompassing role of emotion in cognitive activity remains largely unexplored in cognitive models for intelligent agents [4]. We explore this line of evidence by proposing that a symbiotic integration between emotion and cognition is a key aspect for the implementation of agents capable of intelligent behavior in complex, dynamic and uncertain conditions, typical of real environments. In this paper we concretize this view by presenting an agent model where emotion and cognition are modeled as two integrated aspects of intelligent behavior, enabling the adaptation to uncertain and dynamic environments and allowing to focus the high level cognitive processes, such as reasoning, to cope with their computational complexity. The paper is organized as follows: in section 2, we present an overview of the emotional model that supports the proposed approach; in section 3, we build upon that foundational framework to define an agent model integrating emotion and cognition; in section 4 we report experimental results that illustrate how the proposed model supports focusing reasoning and deliberation through emotional mechanisms; in section 5, we establish comparisons with related work and draw some conclusions and directions for future work.

2 MODELING EMOTIONAL AGENTS

Although the relationship between emotion, reasoning and decision-making has been an active area of research, few cognitive models take into account this relationship [4]. Interesting examples are the models proposed by Botelho and Coelho [5] or by Sloman [6], where emotion is considered at the agent architecture level. However, these models do not address the dynamic and continuous nature of emotional phenomena. Other models (e.g. [7, 8]) address this dynamic nature, but maintain an emphasis on discrete sets of emotional labels. As Scherer refers [9] both the dynamic and the continuous aspects are fundamental to understand the relation between emotion and cognition and, from our point of view, both are essential to define cognitive mechanisms able to cope with the adaptive and computational complexity problems.

2.1 The Flow Model of Emotion

We propose an alternative view where emotional phenomena result from the dynamics of cognitive activity. This view is in line with emotional models proposed by some authors (e.g. [9, 10]). However, a distinctive aspect of the proposed model is the fact that those dynamics are rooted on the dynamics of energy exchange between the agent and the environment. This is possible due to a conception of an agent as an open system that maintains itself in a state far from equilibrium, yet keeping an internally stable overall structure. This kind of systems is known as dissipative structures [11]. Adopting this view, the agent-environment relation is determined by the relation between the agent's internal potential, its *achievement potential*, and the agent-environment coupling conductance, the *achievement conductance*. The achievement potential represents the potential of change that the agent is able to produce in the environment to achieve the intended state-of-affairs. The achievement conductance represents the degree of the environment's conduciveness or resistance to that change, which can also mean the degree of environment change that is conducive, or not, to the agent intended state-of-affairs. In a dissipative system the achievement potential can be viewed as a force (P) and the achievement conductance as a transport property (C). The behavioral dynamics of an agent can therefore be characterized as a relation corresponding to a flow, called *achievement flow*, defined by:

$$F = C \, . \, P \tag{1}$$

The behavioral forces that arise from the dynamic relation between achievement potential and achievement conductance, expressed as energy flows, generate behavioral dynamics that underlie the cognitive activity of an agent and lead to the change of the agent's hedonic state, therefore underlying the corresponding emotional state. These forces are described as a vectorial function *ED*, called

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emotional disposition [12], defined as:

$$ED \equiv (\delta P, \delta F) \quad \text{where} \quad \delta P = \frac{dP}{dt} \quad \text{and} \quad \delta F = \frac{dF}{dt} \tag{2}$$

As can be seen in figure 1.a, at a given instant $t = \tau$ an emotional disposition vector has a quality, defined by its orientation (or argument) and an intensity defined by its module. That is:

$$Quality(ED) \equiv \arg(ED) \tag{3}$$

$$Intensity(ED) \equiv |ED| \tag{4}$$

Each quadrant of the two dimensional space $\delta P \times \delta F$ can be directly related to a specific kind of *emotional disposition quality* [12] as indicated in figure 1.b. As an example, quadrant Q–III ($\delta P < 0$ and $\delta F < 0$) corresponds to situations where the agent does not have capacity to handle the "adversities", which is typical of fear situations.

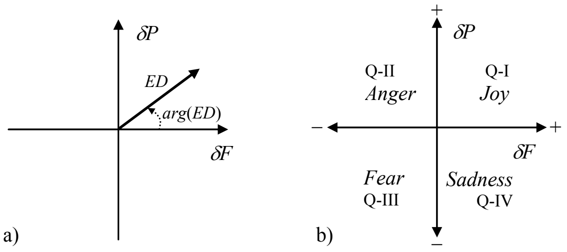


Figure 1. Vector *ED* as a function of δP and δF (a); relation between *ED* quadrants and emotional quality tendency (b).

It is important to note that the emotional tendency associated to each quadrant (joy, anger, fear, sadness) is only indicative of its main nature, since the quality of the emotional disposition is continuous. This is consistent with phenomenological well-known emotion blends.

We will not discuss the aspects related to emotional modeling, however it is important to note that *emotional disposition* is defined as an action regulatory disposition or tendency, but it does not constitute in itself an emotion. Emotions are considered emergent phenomena that result from agents' cognitive dynamics.

3 THE AGENT FLOW MODEL

By defining a foundational framework where emotional phenomena result from the dynamics of cognitive activity, the Flow Model of Emotion provides the support for an agent model where the base notions of potential and flow can be rendered concrete and cognitive structure and mechanisms can be defined. We called that model *Agent Flow Model*. In this section we will present its overall structure.

3.1 Cognitive Elements

One of the main ideas underlying the Agent Flow Model is that interactions between cognitive elements occur as forces resulting from the flow of energy, acting as behavioral driving forces and forming the basis of emotional phenomena. On the other hand, there is much experimental and theoretical evidence that biological cognitive activity is based on the composition of basic components (e.g. [13, 14]). Based on these evidences, cognitive potentials and flows are characterized as energetic signals with a specific frequency (its *quality*), and an amplitude (its *intensity*) varying in time. Through superposition, aggregates of potentials can be formed. These aggregates of potentials, which we call *cognitive elements*, are the base of the cognitive structure and activity of an agent. Formally, a cognitive potential is defined as:

$$p(t) = a(t).\varphi(\omega,t) \tag{5}$$

where $\varphi(\omega,t)$ is a *base signal* that represents some aspect of the agent's cognitive "reality" with a specific quality ω, and $a(t)$ is a *modulating signal* determining the intensity (amplitude) and the specific quality (frequency shift) of the cognitive potential.

The base signals that characterize the cognitive potentials are orthogonal among each other, which implies superposition of energy. Therefore a cognitive element $\sigma(t)$ is defined as a superposition of cognitive potentials. That is:

$$\sigma(t) = \sum_{i=1}^{N} p_i(t) \tag{6}$$

where N is the number of potentials in the aggregate.

3.2 Cognitive Space

The base signals that compose potentials and cognitive elements form a signal space underlying the cognitive structure of an agent, which we call a *cognitive space*. A cognitive space is characterized as a multi-dimensional signal space where each base signal defines a dimension.

Formally, a cognitive space CS_K is defined by a set of K orthonormal basis functions $\Phi = \{\varphi_i\text{: i} = 1, 2, \ldots, K\}$ with $K \in \aleph$. Each basis function φ_i corresponds to a base signal $\varphi(\omega_i,t)$ with a specific quality ω_i.

Cognitive elements correspond to specific positions in the cognitive space. Since cognitive elements change with time, at successive time instants they occupy different positions, describing trajectories that reflect the behavior of the agent. At some instant $t = \tau$, a cognitive element $\sigma(t)$ is represented in a cognitive space CS_K as a vector σ, defined as:

$$\sigma = (a_0, a_1, \ldots, a_k) \tag{7}$$

where the dimensional factors $a_i \in \mathbb{C}$ represent the intensity and frequency shift of quality ω_i in the cognitive element.

3.3 Cognitive Dynamics

One of the main characteristics of intelligent behavior is the orientation towards the achievement of motivations. These motivations can take various forms according to the cognitive context (e.g. drives, desires), but they all share two fundamental characteristics: (i) they represent an intended situation; (ii) they act as a motivating force driving agent's behavior. A cognitive element that represents an intended situation is called a *motivator*. On the other hand, an intended situation is relative to a current situation, represented by cognitive elements called *observations*, which result from inward flows associated to activities like perception.

The difference between observations and motivators produce the main forces underlying agent's cognitive dynamics. The cognitive activity is consequently guided by the maximization of the flows that lead to the reduction of the distance between observations and motivators. For an agent to succeed in reducing that distance, it needs some form of mediation that supports the transformation of the motivating force into applied force to act in order to change the current situation. When a cognitive element plays this role we call it a *mediator*. The commitment to apply a motivating potential through a specific mediator results in a new element called an *achiever*, which support the concrete action that leads to the change of the current situation and to the corresponding movement of the observations in the cognitive space, as illustrated in figure 2.a.

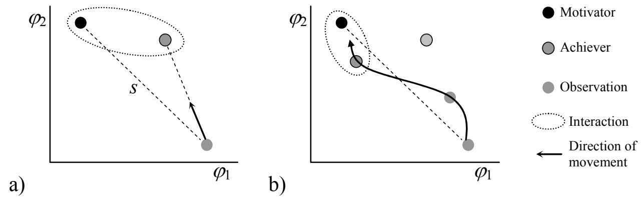


Figure 2. Elements participating in the achievement of a motivator (two-dimensional cognitive space - intensity information not shown).

As we can observe in figure 2.a, the direction of the observation's movement may not be the exact direction of the motivator. Besides that, the velocity of the movement can also change during the achievement process. Even if the achiever is aligned with the motivator, the dynamics of the environment (either internal or external) can influence the movement of the observation. This means that the agent must continuously adjust its behavior in order to succeed in the achievement of its motivators, especially in uncertain and dynamic environments. Figure 2.b shows a possible trajectory resulting from the adjustment of agent's behavior by switching to a different achiever. This second achiever can be a new option or a refinement of the previous achiever through a planning process. Independently of the specific processes that generated the new achiever, the forces that led to that change underlie all the cognitive dynamics of the agent. In the Flow Model the emotional phenomena are considered the expression of those forces, which can be characterized as *emotional dispositions*, as presented before.

In the cognitive space, the cognitive dynamics can be described by the movements of cognitive elements, and the associated emotional disposition defined by the evolution of the distance s and velocity v relative to the motivators. That is:

$$ED \equiv (\delta s, \delta v) \quad \text{where} \quad \delta s = -\frac{ds}{dt} \quad \text{and} \quad \delta v = \frac{dv}{dt} \tag{8}$$

Considering two generic cognitive vectors σ_1 and σ_2 at some instant $t = \tau$, distance s and velocity v are defined as follows:

$$s = \|\sigma_1 - \sigma_2\| \quad \text{with} \quad \|\sigma\|^2 = \langle \sigma, \sigma \rangle \quad \text{and} \quad v = \frac{ds}{dt} \tag{9}$$

where $\langle x, y \rangle$ represents the scalar product of vectors x and y.

These emotional disposition tendencies are behavioral forces that constrain the cognitive processes of an agent. Therefore, the dynamics resulting from these forces are, at the same time, a result of the cognitive activity and a constraint that influences it, reflecting the symbiotic relation between emotion and cognition, as we proposed initially.

3.4 Base Cognitive Mechanisms

The relation between adaptive behavior, emotion and high level cognitive processes is a main characteristic of the proposed model, allowing the adaptation to uncertain and dynamic environments and to focus the high level cognitive processes, such as reasoning, to cope with their computational complexity. Underlying these characteristics is the ability to take advantage of past experiences. These experiences are reflected in the evolution of cognitive elements, producing trajectories in the cognitive space. Depending on the agent type and complexity, these trajectories are assimilated, or not, into the agent's cognitive structure. For instance, simple agents may just depend on the instantaneous flows associated to affective forces. The *kinesis* of some organisms are an example of this type of behavior (e.g. bacterial *chemotaxis*) [15]. On the other hand, complex agents are able to assimilate these trajectories into the cognitive structure forming affective memories of past experiences. The cognitive processes of these agents are then able to use the past experience trajectories to anticipate future situations in order to maximize the achievement flows that lead to the achievement of their motivators.

Considering discrete time $t = 1, 2, \ldots n$, where $n \in \aleph$ represents the current instant, a trajectory σ^* of a cognitive element $\sigma(t)$ is represented as an ordered set of signal vectors representing the cognitive element at successive time instants. That is:

$$\sigma^* = (\sigma^1, \sigma^2, \ldots, \sigma^n) \tag{10}$$

When an observation is assimilated into the cognitive structure, an affective potential, corresponding to the energy of the associated emotional disposition, is also assimilated forming an affective memory, which can be related to what is referred by other authors as *emotional memories* (e.g. [1, 5]). These accumulated affective potentials will thereafter constrain the cognitive activity of the agent. Three main mechanisms underlie the cognitive activity of an agent with trajectory assimilation ability: activation mechanism; attention mechanism; and combining mechanism.

Activation Mechanism. The activation mechanism, produces activated affective potentials resulting from interactions between the elements in the cognitive structure. An activated affective potential p_{act} is a composition of the affective potentials p_{af}, accumulated from past experiences, according to the intensity of the interaction between the cognitive elements. Considering a cognitive element $\sigma_1(t)$ interacting with another cognitive element $\sigma_2(t)$ at some instant n, the activated affective potential p_{act} is:

$$p_{act}(\sigma_1^n) = \sum_{\tau=1}^{n} \eta(\sigma_1^n, \sigma_2^\tau).p_{af}(\sigma_2^\tau) \tag{11}$$

where η is the interaction gain, which is determined by the similarity between elements and defined as:

$$\eta(\sigma_1^i, \sigma_2^j) = \frac{1}{1 + \left\|\sigma_1^i - \sigma_2^j\right\|^2} \tag{12}$$

The activated affective potentials determine the susceptibility of an element to participate in cognitive processes.

Attention Mechanism. The attention mechanism focuses the attention of the cognitive processes to specific cognitive elements according to their activated affective potential. This mechanism acts like an energetic barrier, producing an *attention field* formed by the elements with enough activated affective potential to bypass the barrier. Only the elements in the attention field are considered by the high-level cognitive processes, such as reasoning and deliberation. This is the main mechanism responsible for focusing the high-level cognitive processes.

Combining Mechanism. During cognitive activity multiple cognitive potentials and flows are generated and changed. For instance, reasoning processes shape the overall form of a cognitive element by changing the characteristics of its potentials, producing potentials and flows that reflect the subjective evaluations made during the reasoning activities. At the same time, emotional disposition potentials and flows are generated under the influence of different motivators. The base mechanisms responsible for combining these multiple influences are generically called combining mechanism. Motivators are the key elements in this mechanism, producing the driving force of an agent's cognitive activity. The evolution of cognitive elements is therefore related to the influence of the motivators. This influence is determined by the motivators' intensity and by the interaction gain between a cognitive element and each motivator, and it is regulated by the combining mechanism. For instance, the potential generated by an observation moving towards some motivator is attenuated or amplified according to the motivator intensity and the interaction gain between them. The variation of the motivators' intensity allows the agent to adapt its cognitive activity according to the situation, by emphasizing different influences. Due to space limitations it is not possible to detail these mechanisms further. However, they are the base machinery underlying the cognitive activity of an agent. In fact, these mechanisms are different aspects of the cognitive activity, operating together. Their combined activity generates cognitive dynamics that lead to decision-making and determine the overall agent behavior. Next we will concretize these aspects by showing how the balance between the influence of different motivators and the variation of the attention level allows focusing the reasoning processes.

4 EXPERIMENTAL RESULTS

To illustrate how the proposed model allows to focus the high level cognitive mechanisms, such as reasoning, we will consider the problem of reasoning under uncertain and changing conditions in a social interaction context. The experimental framework was implemented using the *AFlow* prototype testbed and consists of an agent society where the agents have different behavior profiles and are able to reason about the other agents in order to coordinate their activities. Each agent is characterized by a reliability profile with achievement level in the interval [0, 1] (0 representing total failure and 1 representing complete success) and by coordination characteristics that allow to determine the interest of a joint coordination from the point of view of the reasoning agent. Three sets of coordination characteristics were defined: *low-favorable* coordination; *average-favorable* coordination; and *highly-favorable* coordination. To simulate an uncertain and dynamic environment, both the reliability profile and the coordination characteristics were specified by random distributions, the coordination characteristics with uniform distribution, and the reliability profiles with a normal distribution, as shown in table 1.

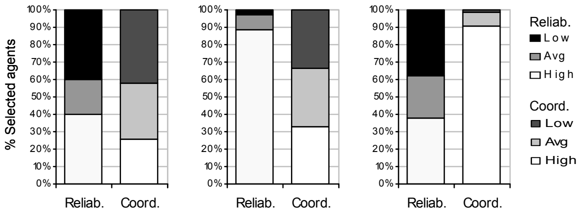
Table 1. Reliability profiles.

	Normal distribution, std. dev. = 0.1
Profile	*Mean Achievement Level*
Low	0.2
Average	0.5
High	0.8

Reliability profiles and coordination characteristics correspond to two distinct types of environmental conditions. In the first case, although the conditions are relatively adverse due to high uncertainty and change, it is possible to use past experience to deal with future situations. In the case of coordination characteristics the conditions are extreme, since it isn't possible to extract any information from past interactions due to uniformly random change.

Three experiments will be reported regarding different aspects of the proposed model. In these experiments one specific agent was observed. This agent has a reliability motivator, mot_{Reliab}, driving the agent to select highly reliable agents, and a coordination motivator, mot_{Coord}, driving the agent to select agents with highly favorable coordination characteristics. The intensity ε of these motivators changed according to the experiment. The intensity of the energetic barrier, which determines the contents of the attention field, was regulated by a normalized *attention level* parameter $\gamma \in [0,1]$, determining the proportion of total options in the attention field (when $\gamma = 0$ only one option is allowed in the attention field). Each option corresponds to a specific agent. The environment was composed by 30 agents. The results presented are average values over 10 runs of 1000 agent coordination episodes per experiment.

In the first experiment the *attention level* was set to $\gamma = 0$ (only one option is allowed in the attention field). In this way the behavior of the agent is determined only by emotional disposition forces (no alternative options to ponder by reasoning). To study the specific influence of each motivator only one motivator was active at each time. Figure 3.a show the results for the coordination motivator and figure 3.b show the results for the reliability motivator.



a) $\gamma = 0$
$\varepsilon(mot_{\mathrm{Coord}}) = 1$
$\varepsilon(mot_{\mathrm{Reliab}}) = 0$

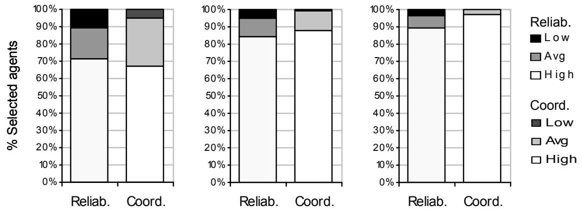
b) $\gamma = 0$
$\varepsilon(mot_{\mathrm{Coord}}) = 0$
$\varepsilon(mot_{\mathrm{Reliab}}) = 1$

c) $\gamma = 0.1$
$\varepsilon(mot_{\mathrm{Coord}}) = 1$
$\varepsilon(mot_{\mathrm{Reliab}}) = 0$

Figure 3. Environmental and cognitive influences on agent behavior (reliability and coordination characteristics of the selected agents).

As we can observe in figure 3.a, under the exclusive influence of the coordination motivator the emotional influence was maladaptive, leading the agent to select mainly agents with low reliability and coordination characteristics. This is a result of the random change of coordination characteristics, not providing any useful information from past experiences to guide the agent behavior. By contrast, in figure 3.b we can observe that when there were exploitable environmental regularities, as was the case under the exclusive influence of the reliability motivator, the agent was very efficient in its adaptation.

In the second experiment, the *attention level* was set to $\gamma = 0.1$ to allow more than one option in the attention field (10% of total options were allowed). Figure 3.c shows the results under the exclusive influence of the coordination motivator. As we can observe, in this case the agent was very efficient in selecting agents with highly favorable coordination characteristics. This improvement results from the possibility to reason about different options, which clearly indicates the importance of reasoning to balance emotional influence. However, the affective-emotional aspects are determinant to focus the reasoning processes. This balance between emotional and reasoning influence can be regulated through the variation of the *attention level*. Figure 4 shows the results of the combining influence of both motivators under different *attention level* values.



a) $\gamma = 0.1$
$\varepsilon(mot_{\text{Coord}}) = 1$
$\varepsilon(mot_{\text{Reliab}}) = 1$

b) $\gamma = 0.3$
$\varepsilon(mot_{\text{Coord}}) = 1$
$\varepsilon(mot_{\text{Reliab}}) = 1$

c) $\gamma = 0.5$
$\varepsilon(mot_{\text{Coord}}) = 1$
$\varepsilon(mot_{\text{Reliab}}) = 1$

Figure 4. Agent behavior with different attention level values.

As we can observe, even with high focusing of the reasoning processes it is possible to obtain effective results. For instance, with a 50% reduction of the considered options, the agent achieves a near-optimal behavior. The effect of the *attention level* variation is more visible on the coordination results due to their direct dependence of the reasoning processes. However, due to the combined influence of both motivators, the coordination results also have influence on the emotional disposition formation, leading to the reduction of the exploratory behavior of the agent, which improves its reliability results as more experiences occur. This is an example of how the symbiotic integration between emotional and cognitive aspects leads to an improved overall agent behavior in dynamic and uncertain conditions, as is the case.

5. DISCUSSION

The relationship between emotion, reasoning and decision-making has been an active area of research, in particular after relevant theoretical and experimental work (e.g. [1, 2]) presented concrete evidence of this relationship. However, the focus of the work concerning emotions in intelligent agents has been on modeling and implementing emotional aspects and not much in combining emotion and cognition. In this area, one main line of research has been on appraisal theories based models (e.g. [16]). Appraisal theories emphasize the structural aspects of emotion elicitation, but don't say much about the underlying processes [17]. On the other hand, the aspects of adaptation and learning, which are directly related to emotion, as experimental studies show [2] are not addressed. A complementary line of research addresses these limitations by adopting a "design-based" approach (e.g. [6]) where emotional mechanisms are embedded within an overall architecture in a resource-bounded agent. Although this approach explicitly addresses the problem of integrating emotion and cognition for intelligent behavior under resource-bounded conditions, a sharp line is drawn between cognitive and emotional processing, where emotion plays essentially an interruptive role [18, 19], shifting the attention of the cognitive processes due to environmental contingencies or when a conflict exists between goals and current state.

Our proposal departs from these approaches by modeling emotion and cognition as two symbiotically integrated aspects of agent cognitive activity. This means that the relation between emotion and cognition occurs not only at a functional specialization level. Instead it is intrinsic to all cognitive activity and to the nature of the involved cognitive elements. Recent experimental results support this view, indicating that in humans, emotion and higher cognition can be truly integrated, that is, at some point of processing, functional specialization is lost and emotional and cognitive influences inseparable [3]. On the other hand, two important aspects characterize emotional phenomena, the relation with adaptive behavior and the relation with reasoning and decision-making. This two-sided relation has remained almost unexplored in cognitive models due to the strong emphasis on functional division, which hinders the intrinsic relation of emotion and cognition as a whole. However, as some authors have proposed (e.g. [20]), it is a fundamental aspect that enables effective intelligent behavior in concrete environments. This relation between adaptive behavior, emotion and high level cognitive processes is a main characteristic of the proposed model, enabling the adaptation to uncertain and dynamic environments and allowing to focus the high level cognitive processes.

Future research will aim at further refining the integration of emotional and cognitive aspects in planning processes, and to study related aspects such as the dynamical stability of the cognitive processes under the influence of multiple motivators.

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