Ontology-Based Resource Interoperability in Socio-Cyber-Physical Systems

Collaboration scenario

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***Abstract*—The paper proposes a core ontology of socio-cyber-physical systems for resource interoperability. The ontology comprises the main concepts and relationships which are identified as relevant to model such systems. The approach considers a socio-cyber-physical system comprising cyber space, physical space, and mental space. In the ontology, these spaces are represented by sets of resources. The ontology provides the resources with a common vocabulary to share information and services and therefore makes these resources interoperable. The core ontology is specialized for a socio-cyber-physical system embedded in robotics domain. Technology of online communities is proposed to be used for resource communication.**

Keywords—socio-cyber-physical system; ontology; interoperability; collaboration

I. Introduction

Socio-Cyber-Physical Systems (SCPSs) are a new generation of networked systems, wherein human resources are an integral part. In these systems, humans are not only service consumers, but "collaborators" as well. Collaboration of humans and cyber resources provide great benefits. For instance, cyber resources can learn from humans in the process of their collaboration and then, if it is possible, to substitute the humans. Humans and cyber resources can jointly do a job that cyber resources themselves are not able to do. Distribution of a task assuming combination of routing work and intelligence between cyber resources and humans may facilitate task execution or even lead to new task solutions. Many other examples of beneficial cyber- and human collaboration can be found. The SCPSs uniting cyber- and social worlds naturally, provide a great opportunity to take advantages from collaboration of humans and cyber resources.

Resource interoperability is a prerequisite ensuring that the collaboration can emerge. Partners must communicate to maintain a set of shared beliefs and to coordinate their actions towards the shared goal [1]. The key to the interoperability between systems (applications, agents, resources, etc.) is sharable information and services. Ontologies provide the means for the information and services become sharable due to the explicitly specified semantics [2].

Interoperability of SCPSs' resources is the focus of the present research. A core ontology of socio-cyber-physical systems is proposed. This ontology is specialized for a resource collaboration task. Resource communication is organized through an online community by messaging. The main advantage of this is an explicit form of information being communicated.

The rest of the paper is structured as follows. Section 2 provides an overview of the related research. Ontology of a socio-cyber-physical system is proposed in Section 3. In Section 4 two collaboration scenarios for cyber- and human resources are discussed. Some concluding remarks are summarized in the Conclusion.

II. Related Research

The problem of interoperability in cyber-human environments is treated as the problem of meaningful communication between the partners from different worlds. In this direction, an ontological semantic technology was proposed [3]. The technology relies upon repositories of world and linguistic knowledge. The repositories consist of the ontology, containing language independent concepts and relationships between them; one lexicon per supported language; and the Proper Name Dictionary (PND), which contains names of people, countries, organizations, etc., and their description anchoring them in ontological concepts and interlinking them with other PND entries [4]. This technology is used, for instance, for robotic reasoning [5], for communication between a firefighting-robot and a human [6], and for human-robot collaboration in CHARMS – an environment of hybrid human-robot-agent-collaboration [7].

The analysis of ontologies used in cyber-human environments has shown that most approaches tend to develop own ontologies. Some of these approaches take a general ontology as the basis for domain-specific ontologies. For instance, DOLCE[1] ontology is used in the manufacturing control area for communication between autonomous and cooperative holons (physical resources and logic entities) [8]. UFO (Unified Foundational Ontology)[2] is proposed to be used for business modeling [9] and to integrate several collaborative software applications aiming at effectively collaboration

[1] http://www.loa.istc.cnr.it/old/DOLCE.html
[2] https://oxygen.informatik.tu-cottbus.de/drupal7/ufo/?q=node/1

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support within organizations [10]. UFO and SUMO (Suggested Upper Merged Ontology)[3] were investigated as the upper-level ontologies to build the foundation of an IEEE standard ontology for robotics and automation [11].

OpenCyC[4] and UFO ontologies seem to be the most popular to model enterprises and particularly SCPSs (e.g., [12], [13]). The popularity of OpenCyC is due to the presence of common sense knowledge. Such knowledge can be naturally used to organize communication between cyber resources (e.g., robots) and humans. UFO ontology was constructed with the primary goal of developing foundations for conceptual modelling. The engaging quality of this ontology is a detailed account of universals such as unary or binary relations [14]. A core ontology suitable to model SCPSs is expected as a result of the NIST project "Reference Architecture for Cyber-Physical Systems" [15]. The project addresses the development of a cyber-physical system framework with common vocabulary, analysis methodology, reference architecture concepts and use cases to serve as the basis for shared development, information exchange, and new formal methods applicable across domains. This project is in progress so far.

The research discussed in this paper proposes concepts and relationships to model a SCPS at the resource level, i.e. to represent the SCPSs' resources, their properties, actions they are carrying out, relationships between them, etc. in the given situation. The proposed ontology can be extended and specialized in a concrete application domain. At the same time, the upper concepts of the proposed ontology can be related to general concepts of existing general ontologies.

III. Ontology of Socio-Cyber-Physical System

The ontology of SCPS (Fig. 1) comprises the main concepts and relationships which are identified as relevant to model such systems. This ontology is inspired by the ontology for resource self-organization in socio-cyber-physical systems [16]. As it is known, a SCPS consists of cyber space, physical space, and mental space [17]. These spaces are represented by sets of *resources*. The physical space consists of various *physical devices*. These devices are supplied with computing components. Such components allow the devices to perform computations, process data, information and knowledge, communicate, and as a consequence be interoperable. The physical devices united on the communication basis organize the *cyber space*. This space in the ontology is represented by *cyber resources*. Inherence of computing components in cyber resources is modelled by the equivalence axiom:

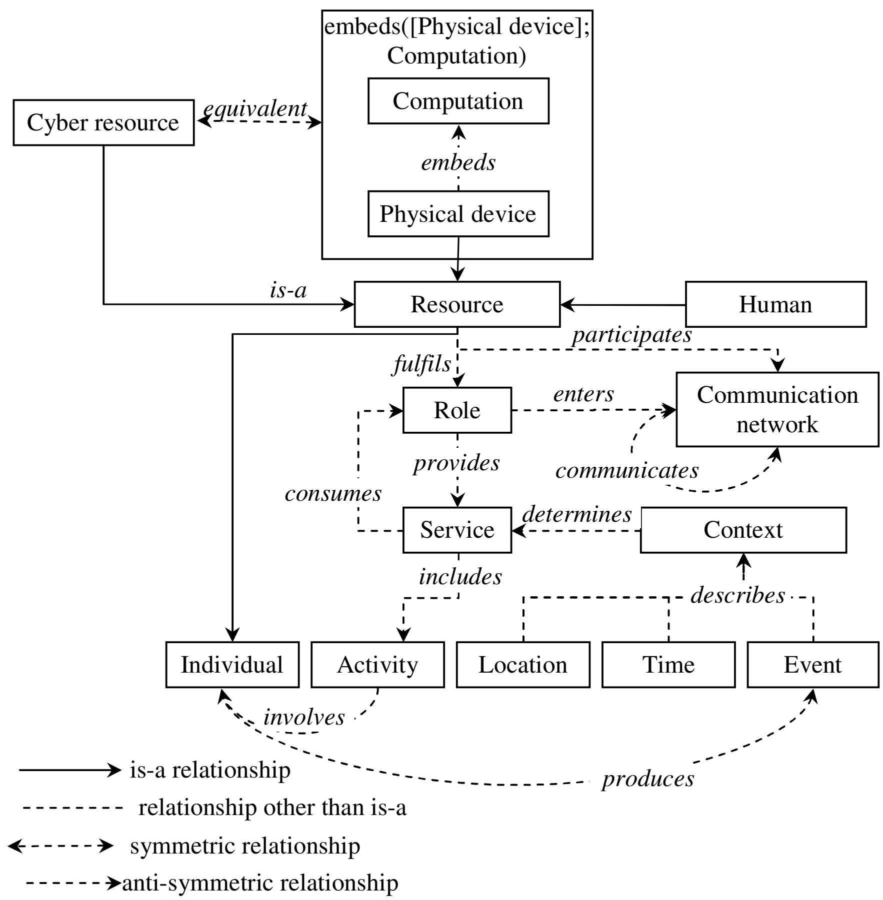

Fig. 1. Ontology of socio-cyber-physical Systems.

[3] http://www.adampease.org/OP/

[4] http://www.opencyc.org

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(is-a Physical device) and (embeds some Computation) ≡
≡ Cyber resource.

The mental space is represented by *humans* with their knowledge, mental capabilities, and sociocultural elements.

Resources provide *services* in accordance with *roles* which these resources *fulfill* in the current situation (context). In the ontology this idea is modelled as the resources fulfill *roles* and the roles, in turn, provide *services*. *Role* is a position that a resource can take in the context. The ontology describes an abstract role. Corresponding specialization of this concept is required to denote a specific resource's role. Roles can be specialized for the SCPS, the communication network, or the application domain. The resources may change their roles in the process of scenarios executions. *Services* provided by one resource role are *consumed* by other ones.

Service is some action or effort that is done to satisfy a need or to fulfill a demand. In other words, a service *includes* some *activity*. Services can be a simple service that a certain resource provides or a complex service requiring collaboration of several resources. Sorts of the services depend on the domain in which the SCPS is used. They may be computational functions, actions, communication services, etc. Different service perspectives are harmonised in the core reference ontology for services (UFO-S ontology) [14]. This ontology deals with services in terms of commitments attained at three phases of the service life-cycle: service offer, service negotiation, and service delivery.

The service concept in the ontology proposed in this paper is reconciled with the core reference ontology for services (Fig. 2). The service life-cycle phases take place in the result of *service event*. The role of resources offering services is *service provider*; the role of resources consuming the services is *service consumer*. *Service offer* is the initial phase in which services are *presented* to target customers. *Service negotiation* is characterized by the *interaction* between customer and provider in order to establish an agreement about their responsibilities. *Service delivery* concerns the execution of actions needed to fulfill the established commitments. The concept *service* from the SCPS ontology is declared as equivalent to the "service delivery" concept from the service ontology (*Service delivery* ≡ *Service*).

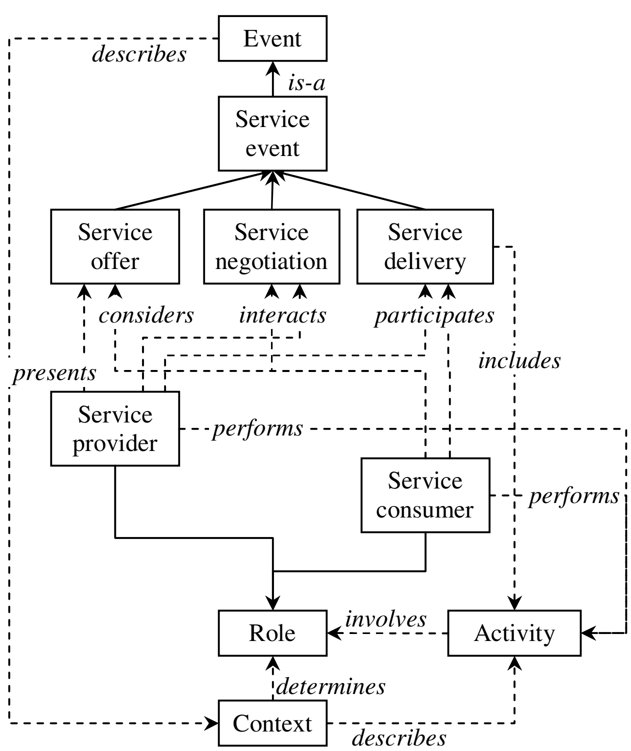

Fig. 2. Service event.

Services expected in the current situation are determined by *context*. Information systems use various inferences, procedures, rules, etc. to analyze context and determine what services are expected. In ubiquitous and pervasive environments, a widely adopted definition of *context* is any information that can be used to characterize the situation of an entity [18]. Such context is characterized by categories of individuality, activity, location, time, and relations [19]. On the other hand, *context* is a situation, which could be seen as a course of events; this situation evolves organizing new relationships between the entities involved in it [20]. Uniting the two perspectives, the ontology proposes to characterize context by categories of *individual*, *activity*, *location*, *time*, and *event*. The *individual* category describes the entity itself. *Location* and *time* provide the spatio-temporal coordinates of the entity. *Activity* is a process of performance of the task the entity is involved in. *Event* is occurrence happening at a determinable time and place; event can be produced by either some entity or some factors. Events are instantaneous, activities last in time [21]. The relations category is omitted since it is not a contextual category. It is a standard category used to characterize ontology concepts and comprises all the relationships specified in the ontology.

Interoperability of the SCPS' resources is supported by communication mechanisms. *Communication network* is an association of resources interconnected to information exchange. The resources joint this network with communication *roles* defined for this network. This perspective complies with the Core Ontology for Semantically-Interlinked Online Communities (SIOC) [22].

In the paper, the resources are proposed to use the technology of online communities to communicate, i.e. in the ontology, *online community* is a kind of *community network*. *Online community* is a virtual community whose members interact with each other via the Internet. As opposed to social networks, an online community unites its members (cyber- and social resources here) based on a common interest or goal. The specialization of the proposed ontology for resource communication through online community is represented in the ontology slice (Fig. 3).

The presented ontology is considered as a core ontology [23]. In the domains of ontology usage, the ontology concepts are supposed to be extended and specialized.

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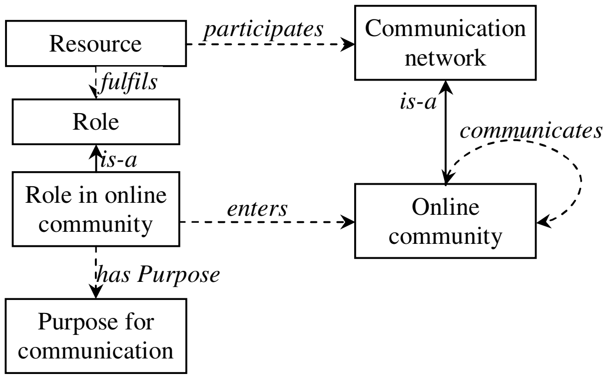

Fig. 3. Ontology specialization for online communities.

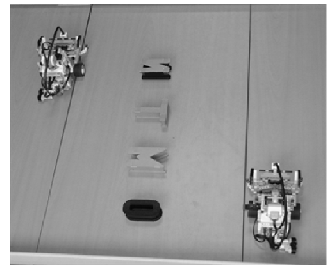

Fig. 4. Robots assemble "ITMO" word

IV. Resource Interoperability in Collaboration Scenarios

Ontology-based resource interoperability is demonstrated by two scenarios of resource collaboration. In these scenarios cyber resources are represented by Lego Mindstorms EV3-based robots. The robots have a task to assemble the word "ITMO" from mosaic Russian 3D characters (Fig. 4). The characters are scattered along the robots' ways. Each character is of a unique color because of the robots cannot identify types of the characters (letters), but they can recognize colors. The robots are capable to search for, pick up, and relocate characters.

The SCPS ontology specialized to the task above is presented in Fig. 5. The assembly scenario supposes that either one robot participates in the *assembly* process or several robots collaborate to perform the *assembly task*. In the former case, *assembly task* is accomplished by one instance of the concept *Robot*, in the latter case, by a set of instances. The assembly task is to assemble a *product* from *components*. The word "ITMO" is specified as an instance of the concept *Product* in the ontology; the characters are instances of the concept *Component*.

The scenario distinguishes the following resources' roles. For the SCPS, the role of *executives* for robots and the role of *consultants* for humans are provided for. In the online community, robots may fulfill the roles of *knowledge recipient* and *knowledge providers*; the humans' role is *knowledge provider*. The resources are jointed the community automatically. At first, robots are considered to fulfill the role of *knowledge recipient.*

The robots' knowledge is represented in their own ontologies. The assembly task in these ontologies is specified as a sequence of actions. These actions correspond to subclasses of the *Activity* concept specified in the SCPS ontology. Each action is characterized by preconditions (inputs) for the start of the action and effects (outputs) the action results in. The sequence of action for the considered task is "Search for a character → Character recognition → Character relocation". The action of character recognition assumes recognition of the type of the found character and determination if this character belongs to the word being assembled. If the word does not include the character, the following action is "Search for a character" again.

The scenario does not consider the concept of services to the full extent. It is limited to the service delivery phase. At this phase, the role of *knowledge recipient* corresponds to the role of *service consumer* and the role of *knowledge provider*

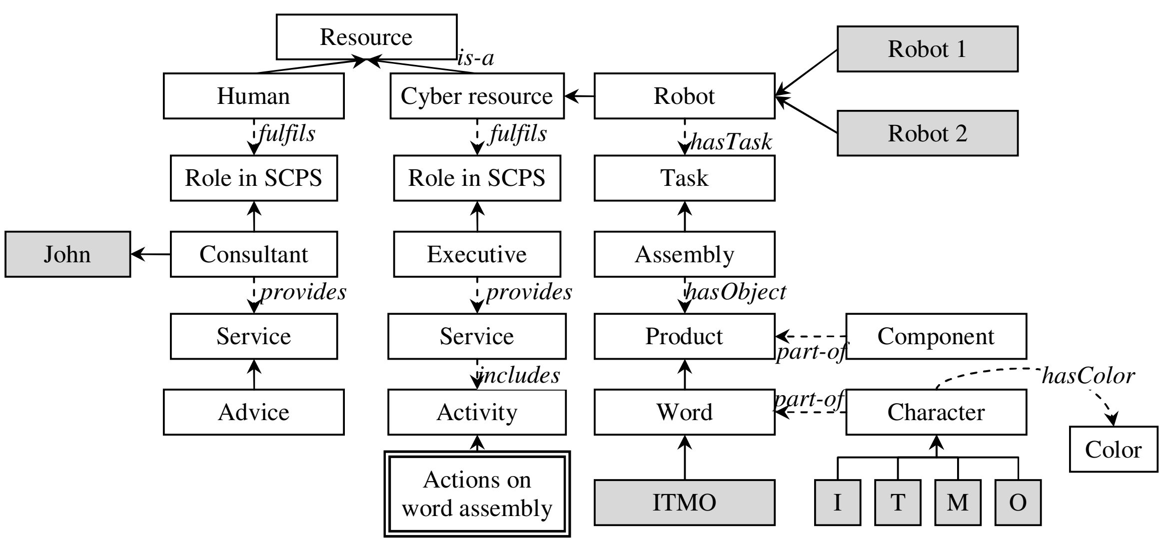

Fig. 5. Word assembly task.

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corresponds to the role of *service consumer*.

A. Robot-Robot Collaboration

Two robots with the same functionality participate in the scenario in question. Initially, the assembly task does not imply collaboration. The process of assembling is distributed between the robots as follows. Each robot knows the character which it should search for and relocate, and the spot for this character in the word being assembled.

When a robot puts a found character in its place, it communicates with the other robot to inform it about which character (to be more precise, character of which color) and in which position is placed. The mutual communications provides the both robots with knowledge about all the characters comprising the word and their positions. As a result the robots become capable of collaborating.

The communication process through the online community is organized as follows. The robot that has fulfilled a part of the task enters the online community with the role knowledge provider. It sends an informing message into the community. In the message the ontology vocabulary is used. The message format is

<*Type, Resource_Send, Resource_Recip, Product, Component, Service, Content, Status*>,

where *Type* is a message type, *Resource_Send* is a resource name (an instance of the concept Resource) sending the message, *Resource_Recip* is a name of the resource or to that the message is intended for (if this name is omitted, the message has no specific recipient and sent into the community as a public message), *Product* is a name of the product being assembled (an instance of the concept Product), *Component* is a name of the component the resource deals with (an instance of the concept Component), *Service* is a service, procedure, function, or action that the resource has been performing, *Content* is specific information relating to the task, *Status* is a status of the task execution (status can be one of Ready, Failed, or Suspended). *Resource_Recip* may be represented by a role name, which means that the message is addressed to a set of resources fulfilling the given role.

For the scenario under consideration, a robot informs the online community that it has relocated the character "T" into the position with coordinates XYZ: <*Notify, Robot1, , ITMO, T, Character relocation, T, x1, y1, z1, Ready*>. The content of this message (T, x1, y1, z1) represents inputs (T) and outputs (x1, y1, z1) for the action of character relocation. Robots caring out the task on assembly of the ITMO product read this message and if the knowledge containing in the message is new for them, they supplement their ontology with it. When the word has been assembled, all the robots participating in the process (two robots in the given scenario) know the whole procedure of task execution.

In the paper, implicit and explicit forms of robot collaboration scenarios are proposed. The both forms suppose that initially robots are not aware if they have any partners to collaborate.

In the implicit form of the scenario the online community plays a role of black box. A robot moves along its way, finds a character and checks if this character belongs to the assembled word. If the word comprises the found character then the robot picks it up, informs the community that it is going to carry the character to the position designated for it, and does this. The other robot fulfilling the same task becomes aware of the character that has been found and relocated. Going along its way, it selects any character lacking in the word currently and follows the scenario with informing the community appropriately.

In the explicit form, a robot, which found an appropriate character, informs the online community about this. If there is a robot that is fulfilling the same task then this robot sends a notification message directly to the first robot. The message contains information which robot is ready to collaborate. Namely, which robot is fulfilling the same task and what it has been doing. Further communications are made between the two robots.

B. Human-Robot Collaboration

The scenario of robot-human collaboration supposes that humans support robots in their actions. In this scenario, robots are not aware of characters positions in the word. Humans control the locations of the characters in order to these characters would form the word. When a robot finds a character it recognizes it and asks humans about the character position. If the word being assembled comprises the found character then a human consultant informs the robot about the coordinates where it should put the character. Otherwise the robot receives a message to go on its way. As soon as the word has been assembled, the robots stop acting.

The communication process through the online community in this scenario is as follows. The robot enters the online community with the role of knowledge recipient. It sends a message in the form

<*Request, Robot1, Consultant, ITMO, T, Character relocation, T, ?, ?, ?, Suspended*>,

where *Request* is the message type, *Robot1* in the name of the robot sending the message, *Consultant* is the resource role (the message is addressed to anyone who fulfils the role of consultant), *ITMO* is the product, *T* is the product component, *Character relocation* is the action being performed, *Suspended* status means that the action is stopped for some period. The content in the form *T, ?, ?, ?* informs that component *T* is the input for the action and that values for outputs (coordinates) are the subject of the request.

Using the ontology (Fig. 5) the message above is transformed into human-readable view as follows. To any consultant from Robot1: Robot1 is assembling the word "ITMO". Robot1 is dealing with the character T. Robot1 is ready to start the action "Character relocation". Robot1 asks coordinates x, y, z for the character "T".

According to the scenario, a human consultant (generally, the consultant is not mandatory human) should reply to the robot with coordinate values. In order to the human messages would be understandable by robots, humans are provided with templates. The template is produced based on the robot request.

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For the request of Robot1 the consultant replies in the following form:

coordinate x for character T is *value*,
coordinate y for character T is *value*,
coordinate z for character T is *value,*

where *value* is the value provided by the consultant. It is assumed here that the consultant is trained for the task in question. He/she uses a special procedure to determine the coordinated. The consultant judges the value of the coordinate y. This value assigns the line along which the word is assembled. The values v_x of the coordinate x are calculated as $v_x = x_0 + (i-1)w$, where x_0 – the value of the coordinate x corresponding to the location of the first character of the word, i – the position of the character in the word, w – constant ($w = 2w_l$, where $w_l -$ the average width of the characters).

V. Conclusion

The paper focus is resource interoperability in socio-cyber-physical systems. A core ontology of SCPSs intended to provide the resources with semantics is discussed. The ontology comprises general concepts and relationships for modelling SCPSs; it is supposed to be extended and specialized in real-world application domains. In the paper, the ontology is specialized for the robotics assembly task. Grounding the proposed ontology in a foundational ontology, such as DOLCE, UFO, or SUMO will enable to achieve a good quality ontology [9], [24]. It is a possible future research direction.

The presented ontology is used at resource collaboration scenarios for information exchange through an online community. At present, online communications become common human practice. Adaptation of this form to cyber resources allows the resources from different worlds share the common way of communication and enables to avoid recognition of different communication modalities.

The common ontology imposes some limitation. The resources have to use the ontology vocabulary to be understood by each other. If a resource is new regarding the socio-cyber-physical system, the vocabulary of this resource needs to be matched against the ontology in order to the resource would be capable to share its services. Matching is a time consuming process that requires additional efforts.

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