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# The Information Flow Problem in multi-agent systems

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A B S T R A C T

One of the problems related to the multi-agent systems area is the adequate exchange of information within the system. This problem is not only related to the availability of highly efficient and sophisticated message-passing mechanisms, which are in fact provided with by current multi-agent platforms, but also to the election of an appropriate communication strategy, which may also greatly influence the ability of the system to cope with the exchange of large amounts of data. Ideally, the communication strategy should be compatible with how the information flows in the system, that is, how agents share their knowledge with each other in order to fulfill the system-level goals. In this way, MAS designers must deal with the problem of analyzing the multi-agent system with respect the communication strategy that best suits the way the information flows in that particular system. This paper presents a formalization of this problem, which has been coined as the *Information Flow Problem*, and also presents a complete case study with an empirical evaluation involving four well-known communication strategies and eight typical multi-agent systems.

## 1. Introduction

The Multi-Agent Systems (MAS) paradigm is progressively becoming one of the most successful paradigms for developing complex applications, especially in distributed scenarios where communication among different entities is one of the key features. The paradigm is mainly based on the use of cooperative agents, where each agent handles some particular knowledge and a small set of specialized tasks, and is able to cooperate with the other agents in order to achieve some system-level goals, which produces a high degree of flexibility (Gruver, 2004). In fact, it is the social behavior of agents and how they interact, more than their individual capabilities, what makes multi-agent systems so powerful and versatile in many scenarios (Búrdalo et al., 2011). Lately, multi-agent systems have become increasingly sophisticated, with a growing potential to handle large volumes of data and to coordinate the operations of many organizations (Helsinger et al., 2004). In this context, one of the problems related to this distributed computing is the *exchange of information* within the system. Thus, the multi-agent architecture must necessarily provide a robust communication layer with appropriate message-passing mechanisms that enable the interaction processes, since they condition how the intelligent agents are able to interact and coordinate with each other.

However, nowadays the availability of such message-passing mechanisms is not the main issue to consider since, in fact, many current systems are already provided with highly efficient and sophisticated mechanisms. In real systems, the election of an appropriate communication *strategy* may also greatly influence the ability of the system to cope with large amounts of data, especially in open systems with a large number of agents that may dynamically enter or exit the system. Ideally, the communication strategy should be compatible with how the information *flows* in the system, that is, how agents interact and share their knowledge with each other in their way to achieve the system-level goals. Conversely, a strategy badly adapted to such information flow may produce a significant communication effort, which in turn may hinder the agents' cooperation. We have coined this problem as the *Information Flow Problem* (IFP), which is defined as how to exchange information in the most efficient and effective way in a multi-agent system, depending on the characteristics of the system. Basically, the IFP is related, first, to identifying the significant characteristics of multi-agent systems related to the information exchange, and second, to be able to relate the values of such characteristics in a particular multi-agent system to the communication strategy that best suits the way the information flows in that particular system.

In this context, the study presented in this paper proposes a generic formalization model of the IFP, the instantiation of the model in order to define some MAS scenarios or scenes, each with a typical information flow, and an empirical analysis comparing the performances of four well-known communication strategies in these scenes. For the empirical

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analysis, an evaluation framework has been developed. This framework first generates a series of synthetic test multi-agent applications according to some predefined characteristics in the model, and then executes each application on a real MAS called Magentix2, once for each communication strategy. For each execution, the framework collects some run-time information about the message-exchange process. Then, the paper introduces a set of performance metrics, directly derived from such run-time information, in order to quantitatively analyze and compare the behavior of the strategies.

In addition to the general contributions regarding the IFP, part of the work proposed in this paper can also be considered a step towards solving one of the problems of Agent-Oriented Software Engineering (Jennings, 1999), namely the availability of testing techniques which can provide the MAS developers with appropriate software development processes and tools (Houhamdi, 2011). The idea of these interaction tests is to observe emergent properties, collective behaviors or just to ensure that all agents in a group work properly together. Different approaches have tried to include or derive test cases during the development process. In Carrera et al. (2014), test cases skeletons are automatically generated while developing the MAS, while (Nguyen et al., 2009) or (Thangarajah et al., 2011) try to extend well-known agent-oriented methodologies including some types of scenario testing. In this context, both the evaluation framework and the performance metrics proposed in this paper can be used to analyze the system and to determine to which extent some particular factors or characteristics in a MAS affect the behavior of current, well-known communication strategies. Thus, such tools can be considered a testing environment from which MAS developers can benefit.

The rest of the paper is structured as follows. Section 2 introduces the Information Flow Problem in MAS. Section 3 presents the formalization of the problem. Section 4 uses the formalization in order to describe eight typical multi-agent systems, or scenes. Section 5 introduces the case study, including the description of the four communication strategies under study and the evaluation framework where the strategies have been incorporated; this framework is used to generate and execute several hundred test applications corresponding to the previously defined scenes. Section 6 presents the analysis of the results obtained from these executions, for which some performance metrics are defined. Finally, Section 7 presents the conclusions of the paper.

## 2. The information flow problem

In multi-agent systems, it is commonly accepted that communication among agents is no longer an issue. Agents usually communicate by some sort of peer-to-peer messaging mechanism, which is provided by the platform middleware and allows any agent to send information to any other agent (or to some sort of agent aggregation) in the system. In this context, this paper focuses not on the mechanism used by agents to communicate with each other, but rather on the information being communicated. In particular, the paper studies how this information or knowledge being shared by agents is exchanged, or *flows*, through the system (Zhuge, 2002). This section presents first a brief review of some of the most relevant information exchange strategies in the literature, and then introduces the concept of *information flow problem* as a general way to analyze the appropriateness of such strategies to different multi-agent system scenarios.

Many strategies in the literature have addressed the information exchange among agents. Some of these strategies have focused on making every piece of information in the system to reach all agents, like *broadcasting* or by using a *blackboard* (Corkill, 1991). These strategies have been suggested in scenarios in which global knowledge is required, or as a straightforward way to ensure that agents are always informed about any particular datum they may need. In scenarios where such global communication is not appropriate (or affordable, in terms of computational resources), and agents need to locate first the particular agents they want to communicate to, middleman (or *middle agent*) strategies have been used, with the middle agent usually being either a *matchmaker* (Sycara et al., 1999) or a *broker* agent (Wong and Sycara, 2000). A third group of strategies are based on the idea of *indirect* communication, such as overhearing, which is defined as indirect interaction whereby an agent receives information for which it is not addressee (Busetta et al., 2001; Legras and Tessier, 2003; Dignum and Vreeswijk, 2004; Kaminka et al., 2002). Proposed in several different scenarios, indirect communication schemes have been used to maintain social situational and organizational awareness (Rossi and Busetta, 2004; Tummolini et al., 2005; Gutnik and Kaminka, 2006), to enable team organizations (Legras Onera, 2002; Legras and Tessier, 2003), to monitor teams in a non-intrusive way (Kaminka et al., 2002; Alberola et al., 2011), to improve information spreading (Maity et al., 2013), and to develop advising systems (Aiello et al., 2002; Busetta et al., 2002). However, most of the times, overhearing is internally implemented by using message broadcasting, which is simple but computationally expensive, and may also be considered conceptually contradictory. This is because the overhearer role, as defined in (Malouf, 1995) for multi-party dialogues, is defined to exist in situations where the sender (speaker) is not always aware of who is receiving its (her) messages, apart from the specified receivers (addressees). An alternative technique for indirect communication is the use of tracing facilities, as it has been recently proposed by Búrdalo et al. (2011). Tracing in multi-agent systems has been traditionally focused on providing human users with debugging or monitoring information (Bellifemine et al., 2007; Collis et al., 1998; Serrano et al., 2012); but some other examples show the usefulness of tracing as a general indirect information scheme available to agents, as in Criado et al. (2013), where norm control in open MAS is performed by using an event-tracing approach.

Other approaches in the literature have focused on the analysis of the communication process within multi-agent systems, with the purpose of helping MAS designers by offering tools capable to optimize the communication processes among the designed agents. One of the most well-known approaches is Goldman and Zilberstein (2003), which tries to value communication decisions of agents by using minimum time as a performance-based metric. There are more recent approaches, such as Althnian and Agah (2015), where authors propose a genetic algorithm-based approach for learning the most appropriated communication strategy. In Wei et al. (2014), the performances of different coordination protocols for cooperative multi-robot teams are compared. Another interesting work is proposed in González-Pardo et al. (2010), where authors search for an optimal communication topology in order to avoid overhead in the communication process among agents. Finally, a proposal for computing optimal communication policies is presented in Chakraborty and Sen (2007). Most of the proposed solutions are static, theoretical models that typically need to be specified by defining closed environments where a lot of information about the communication processes must be fixed and known a priori. Moreover, most of the analyzed solutions also assume some constraints and requirements which limit their use in more open or dynamic environments. Conversely, the proposed model presented in this paper is generic enough to be used in the specification of a wide range of systems, including open and dynamic ones. Another advantage of this proposal, as explained below, is the evaluation framework associated with the model, which can be used to observe emergent properties in the communication flows resulting from agent interactions, and to make sure that a group of agents work correctly together according to the expected information flow.

On a separate, but related, issue, MAS have also been used as a tool to study the behavior of humans organizations by taking into account how information (or knowledge) flows through their members. An example of this is the simulation framework developed in Jolly and Wakeland (2009), where the goal is to examine the result of the interactions between individuals in an organization with different preferences regarding knowledge sharing, using game-theoretic analysis and a Netlogo agent-based simulation model. In a similar way, Zhuge (2006) proposes techniques for planning and simulating the knowledge flow networks of