An Approach to Modularization of Distributed Systems

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Abstract—Modularization is an important architectural principle underlying many types of complex systems. It tends to tame the complexity of systems, to facilitate their management, and to enhance their flexibility with respect to evolution. In software, modularization has been practiced and studied thoroughly in local, i.e. non-distributed systems. But very little attention has been paid so far to modularization in distributed systems. This is, in part, because distributed systems are inherently modularized, in the sense that the internals of each component of such a system is inaccessible to other components, thus satisfying the Parnas hiding principle. It is, however, the thesis of this paper that there is much to be gained by being able to treat groups of distributed components as modules, which we call distributed modules (or d-modules for short). In an analogy to conventional modules, a d-module should be able to hide its “internals,” by which we mean that only specified component parts of a given module—i.e., the distributed components that belong to this module—can be reached via a specified types of messages from the rest of the system. Moreover, we maintain that distributed modularization should provide some additional capabilities, which rarely, if ever, figure in conventional modularized systems. These capabilities include: (1) The ability to limit access to the internals of a given module to certain part of the system. (2) The ability to impose constraints on which kind of messages can be sent from a given distributed-module to its outside; and the ability to create AOP-like crosscutting modules. This paper introduces a model of modular distributed system, or MDS, which satisfies such capabilities, and which is implemented via the LGI middleware.

I. INTRODUCTION

Modularization is an important architectural principle underlying many types of complex systems. It tends to tame the complexity of systems, to facilitate their management, and to enhance their flexibility with respect to evolution. Indeed, modularity is clearly manifested in biological systems, and it has been employed in many types of physical artifacts.

In software, modularization has been practiced and studied thoroughly in local, i.e. non-distributed systems. And the constraints required for effective modularization in such systems is usually supported by programming languages.

But very little attention has been paid so far to modularization in distributed systems. This is, in part, because distributed systems are inherently modularized, in the sense that the internals of each component of such a system is inaccessible to other components, thus satisfying the Parnas hiding principle. This may seem to be a sufficient degree of modularization. And, it may not be obvious what other kind of modularization is relevant, or even possible, in distributed systems. Indeed, the literature seems to be silent on this issue.

It is, however, the thesis of this paper that there is much to be gained by being able to treat groups of distributed components as modules, which we call distributed modules (or d-modules for short). In an analogy to conventional modules, a d-module should be able to hide its “internals,” by which we mean that only specified component parts of a given module—i.e., the distributed components that belong to this module—can be reached via a specified types of messages from the rest of the system. Moreover, we maintain that distributed modularization should provide some additional capabilities, which rarely, if ever, figure in conventional modularized systems. These capabilities include: (1) The ability to limit access to the internals of a given module to certain part of the system. (2) The ability to impose constraints on which kind of messages can be sent from a given d-module to its outside. (3) The ability of different modules to overlap with each other. And (4) the ability to construct modules that implement AOP-like crosscutting concerns.

Such distributed modularization, we maintain, is particularly important for the increasingly fragmented distributed systems, consisting of highly heterogeneous components dispersed over the Internet, which may be written in different languages, may run on different kinds platforms, and may be designed, constructed, and even maintained under different administrative domains. We refer to such systems as having an open architecture, or simply being open. For a prominent example of this class of systems consider the concept of service oriented architecture (SOA)—which is being adopted by a wide range of complex distributed systems, such as enterprise systems, federations such as grids, virtual organizations (VOs), and supply chains.

The question is how to formulate and enforce the constraints on communication between system components, which is required for establishing distributed modularization. This cannot be done by means of programming language, as the various components of a given distributed system may be written in many different languages. And it cannot be done by controlling the code of the various components—particularly not in open systems—because one may have no access to the code of many of them, and no ability to control such codes.

1We prefer the term “local” over the more common, but somewhat awkward, “non-distributed” systems.

2The term “open system,” as used here, has nothing to do with the concept of open source.
It is, however, possible to enforce the required constraints on communication between components by means of a suitable middleware that is oblivious of the code of the communicating components, and is thus independent of it. Using such a middleware, we introduce in this paper a model of a modular distributed system, or MDS, which possesses the capabilities outlined above. And we provide a proof of concept for this model via an experimental implementation of it.

The rest of this paper is organized as follows: Section II motivates the need for distributed modularization via two examples. Section III introduces basic set of requirements that an MDS, and its implementation, needs to satisfy to be effective. Section IV discusses the type of middleware required for the implementation of our concept of MDS, and describes the specific middleware we use for this purpose. Section V describes a basic model of MDS; and Section VI extends this simplified model to our complete MDS model. Finally, Section VII outlines some open problems by our model of MDS; and we conclude in Section VIII.

II. MOTIVATING EXAMPLES

We consider here two examples of groups of components of a distributed system that provide a motivation for distributed modularization, and suggest some of the properties it should have.

A Monitoring Service: Consider a monitoring service (MS) designed for the management of large and geographically distributed system S. The function of this service is to log various events occurring in S, analyze them, and provide reports about the results of this analysis to certain qualified components of S; and to certain Internet cites outside of S, such as cites that represent outside auditors.

Suppose that MS consists of a group of components within S, partitioned into three disjoint sets: (1) the logs that accept and maintains various types of logging notices about events occurring in different parts of system S; (2) the analyzers that analyze the various logs, for various purposes; and (3) the reporters, who prepare reports of various results of this analysis for stakeholders such as auditors, managers, and performance optimizers—inside the system, or outside of it.

Suppose also that the APIs of these components provide the following operations, among others, intended for the use of clients outside of the MS group. The logs feature the operations: (a) store, which logs a given event, and (b) retrieve, which gets some information from a log. And the reporters feature and operation disclose which sends to the requester the type of reports it requires, if it is deemed to have the right for it.

Now, it should be clear that the information handled by the MS group of components could be very sensitive, depending on the nature of the system S itself. So that the integrity and confidentiality of this information could be critical and should be protected. One way to provide such protection is to ensure that the following constraint on communication of components of MS with the rest of the Internet are strictly enforced.

- The retrieve operation of logs should not be visible outside the MS group. (This is because the raw data in logs may be very sensitive, and should not revealed, uninterpreted, to anybody outside of MS. It should, of course, be accessible to other components of MS itself.)
- The disclose operation of reporters, is to be visible only to certain clients, inside S or outside of it, that represent stakeholder (such as auditors, and system managers) that have the need to get logging reports, and have the right (however defined) to see them.
- No other communication between components of MS and Internet cites outside of S is permitted.
- All other APIs provided by the components of MS are for internal use, and must be hidden from the rest of the system.

Distributed Sandbox: Systems need sometimes to use untrusted code—untrusted because the code has been developed by untrusted third parties, or if it is a newly developed part of the system, which has not been fully tested yet. The safety of the host system requires that the communication of such code with the rest of the host system, and with the Internet outside of the system, be carefully circumscribed and monitored. More specifically, one generally needs to impose constraints on which part of the host system can send what kind of messages to the untrusted code. And, perhaps more importantly, one need to constraint the kind of messages that the untrusted code can send to the rest of the host system.

In local systems this is accomplished by placing the untrusted code in what has come to be known as a sandbox, whose interaction with the host system is strictly constraints. Such constraints are generally imposed either by the language in which the host system and the untrusted code are written, or by the platform on which the system runs.

But when dealing with a distributed system, where the untrusted code can be distributed as well, we do not have a programming language to rely on establishing a sandbox, as different system components can be written in different languages. Nor can we rely on the platforms on which components run, as there may be many different platforms used by the system.

III. DESIRABLE PROPERTIES OF MODULAR DISTRIBUTED SYSTEMS

As a first step towards the introduction of our model of a modular distributed system (MDS) we describe in this section some of the properties that such a system should satisfy. These properties are realized by our basic model of MDS introduced in Section V which is a special case of the complete MDS model introduced in Section VI.

We start this section with a schematic description of the structure of an MDS, along with the terminology to be used throughout this paper. We then characterize and motivate the type of controls that one may want to impose over the flow of messages into d-modules and from them. And we conclude with some basic properties that the implementation of an MDS should satisfy.
A. The Basic Concepts and Terminology of MDS:

Schematically, an MDS is a set of distributed components grouped into a disjoint set of d-modules. (We will often refer to a d-module simply as a module, while the conventional language-based module will be referred to as a traditional module). Every d-module is composed of a set of one or more distributed components. But this is not a physical composition, but a logical one; having to do with the constraints on communication imposed on all component parts of a module. The modules of a given MDS are identified uniquely by their names, and each module can carry a profile consisting of an arbitrary list of labels. A module that contains just a single component is called a singleton.

We use the following notation for various structural aspects of a given MDS S. Specific modules of S are denoted by capitalized symbols, such as M, N, or M_i; and individual components of S are denoted by lower case symbols such as c, d, or c_i. A component c that belongs to module M is denoted by c^M; and the complement of module M with respect to the entire system S, is denoted by S\setminus M. Finally, actors operating over the Internet that do not belong to S are called the outside of S, denoted by S\setminus S.

Due to the focus of MDS on the flow of messages into and out of modules, we introduce the following notations about flow of messages with respect to a given module M of S:

- **inflow(M)** is the receipt by a component of M of a message sent from somewhere in S\setminus M.
- **outflow(M)** is the sending by a component of M of a message addressed to some components in S\setminus M.
- **import(M)** is the receipt by a component of M of a message sent from somewhere in S\setminus S.
- **export(M)** is the sending by a component of M of a message addressed to somewhere in S\setminus S.
- **innerFlow(M)** is the exchange of a message between the components of M;

These types of flows are depicted in Figure 1 which represents a system S whose components are partitioned into two types: (a) the components that belong to a module M, depicted by ovals: and (b) the rest of the components of S, depicted by squares. Also, shown, by irregular forms, two actors outside of S, somewhere over the Internet. Note that the components of M, in this figure, are intermixed with the other components of S, with no physical boundary that marks them as belonging to a single module—we shall see in Section V what makes a group of components into a module. The five types of flow defined above are depicted in this figure by different forms of arrows directed into a specific component c of M, or away from it.

B. Control Over the Flow of Messages in an MDS

The main purpose of modularization of distributed systems is to control the flow of messages into and out of the various modules of a system. The following is a presentation of the controls we require over the various types message-flow identified above. The definition of each of this type of control is followed by a discussion written in italics, and enclosed in a pair of curly brackets.

- **Inflow Control**: The imposition of constraints over which component of M can receive which kind of messages from which other modules of S.

  {Discussion: This control is analogous to the conventional concept of interface of the traditional modules. But it is significantly more general than the interface supported by most programming languages, in the following sense: While the conventional interface makes certain methods of a module visible everywhere in the system, the inflow control under MDS can make certain APIs of a module accessible only to specified modules. The need for such selective accessibility has been demonstrated in Section IV by the monitoring service (MS) example, where the disclose operation is to be accessible only to selected modules. Indeed such selective accessibility is featured by Eiffel [4], where it is called “selective export,” but most programming languages do not support this capability.}

- **Outflow Control**: The imposition of constraints over which component of M can send which kind of messages to which other modules of S.

  {Discussion: While inflow control—the only control provided by traditional modularization—is effective in protecting the internals of a given module M from the rest of the system (namely from S\setminus M) it does not protect M from M. Because the inflow control leaves the internals of M free to send arbitrary messages to components in S\setminus M, which may change the behavior of the system in unpredictable manner. This means, in particular, that the statement often made about conventional modularization

\[3^\text{This is a simplification, d-modules do not have to be disjoint under our complete MDS model.}\]
that the hidden internal of a module can be changed freely without affecting the system—as long as the public interface is implemented correctly—is not justified. This problem is particularly stark in the case of untrusted code discussed in Section [II] which needs to be placed in a sandbox to protect the system against it. But outflow control can address this problem quite effectively.

- **Export and Import Control:** The imposition of constraints over which component of M can send (or receive) which kind of messages to (or from) outside(S).

  {Discussion: An example of the potential importance of such control over the communication of a module with the outside of the system is provided by the monitoring service (MS) example in Section [II] The MS group of components contains sensitive information that needs to be shared with certain specific actors outside of the system, but should not be leaked to anybody else over the Internet.}

  In conventional distributed systems such controls is provided by firewalls. But exercising such controls under an MDS has several important advantage over the firewall base control. In particular, a single set of constraints, specified at a level of a module, can replace a whole collection of distributed firewalls.

- **InnerFlow control:** The imposition of constraints over the exchange of messages among the components of module M.

  {Discussion: Since the components belonging to a given module may be constructed and managed under different administrative domains, one may want to impose constraints over their interaction. In the case of the monitoring service of Section [II] for example, one may want the reporters, which are supposed to get their information from the analyzers, not to have a direct access to the logs, lest they reveal raw data that needs to be private. It should be pointed out that out of all the control types presented here, this is probably the only one that is irrelevant to local systems.}

C. Required Properties of the Implementation of MDS:

We introduce and motivate below three key requirements from any implementation of the concept of MDS.

- **(R1) Independence of the Modular Structure of an MDS from the Code of System Components:** Modularization in distributed systems should be independent of the code of the components of the system, and of the programming languages in which they are written. The constraint on the flow of messages should be enforced by a middleware that views the components as communicating black boxes. The reasons for this requirement are: (a) the code of different components may be written in many different languages, and is not generally available for inspection and for control by any single mechanism; and (b) the modularization-based constraints should be invariant of the evolution of the code.

- **(R2) Modularity of the Specification of the Modular Structure of an MDS:** The specification of the constraints on the message flow into a given module, and out of it, should be completely independent of such specification with respect to other modules.

- **(R3) Local Control:** The control over the flow of messages into or from a given component c of a given module M should be carried out locally, at c—or be carried out by a device dedicated to mediate the interaction of c with others. In other words, the control over flow into and out of a component cM should not be done by a mediator that represent module M, mediating the message flow of all components of M. Because the existence of a mediator for each module would complicate the system, and reduce the efficiency of mediation (This is particularly true in the presence of hierarchy of modules under the complete MDS model, to be discussed in Section [VI]) Also, this control should not be carried out via a system-wide mediator, because such a mediator would constitute a single point of failure and an obvious target for attacks; and it would be unscalable to boot. Moreover, a system-wide mediator would be inconsistent with the R2 requirement above.

IV. ON A MIDDLEWARE UNDERLYING MODULAR DISTRIBUTED SYSTEMS

The function of the middleware in the context of an MDS is to enable the formulation of constraints over the messaging activities of distributed components, and to carry out the enforcement of such constraints. Since messages are the means for interaction between distributed components, we call such constraints interaction-laws or simply laws. And as we shall see in Section [V-A], we will define a d-module to be the set of components whose interactive activities are governed by a specific interaction-law—which makes such laws central to our concept of MDS. The following are some key requirements, regarding interaction-laws, posed by our concept of MDS.

1) The enforcement of interaction-laws needs to be decentralized, for several reasons: (a) to realize the requirement R2 and R3 above; (b) for the sake of scalability; and (c) to avoid having a single point of failure, and a critical target for attacks.

2) Interaction-laws need to be stateful, so they can be sensitive to the history of interaction. (This aspect of interaction-laws is required for MDS for dealing with crosscutting concerns, that involve coordination between system components, as hinted in Section [VI-B].)

3) It should be possible to impose multiple interaction-laws over a single distributed system in order to represent different modules, independently of each other. And these laws need to interoperate seamlessly, and be organized into what we call conformance hierarchy. (This requirement will be explained and motivated in due course.)

We employ here a middleware called law governed interaction (LGI) that fulfills these requirements. Although LGI has been published extensively, there is no single paper that describe all the above mentioned properties of it. We outline, therefore, the LGI mechanism below, paying particular attention to how it satisfies the above requirements.
A. The Law-Governed Interaction (LGI) Middleware—an Overview:

LGI is a middleware that can govern the interaction (via message exchange) between distributed actors, by enforcing an explicitly specified law—and possibly multiple laws—about such interaction. By the term “actor” we mean here an arbitrary autonomous process of computation, whose structure and behavior is left unspecified, and is viewed as a black box by LGI. Thus, an actor can be such things as a software component, an hardware device, or a person communicating via a smart-phone.

We provide here a brief, and rather abstract, overview of LGI; focusing on the properties of it which are the most relevant to this paper. A more detailed presentation of LGI, and a tutorial of it, can be found in its manual [5]—which describes the release of an experimental implementation of the main parts of LGI. For additional information and examples the reader is referred to a host of published papers[4], of which will be cited explicitly in due course.

The rest of this section is organized as follows. We start, in Section IV-A1 with the local nature of the laws supported by LGI—a key characteristics of this middleware, which underlies the above mentioned properties. In Section IV-A2 we describe the law enforcement mechanism of LGI. And in Section IV-A3 we discuss the need for multitude of laws, and the hierarchical organization of such laws.

1) The Local Nature of Interaction Laws Under LGI::

Although the purpose of interaction laws is to govern the exchange of messages between different distributed actors, they do not do so directly under LGI. Rather, a law governs the interactive activities of any actors operating under it, in particular, by imposing constraints on the messages that such an actor can send and receive. The ruling of such a law for an interactive event that may occur at any actor—such as the sending of a message by x, or the arrival of a message at it—can depend on the interactive state, of the actor in question, by which we mean, some function of the history of interaction of this actor with the rest of the system. The exchange of messages between two actors, is therefore, governed by the laws under which each of them operates, which may or may not be the same law, as we shall see.

This types of laws are local in the sense that they can be enforced locally, with no knowledge of, or dependency on, the interactive state of any other actor of the system. This means that the exchange of a message between two actors requires their respective laws to be enforced separately, first at the sender of the message, and then at its receiver. Such decentralized enforcement, is, of course, very scalable, even for highly stateful laws. Note that without locality one would need to employ a central mediator (or reference monitor) to mediate the interactions between all actors, as is done under conventional AC mechanisms, such as XACML. And interaction via a central mediator is inherently unscalable for stateful policies. (This is the case even if the mediator is replicated, as has been shown in [7].)

2) The Law Enforcement Mechanism of LGI:: The LGI law-enforcement is carried out, broadly, as follows: For an actor x to conduct its interactive activities under a given law L, it needs to adopt a software entity called controller to serve as its private mediator, subject to law L. The controller itself is generic, as it is able to operate under any well formed LGI-law. So its adoption by x involves loading the specific law L into it, which creates a pair (x, T′x), where T′x is the controller mediating the interactive activities of x under law L. This pair is called an L-agent, since its interactive behavior, as seen by other actors, is forced to conform to law L. (Note that the act of adoption is one of the interactive events of LGI, which signifies the birth of an agent, which may be followed by an initialization procedure, as require by the law.)

The trustworthiness of the controllers is discussed in [5].

Figure 2 depict the manner in which a pair of actors, operating via different controllers, under possible different laws, interact with each other. Note that, depending on security considerations, the controllers may reside on the hosts of their respective actors, or they may be anywhere over the Internet, but managed by a controller service (CoS).

On the Performance of LGI: An extensive study of the overhead incurred due to the use of LGI has been reported in [7], indicating that this overhead is generally reasonably small. The evaluation of the law takes about 50μs, using a fairly standard PC, and for a relatively simple laws, of the kind one expect to use for MDS. This is often negligible, particularly for communication over WAN.

3) About the Concept of Conformance Hierarchy of Laws::

As noted at the top of Section IV an MDS-based system would need to be governed by multiple laws, organized into, what we call, a conformance hierarchy, which we denote by H. In fact such organization of laws is required for many complex applications, and it is supported by LGI. Here we provide only a brief outline of this concept. For a formal and more detailed description of conformance hierarchies of laws the reader is referred to [1].

The Structure of a Conformance Hierarchy of Laws:: A conformance hierarchy H is a tree of laws rooted by a law L_R, such that every law L’ in H, except its root law, is derived from its superior law L via a derivation mechanism that ensures that L’ conforms to L—in the sense to be described below—and that this conformance is transitive.

Rather than using a uniform definition of conformance—

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4These papers are available at http://www.cs.rutgers.edu/~minsky/pubs.html.
such as requiring that a subordinate law can deviate from its parent only by being more restrictive than it, which is a common view concerning access control policies—we let each law define what it means for its subordinates to conform to it. This is done as follows: For a law to belong to a law hierarchy it needs to have two different parts, which we call the ground part and the meta part. The ground part of a law \( \mathcal{L} \) imposes constraints on interactive behavior of the actors operating directly under this law. While the meta part of \( \mathcal{L} \) circumscribes the extent to which a laws subordinate to \( \mathcal{L} \) are allowed to deviate from the ground provisions of it.

As a simple example, the root law \( \mathcal{L}_R \) may prohibit all interaction between components, while enabling subordinate laws to permit any kind of interaction under their purview. Alternatively, law \( \mathcal{L}_R \) may permit all interaction, while enabling subordinate laws to prohibit selected interactions.

This very flexible concept of conformance is somewhat analogous to the manner in which state laws in the US conform to the federal laws. And such conformance turns out to be very useful for the governance of complex distributed systems as well, as we shall see in Section V-B.

The Formation of a Conformance Hierarchy of Laws:

A conformance hierarchy \( \mathcal{H} \) is formed incrementally via a recursive process described informally below. First one creates the root law \( \mathcal{L}_R \) of \( \mathcal{H} \). Second, given a law \( \mathcal{L} \) already in \( \mathcal{H} \), one defines a law \( \mathcal{L}' \), subordinate to \( \mathcal{L} \), by means of a law-like text called delta, denoted by \( \Delta(\mathcal{L}, \mathcal{L}') \), which specifies the intended differences between \( \mathcal{L}' \) and \( \mathcal{L} \). This is done in a manner that ensures that law \( \mathcal{L}' \) conforms to its superior law \( \mathcal{L} \)—for a formal model of this derivation see Fig. 3.

V. A Basic Model of MDS

An MDS, according to this basic model, is a triple \( (C, H, E) \), where \( C \) is a set of distributed components that populate the system; \( H \) is a conformance hierarchy of laws (also called the law ensemble) that defines the modular structure of a system; and \( E \) is the LGI-based mechanism that enforces the laws of \( H \), thus establishing this structure.

The only assumption made by this model about the components of \( C \) is that they all communicate via LGI, subject to laws in \( H \). We will justify this assumption in Section VI-C under certain conditions, and will qualify it when these conditions are not satisfied. The law ensemble \( H \) is bi-level under this basic model, but as we shall see in Section VI it can be extended to arbitrary depth. And the enforcement mechanism \( E \) is a middleware consisting of LGI controllers that mediate the interaction between the components of \( S \), subject to the various laws in \( H \).

The rest of this section is organized as follows: we start with the gist of this model, which explains how modules of MDS are to be defined, and how the overall modular structure of a system is established. Section V-B is a rather generic case study that illustrates how the modular structure of an MDS is defined. Section V-C elaborates on our assumption that the laws in \( H \) are strictly enforced; and Section V-D discusses the construction of an MDS.
to module $M$, adopt an LGI controller with law $\mathcal{L}_M$ that
defines this module. The interactive activities of $c$ would then
be governed by law $\mathcal{L}_M$ of the module to which it belongs;
and, indirectly, by the root law $\mathcal{L}_S$ to which law $\mathcal{L}_M$ conforms
due to the hierarchical structure of $H$. A system of this kind
is depicted schematically in Figure 4—which is an elaboration
of Figure 1. It shows two modules, called $M$ and $K$, whose
components are dispersed over the Internet (the components
belonging to module $M$ are represented in this figure by
ovals, and those belonging to $K$ are represented by triangles.).
There is no physical boundary enclosing the members of
a module; their membership is defined by the laws—$\mathcal{L}_M$
and $\mathcal{L}_K$, respectively—under which they communicate. This
figure also depicts the various flow of messages into and from
components $c$ of module $M$.

It is worth pointing out here that this basic model provides
no control over which components can belong to which
modules, but such control is provided by the complete MDS
model, introduced in Section [V].

An important consequence of this model is that modules
have no physical embodiment. Rather, a modules is defined as
a set of of components whose interactive activity is governed
by the same law. And as required in Section [II-C] the
enforcement of the law of a module is carried out by the private
controller associated with each component. The only physical
manifestation of a module is its law, which is maintained at
the controllers of the various components operating under it,
and at the law-server.

Finally, it should be pointed out that a singleton module
$N$, i.e., a module that contains a single component $c$ has
advantages over a having $c$ not be contained in this module.

Because the law $\mathcal{L}_N$ of $N$ can provides guarantees to the
rest of the system that cannot be obtained otherwise. This, by
limiting the outflow and the export and import that can be
carried out by $N$.

B. Establishing the Modular Structure of an MDS—a Generic Case Study:

To illustrate how a modular structure of an MDS can be
defined by its law ensemble $H$—and enforced by $E$—we
describe here the law ensemble of a more or less generic case
study.

The various laws in $H$ are described here broadly and
informally. A reader who wishes to see how such laws are
actually written under LGI is referred to [1], where a fairly
sophisticated hierarchical ensemble of laws is introduced in
details. Here are some comments about our informal descrip-
tion of $H$. A typical law consists of several rules, which
represent different provisions regarding different aspects of the
modular structure. And all but the root law of this hierarchy
are represented by their deltas, which specify the differences
between the law at hand and its superior. We employ here
the following convention about the meta part of any given
law $L$ in the hierarchy: (a) if $L$ has a rule that addresses a
certain aspect of messaging activity of a component subject to
this law—such as the sending of a certain type of message—
then this rule cannot be deviated from by subordinate (and
transitively subordinate) laws of $L$, unless such deviation is
explicitly permitted by the meta part of $L$—such meta per-
missions are denoted by bracketed text in bold italic font; and
(b) if $L$ has nothing to say about certain aspect of interaction,
then subordinate laws have the freedom of legislation about
it. We start with law $\mathcal{L}_S$, and then continue with an example
of a module-law subordinate to it.

1) The Root Law $\mathcal{L}_S$ of $H$:: Due to the conformance nature
of the hierarchical law ensemble $H$, its root law $\mathcal{L}_S$ has domin-
ion over all the laws in $H$. Consequently, this law governs all
the messaging activities of components of the system at hand.

Some of the rules of this law are stated categorically, not
allowing any deviation from them by the subordinate module-
laws—thus establishing system regularities. Other rules in this
law, which permit deviations from them by module laws, can,
be viewed as establishing defaults. Note that most of the rules
below are followed by a discussion—in italics enclosed in
curly brackets—that elaborates on the rule, providing some
clarification of it and motivation for it.

1) Initialization: The name $M$ of the module-law $\mathcal{L}_M$
that has been adopted by a component $c$ is to be stored in
the state of its adopted LGI-controller.

[But the module-law itself may add conditions to this
rule, and may require various operations to be carried
out by the]{\textsuperscript{*}}
out upon adoption, perhaps for adding information that further identifies the module.)

{Discussion: Having the unique name of a module, represented at every component of it, is essential for flow control as is explained in the context of Rule 2 below. }

2) Sender identification: Every message sent is to be concatenated with the name and profile of the module to which the sender-component belongs. This identifier is to be stripped from the message, before it is delivered to the target component itself.

{Discussion: This sender identification is needed by the receiver of the message, for it to be able to determine if this message satisfies its own inflow-control rules, and thus ought to be accepted—the profile can be specified by the module law, as discussed in Section V.B2. Note that this identification is intended mainly for the controller of the receiver, and it is stripped from the message, before it is delivered to the component itself. This, in order to accommodate legacy components, which would not know what to do with the extra information added to messages by the law. It is worth pointing out here that a component written with knowledge of this law can get the identifying information by explicitly asking its controller to disclose it. But such disclosure needs to be permitted by the law under which one operates. }

3) Default inflow control: All inflows of messages are prohibited, [unless permitted by the subordinate module-law in question]

4) Default outflow control: All outflows of messages are permitted, [unless prohibited by the subordinate module-law in question]

5) Default export/import control: All exports and imports are prohibited, [unless permitted by the subordinate module-law in question].

6) Default innerFlow control: All message exchanges between member of a module are permitted, [unless prohibited by the subordinate module-law in question]

{Discussion: The above four rules establish defaults controls over inflow, outflow, export/import and innerFlow. But they allow individual module-laws to override these defaults. The rationale of these particular defaults is as follows: Regarding inflow control, assuming that relatively few inflows of messages into a module would end up being allowed, Rule 3 prohibit them all, as a default. But it enables individual module-laws to permit arbitrary inflows. The other three default rules above can be justified by similar consideration. But one can, of course, design different kinds of default rules. }

2) Module-Laws: We discuss here a single module-law $L_M$ of some module $M$. This law is a subordinate to the system-law $L_S$, which is derived from $L_S$ via a delta $\Delta(L_S,L_M)$. Below is an informal description of a typical such delta, distinguishing between two aspects of it: (a) initialization, to be done upon the adoption of a controller with $L_M$; and (b) imposition of control over the flow of messages into $M$ and from it.

Initialization: Law $L_M$ may mandate that a given set of labels would be added to the state of each component operating under this law, as the profile of the module. Recall, that as required by the system-law $L_S$, this profile would be appended to every message sent by every component of module $M$, in order to identify it.

Flow Control: Recall that the system-law $L_S$ establishes defaults for all four types of flows of messages we identified, allowing module-laws to change these defaults arbitrarily. In particular, law $L_s$ prohibited all inflows. But law $L_M$ can permit specific types of inflows, as follows: It can permit certain types of messages from anywhere in the system—which is equivalent to conventional concept of an interface of a module. Or, it can permit such messages to come from one or several modules, which can be specified by their names, or by their profiles. The defaults of other types of message flow can be changed in a similar way.

C. About the Enforcement of the law-hierarchy of an MDS:

We have assumed above that all components of $S$ satisfies the following conditions: (a) they communicate via LGI, and (b) they operate subject to laws in $H$. Under this twofold assumption the law ensemble $H$ is clearly enforced by the trusted LGI controllers. But how can one ensure that this assumption is valid?

First note that if part (a) of this assumption is satisfied, than its part (b) can be established simply by having the system-law $L_S$ require that messages can be received only if they are sent by component operating under laws that are subordinate to $L_S$—that is, laws in $H$. So, if a component chooses to operate under LGI law that does not belong to $H$, it will not be able to communicate with any components operating under $H$, and could than be considered not to belong to $S$. But part (a) of this assumption is more problematic, because we may have no control over how a set of distributed software components communicate with each other.

Assumption (a) can be forced to be satisfied if all components of $S$ are on a single Intranet, or on a set of Intranets managed under a single administrative domains, where one has control over the local network (or networks) and its firewalls. This has been demonstrated in [2].

But even when of a given system is dispersed throughout the Internet, its components may often be virtually compelled to operate under some law in $H$, or even under a particular law $L$ in $H$. Broadly, this is the case for a component that needs to communicate with other components, which require their interlocutors to operate under a given law $L$, or under any subordinate law to it. This is so, basically, because one can detect whether its interlocutor operates under LGI, and can identify the law under which it operates—this is one of the essential features of LGI, called “law-based trust” [6].

8
D. The Construction of an MDS

The construction of an MDS \( \langle C, H, E \rangle \) from scratch is fairly straightforward: One first defines the the modular structure of the system via the law hierarchy \( H \), and then associates components with the various modules, by having them adopt the suitable laws in \( H \). Of course, it may not be that simple, because one often needs to change the modular structure, incrementally, during the construction process. We will address this issue when discussing the evolution of an MDS, in Section VII. The conversion of a legacy system to an MDS is an open problem, also discussed in Section VII.

VI. THE COMPLETE MDS MODEL

Our complete MDS model provides the following capabilities omitted, for simplicity, from the basic model: (1) controlling and reporting the membership of modules; (2) virtual nesting of modules; (3) allowing modules to overlap; and (4) implementing crosscutting modules. We introduce these capabilities below, including their motivation and implementation. It is worth pointing out that these capabilities do not require any change in the underlying structure of the basic model, or in the present state of LGI.

A. Controlling and Recording the Membership of Modules:

Note that the basic MDS model provided no means for imposing constraints on which components can belong to a given module, and for recording the actual membership of a given module, at a given moment in time. This is unacceptable for many reasons. In particular, not being able to constrain the membership of a module may pose serious security risks, as it may allow a rogue component to enter some sensitive module, such as one that implements the monitoring service of Section III. And not being able to record the membership of module would make the management of a system very difficult. However, these capabilities can be provided under the complete model of MDS, in several ways—such as described below.

Controlling the Membership of a Module: Suppose that each component of a given system \( S \) has a private key, and that there is a certification authority (CA) that provides each component with a digital certificate that identifies its unique name (unique with respect to system \( S \)), and the module (or modules) to which it is allowed to belong. Under this condition, the module-law of a given module \( M \) can be written to require such a certificate upon the adoption of this law, and to refuse to be adopted if the right certificate is not presented. In fact, such control over membership may be made into a system regularity, if the above is done not by individual component-laws but in the system-law \( L_S \).

Recording the Membership of Modules: Suppose that a given system employs a server—called system registry—to maintain the list of system components, each identified by its name, IP address, and by the module (or modules) to which it belong. This server can be fed with the required information, by having the system-law \( L_S \) mandate that whenever a components adopts a controller under a given component-law, a message will be sent automatically to the registry, with its identification, and with the name of the module it operating from.

B. Virtual Nesting of Modules Under MDS:

Modules can be nested under MDS, simply by extending the depth of the conformance hierarchy of laws \( H \) to more then 2, as depicted by dashed lines in Figure 3. Of course, we do not mean physical nesting, but a logical one, in terms of the constraints imposed on the messages that can flow into and out of the components of the nested modules.

For example, consider a module \( M \) defined by law \( L_M \), anywhere in \( H \) below \( L_S \), and a module \( M' \) defined by law \( L_M' \) subordinate to \( L_M \). Given the nature of conformance under LGI, the components of \( M' \) operate under the same restrictions on their communication, as the components of \( M \) itself—unless \( L_M \) permit its subordinates laws to deviate from it in some sense. Suppose, in particular, that \( L_M \) permit its subordinate laws to strengthen (but not weaken) its own constraints on communication. Then \( L_M' \) may impose additional constraints on how its own components interact with the rest of the system. The potential benefits of such an hierarchical organization of modules, particularly for very large and complex systems, seems self evident.

It is worth pointing out that this concept of nesting enables us to view the entire system as a single universal module, defined by the system-law \( L_S \) of \( H \), which has the other modules nested within it.

C. The Ability of Modules to Overlap:

Modules can overlap in the sense that a single component may belong to several modules. This can be done by a component simply by adopting several LGI controllers, under several different module-laws. This basic capability of LGI may be useful for several reasons, the following is of them; another reason is presented in Section VI-D below.

Consider a web server that provides several different services. Such services may need to belong to different modules, because they may need to interact with different set of components, and may require different inflow, outflow and export/import controls. This is possible to do with the overlap capability.

D. Crosscutting Modules:

The ability of components of an MDS to belong to several modules enables the implementation of a distributed version of crosscutting modules, thus extending to open distributed systems an important concept introduced under aspect oriented programming AOP [3]. We illustrate this capability of MDS with the following example.

Consider an MDS-based system \( S \) in which several components that belong to several different modules engage in sending purchase orders (POs) to Internet cites outside of \( S \). And suppose that the sending of POs is required to comply with a given system wide protocol that involves an approval workflow and logging of the POs themselves. Normally one
would have to program this protocol into every component that issues POs—which is laborious and error prone process. But we can ensure that this protocol is observed for sending POs, by anybody who does it, simply by localizing the sending of POs in a single, crosscutting module, say \( P \). This can be done as follows.

First, we write a module-law \( L_P \) that enforces the required protocol, for every PO being sent. Second, we have to write the root law \( L_S \) so that it prohibits the sending of POs from anywhere, except from module \( P \). This would force components that need to send POs to enter module \( P \)—in addition to their native module—by adopting its law \( L_P \).

**Related Work:** It should be pointed out that this is not the first implementation of crosscutting concerns in distributed system. In particular, the DaDO system \([10]\) implemented such concerns by planting appropriate mediators, called adaptlets, in the code of the relevant components. Adaptlets are analogous to our controllers with specific laws. But planting them into the code of the various components, is overly laborious and unsafe. In any case, unlike in DaDO, the crosscutting concerns under MDS are simply an integral part of the more general concept of modularization.

**VII. SOME OPEN PROBLEMS**

Although the MDS model can be used in its present form, it raises several issues that require further research and experimentation. Two such open issues are presented below.

1. **The Evolution of an MDS.** Both the base system of an MDS \( S = (C, H, \mathbb{E}) \), (i.e., the code of the set of components \( C \) of \( S \)), and its modular structure defined by \( H \), are bound to evolve. The evolution of the code of the system presents no new problems under MDS. Quite the contrary, such evolution becomes safer, because no changes in the code can violate the constraints imposed by the modular structure \( H \). This is, in fact, one of the most significant and advantageous aspects of the concept of MDS. However, the evolution of \( H \), which defines the modular structure of \( S \), confronts the following presents difficulties: (1) the potentially disruptive effect that a change of \( H \) may have on the system governed by it; and (2) the difficulties in carrying out changes of non-leaf laws that belong to the law-hierarchy \( H \) (note that changes in leaf laws of \( H \) present no difficulty.)

2. **Evaluation of the Potential Impact of MDS on the Engineering of Distributed Systems.** The model of MDS introduce here has been tested experimentally on a couple of small systems, as a proof of concept. But the real usefulness of MDS, and its potential impact on the engineering of distributed system, cannot be validated without applying it to large, complex and open distributed system. This calls for three kinds of experiments: (a) constructing a complex MDS from scratch; (b) converting a large and complex legacy system to an MDS; and (c) subjecting one of such systems to a process of evolution. Such experiments are yet to be done.

**VIII. CONCLUSION**

We have introduced the concept of modular distributed system, composed of what we have called distributed modules. Each such module is comprised of a set of one or more distributed components, whose communication with other modules of that system, and with the outside, is tightly circumscribed. In other words, an MDS erects virtual, selectively permeable, boundaries between groups of components dispersed over the Internet. This modular structure is established via a decentralized middleware, and is, therefore very scalable.

This concept is inspired by modularization in local (non-distributed) systems, and it is similar to it in that it provides for hiding. But MDS has several important features that are rarely, if ever, supported by conventional modularization. These include constraints on the ability of the body of a module to send messages to other modules, or to the outside of the system; the ability of different modules to overlap; and the ability to construct crosscutting modules.

Although the full evaluation of the potential impact of the MDS model has not been done yet, this impact is expected to be substantial, particularly once the open problems presented in Section [VII] are solved.

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