**X-KLAIM and KLAVA: Programming Mobile Code**

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**Abstract**

Highly distributed networks have now become a common infrastructure for a new kind of wide-area distributed applications whose key design principle is network awareness, namely the ability to deal with dynamic changes of the network environment. Network-aware computing has called for new programming languages that exploit the mobility paradigm as the basic interaction mechanism. In this paper we present the KLAIM (*Kernel Language for Agent Interaction and Mobility*) framework for programming mobile code applications, namely the X-KLAIM programming language and the Java-based run-time system KLAVA. In particular, we illustrate how KLAVA handles mobile code. Finally, an example is shown that is implemented using this framework.

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**1 Introduction**

Highly distributed networks have now become a common infrastructure for many applications which use network facilities to access remote resources and services. The Internet and the World Wide Web have surely contributed to this growth, making a network connection available to everyone, not confined to research laboratories or large enterprises. Both programmers and users have to deal with a new kind of wide-area distributed applications whose key design principle is *network awareness*, namely the ability to deal with dynamic changes of their network environment.

Network-aware computing has called for new programming languages and paradigms that support migratory applications as a new model of interactions among clients and servers. *Mobile code*, i.e. software that can be sent to remote sites and can be executed on arrival, has been advocated as the basic paradigm to support network-aware programming (see, e.g., [23,12]). In the literature the term *mobility* is used to denote different mechanisms, ranging from simple ones, which only supply the ability of downloading code for execution (e.g. [3]), to more sophisticated ones, which support migration of entire computations (e.g. [25,1,21]).

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In this paper we present the framework, which relies on Java, for programming in KLAIM, where mobile code applications and their interaction strategies can be naturally programmed. KLAIM (Kernel Language for Agent Interaction and Mobility) [14] is an experimental kernel language specifically designed to program distributed systems composed of several components interacting through multiple tuple spaces and mobile code. X-KLAIM (eXtended KLAIM) [6] is an imperative programming language obtained by extending KLAIM with variable declarations, operations with time-out, assignments, conditionals, sequential and iterative process composition. The implementation of KLAIM consists of two layers:

- a Java package, called KLAVA, which contains all the classes that implement the X-KLAIM runtime system and operations;
- the X-KLAIM compiler that translates X-KLAIM programs into Java programs that use the package KLAVA.

The structure of the KLAIM framework is depicted in Figure 1. X-KLAIM and KLAVA are available on line at http://music.dsi.unifi.it. KLAVA is briefly described in [6] and presented in detail in [4,7].

Let us briefly show how the framework can be used. If X-KLAIM source code is stored in a file called foo.xklaim, it can be compiled by means of the X-KLAIM compiler and the result will be the file foo.java. This last file can be compiled and executed by means of the standard jdk commands. When the program is executed, the host and the port number of the Net server, which is a class in the package KLAVA, must also be specified. This server keeps track of the physical localities of the nodes which are part of the net and must be started before any other node. Further details will be supplied in the next sections. Thus, X-KLAIM can be used to write the highest layer of distributed applications while KLAVA can be seen both as a middleware for X-KLAIM programs and as a Java framework for programming according to the KLAIM paradigm.

The rest of the paper is organized as follows. Section 2 introduces the language KLAIM and its implementation X-KLAIM. The Java package KLAVA and its general architecture are presented in Section 3, while the features specifically concerning code mobility are described in Section 4. In Section 5 we show how to program a simplified news gatherer that relies on mobile agents.
for retrieving information on remote sites, in particular we will implement this example both in X-Klaim and in Klava. Section 6 draws some conclusions and hints future work.

2 An overview of Klaim and X-Klaim

X-Klaim (eXtended Klaim) [6] is an experimental programming language specifically designed to program distributed systems composed of several components interacting through multiple tuple spaces and mobile code. It is based on the kernel language Klaim [14] and is inspired by the coordination language Linda [18], hence it relies on the concept of tuple space. A tuple space is a multiset of tuples; these are containers of information items, called fields. There are two kinds of fields: actual fields, i.e. expressions, processes, localities, constants, identifiers, and formal fields, i.e. variables. Syntactically, a formal field is denoted with !ide, where ide is an identifier.

Tuples are anonymous and content-addressable and pattern-matching is used to select tuples in a tuple space. Two tuples match if they have the same number of fields and corresponding fields match: a formal field matches any value of the same type, and two actual fields match only if they are identical (but two formals never match). For instance, if Val is an integer variable, then tuples (“foo”, “bar”, !Val) and (“foo”, “bar”, 300) do match. After matching, the variable of a formal field gets the value of the matched field: in the previous example, after matching, Val will contain the integer value 300.

In Linda there is only one global shared tuple space; Klaim extends Linda by handling multiple distributed tuple spaces. Tuple spaces are placed on nodes (or sites), which are part of a net. Each node contains a single tuple space and processes in execution, and can be accessed through its locality. There are two kinds of localities: physical localities are the identifiers through which nodes can be uniquely identified within a net; logical localities are symbolic names for nodes. A reserved logical locality, self, can be used by processes to refer to their execution node. Physical localities have an absolute meaning within the net, while logical localities have a relative meaning depending on the node where they are interpreted and can be thought as aliases for network resources. Logical localities are associated to physical localities through allocation environments, represented as partial functions. Each node has its own environment that, in particular, associates self to the physical locality of the node.

Klaim processes may run concurrently, both at the same node or at different nodes, and can execute the following operations over tuple spaces and nodes.

- **in(t)@l**: evaluates tuple t and looks for a matching tuple t’ in the tuple space located at l. Whenever a matching tuple t’ is found, it is removed from the tuple space. The corresponding values of t’ are then assigned to the formal fields of t and the operation terminates. If no matching tuple is
found, the operation is suspended until one is available.

- **read**(t)@l: differs from **in**(t)@l only because the tuple t’ selected by pattern-matching is not removed from the tuple space located at l.

- **out**(t)@l: adds the tuple resulting from the evaluation of t to the tuple space located at l.

- **eval**(P)@l: spawns process P for execution at l.

- **newloc**(l): creates a new node in the net and binds its physical locality to l. The node can be considered as a “private” node because it can be accessed by the other nodes only if the creator communicates the value of variable l, which is the only way to access the fresh node.

During tuple evaluation, expressions are computed and logical localities are translated into physical ones. Evaluating a process implies substituting it with its closure (i.e. the process along with the environment of the node where the evaluation is taking place). This means that, e.g., **out**(P)@l adds the closure of P to the tuple space located at l, while **eval**(P)@l sends P, not its closure, for execution at l. Therefore, if node s1 performs **out**(P)@s2, then, when P is executed at s2, **self** will actually refer to s1. This means that static scoping is used. On the contrary, if s1 performs **eval**(P)@s2, no closure is sent: P will refer to s2 when using **self** and dynamic scoping is used.

**X-Klaim** extends **Klaim** with a high level syntax for processes: it supplies variable declarations, operations enriched with **time-out**, assignments, conditionals, sequential and iterative process composition. Time-outs are added by supplying variants of the **Klaim** blocking operations (**read** and **in**) that limit the waiting to a fixed amount of time. When operating over Wide Area Networks, this is necessary to deal with failures and performance degradation.

The **X-Klaim** complete syntax can be found on-line, at the **Klaim** site: [http://music.dsi.unifi.it](http://music.dsi.unifi.it), while in Table 1 we report only the part concerning processes. We just briefly recall the more relevant features. If a timeout (expressed in milliseconds) is specified for an operation, through the keyword **within**, we get a boolean expression that can be tested in order to establish if the operation succeeded:

```
if **in**( !(x, y )@l **within** 2000) then ... success! else ... timeout occurred endif
```

Comments start with the symbol #, and local variables of processes are declared in the **declare** section of the process definition. Standard base types are available (**str**, **int**, etc.) as well as **X-Klaim** typical types, such as **loc** for locality variables, **process** for process variables and **ts**, i.e. tuple space, for implementing data structures by means of tuple spaces, e.g. lists, that can be accessed through standard tuple space operations. Logical localities are declared by using the type **locname**.

I/O operations in **X-Klaim** are implemented as tuple space operations. For instance the logical locality **screen** is actually attached to the output device. Hence, operation **out**("foo\n")@**screen** displays the string “foo\n”
RecProcDefs ::= \texttt{rec id formalparams probody}
  | RecProcDefs ; RecProcDefs
formalParams ::= \texttt{\epsilon} \mid \texttt{[paramlist]}
paramlist ::= \texttt{\epsilon} \mid \texttt{id : type} \mid \texttt{paramlist , paramlist}
procbody ::= declpart \texttt{begin proc end}
declpart ::= \texttt{\epsilon} \mid \texttt{declare decl}
decl ::= \texttt{const id := expression}
  | \texttt{locname id}
  | \texttt{var idlist : type}
  | \texttt{decl , decl}
idlist ::= id \mid idlist , idlist
proc ::= KAction \mid \texttt{nil}
  | \texttt{id := expression} \mid \texttt{proc ; proc}
  | \texttt{if expression then proc else proc endif}
  | \texttt{while expression do proc enddo}
  | \texttt{if KAction within expression then proc else proc endif}
  | \texttt{procCall | call id | ( proc )}
KAction ::= \texttt{out( tuple )@id} \mid \texttt{in( tuple )@id} \mid \texttt{go@id}
  | \texttt{eval( proc )@id} \mid \texttt{read( tuple )@id} \mid \texttt{newloc( id )}
tuple ::= \texttt{expression} \mid \texttt{proc ! id} \mid \texttt{tuple , tuple}
procCall ::= \texttt{id ( actuallist )}
actuallist ::= \texttt{\epsilon} \mid \texttt{expression} \mid \texttt{proc} \mid \texttt{id} \mid \texttt{actuallist , actuallist}
id ::= \texttt{string}
type ::= \texttt{int} \mid \texttt{str} \mid \texttt{loc} \mid \texttt{process} \mid \texttt{ts} \mid \texttt{bool}

Table 1: X-KLAIM process syntax.

on the screen. X-KLAIM also supplies strong mobility by means of action \texttt{go@l} [5] that makes an agent migrate to \textit{l} and resume its execution at \textit{l} from the instruction following the migration.

The KLAIM and X-KLAIM Linda-like communication paradigm fits for coordinating heterogeneous, distributed and mobile applications. The underlying coordination model permits full space uncoupling of communicating objects because it requires a single interface: the operations over tuple spaces. This approach is also called flow-of-objects [2] as opposed to method invocation, which requires many interfaces for the operations supplied by remote objects. The Linda asynchronous communication model, known as Generative Communication [18], also permits time uncoupling, because it makes tuples’ life time independent of the producer process’ life time, and destination uncoupling, because the creator of a tuple is not required to know the future use or the destination of that tuple. Moreover, message selection is associative (by means of pattern matching) and anonymous, thus only the structure of a message has to be known.

3 The Klava package and its architecture

KLAVA (KLAIM in Java) is a Java package which contains all Java classes for implementing the runtime system support for X-KLAIM operations. KLAVA can be seen both as a middleware for X-KLAIM programs and as a Java framework for programming according to the KLAIM paradigm.
Java [3] has been chosen as the implementation language for X-KLAIM because it supplies a natural support for programming distributed applications with mobile code. Indeed, Java supplies architectural independence, i.e. on-line portability [11], class libraries for network programming, tools for synchronization, dynamic class loading and customizable security mechanisms.

A KLAVA net is implemented by the KLAVA net server, which coordinates KLAVA nodes that are part of the net, by letting them communicate with each other. In order to become part of a KLAVA net, a node has to log into the net server by specifying its own physical locality, through which it will be uniquely identified and addressed within that net.

In the rest of this section, we shall present the “specializable” classes of the package Klava. Some of these classes can already be used as they are (e.g. class Tuple), while others have to be specialized through inheritance and methods overriding (e.g. class KlavaProcess).

The class Tuple provides methods for handling tuples (creating a tuple, adding elements to a tuple, getting an element of a tuple, etc.). A tuple can be created by passing a Vector object, containing all tuple elements, to the Tuple constructor, or by first creating an empty tuple and then adding elements using the method add(Object o). To express a formal field, a Class object can be used. For instance, to create a tuple with a formal field of type String and an actual field of type Integer with value 10, one can write

Tuple t1 = new Tuple((new String()).getClass(), new Integer(10));

or

Tuple t1 = new Tuple(Class.forName("java.lang.String"), new Integer(10));

Another method of the class Tuple is match, that gets a tuple as parameter and checks the matching with the current tuple. For instance, the previous tuple matches the following one:

Tuple t2 = new Tuple(new String("Hello"), new Integer(10));
   t2.match( t1 ) ;

match also performs the binding of the formals; after matching, the value bound to a formal field can be retrieved using the method Object getItem(int index).

The interface TupleItem can also be used for handling tuple fields. Its methods are used by the matching algorithm: isFormal to test whether a tuple field is a formal, setValue to update a formal field with an actual value, and equals to test whether two actual fields match. As usual, the semantics of these methods must be specified by the classes that implement the interface.

The package Klava makes available some classes for standard data types that implement this interface: KString, KInteger, KBoolean and KVector. It is assumed that an object of a class implementing TupleItem that has been created with the default constructor (i.e. with no parameters) is a formal. It is not necessary to use getItem to retrieve the value of formals: if TupleItems
are used as formal fields, fields values are automatically updated by means of the method `setValue`. Of course, since types are used for matching, a `KString` will never match a `String`.

The class `TupleSpace` provides methods to place tuples in and retrieve tuples from a tuple space. In particular, operations `out`, `in`, `read` and their non-blocking versions are implemented as methods of this class.

In KLAVA, localities (both logical and physical) are nothing but strings: the only Internet address that has to be known is the address (and port) of the host in which the net server is running. There are three classes that handle localities. The abstract class `Locality` is the base class. The other two classes `LogicalLocality` and `PhysicalLocality` are derived from this base class. A variable which represents a locality should always be declared as a `Locality` so that polymorphism can be used extensively. Physical localities are not IP addresses, but are simply the names with which `Node` objects register themselves into the `Net` object. In this way we have an additional abstraction level and a `Node` is independent from its IP address. All locality related classes implement the interface `TupleItem`, and thus localities can be used in tuples.

The class `Node` implements a node of a KLAVA net. A `Node` object contains a single tuple space and exports methods to access this tuple space. These methods will redirect operations to the corresponding methods of the tuple space of the node. The difference is that these methods also take a locality as parameter. Additionally, the class `Node` also provides the method `newloc`, that creates a new node in the net and returns its locality, and the method `eval`, that spawns a new process for execution. A `Node` object must log in a `Net` server, and hence has to know the exact IP address of the latter (host and port number). It must also specify its own physical locality; in case the proposed locality is already in the net, the net server will refuse registering the node. Two nodes can be started on the same machine, as long as they specify two different physical localities; indeed a physical locality is just a name, and not an Internet address. Every `Node` has two fields: `self` (of class `LogicalLocality`) and `here` (of class `PhysicalLocality`). `here` represents the physical locality of the node within the net. The environment of a `Node` can be specified with the method `void addToEnv(String logLoc, String phyLoc)`.

Due to network latency bandwidth, network communications can be quite slow, hence, retrieving information can require more time than one is willing to wait. Moreover, the absence of a tuple could block a process executing an `in/read` operation. To tackle these problems, a `time-out` can be used: if this expires before an operation returns, then a `KlavaTimeOutException` exception will be thrown. Time-outs can thus be handled in a `try...catch` block. For instance, a process can execute
try {
  in( s, loc1, 5000 ); // no more than 5 secs
  System.out.println( "I found " + s + " at locality " + loc1 );
  ...
} catch ( KlavaTimeOutException toe ) {
  System.out.println( "TIME OUT!!!" );
  ...
}

Nodes communicate through messages and streams (connected to sockets). The class NodeMessage implements messages exchanged in the KLAVA system (the content of a message can be any serializable Object). A message also contains the physical locality of the sender and of the receiver.

The class KlavaProcess is an abstract class that must be derived to create processes. The derived classes must implement the method execute that will be invoked when a process is executed (just like run for threads). A process must be executed within a node, which makes its execution environment [12]. To start a process within a new Node, one can invoke the method addProcess(KlavaProcess P), as follows:

Node n = new Node( ... ) ;
  n.start ( ) ;
  n.addProcess( new myProc() ) ;

KlavaProcess also offers all the methods to access tuple spaces; these methods transparently call the homonymous methods of the class Node. Even processes can own an allocation environment for localities. When a logical locality must be translated into a physical one, first the environment of the process (if it has one) is used, and then, if the interpretation fails, the environment of the node is used. Thus sending a closure (as explained in Section 2) consists in sending a process after setting its environment.

The class Net implements the server that manages a KLAIM net. A Net object keeps track of the physical localities of the nodes which are part of the net. It is a multithreaded server and can also be seen as a name registry server. There is exactly one net server for every KLAVA net. When a Net object receives a login request from a node, a new NodeHandler thread is spawned to handle the connection. NodeHandler will be a proxy for the node within the net and will handle the delivery of node’s messages to other nodes; this form of inter node communication is depicted in Figure 2, where Nodes is a table mapping node physical localities into NodeHandlers.

In this scenario communications take place indirectly, through the net server. Direct connections are also allowed: a node can ask the net server for the IP address of another node and then it can establish a direct connection to that node; in this case messages are delivered to the receiving node directly. Note that in case of firewalls or network restrictions the access to a remote site may be allowed only through a net server: e.g., an applet, by default, can only open a network connection to the computer it has been downloaded
4 Code Mobility in Klava

Processes can be sent along with a message and executed at destination sites, where however their Java classes (i.e. their code) may be unknown. It is necessary to make such a code available for execution at remote hosts. Instead of an on-demand approach (where the code is requested to the server from which an agent is downloaded when it is needed), we prefer to collect all the code that a process needs, before dispatching it. This approach better complies with the mobile agents paradigm: during a migration, an agent will bring all the information that it may need for later executions. Moreover, our choice has the advantage of simplifying the handling of disconnected operations [22].

Therefore, a process must be sent along with its class binary code, and with the class code of all the objects the process uses. Clearly, only the code of user defined classes has to be sent, as the other code (e.g. Java and Klava classes) is common to every Klava application. The names of user defined classes can be retrieved by means of class introspection (Java Reflection API). Just before dispatching a process to a remote site, a recursive procedure is called for collecting all classes that are used by the process when declaring data members, objects returned by or passed to a method/constructor, exceptions thrown by methods, inner classes, the interfaces implemented by its class, the base class of its class. The byte code of these classes is then sent, along with the migrating process.

All the nodes that are willing to accept remote processes (due to security problems, a node may refuse accepting remote processes for execution) must have a custom class loader: a NodeClassLoader, provided in the Klava pack-
age. When a class code is needed, if the class loader cannot find the code among the local packages, it will try to find it in its own local table of class binary data. Therefore, when a process is received from the network, before using it, the node must add the class data (received along with the process) to its class loader’s table.

Due to security concerns Java does not allow dynamic inspection of byte code stack; this makes impossible to save the execution state for later use. For this reason, KLAVA can only permit weak mobility of agents that have to be restarted after the migration, while X-KLAIM, by relying on a source level transformation [5], also provides strong mobility by means of go@l operation (the mobile agent automatically resumes execution from the point after the migration). A more detailed description of forms of mobility can be found in [13,20].

Downloading code from the net exposes the executing machine to security risks, since this code could execute dangerous operations that could damage the system or the other executing processes. Klava provides a KlavaSecurityManager, which, if activated by the node, does not allow processes, downloaded from the net, or sent by remote nodes, to execute operations on system resources (such as files, and system properties). We are going to implement new security mechanisms that exploit the new Java security model [19].

5 An example of mobility: a News Gatherer

In this section we will show how to program a news gatherer, that relies on mobile agents for retrieving information on remote sites, using our framework. In particular we will implement this example both in X-KLAIM and in KLAVA. We assume that some data are distributed over the nodes of a KLAVA net and that each node either contains the information we are searching for, or the locality of the next node to visit in the net. This example is taken from [14], and in KLAIM can be specified\(^1\) as shown in Listing 1.

```klaim
NewsGatherer(item, retLoc) =
  read(item, !itemVal)@self.out(itemVal)@retLoc.nil
+  read(item, !nextLoc)@self.eval(NewsGatherer(item, retLoc))@nextLoc.nil
```

*Listing 1*: The news gatherer specified in KLAIM.

The agent NewsGatherer tries to read one of two possible tuples: the first tuple contains information we are searching for and the second one the locality of the next node to visit. In the first case, the agent communicates the result

\(^1\) P\(_1\) + P\(_2\) spawns both processes P\(_1\) and P\(_2\), but only one of the two will continue its execution.
to its owner and terminates, in the other case it simply spawns itself to the next node (Figure 3).

![Diagram of the news gatherer example](image)

**Fig. 3:** The news gatherer example (ng is the news gatherer agent).

The implementations in **X-Klaim** and in **Klava** are reported, respectively, in Listing 2 and 3. If the result of the query is a locality, a new instance of the process `NewsGatherer` is remotely spawned by means of an `eval`. We use a timeout to test the presence of the tuple containing the information: if this is not found within two seconds, we retrieve the locality of the next node to visit. Notice that, also in **Klava**, for spawning a new process on a remote site, only an `eval` invocation is required: the underline system will take care of serializing the process through the network together with code and the code of all the classes it will use and the values of its fields. The two implementations are quite similar, and indeed the code generated by the **X-Klaim** compiler is not much different from the one shown in Listing 3.

```plaintext
rec NewsGatherer[ item : str, retLoc : loc ]
    declare
    var itemVal : str ;
    var nextLoc : loc
    begin
        if read( item, !itemVal )@self within 2000 then
            out( itemVal )@retLoc
        else
            read( item, !nextLoc )@self ;
            eval( NewsGatherer( item, retLoc ) )@nextLoc
        endif
    end
```

**Listing 2:** The implementation of the news gatherer in **X-Klaim**.

In **X-Klaim** strong mobility can be exploited, thus the same example can be implemented by using the `go` operation, as illustrated in Listing 4.
Listing 3: The implementation of the news gatherer in KLAVA.

Listing 4: X-KLAIM implementation exploiting strong mobility.

6 Conclusions and Future Work

We presented the KLAIM framework. The underlying programming model enables space uncoupling, time uncoupling and destination uncoupling, and asynchronous, associative and anonymous communication. We believe that the KLAIM framework is suitable for programming distributed applications, mobile agents, and, more in general, mobile code. An interesting spin-off of
our approach is that since it is based upon the KLAIM formal model, some
properties of systems can be formally established. Indeed, a modal logic for
KLAIM is being studied [17] and a system to automatically prove KLAIM
system properties is under development.

A number of extensions have been made to the original KLAIM model
of computation. In [15,16], KLAIM is extended with a capability-based type
system that provides direct support for expressing and for using policies that
control accesses to resources and data. In [8], KLAIM is enriched in order to
transform the underlying flat model into a hierarchical model, that permits
modelling structured nets, and in [9,10] node connectivity is made explicit.
We plan to implement all these new features in the near future.

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