Extending Erlang for Safe Mobile Code Execution

Lawrie Brown[*], Dan Sahlin[†]

[*]School of Computer Science, Australian Defence Force Academy, Canberra 2600, Australia
[†]Computer Science Laboratory, Ericsson Utvecklings AB, S-125 25 Älvsjö, Sweden

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[*]Phone: +61 2 62688184, Fax: +61 2 62688581, Email: Lawrie.Brown@adfa.edu.au
[†]Phone: +46 8 7198187, Fax: +46 8 7198988, Email: dan@cslab.ericsson.se

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Abstract

This paper discusses extensions to the functional language Erlang which provide a secure execution environment for remotely sourced code. This is in contrast to much existing work which has focused on securing procedural languages. Using a language such as Erlang provides a high degree of inherent run-time safety, which means effort can be focused on providing a suitable degree of system safety. We found that the main changes needed were the use of unforgeable (capability) references with access rights to control the use of system resources; the provision of a hierarchy of execution nodes to provide custom views of the resources available and to impose utilisation limits; and support for remote module loading. We then discuss prototype implementations of these changes, used to evaluate their utility and impact on visibility for the users of the language, and mention work in progress using this foundation to specify safety policies by filtering messages to server processes.

1 Introduction

We present some extensions to the functional language Erlang [4] which provide a secure execution environment for mobile code. Supporting safe mobile code is an area of considerable recent research, particular with the increasing use of Java and similar languages (see surveys such as [14] [1]). However much of the work has focused upon securing traditional procedural languages or their derivatives. This paper considers the changes needed to secure a production use functional language, Erlang. We believe that using a functional language can provide significant benefits in productivity and maintenance of large applications, and that it would be beneficial to provide these benefits for applications requiring the use of remotely sourced code. Further, we believe that functional languages have a very high degree of intrinsic run-time safety, which means the changes required to provide a safe execution environment are much smaller than those needed to secure a procedural language. This paper will discuss the results of our initial prototypes of a safer Erlang, used to investigate these assertions.

We will use the term *mobile code* to refer to any code sourced remotely from the system it is executed upon. Because the code is sourced remotely, it is assumed to have a lower level of trust than locally sourced code, and hence needs to be executed within some form of *constrained* or *sandbox* environment to protect the local system from accidental or deliberate inappropriate behaviour. A key assumption is that the local system is trusted, and provides adequate access control mechanisms. We also assume that appropriate protection of inter-node communications, using either encryption techniques (eg IPSEC, SSL) or physical isolation, is provided.

In his taxonomy of issues related to distributed hypermedia applications, Connolly [11] in particular distinguishes between *Run-time Safety* — which is

concerned with whether the runtime system will guarantee that the program will behave according to its source code (or abort); and *System Safety* — which is concerned with whether it is possible to control access to resources by a piece of executing code. A similar emphasis on constraining resource access or certifying code is identified by Hashii et al. [14], Rubin and Geer [24], or Adl-Tabatabai et al. [1] amongst others.

Traditionally the necessary protection and access control mechanisms needed for system safety have been supplied using heavyweight processes with hardware assisted memory management. These have a long and successful history as a proven means of providing safety in traditional computing environments. However, we believe that in applications with rapid context changes, such as would be found when loading and running code from a wide range of sources of varying trust levels, such mechanisms impose too great an overhead. Further they also tend to restrict the portability of the code sourced. Here we are interested in the use of lightweight protection mechanisms, which typically rely on the use of language features and an abstract machine to provide the necessary safe execution environments for portable code. This has been the approach of most recent into safe mobile code, and may be regarded as a combination of the Sandbox and Proof-Carrying code approaches identified by Rubin and Geer [24].

The traditional focus for safe mobile code execution has been on securing procedural languages and their run-time environment. The best known example is the development of Java [6] from the production C++ language. Other examples include: SafeTCL [23], Omniware [19, 1], and Telescript [28] (see overviews by Brown [8], Thorn [29]). With these languages, much effort has to be expended to provide a suitable degree of run-time safety in order that the system safety can then be provided. In part this has been due to the ease with which types can be forged, allowing unconstrained access to the system. A number of attacks on these systems have exploited failures in run-time safety (cf Dean et al. [13], McGraw and Felten [20], Oaks [22], or Yellin [31]).

We are interested in providing safe mobile code support in a functional language. This is motivated by evidence which suggests that the use of a functional language can lead to significant benefits in the development of large applications, by providing a better conceptual match to the problem specification. This has been argues conceptually by Hughes [15] for example. Further, significant benefits have been recently reported with large telecommunications applications written in Erlang, see Armstrong [3].

In addition, we believe a dynamically typed, functional language can provide a very high degree of intrinsic run-time safety, since changing the type interpretation should be impossible (except perhaps via explicit system calls). This is noted by Connolly [12], who observes that languages like Objective CAML and Scheme48 provide a high degree of run-time safety, though they need further work to provide an appropriate level of system safety. This should greatly reduce the work required to support safe mobile code execution with such languages. We do need to assume that the basic run-time system correctly enforces type accesses, though the language semantics make checking and verifying this considerably easier.

The work on Objective CAML [18] is perhaps closest in some respects to the Safe Erlang system we discuss. However whilst Objective CAML has the necessary features for run-time safety, its system safety relies on the use of signed modules created by trusted compilation sites. Our approach however, provides appropriate system safety by constraining the execution environment into nodes and controlling resource access, so that untrusted imported code is unable to access resources beyond those permitted by the policy imposed upon the node within which it executes.

1.1 Erlang

For the work discussed in this paper, the authors, initially independently, decided to concentrate on the language Erlang [4, 3, 5, 25, 30]. Erlang is a dynamically typed, single assignment language which uses pattern matching for variable binding and function selection, which has inherent support for lightweight concurrent and distributed processes, and has error detection and recovery mechanisms. It was developed at the Ericsson Computer Science Laboratory to satisfy a requirement for a language suitable for building large soft real-time control systems, particularly telecommunications systems. The Erlang system has now been released as an open source product[26], and is freely available for download. Most of the Erlang system is written in Erlang (including compilers, debuggers, standard libraries), with just the core run-time system and a number of low-level system calls (known as BIFs for BuiltIn Functions) written in C. Distributed use is almost transparent, with processes being spawned on other nodes, instead of locally. An Erlang node is one instance of the run-time environment, often implemented as a single process (with many threads) on Unix systems.

Erlang is currently being used in the development of a number of very large telecommunications applications, and this usage is increasing [3]. In future it is anticipated that applications development will be increasingly outsourced, but that they will be executed on critical systems. Also that there will be a need to support applications which use mobile agents, which can roam over a number of systems. Both of these require the use of mobile code with the provision of an appropriate level of system safety. The extensions we have proposed would, we believe, provide this.

2 Current Limitations of Erlang

Using Erlang as the core language for a safe execution environment provides a number of advantages. For instance, *pure* functional language use, where functions manipulate dynamically typed data, and return a value, is intrinsically safe (apart from problems of excessive utilisation of cpu, memory etc). It is only when these functions are permitted to have side-effects that they may threaten system safety. Side effects are possible in Erlang when a function:

accesses other processes by sending and receiving messages or signals, viewing process information, or changing its flags.

accesses external resources outside the Erlang system (files, network, hardware devices etc), using the `open_port` BIF.

accesses permanent data in databases managed by the database BIFs.

Thus, a safer Erlang requires controls on when such side-effects are permitted.

In Erlang, a *process* is a key concept. Most realistic applications involve the use of many processes. A process is referred to by its *process identifier (pid)*, which can be used on any node in a distributed Erlang system. Given a pid, other processes can send messages to it, send signals to it (including killing it), or examine its process dictionary, amongst other operations. Erlang regards external resources (devices, files, other executing programs, network connections etc) also as processes (albeit with certain restrictions, in much the same way that Unix regards devices as a special sort of file). These processes are called *ports* and are referred to by their port number, which is used like a pid to access and manipulate the resource.

Consider the following code excerpt from an account management server, which when started, registers itself under the name `bank`, and then awaits transactions to update the account balance:

```
-module(bankserver).
-export([start/1]).
start(Sum) ->                 % start account server
    register(bank,self()),    % register as 'bank'
    account(Sum).             % process transactions
account(Sum) ->               % transaction processing loop
    receive                   % await transaction
      {Pid, Ref, Amount} ->   % account update msg received
        NewSum = Sum+Amount,  % update sum
        Pid ! {Ref,NewSum},   % send response back
        account(NewSum);      % loop (recurse)
      stop -> nil             % end server msg received
    end.
```

This could be started with a balance of 1000, and updated, as follows:

```
...
% spawn a bank account process with initial Sum 1000
Bank_pid = spawn(BankNode,bankserver,start,[1000]),
...
Ref = make_ref(),             % make a unique ref value
Bank_pid ! {self(),Ref,17},   % send msg to server
receive                       % await reply from server
    {Ref,New_balance} ->      % reply says updated ok
        ...
end,
...
```

In standard Erlang a pid or port identifier used to access processes or external resources is both forgeable and too powerful. Apart from legitimately obtaining a pid by being its creator (eg `Bank_pid = spawn(BankNode,bankserver,account,[1000])` in the example above which creates a new process and returns its pid), receiving it in a message (`receive Bank_pid -> ok end,`), or looking it up via a registered name (`Bank_pid = whereis(bank)`); it is also possible to obtain a list of all valid pids on the system (`AllPids = processes()`), or to simply construct any arbitrary pid from a list of integers (`FakePid = list_to_pid([0,23,0])`). These latter features are included to support debugging and other services, but open a significant safety hole. Further, once a valid pid has been obtained, it may be used not only to send messages to the referenced process (`FakePid!{self(),Ref,-1000}`), but to send it signals, including killing it (`exit(FakePid,kill)`), or inspect its process dictionary (`process_info(FakePid)`). There is no mechanism in the current specification of the Erlang language, to limit the usage of a pid (to just sending messages, for example).

Another limitation of the current Erlang system from a safety perspective is the fact that a given Erlang system (that is, one instance of the run-time environment) forms a single node. All its processes have the same privileges and the same access to all resources (file system, modules, window manager, devices) managed by the system. There is no mechanism to partition access within a system, so that it may be mediated via a trusted server process. The only current method for providing this is to run a separate system in a separate heavyweight process, at a considerable cost in system (cpu, memory etc) resources. There is also no means to limit the resources utilised by processes, apart from imposing restrictions on the entire system.

Lastly, there is a need to provide a remote module loading mechanism in order to properly support mobile agents. Whilst Erlang currently supports distributed execution and remote spawning of processes, the module containing the code to be executed must exist on the remote system in its default search path. Further, any modules referenced in the loaded module will also be resolved on the remote system. The code loading must, however, be implemented in such a way that the remote code server cannot be tricked into sending code that is secret. Note that pid and port identifiers are globally unique, so they may be passed in messages between nodes whilst maintaining their correct referent.

3 Extensions for a Safer Erlang

In order to address the deficiencies identified above, we believe that extensions are required in the following areas:

capabilities may be used to impose a finer granularity of control on the use of process (and other resource) identifiers, making these unforgeable with a specified set of rights on the use of any specific instance.

nodes that form a hierarchy within an Erlang system (one instance of the

runtime environment), to provide a *custom context* of services available, to restrict the use of code with access to external resources, and to impose utilisation limits (on cpu, memory etc).

remote module loading may be used to allow execution of code modules sourced on another system, retaining knowledge of the source system so that subsequent module references can also be sourced from that system, rather than the local module library.

3.1 Capabilities

We define a *capability* as a globally unique (in time and space), unforgeable name for (a specific instance of) some resource, and a list of rights for operations permitted on the resource by holders of the capability. We use such capabilities to replace the existing forgeable, unconstrained identifiers for nodes, ports, processes etc.

The same resource may be referred to from different capabilities giving the owners of those capabilities different rights. We are using capabilities to ensure that these identifiers cannot be forged, and to limit their usage to the operations desired. A capability is always created (and verified upon use) on the node which manages the resource which it references, and these resources never migrate. This node thus specifies the *domain* for the capability, and is able to select the most appropriate mechanism to provide the desired level of security. Further, the resources referenced are never reused (a new process, even with the same arguments, is still a new instance, for example), so revocation is not the major issue it traditionally is in capability systems. In our usage capabilities are invalidated when their associated resource is destroyed (eg. the process dies). Other processes may possess invalid capabilities, but any attempt to use them will raise an *invalid capability* exception.

The use of capabilities to control resource access echoes it use to provide safe resource use in systems such as Amoeba [27]. However Amoeba was a general operating system, which had to use heavyweight protection mechanisms to isolate processes running arbitrary machine code from each other, and to provide custom contexts. Here we rely on the language features and an abstract machine to provide lightweight protection mechanisms at much lower cost in system resource use.

Capabilities may be implemented in several ways, including:

Encrypted (hash) Capabilities use a cryptographic hash function (cf [17]) to create a encrypted check value for the capability information, which is then kept in the clear. Only the node of creation for the capability can create and check this hash value. The overhead of validating the check value can be minimised if any *local* encrypted capabilities are checked once on creation (or import) and then simply flagged as such (say by amending the hidden data type tag to indicate that it has been verified). Subsequent use of the capability then incurs no overhead. Further, for *remote* capabilities, any delays due to cryptographic overheads are likely to be swamped by network latencies. Each

node would keep the key used to create and validate its capabilities secret, and this key could be randomly selected when the node is initialised. Any previously created capabilities must refer to no longer extent (instances of) resources (from a previous incarnation of the node), so there is no requirement to continue to be able to validate them. This approach could be attacked by attempts to guess the key used, and verifying the guess against intercepted capability data. The likelihood of success will depend on the type of hash function used, so some care is needed in its selection to avoid known flaws in some *obvious* modes of use [7].

Password (sparse) Capabilities [2],[27] use a large random value (selected sparsely from a large address space) to protect the capability, with the node of creation maintaining a table of all its valid capabilities. This table is checked whenever it is presented with a capability, and capabilities may be revoked by removal from this table. One disadvantage of this approach is the size this table may grow to, particularly for long running server processes, or when user defined capabilities are used, where it is impossible to know when they have no further use. Another is that large tables may take some time to search, though careful selection of the table mechanism can reduce this to a minimum. It is possible to try and forge such a capability, but success is statistically highly improbable, and attempts should be detectable by abnormally high numbers of requests presenting invalid capabilities.

There is thus a tradeoff between these alternatives — trading some level of security with encrypted capabilities for space with password capabilities. The best alternative is likely to depend on the target environment.

Experience with the prototypes has shown that it is important for efficient execution that all information needed to evaluate guard tests or pattern matches be present locally in the capability. This information must include the type (eg node, port, process) and the value (to test if two capabilities refer to the same object). Because different applications may wish to choose between the security tradeoffs, we decided to support both hash and password capabilities, chosen on a node by node basis, in an interoperable mechanism, where only the node of creation need know the actual implementation. Thus, we have chosen to use capabilities with the following components:

`<Type,NodeId,Value,Rights,Private>`, where:

Type the type of resource referenced, eg. module, node, pid, port, or user.

NodeId the node of creation, which can verify the validity of the capability or perform operations on the specified resource.

Value the resource instance referenced by the capability (module, node, process identifier, port identifier, or any Erlang term, respectively)

Rights a list of operations permitted on the resource. The actual rights depend on the type of the capability. For a process capability these could include: `[exit,link,register,restrict,send]`.

Private an opaque term used by the node of creation to verify the validity of the capability. It could either be a cryptographic check value, or a random password value: only the originating node need know.

A capability may be restricted (assuming it permits it). This results in the creation of a new capability, referencing the same resource, but with a more restricted set of rights. Using this, a server process can, for example, register its name against a restricted capability for itself, permitting other processes to only send to it. eg. `register(bank, restrict(self(),[send,register]))`

Capabilities would be returned by or used instead of the existing node names, pids, or ports, by BIFs which create or use these resources.

3.2 Nodes

We have provided support for a hierarchy of **nodes** within an Erlang run-time system (an existing Erlang **node**). These provide a *custom context* of services available, restrict the use of code with side-effects, and impose utilisation limits (eg on cpu, memory etc). Functionally, these would be similar to existing Erlang **nodes** with some additional features.

A **custom context** for processes is provided by having distinct:

registered names table of *local* names and associated capability identifiers, used to advertise services. These names are not visible on other nodes.

module alias table which maps the name used in the executing code to the name used locally for the loaded module. This module name *aliasing* mechanism is used to support both redirection of names to *safer* variants of modules, as well as to provide unique names for modules loaded from remote systems (for agents or applets). This table is consulted to map the module name on all external function calls, applys, and spawns.

capability data which is all the information (eg. keys or table) necessary to create and validate unforgeable capabilities for the node.

Restrictions on **side-effects** are enforced by specifying whether or not each of the following are permissible for all processes which execute on the node:

open_port for direct access to external resources managed by the local system.

external process access for access to processes running on other Erlang systems, which could provide unmediated access to other resources, or reveal information about the local system to other nodes.

database BIFs usage for access to permanent data controlled by the local database manager.

When disabled, access to such resources would have to be mediated by server processes running on the local system, but in a more privileged node, trusted to enforce an appropriate access policy for safety. Typically these servers are advertised in the registered names table of the *restricted* node.

Utilisation limits can be imposed by a node for all processes executing within the node, or any descendent child nodes of it. Limits could be imposed on some of cpu usage, memory usage, max no reductions; or perhaps on combinations of these.

The general approach to creating a controlled execution environment is as follows. First, a number of servers are started in a node with suitable privileges to provide controlled access to resources. Then a node would be created with *side-effects* disabled. Its *registered names* table would be pre-loaded to reference these servers, its *loaded modules* table pre-loaded with appropriate local library and safe alias names; and appropriate utilisation limits set. Processes would then be spawned in this node to execute the desired *mobile code* modules, in a now appropriately constrained environment. eg. `BankNode=newnode(node(),ourbank,[{proc_rights,[]}])`

3.3 Remote Module Loading

Our prototypes do not directly support mobile processes as once started, a process may not migrate. However, a new process may be spawned off at a remote node. We have included extensions which ensure that subsequent module references from within a remotely loaded module are also sourced from the originating node, rather than being resolved from the local module library. This is to ensure that a package of multiple modules will execute correctly, remotely, and not be confused with local modules that may have the same name.

Supporting this required an extension of the `apply` BIF handler so that it checks whether the originating module is local or remote, and proceeds accordingly to interpret the module requested in context, querying the code server on the remote node for the module, if necessary. Some care is needed in managing the acquisition of an appropriate capability for requested module. This is issued by the remote code server upon receipt of a request which includes a valid capability for the parent module, and is then used to request the loading of the requested module.

4 Prototypes

A number of prototypes of a safer Erlang environment, with differing goals and features supported, have been trialed.

SafeErlang was developed by Gustaf Naeser and Dan Sahlin in during 1996 [21]. The system supports a hierarchy of subnodes to control resource usage and to support remotely loaded modules; *encrypted capabilities* for pids and nodes to control their usage; and remote module loading. Whilst this prototype was successfully used to trial a mobile agent application, limitations were found

with the complexity of its implementation, the incomplete usage of capabilities for all resource items (in particular for ports), and the use of fully encrypted capabilities and the consequent need to decrypt them before any information could be used.

In Uppsala, as a students project, a design for safe mobile agents, was implemented in 1996 [16]. Distributed Erlang was not used in that system, which instead was based on KQML communication. Safety was supported by protected *secure domains* spanning a number of nodes, where it was assumed that all nodes within a single domain were friendly.

More recently the *SSErl* prototype was developed by Brown [10] to address the perceived deficiencies of the previous prototypes. It supports a hierarchy of nodes on each Erlang system which provide a *custom context* for processes in them, the use of both *hash* and *password capabilities* for pids, ports, and nodes to constrain the use of these values; and remote module loading. This prototype has evolved through a number of versions in the process of refining and clarifying the proposed changes.

Both of the latter prototypes implement the language extensions using glue functions for a number of critical BIFs. These are substituted by a modified Erlang compiler (which itself is written in Erlang). The glue routines interact with *node* server processes, one for each distinct node on the Erlang system. Most of the SSErl glue functions have the form:

- possibly resolve a registered name to capability
- check with the node manager to see if the operation is permitted by the capabilities rights, and if not, to throw an exception
- otherwise some key information is returned (eg a real pid or capability)
- perform the desired operation (in the user4s process)

For example, the `k_exit` glue routine look as follows:

```
k_exit(CPid,Reason) ->
    Pid = node_request(check,CPid,?exit), exit(Pid,Reason).
```

Both support a hierarchy of **nodes** within an Erlang run-time system (an existing Erlang **node**). Each node is represented by a node manager process, which manages the state for that node, and interacts with the glue routines to manage resource access.

SSErl capabilities are a tuple with the components identified previously: `{Type,NodeId,Value,Rights,Private}` which specify the type of resource the capability references, the node managing that resource, the resource instance, the list of access rights permitted on the resource, and the opaque validation value (crypto hash or password) for the capability.

To support these new features, SSErl provides some new BIFs:

check(Capa,Op) checks if the supplied capability is valid and permits the requested operation, throwing an exception if not. This is not a guard test as it must consult the originating node to validate the capabilities check value.

halt(Node) halt a node along with all its nodes and processes.

make_capa(Value) create a user capability with value given.

make_mid(Module) create a module (mid) capability for the named module.

newnode(Parent,Name,Opts) creates a new node as a child of the Parent, with the specified context options.

restrict(Capa,Rights) creates a new version of the supplied capability, referring to the same resource, but with a more restricted set of rights.

same(Capa1,Capa2) guard testing whether the supplied capabilities refer to the same resource, without verifying the check value (for efficiency reasons).

Except when explicitly configuring the execution environment, the new features are mostly invisible to existing user programs. The SSErl prototype successfully compiles many of the standard library modules (only those interacting with ports require some minor, systematic, changes necessitated by the protocol currently used). It is now being used to trial some demonstration applications.

These prototypes have demonstrated that the Erlang language can be successfully extended to support safe execution environments with minimal visible impact on most code. In the future we anticipate that these extensions will be incorporated into the Erlang run-time environment. This should remove some unavoidable incompatibilities (such as with ports) found in the prototypes, as well as ensuring that these safety extensions cannot be bypassed.

4.1 Safe Erlang Applications

Our work has mainly concentrated on design and implementation issues. However, a couple of simple applications have been successfully implemented within the prototypes, validating the basic approach we have proposed.

In 1998, Otto Björkströ, implemented a distrubuted game where a number of players share a common board, each taking their turn in order.

The board itself is implemented with a server, and to enter the game a player only needs to send a message to the server containing a reference to a local protected node where the server will spawn off a process representing the player. Code loading is thus made transparent. The local process is quite restricted, but may draw any graphics within a certain window on the player's screen.

Being able to draw any graphics on a screen makes the user vulnerable to a "Trojan Horse" attack as the process might draw new windows asking for

sensitive information such a passwords. We have been contemplating drawing a distinctive border around windows controlled by remote code to warn the user about this potential hazard.

The second application implemented concerned the remote control of a telephone exchange. Here no code was spawned, and the essential functionality was to prevent anybody else from taking over control of the exchange. In fact, a system without encryption, just having an authentication mechanism would be sufficient for this application. In countries where use encryption is restricted, this might be an interesting mode of operation.

5 Further Work - Custom Safety Policies

The extensions described above provide mechanisms necessary to impose an appropriate safety policy, without enforcing any specific policy. Work is now continuing on providing an appropriate level of *system safety* by executing the mobile code in a constrained environment created using these extensions, trusted to prevent direct access to any external resources by the executing mobile code, and then applying filters to messages between the mobile code and server processes which mediate the access to resources. This allows the use of standard servers, but with distinct policies being imposed for each instance. By restricting the security problem domain to just verifying that the messages conform to the desired policy, the problem should be considerably more tractable than approaches based on proofing the imported code directly, for example. It is also much more efficient than approaches which attempt to validate all function calls. The use of such a safety check function on client-server messages was sketched in Brown [9].

6 Conclusions

This paper describes proposed extensions to Erlang to enhance its ability to support safe execution of remotely sourced code. The changes include the provision of a hierarchy of nodes to provide a *custom context*, restrictions on *side-effects*, and resource limits; and the use of unforgeable references (capabilities) with associated rights of use for modules, nodes, processes, ports, and user defined references. Also, extensions are needed to support remote code loading in context. Two experimental prototypes, used to evaluate the utility of these extensions, are then described. Finally, mention is made of ongoing work using this safe execution environment as a foundation for imposing custom safety policies by filtering messages to server processes.

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