A Program Instrumentation for Prefix-Based Tracing in Message-Passing Concurrency

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Abstract. The execution of concurrent programs generally involves some degree of nondeterminism, mostly due to the relative speeds of the concurrent processes. As a consequence, reproducibility is often challenging. This problem has been traditionally tackled by a combination of tracing and replay. In this paper, we introduce a program instrumentation for prefix-based tracing that combines both tracing and replay. In the general case, the program is instrumented with a partial trace, so that the execution first follows the partial trace (replay) and, then, proceeds nondeterministically, eventually producing a trace of the complete execution as a side effect. Observe that traditional tracing and replay are particular cases of our approach when an empty trace is provided (pure tracing) and when a full trace is provided (pure replay), respectively.

1 Introduction

Message-passing concurrency mainly follows the so-called actor model. At runtime, concurrent processes can only interact through message sending and receiving (i.e., there is no shared memory). In this paper, we further consider that communication is asynchronous. Each process has a local mailbox (a queue) and each sent message is eventually stored in the mailbox of the target process. Moreover, we consider that processes can be dynamically spawned at runtime. The programming language Erlang mostly follows this model.

In this context, computations are typically nondeterministic because of the relative speeds of processes. Consider, for instance, three processes, p1, p2, and p3. If p1 and p2 both send a message to process p3, the order in which these messages are received is not fixed. Here, we say that these messages race. Considering all alternatives for message races is the purpose of state-space exploration techniques like stateless model checking or reachability testing. Intuitively speaking, these techniques start with an arbitrary execution, then consider some message race in this execution and, then, replay the execution up to the message race but then consider a different alternative. Executing a program deterministically up to a point and then let it proceed nondeterministically is called

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1 In practice, some Erlang built-in’s involve shared-memory concurrency, but we will not consider them in this work.
prefix-based testing in [9]. Other approaches, like [1], follow a similar process by inserting preemptive points in the code and, then, forcing the program to follow a particular interleaving up to a given point.

The nondeterminism of concurrent programs is also problematic for program debugging, since reproducing a buggy execution in a debugger is often challenging. To overcome this problem, so-called record-and-replay debuggers are often used. Here, the program is first instrumented in order to produce a trace of the execution as a side effect. Then, if some execution exhibits an incorrect behavior, the user can load both the program and the trace into a replay debugger in order to reproduce the considered computation. This is the case, e.g., of the reversible debugger CauDEr for Erlang programs [5,4]. In contrast to other debuggers, CauDEr is causal-consistent, which means that an execution is not reproduced in exactly the same order as the original, recorded one; rather, it allows the user to focus on the actions of a particular process, so that the actions of other processes are only performed if there exists a dependency with the actions of the considered process. Replay debugging in CauDEr is driven by the trace of an execution, i.e., by the sequence of actions that must be performed by each process. A trace can be seen as a partial order (i.e., it represents the class of all interleavings which give rise to causally equivalent computations).

In this work, we propose a new program instrumentation that can be used both in the context of state-space exploration methods and record-and-replay debugging. Our technique, called prefix-based tracing, takes a program and a (possibly partial) execution trace as input. When executing the instrumented program in the standard runtime environment, each process will follow the considered trace until all the actions in this trace have been performed. From this point on, the program will proceed nondeterministically, eventually producing a trace of the complete execution as a side effect. Observe that traditional tracing and replay are particular cases of our approach when an empty trace is provided (pure tracing) and when a full trace is provided (pure replay), respectively.

2 Prefix-Based Tracing: (Partial) Logs and Traces

In this section, we introduce some notions on tracing for message-passing concurrent programs. Here, we consider an Erlang-like language with asynchronous message passing. In the following, we focus on the concurrent component of the language and omit the evaluation of expressions (that follows an eager functional semantics; see, e.g., [6]). We consider the following concurrent actions:

- \texttt{spawn(mod, fun, args)}, which is used to dynamically create a new process to evaluate function \texttt{fun} (defined in module \texttt{mod}) with arguments \texttt{args} (a list).
  E.g., \texttt{spawn(test, client, [S, c1])} spawns a process that evaluates the expression \texttt{client(S, c1)}, where function \texttt{client} is defined in module \texttt{test}.\footnote{As in Erlang, functions and atoms (constants) begin with a lowercase letter while variables start with an uppercase symbol. The language has no user-defined data constructors, but allows the use of lists—following the usual Haskell-like notation—and tuples of the form \{e_1, \ldots, e_n\}, n \geq 1 (a polyadic function).}
  A spawn
expression reduces to a fresh identifier, called pid (for process identifier), that uniquely identifies the new process.

- \( p!v \), which sends the value \( v \) (the message) to process \( p \) (a pid). The expression reduces to \( v \) and eventually stores this value in the mailbox of process \( p \) as a side effect. Sending a message is an asynchronous operation, so the process continues immediately with the evaluation of the next expression.

- receive \( p_1 \rightarrow e_1; \ldots; p_n \rightarrow e_n \) end, which looks for the oldest message in the process mailbox that matches some pattern \( p_i \) and, then, continues with the evaluation of \( e_i \). When no message matches any pattern, execution is blocked until a matching message reaches the mailbox of the process.

In order to model a running application, [6] introduces a global mailbox \( \Gamma \) that represents the network (which is similar to the notion of ether in [10]). When a message is sent, it is first stored in \( \Gamma \). Typically, each message in \( \Gamma \) is stored as a tuple, including the pid of the sender, the pid of the target process, and (in the tracing semantics) a tagged message. Tags were introduced in [7] in order to uniquely identify each message so that the sending and receiving of a message can be tracked. The messages that are sent directly between two given processes are stored in a single queue so that the order is kept. In contrast, when the senders are different, messages can reach the target process in any order.

The semantics in [6] has a rule for each concurrent action, together with an additional rule to nondeterministically deliver a message, i.e., move a message from \( \Gamma \) to the local (private) mailbox of the target process. In general, given a process \( p \), we might have several queues of messages associated to different senders: \( \{p_1, p, q_1\}, \{p_2, p, q_2\}, \ldots, \{p_n, p, q_n\} \), where \( pi \) are the pids of the sender processes and \( qi \) are the corresponding queues of messages sent from \( pi \) to \( p \), \( i = 1, \ldots, n \). This rule to deliver messages was removed from the semantics of [7,8] since the goal was to define a replay semantics and, in this case, the order in which the messages must be received is fixed by a given trace.

In the following, we consider that an execution trace consists of a collection of sequences of actions, one per process. The considered actions are the following:

- spawn(\( p \)), where \( p \) is the pid of the spawned process;
- send(\( \ell \)), where \( \ell \) is the tag of the sent message, which is (initially) stored in the global mailbox \( \Gamma \);
- deliver(\( \ell \)), where \( \ell \) is the tag of the delivered message, which is moved from \( \Gamma \) to the local mailbox of the target process;
- receive(\( \ell \)), where \( \ell \) is the tag of the message consumed from the local mailbox.

We note that deliver events are attributed to the target of the message.

Let us consider the simple message-passing diagram shown in Figure 1. The associated trace can be represented as follows:

\[
\{p_1, \text{spawn}(p_3), \text{spawn}(p_2), \text{spawn}(p_4), \text{send}(\ell_1)\}\nn\{p_2, \text{send}(\ell_2), \text{deliver}(\ell_3), \text{receive}(\ell_3), \text{send}(\ell_4)\}\nn\{p_3, \text{deliver}(\ell_1), \text{deliver}(\ell_2), \text{receive}(\ell_1), \text{send}(\ell_3), \text{receive}(\ell_2), \text{deliver}(\ell_4), \text{receive}(\ell_4), \text{receive}(\ell_5)\}\nn\{p_4, \text{send}(\ell_5)\}\n\]
Observe that we do not need to fix a particular interleaving for all the actions in the trace. Only the order within each process matters; i.e., a trace represents a partial order (analogously to the SYN-sequences of [9]).

In [7,8], local mailboxes are abstracted away and there is no rule for message delivery (messages are directly consumed from the global mailbox $\Gamma$). Therefore, we have no deliver actions and the trace of the example above would be as follows:

\begin{verbatim}
{p1, [spawn(p3), spawn(p2), spawn(p4), send(\ell_1)]}
{p2, [send(\ell_2), receive(\ell_3), send(\ell_4)]}
{p3, [receive(\ell_1), send(\ell_3), receive(\ell_2), receive(\ell_4), receive(\ell_5)]}
{p4, [send(\ell_5)]}
\end{verbatim}

Despite the removal of deliver events, the resulting trace (called log in [7,8]) suffices to replay a given execution [8, Theorem 4.22]. Nevertheless, the deliver events might be useful for other purposes (e.g., to compute message races).

Therefore, in the following, we distinguish logs (as in [7,8], without deliver events) and traces (with deliver events). For instance, we say that the sequences in (1) represent a trace while those in (2) represent a log.

Observe that there are two message races in the execution of Figure 1. First, we have a race for $p_3$ between messages $\ell_1$ and $\ell_2$. If we swap the delivery of these messages, we can have a new execution which is not causally equivalent to the previous one and, thus, may give rise to a different outcome. A similar situation occurs with messages $\ell_4$ and $\ell_5$. Here, one might be interested in considering a partial log in order to explore an alternative execution. E.g., by assuming that message $\ell_2$ reaches first process $p_3$, we can produce the following partial log:

\begin{verbatim}
{p1, [spawn(p3), spawn(p2), spawn(p4), send(\ell_1)]}
{p2, [send(\ell_2)]}
{p3, [receive(\ell_2)]}
{p4, [send(\ell_5)]}
\end{verbatim}

Fig. 1: Processes ($p_i$, $i = 1, \ldots, 4$) are represented as vertical dashed arrows (time flows from top to bottom). Message sending and delivery is represented by solid arrows labeled with a message tag ($\ell_i$), from a sending event ($s_i$) to a delivery event ($d_i$), $i = 1, \ldots, 5$. Receive events are denoted by $r_i$, $i = 1, \ldots, 5$. Note that all events associated to a message $\ell_i$ have the same subscript $i$. 

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{p1, [spawn(p3), spawn(p2), spawn(p4), send(\ell_1)]}
{p2, [send(\ell_2)]}
{p3, [receive(\ell_2)]}
{p4, [send(\ell_5)]}
\end{verbatim}
Now, we could be interested in executing a program in replay mode until the log is consumed and, then, continue nondeterministically, eventually producing a trace of the complete execution. This is the goal of *prefix-based* tracing.

### 3 The Program Instrumentation

In this section, we focus on the design of a program instrumentation to perform prefix-based tracing of (a subset of) Erlang programs. In a nutshell, our program instrumentation proceeds as follows:

- First, we introduce a new process, called the *scheduler* (a server), that will be run as part of the source program.
- The scheduler ensures that the actions of a given log are followed in the same order, and that the corresponding trace is eventually computed. It also includes a data structure that corresponds to the global mailbox $\Gamma$. In the instrumented program, all messages will be sent via the scheduler.
- Finally, the sentences that correspond to the concurrent actions *spawn*, *send* and *receive* are instrumented in order to interact with the scheduler. The remaining code will stay untouched.

The scheduler uses several data structures called *dictionaries*, a typical key-value data structure which is commonly used in Erlang applications. Here, we consider the following standard operations on dictionaries:

- $\text{fetch}(k, \text{dict})$, which returns the value $\text{val}$ associated to key $k$ in $\text{dict}$. We write $\text{dict}[k]$ as a shorthand for $\text{fetch}(k, \text{dict})$.
- $\text{store}(k, \text{val}, \text{dict})$, which updates the dictionary by adding (or updating, if the key exists) a new pair with key $k$ and value $\text{val}$. In this case, we write $\text{dict}[k] := \text{val}$ as a shorthand for $\text{store}(k, \text{val}, \text{dict})$.

In particular, we consider the following dictionaries:

- *Pids*, which maps the pid of each process to a (unique) reference, i.e., $\text{Pids}[p]$ denotes the reference of pid $p$. While pids are relative to a particular execution (i.e., the pid of the same process may change from one execution to the next one), the corresponding reference in a log or trace is permanent. This mapping is used to dynamically keep the association between pids and references in each execution. For instance, an example value for *Pids* is $\{\{0.80.0, p1\}, \{0.83.0, p2\}\}$, where $\langle0.80.0\rangle$ and $\langle0.83.0\rangle$ are Erlang pids and $p1$, $p2$ are the corresponding references.
- *LT*, which is used to associate each process reference with a tuple of the form $\{ls, as\}$, where $ls$ is a (possibly empty) list with the events of a log and $as$ is a (possibly empty) list with the (reversed) trace of the execution so far. The log is used to drive the next steps, while the second component is used to store the execution trace so far. The list storing the trace is reversed for efficiency reasons (since it is faster to add elements to the head of the list).

E.g., the initial value of *LT* for the partial log displayed in (3) is as follows:

\[
\begin{align*}
\{p1, \{\text{spawn}(p3), \text{spawn}(p2), \text{spawn}(p4), \text{send}(\ell_1), [\ldots]\}\}, \\
\{p2, \{\text{send}(\ell_2), [\ldots]\}, \{p3, \{\text{receive}(\ell_2), [\ldots]\}, \{p4, \{\text{send}(\ell_5), [\ldots]\}\}
\end{align*}
\]
– **MBox**, which represents the global mailbox $\Gamma$. The key of this dictionary is the pid of the target process, and the value is another dictionary in which the keys are pids (those of the sender processes) and the values are lists of (tagged) messages. For instance, the value of **MBox** after sending the first two messages of the execution shown in Figure 1 could be as follows:

\[
\{(0.84.0), \{(0.80.0), [\{\ell_1, v_1\}\}], \\
\{(0.83.0), [\{\ell_2, v_2\}\]}
\]

where $\langle 0.80.0 \rangle$, $\langle 0.83.0 \rangle$, $\langle 0.84.0 \rangle$ are the pids of $p_1$, $p_2$, $p_3$, respectively, $v_1$ and $v_2$ are the message values and $\ell_1$ and $\ell_2$ are their respective tags.

Let us now describe the instrumentation of the source code. First, every expression of the form `spawn(mod, fun, args)` is replaced by a call to a new function `spawn_inst` with the same arguments. The new function is similar to the original function `spawn` but additionally (1) sends the message $\{P_1, \text{spawn}, P_2\}$ to the scheduler, where $P_1$ is the pid of the current process and $P_2$ is the pid of the spawned process, and (2) inserts a receive expression to make this communication synchronous. The reason for (2) is that every message of the form $\{P_1, \text{spawn}, P_2\}$ must add $P_2$ to the data structure `Pids`, either with a new reference or with the one in the current log. We require this operation to be completed before either the spawned process or the one performing the spawn can proceed with any other action. Otherwise, the scheduler would run into an inconsistent state.

The instrumentation of message sending is much simpler. We just perform the following rewriting:

\[ e_1!e_2 \Rightarrow \text{sched}!\{\text{self()}, \text{send}, e_1, e_2\} \]

where `sched` is the pid of the scheduler and `self()` is a predefined function that returns the pid of the current process. Finally, the instrumentation of a receive expression rewrites the code as follows:

\[
\text{receive } p_1 \rightarrow e_1; \ldots; p_n \rightarrow e_n \text{ end} \\
\Rightarrow \text{receive } \{L_1, p_1\} \rightarrow \text{sched}!\{\text{self()}, \text{receive}, L_1\}, e_1; \ldots; \\
\{L_n, p_n\} \rightarrow \text{sched}!\{\text{self()}, \text{receive}, L_n\}, e_n \text{ end}
\]

where $L_1, \ldots, L_n$ are fresh variables that are used to gather the tag of the received message and send it to the scheduler.

The main algorithm of the scheduler can be found in Algorithm 1. First, we have an initialization where the pid of the main process is associated with the reference $p_1$ in `Pids`, the initial logs are assigned to `LT`, and the mailbox is initially empty. As is common in server processes, the scheduler is basically an infinite loop with a receive statement to process the requests. Here, we consider three requests, which correspond to the messages sent from the instrumented source code. Let us briefly explain the actions associated to each message:

– If the message received has the form $\{p, \text{spawn}, p'\}$, where $p, p'$ are pids, we look for the tuple associated to process `Pids[p]` in `LT`. If the log is empty,
Algorithm 1 Scheduler

Initialization

\[ \text{Pids} := \{\text{self, p1}\}; \quad \text{LT} := */ prefix logs */; \quad \text{MBox} := \{\}\; \]

repeat receive \{p, spawn, p’\} →

case \[\text{LT}[\text{Pids}[p]]\] of

\{[]\}, as → /* trace mode */

r’ := new unique ref();

update_pids(p’, r’, Pids);

\[\{\text{spawn}(r’)|ls, as\} → /* replay mode */\]

update_pids(p’, r’, Pids);

\[\text{LT}[\text{Pids}[p]] := \{ls, \text{spawn}(r’)|as\}\; \]

\p! ack;

try deliver(p)

\{p, send, p’, v\} →

case \[\text{LT}[\text{Pids}[p]]\] of

\{[]\}, as → /* trace mode */

ℓ := new unique ref();

\[\text{LT}[\text{Pids}[p]] := \{[], \text{send}(ℓ)|as\}\; \]

\[\text{process_new_msg}(\{p, p’, ℓ, v\}, \text{MBox}, \text{LT})\; \]

\{send(ℓ)|ls, as\} → /* replay mode */

\[\text{LT}[\text{Pids}[p]] := \{ls, \text{send}(ℓ)|as\}\; \]

\[\text{process_msg}(\{p, p’, ℓ, v\}, \text{MBox}, \text{LT})\; \]

\try\ deliver(p)

\{p, receive, ℓ\} →

case \[\text{LT}[\text{Pids}[p]]\] of

\{[]\}, as → /* trace mode */

\[\text{LT}[\text{Pids}[p]] := \{[], \text{receive}(ℓ)|as\}\; \]

\{receive(ℓ)|ls, as\} → /* replay mode */

\[\text{LT}[\text{Pids}[p]] := \{ls, \text{receive}(ℓ)|as\}\; \]

\try\ deliver(p)

until true

we can proceed nondeterministically and just need to keep a trace of the execution step. Here, we obtain a fresh reference, \(r’\), add the pair \(\{p’, r’\}\) to \text{Pids}, and update the trace in \text{LT} with the new action \text{spawn}(r’). If the log is not empty, we proceed in a similar way but the reference is given in the log entry. Finally, we have to acknowledge the reception of this message since this communication is synchronous (as explained above).

- If the message received has the form \{p, send, p’, v\}, we again distinguish the case where the process log is empty. In this case, we obtain a fresh reference \(ℓ\) (the message tag) and update \text{LT} with the new action \text{send}(ℓ). Finally, we use the auxiliary function \text{process_new_msg} to check the log of the target process, \(p’\), and then it proceeds as follows:

  - If the log of \text{Pids}[p’] is empty, we add the action \text{deliver}(ℓ) to the trace of \text{Pids}[p’] and then send the message to the target process: \(p’!\{ℓ, v\}\), i.e., we
apply an instant-delivery strategy, where messages are delivered as soon as possible (this is the usual action in the Erlang runtime environment).

- If the log is not empty, we do not know when this message should be received. Hence, we add a new (tagged) message \( \{\ell, v\} \) from \( p \) to \( p' \) to the mailbox \( \text{MBox} \), and add an action \( \text{deliver}(\ell) \) at the end of the current log.

Note that computed logs (as in [7,8]) should not contain deliver actions. This one is artificially added to force the delivery of message \( \ell \) as soon as possible (see function \text{try_deliver} below).

If the log is not empty, we proceed in a similar way but the message tag is given by the log and we call the auxiliary function \text{process_msg} instead. This function checks the log of the target process, \( \text{Pids}[p'] \), and then proceeds as follows:

- If the next action in the log is \( \text{receive}(\ell) \), we add the action \( \text{deliver}(\ell) \) to the trace of \( \text{Pids}[p'] \) and send the message to the target process: \( p'!\{\ell, v\} \).

- If the first action is not \( \text{receive}(\ell) \), we add a new (tagged) message \( \{\ell, v\} \) from \( p \) to \( p' \) to the mailbox \( \text{MBox} \). Finally, if the log of \( \text{Pids}[p'] \) contains an action \( \text{receive}(\ell) \), we are done; otherwise, an action of the form \( \text{deliver}(\ell) \) is added to the end of the log of process \( \text{Pids}[p'] \), as before.

Finally, when the received message has the form \( \{p, \text{receive}, \ell\} \), we just update the trace with the new action \( \text{receive}(\ell) \) and, if the log was not empty, we remove the first action \( \text{receive}(\ell) \) from the log.

Each of the above cases ends with a call \text{try_deliver}(p)\), which is basically used to deliver messages that could not be delivered before (because it would have violated the order of some log). For this purpose, this function checks the next action in the log of process \( \text{Pids}[p] \). If it has either the form \( \text{receive}(\ell) \) or \( \text{deliver}(\ell) \), and the message tagged with \( \ell \) is the oldest one in one of the queues of \( \text{MBox} \) with target \( p \), then we send the message to \( p \), remove it from \( \text{MBox} \) and add \( \text{deliver}(\ell) \) to the trace of process \( \text{Pids}[p] \). Furthermore, in case the element of the log was \( \text{deliver}(\ell) \), we recursively call \text{try_deliver}(p)\) to see if there are more messages that can be delivered. In any other case, the function does nothing.

4 Concluding Remarks

In this work, we have presented a program instrumentation for prefix-based tracing of message-passing concurrent programs with asynchronous communication. An implementation to instrument Erlang programs has been undertaken, which is publicly available from

https://github.com/mistupv/cauder/tree/paper/prefix-based-tracing.

As future work, we plan to first formalize a conservative extension of the standard semantics in order to perform prefix-based tracing (e.g., extending the logging semantics in [7,8]). Then, we will prove the correctness of the program instrumentation w.r.t. the prefix-based tracing semantics. Finally, we plan to extend the causal-consistent reversible debugger CauDER in order to use prefix-based tracing (e.g., as part of a state-space exploration method).
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