Collecting Graphical Abstract Views of Mercury Program Executions

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Abstract

A program execution monitor is a program that collects and abstracts information about program executions. The collect operator is a high level, general purpose primitive which lets users implement their own monitors. Collect is built on top of the Mercury trace. In previous work, we have demonstrated how this operator can be used to efficiently collect various kinds of statistics about Mercury program executions. In this article we further demonstrate the expressive power and effectiveness of collect by providing more monitor examples. In particular, we show how to implement monitors that generate graphical abstractions of program executions such as proof trees, control flow graphs and dynamic call graphs. We show how those abstractions can be easily modified and adapted, since those monitors only require several dozens of lines of code. Those abstractions are intended to serve as front-ends of software visualization tools. Although collect is currently implemented on top of the Mercury trace, none of its underlying concepts depend of Mercury and it can be implemented on top of any tracer for any programming language.
1 Introduction

A program execution monitor is a program that collects and abstracts information about program executions. The monitoring functionalities of existing systems are built on top of ad hoc instrumentations. Most of them are implemented by subtle modifications of the runtime system; therefore, implementing such monitors require an in-depth knowledge of the system. The best people to implement these instrumentations are generally the implementors of the compiler. They, however, cannot decide which data to gather. Indeed, hundreds of variants can be useful and only end-users know what they want.

Collect is a high level, general purpose, foldl-like operator which lets users implement their own monitors. We have demonstrated in [11] how this operator can be used to collect various kinds of statistics about Mercury program executions such as counting the number of predicate calls, the number of events for each event type (port), or the number of events at each depth. We have also showed how it is possible to perform test coverage ratio; this information is useful to assess the quality of a test set. The aims of these examples were twofold: demonstrating the expressive power of collect and the efficiency of the resulting monitors. In this article, we propose more program abstractions implemented with collect. The goal is to further assess the expressive power of collect in a pragmatic way by implementing a wider range of monitors and to check that the resulting monitors are still reasonably efficient. The monitors described in this article requires slightly more programming effort than the ones in [11]. In particular, we show how to implement monitors that generate graphical abstractions of program executions such as proof trees, control flow graphs and dynamic call graphs. We show how those abstractions can be modified and adapted. We believe that collect could be the basis of software visualization tools [20]. This article also aims to be a tutorial about how to implement (Mercury) program monitors with collect.

All the monitors given in this article are run under the Morphine trace analysis system. Morphine [12] is a Prolog interpreter enhanced with primitives (collect included) to communicate with a Mercury program’s execution. Morphine is a fully programmable command line interface for interactively monitoring and debugging Mercury program executions. The use of collect is independent of other Morphine concepts though; we only use the Prolog part of Morphine to post-process monitor’s results. All the examples are verbosely paraphrased so no knowledge about Mercury or Prolog should be required to
understand them. Section 2 gives a quick overview of the language and the trace system of Mercury, as well as an informal presentation of collect. Sections 3.1, 3.2, and 3.3 show how to implement monitors that generate control flow graphs, dynamic call graphs and proof trees respectively. Section 4 describes how monitors can be merged. Section 5 discusses performance issues and Section 6 related work.

2 Flexible and efficient monitoring of Mercury

The collect operator [11] is a generic primitive designed to let users implement easily efficient Mercury program monitors. In this section, we give a brief review of the Mercury programming language and of the collect monitoring operator.

2.1 A brief introduction to Mercury

Mercury [19] is a purely declarative, logical and functional programming language. Its syntax is very similar to the one of Prolog. The main difference with Prolog is that users must declare the type, the mode and the determinism of predicates (and functions) they define. These declarations let the Mercury compiler produce very robust and efficient code.

```mercury
:- pred queen(list(int)::in, list(int)::out) is nondet.
queen(Data, Out) :- qperm(Data, Out), safe(Out).
```

Figure 1: The Mercury predicate queen/2

Figure 2.1 shows an example of Mercury code. It is a predicate of a Mercury program that solves the well known $n$ queens problem. This program is given in Appendix 1. The first line is the type and mode declaration of predicate queen/2. This line states that the first argument of queen/2 is a list of integers and this argument is an input (in). It also states that its

1 queen/2 denotes a predicate named queen of arity 2.
second argument is a list of integers and it is an output (\texttt{out}). The non\texttt{det} determination marker means that this predicate can have any number of solutions. Actually, it has two solutions. The list of integers codes the board. The predicate \texttt{qperm/2} generates all the possible configurations by producing all the permutations of the list of integers. Then \texttt{safe/2} checks that a given configuration is a solution, namely, that there is no more than one queen per diagonal.

**The Mercury trace** A \textit{trace} is a sequence of events. An \textit{event} is a tuple of event attributes. An \textit{event attribute} is an elementary piece of information that can be extracted from the current state of particular points of the program execution. The program points of the Mercury trace are chosen according to a trace model that is called Byrd’s box model \cite{2}: a \textit{call} event is generated when a predicate is called; a \textit{exit} event is generated if it succeeds; a \textit{fail} event is generated if it fails; a \textit{redo} event is generated if the execution backtracks on a predicate to see if it can produce other solutions. Actually, the Mercury trace is an extended version of Byrd’s box model because events are also generated when the execution enters a branch of a disjunction or of an if-then-else. In the following, these events are called \textit{internal} and the Byrd’s event are called \textit{external}. The complete list of Mercury event attributes is given in Appendix 2.

### 2.2 The \textit{collect} monitoring operator

Debugging and monitoring can be seen as a list of events processing activity. The standard functional programming operator \textit{foldl} encapsulates a simple pattern of recursion for processing lists\footnote{The \textit{foldl} operator takes as argument a function, a list, and an initial value of an accumulator; it outputs the final value of the accumulator; this final value is obtained by applying to the function the current value of the accumulator and each element of the list successively; the \texttt{l} at the end of \textit{foldl} means that this list is processed from left to right.}. As demonstrated by Hutton \cite{10}, \textit{foldl} has a great expressive power for processing lists. Therefore \textit{foldl} is likely to be a good abstraction to implement dynamic analysis tools.

However, implementing monitors by collecting the whole execution trace into a list of events, and then applying a \textit{foldl} to that list would be far too inefficient. It would require to create and process a list of possibly millions of events. To implement efficient monitors, runtime information needs to be collected and analyzed on the fly. The primitive \textit{collect} \footnote{The \textit{collect} operator takes as argument a predicate, and a list; it outputs the list of event attributes produced by this predicate and the execution of the list of integers.} is a \textit{foldl} operator
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which is directly plugged into the trace system. First, a global variable is created and initialized. Then, whenever an event occurs, the collect interface is called instead of the standard debugger. The collect interface calls the filtering predicate which updates the global variable and then gives control back to the execution.

It is important to note here that for performance reasons, there is no coroutining between different Operating System (OS) processes (the program and its monitor) but only procedure calls that update a global variable. This design decision was made to avoid those expensive OS level context switches induced by coroutining that the collect operator was initially designed (see related work section).

For the time being, the only implementation of collect we have is done on top of the Mercury trace. The trace component of the Mercury system has been extended so that it is able to call the collect interface rather than the Mercury debuggers [18]. To implement monitors using collect, users need to give an initial value to the accumulator by defining a Mercury predicate named initialize/1, and to update the accumulator at each event by defining a Mercury predicate named filter/4. Since Mercury is a typed language, users also need to define the type of the collecting variable collected_type.

% 1 - Importation of Mercury library modules:
:- import_module < Mercury modules >.

% 2 - Definition the type of the collecting variable:
:- type collected_type == < A Mercury type >.

% 3 - Initialization of the collecting variable:
initialize(Accumulator) :-
  < Mercury goals which initialize the collecting variable >.

% 4 - Updating of the global variable:
filter(Event, AccumulatorIn, AccumulatorOut, StopFlag) :-
  < Mercury goals which update the collecting variable >.

Figure 2: What the user needs to type to define a monitor with collect

This is summed up in Figure 2: predicates initialize/1 and filter/4 should follow the following Mercury declarations:
The type `event` is a structure which contains all the Mercury event attributes. To access those attributes, the monitor designer can use attribute accessor functions whose prototypes are of the form:

```prolog
:- func <attribute_name>(event::in) = <attribute_type>::out.
```

For example, the function `depth(Event)` returns the depth of the event `Event` (the full list of `attribute_name` is given in Appendix 2). The fourth argument of `filter/4` is a binary flag that can be set to `stop` or `continue` depending on whether or not one wants to stop the monitoring process before the end of the execution is reached. The current front-end of `collect` is a Prolog interpreter. Having a full programming environment is very useful to post-process the results of the monitor. If a file called `my_monitor` contains a definition of `initialize/1` and `filter/4`, then the call `collect(queens, my_monitor, Result)` binds `Result` with the result of the monitor specified in `my_monitor` to the Mercury program `queens`. For example, Figure 2 contains the full code of a monitor that counts the number of predicate calls. If this code is in a file called `count_call`, then the query `collect(queens, count_call, Result)` will bind `Result` to the number of predicate calls that occurs during the execution of the program `queens`.

```prolog
:- mode initialize(collected_type::out) is det.
:- pred filter(event::in, collected_type::in,
    collected_type::out, stop_or_continue::in) is det.
```

Here is a line by line description of the code of Figure 3. To do that, here and in the following descriptions of monitors defined in this article, we
successively describe each of the four points that need to be addressed to define a monitor using `collect`. (1) Importing necessary Mercury modules: here, we only need to import the library module `int` that defines everything that is concerned with integers. (2) Defining the type of the collecting variable: here, it is an integer. (3) Initializing the collecting variable: here, it is initialized to 0. (4) Defining the filtering predicate: here, it increments the global variable whenever the current event port attribute is `call`.

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Figure 4: the various involved components and their relation when the user invoke the command "`collect(queens, count_call, Result)`".

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Figure 4 shows the various involved components and their relation when the user invoke the command “`collect(queens, count_call, Result)`.” at the Morphine prompt. Square boxes represent source files. Circle boxes represent object and executable files. The file containing the definition of the monitor, `count_call`, is transformed by Morphine into a Mercury module. The arrows labeled with `mmc` denote a call to the Melbourne Mercury compiler. The compilation of `count_call.m` and `queens.m` is only done if necessary, i.e., if something has changed in the source code since the last time it was compiled. The executable file `queens-count_call` is obtained by dynamically linking the executable file `queens` and the objet file `count_call.o`. The output of this program, 157, is unified with the logical variable `Result` at the Morphine prompt.

3 **Collecting graphical abstract views**

In this section, we show how to generate several kinds of program execution abstract views based on graphs. All the graphs of this section are visualized with the dot drawing tool [16]. The final objective is to have more sophisticated back-ends such as the visualization tools presented in [20]. The point
of this section is not to provide an exhaustive set of graphical abstractions. The point is to show how easy it can be to implement them and, more interestingly, how easy it is to get a variant of an existing abstraction. Indeed, different visualization tools often need slightly different images of the execution. The full code that implements the production of these graphs is available in the control flow scenario of the Morphine distribution.

3.1 Control flow graphs

Figure 5: The control flow graph of n queens program

We define the control flow graph of a logic program execution as the directed graph where: nodes are predicates of the program; and arcs indicate that the program control passed from the origin to the destination node during the execution. Control flow graphs are useful execution abstractions for users to understand what a program actually do. They are also the basis of a lot of dynamic analyses. The control flow graph of the n queens program is given in Figure 5. We can see that, during the program execution, the control passed from predicate main/2 to predicate data/1, from predicate data/1 to predicate data/1 (recursive call) and predicate queen/2, etc. An implementation of a monitor that performs such a graph is given in Figure 6.

3http://www.irisa.fr/lande/jahier/download.html
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```prolog
:- import_module set.

:- type predicate ---> proc_name/arity.
:- type arc ---> arc(predicate, predicate).
:- type graph == set(arc).
:- type collected_type ---> collected_type(predicate, graph).

initialize(collected_type("user"/2, set__init)).

filter(Event, Acc0, Acc, continue) :-
  Port = port(Event),
  ( if (Port = call ; Port = exit ; Port = fail ; Port = redo) then
    Acc0 = collected_type(PreviousPred, Graph0),
    CurrentPred = proc_name(Event) / proc arity(Event),
    Arc = arc(PreviousPred, CurrentPred),
    set__insert(Graph0, Arc, Graph),
    Acc = collected_type(CurrentPred, Graph)
  else
    % internal events
    Acc = Acc0
  ).
```

Figure 6: Monitor that calculates control flow graphs
Monitor of Figure 6 is defined as follows. (1) The set module of the Mercury library is imported. (2) Graphs are encoded by a set of arcs, and arcs are terms made up with two predicates. The collecting variable is made of a predicate and a graph. The predicate is used to remember the previously visited node. (3) The collecting variable is initialized with the predicate main/2, the top level predicate of every Mercury program, and the empty graph (set__init/0). (4) For every external event, we insert in the graph (set__insert/3) an arc from the previous predicate to the current one. When the program execution has terminated, we post-process the result with dot [16], a system that takes a graph description and that displays a pretty post-scripted version of it. Figure 5 is the output of such a post-processed result with the monitor of Figure 6. This post-processing stage only requires a few dozen lines of Prolog code. In our definition of control flow graph, the number of times each arc is traversed is not given. Even if the control passed between two nodes more than once, only one arc is represented. One can imagine variants where, for example, arcs are labeled by a chronological counter. The corresponding monitor can be implemented by replacing arc(predicate, predicate) by arc(predicate, chrono, predicate) in the type definition of arc, and replacing the goal Arc = arc(PreviousPred, CurrentPred) by Arc = arc(PreviousPred, chrono(Event), CurrentPred) in the definition of filter/4.

3.2 Dynamic call graphs

We define the dynamic call graph of a logic program execution as the subgraph of the (static) call graph composed of the nodes that has been exercised during the execution. In other words, it is an execution slice of the program call graph. For example, we can see that predicate main/2 called predicates data/1, queen/2 and print_list/2. An implementation of a monitor that performs this graph is given in Figure 8.

Here is a line by line description of the code of Figure 8. (1) Library modules set and stack are imported. (2) In order to define this monitor, we use the same data structures as for the previous monitor, except that we replace last exercised predicate by the whole call stack in the collected variable type. This call stack is computed on the fly. (3) The stack and the set of arcs are initialized to the empty stack and to the empty set respectively. (4) At call events, we insert an arc from the previous predicate to the current one and we push (function stack__push/2) the current predicate on the stack.
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At redo events, we only update the call stack by pushing on it the current predicate. At fail and exit events, we remove the top element of the stack (predicate `stack__pop_det/3`). The post-processed result of the execution of this monitor on the \( n \) queens program is given in Figure 7.

In the current implementation of `collect`, the call stack is not passed as an event attribute. The reason for that is that the call stack can be very large, which would slow down the `collect` monitors. Another reason is that, as demonstrated in this example, it is very easy to reconstruct this information. It is also interesting to note that the impact on the performance of handling the stack on the fly as we do here is hardly noticeable.

### 3.3 Proof Trees

Another widely used program abstract view in the logic programming community are proof trees. A proof tree of a program execution is the dynamic call graph where all the fail nodes are omitted. Thus, for example, a failing request produces an empty proof tree. We do not give the code of the monitor that implements the proof tree, but rather briefly explains how it can be done with `collect`. The idea is to maintain a table of proof trees and a table of goal immediate successors both indexed by goal numbers (each goal is uniquely defined by its goal number). When predicates successfully exit, we construct the proof tree of the current goal. We can do that because at that port, we have the whole list of the current goal immediate successors.
:- import_module set, stack.

:- type predicate ---> p(proc_name, arity).
:- type arc ---> arc(predicate, predicate).
:- type graph == set(arc).
:- type collected_type ---> ct(stack(predicate), graph).

initialize(ct(Stack, set__init)) :-
    stack__push(stack__init, p("user", 0), Stack).

filter(Event, ct(Stack0, Graph0), Acc, continue) :-
    Port = port(Event),
    CurrentPred = p(proc_name(Event), proc_arity(Event)),
    update_call_stack(Port, CurrentPred, Stack0, Stack),
    ( ( Port = call ) -> 
        PreviousPred = stack__top_det(Stack0),
        set__insert(Graph0, arc(PreviousPred, CurrentPred), Graph),
        Acc = ct(Stack, Graph)
    ;
    Acc = ct(Stack, Graph0) ).

:- pred update_call_stack(trace_port_type::in, predicate::in,
    stack(predicate)::in, stack(predicate)::out) is det.

update_call_stack(Port, CurrentPred, Stack0, Stack) :-
    ( ( Port = call ; Port = redo ) ->
        stack__push(Stack0, CurrentPred, Stack)
    ; ( Port = fail ; Port = exit ) ->
        stack__pop_det(Stack0, _, Stack)
    ; % internal ports
        Stack = Stack0 ).

Figure 8: Monitor that calculates dynamic call graphs
and we know the proof trees of each of these successors. At redo ports, those proof trees are removed from the table of proof trees. In order to calculate the list of immediate successors, we also need to maintain a stack of goal numbers, in exactly the same manner as in the two previous monitors.

The post-processed result of the execution of this monitor on the $n$ queens program is given in Figure 9. It is also possible to construct SLD-trees with the same kinds of monitors, but we lack the necessary space to describe it here\footnote{The source code of all those monitors, included SLD-tree, is available at the Morphine web site [http://www.irisa.fr/lande/jahier/download.html]}. We have not included the predicate arguments in the graphs node, but that could have easily been done. We could add all the event attributes in the graph nodes actually. But then we would really need a visualization tool back-end that, for example, would display all those informations on request by clicking on nodes.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{proof_tree.png}
\caption{The proof tree of $n$ queens program}
\end{figure}
4 Merging monitors

Figure 10: A set of monitor indexed by $i \in \{1, ..., n\}$

A nice property of collect is that it implements monitors that can easily be merged. All the monitors can therefore collect their data in only one program execution. Indeed, consider the $n$ monitors of Figure 4 where: $i$ is in $\{1, ..., n\}$; $\text{type}_i$ is an arbitrary Mercury type; $\text{initialize}_i$ a predicate that outputs a term of type $\text{type}_i$; and $\text{filter}_i$ a predicate that takes an event, a term of type $\text{type}_i$ and outputs a term of type $\text{type}_i$. We suppose that there are no name clashes between $C_i$, $C_i\text{In}$ and $C_i\text{Out}$. Then all those monitors can be merged as shown in Figure 4.

Figure 11: The monitor obtained by merging the $n$ monitors of Figure 4

The collecting variable type of the resulting monitor is a functor with arguments the $n$ monitors collecting variable types. The initialization (resp. filtering) predicate successively initializes (resp. updates) each collecting...
variable using the initialization (resp. filtering) predicate of the sub-monitors. This can easily be done automatically.

5 Performance issues

We have seen in the previous sections how it is possible for users, without any knowledge about the Mercury trace system, to implement their own monitors. This genericity has as price: efficiency. In this section, we try to exhaustively examine the source of performance overheads of our approach compared with hand-crafted ad-hoc monitors implemented inside the compiler.

Granularity of the instrumentation The principal source of overhead is due to the fact that not all the monitors need such a fine grained instrumentation as the trace system have. The only control we have over the granularity of the instrumentation is the possibility to generate only external events when compiling programs. In order to assess this overhead, we have compared the execution times of Mercury programs executed normally with programs executed within the control of the trace system. We mean by executed under the control of the trace system that, at each event, the trace system is called and then simply returns. We have measured a slowdown of around a factor of two if internal events are not generated, and a factor of four if they are generated.

Unused event attributes A second source of overhead is due to the fact that we systematically pass to filter all event attributes, even if they are not used. Actually, this is not really a problem since it is possible to dynamically choose the event attributes that are available in the event structure. In the current implementation of collect, it is already the case for the list of live arguments. Indeed, since this attribute can be very large, we want to avoid the cost of handling it when it is not necessary. To assess this source of overhead for the other attributes, we have measured an implementation of collect that handles all the event attributes versus a version that handles none of them (leading to monitors that can not do anything useful but counting the number of events). The slowdown was smaller than 10%.

Scaling up the approach Performance problems might occur when the monitoring data become very large. A possible solution is to bufferize the
data collecting by sending intermediate data to the Morphine process every N events. This is possible thanks to the collect fourth argument flag, which allows to stop the monitoring process at any events. Then Morphine, which is based on a full existing Prolog programming environment, can manage the analysis of the collected data and then start a new collect call to finish the execution monitoring. Moreover, on a two processors machine, we can even process those partially collected data asynchronously and thus perform the collecting and the analysis steps in parallel.

6 Related Work

Programmable debuggers Ducassé designed Coca [4] and Opium [5], programmable debuggers for C and Prolog respectively. Coca and Opium are based on a Prolog interpreter plus an handful of coroutining primitives connected to the trace system. Those primitives allow the Prolog interpreter to communicate with the debugged program. Coca and Opium are full debugging programming languages in which all classical debuggers commands can be implemented straightforwardly. However, it appears that the set of coroutining primitives of Coca and Opium are not well suited for monitoring. All the monitors implemented with collect can easily be implemented with this set of primitives, but the resulting monitors require too much Operating System level context switches and too much socket traffic between the program and the monitor. With program of several million of execution events, such monitors are several orders of magnitude slower than their counterparts that use collect [13].

The collect primitive does not only extend the Coca/Opium primitives in terms of efficiency, but also in terms of expressiveness. Using the existing primitives to implement monitors, one typically duplicate the code that (1) makes the execution move one event forward, (2) checks if the end of the execution is reached. Those two steps are automatically done when using collect. In other words, the expressiveness improvement between collect and the existing primitives of Coca/Opium is the same as the improvement we have between using foldl and processing lists manually. As a matter of fact, collect can be seen as a generalization of Opium/Coca coroutining primitives since they can all be implemented with it.
Automated development of monitors  Jeffery and al. designed Alamo \[14\], an architecture that aims at easing the development of monitors for C programs. As in our approach, their monitoring architecture is based on events filtering and monitors can be programmed. Their system deals with trace extraction whereas we rely on an already available tracer; this saves us from a low level and tedious task which has already been done and optimized. On the other hand, we do not have the control on the information available in the trace. Note however that lacking information can sometimes be recovered as we did for example to perform the call stack. Moreover, to avoid code explosion, they perform part of the events filtering at compilation time. Hence they need to recompile the program each time they want to execute another monitor whereas we only need to dynamically link the monitor to the monitored program. Alamo and the monitored program are running in coroutining, but within the same address space. Alamo has therefore less problems of efficiency than Coca and Opium for monitoring. Eustace and Srivastava developed Atom \[8\], a system that also aims at easing the building of monitors. The difference with Alamo is that monitors are implemented with procedure calls and global variables which is much more efficient than coroutining. However, the language Atom provide is far less expressive than the one of Alamo. Alamo and Atom have influenced the design of collect and we tried to take the best of both; a full and high level programming language implemented by procedure calls.

Kishon and al. \[15\] use a denotational and operational continuation semantics to formally define monitors for a simple functional programming language. The kind of monitors they define are profilers, debuggers, and statistic collectors. From the operational semantics, a formal description of the monitor, and a program, they derive an instrumented executable file that performs the specified monitoring activity. The semantics of the original programs is preserved. Then, they use partial evaluation to make their monitors reasonably efficient. The main disadvantage with this approach is that they are rebuilding a whole execution system from scratch, without taking advantage of the existing compiler. We strongly believe that it is important to have the same execution system for debugging and for producing the final executable program. As noted by Brooks and al. \[1\], some errors only occur in presence of optimisations, and vice versa; some programs can only be executed in their optimized form because of time and memory constraints; when searching for “hot spots”, it is better to do it with the optimized program as lots of things can be optimized away; and finally, sometimes, the error comes
from the optimisations themselves.

**Efficient monitoring**  Patil and Fisher [17] tackles the problem of performance monitoring by delegating the monitoring activities to a second processor that they call a shadow processor. Their approach is very efficient; the monitored is nearly not slowed down. However, the set of monitoring commands they propose cannot be extended.

**Invariant Detection**  Explicitly stated program invariants can help users to identify program properties which must be preserved when modifying code. Invariant discovery is generally done statically [3]. However, static analyses miss true but uncomputable properties and properties that depend of the program inputs. Ernst and al. investigate a complementary approach [6] that consists of dynamically detecting program invariants. The idea is to run instrumented versions of programs on a sufficiently large set of test cases, and then examine the values they compute, looking for patterns and relationships among those values. Useless invariants are filtered [7]. A prototype implementation, Daikon, demonstrates the feasibility of this approach. Despite its intrinsic unsoundness, Ernst and al. report that dynamic invariant discovery can be very useful in practice. We believe that it could be an interesting application of *collect*.

7 Conclusion

For a given monitor, provided that the whole necessary information is in the trace, (1) is it always possible to implement a given monitor? (2) is it always easy to implement it? (3) is it always possible to implement it efficiently? Since it is possible to collect the whole execution trace, the answer to the first point is yes. This would be the most inefficient way of implementing monitors though as the trace can be huge. The second point is more difficult to assess. However, we believe that *collect* has the right level of abstraction to allow that. Processing a trace with *collect* is the same as processing a list with a *foldl* operator; and the *foldl* operator is very expressive, as argued by Hutton [10]. Indeed, processing lists using a *foldl* operator has significant advantages over processing lists manually. This article contributes to give an experimental assessment of the second point by demonstrating how easy a wide range of monitors can easily be implemented with *collect.* With regards
to the third point, the measurements we made let us believe that the cost of monitors implemented with collect is acceptable. We believe that all the monitors implemented with collect executes in the same order of magnitude of time as their hand-crafted counterparts.

The choice of Mercury to implement initialize and filter is arbitrary. The reasons to use Mercury in this context is that people who want to monitor Mercury programs are very likely to be Mercury users. Moreover, since filter will be called possibly millions of times, it makes sense to use a highly optimized compiler such as the one of Mercury.

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Appendix 1 - The n-queens program in Mercury

```mercury
:- module queens.
:- interface.
:- import_module io.
:- pred main(io__state, io__state).
:- mode main(di, uo) is cc_multi.

:- implementation.
:- import_module list, int.

main -->
( { data(Data), queen(Data, Out) } -->
    print_list(Out)
;    io__write_string("No solution\n")
).

:- pred data(list(int)).
:- mode data(out) is det.

:- pred queen(list(int), list(int)).
:- mode queen(in, out) is nondet.

:- pred qperm(list(T), list(T)).
:- mode qperm(in, out) is nondet.

:- pred qdelete(T, list(T), list(T)).
:- mode qdelete(out, in, out) is nondet.

:- pred safe(list(int)).
:- mode safe(in) is semidet.

:- pred nodiag(int, int, list(int)).
:- mode nodiag(in, in, in) is semidet.

data([1,2,3,4,5]).

queen(Data, Out) :-
    qperm(Data, Out),
    safe(Out).

qperm([], []).
qperm([X|Y], K) :-
    qdelete(U, [X|Y], Z),
    K = [U|V],
    qperm(Z, V).
```

```mercury
:- module queens.
:- interface.
:- import_module io.
:- pred main(io__state, io__state).
:- mode main(di, uo) is cc_multi.

:- implementation.
:- import_module list, int.

main -->
( { data(Data), queen(Data, Out) } -->
    print_list(Out)
;    io__write_string("No solution\n")
).

:- pred data(list(int)).
:- mode data(out) is det.

:- pred queen(list(int), list(int)).
:- mode queen(in, out) is nondet.

:- pred qperm(list(T), list(T)).
:- mode qperm(in, out) is nondet.

:- pred qdelete(T, list(T), list(T)).
:- mode qdelete(out, in, out) is nondet.

:- pred safe(list(int)).
:- mode safe(in) is semidet.

:- pred nodiag(int, int, list(int)).
:- mode nodiag(in, in, in) is semidet.

data([1,2,3,4,5]).

queen(Data, Out) :-
    qperm(Data, Out),
    safe(Out).

qperm([], []).
qperm([X|Y], K) :-
    qdelete(U, [X|Y], Z),
    K = [U|V],
    qperm(Z, V).
```
Appendix 2 - The Mercury trace

There are three kinds of attributes: attributes containing information relative to the control-flow (numbered from 1 to 6 in the following), to the data-flow (7 and 8) as well as information relative to the source code (9 and 10). The different attributes provided by the Mercury tracer are listed below.

1. Event number (chrono). It is the rank of the event in the trace.

2. Goal invocation number (call).

3. Execution depth (depth).

4. Event type or port (port). There are the 4 traditional ports call, exit, fail and redo introduced by Byrd [2] for Prolog. Mercury also generates internal events describing what occurs inside a call: an event of type disj is generated each time the execution enters a branch of a disjunction, of type switch if this disjunction is a switch, of type then if it is the “then” branch of a if-then-else and of type else if it is the “else” branch.

5. Determinism (deter). It characterizes the number of potential solutions for each procedure. The different determinism markers are described in section [7.1]

6. Procedure (proc). It is characterized by: a flag indicating if the current procedure is a function or a predicate (proc_type), a module name (module), a procedure name (proc_name), an arity (arity) and a mode number (mode_num).

7. List of live arguments (arg). A variable is said to be live at a given point of the execution if its instantiation is still available.

8. List of local live variables (local_var). It is the live variables that are not arguments of current procedure.

5 A switch is a disjunction in which each branch unifies a ground variable with a different function symbol. In that case, at most one disjunction will provide a solution.
6 The mode number encodes the mode of a predicate or a function: when a predicate has one mode, this number is 0. If not, this number corresponds to the rank of appearance in the code of the mode declaration; 1 for the first, 2 for the second, etc.
9. *Goal Path (goal_path).* It is a list indicating in which branch of the code the current event takes place. The branches *then* and *else* of a *if-then-else* are represented by *t* and *e* respectively; the *conjunctions, disjunctions* and the *switches* are represented by *ci, di* and *si* respectively, where *i* is the number of the conjunction, disjunction, or the switch. For example, an event whose path is [*c3;e;di*] corresponds to an event which occurs in the first branch of a disjunction, which is itself part of an else branch of an if-then-else, which is in the third conjunction of the current procedure. For efficiency reasons, this attribute is only available at internal events.

10. *Ancestor stack (ancestors).*

A more detailed description of the contents of the Mercury trace is made in the Mercury language reference manual [4] and in the user’s manual of Morphine [12].