Temporal Debugging using URDB

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Abstract

A new style of temporal debugging is proposed. The new URDB debugger can employ such techniques as temporal search for finding an underlying fault that is causing a bug. This improves on the standard iterative debugging style, which iteratively re-executes a program under debugger control in the search for the underlying fault. URDB acts as a meta-debugger, with current support for four widely used debuggers: gdb, MATLAB, python, and perl. Support for a new debugger can be added in a few hours. Among its points of novelty are: (i) the first reversible debuggers for MATLAB, python, and perl; (ii) support for today’s multi-core architectures; (iii) reversible debugging of multi-process and distributed computations; and (iv) temporal search on changes in program expressions. URDB gains its reversibility and temporal abilities through the fast checkpoint-restart capability of DMTCP (Distributed MultiThreaded Checkpointing). The recently enhanced DMTCP also adds ptrace support, enabling one to freeze, migrate, and replicate debugging sessions.

1 Introduction

Programmers have long struggled under the curse of temporality in debugging complex code. An unknown program fault corrupts the logic of the program, but the resulting bug may be exposed only much later in that program. Debuggers assist one in analyzing the logic near the error, but only in order to build a hypothesis that might explain the original cause or fault of the bug. Upon producing a hypothesis, the programmer again executes the program under debugger control with the hope of obtaining more conclusive proof that the hypothesis is correct.

This style of iterative debugging is only a little better than print-style debugging. A better solution would be a style of temporal debugging. The debugger would employ temporal search in order to search both backwards and forwards over the process lifetime in order to verify or falsify the hypothesis about the fault. The entire process lifetime is made available for analysis by the debugger.

Such a valuable temporal search technique is outside the current state of the art. There are several reasons for this. First, many real-world programs have multiple threads running on multiple cores, that spawn child processes or even an entire distributed computation. Hence, temporally
debugging a single thread would mean taking all of the threads and processes of the rest of the world backwards and forwards through time alongside that single thread.

A second reason for the lack of temporal search is that the program fault and error are often widely separated in time. While a number of reversible debuggers have been developed over the last 40 years (see Section on related work), all of these reversible debuggers have been based on some form either of logging of instructions or of events for later replay, or of both. Such logging requires large amounts of storage, and so reversible debugging has until now usually been limited to a span of time short enough so that the debugger log does not overflow memory.

A third and more recent reason for the lack of temporal search is that we now live in a multi-core world in which efficient programs typically employ multiple threads. Hence, program execution is no longer determined by a single sequential instruction stream, but instead by multiple instruction streams corresponding to multiple threads. Hence, any straightforward logging-based approach to multi-core computing is doomed to be extreme inefficiency, due to the high overhead of sequentializing the multiple instruction streams.

Finally, a fourth reason is that it is no longer true that most computations run as single processes. It is common to use a scripting language that frequently spawns other processes. Both parallel and distributed computation have become widespread. Problem-solving environments employ specialized processes that communicate among each other. High-level interactive technical languages such as MATLAB employ helper processes. Hence, moving a single process backwards in time may require moving backwards in time the associated mini-world of that process.

We present a new temporal debugger, URDB, that enables such technologies as temporal search, above. URDB stands for *Universal Reversible Debugger*. It is freely available as open source software [URD09]. URDB supports temporal debugging both on multi-threaded SMP architectures and on multi-process architectures over distributed nodes. URDB is built on top of existing debuggers. It currently has four *personality* modules, which support: gdb; MATLAB; python (pdb); and perl (perl -d). It runs as a monitor on top of the debugger, and requires no modification of the debugger itself.

URDB gains its temporal feature through the use of DMTCP (Distributed MultiThreaded CheckPointing), a fast checkpoint-restart package. Because URDB is based on checkpoints (temporal snapshots of the computation) that are saved on disk, URDB does not require any logs. Hence, it is practical to use URDB to debug computations that may continue for days or even weeks.

URDB is implemented as a “wrapper” around the target debugger. The wrapper consists of a relatively thin *debug monitor* to implement a simple algorithm for reversible execution (see Section on related work). No source code for the target debugger is required, and the target debugger is not modified. For example, the reversible MATLAB debugger based on URDB was developed without access to the MATLAB source code. The checkpoint-restart software and the debug monitor are written and debugged once, and then used in many reversible debuggers.

Current *URDB personalities* (target debuggers) include gdb, MATLAB, python (pdb) and perl (perl -d). A personality for a new debugger can be developed in a few hours by modifying a 250-line python template. As a demonstration of this, URDB was used to add reversibility to the classic curses-based BSD UNIX games of rogue and robots. This generality is expected to be useful in interactive simulations. One can go back in time and search for those user inputs that optimize the outputs.

The URDB process-level approach uses no logging, unlike the virtual machine approach or the
reverse execution approach of gdb-7.0. Hence, URDB, and checkpoint/re-execute in general, lacks
the deterministic replay feature of the other two approaches. However, record/reverse-execute and
record/replay are not able to support multiple threads in their current incarnations. In contrast,
checkpoint/re-execute, as exemplified by URDB, can support multiple threads, multiple cores and
multiple processes — even over the multiple nodes of a distributed computation. To the authors’
knowledge, no previous reversible debugger has been able to support a multi-core SMP architecture.
Furthermore, determinism can potentially be added back in through several orthogonal techniques
described in Section 1.1 on related work, such as [OAA09, DLC09, PXY+09].

In effect, we are viewing checkpoints as the “pearls of time” in a process lifetime. Where
race conditions may alter events upon re-execution, re-executing past the previous checkpoint may
lead to a slightly altered, or “parallel worlds”. The parallel worlds can be tied more closely to
their antecedents by logging, by orthogonal techniques for enforcing determinism, or by inserting
additional checkpoints to provide a tighter thread with which to string together the pearls of time.

The temporal search abilities of URDB are demonstrated by the implementation of reverse
expression watchpoints: for a given expression, finding a previous statement and a point in the
process lifetime such that the expression value was different from the current value, but will change
to the current value upon executing the immediately following statement. The temporal search
uses a binary search algorithm. Instead of evaluating an expression \( n \) times over \( n \) statements as
with a traditional debugger, URDB requires only \( \log_2 n \) evaluations.

For example, if the user implements a linked list of bounded length, and if the user program
aborts with the report \( \text{linked list len}(X) > N \), then in a normal debugging process, the user
would add frequent assert statements to detect when that expression becomes true. But frequent
calls to \( \text{linked list len}() \) is computationally expensive. So in URDB, the user executes a reverse
expression watchpoint on the expression \( \text{linked list len}(X) < N \) to discover the last instruction
for which the consistency condition was still true. This type of approach can be especially valuable
for such notoriously error-prone tasks as writing a garbage collector.

A further novelty of URDB is the ability to reversible debug distributed computations by syn-
chronously rolling back all participating processes of a distributed computation. All communication
through sockets and other mechanisms is also consistently rolled back. Again, as is the case of tra-
ditional debuggers, users must be aware of issues of non-determinism when running distributed
computations.

While not available in the current implementation, support for OpenMPI is planned for the
near future. This will provide a demonstration of the more general ability of DMTCP to support
distributed computations (see Section 3.3). The experimental section of this paper does provide
some more limited examples of debugging multiple processes within a single computer.

Section 1.1 presents a brief history of reversible debugging. Section 2 provides background
information on DMTCP. Section 3.1 describes the reversibility algorithms of the URDB monitor.
Temporal search, and in particular, reverse expression watchpoints, are described in Section 3.2
Reversible debugging of distributed computations is described in Section 3.3 (although the imple-
mentation for that work is still in progress). Section 3.4 describes the URDB implementation.
Finally, Section 4 presents the experimental results followed by the conclusion in Section 5.

1.1 Related Work

Reversible debuggers (sometimes called time-traveling debuggers) have existed at least since the work
of Grishman in 1970 [Gri70] and Zelkowitz in 1973 [Zel73]. These debuggers are based on logging
and reverse execution of individual instructions: record/reverse-execute. This first approach was further developed through such landmarks as the reversible debugger for Standard ML by Tolmach and Appel [TA90, TA95], and the recent reversible execution feature of gdb-7.0 (released in October, 2009).

About five years ago, a second approach, record/replay was implemented with virtual machines using record/replay technology. This work was based on virtual machine snapshots and event logging. It was first demonstrated in the work of King et al. [KDC05], followed by VMware’s Lewis et al. [LDC08], and still other examples.

Both record/replay and record/reverse-execute emphasize the advantages of deterministic replay. Both approaches have difficulties in supporting SMP multi-core architectures, where logging a serialization of synchronous instructions appears to be difficult.

1. Record/reverse-execute: Instruction logging records the state as each instruction is executed. The logging contains sufficient information to “undo” an instruction. In addition to logging instructions, one can log external I/O, signals, and other events, for better determinism. While the benefits are clear, there are also significant disadvantages. The need for logging prevents a debugger from executing code at full native speed. Further, the size of the log files can also be significant. Finally, sequential logging of multiple threads is difficult without operating system support.

An early example of such a reversible debugger was the AIDS debugger built by Grishman [Gri70] in 1970. It was used to debug FORTRAN and assembly language on the Control Data 6600 main-frame computer. A similar example was the work of Zelkowitz [Zel73] in 1973. A notable continuing success using this approach is the work of Appel and Tolmach [TA90, TA95], on a reversible debugger for Standard ML.

In order to more quantitatively measure the pros and cons of instruction logging, we tested gdb-7.0, which was released on Oct. 7, 2009. It includes a reversible debugging capability based on instruction logging [GDB09].

Gdb-7.0 presents an excellent interactive user feel, whether single-stepping or reverse-stepping through a C program. Nevertheless, one presumes that gdb-7.0 reversible debugging was designed for relatively short runs that would normally execute over seconds or minutes.

Specifically, our experiments show that gdb-7.0, when running in the forward direction with logging (target record), gdb was measured on a simple C program for hashing at 96,873 times slower than the corresponding speed of gdb-6.8. The average memory consumption per C statement for logging was measured at 104 bytes per program statement. Further, as expected, the instruction logging in gdb-7.0 did not support a multi-threaded program.

2. Record/replay: This approach is traditionally implemented through virtual machines. Snapshots record the state of the machines at given intervals. A reproducible clock is achieved through values of certain CPU registers, such as the number of loads and stores since startup. This allows asynchronous events to be replayed according to the time of the original clock when they occurred. Since 2005, at least two virtual machine-based reversible debuggers have been developed: for gdb [KDC05] and for Visual Studio with C/C++ [LDC08]. Snapshots have the huge advantage that forward execution can be extremely fast, close to full native speed — depending on the frequency and overhead of snapshots, and the overhead of event logging. However, event logging is an important requirement for virtual machine approaches, because they depend on sensitive timing
at the instruction level. If external events are replayed differently from how they were originally recorded, timing is thrown off. In particular, the interval timer used by operating systems for context switching is thrown off, and processes are context switched at the wrong time, with a resulting cascade of errors as processes interact with each other at the wrong times.

Additionally, the cost of virtual machine snapshots is high. They typically require about 100 MB of disk space and 30 seconds, as opposed to a typical 10 MB and 2 seconds for DMTCP to checkpoint a gdb session. (The cost of DMTCP checkpoints is expected to become still cheaper with the planned introduction of incremental checkpoints.)

3. Checkpoint/re-execute: The natural level of interaction for this approach is at the process level: intermediate between the instruction level of record/reverse-execute and the operating system level of record/replay. URDB employs checkpoint files on disk. However, an alternative strategy would be live checkpoints. In this approach, checkpoints are created by forking of a child process of the debugged application. Process-based checkpointing is limited by the number of processes that one can simultaneously maintain. Gdb-6.8 and Srinivasan et al. [SKAZ04] have implemented live checkpoints. These can be used to execute a limited form of a reverse-continue command (restore previous checkpoint, and forward continue until next to last breakpoint). Further the ocamldebugger [LDG08, Part III, Chapter 16] for Objective Caml combines live checkpointing with the method of Appel and Tolmach [TA95] for reversible debugging of Standard ML.

Determinism and debugging The DMTCP-based approach of process checkpoints does not currently employ determinism (although this could be added using complementary software). Instead, DMTCP checkpoints and restarts all processes and threads of a computation. For example, in a distributed MPI computation, reverse execution will quite literally reverse the execution of the processes of the multiple hosts in a synchronous manner. Hence, successive executions from a checkpoint may return different results.

The issue of determinism is a particularly sticky one when running on SMP multi-core hardware. A logging-based approach to reversible debugging (e.g. record/replay or record/reverse-execute) is difficult due to the ordering of concurrent instructions on distinct processors. This can alter the result of a computation.

Although not implemented in this current work, there are potential approaches to orthogonally add determinism to URDB while running on a multi-core architecture. Two examples of adding determinism to multi-core architectures are Kendo [OAA09] and DMP [DLCO09]. A method for adding only partial determinism is described for PRES [PXY09]. The PRES technique of using Feedback generation from previous replay attempts is especially interesting for its synergy with the URDB reversible debugger, since a generalization of URDB would allow URDB to run PRES on an application, while giving PRES program control with which to direct URDB when to create checkpoints, and when to repeatedly re-execute from a given checkpoint. Finally, logging of I/O and certain other events can also be added through wrappers around system calls.

2 Background: DMTCP Software

A technical overview of the DMTCP software is presented. Further details are in [ACA09]. DMTCP is free software distributed from [http://dmtcp.sourceforge.net](http://dmtcp.sourceforge.net). It was developed over five
years [ACA09, CAM06, RAC06], and as of this writing, it is experiencing approximately 100 downloads per month. Dynamic libraries are saved and restored as part of the user-space memory. A target application can autonomously request its own checkpoint with the dmtcpaware library API.

DMTCP employs a centralized coordinator, to which each process of a distributed computation connects. The centralized DMTCP coordinator is stateless. If the coordinator process dies, then one kills the other processes of the computation and starts a new DMTCP coordinator. Processes are restarted from the checkpoint images: dmtcp_restart ckpt_*_dmtcp. Process migration is accomplished by moving the checkpoint images to new computer nodes.

![Figure 1: Steps for checkpointing a simple system with 2 nodes, 3 processes, and 5 threads.](image)

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![Figure 2: Steps for restarting the system checkpointed in Figure 1. The unified restart process and subsequent fork are required to recreate sockets and pipes shared between processes.](image)

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Figures 1 and 2 pictorially describe the stages of checkpointing and restarting. Three basic requirements of distributed, user-space checkpointing are accomplished:

1. restoring user space memory;
2. restoring kernel status; and
3. restoring network data in flight.
The solid horizontal lines refer to distributed barriers. The centralized server is needed: to enforce the distributed barriers; and to act as a nameserver where end-user processes register themselves upon restart, in order to discover their peers for reconnecting socket connections.

Among the features automatically accounted for by DMTCP are:

- fork, exec, ssh, mutexes/semaphores, TCP/IP sockets, UNIX domain sockets, pipes, ptys (pseudo-terminals), terminal modes, ownership of controlling terminals, signal handlers, open file descriptors, shared open file descriptors, I/O (including the readline library), shared memory (via mmap), parent-child process relationships, pid and thread id virtualization.

The technical implementation uses `LD_PRELOAD` to preload a DMTCP library, dmtcphijack.so, into each application process. The preloaded library creates an additional checkpoint thread for each application process. The checkpoint thread creates a connection to the centralized coordinator and listens for commands. Signals and a signal handler are used for the checkpoint thread to capture the “attention” of the end-user threads. Wrappers around the fork and exec system calls are used to ensure that dmtcphijack.so is preloaded into child processes. A wrapper around exec captures any calls to “ssh”. Upon `ssh exec ...`, it preloads dmtcphijack.so into the new, remote processes. DMTCP implements wrappers for the dynamic library `libc.so`. Further implementation details are in [ACA09].

3 The Debugger Monitor

The URDB package consists of the DMTCP checkpoint-restart package and a python-based debug monitor. This prototype supports the four debuggers: MATLAB, python, perl and gdb. Additional debuggers can be supported by filling in a python-based template of about 250 lines with the names of debugger commands and regular expressions to capture their output format. An example of the MATLAB debugger operating within URDB is presented in Figure 3.

URDB takes advantage of DMTCP’s capability for checkpointing multi-threaded processed and multiple distributed processes. If the debugger is debugging multiple threads, then it is assumed that the use of URDB is restricted to sending debug commands to only one of the threads. Similarly, for distributed computations, it is assumed that the debugger is attached only to one of the multiple processes of the computation.

In the case of multi-threaded programs, race conditions may alter the execution path of a process. For traditional debugger targets, a user must be aware of the potential for non-determinism caused by race conditions. URDB does not pretend to solve this, although the future integration of other techniques for enforcing determinism [OAA09, DLCO09] may alleviate this problem.

URDB also uses DMTCP’s support for checkpointing ptrace-based applications. Gdb uses ptrace, while MATLAB, python and perl do not.

3.1 Algorithm

The debug monitor sits between the end user and the target debugger. For the most part, it passes user commands to the debugger and returns the debugger output (including interrupts (^C) by the user). Certain URDB commands are intercepted by the debug monitor, whereupon the debug monitor converses with both the target debugger and the DMTCP checkpoint-restart system. The target debugger is assumed to support four standard debugger commands: `next` (do not step into
any function calls); \texttt{step} (step into a function call); \texttt{breakpoint} (set a breakpoint); and \texttt{continue} (until next breakpoint). Where the debugger also provides \texttt{finish} (until end of function), URDB will support the use of that command by the end user. The history of executions of these commands is recorded in a user command history.

Commands supported by the debug monitor include: \texttt{checkpoint}, \texttt{restore}, \texttt{undo-command}, \texttt{reverse-next}, \texttt{reverse-step}, \texttt{reverse-continue}, \texttt{reverse-finish}, and \texttt{reverse-watch}. Undo-command undoes the last command to the debugger. Reverse-next (or reverse-step) takes the process backwards in time to the earliest statement such that a “next” debugger command (or “step” debugger command) would return the process to the current state. (If the process is at the first statement of a function, then reverse-next returns the process back to the statement that called the current function.) Reverse-finish returns the process to the statement of the function that called the current function. For ease of exposition, we speak of statements, but in fact, a statement event is intended, the last time prior to the present when the indicated statement was executed.

The last command, \texttt{reverse-watch}, uses binary search on expressions. If a process executes \(n\) statements, then binary search will evaluate the expression at most \(\log_2 n\) times. This is intended as a more general variation of data watchpoints, since the expression may depend on many addresses in RAM. While some standard debuggers also provide expression watchpoints, the URDB approach is more efficient, since standard debuggers must evaluate the expression before each of the statements. See Section 3.2 for a fuller description.
The debug monitor spontaneously generates additional checkpoint images (not necessarily requested by the user) when the time since the last checkpoint grows beyond a specified threshold.

**Timeout for “continue”**. Since the command `continue` followed by `reverse-step` is problematic if the “continue” command had executed for a long time, URDB places a timeout on “continue”. If “continue” executes beyond the timeout interval, then URDB tells the target debugger to stop execution. URDB then creates an additional checkpoint, and then URDB issues an additional “continue” command.

The timeout interval is chosen so as to maintain a reasonable user response time for URDB. The “continue” command executes natively in many debuggers, while the “step” command is interpreted. Hence the specified timeout interval guarantees that if a single “continue” command is expanded into a series of “step” commands, then the resulting interpreted execution (step-by-step) will complete in reasonable time. This turns out to be important to guarantee reasonable response times for the algorithms below.

**Algorithmic notation.** The algorithm can be expressed more clearly using a modified rewrite rule notation. A user command history is available at each moment when the target debugger is stopped. The command history is maintained for three target debugger commands: “step”, “next”, and “continue” (and optionally “finish”). The commands are notated by the four characters, s, n, c, and f, respectively. A regular expression-like notation is used for command histories. An asterisk, “*”, denotes 0 or more occurrences of a target debugger command. A question mark, “?”, denotes exactly one target debugger command. A period, “.” is used to syntactically separate tokens and has no further significance. Hence, a command history *c.n denotes an arbitrary sequence of commands followed by `continue` and `next`.

A rewrite rule, *.n →*, denotes to match a command history for which the last command was `next`. If a match is found, then truncate the final “next” command from the command history, and use the checkpoint-restart facility of DMTCP to re-execute the debugging session from the last checkpoint until just before the “next” command was issued. Similarly, a rule * →*.c says to simply execute the “continue” command in the target debugger. Thus, the URDB command `undo-command` would be algorithmically described by *.? →*.

**Process state.** At any given time, the target application being debugged is in a unique process state. In particular, there is a distinguished process state, `ORIG_STATE`, representing the state of the process at the time that a URDB command is issued. As rewrite rules are executed, the process will travel backward and forward in time, and the command history will be adjusted accordingly. The URDB algorithm never travels beyond `ORIG_STATE` (see Section 3.4).

As the rewrite rules execute, the process will have a current state will be exactly one of three states: DEEPER, SHALLOWER, SAME. This is important, since the current state will determine which set of rewrite rules should be applied. If the stack depth (number of call frames on the stack) at the current time is greater than the original stack depth (depth at the time of `ORIG_STATE`), then the current state is denoted DEEPER. Similarly, if the stack depth is less than original stack depth, then the current state is SHALLOWER. Finally, if the stack depths are equal, then the current state is SAME.

The state SAME is divided into two substates: `ORIG_STATE` (which we saw above), and `NOT_ORIG_STATE`. Since the algorithm never travels forward in time beyond
The algorithms. The algorithm begins execution in state SAME/ORIG_STATE. Rewrite rules from the current state are executed until a “Return” statement is executed. If two rewrite rules within a given state both match the current user command history, then only the first of the two rewrite rules is applied. The notation \( \text{STATE}(\ast \rightarrow \ast.n) \) denotes the state that would result from executing the indicated rewrite rule. If a rewrite rule contains an action in square brackets, then the action is executed after the rewrite rule is executed. A function \( \text{LEVEL}(\ast.n) \) indicates the stack depth of the user command history from the corresponding rewrite rule.

Algorithm REVERSE_NEXT ( ORIG_STATE ) :
  case DEEPER:
    If \( \text{STATE}(\ast \rightarrow \ast.n) = \text{ORIG_STATE} \), then:
      Call Algorithm BACK_UP_TO_SAME()
    \( \ast \rightarrow \ast.n \)
  case SHALLOWER:
    \( \ast \rightarrow \ast.s \)
  case SAME:
    case ORIG_STATE:
      \( \ast.n \rightarrow \ast \) [ If \( \text{LEVEL}(\ast.n) = \text{LEVEL}(\ast) \), then Return ]
      \( \ast.s \rightarrow \ast \) [ If \( \text{LEVEL}(\ast.s) >= \text{LEVEL}(\ast) \), then Return ]
      \( \ast.? \rightarrow \ast \)
    case NOT_ORIG_STATE:
      \( \ast \rightarrow \ast.n \)

Algorithm BACK_UP_TO_SAME () :
  case DEEPER:
    \( \ast.? \rightarrow \ast \)
  case SHALLOWER:
    \( \ast \rightarrow \ast.c \)
  case SAME:
    Return

Algorithm REVERSE_STEP ( ORIG_STATE ) :
  case DEEPER:
    If \( \text{STATE}(\ast \rightarrow \ast.n) = \text{ORIG_STATE} \), then:
      Call Algorithm BACK_UP_TO_SAME()
    \( \ast \rightarrow \ast.n \)
  case SHALLOWER:
    \( \ast \rightarrow \ast.s \)
  case SAME:
    case ORIG_STATE
      \( \ast.s \rightarrow \ast \); then Return
    \( \ast.? \rightarrow \ast \)
    case NOT_ORIG_STATE
If \( \text{STATE}(\ast \rightarrow \ast.s) = \text{ORIG\_STATE} \), then:
\[
\ast \rightarrow \ast.s
\]
Else if \( \text{STATE}(\ast \rightarrow \ast.n) = \text{ORIG\_STATE} \), then:
\[
\ast \rightarrow \ast.s
\]
Else:
\[
\ast \rightarrow \ast.n
\]

The algorithms \text{REVERSE\_CONTINUE} and \text{REVERSE\_FINISH} are presented in higher level pseudo-code.

\begin{verbatim}
\text{REVERSE\_CONTINUE} () :
BEGIN: Restore last checkpoint
Repeat continue until \text{ORIG\_STATE}
if more than one previous breakpoint found
Restore last checkpoint and re-execute until following breakpoint
If no previous breakpoint found,
set \text{ORIG\_STATE} to state (time) as of last checkpoint
Restore checkpoint previous to last checkpoint
GOTO BEGIN
\end{verbatim}

Here, \text{REVERSE\_FINISH} is defined as going backward in time to the site at which the current function was called.

\begin{verbatim}
\text{REVERSE\_FINISH} ( \text{ORIG\_STATE} ) :
Repeat
\text{REVERSE\_NEXT}()
Until reaching shallower level.
Repeat
\text{REVERSE\_NEXT}()
Until reaching beginning of that function
\end{verbatim}

In situations where the time interval of \text{REVERSE\_CONTINUE} is excessively long, a binary search strategy can be used as for expression watchpoints.

When a user requests \textit{undo-command} \( k \) for some integer \( k \), URDB restores the last checkpoint and then re-executes the first \( n - k \) of the user commands since the last checkpoint.

The \text{reverse-continue} command is implemented in one of two ways. If the time since the last checkpoint is small enough, then repeated \textit{continue} commands are executed from the last checkpoint. (A breakpoint is set at the current position so that the checkpoint does not go beyond the current time.) A count of the number \( n \) of \textit{continue} commands is maintained. Upon discovering the last breakpoint, prior to the current time, the process is re-executed with \( n - 1 \) \textit{continue} commands.

If no breakpoints were hit between the last checkpoint and the current time, then the checkpoint prior to that one is restored, with the “current time” being set to the last checkpoint. The \text{reverse-continue} algorithm is then repeated.

Finally, it can happen that the time from the last checkpoint to the current time is above the specified threshold. In that case, a binary search strategy is employed (see Section 3.2), with the condition of the binary search being to test whether a breakpoint was seen. If a breakpoint is found
in both the first and second half of a binary search, search recursively explores the second half, in
order to determine the last breakpoint encountered. When the time interval being explored falls
below a specified threshold, the reverse-continue algorithm falls back to the previous strategy
of repeated continue commands.

### 3.2 Temporal Search: Reverse Expression Watchpoints via Binary Search

Reverse expression watchpoints are implemented as a showcase for the method of temporal search. Additional temporal search methods can be added in the future.

A user executing a reverse expression watchpoint asks for the last time that an expression had
a value different from the current value. The term reverse is used to emphasize that the expression
to search on is declared only after the program has finished executing the region of interest.

We use the term expression watchpoint because this feature can also be viewed as a generalization
of the well-known data watchpoints that many debuggers. Current debuggers are either limited
to data watchpoints (detecting a change of contents at a specified memory address) in order to
take advantage of virtual memory hardware support; or else they support expression watchpoints
inefficiently by single-stepping through a program and testing at each step if the value of the given
expression has change. Unlike current debuggers, URDB supports expression watchpoints running
natively at the full speed of the CPU.

Hence, if a program is run for $n$ steps, then traditional expression watchpoints require $n$ executions
of the target expression. For large $n$, this is inefficient. The binary search algorithm presented
here uses only $O(\log n)$ executions of debugger commands (step, next, and continue) along with
$O(\log n)$ evaluations of the expression, and $O(\log n)$ checkpoints and restart. Hence for moderate
or large $n$, the extra cost of checkpoint and restart is justified by the savings in not having to
execute the target expression $n$ times. The linked list example of Section 1 presents an example
where expression watchpoints are desirable.

URDB has two modes of operation for binary search: command history-based binary search and
time-based binary search. In time-based binary search, the binary search executes for half of the
total time duration between the start point and the process state at which the reverse expression
watchpoint command was given. Once the time interval of the binary search is reduced below a
specified threshold, URDB switches to a command history-based binary search. (As of this writing,
time-based binary search is still being implemented.)

In command history-based binary search, we take advantage of a natural hierarchy of debugging
commands. In URDB, this hierarchy consists of commands to:

1. restart from the next checkpoint image.
2. issue a “continue” command until the next breakpoint.
3. issue a “next” command that steps over any function calls.
4. issue a “step” command that steps into any function calls.

Recall that the “continue” and “next” debugger commands are always limited in time. This is
because URDB interrupts the computation if a debugger command has not completed within a
specified timeout. It then creates an additional checkpoint image. For “continue”, an additional
“continue” command is issued after creating the checkpoint image. For “next”, URDB inserts a
temporary breakpoint at the statement following the statement at which “next” was issued. Then,
an additional “continue” command is issued, as in the previous case. (This use of timeouts is still under implementation.)

Hence, any command history can always be converted into a relatively short sequence of commands by replacing some commands by a command to restart from the next checkpoint image. Binary search then uses the sequence of debugger commands in the user history as the process “time”. Through binary search, URDB determines a prefix of the user history such that the expression under consideration has a different value from the current one after executing the prefix of the history, but the expression would have the same value upon executing the next debugger command of the history. (Note that such a prefix is not necessarily unique, depending on the expression chosen by the user.)

Next, if the debugger command immediately following the prefix is “go to next checkpoint image”, then it is replaced by repeated “next” statements, and binary search is performed on that sequence. If it is “continue”, it is replaced by MAX_SEQ repeated “next” commands, followed by a “continue”, and binary search is performed on that sequence. If it is “next”, it is replaced by “step” followed by MAX_SEQ repeated “next” commands, and binary search is performed on that sequence. If it is “step”, then we are guaranteed to have found the statement satisfying our temporal search.

Since the time between checkpoints is limited, the number of repeated “next” commands is limited. But it may still be very large. So, the value of MAX_SEQ must be tuned. One possible heuristic is to set it initially to the length of the current history (so as to double the history size). If there is no difference in the value of the expression between the beginning and end of the history, then one can double MAX_SEQ and try again. Hence, the number of debugging statements executed in this phase, to determine when the expression value changes, can be proved to never be more than four times the optimal number of statements. Further, this adds at most \( \log_2 n \) evaluations of the expression where \( n \) is the optimal number of statements before the expression value changes.

Of course, the success of these heuristics depends on the user expression being well-behaved. For expression values that change monotonically over the process execution, and even for some still more general situations, the heuristics above can be proved to work efficiently.

### 3.3 Reversible Debugging of Distributed Computations

The ability of DMTCP to checkpoint distributed computations allows URDB to reversibly debug distributed computations, subject to the same caveats as for multi-threaded debugging. It is assumed that the user is aware of the issues of non-determinism for distributed computations. Hence, after executing a reverse-next, for example, it can happen that the process is in a different state than originally, due to race conditions.

URDB can produce this undesirable behavior in the presence of race conditions. Nevertheless, the capability to reversibly debug over shorter intervals (where there may be few or no race conditions) is potentially valuable. An example of where this can be useful is in debugging how one arrived at a deadlock or livelock situation.

Further, many distributed computations produce only “local race conditions” that only affect program execution over a limited time interval, while maintaining convergence toward a globally unique solution. This is related to the output determinism concept of Park et al. [PXY+09]. In these situations, non-deterministic reversible debugging may also prove useful. We are still gaining
experience from the end user perspective concerning the benefits of non-deterministic reversible debugging.

3.4 Implementation of the Debug Monitor

The debug monitor uses the concept of breakpoint events. A breakpoint event is a process state (time) at which a breakpoint was hit. If one hits the same breakpoint multiple times, one must distinguish the different breakpoint events. In gdb and some other debuggers, one can determine a unique breakpoint event as the debugger travels backward and forward in time. One does this by noting the number of times that a breakpoint was hit by the debugger. For example, gdb reports that number through the gdb command `info breakpoints`.

For debuggers that do not associate a number with each breakpoint, the filename and line number of that breakpoint serve the same purpose. Some debuggers do not record the number of times a particular breakpoint was hit. In those cases, URDB can increment a variable of the target debugger (or even a global variable in the target application) with the total number of breakpoints hit so far. As the process moves backward and forward in time, this number is automatically updated. In this case, a breakpoint event is simply the number of breakpoint hits encountered since the beginning of the process.

A key to the URDB algorithm is being able to recognize the ORIG_STATE of the preceding section. The implementation defines a process state to be a triple: (filename, line number, last breakpoint event seen). The current process state is considered to be in the ORIG_STATE when it has the same value of the triple. There may be more than one process state having the same triple. The key to the correctness of the algorithm is that when the current process state has the same triple as the original process state, then the two process states must have the same command history through the last “continue” statement. Hence, any potential differences in the command history concern only sequences of “step” and “next” instructions, which are directly handled by the algorithm.

As an optimization, coalescing of debugger commands such as “next” and “step” is employed. For example, a debugger command “next; next; next” can be replaced by “next 3” for greater efficiency. The issue of debugger breakpoints adds a subtle point to the implementation. All breakpoints must be temporarily disabled or deleted during a repeated “next”. Yet breakpoints and disable/delete commands in the user history must continue to be faithfully re-executed.

4 Experimental Results

Unless otherwise indicated, all experiments are done under Ubuntu 9.04 with a Linux kernel 2.6.28. The computer used has two Intel Core 2 Duo CPUs (four cores) running at 3.0 GHz. The experiments used gcc 4.3.3, gdb-6.8, python 2.6.2, perl 5.10.0 and MATLAB 7.4.0. MATLAB was used on a four-core Intel Xeon running at 1.86 GHz. The version of DMTCP used was revision 393 (unstable branch with support for ptrace) of the DMTCP subversion repository. URDB revision 109 of the URDB subversion repository was used. DMTCP was configured to not use compression. This produces larger checkpoint images, but checkpoint and restart are faster.

URDB consists of a python-based debug monitor (and a smaller C++ file). The python monitor component contains 1,000 lines of code. URDB also requires a debugger-specific python file. For each of its four target debuggers. The python-based personality template expands to a debugger-specific file containing: 204 lines of code for MATLAB; 242 lines of code for python (pdb module);
162 lines of code for perl (perl -d); and 258 lines of code in the case of gdb. DMTCP consisted of 22,300 lines of code.

The experiments are grouped into four parts:

1. tests done across all four personalities (target debuggers);

2. tests done only on the gdb personality (implementation is planned later for the remaining personalities);

3. scalability tests with the gdb personality; and

4. demonstrations of unusual URDB applications.

| Language | reverse-next (s) | reverse-step (s) | checkpoint (s) |
|----------|-----------------|-----------------|---------------|
| gdb-6.8  | 0.68            | 3.17            | 4.52          |
| MATLAB   | 0.72            | 0.92            | 6.08          |
| perl     | 0.97            | 1.78            | 4.37          |
| python   | 0.29            | 2.90            | 4.33          |

Table 1: Times for reverse-next, reverse-step, checkpoint

| Language | checkpoint | restart | size of checkpoint files |
|----------|------------|---------|--------------------------|
| gdb-6.8  | 1.08       | 0.42    | 11.08                    |
| MATLAB   | 4.65       | 1.69    | 32.30                    |
| perl     | 0.43       | 0.20    | 3.42                     |
| python   | 0.45       | 0.19    | 3.66                     |

Table 2: Times for checkpoint and restart (seconds), as well as the sizes of the checkpoint image files (MB)

**Experiments across reversible debuggers.** Timings for the URDB reversible debugger commands for each of the four target debuggers are contained in Table 1. The reversible debuggers tested are for gdb 6.8, MATLAB, python (pdb module), and perl (perl -d). (The more recent gdb 7.0 debugger became available only during the final phases of the current work.) Tests are reported for reverse-next, reverse-step, and time of URDB to checkpoint. Checkpoint image sizes under URDB are within 0.1% of the sizes for DMTCP alone, as given in Table 2.

Gdb was tested with a main function with a loop, and the body of the loop calling a second function. MATLAB was tested on a short program with three functions (function A calling function B, which called function C). Python and perl were similarly tested, except with just four functions (a main function with a loop, and the body of the loop calling each of function A, function B, and function C).

Table 2 reports on the underlying times and storage for DMTCP alone (without using URDB). Times for checkpoint, restart, and the size of the checkpoint image files are reported. In the case of gdb, there are two checkpoint images: gdb (9.5 MB); and the target application a.out (1.6 MB). MATLAB employs two checkpoint images: MATLAB (30.3 MB); and matlab_helper (2.0 MB).
Python and perl consist of a single checkpoint image each of sizes 3.66 and 3.42 MB, respectively. The sizes of the checkpoint image files are reported in Table 2. In the case of gdb and MATLAB, Table 2 reports the combined sizes of the two checkpoint images.

**Experiments specific to the gdb reversible debuggers.** The following additional URDB functionality is currently gdb-specific, but will soon be ported to all reversible debuggers. As of this writing, URDB also supports reverse-continue, reverse-finish and reverse expression watchpoints. Table 3 reports the corresponding times.

| Command                        | Time  |
|--------------------------------|-------|
| reverse-continue               | 1.13  |
| reverse-finish                 | 2.11  |
| reverse expression watchpoint  | 36.86 |

Table 3: Times for reverse-continue, reverse-finish and reverse expression watchpoint (seconds)

| Command      | After 10 commands | After 100 commands | After 1000 commands |
|--------------|-------------------|--------------------|---------------------|
| reverse-next | 0.57              | 0.69               | 0.79                |
| reverse-step | 0.75              | 0.94               | 0.87                |

Table 4: Times for reverse-next and reverse-step after 10/100/1000 “next” and “step” commands, respectively. All times are in seconds.

**Experiments for scalability.** The scalability experiments were performed using gdb-6.8. Table 4 reports on scalability trends. Similar trends are expected for the other reversible debuggers. The primary programs for testing were a recursive version of factorial and an iterative version of factorial. Both versions use floating point arguments instead of integers in order to be able to run on longer computations. The base case tests if the argument \(x\) is between 0.5 and 1.5 and then returns 1.0 for \(\text{factorial}(x)\) for such \(x\). Reverse-next is tested on the iterative version of factorial for the sake of the long execution sequence within a single function. Reverse-continue implicitly requires function calls, and hence is tested on the recursive version of factorial.

In each case, a checkpoint was previously taken at the beginning of main, and the program is run for the indicated number of statements. The dominating time is the time for the checkpoint. Hence, the decreased time for the largest number of “step” commands is due to the variation in times for restarting from the checkpoint. This is because these examples use coalescing of debugger commands (see Section sec:monitorImplementation). In the case of reverse-step, every two debugger “step” commands cause the application to enter a new call frame. The corresponding times for the same experiment, with coalescing turned off, are shown in Table 5.

**Demonstrations of unusual URDB applications.** URDB was also tested on two more unusual applications in order to demonstrate the generality of URDB. The two examples are:

1. *interactive simulations and games:* Two classic 1980-era BSD UNIX curses-based games, robots and rogue, were chosen to demonstrate this category. (See the Wikipedia articles
Table 5: Times for reverse-next and reverse-step after 10/100/1000 “next” and “step” commands, respectively, without using coalescing. All times are in seconds.

| Command       | After 10 commands | After 100 commands | After 1000 commands |
|---------------|--------------------|-------------------|--------------------|
| reverse-next  | 0.80               | 4.57              | 40.75              |
| reverse-step  | 1.06               | 4.75              | 41.13              |

“Rogue (computer game)” and “Robots (computer game)”.) A modified URDB was employed with control-E/control-T for checkpoint/undo, respectively, since interactive games do not read commands through standard input.

2. *debugging multiple processes:* the example of gdb debugging a second gdb process that was itself debugging an application a.out process. This example is interesting since the first gdb is using ptrace to trace the second gdb, while the second gdb is similarly using ptrace to trace the a.out application.

The version of “robots” used was version 2.16 of the bsdgames Ubuntu package, while “rogue” was version 2.17 of the bsdgames-nonfree Ubuntu package. The times for checkpoint and undo for robots were 3.67 and 0.04 seconds, respectively. Similarly, the times for checkpoint and undo for rogue were 3.21 and 0.05, respectively. The checkpoint images were of size 12.5 and 12.8 MB for robots and rogue, respectively.

Table 6: Times for reverse-next, reverse-step and checkpoint for gdb debugging gdb debugging a.out (seconds)

| Command    | Times |
|------------|-------|
| reverse-next | 0.90  |
| reverse-step | 0.94  |
| checkpoint  | 5.17  |

Times and sizes for reverse-next, reverse-step, and checkpoint are reported for gdb debugging a second gdb that in turn was debugging a.out in Table 5.

4.1 *Future Directions: Meta-Programming on Process Lifetimes*

We view the demonstration of universal reversible debugging not as an end in itself, but rather as a beginning with multiple other possibilities. The URDB approach demonstrates the possibility of meta-computing over process lifetimes for arbitrary processes. Expression watchpoints (see Section 3.2) provide an example of meta-computing, in which we execute binary search over a process lifetime.

Eventually, URDB will be extended into a meta-computing language that treats processes as *first class objects*. Files can be replicated, copied to new hosts, be modified, and support seeks to arbitrary locations in the file. The same will be true of can processes.

In particular, *speculative execution of programs* and *program introspection* becomes possible under the control of the program itself. As an example of the former possibility, programs can speculatively execute themselves and avoid crashes, deadlocks and livelocks. As an example of the
latter possibility, upon finding a solution to a problem, a program can use program introspection to inspect its execution history and produce a short explanation of steps needs to produce the solution.

Another novel use is comparison of two versions of the same program. One can request, for example, to ignore all call frames except the first four. One then begins execution of the two programs and asks for the first statement for which some user-specified expression differs for the two programs.

Building on this capability, one can imagine producing a dataflow description (or dependency graph) of variable occurrences on which a later variable occurrence depends. While this is normally a difficult task, speculative execution allows one to heuristically test whether a dependency exists between an original variable occurrence and a later variable occurrence. One heuristically tests by varying the value of the original variable occurrence and determining if the later variable occurrence changes its value. For this purpose, a segmentation fault before obtaining the value of the later variable occurrence is considered to be a change of its value.

Interactive simulations also benefit. Assume the program execution depends on inputs from a human user and is otherwise deterministic. Hence, the program execution uniquely depends on an input trace. One specifies a figure of merit for a simulation (similarly to the use of expressions in expression watchpoints). One can take checkpoints, and represent a process state by the most recent checkpoint, followed by an input trace. Thus, the storage cost of the checkpoint is amortized over many potential process states. (The cost can be still further reduced through the use of incremental checkpointing.) This representation allows one to then employ best-first search, A* search, branch-and-bound, multiple simulation annealing runs, and other such classical search techniques. The enabling technology is the ability to treat processes (or process states here) as first class objects.

A similar idea can be employed for capturing broad test coverage in software testing. One employs a similarity measure on process states. One then employs search techniques to produce all possible “unique process states”, where the similarity measure determines if two process states are to be considered the same process state for this purpose. The similarity measure can be applied to the process especially easily if the process is running under a debugger that has access to its internal variables.

5 Conclusion and Future Work

Incremental checkpointing is planned for a future version of URDB in order both to reduce the size of each checkpoint and to improve the times for checkpointing. The use of temporary checkpoints of debugger commands will then be added to greatly enhance the speed of expression watchpoints.

Experiments that mix the URDB approach with event logging are also planned.

Finally, expression watchpoints are an example of program-based introspection: when in my process lifetime did this expression change its value? The demonstrations for the interactive games rogue and robots are a form of speculative program execution. These rudimentary examples open the way for more sophisticated applications of: time-traveling program-based introspection; and speculative program execution.
6 Acknowledgement

We wish to thank Priyadarshan Vyas for his contributions to an earlier version of the monitor able to support the undo command described in this paper. We also thank Shobhit Agarwal and Amruta Chougule for their earlier identification of several issues and suggested solutions for checkpointing gdb with DMTCP. We also wish to thank Peter Desnoyers and Jason Ansel for their helpful discussions and insights.

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