Sequential Debugging at a High Level of Abstraction

RONALD A. OLSSON, RICHARD H. CRAWFORD,
W. WILSON HO, and CHRISTOPHER E. WEE
University of California at Davis

> Sequential debuggers are lacking, but little effort is spent researching ways to improve them. This system, based on high-level abstraction, helps redress this shortcoming.

Debugging research seems to focus almost exclusively on the debugging of concurrent programs and on graphical interfaces for debuggers. While those areas are very important, the emphasis on them tacitly assumes that the problems of debugging sequential programs have been solved. We disagree. We find state-of-the-art sequential debuggers to be lacking, so we have developed our own sequential debugger to demonstrate that significant further progress can be achieved.

A trend over the years has been for sequential debuggers to provide mechanisms that let users interact with their programs at higher levels of abstraction, closer to the abstractions in their programs. Debugging tools have evolved from programs that let you examine contents of memory locations to modern, source-level debuggers that let you interact with your program at the source-code level, since they understand abstractions like variables, procedures, and statements. Fundamental to such debuggers is the concept of a breakpoint, a programmer-defined location in the code at which execution is to be suspended so you can examine variables or so the debugger can execute some debugging code.

Some source-level debuggers, like Sun Microsystems' DBX Tool and the Saber C and Turbo debuggers, provide graphical interfaces to simplify how you interact with the debugger and to help you visualize program behavior. Unfortunately, these widely used debuggers do not go far enough: They still require you to interact at a very detailed level. These debuggers typically have two significant inadequacies:

♦ They provide only very limited control over the actions taken when a break-

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```
# Dalek procedure to print out value
# field of nodes in a circularly linked list
# (in the program being debugged)
# starting at $head. Assumes $head is a
# dummy node whose next field
# prints to itself if the list is empty.
function $print_list($head)
  {
  local $p
  set $p = $head–>next
  while ($p != $head)
    printf "%d\n", $p–>value
    set $p = $p–>next
  endwhile
  }
end
```

Figure 1. *A Dalek procedure to print a linked list.*

point occurs. Often, they provide only conditional execution of the entire block of commands associated with a breakpoint. More powerful and discriminating means of control are desirable, like a loop to print out the contents of a linked list or a loop to single-step the code being debugged until one variable is greater than another. (The Digital Equipment Corp. VAX/VMS Debug and the Saber C debuggers do provide some such features.)

♦ They provide no way of conveniently or safely correlating the occurrence of several logically related breakpoints into a single, more abstract occurrence. This capability is desirable because abstractions in a program often require a series of procedure calls. You can easily be overwhelmed by all the information output by a debugger and might fail to realize the significance, when taken together, of two pieces of information that a debugger prints at different times.

Our debugger, Dalek, remedies both inadequacies. (The name comes from the semimechanical alien life form in the British television series *Doctor Who* that tried to exterminate everything in sight.) Dalek's language provides conditional and looping statements, blocks, local variables, procedures, and functions. (The box below defines some Dalek tokens used in this article.) This approach is similar to that taken by Mark Johnson,[1] except Dalek includes these mechanisms as part of a conventional (and modern) debugger rather than in an interpretive environment.

Dalek also provides support for events — occurrences of interesting activities in the code execution — as a way to form higher level abstractions during execution.

DALEK COMMANDS

Most Dalek commands and predefined functions have obvious meanings. But a few may not:

Special characters

# introduces a comment, which continues until the end of the line.

$ indicates the start of a name of a convenience variable or a predefined or a user-defined function.

‘ indicates the start of an event or attribute name.

Commands

Break sets a breakpoint at a specified line, address, or function entry.

Proc-break sets (broadcasts) a breakpoint at entries of a group of procedures.

Silent suppresses the default announcement that a breakpoint has occurred.

Backtrace prints a backtrace of stack frames.

Predefined functions

$value accesses an attribute of a token on a specified event queue.

$quiet_finish lets the executing function in the program being debugged return naturally. This function returns as its own value the value that was returned by the procedure.

$top_frame returns the number of frames where the top-level frame is executing above the current frame.

Dalek uses a novel, coarse-grained dataflow approach for combining events in which the dataflow graph's nodes contain fragments of code written in the Dalek language.

OVERVIEW

Dalek is similar to many other modern debuggers in its overall operation. Dalek and the code being debugged execute as separate processes, with Dalek controlling, observing, and altering the code's execution according to code written in the Dalek language. You can specify Dalek code dynamically during a debugging session, so you can specify what is of interest as you glean information during execution. Also, such code can be read from a file. Dalek code can be executed from the debugger's command level or automatically at a breakpoint or when an event is triggered. Dalek operates on compiled C programs; the source code is not modified, recompiled, or relinked as a result of debugging.

Dalek is based on GDB, the Free Software Foundation's Gnu Project's debugger. It enhances GDB's functionality in two significant ways.

First, Dalek extends the original GDB language with mechanisms that make it more like a general-purpose language. Because the new mechanisms are completely integrated with the standard debugging features, the Dalek language is fully programmable. The new mechanisms supported by Dalek include

♦ a conditional statement,

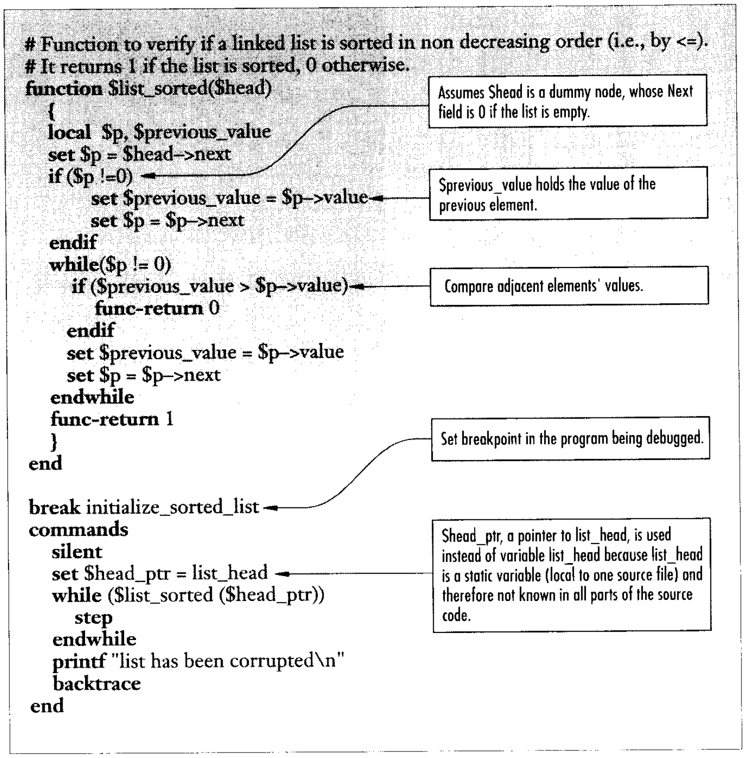
♦ a looping construct,

♦ blocks with local convenience variables (a convenience variable is a variable that the user defines and manipulates within the debugger; GDB provides only global convenience variables), and

♦ procedures and functions.

Second, Dalek provides ways to define, raise, recognize, and combine events.

To illustrate the Dalek language, consider the Dalek code in Figure 1. The code defines a $print_list( ) procedure, which can be invoked interactively from Dalek's command level or from any point during code execution by simply setting a break-



```
# Function to verify if a linked list is sorted in non decreasing order (i.e., by <=).
# It returns 1 if the list is sorted, 0 otherwise.
function $list_sorted($head)
  {
  local $p, $previous_value
  set $p = $head->next
  if ($p !=0)
       set $previous_value = $p->value
       set $p = $p->next
  endif
  while($p != 0)
     if ($previous_value > $p->value)
        func-return 0
     endif
     set $previous_value = $p->value
     set $p = $p->next
  endwhile
  func-return 1
  }
end

break initialize_sorted_list
commands
   silent
   set $head_ptr = list_head
   while ($list_sorted ($head_ptr))
      step
   endwhile
   printf "list has been corrupted\n"
   backtrace
end
```

Assumes $head is a dummy node, whose Next field is 0 if the list is empty.

$previous_value holds the value of the previous element.

Compare adjacent elements' values.

Set breakpoint in the program being debugged.

$head_ptr, a pointer to list_head, is used instead of variable list_head because list_head is a static variable (local to one source file) and therefore not known in all parts of the source code.

Figure 2. *Dalek code to uncover a list-corruption bug.*

point whose commands include a call to the procedure. As a simple example, $print_list( ) can be invoked from a breakpoint at line 27 of the file Goo.c by the commands

```
break goo.c : 27
commands
   silent
   call $print_list(symtab_head)
   cont
end
```

Silent suppresses the default announcements of encountering a breakpoint, the Call statement calls the $print_list procedure, passing Symtab_head as an argument, and Cont continues execution of the program being debugged.

We could have written the body of $print_list( ) in-line as commands, but we wrote it as a function so it can be invoked directly from the command level or from another breakpoint, if desired.

Similar to the $print_list( ) example, you can write Dalek code to ensure that the code being debugged maintains certain invariants about its data structures. For example, you could invoke code to check that a circularly linked list is indeed circular on entry to and exit from each procedure that manipulates the list, or even at every step of the code. This approach is more flexible than using compiled-in assertion checks (like the Assert macro in C), since you can decide what invariants to check and where to check them as you find it necessary during actual debugging. You can save the invariant-checking code for use in later debugging sessions.

To see further how you can use Dalek to attack a debugging problem, consider a program containing a module that maintains a sorted linked list. This sorted list is kept local to the module and cannot be accessed directly anywhere outside this module's scope. All operations on the list are performed through a few explicitly exported functions. When this module is combined with other parts of the program and the program is executed, the contents of this list are somehow corrupted. Careful examination of the list module leads you to believe that it is not the source of the corruption. Therefore, some other part of the program must contain erroneous code that has overwritten this linked list.

This kind of bug is common in programs written in languages like C that allow the use of pointers. Most likely, it is caused by a pointer incorrectly referencing a memory location occupied by the linked list.

The debugging problem is to locate the erroneous code, since it could be in any part of the program. To narrow the bug's possible location, you can trace, step by step, the program's execution.

Figure 2 shows Dalek code that automates the program tracing. The function $list_sorted( ) verifies the validity of the sorted list and returns 0 when the list is no longer sorted. A breakpoint is set in the function Initialize_sorted_list( ), where the sorted list is first used. The command block associated with this breakpoint begins with a loop that single-steps execution of the program, stopping when the list is first found to be corrupted. It then prints a trace of the current call stack. (We consider this kind of debugging to be the last resort — you use this technique after failing with the more standard ones.)

The key to success here is that Dalek allows single-stepping within While loops. You could also use hardware data watchpoints, available in some architectures, to help solve this kind of debugging problem. They let specified memory cells be monitored, generating an interrupt when such a cell is read or written. However, some way of filtering through the enormous number of generated interrupts is needed.

EVENTS

You can define an event in Dalek to capture the occurrence of any interesting activity in the code execution. To define an event, you declare names for it and

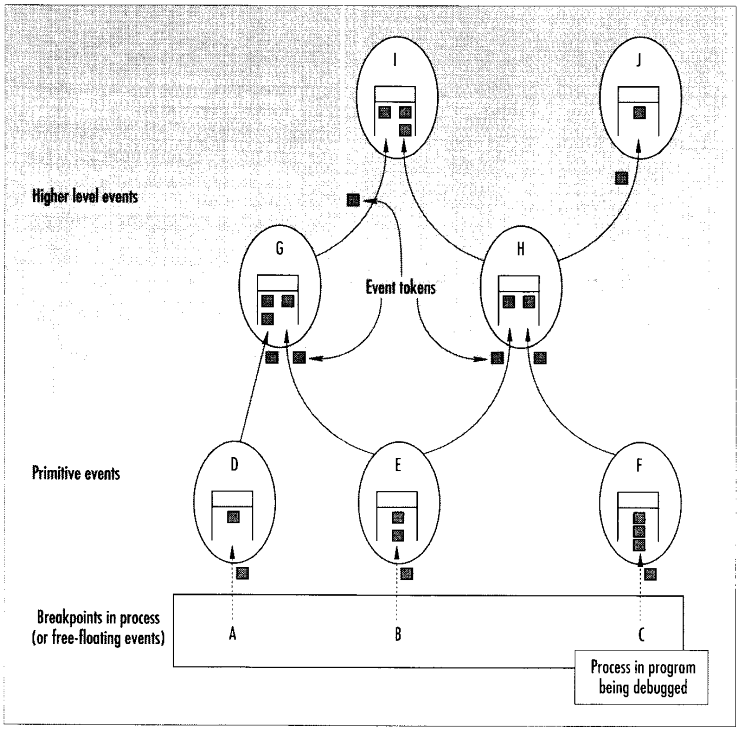


Figure 3. Dataflow graph for event recognition.

for its attributes and write a block of Dalek code. How does Dalek know when to execute an event's code? The simplest way is to explicitly raise that event by name. We call events activated this way *primitive* events, and they are typically raised by an event-raise command executed at a breakpoint. The code associated with an event will then try to recognize a valid occurrence of that event. The attributes associated with an event contain information meant to characterize a particular occurrence of the event. The Dalek code you write for an event's definition can assign values to its attributes from variables in the original code, debugger-convenience variables, or computation based on those variables.

Dalek also supports *high-level* events. When defining a high-level event, you must specify the names of other events on which it depends. A high-level event is not explicitly raised; instead, Dalek can automatically execute a high-level event's code whenever an occurrence of a primitive event on which it depends is successfully recognized.

Dalek provides a coarse-grained dataflow view of events. In most models of dataflow, tokens flow between the nodes of a directed graph. In Dalek, the leaves of this graph represent primitive events (independent sources of tokens), and the interior nodes represent higher level events whose activation and subsequent behavior depend on those primitive events. Thus, the structure of the dataflow graph is implicit in the events you define. Dalek derives it automatically from the dependencies you explicitly specify between primitive and higher level events.

Activity in the code being debugged — like reaching a breakpoint — can raise a primitive event, which if recognized will generate a token. This token carries copies of the attributes characterizing that instance of the primitive event, letting that occurrence be distinguished from other occurrences of the same primitive event. The tokens generated by recognizing a valid instance of a primitive event flow to any high-level events that depend on the primitive event. The arrival of such a token at a high-level event can trigger that high-level event, which in turn can generate tokens that trigger yet higher level events. Figure 3 shows a dataflow graph that summarizes Dalek's approach to event recognition.

When a high-level node in Dalek's event-dataflow graph is triggered, it executes its own Dalek code to decide whether to recognize a valid instance of that high-level event. In making that decision, the code associated with a high-level event has access to the tokens (and their attribute values) from all occurrences of the lower level constituent events on which the high-level event depends. The tokens from a high-level event's lower level constituents are stored on its own private queues and are accessed with predefined Dalek functions.

If the Dalek code associated with an event decides that it should recognize an instance of that event, it assigns values to its own attributes, as we described earlier. A high-level event then generally removes from its incoming queues the tokens on which the event's code based its decision to avoid repeated recognition of the same tokens when it is triggered later. When the high-level event's code finishes execution, tokens embodying the new event instance propagate to all higher level events that depend on it, and the recognition phase begins anew.

If the high-level event's code decides that an appropriate combination of tokens from constituent events does not exist on its incoming queues or that their attributes fail to satisfy the desired relationships, the code can execute Dalek's Dont-propagate command. This suppresses the normal generation of tokens representing this event and the subsequent passing of those tokens to any higher level events that depend on it.

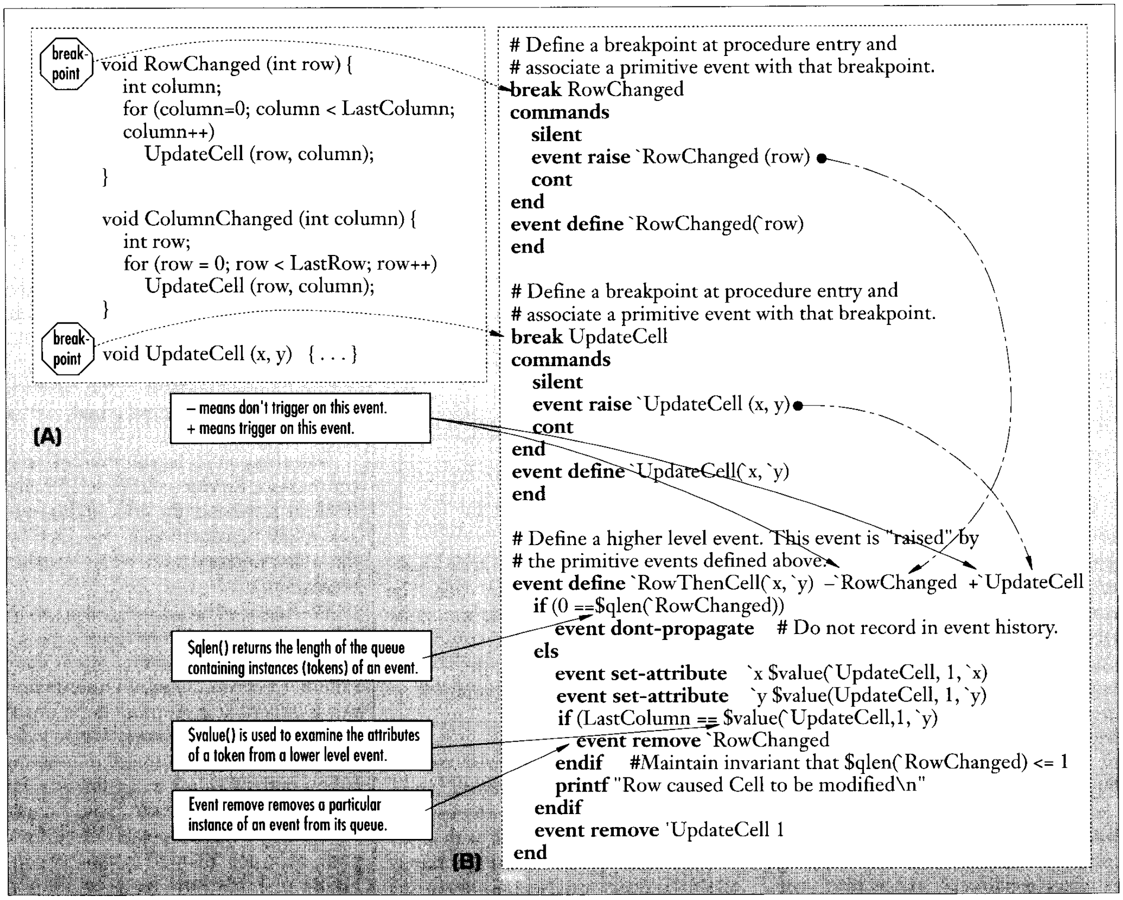
An event history records all recognized event occurrences and their attributes. It may be browsed selectively by the user in interactive mode or accessed programmatically via predefined functions in the Dalek language.

To demonstrate events concretely, Figure 4 shows a spreadsheet program and Dalek debugging code. It has two bound primitive events (raised at breakpoints) that are combined into a higher level event. Figure 5 shows another example of how you can use events. In this example, the primitive events are free-floating — unlike the primitive events in Figure 4, the primitive events in Figure 5 are raised during execution of Dalek code that is not bound to any particular breakpoint.

EXAMPLE APPLICATIONS

Dalek's debugging language makes it suitable for many applications, three of which we present here: an alternative to code patching, procedure tracing, and performance measurement and code profiling. These applications further show the versatility and power provided by Dalek's full programmability and its event mechanisms. Although some people might not consider these applications to fall in the realm of traditional debugging, we have found that the interpretive-like environment Dalek provides for compiled programs encourages the integration of previously separate activities (program testing is another example).

Alternative to code patching. You can use



```
void RowChanged (int row) {
   int column;
   for (column=0; column < LastColumn;
   column++)
      UpdateCell (row, column);
}

void ColumnChanged (int column) {
   int row;
   for (row = 0; row < LastRow; row++)
      UpdateCell (row, column);
}
void UpdateCell (x, y)  { . . . }
```

```
# Define a breakpoint at procedure entry and
# associate a primitive event with that breakpoint.
break RowChanged
commands
   silent
   event raise `RowChanged (row)
   cont
end
event define `RowChanged(`row)
end

# Define a breakpoint at procedure entry and
# associate a primitive event with that breakpoint.
break UpdateCell
commands
   silent
   event raise `UpdateCell (x, y)
   cont
end
event define `UpdateCell(`x, `y)
end

# Define a higher level event. This event is "raised" by
# the primitive events defined above.
event define `RowThenCell(`x, `y)  –`RowChanged  +`UpdateCell
   if (0 ==$qlen(`RowChanged))
      event dont-propagate    # Do not record in event history.
   els
      event set-attribute    `x $value(`UpdateCell, 1, `x)
      event set-attribute    `y $value(UpdateCell, 1, `y)
      if (LastColumn == $value(`UpdateCell,1, `y)
         event remove `RowChanged
      endif    #Maintain invariant that $qlen(`RowChanged) <= 1
      printf "Row caused Cell to be modified\n"
   endif
   event remove 'UpdateCell 1
end
```

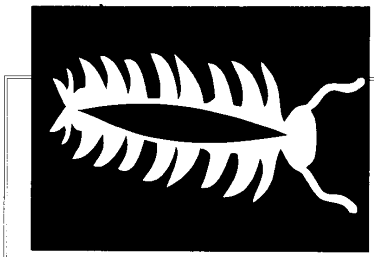
– means don't trigger on this event.
+ means trigger on this event.

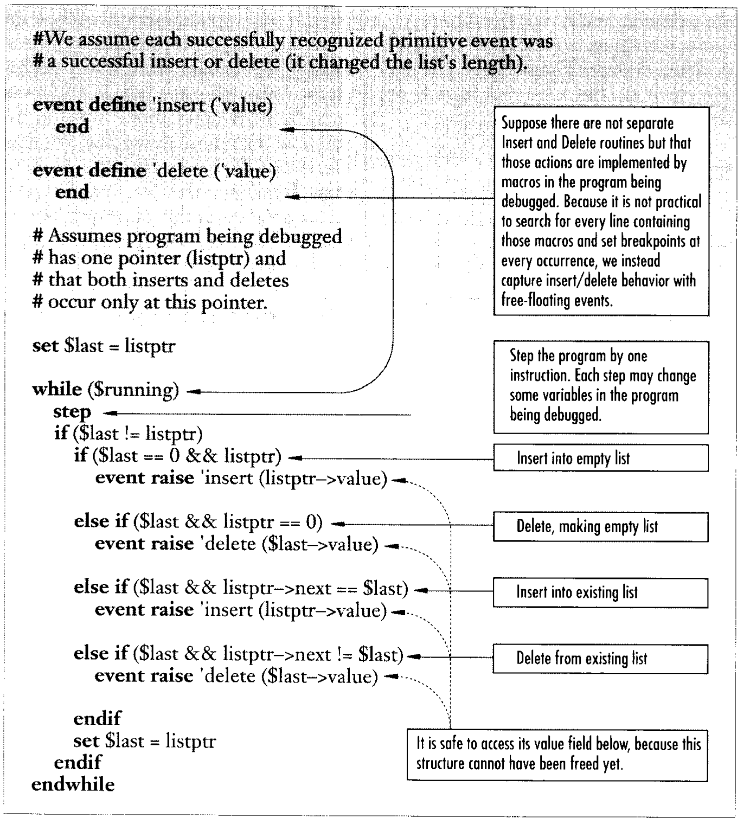
Sqlen() returns the length of the queue containing instances (tokens) of an event.

Svalue() is used to examine the attributes of a token from a lower level event.

Event remove removes a particular instance of an event from its queue.

Figure 4. Spreadsheet example: (A) Excerpt from a spreadsheet program and (B) Dalek commands and definitions. In the example, both RowChanged() and ColumnChanged() call UpdateCell(). Suppose you are interested only in execution paths that run through RowChanged() and then UpdateCell(). You would use Dalek's dataflow mechanism to filter out all UpdateCell() invocations that do not first invoke RowChanged().





```
#We assume each successfully recognized primitive event was
# a successful insert or delete (it changed the list's length).

event define 'insert ('value)
    end

event define 'delete ('value)
    end

# Assumes program being debugged
# has one pointer (listptr) and
# that both inserts and deletes
# occur only at this pointer.

set $last = listptr

while ($running)
    step
    if ($last != listptr)
        if ($last == 0 && listptr)
            event raise 'insert (listptr->value)

        else if ($last && listptr == 0)
            event raise 'delete ($last->value)

        else if ($last && listptr->next == $last)
            event raise 'insert (listptr->value)

        else if ($last && listptr->next != $last)
            event raise 'delete ($last->value)

        endif
        set $last = listptr
    endif
endwhile
```

Suppose there are not separate Insert and Delete routines but that those actions are implemented by macros in the program being debugged. Because it is not practical to search for every line containing those macros and set breakpoints at every occurrence, we instead capture insert/delete behavior with free-floating events.

Step the program by one instruction. Each step may change some variables in the program being debugged.

Insert into empty list

Delete, making empty list

Insert into existing list

Delete from existing list

It is safe to access its value field below, because this structure cannot have been freed yet.

Figure 5. Free-floating events.

Dalek to effectively replace code in the program being debugged with code written in Dalek. This alternative to patching machine code has a temporary effect, affecting only how the code being debugged executes while under control of the debugger; it does not modify the program's executable file or the source code. We have used this kind of patching to find and fix multiple errors without exiting the debugger and recompiling the source code.

Although you can use this technique with many other debuggers, it is easier to use it in Dalek because Dalek's language provides conditional and looping statements and functions. These let you easily replace groups of statements or entire functions, or add new code to, for example, initialize variables.

The basic technique is to set a breakpoint at the start of the faulty code. The Dalek code associated with the breakpoint can then perform the desired action, and, if necessary, can execute a special jump command to skip over code that should no longer be executed.

Procedure tracing. Dalek does not provide a separate trace command; instead, it provides a more general mechanism — broadcast breakpoints — that, with its full programmability, makes getting a trace of selected procedure calls simple as a special case. Broadcasting lets you give a single command to establish an ordinary breakpoint at the entry to every procedure whose name matches a regular expression, and broadcasting lets you associate a common block of debugging commands with those breakpoints. Without a broadcast-breakpoint facility, you would have to individually establish a breakpoint and give the associated breakpoint code at each procedure — a tedious activity.

Thus, to have Dalek print out the names of all procedures entered during program execution, you just specify a single broadcast-breakpoint command with the wild card * as its regular expression and the following code as its command block:

```
silent
printf "%s\n", $func(0)
cont
```

The predefined Dalek function $func(*n*) returns the name of the function in the code being debugged that is associated with the *n*th frame of the procedure-call stack. When *n* equals 0, as in this case, it returns the name of the procedure in which the code being debugged is executing.

More selective tracing is also possible by specifying a more restrictive regular expression or by refining the code in the broadcast breakpoint's command block. Two examples of the latter include

- ♦ printing only when a certain procedure appears somewhere on the call stack (the call stack can be searched with a While loop) and
- ♦ printing only when the value of some convenience variable satisfies an arbitrary Boolean expression (the value of this variable might be conditionally modified by the code associated with events or other breakpoints).

We have used broadcast breakpoints to get information used in correlating the activities by which programs access their runtime (procedure) stacks. This information is important in assessing the utility of certain architectural features. The conditional probabilities we needed to measure were a push of a stack frame followed by the push of another stack frame, a push followed by a pop, a pop followed by a push, and a pop followed by another pop. Figure 6 shows how we programmed Dalek to gather and compute such information.

We have also used broadcast breakpoints to solve debugging problems like the one in Figure 2. Broadcast breakpoints are faster than the single-stepping used in Figure 2, but their granularity is coarse, since they occur only when a procedure is entered: Using them will give you only the name of the routine invoked after the routine in which the contents of the list were corrupted, rather than the source statement actually causing the corruption. Thus, the fastest way to zero in on such a bug is for the broadcast-breakpoint commands to increment a counter to determine how many times procedures are invoked, rerun the code until one procedure call before that state, and only then initiate the While loop that single-steps.

Performance measurement and code profiling. You can use Dalek to time parts of a program and to profile sections of code. A considerable advantage in using Dalek for these tasks is that you can interactively and dynamically specify the part of the program for which information is to be gathered, as well as the precise information to be gathered — without modifying, recompiling, and relinking the source code.

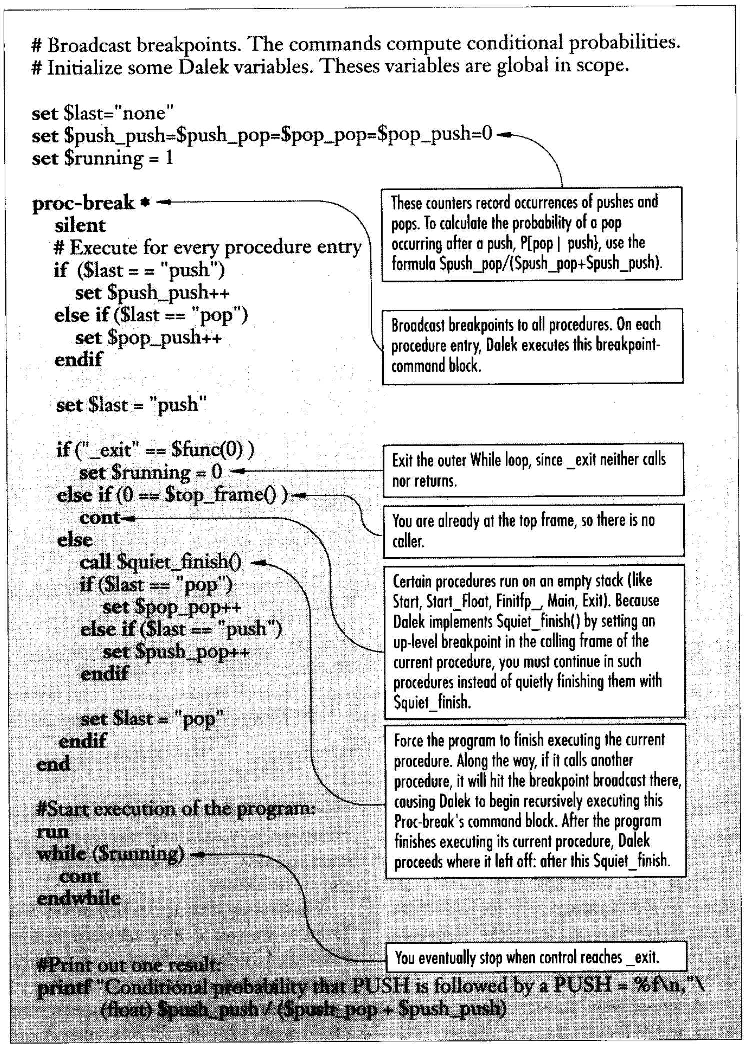
Dalek provides three predefined functions that return the CPU time used by the process in the code being debugged, corresponding to how Unix reports CPU times. The Dalek function $utime( ) returns the user time, $stime( ) returns the system time, and $ttime( ) returns the total time. User time is the time the CPU spends executing the instructions in the process's address space, while system time is the time the CPU spends executing system calls invoked by the code.

Unfortunately, only $utime( ) is accurate. $stime( ), and therefore $ttime( ), is not accurate because some of the cost of the debugger controlling the process being debugged is charged as system time to the debugger. And even $utime( ) is not always accurate on all machines. For example, on machines that use instruction pipelining, $utime( ) can be affected by what instructions are in the pipeline; the pipeline is flushed when the operating system switches contexts, which occurs in alternating execution between the process being debugged and the debugger.

Still, you can use these timing functions in the debugger code that is executed as part of a breakpoint or event, and therefore interactively change what parts of the code being debugged are monitored.

One use of Dalek's timing functions is to tune a program's performance. For example, suppose you want to determine the times for both successful searches and unsuccessful searches of a symbol table. This information can give you feedback on the appropriateness of your data-structure representation, perhaps suggesting that a hash table would perform better than a linked list.

To get these times, you can set one breakpoint on entry to the search function and another breakpoint right before the



```
# Broadcast breakpoints. The commands compute conditional probabilities.
# Initialize some Dalek variables. Theses variables are global in scope.

set $last="none"
set $push_push=$push_pop=$pop_pop=$pop_push=0
set $running = 1

proc-break *
   silent
   # Execute for every procedure entry
   if  ($last = = "push")
      set $push_push++
   else if ($last == "pop")
      set $pop_push++
   endif

   set $last = "push"

   if ("_exit" == $func(0) )
      set $running = 0
   else if (0 == $top_frame() )
      cont
   else
      call $quiet_finish()
      if ($last == "pop")
         set $pop_pop++
      else if ($last == "push")
         set $push_pop++
      endif

      set $last = "pop"
   endif
end

#Start execution of the program:
run
while ($running)
   cont
endwhile

#Print out one result:
printf "Conditional probability that PUSH is followed by a PUSH = %f\n,"\
        (float) $push_push / ($push_pop + $push_push)
```

These counters record occurrences of pushes and pops. To calculate the probability of a pop occurring after a push, P[pop | push}, use the formula Spush_pop/(Spush_pop+Spush_push).

Broadcast breakpoints to all procedures. On each procedure entry, Dalek executes this breakpoint-command block.

Exit the outer While loop, since _exit neither calls nor returns.

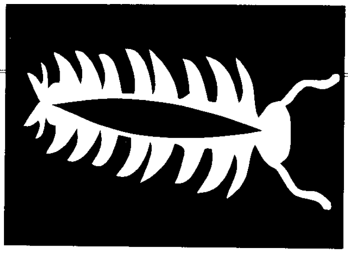
You are already at the top frame, so there is no caller.

Certain procedures run on an empty stack (like Start, Start_Float, Finitfp_, Main, Exit). Because Dalek implements Squiet_finish() by setting an up-level breakpoint in the calling frame of the current procedure, you must continue in such procedures instead of quietly finishing them with Squiet_finish.

Force the program to finish executing the current procedure. Along the way, if it calls another procedure, it will hit the breakpoint broadcast there, causing Dalek to begin recursively executing this Proc-break's command block. After the program finishes executing its current procedure, Dalek proceeds where it left off: after this Squiet_finish.

You eventually stop when control reaches _exit.

Figure 6. Computing conditional probabilities for stack usage.



```
# After-the-fact use of history list to derive
# new information: the maximum
# length reached by a linked list.

# Run the program; Dalek records
# interesting events.
# Consult Dalek's history list of interesting events
# and calculate maximum  length of the list.
printf "%d\n", $max_length()
```

(A)

```
# Using Dalek's history mechanism, you walk through the execution history
# of the program and
# examine the occurrences of two important events -- `insert and `delete, thus
# letting you calculate
# the maximum length of the linked list.
function $max_length ()
   {
   local $len, $max_len, $ins_q_index, $del_q_index
   set $len = $max_len = 0
   set $ins_q_index = $del_q_index = 1

   while ($ins_q_index <= $hlen (`insert) && $del_q_index <= $hlen (`delete))
      if ($htime(`insert, $ins_q_index) < $htime(`delete, $del_q_index) )
         set $len++
         set $ins_q_index++
      else
         set $len--
         set $del_q_index++
      endif
      if ($len > max_len)
         set $max_len = $len
      endif
   endwhile

   # There may have been a tail of inserts with no more deletes, so:
   set $len += $hlen (`insert) - $ins_q_index + 1
   if ($len > $max_len)
      set $max_len = $len
   endif
   func-return $max_len
   }
end
```

Shlen() returns the length of the history list associated with an event.

Shtime() returns the time at which that event occurrence was recorded.

(B)

***Figure** 7. (A)Using the event-history list to examine program behavior. The free-floating events for 'insert and 'delete are defined and the attributes set as in Figure 5. (B) The definition of the $max_length function used by the event-history examination routine.*

search function returns. The first breakpoint records the starting user time; the second adds the difference between the current user time and the starting user time to the running sum for either successful searches or unsuccessful searches, according to the value the search function is returning.

Alternatively, the breakpoints could raise events that include the time information as attributes. That would allow a more detailed analysis, for example, to compute averages and variances, since each instance of an event is recorded on the event history.

Gathering timing information with Dalek — instead of using standard profiling tools like Unix's Gprof tool — or including timing code in the source program gives you more control over what is being measured, plus it is not intrusive. Profilers do not provide control as fine-grained as Dalek's timing functions. While including timing code in the source program is viable, doing so requires recompilation and can affect overall user-time measurements. The number and kinds of changes to the source code required by that approach can also become unwieldy.

For example, suppose you want to find the cumulative time spent executing in procedure *P* but only when it is invoked directly or indirectly from procedure *Q*. To do such measurements by modifying the source code would require either an additional parameter in *P*'s interface or a global variable; either of these changes would be cumbersome in a program of any size. By contrast, Dalek code to do such measurements simply uses the $func predefined function described earlier to determine if *Q* is on the procedure-call stack.

You can also use Dalek as a simple code profiler and to gather other useful statistics about program behavior. For example, we have used Dalek to count how often a procedure or statement is executed, to find the maximum length a linked list reaches during execution, and to measure runtime-stack frame behavior. This kind of information is easily obtained by setting breakpoints at appropriate points in the code and specifying breakpoint commands to maintain convenience variables; you would use control statements and functions for the more complicated measurements.

You can analyze more complicated program behavior by using the event history. Figure 7 shows how you can use the event history to determine the maximum length a linked list reached during execution, without having to rerun the code being debugged.

DEBUGGING STYLE

Dalek encourages a very interactive, dynamic style of debugging, as the examples in this article show. Dalek's full programmability provides the benefits of a debugger fully integrated with an interpretive environment, despite the fact that it operates on a compiled source program.

You can write Dalek code when you find it necessary, like when execution of the code being debugged is suspended at a breakpoint in the source code or even when suspended at a breakpoint somewhere in the Dalek code.

This approach lets you explore a program during its execution, adding debugging code as desired by defining a new high-level event or a new debugging function, like $list_sorted( ) in Figure 2.

Often in debugging, you have arduously brought the code being debugged to a critical point in its execution under the debugger's control before you discover the need for such debugging code. Without full programmability like Dalek's, you would need to limp along without these capabilities or to inject debugging statements (like Assert statements) into the source code, perhaps with conditional compilation. Not only would this require you to terminate the debugging session, modify the source code, and recompile and relink the executable file, but making such seemingly minor modifications to the source code could substantially alter the symptoms exhibited by bugs, especially if pointers are involved.

One drawback of the kind of high-level debugging encouraged by Dalek is that it requires a fair amount of interaction between the debugger process and the process being debugged. Unfortunately, that kind of interaction is generally expensive because it requires system calls and their concomitant context switches. But although such high-level debugging might require a few minutes of computer time, it can save you hours of *your* time.

Another potential drawback of any approach to debugging is that the debugger code may itself contain bugs. Dalek code is as susceptible to bugs as any other debugging code, perhaps more so since it supports and encourages the use of more complex features. To aid the debugging of the debugging code, Dalek provides a verbose mode in which Dalek displays each command as it is interpreted. Dalek also provides several ways to pause its execution as it interprets the debugging code: It lets you single-step through and set breakpoints in your debugging code.

OTHER APPROACHES

Our approach to event recognition differs considerably from other approaches, including those used by several debuggers for concurrent programs that support various forms of events.[2] We use a dataflow graph with programmable nodes to specify how lower level events should be combined into higher level ones. Thus, event recognition in Dalek is an active process. Other event-based approaches typically use a special notation (often based on pattern matching) to specify event recognition. Dalek's notion of persistent, user-definable attributes to characterize each occurrence of an event is also uncommon.

Our approach to event recognition is intentionally low-level to provide maximum flexibility. Unlike the other approaches, it does not constrain event recognition by preconceived notions of how higher level events will be formed. But one drawback of our approach is that even common patterns must be explicitly programmed. We will remedy that, after gaining further experience with Dalek, perhaps by extending the Dalek language to include higher level mechanisms or by providing a macro facility or event libraries. We anticipate the resulting language will retain most of its current low-level mechanisms.

A few sequential debuggers have used the event-based model or a similar one. For example, the notion of event associations in Snobol-4[3] lets event recognition be an active process, but it is not possible to define high-level events or to maintain an event history. Another approach using generalized path expressions[4] lets you define a variant of Dalek's high-level events, but its event recognition is not active and it does not provide any feature like Dalek's notion of persistent attributes. Also, that approach is not fully programmable. Being effectively limited to global integer convenience variables, this deficiency limits the type of information that can be communicated between path expressions. By limiting the event history to storing only counts of event occurrences (in contrast to recording the time stamp as well as the attributes for each occurrence), the practical value of that database is severely constrained.

Higher level debugging mechanisms, like those Dalek provides, considerably simplify the debugging of sequential programs. We have found Dalek's response time for high-level debugging to be reasonable, and — critically important — certainly much less than would be required for a user to do the same work with an existing sequential debugger: minutes rather than hours. Despite good software-development and software-engineering practices, lengthy debugging sessions unfortunately do occur in practice.

Dalek is not just a prototype: All the features described here (as well as other features) have been implemented.[5,6] And the Free Software Foundation is considering incorporating Dalek's features into a future release of GDB.

Our research on debugging will include refining Dalek's language and implementation and generalizing our approach to allow the debugging of concurrent programs. It would also be nice to incorporate a graphical interface into Dalek. ♦

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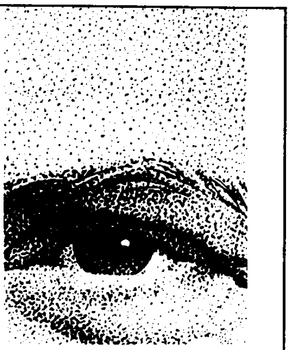
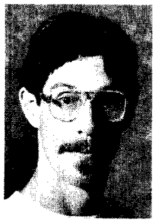
ACKNOWLEDGMENTS

Our work was aided greatly by basing Dalek on GDB. We thank Richard Stallman and the Free Software Foundation for making GDB available to the public. We also thank Carole McNamee and the anonymous referees for their useful comments on earlier drafts of this article. Our early work on Dalek was supported in part by System Integrators and the State of California under the Micro program.

Ronald A. Olsson is an assistant professor of computer science at the University of California at Davis. His research interests include systems software and concurrent programming languages — focusing on issues in design, implementation, optimization, and debugging.

Olsson received a BA in both mathematics and computer science and an MA in mathematics from the State University of New York at Potsdam, an MS in computer science from Cornell University, and a PhD in computer science from the University of Arizona.





Richard H. Crawford is a postgraduate researcher in computer science at the University of California at Davis. His research interests include debugging, programming environments, computer security, coding theory, self-replication and fixed points, and modal and other nonstandard logics.

Crawford received a BS in mechanical engineering from the University of California at Berkeley and a MS in computer science at the University of California at Davis.

W. Wilson Ho is a graduate student and PhD candidate in computer science at the University of California at Davis. His research interests include debugging of distributed programs, distributed file systems, and programming environments.

Ho received a BS in computer science from the University of Hong Kong and an MS in computer science from the University of California at Davis.

Christopher E. Wee is a graduate student in computer science at the University of California at Davis. His research interests include real-time programming, debugging of real-time programs, and object-oriented programming.

Wee received a BS in computer science and engineering from the University of California at Davis.

Address questions about this article to the authors at Computer Science Div., University of California, Davis, CA 95616-8562; Internet debug@cs.ucdavis.edu.