umlsim — A UML-based simulator[*]

Werner Almesberger
werner@almesberger.net

September 28, 2003

Abstract

umlsim provides an environment that allows the use of regular Linux kernel or application code in event-driven simulations. It consists of an extension of user-mode Linux (UML) to deterministically control the flow of time as seen by the UML kernel and applications running under it, and a simulation control system that acts like a debugger, and that can be programmed in a Perl-like scripting language.

umlsim will be useful for a wide range of applications in research and kernel development, including simulations involving the networking code, regression tests, proof of race conditions, validation of configuration scripts, and also performance analysis.

This paper describes the design and implementation of umlsim, gives a brief overview of the scripting language, and concludes with a real-life usage example.

1 Introduction

Simulation is an effective means for examining properties of systems that are too complex, too volatile, too expensive, or simply too large to build and test in real life.

In the development of the Linux kernel, simulations only play a niche role, and are rarely used for more than helping in the design of individual components. Also for performance evaluation, there is broad reliance on benchmark suites, but only little use is made of simulations, which would allow to pinpoint bottlenecks and regressions with much more accuracy.

umlsim provides an environment that allows the use of regular Linux kernel or application code in event-driven simulations. It consists of an extension of user-mode Linux (UML, [1]) to control the flow of time as seen by the UML kernel and applications running under it, and a simulation control system that acts like a debugger, and that is programmed in a C and Perl-like scripting language.

The key feature of umlsim is that – unlike most other simulators, which implement an abstract model of the system being simulated – it uses the original Linux kernel code, with only minor changes. This reduces the risk of creating simulations that differ in some important details from the original, avoids code forking, and generally shortens the process of designing and building a simulation.

The simulation environment is deterministic, i.e. running a simulation multiple times will produce exactly the same results, although one can of course also introduce real or pseudo randomness. This makes umlsim suitable for regression tests, and for exercising specific execution patterns that exhibit problems.

The project's home page is at http://umlsim.sourceforge.net/

This paper is intended for two different audiences: first, it aims to introduce the capabilities and concepts of umlsim to prospective users. Second, it gives other kernel developers an overview of the kernel changes, and describes mechanisms that could also be useful in other projects.

This introduction continues with a brief overview of uses of the simulator, some historical background, and related work. Section 2 discusses overall design and implementation aspects, and section 3 describes the most important elements of the scripting language. A real-life simulation example is given in section 4. We conclude with a discussion of future uses and improvements.

[*] Most the work presented in this paper was conducted as part of the FAST project at the California Institute of Technology,
http://netlab.caltech.edu/FAST/

Type of operation	Point of interaction	
	External	Internal
Observe	Simulator only sees well-defined interfaces, such as network devices, or measures overall performance characteristics, such as the simulation time needed to perform an operation. Example: measurement of TCP throughput over a simulated network connection.	Simulator also monitors variables in the kernel or in applications. Example: observation of how TCP's congestion window changes in the presence of packet losses.
Manipulate	Simulator controls the order of execution, and generates or modifies external events. Example: simulation of a network link with a specific delay and loss probability.	Simulator changes variables or replaces functions in the kernel or in an application. Example: comparison of system behaviour with and without a bug fix.

Table 1: The simulator can interact in four ways with the system(s) used in the simulation.

1.1 Uses of umlsim

The simulator can be used to observe the behaviour of Linux systems, but also to manipulate them. In both cases, it can treat the systems as black boxes, or it can access their internals. Table 1 describes these four possibilities, which are frequently combined in a simulation. The example in section 4 illustrates of external, and both observation and manipulation of internal behaviour.

In addition to all this, the simulator also acts as "glue" between the systems used in the simulation, running them in the right sequence, and taking care of the communication between them.

One of the first uses of umlsim is to examine the behaviour of Linux TCP, but it will also be useful for many other applications in research and kernel development, including regression tests, examination of race conditions and other kernel bugs, validation of configuration scripts, and performance analysis.

1.2 History

The basic concept behind umlsim, namely to use original kernel and user space code in simulations, was already explored by the author in the earlier tcng ("Traffic Control Next Generation" [2]) project.

tcng generates configuration scripts for the traffic control subsystem in the Linux kernel. A simulator called tcsim is used to validate that these commands are formally correct, and that they also yield the desired behaviour. tcsim extracts kernel and user space code involved in traffic control setup and operation, and adds a simple configuration and simulation engine.

This proved to be tremendously useful for regression tests, and allowed additional automated testing of the original code with powerful user-space debugging tools like ElectricFence [3] and valgrind [4]. Unfortunately, the process of extracting precisely the right amount of kernel code, and merging it with the simulation environment, turned out to be very fragile, and requires adjustments even after only slight kernel changes.

Another limitation of tcsim is that it only covers a very small part of the networking stack. For instance, it would be interesting to use TCP as a reactive traffic source.

umlsim therefore takes this approach to the logical extreme, and instead of moving the interesting bits from the kernel into the simulator, it moves (parts of) the simulator into the kernel. It builds on UML, where all the work of making the Linux kernel run in user space has already been done.

1.3 Other simulators

Particularly in the area of networking, simulators are rather common tools. In many cases, they focus only on a very limited set of functions, such as a specific protocol. Among the more general simulators, the network simulator ns-2 [5] is certainly the one most widely known.

ns-2 consists of a modular simulation core written in C++, which is configured through scripts written in an extended version of the Tcl scripting language. The core provides network elements, protocol engines, and traffic generators.

umlsim also has a “core”, but this core provides only very low-level primitives, and higher level functions are implemented by scripts. On the other hand, large subsystems, such as TCP, are simply reused without needing any special treatment in the simulator, and they behave in every detail like in a real system.

ns-2 is much faster than umlsim, and will probably always be, while umlsim is more general and can also be used for simulations involving other subsystems, instead of or in addition to networking.

umlsim has a close competitor in the form of NCTUns [6] on FreeBSD. NCTUns adds some of its simulation infrastructure directly to the kernel actually running on the host machine. By using UML instead of tampering with the host kernel, umlsim can run multiple simulation kernels on the same physical host, does not risk interferences with other system operation, and makes it easier to develop simulations aggressively modifying kernel behaviour.

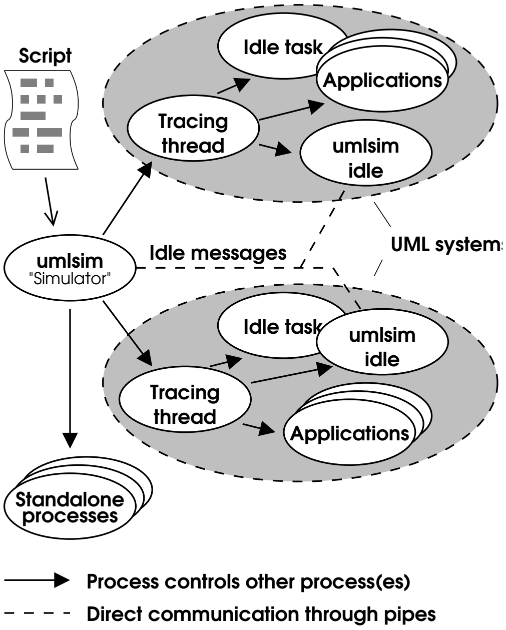


Figure 1: The simulator controls UML systems and other processes. Each UML system in turn consists of several processes.

2 Simulator design

umlsim consists of a simulation control process (we shall call it simply “the simulator”), and the UML systems that are being studied in the simulation. Besides UML systems, a simulation can also include other processes, e.g. to implement communication services. The general structure of a simulation system is shown in figure 1.

The simulator executes a script in a language that combines elements from C and Perl. Scripts serve two purposes: (1) they define the simulation and control its execution, and (2) they provide the “glue” between the actual simulation and the processes used in it, and also between elements in these processes.

As explained in section 1.1, a simulation can choose how closely the simulator and the UML systems interact, i.e. the simulator may just watch a few variables and perform basic synchronization, but exercise no further control over execution, but it may as well intercept even the slightest activity, manipulate variables in the UML kernel, and even alter the flow of execution. Typically, umlsim controls UML at a very low level, but hides most of these interactions inside the simulator and behind library functions that provide a higher level of abstraction.

The simulator basically acts like a debugger, and places breakpoints into the UML kernel. When the kernel is stopped, the simulator can read and change variables. The simulator can also call functions, make them return, etc.

In addition to this, the simulator exchanges time updates with the umlsim idle thread described in the next section directly through a pair of pipes.

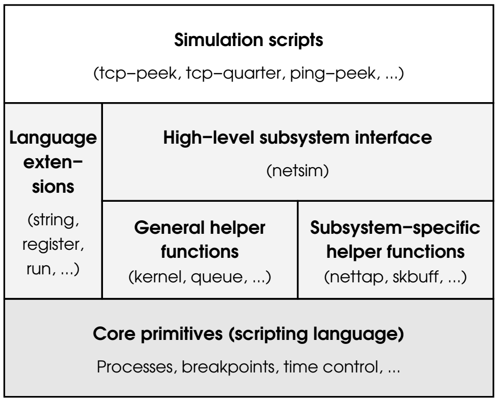

Simulation scripts
(tcp–peek, tcp–quarter, ping–peek, ...)
Language exten–sions
(string, register, run, ...)
High–level subsystem interface
(netsim)
General helper functions
(kernel, queue, ...)
Subsystem–specific helper functions
(nettap, skbuff, ...)
Core primitives (scripting language)
Processes, breakpoints, time control, ...

Figure 2: Organization of libraries in umlsim.

Figure 2 shows the current structure of libraries. Work in this area of umlsim is still very much in progress.

2.1 Virtual time

It is frequently desirable to run simulations in a deterministic virtual time instead of real time. umlsim can accomplish this by adding code to the kernel that intercepts all functions reporting or advancing time, and puts them under its own control. This code also introduces a umlsim-specific idle thread that yields to all other tasks, except the kernel's regular idle task.

Whenever the kernel is idle (i.e. no process is scheduled to run), the umlsim code in the kernel does one of the following:

- if a soft-interrupt is pending: it generates a timer interrupt, but does not advance time
- if a timer will expire within the next jiffy:[1] it generates a timer interrupt, and allows do_timer to advance time by one jiffy
- if the next timer will expire in the future: the UML kernel reports this back to the simulator, and waits for further instructions

Since the kernel always runs some timers (such as neigh_periodic_timer and rt_check_expire), umlsim does not need to handle the case of a timeout without further activity.

The kernel can also become active when a device interrupt arrives. umlsim currently only handles network events. Instead of using signals (which correspond to interrupts in UML), it calls the functions invoked by interrupt handlers directly.

When all kernels in a simulation report that they are waiting for a timer, the simulator picks the earliest expiration time among these timers (or a timeout specified in the wait command, if it is earlier), sets the global simulation time to that value, and updates the local time in all kernels.

Another source of kernel activity can be pending read-copy updates [7]. umlsim currently ignores them, assuming that their side-effects do not affect any parts of the system monitored by the simulation. In the future, umlsim will also consider read-copy updates for its scheduling decisions.

2.2 Running UML under a debugger

When running UML under a debugger or a similar program (such as strace), the tracing thread watches the debugger with ptrace, intercepts calls to functions like ptrace and waitpid, and emulates them or redirects them to the process currently executing the kernel. This part of UML is called the "ptrace proxy".

Unfortunately, this design allows only a single UML system per debugger, because a process can be watched with ptrace by at most one process at any given time.

In order to control multiple UML systems, umlsim forks a forwarder process for each such system. This process communicates with the main simulator through pipes, and executes the ptrace calls on its behalf. This is shown in figure 3.

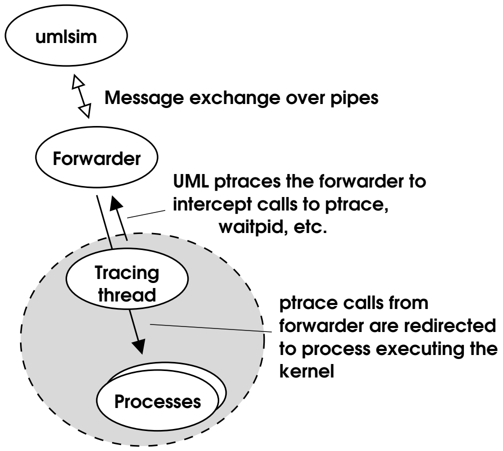

umlsim
Message exchange over pipes
Forwarder
UML ptraces the forwarder to intercept calls to ptrace, waitpid, etc.
Tracing thread
ptrace calls from forwarder are redirected to process executing the kernel
Processes

Figure 3: umlsim uses an intermediate forwarder process to "debug" the UML system.

As an example, figure 4 shows a simplified flow of control when the simulator performs a ptrace call on a UML system.

2.3 Debugging the kernel

There are several idiosyncrasies of kernel code and of the way gcc compiles it that need special attention in umlsim. This section describes some of them.

Because the jiffies variable is defined in the linker, the debugging information generated by the compiler only contains its declaration, but not its location. umlsim therefore retrieves this information from the symbol table of the kernel

[1] The "jiffy" is the basic time unit in the kernel. One jiffy typically equals 1–10 ms.

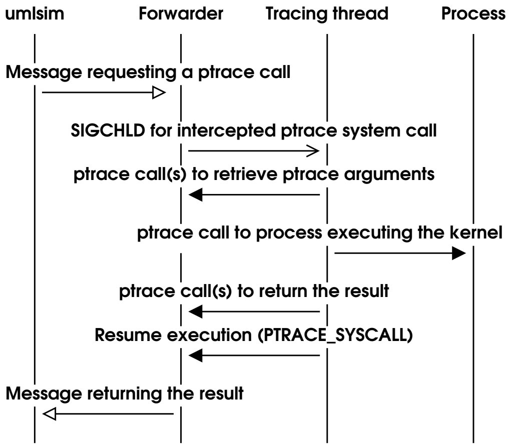

umlsim
Forwarder
Tracing thread
Process
Message requesting a ptrace call
SIGCHLD for intercepted ptrace system call
ptrace call(s) to retrieve ptrace arguments
ptrace call to process executing the kernel
ptrace call(s) to return the result
Resume execution (PTRACE_SYSCALL)
Message returning the result

Figure 4: Simplified control flow when the simulator performs a ptrace call on a UML system.

executable, and augments the declaration with it.

Some functions pass arguments in registers registers instead of using the stack (e.g. those declared with FASTCALL). umlsim currently does not support or even recognize this.

The kernel makes heavy use of inline functions. One peculiarity of inline functions is that breakpoints in an inline function need to be repeated for each instance of this function. Furthermore, gcc rearranges and sometimes even removes labels (the ones used as targets for goto statements) when optimizing. umlsim introduces a mechanism called "reliable markers" that includes an explicit label in the function, which can then be used for breakpoints. Reliable markers also work in functions that are not inlined, and are used as follows:

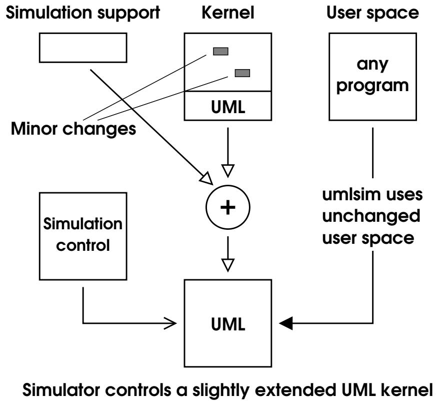
```
void some_function(int a)
{
    int b = 10;

    MARKER(label_name,a,b);
...
```

Variables that may be accessed by the simulator when stopped at the location of the marker are listed after the label name. This makes sure that the variables in question have a memory location, that they are not cached in registers when passing the marker, and that no code accessing these variables gets moved across the marker. (E.g. in the example above, the compiler might otherwise try to move the initialization of b after the marker.)

Also, since many low-level service functions are declared static inline, they cannot be called directly. umlsim generates callable instances of the most common inline functions by including their definitions in a file compiled with -fkeep-inline-functions.

2.4 Kernel changes

The kernel changes required for umlsim are comparably minor, and most of them are in the area specific to the UML architecture.



Simulator controls a slightly extended UML kernel

Figure 5: umlsim is modular, and requires only very minor changes to the base kernel.

umlsim requires the following changes in generic kernel code:

- calibrate_delay explicitly waits for a timer interrupt, which would never happen under umlsim, because at that time, the umlsim idle thread does not yet exist. Therefore, umlsim simply skips calibrate_delay when using virtual time, and sets loops_per_jiffy to one.
- functions are added to timer.c to retrieve the expiration time of the next timer.

umlsim replaces the following functions using the linker's --wrap mechanism:

- do_gettimeofday and gettimeofday return the simulation time instead of the system's real time.
- setitimer becomes a no-op, because umlsim generates all timer interrupts under its own control.
- a switch is added to control whether a timer interrupt invokes do_timer. This way, timer interrupts can be used to run soft-interrupts without advancing the jiffies count.

- idle_sleep leads to the timeout handling code of umlsim.

The timeout handling code decides which actions to take (e.g. to raise a timer interrupt if there are pending soft-interrupts), communicates with the simulator, and maintains the various "current time" variables.

The umlsim patches also add the reliable markers, and callable definitions of common inline functions, which are both described in the previous section.

2.5 Network simulation

When simulating network elements, umlsim builds on the infrastructure used by the dummy device, but the script intercepts the transmit function and provides the actual transport and low-level packet manipulation functionality.

Figure 6 shows the key functions invoked when sending and receiving packets.

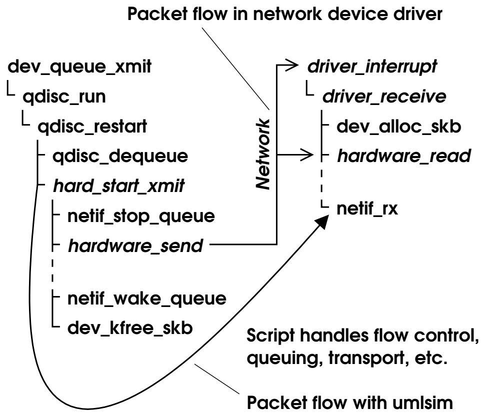


Figure 6: Call sequence and packet flow with and without umlsim (simplified).

umlsim currently only provides a single-link model, which will be extended and generalized in the near future. Figure 7 shows how the device interface and link are implemented. This code can be found in the files include/netsim.umlsim and include/nettap.umlsim of the umlsim distribution.

When reaching the breakpoint dummy_xmit, umlsim retrieves the packet, calculates the queuing delay, and stores it in an internal queue. If the device queue is full, the script calls the flow-control function netif_stop_queue.

When the packet is due for sending, it is dequeued and put into the link queue, from which it emerges after the transfer delay. umlsim then invokes basically the same functions as the "daemon" device of UML, and finally pushes the packet to the stack by calling netif_rx.

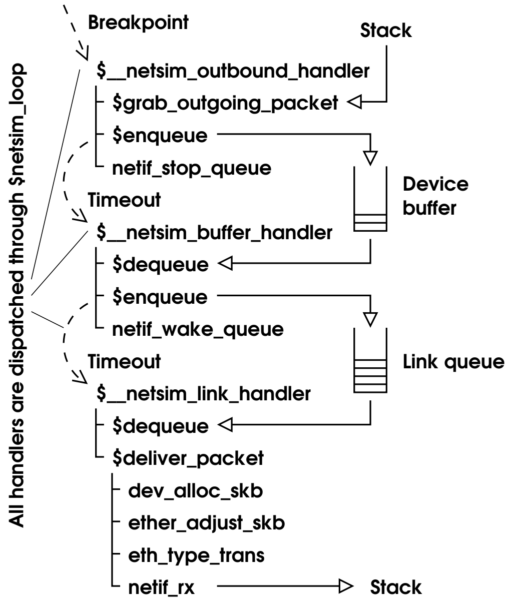


Figure 7: Control flow in script implementing network device and link.

3 The scripting language

The scripting language is mainly based on C and Perl, but it also borrows concepts from the Bourne shell, Pascal, and LISP. This section gives a brief overview of the most important concepts, and differences to similar languages.

umlsim passes scripts through the C preprocessor, so the usual comment handling, macro capabilities, and include files are available.

3.1 Variables and functions in the simulator

The names of variables in the simulator always begin with a dollar sign, like in Perl. Also like in Perl, variables can be used without prior declaration, their value can be of any type, and the type can be change.

An uninitialized variable has the so-called *undefined value*. The undefined value can also be used explicitly, with the construct undef, and one can test whether an expression yields the undefined value with defined *expression*.

The scripting language, like C, uses lexical scoping, i.e. the visibility of a variable is determined by its location in the program, but not by the sequence of function calls that leads to a specific access.

By default, variables are visible within the enclosing function, but not in other functions. This can be changed by either declaring them local, which creates a new, uninitialized instance that is visible in the current block and any blocks inside it, or by declaring them global, which creates a new instance in the current function, which is visible also in functions defined inside this function. Example:

```
$a = 5;
{
    local $a = 0;

    $a++;
    {
        $a++;
        printf("inner %d\n",$a);
    }
    printf("middle %d\n",$a);
}
printf("outer %d\n",$a);
```

yields

```
inner 2
middle 2
outer 5
```

The goal of these slightly unusual scoping rules is to avoid explicit declarations as much as possible, but also to avoid the problem of functions accidentally altering global variables, which is common in other scripting languages.[2]

Functions are anonymous, similar to lambda expressions in LISP. In order to reference a function by name, the function has to be stored in a variable. Example:

```
global $gcd = function ($a,$b)
{
    if ($a == $b) return $a;
    return $a > $b ?
      $gcd($a-$b,$b) : $gcd($a,$b-$a);
};

print $gcd(300,90);
```

The scripting language also supports associative arrays. Indices can be integers, pointers, strings, processes, or breakpoints. Elements can be of any type, including arrays. Examples:

```
$a[0] = 3;
$a["string"] = $a;
print $a["string"][0];
```

3.2 Printing and files

The scripting language has two output statements: the C-like printf, and the "smart" and somewhat Perl-like print.

print accepts a list of items to print, appends a newline after the last item, and pretty-prints structured types. Example:

```
$proc = uml("linux");
print "xtime = ",xtime;
```

yields

```
xtime = {
    tv_sec = 0 (0x0)
    tv_nsec = 0 (0x0)
}
```

print outputs integers as decimal and as hexadecimal numbers, enumeration type members by name, strings and signed character arrays as text strings, and arrays of unsigned characters as a hexdump. Like in Perl, a separator between printed arguments can be introduced by setting the special variable $,.

To send output to a file, the file first has to be opened with the open function, which has a file name argument using the same meta-characters as Perl's open, but returns a file handle. Then, the file handle can be used as the first argument of print or printf. Example:

```
$file = open(">tmp");
print $file,"example data";
printf($file,"answer = %d\n",42);
close($file);
```

Data can be read from files with the read function, but this is rarely used.

3.3 Control statements

if-else, while (with break and continue), and for work exactly like in C. There is no do-while loop, because while can be used in its stead.[3]

switch-case is similar to C, with the difference that variable expressions can be used for case labels.

There is no goto.[4]

[2] Only time – and users – will tell whether this is indeed an improvement over more traditional scoping rules. Users preferring to declare all their variables can set the -Wundeclared option to enable warnings when trying to access undeclared variables.

[3] ... and because the way programs are represented internally makes do-while somewhat difficult to express. It may be added at a later time.

[4] Religious issues aside, umlsim should in the future support goto, in order to make it easier to copy-and-paste C functions into simulation scripts. Section 4 illustrates such a process.

3.4 Processes

Simple programs are started with the function run, and UML systems are started with the function uml. Both functions return a handle that identifies the process. They also set the "magic" variable $$ to this value. $$ always identifies the *current* process, i.e. the process that has most recently been created or stopped, and that is currently being manipulated. $$ can be changed by the simulator (when a different process becomes current) and by the script (if one wants another process to be current).

run and uml also support some basic IO-redirection, e.g. run("/bin/date",">/tmp/xyz")

After run or uml, the process is in the *starting* state, but not yet running. A starting or *stopped* process is run with the continue statement.[5]

The wait statement is used to make the simulator wait for the next event (process termination, breakpoint, timeout, etc.). If the event is related to a process, wait sets $$ to this process. Example:

```
$proc = run("/bin/echo","hello world");
continue();
wait();
print $$ == $proc;
```

yields[6]

```
hello world
1 (0x1)
```

3.5 Breakpoints, functions, and timeouts

Breakpoints can be placed at function entry, at the point to which the current function returns, at labels, and at the reliable markers described in section 2.3. Breakpoints are set with the break function, which returns a handle that identifies the breakpoint.

In the example below, we set breakpoint $b1 at the entry of the main function in the current process, breakpoint $b2 at the label or reliable marker label inside the main function, and breakpoint $b3 at the location to which the current function returns.

```
$b1 = break(main);
$b2 = break(main.label);
$b3 = break(return);
```

When reaching a breakpoint, umlsim sets $$ to the process in which the breakpoint is located, and $! to the breakpoint handle.

When calling a function in the process, also a breakpoint is generated. This breakpoint is triggered when the function returns. The return value of the function is stored in the special variable $?. Example:

```
$b = call fn(1,2,3);
continue();
...
wait();
if ($! == $b) printf("result = %d\n",$?);
```

The call shown in this example is called *asynchronous*, because other breakpoints, timeouts, or events in other processes can be handled before the function returns. If this flexibility is not needed, one can use the simpler *synchronous* form, which does not change $! or $?. Example:

```
printf("result = %d\n",fn(1,2,3));
```

Breakpoints can be removed implicitly, by destroying all references to them, or explicitly with delete(*breakpoint*);

A script can not only call functions in a process, but it can also make a function return. For example, $__netsim_outbound_handler in figure 7 forces dummy_xmit to return, without executing any code of that function, with $$.return 0;.

Besides terminating or reaching a breakpoint, a process may also stop with a timeout. Timeouts are specified with a time argument to wait. When the specified absolute time is reached, wait sets $$ to the undefined value, and the "current time" variable $@ to the timeout, rounded up to the next nanosecond. Example:

```
wait(10.2); /* wait until t = 10.2 seconds */
if (!defined $$) print $@;
```

If more than one timeout can occur at a given time (e.g. packets arriving within the same nanosecond at different points in the simulation), wait($@) must be called after handling each event, so that breakpoints reached when handling a timeout can be processed before handling further timeouts. An example for using wait($@) can be found in the event loop at the end of include/netsim.umlsim in the umlsim distribution.

[5] This form of continue has the process handle as argument, in parentheses, and therefore differs syntactically from the continue control statement. If continuing the current process, the parentheses can be left empty.

[6] After warning that /bin/echo has neither symbols nor debugging information, so there is very little umlsim can do with this process.

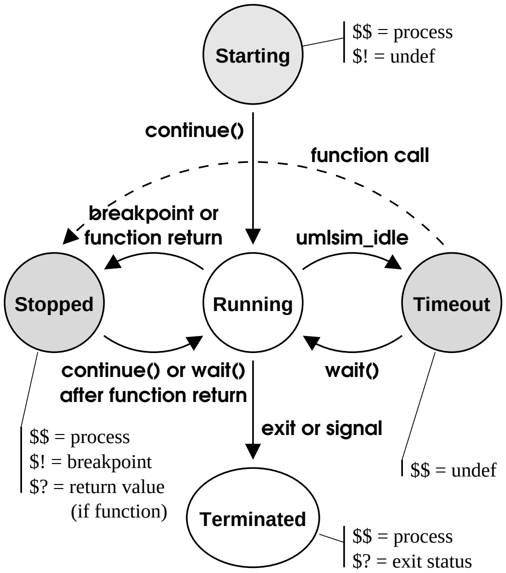


Figure 8: User-visible process states. "Function call" and "return" refer to asynchronous function calls.

Figure 8 summarizes the process states described in this section. States shown in grey allow manipulations of the process, such as the creation of new breakpoints, access to variables, or function calls. A function call from *timeout* puts the process in a state equivalent to *stopped*, but it does not affect any of the special variables.

3.6 Data in a process

umlsim scripts can directly read and write variables in a process, follow pointers, select struct or union members, and so on.

The basic operation is to access a variable. In many cases, simply specifying the variable's name is enough, e.g. given the example program below, foo retrieves the value 42.

```
static int foo = 42;

int main(void)
{
    static int bar = 5;

    MARKER(stop_here,bar);
    return bar;
}
```

Accessing bar is more complicated. If the program has not been started yet, umlsim looks for variables only in the global scope. To access a variable local to a function, it has to be qualified with the function name, i.e. main.bar.

If the program is stopped at the label main.stop_here, umlsim searches the local scope first, so just bar is sufficient.

Variables, functions, and labels can also be qualified with the process and the compilation unit. Compilation units are in double quotes. Examples:

```
$b1 = break($proc.main);
$b2 = break("fs/ext2/super.c".parse_options);
"drivers/net/tun.c".debug = 1;
"tun.c".debug = 0;
```

Since distinct processes may use the same name for different types, also struct or union tags can be qualified, e.g. struct $proc_a.sk_buff.

Type definitions with typedef differ from C in that umlsim cannot usefully distinguish at parse time between typedef names and other identifiers. Therefore, typedef names are always prefixed with the keyword typedef, e.g. typedef pte_addr_t. Like all other names, they can be qualified. For convenience, the C99 standard integer types uint32_t, int8_t, etc. are predefined.

Conflicts between C identifiers and keywords of the scripting language (e.g. printf) can be resolved by escaping the word with a backslash when the C identifier is meant, e.g. \printf.

A peculiarity in the way umlsim handles data are array copies: when accessing an object of array type, the entire array is copied. To obtain a pointer to the array, the & operator must be used. Example:

C program fragment:

```
int a[10];
int b[10];
```

umlsim script:

```
$array = a;
b = a; /* memcpy equivalent */
$ptr = &a;
```

This can also be used in type casts. E.g. the following construct copies the content of a network packet:

```
$pkt = (unsigned char [skb->len])
  skb->data;
```

4 Simulation example

In this section, we use umlsim to demonstrate a bug in Linux TCP, and to show the effect of a possible fix. The problem in question, which was first observed on a simulator by Cheng Jin, is that Linux TCP[7] decreases the congestion window (*cwnd*, TCP's estimate of how many packets can be "in flight" for a given connection) too much if there are multiple packet losses in a single round-trip time.

When a packet is lost, TCP assumes that this was due to congestion, and reduces *cwnd* by half. However, if multiple losses occur within a single round-trip time, they should be treated only like a single loss. Linux TCP does not do this, and may reduce *cwnd* to as low as a quarter of the original value. This causes TCP to send data a little slower than it would be allowed to.

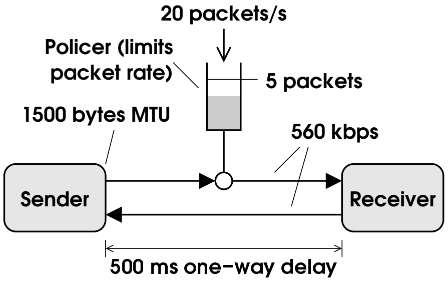


Figure 9: Network setup used in the simulation.

Figure 9 shows the network configuration used in the simulation: the TCP sender and receiver are connected by a single link with a round-trip time of one second. The maximum throughput is rate-limited to twenty packets per second. We simulate the transfer of a 1 MB file.

The left-hand side of figure 10 shows the transfer with an unchanged 2.5.66 kernel. snd_cwnd is the congestion window, in segments. snd_ssthresh marks the point where TCP switches between "slow start" and "congestion avoidance" mode. snd_cwnd should not fall below snd_ssthresh. snd_una is the number of bytes that have been acknowledged by the receiver. packets lost is the cumulative number of packets dropped by the rate limiter.

The culprit is the function tcp_cwnd_down, which decreases snd_cwnd while it is greater than half of snd_ssthresh, but the latter has already been halved. This is the original tcp_cwnd_down function:

```
static void tcp_cwnd_down(struct tcp_opt *tp)
{
        int decr = tp->snd_cwnd_cnt + 1;

        tp->snd_cwnd_cnt = decr&1;
        decr >>= 1;

        if (decr &&
            tp->snd_cwnd > tp->snd_ssthresh/2)
                tp->snd_cwnd -= decr;

        tp->snd_cwnd = min(tp->snd_cwnd,
            tcp_packets_in_flight(tp)+1);
        tp->snd_cwnd_stamp = tcp_time_stamp;
}
```

For the second simulation, we use the same kernel, but set a breakpoint at the beginning of tcp_cwnd_down, and execute a replacement in the script instead of the original function. This replacement implements a fix that keeps *cwnd* from being lowered too far:

```
$tcp_cwnd_down = function ($tp)
{
    $min = function ($a,$b)
    {
        return $a < $b ? $a : $b;
    };

    $decr = tp->snd_cwnd_cnt+1;

    $tp->snd_cwnd_cnt = $decr&1;
    $decr >>= 1;

    if ($decr &&
      $tp->snd_cwnd > $tp->snd_ssthresh)
        $tp->snd_cwnd -= $decr;

    $tp->snd_cwnd = $min($tp->snd_cwnd,
        tcp_packets_in_flight($tp)+1);
    $tp->snd_cwnd_stamp = tcp_time_stamp;
};
```

The code fragment that makes this replacement looks like this:

```
...
$brk_b_tcp_cwnd_down = break($b.tcp_cwnd_down);
...
    $netsim_loop(undef);
    switch ($!) {
    ...
        case $brk_b_tcp_cwnd_down:
            $tcp_cwnd_down(tp);
            $$.return;
            break;
...
```

As can be seen on the right-hand side of figure 10, with this work-around in place, snd_cwnd never falls below snd_ssthresh, and the transfer finishes considerably earlier than in the buggy version.

[7] Most if not all 2.4 and 2.5 kernels are affected. At the time of writing, this bug still exists in the mainstream kernel. The entire discussion can be found at [8].

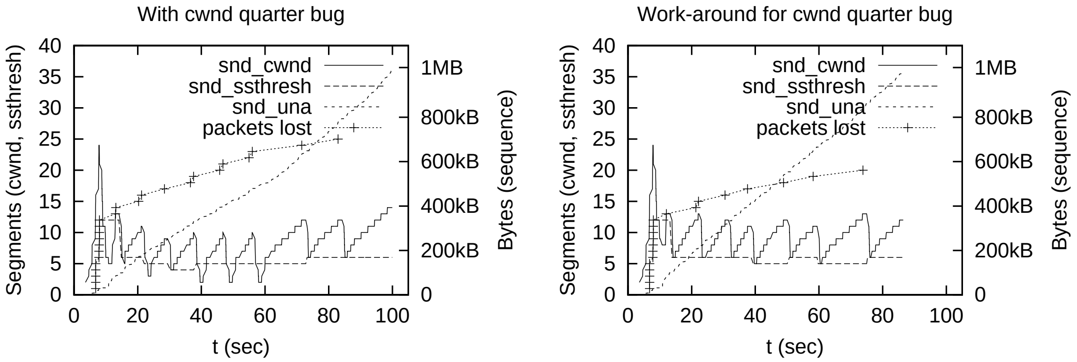


Figure 10: Simulated transfer with and without the “cwnd quarter” bug.

5 Future work

As a complex but relatively young project, umlsim still has shortcomings in many areas. This section discusses some of the problems, and outlines approaches for solving them.

Future work on umlsim will primarily focus on the needs of network simulations, and in particular the analysis of TCP behaviour.

5.1 Functionality

Networking simulations are essentially limited to a single-link scenario at the time of writing. Work is under way for providing building blocks that allow the construction of arbitrary network topologies.

Another issue all but ignored so far is portability to architectures with other byte order or word size than ia32. Also support for multiprocessing is absent so far.

The simulator has currently no direct control over processes running in the user space under a UML kernel. It would be useful if simulations could treat such processes like ordinary processes, i.e. by launching them with a simple command, by placing breakpoints, etc.

It would be interesting to explore the possibility of using umlsim to reconstruct the internal state of the kernel, based on traces obtained from “live” systems. For example, this could be used to explain anomalies in network activity captured with tcpdump. The open issue here is how quickly unavoidable time differences and events not recorded in the trace (such as soft-interrupt execution after a hardware interrupt) will cause the simulation to diverge from the original system, and how such errors can be compensated.

5.2 Usability

umlsim today is clearly a hacker’s toy. Most users will want high-level components when implementing their simulations, and the scripting language could also use some minor cleanup.

Dark corners of the language include the cast operator, pointers to data in the simulator, inconsistencies in the syntax (e.g. normally, $$.*thing* is equivalent to just *thing*, but return is very different from $$.return), and subtle differences in the semantics of array indices and case expressions.

To be useful outside the kernel hacker community, umlsim needs libraries with application-oriented building blocks that provide a convenient level of abstraction. At the time of writing, such a library is slowly emerging for networking, with the main focus on TCP.

Beyond libraries, also preprocessors that translate simpler application-oriented languages, like the one used by tcsim, to umlsim may be useful.

One of the most important aspects of simulations is the visualization of results. While it is desirable to retain a maximum of flexibility, examples for data formats, and visualization packages for common tasks will help users to obtain results more rapidly.

Also, as befits a hacker’s toy, documentation is incoherent and spotty.

5.3 Performance

At the time of writing, umlsim is rather slow. While some optimization work has been done to reduce startup time and to accelerate some lookup operations, and more recently also to accelerate the communication between the simulator and the UML processes, several areas remain where major speed improvement are possible.

First of all, ptrace is a rather inefficient means for accessing process memory. It would be better if the simulator entirely bypassed the tracing thread when reading or changing variables, and accessed the address space of the UML processes directly.

Also the performance of UML itself is the object of on-going work [9]. In particular, the so-called "skas mode" ("skas" stands for "Separate Kernel Address Space") has been added recently, to accelerate context switches of processes under UML [10]. By following these changes, umlsim will permit UML to run faster, which in turn will benefit overall system performance, and also umlsim itself will be able to access UML systems more efficiently.

Last but not least, several algorithms and data structures inside the simulator are rather inefficient, and will have to be improved for larger simulations. For example, results of identifier lookups should be cached.

6 Conclusion

umlsim provides the infrastructure for turning the (UML) Linux kernel into a versatile event-driven simulator, that can be customized using a scripting language most programmers will find easy to learn.

The next challenges in the project will be to bring performance closer to that of comparable simulators, to improve overall usability, to apply umlsim to concrete problems, and to use experience gained from such real-life applications to further improve the simulator.

References

[1] Dike, Jeff; et al. *The User-mode Linux Kernel Home Page*, http://user-mode-linux.sourceforge.net/

[2] Almesberger, Werner. *Traffic Control – Next Generation*, http://tcng.sourceforge.net/

[3] Perens, Bruce. *Electric Fence*, ftp://ftp.perens.com/pub/ElectricFence/

[4] Seward, Julian; Nethercote, Nick. *Valgrind, an open-source memory debugger for x86-GNU/Linux*, http://developer.kde.org/~sewardj/

[5] *The Network Simulator - ns-2*, http://www.isi.edu/nsnam/ns/

[6] S.Y. Wang, C.L. Chou, C.H. Huang, C.C. Hwang, Z.M. Yang, C.C. Chiou, and C.C. Lin. *The Design and Implementation of the NCTUns 1.0 Network Simulator*, Computer Networks, Vol. 42, Issue 2, June 2003, pp. 175–197. http://www.csie.nctu.edu.tw/~shieyuan/publications/NCTUNSDesign.pdf

[7] McKenney, Paul E. *Read-Copy Update*, http://www.rdrop.com/users/paulmck/rclock/

[8] Almesberger, Werner; Jin, Cheng; Kuznetsov, Alexey. *snd_cwnd drawn and quartered*, Discussion thread on the netdev mailing list, December 25, 2002. http://marc.theaimsgroup.com/?t=104078129500001

[9] Dike, Jeff. *Making Linux Safe for Virtual Machines*, Proceedings of Ottawa Linux Symposium 2002, pp. 107–116, June 2002. http://www.linux.org.uk/~ajh/ols2002_proceedings.pdf.gz

[10] Dike, Jeff. *skas mode*, http://user-mode-linux.sourceforge.net/skas.html