OpenFest 2015

System Call Tracing with strace

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Outline

1. Preamble
2. Getting started
3. Tracing child processes
4. Filtering strace output
5. Further strace options

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1 Preamble

2 Getting started

3 Tracing child processes

4 Filtering strace output

5 Further strace options

Who am I?

- Maintainer of Linux man-pages (since 2004)
  - Documents kernel-user-space + C library APIs
    - ˜1000 manual pages
    - http://www.kernel.org/doc/man-pages/
- Linux involvement: API review, testing, and documentation
- “Day job”: trainer, writer, programmer

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Audience

- Programmers?
- C/C++ Programmers?

What is a system call?

- Various possible answers, from different perspectives
- Answer 1: **request to kernel to perform a service**
  - Open a file
  - Execute a new program
  - Create a new process
  - Send a message to another process
- Answer 2 (programmer's perspective): "call a function"
  - `fd = open("myfile.txt", O_CREAT|O_RDWR, 0644);`
  - System call **looks like** any other function call

What is a system call?

- Answer 3: entry point providing **controlled mechanism to execute kernel code**
- User-space programs **can't** call functions inside kernel
- Syscall = one of few mechanisms by which program can ask to execute kernel code
  - Others: `/proc`, `/sys`, etc.
- Set of system calls is:
  - Operating-system specific
    - Can't run Linux binaries on another OS, and vice versa
  - Limited/strictly defined by OS
    - Linux kernel provides 400+ syscalls
    - *syscalls(2)* man page

Steps in the execution of a system call

1. Program calls wrapper function in C library
2. Wrapper function
    - Packages syscall arguments into registers
    - Puts (unique) syscall number into a register
3. Wrapper flips CPU to kernel mode (user-mode ⇒ kernel-mode)
    - Execute special machine instruction (e.g., `sysenter` on x86)
    - Main effect: CPU can now touch memory marked as accessible only in kernel mode
4. Kernel executes syscall handler:
    - Invokes **service routine** corresponding to syscall number
        - **Do the real work**, generate result status
    - Places return value from service routine in a register
    - Switches back to user mode, passing control back to wrapper
        - (kernel-mode ⇒ user-mode)
5. Wrapper function examines syscall return value; on error, copies error number to *errno*

Outline

1 Preamble

2 Getting started

3 Tracing child processes

4 Filtering strace output

5 Further strace options

strace(1)

- A tool to trace system calls made by a user-space process
    - Implemented via *ptrace(2)*
- Or: a debugging tool for tracing **complete conversation between application and kernel**
    - Application source code is not required
- Answer questions like:
    - What system calls are employed by application?
    - Which files does application touch?
    - What arguments are being passed to each system call?
    - Which system calls are failing, and why (*errno*)?

strace(1) output

- Log information is provided in **symbolic form**
    - **System call names** are shown
    - We see **signal names** (not numbers)
    - **Strings** printed as characters (up to 32 bytes, by default)
    - **Bit-mask arguments displayed symbolically**, using corresponding bit flag names ORed together
    - **Structures** displayed with **labeled fields**
    - ***errno*** **values** displayed symbolically + matching error text
    - "large" arguments and structures are abbreviated by default

```
fstat(3, {st_dev=makedev(8, 2), st_ino=401567,
  st_mode=S_IFREG|0755, st_nlink=1, st_uid=0, st_gid=0,
  st_blksize=4096, st_blocks=280, st_size=142136,
  st_atime=2015/02/17-17:17:25, st_mtime=2013/12/27-22:19:58,
  st_ctime=2014/04/07-21:44:17}) = 0

open("/lib64/liblzma.so.5", O_RDONLY|O_CLOEXEC) = 3
```

Simple usage: tracing a command at the command line

- A very simple C program:

```
int main(int argc, char *argv[]) {
#define STR "Hello world\n"
    write(STDOUT_FILENO, STR, strlen(STR));
    exit(EXIT_SUCCESS);
}
```

- Run *strace(1)*, directing logging output (*–o*) to a file:

```
$ strace -o strace.log ./hello_world
Hello world
```

  - (By default, strace output goes to standard error)

- ⚠ On some systems, may first need to:

```
# echo 0 > /proc/sys/kernel/yama/ptrace_scope
```

  - Yama LSM disables *ptrace(2)* to prevent attack escalation; see man page

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Simple usage: tracing a command at the command line

```
$ cat strace.log
execve("./hello_world", ["./hello_world"], [/* 110 vars */]) = 0
...
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT
(No such file or directory)
open("/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
fstat(3, {st_mode=S_IFREG|0644, st_size=160311, ...}) = 0
mmap(NULL, 160311, PROT_READ, MAP_PRIVATE, 3, 0) = 0x7fa5ecfc0000
close(3)                                = 0
open("/lib64/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
...
write(1, "Hello world\n", 12)           = 12
exit_group(0)                           = ?
+++ exited with 0 +++
```

- Even simple programs make lots of system calls!
  - 25 in this case (many have been edited from above output)
- Most output in this trace relates to finding and loading shared libraries
  - First call (*execve()*) was used by shell to load our program
  - Only last two system calls were made by our program

Simple usage: tracing a command at the command line

```
$ cat strace.log
execve("./hello_world", ["./hello_world"], [/* 110 vars */]) = 0
...
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT
(No such file or directory)
open("/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
fstat(3, {st_mode=S_IFREG|0644, st_size=160311, ...}) = 0
mmap(NULL, 160311, PROT_READ, MAP_PRIVATE, 3, 0) = 0x7fa5ecfc0000
close(3)                                = 0
open("/lib64/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
...
write(1, "Hello world\n", 12)           = 12
exit_group(0)                           = ?
+++ exited with 0 +++
```

For each system call, we see:

- Name of system call
- Values passed in/returned via arguments
- System call return value
- Symbolic *errno* value (+ explanatory text) on syscall failures

A gotcha...

- The last call in our program was:

```
exit(EXIT_SUCCESS);
```

- But *strace* showed us:

```
exit_group(0)                           = ?
```

- Some detective work:
  - We “know” *exit(3)* is a library function that calls *_exit(2)*
  - But where did *exit_group()* come from?
  - *_exit(2)* man page tells us:

```
$ man 2 _exit
...
C library/kernel differences
 In glibc up to version 2.3, the _exit() wrapper function
 invoked  the kernel system call of the same name.  Since
 glibc 2.3, the wrapper function  invokes  exit_group(2),
 in order to terminate all of the threads in a process.
```

- ⇒ may need to dig deeper to understand *strace(1)* output

Outline

1 Preamble

2 Getting started

3 Tracing child processes

4 Filtering strace output

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Tracing child processes

- By default, *strace* does not trace children of traced process
- *–f* option causes children to be traced
  - Each trace line is prefixed by PID
  - In a program that employs POSIX threads, each line shows kernel thread ID (*gettid()*)

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Tracing child processes: strace/fork_exec.c

```c
int main(int argc, char *argv[]) {
    pid_t childPid;
    char *newEnv[] = {"ONE=1", "TWO=2", NULL};

    printf("PID of parent: %ld\n", (long) getpid());
    childPid = fork();
    if (childPid == 0) {          /* Child */
        printf("PID of child:  %ld\n", (long) getpid());
        if (argc > 1) {
            execve(argv[1], &argv[1], newEnv);
            errExit("execve");
        }
        exit(EXIT_SUCCESS);
    }
    wait(NULL);             /* Parent waits for child */
    exit(EXIT_SUCCESS);
}
```

```
$ strace -f -o strace.log ./fork_exec
PID of parent: 1939
PID of child:  1940
```

Tracing child processes: strace/fork_exec.c

```
$ cat strace.log
1939 execve("./fork_exec", ["./fork_exec"], [/* 110 vars */]) = 0
...
1939 clone(child_stack=0, flags=CLONE_CHILD_CLEARTID|
  CLONE_CHILD_SETTID|SIGCHLD, child_tidptr=0x7fe484b2ea10) = 1940
1939 wait4(-1,  <unfinished ...>
1940 write(1, "PID of child:  1940\n", 21) = 21
1940 exit_group(0)                     = ?
1940 +++ exited with 0 +++
1939 <... wait4 resumed> NULL, 0, NULL) = 1940
1939 --- SIGCHLD {si_signo=SIGCHLD, si_code=CLD_EXITED,
  si_pid=1940, si_uid=1000, si_status=0, si_utime=0,
  si_stime=0} ---
1939 exit_group(0)                     = ?
1939 +++ exited with 0 +++
```

- Each line of trace output is prefixed with corresponding PID
- Inside glibc, *fork()* is actually a wrapper that calls *clone(2)*
- *wait()* is a wrapper that calls *wait4(2)*
- We see two lines of output for *wait4()* because call blocks and then resumes
- *strace* shows us that parent received a SIGCHLD signal

Outline

1 Preamble

2 Getting started

3 Tracing child processes

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5 Further strace options

Selecting system calls to be traced

- *strace –e* can be used to select system calls to be traced
  - Syntax is a little complex ⇒ we'll look at simple, common use cases
- *–e trace=<syscall>[,<syscall>...]*
  - Specify system call(s) that should be traced
  - Other system calls are ignored

```
$ strace -o strace.log -e trace=open,close ls
```

- *–e trace=!<syscall>[,<syscall>...]*
  - **Exclude** specified system call(s) from tracing
    - Some applications do bizarre things (e.g., calling *gettimeofday()* 1000s of times/sec.)
  - ⚠ "!" needs to be quoted to avoid shell interpretation

Selecting system calls by category

- *–e trace=<syscall-category>* specifies a category of system calls to trace
- Categories include:
  - *file*: trace all system calls that take a filename as argument
    - *open()*, *stat()*, *truncate()*, *chmod()*, *setxattr()*, *link()*...
  - *desc*: trace file-descriptor-related system calls
    - *read()*, *write()*, *open()*, *close()*, *fsetxattr()*, *poll()*, *select()*, *pipe()*, *fcntl()*, *epoll_create()*, *epoll_wait()*...
  - *process*: trace process management system calls
    - *fork()*, *clone()*, *exit_group()*, *execve()*, *wait4()*, *unshare()*...
  - *network*: trace network-related system calls
    - *socket()*, *bind()*, *listen()*, *connect()*, *sendmsg()*...
  - *memory*: trace memory-mapping-related system calls
    - *mmap()*, *mprotect()*, *mlock()*...

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Filtering signals

- *strace –e signal=set*
  - Trace only specified set of signals
  - “sig” prefix in names is optional; following are equivalent:

```
$ strace -o strace.log -e signal=sigio,int ls > /dev/null
$ strace -o strace.log -e signal=io,int ls > /dev/null
```

- *strace –e signal=!set*
  - Exclude specified signals from tracing

Filtering by pathname

- *strace –P pathname*: trace only system calls that access file at *pathname*
    - Specify multiple *–P* options to trace multiple paths
- Example:

```
$ strace -o strace.log -P /lib64/libc.so.6 ls > /dev/null
Requested path ’/lib64/libc.so.6’ resolved into
  ’/usr/lib64/libc-2.18.so’
$ cat strace.log
open("/lib64/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\3\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0p\36
  \2\0\0\0\0\0"..., 832) = 832
fstat(3, {st_mode=S_IFREG|0755, st_size=2093096, ...}) = 0
mmap(NULL, 3920480, PROT_READ|PROT_EXEC,
  MAP_PRIVATE|MAP_DENYWRITE, 3, 0) = 0x7f8511fa3000
mmap(0x7f8512356000, 24576, PROT_READ|PROT_WRITE,
  MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x1b3000)
  = 0x7f8512356000
close(3)                                = 0
+++ exited with 0 +++
```

    - *strace* noticed that the specified file was opened on FD 3, and also traced operations on that FD

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Obtaining a system call summary

- *strace –c* counts time, calls, and errors for each system call and reports a summary on program exit

```
$ strace -c who > /dev/null
% time     seconds  usecs/call     calls    errors syscall
------ ----------- ----------- --------- --------- --------------
 21.77    0.000648           9        72           alarm
 14.42    0.000429           9        48           rt_sigaction
 13.34    0.000397           8        48           fcntl
  8.84    0.000263           5        48           read
  7.29    0.000217          13        17         2 kill
  6.79    0.000202           6        33         1 stat
  5.41    0.000161           5        31           mmap
  4.44    0.000132           4        31         6 open
  2.89    0.000086           3        29           close
  2.86    0.000085          43         2           socket
  2.82    0.000084          42         2         2 connect
...
------ ----------- ----------- --------- --------- --------------
100.00    0.002976                   442        13 total
```

Tracing live processes

- *–p PID*: **trace running process** with specified PID
    - Type *Control-C* to cease tracing
    - To **trace multiple processes**, specify *–p* multiple times
    - Can only trace processes you own
    - ⚠ tracing a process can **heavily affect performance**
        - E.g., two orders of magnitude
        - Think twice before using in a production environment
- *–p PID -f*: will **trace all threads** in specified process

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Further *strace* options

- *–v*: don't abbreviate arguments (structures, etc.)
  - Output can be quite verbose...
- *–s strsize*: maximum number of bytes to display for strings
  - Default is 32 characters
  - Pathnames are always printed in full
- Various options show start time or duration of system calls
  - *–t*, *–tt*, *–ttt*, *–T*
- *–i*: print value of instruction pointer on each system call

Thanks!

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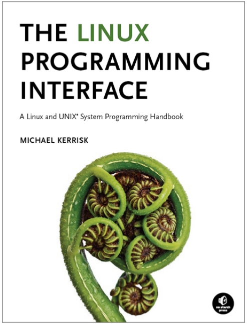
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