Userspace live patching with Libpulp

Gabriel F. T. Gomes

gagomes@suse.de
gabriel@inconstante.net.br

Agenda

- Introduction
- Basics
- Live demo
- Details
- How to get started
- Contributing
- Q&A
- More details

Introduction

- Kernel live patching
- Program classes
- Shared libraries
  - Application-Library boundary
    - Two tracking methods
  - Program consistency

Basic operation

(function prologues with -fpatchable-function-entry)

Before patching

```
<function-22> : nop
<function-21> : nop
...
<function-1>  : nop
<function>    : nop (2-bytes)
<function+2>  : ...
```

After patching

```
<function-22> : push %rdi
<function-21> : mov  $0x17,%rdi
<function-14> : jmpq *0x0(%rip)[1]
<function-8>  : <data>
<function>    : jmp  <function-22>
<function+2>  : ...
```

[1] replaced with the runtime address of the version handling routine

How to change memory?

- ptrace(2)
  - PTRACE_ATTACH (to all threads)
  - Steal the context of a thread to run Libpulp functions
  - Restore the context
  - PTRACE_DETACH (from all threads)
  - PS: Like GDB does

Libpulp functions

- Provided by libpulp.so
- *Executed* from Libpulp's tools
  - ulp_trigger, ulp_check, etc.
  - The tools ptrace into the target process.

In a nutshell

- Start a process with livepatching support:

```
$ LD_PRELOAD=libpulp.so program

$ echo $(pidof program)
123
```

- Use the tools to attach to the process:

```
$ ulp_check -p 123 livepatch.ulp
ulp: patch not yet applied

$ ulp_trigger -p 123 livepatch.ulp
ulp: live patching succeeded

$ ulp_check -p 123 livepatch.ulp
ulp: patch already applied
```

Real-world example (not so real)

Pause for live demo
(backup slides available)

Real World Testing (backup slide)

```
# LD_PRELOAD=/usr/lib64/libpulp.so.0 /usr/sbin/nginx
[1] 1234
libpulp loaded...

# nmap –script=ssl-heartbleed -p 443 localhost
...
PORT    STATE SERVICE
443/tcp open  https
| ssl-heartbleed:
|   VULNERABLE:
|   The Heartbleed Bug is a serious vulnerability ...
```

Real World Testing (backup slide)

```
# ulp_trigger 1234 /usr/lib64/openssl-1_1-livepatches/heartbleed.ulp
Ulp: Patching 1234 successful.

# nmap –script=ssl-heartbleed -p 443 localhost
... (longer than before)
PORT    STATE SERVICE
443/tcp open  https

Nmap done: 1 IP address (1 host up) scanned in 5 seconds
```

Real World Testing - Heartbleed

- Buggy functions:
  - dtls1_process_heartbeat
  - tls1_process_heartbeat
- Luckily, very simple:
  - Only two functions
  - Leaf functions

Anatomy of a live patch

- Live patch source example:

```
#include <stdio.h>
void function_new(void) {
    printf("patched\n");
}
```

- Build as a library:

```
$ gcc livepatch.c -shared -fPIC -o livepatch.so
```

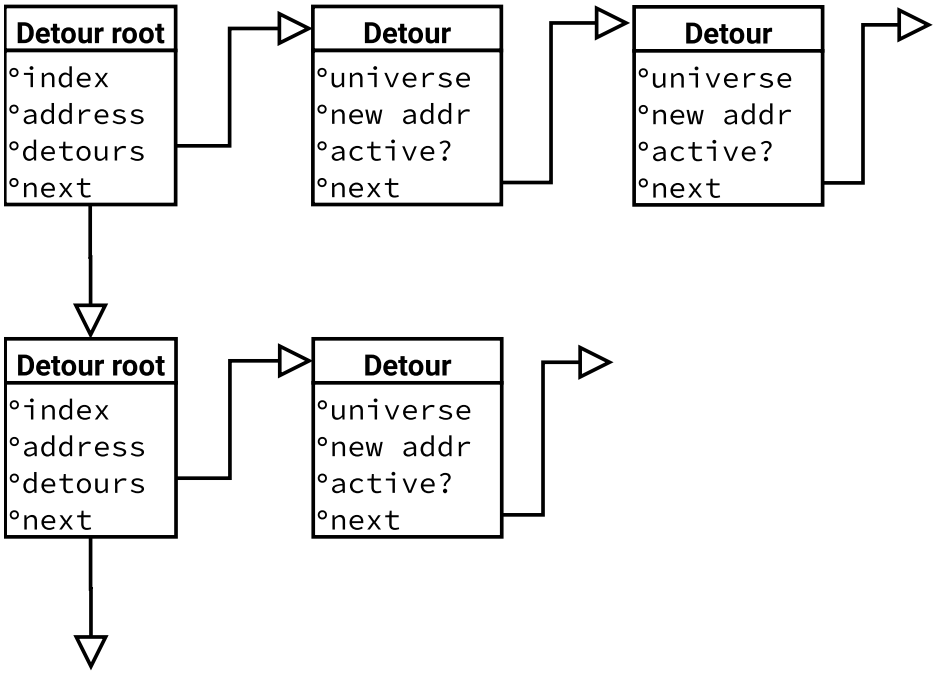
Anatomy of a live patch

- Metadata file (.ulp)
  - Built from a description file:

```
1. /path/to/livepatch.so
2. @/path/to/target/library.so
3. function:function_new
4. function_2:new_function_2
```

- Live patch DSO
- List of replacement functions

Version handling routines



- Vertically: functions
- Horizontally: versions

How to get started - too late? ;P

```
$ git clone git@github.com:SUSE/libpulp.git
$ ./bootstrap [1]
$ ./configure [2]
$ make
$ make check
```

Notes

1. needs autoconf, automake and libtool
2. missing requirements should produce useful warnings

Please report bugs! :) S2

Test cases

```
XFAIL: blocked.py
PASS: syscall_restart.py
PASS: pagecross.py
PASS: parameters.py
PASS: asunsafe_conversion.py
PASS: constructor.py
XFAIL: hidden.py
PASS: numserv_bsymbolic.py
PASS: memory_protection.py
PASS: numserv.py
PASS: exception_handling.py
PASS: revert.py
XFAIL: contract.py
PASS: redzone.py
PASS: cancel.py
PASS: terminal.py
PASS: deadlock.py
PASS: recursion.py
```

Please report bugs! :) S2

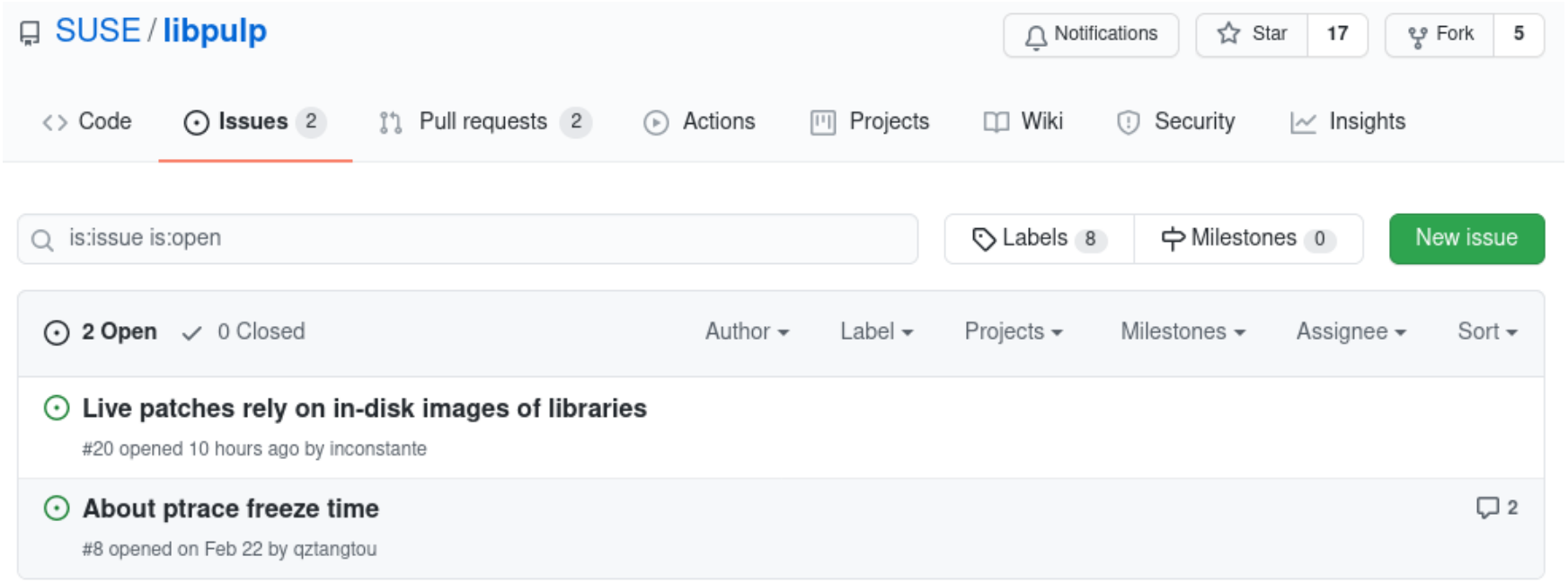
Project structure

- lib
  - Runtime support (libpulp.so)
- tools
  - Command-line tools (ulp_trigger, ulp_check, etc.)
  - Process introspection (Elf, ptrace)
- tests
  - Python’s pexpect
  - Live patches
- man
  - Documentation

Contributing

- https://github.com/SUSE/libpulp
  - Issues, pull requests (CI tested)
- ulp-devel@opensuse.org
  - https://lists.opensuse.org/archives/list/ulp-devel@lists.opensuse.org
- README.md
  - Just guidelines

Contributing



Thanks!

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Backup slides

Asynchronous signal safety

- AS-Unsafe functions in use:
  - dlopen
  - dlsym
  - calloc
- Problems
  - Deadlocks during live patch application
  - AS-Unsafe conversion during regular execution

Deadlocks

Due to malloc locks

```
(gdb) bt
#0  0x00007f2622e54e37 in __lll_lock_wait_private () from /lib64/libc.so.6
#1  0x00007f2622e5b2a3 in calloc () from /lib64/libc.so.6
#2  0x00007f2622fbeb18 in _dlerror_run () from /lib64/libdl.so.2
#3  0x00007f2622fbe2e4 in dlopen@@GLIBC_2.2.5 () from /lib64/libdl.so.2
#4  0x00007f2622fcc780 in load_so () at /root/src/libpulp/lib/ulp.c:463
#5  0x00007f2622fcb99a in load_so_handlers () at /root/src/libpulp/lib/ulp.c:264
#6  0x00007f2622fcc751 in parse_metadata () at /root/src/libpulp/lib/ulp.c:454
#7  0x00007f2622fcbaff in load_metadata () at /root/src/libpulp/lib/ulp.c:304
#8  0x00007f2622fcc7dc in load_patch () at /root/src/libpulp/lib/ulp.c:478
#9  0x00007f2622fcb628 in __ulp_apply_patch () at /root/src/libpulp/lib/ulp.c:99
#10 0x00007f2622fce542 in __ulp_trigger () at /root/src/libpulp/lib/ulp_interface.S:44
#11 0x00007f2622f8f7e0 in ?? () from /lib64/libc.so.6
#12 0x00007ffe1ce89930 in ?? ()
#13 0x00007f2622f8f7e0 in ?? () from /lib64/libc.so.6
#14 0x0000000000000000 in ?? ()
```

Deadlocks

Due to dlfcn locks

```
(gdb) bt
#0  0x00007fbc87fb3f5c in __lll_lock_wait () from /lib64/libpthread.so.0
#1  0x00007fbc87fac8f1 in pthread_mutex_lock () from /lib64/libpthread.so.0
#2  0x00007fbc87ff5b06 in _dl_open () from /lib64/ld-linux-x86-64.so.2
#3  0x00007fbc87fc9258 in dlopen_doit () from /lib64/libdl.so.2
#4  0x00007fbc87f14960 in _dl_catch_exception () from /lib64/libc.so.6
#5  0x00007fbc87f14a1f in _dl_catch_error () from /lib64/libc.so.6
#6  0x00007fbc87fc9a65 in _dlerror_run () from /lib64/libdl.so.2
#7  0x00007fbc87fc92e4 in dlopen@@GLIBC_2.2.5 () from /lib64/libdl.so.2
#8  0x00007fbc87fd7780 in load_so () at /root/src/libpulp/lib/ulp.c:463
#9  0x00007fbc87fd699a in load_so_handlers () at /root/src/libpulp/lib/ulp.c:264
#10 0x00007fbc87fd7751 in parse_metadata () at /root/src/libpulp/lib/ulp.c:454
#11 0x00007fbc87fd6aff in load_metadata () at /root/src/libpulp/lib/ulp.c:304
#12 0x00007fbc87fd77dc in load_patch () at /root/src/libpulp/lib/ulp.c:478
#13 0x00007fbc87fd6628 in __ulp_apply_patch () at /root/src/libpulp/lib/ulp.c:99
#14 0x00007fbc87fd9542 in __ulp_trigger () at /root/src/libpulp/lib/ulp_interface.S:44
```

Deadlocks

- Take 1 (exposing internal state of locks in glibc):
  - `__libpulp_dlopen_checks`
  - `__libpulp_malloc_checks`
- Take 2 (interpose glibc functions)
  - malloc, calloc, memalign, free, etc.
  - dlopen, dlsym, etc.

Consistency checks

- Process hijacking
- Live patch application
  - Loads live-patch DSO (dlopen and friends)
  - Needs memory (malloc and friends)
- Early checking of all threads
- ~~Per-thread universe counter updates~~

Consistency checks

```
ulp: beginning live patch application.
ulp: advertising live patch location to libpulp.
ulp: >>> running libpulp functions within target process...
ulp: >>> done.
ulp: libc/libdl locks were busy: patch not applied.
ulp: live patching 192846 failed (attempt #1).
ulp: exiting the critical section (process release).
```

AS-Unsafe conversion

- Universe handling routines
  - Executed between call and actual target function
    - Similar to how the C runtime resolves function addresses
      - e.g.: `call strdup → strdup@plt → _dl_*`
      - Calls are allowed: but not AS-Unsafe functions.
  - May not call AS-Unsafe functions
    - Otherwise, live patched functions become AS-Unsafe

Memory protection bits

- Patch prologues in executable segments
- Make segment writable
  - Tweak protection bits
  - Write to the memory
  - w^x violation?
    - All threads stopped (ptraced)
- Respect user settings

Patching Prologues

- Granularity
  - Concurrent execution?
    - All threads stopped under ptraced (like gdb)
    - 2-bytes nops at <function..function+1>
- Page crosses
  - Silent seg fault (under ptrace).

```
void patch_prologue(void *old_fentry, unsigned int function_index)
{
  memcpy(old_fentry, ulp_prologue, sizeof(ulp_prologue));
  memcpy(old_fentry + 4, &function_index, 4);
}
```

Stack frame stealing

Regular call

```
Call site:
0x1234  call fn
0x1239  ...

Stack:
      0x1239
%rsp: ...
```

Call through tracker

```
Call site:
0x1234  call fn
0x1239  ...

Tracker (__ulp_entry):
0x4321  pop area@TLS
0x4322  call %r11 <target fn>
0x4323  ...
0x5000  push area@TLS
0x5001  ret

Stack:
      0x4323
%rsp: ...
```

Stack frame stealing

- Breaks unwinding:

```
(gdb) bt
#0  0x00007f9414e9714f in hello () from libblocked.so.0
#1  0x00007f9414e9718a in hello_loop () at libblocked.c:37
#2  0x00007f9414e97248 in __ulp_entry () at trm.S:153
Backtrace stopped: frame did not save the PC
```

Stack unwinding

- Thread cancellation
- Exception handling
- Upheaval in consistency checking
  - No more tracking
  - No more stealing of stack frames
  - Pushes the burden onto live patch creation

Red zone

- Signal handler
- Hijacking
  - `PTRACE_GETREGS`
  - Modify `%rip`
  - `PTRACE_SETREGS`
  - What about `%rsp`?

Library entrance tracking

- Non-standard glibc function:
  - `__libpulp_tls_get_addr`
  - Less pushing and popping of regs

Library entrance tracking

```
#ifndef HAVE___LIBPULP_TLS_GET_ADDR
pushq   %r10
pushq   %r9
pushq   %r8
pushq   %rsi
pushq   %rdx
pushq   %rcx
#endif
pushq   %rdi
pushq   %rax
leaq    __ulp_ret@tlsld(%rip), %rdi
#ifndef HAVE___LIBPULP_TLS_GET_ADDR
call    __tls_get_addr@PLT
#else
call    __libpulp_tls_get_addr@PLT
#endif
```

Universe counters

- Global counter (one)
  - per process
- Local counters (many)
  - per thread
  - per library

Local counter update

```
leaq __ulp_ret@tlsld(%rip), %rdi
call __tls_get_addr@PLT [1]
cmp  $0x0, __ulp_ret@dtpoff(%rax)
jnz  __ulp_entry_bypass
movq __ulp_global_universe@GOTPCREL(%rip), %rdi
movq %rdi, __ulp_thread_universe@dtpoff(%rax)
```

[1] source of overhead

Multiple libraries

Before

```
.weak   __ulp_global_universe
.section .data
.type __ulp_global_universe, @object
.size __ulp_global_universe, 8
__ulp_global_universe:
.zero 0x8
```

After

```
.weak   __ulp_global_universe
```

No local definition

Multiple libraries

```
+// Check if the address of the global counter has been filled in the
+// GOT entry during initialization (only happens when libulp.so has
+// been LD_PRELOAD'ed).  In case it has, read the contents.
+// Otherwise, the uninitialized value, zero, can be used directly.
 movq    __ulp_global_universe@GOTPCREL(%rip), %rdi
+test    %rdi, %rdi
+jz      __ulp_thread_counter_update
 movq    (%rdi), %rdi
+__ulp_thread_counter_update:
 movq    %rdi, __ulp_thread_universe@dtpoff(%rax)
```