Instrumenting, Introspection, and Debugging with QEMU

Pavel Dovgalyuk

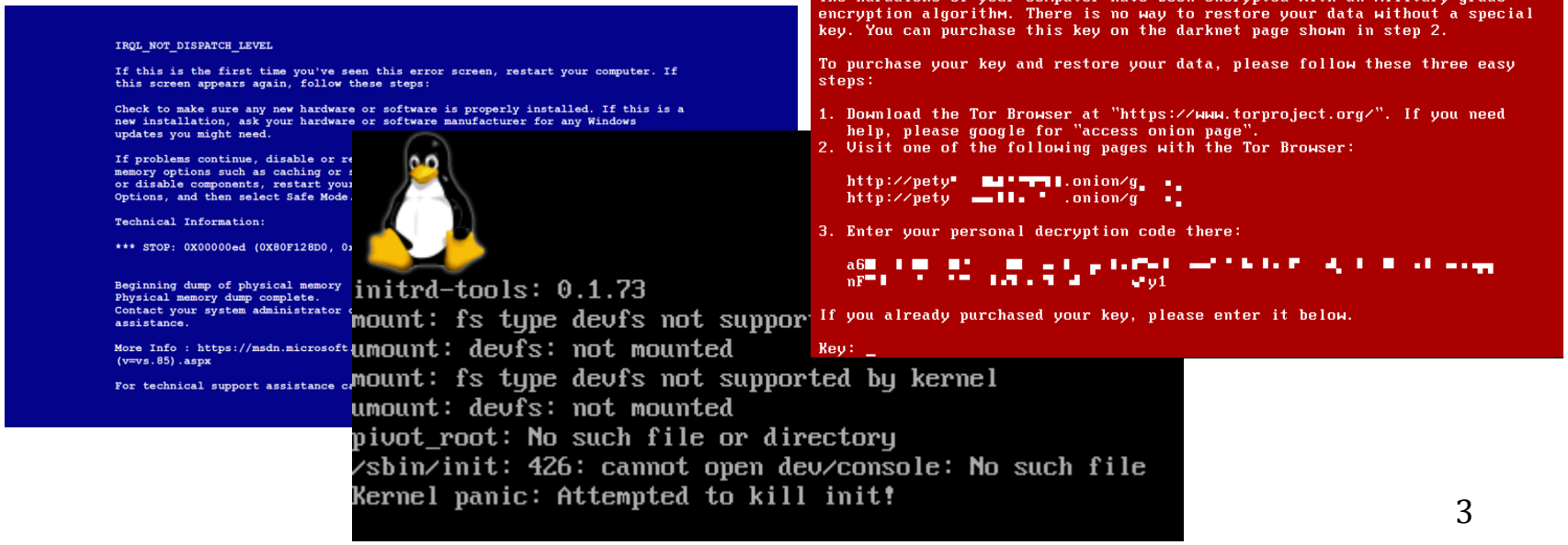
Institute for System Programming
of the Russian Academy of Sciences

Our projects

- Working on QEMU projects since 2010 (version 0.13)
- Software analysis for x86
- Deterministic replay
- Reverse debugging
- Now working on introspection and debugging projects

In-VM software development and debugging

- Creating new kernels/drivers
- Simulating new platforms
- Reverse engineering



Logging from QEMU

-d in_asm,exec,nochain

```
IN:
0x000ef407:  lea    0x1(%esi),%eax
0x000ef40a:  mov    %eax,0x4(%esp)
0x000ef40e:  jmp    0xef1c6

Trace 042113a0 [0: 000ef407]
Trace 04211450 [0: 000ef1c6]
Trace 04210f20 [0: 000ef1d5]
Trace 04210f90 [0: 000ef278]
Trace 04211040 [0: 000eda1b]
Trace 04211170 [0: 000eda10]
Trace 042112c0 [0: 000eda22]
```

Analyzing dumps with Volatility

- Scripts to extract information from the dumps
- Only static analysis

```
$ python vol.py -f win7.vmem --profile=Win7SP1x86 pslist Volatility
Foundation Volatility Framework 2.4
Offset(V) Name PID PPID Thds Hnds Sess Wow64 Start Exit
0x84133630 System 4 0 93 420 ------ 0 2011-10-20 15:25:11 UTC+0000
0x852add40 smss.exe 276 4 4 29 ------ 0 2011-10-20 15:25:11 UTC+0000
0x851d9530 csrss.exe 364 356 9 560 0 0 2011-10-20 15:25:15 UTC+0000
0x859c8530 wininit.exe 404 356 7 88 0 0 2011-10-20 15:25:16 UTC+0000
0x859cf530 csrss.exe 416 396 10 236 1 0 2011-10-20 15:25:16 UTC+0000
   [snip]
```

GDB

- Remote debugging
- Can load binaries and sources to get debug information
  - Not very easy with enabled ASLR
- Guest system is executed as a single program
- Process information is not available
- Cannot break on interrupts/exceptions and other events
- Single-stepping may change the execution result

Deterministic and reverse debugging

- It's gonna take you back to the past
- icount for deterministic timers
- VM snapshots for faster rewind to the desired moment of execution
- GDB reverse debugging commands
  - reverse-continue, step, next, finish
- Still work-in-progress for mainline QEMU

GDB protocol

- GDB interacts with QEMU using complex packets
- Conditional breakpoints lead to many VM stops and debugger-QEMU communication
  - stop, request registers, recover the context, evaluate equation, continue execution
- Very slow for runtime analysis
  - Using conditional breakpoints inside the inner loops is not practical

WinDbg

- Support stealth Windows debugging with WinDbg
- More information than in GDB
- Communication is also slow

- Submitted to qemu-devel
- https://github.com/ispras/qemu/tree/windbg

QEMU API for analysis

- Instrumenting guest or TCG code
- Callbacks for memory accesses, MSR/CR changes, and interrupts
- Memory and CPU state query interface

- Communication is faster than GDB, WinDbg, QMP, …

QEMU-based dynamic analysis frameworks

- PyREBox
- PANDA
- DECAF
- ISP RAS
- and other less mature systems

PyREBox

- PyREBox – Python scriptable Reverse Engineering sandbox
- QEMU 2.10
- Uses Volatility memory forensics
- Python scripting for automated analysis

- https://github.com/Cisco-Talos/pyrebox/

PANDA

- Platform for Architecture-Neutral Dynamic Analysis
- QEMU 2.8.50
- VM introspection plugins
- Taint analysis
- CPU record-replay

- https://github.com/panda-re/panda

DECAF

- Dynamic Executable Code Analysis Framework
- QEMU 1.0
- VM introspection plugins
- Taint analysis

- https://github.com/sycurelab/DECAF

ISP RAS

- Our own approach
- QEMU 2.8.50
- Subsystem for dynamically loaded plugins
- Plugins for syscall and API logging in i386 Windows/Linux
- https://github.com/ispras/qemu/tree/plugins

Requirements for QEMU analysis API

- Translation events
- Memory operation events
- Execution events
- Exception events
- Disk and DMA events
- Keyboard and network events
- TLB events
- Monitor commands

Instruction instrumentation

- Instrument at translation – check whether callback is needed
  - Specific instructions
  - Specific addresses
  - Specific process
- Get callbacks at execution

Instruction instrumentation

```
0xb7707010: mov %ebx,%edx
0xb7707012: mov 0x8(%esp),%ecx
0xb7707016: mov 0x4(%esp),%ebx
0xb770701a: mov $0x21,%eax
0xb770701f: int $0x80
```

```
---- b770701f 00000000
movi_i64 tmp13,$0xb7707020
movi_i64 tmp14,$0x7fef9a788670
call start_system_call, $0x0,$0,tmp13,tmp14
movi_i32 tmp3,$0xfffffffffb770701f
st_i32 tmp3,env,$0x20
movi_i32 tmp11,$0x2
movi_i32 tmp12,$0x80
call raise_interrupt, $0x0,$0,env,tmp12,tmp11
set_label $L0
exit_tb $0x7fef8e6dca13
```

Instruction instrumentation requirements

- Translation callback
  - cpu, pc, tcg_ctx
- Memory read function
- TCG functions
  - variable allocation, code generation

TCG Instrumentation

- Platform-independent instrumentation
- Used for taint analysis in DECAF and PANDA
- Not complete because of helpers
  - PANDA instruments them with LLVM

Memory accesses instrumentation

- Memory ops performed through softmmu-callbacks and translated code
  - From cpu_ldst_template.h – invoke the callback
  - From tcg_op.c – embed the callback into TB
- Memory forensics through exported load functions

Memory accesses instrumentation

- Logging
- Cache simulator
- Forensics
- Anomalies detection

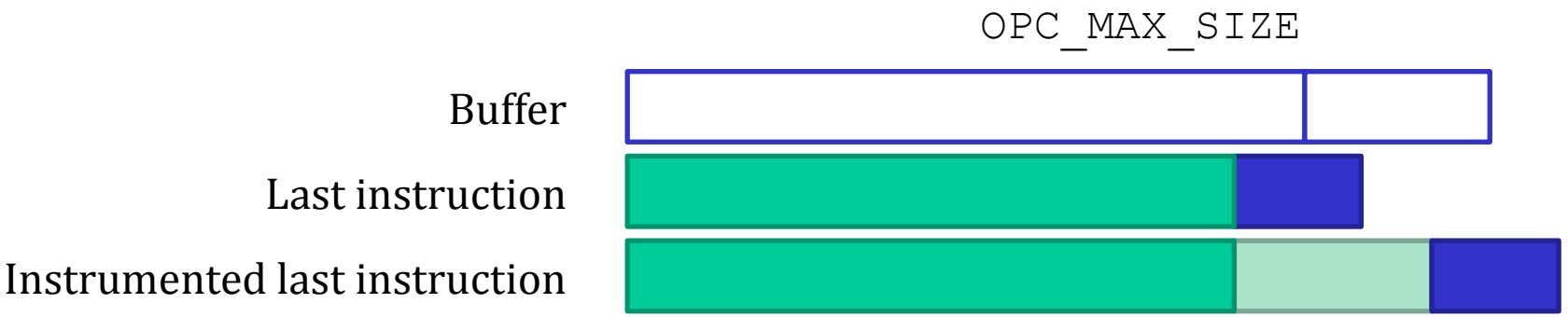
Memory log sample

```
Load 0x84@8 virt:ef1cd phys:ef1cd
Load 0xd2@8 virt:ef1ce phys:ef1ce
Load 0xf@8 virt:ef1cf phys:ef1cf
Load 0x84@8 virt:ef1d0 phys:ef1d0
Load 0x23e@32 virt:ef1d1 phys:ef1d1
---------------
IN:
0x000ef1c6:  mov    0x4(%esp),%esi
0x000ef1ca:  movsbl (%esi),%edx
0x000ef1cd:  test   %dl,%dl
0x000ef1cf:  je     0xef413

Trace 043b1450 [0: 000ef1c6]
Load 0xf357d@32 virt:6fa4 phys:6fa4
Load 0x65@8 virt:f357d phys:f357d
```

Generated code problems

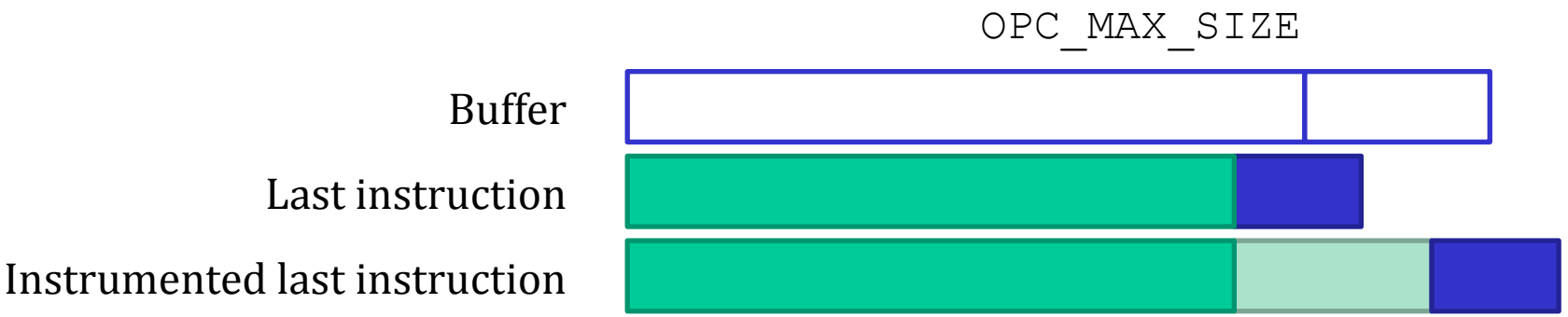
- TCG buffer overflow protection is weak




```
#define MAX_OPC_PARAM (4 + (MAX_OPC_PARAM_PER_ARG *
   MAX_OPC_PARAM_ARGS))
#define OPC_BUF_SIZE 640
#define OPC_MAX_SIZE (OPC_BUF_SIZE - MAX_OP_PER_INSTR)
```

Generated code problems

/* XXX: make safe guess about sizes */




```
#define MAX_OPC_PARAM (4 + (MAX_OPC_PARAM_PER_ARG *
   MAX_OPC_PARAM_ARGS))
#define OPC_BUF_SIZE 640
#define OPC_MAX_SIZE (OPC_BUF_SIZE - MAX_OP_PER_INSTR)
```

Interrupts and exceptions

- Only asynchronous callbacks
- Logging peripheral interrupts
- Detecting page mapping

Instrumentation applications

- Logging syscalls
- Logging API
- Logging memory accesses
  - for cache simulator
  - for complementing in_asm+exec log
- Building more complex introspection tools

QEMU instrumentation API

- 10+ attempts to add instrumentation API
- Does it have to be included into mainline?
- QEMU interface may be very narrow
  - ~20 callbacks
  - ~50 exported functions