Bochspwn: Identifying 0-days via system-wide memory access pattern analysis

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Agenda

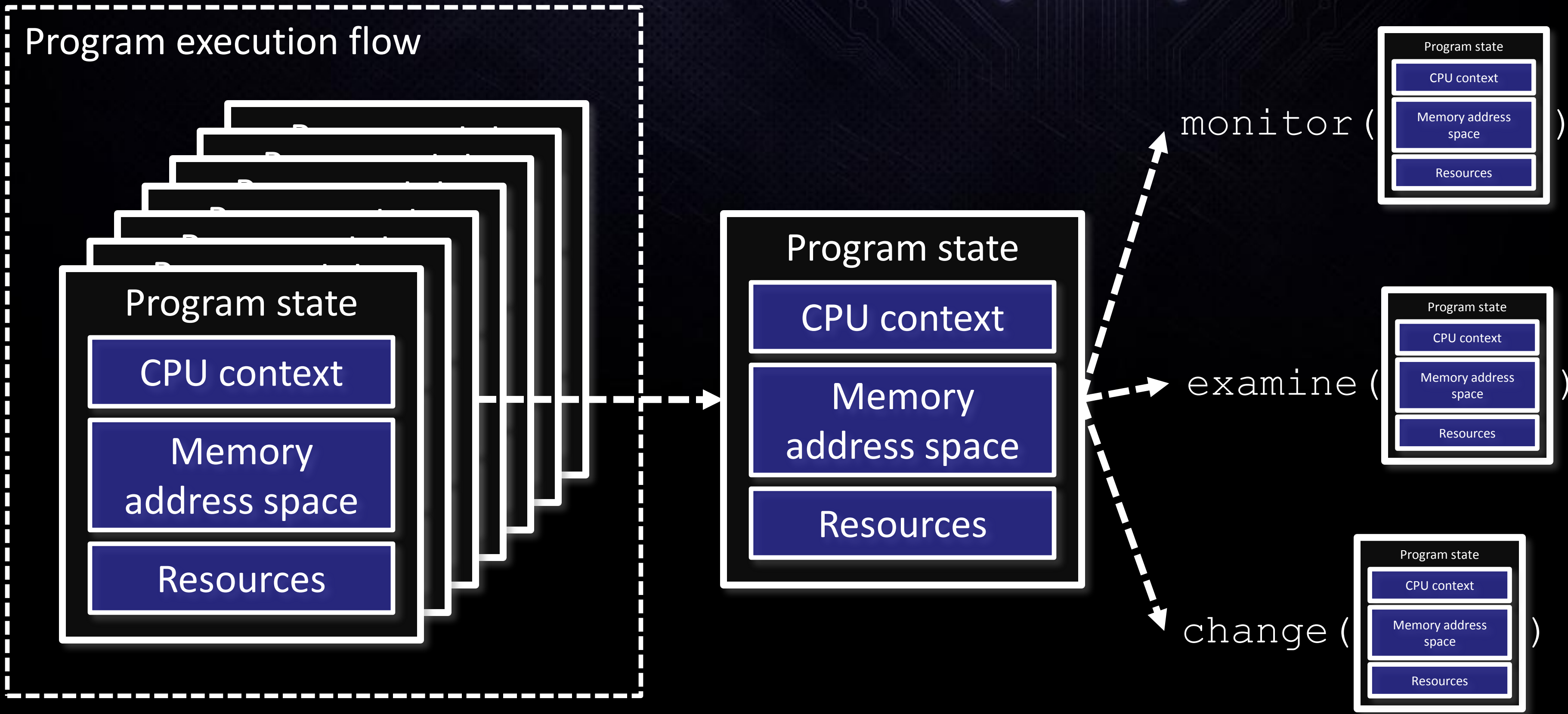
- Software instrumentation in security
  - what? why? how?
  - what about kernels?
- Bochspwn and double fetches
  - Microsoft Windows
  - Linux
  - BSD
- Other projects
  - Bochspwn:msan sneak peek
- Future work

D E M O

WINDOWS 7 SP1 32-BIT ELEVATION OF PRIVILEGES

SOFTWARE INSTRUMENTATION TRIVIA

The basics of instrumentation



Important points

- Instrumentation only operates on existing program states.
  - doesn’t generate new ones, we can only „feed” it.
  - the pros: can reason about real software behavior and identify real bugs.
  - the cons: limited to actual code coverage.
- We end up with two separate problems
  - the more different states
  - the better instrumentation

the more knowledge about program logic

Existing technology

- User-mode instrumentation widely spread nowadays
  - DBI
    - extensible frameworks: Intel Pin, DynamoRIO
    - run-time program verification projects: the valgrind suite, Microsoft Application Verifier
  - compile-time solutions
    - {Address, Memory, Thread} Sanitizer
    - IOC
    - gprof
    - stack / heap protectors are kind of, too.

Known applications in security

- Code coverage analysis
  - corpus distillation, exploring program state tree, various "smart fuzzing" techniques
- Detection of security-relevant conditions
  - memory corruption, out-of-bounds access (ASan, valgrind)
  - dynamic allocator issues, e.g. double free (ASan, valgrind)
  - use of uninitialized memory (MSan, valgrind)
  - data races (TSan, valgrind)
  - integer overflows (IOC)
  - API misuse (AppVerifier)

Known applications in security

- Fault injection
  - stability testing, e.g. failing every n^{th} allocation (AppVerifier)
  - in-memory fuzzing
- Detection of active exploitation (malware pipelines)
  - running code outside of executable images and JIT regions → shellcode indicator
  - no CALL before RETN → ROP indicator
  - etc.

Results in examples

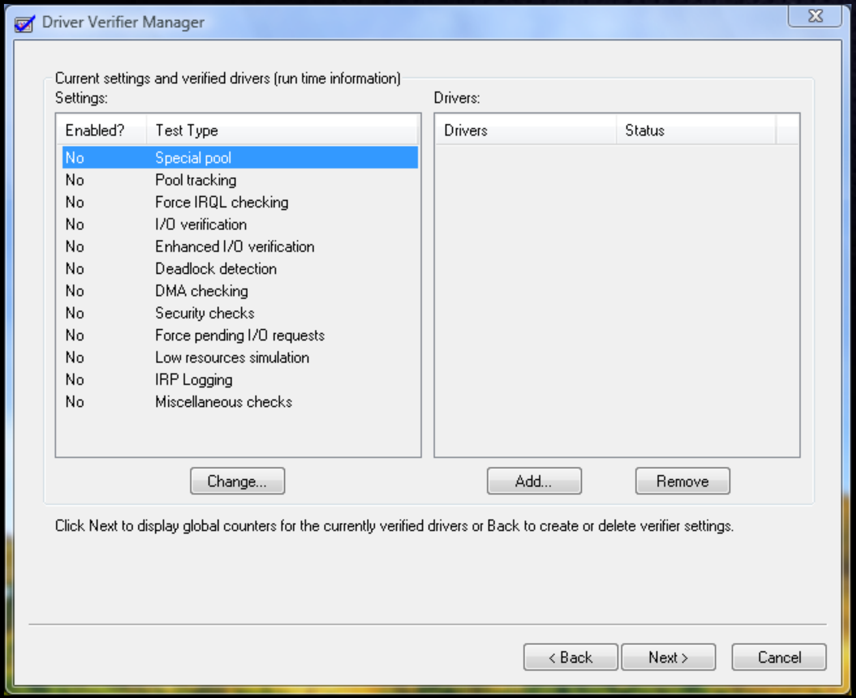
- Coverage-based corpus distillation helped Google find tons of bugs
  - proprietary: Adobe Flash, Adobe Reader, Chrome PDF Reader, ...
  - open-source: FFmpeg, FreeType2, libexif, libtiff, ...
- AddressSanitizer contributed, too:
  - 1000+ vulnerabilities in Chromium, WebKit, Mozilla, webrtc, Perl, PHP, ...
- Too many to list them all.

If it works so well…

… why not apply it to whole operating system kernels instead of individual programs?

e.g. for vulnerability discovery.

Well, there is something…



Driver Verifier

- Microsoft tool.
- Tests device drivers for common mistakes.
- Limited subset of detectable bad states.
  - mostly API misuse.

Not much beyond it, though (for Windows at least).

NOT ENOUGH.

(feels like a highly underestimated potential)

Motivation

- If there is a buffer overflow or double free(), the kernel will crash anyway...

but

- It turns out there are a number of vulnerability classes which don't explicitly manifest themselves in the kernel.
  - even though they're triggered all the time.
- We could detect them!

Motivation (cont'd)

- Kernels do have vulnerabilities.
  - mostly local (elevation of privileges)
  - these are becoming an important component in remote exploit chains (sandbox escapes)
- Kernel-wide instrumentation is a largely unexplored area.
- Vulnerability hunting automation is cost effective.
  - especially for bugs otherwise difficult to find with manual auditing.

Approach: extending fuzzing

- Normally, `is_violation()` would be `is_exception()`
  - here, we add several additional checks.
  - memory corruption doesn't always result in immediate crash.
  - smart `is_violation` can pinpoint the precise point of failure.

Approach: extending fuzzing

- For a kernel, program execution flow includes:
  - booting up
  - execution of all active device drivers in addition to the kernel
  - coverage from normal operation (running services, shell etc.)
  - artificially provoked code paths
  - system termination

Detection: cross-platform kernel bugs

- Memory corruption
  - {stack, heap, static} oob {reads, writes}, use-after-free
- Double memory fetch from ring-3
  - (a.k.a. *time-of-check-to-time-of-use*, *tocttou*)
- Use of uninitialized memory
  - stack variables, pool/heap allocations and so forth.
- Copying uninitialized memory to user-mode
  - disclosure of potentially sensitive information processed by the kernel.

Detection: system-specific bugs

Breaking core security assumptions being part of the operating system design or making incorrect ones.

Windows examples:

- Referencing user-mode pointers while "*Previous Mode*" is *KernelMode*.
- Calling *ObReferenceObjectByHandle* with *Type=NULL* in non handle type-agnostic contexts.

Detection: other kernel bugs

In theory, we could target any *wrong* behavior or system state, as long as there is a simple model we can use to detect it.

The simpler the model, the better.

Or just gather information and save it instead of active state examination.

Performance instrumentation

- Regular code coverage techniques can be applied to kernels similarly to client applications.

- Imagine:
  - instrumenting kernel file format parsing for corpus minimization.
    - *win32k.sys* with bitmaps, fonts, metafiles, …
    - *nt* and keyboard layouts.
  - instrumenting *nt* / *win32k.sys* to find coverage improving syscall invocations (paired with a guest ring-3 fuzzer).

Sky is the limit

- All other techniques originating from user-mode also apply.
  - e.g. the implementation of different valgrind utilities could be ported to kernel-mode*

Basically, sky is the limit.

* not necessarily trivial

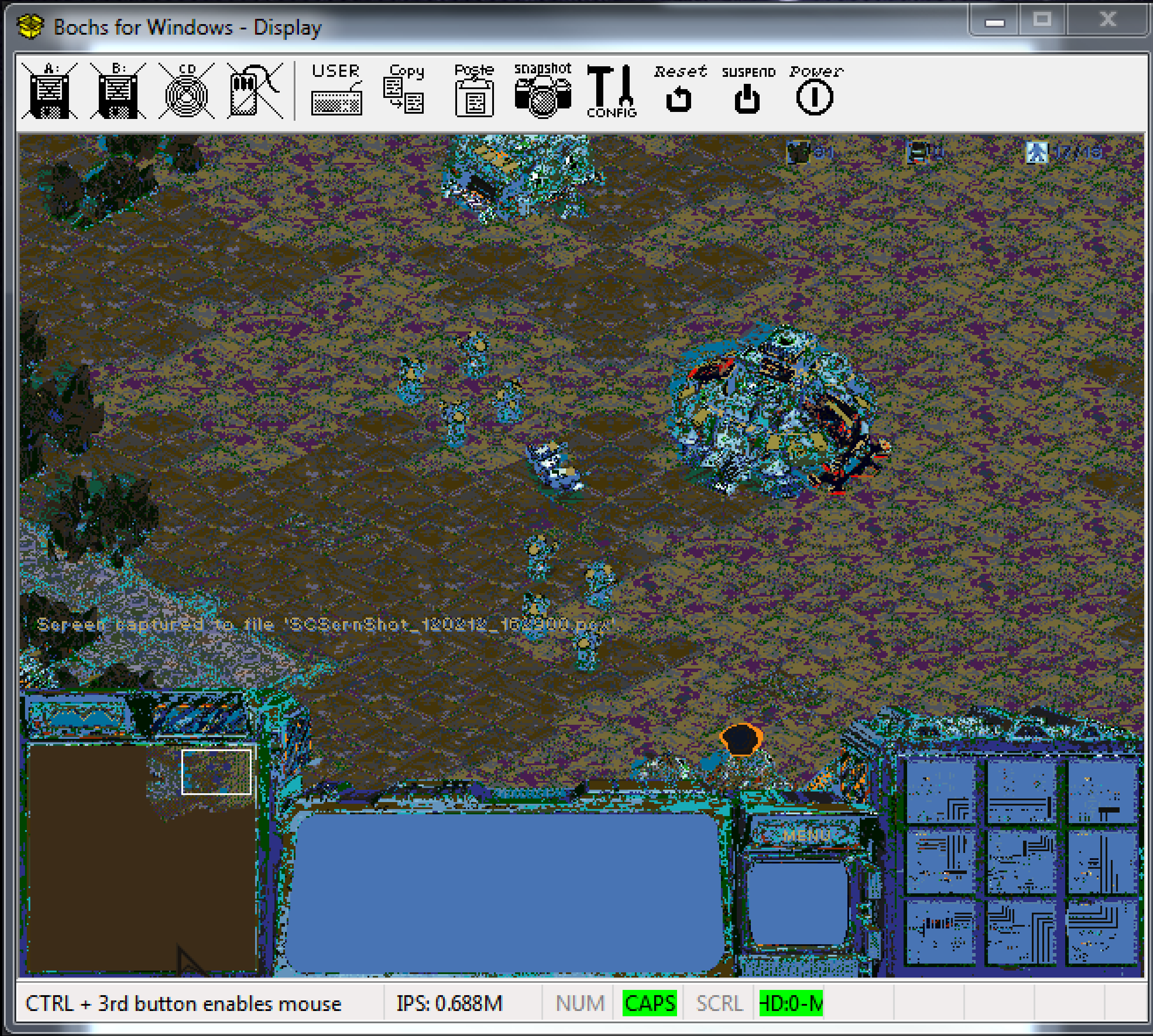
KERNEL INSTRUMENTATION

Initial assumptions

- Instrument software platforms
  - Microsoft Windows
  - Linux
  - FreeBSD, OpenBSD, NetBSD
  - possibly Mac OS X
- Hardware platform: x86 and / or x86-64.
- Instrumentation granularity:
  - per instruction
  - per basic block
  - per memory access
  - per execution of instruction at a specific address („breakpoints”)

How do you instrument?

There are several options.



Bochs for Windows - Display
USER
Copy
Paste
snapshot
CONFIG
Reset
SUSPEND
Power
MENU
CTRL + 3rd button enables mouse
IPS: 0.688M
NUM
CAPS
SCRL
HD:0-M

Software emulators (bochs)

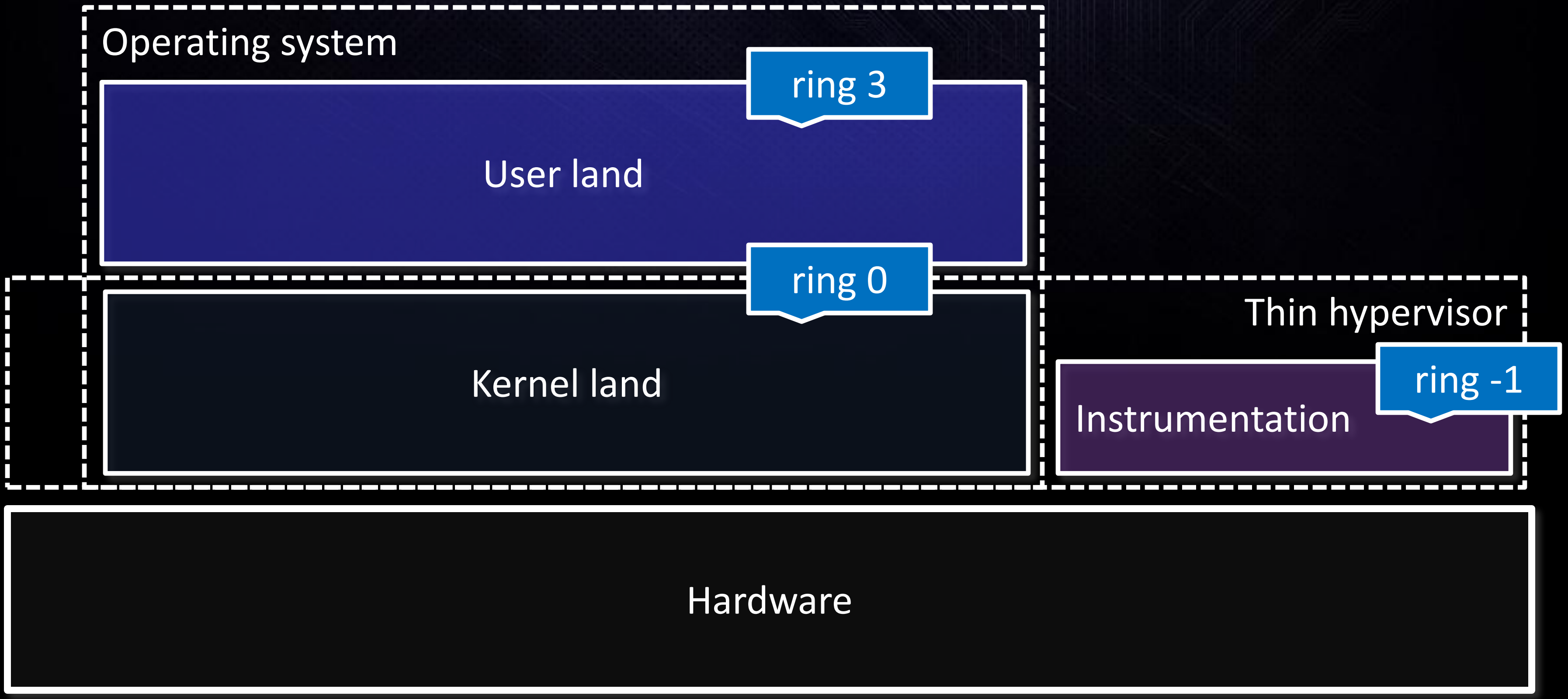
Pros

- Full access to the CPU logic
  - including the ability to change
  - 100% control over the execution environment.
- Ease of development.
- Ease of debugging.

Cons

- Extremely, painfully slow.
- Even slower with additional instrumentation running.
- Limited to virtual (emulated) hardware.

Virtualization: VT-x or SVM



VMM - thin hypervisor

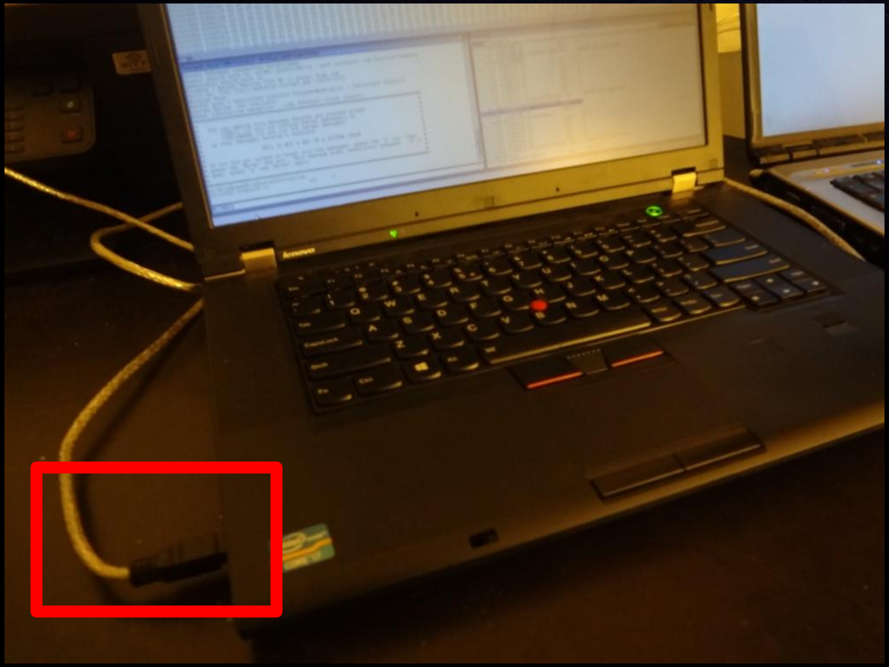
Pros

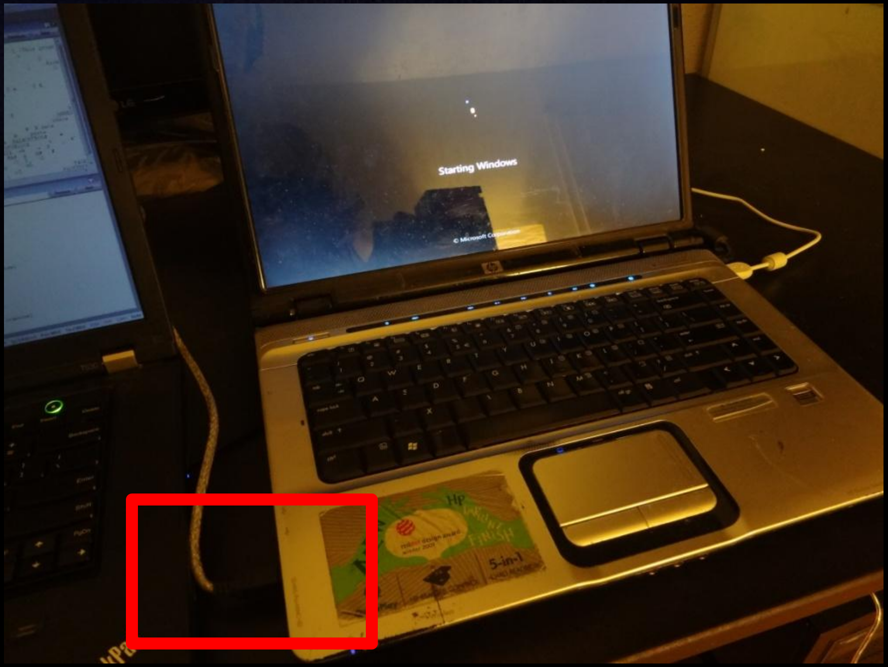
- Extremely low overhead.
  - compared to emulators.
- Running on real hardware (and their device drivers).

Cons

- Tricky implementation.
- Difficult debugging.
- Partially system-specific.
  - e.g. kernel module running the VMM
- CPU-specific.
  - might require at least model “x” from manufacturer “y”
- Limited ability to change CPU logic.

External scripted debugger (e.g. WinDbg via 1394)





External scripted debugger

Pros

- Relatively easy to implement.
  - depending on debugger scripting language. WinDbg + Python is easy.
- Relatively low overhead.
- Real hardware (in case of physical debugging).

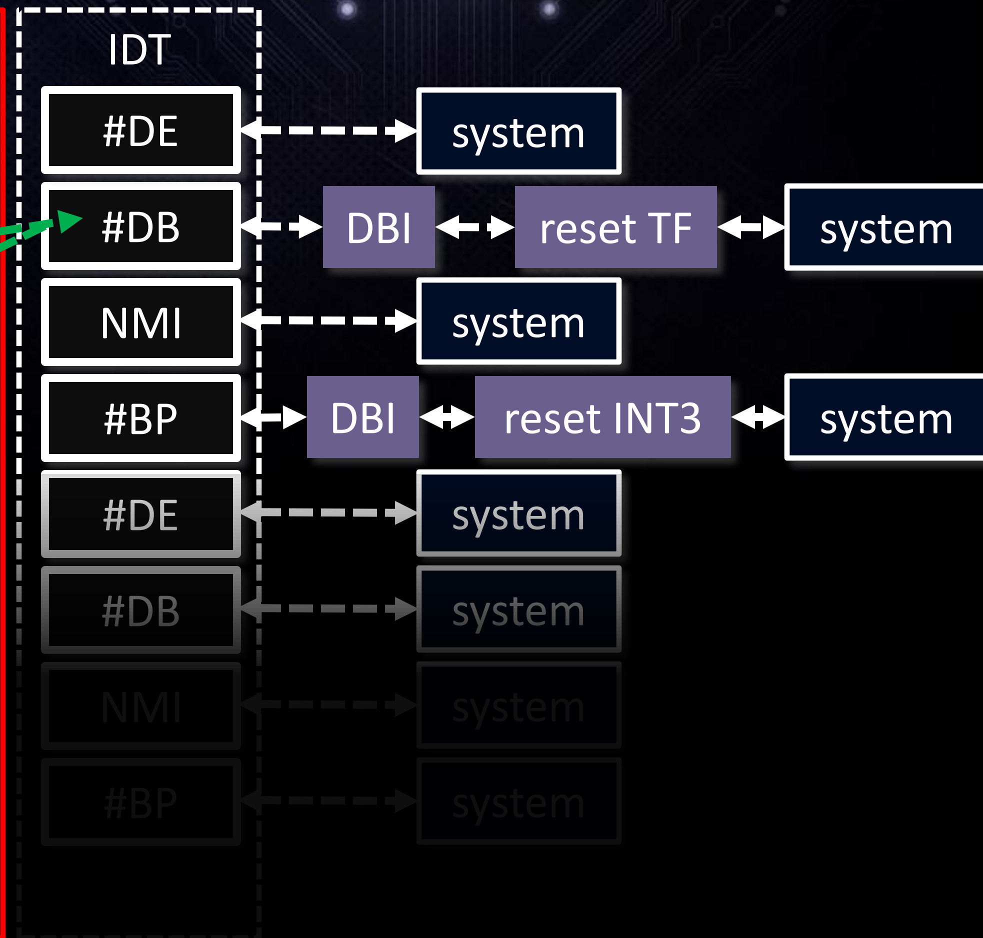
Cons

- Slower than VMM
- System-specific (WinDbg vs kgdb vs ...)
- Limited ability to change the CPU logic.

x86 trap hijacking

Kernel execution flow

```
        ...
mov     edi, edi
push    ebp
mov     ebp, esp
mov     eax, [ebp+arg_0]
mov     edx, [ebp+arg_4]
push    esi
mov     esi, eax
sub     esi, edx
        ...
```



x86 trap hijacking

Pros

- Low overhead.
- Real hardware.
- Debuggable.

Cons

- **Tricky implementation with lots of pitfalls.**
- Not very elegant.
- Partially system-specific.
- Limited ability to change CPU logic.

IA-32 hardware debugger

IA-32 hardware debugger

Pros

- Nearly native speed.
- Real hardware.

Cons

- We don’t have a hardware debugger ☹
- Significantly more expensive than other solutions discussed.
- Unsure about scripting capabilities.
- Still unable to modify some internals of the CPU ☹


AND THE WINNER IS...

- Bochs is a full IA-32 and AMD64 PC emulator.
  - CPU plus all basic peripherals, i.e. a whole emulated computer.
- Written in C++.
- Supports all latest CPUs and their advanced features
  - SSE2, SSE3, SSSE3, SSE4, SSE5, AVX, both SVM & VT-x etc.
- Correctly hosts all common operating systems.
- Provides extensive instrumentation API.
- A-W-E-S-O-M-E!

Bochs instrumentation callbacks

```
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BX_INSTR_EXIT_ENV
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BX_INSTR_EXIT
BX_INSTR_RESET
BX_INSTR_HLT
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BX_INSTR_TLB_CNTRL
BX_INSTR_PREFETCH_HINT
BX_INSTR_BEFORE_EXECUTION
BX_INSTR_AFTER_EXECUTION
BX_INSTR_REPEAT_ITERATION
BX_INSTR_LIN_ACCESS
BX_INSTR_PHY_ACCESS
BX_INSTR_INP
BX_INSTR_INP2
BX_INSTR_OUTP
BX_INSTR_WRMSR
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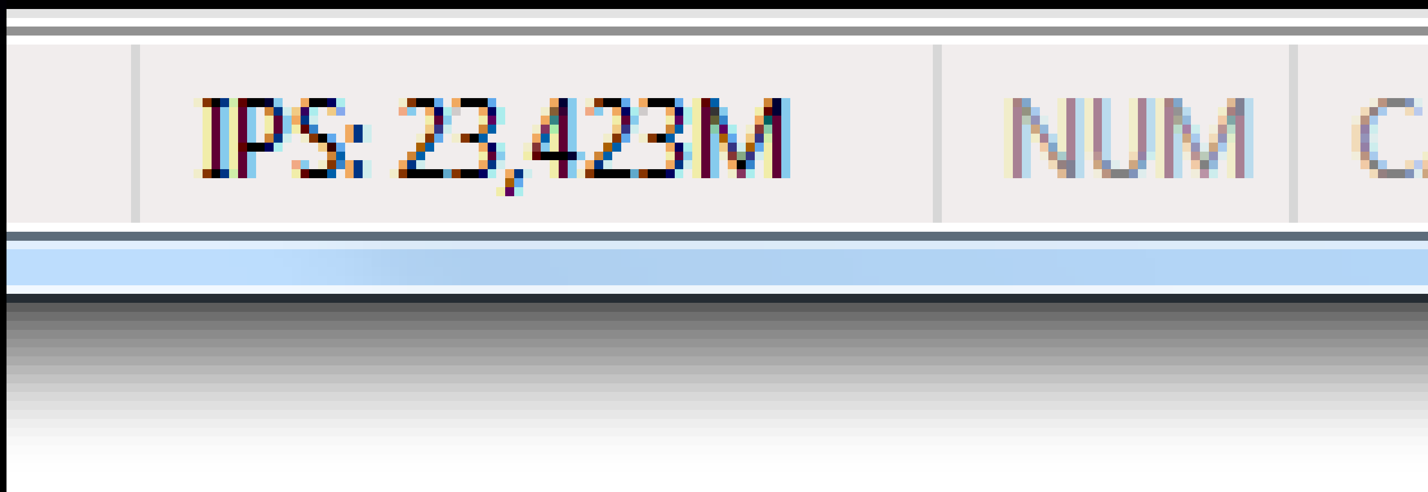
Performance (short story)



Performance (long story)

- On a modern PC (decent i7), non-instrumented guests run at up to 80MHz.
  - sufficient to boot up a system in reasonable time (<5 minutes)
  - environment fairly responsive, at between 1-5 frames per second.
- Instrumentation incurs a severe overhead.
  - Performance can drop to 1-40MHz.
    - still acceptable for research purposes (not regular work).
  - Simple logic and optimal implementation is a key to success.

Having the technical ability to instrument any operating system in any way... what shall we start with?

DOUBLE FETCHES

Quick introduction

Time-of-check-to-time-of-use

„Inconsistency between the checking of a condition and the use of the results of that check."

- *Double fetch* is a specific case of *tocttou*
  - user address space is shared across ring0 / ring3.
  - userland memory can be modified at any time by concurrent ring3 thread.
  - if the kernel assumes consistency of a userland value between any two points in time, it's (most likely) a bug.

Example and how it all started

`win32k!SfnINOUTSTYLECHANGE` 6 months ago

```
.text:BF8C3120 mov eax, _W32UserProbeAddress
.text:BF8C3125 cmp     ecx, eax
[...]
.text:BF8C3154 cmp [ecx+8], eax
.text:BF8C3157 jnb short loc_BF8C315C
.text:BF8C3159 mov eax, [ecx+8]
```

- 27 instances identified in win32k.sys in Q4 2012.
- Fixed in February 2013.
- Allowed for disclosure of arbitrary kernel memory to ring-3.

Trivia

- Double fetches occur within consistent code blocks.
  - single system call, single IOCTL handler.
- Only local vulnerabilities (code execution required)
  - Elevation of Privileges
    - primarily buffer overflows and write-what-where conditions.
  - Information Disclosure
    - arbitrary reads and under-filled buffers.
  - all sorts of Denial of Service
    - due to failed exploitation of the two previous items.

Exploitation

- They are race conditions after all – exploitation takes some advanced CPU-delaying and scheduler feng shui.
  - Some exploitation techniques detailed by *sgrakkyu* and *twiz* in 2007 [1].
  - Check our SyScan 2013 slides [2], white-paper [3] and follow-up post [4].

Detection via instrumentation – general idea

<u>Step 1</u>

Collect information about <u>all</u> memory accesses throughout the operating system lifespan.

<u>Step 2</u>

Find pairs of kernel→user references such that both:

- are within the same thread.
- are within the same system call invocation.
- access the same memory location.

<u>Step 3</u>

Filter out known false positives and manually inspect remaining reports in search of actual bugs.

Memory access characteristics

- Quite a lot of information is required to describe each access.
  - linear address of accessed memory
  - length of access ∈ {1, 2, 4, 8, 10, 16, 32}
  - access type ∈ {read, write, read+write, execute}
  - linear address of accessing instruction
  - unique identifier of syscall invocation
  - system call number
  - process name
  - unique thread id: (pid, tid, creation_time)
  - complete callstack
    - module name
    - module base
    - offset from base
  - instruction disassembly (or opcode bytes)

Characteristics by purpose

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double-fetch detection logic

double-fetch analysis

report uniquization

Characteristics by source

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    - module base
    - offset from base
  - instruction disassembly (or opcode bytes)

BX_INSTR_LIN_ACCESS

BX_INSTR_BEFORE_EXECUTION

guest system memory

Our implementation

- Create a „memlog.bin” database of all memory accesses by running OS through instrumented Bochs for a few days.
- Split the file into thread-specific logs.
- Run the *doublefetch* utility over each of them.
- Symbolize the resulting reports.

Ready for manual examination.

Bochspwn report

```
[pid/tid/ct: 00000049/00000049/0028fc4cf5dbe580] {init}
   00000003, 0000000b: READ of 950226c (7 * 4 bytes),
   pc = c12d89d1 [ mov edx, dword ptr ds:[eax-3] ]

 #0  0xc12d89d1 (kernel+002d89d1)
          __get_user_4    arch/x86/lib/getuser.S:69

 #1  0xc115a910 (kernel+0015a910)
    do_execve_common    fs/exec.c:1553

 #2  0xc115aa27 (kernel+0015aa27)
           do_execve    fs/exec.c:1621

 #3  0xc1019517 (kernel+00019517)
          sys_execve    arch/x86/kernel/process.c:356

 ...
```

Platform differences

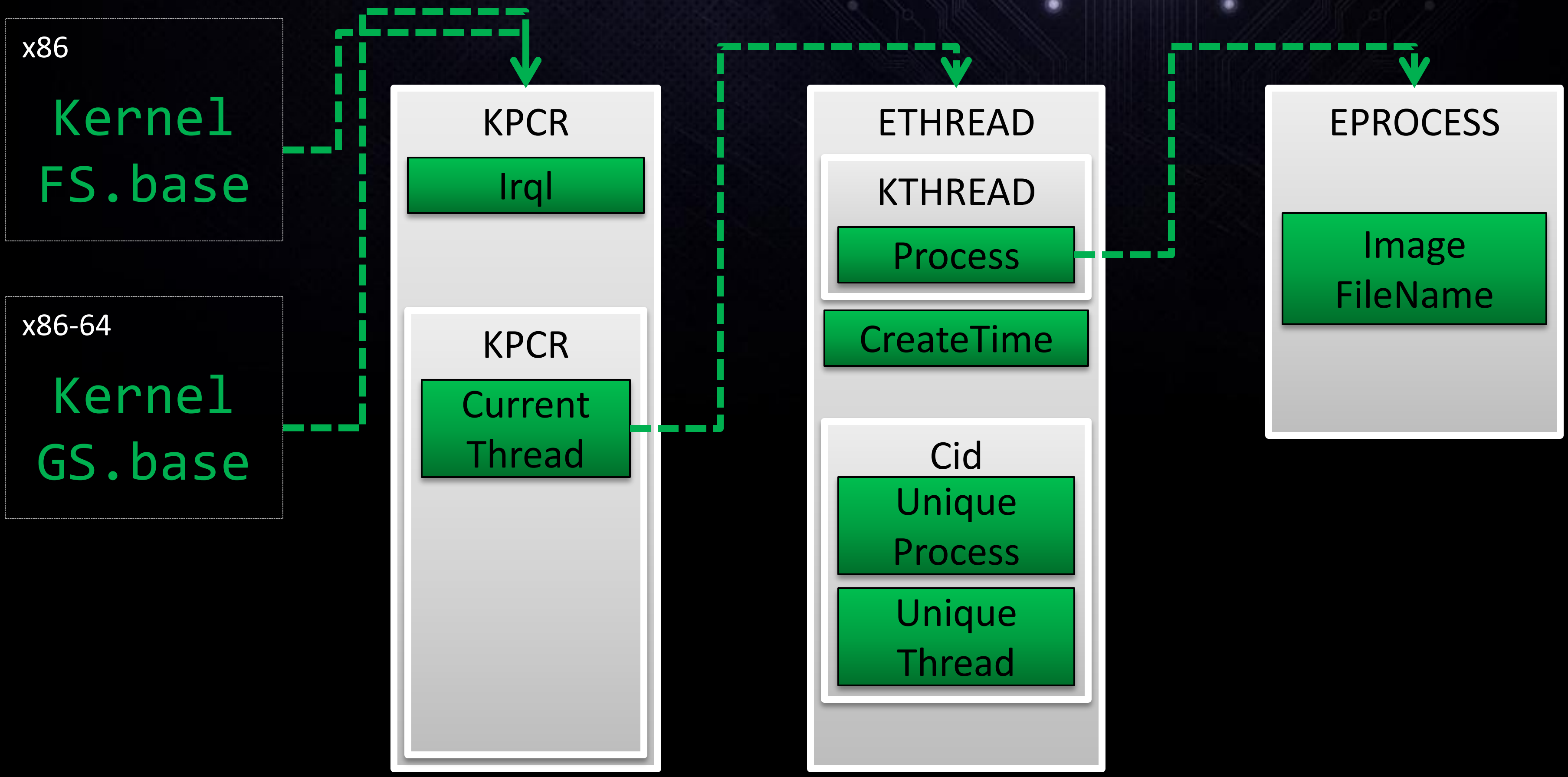
- Generic idea, largely system-specific implementation
  - different distinction between „user” and „kernel” address space
  - different system structures to traverse
  - different ways to generate code coverage
  - different false positives in reports
  - different results ☺
- Let’s look into each of them separately.

MICROSOFT WINDOWS

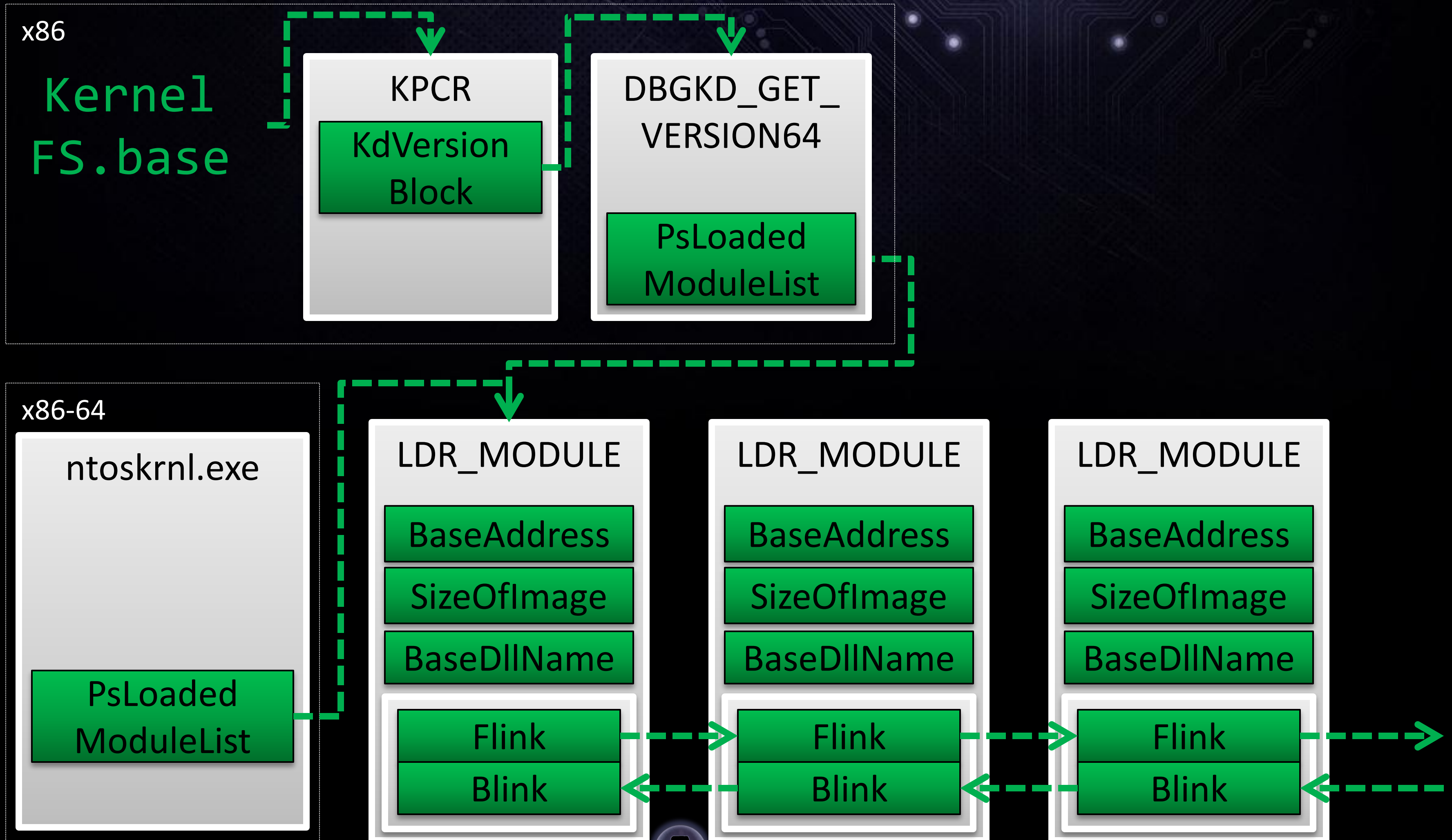
Memory boundaries

- Virtual address space divided in two (user / kernel)
  - simple „less than” and „greater than” can be applied to Eip.
- Windows x86
  - boundary `0x80000000`, user land below, kernel land above
  - can be `0xc0000000` for /3G switch, we didn’t use it
- Windows x86-64
  - non-continuous address space
  - below `0x000007ff00000000` user land.
  - above `0xfffff80000000000` kernel land.

Process/thread structure traversal



Device driver list traversal



Common false positives

- Reports originating from the „System” process during early boot-up
  - the user/kernel boundary doesn’t apply yet.
  - neutralized by ignoring the process entirely.
    - i.e. discard memory accesses from `pid=0` and `pid=4`
    - also speeds up the guest significantly
- Reports from APC-related kernel routines
  - Neutralized by reading Irql from KPCR and ignoring all `Irql=APC_LEVEL` references.

Common false positives

- Reports originating from the `CI.dll` kernel module (digital executable signatures)
  - filtered out by removing all database entries with “CI.dll” somewhere in the callstack in post-processing.
- Numerous false positives in messaging related routines in win32k.sys
  - filtered out by filtering the final logs against a black-list of known bad functions.

Memory probing

- The Windows kernel has several ways to probe user memory
  - public ProbeForRead, ProbeForWrite API
  - internal functions and macros (inlined in the code)
- Two most prevalent patterns

```
; ecx = user-provided address
mov eax, [ecx]
mov [ecx], eax
```

```
; ecx = user-provided address
mov al, [ecx]
```

Memory probing

- First pattern mitigated by:
  - logging all 4-byte “write” accesses in addition to “read”
  - implementing an anti-probe mechanism in *doublefetch.cc*
    - if a “write” of the same (address, size) immediately follows a “read”, discard the “read”.
- Second pattern mitigated by ignoring all reads of less than two 2 bytes.
  - extremely rare, ~99% of 1-byte reads is probing.

Symbolization

- Microsoft supports a “Debug Help” DLL – DbgHelp.dll
  - has API for symbol resolving
  - `SymInitialize`, `SymLoadModule64`, `SymFromAddr`
- Required PDB to be downloaded from Microsoft Symbol Server
  - http://msdl.microsoft.com/download/symbols
- Trivial to implement one’s own resolver.

Results

- 89 potential new issues discovered
  - part of the initial 27 bugs were also rediscovered
  - all reported to Microsoft (November 2012 – January 2013)
- 37 EoPs officially addressed by MS13-016, MS13-017, MS13-031, MS13-036, MS13-046
- 13 issues were classified as "Local DoS" only
- One big problem is still being worked on, and three cases are under re-investigation.
- The rest were non-exploitable / non-issues / etc.

The less official results

- Microsoft were very receptive to the reports.
- There is evidence that extensive variant analysis was performed.
  - `nt!ApphelpCacheQuery`, `win32k!NtUserDisplayConfigGetDeviceInfo`, examples are all around.
  - also three of our original reports were fixed as variants with no CVE.
  - we have no idea how many internal discoveries were fixed, but probably a few dozens.
- We also shared Bochspwn with MSFT, but have no official confirmation on whether they use the code or concept. ☹

The logs are out

- We are releasing all valid Bochspwn reports from our runs against Windows, Linux, FreeBSD.
  - MSFT assessed a majority of the reports as DoS or non-issue.
    - we don’t have resources to investigate them all.
    - let the larger collective confirm.
  - Some Windows issues have not been fixed for 9 months after the original reports. This is by far too long.
  - Logs from other systems are released for reference, and again, verification.

Final thoughts

- Windows kernel is designed/written poorly with regards to reading user land data
  - no pointer annotations (in contrast to Linux `__user`)
  - no dedicated fetch functions (in contrast to `copyin` / `copyout`)
  - no strict data-fetching policies; everyone do as they will.
- Bugs are bound to occur.
- The only problem: generating coverage.
  - imagine: we found ~40 and motivated the discovery of dozens of further bugs by not much more than just booting the system up.

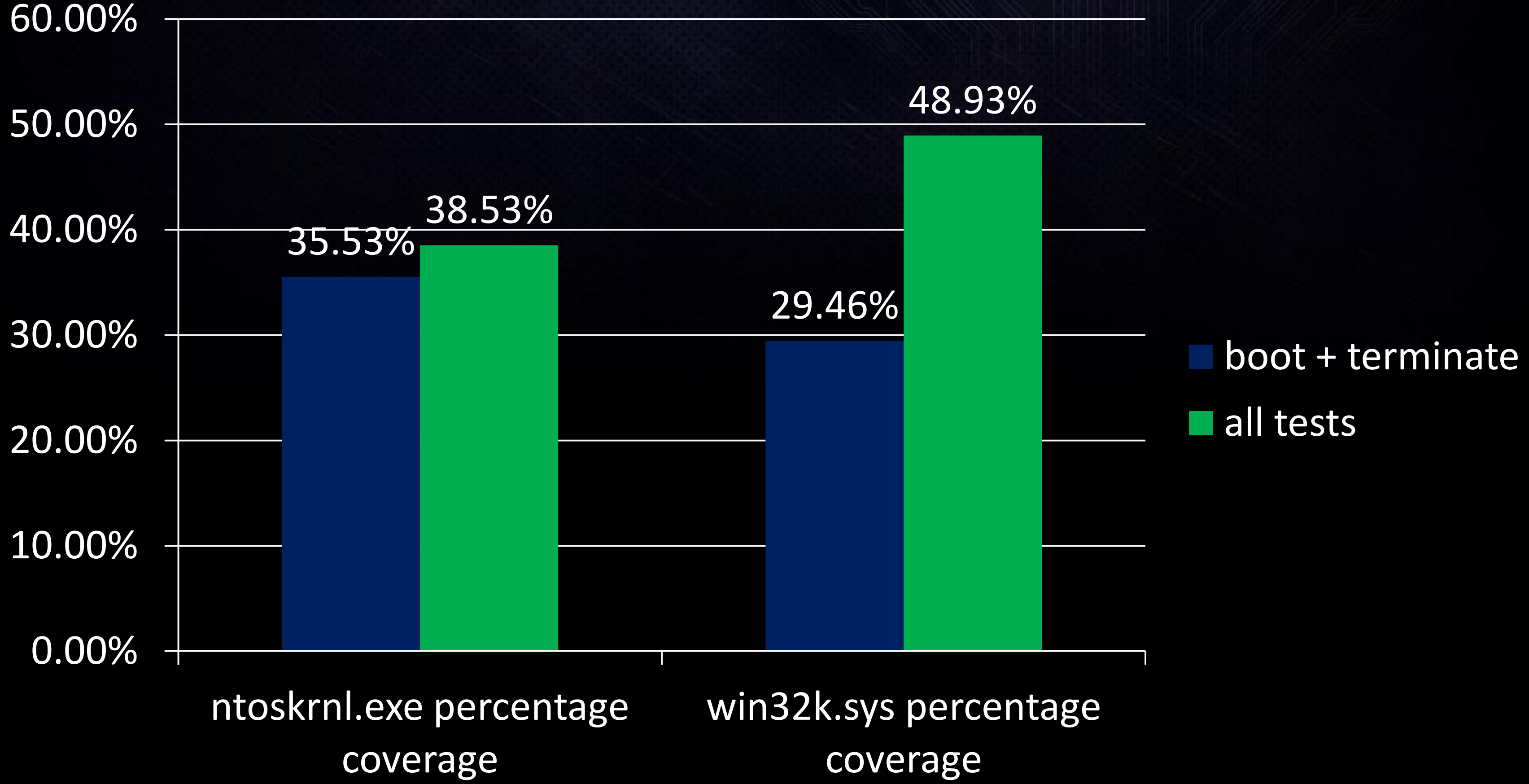
Improving code coverage

- What we did:
  - system boot up
  - typical navigation in the system: Internet Explorer, Wordpad, Notepad, Registry Editor, Control Panel, builtin games
  - playing multimedia (video, audio)
  - starting Starcraft 1
  - running the Wine Conformance Tests
- Far too little.

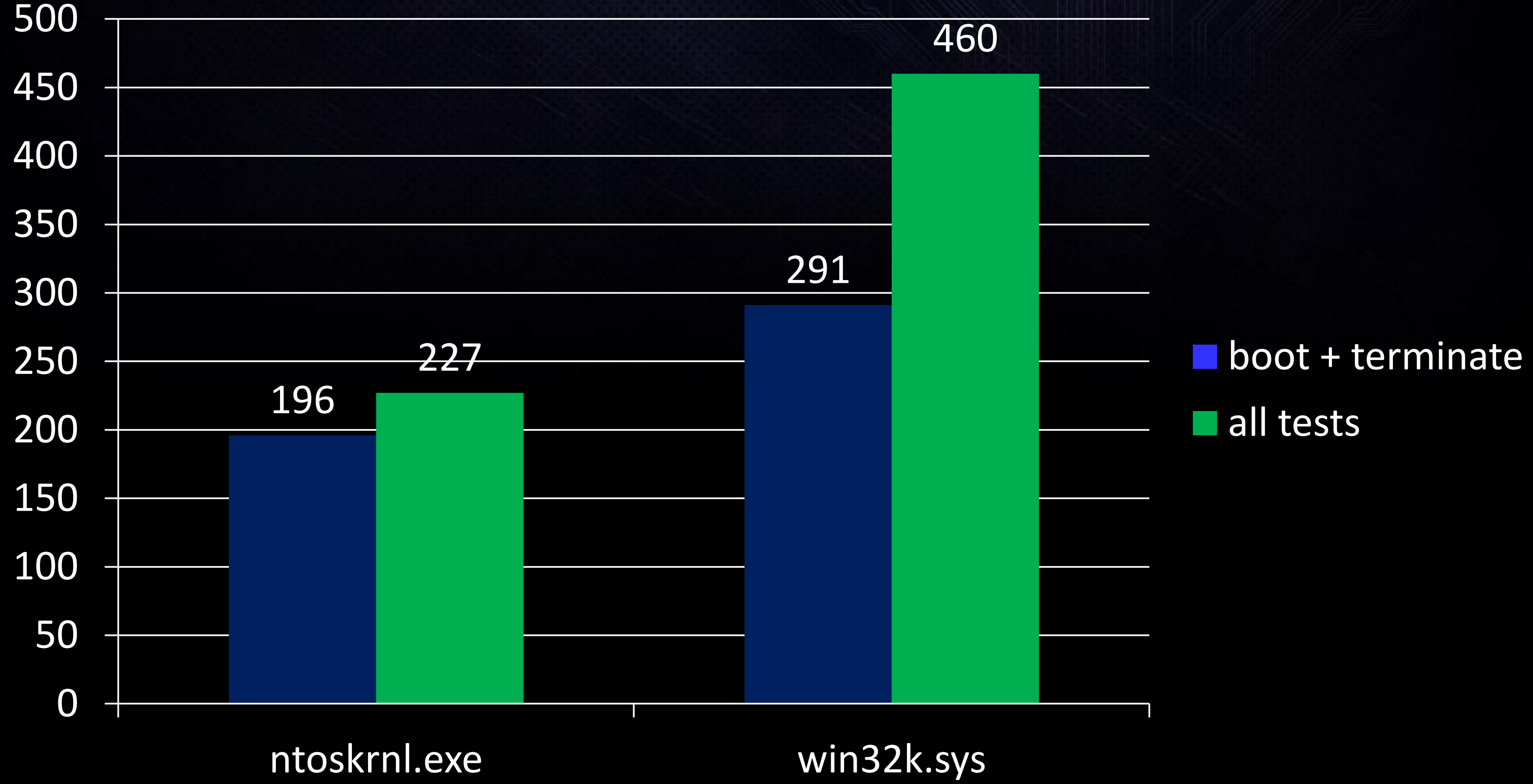
Improving code coverage

- All further ideas are extremely welcome.
- We currently believe a moderately-smart system call fuzzer should dramatically improve the coverage.
  - in the works. new Windows double-fetch iterations will follow soon. ☺

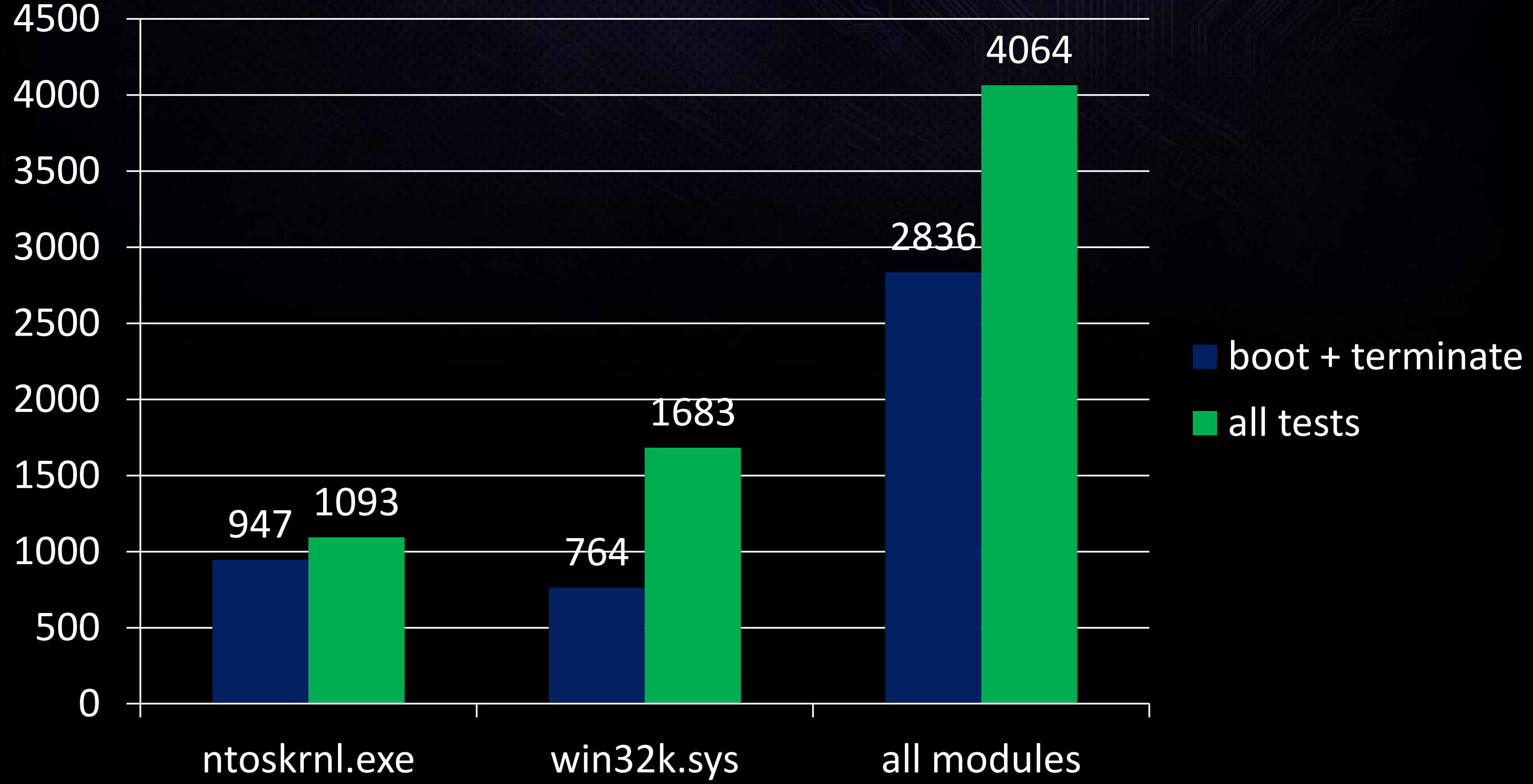
Coverage: instructions in base images



Coverage: system calls invoked



Coverage: fetch instructions executed



LINUX

Bochspwn vs Linux

- And by Linux we mean:
  Ubuntu Server 13.04 64-bit
- Stock kernel: **Linux 3.5.0-23-generic**

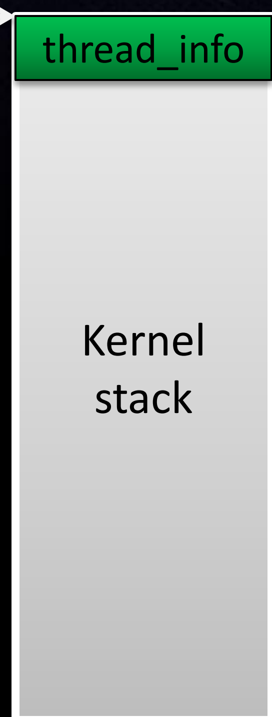
Linux: process and thread information

- Getting to thread-specific data.
  - Step 1. Get kernel-mode stack pointer.

Linux: process and thread information

- Step 2: Getting to thread_info.

struct **thread_info**
(top of the stack)

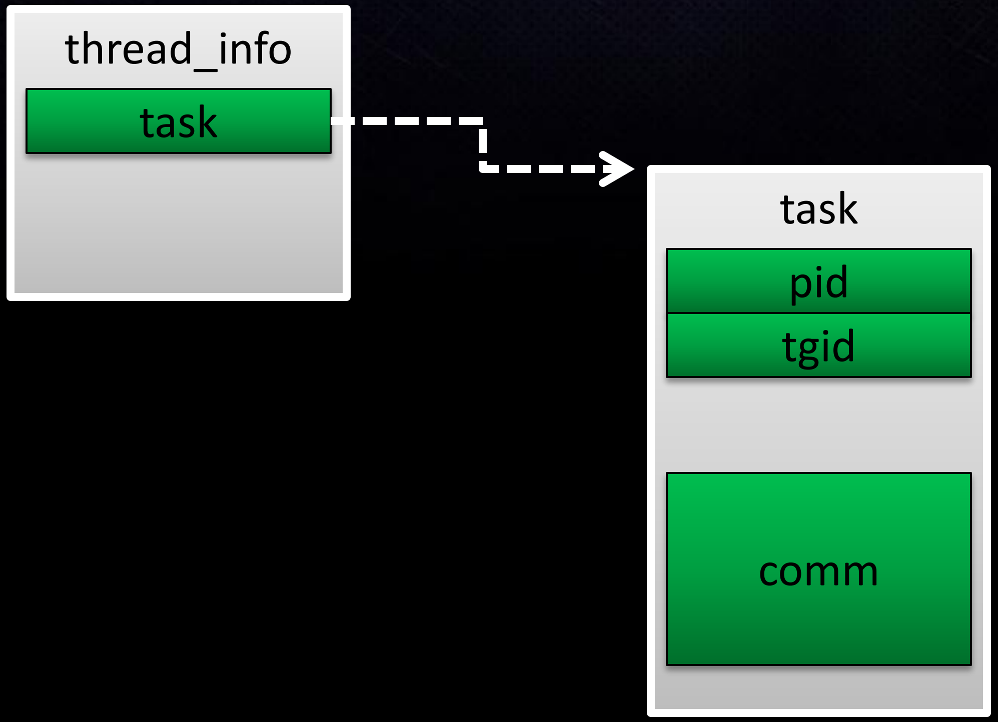


Kernel-mode RSP

$$(\texttt{struct thread\_info *})\ (\texttt{RSP}\ \&\ \underbrace{\sim(\texttt{THREAD\_SIZE} - 1)}_{\texttt{FFFFFFFFFFFFE000}})$$

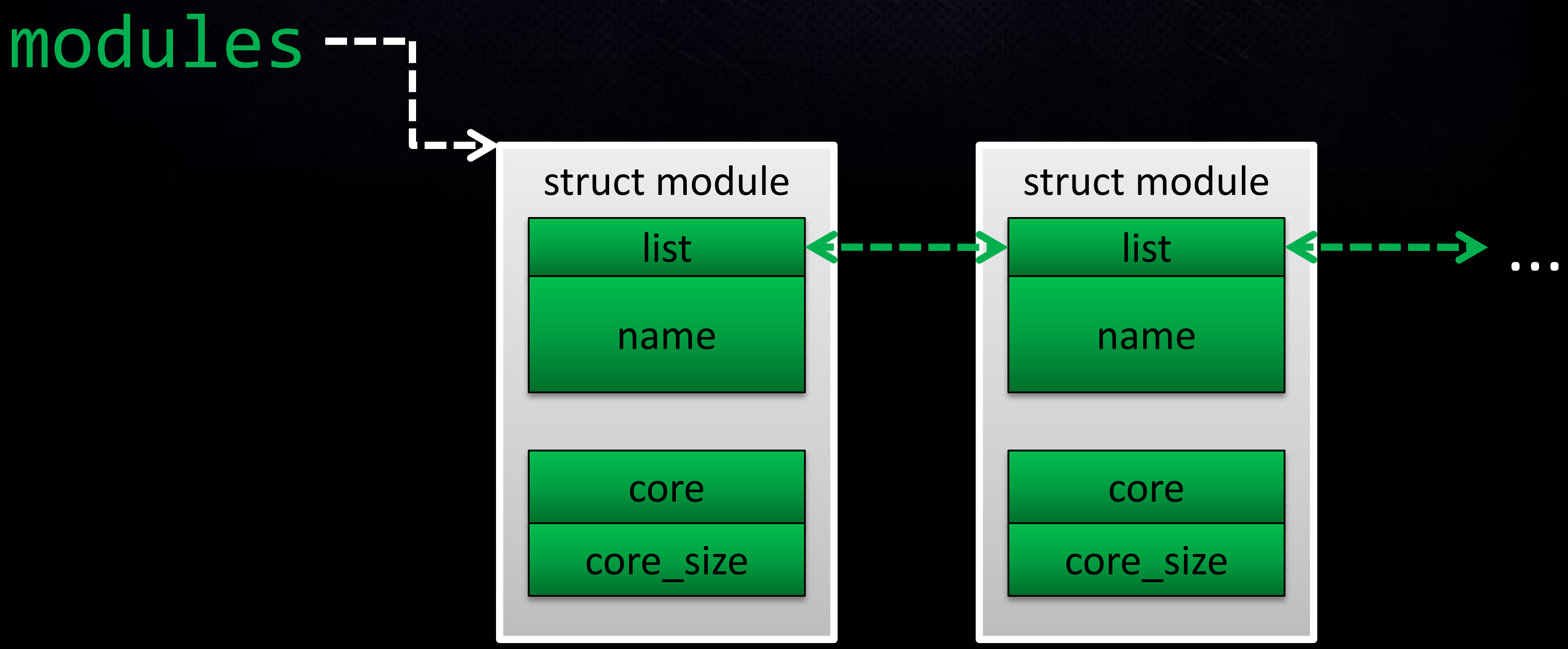
Linux: process and thread information

- Step 3: Diving deeper.



Linux: module information

- Getting to the modules



Linux: callstack

Stock kernel is compiled with frame pointers (RBP)

Linux: callstack

- Callstack
  - Sometimes missing second frame?

```
#0 0xc12d89d1 __get_user_4      getuser.S:69
#? ?????????? ???????????????? ?????????:???
#1 0xc115a910 do_execve_common exec.c:1553
#2 0xc115aa27 do_execve        exec.c:1621
#3 0xc1019517 sys_execve       process.c:356
#4 0xc15e9eee ptregs_execve    entry_32.S:730
```

Linux: callstack

- Callstack
  - Sometimes missing second frame?
    - Functions in .S do not preserve frame pointers.
    - What can we do about it?
      - Save (per thread) call stack – it’s slow.
      - Limit it only to .S functions which trigger events.
      - Record only the last one (.S is always #0).

Linux: callstack

- Callstack
  - Sometimes missing a frame?
    - Inline functions.
      - Compile with ignoring inline requests.
      - Actually a symbolization problem.

Linux: symbolization

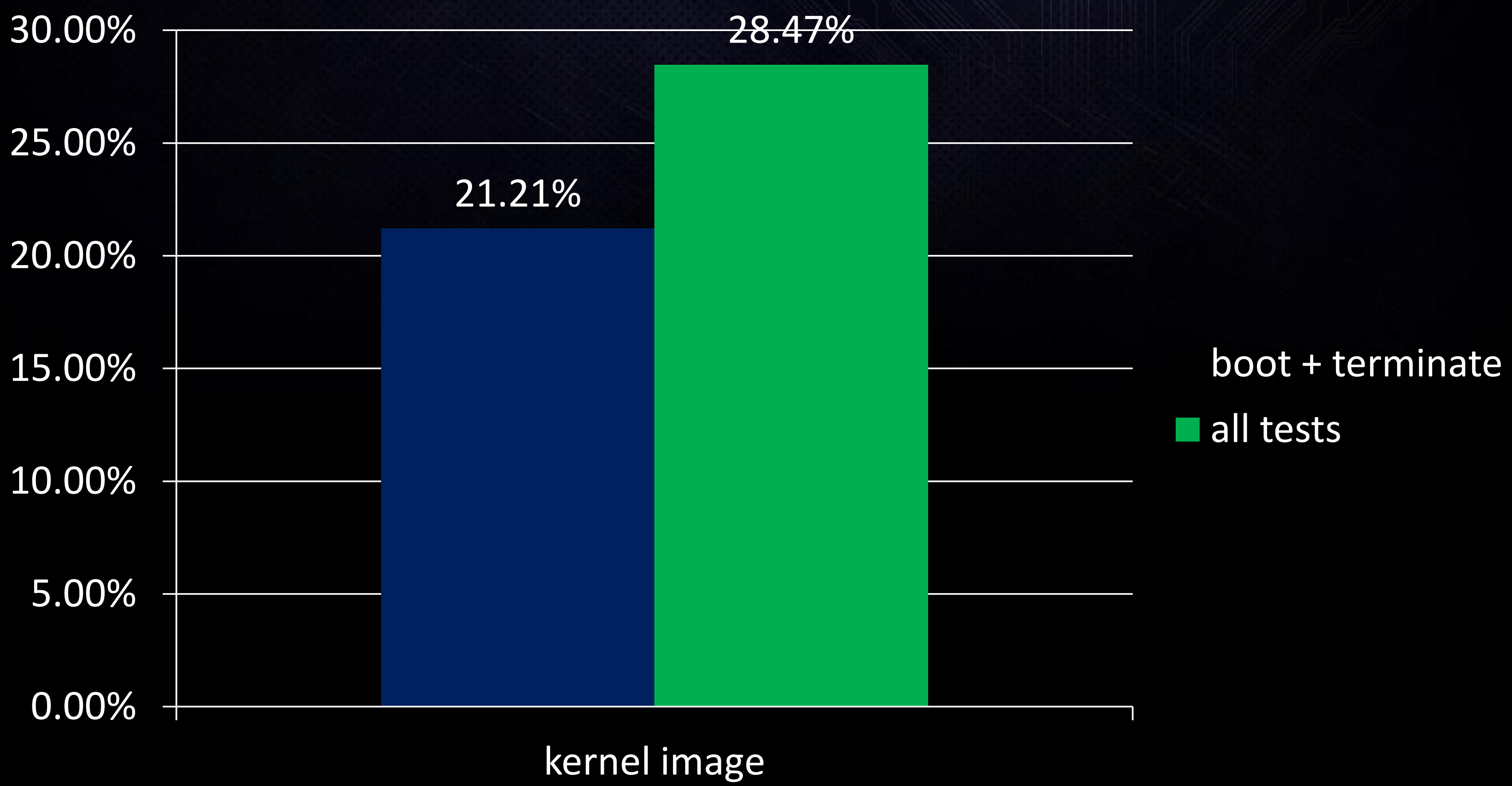
- Stock kernel symbols available in repositories.
  - Go to http://ddebs.ubuntu.com/pool/main/l/linux/ and look for your kernel.

- GNU addr2line tool + a short python script.

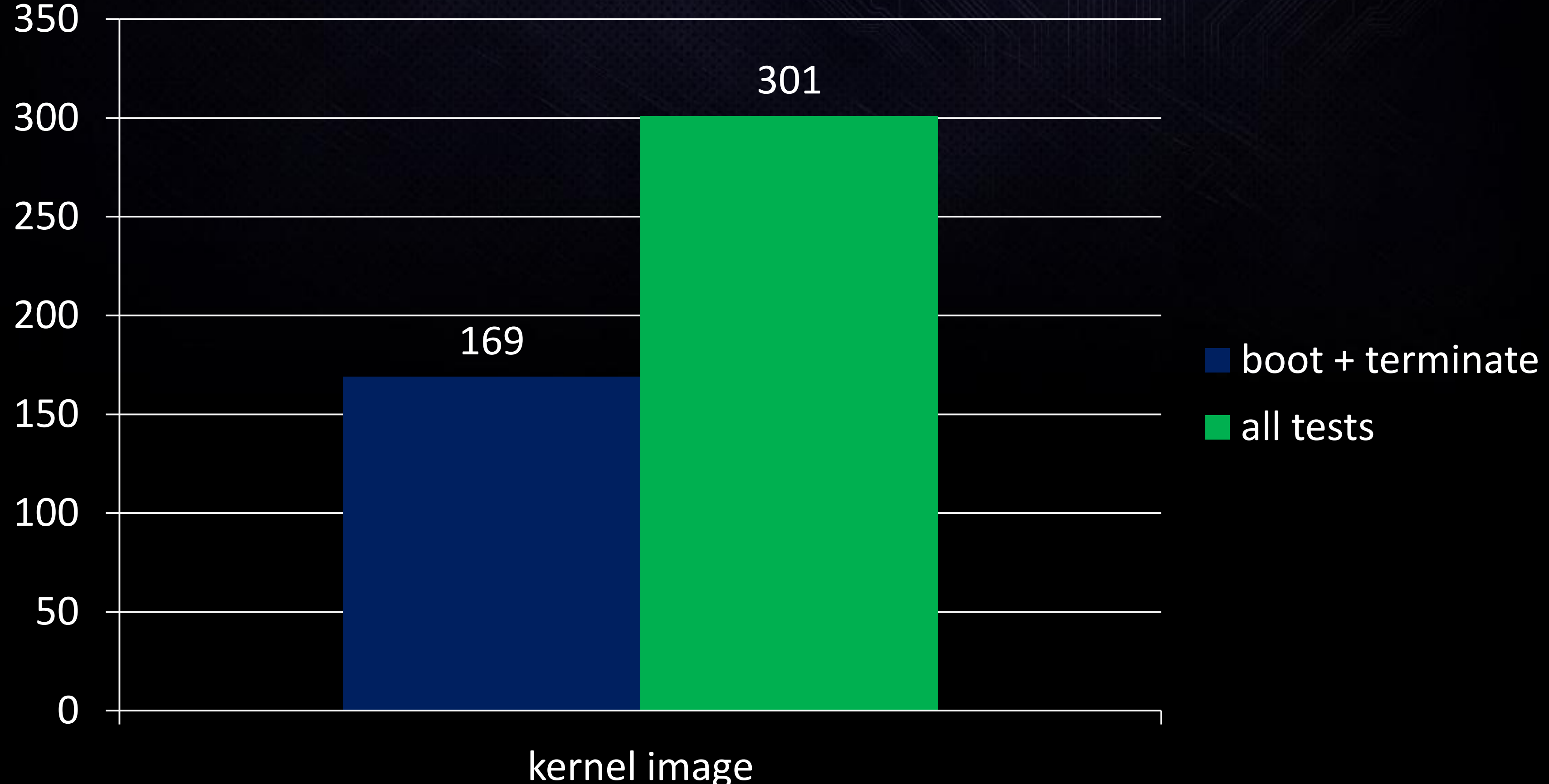
Linux: coverage

- Getting decent coverage
  - Fuzzers:
    - iknowthis - https://code.google.com/p/iknowthis/
    - Trinity - http://codemonkey.org.uk/projects/trinity/
    - fsfuzzer
    - other
  - Tests
    - Linux Test Project (ltp) - http://ltp.sourceforge.net/

Coverage: instructions in base images



Coverage: system calls invoked



Linux: coverage statistics

- Log sizes:
  78 MB to 189 GB
- Total unique threads in all runs:
  c.a. 50k
- Double fetch logs (unfiltered):
  70 KB to 200 KB

Linux: results

Bochspwn vs GNU/Linux

Final result:

??? bugs found

Linux: results

Bochspwn vs GNU/Linux

Final result:

0?? bugs found

Linux: results

Bochspwn vs GNU/Linux

Final result:

00? bugs found

Linux: results

Bochspwn vs GNU/Linux

Final result:

000 bugs found

Linux: results

- Results:
  - Nothing found.
- Why is that?! (a.k.a. documenting failure)
  - Copy functions.
  - Annotations.
  - Overall design.

Linux: results

- User-to-kernel copy functions
  - do_strncpy_from_user + do_strnlen_user
  - __get_user_{1,2,4,8} and __get_user macro
  - __copy_user_{zeroing | intel | nocache}
  - copy_user_generic_unrolled, copy_user_generic_string, copy_user_enhanced_fast_string
  - other? (copy_page)

Linux: results

- Annotations

```
#define __user              \
  __attribute__((           \
    noderef,                \
    address_space(1)        \
  ))
```

Sponsored by **sparse**:

https://sparse.wiki.kernel.org/index.php/Main_Page

Linux: results

- Overall design
  - No (or not too many) deep structures.
  - Need to call a function to dereference user pointer.

Double fetch conditions (non-issues)

1. Counting the argv [ ] list length (do_execve_common)
2. strlen () + memcpy ()
3. -ESTALE path resolving retry
4. writing to file in a ext4 file system
5. seeding the blocking/nonblocking random pools
6. usage of XSAVE / XRSTOR instructions
7. *_getsockopt implementations

Example of a non-issue (getsockopt)

```
static int do_tcp_getsockopt(struct sock *sk, int level,
        int optname, char __user *optval, int __user
  *optlen)
{
[…]
  int val, len;

  if (get_user(len, optlen))
      return -EFAULT;

  len = min_t(unsigned int, len, sizeof(int));

  if (len < 0)
      return -EINVAL;
```

Example of a non-issue (getsockopt)

```
  switch (optname) {
[…]
  case TCP_INFO: {
      struct tcp_info info;

      if (get_user(len, optlen))
            return -EFAULT;
[…]
      len = min_t(unsigned int, len, sizeof(info));
      if (put_user(len, optlen))
            return -EFAULT;
      if (copy_to_user(optval, &info, len))
            return -EFAULT;
```

Example of a non-issue (getsockopt)

```
    case TCP_CONGESTION:
        if (get_user(len, optlen))
            return -EFAULT;
        len = min_t(unsigned int, len, TCP_CA_NAME_MAX);
[…]

    case TCP_COOKIE_TRANSACTIONS: {
        struct tcp_cookie_transactions ctd;
        struct tcp_cookie_values *cvp = tp->cookie_values;

        if (get_user(len, optlen))
            return -EFAULT;
        if (len < sizeof(ctd))
            return -EINVAL;
[…]
```

FREEBSD

Bochspwn vs FreeBSD

- **FreeBSD 9.1 64-bit**
- Stock kernel (GENERIC)

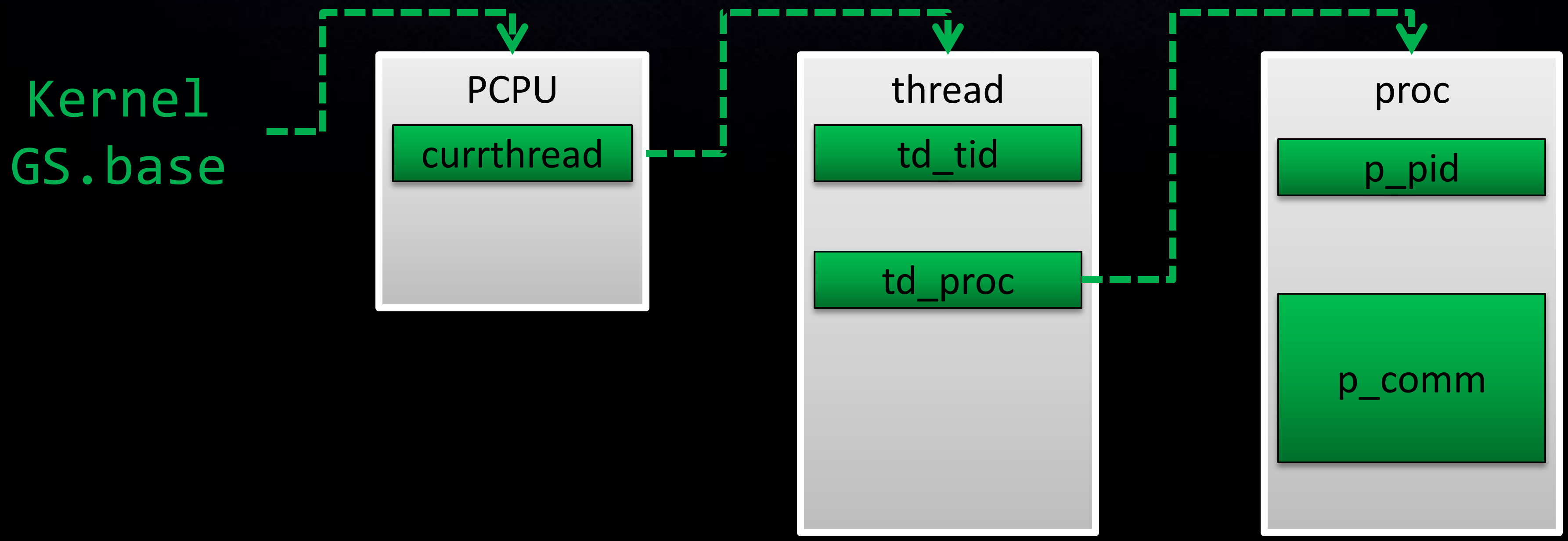
FreeBSD: process and thread

- Getting to thread-specific data.
  - Step 1. Get kernel-mode GS base.

<u>Ring 3</u>	<u>Ring 0</u>
MSR C0000102H (MSR_KERNELGSBase)	GS.base
`pcpu->msr.kernelgsbase`	`pcpu->get_segment_base(BX_SEG_REG_GS)`

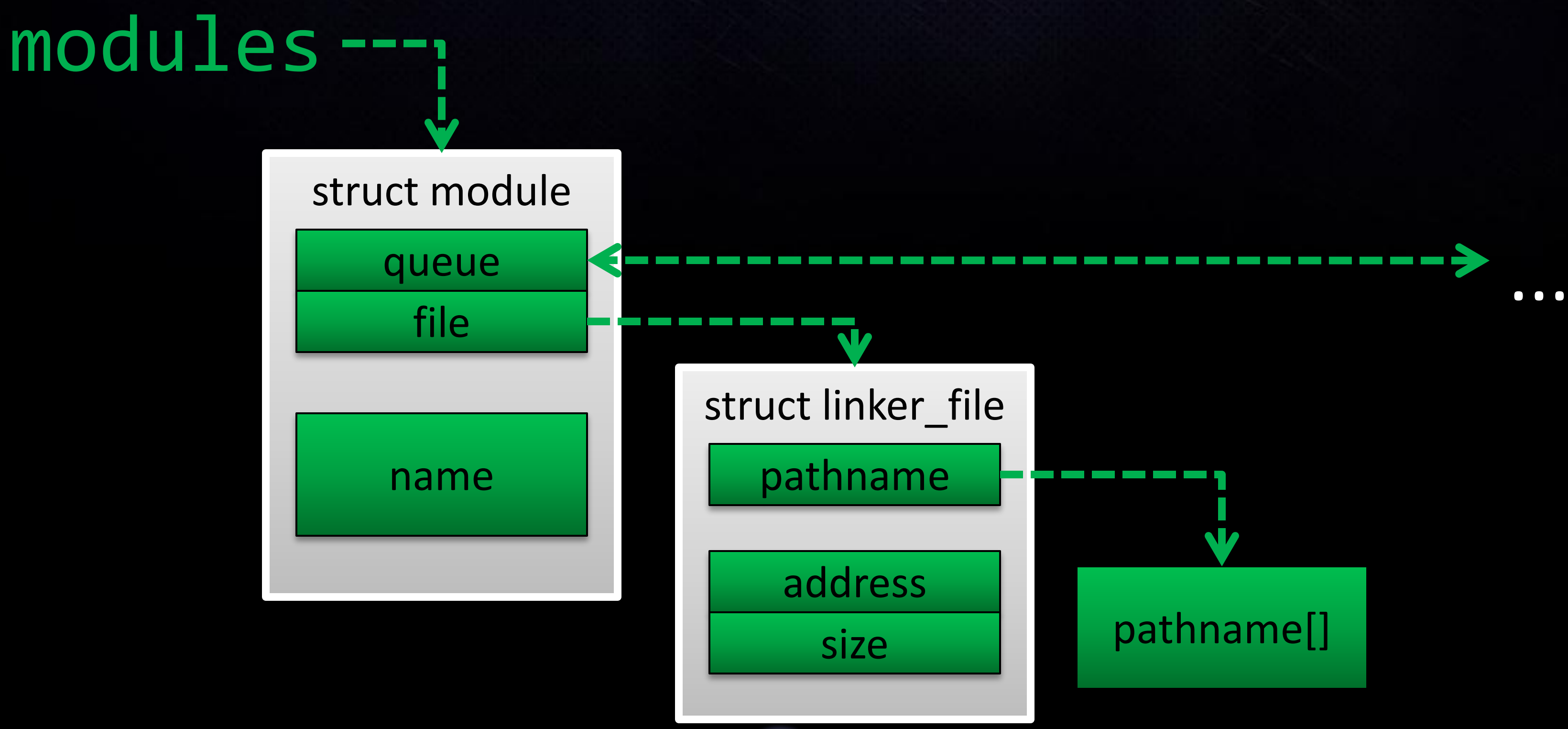
FreeBSD: process and thread

- Getting to thread-specific data.
  - Step 2. Diving deeper.



FreeBSD: modules

- Getting to the modules



FreeBSD: modules

- Getting to the modules?
  - by default there were **477** (sic!) registered modules.
  - ... and all of them were in the kernel image.
  - perhaps we can just ignore them? Yes.
    - Linux emulation layer is an external module.

FreeBSD: callstack

- Callstack & symbolization
  - Exactly the same as in Ubuntu:
    - RBP present in most functions.
    - Assembly function do not preserve RBP on stack.
  - Stock kernel symbols available in:

    `/boot/kernel/kernel.symbols`

FreeBSD: coverage

- Fuzzers
  - If6 and netusse - https://code.google.com/p/netusse/
  - fsfuzzer
  - Trinity
- Tests
  - stress2 - http://people.freebsd.org/~pho/stress/index.html
  - regression - http://svnweb.freebsd.org/base/head/tools/regression/

FreeBSD: results

Bochspwn vs FreeBSD

Final result:

??? bugs found

FreeBSD: results

Bochspwn vs FreeBSD

Final result:

0?? bugs found

FreeBSD: results

Bochspwn vs FreeBSD

Final result:

00? bugs found

FreeBSD: results

Bochspwn vs FreeBSD

Final result:

000 bugs found

FreeBSD: results

- Documenting failure again.
- Nothing found.

FreeBSD: why nothing found?

- Copying functions again: `fubyte/word/word32` and `copyin/copyinstr`
- Historically popular bug class.

FreeBSD: a false positive

- kern_select()
  - Read no. 1: sys_generic.c:**918** - **fubyte**
  - Read no. 2: sys_generic.c:**968** - **copyin**

```
------------------------------ found double-read of address 0x00000008030070e8
Read no. 1:
[pid/tid/ct: 000002ee/000186c9/fffffe00050c4000] {          sshd} 0000005e, 0000005d: READ of 8030070e8 (1 * 1 bytes), pc =
 #0  0xffffffff80bd6053 (kernel+009d5ec3)                 fubyte /usr/src/sys/amd64/amd64/support.S:442
 #1  0xffffffff8093390e (kernel+0073377e)            kern_select /usr/src/sys/kern/sys_generic.c:918
 #2  0xffffffff8093421d (kernel+0073408d)             sys_select /usr/src/sys/kern/sys_generic.c:842
 #3  0xffffffff80bd7ae6 (kernel+009d7956)            syscallenter /usr/src/sys/amd64/amd64/../../kern/subr_syscall.c:135

Read no. 2:
[pid/tid/ct: 000002ee/000186c9/fffffe00050c4000] {          sshd} 0000005e, 0000005d: READ of 8030070e8 (1 * 8 bytes), pc =
 #0  0xffffffff80bd5e7d (kernel+009d5ced)                 copyin /usr/src/sys/amd64/amd64/support.S:293
 #1  0xffffffff80933a48 (kernel+007338b8)            kern_select /usr/src/sys/kern/sys_generic.c:968
 #2  0xffffffff8093421d (kernel+0073408d)             sys_select /usr/src/sys/kern/sys_generic.c:842
 #3  0xffffffff80bd7ae6 (kernel+009d7956)            syscallenter /usr/src/sys/amd64/amd64/../../kern/subr_syscall.c:135
```

FreeBSD: a false positive

- kern_select()

Read no. 1:

```
error = select_check_badfd(fd_in, nd, ndu, abi_nfdbits);

static int
select_check_badfd(fd_set *fd_in, int nd, int ndu, int
  abi_nfdbits)
...
            res = fubyte(addr);
            if (res == -1)
                  return (EFAULT);
```

FreeBSD: a false positive

- `kern_select()`

Read no. 2:

```
#define         getbits(name, x) \
        ...
        error = copyin(name, ibits[x], ncpubytes);     \
        ...

  getbits(fd_in, 0);
  getbits(fd_ou, 1);
  getbits(fd_ex, 2);
```

FreeBSD: a false positive

- kern_select() :
  - Yes, there is a double-fetch.
  - No, it has no security consequences in kernel-mode.

FreeBSD: other false positives

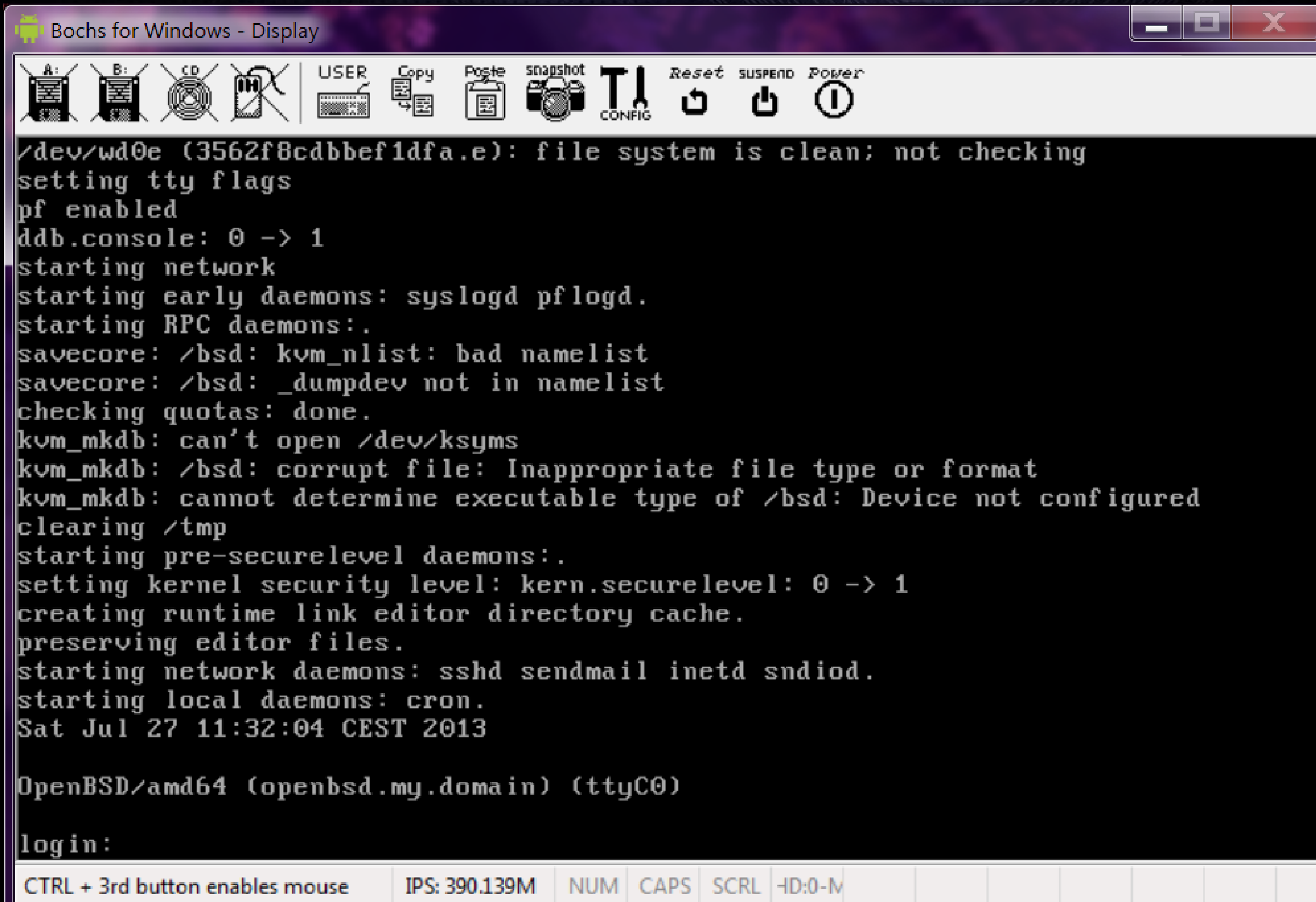
- execve and same address to binary name and `argv[0]`
- syslog write to file and tty
- mutex implementation (has locks)

OPENBSD

Bochspwn vs OpenBSD

- OpenBSD 5.3 64-bit
- Customly compiled kernel (DEBUG) for symbols
- **Work in progress**.

Bochspwn vs OpenBSD

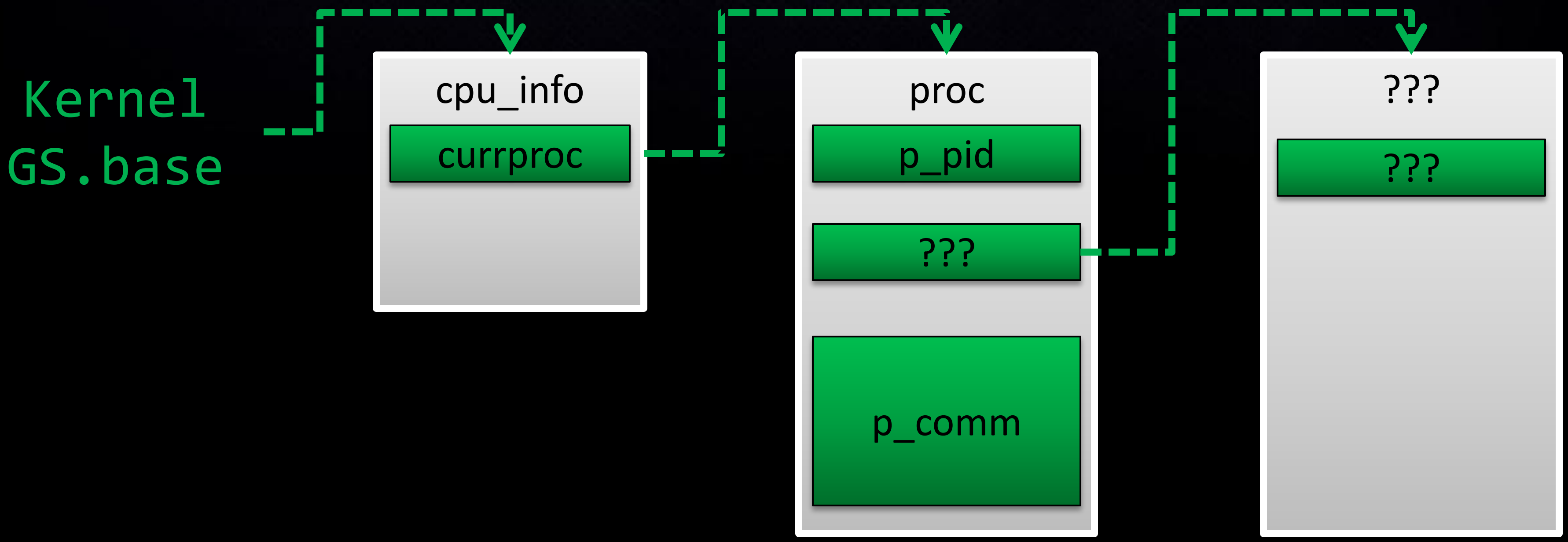


OpenBSD: process and thread

- Getting to thread-specific data.
  - Step 1. Get kernel-mode GS base – exactly the same way as in FreeBSD.

OpenBSD: process and thread

- Getting to thread-specific data.
  - Step 2. Diving deeper.



OpenBSD: modules

Oh. Actually there are no modules on OpenBSD.

OpenBSD: callstack

- Same situation as in FreeBSD/Linux:
  - Stack pointer in RBP / preserved on stack
  - ... but not for functions implemented in assembly.

- Symbolizing:
  - No symbols available for stock kernel.
  - Have to recompile the kernel (DEBUG).
  - GNU addr2line-based script works with no changes.

OpenBSD: left to do

Prepare logs, look for bugs!

Bochspwn vs …

- There are still many systems to explore.
  - NetBSD
  - OSX
  - Solaris
  - other Linux-based distributions?
- And a lot of ground to cover.
  - Dedicated tools for better coverage.

HYPERPWN

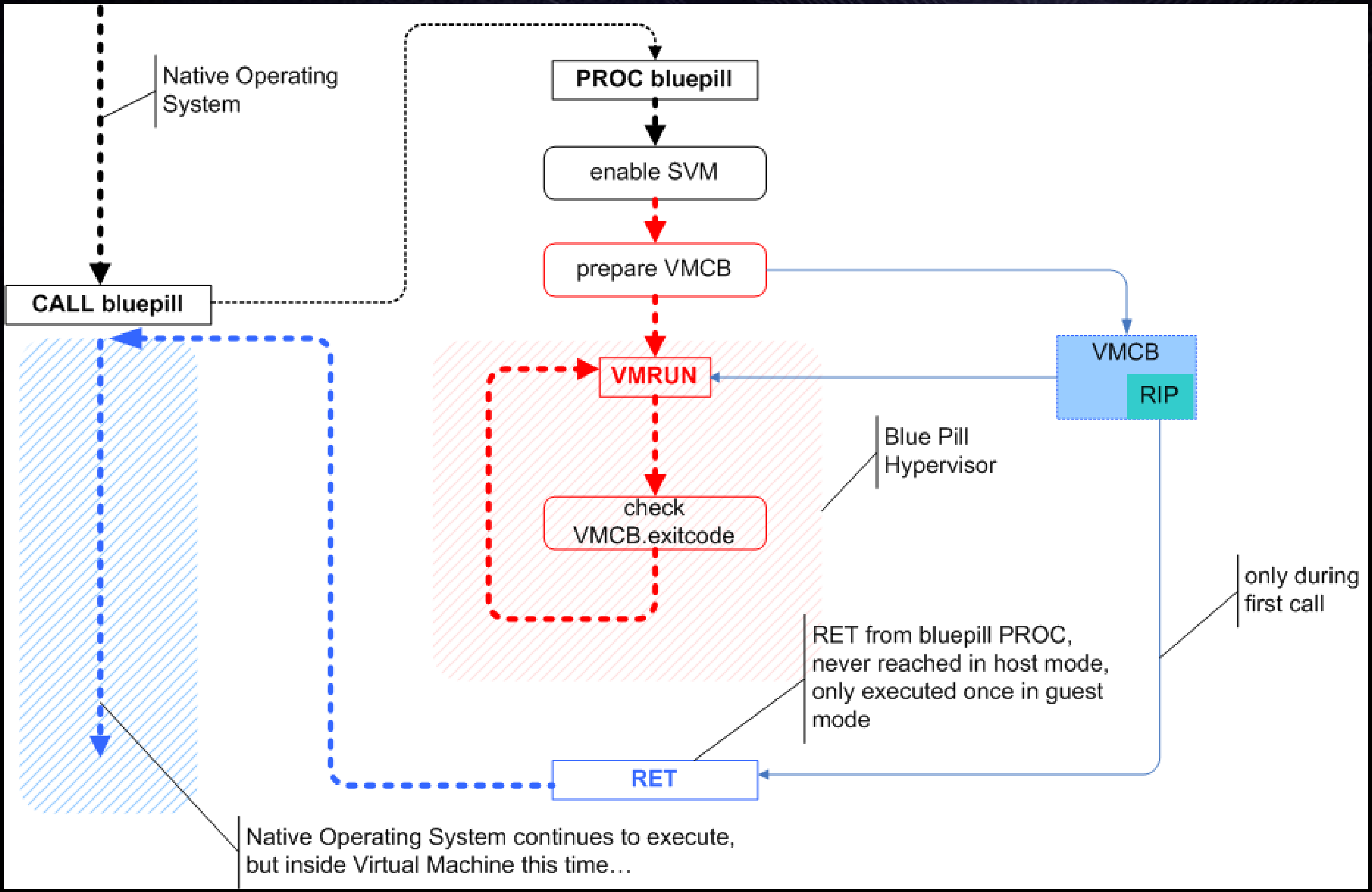
Hyperpwn considerations

- Virtualization is still a great technology for instrumenting memory accesses.
  – all OS instructions execute natively.
  – only instructions of desired type are intercepted.
  – could be ran *seamlessly* on any (your) workstation.
    - detect bugs while you work.
    - only if you don't use VMs, though.
- Not perfect for every instrumentation.

Hyperpwn – initial concept

- Start off with Joanna Rutkowska's BluePill project [5]
  - load a driver which sets up environment, puts OS in a "jail" and run as a VMM.

Hyperpwn – initial concept

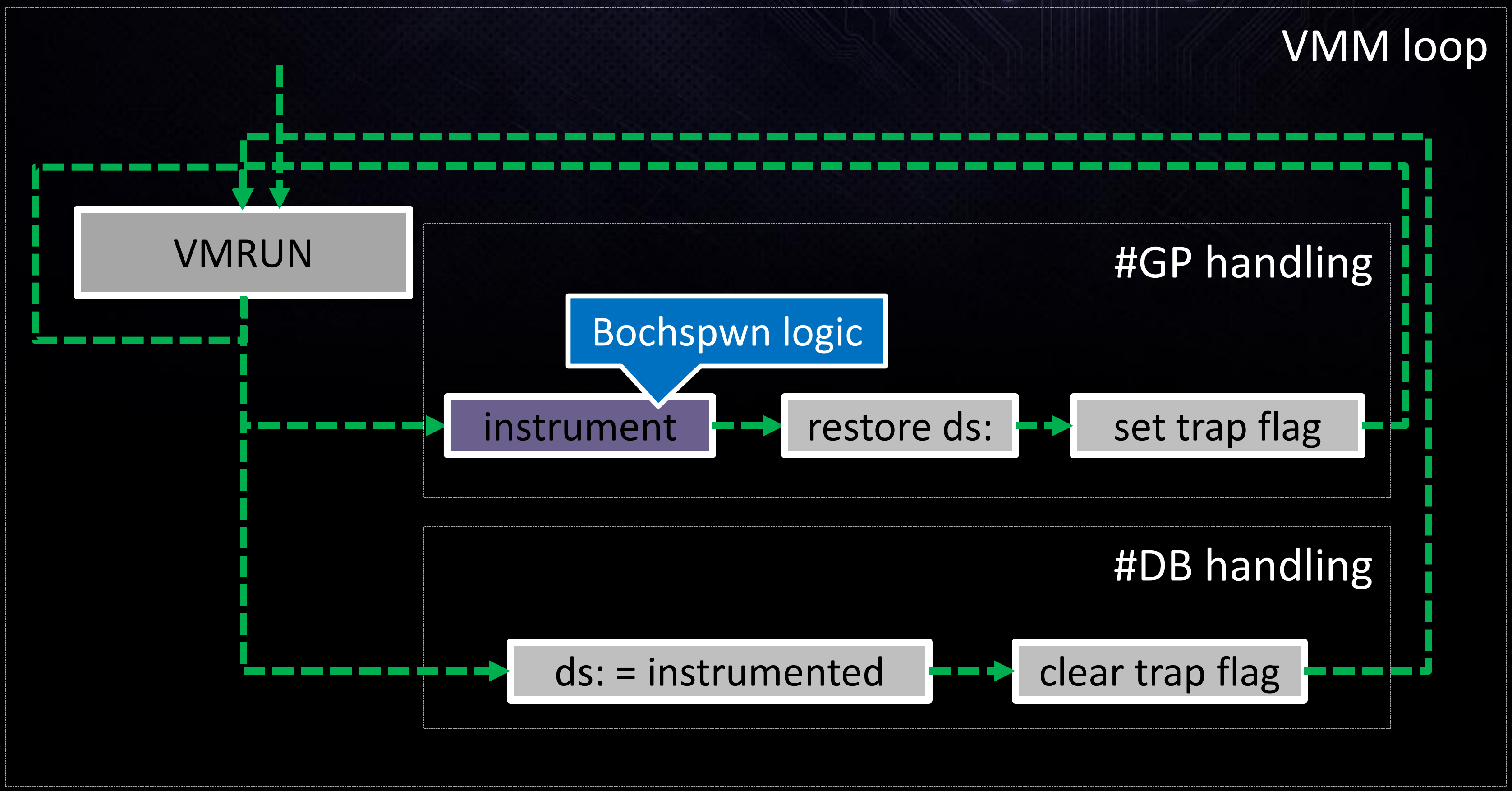


source: J. Rutkowska, Black Hat USA 2006, © BlackHat

Hyperpwn – initial concept

- Instrument only 32-bit operating systems.
- Modify kernel data segment descriptor
  - `LDT_ENTRY.ExpandDown = TRUE`
  - `LDT_ENTRY.Base = 0x00000000`
  - `LDT_ENTRY.Size = 0x80000000`
- All kernel-mode access to `00000000-7fffffff` yield a #GP exception.
- VMM intercepts the #GP, performs instrumentation, restores data segment, sets TF, continues.
- VMM intercepts #DB, sets LDT_ENTRY to instrumented, clears TF, continues.

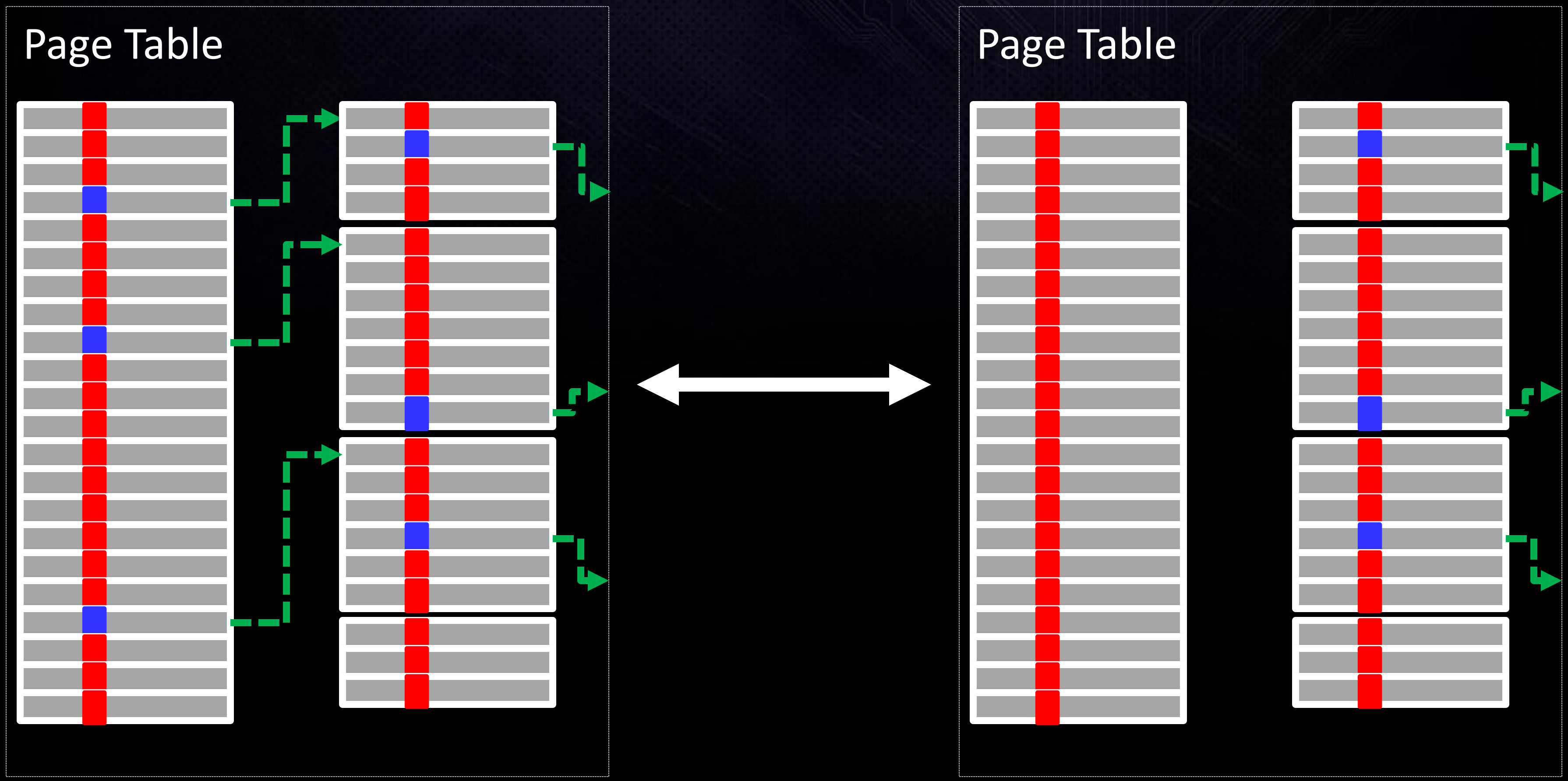
Hyperpwn – initial concept



Hyperpwn – revised concept

- No VT-x / SVM in Protected Mode ☹
- No memory segmentation in Long Mode ☹
- Revised idea: tamper with Page Tables instead of GDT.
  - clear the “Present” flag for all top-level user-mode entries.
  - has the same effect, but more code required.

Hyperpwn – revised concept



Hyperpwn prototype – coming in Fall 2013

(or not)

Double fetches – what else?

- Instrument Mac OS X.
- Instrument Microsoft Windows with improved code coverage.
  - expect another flood of bugs (or not).
- Static analysis approach.
  - symbolic execution model is fairly interesting.
  - mixing static and dynamic: hint the static analyzer with known user data fetch locations.

BOCHSPWN:MSAN

Kernel memory taint tracking

- Kernel instrumentation is <u>really</u> not just about double fetches.
- Example: kernel memory taint tracking.
  - 1 to 2GB wide kernel virtual address space on x86.
  - easily up to 16 bytes of metadata per one kernel byte. that's a lot!
  - how about tracking an "initialized" property for heaps/pools and stack?
- Possible to detect use of uninitialized memory.
  - similarly to user-mode MemorySanitizer.

Kernel memory taint tracking

- Also, feasible detection of leakage of uninitialized kernel bytes to user-mode!
- We implemented a prototype of Bochspwn:msan …
- Ran it against Windows a week before BH USA 2013.

It works!

12 kernel → user pool bytes disclosure vulnerabilities found in Windows 7 and 8.1 and reported to MSFT.

By just booting up the systems.

D E M O

WINDOWS 8.1 32-BIT
KERNEL POOL MEMORY DISCLOSURE 0-DAY

Bochspwn:msan – more on this later this year

CONCLUSIONS

Bochspwn is out

- We are releasing Bochspwn as open-source today.
  - official name of the project: **kfetch-toolkit**
  - instrumentation + post-processing tools
    - Windows, Linux, BSD support included.
  - Apache v2 license.
  - https://github.com/j00ru/kfetch-toolkit
  - read the README for instructions.

Further research

- Kernel instrumentation potential is far from being exhausted.
  - in fact, there are hundreds* of low-hanging fruit waiting to be found.
  - so far it seems most are in Windows.
- Hack on kfetch-toolkit
  - port to other platforms (more exotic?).
  - find novel patterns, models or whole bug classes.
  - improve coverage.
  - test other presented approaches.

* personal estimate.

Final words

1. We really hope the subject will be picked up. ☺
2. If you do and have results (or problems), we're happy to hear from you!
3. Check our blogs for slides, double-fetch reports from the past and updates.

Thanks for coming!

Questions?

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Thanks / shouts to:

Halvar Flake, Solar Designer, Clement Lecigne, Oshogbo, Martynas Venckus, Tavis Ormandy, Vasily Kulikov, Alex Ionescu, ISE

References

[1] http://phrack.org/issues.html?issue=64&id=6#article

[2] http://vexillium.org/dl.php?syscan_slides.pdf

[3] http://vexillium.org/dl.php?bochspwn.pdf

[4] http://j00ru.vexillium.org/?p=1880

[5] http://invisiblethingslab.com/resources/bh07/IsGameOver.pdf