```
BUG: unable to handle kernel NULL pointer dereference at virtual address 0000009c
 printing eip:
c01e41ee
*pde = 00000000
Oops: 0000 [#1]
SMP
Modules linked in:
CPU:    0
EIP:    0060:[<c01e41ee>]    Not tainted VLI
EFLAGS: 00010202   (2.6.18-1-k7 #1)
EIP is at acpi_hw_low_level_read+0x7/0x6a
eax: 00000010   ebx: 00000001   ecx: 00000094   edx: c18e1f80
esi: c18e1f94   edi: 00000000   ebp: 00000000   esp: c18e1f68
ds: 007b   es: 007b   ss: 0068
Process swapper (pid: 1, ti=c18e0000 task=f7b44aa0 task.ti=c18e0000)
Stack: 00000001 c18e1f94 00000000 c01e42ae 00fb3c00 00000000 00000000 c02b670c
       f7fb3c00 c02b6834 c01c21b5 c02b66dc c01c1e26 f7fb3c00 c0344b6c 00000000
       c01c12d0 00000000 c01003e1 c0102b46 00000202 c01002d0 00000000 00000000
Call Trace:
 [<c01e42ae>] acpi_hw_register_read+0x5d/0x177
 [<c01c21b5>] quirk_via_abnormal_poweroff+0x11/0x36
 [<c01c1e26>] pci_fixup_device+0x68/0x73
 [<c01c12d0>] pci_init+0x11/0x28
 [<c01003e1>] init+0x111/0x28e
 [<c0102b46>] ret_from_fork+0x6/0x1c
 [<c01002d0>] init+0x0/0x28e
 [<c01002d0>] init+0x0/0x28e
 [<c0101005>] kernel_thread_helper+0x5/0xb
Code: a0 82 2d c0 76 1b 50 68 85 8c 2a c0 68 f3 00 00 00 ff 35 ac ef 28
c0 e8 c7 80 00 00 31 d2 83 c4 10 89 d0 c3 57 85 c9 56 53 74 5d <8b>
71 08 8b 59 04 89 f7 09 df 74 51 c7 02 00 00 00 00 8a 09 84
EIP: [<c01e41ee>] acpi_hw_low_level_read+0x7/0x6a SS:ESP 0068:c18e1f68
 <0>Kernel panic - not syncing: Attempted to kill init!
```

Is Your Program Memory Safe?

Can we use bounded model checking to find memory safety violations in compiled programs?

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Thesis Seminar, York, 10th July 2008

Motivation

- *"BLASTing Linux Code"* (Mühlberg and Lüttgen, 2006)
- *"Model-checking Part of a Linux File System"*

  (Galloway et al., 2007)
- Results:
  - Memory safety issues are outside of the scope of currently available software model checkers
  - Biggest problem is to abstract a faithful model from a given program

Related Work

- O'Hearn and colleagues: SpaceInvader, Smallfoot

  (Yang et al., 2007)

- Microsoft Research: SLAM, VCC, Hypervisor

  (Ball et al., 2006)

- *"EXE: automatically generating inputs of death"*

  (Cadar et al., 2006)

- *"Analyzing stripped device-driver executables"*

  (Balakrishnan and Reps, 2008)

Memory Safety?

- What I am interested in:
  - Dereferencing invalid pointers
  - Uninitialised reads
  - Buffer overflows
  - Memory leaks
  - Violation of API usage rules for (de)allocation
- Not now: Shape safety

Project Outline

- Why don’t we verify on the compiled code?

Why Object Code? (Balakrishnan et al., 2005)

- Programs are not always available in source code (proprietary stuff, libraries)
- Do properties hold after compilation and optimisation?
- Many bugs exist because of platform specific details
- Programs may be modified after compilation
- Unspecified language constructs, use of inline assembly or multiple languages

Project Outline

- Why don't we verify on the compiled code?
- Find application domain: Linux device drivers

Why Linux Device Drivers?

- Highly critical domain
- Modular software architecture
- Small programs with high complexity
- Almost no tool support for debugging and verification
- Plenty of case studies available to compare results with

Project Outline

- Why don’t we verify on the compiled code?
- Find application domain: Linux device drivers
- Chose an intermediate representation: Valgrind

Intermediate Representation

- IA32 assembly:
  - $\approx$ 500 instructions, 3 byte opcodes
  - lots of instructions with multiple effects (i.e. `POP`, `PUSH`, `CALL`)
  - But still: clear semantics

Intermediate Representation

- Valgrind's IR (Nethercote and Fitzhardinge, 2004)
  - RISC-like assembly language with arbitrary number of temporary registers
  - 12 expressions, $\approx$ 130 operations
  - No side-effects
  - Explicit load/store operations
  - Static single assignment form

Intermediate Representation

push	%ebp	t0 = GET:I32(20) t34 = GET:I32(16) t33 = Sub32(t34,0x4:I32) PUT(16) = t33 STle(t33) = t0
mov	%esp,%ebp	PUT(60) = 0x8048375:I32 t35 = GET:I32(16) PUT(20) = t35
sub	$0x8,%esp	PUT(60) = 0x8048377:I32 t4 = GET:I32(16) t2 = Sub32(t4,0x8:I32) PUT(32) = 0x6:I32 PUT(36) = t4 PUT(40) = 0x8:I32 PUT(16) = t2

Intermediate Representation

- Defining a semantics:

$$
\begin{aligned}
Types &= \{I8, I16, I32\} \\
Addresses &= bvec_{32} \\
Values &= bvec_8 \cup bvec_{16} \cup bvec_{32} \\
Registers &= Integer \to bvec_8 \\
TempRegisters &= Integer \to (type \in Types, val \in Values \cup \{\bot\}) \\
Heap &= Addresses \to bvec_8
\end{aligned}
$$

$$
\begin{aligned}
HeapLocations &= Addresses \to (alloc : Bool, init : Bool \\
&\quad start \in Addresses, size \in bvec_{32})
\end{aligned}
$$

- command-state pair: $\langle c, (t, r, h, l) \rangle$

Intermediate Representation

- Defining a semantics:

$$\frac{t(\text{treg}).val \neq \bot}{\langle \texttt{PUT}(\text{reg}) = \text{treg}, (t, r, h, l)\rangle}$$

$$\leadsto \begin{cases} (t, [r|\text{reg} : t(\text{treg}).val], h, l) & \text{if } t(\text{treg}).type = I8 \\ (t, [r|\langle \text{reg..reg} + 1\rangle : t(\text{treg}).val], h, l) & \text{if } t(\text{treg}).type = I16 \\ (t, [r|\langle \text{reg..reg} + 3\rangle : t(\text{treg}).val], h, l) & \text{if } t(\text{treg}).type = I32 \end{cases}$$

$$\frac{t(\text{treg}).type = \text{type} \wedge t(\text{treg}).val = \bot}{\langle \text{treg} = \texttt{GET} : \text{type}(\text{reg}), (t, r, h, l)\rangle}$$

$$\leadsto \begin{cases} ([t|\text{treg}.val : r(\text{reg})], r, h, l) & \text{if type} = I8 \\ ([t|\text{treg}.val : r(\langle \text{reg..reg} + 1\rangle)], r, h, l) & \text{if type} = I16 \\ ([t|\text{treg}.val : r(\langle \text{reg..reg} + 3\rangle)], r, h, l) & \text{if type} = I32 \end{cases}$$

Intermediate Representation

- And translate the program into a set of bit-vector constraints for Yices (Dutertre and de Moura, 2006):

```
...
(define t34.0x8048374.1::(bitvector 32) (bv-concat
        (bv-concat r19.0x00000001.0.0 r18.0x00000001.0.0)
        (bv-concat r17.0x00000001.0.0 r16.0x00000001.0.0)))
(define t33.0x08048374.1::(bitvector 32)
        (bv-sub t34.0x08048374.1 (mk-bv 32 4)))
...
```

Project Outline

- Why don't we verify on the compiled code?
- Find application domain: Linux device drivers
- Chose an intermediate representation: Valgrind
- For each program location, check safety properties:

Symbolic Execution

- Construct constraint system for each possible path of the program (bounded loop unrolling)
- Registers and heap/stack are initially allowed to hold any possible value
- Add `(assert ...)` for all pointer operations
- `(check)`

Symbolic Execution

```
...
(define t36.0x08048358.1::(bitvector 32) (bv-concat
        (bv-concat (heap.00000010 (bv-add t34.0x08048358.1 (mk-bv 32 3)))
                   (heap.00000010 (bv-add t34.0x08048358.1 (mk-bv 32 2))))
        (bv-concat (heap.00000010 (bv-add t34.0x08048358.1 (mk-bv 32 1)))
                   (heap.00000010 t34.0x08048358.1))))
(define r0.0x08048358.5.1::(bitvector 8)
        (bv-extract 7 0 t36.0x08048358.1))
(define r1.0x08048358.5.1::(bitvector 8)
        (bv-extract 15 8 t36.0x08048358.1))
(define r2.0x08048358.5.1::(bitvector 8)
        (bv-extract 23 16 t36.0x08048358.1))
(define r3.0x08048358.5.1::(bitvector 8)
        (bv-extract 31 24 t36.0x08048358.1))
(define t19.0x0804835b.1::(bitvector 32) (bv-concat
        (bv-concat r3.0x08048358.5.1 r2.0x08048358.5.1)
        (bv-concat r1.0x08048358.5.1 r0.0x08048358.5.1)))
;; checking t19.0x0804835b.1 (r)
(assert (= t19.0x0804835b.1 0b00000000000000000000000000000000))
(check)
```

Project Outline

- Why don't we verify on the compiled code?
- Find application domain: Linux device drivers
- Chose an intermediate representation: Valgrind
- For each program location, check safety properties:

  bounded model checking, symbolic execution

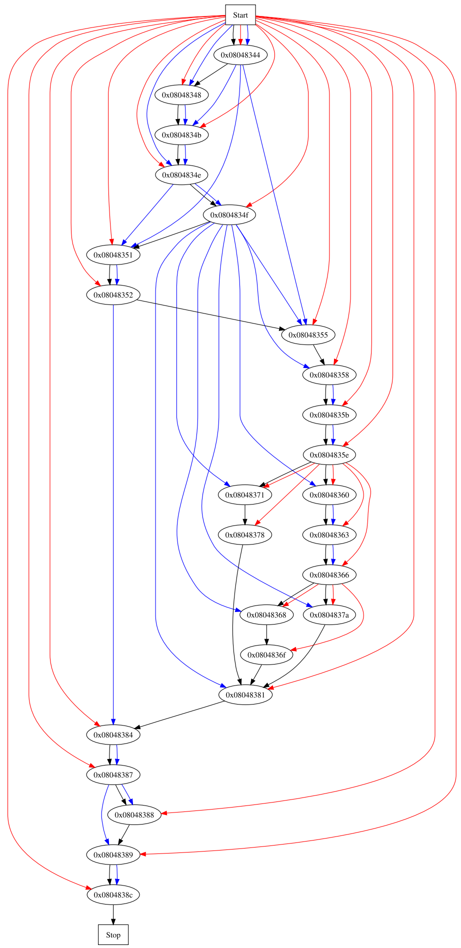
  – Of course it doesn't work. . .

Project Outline

- Why don't we verify on the compiled code?
- Find application domain: Linux device drivers
- Chose an intermediate representation: Valgrind
- For each program location, check safety properties: bounded model checking, symbolic execution, slicing

Slicing Object Code

- Program Slicing: (Weiser, 1981), (Ottenstein and Ottenstein, 1984), (Horwitz et al., 1990)
- Decomposing programs based on control and data flow
- Basically, constructing a *system dependence graph* and searching for nodes the *slicing criterion* depends on



Slicing Object Code

```
push   %ebp              t0 = GET:I32(20)
                         t34 = GET:I32(16)         <-
                         t33 = Sub32(t34,0x4:I32)  <-
                         PUT(16) = t33             <-
                         STle(t33) = t0
```

```
mov    %esp,%ebp         PUT(60) = 0x8048375:I32
                         t35 = GET:I32(16)
                         PUT(20) = t35
```

```
sub    $0x8,%esp         PUT(60) = 0x8048377:I32
                         t4 = GET:I32(16)          <-
                         t2 = Sub32(t4,0x8:I32)
                         PUT(32) = 0x6:I32
                         PUT(36) = t4              <- criterion
                         PUT(40) = 0x8:I32
                         PUT(16) = t2
```

Slicing Object Code

- Now, how do we deal with LD/ST instructions?

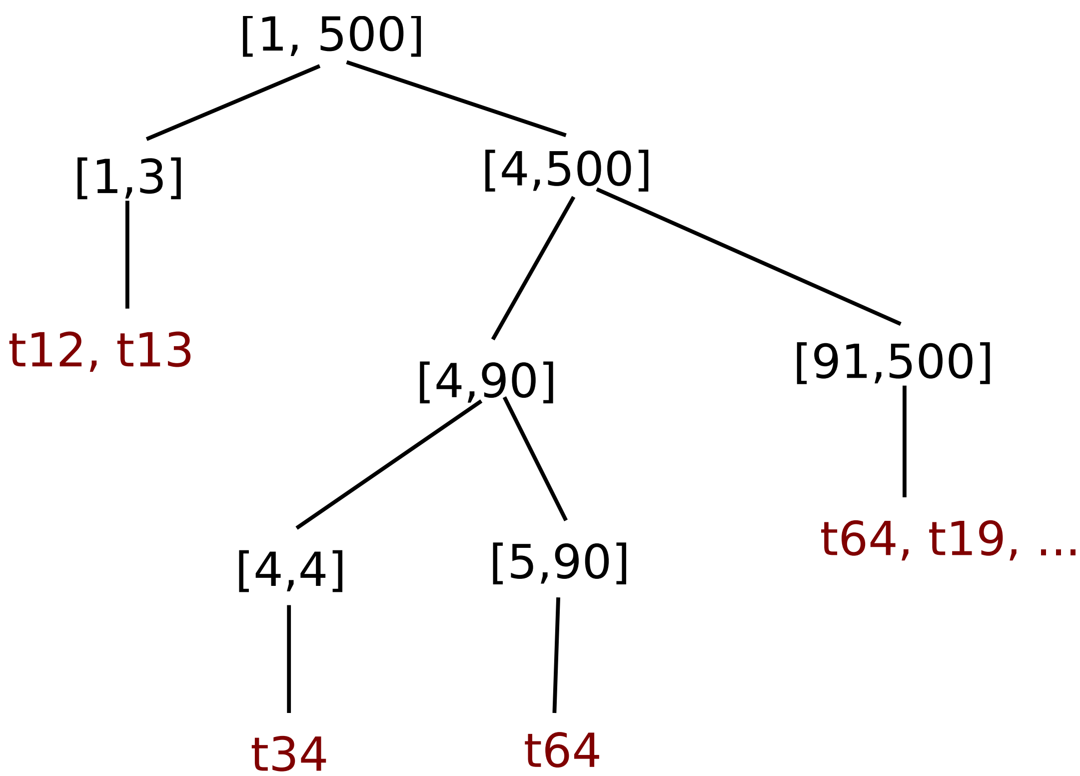
```
...
t64 = LDle:I32(t62)
...
STle(t64) = t63
STle(t34) = t1
...
t17 = LDle:I32(t18)
...
STle(t17) = t12
------------------------
(assert (= t17 0b00000000000000000000000000000000))
(check)
```

Slicing Object Code

- If all pointers evaluate to exactly one value, it's easy
- However, often they don't and we might end up with "symbolic" pointers that may hold any value between $lo \leq$ pointer $\leq up$
- Solution: Heap dependency tree

Slicing Object Code

- Solution: Heap dependency tree



Slicing Object Code

- Bounds have to be computed for all pointers – expensive
- We have to store the dependency tree – expensive as well (but probably okay for device drivers)
- We get very good slices: complete and small!

Slicing Object Code

- Is it any good? **Initial results:**
  - 30 crypto drivers (10 interface functions each, $50 \leq n \leq 3000$ instructions) analysed within less than an hour each, exhaustively
  - Usually ≤ 50 constraints per slice, solved in less than a second; but we got up to 10^3 constr.
  - Works fine for finding NULL-dereferences and access to memory that is not allocated, but lots of meaningless errors yet

Slicing Object Code

- Is it any good? **Less initial results:**
  - It doesn't scale very well.
  - Experiments were executed on 20 network card drivers and 20 file system drivers (up to 50 interface functions, $3000 \leq n \leq 30000$ instructions, lots of dependencies to the kernel)
  - Looks promising but SMT solver runs out of memory quickly

Slicing Object Code

- Optimisations:
  - **PUT/GET removal:** 60% speedup, 50% saving in memory consumption (for big systems)
  - **Constant replacement:** Not implemented yet
  - **Better initial state:** Not implemented yet

Slicing Object Code

- Using different coverage criteria:
  - Currently we do bounded loop unrolling, executing each loop up to 2000 times
  - Requiring a coverage criterion like Condition Coverage to be satisfied results in fewer and shorter paths that can be analysed without exhausting resources

Slicing Object Code

- Some pointers to literature:
  - "Recovery of Jump Table Case Statements from Binary Code" (Cifuentes and Emmerik, 1999)
  - "Interprocedural Static Slicing of Binary Executables" (Kiss et al., 2003)
  - "Analyzing Memory Accesses in x86 Executables" (Balakrishnan and Reps, 2004) and "Recovery of Variables and Heap Structure in x86 Executables" (Balakrishnan and Reps, 2005)

Slicing Object Code

- Some pointers to literature:
  - "New Developments in WCET Analysis" (Ferdinand et al., 2007)

Project Outline

- Why don't we verify on the compiled code?
- Find application domain: Linux device drivers
- Chose an intermediate representation: Valgrind
- For each program location, check safety properties: bounded model checking, symbolic execution, slicing

Project Outline

- Why don't we verify on the compiled code?
- Find application domain: Linux device drivers
- Chose an intermediate representation: Valgrind
- For each program location, check safety properties: bounded model checking, symbolic execution, slicing
- If a property is violated, generate a test case that will make the program crash – quickly

Summary

- Presented an approach to model checking compiled programs in order to find memory safety bugs
- Does not require any abstraction, only path-sensitive program slicing and symbolic execution
- Scalability issues as an artifact of object code; good chance that it scales for device drivers
- Bugs found are reproducible, but not very meaningful due to initial state being "too random"

Work still to do

- Optimisations to get it work
- Experimental evaluation: use drivers with known errors, follow evolution of a driver over a series of releases
- Try more properties (i.e. bounds checking)
- Deal with concurrency: (Flanagan and Godefroid, 2005), (Lal and Reps, 2008)
- Soundness and Completeness?
- Write a thesis

Thank you! Questions?

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