Address Space Layout Randomization

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Reading Assignment

- Shacham et al. “On the effectiveness of address-space randomization” (CCS 2004).
- Optional:
  - PaX documentation (http://pax.grsecurity.net/docs/)
  - Bhatkar, Sekar, DuVarney. “Efficient techniques for comprehensive protection from memory error exploits” (Usenix Security 2005).

Problem: Lack of Diversity

- Buffer overflow and return-to-libc exploits need to know the (virtual) address to hijack control
  - Address of attack code in the buffer
  - Address of a standard kernel library routine
- Same address is used on many machines
  - Slammer infected 75,000 MS-SQL servers using same code on every machine
- Idea: introduce artificial diversity
  - Make stack addresses, addresses of library routines, etc. unpredictable and different from machine to machine

ASLR

- Address Space Layout Randomization
- Randomly choose base address of stack, heap, code segment
- Randomly pad stack frames and malloc() calls
- Randomize location of Global Offset Table
- Randomization can be done at compile- or link-time, or by rewriting existing binaries
  - Threat: attack repeatedly probes randomized binary

PaX

- Linux kernel patch
- Goal: prevent execution of arbitrary code in an existing process's memory space
- Enable executable/non-executable memory pages
- Any section not marked as executable in ELF binary is non-executable by default
  - Stack, heap, anonymous memory regions
- Access control in mmap(), mprotect() prevents unsafe changes to protection state at runtime
- Randomize address space layout

Non-Executable Pages in PaX

- In older x86, pages cannot be directly marked as non-executable
- PaX marks each page as “non-present” or “supervisor level access”
  - This raises a page fault on every access
- Page fault handler determines if the fault occurred on a data access or instruction fetch
  - Instruction fetch: log and terminate process
  - Data access: unprotect temporarily and continue

mprotect() in PaX

- mprotect() is a Linux kernel routine for specifying desired protections for memory pages
- PaX modifies mprotect() to prevent:
  - Creation of executable anonymous memory mappings
  - Creation of executable and writable file mappings
  - Making executable, read-only file mapping writable
    - Except when relocating the binary
  - Conversion of non-executable mapping to executable

Access Control in PaX mprotect()

- In standard Linux kernel, each memory mapping is associated with permission bits
  - VM_WRITE, VM_EXEC, VM_MAYWRITE, VM_MAYEXEC
    - Stored in the vm_flags field of the vma kernel data structure
    - 16 possible write/execute states for each memory page
- PaX makes sure that the same page cannot be writable AND executable at the same time
  - Ensures that the page is in one of the 4 “good” states
    - VM_MAYWRITE, VM_MAYEXEC, VM_WRITE | VM_MAYWRITE, VM_EXEC | VM_MAYEXEC
  - Also need to ensure that attacker cannot make a region executable when mapping it using mmap()

PaX ASLR

- User address space consists of three areas
  - Executable, mapped, stack
- Base of each area shifted by a random “delta”
  - Executable: 16-bit random shift (on x86)
    - Program code, uninitialized data, initialized data
  - Mapped: 16-bit random shift
    - Heap, dynamic libraries, thread stacks, shared memory
    - Why are only 16 bits of randomness used?
  - Stack: 24-bit random shift
    - Main user stack

PaX RANDUSTACK

- Responsible for randomizing userspace stack
- Userspace stack is created by the kernel upon each execve() system call
  - Allocates appropriate number of pages
  - Maps pages to process's virtual address space
    - Userspace stack is usually mapped at 0xBFFFFFFF, but PaX chooses a random base address
- In addition to base address, PaX randomizes the range of allocated memory

PaX RANDKSTACK

- Linux assigns two pages of kernel memory for each process to be used during the execution of system calls, interrupts, and exceptions
- PaX randomizes each process's kernel stack pointer before returning from kernel to userspace
  - 5 bits of randomness
- Each system call is randomized differently
  - By contrast, user stack is randomized once when the user process is invoked for the first time

PaX RANDMMAP

- Linux heap allocation: do_mmap() starts at the base of the process's unmapped memory and looks for the first unallocated chunk which is large enough
- PaX: add a random delta_mmap to the base address before looking for new memory
    - 16 bits of randomness

PaX RANDEXEC

- Randomizes location of ELF binaries in memory
- Problem if the binary was created by a linker which assumed that it will be loaded at a fixed address and omitted relocation information
  - PaX maps the binary to its normal location, but makes it non-executable + creates an executable mirror copy at a random location
  - Access to the normal location produces a page fault
  - Page handler redirects to the mirror “if safe”
    - Looks for “signatures” of return-to-libc attacks and may result in false positives

Base-Address Randomization

- Only the base address is randomized
  - Layouts of stack and library table remain the same
  - Relative distances between memory objects are not changed by base address randomization
- To attack, it's enough to guess the base shift
- A 16-bit value can be guessed by brute force
  - Try 2^{15} (on average) overflows with different values for addr of known library function – how long does it take?
    - Shacham et al. attacked Apache with return-to-libc
    - usleep() is used (why?)
  - If address is wrong, target will simply crash

ASLR in Windows

- Vista and Server 2008
- Stack randomization
  - Find N^{th} hole of suitable size (N is a 5-bit random value), then random word-aligned offset (9 bits of randomness)
- Heap randomization: 5 bits
  - Linear search for base + random 64K-aligned offset
- EXE randomization: 8 bits
  - Preferred base + random 64K-aligned offset
- DLL randomization: 8 bits
  - Random offset in DLL area; random loading order

Bypassing Windows ASLR

- Implementation uses randomness improperly, thus distribution of heap bases is biased
  - Ollie Whitehouse's paper (Black Hat 2007)
  - Makes guessing a valid heap address easier
- When attacking browsers, may be able to insert arbitrary objects into the victim's heap
  - Executable JavaScript code, plugins, Flash, Java applets, ActiveX and .NET controls...
- Heap spraying
  - Stuff heap with large objects and multiple copies of attack code (how does this work?)

Example: Java Heap Spraying

[See Sotirov & Dowd]

- JVM makes all of its allocated memory RWX: readable, writeable, executable (why?)
  - Yay! DEP now goes out the window...
- 100MB applet heap, randomized base in a predictable range
  - 0x20000000 through 0x25000000
- Use a Java applet to fill the heap with (almost) 100MB of NOP sleds + attack code
- Use your favorite memory exploit to transfer control to 0x25A00000 (why does this work?)

Information Leaks Break ASLR

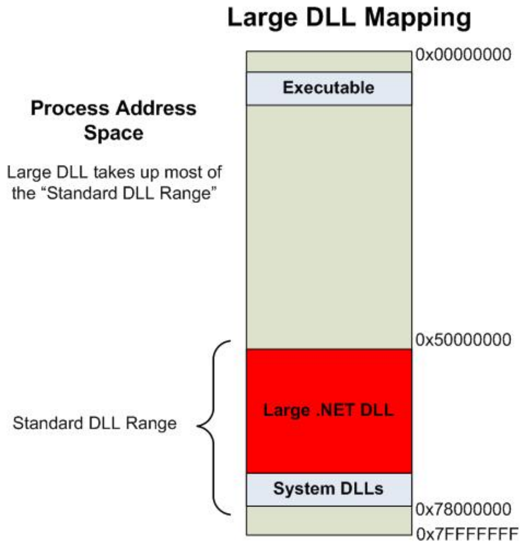
[See Sotirov & Dowd]

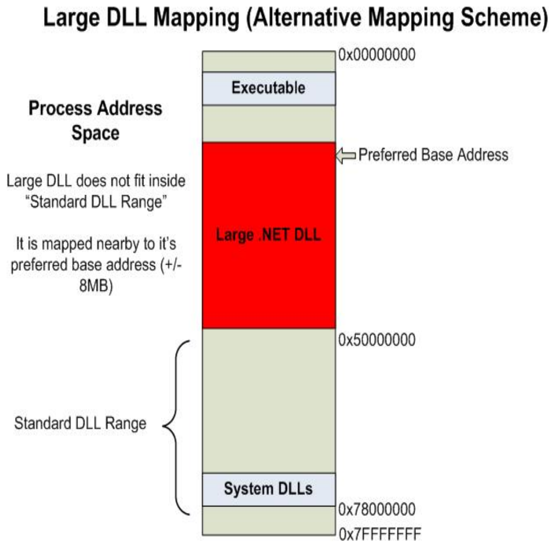
- User-controlled .NET objects are <u>not</u> RWX
- But JIT compiler generates code in RWX memory
  - Can overwrite this code or “return” to it out of context
  - But ASLR hides location of generated code stubs...
  - Call MethodHandle.GetFunctionPointer() ... .NET itself will tell you where the generated code lives!
- ASLR is often defeated by information leaks
  - Pointer betrays an object’s location in memory
    - For example, a pointer to a static variable reveals DLL’s location... for <u>all</u> processes on the system! (why?)
  - Pointer to a frame object betrays the entire stack

.NET Address Space Spraying

[See Sotirov & Dowd]

- Webpage may embed .NET DLLs
  - No native code, only IL bytecode
  - Run in sandbox, thus no user warning (unlike ActiveX)
  - Mandatory base randomization when loaded
- Attack webpage include a large (>100MB) DLL





Dealing with Large Attack DLLs

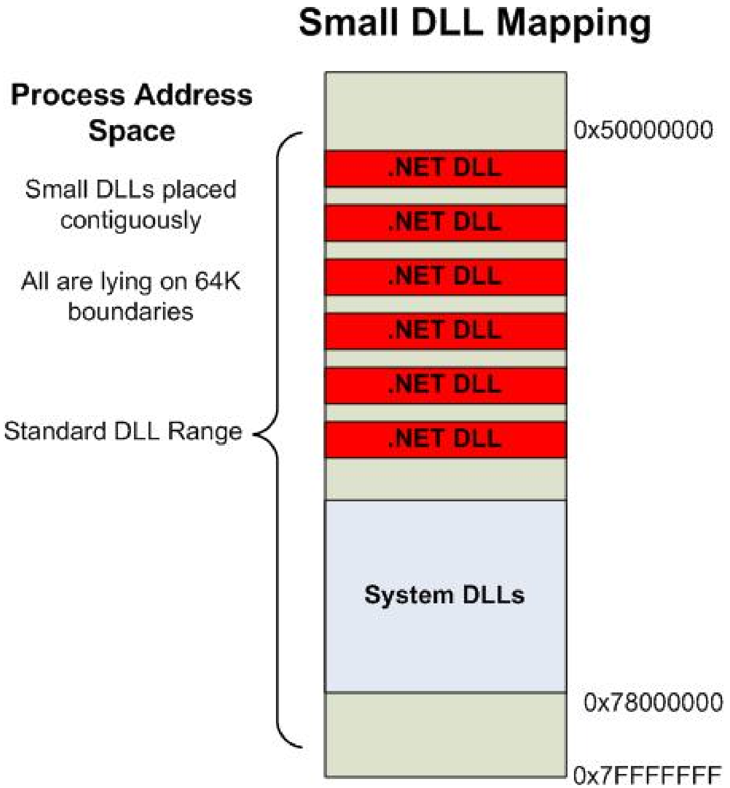
[See Sotirov & Dowd]

- 100MB is a lot for the victim to download!
- Solution 1: binary padding
  - Specify a section with a very large VirtualSize and very small SizeOfRawData – will be 0-padded when mapped
  - On x86, equivalent to add byte ptr [eax], al - NOP sled!
    - Only works if EAX points to a valid, writeable address
- Solution 2: compression
  - gzip content encoding
    - Great compression ratio, since content is mostly NOPs
  - Browser will unzip on the fly

Spraying with Small DLLs

[See Sotirov & Dowd]

- Attack webpage includes many small DLL binaries
- Large chunk of address space will be sprayed with attack code



Turning Off ASLR Entirely

[See Sotirov & Dowd]

- Any DLL may "opt out" of ASLR
  - Choose your own ImageBase, unset IMAGE_DLL_CHARACTERISTICS_DYNAMIC_BASE flag
- Unfortunately, ASLR is enforced on IL-only DLL
- How does the loader know a binary is IL-only?

```
if( ( (pCORHeader->MajorRuntimeVersion > 2) ||
    (pCORHeader->MajorRuntimeVersion == 2 && pCORHeader->MinorRuntimeVersion >= 5) ) &&
(pCORHeader->Flags & COMIMAGE_FLAGS_ILONLY) )
{
pImageControlArea->pBinaryInfo->pHeaderInfo->bFlags |= PINFO_IL_ONLY_IMAGE;
...
}
```

Set version in the header to anything below 2.5

ASLR will be disabled for this binary!

Bypassing IL Protections

[Dowd & Sotirov, PacSec 2008]

- Embedded .NET DLLs are expected to contain IL bytecode only - many protection features
  - Verified prior to JIT compilation and at runtime, DEP
  - Makes it difficult to write effective shellcode
- ... enabled by a single global variable
  - mscorwks!s_eSecurityState must be set to 0 or 2
  - Does mscorwks participate in ASLR? No!
- Similar: disable Java bytecode verification
  - JVM does not participate in ASLR, either
  - To disable runtime verification, traverse the stack and set NULL protection domain for current method

Ideas for Better Randomization (1)

- 64-bit addresses
  - At least 40 bits available for randomization
    - Memory pages are usually between 4K and 4M in size
  - Brute-force attack on 40 bits is not feasible
- Does more frequent randomization help?
  - ASLR randomizes when a process is created
  - Alternative: re-randomize address space while brute-force attack is still in progress
    - E.g., re-randomize non-forking process after each crash (recall that unsuccessful guesses result in target's crashing)
  - This does not help much (why?)

Ideas for Better Randomization (2)

- Randomly re-order entry points of library functions
  - Finding address of one function is no longer enough to compute addresses of other functions
    - What if attacker finds address of system()?
- ... at compile-time
  - Access to source, thus no virtual memory constraints; can use more randomness (any disadvantages?)
- ... or at run-time
  - How are library functions shared among processes?
  - How does normal code find library functions?

Comprehensive Randomization (1)

[Bhatkar et al.]

- Function calls
  - Convert all functions to function pointers and store them in an array
  - Reorder functions within the binary
  - Allocation order of arguments is randomized for each function call
- Indirect access to all static variables
  - Accessed only via pointers stored in read-only memory
  - Addresses chosen randomly at execution start

Comprehensive Randomization (2)

[Bhatkar et al.]

- Locations of stack-allocated objects randomized continuously during execution
  - Separate shadow stack for arrays
  - Each array surrounded by inaccessible memory regions
- Insert random stack gap when a function is called
  - Can be done right before a function is called, or at the beginning of the called function (what's the difference?)
- Randomize heap-allocated objects
  - Intercepts malloc() calls and requests random amount of additional space

Comprehensive Randomization (3)

[Bhatkar et al.]

- Randomize base of stack at program start
- Shared DLLs (see any immediate issues?)
- Procedure Linkage Table/Global Offset Table
- setjmp/longjmp require special handling
  - Must keep track of context (e.g., shadow stack location)

Summary

- Randomness is a potential defense mechanism
- Many issues for proper implementation
- Serious limitations on 32-bit architecture
  - "Thus, on 32-bit systems, runtime randomization cannot provide more than 16-20 bits of entropy"

    – Shacham et al.