StackGuard: A Historical Perspective

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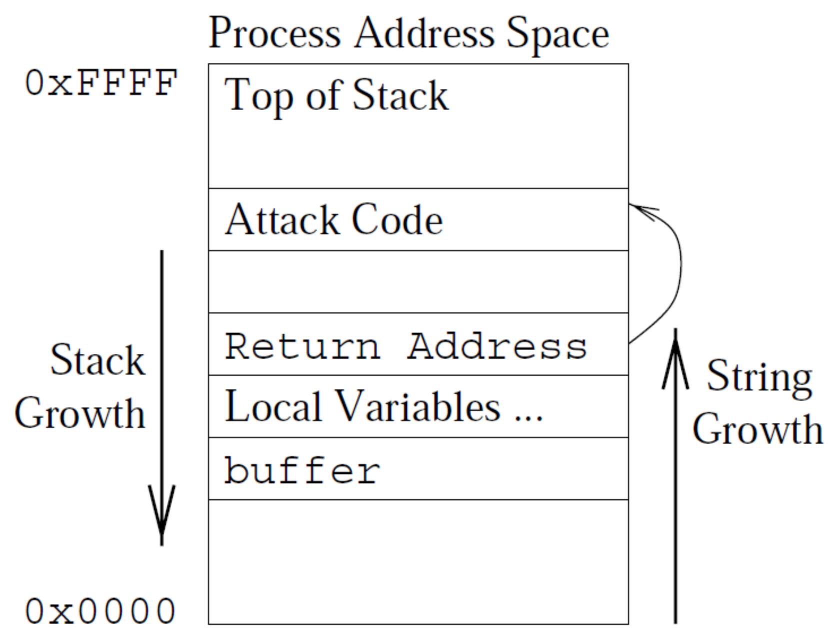
Aleph One Fires The Opening Shot

- "Smashing the Stack for Fun and Profit"
  - Aleph One (AKA Elias Levy), Phrack 49, August 1996
- It is a cook book for how to create exploits for "stack smashing" attacks
- Prior to this paper, buffer overflow attacks were *known*, but not widely exploited
  - "Validate all input parameters" is a security principle going back to the 1960s
- After this paper, attacks became rampant
  - Stack smashing vulns are massively common, easy to discover, and easy to exploit

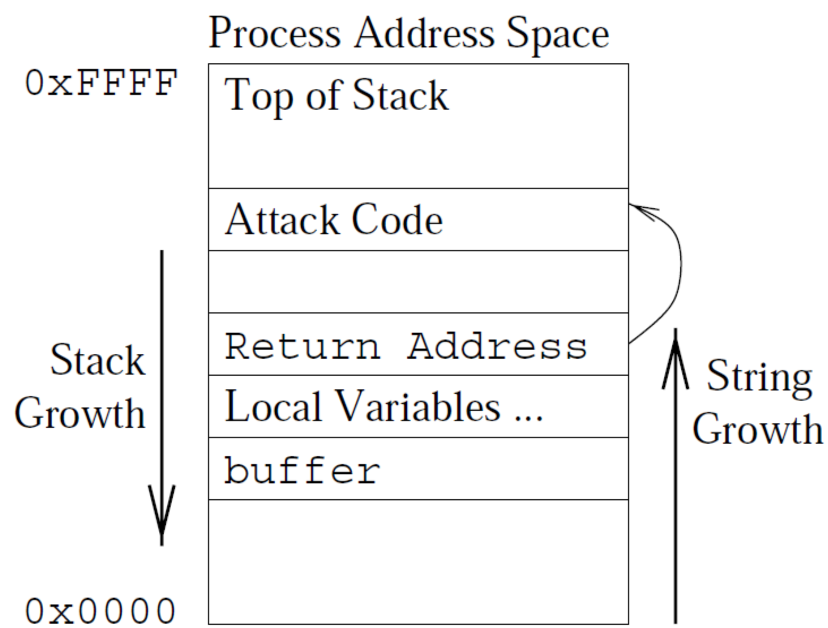
What is a “Stack Smash”?

- Buffer overflow:
  - Program accepts string input, placing it in a buffer
  - Program fails to correctly check the length of the input
  - Attacker gets to overwrite adjacent state, corrupting it
- Stack Smash:
  - Special case of a buffer overflow that corrupts the activation record



What is a “Stack Smash”?

- Return address
  - Overflow changes it to point somewhere else
- “Shell Code”
  - Point to exploit code that was encoded as CPU instructions in the attacker’s string
  - That code does `exec(“/bin/sh”)` hence “shell code”



Why Are We So Vulnerable To Something So Trivial?

- Why are we so vulnerable to something so trivial?
  - Because C chose to represent strings as null terminated instead of (base, bound) tuples
  - Because strings grow up and stacks grow down
  - Because we use Von Neumann architectures that store code and data in the same memory
- But these things are hard to change … mostly

Non-Executable Memory

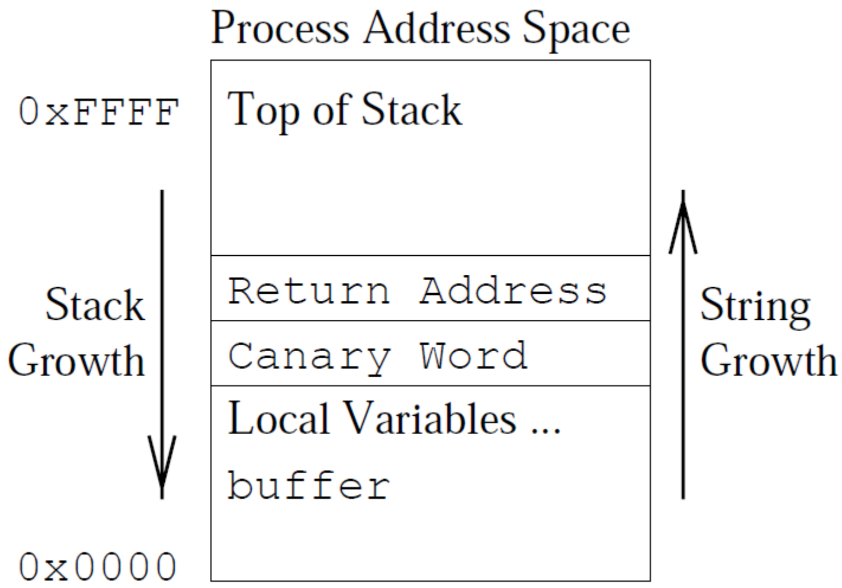
- Try to move away from Von Neumann architecture by making key regions of memory be non-executable
- Problem: x86 memory architecture does not distinguish between “readable” and “executable” per page
  - Only memory segments support this distinction
  - Most other CPU memory systems support non-executable pages, but they also mostly don’t matter ☺

Non-Executable Stack, 1997

- "Solar Designer" introduces the Linux non-executable stack patch
  - Fun with x86 segmentation registers maps the stack differently from the heap and static data
  - Results in a non-executable stack
- Effective against *naïve* Stack Smash attacks
- Bypassable:
  - Inject your shell code into the heap (still executable)
  - Point return address at your shell code in the heap

StackGuard, 1998

- Compile in integrity checks for activation records
  - Insert a "canary word" (after the Welsh miner's canary)
- If the canary word is damaged, then your stack is corrupted
  - Instead of jumping to attacker code, abort the program
  - Log the intrusion attempt



StackGuard Prototype

- Written in a few days by one intern
- Less than 100 lines of code patch to GCC
  - Helped a lot that the GCC function preamble and function post amble code generator routines were nicely isolated
- First canary was hardcoded 0xDEADBEEF
  - Easily spoofable, but worked for proof of concept

Canary Spoof Resistance

- The random canary:
  - Pull a random integer from the OS /dev/random at process startup time
  - Simple in concept, but in practice it is very painful to make reading from /dev/random work while still inside crt0.o
  - Made it work, but motivated us to seek something simpler
- “Terminator” canary:
  - CR, LF, 00, -1: the symbols that terminate various string library functions
  - Rationale: will cause all the standard string mashers to terminate while trying to write the canary → cannot spoof the canary and successfully write beyond it
  - Still vulnerable to attacks against poorly used memcpy() code, but buffer overflows thought to be rare

XOR Random Canary

- 1999, “Emsi” creates the frame pointer attack
  - Frame pointer stored below the canary → corruptible
  - Change FP to point to a *fake* activation record constructed on the heap
  - Function return code will believe FP, interpret the fake activation record, and jump to shell code
  - Bypasses both Terminator and Random Canaries
- XOR Random Canary
  - XOR the correct return address with the random canary
  - Integrity check must match both the random number, and the correct return address

Other Stack Smashing Defenses

- StackShield:
  - Copied valid return addresses to safe memory, check them on function return
  - Implemented as a modified assembler → requires hacking your makefiles
- Libsafe: armored variants of the "big 7" standard string library functions
  - Library code does a plausability check on the parameters; ensure that they are not pointing back up the stack at an activation record
  - Advantage: no recompile necessary
  - Disadvantage: no protection for hand-coded string handling, or anything other than the big-7

Other Stack Smashing Defenses

- StackGhost: uses SPARC CPU hardware to get OS in the loop to armor the stack
- Hardware: numerous papers proposing “slightly” modified CPU hardware to protect against stack smashing
  - Typically protection about as good as StackGuard
  - Advantage: don’t have to re-compile code
  - Disadvantage: do have to re-compile code to run on non-existent hardware, which tends to limit adoption ☺

StackGuard Derivatives: ProPolice

- IBM Research Japan
  - Also a modified GCC
  - Copied StackGuard defense exactly, and acknowledged it
  - Enhanced with variable sorting: sort buffers (arrays) up to the top of local variables, so that they cannot overflow other important values
- Used a different code generator technique
  - More compatible with the newer code generator architecture in GCC 2 and GCC 3
  - Ultimately ProPolice is what is adopted into GCC and became the `-fstack_protector` feature

StackGuard, uh … Concurrent Innovation ☺

- Microsoft Visual Studio: /gs
  - Uses exactly the StackGuard defense
  - Introduced in 2003; people who were there say that it was independently innovated
  - Object lesson: **patent your stuff, even if you intend to GPL it!**
- Even though introduced 5 years after StackGuard, Microsoft beat the Linux/FOSS community into mainstream adoption by several years

All the World Is Not A Stack

- As stack protection matured, attackers do what they always do: move to the next soft target
  - Heap overflows
  - Pointer corruption
  - Printf format string vulnerabilities
  - Integer “underflows”
  - …

Brute Force Defense: Buffer Bounds Checking

- Jones&Kelly built a GCC that had **full** array bounds checking
  - Associate a data structure with every buffer and check every read and write against the buffer’s legitimate size
  - Absolutely memory safe
  - Costly: between 3X and 30X slowdown

Fun With Memory Defense: DEP and ASLR

- DEP: Data Execution Protection
- ASLR: Address Space Layout Randomization
- Microsoft introduced in XPSP2
- Linux introduced bits and pieces in various places:
  - PAX Project also had NX (Like DEP) and ASLR
  - Red Hat ExecShield

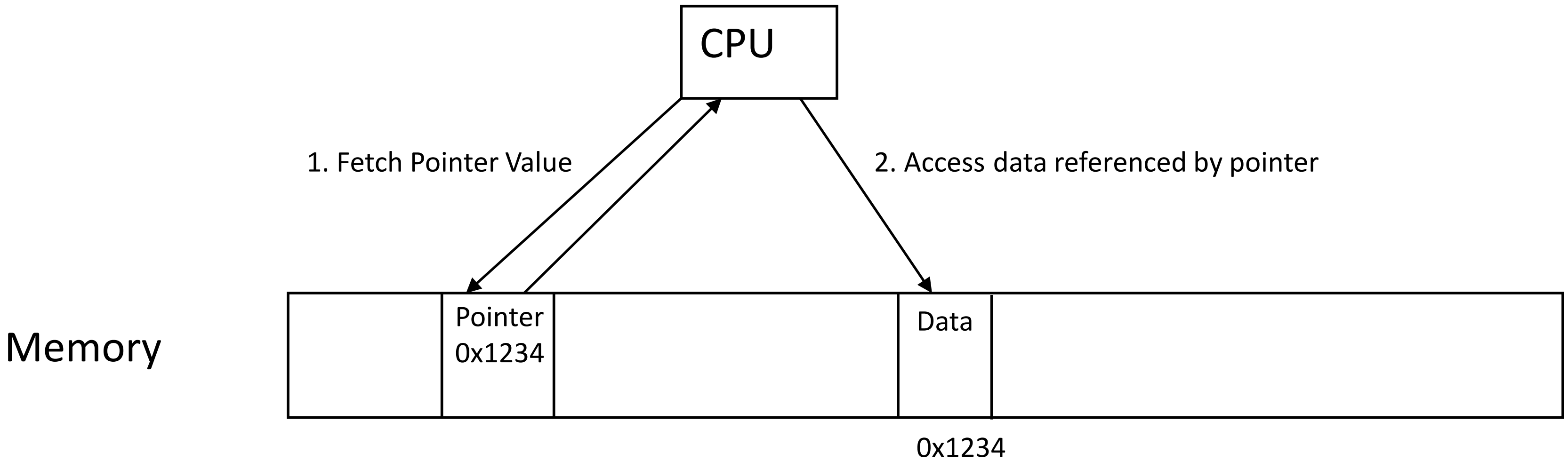
DEP and ASLR Are Critically Interdependent

- ASLR only: not enough bits of randomization
  - Attacker can inject their code surrounded by a “NOP sled”; long sequence of NOPs followed by shell code
  - Only have to jump to somewhere in the NOP sled to succeed
  - Add DEP: cannot inject code into data areas
- DEP only: there is lots of code in memory already that can do the attacker’s job
  - Originally called the “return into LibC” attack; the attacker changes the return pointer to point to some code in LibC that will run exec(“/bin/sh”)
  - Add ASLR: becomes hard for the attacker to hit that delicate target, because they **cannot** surround it with a NOP sled

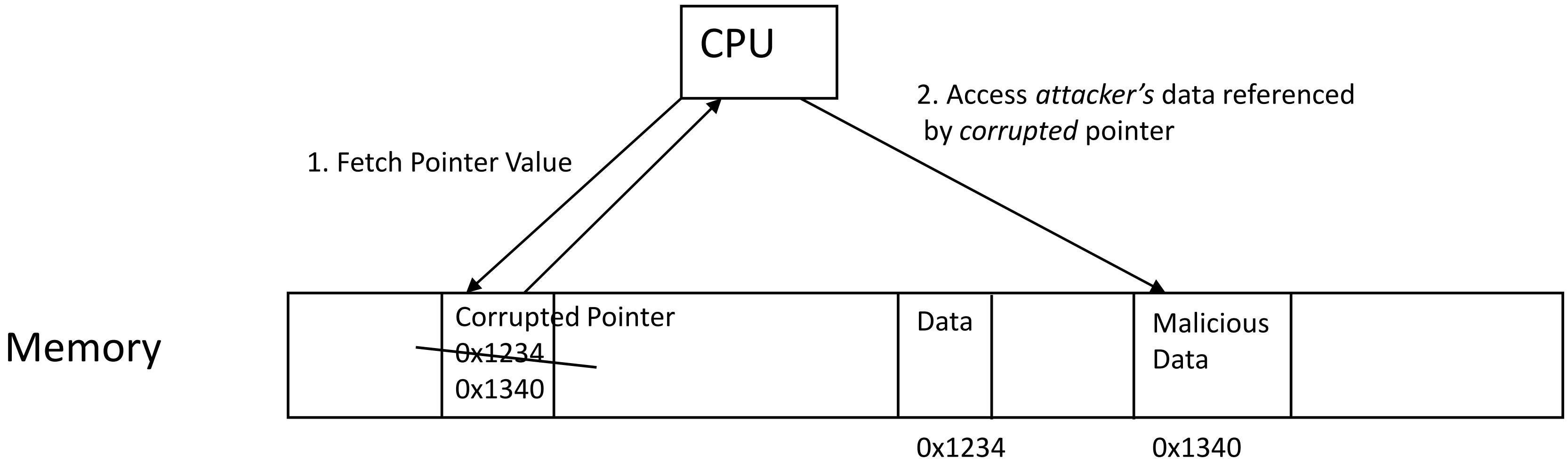
PointGuard

- Cowan et al, USENIX Security 2003
- Hashed pointers; the *dual* of ASLR
- Pointers in memory: can be corrupted via overflow
- Pointers in registers: not overflowable
- PointGuard:
  - Store pointers *encrypted* in memory
  - To dereference a pointer, decrypt it as you load it into a register

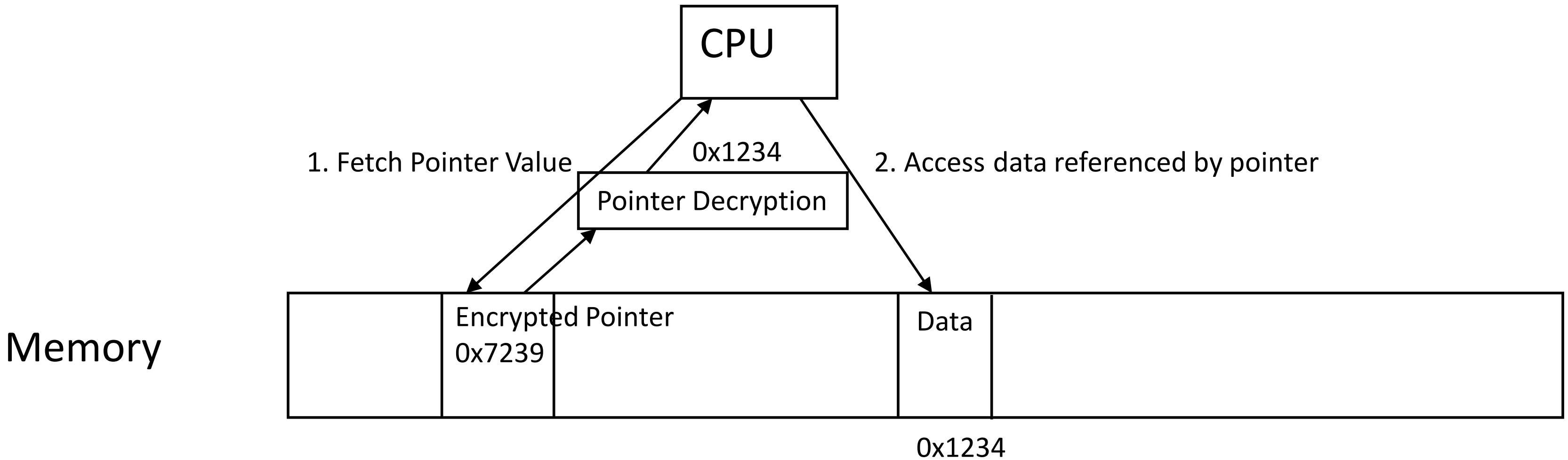
Normal Pointer Dereference



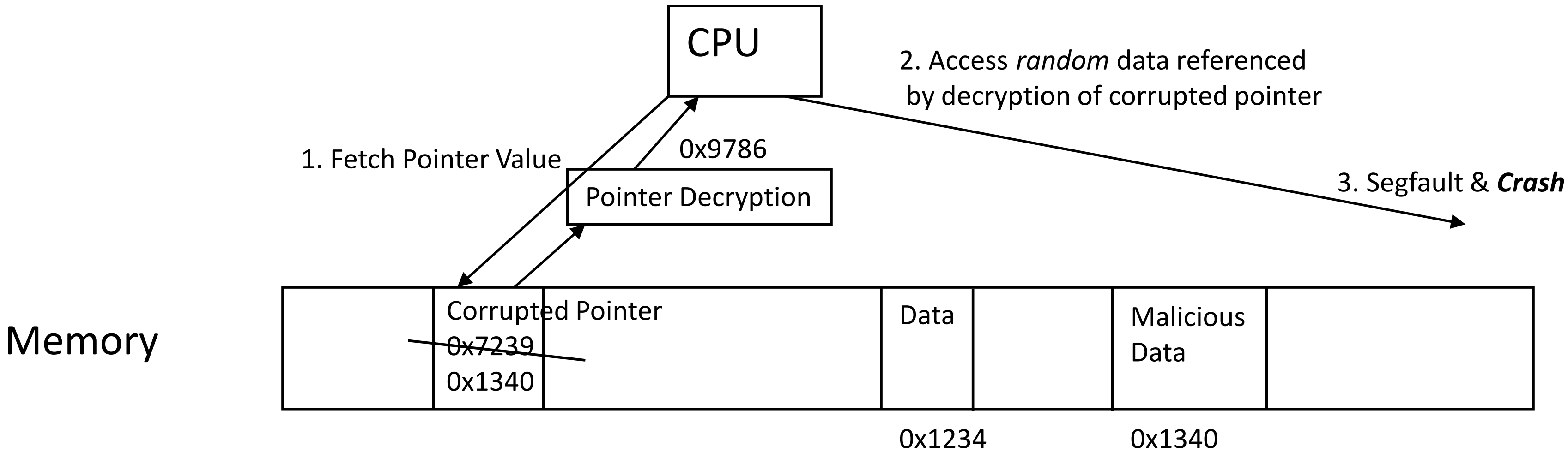
Normal Pointer Dereference Under Attack



PointGuard Pointer Dereference



PointGuard Pointer Dereference Under Attack



PointGuard Problems

- PointGuard had excellent performance
- Compatibility not so good: each PG process had its own random cookie
  - Interfacing PG code with non-PG libraries
  - Interfacing PG code with the kernel
  - Bizzarre casting: real code declares a union of two structs
    - One variant has a field that is a void *
    - Other variant has that same field as an int
    - The code expects a NULL pointer to show up as an int value == 0, which is **not true** under PG
- PointGuard abandoned due to insurmountable compat issues
  - ASLR and DEP can handle this

Buffer Overflows Today

- Heap Spray: fill heap with many many copies of the NOP sled/shell code, to defeat ASLR defenses
- JIT Spray: Heap Spray applied to the storage for JIT code, so as to bypass ASLR *and* DEP
- Wise but useless: whatever code shared an address space with the JIT buffer should have been written in a type safe language
- Research opportunity: find a way to defend against JIT Spray that allows people to share JIT address space with crap code ☺

Conclusion

- This is going to keep happening until people adopt type safe languages: Java, C#, Python, Ruby …
  - **Not** C++: it has the safety of C, and the performance of SmallTalk ☺
- But go ahead, keep writing code in insecure languages
  - It is job security for us security nerds
- Questions?
  - Crispin@microsoft.com