Approaches for Ensuring Memory Safety

- Use a memory-safe language ("safe by design")
- Use a non-memory-safe language, and check bounds in your code
- Use a non-memory-safe language, and harden the code against common exploits

Memory safe languages

- You can spare yourself this work by using a memory-safe language
  - Turns "undefined" memory references into an immediate exception or program termination
  - Now you simply don't have to worry about buffer overflows and similar vulnerabilities
- Plenty to choose from:
  - Python, Java, Go, Rust, Swift, C#, … Pretty much everything other than C/C++/Objective C

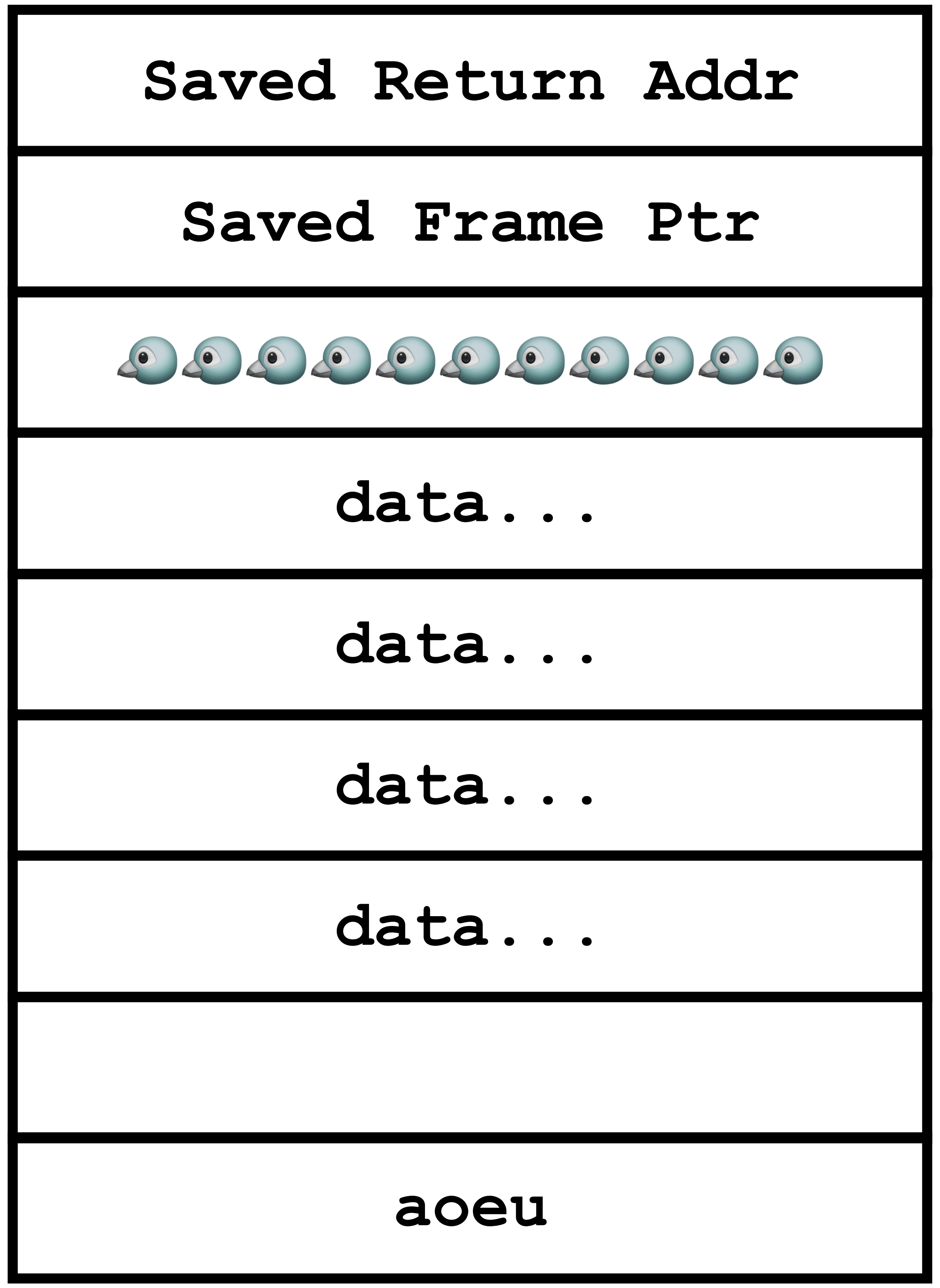
Code Hardening

Defending Legacy Code

- A large back-and-forth arms race trying to prevent memory errors from being ***exploitable for code injection***
  - An attacker can still use them to crash the program
  - An attempt at defense-in-depth
- Stack Canaries
- Non-Executable Pages (aka DEP or W^X)
- Address Space Layout Randomization (ASLR)

Stack Canaries

- Goal: protect the return pointer from being overwritten by a stack buffer…
- Store canary before saved return address
  - “Stack canary” = random value chosen when program starts
  - Function prologue pushes canary, epilogue checks canary against stored value to see if it has changed



Attacks on Stack Canaries

- Learn the value of the canary, and overwrite it with itself
  - e.g., a format string vulnerability, an information leak elsewhere that dumps it
- Random-access write past the canary
  - Canary only defends against consecutive writes
- Overflow in the heap
- Overwrite function pointer or C++ object on the stack
- Bottom line: Bypassable but raises the bar
  - A simple stack overflow doesn't work anymore:
    Need something a bit more robust
  - Minor but nearly negligible performance impact

Attack: Guessing the Canary

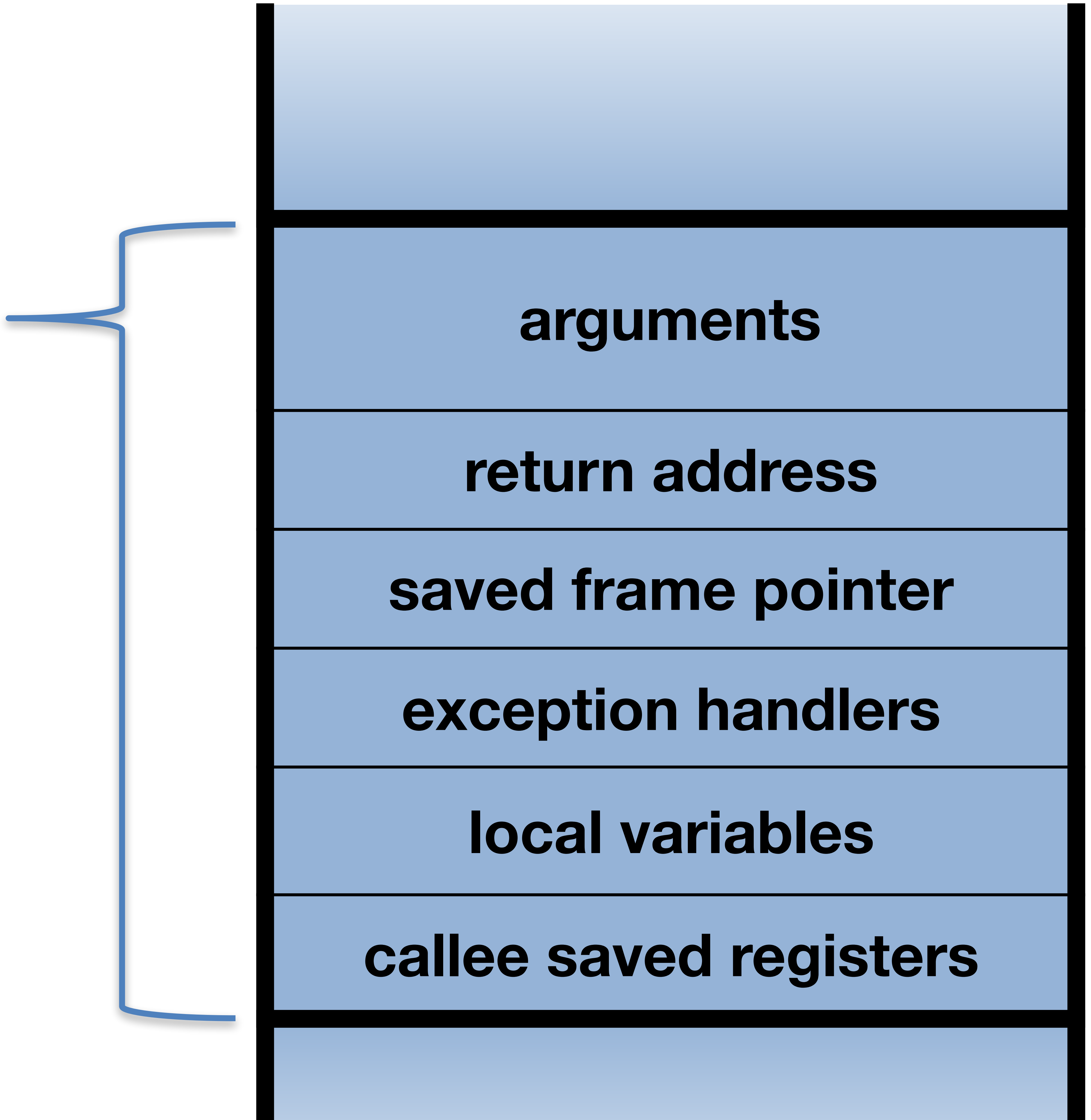
- On 32-bit x86, the canary is a 32-bit value
  - It is 64 bits on x86-64
- One byte of the canary is always 0x00
  - Since some buffer overflows can't include null bytes: e.g. if the vulnerability is in a bad call to **`strcpy`**
- This means you can (possibly) brute-force the canary
  - Need to try about 2^{24} times or so

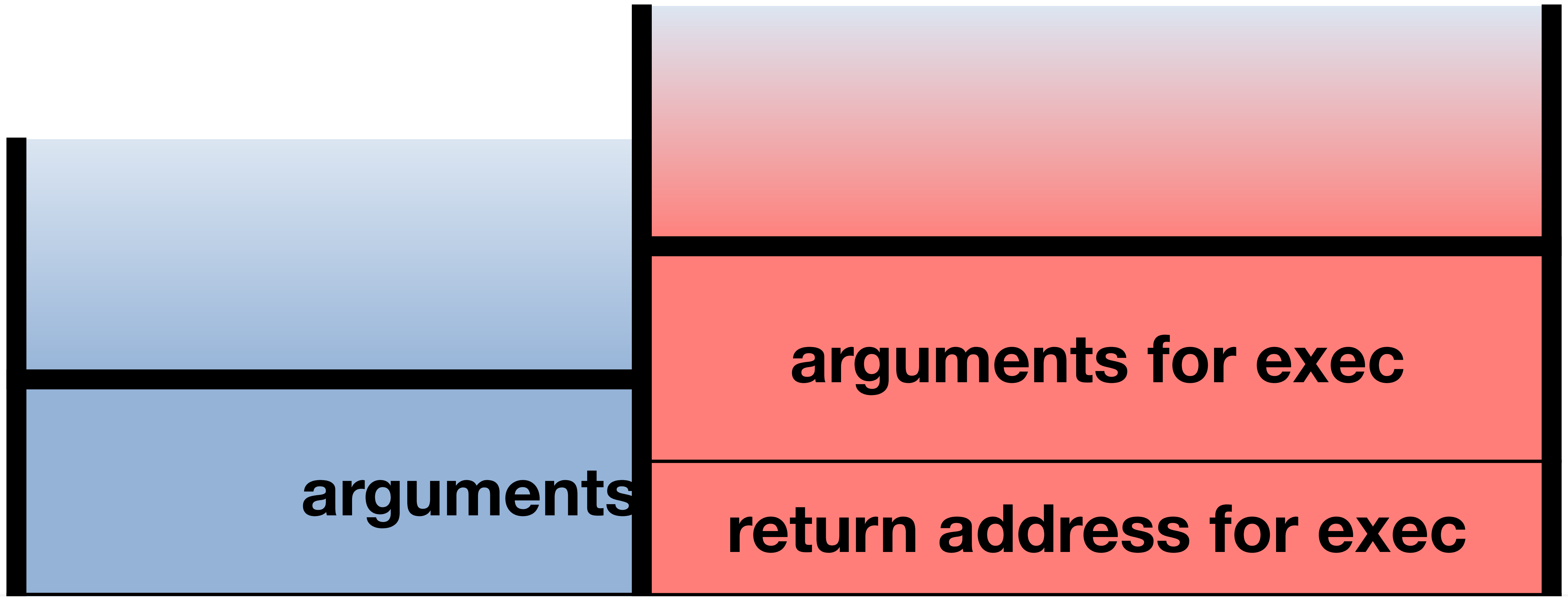
Non-Executable Pages (aka DEP, W^X)

- Each page of memory has separate access permissions:
  - R -> Can Read, W -> Can Write, X -> Can Execute
- Defense: mark writeable pages as non-executable
  - Now you can’t write code to the stack or heap
- No noticeable performance impact

Attacks on Non-Executable Pages

- Return into libc: set up the stack and “return” to exec()
  - Overwrite stuff above saved return address with a “fake call stack”, overwrite saved return address to point to the beginning of exec() function
  - Especially easy on x86 since arguments are passed on the stack
- Return Oriented Programming


arguments
return address
saved frame pointer
exception handlers
local variables
callee saved registers


arguments for exec
arguments
return address for exec

Return Oriented Programming

- Idea: chain together “return-to-libc” idea many times
  - Find a set of short code fragments (gadgets) that when called in sequence execute the desired function
  - Inject into memory a sequence of saved "return addresses" that will invoke them
  - Sample gadget: add one to EAX, then return
- ROP compiler
  - Find enough gadgets scattered around existing code that they’re Turing-complete
  - Compile your malicious payload to a sequence of these gadgets
- Tools democratize things for attackers:
  - Yesterday's Ph.D. thesis or academic paper is today's Intelligence Agency tool and tomorrow's Script Kiddie download

Address Space Layout Randomization

- Randomly relocate everything in memory
  - Every library, the start of the stack & heap, etc…
  - With 64-bit architecture you have lots of entropy
  - 32-bit? Hard to get enough entropy, as segments need to be page-aligned (i.e., start at a 4096-byte boundary), so attacker might be able to brute-force it

ASLR Efficiency

- Performance overhead is close to 0%
  - Everything needs to be ***relocatable*** anyway:
    Modern systems use relocatable code and dynamically load all the desired libraries

ASLR + DEP

- ALSR + DEP make many exploits harder
  - Typically, need two vulnerabilities: both a buffer overrun and a separate information leak (such as a way to find the address of a function)
  - Information leak needed to fill in the return addresses for ROP chain

Defense In Depth in ALSR + DEP: Attacker Requirements

- Attacker first needs to discover a way to ***read*** memory
  - Just a single pointer to a known library will do, however
    - The return address off the stack is often a great candidate
    - Or a **`vtable`** pointer for an object of a known type
- Armed with this, the attacker now can create a ROP chain
  - Since the attacker has a copy of the library of their own and has already passed it through a ROP compiler, it just needs to know the starting point for the library
- Now the attacker needs to ***write*** memory
  - Writes the ROP chain and overwrites a control flow pointer

Defenses-In-Depth in Practice

- Apple iOS uses ASLR in the kernel and userspace, W^X whenever possible
  - All applications are sandboxed to limit their damage: The kernel is the TCB
- The "Trident" exploit was used by a spyware vendor, the NSO group, to exploit iPhones of targets
- So to remotely exploit an iPhone, the NSO group's exploit had to...
  - Exploit Safari with a memory corruption vulnerability
    - Gains remote code execution within the sandbox: write to a R/W/X page as part of the JavaScript JIT
  - Exploit a vulnerability to read a section of the kernel stack
    - Saved return address & knowing which function called breaks the ASLR
  - Exploit a vulnerability in the kernel to enable code execution
- Full details: https://info.lookout.com/rs/051-ESQ-475/images/pegasus-exploits-technical-details.pdf

Safari Exploit: More Details

- Basic idea: can corrupt a JavaScript object (due to interaction with garbage collector) to trigger a use-after-free issue
  - Attacker's JavaScript has access to both objects that share the same memory:
    - Newly allocated object is an array of integers
    - Old object changes the length of the array to be 0xFFFFFFFF
- Now attacker has a "read/write" primitive
  - The array can see a huge fraction of the memory space
    - First thing, find out the offset of the array itself, then any other magic numbers needed
- Turning it into execution
  - Take another JavaScript object that will get compiled (the "Just In Time" compiler)...
  - That object's code pointer will point into space that is writeable and executable

Fuzz testing

- Automated testing is surprisingly effective at finding memory-safety vulnerabilities
- How do we tell when we've found a problem? Program crashes
- How do we generate test cases?
  - Random testing: generate random inputs
  - Mutation testing: start from valid inputs, randomly flip bits in them
  - Coverage-guided mutation testing: start from valid input, flip bits, measure coverage of each modification, keep any inputs that covered new code

Why does software have vulnerabilities?

- Programmers are humans.
  And humans make mistakes.
  - Use tools
- Programmers often aren't security-aware.
  - Learn about common types of security flaws.
- Programming languages aren't designed well for security.
  - Use better languages (Java, Python, …).

Some Approaches for Building Secure Software/Systems

- Run-time checks
  - Automatic bounds-checking (overhead)
- Code hardening
  - Address randomization
  - Non-executable stack, heap
- Monitor code for run-time misbehavior
  - E.g., illegal calling sequences
  - But again: what do you if detected?

Approaches for Secure Software, con't

- Program in checks / "defensive programming"
  - E.g., check for null pointer even though sure pointer will be valid
- Use safe libraries
  - E.g. `strlcpy`, not `strcpy`; `snprintf`, not `sprintf`
- Bug-finding tools
- Code review

Approaches for Secure Software, con’t

- Use a memory-safe language
  - E.g., Java, Python, C#, Go, Rust
- Defensive validation of untrusted input
  - Constrain how untrusted sources can interact with the system
- Contain potential damage
  - Privilege separation, run system components in least-privilege jails or VMs