Control Hijacking

Control Hijacking: Defenses

Recap: control hijacking attacks

Stack smashing: overwrite return address or function pointer

Heap spraying: reliably exploit a heap overflow

Use after free: attacker writes to freed control structure,
which then gets used by victim program

Integer overflows

Format string vulnerabilities

⋮

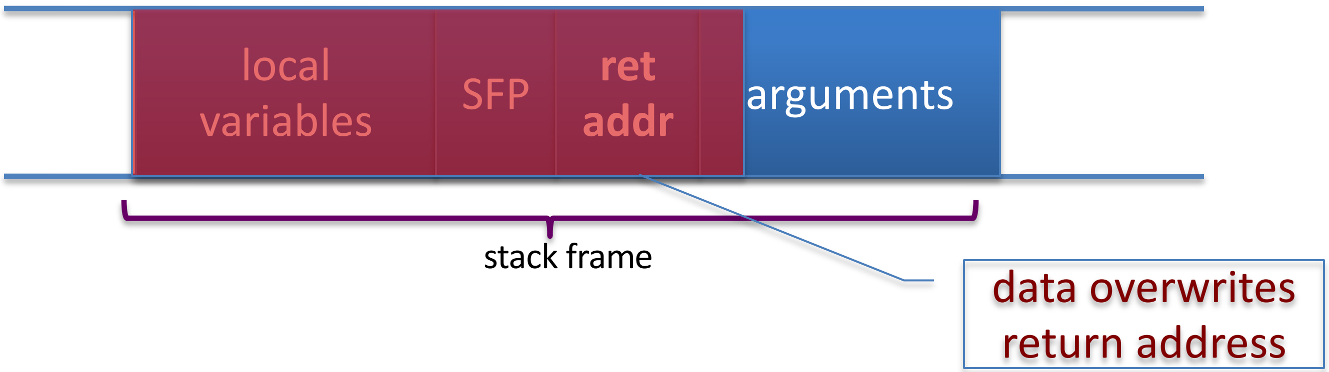
The mistake: mixing data and control

- An ancient design flaw:
  - enables anyone to inject control signals

- 1971: AT&T learns never to mix control and data

Control hijacking attacks

The problem: mixing data with control flow in memory



Later we will see that mixing data and code is also the reason for XSS, a common web vulnerability

Preventing hijacking attacks

1. Fix bugs:
   – Audit software
     - Automated tools: Coverity, Infer, … (more on this next week)
   – Rewrite software in a type safe languange (Java, Go, Rust)
     - Difficult for existing (legacy) code …

2. Platform defenses: prevent attack code execution

3. Harden executable to detect control hijacking
   – Halt process and report when exploit detected
   – StackGuard, ShadowStack, Memory tagging (ASan, MTE), …

Transform:

Complete Breach

Denial of service

Control Hijacking

Platform Defenses

Marking memory as non-execute (DEP)

Prevent attack code execution by marking stack and heap as **non-executable**

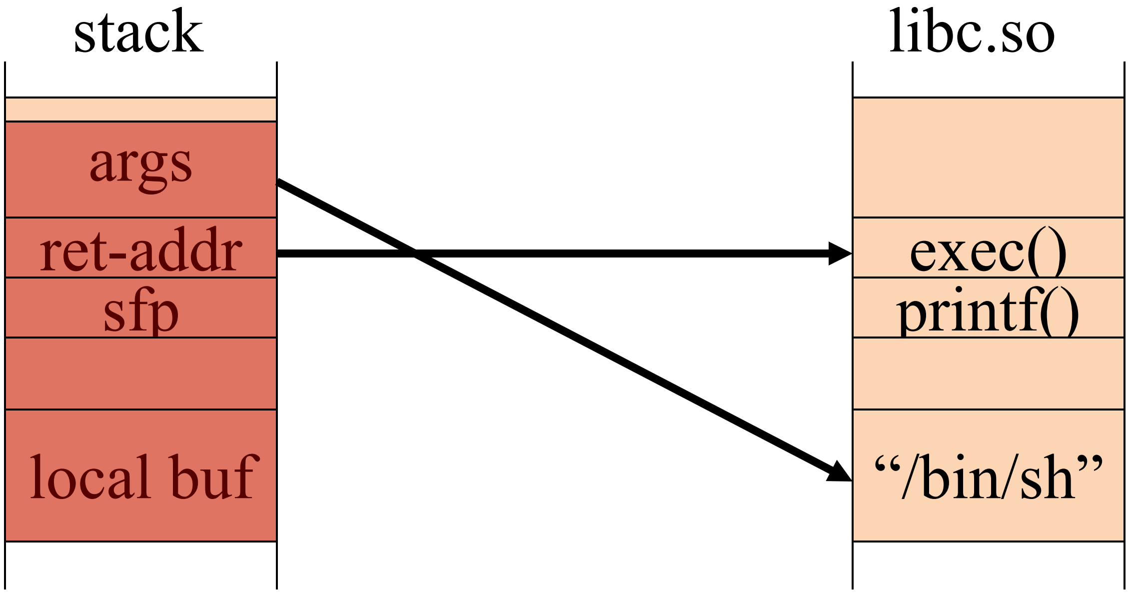
NX-bit on AMD64, **XD-bit** on Intel x86 (2005), **XN-bit** on ARM
- disable execution: an attribute bit in every Page Table Entry (PTE)

- Deployment:
  - All major operating systems
    - Windows DEP: since XP SP2 (2004) (Visual Studio: /NXCompat[:NO])

- Limitations:
  - Some apps need executable heap (e.g. JITs).
  - Can be easily bypassed using **Return Oriented Programming (ROP)**

Attack: Return Oriented Programming (ROP)

Control hijacking **without injecting code**:



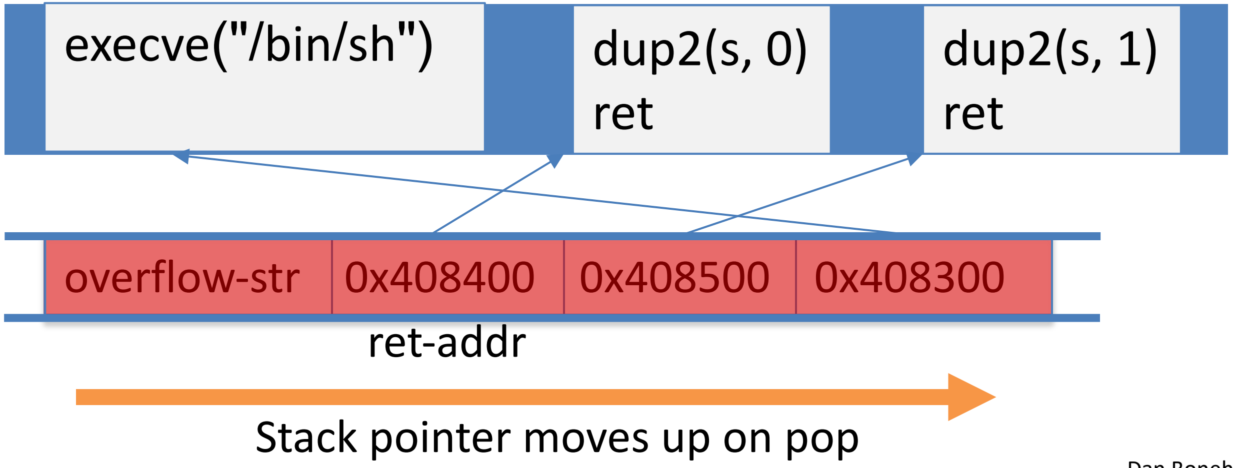
ROP: in more detail

To run /bin/sh we must direct ***stdin*** and ***stdout*** to the socket:

```
dup2(s, 0)          // map stdin to socket
dup2(s, 1)          // map stdout to socket
execve("/bin/sh",  0,  0);
```

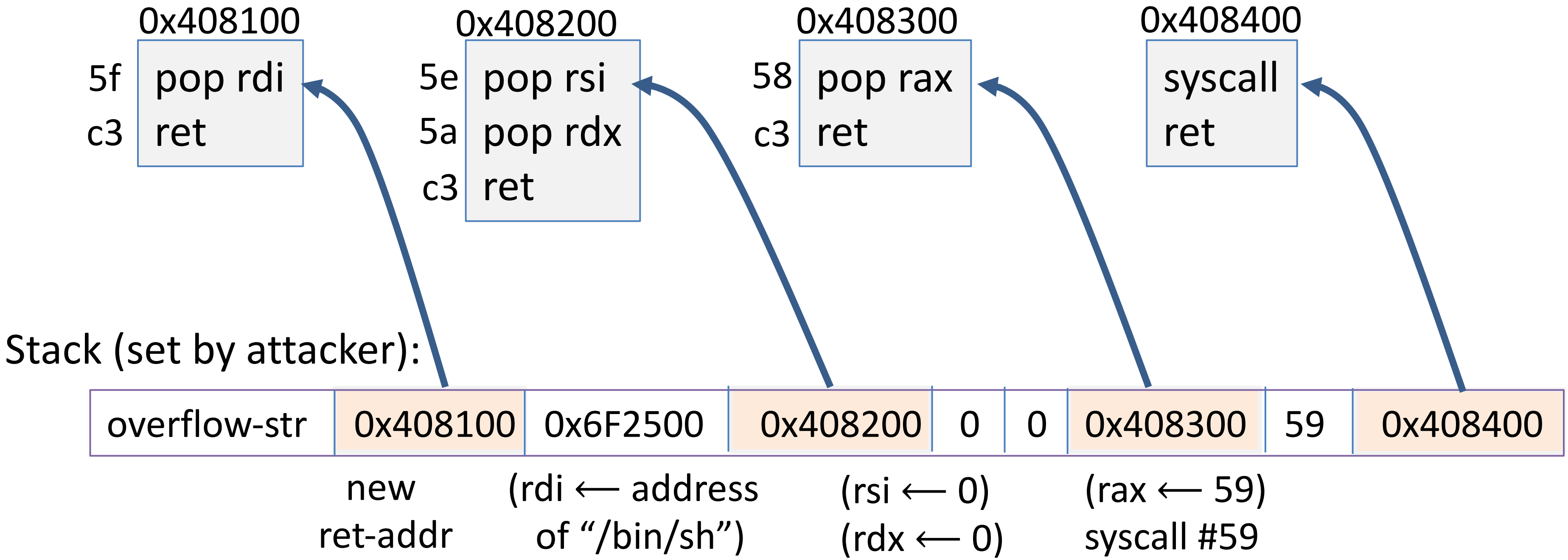
Gadgets in victim code:

Stack (set by attacker):



ROP: in even more detail

execve("/bin/sh", 0, 0): implemented using gadgets in victim code:



What to do?? Randomization

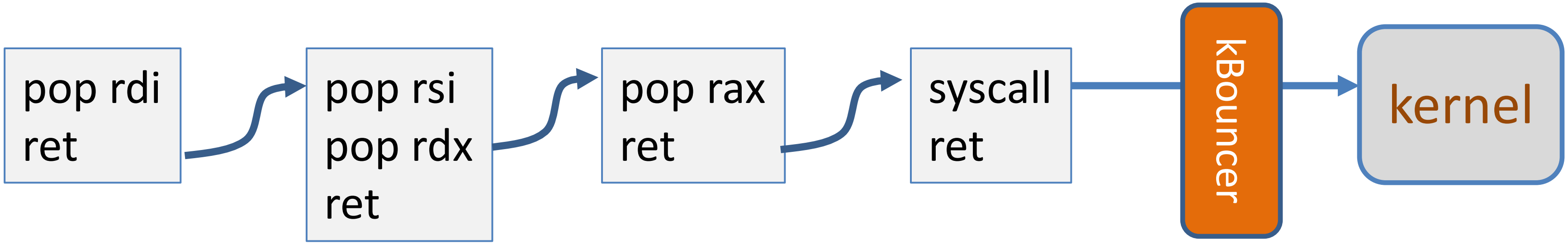
- **ASLR**: (Address Space Layout Randomization)
  - On load: randomly shift base of code & data in process memory

    ⇒ Attacker does not know location of code gadgets

  - Deployment: (/DynamicBase)
    - Since **Windows 8:** 24 bits of randomness on 64-bit processors
    - Base of everything must be randomized on load:
      - libraries (DLLs, shared libs), application code, stack, heap

- Other randomization ideas (not used in practice):
  - Sys-call randomization: randomize sys-call id’s
  - Instruction Set Randomization (ISR)

A very different idea: kBouncer



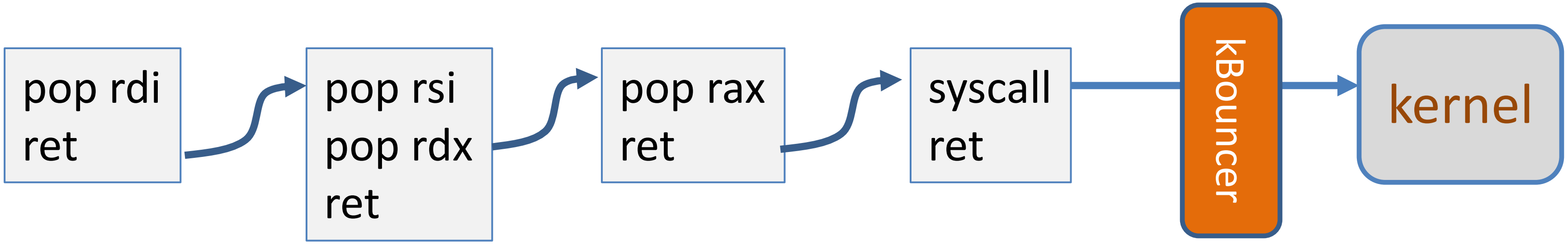
Observation: abnormal execution sequence

- ***ret*** returns to an address that does not follow a ***call***

Idea: before a syscall, check that every prior ret is not abnormal

- How: use Intel's *Last Branch Recording* (LBR)

A very different idea: kBouncer



Inte's **Last Branch Recording** (LBR):

- store 16 last executed branches in a set of on-chip registers (MSR)
- read using ***rdmsr*** instruction from privileged mode

kBouncer: before entering kernel, verify that last 16 ***ret***s are normal

- Requires no app. code changes, and minimal overhead
- Limitations: attacker can ensure 16 calls prior to syscall are valid

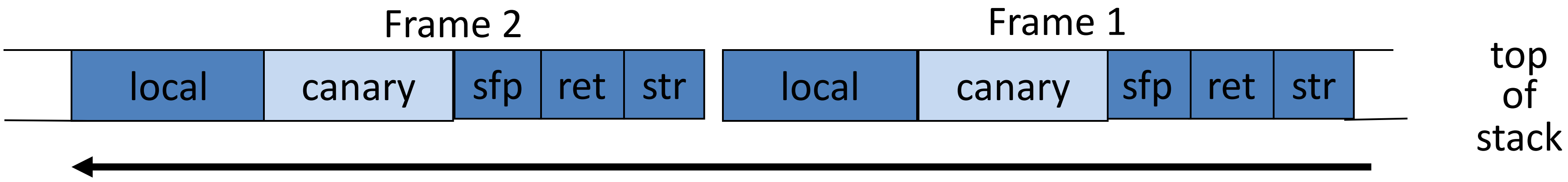
Control Hijacking Defenses

Hardening the executable

Run time checking: StackGuard

- Many run-time checking techniques …
  - we only discuss methods relevant to overflow protection

- Method 1: StackGuard
  - Run time tests for stack integrity.
  - Embed "canaries" in stack frames and verify their integrity prior to function return.



Canary Types

- Random canary:
  - Random string **chosen at program startup**
  - Insert canary string into every stack frame
  - Verify canary before returning from function
    - Exit program if canary changed. Turns potential exploit into DoS.
  - To corrupt, attacker must learn/guess current random string

- Terminator canary: Canary = {0, newline, linefeed, EOF}
  - String functions will not copy beyond terminator
  - Attacker cannot use string functions to corrupt stack.

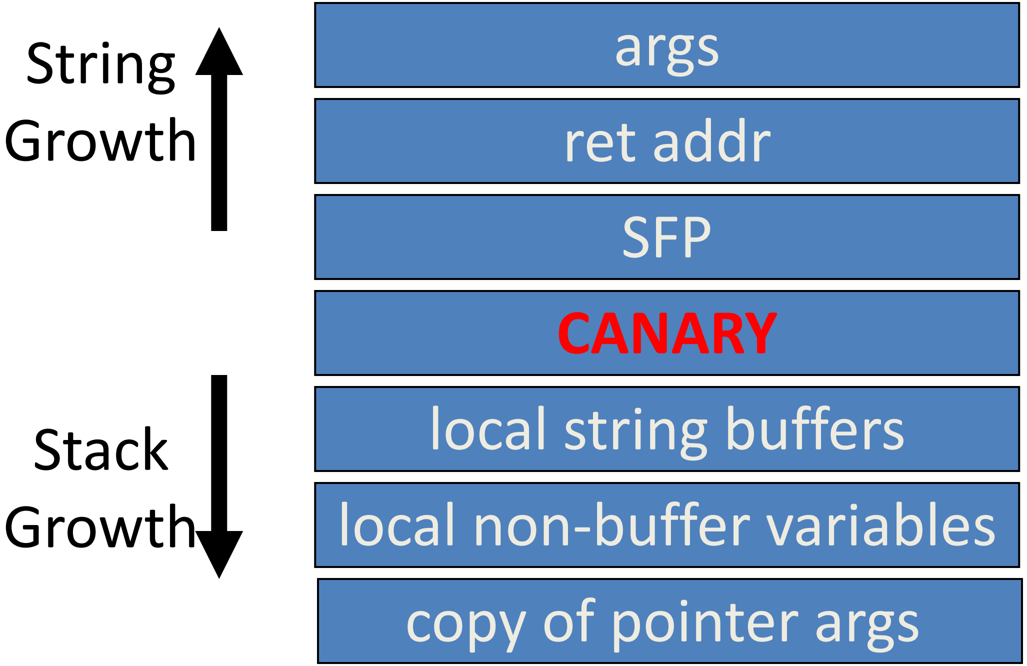
StackGuard (Cont.)

- StackGuard implemented as a GCC patch
  - Program must be recompiled

- Minimal performance effects: 8% for Apache

StackGuard enhancement: ProPolice

- ProPolice - since gcc 3.4.1. (**-fstack-protector**)
  - Rearrange stack layout to prevent ptr overflow.



Protects pointer args and local pointers from a buffer overflow

pointers, but no arrays

MS Visual Studio /GS (BufferSecurityCheck)

Compiler /GS option:

- Combination of ProPolice and Random canary.
- If cookie mismatch, default behavior is to call **_exit(3)**

Function prolog:

```
sub   esp, 4     // allocate 4 bytes for cookie
mov   eax, DWORD PTR ___security_cookie
xor   eax, esp     // xor cookie with current esp
mov   DWORD PTR [esp+4], eax  // save in stack
```

Function epilog:

```
mov   ecx, DWORD PTR  [esp+4]
xor   ecx, esp
call  @__security_check_cookie@4
add   esp, 4
```

Protects all stack frames, unless can be proven unnecessary

Summary: Canaries are not full proof

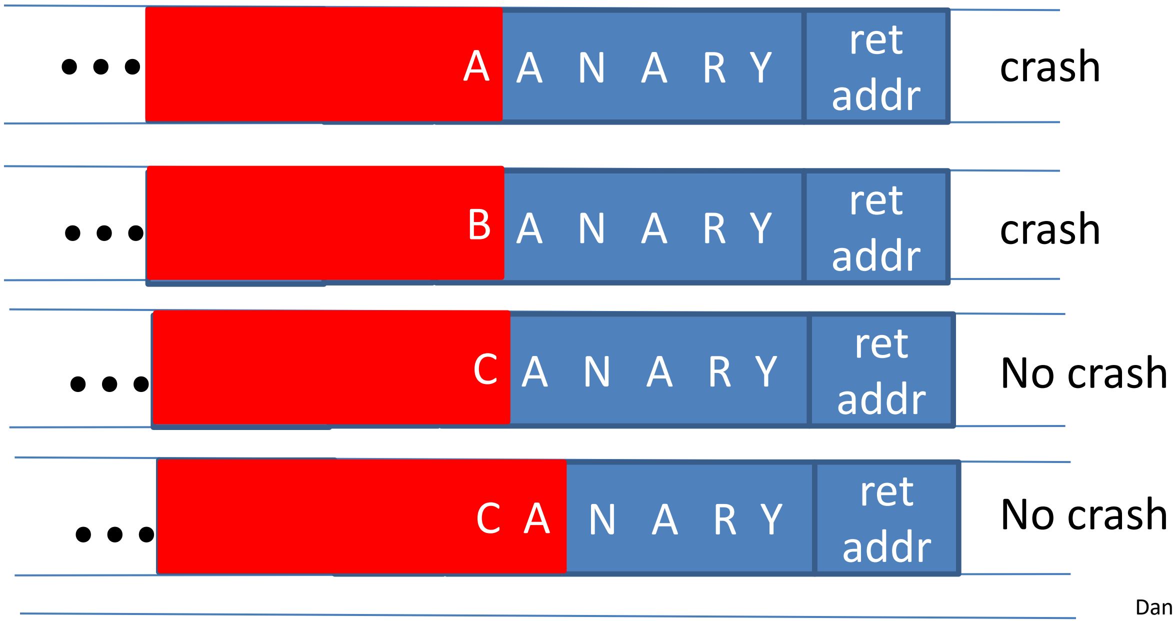
- Canaries are an important defense tool, but do not prevent all control hijacking attacks:
  - Some stack smashing attacks leave canaries unchanged: how?
  - Heap-based attacks still possible
  - Integer overflow attacks still possible

Even worse: canary extraction

A common design for crash recovery:

- When process crashes, restart automatically (for availability)
- Often canary is unchanged (reason: relaunch using fork)

> Danger:
> - canary extraction byte by byte



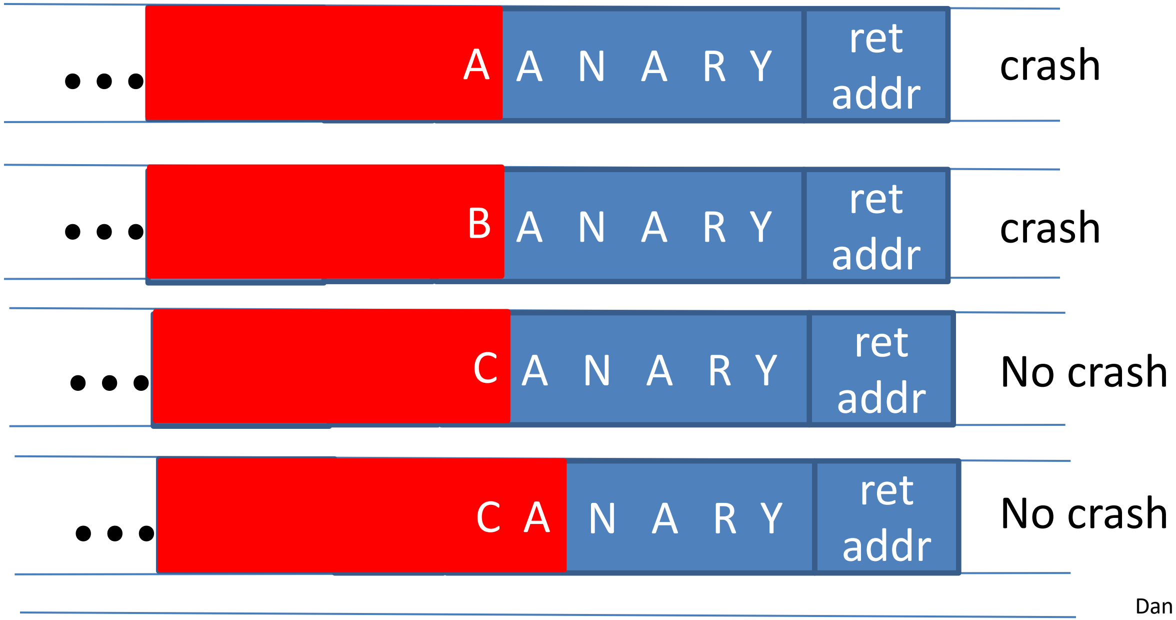
Similarly: extract ASLR randomness

A common design for crash recovery:

- When process crashes, restart automatically (for availability)
- Often canary is unchanged (reason: relaunch using fork)

Danger:

Extract ret-addr to de-randomize app. code ASLR



More methods: Shadow Stack

Shadow Stack: keep a <u>copy</u> of the stack in memory

- **On call**: push ret-address to shadow stack on call
- **On ret**: check that top of shadow stack is equal to ret-address on stack. Crash if not.
- Security: memory corruption should not corrupt shadow stack

Shadow stack using **Intel CET:** (supported in Windows 10, 2020)

- New register SSP: shadow stack pointer
- Shadow stack pages marked by a new “shadow stack” attribute: only “call” and “ret” can read/write these pages

ARM Memory Tagging Extension (MTE)

Idea: (1) every 64-bit **memory pointer** P has a 4-bit “tag” (in top byte)

(2) every 16-byte user **memory region** R has a 4-bit “tag”

Processor ensures that: if P is used to read R then tags are equal

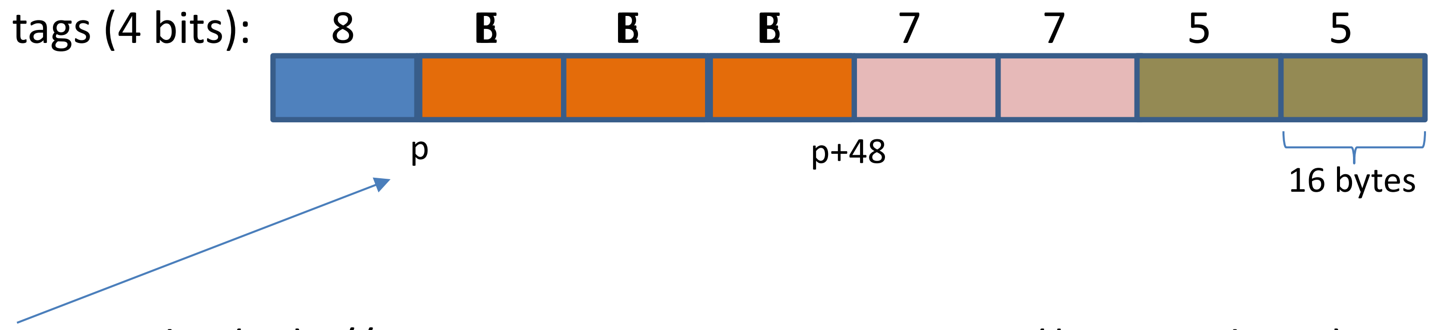
– otherwise: hardware exception

Tags are created using new HW instructions:

- LDG, STG: load and store tag to a memory region (used by malloc and free)
- ADDG, SUBG: pointer arithmetic on an address preserving tags

Tags prevent buffer overflows and use after free

Example:



(1) char *p = new char(40); // p = 0x B000 6FFF FFF5 1240 (*p tagged as **B**)

(2) p[50] = ’a’; // B≠7 ⟹ tag mismatch exception (buffer overflow)

(3) delete [] p; // memory is re-tagged from **B** to **E**

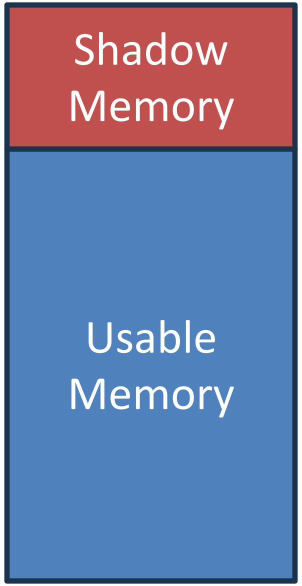
(4) p[7] = ‘a’; // B≠E ⟹ tag mismatch exception (use after free)

Note: out of bounds access to p[44] at (2) will not be caught.

AddressSanitizer (ASan): a software tool

For every 8 bytes of usable memory,
allocate one byte in shadow to record its allocation status:

- 0: all 8 bytes are allocated (e.g., by malloc)
- $1 \leq k \leq 7$: first k bytes are allocated
- negative number: 8 bytes should not be accessed



Compiler places a guard before every memory access. Example:

```
ShadowAddr = (Addr >> 3) + ShadowOffset;   // address in shadow mem
if (*ShadowAddr != 0)  ReportAndCrash(Addr);  // crash if not fully alloc.
t = *Addr;   // program can now read/write address Addr
```

Shadow memory eats up 1/8th of physical memory $\Rightarrow$ expensive

- ASan is mostly used when fuzzing a program (e.g., Chrome)

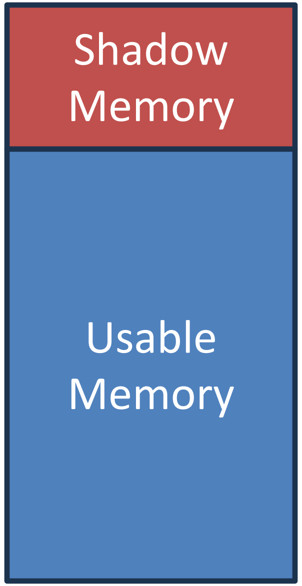
https://storage.googleapis.com/gweb-research2023-media/pubtools/pdf/37752.pdf

AddressSanitizer (ASan): a software tool

Using ASan to detect a buffer overflow on stack or heap:

	rz	mem1	rz	mem2	rz	mem3	rz
tags:	-1	0 0 0 0 0 4	-1	0 0 0 0 0 0 0 0 6	-1	0 0 0 0	-1
in shadow memory		5×8+4 = 44 bytes		8×8+6 = 70 bytes			

overflow will cause an access to a red zone (rz) ⇒ crash program



after mem2 is freed:

	rz	mem1	rz	freed mem2	rz	mem3	rz
tags:	-1	0 0 0 0 0 4	-1	-1 -1 -1 -1 -1 -1 -1	-1	0 0 0 0	-1

use-after-free at mem2 ⇒ crash program

https://storage.googleapis.com/gweb-research2023-media/pubtools/pdf/37752.pdf

Control Hijacking Defenses

Control Flow Integrity (CFI)

Control flow integrity (CFI) [ABEL'05, …]

Ultimate Goal: ensure control flows as specified by code's flow graph

```
void HandshakeHandler(Session *s, char *pkt) {
        ...
        s->hdlr(s, pkt)
}
```

Compile time: build list of possible call targets for s->hdlr

Run time: before call, check that s->hdlr value is on list

Coarse CFI: ensure that every indirect call and indirect branch leads to a valid function entry point or branch target

Coarse CFI: Control Flow Guard (CFG) (Windows 10)

Coarse CFI:

- Protects indirect calls by checking against a bitmask of all valid function entry points in executable

```
rep stosd
mov     esi, [esi]
mov     ecx, esi          ; Target
push    1
call    @_guard_check_icall@4 ; _guard_check_icall(x)
call    esi
add     esp, 4
xor     eax, eax
```

ensures target is the entry point of a function

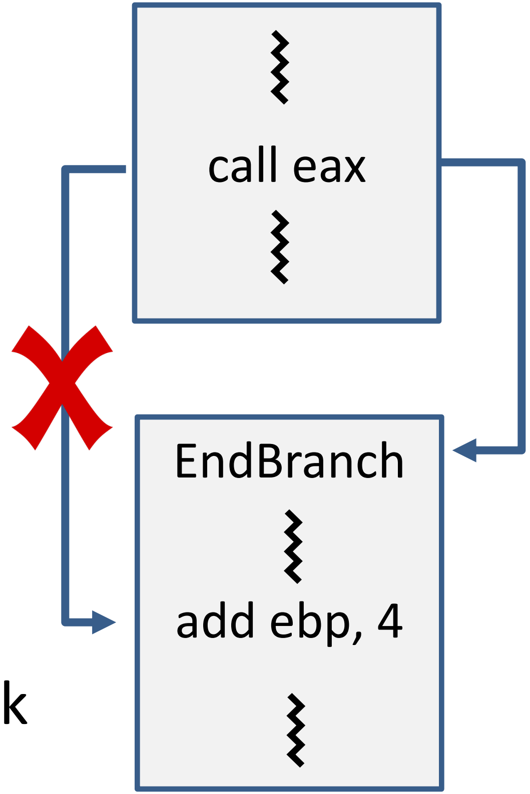
Coarse CFI using **EndBranch** (Intel) and **BTI (ARM)**

New instruction **EndBranch** (Intel) and **BTI** (ARM):

- After an indirect **JMP** or **CALL**:
  the next instruction in the instruction stream must be **EndBranch**

- If not, then trigger a #CP fault and halt execution

- Ensures an indirect JMP or CALL can only go to a valid target address $\Rightarrow$ no func. ptr. hijack
  (compiler inserts EndBranch at valid locations)



CFG, EndBranch, BTI: limitations

Poor

- Pr valid fu

- Does not prevent attacker from causing a jump to a valid **wrong** function

- Hard to build accurate control flow graph statically

```
rep s
mov
mov
push
call     @_guard_check_icall@4 ; _guard_check_icall(x)
call     esi
add      esp, 4
xor      eax, eax
```

s
of a

An example

```
void HandshakeHandler(Session *s, char *pkt) {
    s->hdlr = &LoginHandler;
    ... Buffer overflow over Session struct ...
}

void LoginHandler(Session *s, char *pkt) {
    bool auth = CheckCredentials(pkt);
    s->dhandler = &DataHandler;
}

void DataHandler(Session *s, char *pkt);
```

Attacker controls handler

static CFI: attacker can call **DataHandler** to bypass authentication

Cryptographic Control Flow Integrity (CCFI)
(ARM PAC - pointer authentication)

<u>Threat model</u>: attacker can read/write **anywhere** in memory,
program should not deviate from its control flow graph

<u>CCFI approach</u>: Every time a jump address is written/copied anywhere in memory:
compute 64-bit AES-MAC and append to address

On heap: **tag = AES(k, (jump-address, 0 ll source-address))**

on stack: **tag = AES(k, (jump-address, 1 ll stack-frame))**

Before following address, verify AES-MAC and crash if invalid

Where to store key **k**? In xmm registers (not memory)

Back to the example

void **HandshakeHandler**(Session *s, char *pkt) {

    s->hdlr = &**LoginHandler**;

    ... Buffer overflow in Session struct ...

}

Attacker controls handler

void **LoginHandler**(Session *s, char *pkt) {

    bool auth = **CheckCredentials**(pkt);

    s->dhandler = &**DataHandler**;

}

CCFI: Attacker cannot create a valid MAC for **DataHandler** address

void **DataHandler**(Session *s, char *pkt);

THE END