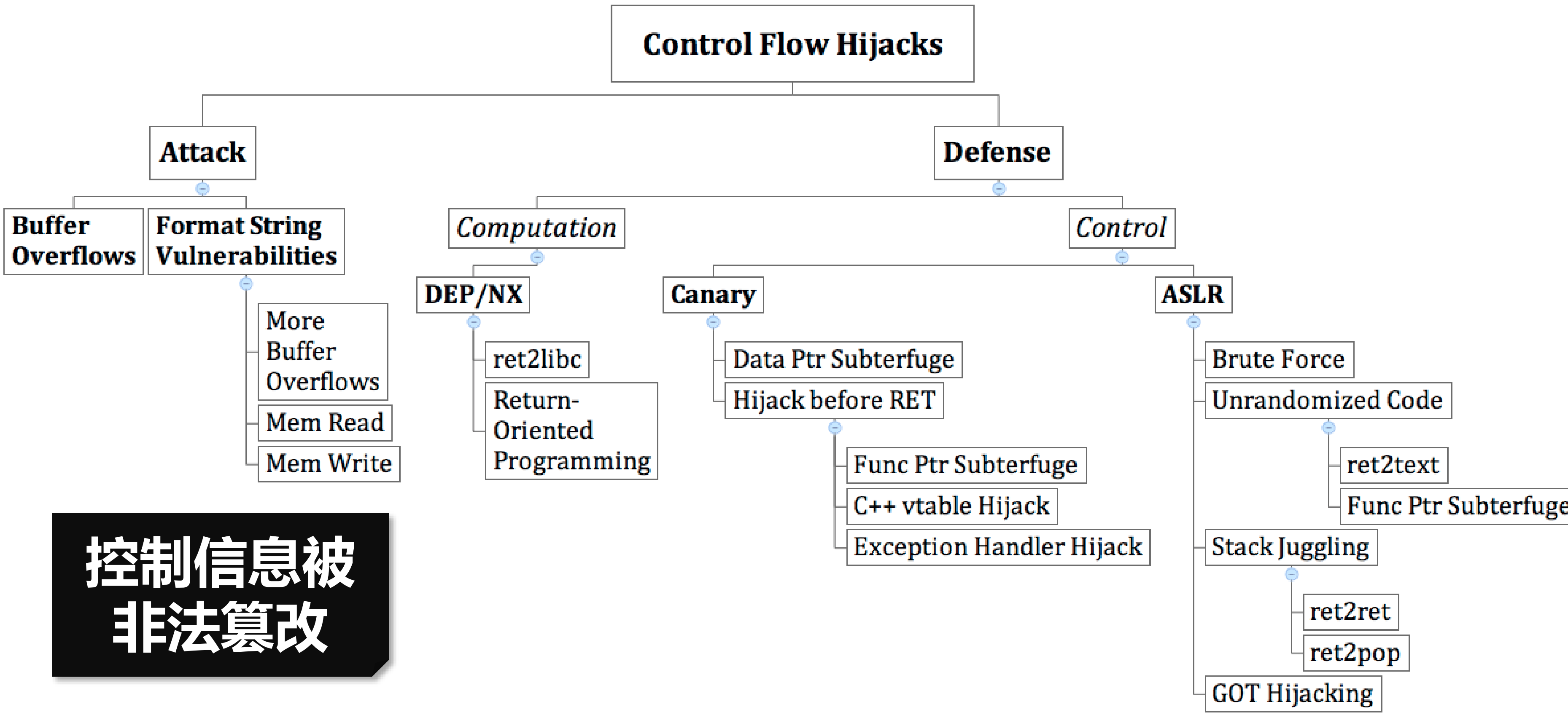
第2讲

软件安全（3）

控制流完整性

控制流劫持



控制信息被非法篡改

Behavior-based Detection

- **Stack canaries, non-executable data, ASLR的目标在于使得攻击步骤复杂化**
  - 但是这些方法仍然可能失败
- **基于行为的检测**
  - 观测程序的行为，即其是否按照我们的期望运行
  - If not，程序可能被compromised

Control-flow Integrity (CFI)

- **Challenges**
  - Define “Expected behavior”
  - Detect deviations from expectation efficiently
  - Avoid compromise of the detector
- **Solutions**
  - Control flow graph (CFG)
  - In-line reference monitor (IRM)
  - Sufficient randomness, immutability

CFI的主要思想

在程序执行期间，每当一条机器指令转移控制时，通过预先构建的控制流图(CFG, Control Flow Graph)，来确定转移目标的有效性。

基本块(Basic Block)

基本块：一个连续的指令/代码序列

- 任何位置的指令比其后面的所有指令先执行
- 没有任何外部指令可以在序列中的两个指令之间执行

```
1. x = y + z
2. z = t + i
```

```
3. x = y + z
4. z = t + i
5. jmp 1
```

```
6. jmp 3
```

```
1. x = y + z
2. z = t + i
3. x = y + z
4. z = t + i
5. jmp 1
```

基本块(Basic Block)

只有基本块开始的位置有跳转目标
只有基本块结束的位置有跳转指令

```
1. x = y + z
2. z = t + i
```

```
3. x = y + z
4. z = t + i
5. jmp 1
```

```
6. jmp 3
```

```
1. x = y + z
2. z = t + i
3. x = y + z
4. z = t + i
5. jmp 1
```

CFG 的定义

静态控制流图：

– 每一个顶点v_i 是一个基本块

– 边 (v_i, v_j) 表示从基本块 v_i 到基本块 v_j的控制转移

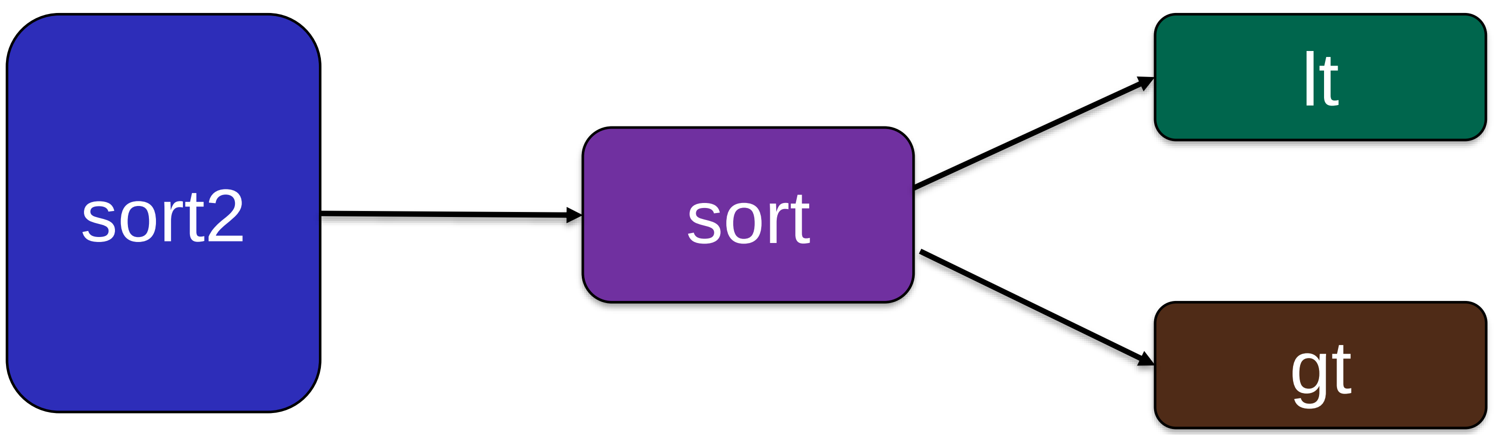
函数/过程内部的基本块构成intra-procedural 范围的CFG

Call Graph

每一个函数是一个节点，边 (v_i, v_j) 表示函数v_i调用函数 v_j

```
sort2(int a[], int b[], int len)
{
    sort( a, len, lt );
    sort( b, len, gt );
}
```

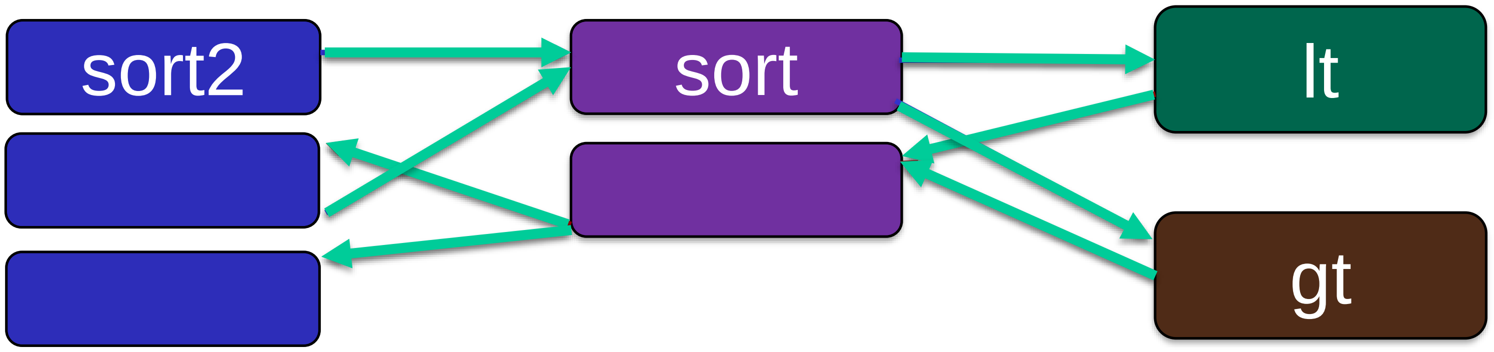
```
bool lt(int x, int y) {
    return x < y;
}

bool gt(int x, int y) {
    return x > y;
}
```



Control Flow Graph

```
sort2(int a[], int b[], int len)
{
    sort( a, len, lt );
    sort( b, len, gt );
}
```

```
bool lt(int x, int y) {
    return x < y;
}

bool gt(int x, int y) {
    return x > y;
}
```



Break into ***basic blocks***

Distinguish *calls* from *returns*

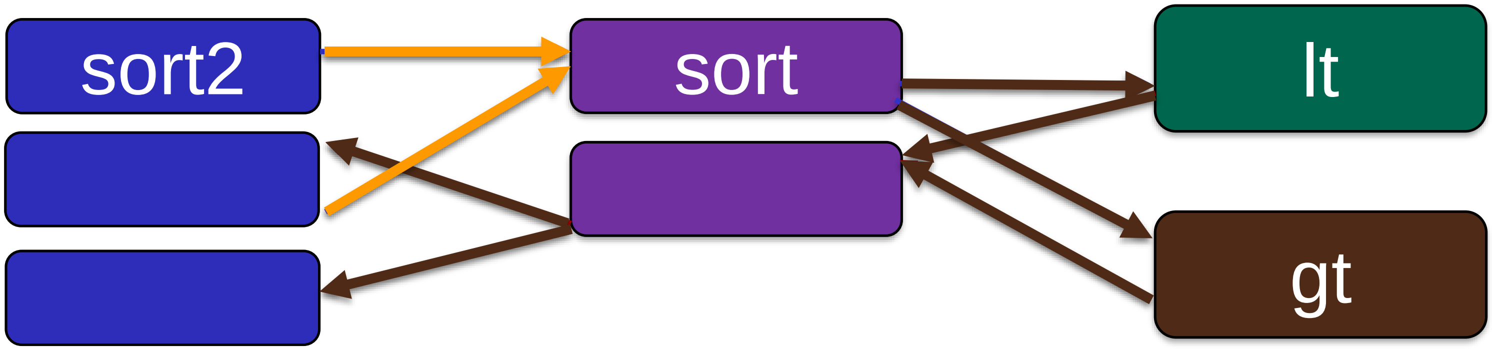
CFI: Compliance with CFG

- **Compute the call/return CFG** in advance
  - During compilation, or from the binary
- **Monitor the control flow** of the program, and ensure that it only follows paths allowed by the CFG
- 直接调用(Direct Calls)、间接跳转(Indirect Calls)
  - 只有间接调用需要被监控
    - jmp, call, ret (via registers)
  - 直接调用不需要被监控
    - Code is immutable
    - Target address cannot be changed

Control Flow Graph

```
sort2(int a[], int b[], int len)
{
    sort( a, len, lt );
    sort( b, len, gt );
}
```

```
bool lt(int x, int y) {
    return x < y;
}

bool gt(int x, int y) {
    return x > y;
}
```



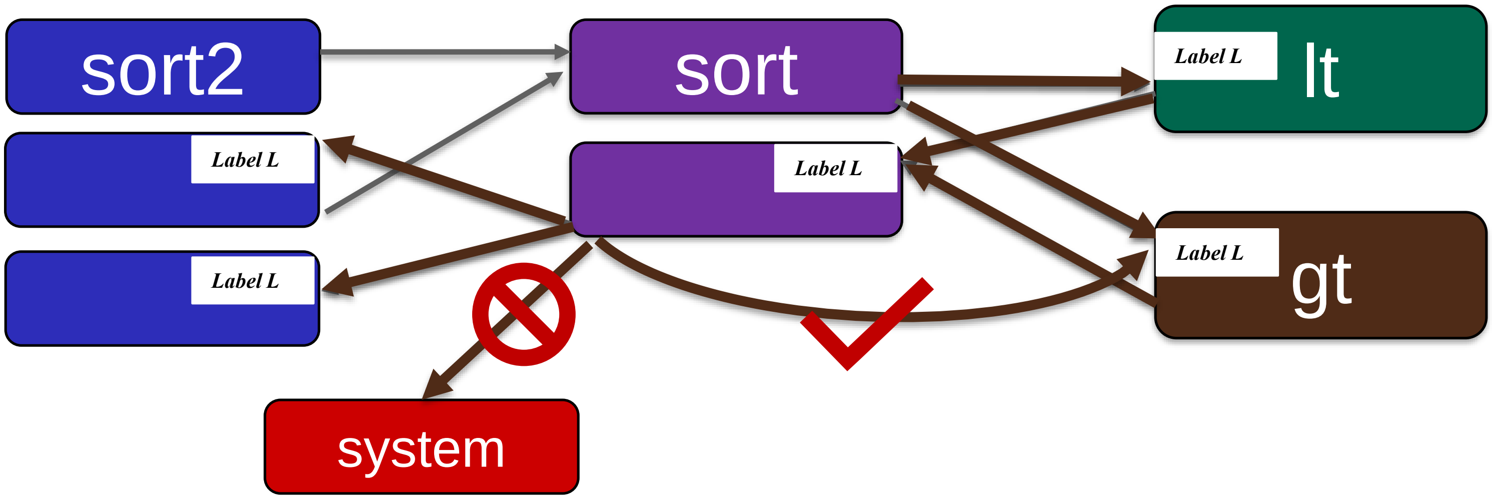
Direct calls

Indirect transfers (`call` via *register*, or `ret`)

In-line Monitor

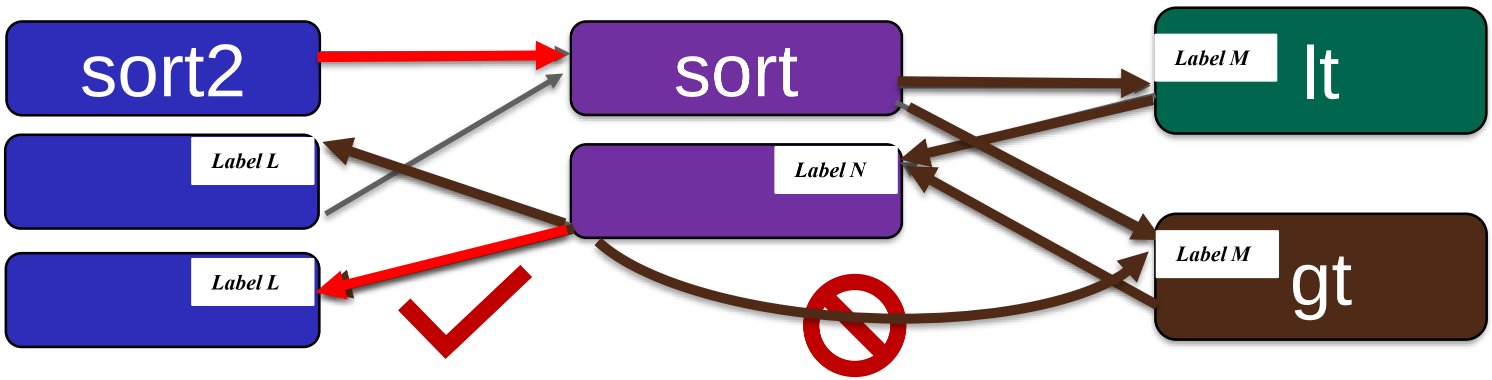
- Implement the monitor in-line, as a **program transformation**
- Insert a **label** **just before the target address** of a indirect transfer
- Insert **code** **to check the label of the target** at each indirect transfer
- The **labels are determined by the CFG**

Simplest labeling



使用相同的label

Detailed labeling



使用不同的label

问题?

Context-insensitive vs. Context-sensitive

基于不同的调用上下文返回不同的地址

上下文敏感示例

```
a = id(4);          void id(int z)
                    { return z; }
b = id(5);
```

4

5

Context-Sensitive

```
a = id(4);          void id(int z)
                    { return z; }
b = id(5);
```

4,5

4,5

Context-Insensitive

CFI-步骤

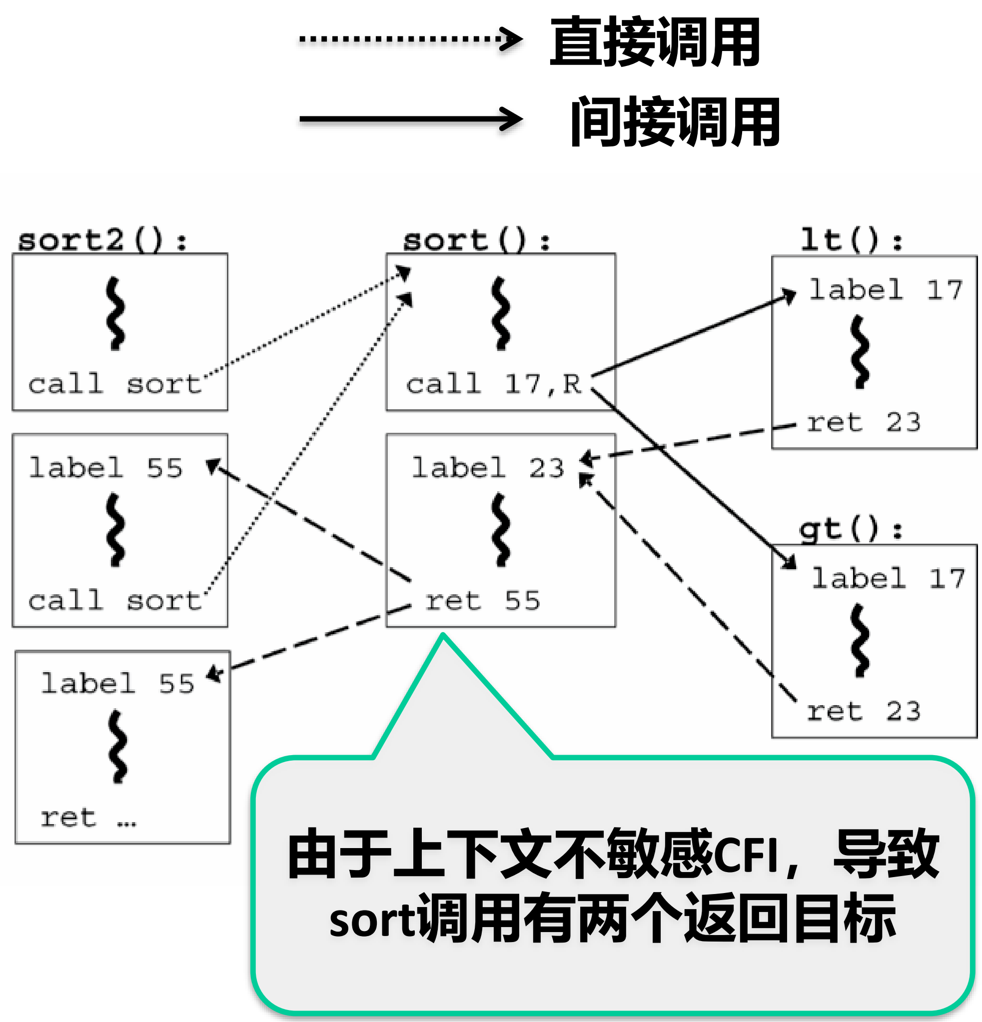
目标：程序执行必须按照控制流图（CFG）的路径执行。

步骤:

- **静态构建CFG，比如在编译期**
- **二进制插桩, 比如在软件安装时**
  - 添加ID和ID checks，维护ID的唯一性
- **在装载时校验CFI的插桩**
  - 直接跳转目标，确保ID和ID checks存在，ID唯一性
- **程序运行时对ID进行检查**
  - 间接跳转具有匹配的ID

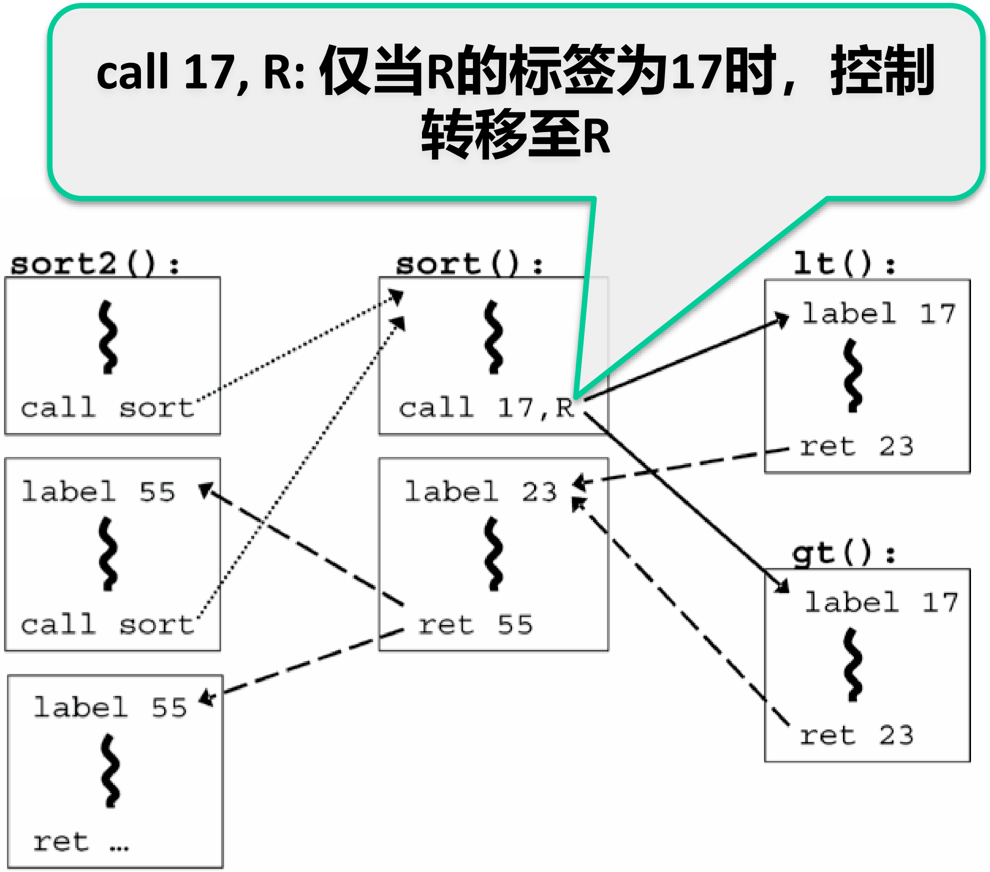
构建 CFG

```
bool lt(int x, int y) {
    return x < y;
}
bool gt(int x, int y) {
    return x > y;
}

sort2(int a[], int b[], int len)
{
    sort( a, len, lt );
    sort( b, len, gt );
}
```



二进制插桩

```
bool lt(int x, int y) {
    return x < y;
}
bool gt(int x, int y) {
    return x > y;
}

sort2(int a[], int b[], int len)
{
    sort( a, len, lt );
    sort( b, len, gt );
}
```



- 在每个目的位置插入一个唯一的ID

插桩示例

原始汇编代码

Source			Destination		
Opcode bytes	Instructions		Opcode bytes	Instructions	
FF E1	jmp ecx	; computed jump	8B 44 24 04	mov eax, [esp+4]	; dst

插装后汇编代码

```
B8 77 56 34 12    mov  eax, 12345677h     ; load ID-1
40                inc  eax                ; add 1 for ID
39 41 04          cmp  [ecx+4], eax       ; compare w/dst
75 13             jne  error_label        ; if != fail
FF E1             jmp  ecx                ; jump to label
```

```
3E 0F 18 05    prefetchnta               ; label
78 56 34 12        [12345678h]           ;     ID
8B 44 24 04    mov  eax, [esp+4]         ; dst
...
```

当目标位置的标签是“12345678”时，
控制跳转到目标位置

在二进制的目标位置插入标签“12345678”

插桩示例

Bytes (opcodes)	x86 assembly code	Comment
FF 53 08	call [ebx+8]	; call a function pointer

is instrumented using `prefetchnta` destination IDs, to become:

检查目标label

8B 43 08	mov eax, [ebx+8]	; load pointer into register
3E 81 78 04 78 56 34 12	cmp [eax+4], 12345678h	; compare opcodes at destination
75 13	jne error_label	; if not ID value, then fail
FF D0	call eax	; call function pointer
3E 0F 18 05 DD CC BB AA	prefetchnta [AABBCCDDh]	; label ID, used upon the return

Bytes (opcodes)	x86 assembly code	Comment
C2 10 00	ret 10h	; return, and pop 16 extra bytes

is instrumented using `prefetchnta` destination IDs, to become:

8B 0C 24	mov ecx, [esp]	; load address into register
83 C4 14	add esp, 14h	; pop 20 bytes off the stack
3E 81 79 04 DD CC BB AA	cmp [ecx+4], AABBCCDDh	; compare opcodes at destination
75 13	jne error_label	; if not ID value, then fail
FF E1	jmp ecx	; jump to return address

检查目标label

校验CFI插桩

- **直接跳转目标(e.g., call 0x12345678)**
  - 根据CFG判断所有目标的有效性
- **IDs**
  - 验证每一个进入点(entry point)后是否有一个ID
  - 验证是否有非法ID
- **ID checks**
  - 验证控制转移的位置前是否有ID check
  - 验证check代码是不遵循 CFG?

安全假设

- **UNQ: Unique IDs**
  - 用来维护CFG的语义
- **NWC: Non-Writable Code（Immutable）**
  - 保证攻击者无法修改label
  - 动态加载和动态生成的代码不满足NWC(例如JIT)
- **NXD: Non-Executable Data**
  - 保证攻击者无法插入的具有合法label的code

安全保证

- **CFI可以防护基于非法控制流转移的攻击**
  - 基于栈的缓冲区溢出攻击， ROP/return-to-libc攻击
- **不能防护不违反程序的原始CFG的攻击**
  - Single-labeled CFG
  - 基于数据的攻击（data leaks or corruptions)
    - heartbleed
  - 对系统调用参数的篡改
  - 替换文件名
  - 错误的逻辑实现

```
void func(char *arg1)
{
  int authenticated = 0;
  char buffer[4];
  strcpy(buffer, str);
  if(authenticated) { …
}
```

CFI实现

- **基于软件（Software-based）**
- **硬件辅助（Hardware-assisted）**

Software-based vs Hardware-assisted CFI Enforcement

- **Software-based Control-flow Integrity Enforcement**
  - 方法: implementing CFI enforcement in software only
  - 举例: Microsoft CFG, RFG; Google VTV, IFCC
  - 优点：更快地实现/产品化，更灵活，适应各种应用场景
- **Hardware-assisted Control-flow Integrity Enforcement**
  - 方法: enforcing CFI with the support of dedicated hardware (new ISA feature etc.)
  - 举例: Intel CET, ARM PAC
  - 优点：更小的性能下降，更有效地抵御攻击/绕过

控制流劫持

- Forward-edge control-flow hijacking
- Backward-edge control-flow hijacking

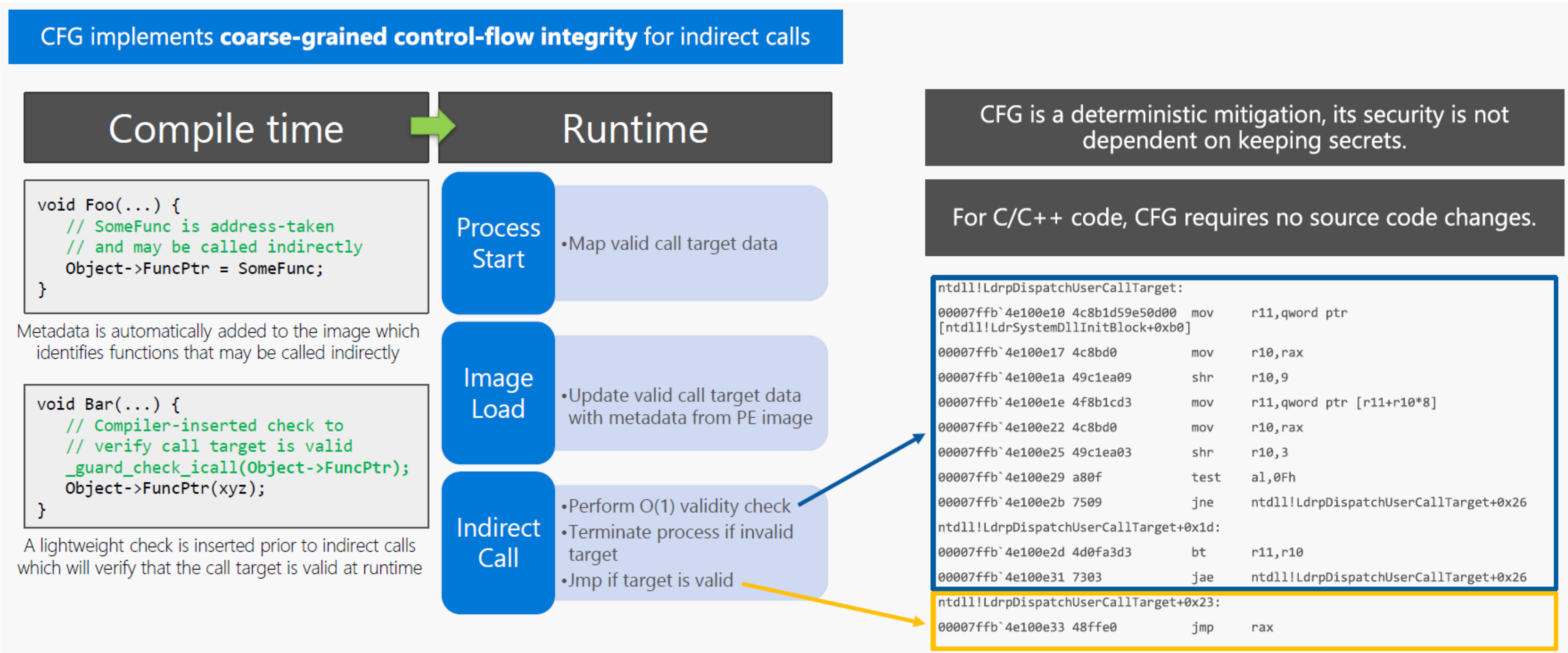
```
typedef int (*func_ptr)(struct foo *);

func_ptr saved_actions[] = {
      do_simple,
      do_fancy,
      ...
};

int action_launch(int idx)
{
     func_ptr action;
     int rc;
...
     action = saved_actions[idx];
...
     rc = action(info);
...
}
```

forward edge

backward edge

```
int do_simple(struct foo *info)
{
     stuff;
     and;
     things;
...
     return 0;
}
```

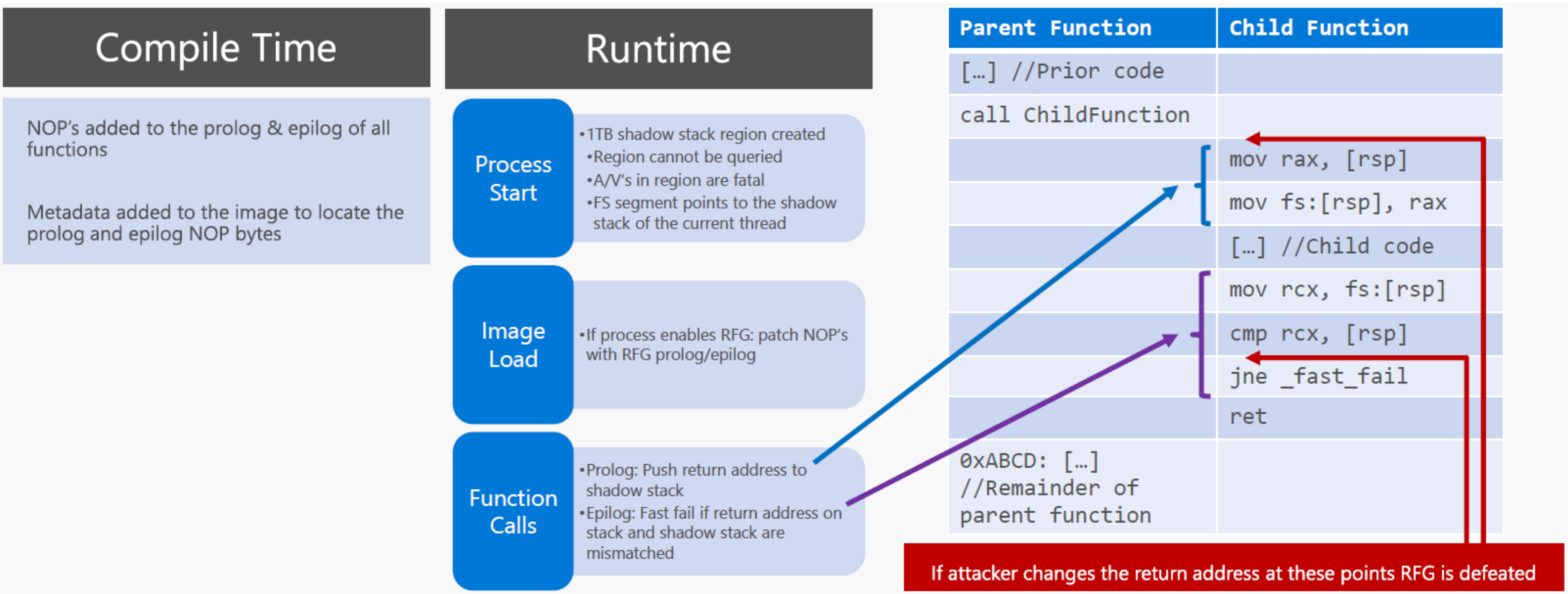
CFG (Control Flow Guard)



CFG不依赖于secret

RFG (Return Flow Guard)

RFG: MS的Software Shadow Stack



RFG依赖于secret，即shadow stack 的虚拟地址

RFG (Return Flow Guard)

- **问题：**
  - 依赖于secret，shadow stack的映射可以被成功的泄露
    - AnC Attack：https://www.vusec.net/projects/anc/
  - Race Condition

"When we have to do it in software, we have to introduce 'no ops'; when you're entering and exiting the function, we pad them with blanks and so people are able to massage the memory, people are able to massage the race conditions of the system and skip the checks completely," Hari Pulapaka, principal group program manager of the Windows kernel team, explained. There's no race condition when the shadow stack is stored in hardware, so the checks don't get skipped.

https://www.techrepublic.com/article/windows-10-security-how-the-shadow-stack-will-help-to-keep-the-hackers-at-bay/

Google's CFI

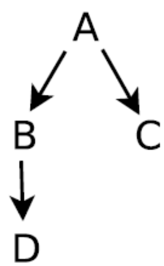
- Forward-Edge CFI for Virtual Calls (VTV, Virtual-Table Verification) 虚表调用？
- Forward-Edge CFI for Indirect Function Calls (IFCC, Indirect Function-Call Checks)

https://clang.llvm.org/docs/ControlFlowIntegrityDesign.html

VTV

```
class A {
public:
   int mA;
   virtual void foo();
}
class B : public A {
public:
   int mB;
   virtual void foo();
   virtual void bar();
}
class C : public A {
public:
   int mC;
   virtual void baz();
}
class D : public B {
public:
   int mD;
   virtual void foo();
   virtual void boo();
}
```

(a) C++ Code



(b) Class Hierarchy

```
C1: A* a = ...
    a->foo();
...

C2: B* b = ...
    b->bar();
```

(c) Sample Callsites

```
C1: $a = ...
(1) $avptr = load $a
(2) $foo_fn = load $avptr
(3) call $foo_fn

C2: $b = ...
(1) $bvptr = load $b
(2) $bar_fn = load ($bvptr+0x8)
(3) call $bar_fn
```

(d) Callsite Instructions

Fig. 1: C++ Example

VTV

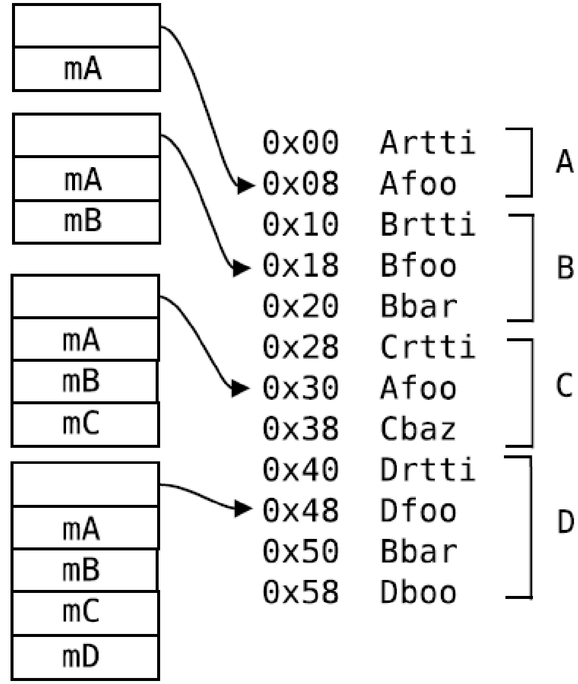


Fig. 2: Normal Vtable Layout in Memory

UAF问题

```
D *d = new D();
...
(1)  delete d;
(2)  // attacker controlled
     // allocation
(3)  // attacker controlled
     // writes to allocation
(4)  d->foo();
     // system called
```

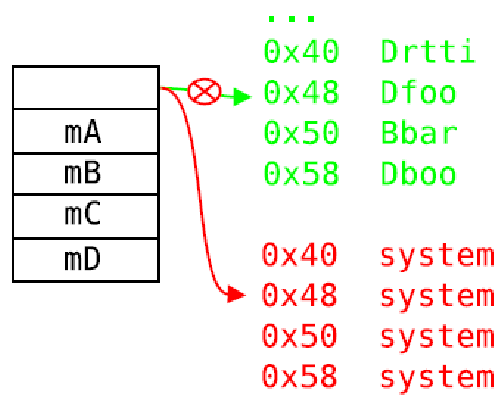


Fig. 3: VTable hijacking example

VTV

```
C1: $a = ...
    $avptr = load $a
    assert isvalid $avptr, A
    $foo_fn = load $avptr
    call $foo_fn

C2: $b = ...
    $bvptr = load $b
    assert isvalid $bvptr, B
    $bar_fn = load ($bvptr+0x8)
    call $bar_fn
```

(a) Abstract Check

```
C1: $a = ...
    $avptr = load $a
    assert $avptr ∈ {0x8,0x18,
        0x30,0x48}
    $foo_fn = load $avptr
    call $foo_fn

C2: $b = ...
    $bvptr = load $b
    assert $bvptr ∈ {0x18,0x48}
    $bar_fn = load ($bvptr+0x8)
    call $bar_fn
```

(b) Vptr check semantics

Fig. 4: Instrumented Callsites

IFCC

- 通过为间接调用目标生成跳转表(jump table);
- 并在间接调用点添加代码来转换函数指针,以保护间接调用，从而确保它们指向跳转表条目;
- 任何未指向相应表的函数指针都被视为CFI违规;

IFCC

1.编译的时候创建跳转表

- Addresses of all functions, which have their addresses taken, are replaced with the addresses of jump table entries.
  - Jump table entry is created with jump to the original function address.
- Indirect calls are replaced with instructions that transform pointers to force function calls into right table. 2.转换为不超过跳转表范围的指针
- Pointer transformation uses jump table base address and a special mask to force every call into the right table. 2.. 使用掩码的方式来进行转换
- Mask depends on sizes of jump table and its entries: for example, if the table size is 32 entries, and each entry is 4 bytes, the mask will be 1111100.
- Simple transformation: Pointer = ((Pointer - BaseAddress) & Mask) + BaseAddress;
- If the pointer already is in the right table, it is unchanged. If not, it is forced into the table.

IFCC

Function	Address
Func_a	1101110
Func_b	1110010

Function	Address
Func_a	1001111
Func_b	1010011

```
FuncPtr fp;

...

fp = 1101110;

...

call fp;
...
// fp is hacked
fp = 1111110;
...

call fp;
```

```
FuncPtr fp;
...
//address replaced
fp = 1001111;
...
// transformation
fp = fp – 1000011;    // 0001100
fp = fp & 1111100;    // 0001100
fp = fp + 1000011;    // 1001111

call fp;

fp = fp – 1000011;   // 0111011
fp = fp & 1111100 ; // 0111000
fp = fp + 1000011;   //  1111011

call fp; // forced to jump table
```

Jump Table

Base Address = 1000011

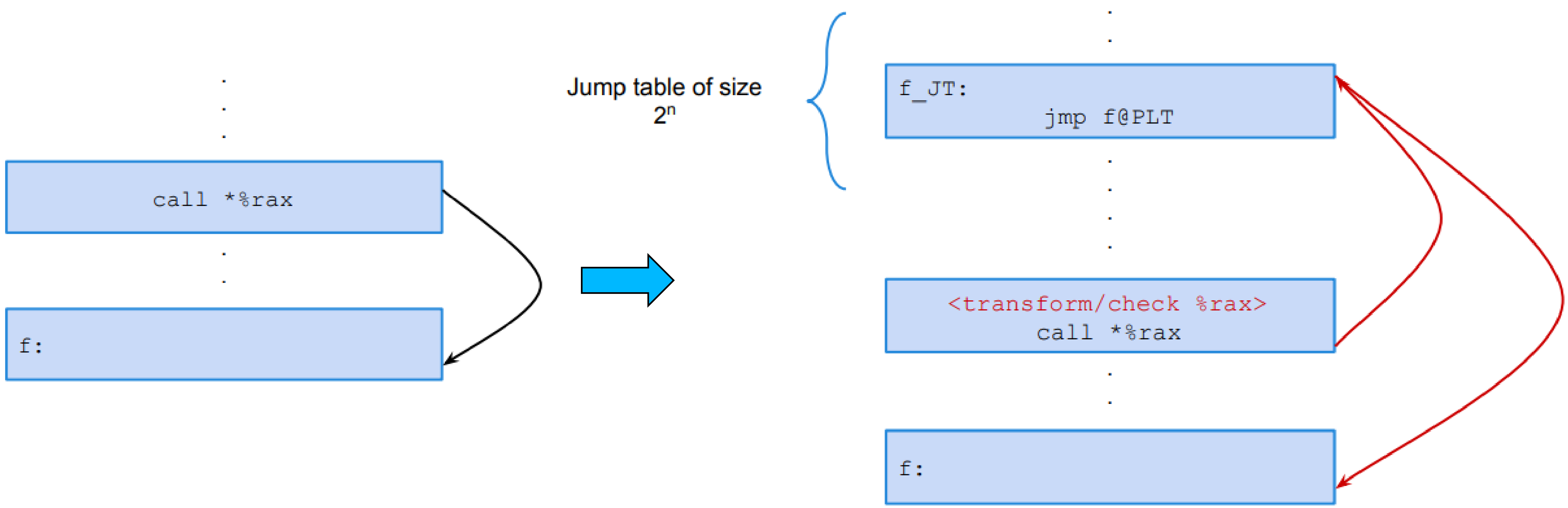
Entry size = 4 bytes

Mask = 1111100

Entry Address	
1000011 + 00000	jmp to crash
1000011 + 00100	jmp to crash
1000011 + 01000	jmp to crash
1000011 + 01100	jmp to 1101110 (Func_a)
1000011 + 10000	jmp to 1110010 (Func_b)
1000011 + 10100	jmp to crash
1000011 + 11000	jmp to crash
1000011 + 11100	jmp to crash

…

IFCC



call *%rax
f:
Jump table of size 2^n
f_JT:
jmp f@PLT
<transform/check %rax>
call *%rax
f:

IFCC

```
<do_simple>:
  201870: xor     %eax,%eax
  201872: retq
...
<do_fancy>:
  201880: mov     0x4(%rdi),%eax
  201883: add     (%rdi),%eax
  201885: retq
```

```
<action_launch>:
  201890: push    %rbx
  201891: movslq %edi,%rax
  201894: mov     0x200550(,%rax,8),%rax



  20189c: mov     $0x203b44,%edi
  2018a1: callq   *%rax
...
```


①根据函数原型一致创建了间接调用表，能间接跳转到do_simple()和do_fancy()

```
<__typeid__ZTSFiP3fooE_global_addr>:
  201860: jmpq    201870 <do_simple>
  201865: int3
  201866: int3
  201867: int3
  201868: jmpq    201880 <do_fancy>
  20186d: int3
  20186e: int3
  20186f: int3
<do_simple>:
  201870: xor     %eax,%eax
  201872: retq
...
<do_fancy>:
  201880: mov     0x4(%rdi),%eax
  201883: add     (%rdi),%eax
  201885: retq
```

```
<action_launch>:
  201890: push    %rbx
  201891: movslq %edi,%rax
  201894: mov     0x200550(,%rax,8),%rax
  20189c: mov     $0x201860,%ecx
  2018a1: mov     %rax,%rdx
  2018a4: sub     %rcx,%rdx
  2018a7: ror     $0x3,%rdx
  2018ab: cmp     $0x1,%rdx
  2018b2: ja      2018dc <action_launch+0x4c>
  2018b4: mov     $0x203b44,%edi
  2018b9: callq   *%rax
...
  2018dc: ud2
```

②rax中获取到的函数指针不再是do_simple()/do_fancy()的地址，而是xxx_global_addr间接调用表中的地址

③在间接调用之前，判断rax中的地址是否合法，方法是：判断rax中的目的地址，是否超过xxx_global_addr间接调用表的最大范围

IFCC

- 举例

```
struct foo {
    int_arg_fn int_funcs[1];
    int_arg_fn bad_int_funcs[1];
    float_arg_fn float_funcs[1];
    int_arg_fn not_entries[1];
};
static struct foo f = {
    .int_funcs = {int_arg},
    .bad_int_funcs = {bad_int_arg},
    .float_funcs = {float_arg},
    .not_entries = {(int_arg_fn)((uintptr_t)(not_entry_point)+0x20)}
};

int idx = argv[1][0] - '0';
f.int_funcs[idx](idx);
```

```
clang -fvisibility=hidden -flto -fno-sanitize-trap=all -fsanitize=cfi -o cfi_icall cfi_icall.c
```

https://github.com/trailofbits/clang-cfi-showcase/blob/master/cfi_icall.c
https://github.com/trailofbits/clang-cfi-showcase

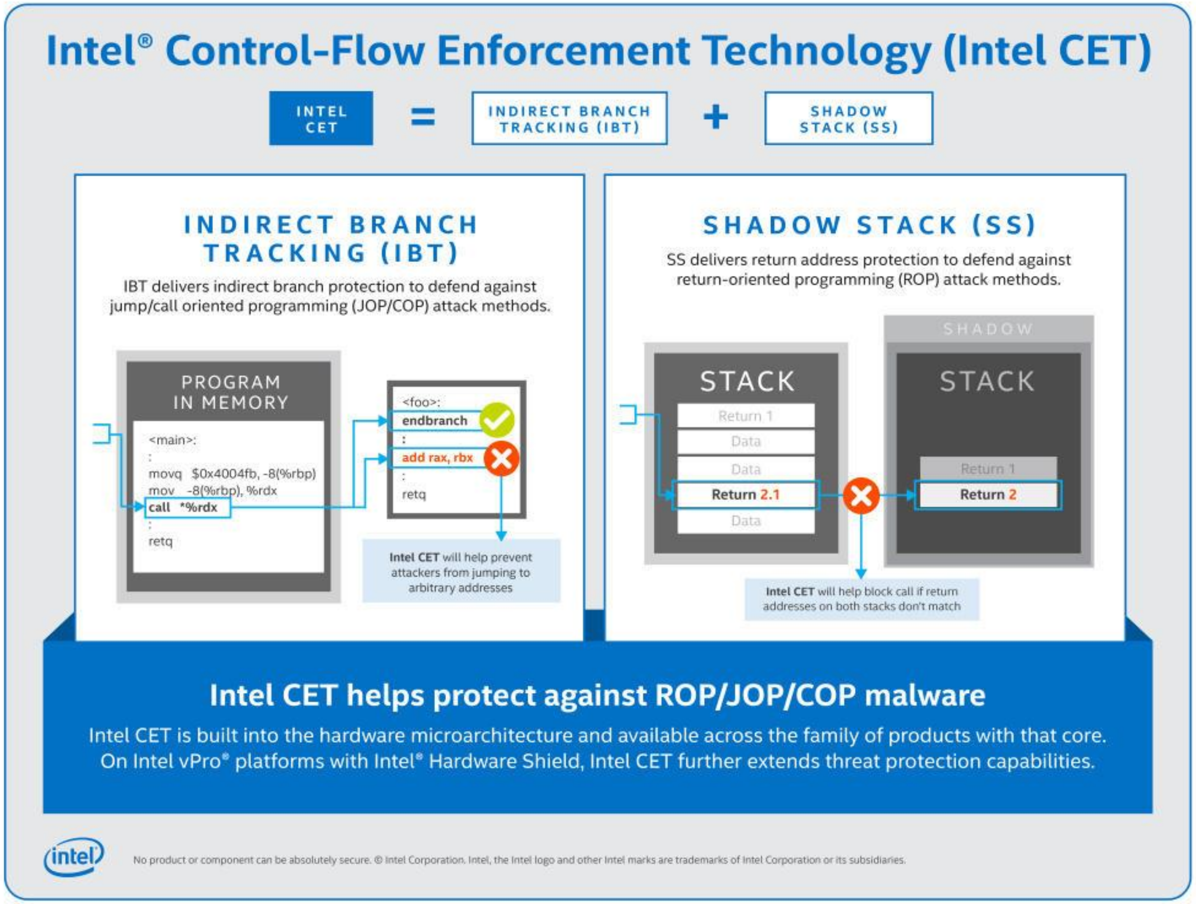
Intel CET

- **两个部分：**
  - Shadow Stack (SHSTK)
  - Indirect Branch Tracking (IBT)

Intel CET (Control-flow Enforcement Technology)

Control-flow Enforcement Technology (CET) provides the following capabilities to defend against ROP/JOP style control-flow subversion attacks:

- Shadow Stack – return address protection to defend against Return Oriented Programming,
- Indirect branch tracking – free branch protection to defend against Jump/Call Oriented Programming.

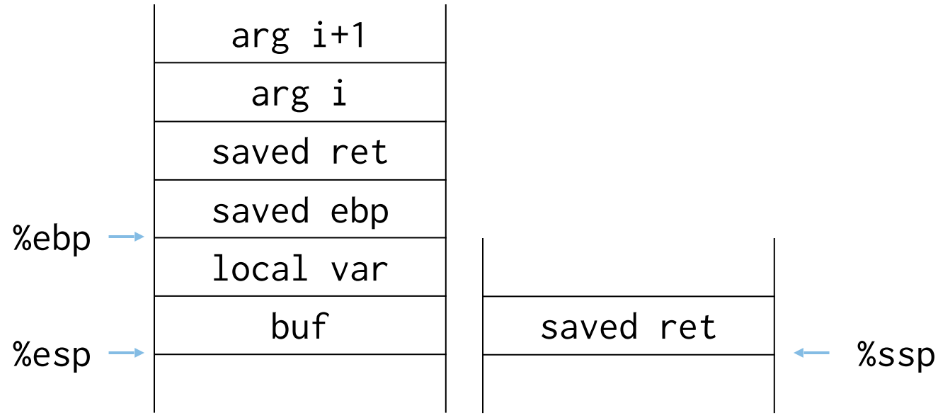


https://software.intel.com/sites/default/files/managed/4d/2a/control-flow-enforcement-technology-preview.pdf

Shadow Stack

- **解决性能和安全问题**
  - ssp (shadow stack pointer)
  - call 和 ret 自动更新 esp和ssp
  - 无法手动更新shadow stack

通过硬件来实现自动更新



Indirect Branch Tracking (IBT)

```
main() {
    int (*f)();
    f = test;
    f();
}

int test() {
    return
}
```

```
<main>:
ENDBR
:
movq    $0x4004fb, -8(%rbp)
mov     -8(%rbp), %rdx
call    *%rdx
:
retq

<test>:
ENDBR
:
add rax, rbx
:
retq
```

ENDBR 标记（指令）
对逻辑无作用，但是可以保证所有的CALL都要指向ENDBR位置而不能指向某个中间位置

which means所有跳转点都要以endbr开始

所有的Indirect Branch 必须以ENDBR开始

微软对CET也有相应的支持

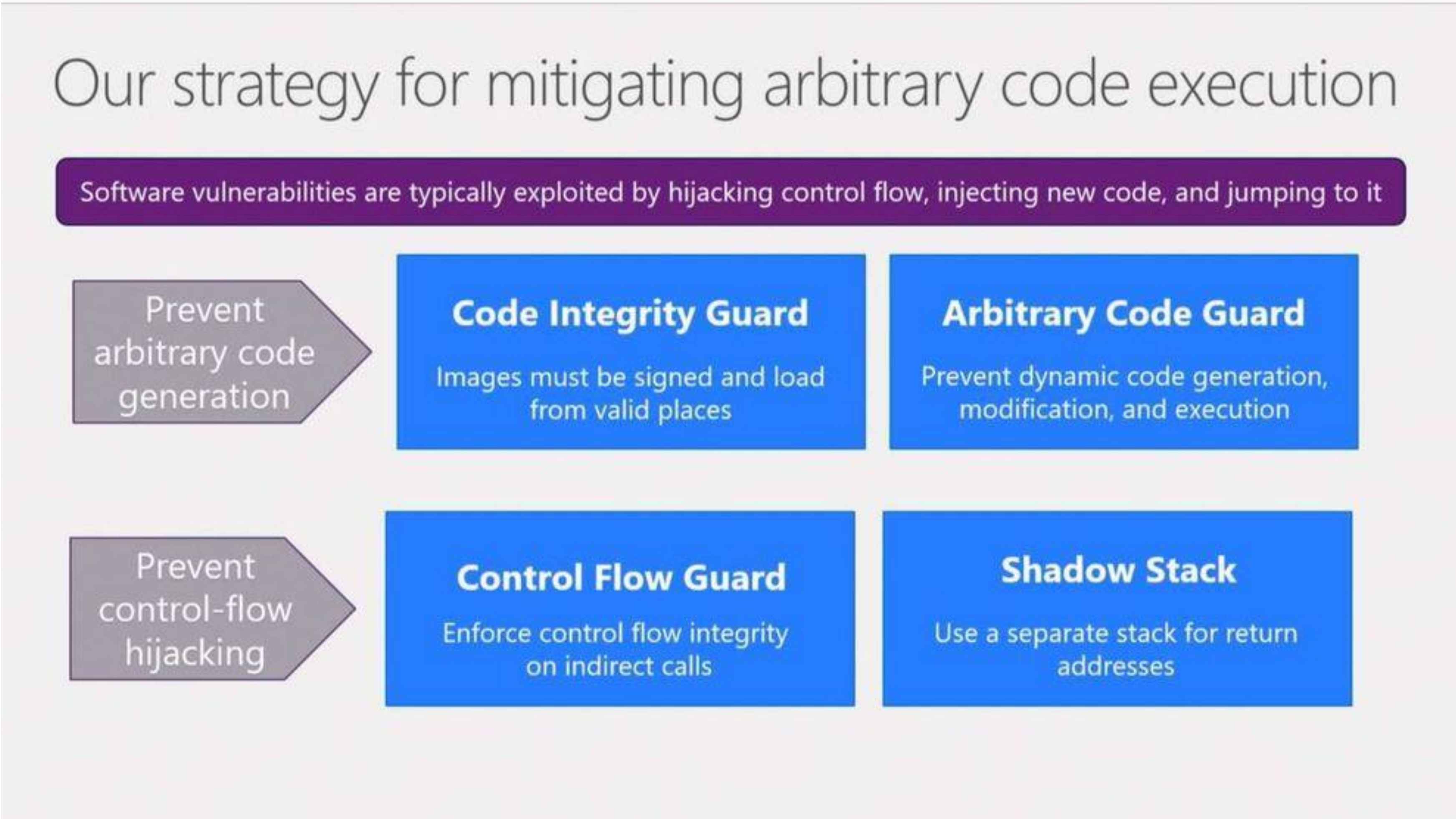
CET Instructions

- RDSSP – Read shadow stack pointer
- INCSSP – Shadow stack unwinding
- RSTORSSP, SAVEPREVSSP – Shadow stack context switching
- SETSSBSY, CLRSSBSY – Mark shadow stack in-use
- ENDBR, No-Track – Indirect branch tracking

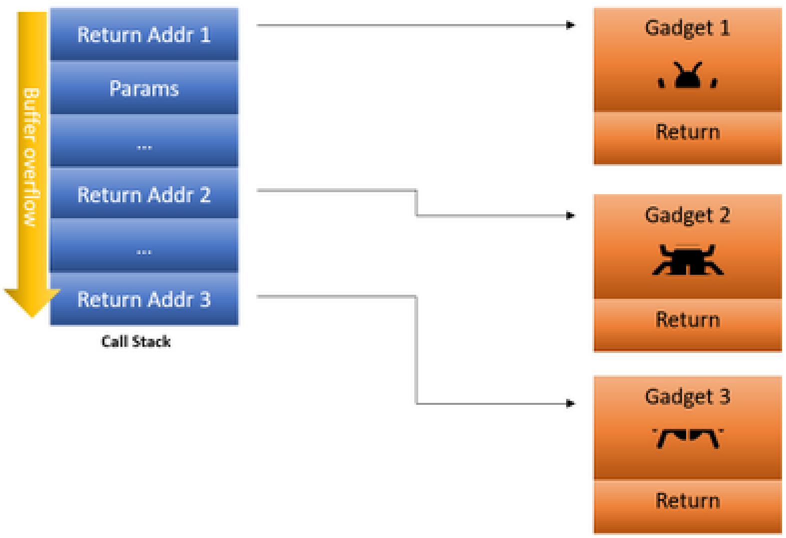
Intel CET

- CET 支持
  - Glibc: https://man7.org/linux/man-pages/man1/gcc.1.html
  - Microsoft: Hardware-enforced Stack Protection, https://www.zdnet.com/article/microsoft-announces-new-hardware-enforced-stack-protection-feature/

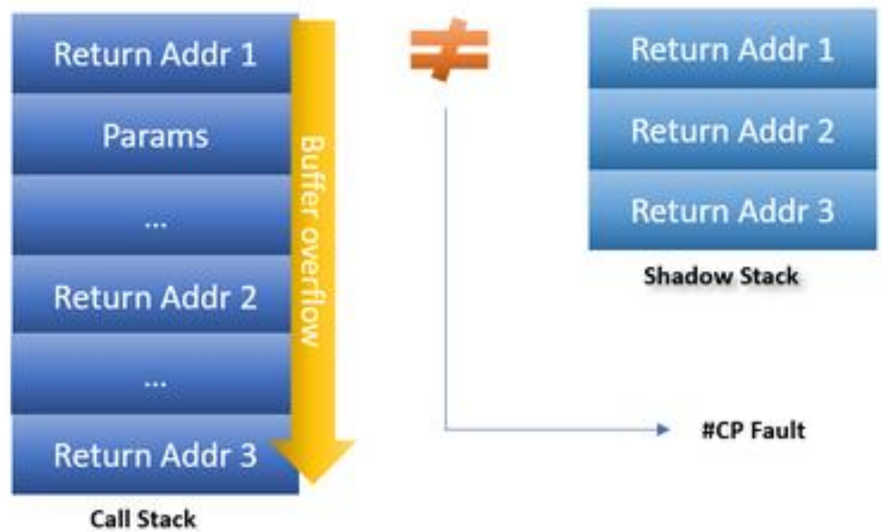
Microsoft: Hardware-enforced Stack Protection



Microsoft: Hardware-enforced Stack Protection



ROP问题



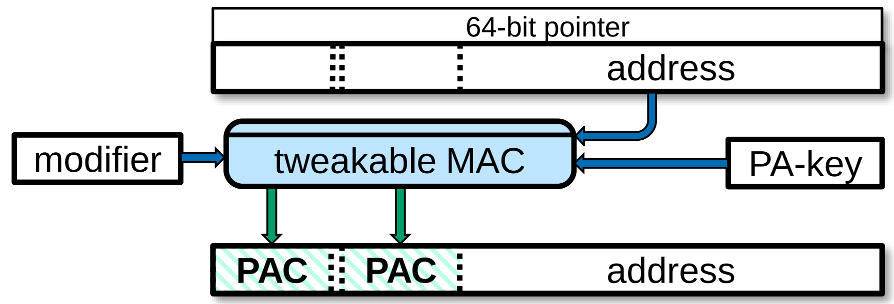
Shadow Stack

每条CALL指令上，返回地址都被压入栈和影子栈上；而在RET指令上，进行比较以确保完整性不受影响。

这也是一个硬件的方法

ARM 8.3-A Pointer Authentication

算法也是一个mAc算法，但是保护的是一个指针



Pointer Authentication Codes (PAC)

- Set in unused bits of virtual address

Key/configuration set at higher privilege level

Instrument with new PAC handling instructions

- Opcode determines used key
- Operands set PA modifier (tweak value)

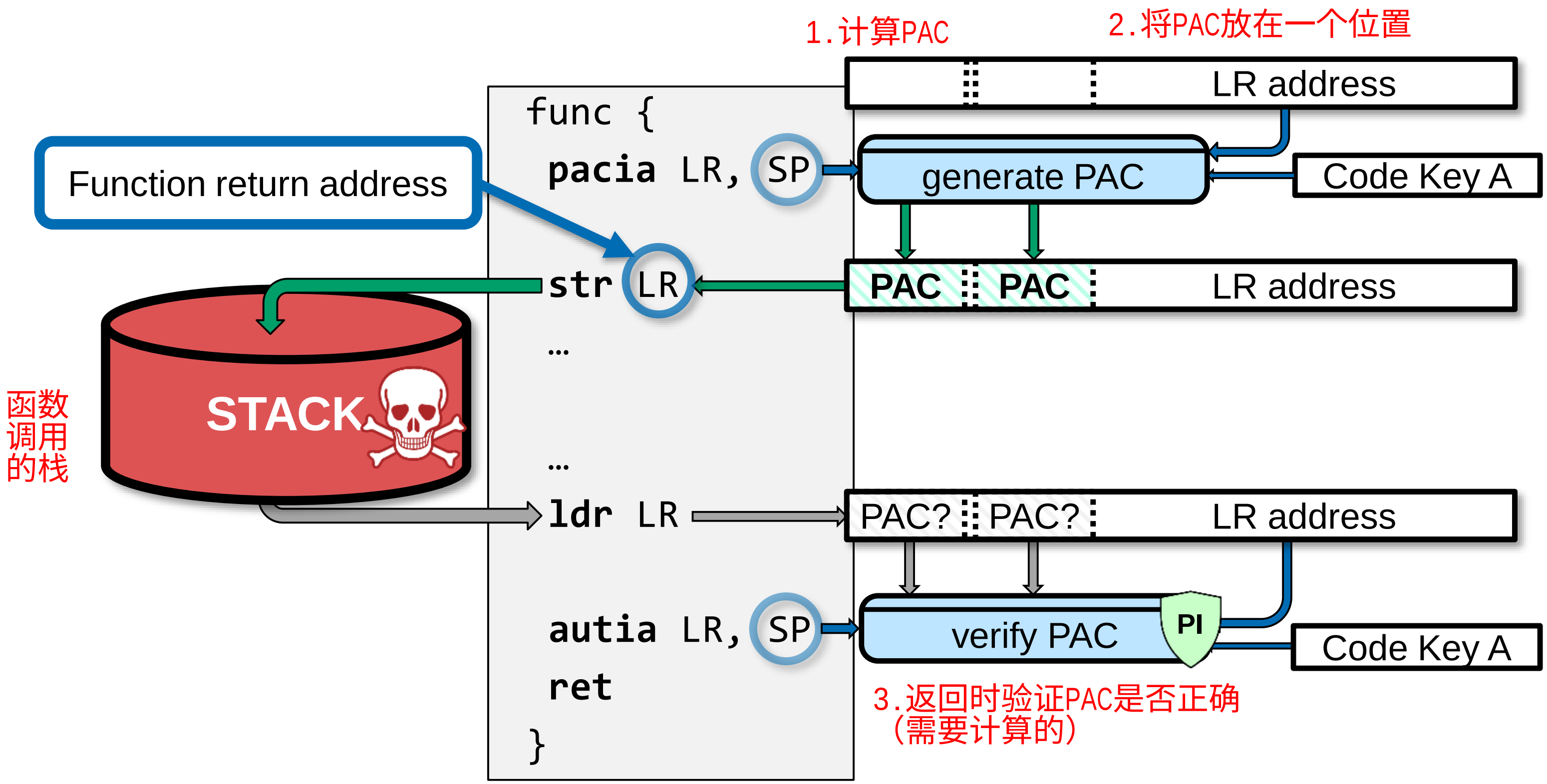
这是一些相应的指令

instructions	Code-key		Data-key		Gen.-key
	A	B	A	B	
pacia	X				
pacib		X			
pacda			X		
pacdb				X	
pacga					X
autia	X				
autib		X			
autda			X		
autdb				X	

返回地址签名

Example: PA-based return address signing

保护返回地址的过程：



Qualcomm “[Pointer Authentication on ARMv8.3]”, whitepaper 2017