Too Subtle to Notice: Investigating Executable Stack Issues in Linux Systems

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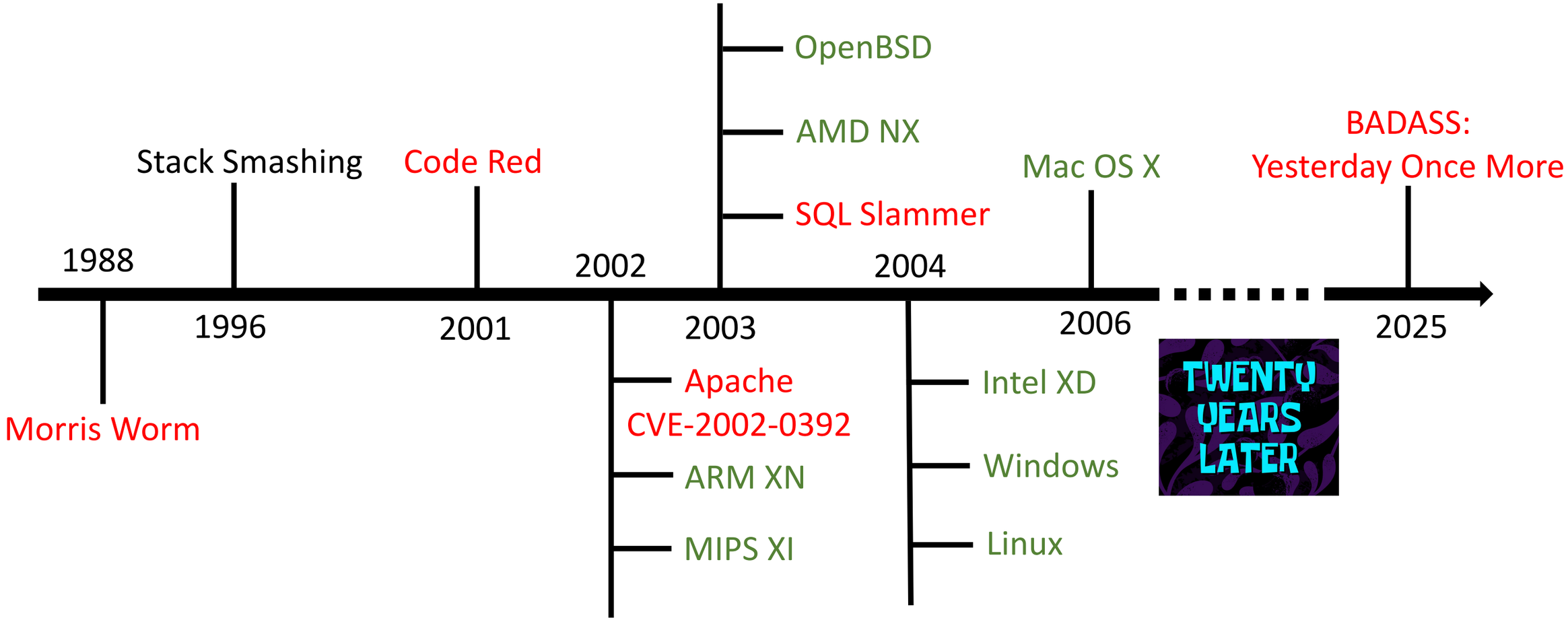
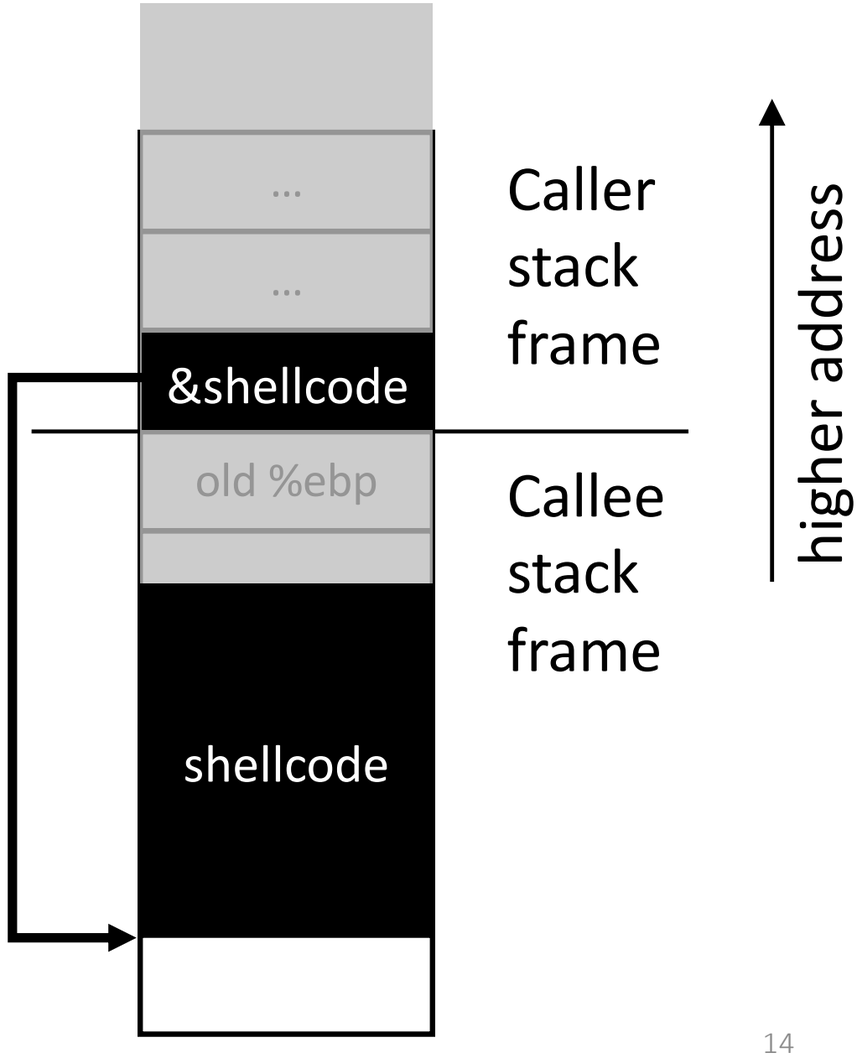
History of Code Injection



Code Injection w/ An Executable Stack 😈

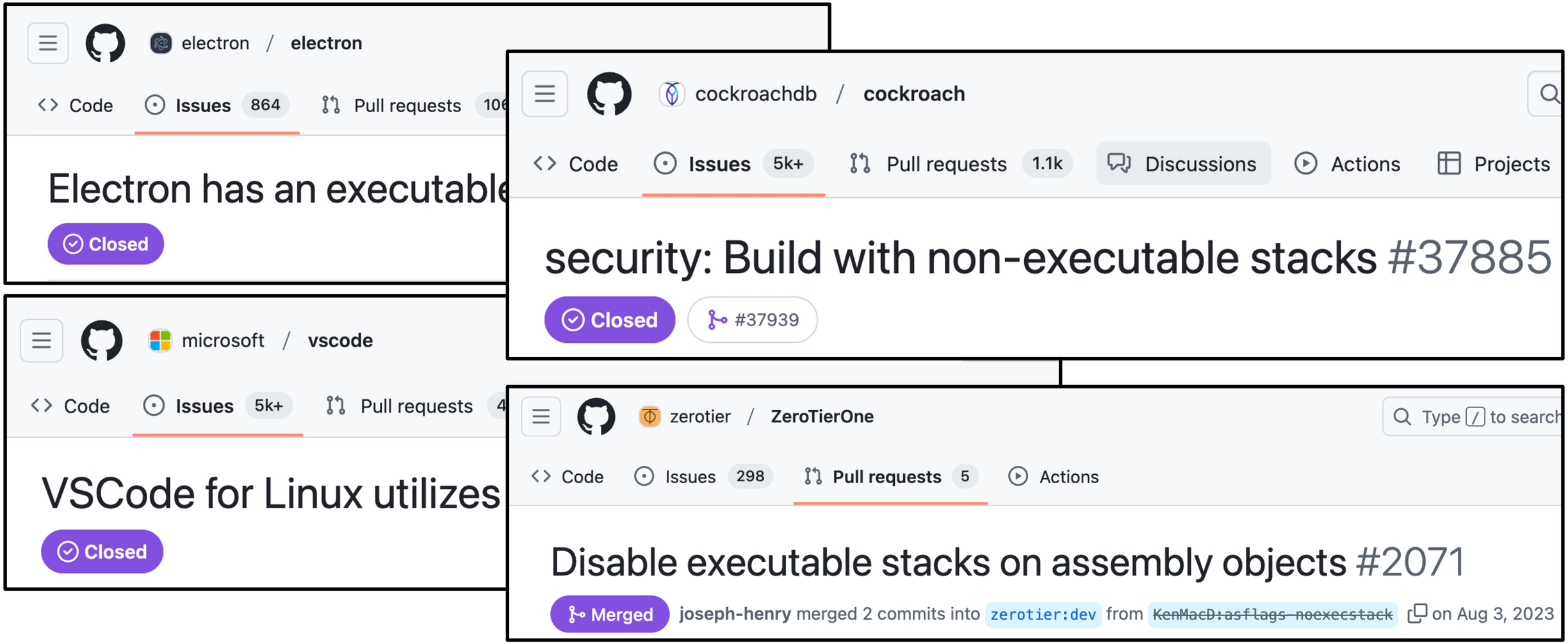
- Stack buffer overflow vulnerability
  - Attackers can insert any content on stack
  1. Place shellcode on stack
  2. Overwrite return address to &shellcode
  3. Return



Stack is NOT Executable Anymore 😇

- W⊕X: writable or executable, not both
- NX bit: most significant bit of the page table entry
  - Managed & set by OS
- Widely deployed & enabled by default

Accidentally Executable Stack



When Your Assembly is Not Good Enough

- Assembly files w/o `.section .note.GNU-stack,” ”,@progbits`
  - Missing `.note.GNU-stack` section ⟶ Executable stack 
- We term this problem *BADASS* 

```
$ cat hello_world.c
#include <stdio.h>
#include <stdlib.h>

int main(int argc, char *argv[]) {
        getchar();
        return 0;
}
$ gcc hello_world.c -o hello_world
$ ./hello_world
^Z[1] + Stopped                    ./hello_world
$ cat /proc/$(pgrep hello_world)/maps | grep stack
7ffc9c370000-7ffc9c391000 rw-p 00000000 00:00 0                          [stack]
```

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7ffc9c370000-7ffc9c391000 rw-p 00000000 00:00 0                          [stack]
$ killall -9 hello_world
[1] + Killed                     ./hello_world
$ cat EMPTY.s
$ gcc hello_world.c EMPTY.s -o hello_world
```

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7fff7cca0000-7fff7ccc1000 rwxp 00000000 00:00 0                          [stack]
```
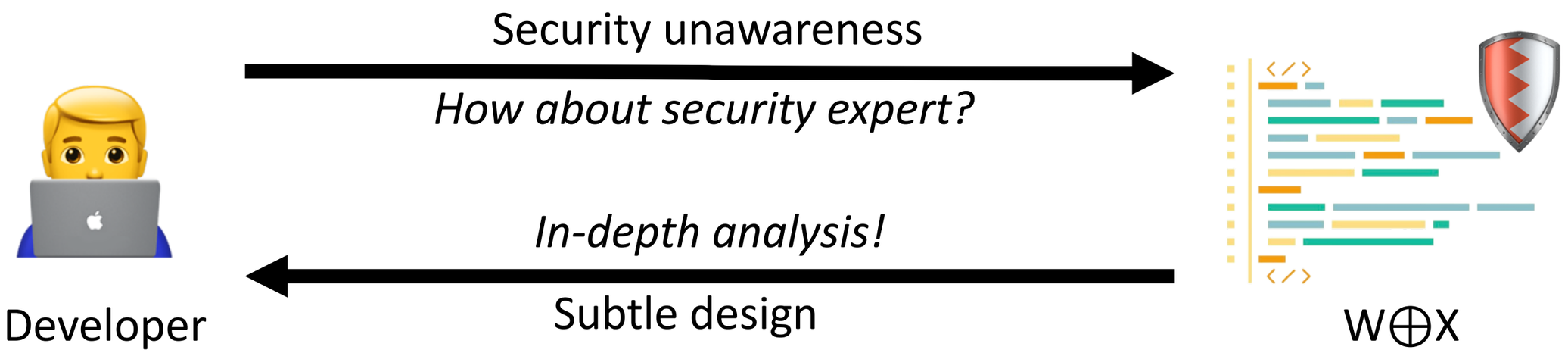

What Happened



Investigating Security Applications

Ideal Target	
Utilize assembly code	
Interact with native ELF binaries	
Open-sourced & work on Linux system	

Investigating Security Applications

Ideal Target	⭐ Inlined Reference Monitor ⭐
Utilize assembly code	Assembly code for security instrumentation
Interact with native ELF binaries	Output hardened binaries
Open-sourced & work on Linux system	Widely open-sourced

Investigating Security Applications

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Utilize assembly code	Assembly code for security instrumentation
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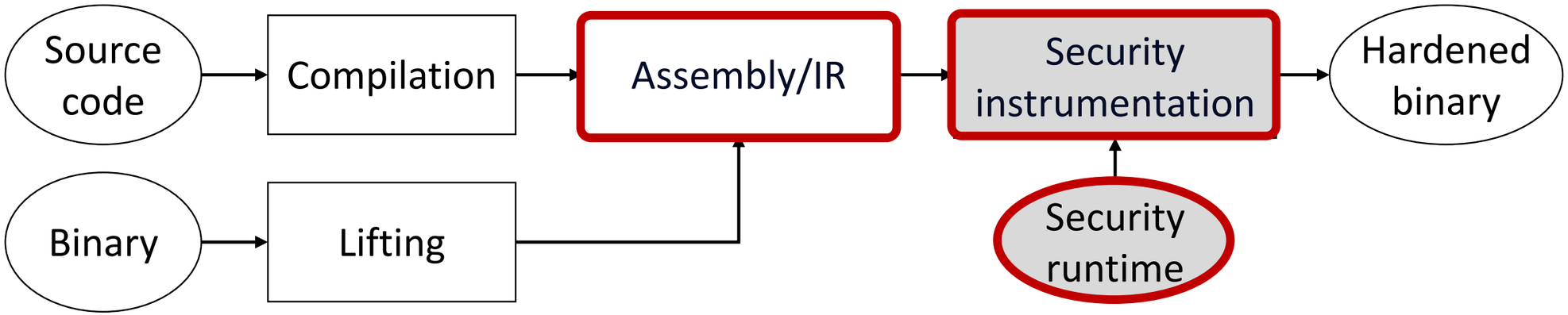
- If: *BADASS* during security instrumentatinon
- Then: executable stack for all “hardened” binaries

Inlined Reference Monitor (IRM)

- Enforce security properties via injecting security checks
  - control flow integrity (CFI), software-based fault isolation (SFI)…



Investigating Security Applications

- 21 open-source IRMs
  - Nine binary rewriters
  - Eight CFI solutions
  - Four others

5/9 Binary Rewriters have *BADASS*

Binary Rewriter	Publication	Generate Assembly?	Executable Stack?	Status
Uroboros	USENIX SEC'15	yes	yes	Checking
Ramblr	NDSS'17	yes	yes	Will fix
Multiverse	NDSS'18	no	no	-
Egalito	ASPLOS'20	no	no	-
RetroWrite	IEEE S&P'20	yes	yes	Fixed
E9Patch	PLDI'20	no	no	-
Ddisasm	USENIX SEC'20	yes	yes	Fixed (before our work)
ARMore	USENIX SEC'23	yes	yes	Fixed
SAFER	USENIX SEC'23	yes	no	-

4/8 CFI Solutions have *BADASS*

CFI	Publication	Generate Assembly?	Executable Stack?	Status
binCFI	USENIX SEC'13	yes	no	-
MCFI	PLDI'14	yes	yes	fixed
LLVM CFI	USENIX SEC'14	no	no	-
RockJIT	CCS'14	yes	yes	fixed
πCFI	CCS'15	yes	yes	fixed
PathArmor	CCS'15	yes	yes	won't fix
μCFI	CCS'18	yes	no	-
Android kCFI	-	no	no	-

2/2 In-process Isolation Methods have *BADASS*

Isolation	**Publication**	**Generate Assembly?**	**Executable Stack?**	**Status**
ERIM	USENIX SEC'19	yes	yes	fixed
Donky	USENIX SEC'20	yes	yes	no risk

Takeaway 1

Security unawareness

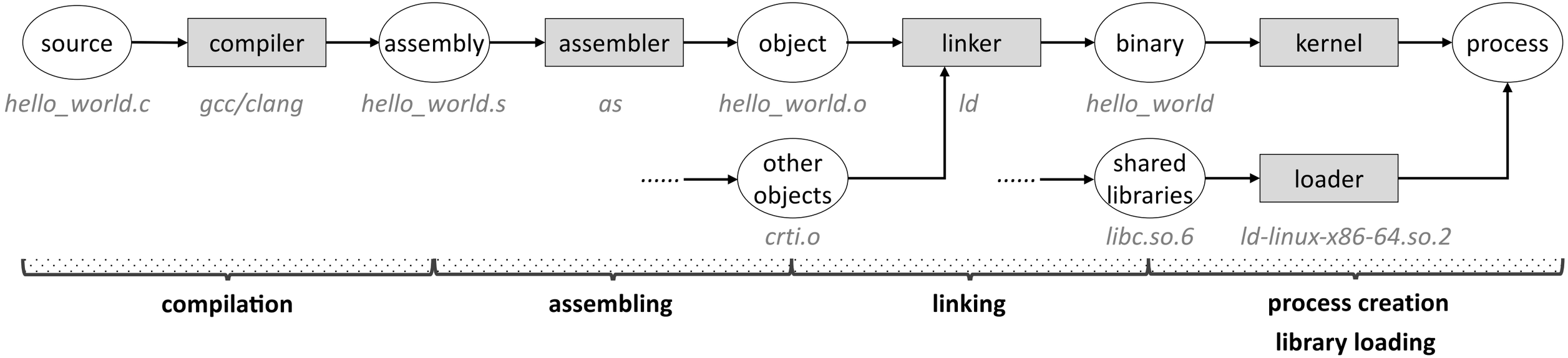
How about security expert?

Developer

W⊕X

- Even experienced security researchers/developers may miss the directive
- Cannot simply attribute *BADASS* issues to the security unawareness
- An in-depth analysis of W⊕X enforcement is necessary

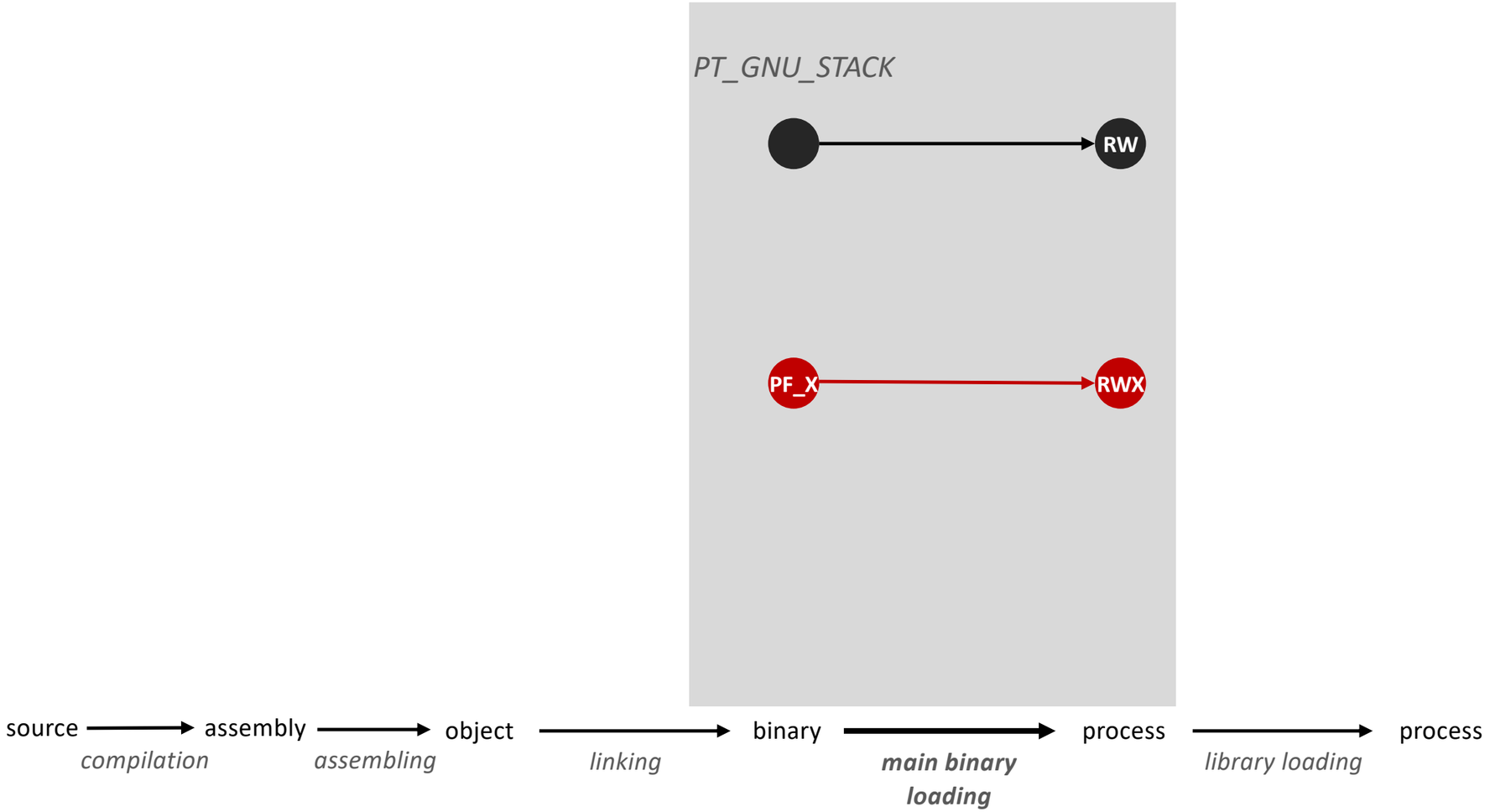
W⊕X Enforcement Analysis



- **ALL** steps are related to stack permission

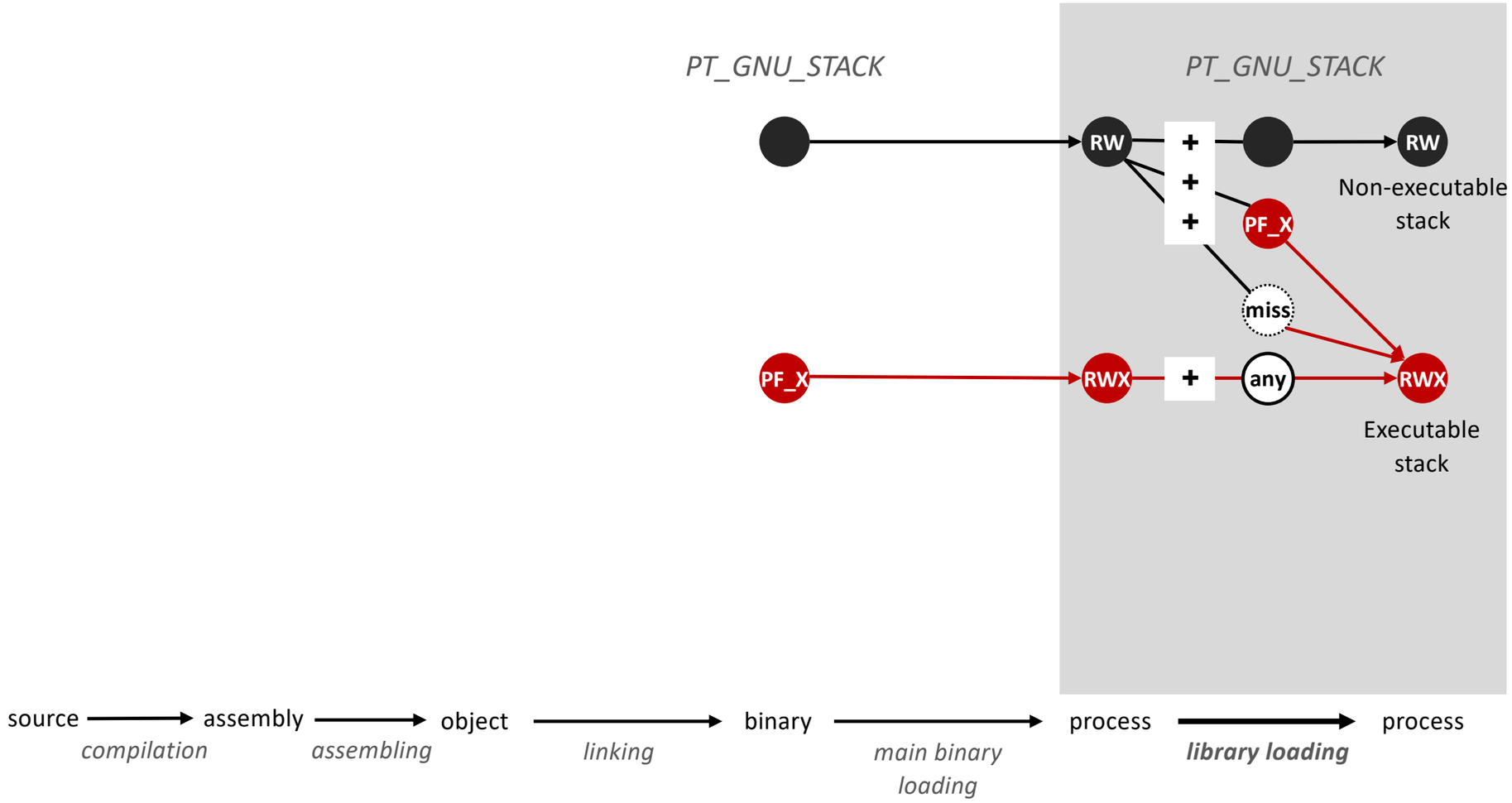
Stack Permission (Process Creation)

- Kernel checks **program header** PT_GNU_STACK of main binary



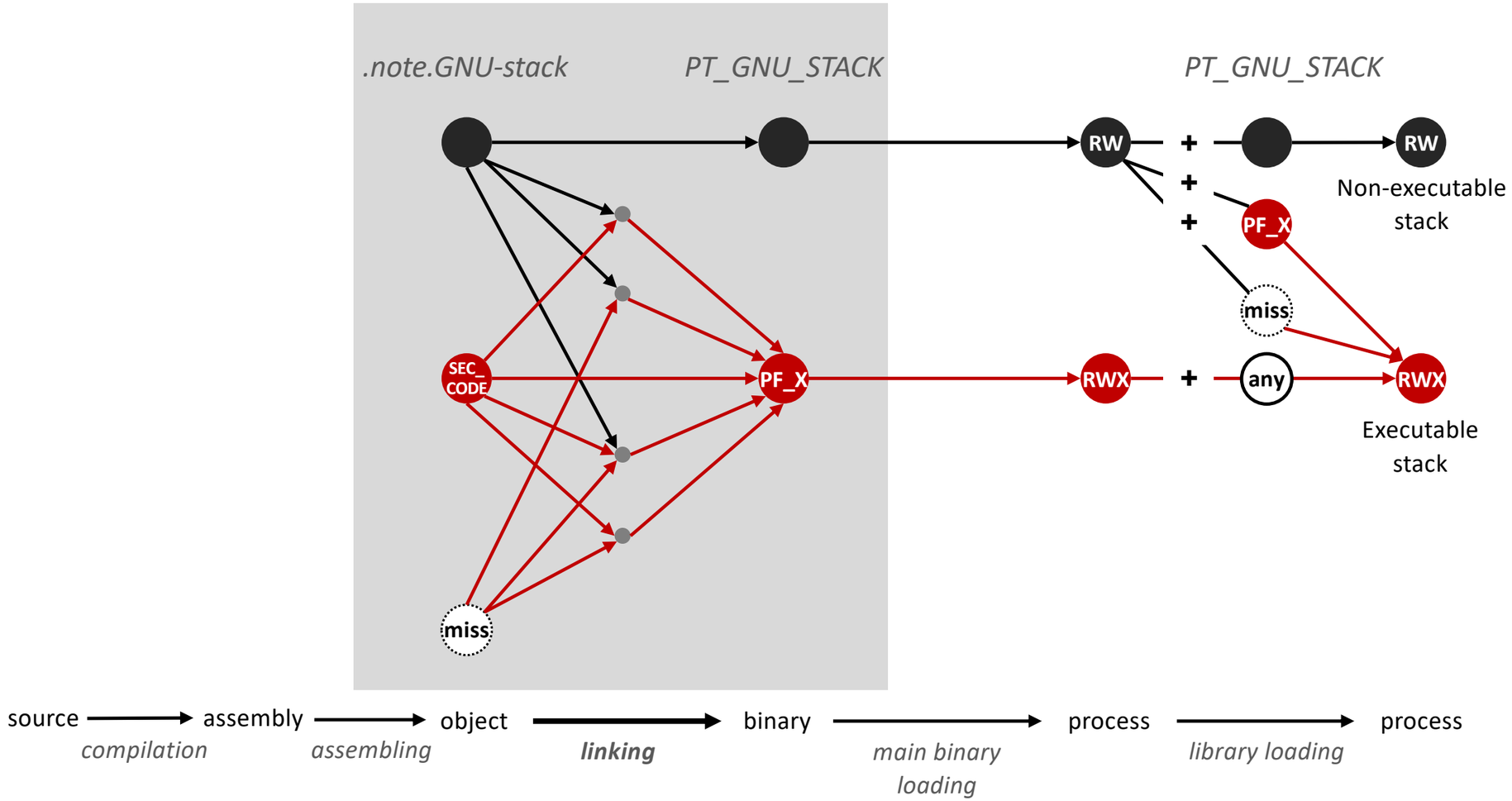
Stack Permission (Dynamic Library Loading)

- Loader checks the **program header** PT_GNU_STACK of each library



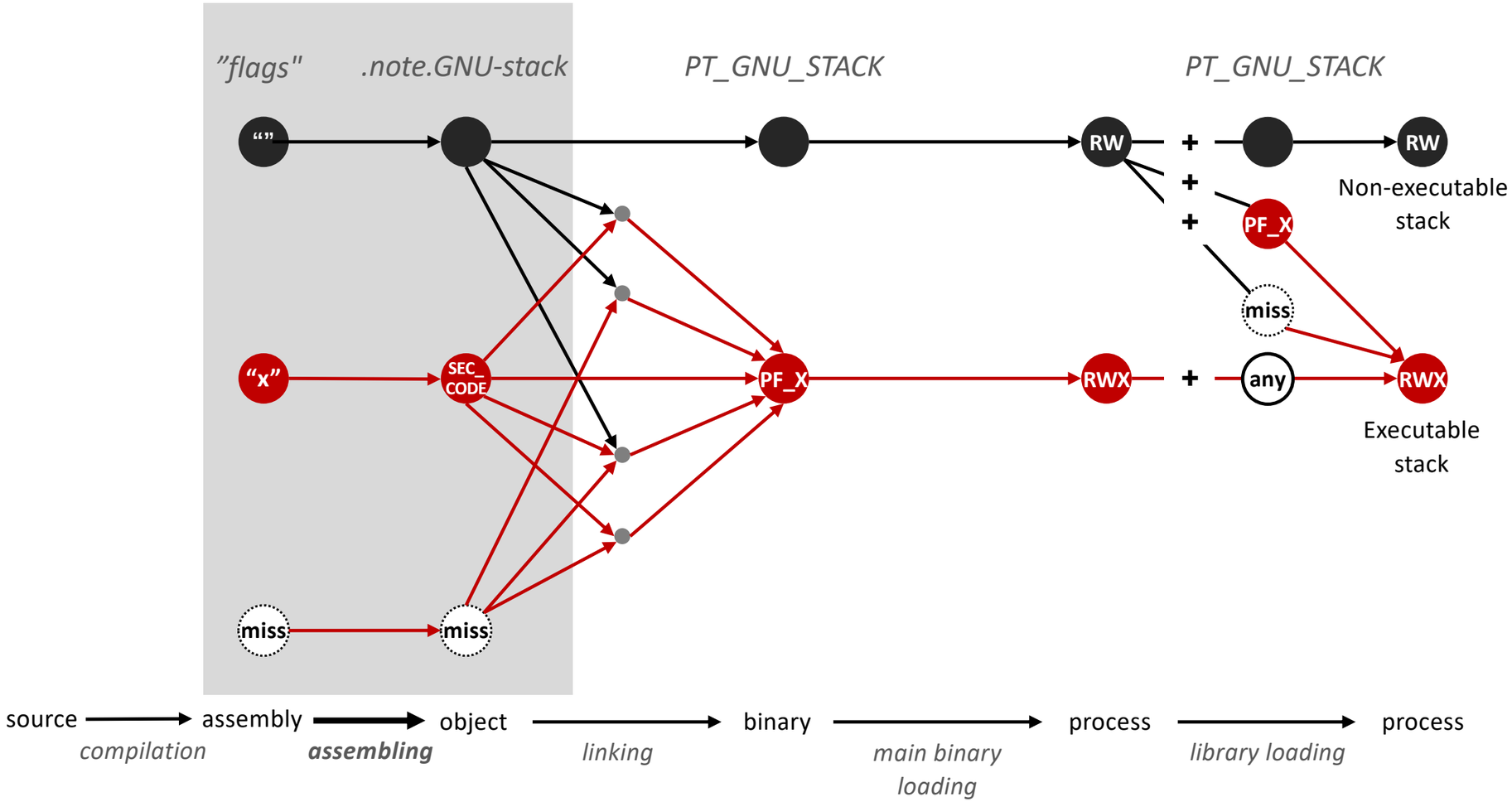
Stack Permission (Linking)

- Linker checks the **section header** .note.GNU-stack of each object file



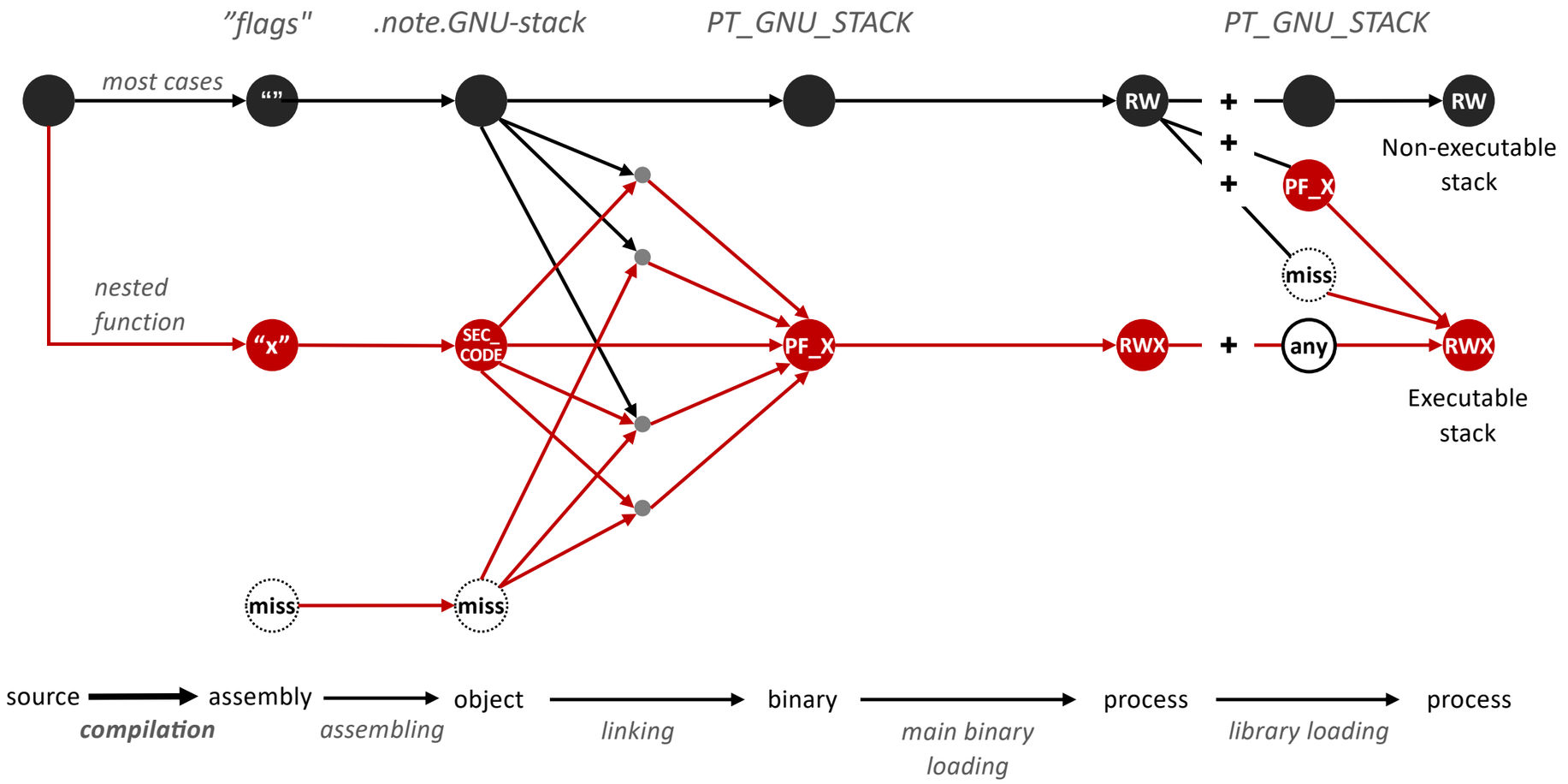
Stack Permission (Assembling)

- Assembler checks assembly file for `.section .note.GNU-stack,"flags”,@progbits`



Stack Permission (Compiling)

- Compiler always produces `.section .note.GNU-stack,"flags”,@progbits`



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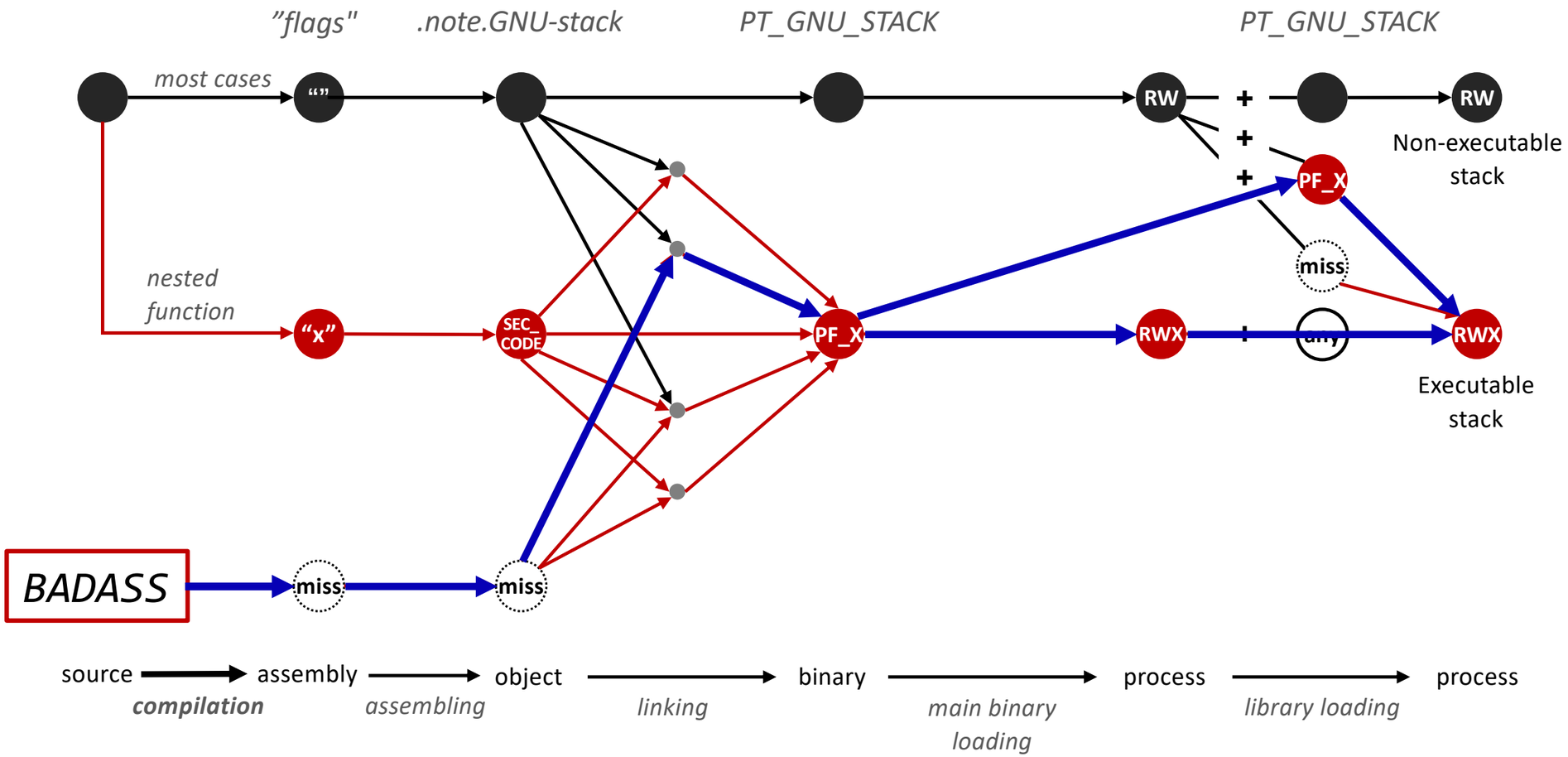
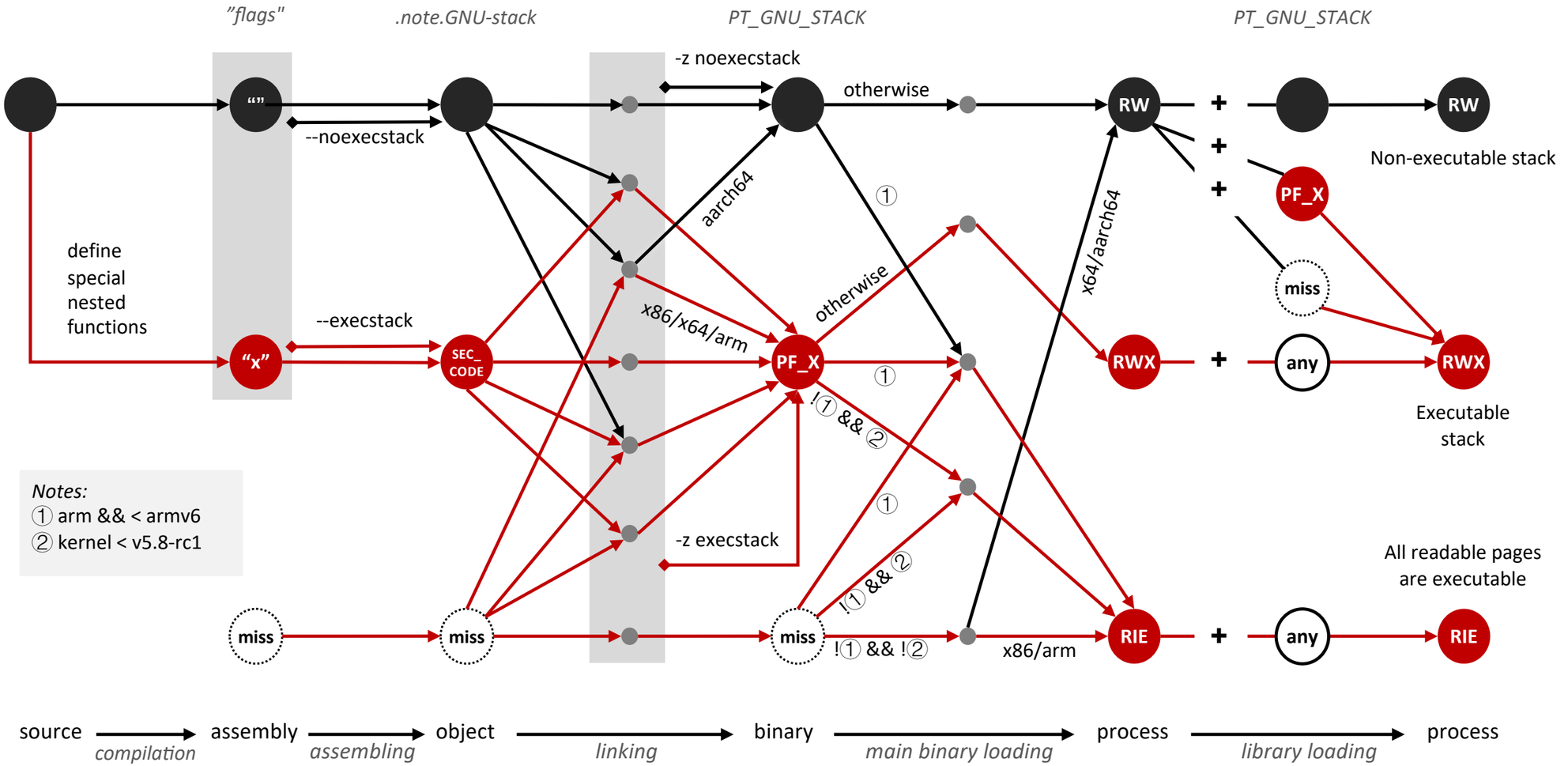


Stack Permission (All Together)

- More complex details in [our paper]



Takeaway 2

In-depth analysis!

Subtle design

Developer

W⊕X

- W⊕X enforcement on Linux requires concerted collaborations
  - Compiler, assembler, linker, loader, and kernel
- Assembly files, not generated by compiler, break the regular enforcement routine
- Subtlety of `.note.GNU-stack` section is the main root cause of executable stacks

Anything Else?

- Missing `.section .note.gnu.property,”a”`
  - GNU_PROPERTY_X86_FEATURE_1_IBT
    - Disable Intel CET IBT
  - GNU_PROPERTY_X86_FEATURE_1_SHSTK
    - Disable Intel CET SHSTK
  - GNU_PROPERTY_STACK_SIZE
    - Trigger stack overflow
  - GNU_PROPERTY_NO_COPY_ON_PROTECTED
    - Evil Copy [1]

[1] Ge, Xinyang, Mathias Payer, and Trent Jaeger. "An Evil Copy: How the Loader Betrays You." NDSS. 2017.

Mitigations

- Disable executable stack by default
  - Only enable via explicit compilation option
    - “--execstack” to assembler **as**
    - “-z execstack” to linker **ld**

- Always include the directive when using assembly
  - `.section .note.GNU-stack,””,@progbits`

- Kernel/loader asks for user confirmation

Stack Permission on Other OSes

- **OpenBSD**
  - Pioneer on W⊕X
  - Mandatory since 2016
- **Windows**
  - Not executable by default
  - Executable w/
    - .def __enable_execute_stack
    - call __enable_execute_stack
- **macOS**
  - Intel CPU
    - Linker option: -allow_stack_execute
    - Program header: ALLOW_STACK_EXECUTION
  - Apple Silicon
    - Always not executable

Conclusion

- *BADASS* in inlined reference monitor
  - 11/21 have *BADASS* issue
  - Even security experts can not avoid
- In-depth analysis of W⊕X enforcement
  - Concerted collaborations
  - Too subtle to notice
- Open source
  - https://github.com/psu-security-universe/badass

Thank You

Question?

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