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

Hengkai Ye Hong Hu

History of Code Injection

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1988

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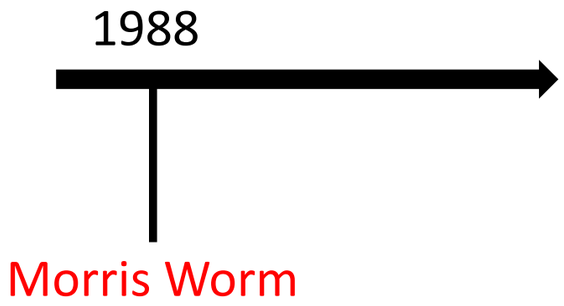

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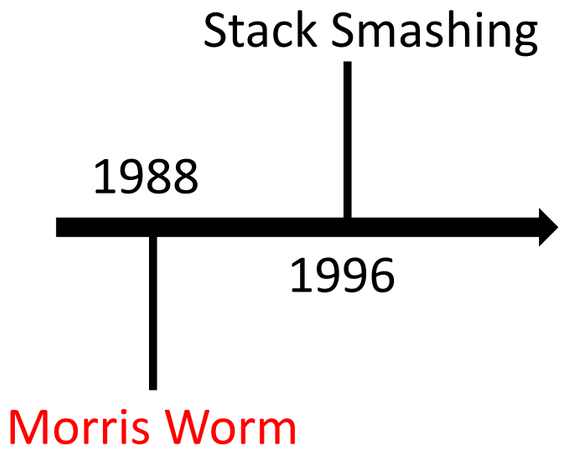

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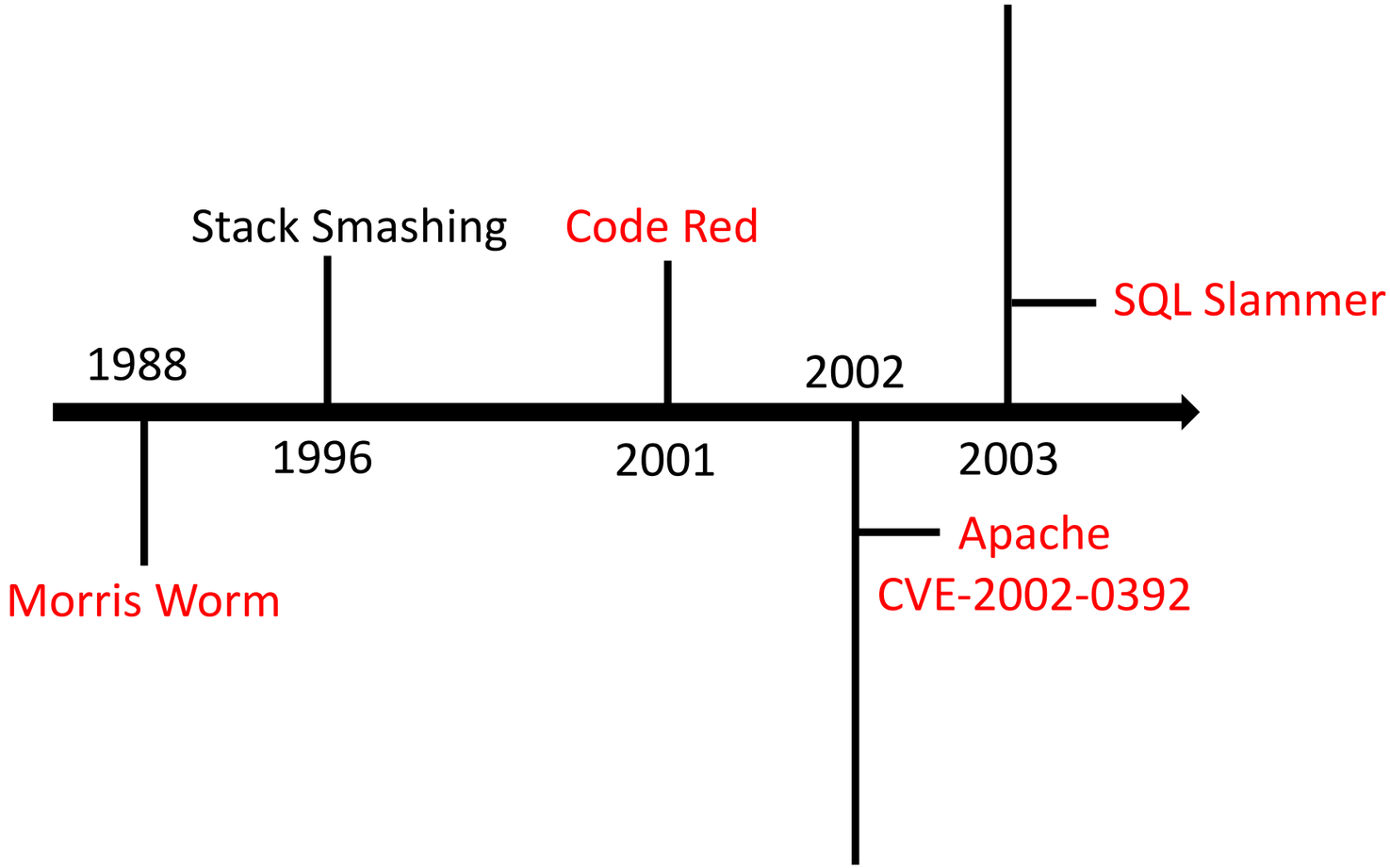

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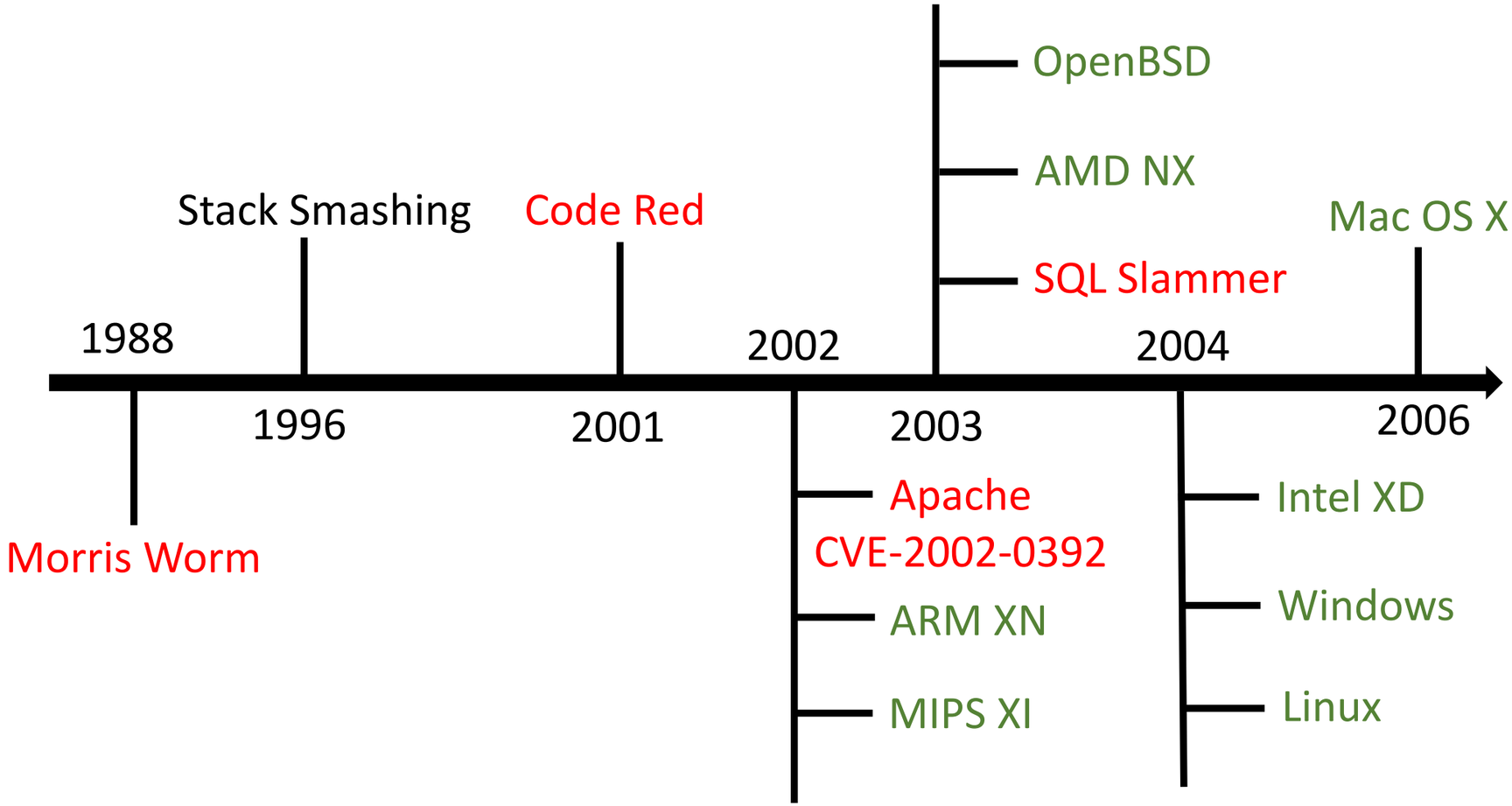

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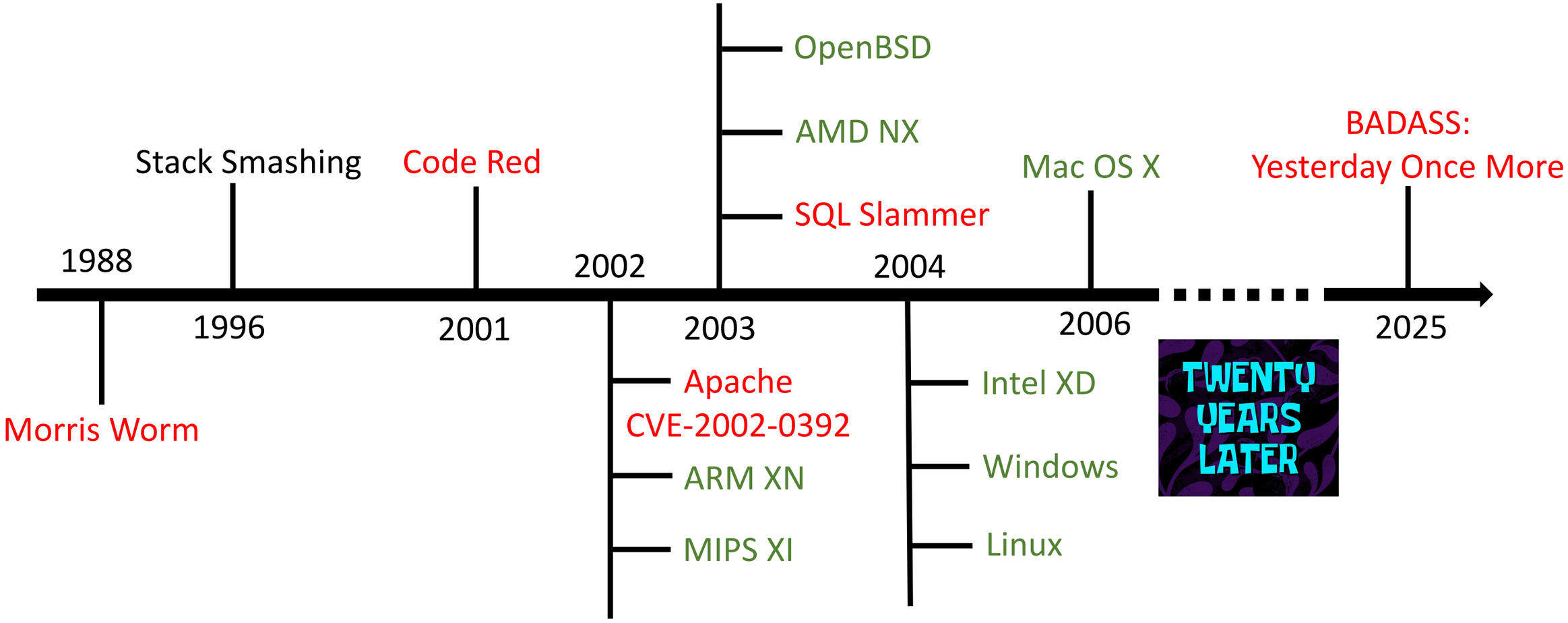

Code Injection w/ An Executable Stack 😈

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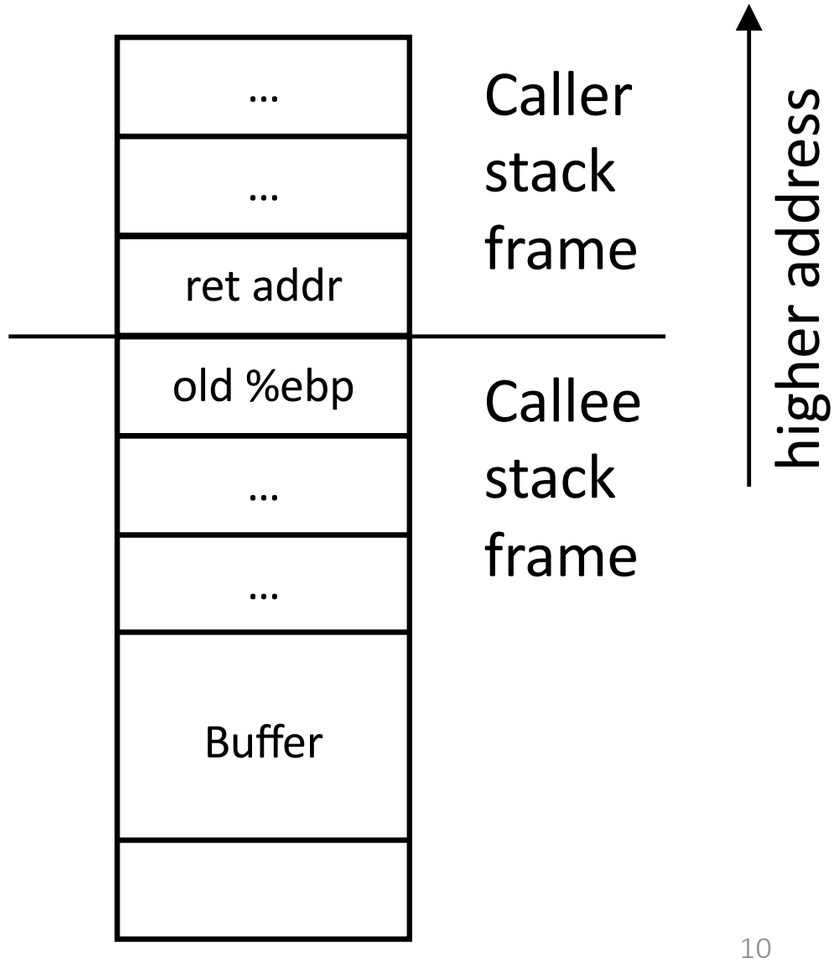
- Stack buffer overflow vulnerability



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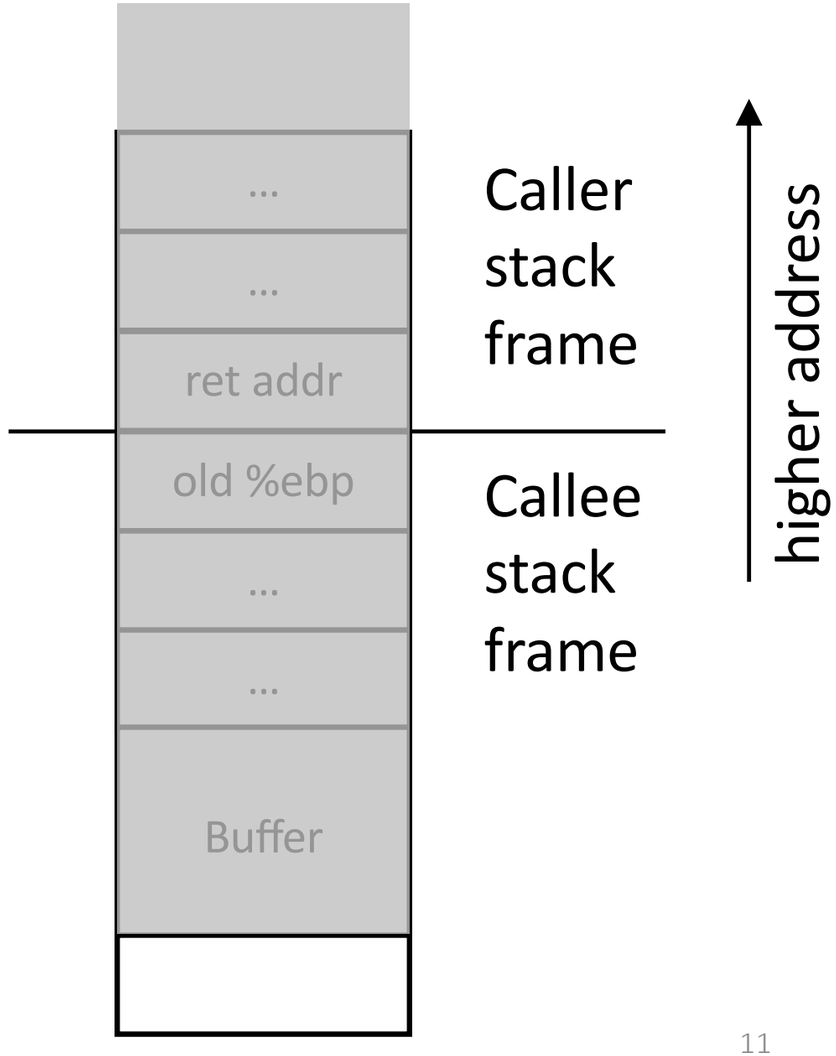
- Stack buffer overflow vulnerability
  - Attackers can insert any content on stack



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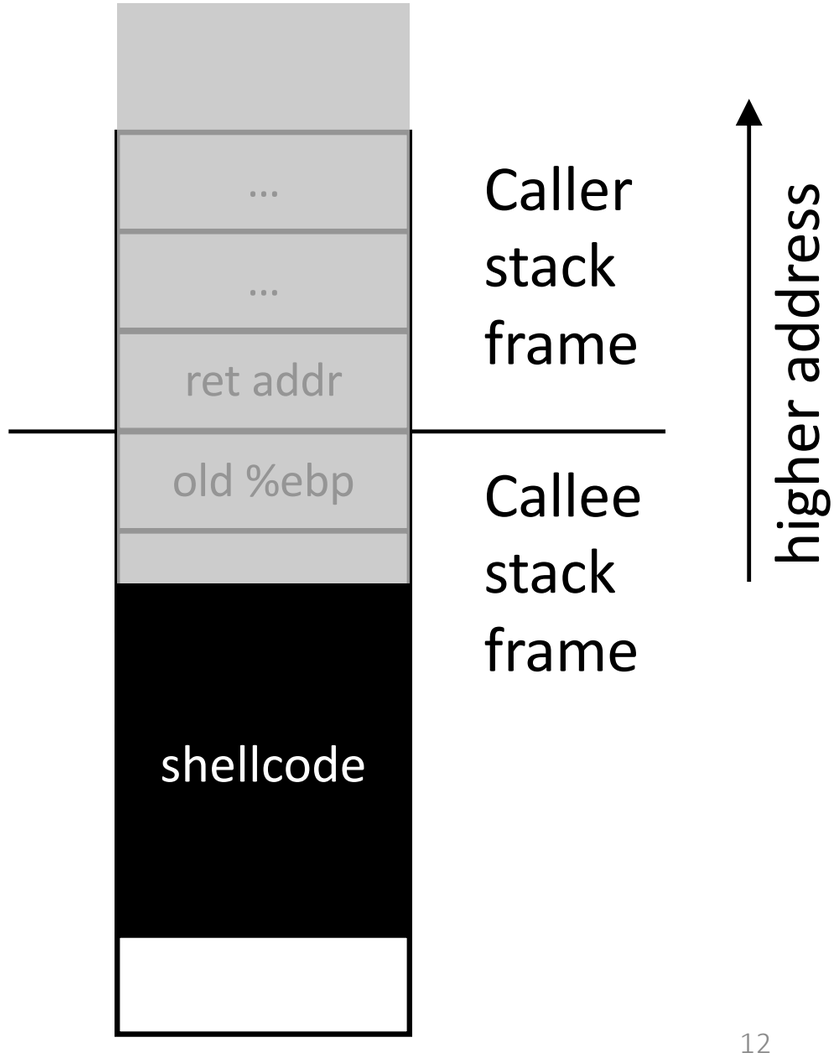
  1. Place shellcode on stack



Code Injection w/ An Executable Stack 😈

- Stack buffer overflow vulnerability
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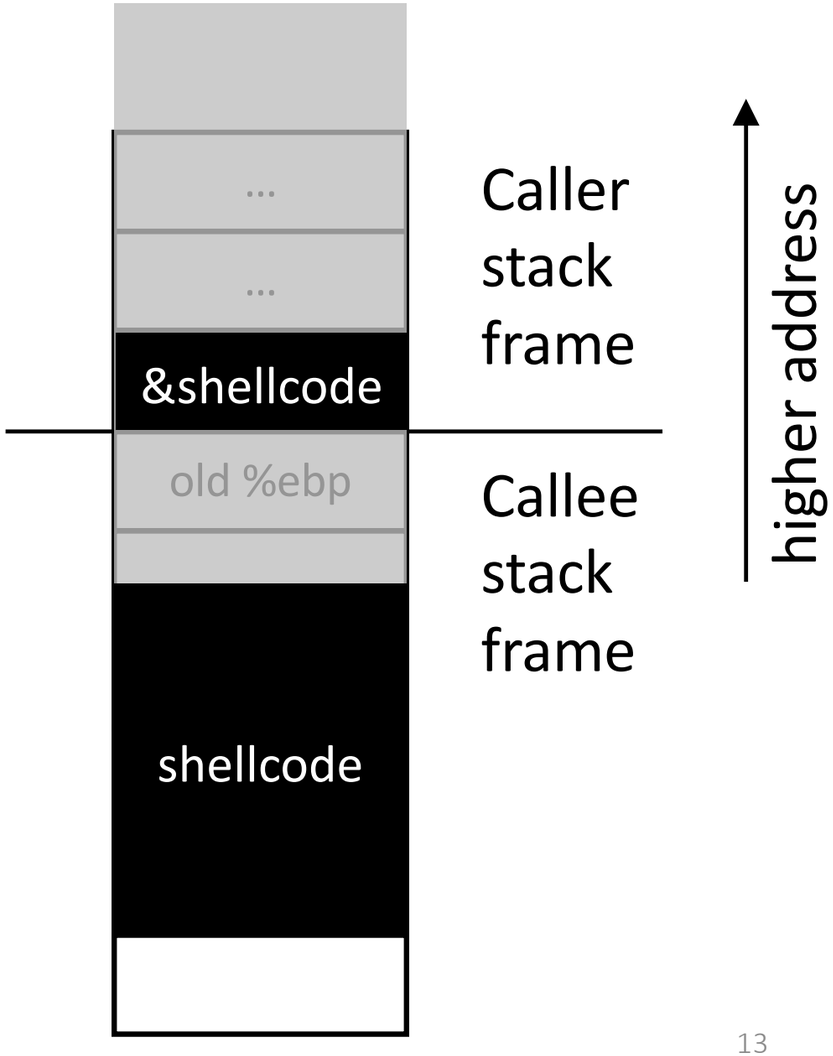
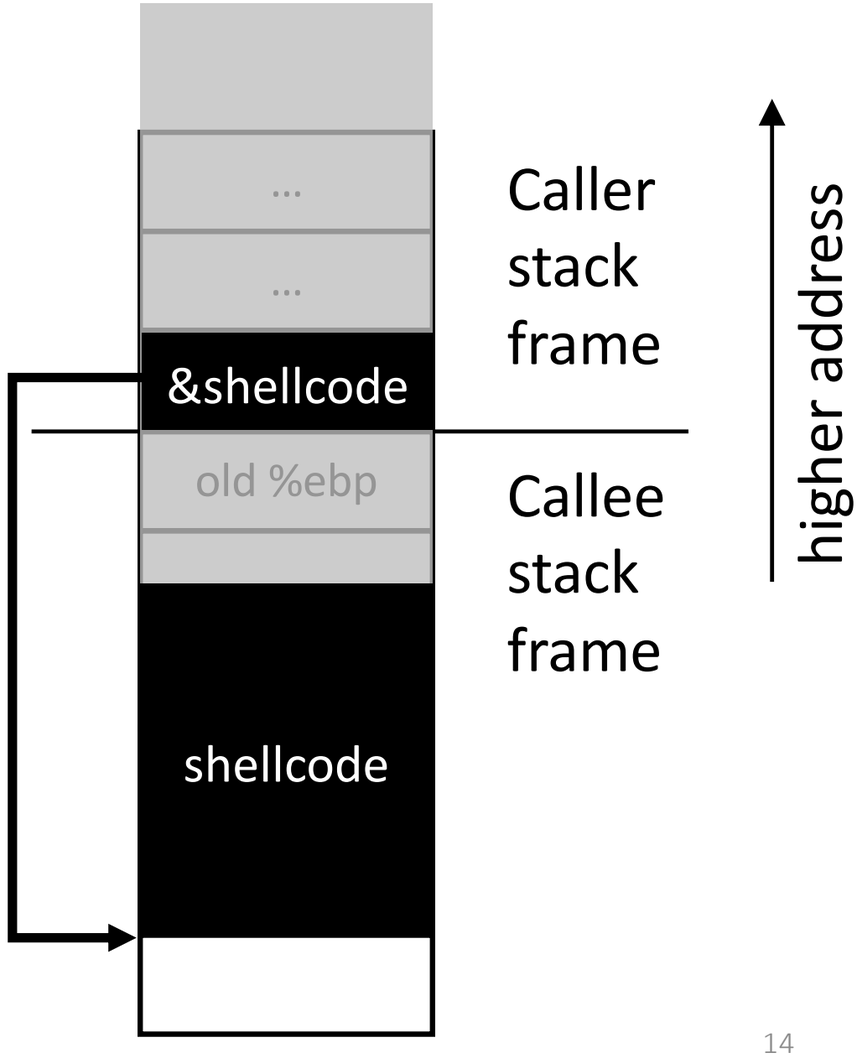
  1. Place shellcode on stack
  2. Overwrite return address to &shellcode



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



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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

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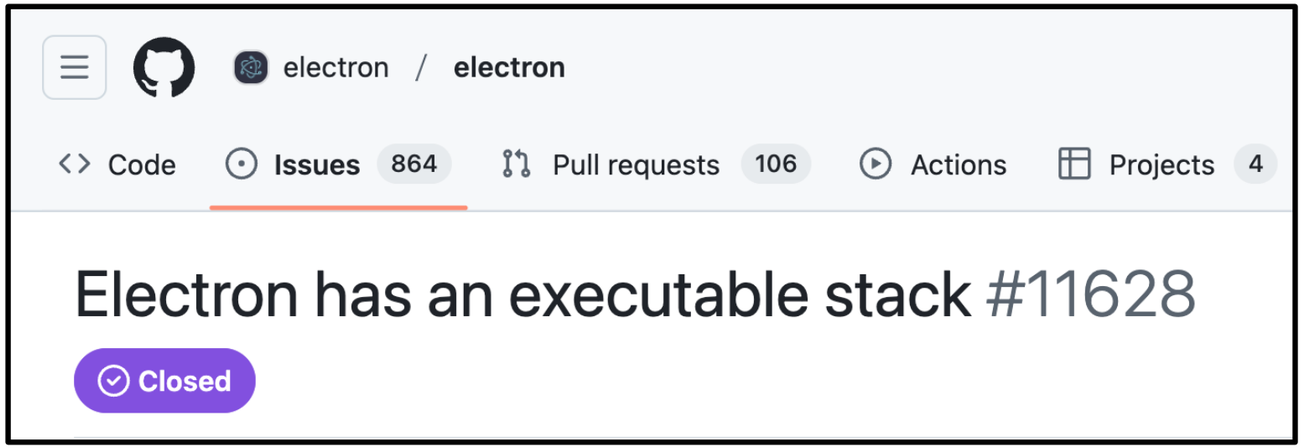

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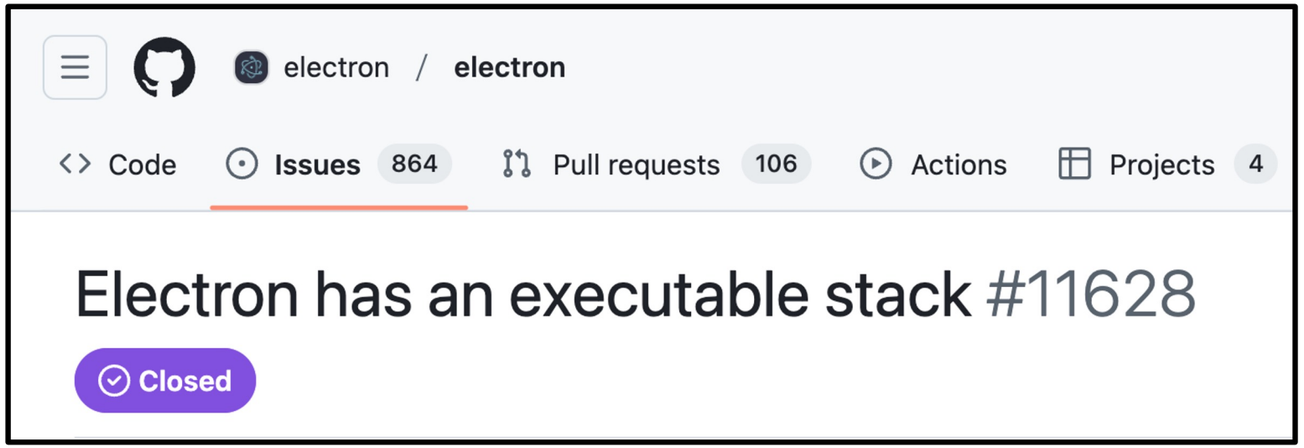

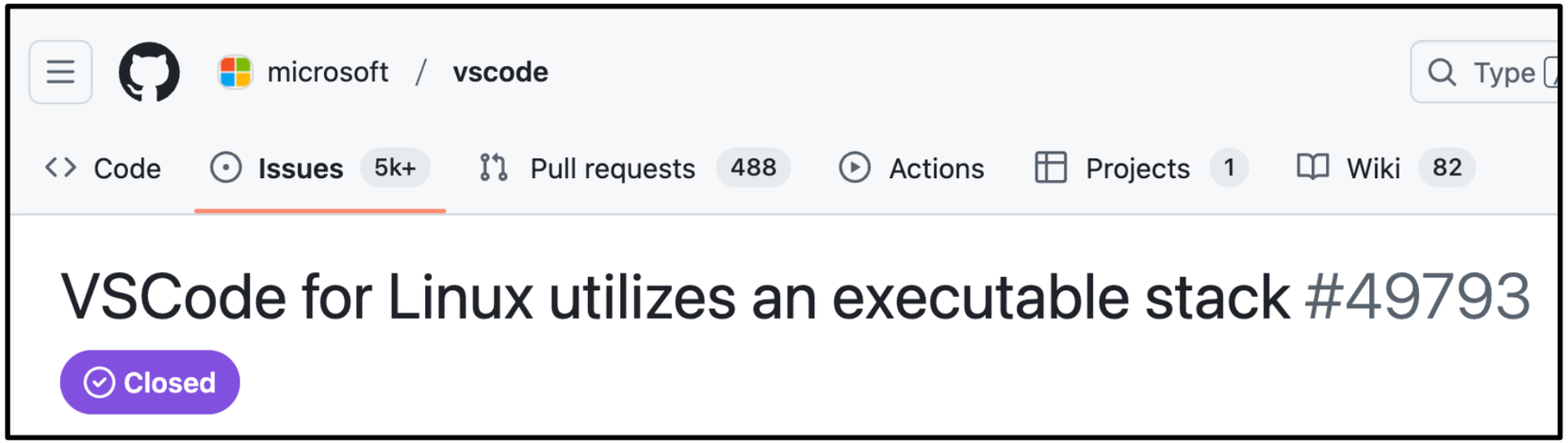

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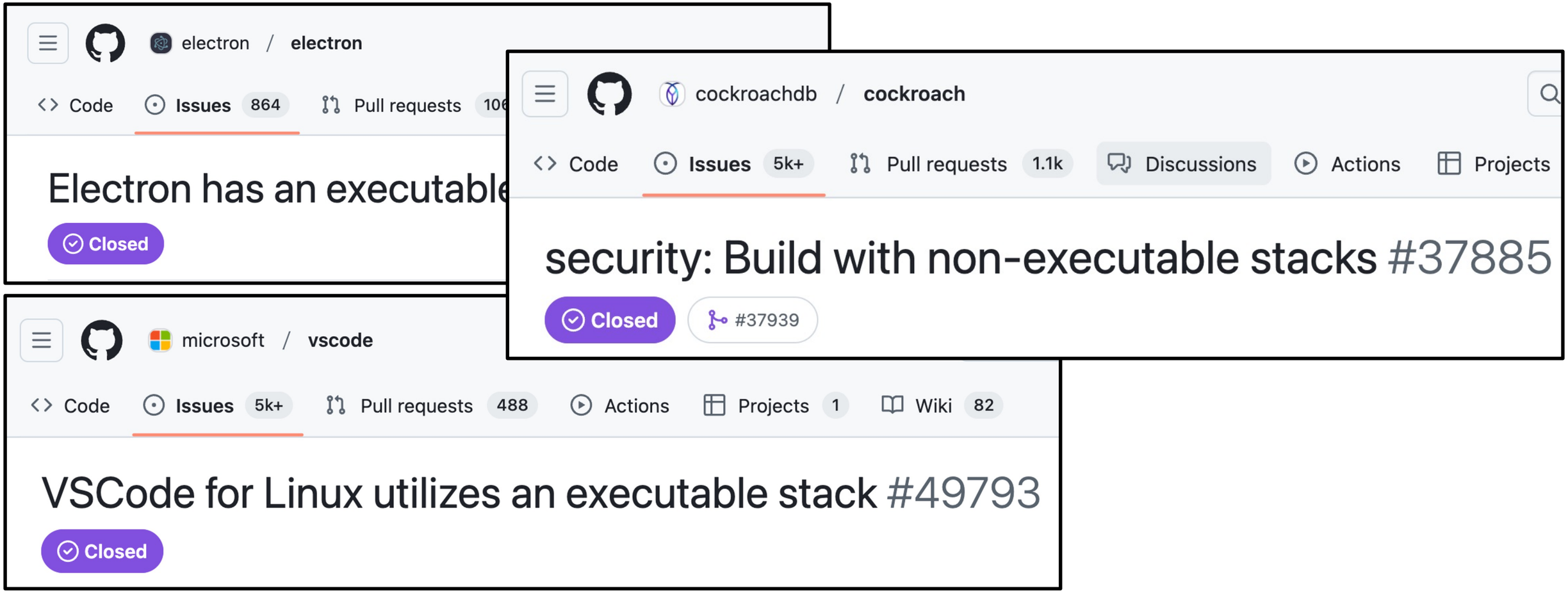

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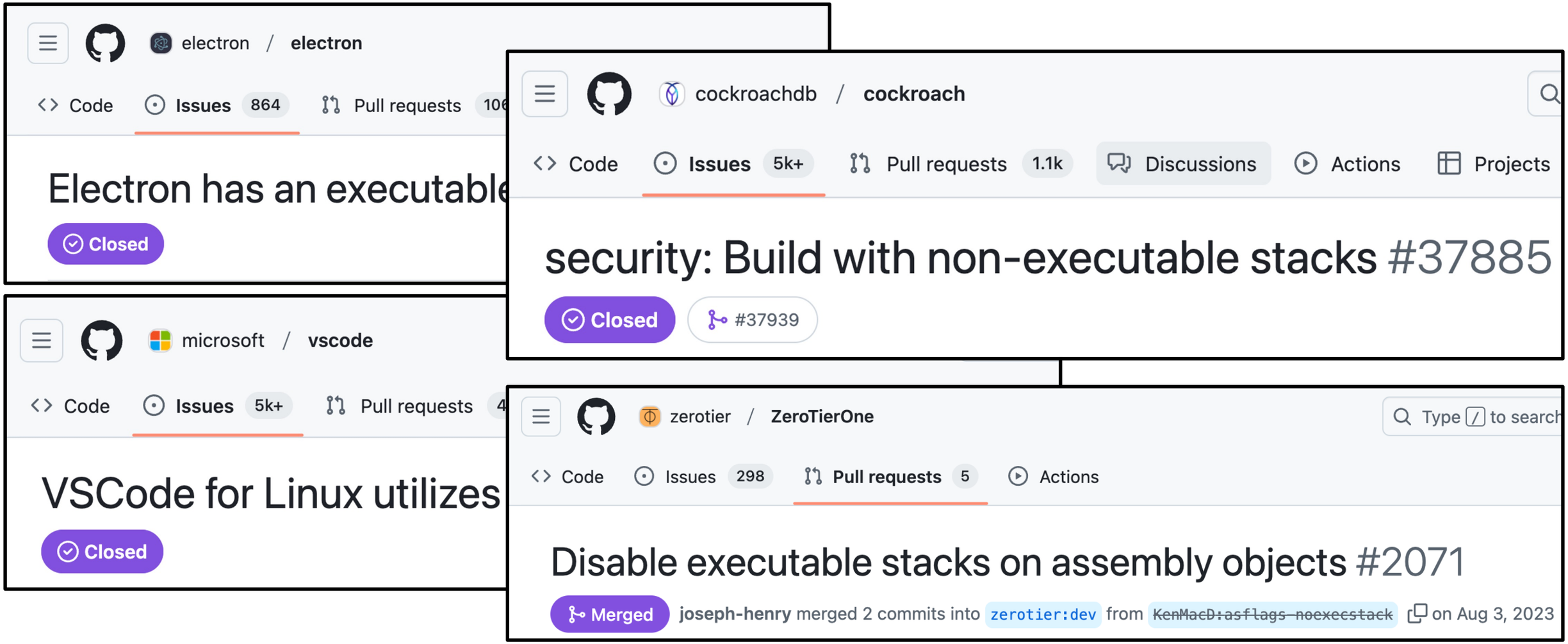

When Your Assembly is Not Good Enough

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- Assembly files w/o `.section .note.GNU-stack,” ”,@progbits`

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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>
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int main(int argc, char *argv[]) {
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What Happened

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Developer

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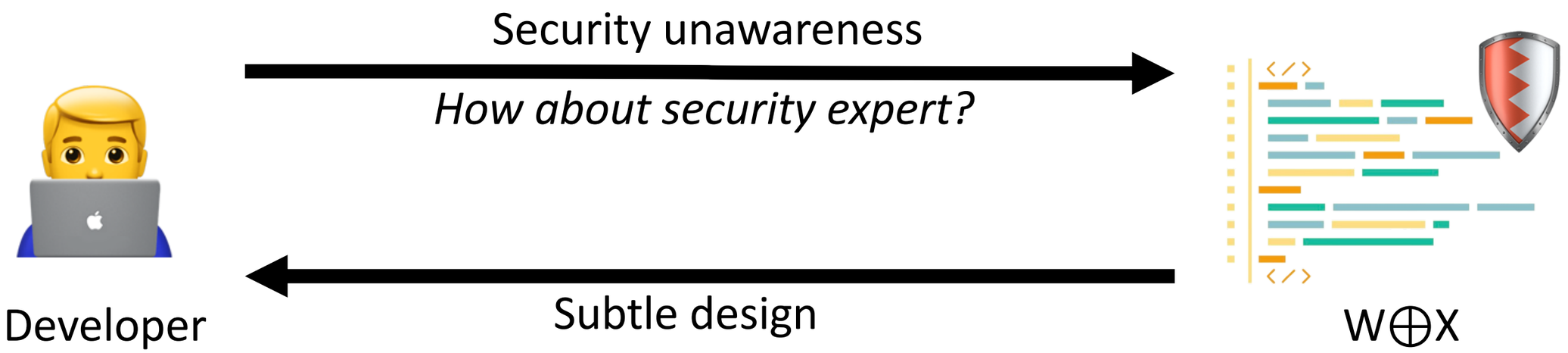

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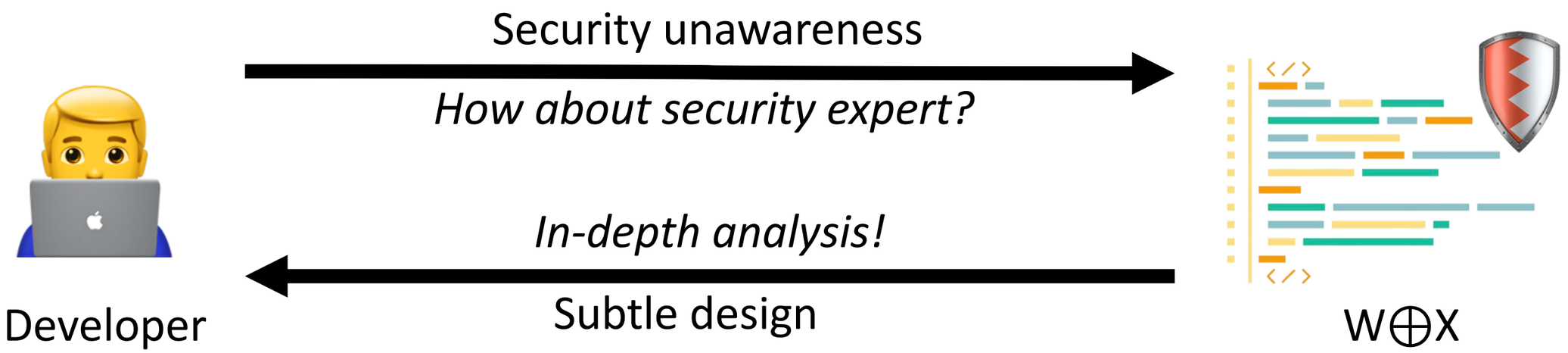

Investigating Security Applications

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Investigating Security Applications

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- If: *BADASS* during security instrumentatinon

Investigating Security Applications

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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

- If: *BADASS* during security instrumentatinon
- Then: executable stack for all “hardened” binaries

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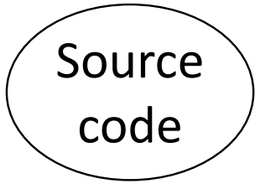

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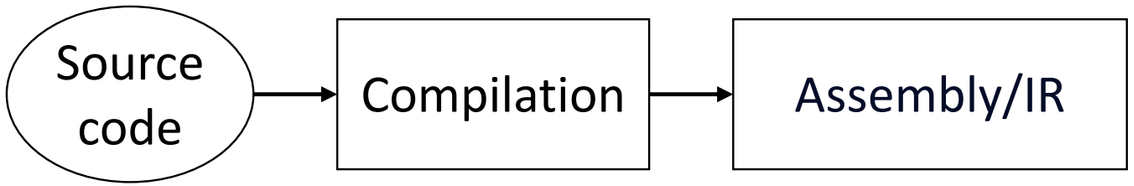

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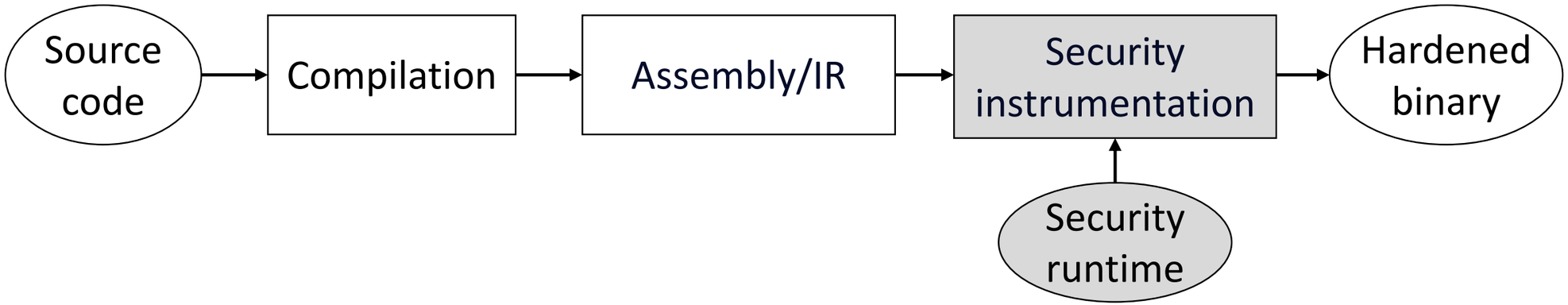

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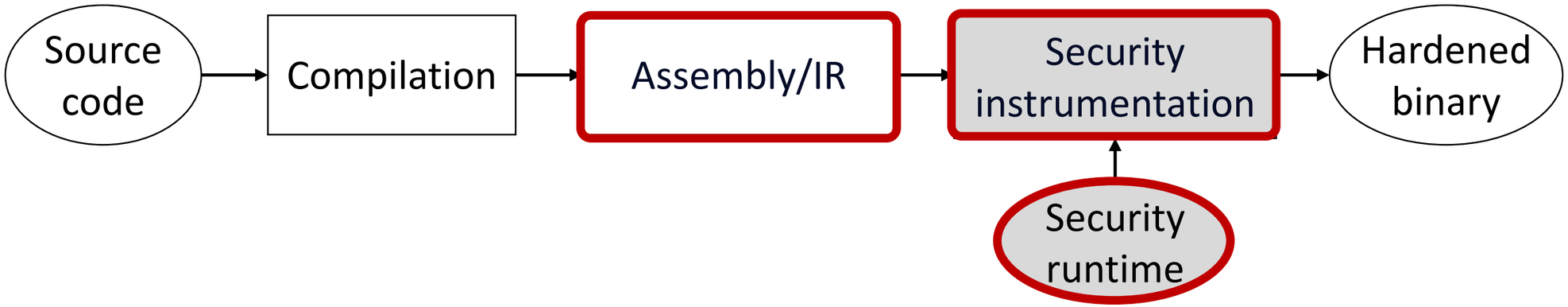

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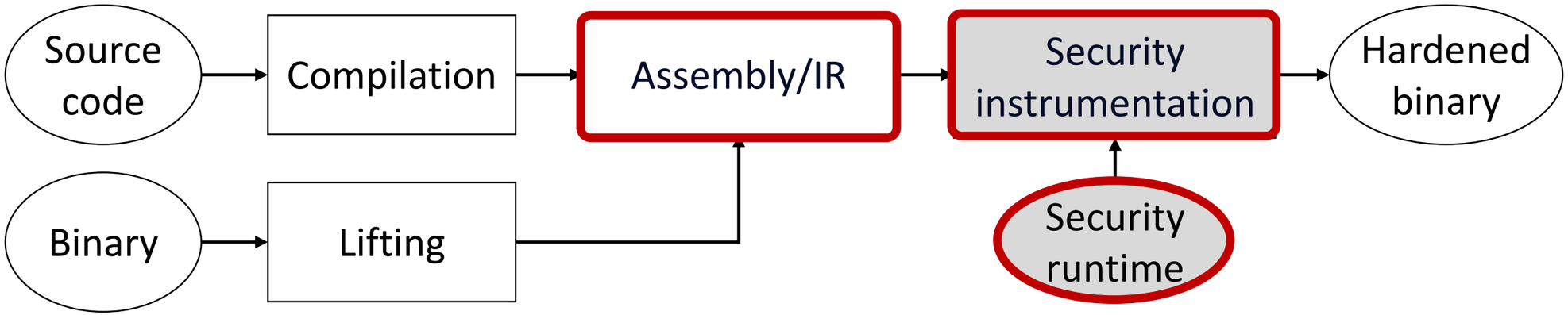

Investigating Security Applications

- 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		
Ramblr	NDSS'17	yes		
Multiverse	NDSS'18	no		
Egalito	ASPLOS'20	no		
RetroWrite	IEEE S&P'20	yes		
E9Patch	PLDI'20	no		
Ddisasm	USENIX SEC'20	yes		
ARMore	USENIX SEC'23	yes		
SAFER	USENIX SEC'23	yes		

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ARMore	USENIX SEC'23	yes	yes	
SAFER	USENIX SEC'23	yes	no	

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		
MCFI	PLDI'14	yes		
LLVM CFI	USENIX SEC'14	no		
RockJIT	CCS'14	yes		
πCFI	CCS'15	yes		
PathArmor	CCS'15	yes		
μCFI	CCS'18	yes		
Android kCFI	-	no		

4/8 CFI Solutions have *BADASS*

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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

Developer

Security unawareness

How about security expert?

W⊕X

Takeaway 1

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- Even experienced security researchers/developers may miss the directive

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- Even experienced security researchers/developers may miss the directive
- Cannot simply attribute *BADASS* issues to the security unawareness

Takeaway 1

Developer

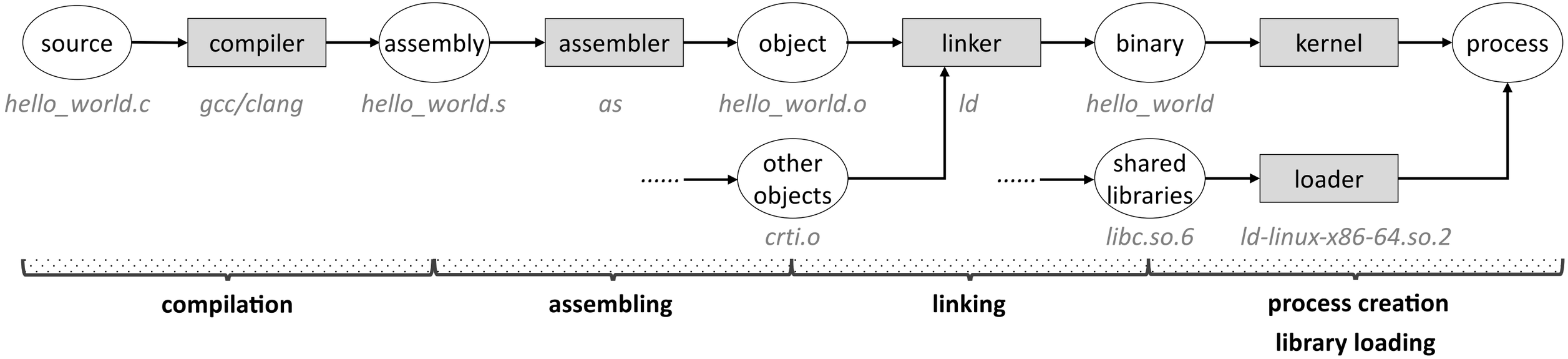
Security unawareness

How about security expert?

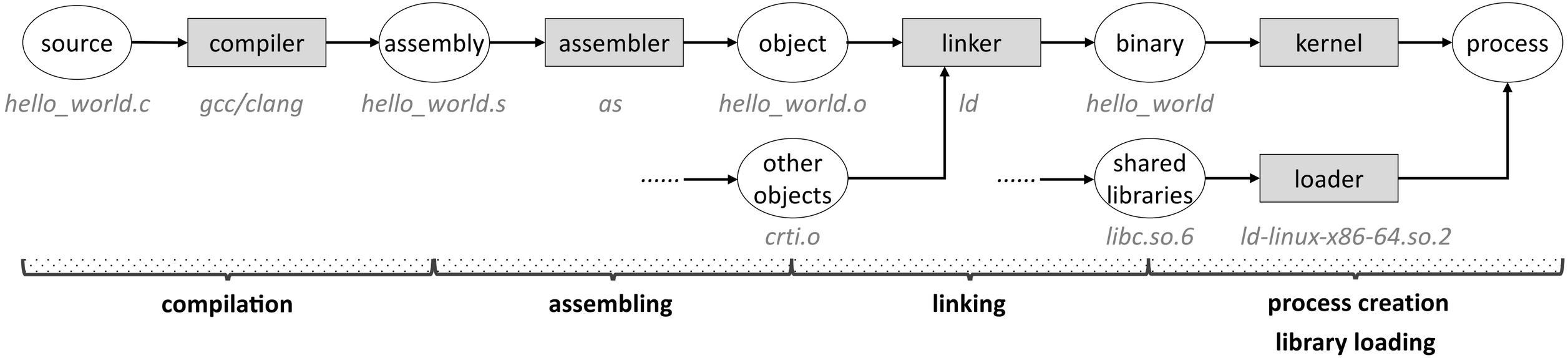
W⊕X

- 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

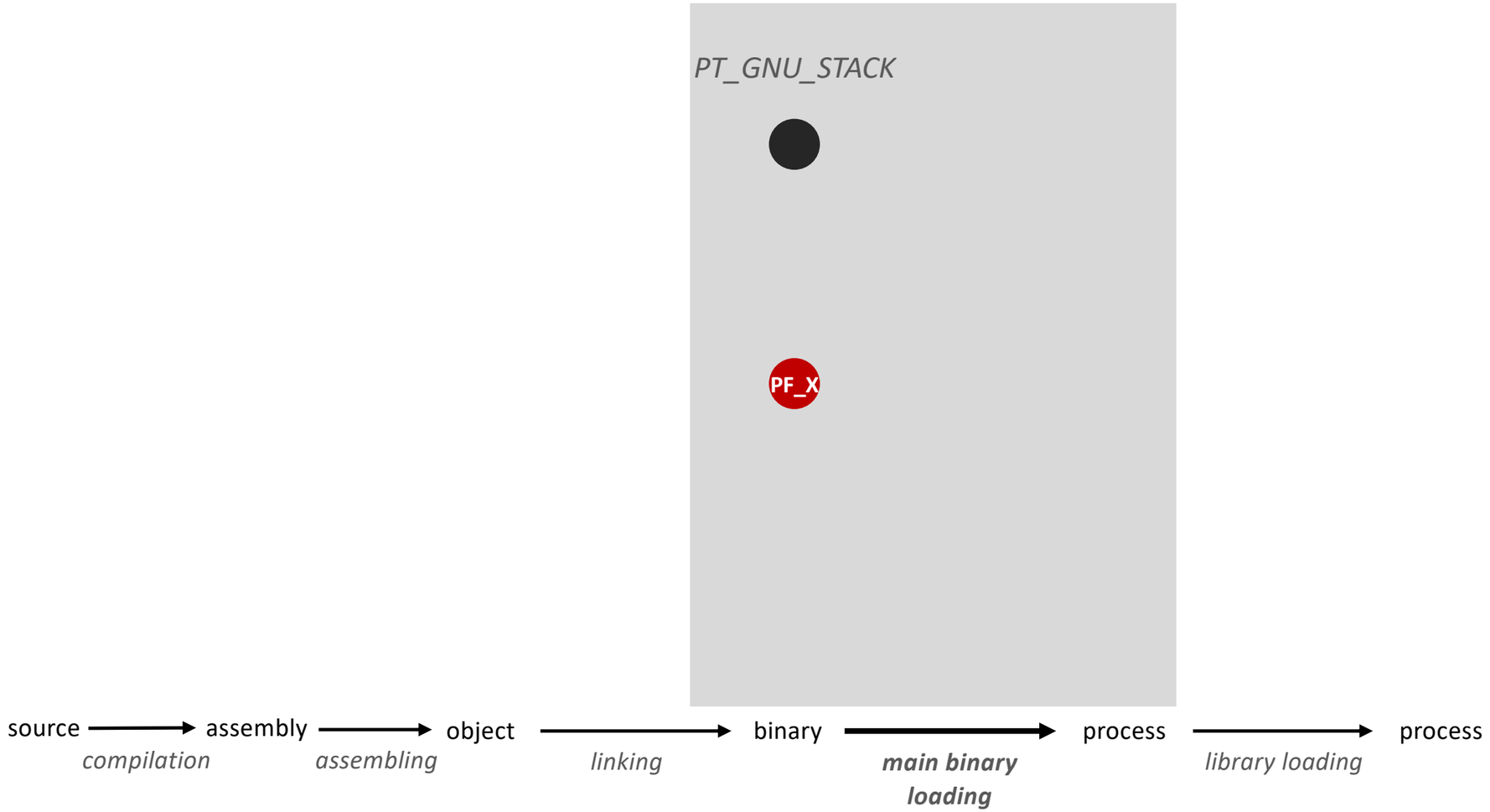


W⊕X Enforcement Analysis



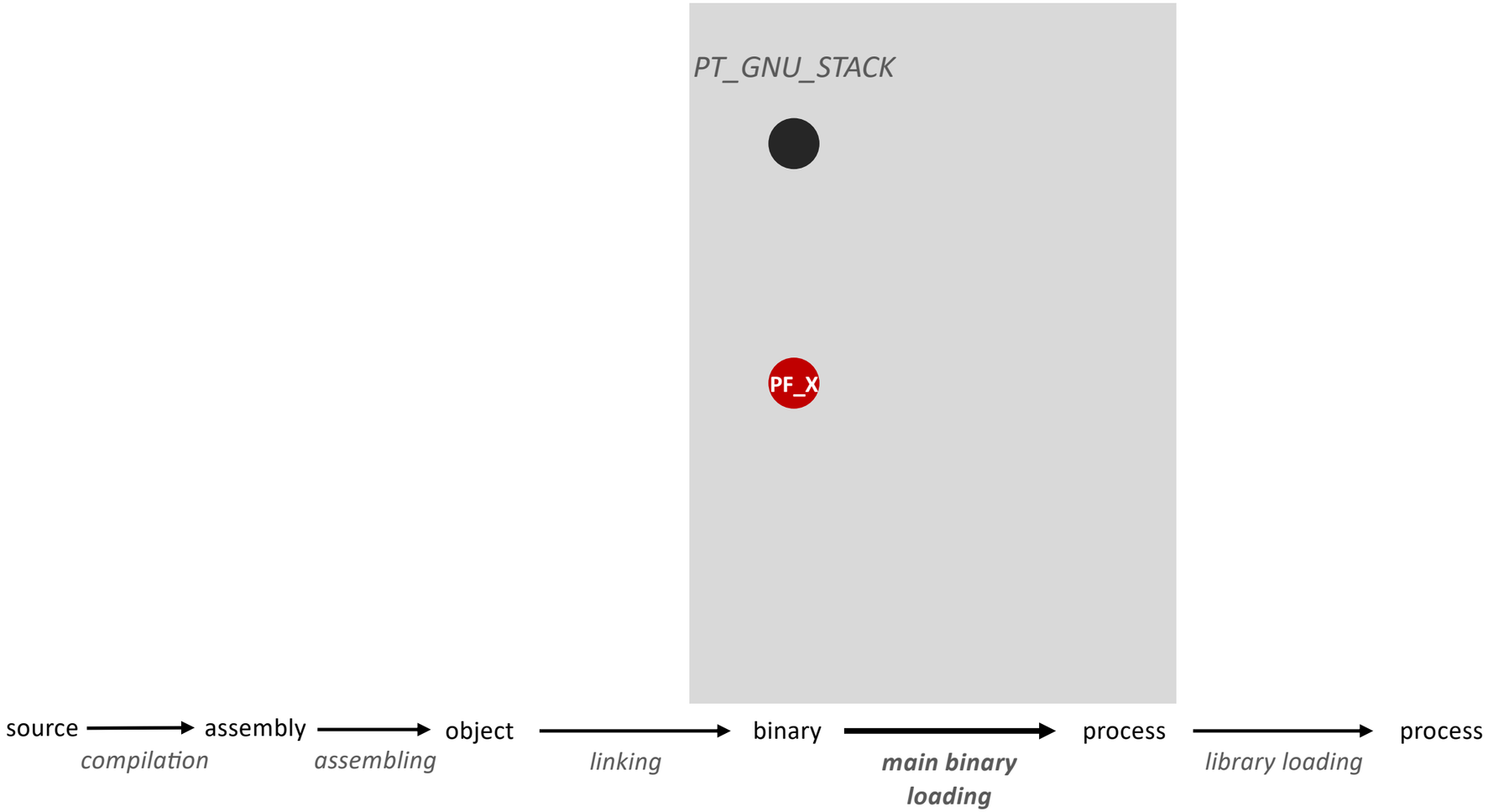
- **ALL** steps are related to stack permission

Stack Permission (Process Creation)



Stack Permission (Process Creation)

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



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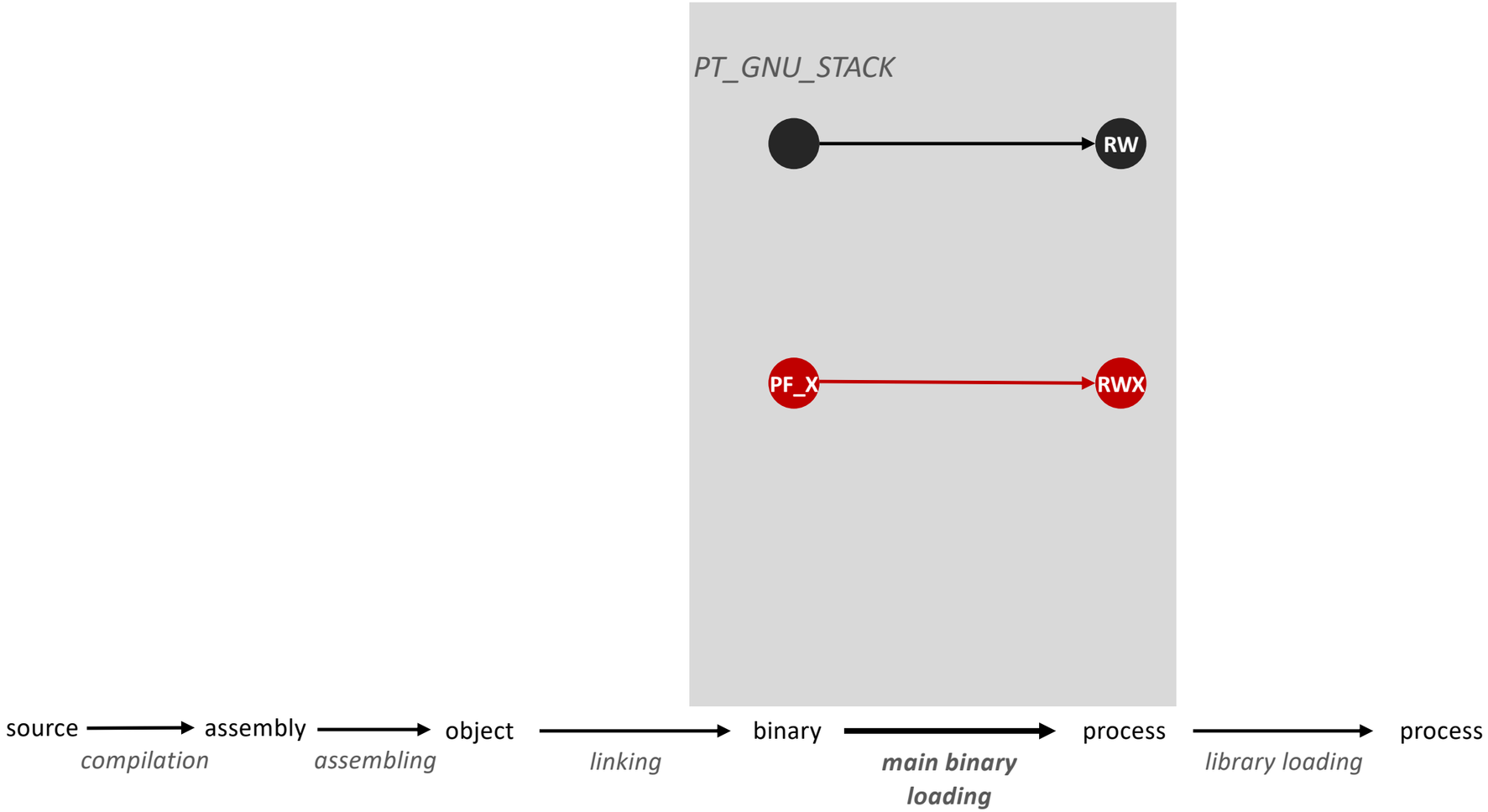
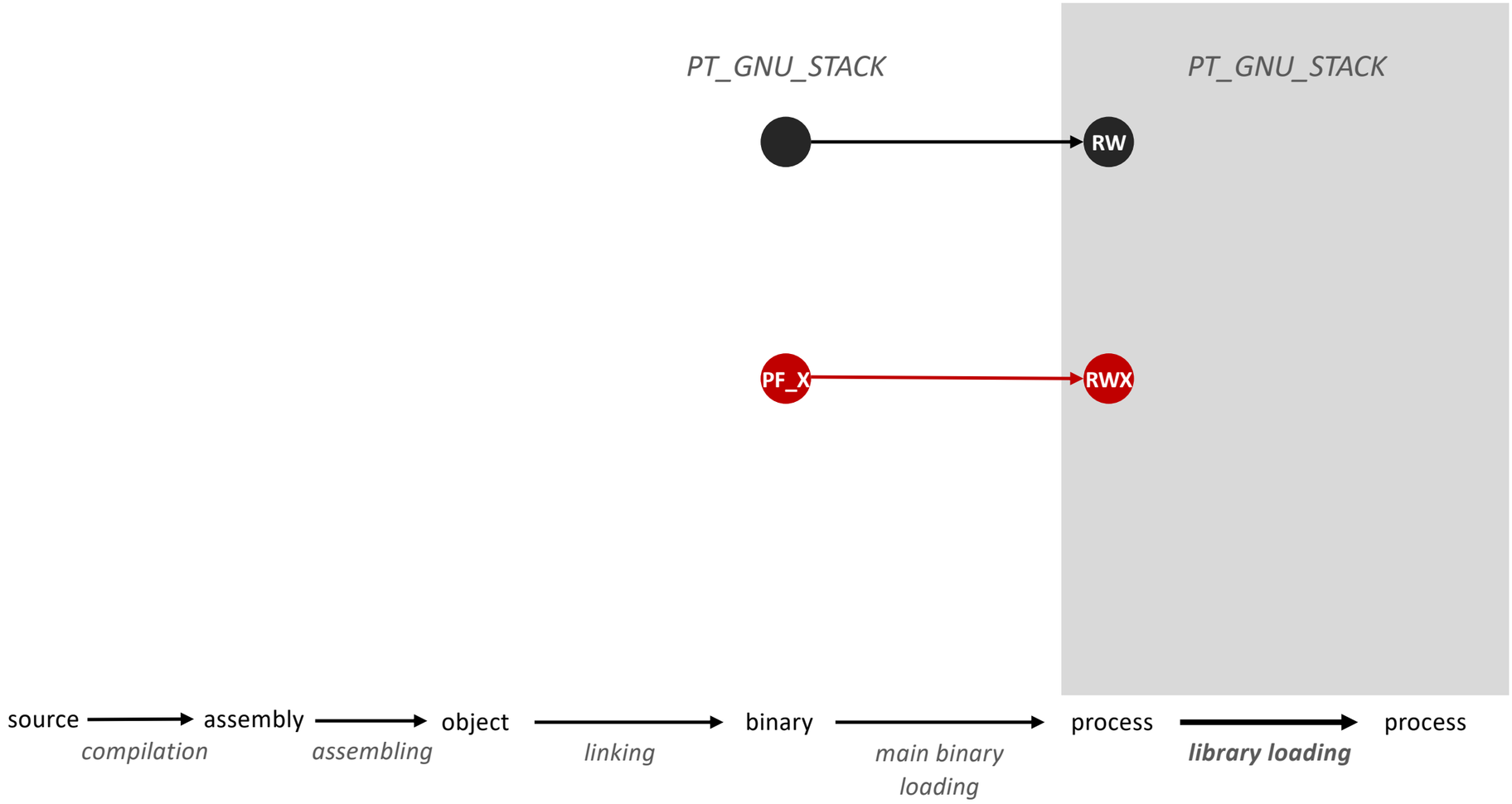
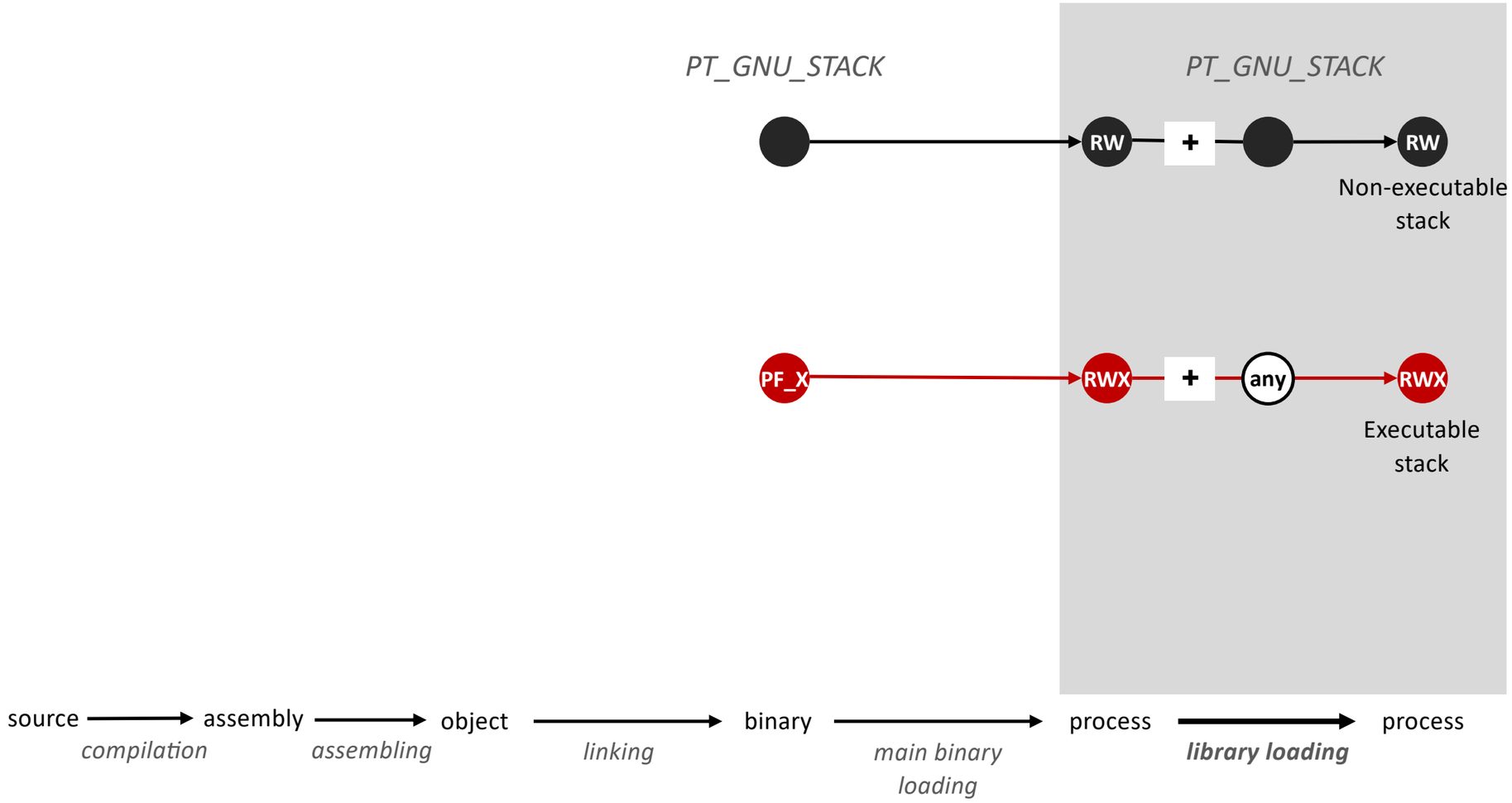


Stack Permission (Dynamic Library Loading)



Stack Permission (Dynamic Library Loading)

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



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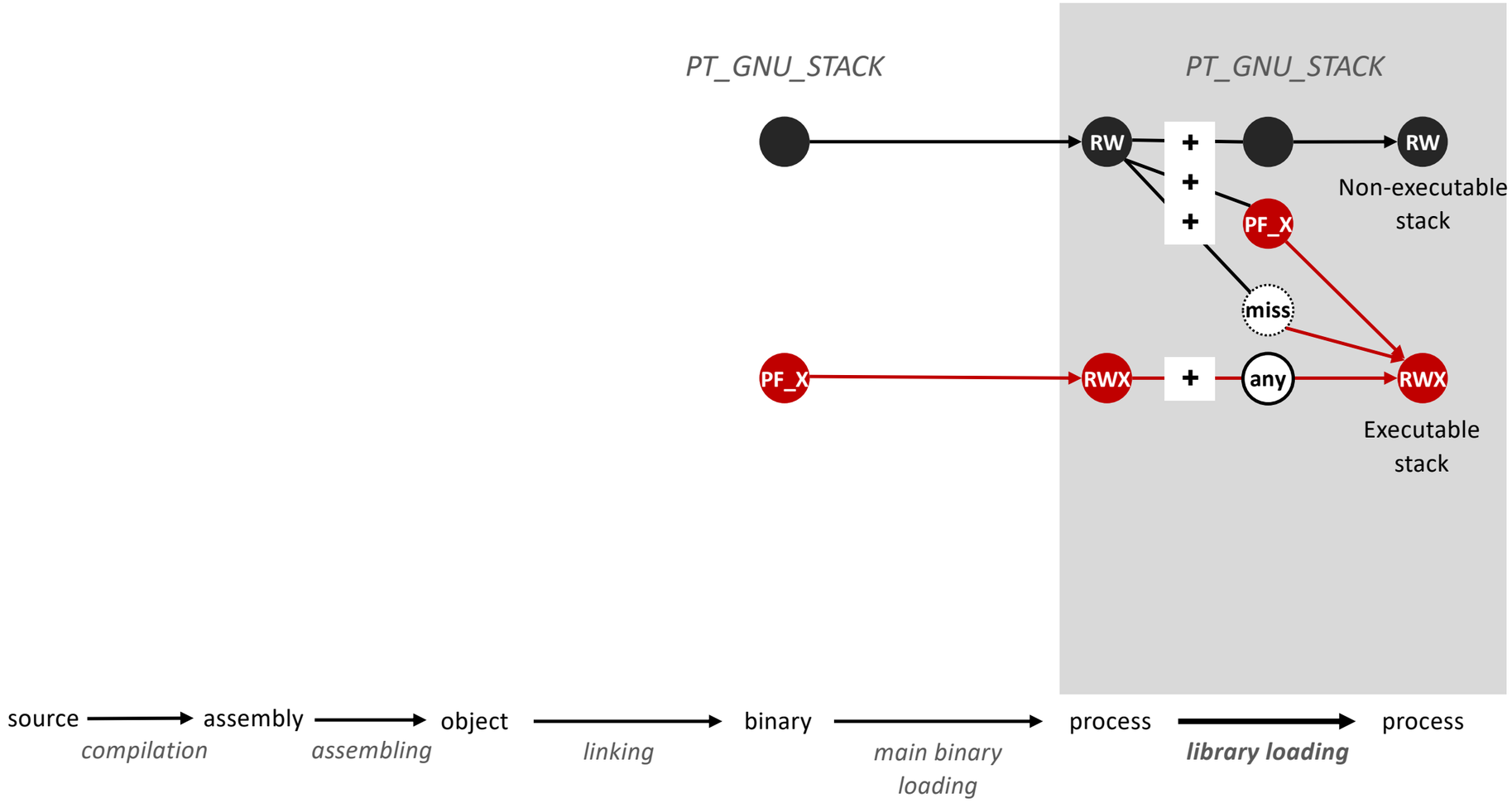
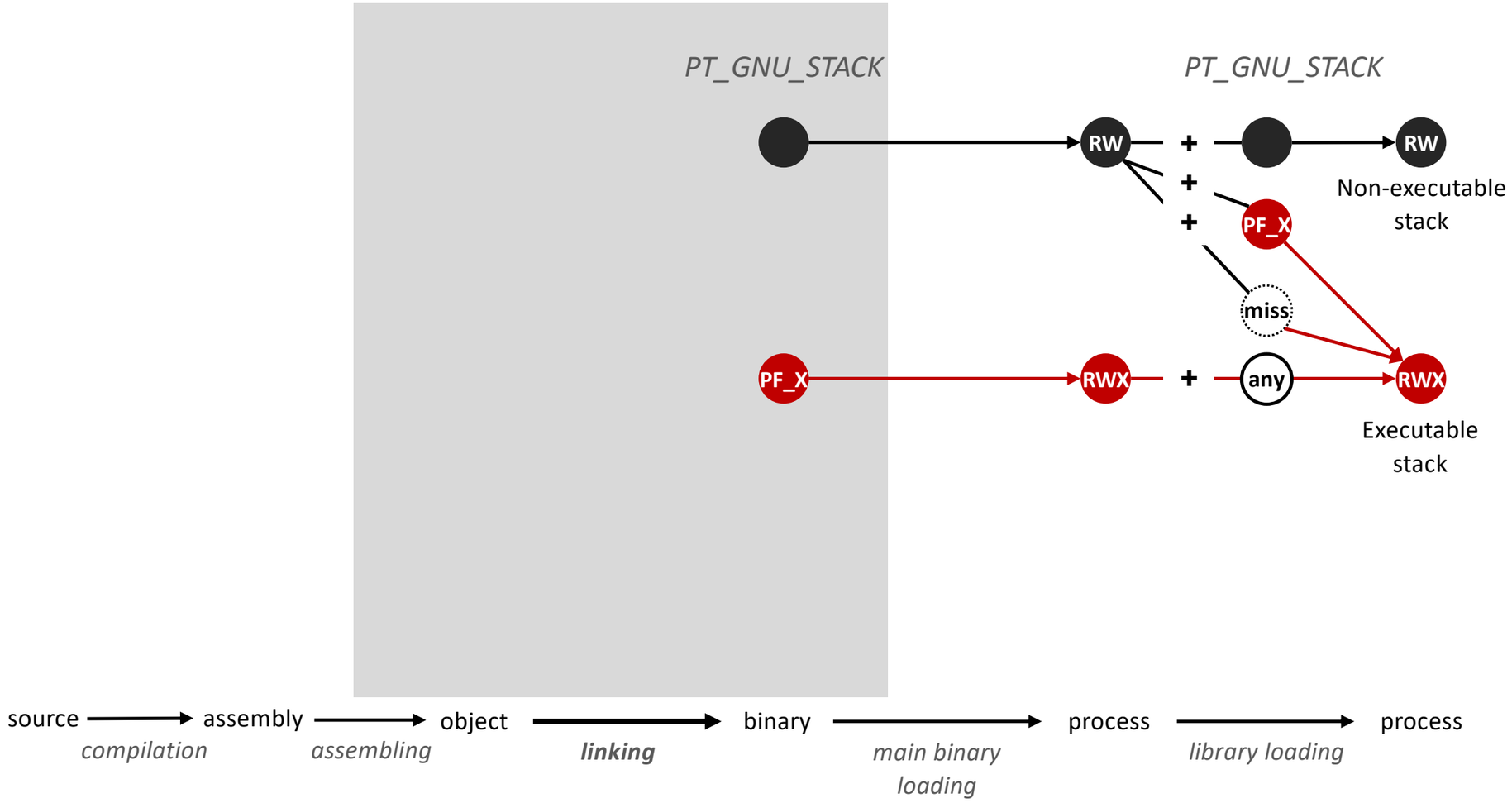


Stack Permission (Linking)



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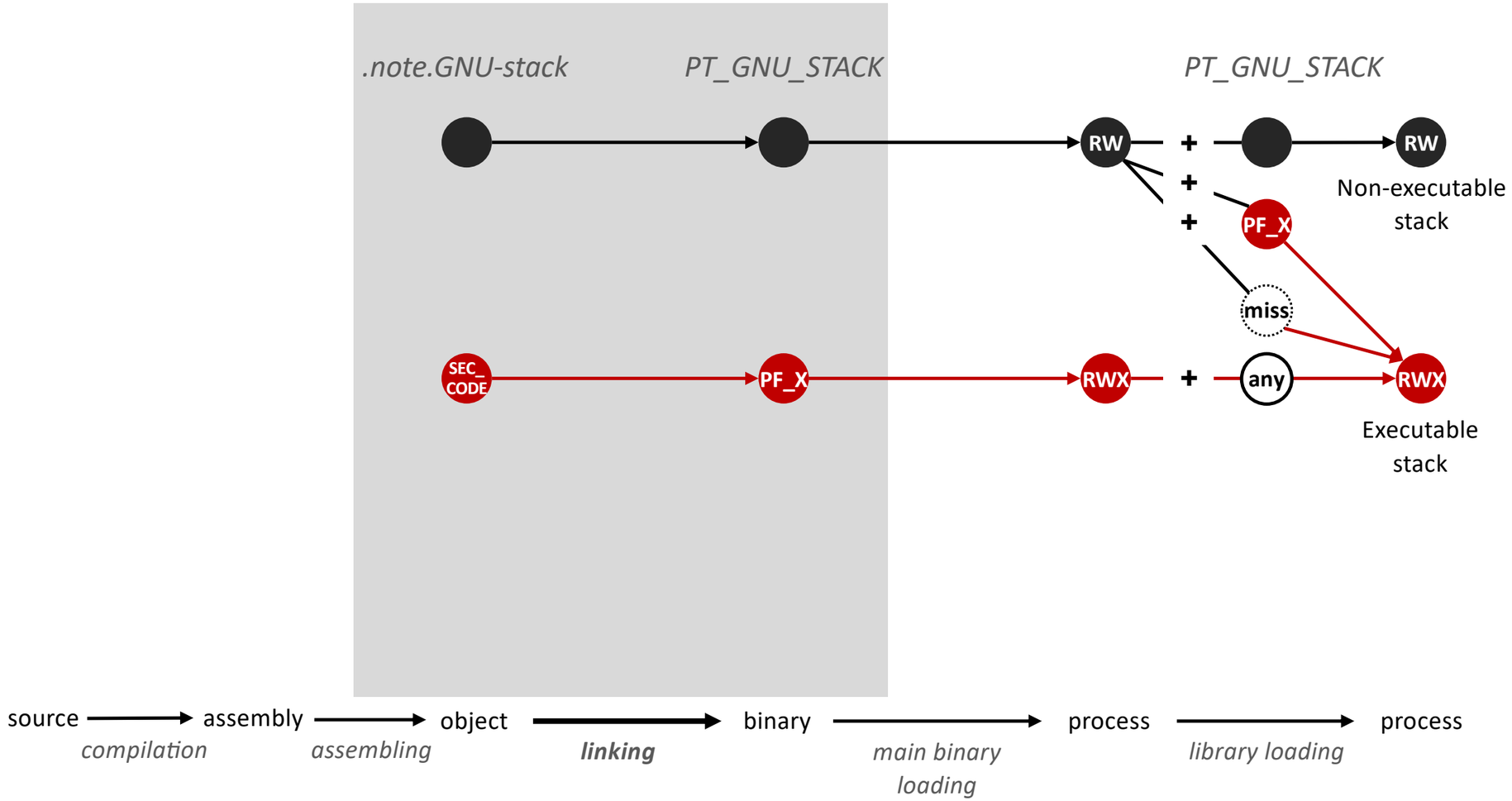
- Linker checks the **section header** .note.GNU-stack of each object file



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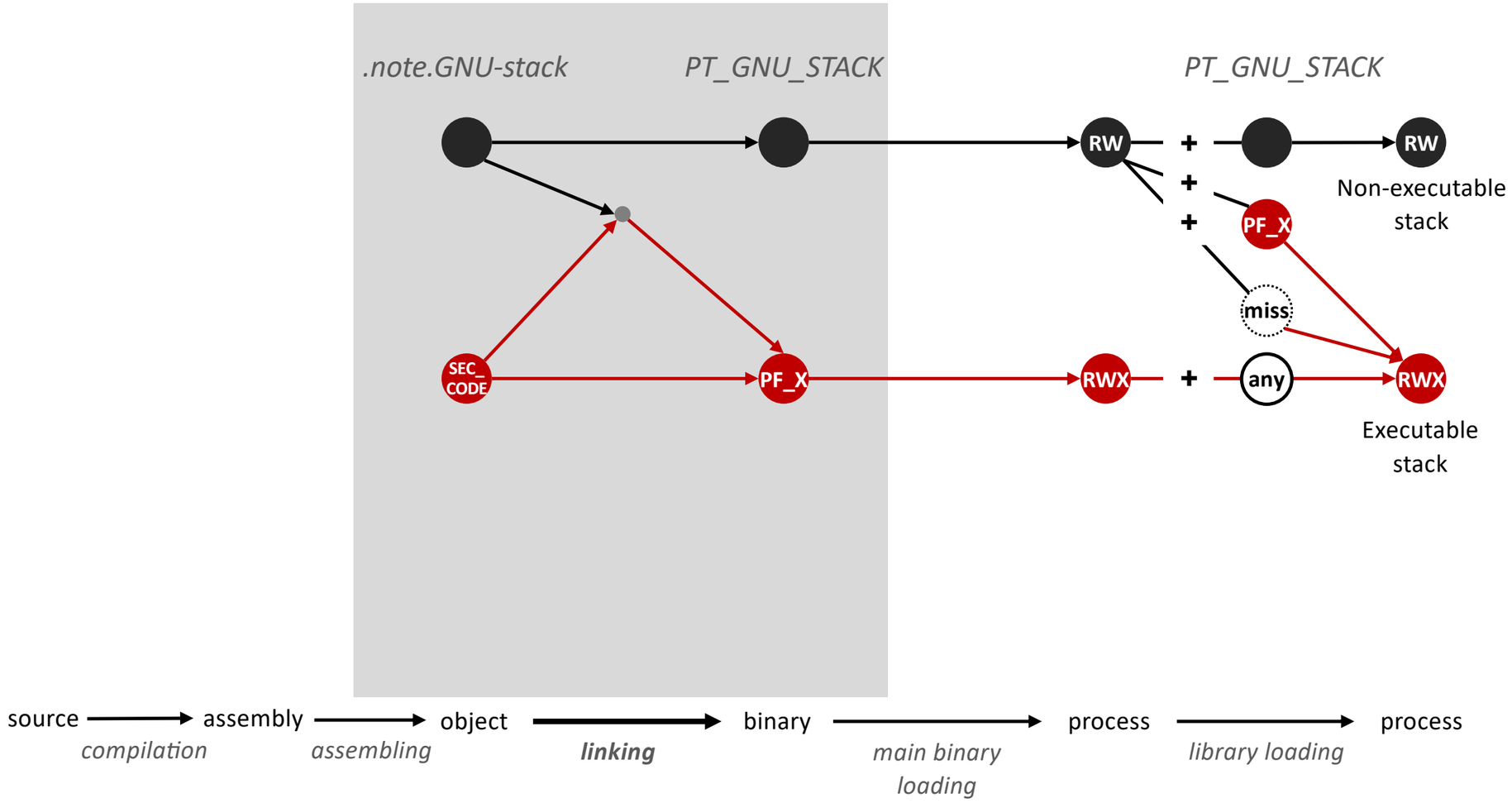

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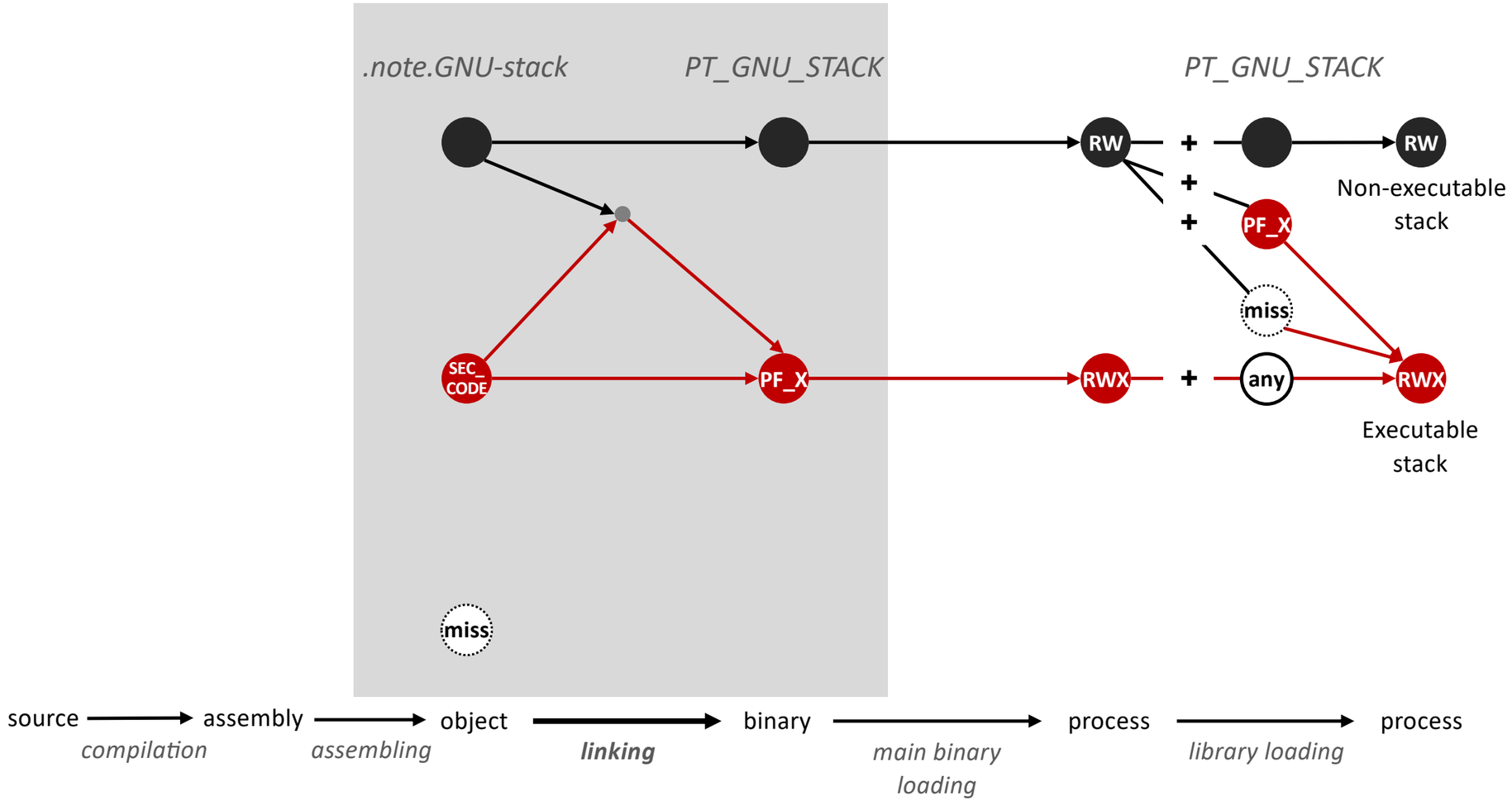

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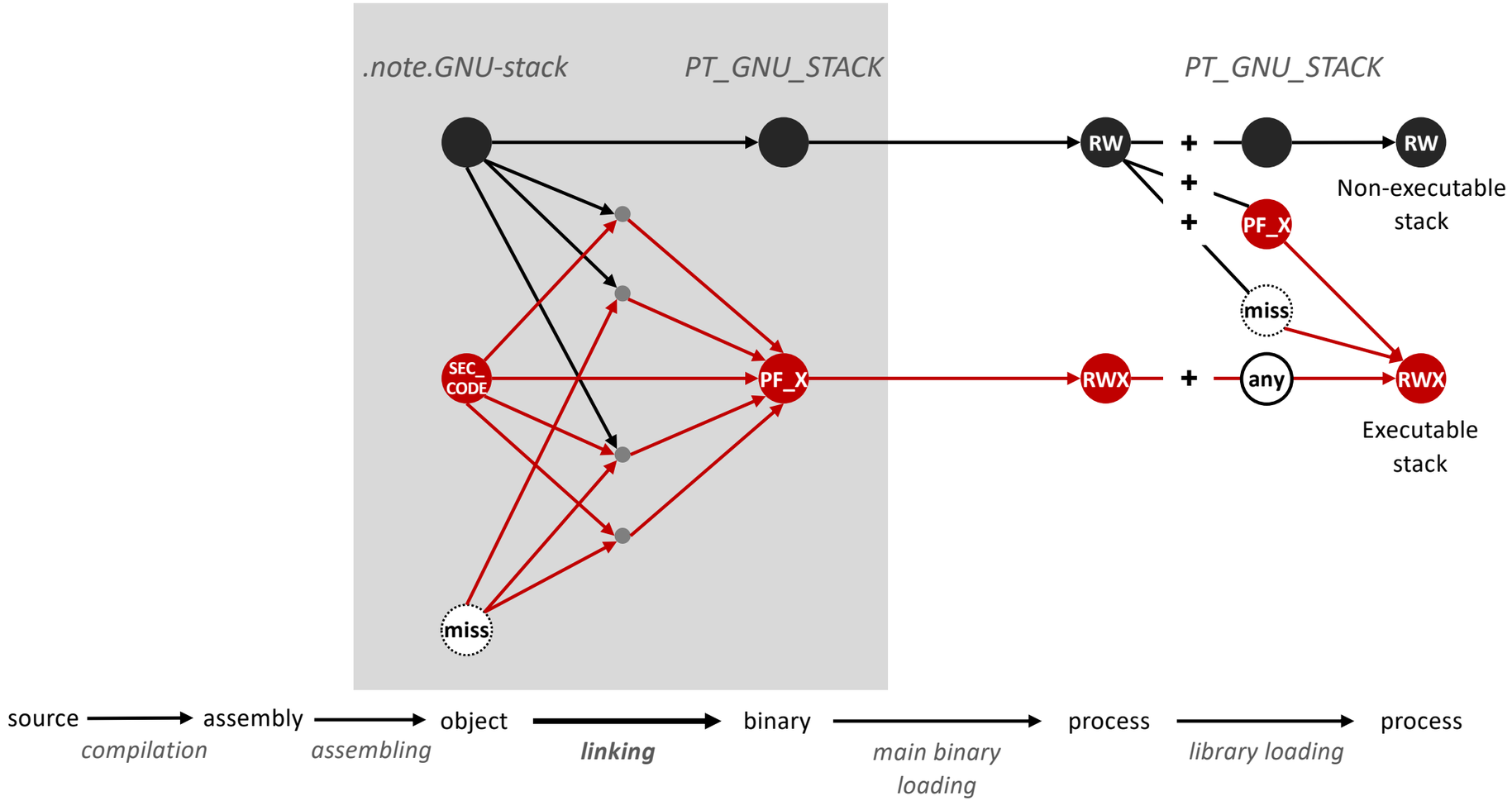
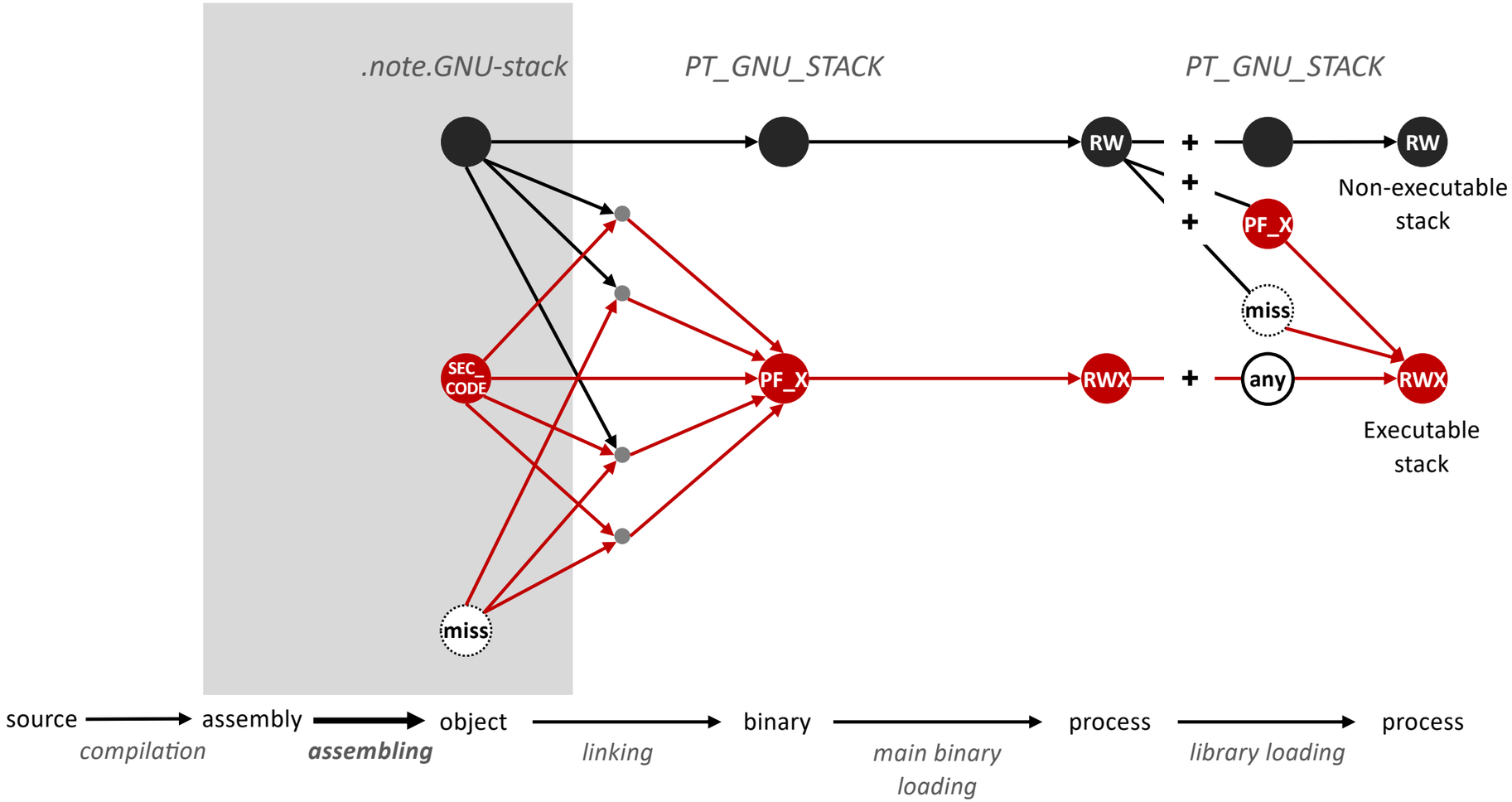


Stack Permission (Assembling)



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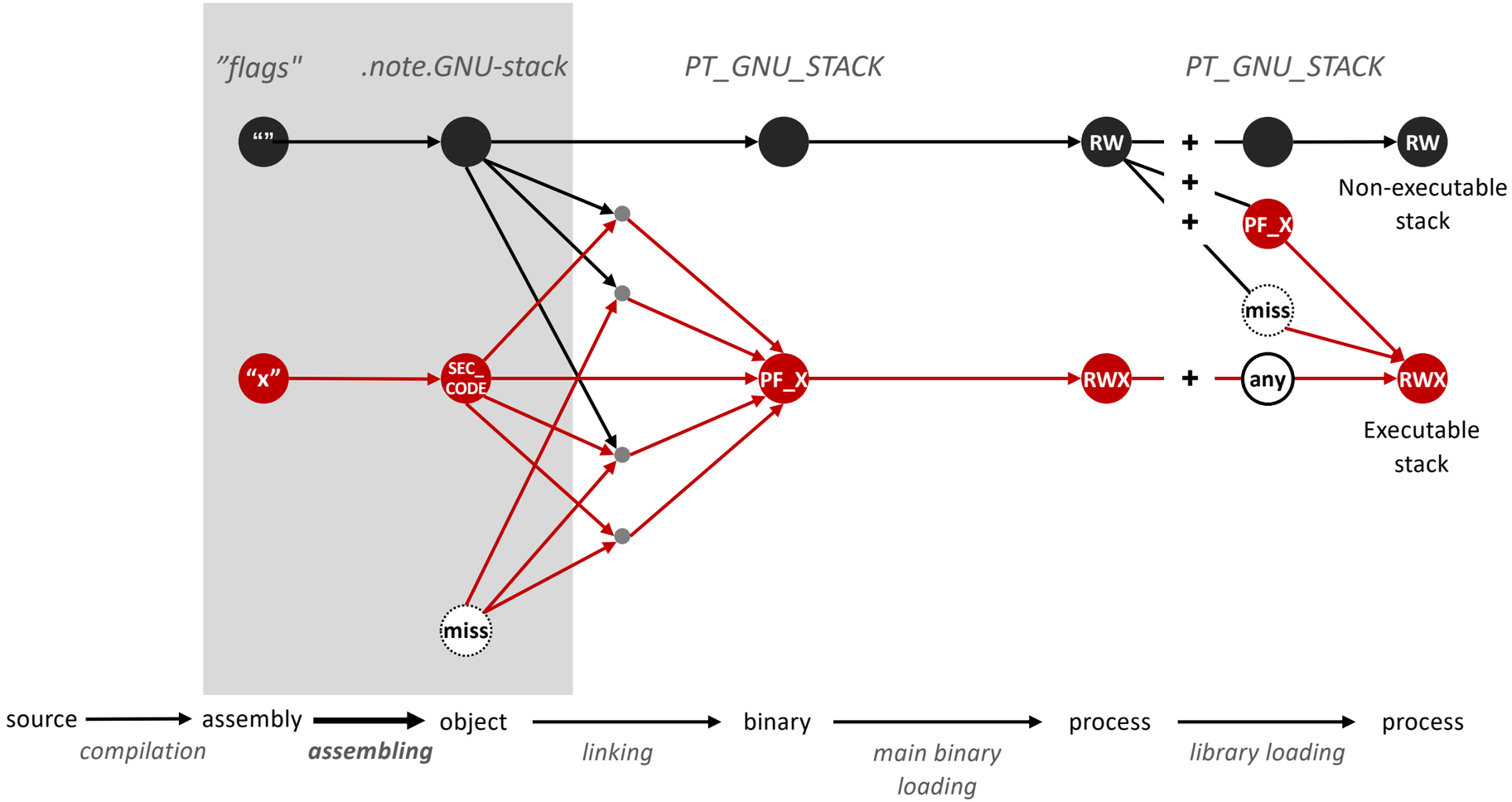
- Assembler checks assembly file for `.section .note.GNU-stack,"flags”,@progbits`



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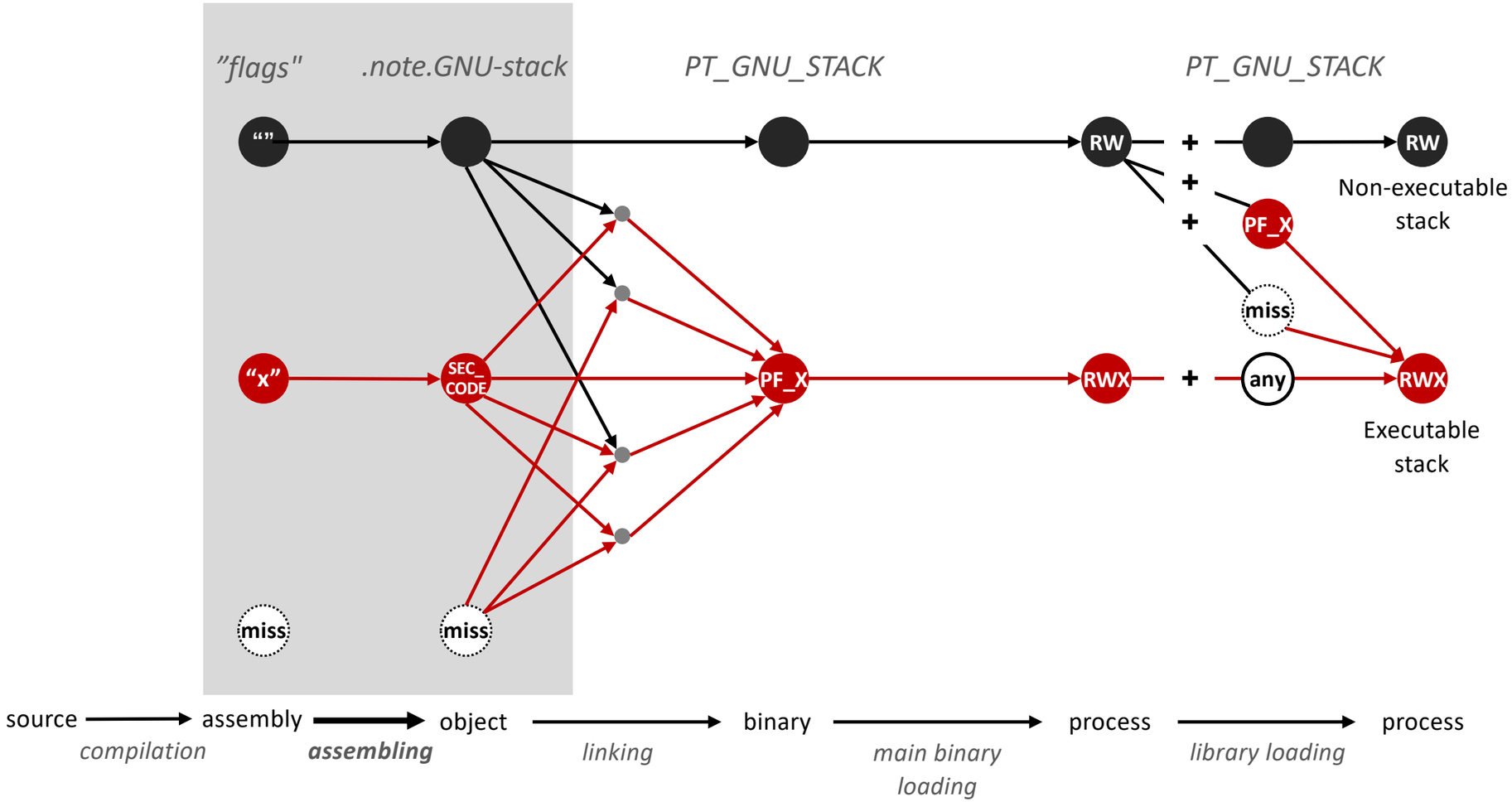

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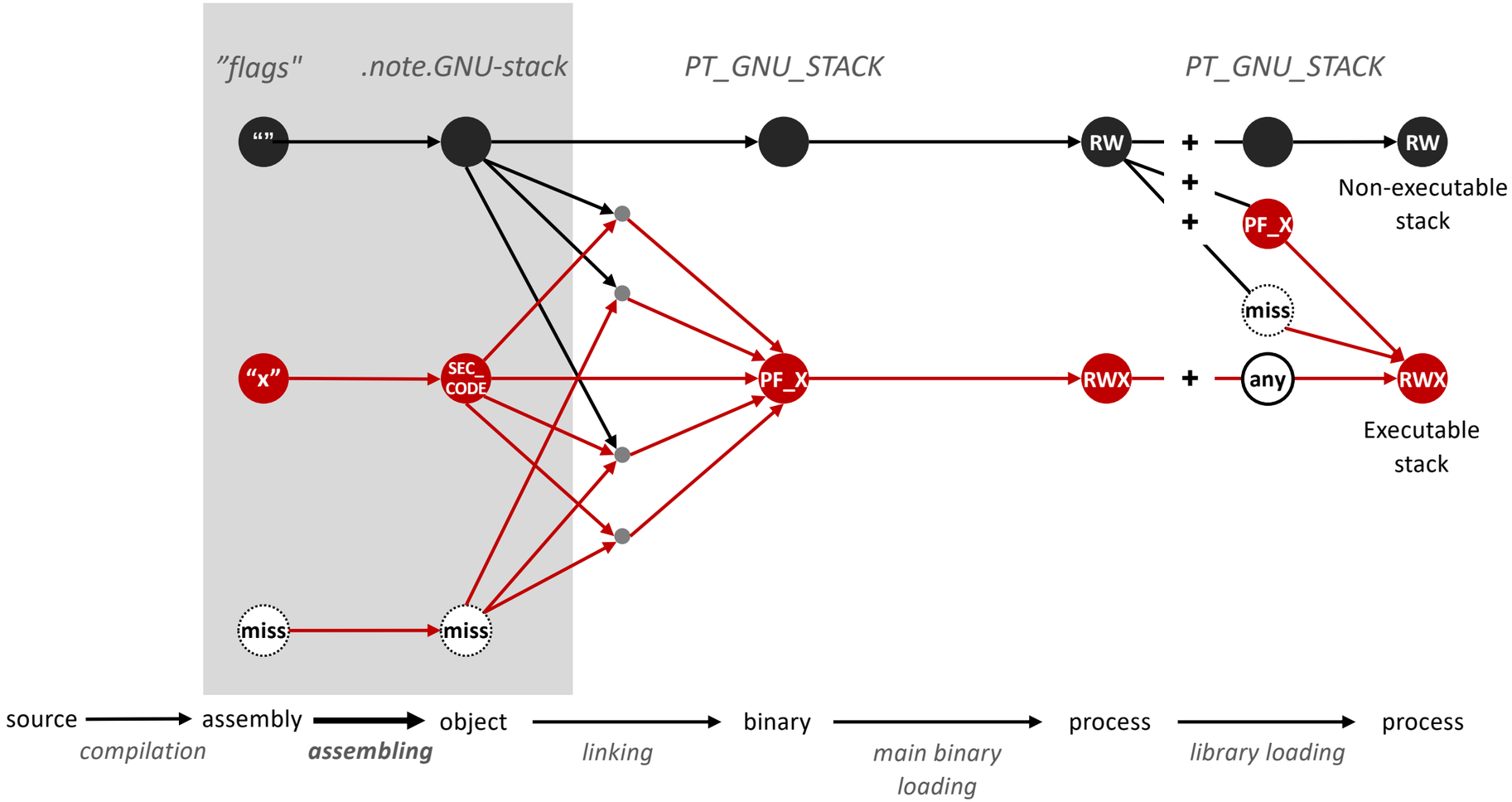

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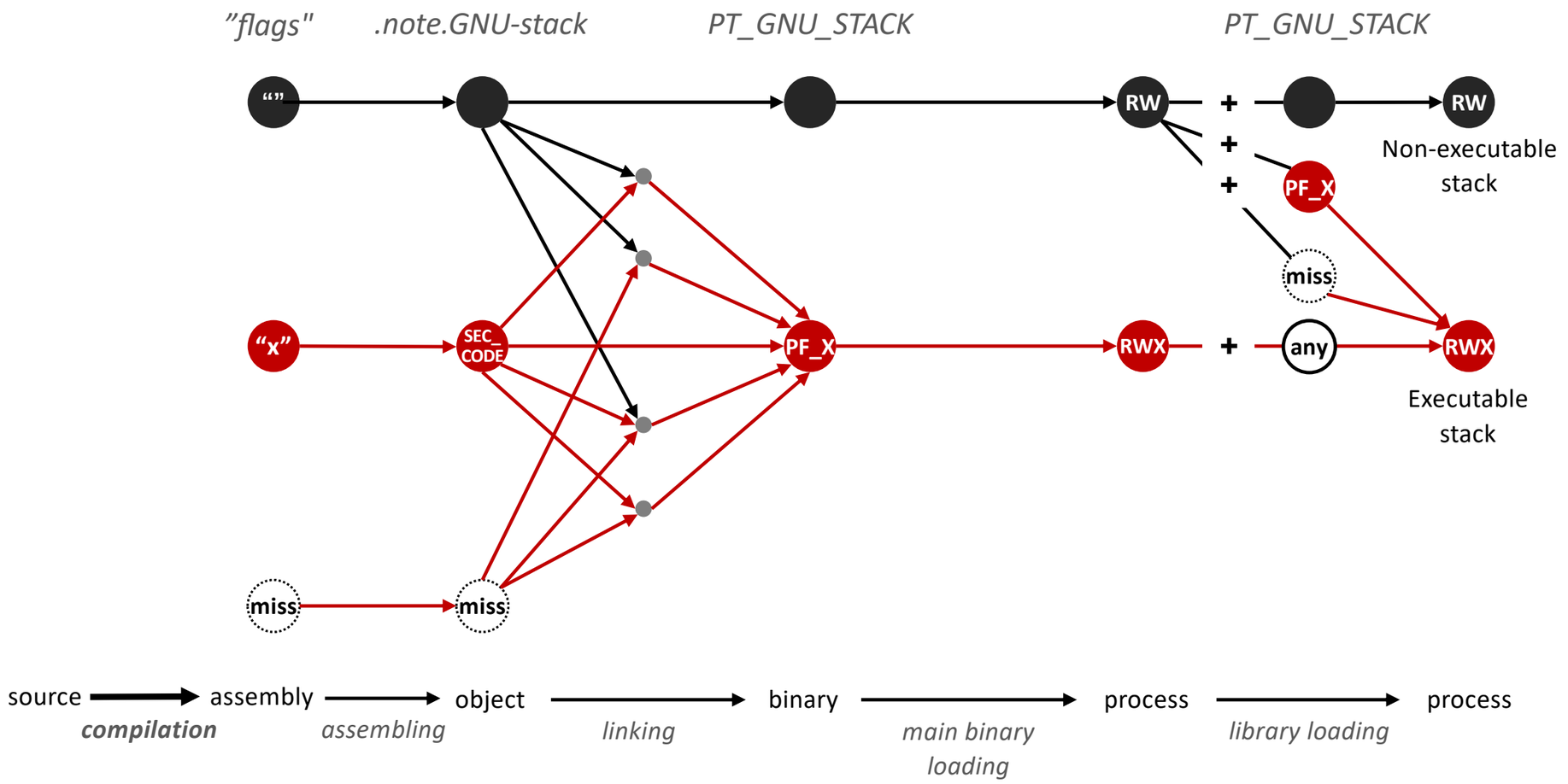

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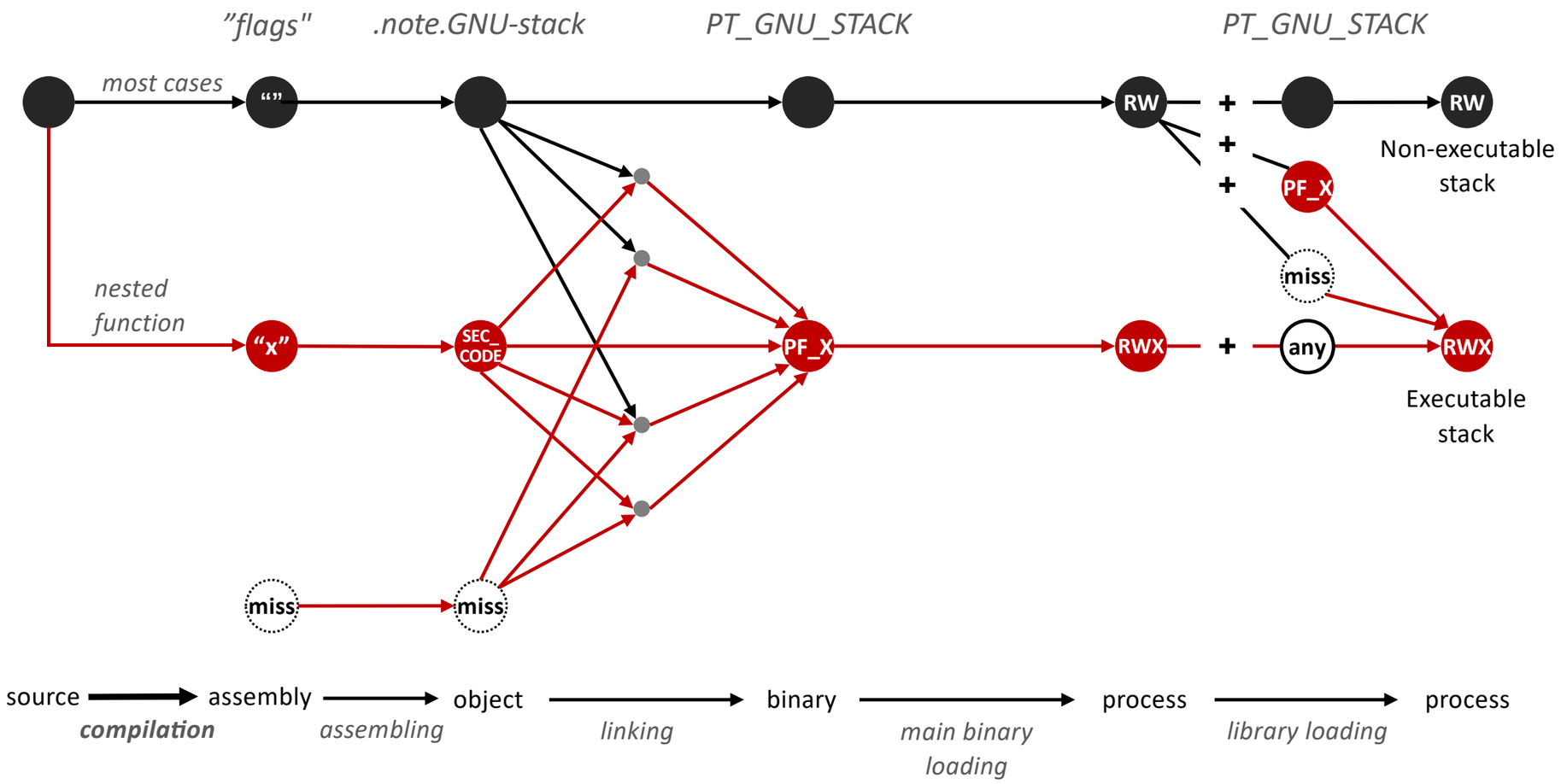

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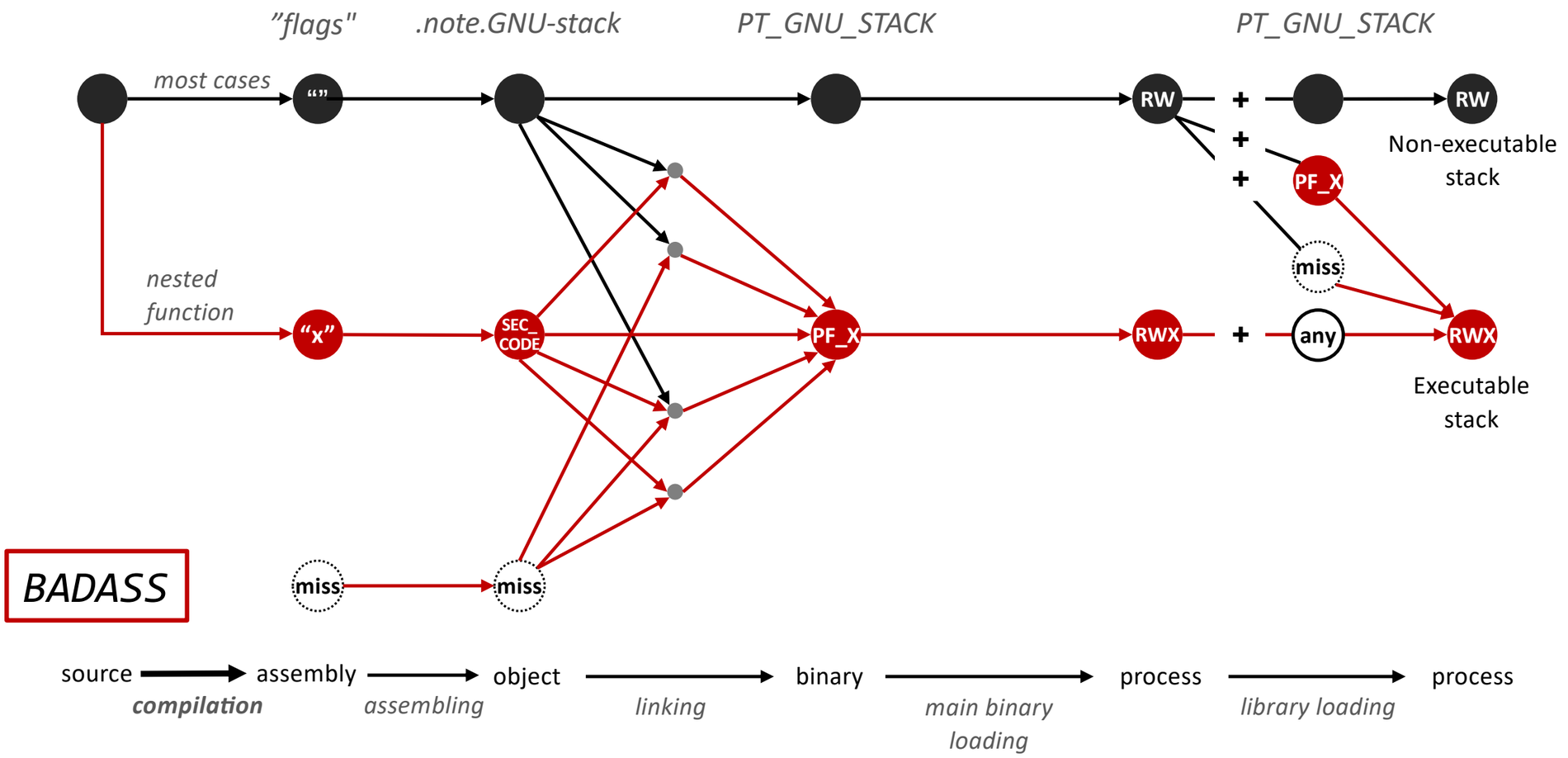

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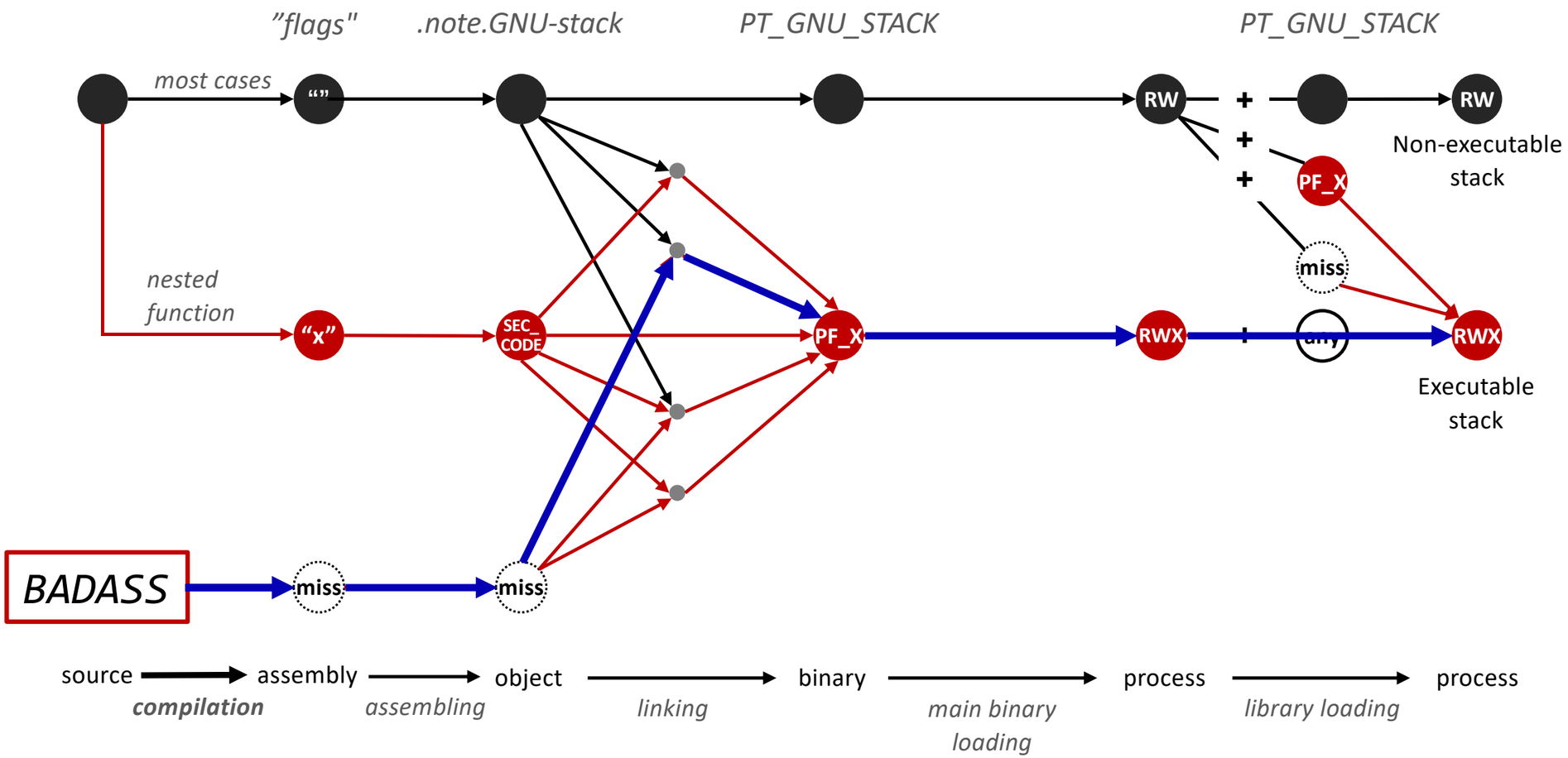

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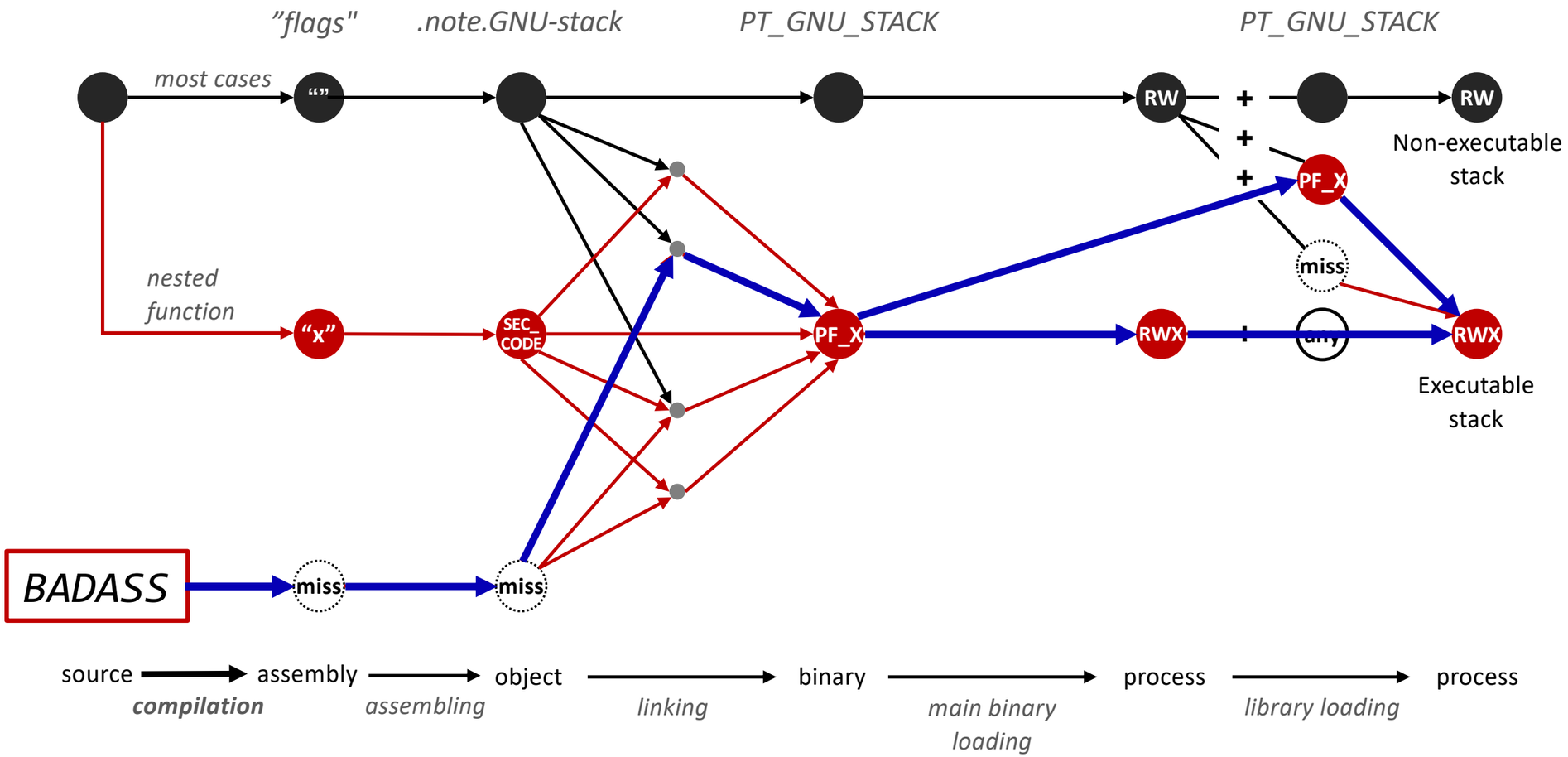
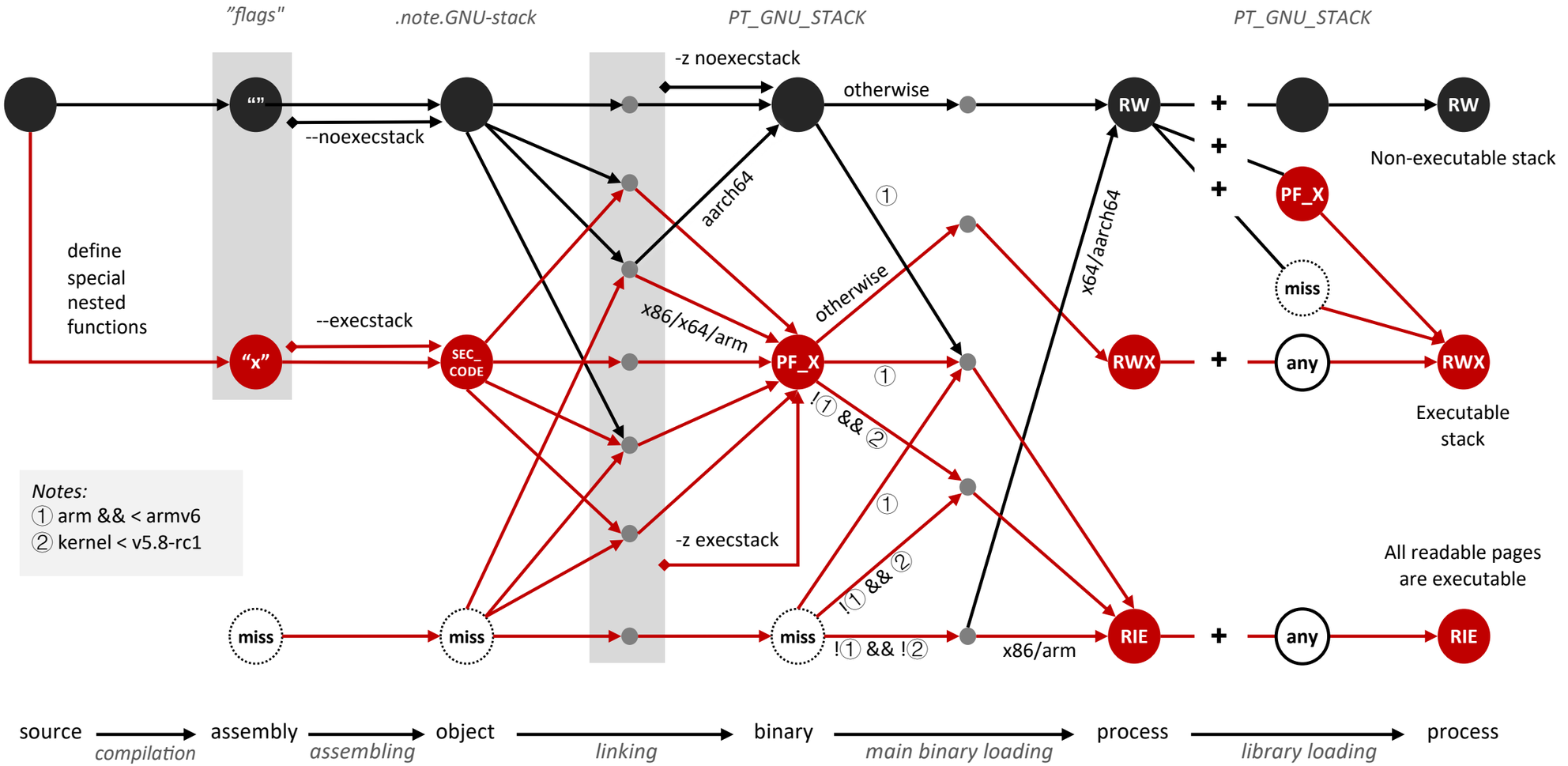


Stack Permission (All Together)

- More complex details in [our paper]



Takeaway 2

In-depth analysis!

Subtle design

Developer

W⊕X

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- W⊕X enforcement on Linux requires concerted collaborations
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- 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

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  - 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.

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- Open source
  - https://github.com/psu-security-universe/badass

Thank You

Question?

hengkai@psu.edu