A Design and Verification Methodology for Secure Isolated Regions

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Berkeley UNIVERSITY OF CALIFORNIA [1]   Microsoft Research [2]

PLDI 2016

Secure Isolated Regions (SIR)

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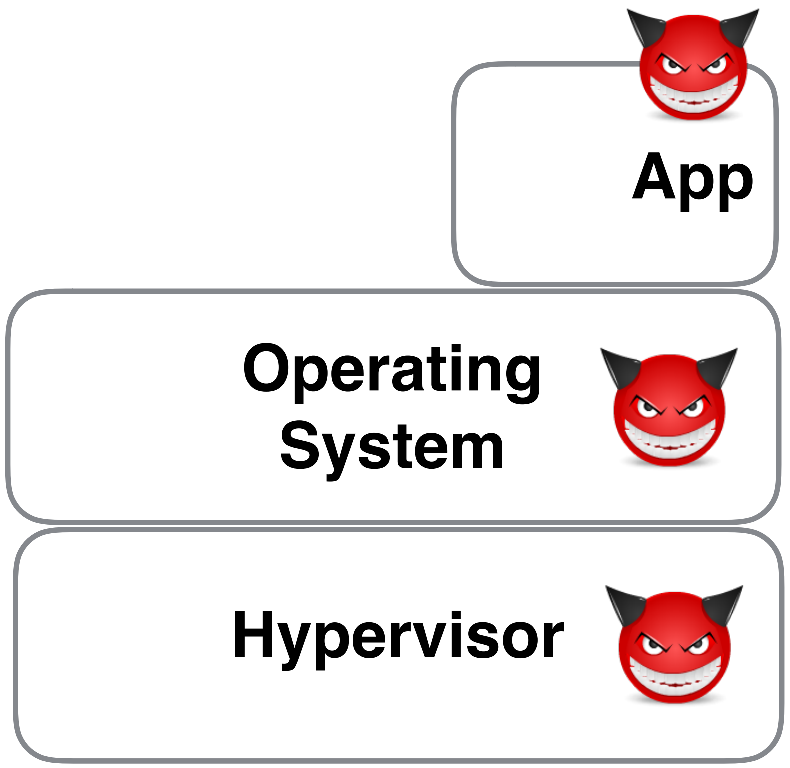

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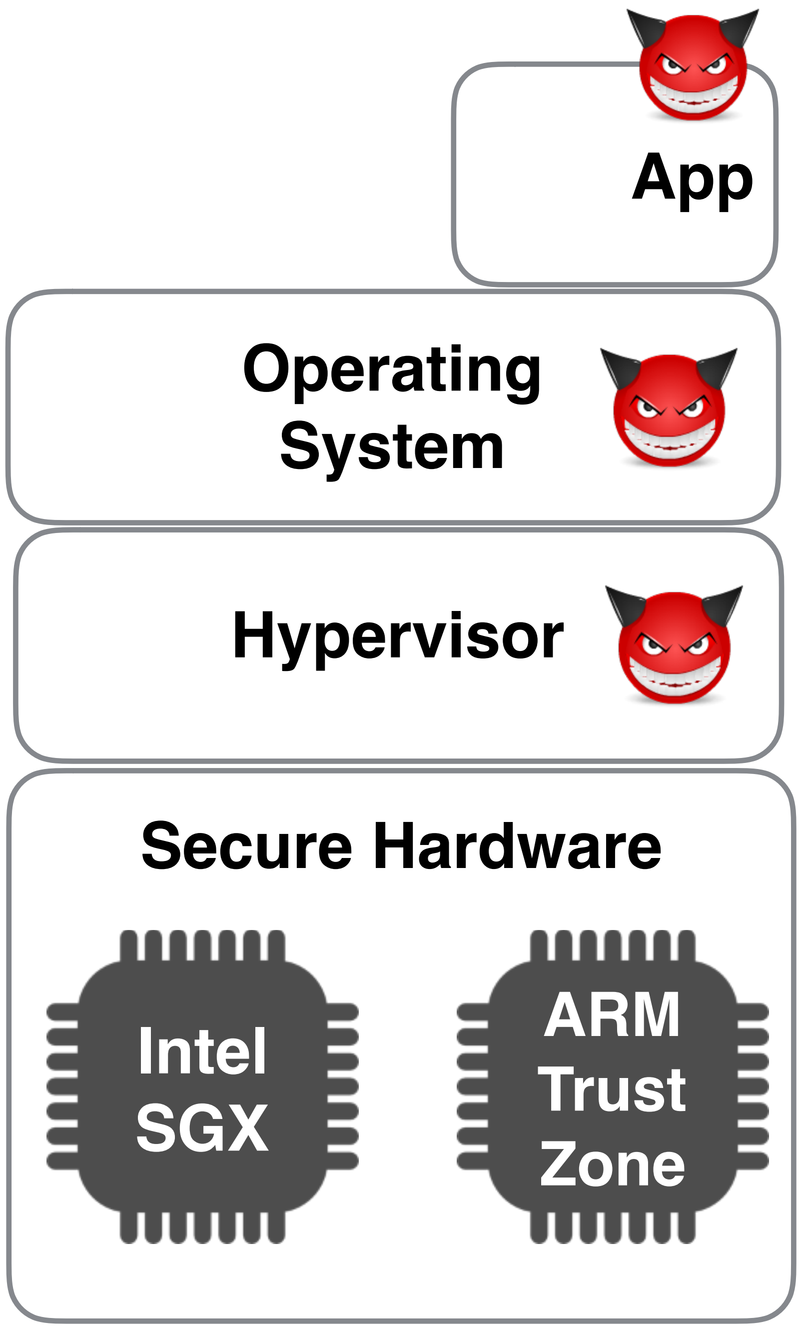

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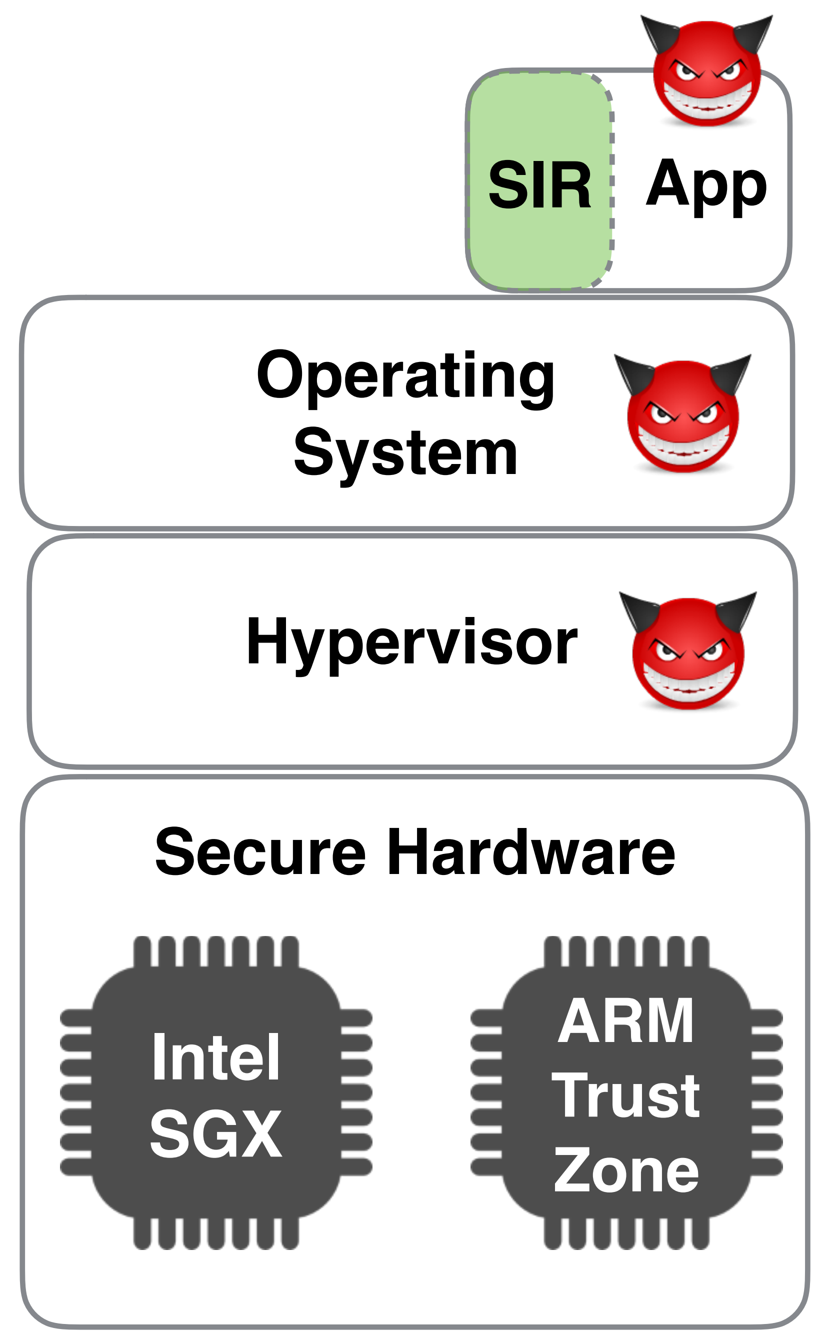

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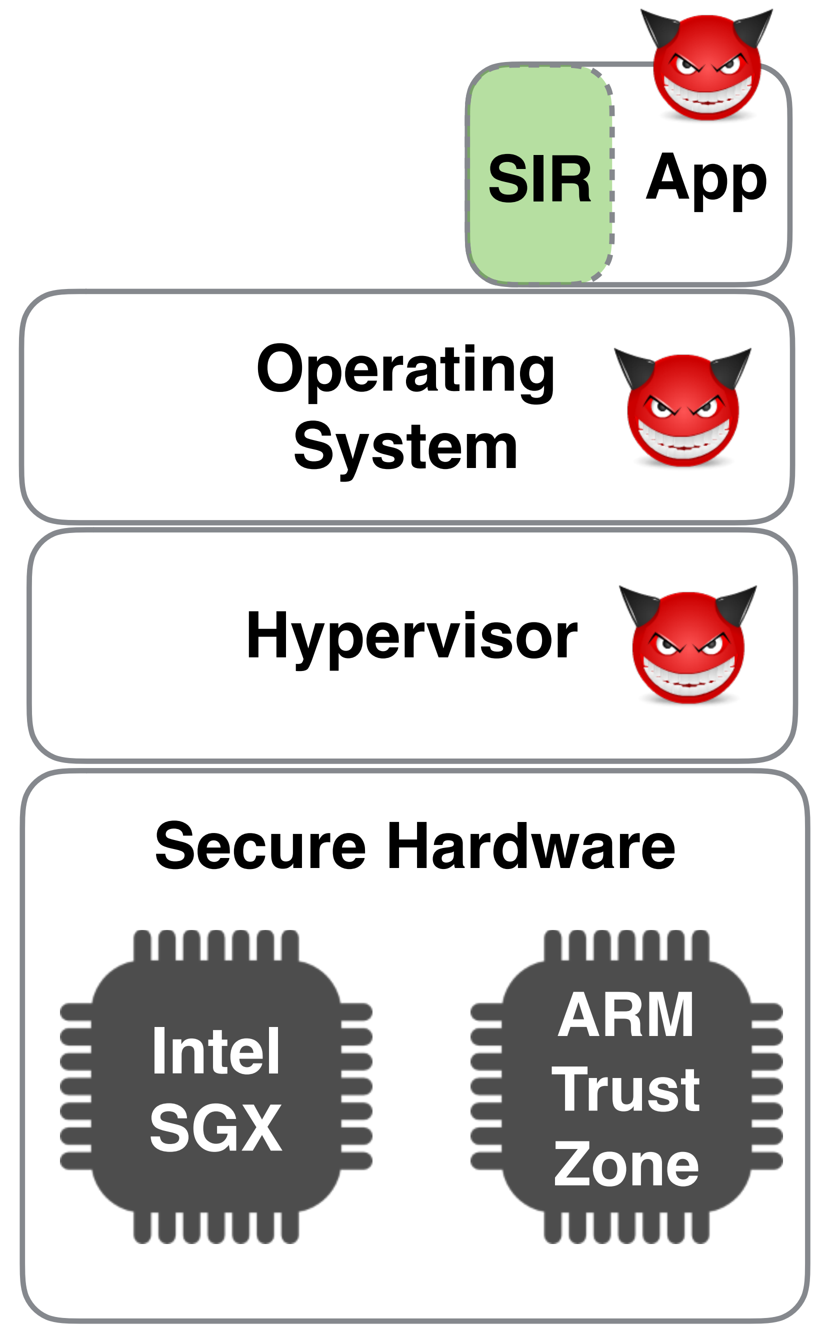

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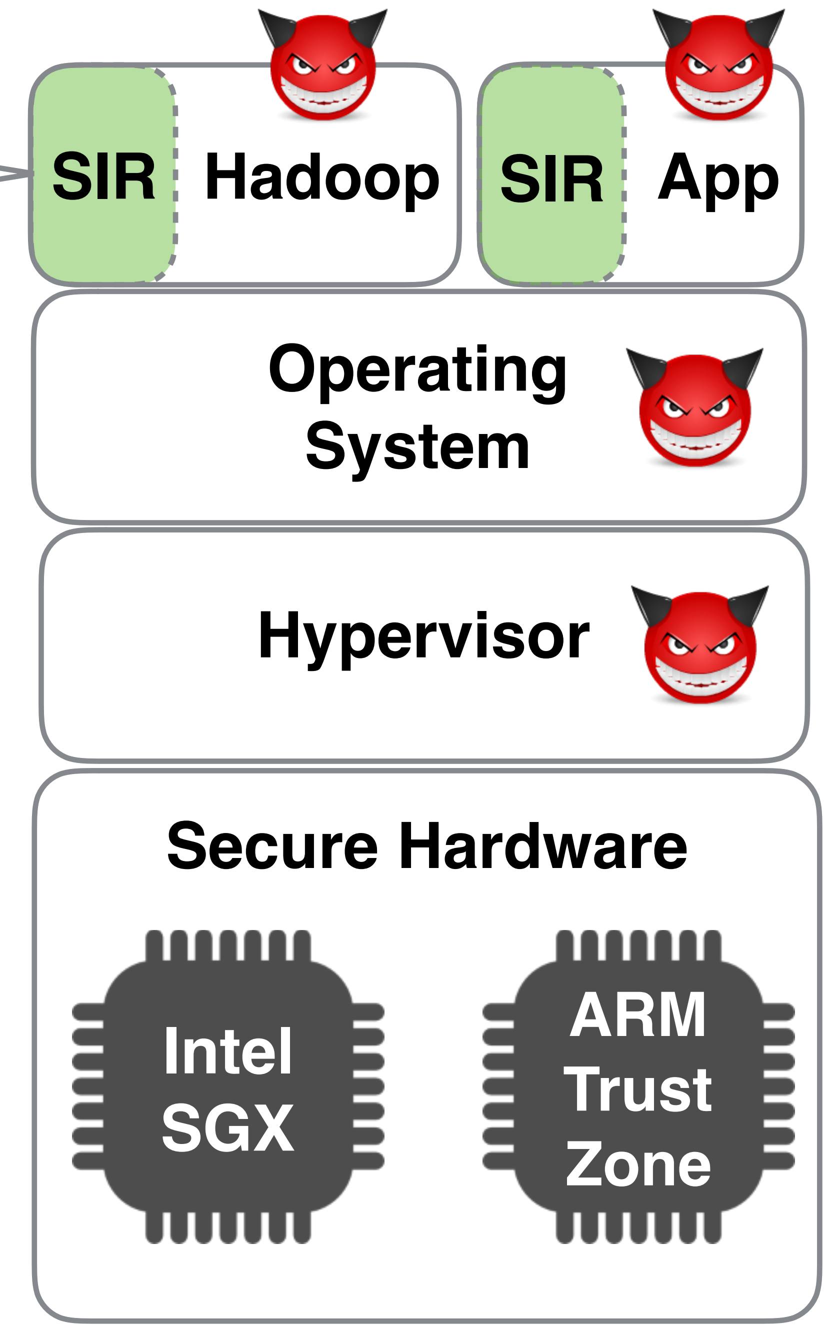
Trusted Computing Base includes the SIR and CPU hardware

Secure Isolated Regions (SIR)

```
void map(...)
{ /* compute on sensitive data */ }

void reduce(...)
{ /* compute on sensitive data */ }
```

VC3: Trustworthy Data Analytics in the Cloud [Schuster et. al., *S&P'15*]



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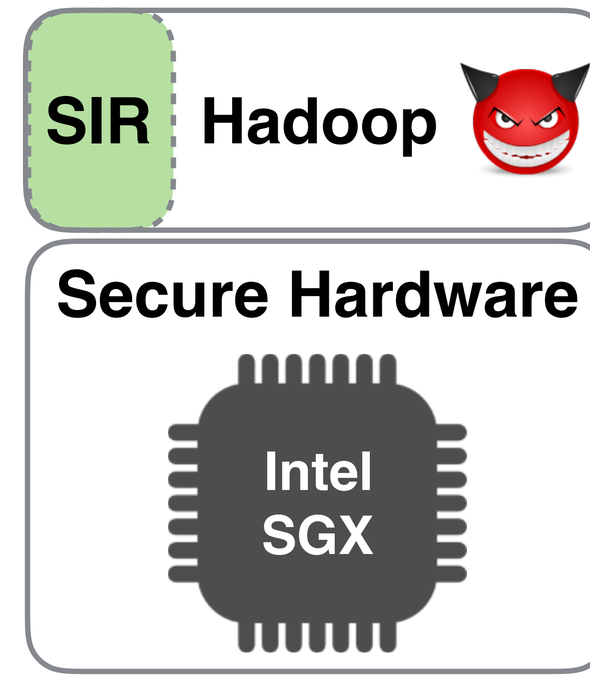
Trusted Computing Base includes the SIR and CPU hardware

Bugs in SIRs can be Exploited



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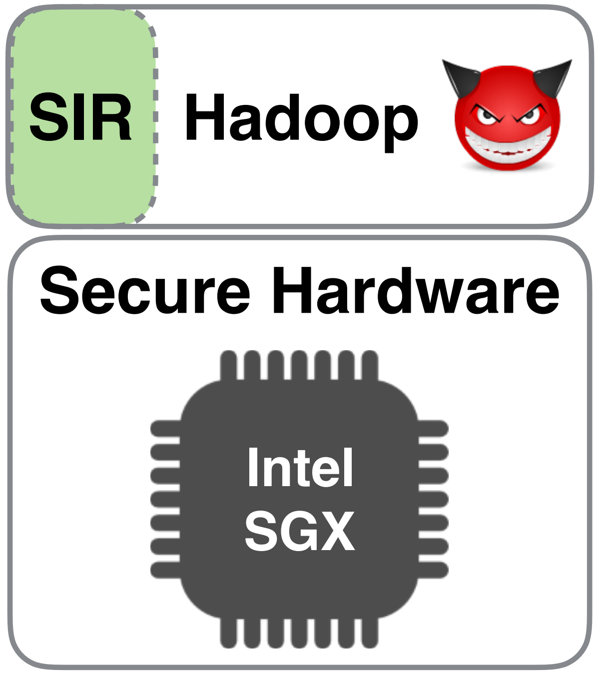

SIR accesses untrusted Hadoop's memory to perform I/O

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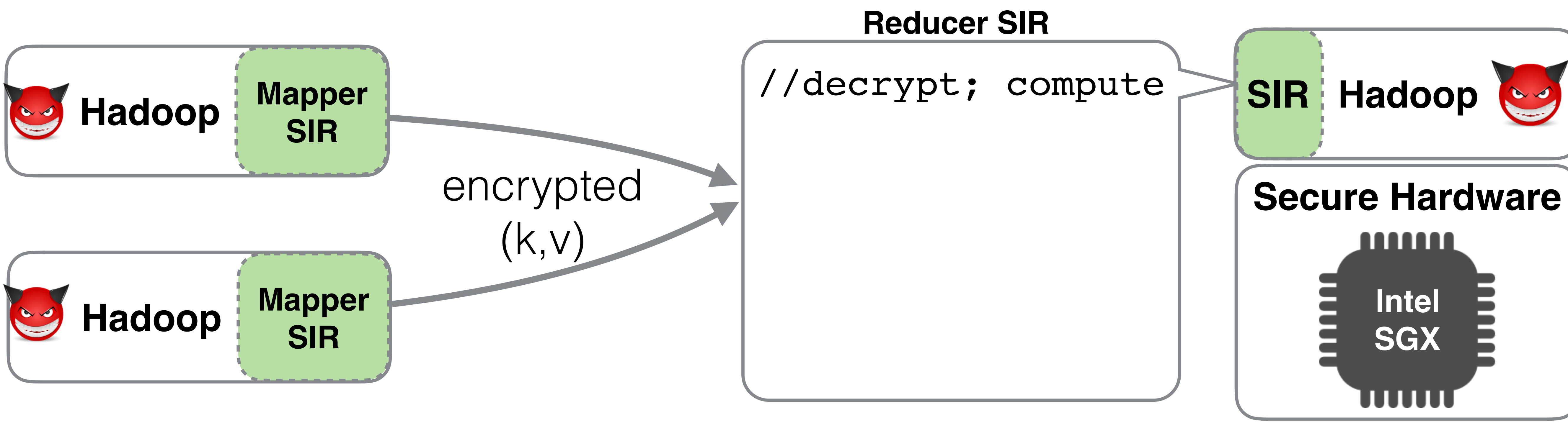

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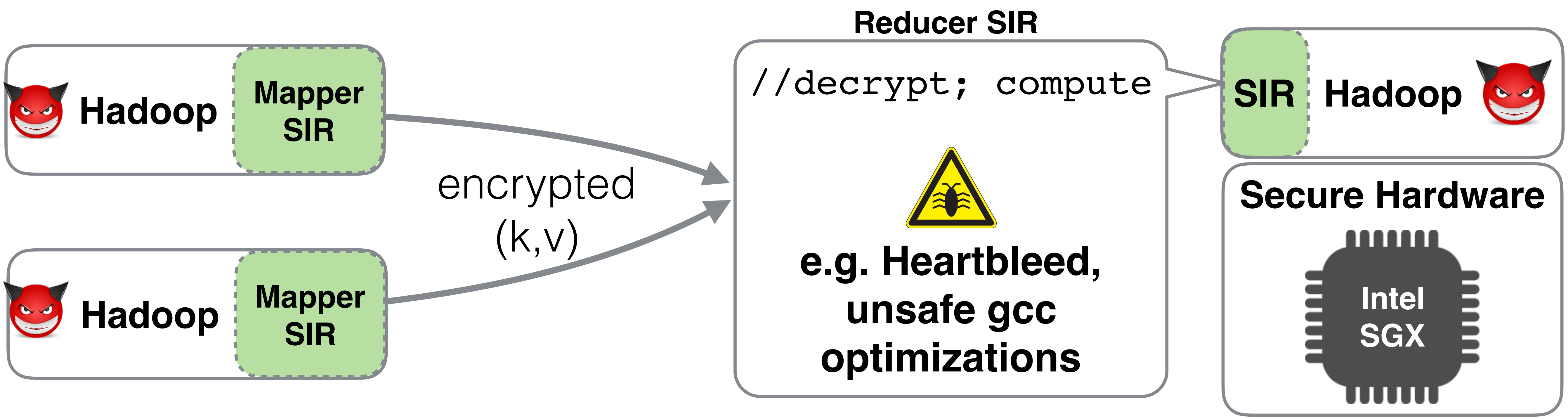

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Adversary can exploit SIRs using I/O interactions

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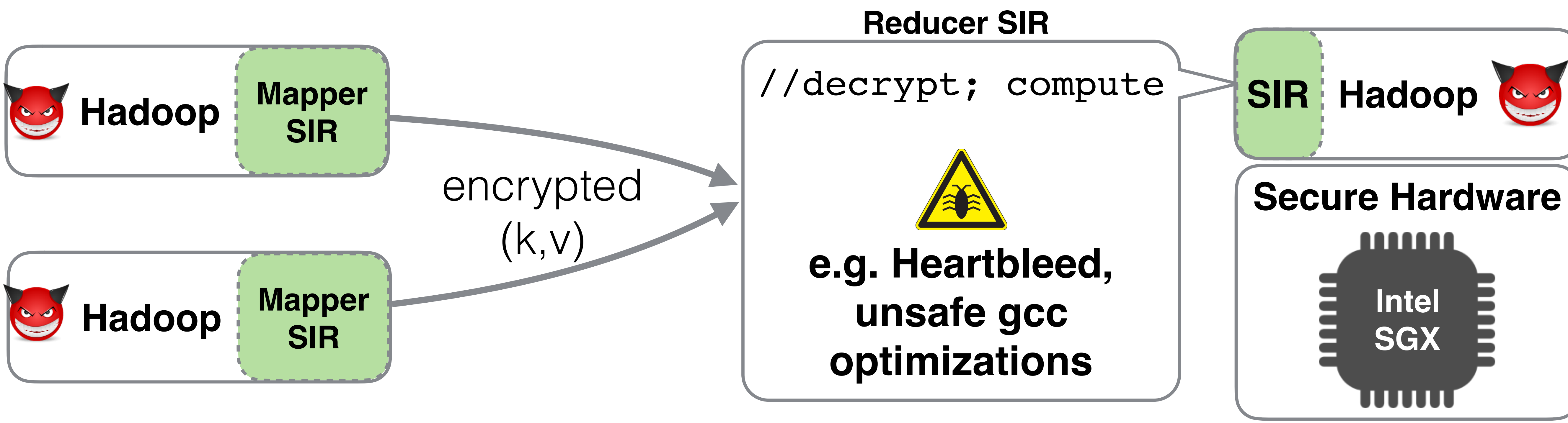

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Our goal: ensure that secrets are not leaked (confidentiality) in the presence of programming errors and compiler bugs

Challenges in Proving Confidentiality

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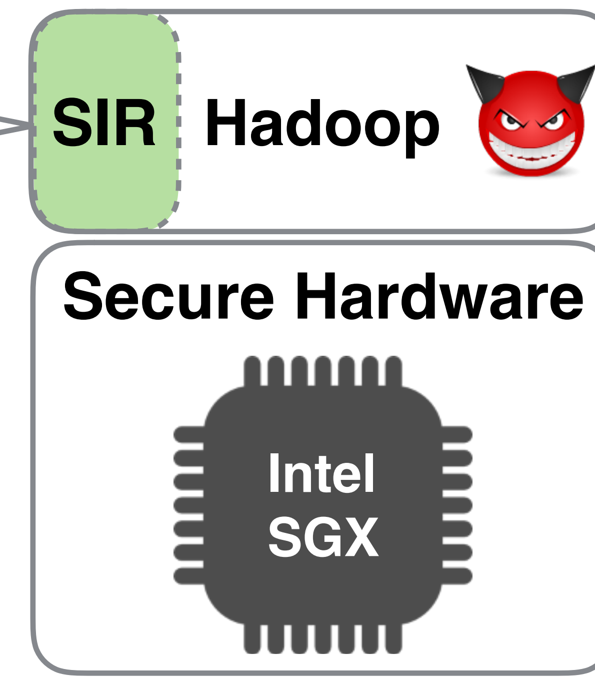
void Reduce(byte *kEnc, byte *vEnc)
{
```



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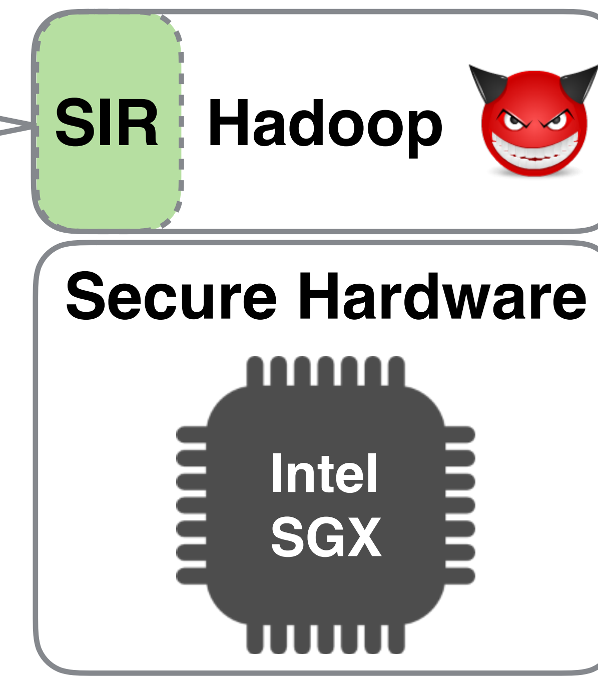

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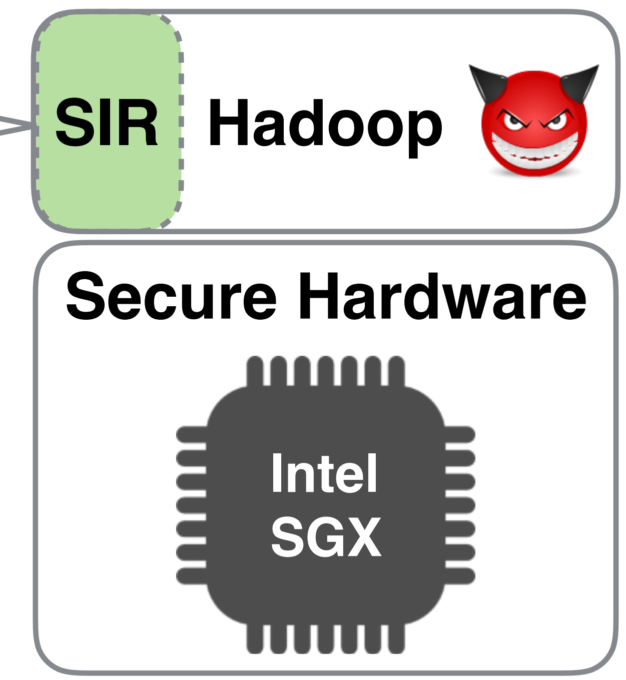

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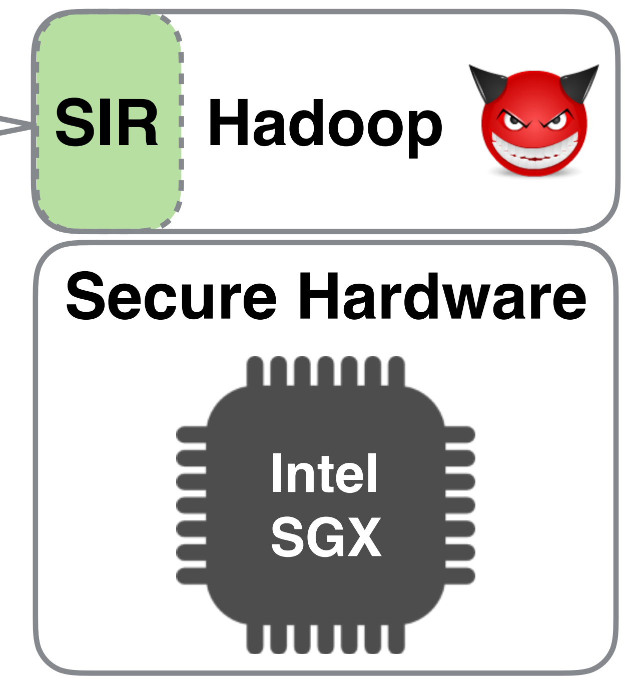

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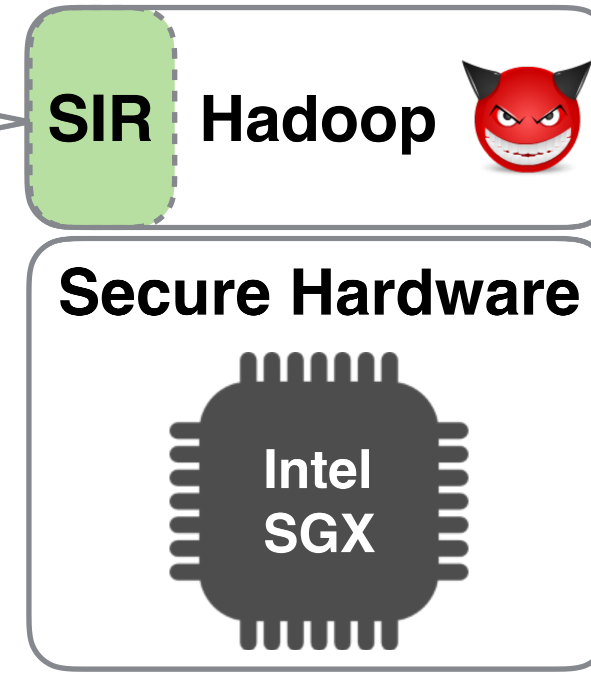

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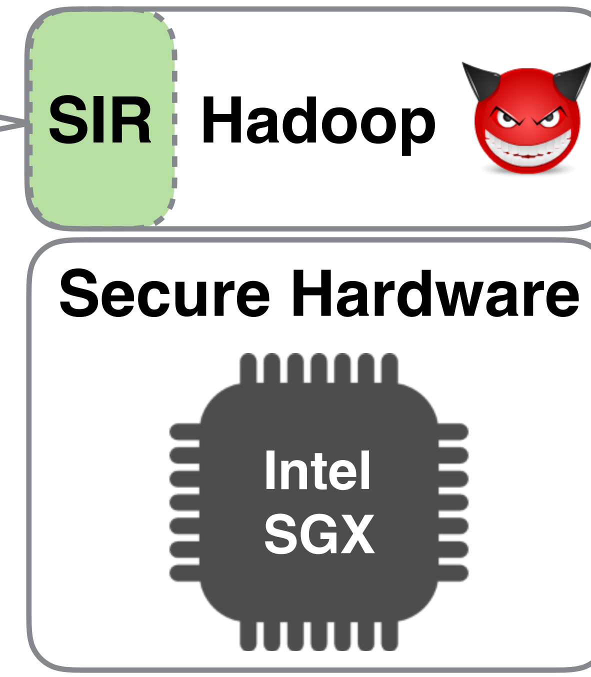

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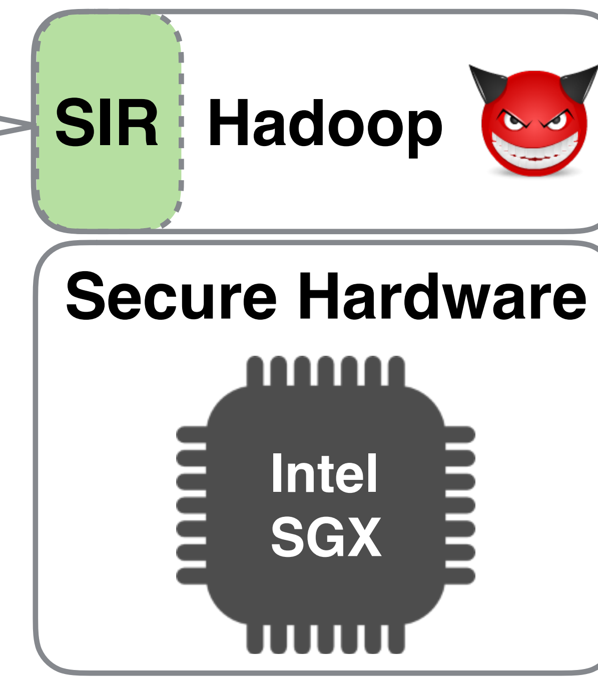

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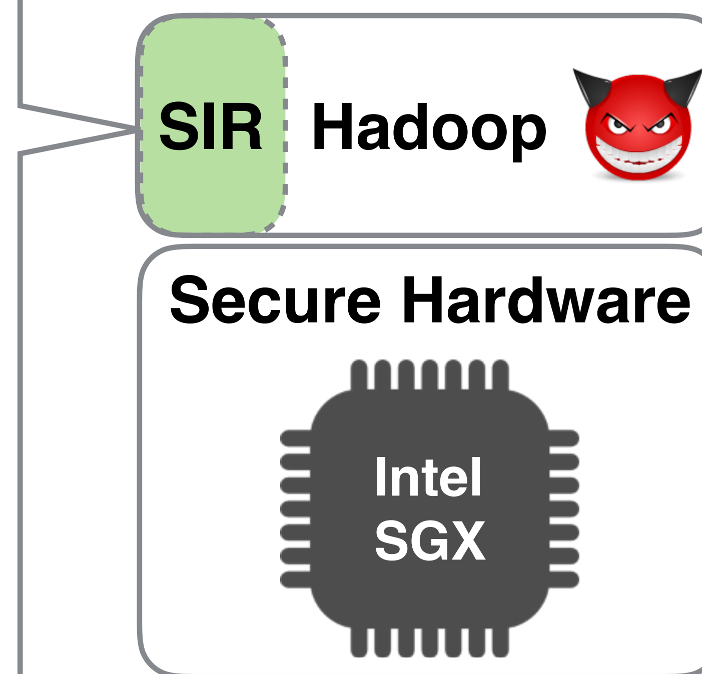

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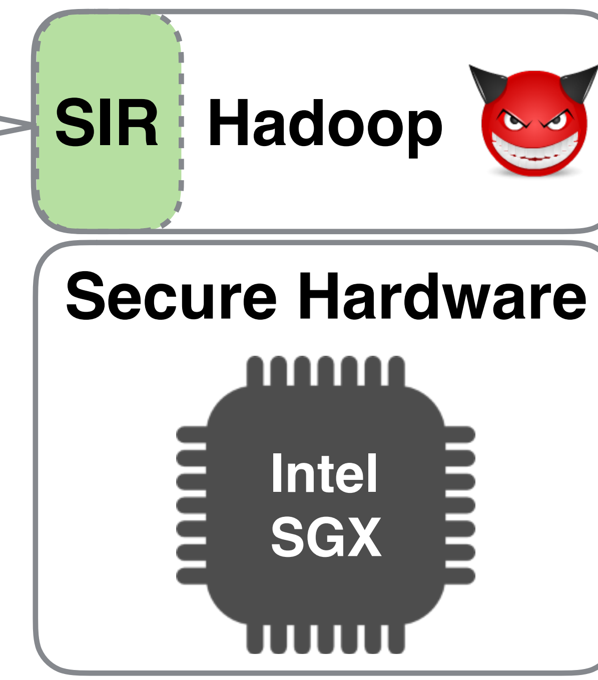

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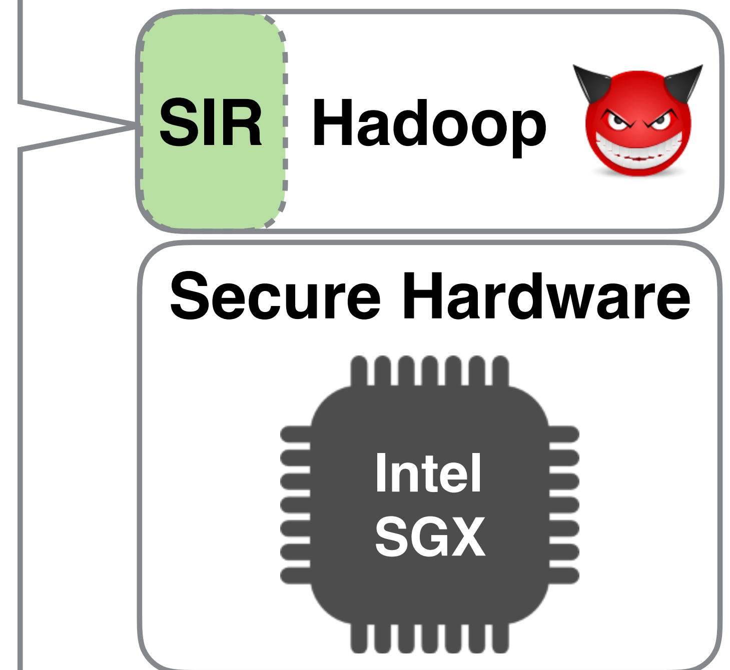

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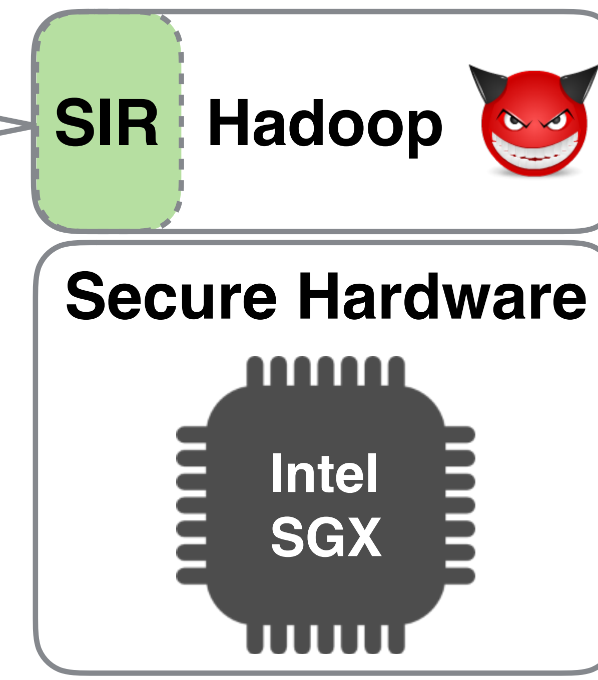

compiler

Information Release Confinement

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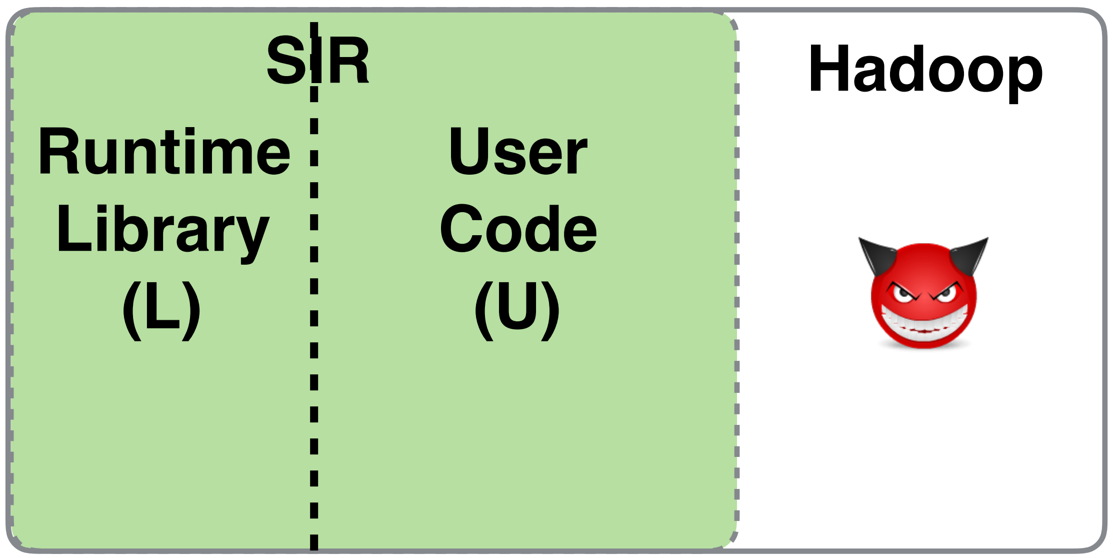

L implements **send**, **recv**, malloc, free

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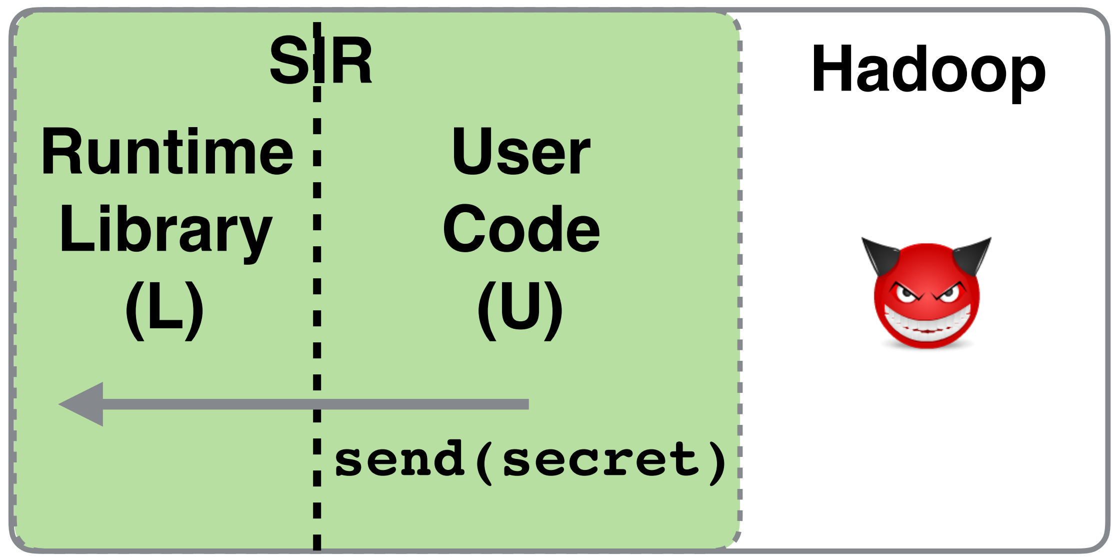

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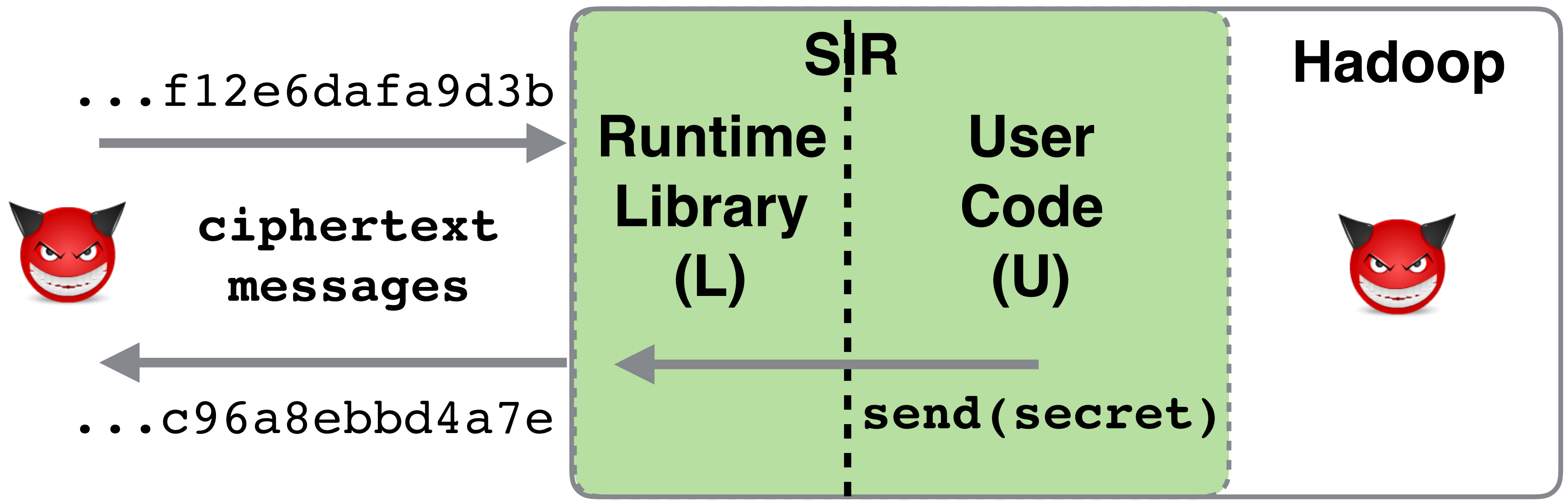

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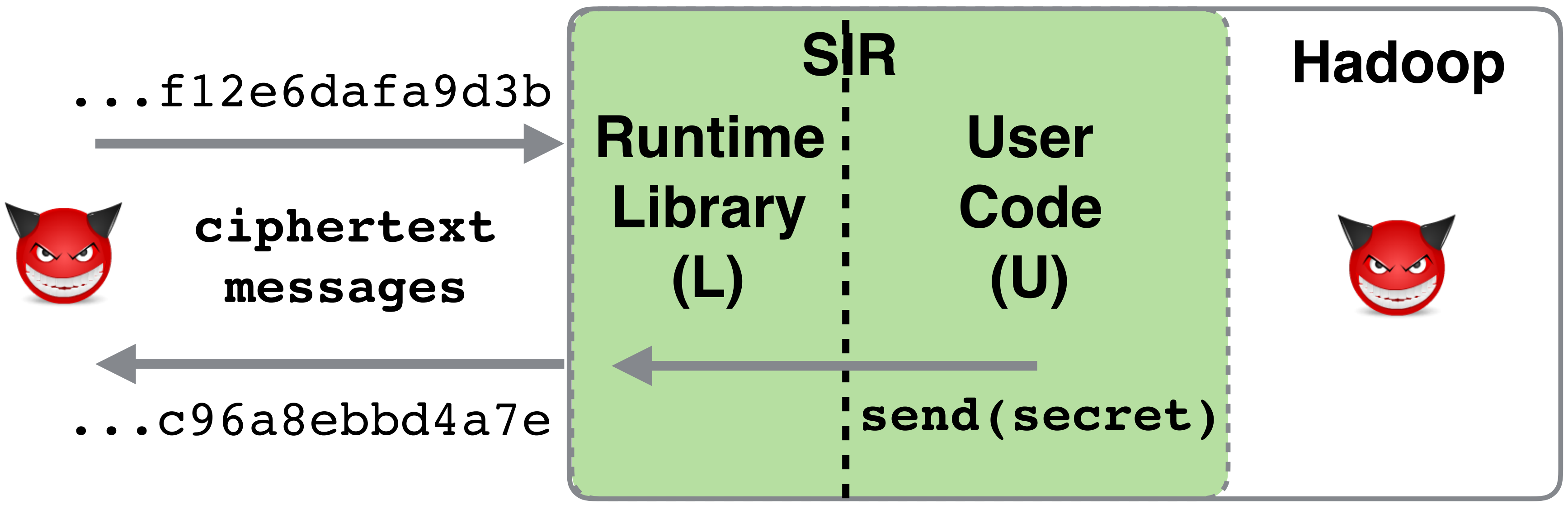

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IRC: All updates to non-SIR memory via L's `send` API

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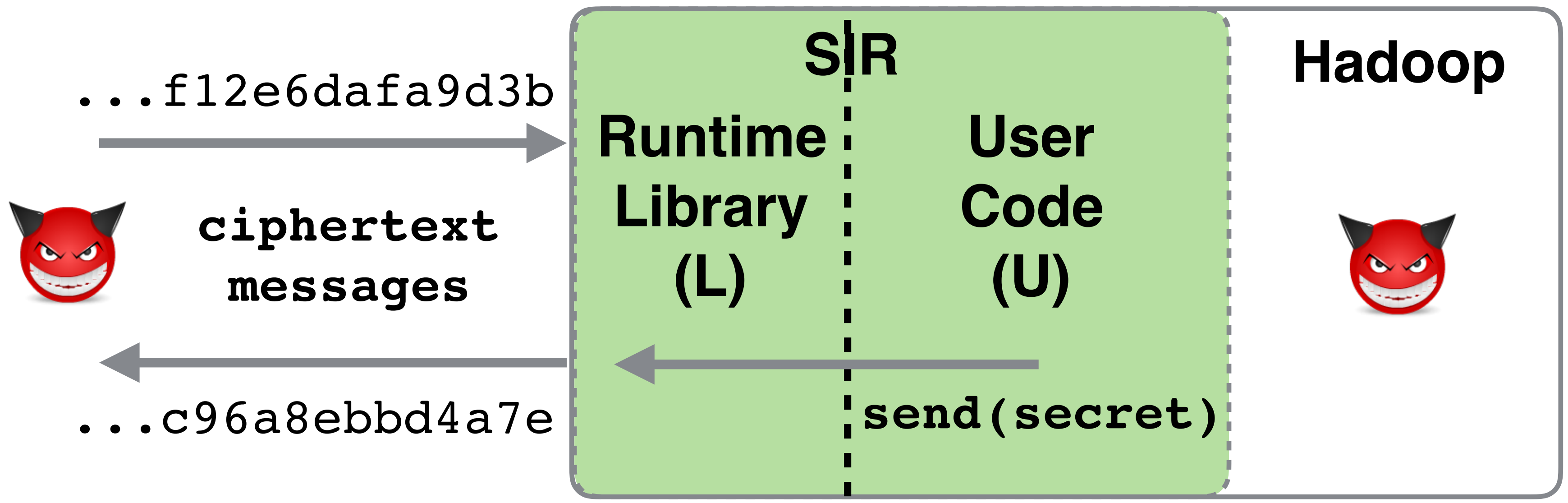

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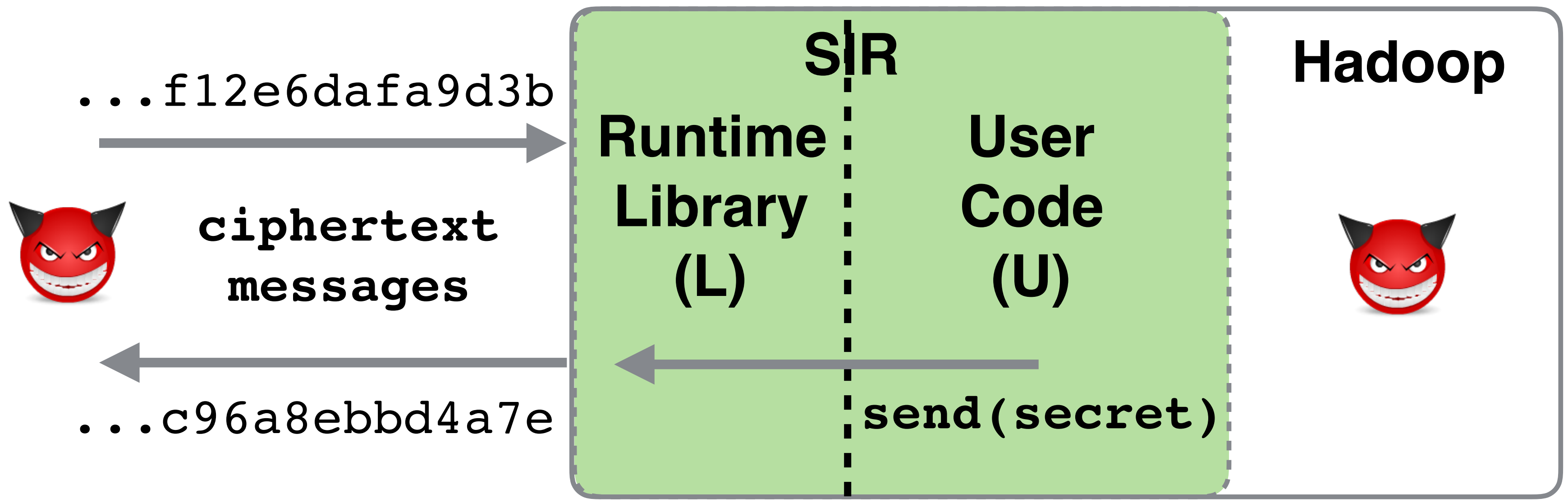

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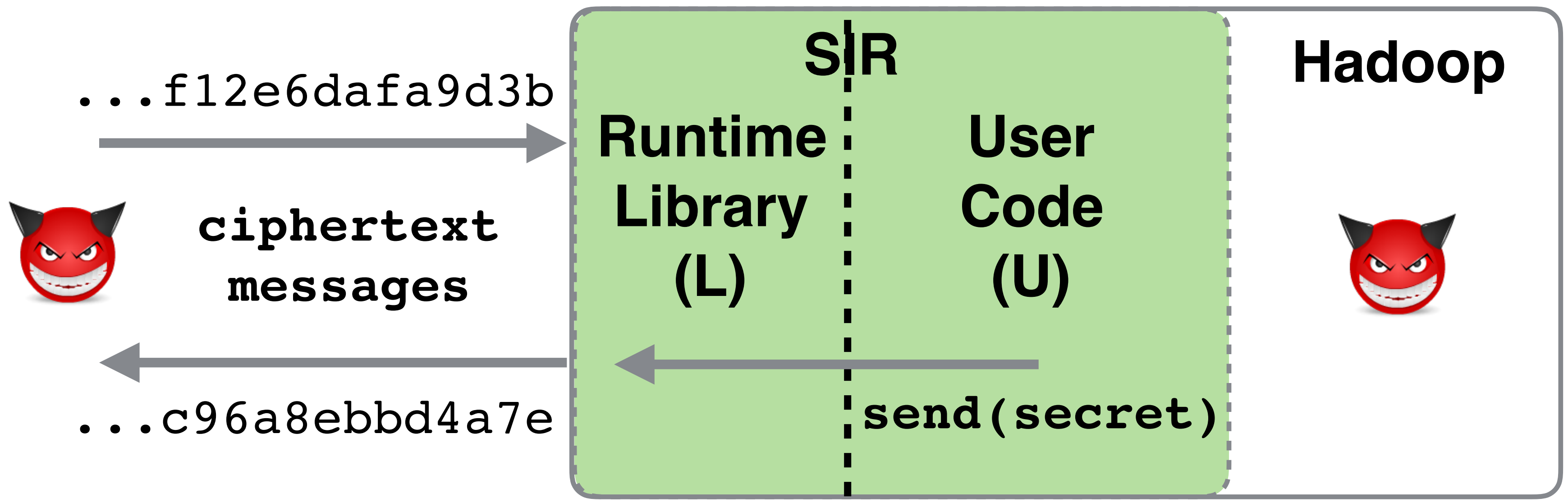

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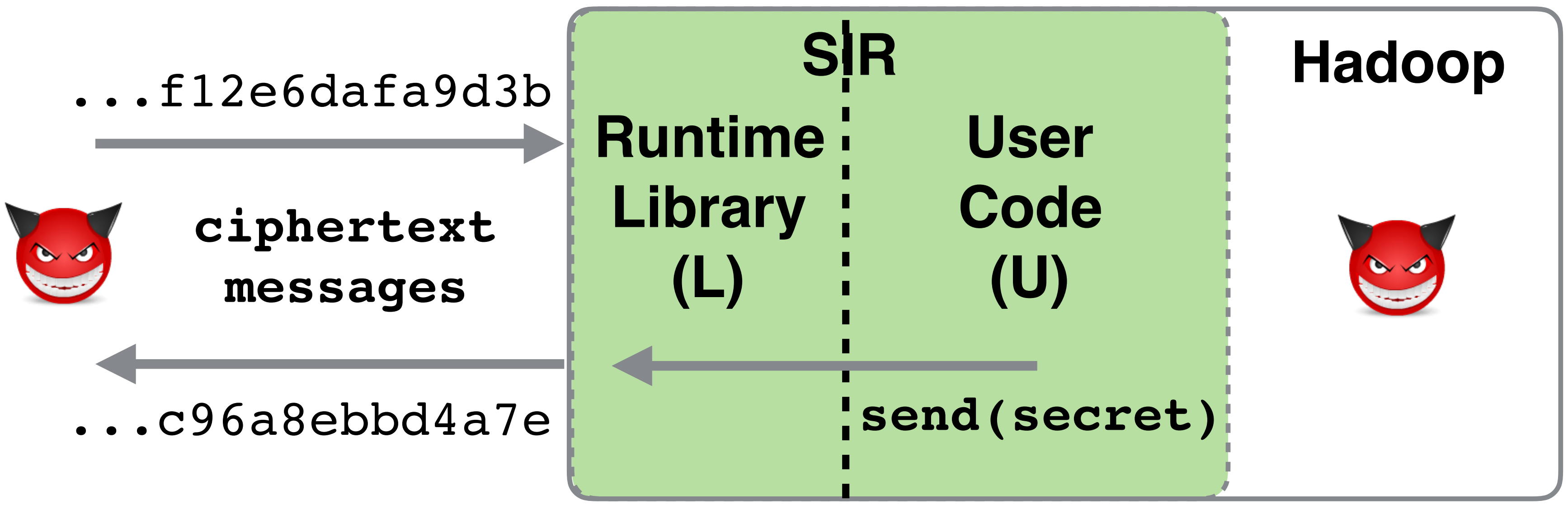

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Separation of concerns:
U does not manage crypto keys or write to untrusted memory

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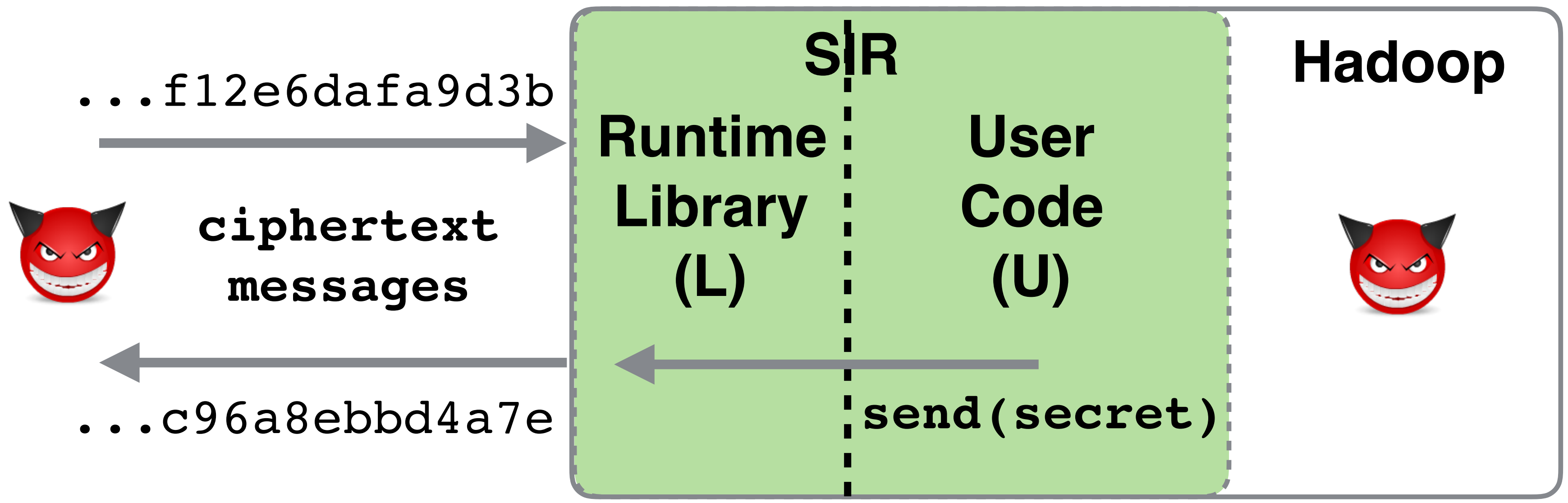

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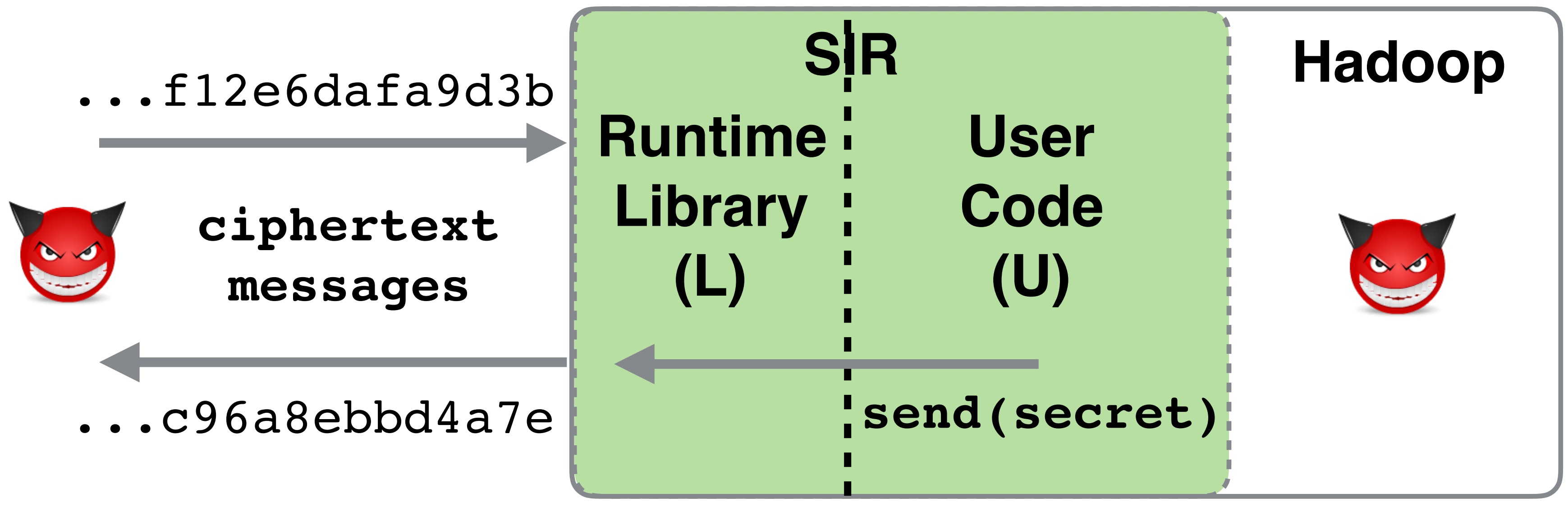

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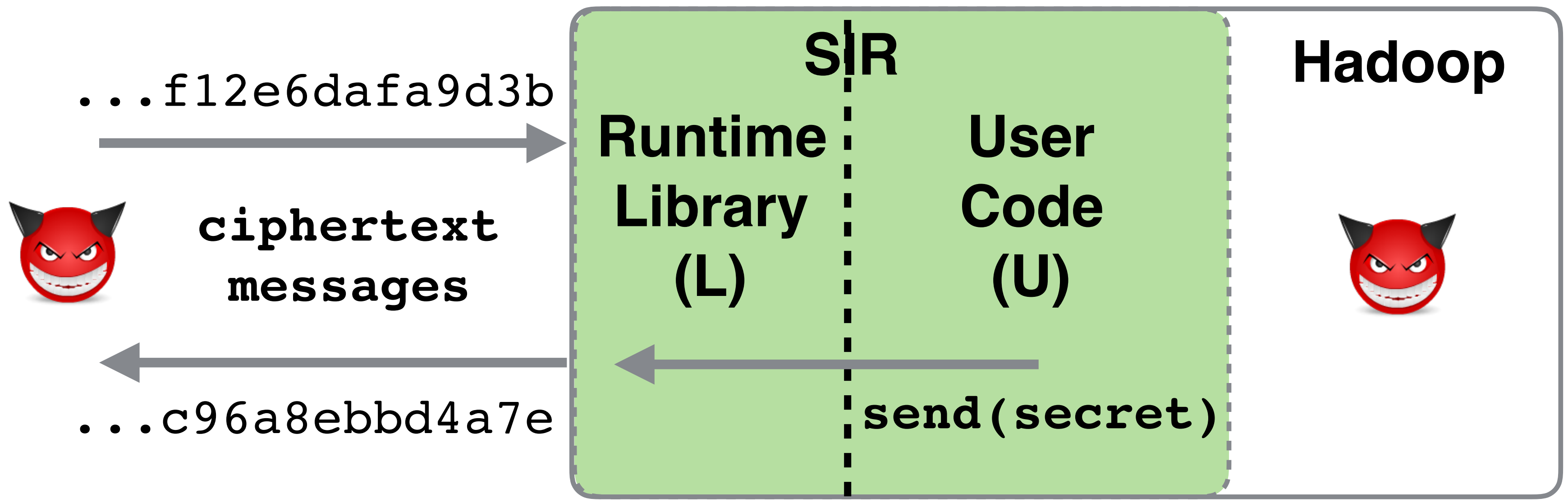

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✓ **Prevents explicit information leaks**: side channels outside scope

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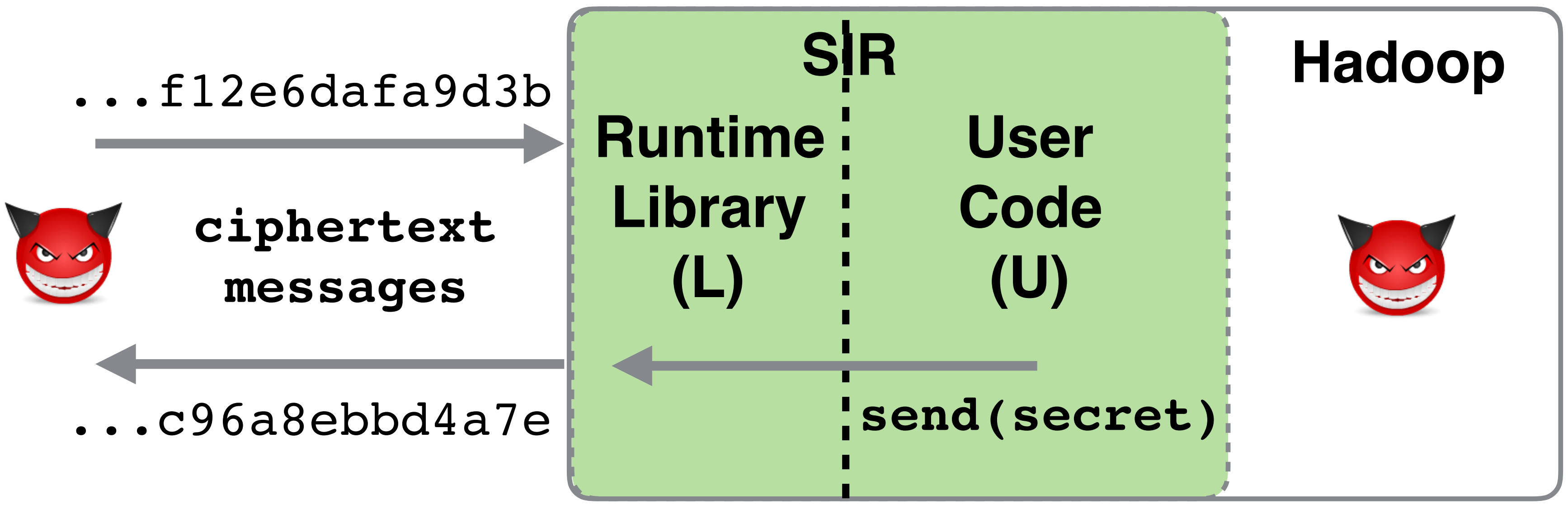

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- ✓ **Prevents explicit information leaks**: side channels outside scope
- ✓ Even if U is buggy, an **adversary only sees encrypted values** in an exploit

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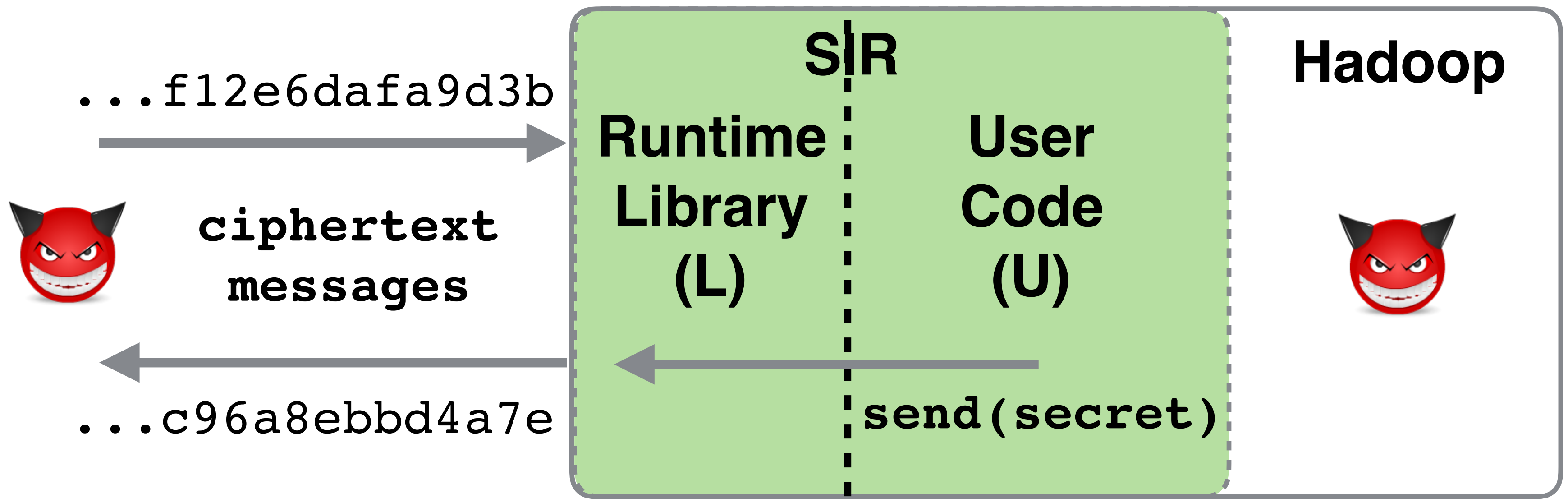

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- ✓ **Prevents explicit information leaks**: side channels outside scope
- ✓ Even if U is buggy, an **adversary only sees encrypted values** in an exploit
- ✓ **Avoids fine-grained tracking of secrets** in U's memory: all of U is secret

Proving Information Release Confinement

SIR satisfies IRC

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Correctness of L

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- ✓ **We don't require full functional correctness of U**
- ✓ **Proof strategy requires no annotations from the developer**

Contributions

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Formal Specification of IRC

IRC as a design methodology for programming SIRs

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Verifier checks against a privileged OS-level adversary

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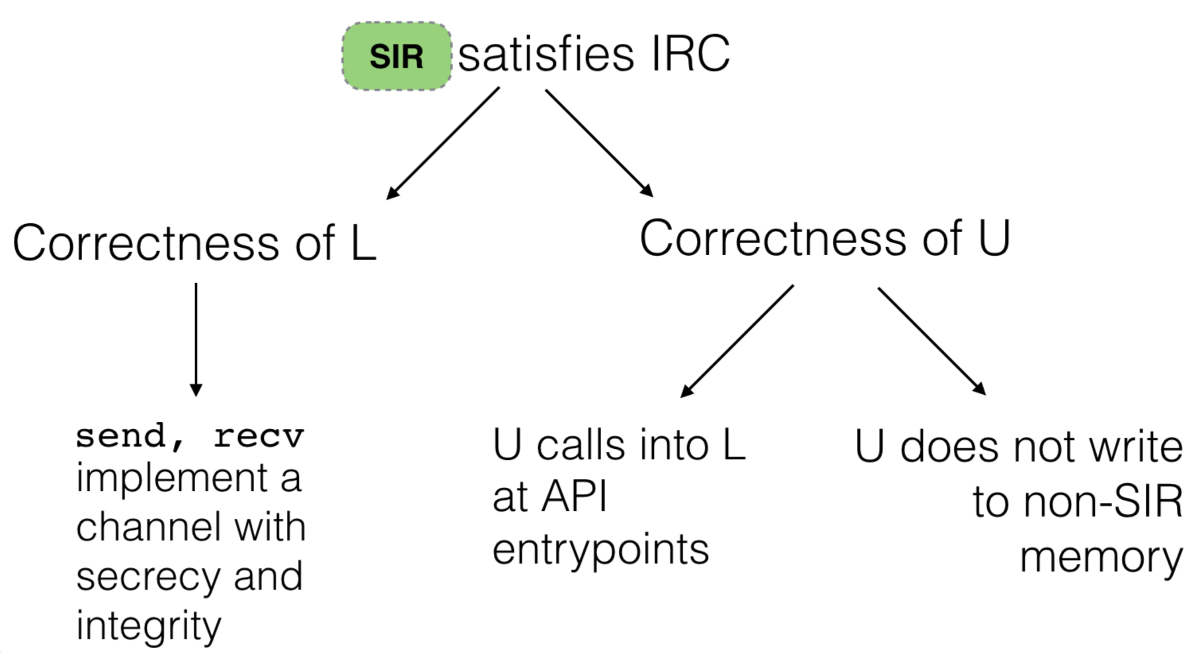

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Evaluation on several SIRs

Map-Reduce benchmarks from VC3

SPEC benchmarks

This Talk: Automatically Proving IRC

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Verifying Calls in U

Verifying that U calls into L at API entrypoints

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Verifying Calls in U Verifying that U calls into L at API entrypoints

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This Talk: Automatically Proving IRC

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This Talk: Automatically Proving IRC

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Verifying U: Calls to L via API Entrypoints

Verifying Calls in U

Verifying Writes in U

Verifying L

Evaluation

Verifying U: Calls to L via API Entrypoints

Potential Code in U

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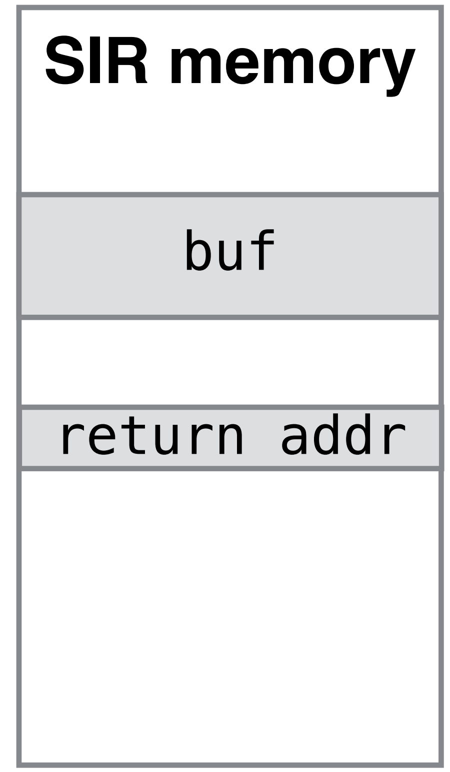

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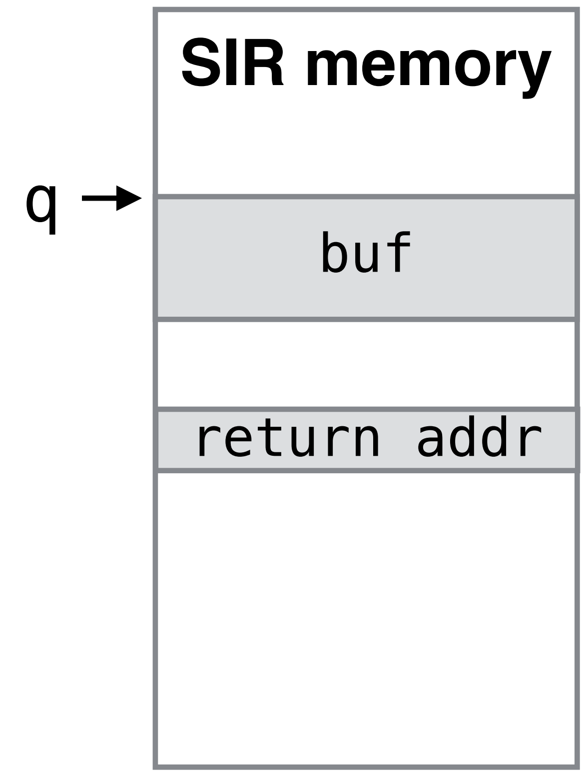

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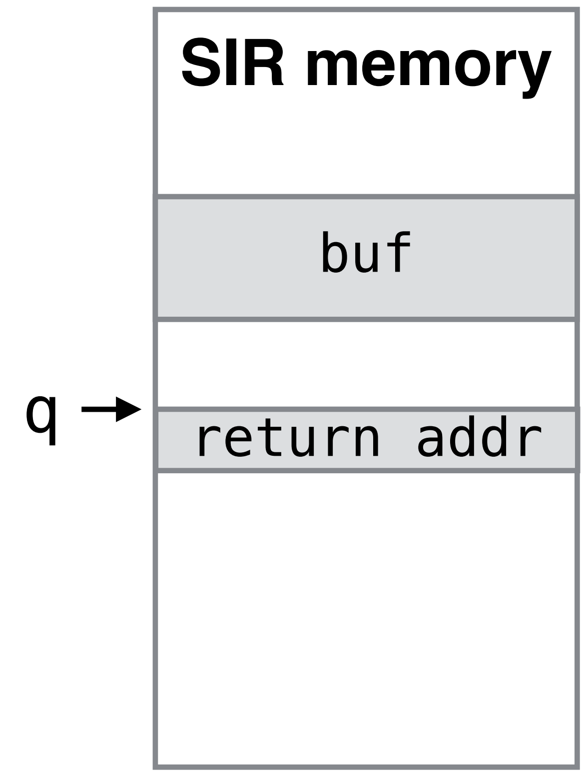

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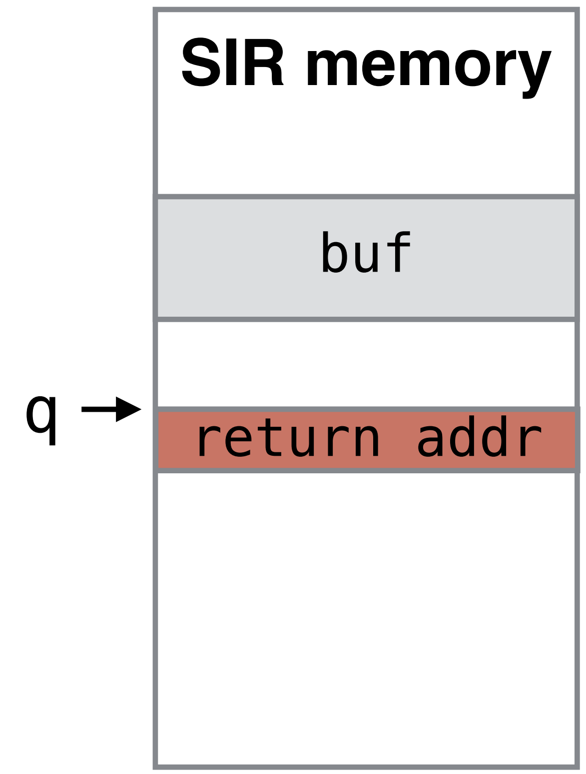

Verifying U: Calls to L via API Entrypoints

Verifying Calls in U

Verifying Writes in U

Verifying L

Evaluation

Potential Code in U

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*q = buf + input;
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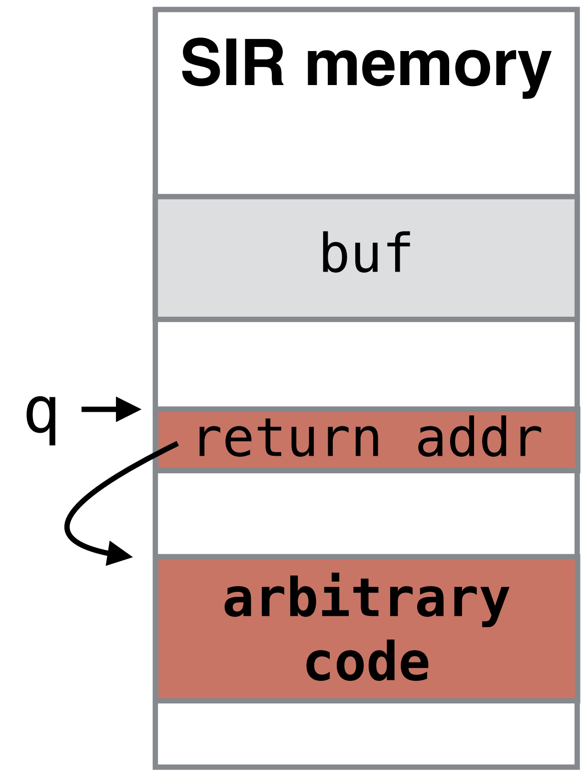

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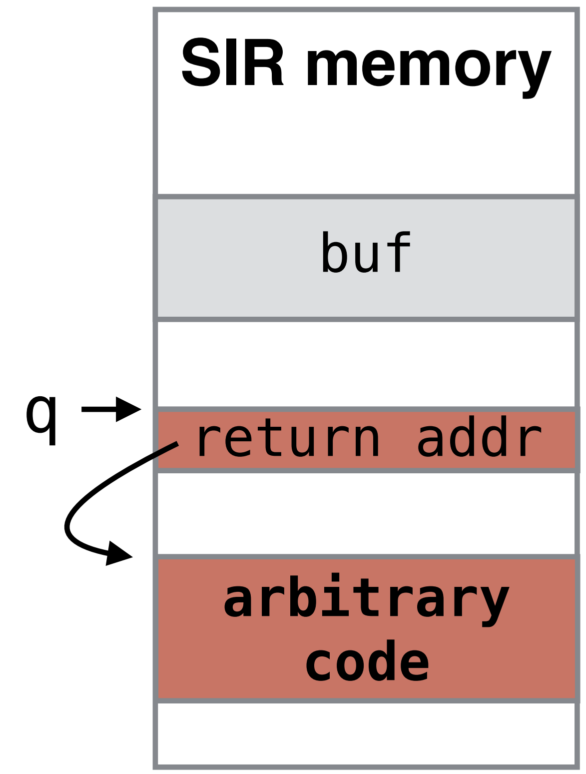

<u>arbitrary code</u>

- middle of x86 instructions
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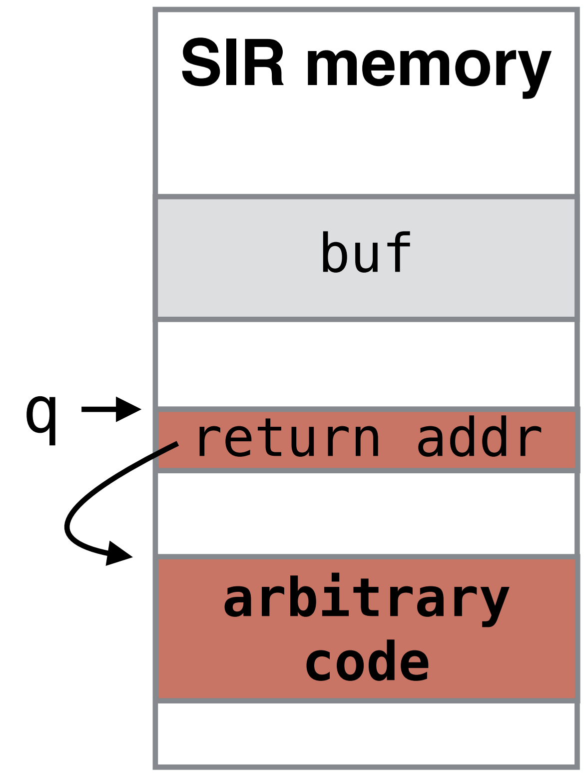

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Verifying U: Calls to L via API Entrypoints

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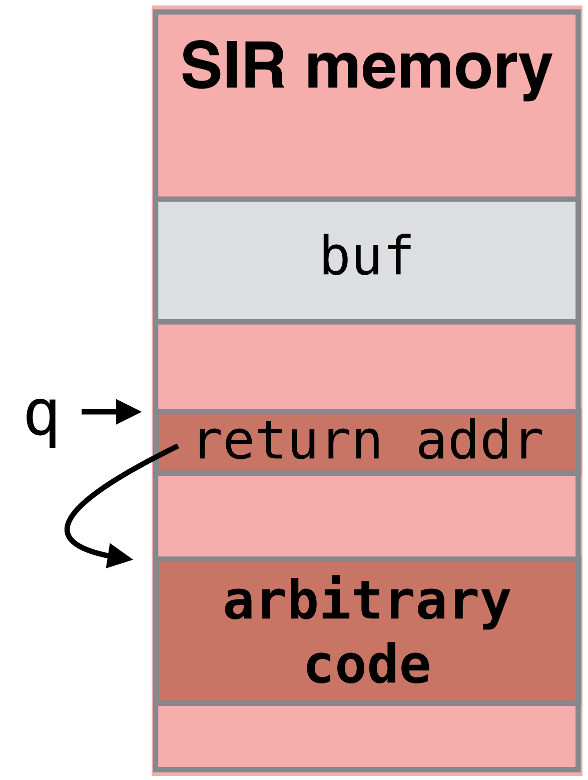

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Verifying U: Calls to L via API Entrypoints

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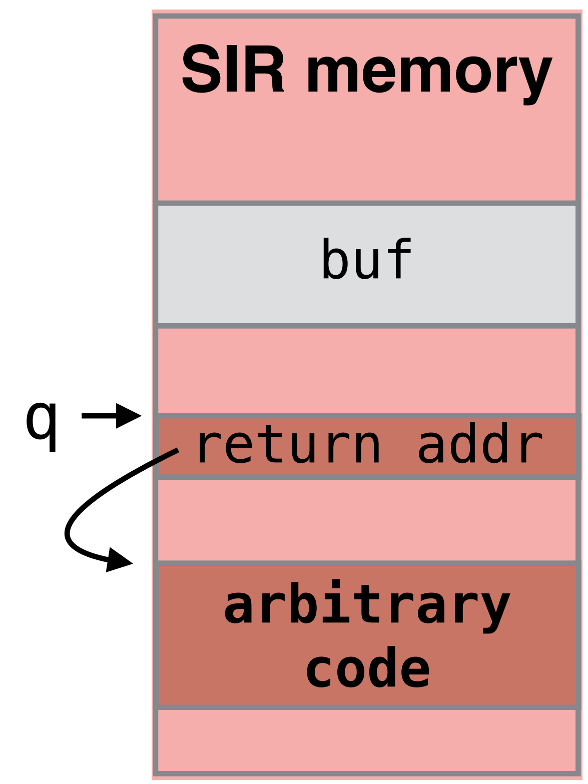

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Control Flow Integrity

Verifying U: Calls to L via API Entrypoints

Verifying Calls in U

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Verifying L

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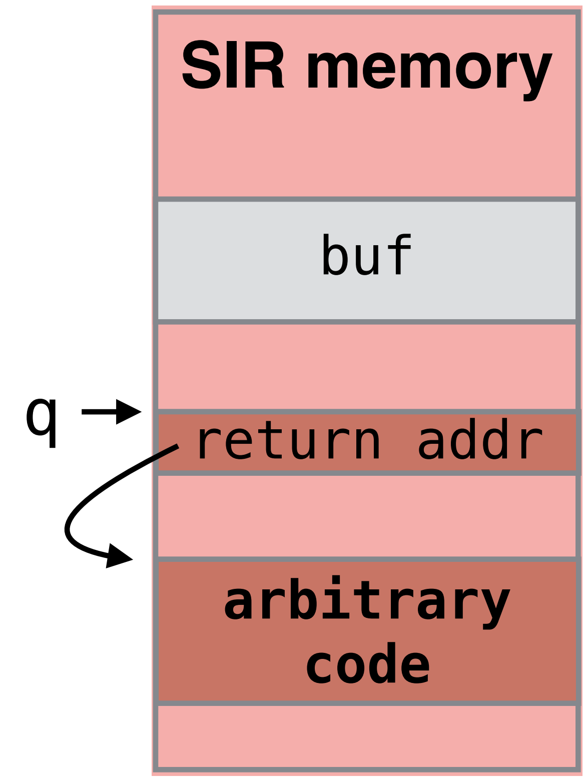

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Control Flow Integrity

✓ A `call` instruction targets the starting address of a procedure in U or API of L

Verifying U: Calls to L via API Entrypoints

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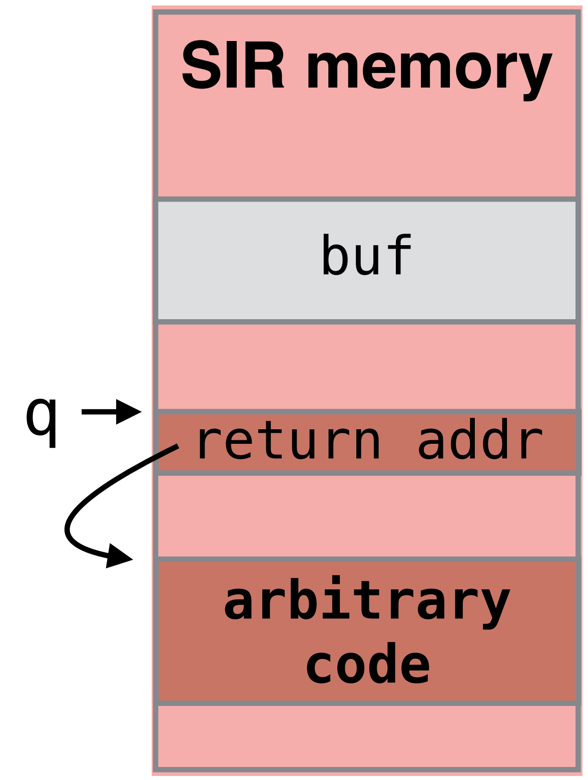

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✓ A `call` instruction targets the starting address of a procedure in U or API of L

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Verifying U: Calls to L via API Entrypoints

Verifying Calls in U

Verifying Writes in U

Verifying L

Evaluation

Potential Code in U

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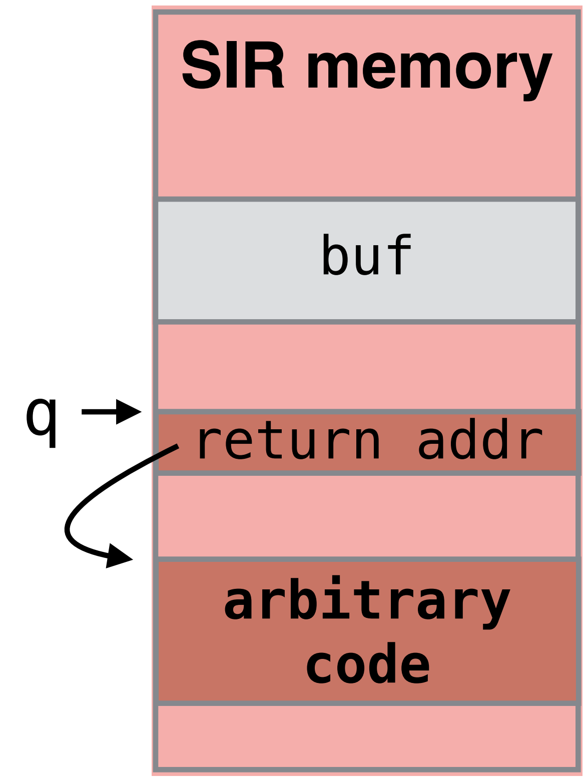

<u>arbitrary code</u>

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Control Flow Integrity

✓ A `call` instruction targets the starting address of a procedure in U or API of L

✓ A `ret` instruction returns back to the caller

✓ A `jmp` instruction targets a legal instruction within the procedure

Verifying U: Calls to L via API Entrypoints

Verifying Calls in U

Verifying Writes in U

Verifying L

Evaluation

Potential Code in U

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*q = buf + input;
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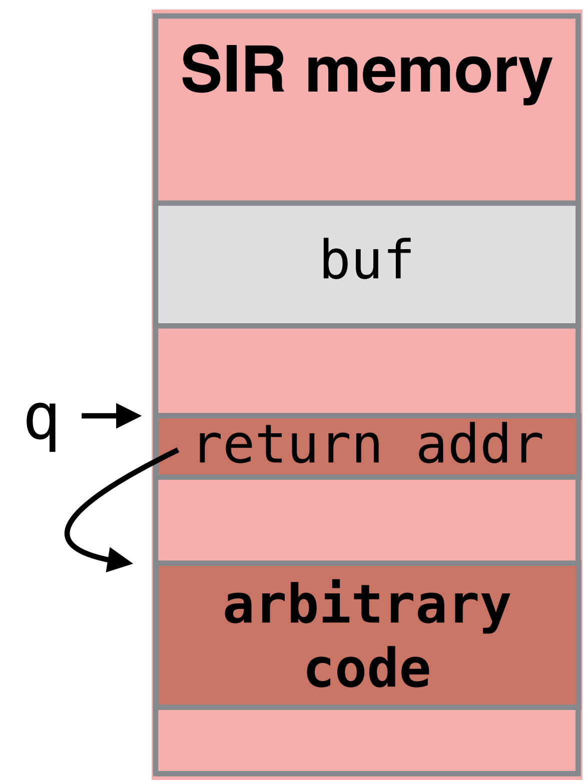

arbitrary code
- middle of x86 instructions
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Weak Control Flow Integrity (WCFI)

- ✓ A `call` instruction targets the starting address of a procedure in U or API of L
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Verifying U: Calls to L via API Entrypoints

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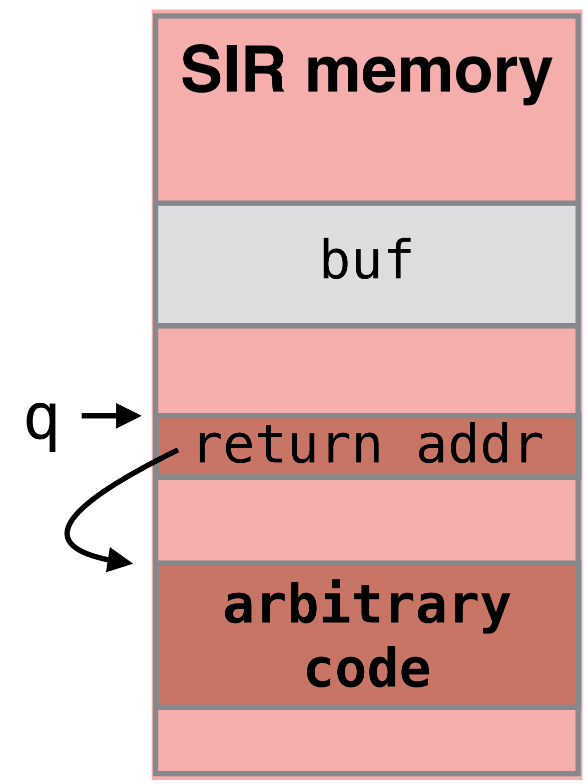

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WCFI ⇒

U calls into L via APIs

Verifying U: Runtime Checks for WCFI

Verifying Calls in U

Verifying Writes in U

Verifying L

Evaluation

Potential Code in U

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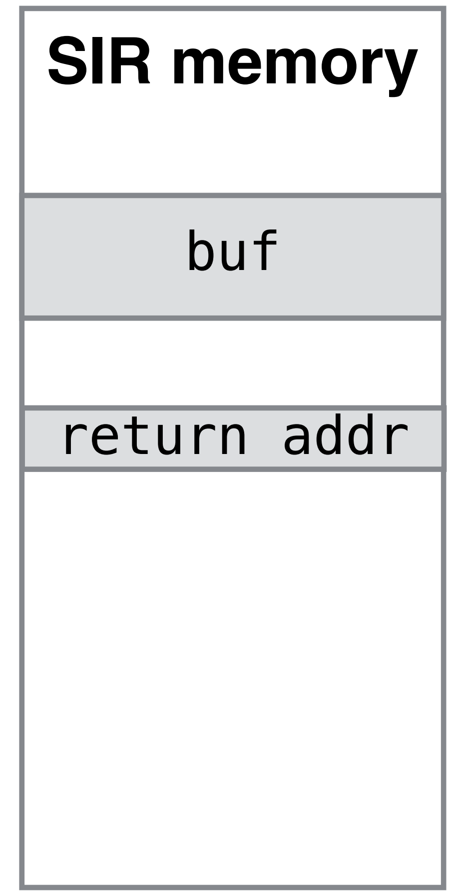

Verifying U: Runtime Checks for WCFI

- Verifying Calls in U
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- Evaluation

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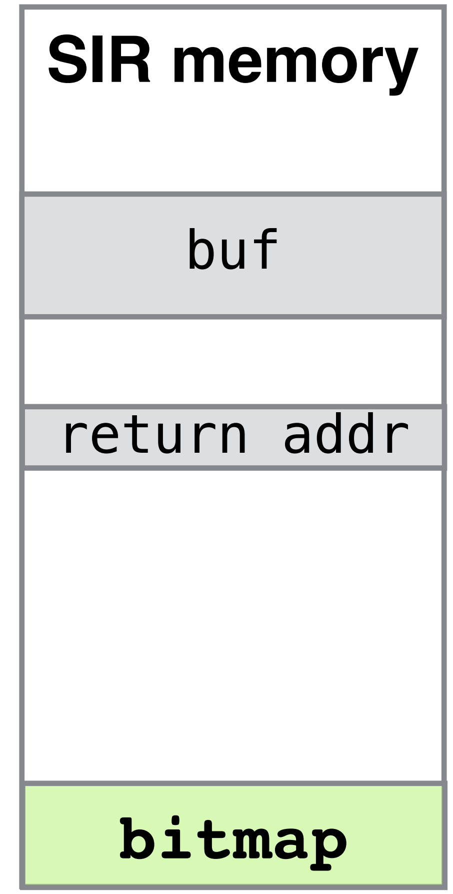
`Runtime check using VC3 compiler:`
`is address of q marked writable in bitmap?`



Verifying U: Runtime Checks for WCFI

- **Verifying Calls in U**
- Verifying Writes in U
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- Evaluation

Potential Code in U

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*q = buf + input;
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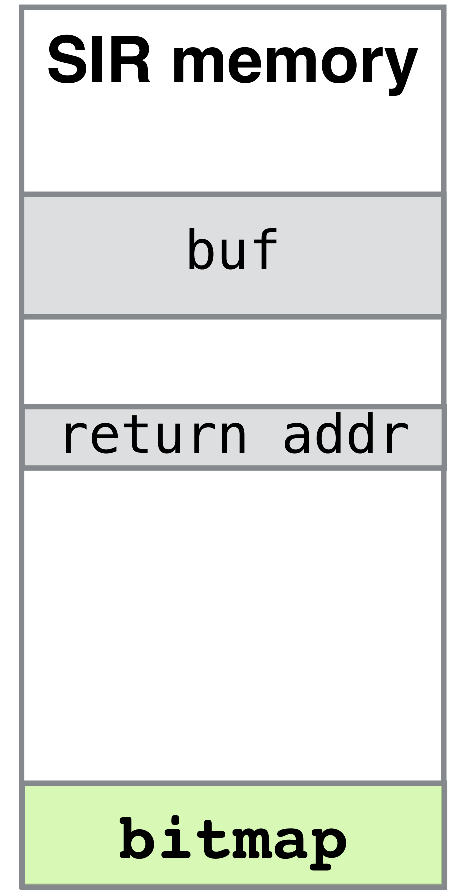

Runtime check using VC3 compiler:
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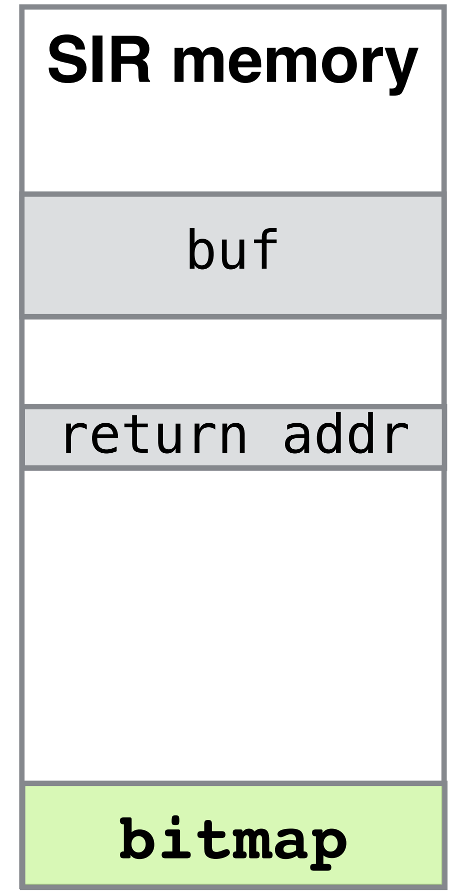

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local vars
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Verifying Calls in U

Verifying Writes in U

Verifying L

Evaluation

Verifying U: Runtime Checks for WCFI

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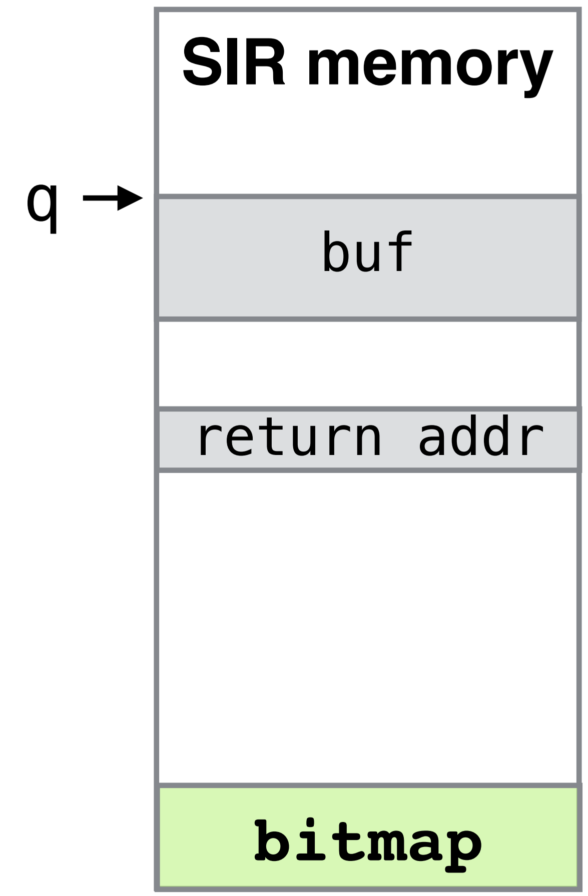

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Verifying U: Runtime Checks for WCFI

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Evaluation

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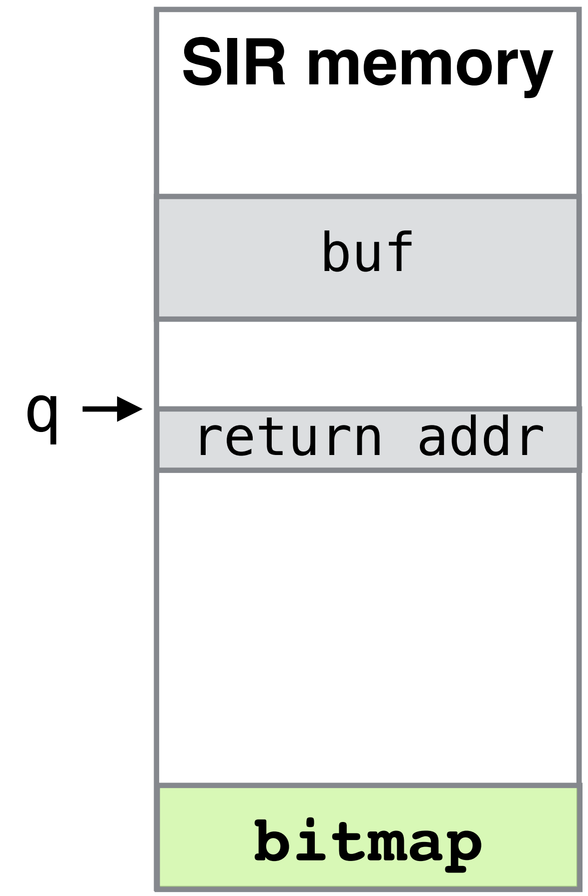

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Verifying U: Runtime Checks for WCFI

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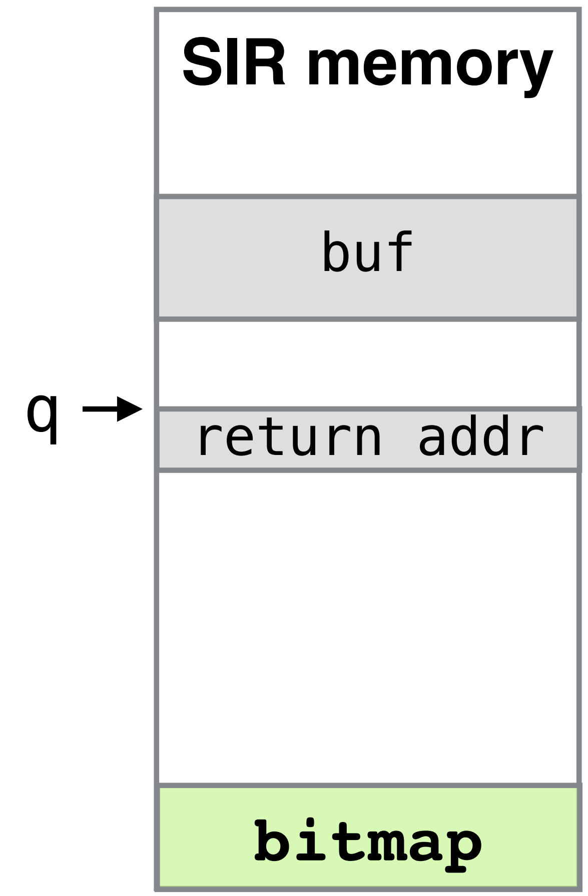

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Verifying U: Runtime Checks for WCFI

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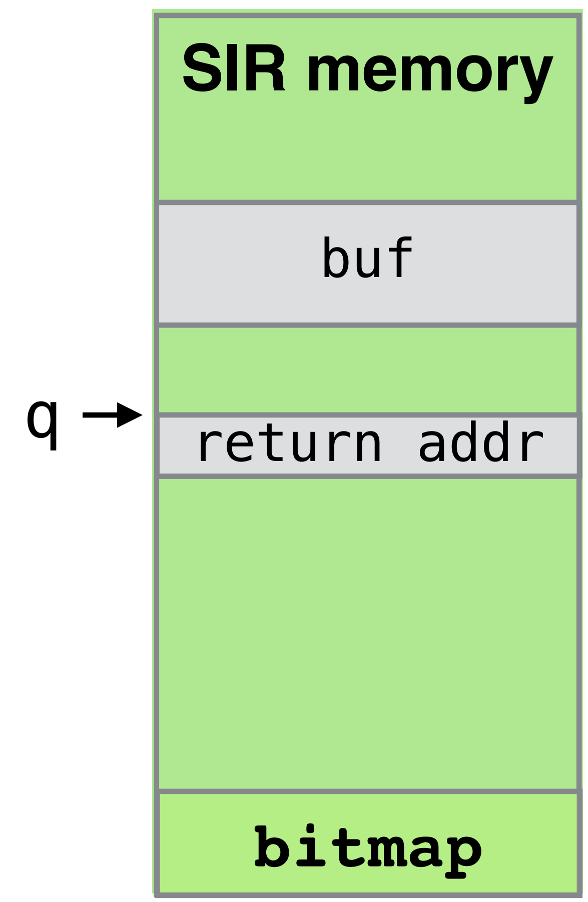
Software TRAP



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Verifying U: Modeling U's Binary

- **Verifying Calls in U**
- Verifying Writes in U
- Verifying L
- Evaluation

Verifying U: Modeling U's Binary

Avoid trusting the compiler:

Long history of bugs

Verifying Calls in U

Verifying Writes in U

Verifying L

Evaluation

Verifying U: Modeling U's Binary

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Compiler optimizes away many runtime checks

Verifying U: Modeling U's Binary

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Evaluation

Avoid trusting the compiler:

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x64 code produced by compiler

```
...
mov rcx, [rax+rbx]
bt rcx, rbx
jb $L2
int 3
$L2: mov [rbx],rdx
...
ret
```

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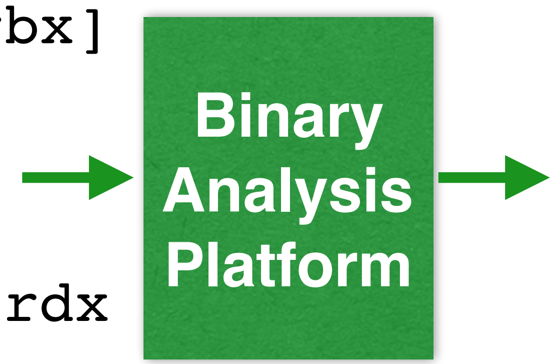

Verifying Calls in U

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→ **Binary Analysis Platform** →

Boogie model

```
...
rcx := load(mem, rax +_64 rbx);
CF := (rcx >>_64 rbx)[1:0];
goto $L1, $L2;
$L1: assume CF == 0;
     assume false;
$L2: assume CF == 1;
     mem := store(mem, rbx, rdx);
...
return;
```

Verifying Calls in U

Verifying Writes in U

Verifying L

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Verifying U: Modeling the Adversary

Verifying Calls in U

Verifying Writes in U

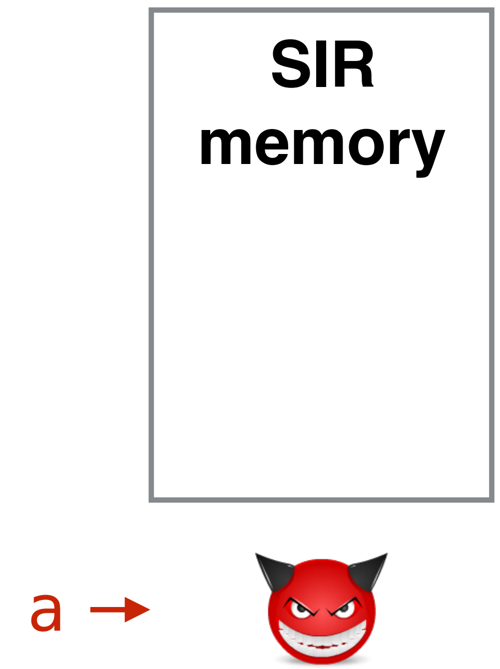
Verifying L

Evaluation

Verifying U: Modeling the Adversary

load from untrusted memory returns arbitrary value *

```
load(mem,a) = ITE(SIR(a), mem[a], *);
```



Verifying U: Modeling the Adversary

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Verifying L

Evaluation

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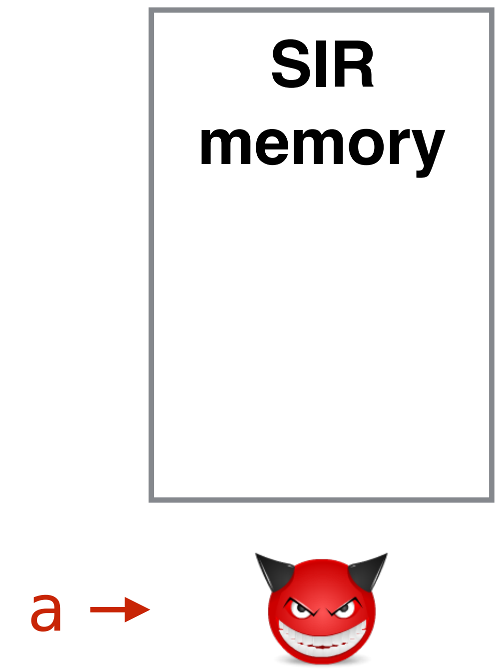

[Moat *CCS'15*]: **models all operations by a malicious OS** e.g. generate interrupts, modify page tables, launch other SIRs, etc.

Verifying U: Proof Obligations

Verifying Calls in U

Verifying Writes in U

Verifying L

Evaluation

Boogie model

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Verifying U: Proof Obligations

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     assert Ψ;
     mem := store(mem, rbx, rdx);
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...
assert φ;
return;
```

Verifying U: Proof Obligations

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Proof Obligations guarantee WCFI ⇒

U calls into L via APIs

Verifying U: Proof Obligations

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Verifying Writes in U

Verifying L

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VC-gen + SMT Solving

Proof Obligations guarantee WCFI ⇒

U calls into L via APIs

Verifying U: Proof Obligations

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VC-gen + SMT Solving

Proof Obligations guarantee WCFI ⇒ U calls into L via APIs

Presence of runtime checks helps SMT solver to prove `assert Ψ`

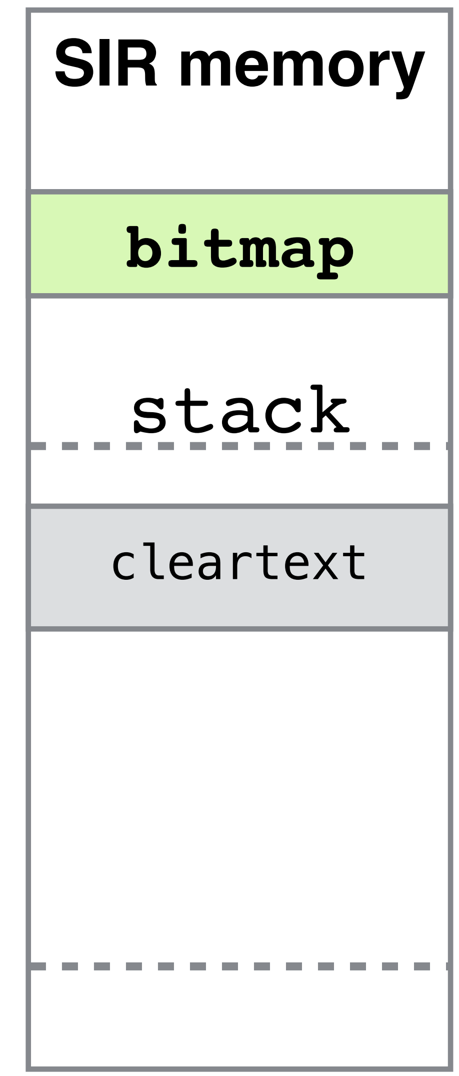
Verifying U: Proof Obligations on `store`

Verifying Calls in U

Verifying Writes in U

Verifying L

Evaluation



Verifying U: Proof Obligations on `store`

Verifying Calls in U

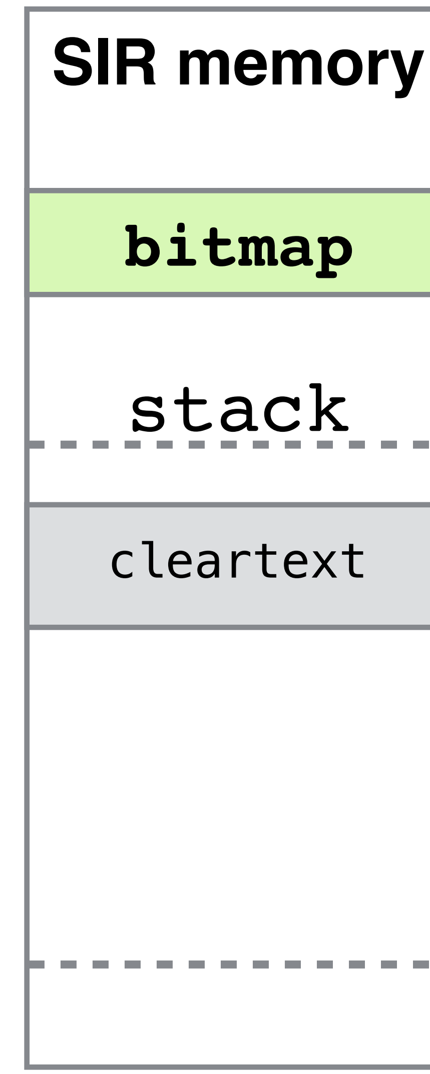
Verifying Writes in U

Verifying L

Evaluation

```
void Reduce(...) {
   ...
   sprintf(cleartext, “%s %lld”,...);
   ...
}

void sprintf(char *cleartext,...) {
   /* write to cleartext */
}
```



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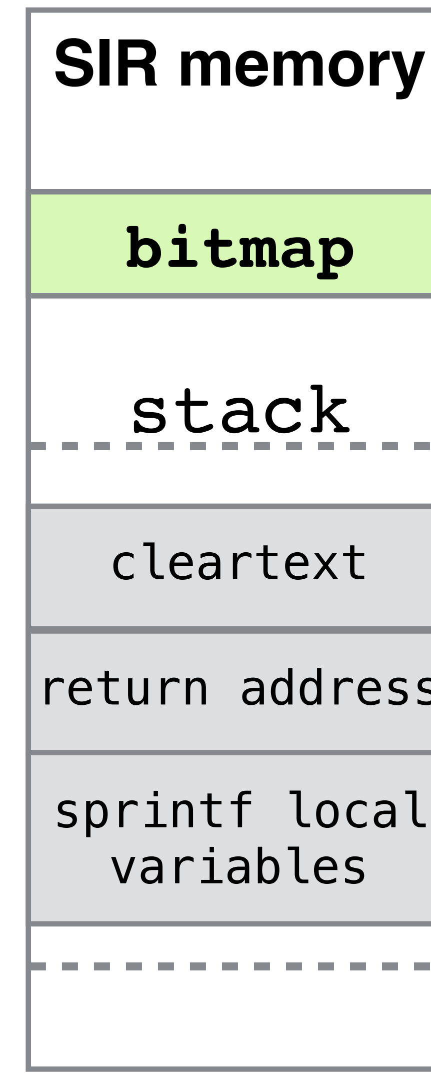

Verifying U: Proof Obligations on `store`

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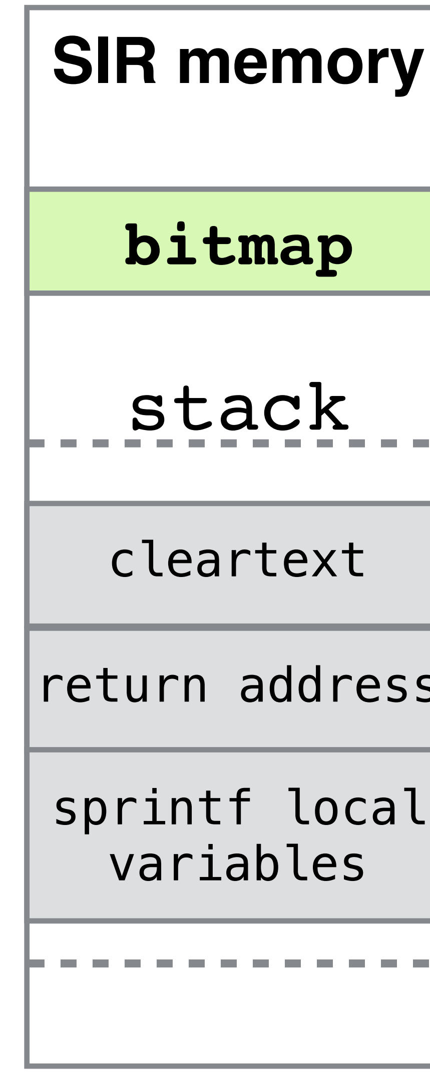
```

verifier **asserts writable(bitmap, addr)** for each store



Verifying U: Proof Obligations on `store`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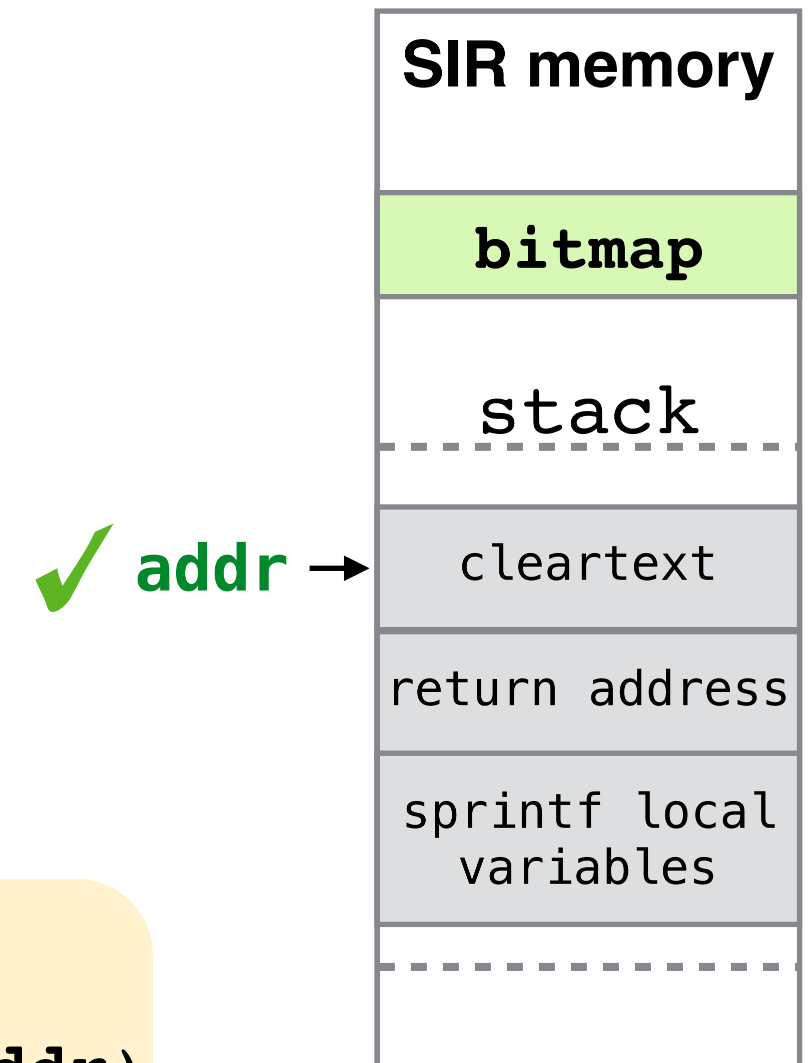

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Verifying U: Proof Obligations on `store`

Verifying Calls in U

Verifying Writes in U

Verifying L

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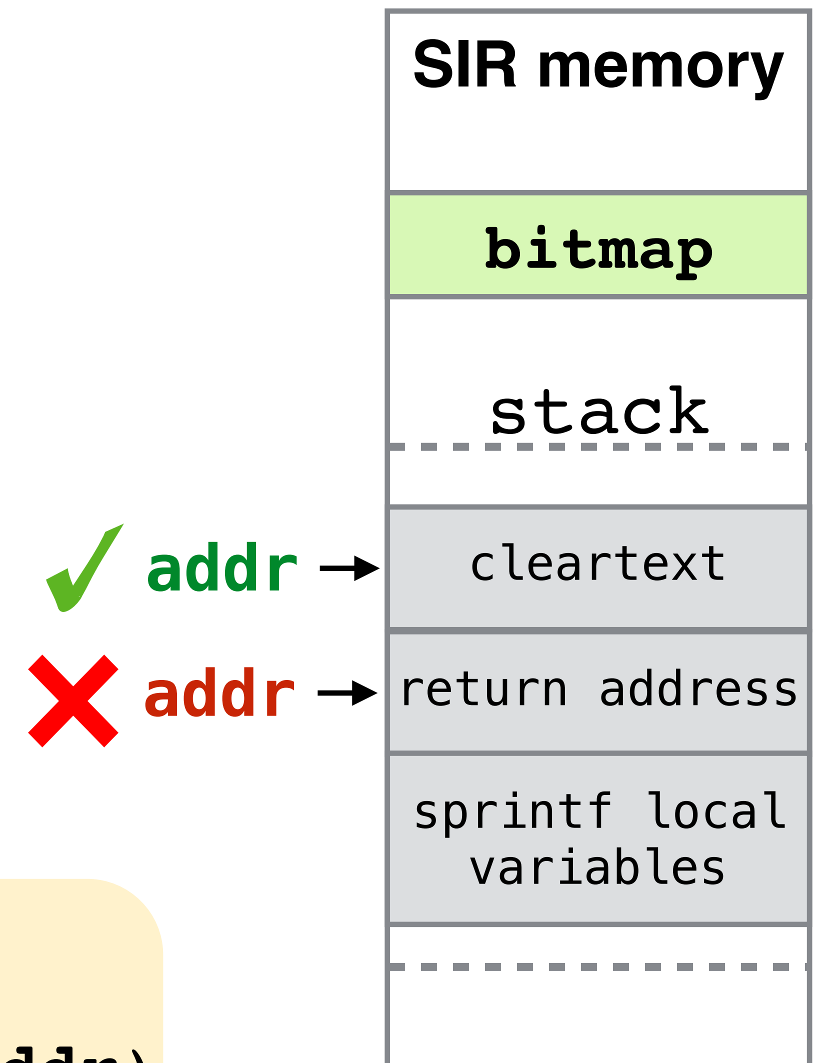

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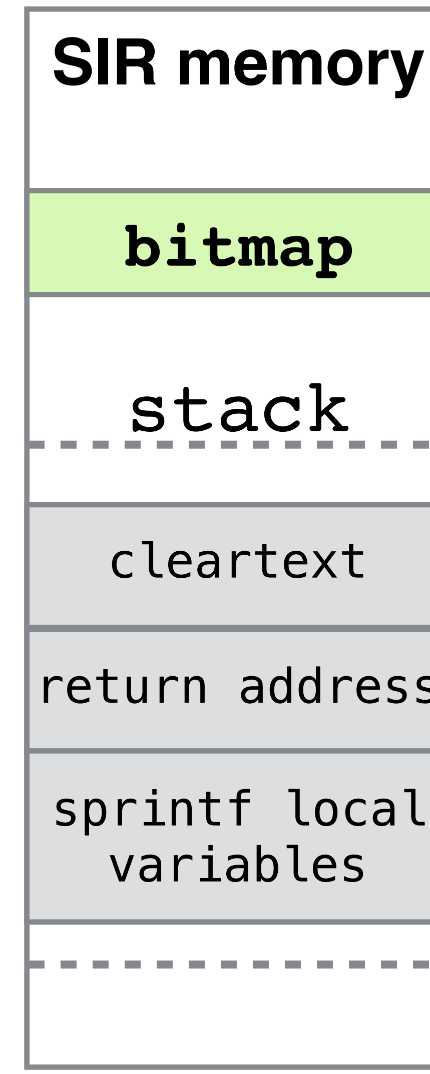
Verifying U: Proof Obligations on `store`



Verifying U: Proof Obligations on `store`

Verifying Calls in U

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Verifying L

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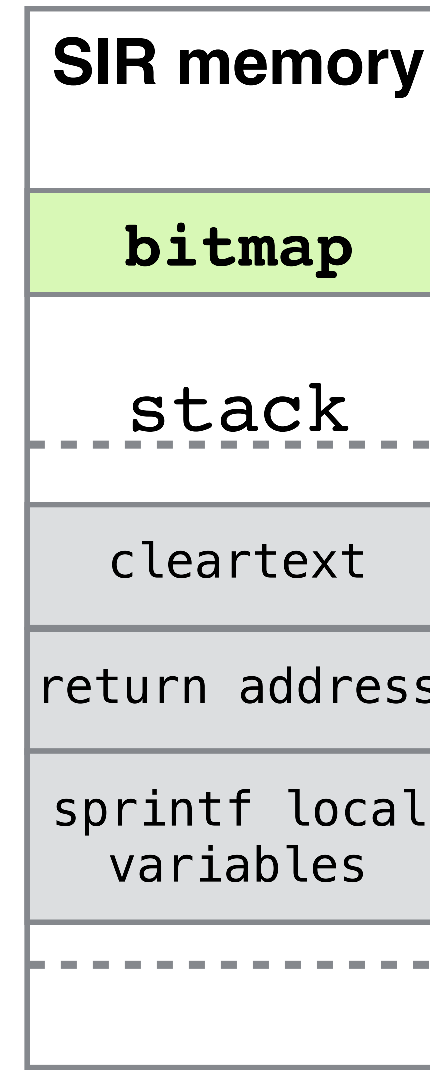
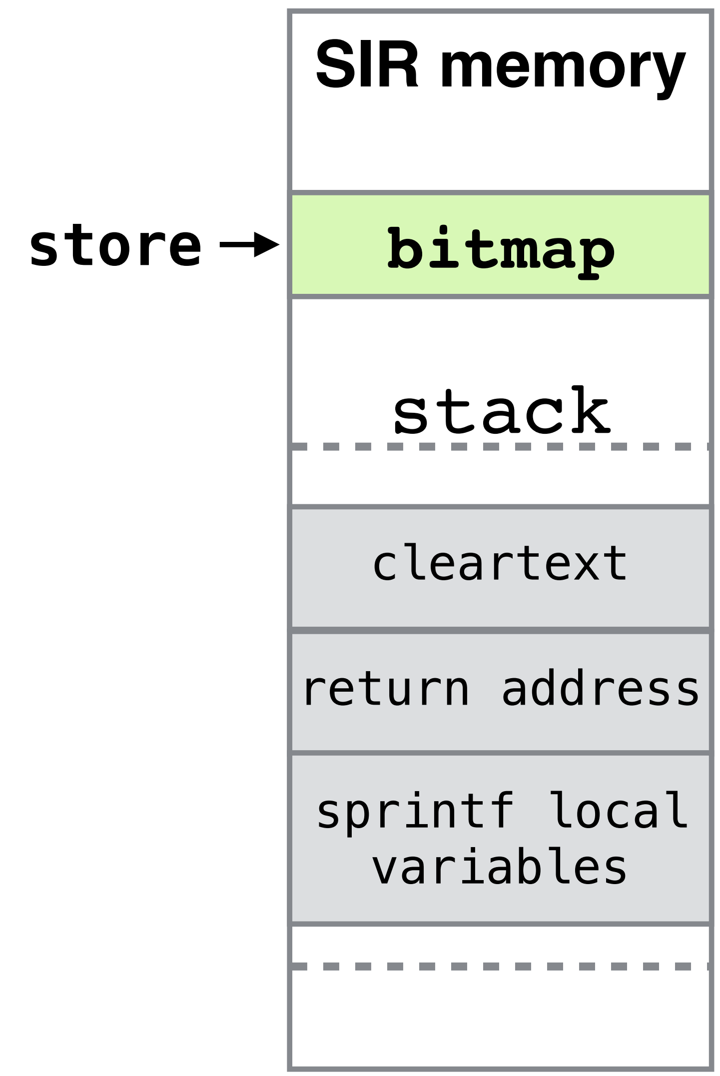


Verifying U: Proof Obligations on `store`

Verifying Calls in U
Verifying Writes in U
Verifying L
Evaluation

```
void Reduce(...) {
 ...
 <compiler makes cleartext writable>
 sprintf(cleartext, "%s %lld", ...);
 ...
}

void sprintf(char *cleartext, ...) {
  /* write to cleartext */
}
```



Verifying U: Proof Obligations on `store`


```
void Reduce(...) {
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 <compiler makes cleartext writable>
 sprintf(cleartext, "%s %lld", ...);
 ...
}

void sprintf(char *cleartext, ...) {
  /* write to cleartext */
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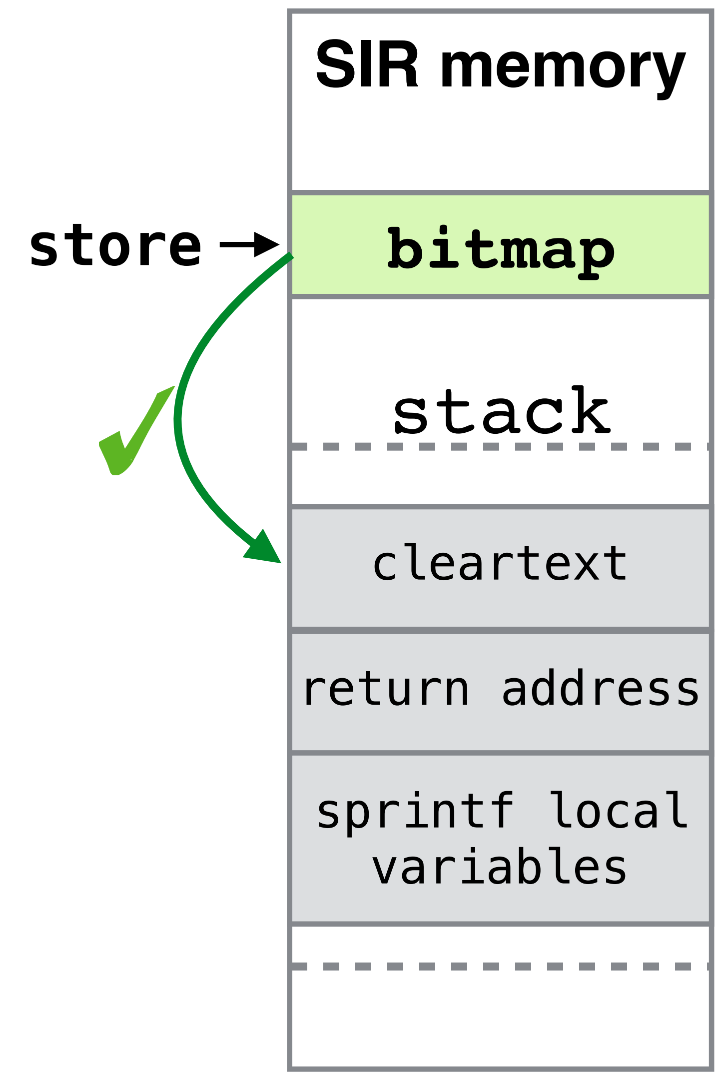
```



verifier **asserts** that
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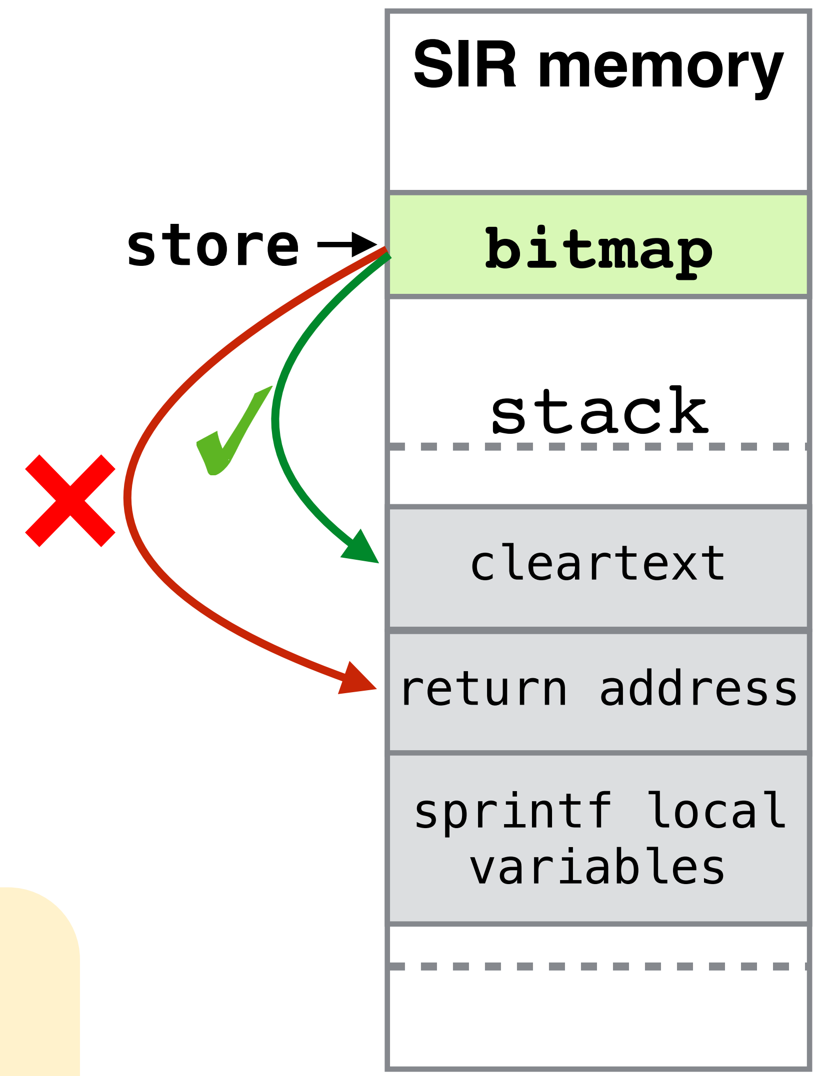

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Verifying U: Soundness

- **Verifying Calls in U**
- Verifying Writes in U
- Verifying L
- Evaluation

Verifying U: Soundness

Verifying Calls in U

Verifying Writes in U

Verifying L

Evaluation

`call:`

assert $\text{policy}(e) \;\wedge\; (\forall i.\ (\text{AddrInStack}(i) \wedge i < \text{rsp}) \Rightarrow \neg\text{writable}(\texttt{mem}, i))$

`ret:`

assert $(\text{rsp} = \text{old}(\text{rsp})) \wedge (\forall i.\ (\text{AddrInStack}(\text{i}) \wedge i < \text{old}(\text{rsp})) \Rightarrow \neg\text{writable}(\texttt{mem}, i));$

`jmp:`

assert $(\text{start}(p) \leq e < \text{end}(p)) \rightarrow \text{legal}(e);$

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Proof obligations imply WCFI ⇒

U calls into L via APIs

Verifying U: Preventing Writes Outside SIR

Verifying Calls in U

Verifying Writes in U

Verifying L

Evaluation

Verifying U: Preventing Writes Outside SIR

- Verifying Calls in U
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```
*q = buf + input;
*q = secret;
...
```

Verifying U: Preventing Writes Outside SIR

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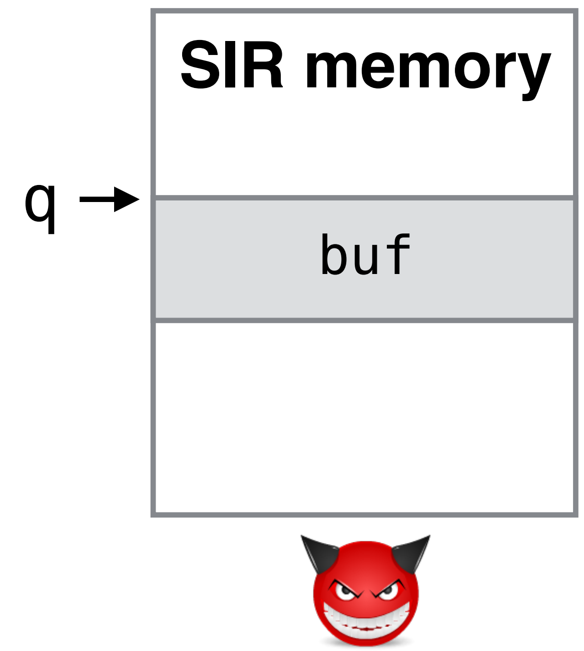

Verifying U: Preventing Writes Outside SIR

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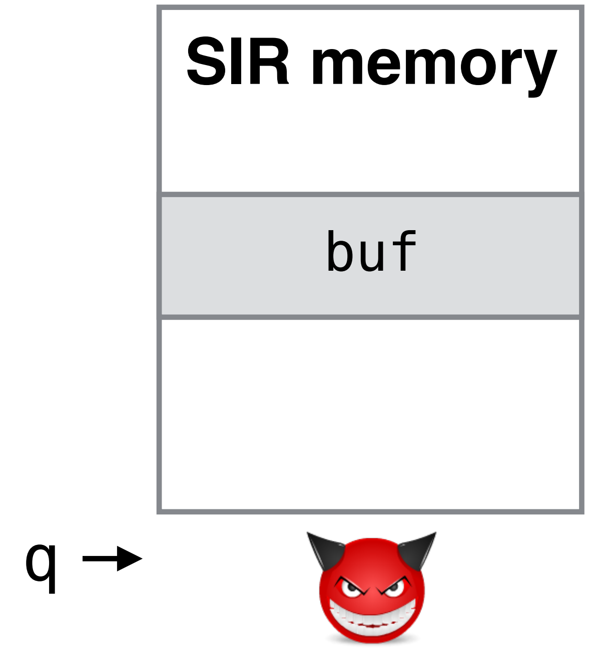

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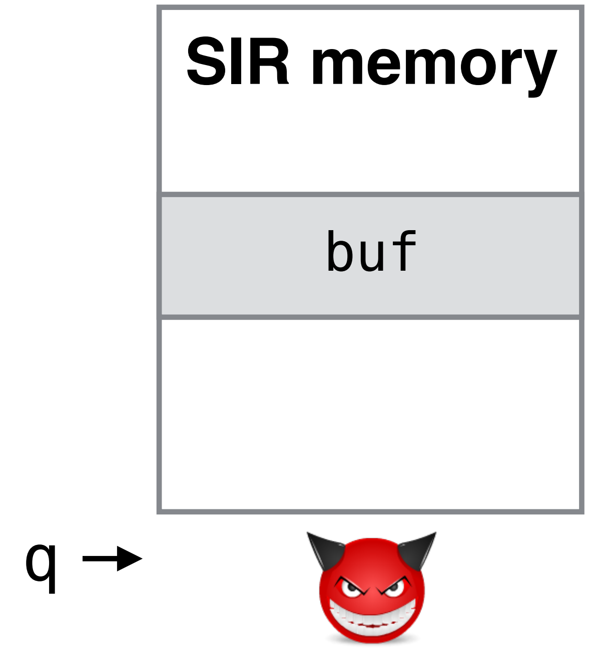

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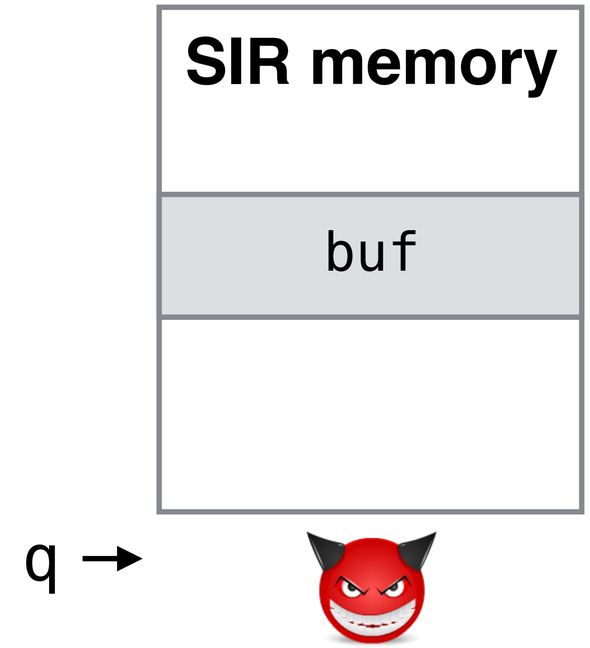

Runtime check using VC3 compiler:
is q within SIR range?

Verifying U: Preventing Writes Outside SIR


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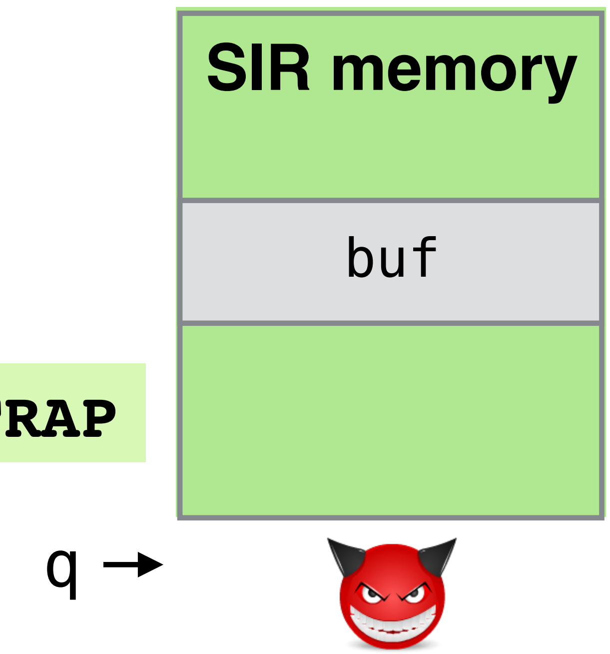
Software TRAP



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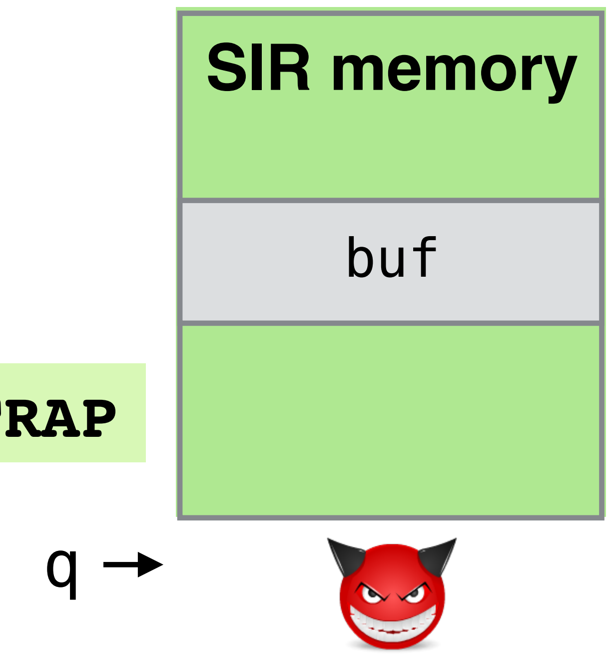
`Software TRAP`



`Runtime check using VC3 compiler:`
`is q within SIR range?`

Since we don't trust the compiler:

`verifier asserts addrInSIR(addr)`
`for each store`

Verifying U: Soundness

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Boogie model

```
...
$L2: assume CF == 1;
     assert Ψ;
     mem := store(mem, rbx, rdx);
...
assert φ;
return;
```

Verifying U: Soundness

Verifying Calls in U

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Proof Obligations for WCFI

Verifying U: Soundness

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Proof Obligations for WCFI

Proof Obligations for writes within SIR

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assert φ;
return;
```

Proof Obligations for WCFI + **Proof Obligations for writes within SIR** = **IRC**

Verifying U: Modular Verification

- Verifying Calls in U
- Verifying Writes in U
- Verifying L
- Evaluation

Verifying U: Modular Verification

Verifying Calls in U

Verifying Writes in U

Verifying L

Evaluation

We perform modular reasoning of U's binary without false positives.

Verifying U: Modular Verification

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The VC3 compiler generates enough runtime checks to allow this.

Verifying U: Modular Verification

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We perform modular reasoning of U's binary without false positives.

The VC3 compiler generates enough runtime checks to allow this.

```
void Reduce(...) {
   ...
   sprintf(cleartext, “%s %lld”, …);
   ...
}
void sprintf(char *cleartext, …) {

   //write to cleartext, which is stack-allocated
}
```

Verifying U: Modular Verification

We perform modular reasoning of U's binary without false positives.

The VC3 compiler generates enough runtime checks to allow this.

```
void Reduce(...) {
   ...
   sprintf(cleartext, "%s %lld", …);
   ...
}
void sprintf(char *cleartext, …) {
    <runtime check that buf is in SIR memory>
   //write to cleartext, which is stack-allocated
}
```

Verification Optimizations

Verifying Calls in U

Verifying Writes in U

Verifying L

Evaluation

Verification Optimizations

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`ret:` `assert`$(\forall i \ : i < \mathsf{rsp} \Rightarrow \neg \mathsf{writable}(\mathsf{mem}, \mathsf{i}))$

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sound strategy for quantifier instantiation

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sound strategy for quantifier instantiation

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Removed hundreds of Z3 timeouts in our experiments

Manual, One-time Verification of L

Verifying Calls in U

Verifying Writes in U

Verifying L

Evaluation

Manual, One-time Verification of L

Verifying Calls in U

Verifying Writes in U

Verifying L

Evaluation

```
void send(void *buf, size_t size)
void recv(void *buf, size_t size)
```

Manual, One-time Verification of L

Verifying Calls in U

Verifying Writes in U

Verifying L

Evaluation

```
void send(void *buf, size_t size)
void recv(void *buf, size_t size)
// ensures no unsafe modification to U
```

Manual, One-time Verification of L

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Verifying L

Evaluation

```
void send(void *buf, size_t size)
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Manual, One-time Verification of L

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Manual, One-time Verification of L

- Verifying Calls in U
- Verifying Writes in U
- **Verifying L**
- Evaluation

```
void send(void *buf, size_t size)
void recv(void *buf, size_t size)
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// ensures ...

void *malloc(size_t size)
void free(void *buf)
```

Manual, One-time Verification of L

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No requires clause on U

Evaluation

Verifying Calls in U

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`Runtime checks incur 15% performance hit [Schuster et al.: VC3]`

Verifying Calls in U

Verifying Writes in U

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Runtime checks incur 15% performance hit [Schuster et al.: VC3]

Benchmark	Code Size	Verified Asserts	Timed out Asserts	False Positives
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IoVolumes	17 KB	2391	2	0
Revenue	18 KB	1534	3	0
lbm	38 KB	1192	0	0
astar	115 KB	6468	2	0
bzip2	155 KB	10287	36	0

timeout:
30 mins

Evaluation

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in 4 hours

Verifying Calls in U

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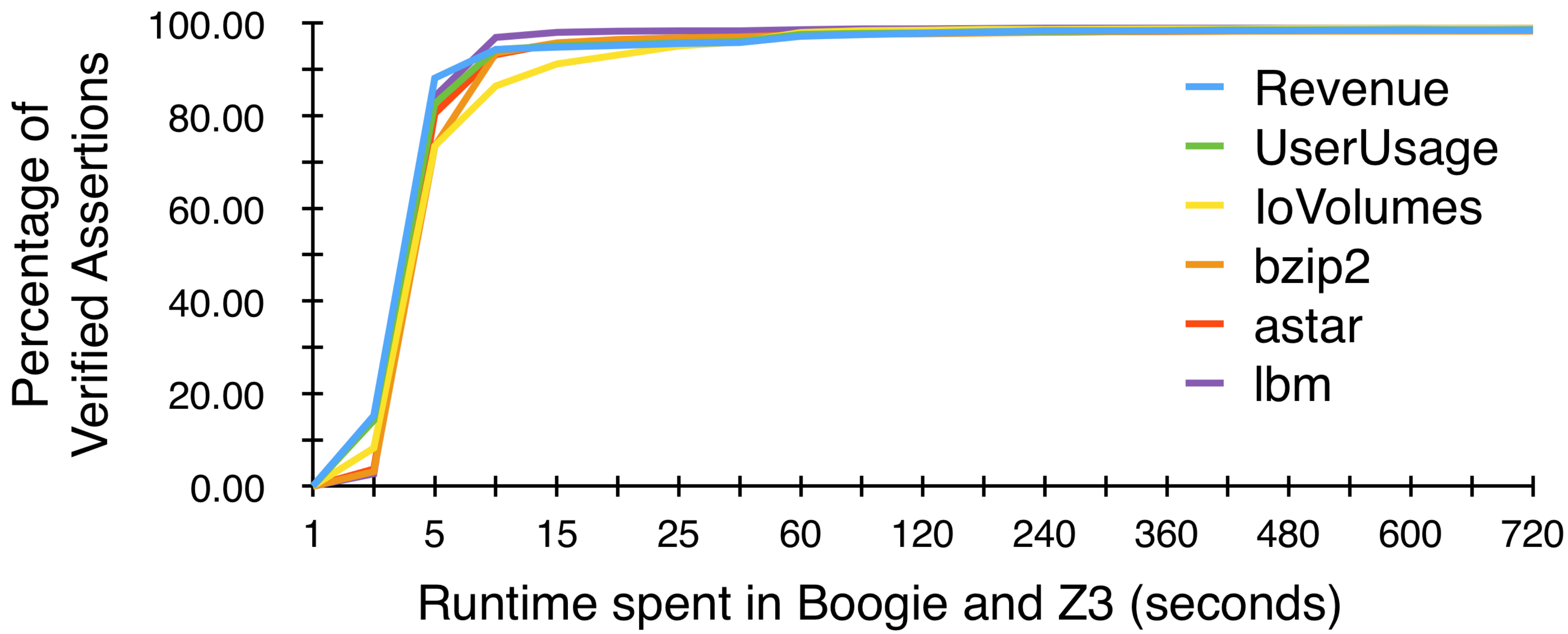

Related Work

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Work	Application	Technique	Comparison

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Morisett et al: Rocksalt *PLDI'12*	Software Fault Isolation	Verified Machine Code Checker extracted from Coq	different goal 64-bit version requires 100GB address space

Takeaway Points

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IRC as a design principle for SIRs:

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Automatic, modular verification of IRC on SIR binaries, with a small trusted computing base

Takeaway Points

Fork me on GitHub

IRC as a design principle for SIRs:

- easier to verify than full functional correctness
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Automatic, modular verification of IRC on SIR binaries, with a small trusted computing base

https://github.com/TrustedCloud/slashconfidential