Secure Delivery of Program Properties through Optimizing Compilation

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Arm
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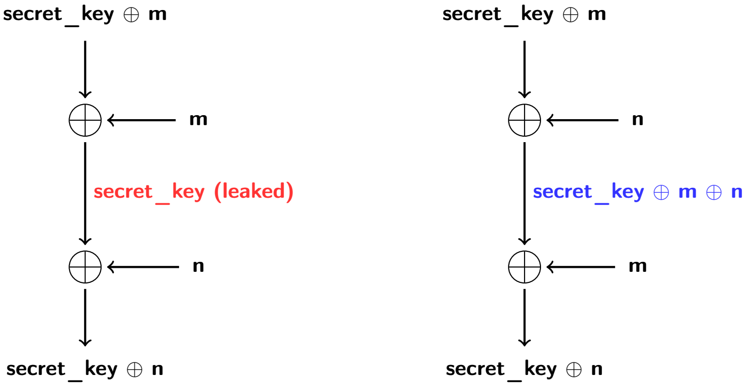
Background and Motivation: WYSINWYX phenomenon

- Assuming a functionally-correct, well-defined program
- Mismatch between
  1. Behavior intended by the programmer (source code)
  2. What is actually executed by the processor (machine code)
- Open issue for security engineering: e.g. cryptographic mask changing (so that observable results are statistically uncorrelated to secret data)



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void compute(int *mk, int m) {
  ...
  int n = rand();

  *mk = (*mk ^ n) ^ m;
  ...
}
```

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secret_key* $\oplus$ *m

```
void compute(int *mk, int m) {
  ...
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}
```

De-masking of old mask *m*

Re-masking of secret key with new mask *n*

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Security property:
Re-masking before De-masking

```
void compute(int *mk, int m) {
  ...
  int n = rand();

  *mk = (*mk ^ n) ^ m;
  ...
}
```

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void compute(int *mk, int m) {
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  int n = rand();

  *mk = (*mk ^ n) ^ m;
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}
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Evaluation reordering

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void compute(int *mk, int m) {
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Property not respected

Evaluation reordering

```
void compute(int *mk, int m) {
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  int n = rand();

  *mk = (*mk ^ n) ^ m;
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}
```

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```
void compute(int *mk, int m) {
  ...
  int n = rand();
  int tmp = *mk ^ n;
  *mk = tmp ^ m;
  ...
}
```

Use of temporary variable to fix evaluation order

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Temporary variable optimized out
+
Evaluation reordering

```
void compute(int *mk, int m) {
  ...
  int n = rand();
  int tmp = *mk ^ n;
  *mk = tmp ^ m;
  ...
}
```

```
void compute(int *mk, int m) {
  ...
  int n = rand();

  *mk = *mk ^ m ^ n;
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}
```

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void compute(int *mk, int m) {
  ...
  int n = rand();
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void compute(int *mk, int m) {
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Coding trick: *volatile* + *asm*

```
void compute(int *mk, int m) {
  ...
  int n = rand();
  int tmp = *mk ^ n;
  *mk = tmp ^ m;
  ...
}
```

```
void compute(int *mk, int m) {
  ...
  int n = rand();
  volatile int tmp = *mk ^ n;
  __asm__ __volatile__
        ("":::"memory");
  *mk = tmp ^ m;
  ...
}
```

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Coding trick: *volatile* + *asm*

Fragile and not portable:
***volatile int* may be ignored**

```
void compute(int *mk, int m) {
  ...
  int n = rand();
  int tmp = *mk ^ n;
  *mk = tmp ^ m;
  ...
}
```

```
void compute(int *mk, int m) {
  ...
  int n = rand();
  volatile int tmp = *mk ^ n;
  __asm__ __volatile__
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```
void compute(int *mk, int m) {
  ...
  int n = rand();
  int tmp = *mk ^ n;
  *mk = tmp ^ m;
  ...
}
```

How to reliably prevent the compiler from optimizing out *tmp* thus respect the evaluation order?

Background and Motivation: WYSINWYX phenomenon

- Needs for analysis and verification of binary programs [Balakrishnan and Reps, 2010] [Bréjon et al., 2019]

- Needs for program properties in the executable binaries (e.g. countermeasure oracles, ...) [Bréjon et al., 2019]

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⇒ Needs for preserving program properties throughout the optimizing compilation flow

Property Preservation Through Compilation: Outline

1. Definition of *property preservation through compilation*
2. Our approach to preserve program properties
3. Implementation of our approach in LLVM
4. Validation of our approach and implementation on security applications

Definitions

Functional Property

A functional property (*Prop*, *ObsPt*) is

- *Prop* a propositional logic formula expressing a program behavioral property
- *ObsPt* an observation point at which *Prop* is expected to hold

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  int tmp = *mk ^ n;
  here: PROP(tmp == *mk ^ n)
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  ...
}
```

Implicitly equivalent to
"Re-masking before De-masking"

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ObsPt ← here:

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ObsPt ***Prop***

Definitions

Functional Property and Partial State

A functional property (*Prop*, *ObsPt*) defines a partial state (*ObsPt*, *ObsVar*, *ObsMem*):

- *ObsPt* the observation point defined by the property

ObsPt ← here:

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void compute(int *mk, int m) {
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- *ObsVar* $= \{(var, val) \mid var$ observed variable occurring in *Prop*$\}$

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ObsPt

ObsVar:
{(tmp, 4860); (n, 5678)}

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}
```

ObsPt

ObsMem:
{(mk, 1234)}

ObsVar:
{(tmp, 4860); (n, 5678)}

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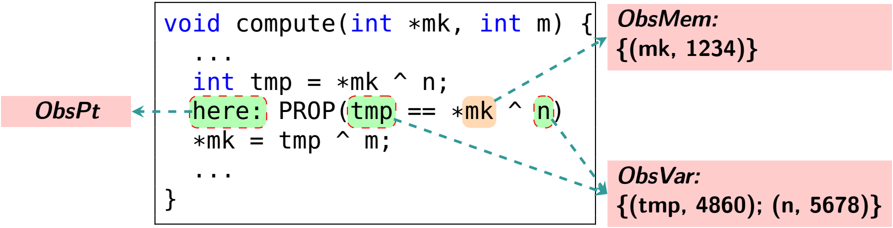

Partial State:
(*ObsPt*, *ObsVar*, *ObsMem*)

Definitions

Observation trace

An observation trace is

- the sequence of partial states defined by functional properties
- encountered during a given execution of the program

```c
int main() {
  ...
  compute(mk1, m1);
  compute(mk2, m2);
  compute(mk3, m3);
  ...
}
```

Observation trace:
...
@here: (tmp, 4860); (mk, 5678); (n, 1234)
@here: (tmp, 5171); (mk, 1234); (n, 4321)
@here: (tmp, 1029); (mk, 2187); (n, 3214)
...

Definitions

Functional Property Preservation

A transformation $\tau()$ preserves functional properties of program P if

- P and $\tau(P)$ produce equal observation traces given the same input
- for any input vector

Source Program

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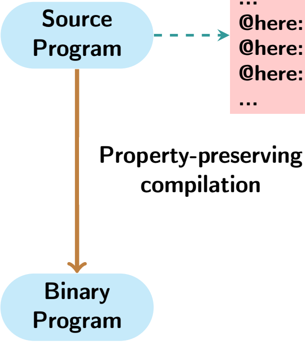

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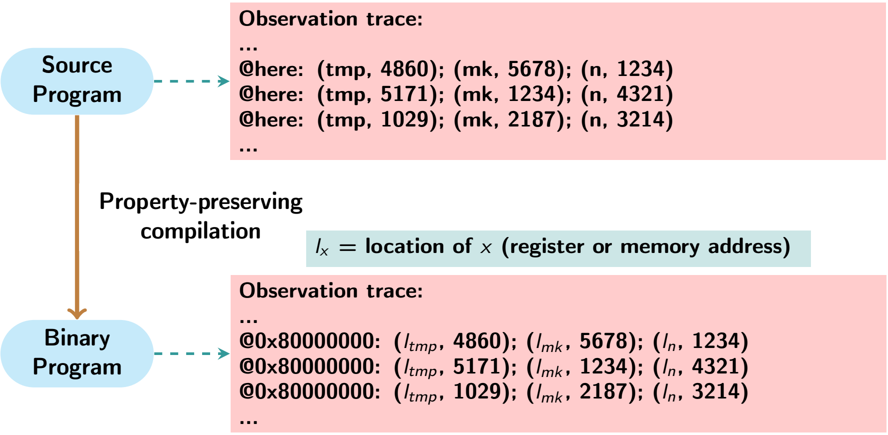

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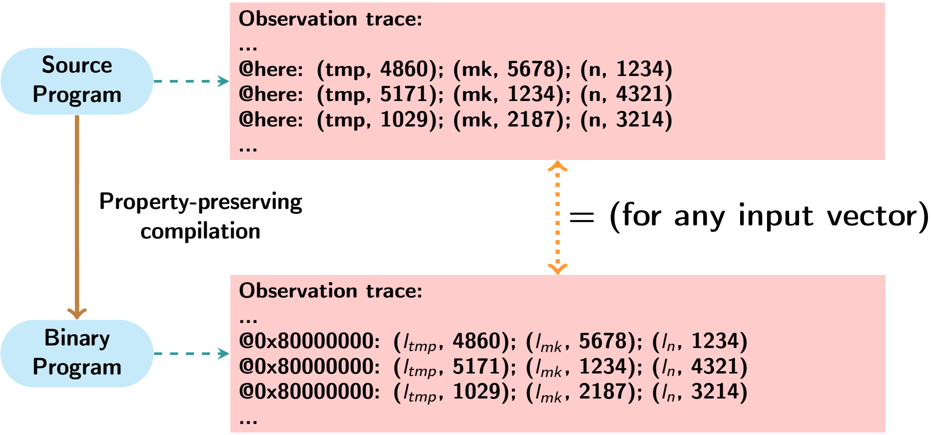
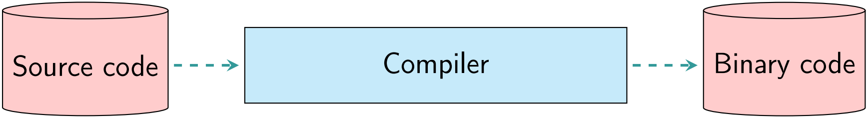


Preserving Properties Through Compilation: Overview



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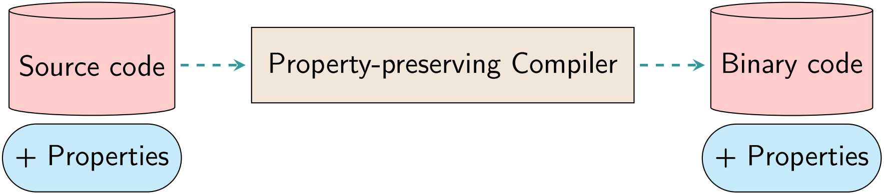

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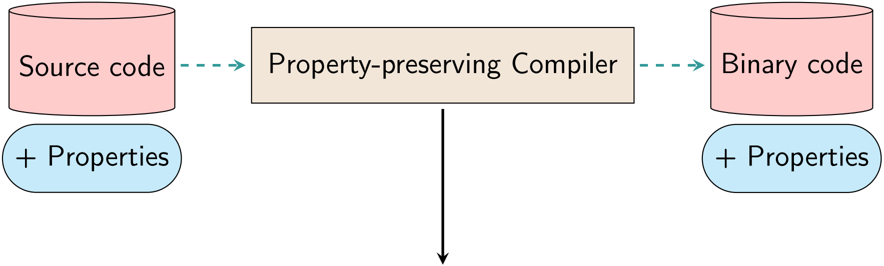

- Existing work: tuning optimization passes one-by-one to teach them about properties [Zarzani, 2013] [Namjoshi and Zuck, 2013] [Namjoshi, Tagliabue, and Zuck, 2013]

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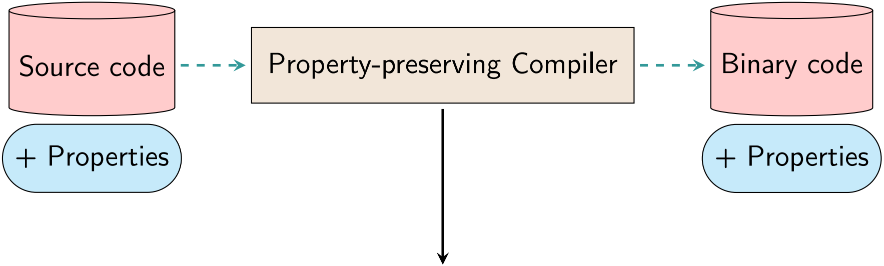

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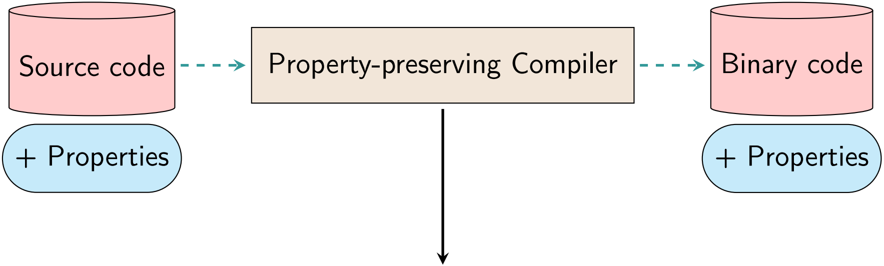

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⇒ can be implemented in a production compiler (LLVM)

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Preserving Properties Through Compilation: Our Approach

- Preserving Property = Preserving Partial State

```
void compute(int *mk, int m) {
  int n = 0;  // def 1
  ...
  n = rand(); // def 2
  int tmp = *mk ^ n;
  here: PROP(tmp == *mk ^ n)
  *mk = tmp ^ m;
  ...
  n = 42;  // def 3
  ...
}
```

Preserving Properties Through Compilation: Our Approach

- Preserving Property = Preserving Partial State
- Preserving Partial State = Preserving

```
void compute(int *mk, int m) {
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locations + values of observed variables

locations + values of observed memory locations

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locations + values of observed variables

locations + values of observed memory locations

an equivalent observation point (w.r.t. the observed entities)

Preserving Properties Through Compilation: Our Approach

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  ...
  n = 42;  // def 3
  ...
}
```


```
entry:
  %n1 = 0 ;SSA def 1
  ...
  %n2 = call rand() ;SSA def 2
  %mk1 = load %mk.addr
  %tmp1 = xor %mk1, %n2

  %mk2 = xor %tmp1, %m1
  ...
  %n3 = 42 ;SSA def 3
  ...
```

Preserving Properties Through Compilation: Our Approach

Preserve observed memory locations

memory-barrier, side-effecting: cannot be removed

```
entry:
  %n1 = 0 ;SSA def 1
  ...
  %n2 = call rand() ;SSA def 2

  %mk1 = load %mk.addr
  %tmp1 = xor %mk1, %n2

  call obs.pt(              ) ;tmp == *mk^n
  %mk2 = xor %tmp1, %m1
  ...
  %n3 = 42 ;SSA def 3
  ...
```

Preserving Properties Through Compilation: Our Approach

SSA variables to be preserved

```
entry:
  %n1 = 0 ;SSA def 1
  ...
  %n2 = call rand() ;SSA def 2

  %mk1 = load %mk.addr
  %tmp1 = xor %mk1, %n2

  call obs.pt(%n2 , %tmp1 ) ;tmp == *mk^n
  %mk2 = xor %tmp1, %m1
  ...
  %n3 = 42 ;SSA def 3
  ...
```

Preserving Properties Through Compilation: Our Approach

```
entry:
  %n1 = 0 ;SSA def 1
  ...
  %n2 = call rand() ;SSA def 2
  %n20 = call artificial.def(%n2)
  %mk1 = load %mk.addr
  %tmp1 = xor %mk1, %n20

  call obs.pt(%n20, %tmp1 ) ;tmp == *mk^n
  %mk2 = xor %tmp1, %m1
  ...
  %n3 = 42 ;SSA def 3
  ...
```

Preserving Properties Through Compilation: Our Approach

```
entry:
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  %n2 = call rand() ;SSA def 2
  %n20 = call artificial.def(%n2)
  %mk1 = load %mk.addr
  %tmp1 = xor %mk1, %n20
  %tmp10 = call artificial.def(%tmp1)
  call obs.pt(%n20, %tmp10) ;tmp == *mk^n
  %mk2 = xor %tmp10, %m1
  ...
  %n3 = 42 ;SSA def 3
  ...
```

Preserving Properties Through Compilation: Our Approach

opaque, side-effecting: cannot be analyzed or removed

```
entry:
  %n1 = 0 ;SSA def 1
  ...
  %n2 = call rand() ;SSA def 2
  %n20 = call artificial.def(%n2)
  %mk1 = load %mk.addr
  %tmp1 = xor %mk1, %n20
  %tmp10 = call artificial.def(%tmp1)
  call obs.pt(%n20, %tmp10) ;tmp == *mk^n
  %mk2 = xor %tmp10, %m1
  ...
  %n3 = 42 ;SSA def 3
  ...
```

Preserving Properties Through Compilation: Our Approach

must be kept through the whole compilation flow, removed during code emission: no interference with original program

```
entry:
  %n1 = 0 ;SSA def 1
  ...
  %n2 = call rand() ;SSA def 2
  %n20 = call artificial.def(%n2)
  %mk1 = load %mk.addr
  %tmp1 = xor %mk1, %n20
  %tmp10 = call artificial.def(%tmp1)
  call obs.pt(%n20, %tmp10) ;tmp == *mk^n
  %mk2 = xor %tmp10, %m1
  ...
  %n3 = 42 ;SSA def 3
  ...
```

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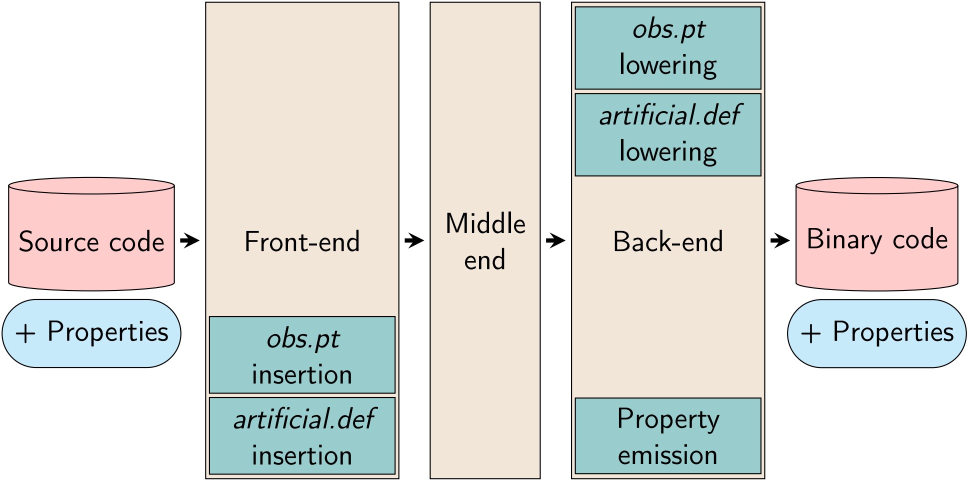
Preserving Properties Through Compilation: LLVM flow



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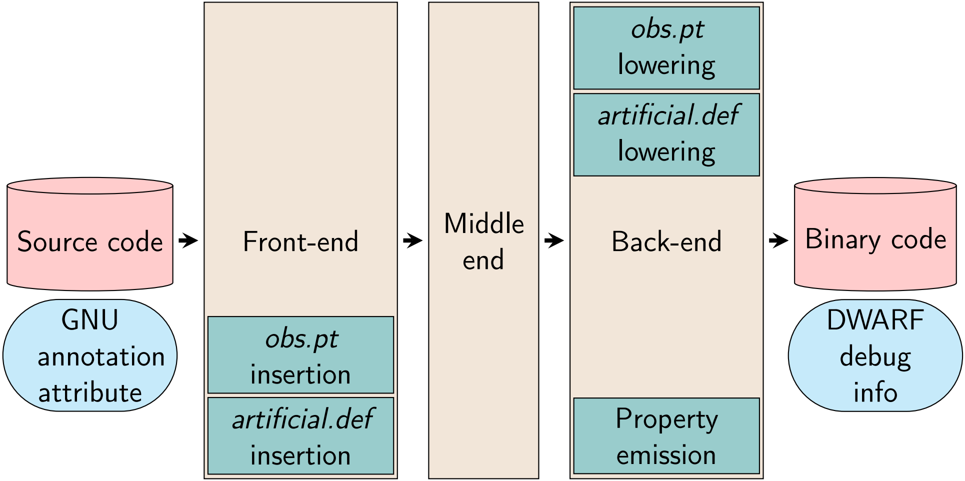

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Property Preservation Validation: Outline

1. General Validation Methodology
2. Validation on Functional Properties
3. Validation on Security Properties
4. Performance Overhead Evaluation

Experimental Validation Methodology

Property preservation = Equality of observation traces

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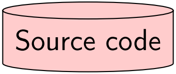

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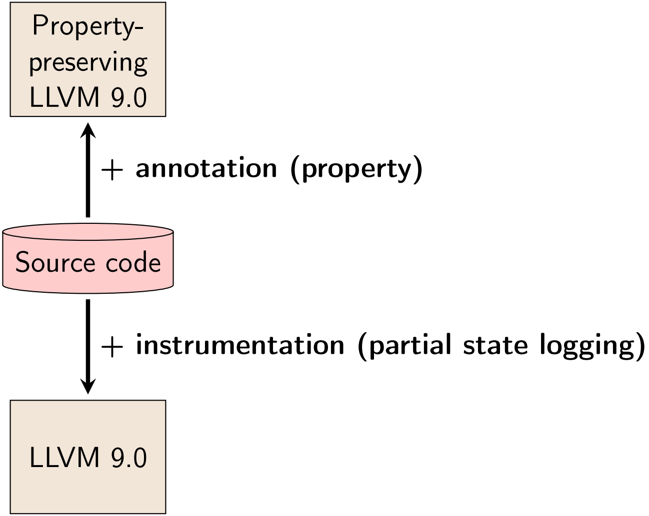
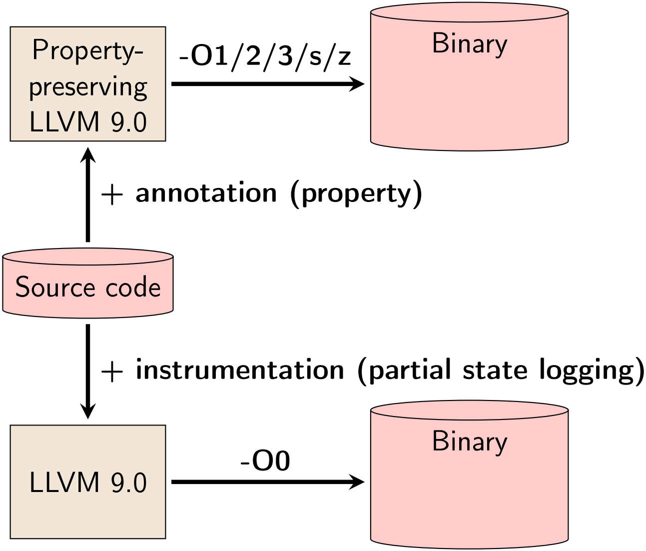


Experimental Validation Methodology

Property preservation = Equality of observation traces



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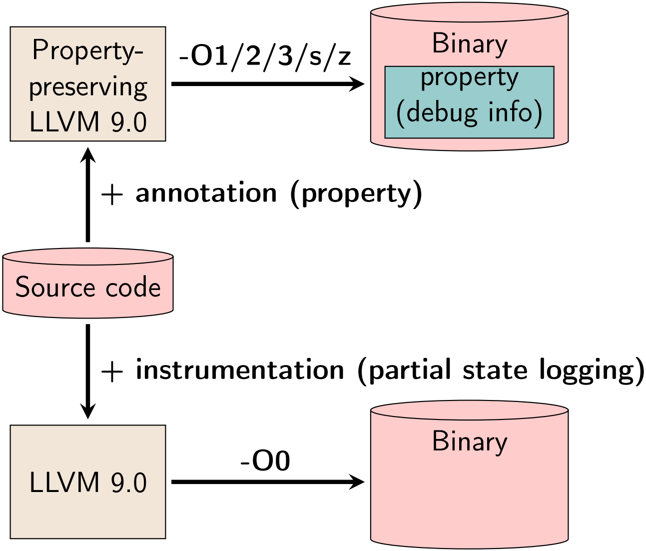

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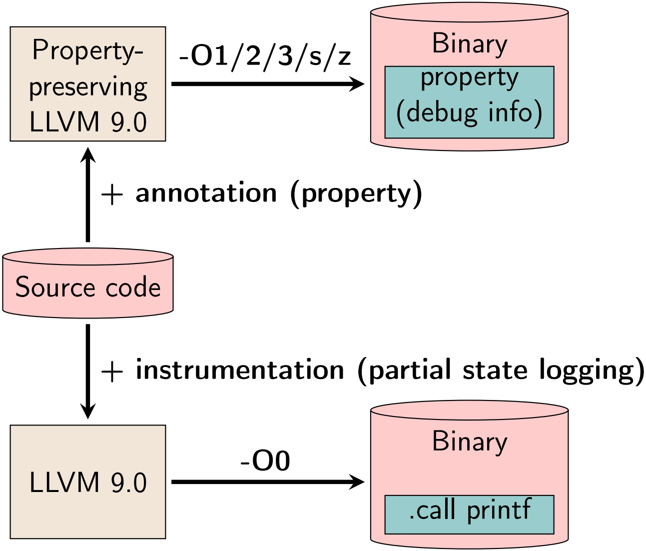

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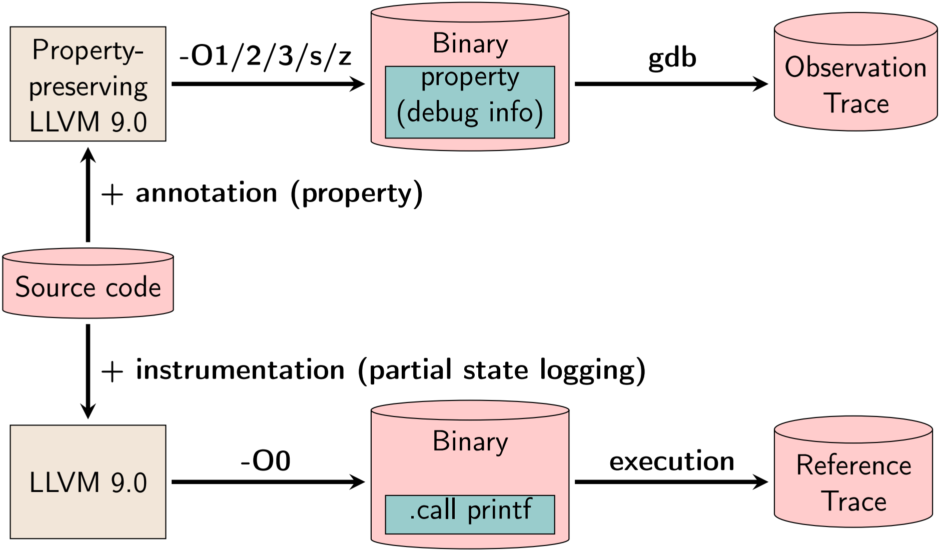

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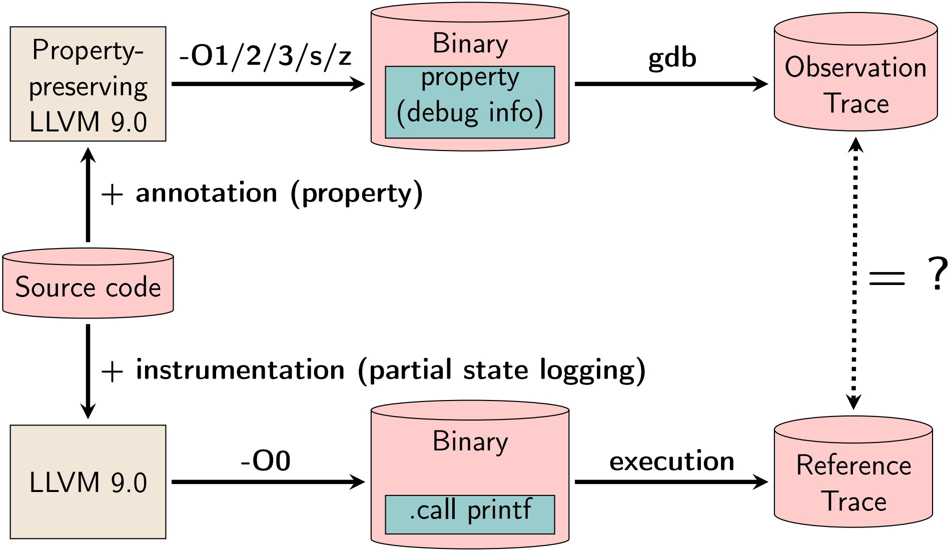
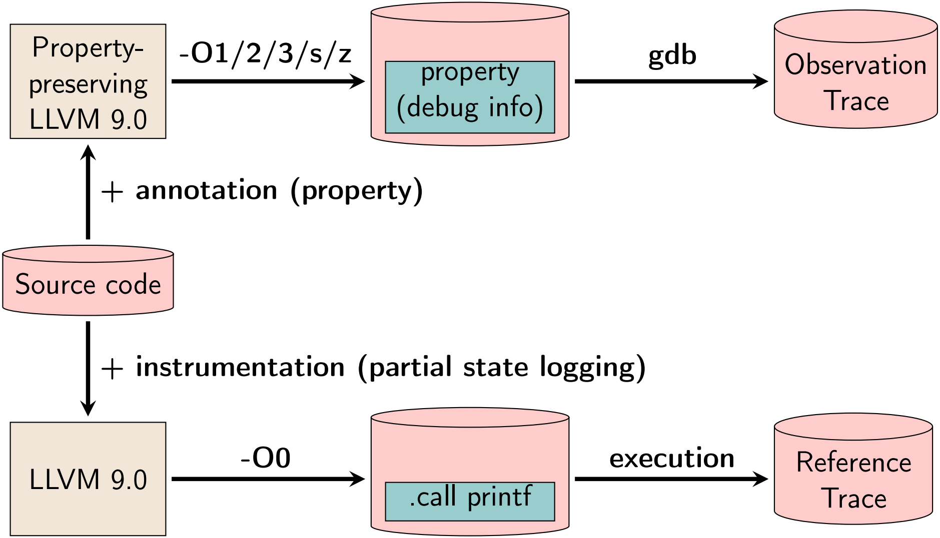
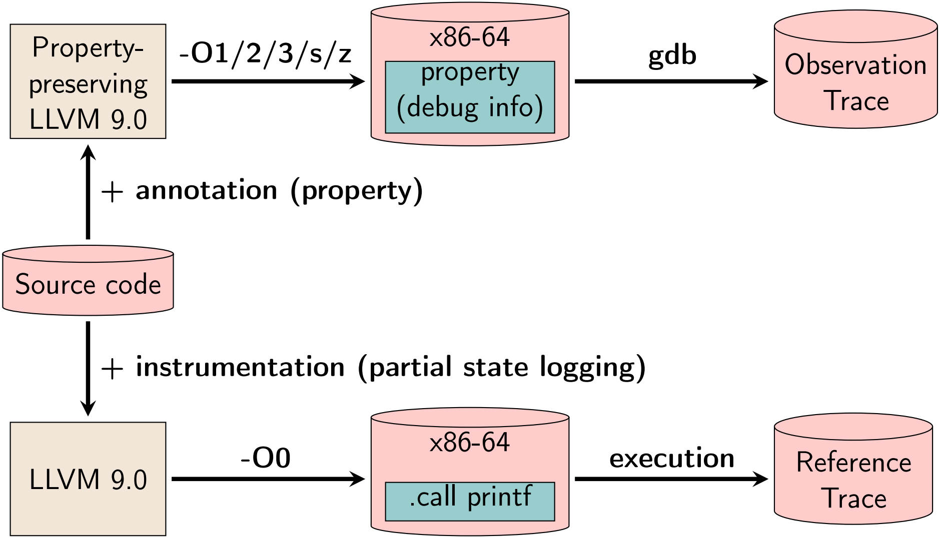


Functional Validation

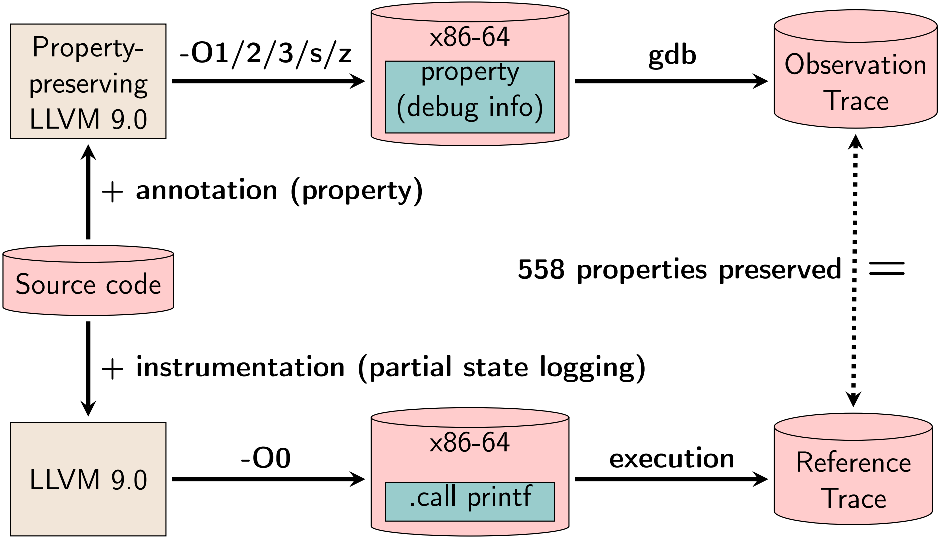
- Goal: propagating functional properties used for program static analysis from source to binary level
- Programs from *Framework for Modular Analysis of C programs* (Frama-C) test suite [Cuoq et al., 2012]
- 558 functional properties (C boolean expressions), verifying expected values of variables at a given program point

Functional Validation




Property-preserving LLVM 9.0
-O1/2/3/s/z
x86-64
property (debug info)
gdb
Observation Trace
+ annotation (property)
Source code
+ instrumentation (partial state logging)
LLVM 9.0
-O0
x86-64
.call printf
execution
Reference Trace

Functional Validation



Application to Security Properties

Considered properties:

Attack			
Protection			
Property			

Application to Security Properties

Considered properties:

Attack	Side-channel		
Protection	Masking of secret data		
Property	Instruction ordering in masking operations		

Application to Security Properties

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Attack	Side-channel	Data remanence	
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Application to Security Properties

Considered properties:

Attack	Side-channel	Data remanence	Fault injection	
Protection	Masking of secret data	Inserting code to erase secret data	Inserting redundant data and/or protection code	
Property	Instruction ordering in masking operations	Presence of secret memory data erasure	Interleaving of functional and protection code	Presence of redundant data detecting fault injections

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⇒ these security properties are non-functional (refer to notions not clearly defined in the source program semantics)

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⇒ these security properties are non-functional (refer to notions not clearly defined in the source program semantics)

⇒ preserving source-level protections by forcibly observing its variables at specific program points

Application to Security Properties

- Defining new predicate *observe(v)* which includes *v* into the partial state to be preserved

```
void compute(int *mk, int m) {
  int n = 0;  // def 1
  ...
  n = rand(); // def 2
  int tmp = *mk ^ n;
  here: PROP(observe(tmp))
  *mk = tmp ^ m;
  ...
  n = 42;  // def 3
  ...
}
```

Proper Interleaving of Functional code and Protection

A source-level countermeasure against fault attacks altering the program control flow [Lalande, Heydemann, and Berthomé, 2014]

```
if (cond) {
  stmt1

  stmt2

}
```

Proper Interleaving of Functional code and Protection

A source-level countermeasure against fault attacks altering the program control flow [Lalande, Heydemann, and Berthomé, 2014]

```
int cnt_if = 0;
if (cond) {
  stmt1

  stmt2

}
```

1. Defining step counter at each control construct

Proper Interleaving of Functional code and Protection

A source-level countermeasure against fault attacks altering the program control flow [Lalande, Heydemann, and Berthomé, 2014]

```
int cnt_if = 0;
if (cond) {
  stmt1
  cnt_if++;
  stmt2
  cnt_if++;
}
```

1. Defining step counter at each control construct

2. Incrementing step counter after *every* C statement of the construct

Proper Interleaving of Functional code and Protection

A source-level countermeasure against fault attacks altering the program control flow [Lalande, Heydemann, and Berthomé, 2014]

```
int cnt_if = 0;
if (cond) {
  stmt1
  cnt_if++;
  stmt2
  cnt_if++;
}
if (cond && cnt_if != 2)
  exception_handler();
```

1. Defining step counter at each control construct

2. Incrementing step counter after *every* C statement of the construct

3. Checking counters against their expected values at the end of the construct, calling exception handler when it fails

Proper Interleaving of Functional code and Protection

A source-level countermeasure against fault attacks altering the program control flow [Lalande, Heydemann, and Berthomé, 2014]

```
int cnt_if = 0;
if (cond) {
  stmt1
  cnt_if++;
  stmt2
  cnt_if++;
}
if (cond && cnt_if != 2)
  exception_handler();
```

```
int cnt_if = 0;
if (cond) {
  stmt1
  stmt2
  cnt_if += 2;
}
```

Optimizations will remove counter checks and group counter incrementations

Proper Interleaving of Functional code and Protection

A source-level countermeasure against fault attacks altering the program control flow [Lalande, Heydemann, and Berthomé, 2014]

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int cnt_if = 0;
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```
int cnt_if = 0;
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  stmt1
  stmt2
  cnt_if += 2;
}
```

Optimizations will remove counter checks and group counter incrementations

Traditional secure approach: compiling at `-O0` (disabling optimizations)

Proper Interleaving of Functional code and Protection

Our approach based on property preservation:

```
int cnt_if = 0;
if (cond) {
  stmt1

  cnt_if++;
  stmt2

  cnt_if++;
}
if (cond && cnt_if != 2)
  exception_handler();
```

Proper Interleaving of Functional code and Protection

Our approach based on property preservation:

```
int cnt_if = 0;
if (cond) {
  stmt1
  here1: PROP(observe(cnt_if))
  cnt_if++;
  stmt2
  here2: PROP(observe(cnt_if))
  cnt_if++;
}
if (cond && cnt_if != 2)
  exception_handler();
```

1. Observe counter before incrementation to prevent optimizations from removing it

Proper Interleaving of Functional code and Protection

Our approach based on property preservation:

```
int cnt_if = 0;
if (cond) {
  stmt1
  here1: PROP(observe(cnt_if, cond, ...))
  cnt_if++;
  stmt2
  here2: PROP(observe(cnt_if, cond, ...))
  cnt_if++;
}
if (cond && cnt_if != 2)
  exception_handler();
```

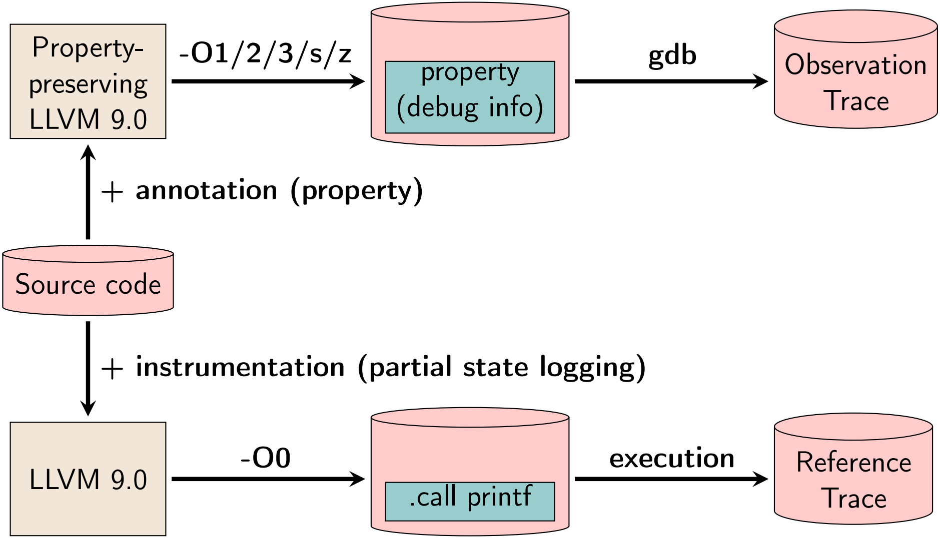
1. Observe counter before incrementation to prevent optimizations from removing it

2. Observe all variables + memory locations to guarantee the proper interleaving of functional code and incrementation

Security Property Preservation Validation

Attack	Side-channel	Data remanence	Fault injection	
Protection	Masking of secret data	Inserting code to erase secret data	Inserting redundant data and/or protection code	
Property	Instruction ordering in masking operations	Presence of sensitive memory data erasure	Interleaving of functional and protection code	Presence of redundant data detecting fault injections
Application	aes-herbst	rsa-encrypt	pin-sci	loop-redundant
		rsa-decrypt	aes-sci	

Security Property Preservation Validation



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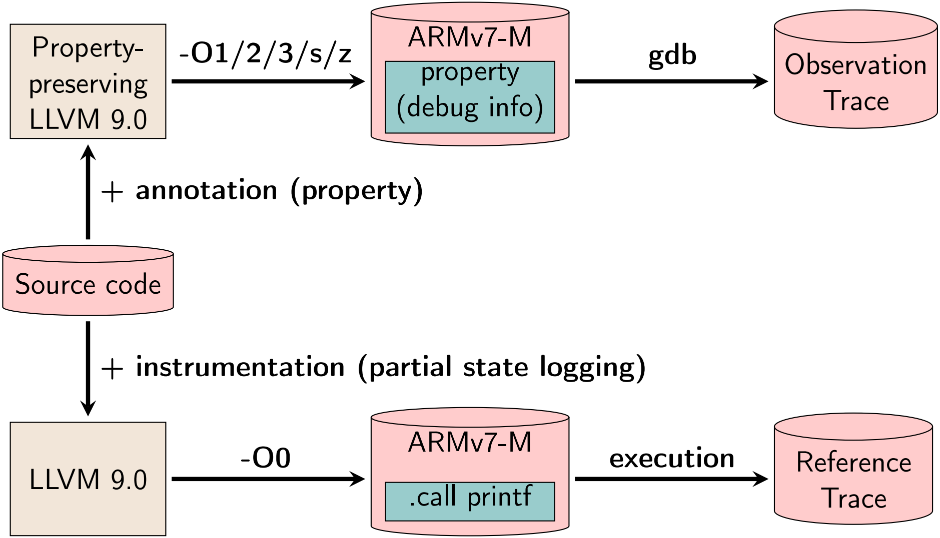

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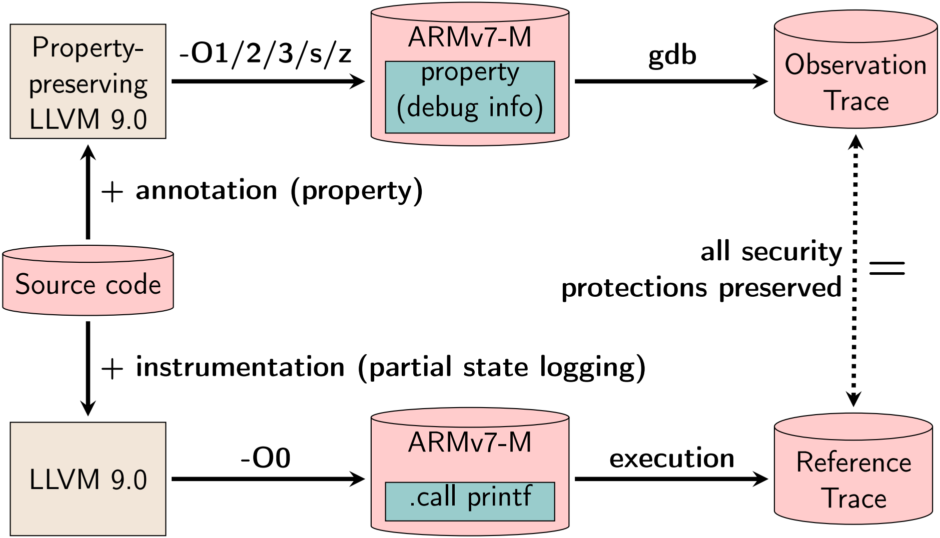

Performance Evaluation

Is the performance penalty due to blocking some optimizations acceptable?

Attack	Side-channel	Data remanence	Fault injection	
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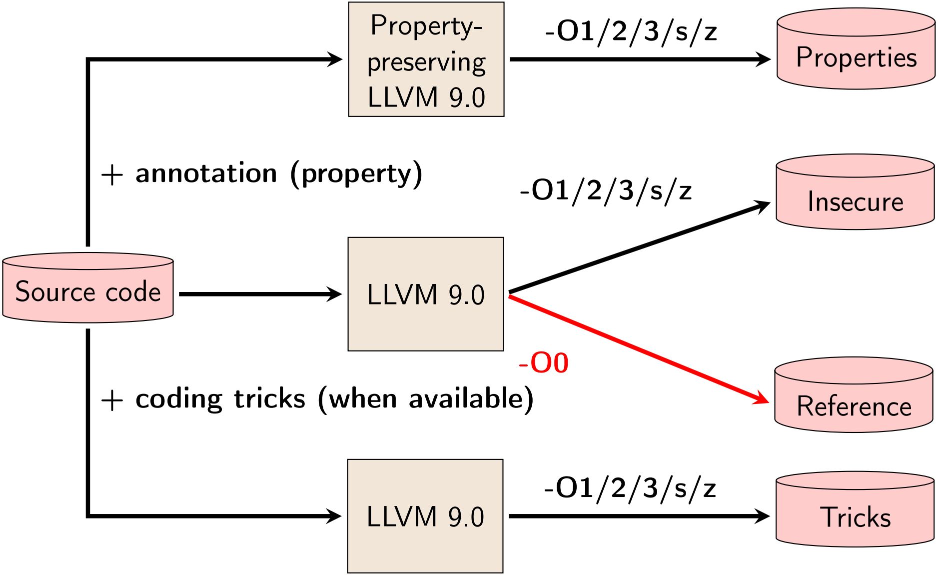
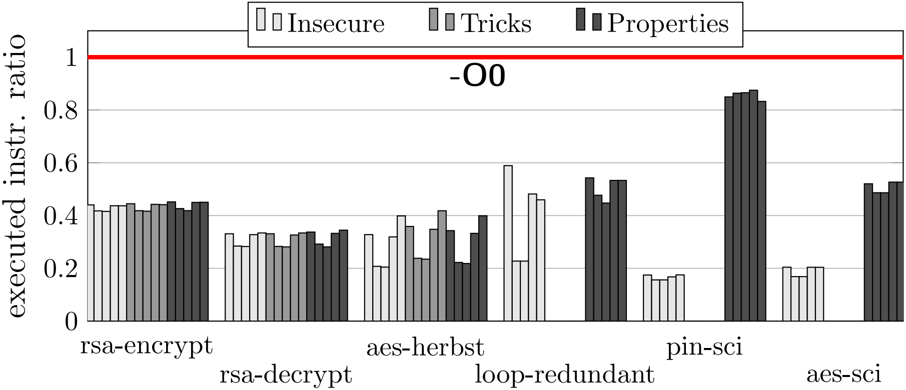
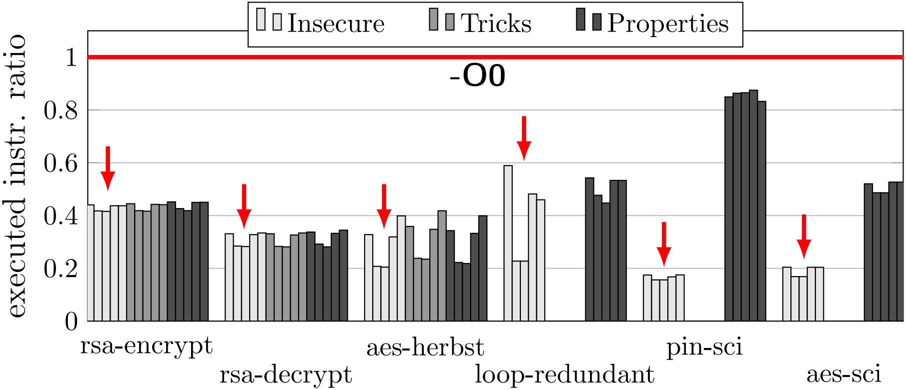
Application	aes-herbst	rsa-encrypt	pin-sci	loop-redundant
		rsa-decrypt	aes-sci	


Property-
preserving
LLVM 9.0
-O1/2/3/s/z
Properties
+ annotation (property)
-O1/2/3/s/z
Insecure
Source code
LLVM 9.0
-O0
Reference
+ coding tricks (when available)
LLVM 9.0
-O1/2/3/s/z
Tricks

Performance Evaluation

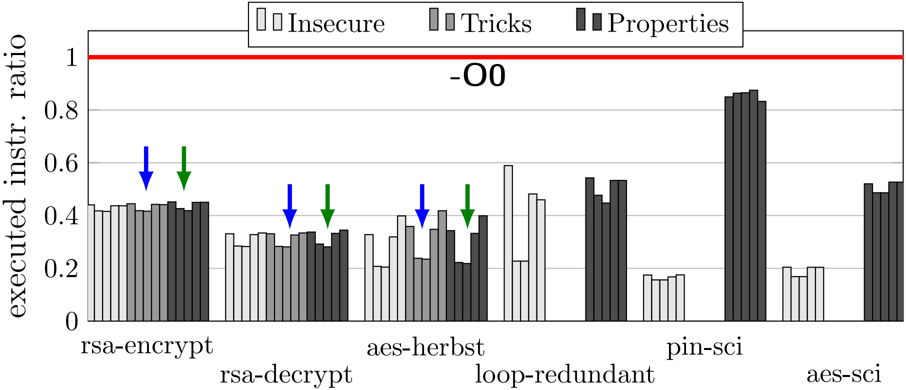


Performance Evaluation



- Insecure: fastest executables but protections are modified or removed when optimizations enabled

Performance Evaluation



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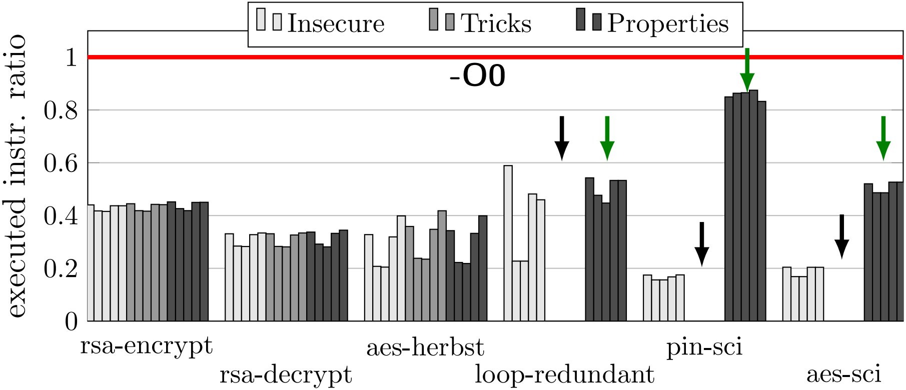
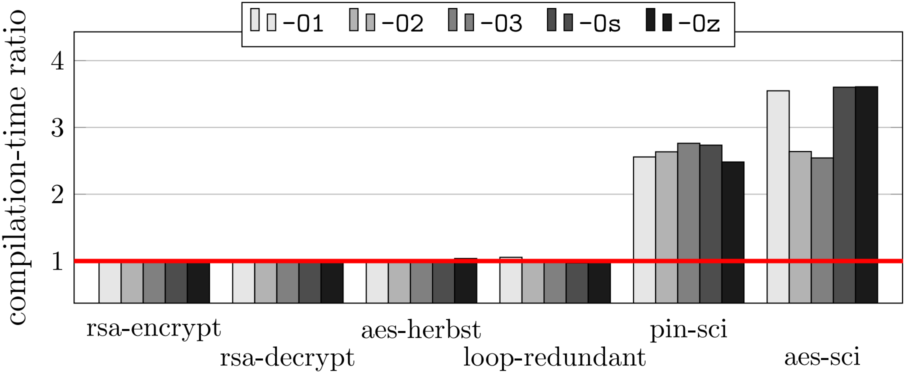


- Insecure: fastest executables but protections are modified or removed when optimizations enabled
- Properties **preserve** source-level protections
  - with similar performance compared to fragile tricks
  - with performance improvement over programs compiled at `-O0` when no trick exists

Conclusion

- Mechanism to preserve functional properties through optimizing compilation, enabling automated analyses and verifications at binary level [Bréjon et al., 2019]
- Application to preserving source-level protections
- Current work: formalization of a lightweight approach to preserve security protections, based on data-dependence.
- Perspective: contribute this work to the community, graduate and get a position!

Compilation-time Evaluation



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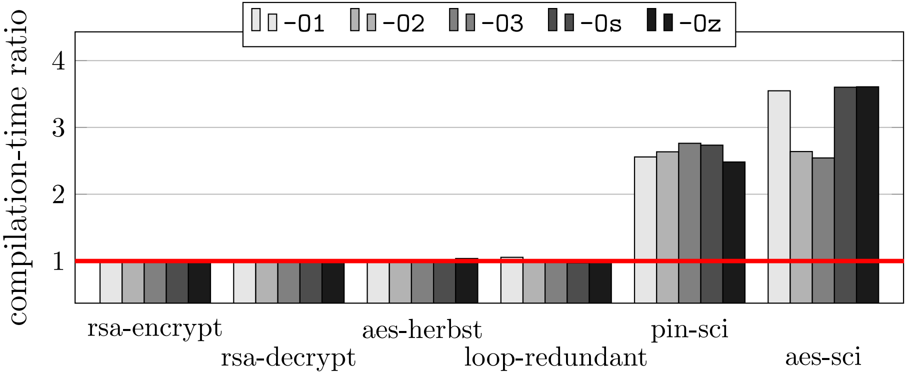

- Compilation-time overhead compared to the original program compiled with the same optimization flag
- High overhead for step counter incrementation protection

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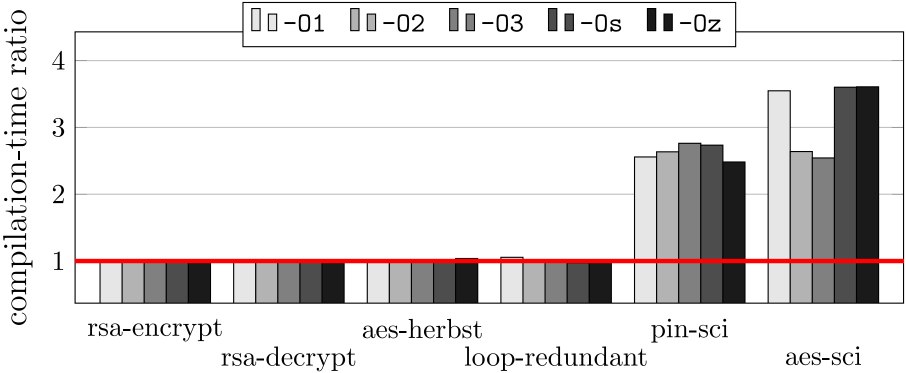

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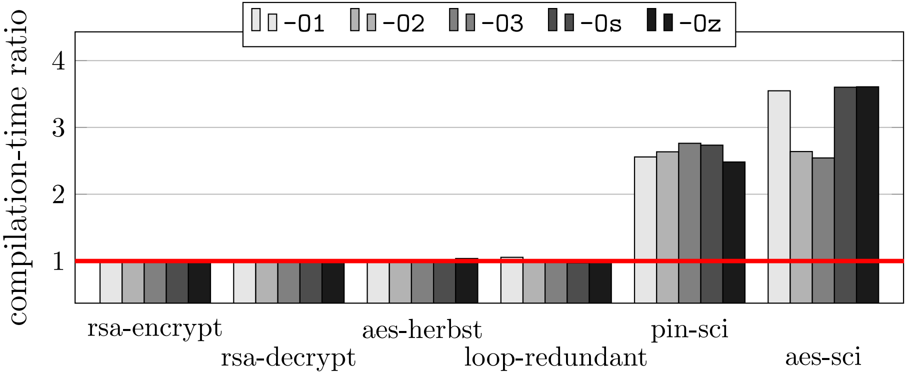

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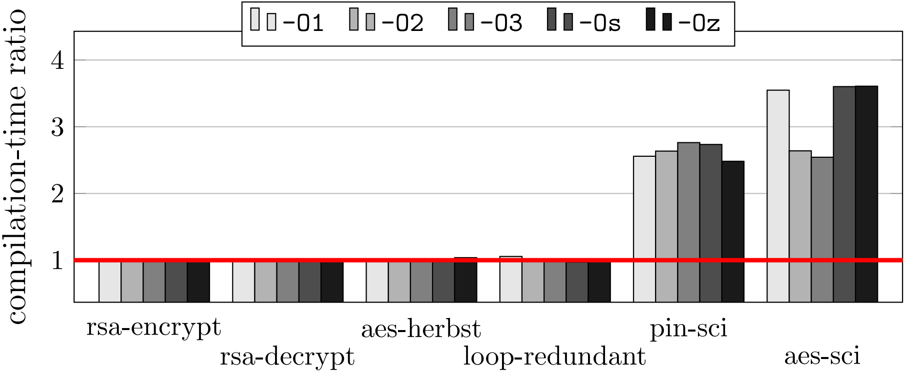

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$\Rightarrow$ worst-case scenario for our approach

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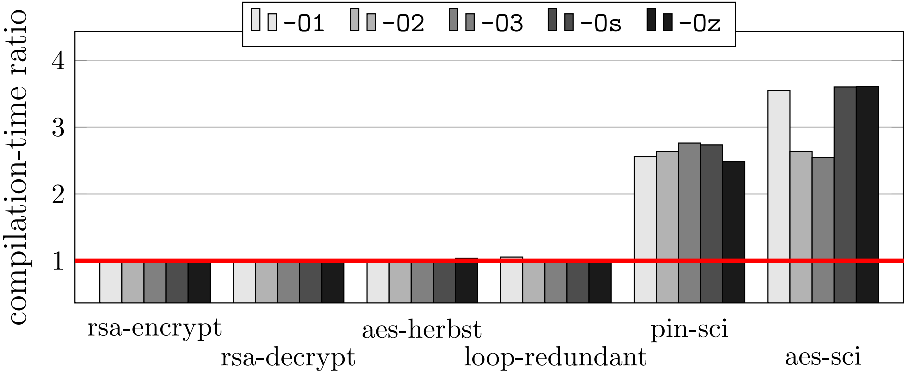

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  ⇒ worst-case scenario for our approach

⇒ price worth paying for preserving source-code protections