Secure Compilation (?)

Øresund Security Days

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Compilers introduce vulnerabilities!

Preservation of semantic correctness

- Lots of work have been done on semantic preservation of compilers
- CompCert, Vellvm, CakeML, etc.

Gap between correctness and security [D'Silva et al., SPW15]

- Correctness is not enough
- Does not guarantee preservation of security properties enforced at source level
- Compilation may
  - Introudce timing channels in carefuylly crafted constant-time code,
  - remove security-critical instructions.

Information-Flow Preservation

- Programs deal with sensitive data that we do not want to reveal
- Security guideline: "do not store secret data longer than necessary".
- But what would a moderately intelligent compiler do with this code?

```
crypt(key, t):
   c = key ^ t
   key = 0
   return c
```

Information-Flow Preservation

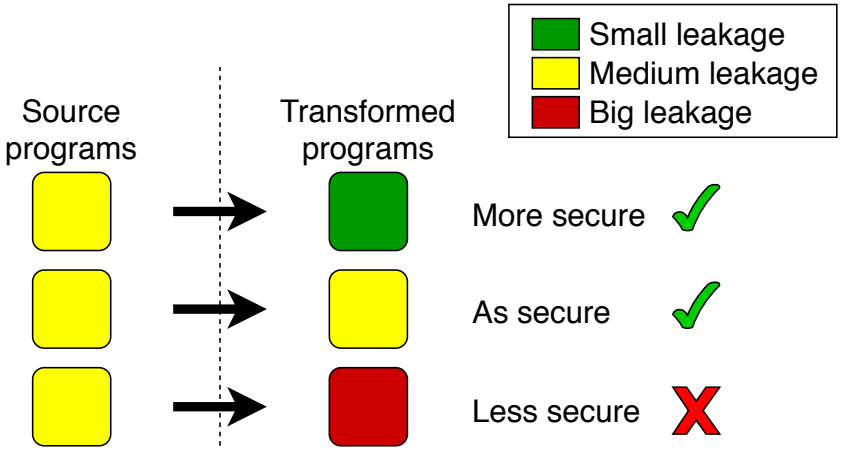
- Current programs deal with sensitive data that we do not want to leak
- Protections are not always preserved during compilation
- Simple example of *Dead Store Elimination*

```
crypt(key, t):
   c = key ^ t
   key = 0
   return c
```

```
crypt(key, t):
   c = key ^ t
   Skip
   return c
```

Preservation and not enforcement

- Our goal is not to produce secure programs
- Transformed programs should be at least as secure as their source



Our work

Objective

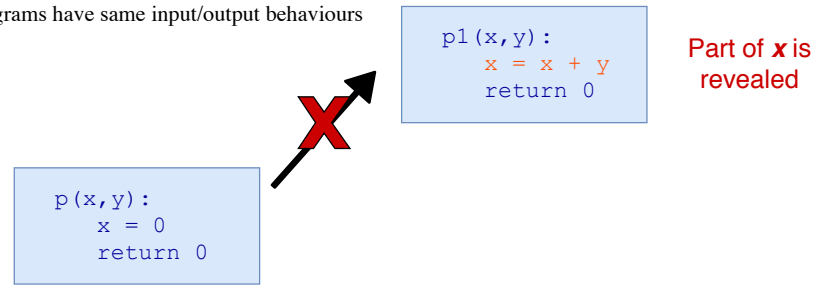
Preventing a transformed program from leaking more information
than the source program

Content of the talk

- Formal definition of an IFP* transformation
- Proof technique to certify that a transformation is IFP
- Application to two compiler transformations
  - Secure *Dead Store Elimination*
  - Validator for *Register Allocation* *Information Flow Preserving

Getting familiar with IFP

The programs have same input/output behaviours



Part of ***x*** is revealed

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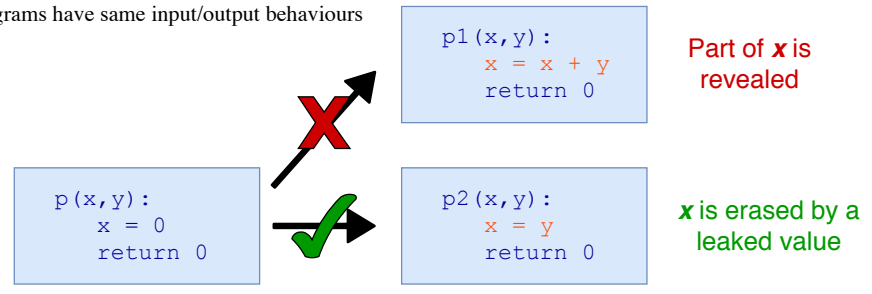

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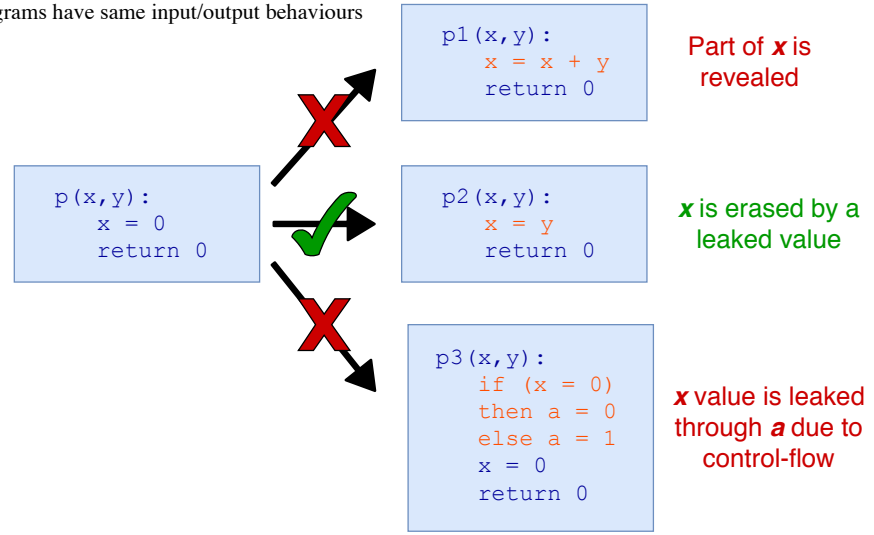

Part of ***x*** is revealed

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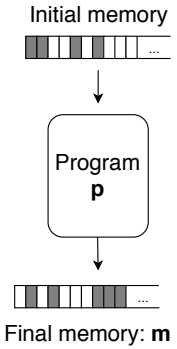
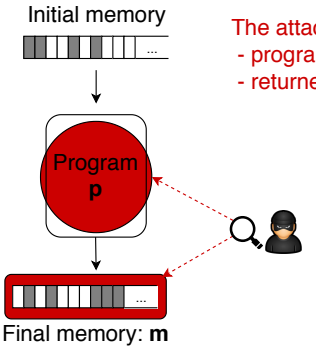
x value is leaked through ***a*** due to control-flow

Execution model

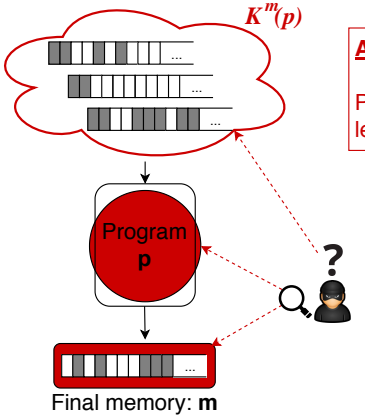


Attacker model



The attacker observes:
- program code
- returned memory

Attacker knowledge [Askarov and Sabelfeld, CSF12]



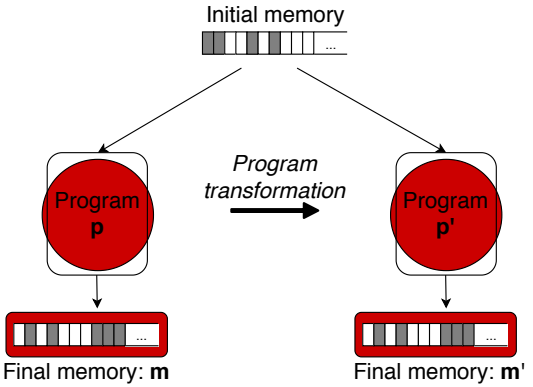
Attacker knowledge

Possible initial memories leading to the final memory ***m***

Attacker knowledge [Askarov and Sabelfeld, CSF12]

IFP transformation

p' is at least as secure as p iff:



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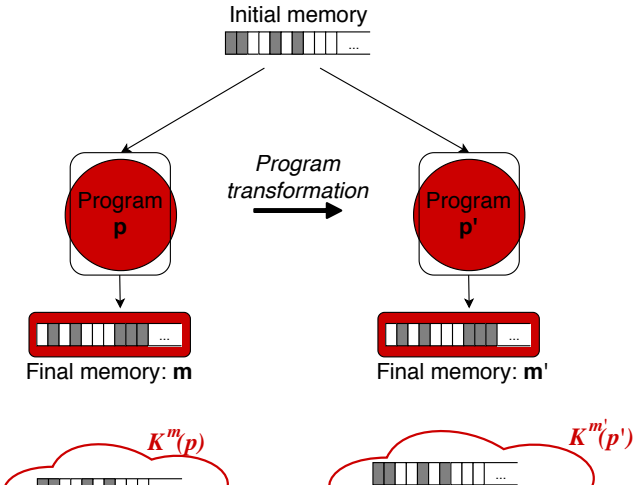
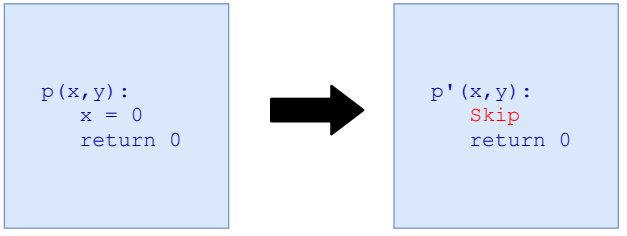


Is it the right definition? (1/2)

- We want to reject this transformation from p to p'
- We need to find a counter-example to IFP where $\mathcal{K}^m(p) \not\sim \mathcal{K}^{m'}(p')$



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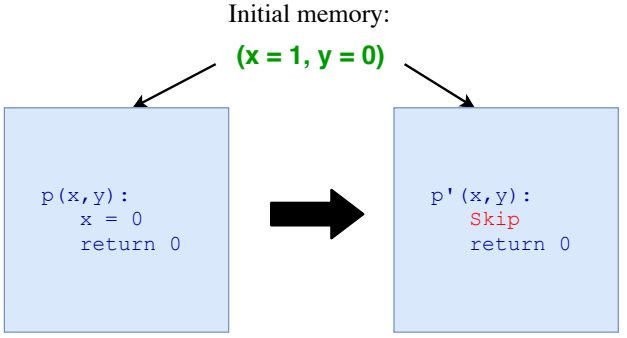

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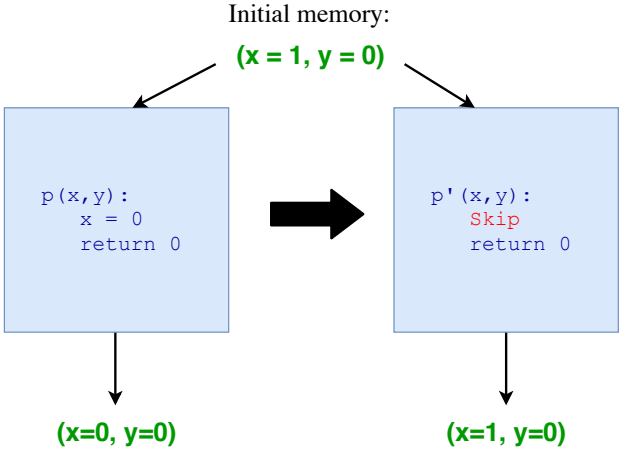

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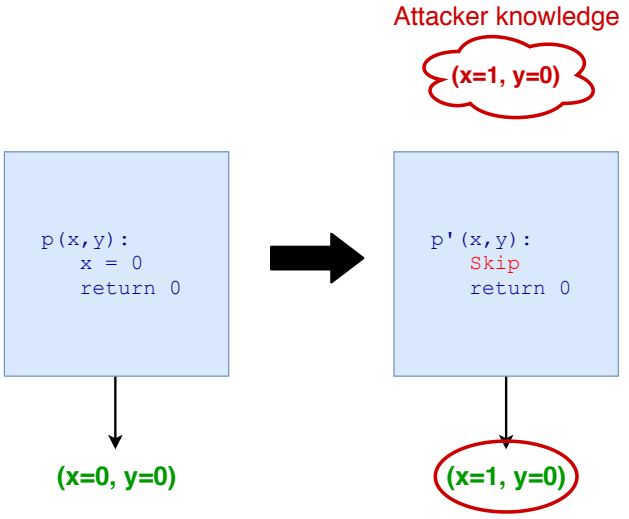

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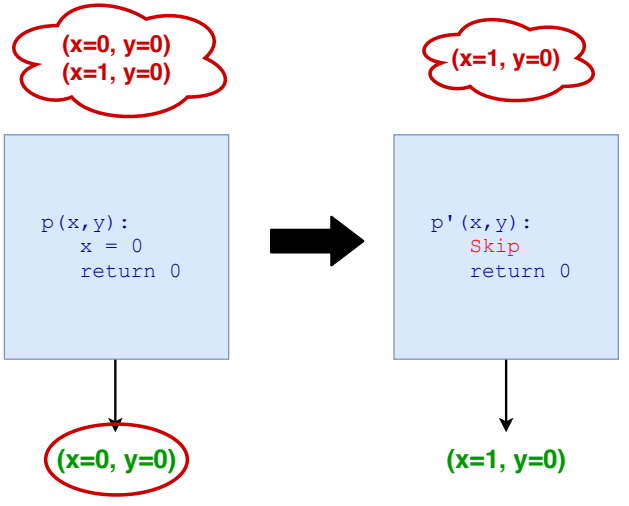

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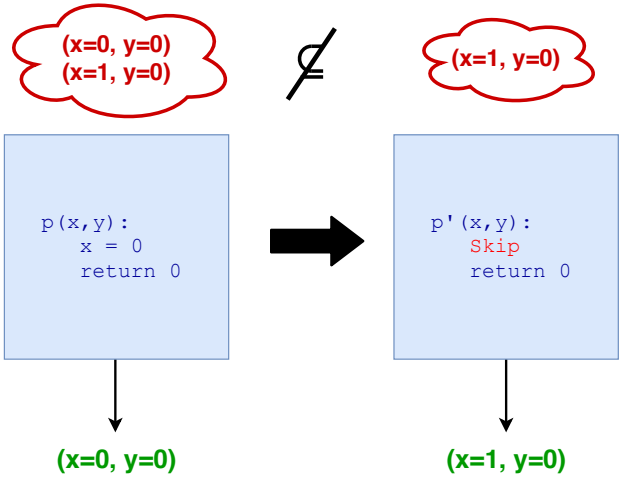

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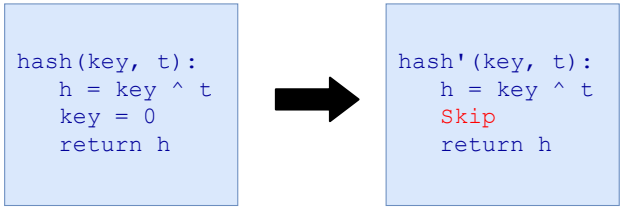

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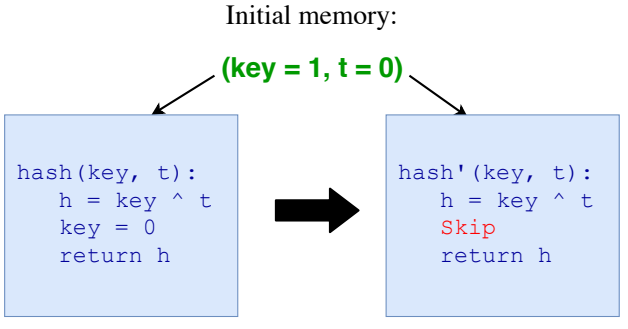

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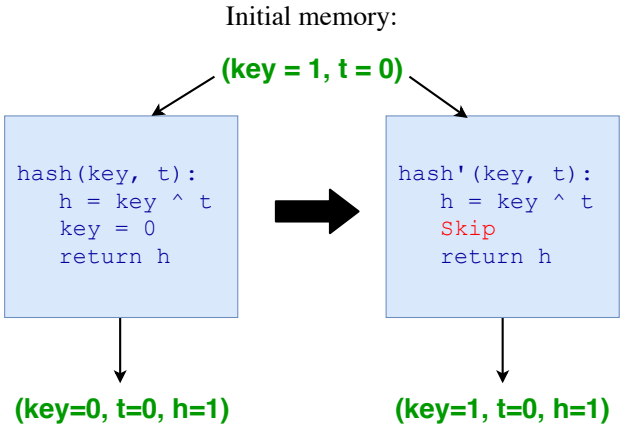

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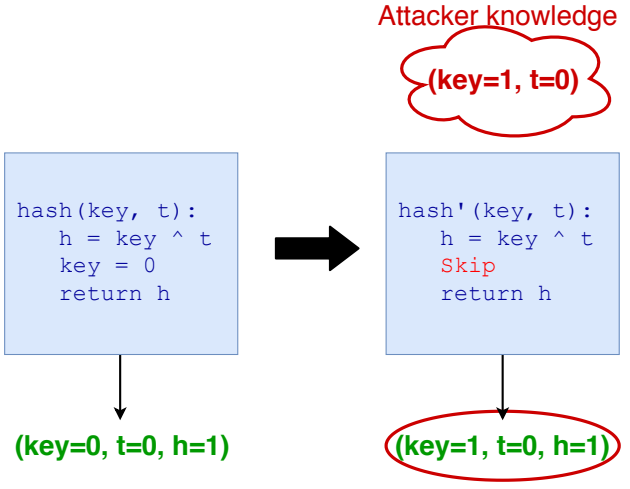

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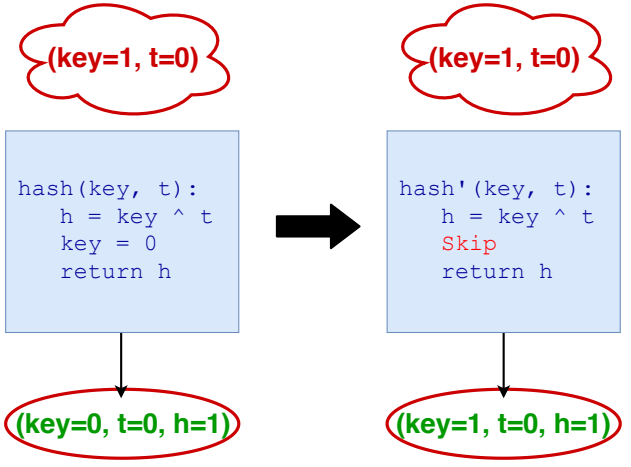

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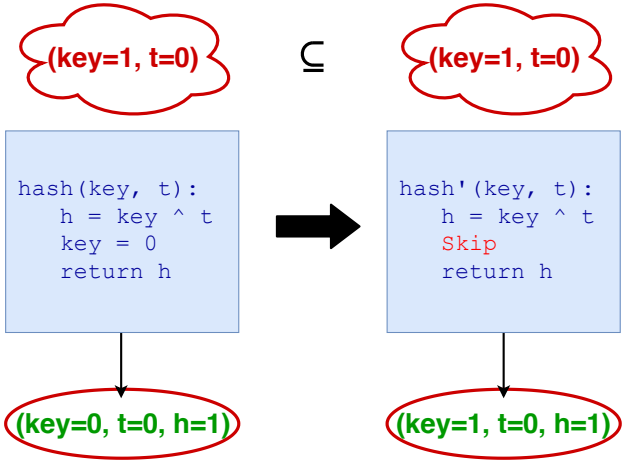

Choosing the right adversary

Imagine that you are appointed manager of the DTU football team ...

Choosing the right adversary

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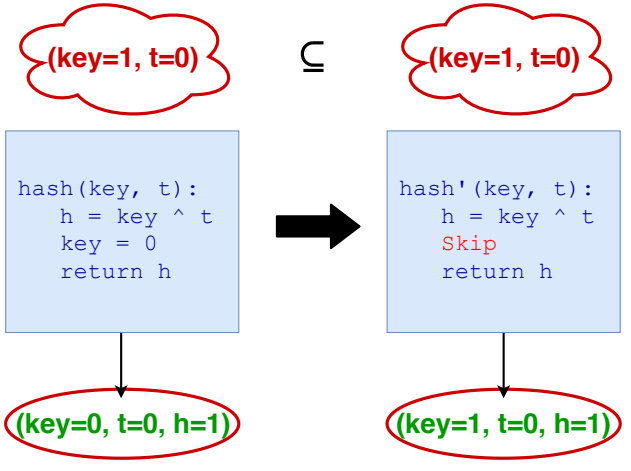
A good choice of adversary?

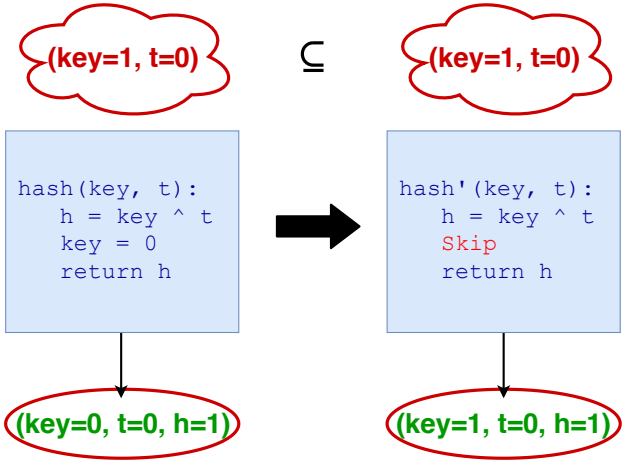
Shortcomings of the current model

- Leakage is the same in *hash'* and *hash* but is easier to obtain in *hash'*
- Our attacker is **not precise enough** and does not capture the subtelty

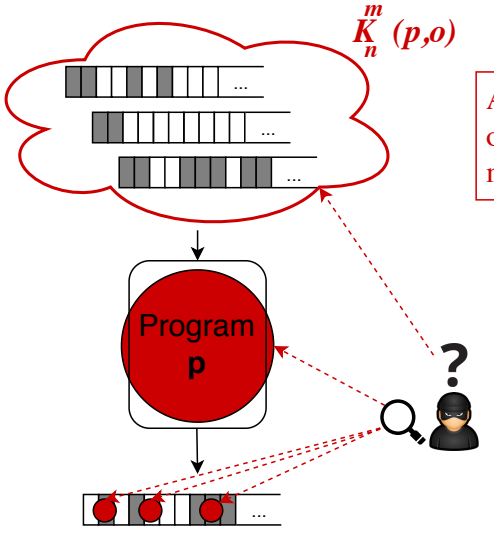


Shortcomings of the current model

- Leakage is the same in *hash'* and *hash* but is easier to obtain in *hash'*
- Our attacker is **too powerful** and does not capture the subtelty
- **We add attackers with smaller observation power**



Partial Attacker Knowlege

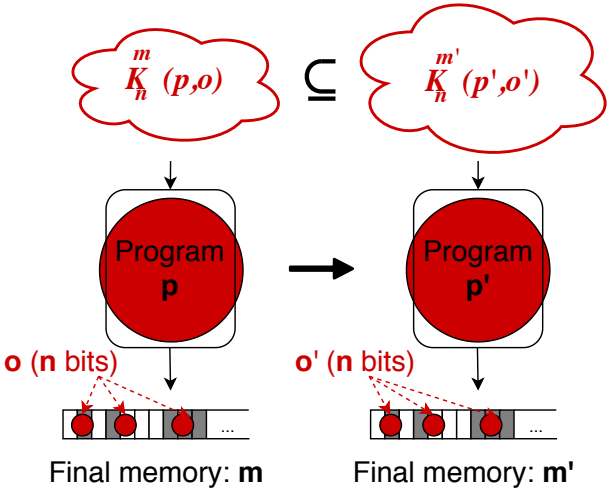


A partial attacker makes an observation **o** of **n** bits on the final memory **m**

Remark

Partial attacker knowledge with observation power $\mathbf{n} \rightarrow \infty$ is the same as attacker knowledge

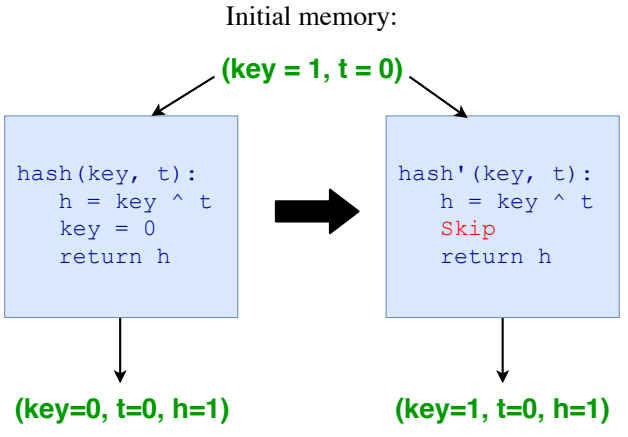
New Security Relation



Secure Relation

Back to our example

- We want to reject this transformation from $hash$ to $hash'$
- We need a counter-example to IFP where $\forall o.\ K_{\sim}^{m}(p, o) \not\subset K_{\sim}^{m'}(p', o')$



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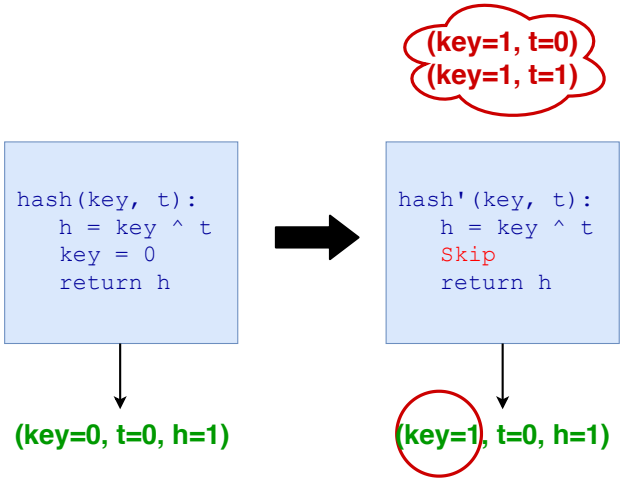

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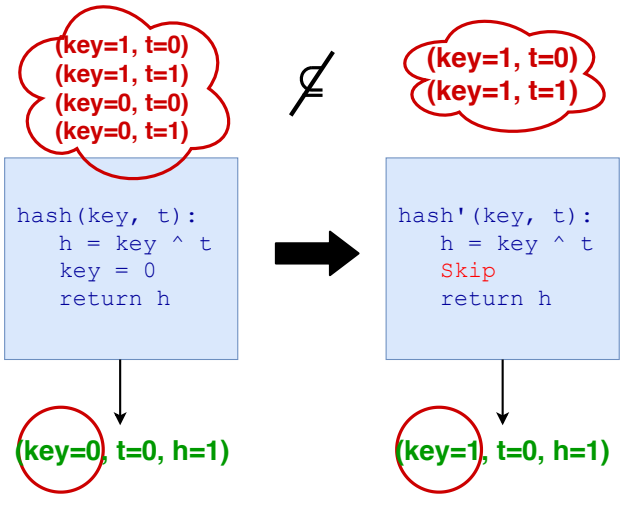

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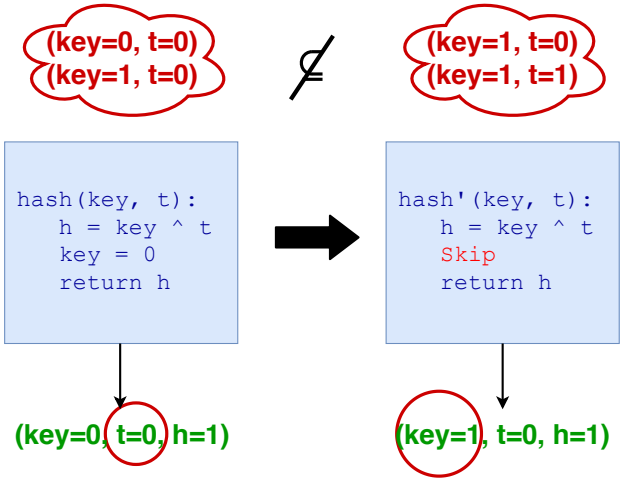

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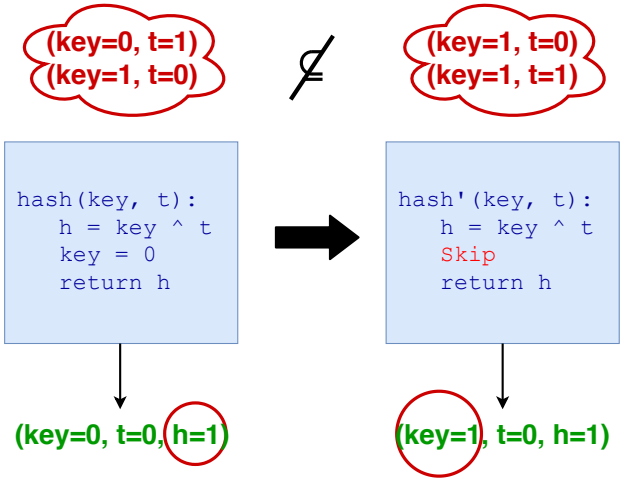


Using our IFP definition

Proof technique

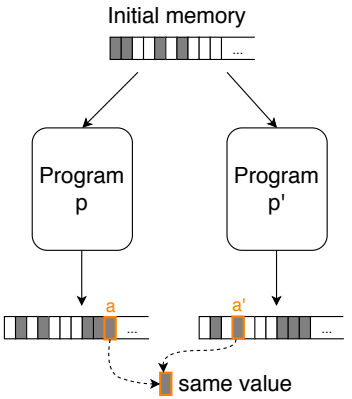
- Introduction of a proof technique to prove that a transformation is IFP

Application

Demonstration of our proof technique on two compiler transformations:

1. secure *Dead Store Elimination*
2. validator for *Register Allocation*

Proof technique

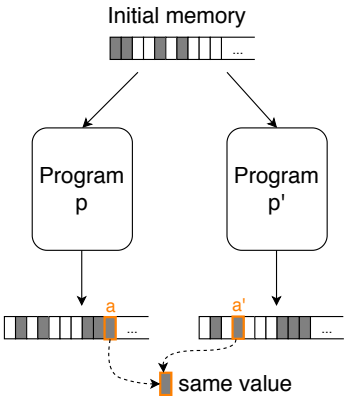


Matching addresses

Values at addresses a and a' are always equal in the final memories:

$$\_ \_ \_ \_'$$

Proof technique



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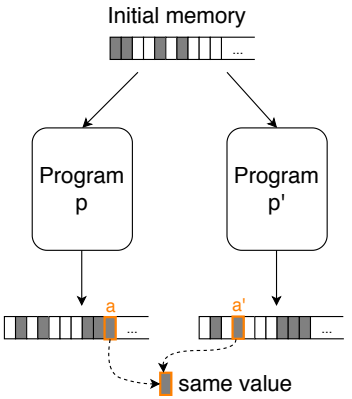

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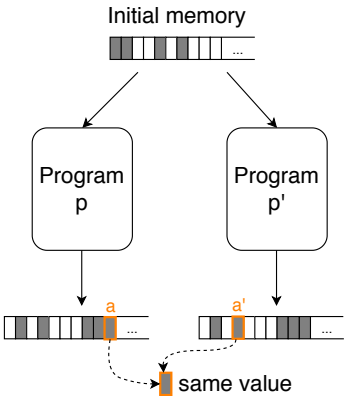

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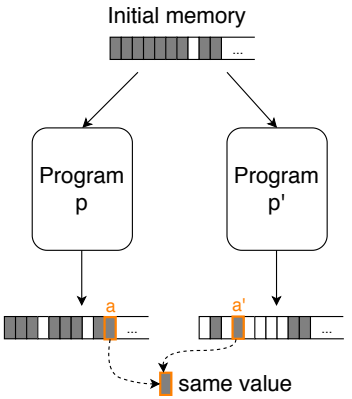


Theorem

$$\forall a'.\ \exists a.\quad p \ {}_a{\equiv}_{a'}\ p'$$
$$\Rightarrow$$

Dead Store Elimination

Application of our proof technique

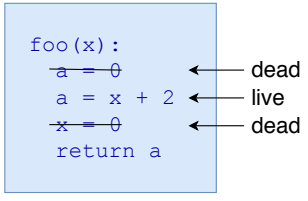
- We want to use our proof technique to create an IFP DSE*
- source and transformed programs must return identical final memories
- this is not the case for a classic DSE

*Dead Store Elimination

Classic DSE

Principle

- Remove write instructions that do not affect the **returned value**

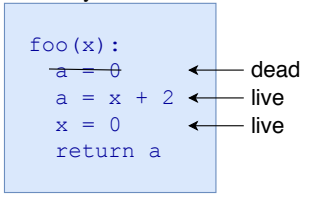


The final value of **a** is preserved

Secure DSE

Modified liveness analysis

- Source and transformed programs must return the same final memory

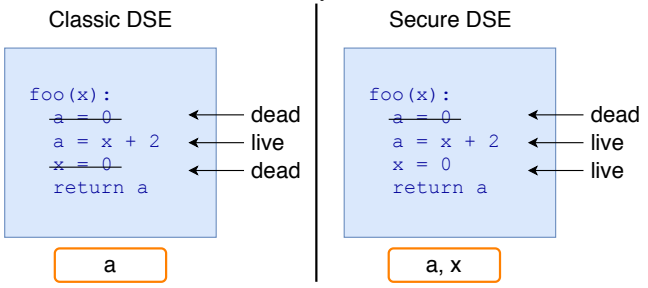


We preserve the whole final memory.
Here: **a** and **x**

- Keep "stores" that affect the **whole final memory**

Comparison

- less aggressive optimization
- preserves the state of the final memory



Register Allocation breaks IFP

A register allocation to an architecture having 2 registers

```
cryp(key, t, salt):


   tmp = t ^ salt

   key = tmp ^ key
   return key
```

Register allocation

```
cryp'(r1, r2, T_salt):
   T_key = r1
   r1 = T_salt
   r1 = r2 ^ r1
   r2 = T_key
   r2 = r1 ^ r2
   return r2
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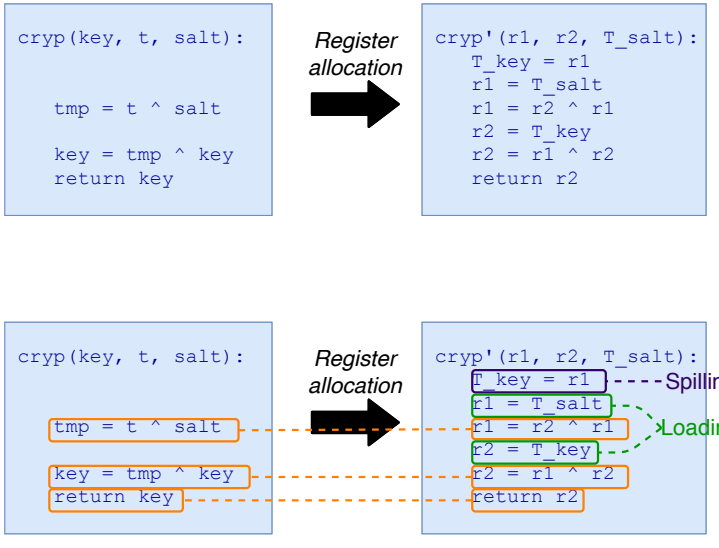

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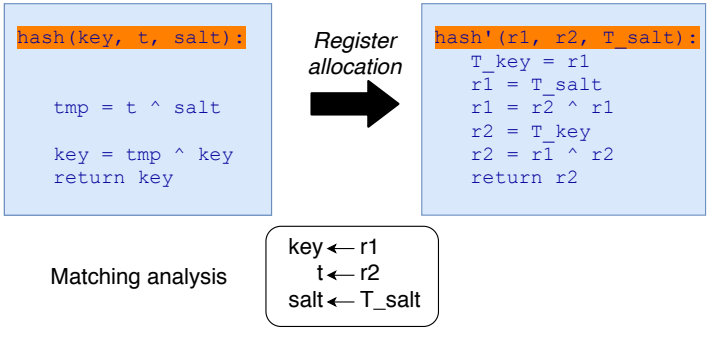
Validating Register Allocation

- Validator goal: $\forall a'.\, \exists a.\quad hash\ {}_{a}{\equiv}_{a'}\ hash'$
- Build an analysis matching locations of *hash'* to locations of *hash*



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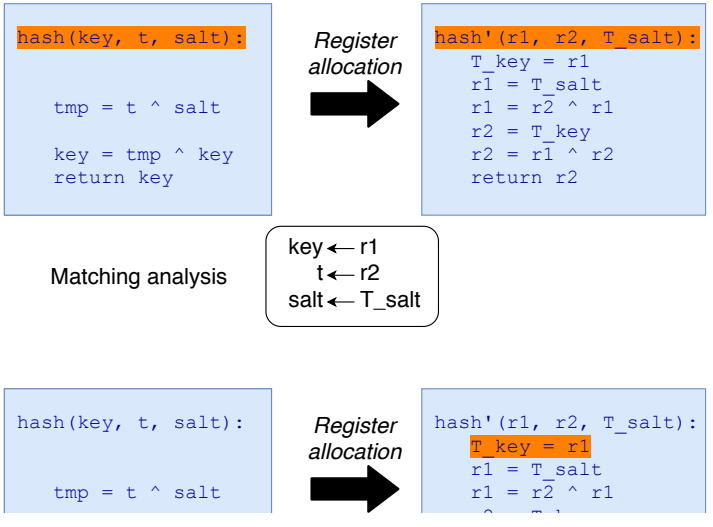
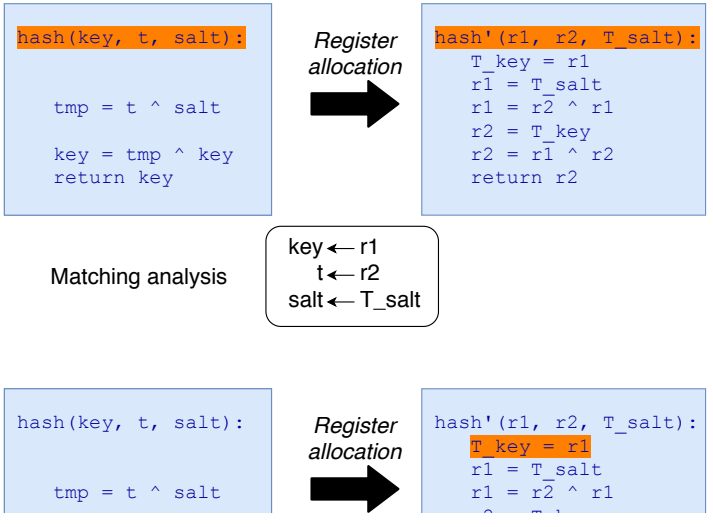


Validating Register Allocation

- Validator goal: $\forall a'.\, \exists a.\quad hash\ {}_{a}{\equiv}_{a'}\ hash'$
- Build an analysis matching locations of *hash'* to locations of *hash*



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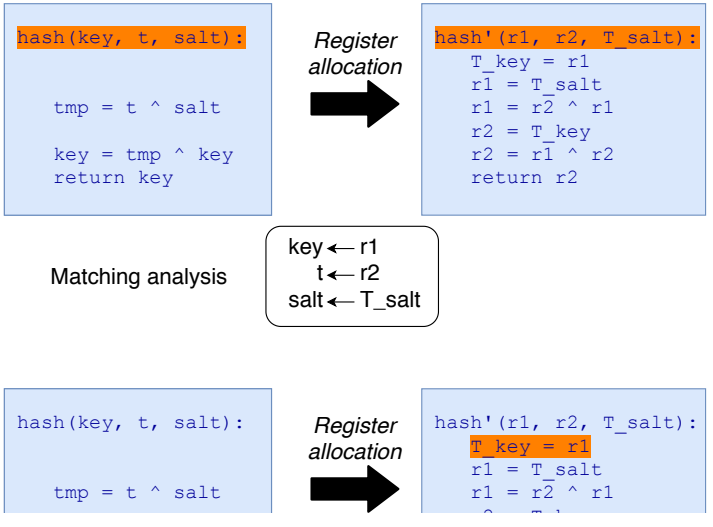

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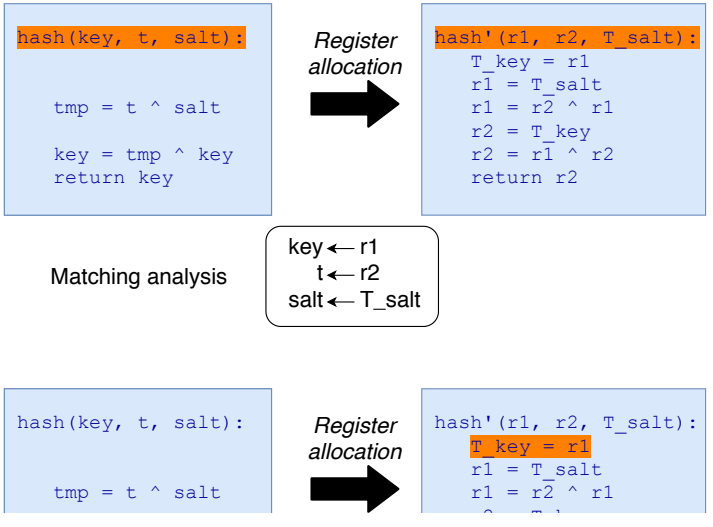

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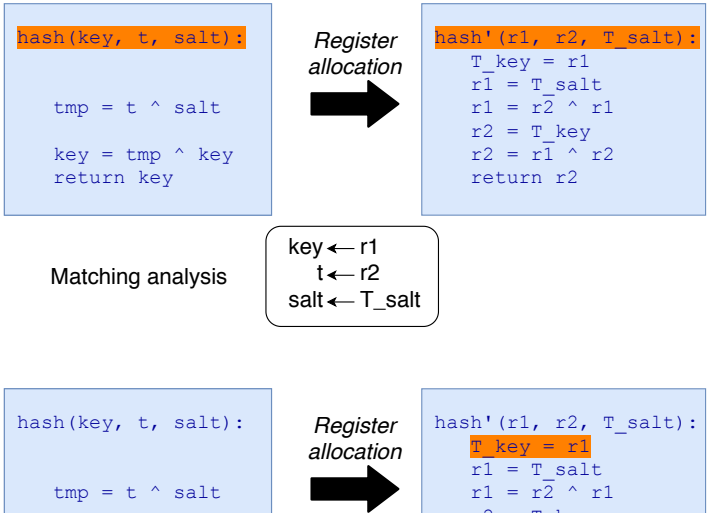

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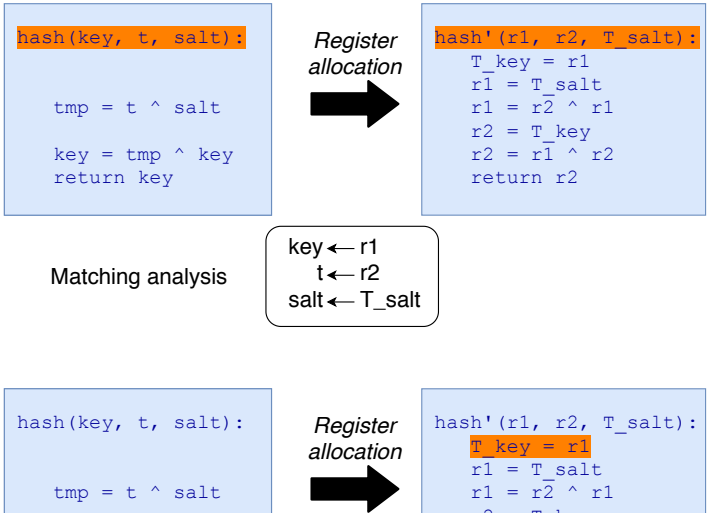

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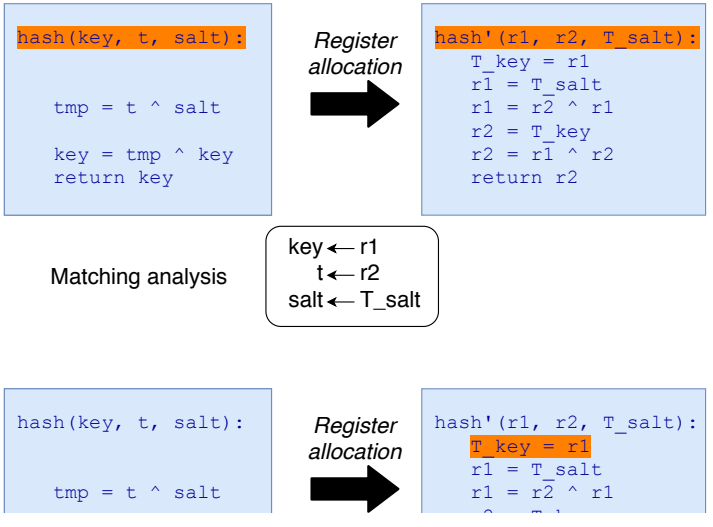

Securing Register Allocation

We patch the previous leakage using our matching analysis

```
hash(key, t, salt):

    tmp = t ^ salt

    key = tmp ^ key

    return key
```

```
hash'(r1, r2, T_salt):
    T_key = r1
    r1 = T_salt
    r1 = r2 ^ r1
    r2 = T_key
    r2 = r1 ^ r2
    T_key = r1
    return r2
```

Matching analysis

tmp ← r1
key ← r2
salt ← T_salt
tmp ← T_key

Transformation is IFP

Related Work

Preservation of non-interferent programs [Deng and Namjoshi, SAS16]

- preserve programs which do not leak
- does not differentiate between leaking 1 bit or n bits

Preservation of side-channel countermeasures [Barthe et al., CSF18]

- framework to preserve security properties against side-channels
- use 2-simulation property that we can avoid

Summary

Formal definition of IFP

- Partial Attacker Knowledge able to capture multiple level of leaks
- Security relation between two programs

Applications

- Proof technique to prove that a transformation is IFP
- Secure *Dead Store Elimination*
- *Register Allocation*
  - Validation algorithm
  - Secure transformation using the validation

Other results

Stronger preservation property

- Current property is end-to-end
- Works also for stronger attacker model making multiple observations during an execution (see CSF'19).

Application to other compilation transformations

- Transformations breaking IFP
- Inlining, code motion, ...

Development

- Implemented an actual DSE and validator for CompCert
- Evaluation of cost of repairing security leaks:
  - Code size increase about 20%
  - but the instructions are rarely executed.