香港科技大學
THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

NDSS SYMPOSIUM/2025

MTZK: Testing and Exploring Bugs in Zero-Knowledge (ZK) Compilers

NDSS Symposium 2025

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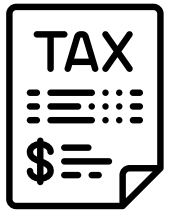
The Hong Kong University of Science and Technology

Are You Concerned About…?

Income > 2K

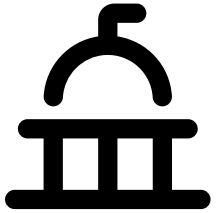
Salary slips?

Bank



Regulatory compliance

Business details?



Government

Carbon neutral

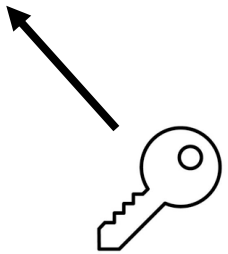
Industrial Data?

Global organization

Zero-Knowledge (ZK) Proofs

Verifier V

Prover P



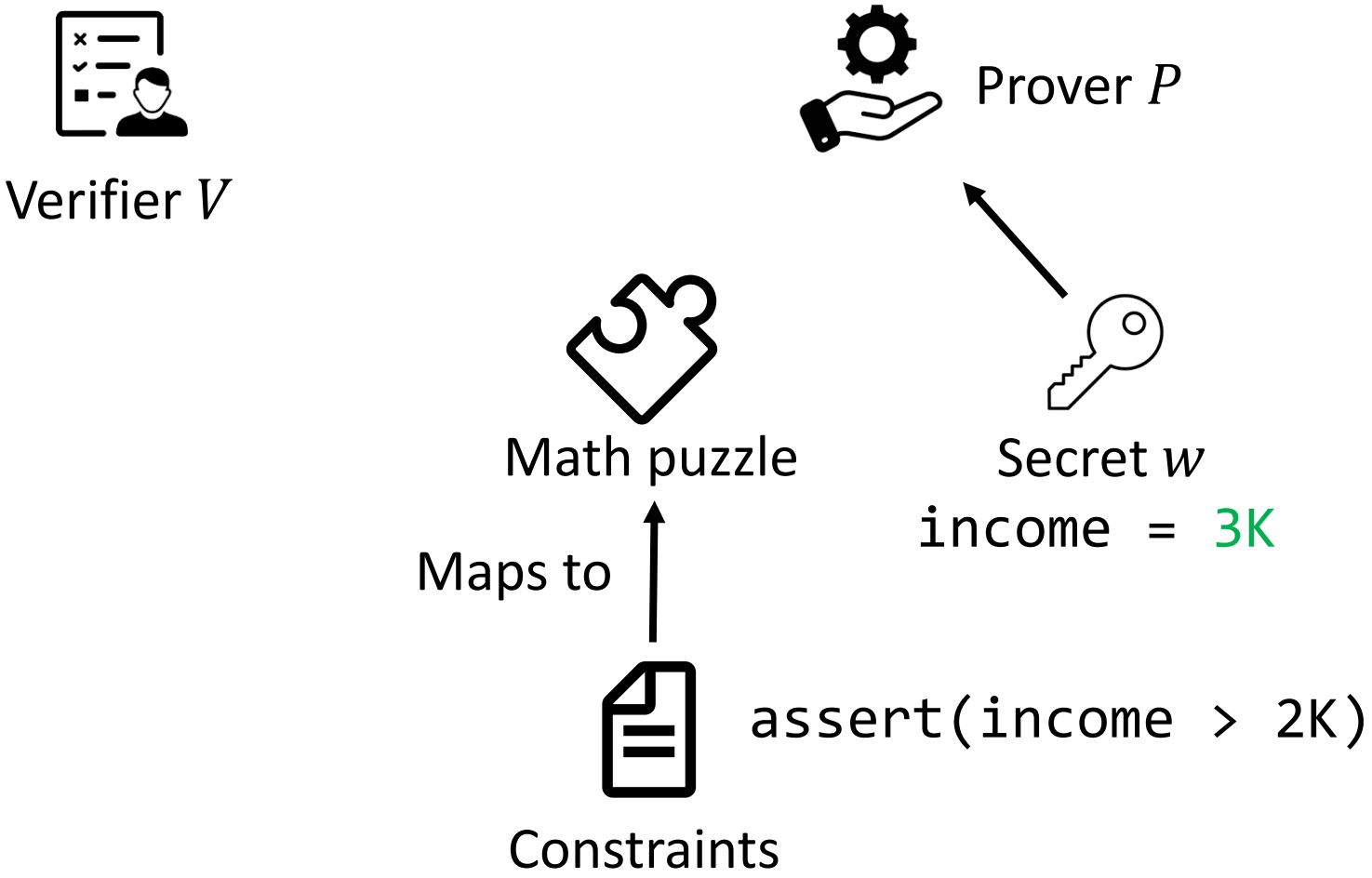
Secret w

```
income = 3K
```

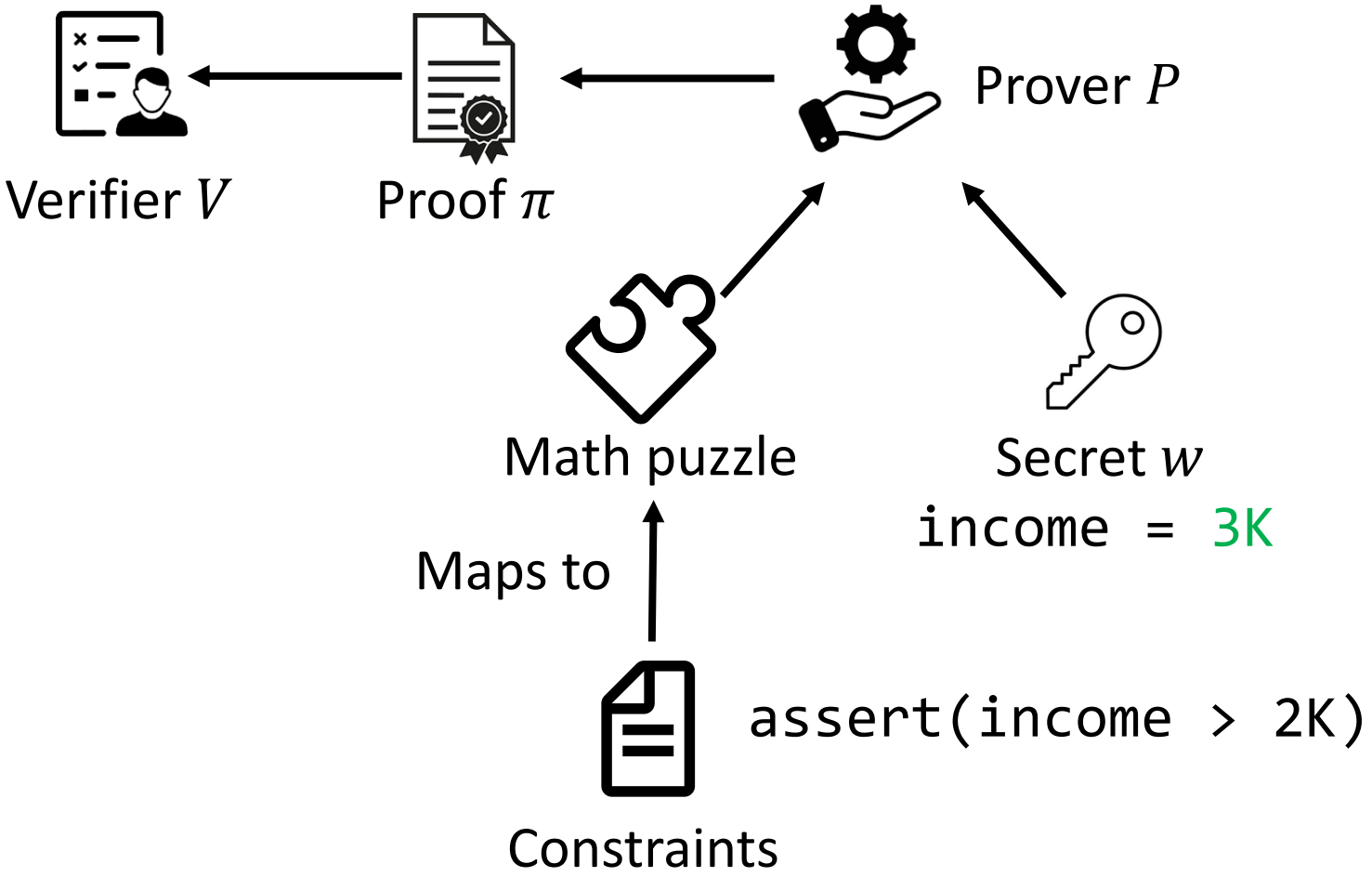
```
assert(income > 2K)
```

Constraints

Zero-Knowledge (ZK) Proofs



Zero-Knowledge (ZK) Proofs



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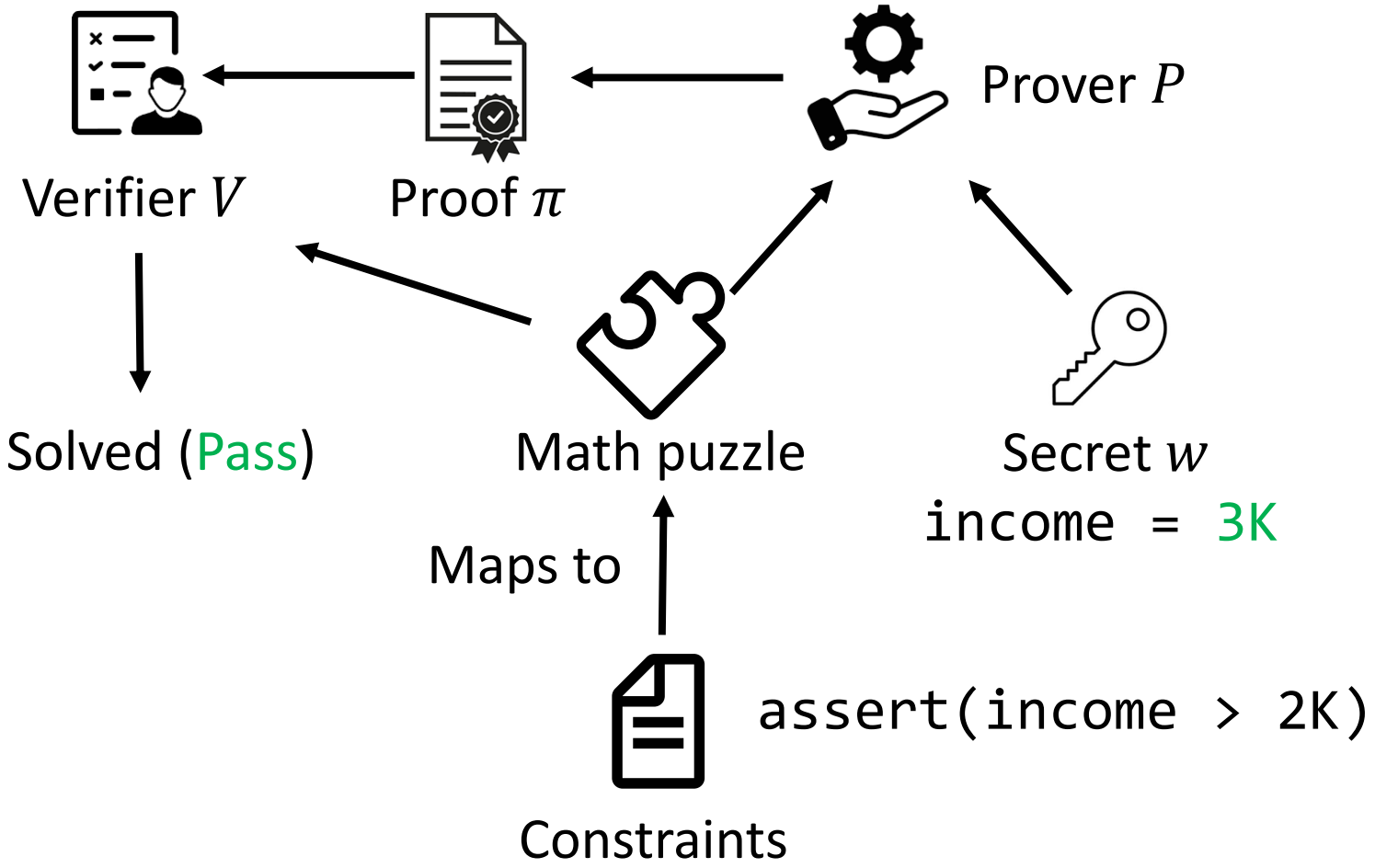

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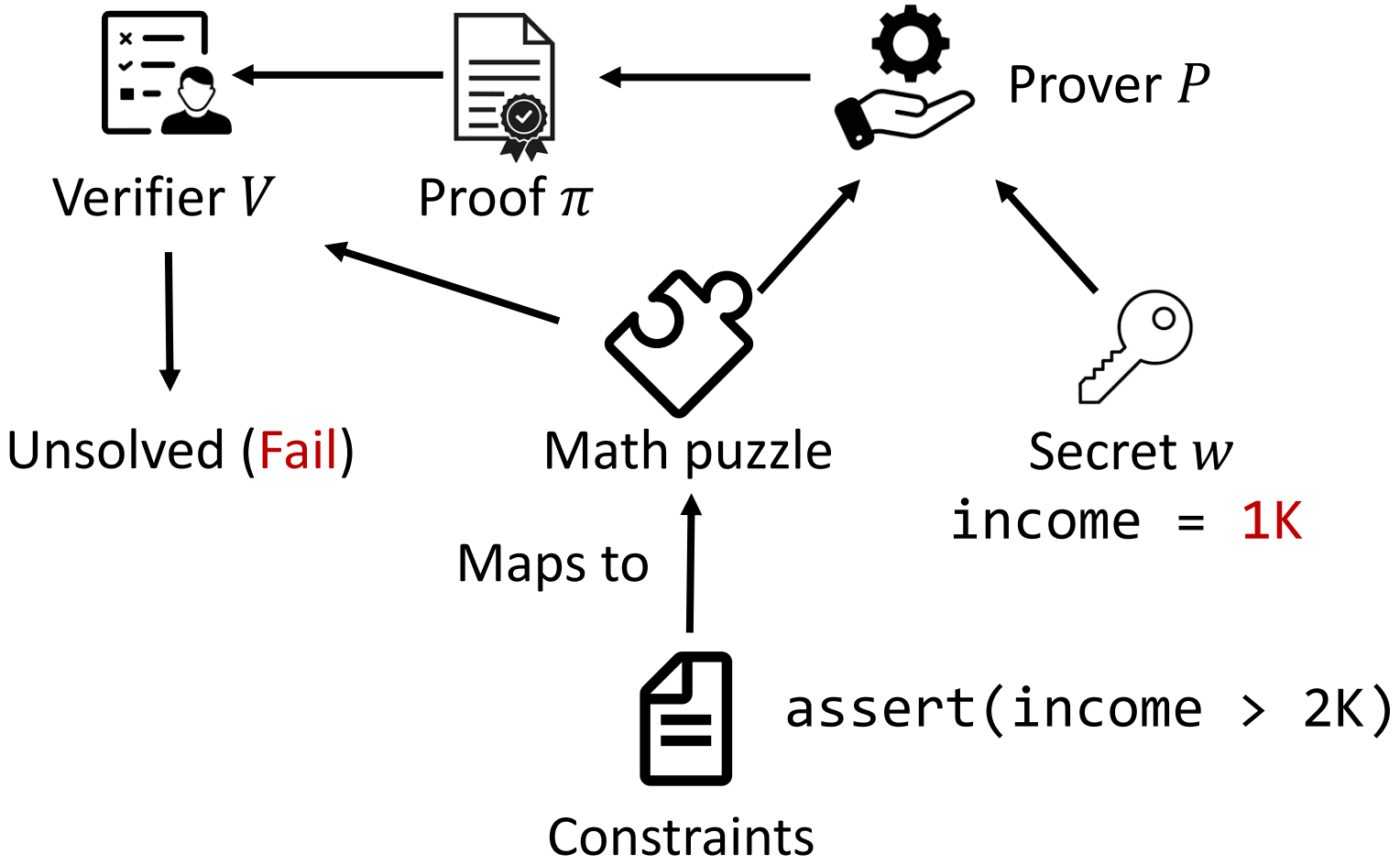

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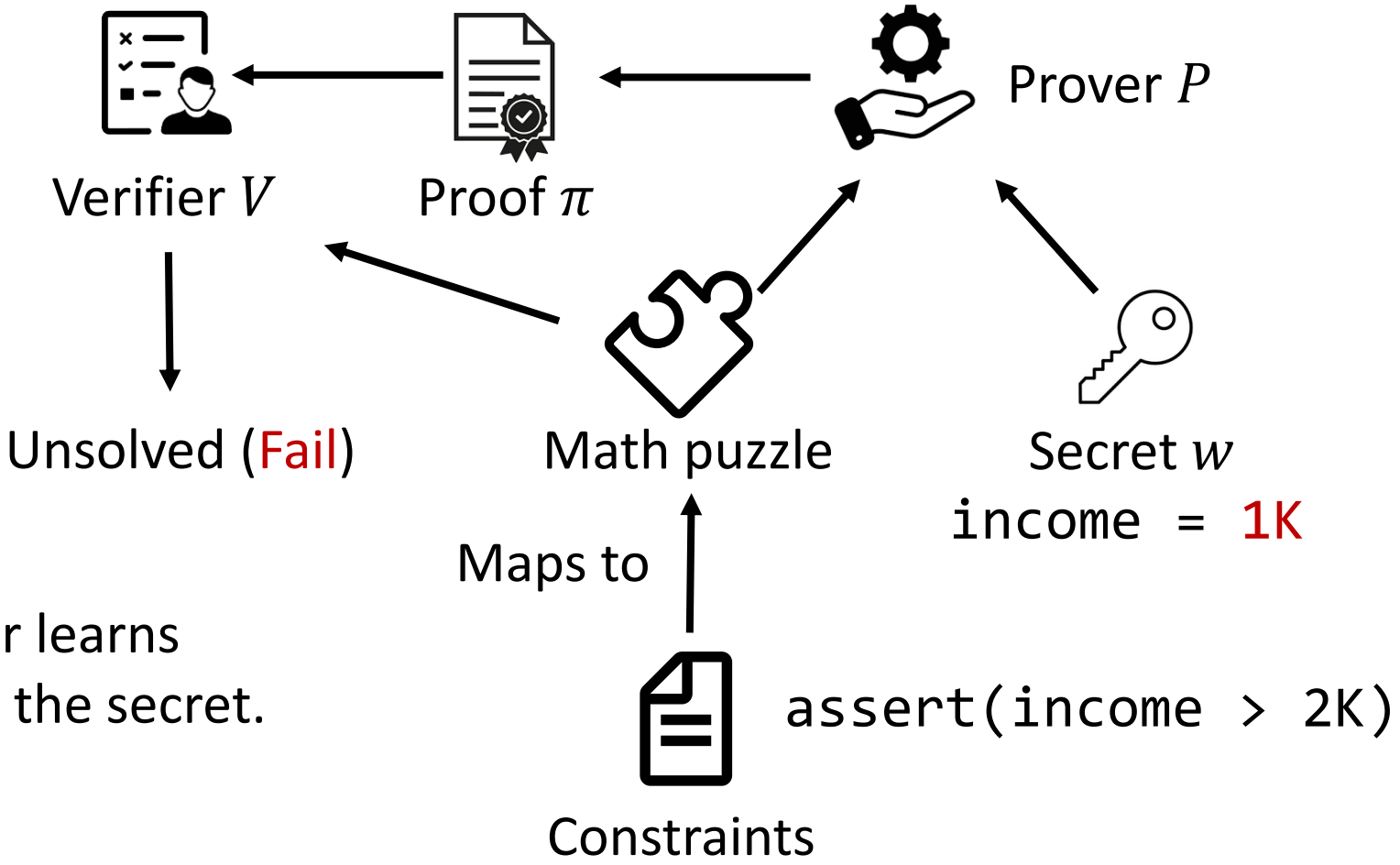
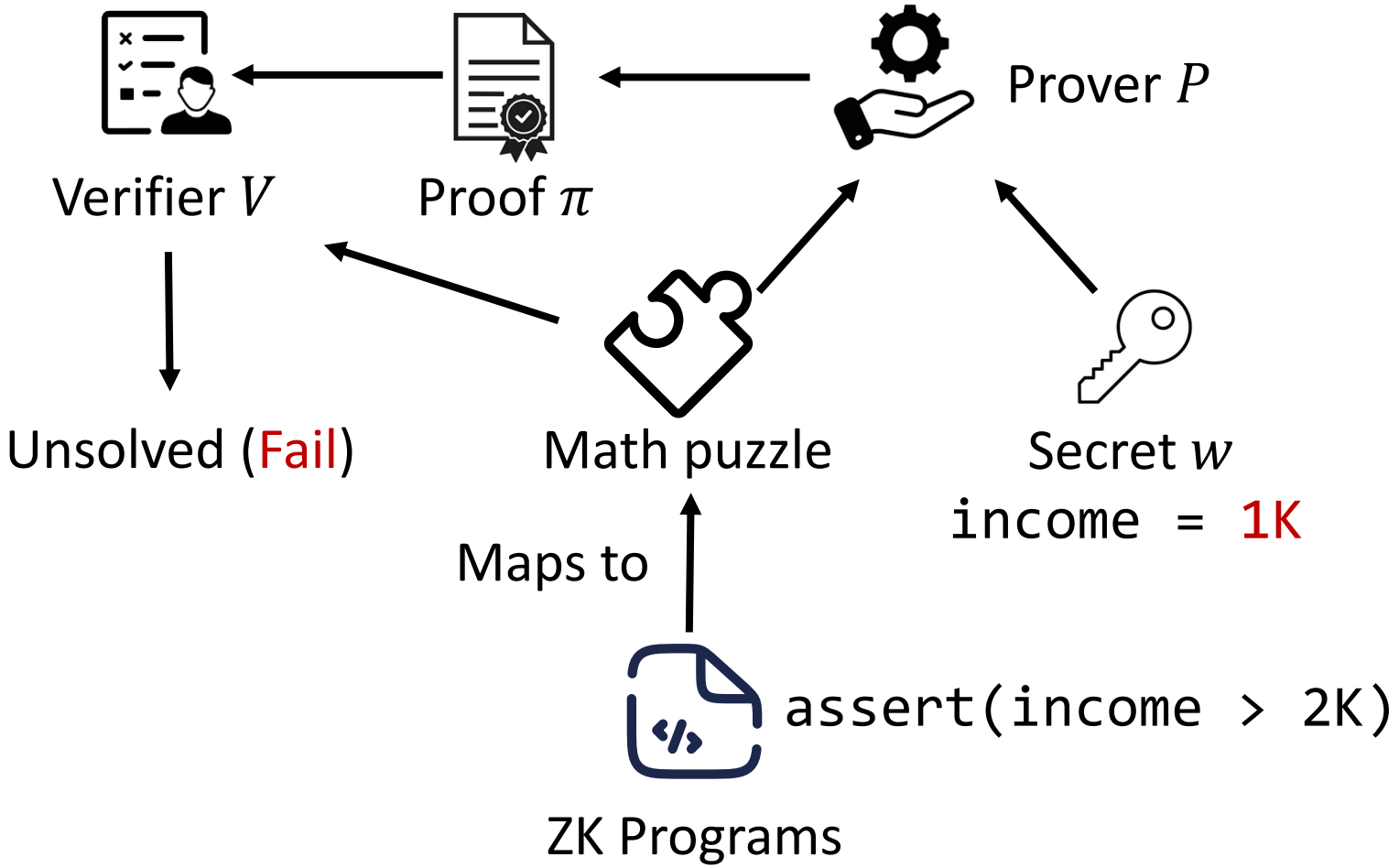


ZK: The verifier learns nothing about the secret.

Zero-Knowledge (ZK) Proofs



ZK Domain-Specific Language (DSL)

```
def main(public int tax_allowance,
         private int gross_income):
  int taxable_income = gross_income -
                       tax_allowance
  if (taxable_income < 0)
    taxable_income = 0
  int tax = taxable_income >> 2
  int net_income = gross_income - tax
  assert(net_income >= 2000)
```

⇦ Tax rate is 25% (right-shift by 2)

A ZK program checking whether net income >= 2K

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- Visibility modifiers:
  - Public: visible to both prover and verifier

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- Visibility modifiers:
  - Public: visible to both prover and verifier
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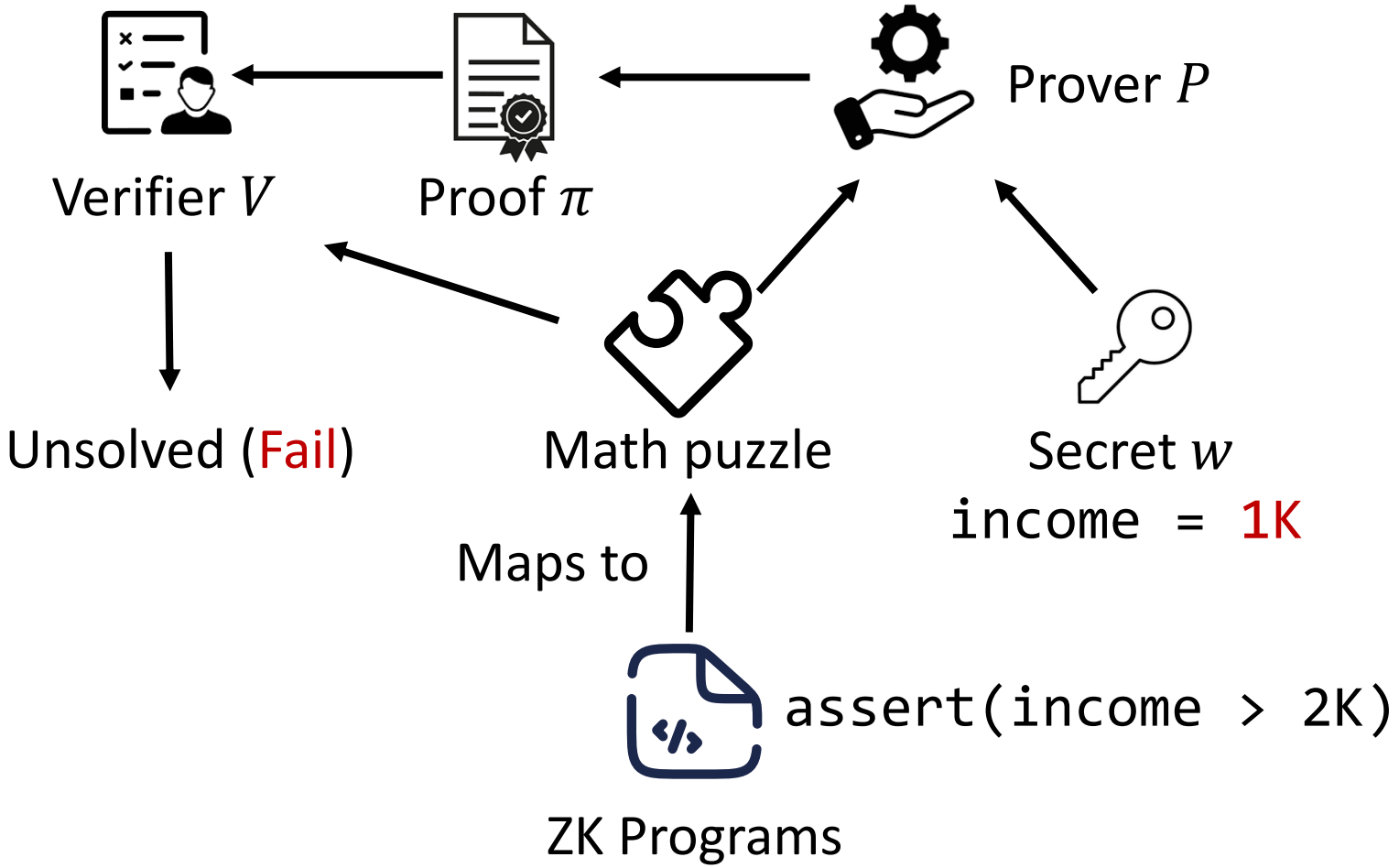
- Constraints to check

A ZK program checking whether net income >= 2K

Zero-Knowledge (ZK) Proofs



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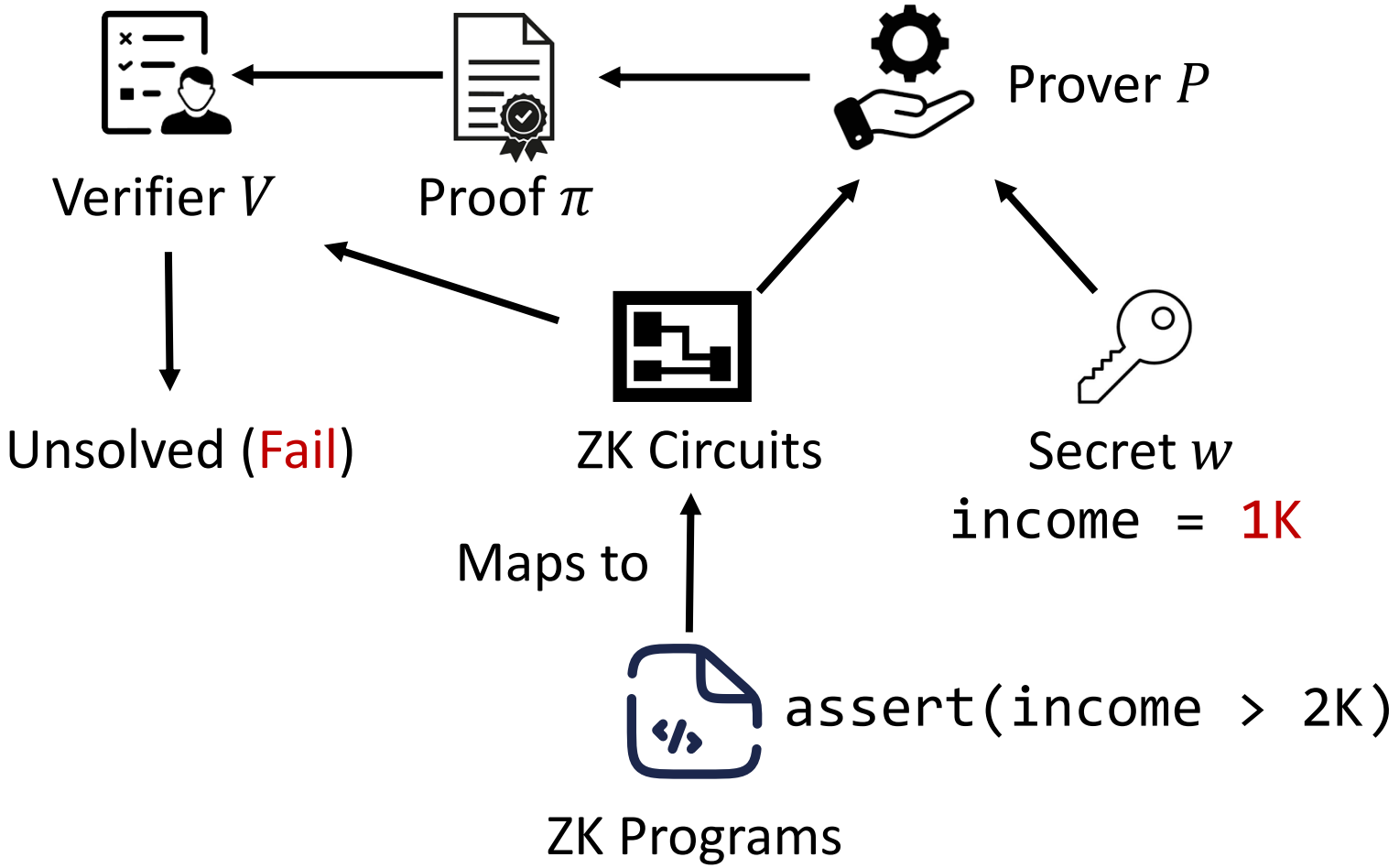

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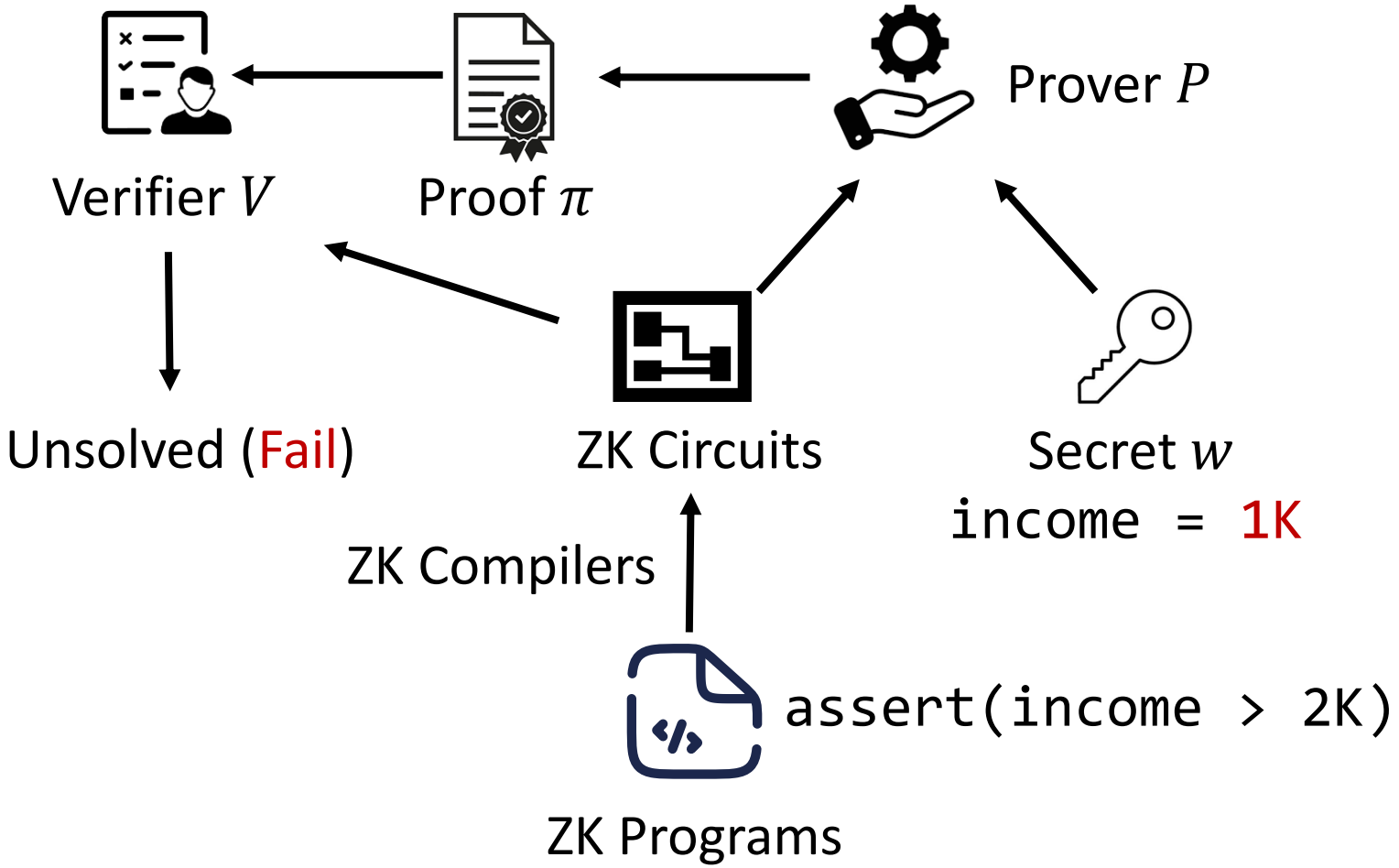
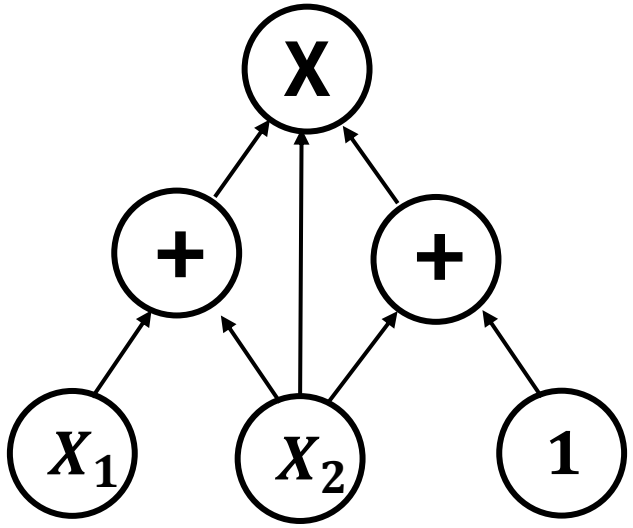


ZK Circuits

- No control flow
- Only addition and multiplication
- Represent crypto primitives
- Everything is bits



ZK Compilers

- Flatten If, For, While statements
- Arithmetization
- Crypto-aware optimizations
- Convert all data types to bits

Flattener

Visibility Checker

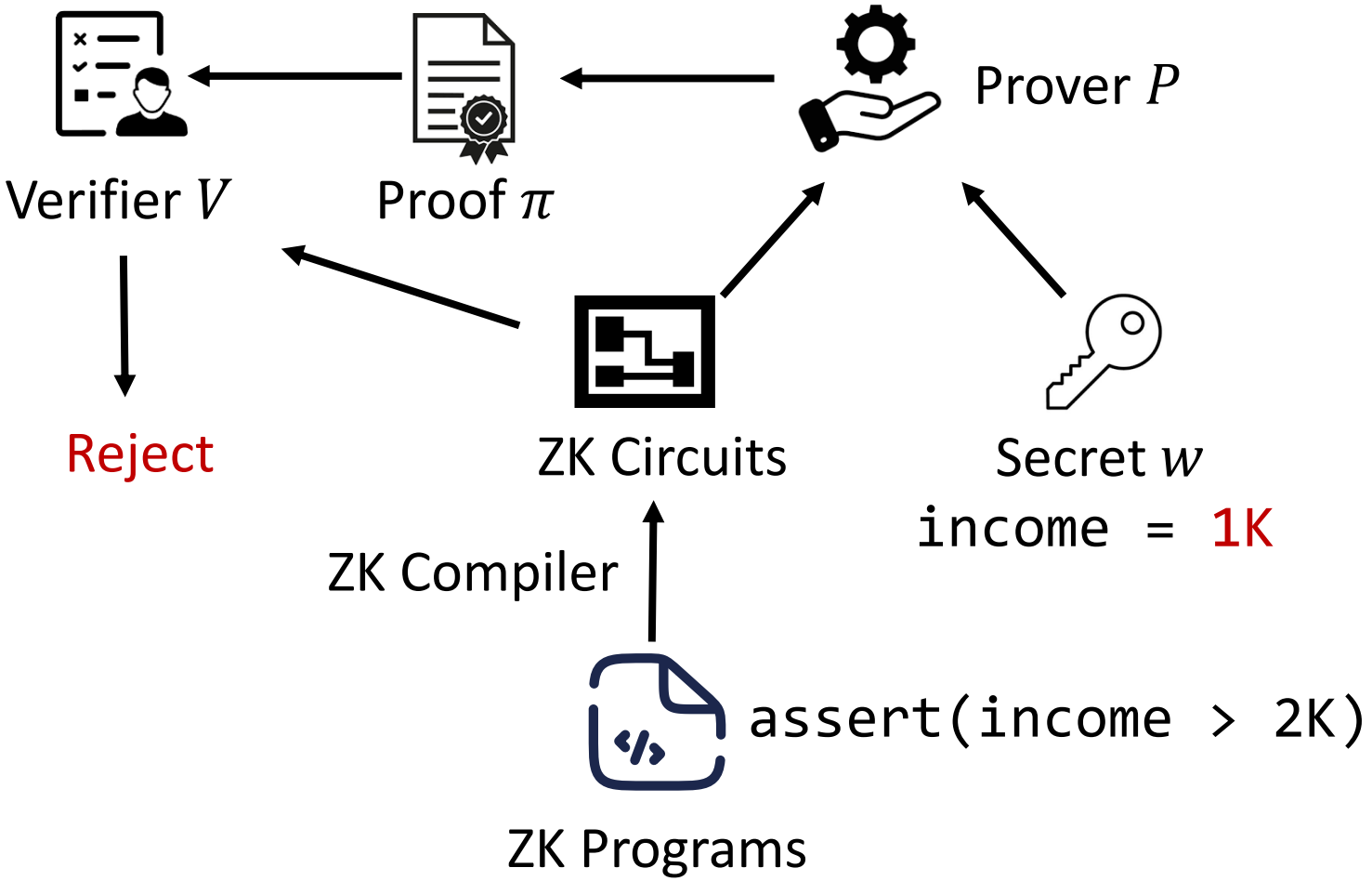
Front-end Optimizer

Lowering

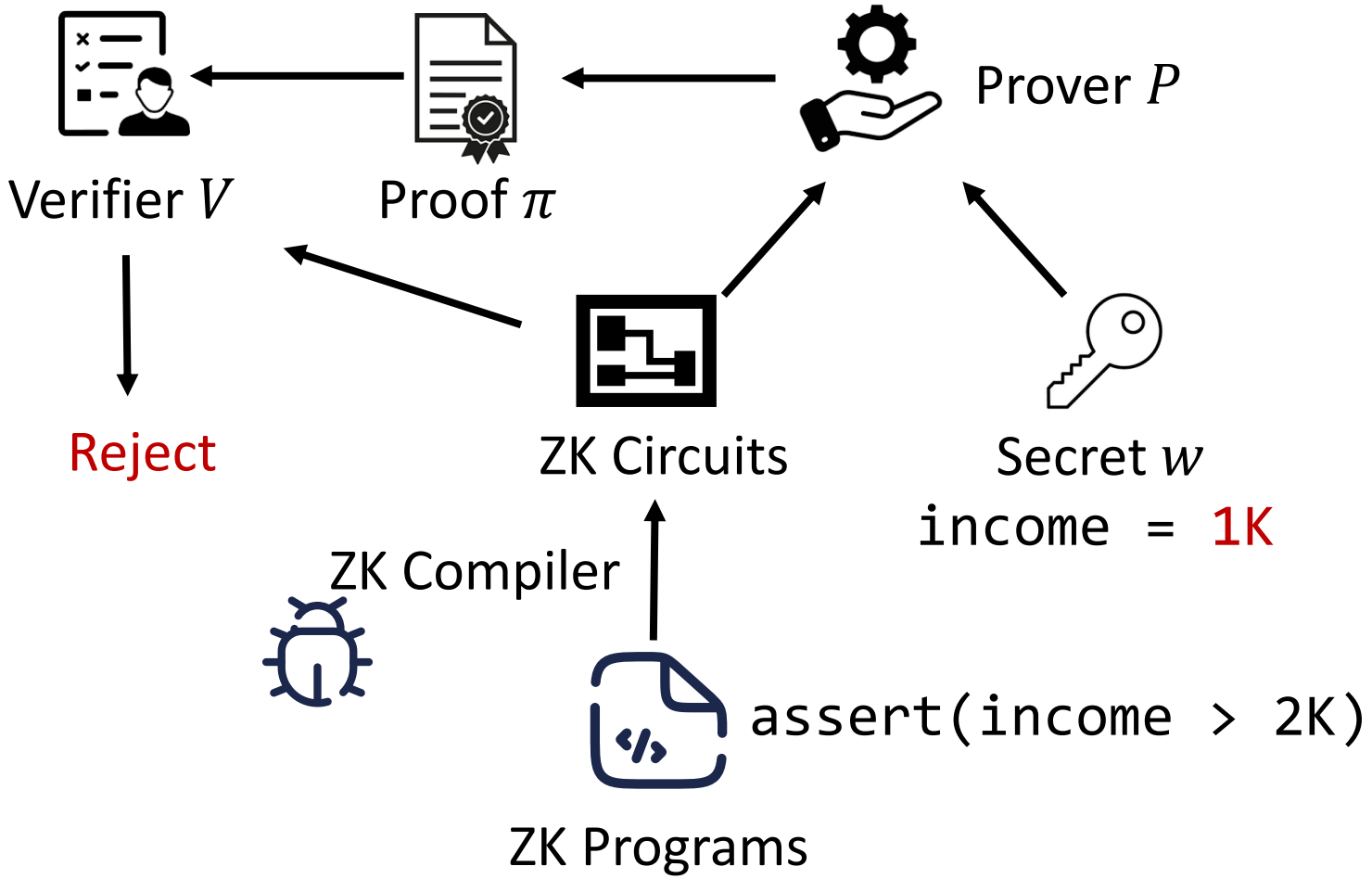
Arithme-tization

Back-End Optimizer

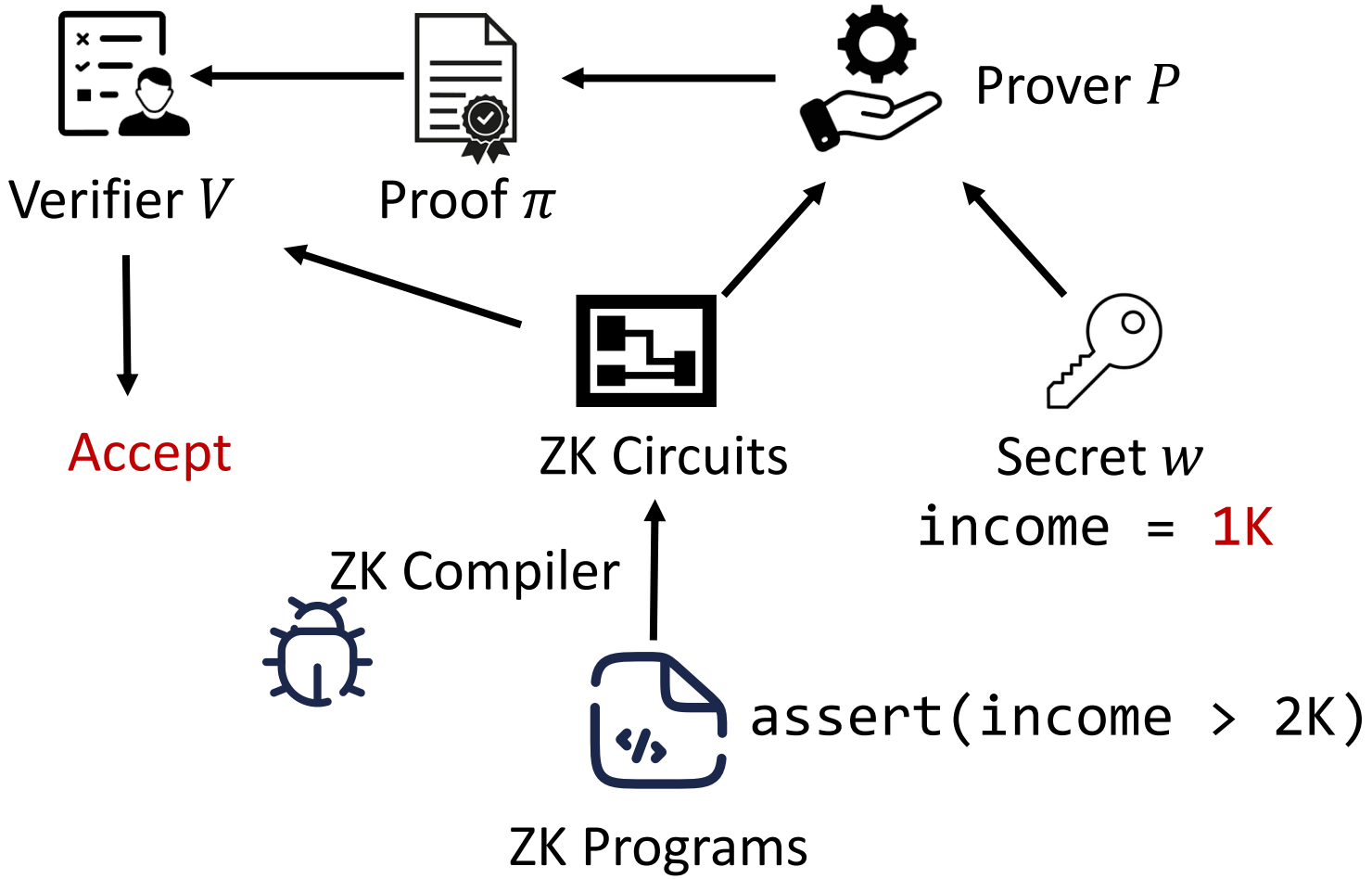
Correct Compilation Refuses the Unqualified



Erroneous ZK Compilers



Erroneous ZK Compilers



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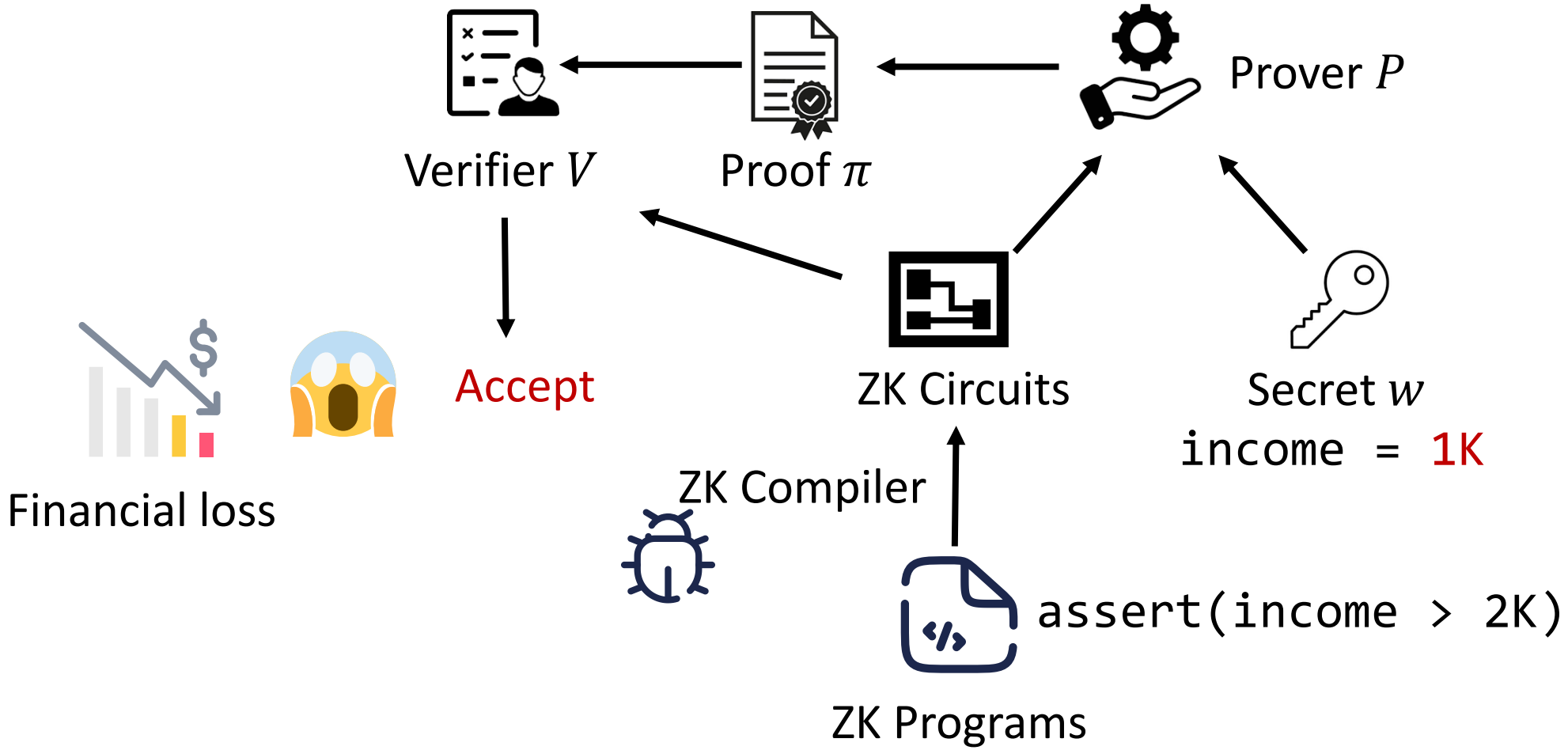

Real-world ZK Bugs Affecting Blockchains

1. Lack of range constraints for the `tree_index` variable

Description of bug:

The index (i.e. position) of a note in the Aztec 2.0 tree was used in the computation of the note nullifier. The code assumed this to be a 32-bit integer, and so used only the last 32-bits of this element as the tree index. However, the field element representing this position was not actually constrained to be 32 bits. Therefore, the entire field element was used as an input for computing the nullifier.

Summary

During the final activation phase of the Aave v3 ZKSync pool on August 21th [36], a problem with its behaviour was detected. Consequently, a global pause of all assets was enacted by the Aave Guardian, delaying the activation of the new instance.

The company behind the privacy-minded cryptocurrency zcash has revealed that it fixed a catastrophic code bug last year that could have been used to print infinite coins.

https://governance.aave.com/t/bgd-aave-v3-zksync-activation-issue-report/18819
https://hackmd.io/@aztec-network/disclosure-of-recent-vulnerabilities
https://www.coindesk.com/markets/2019/02/05/zcash-team-reveals-it-fixed-a-catastrophic-coin-counterfeiting-bug

Real-world ZK Bugs Affecting Blockchains

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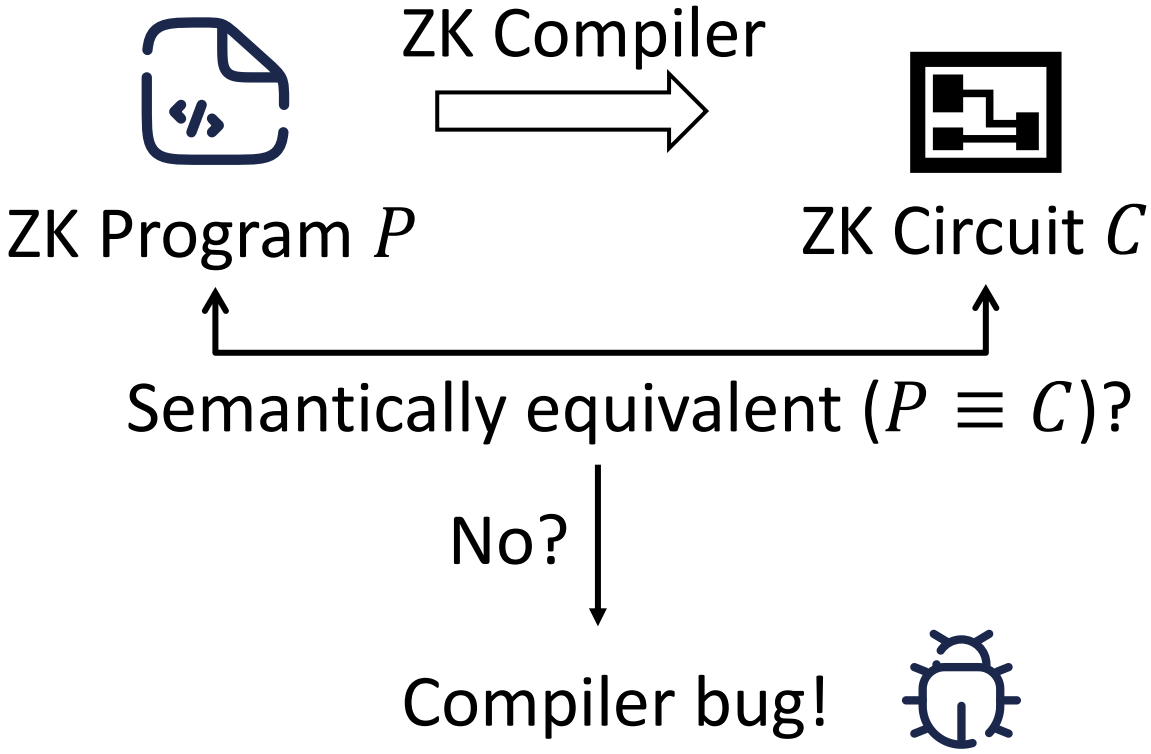
How can we automatically test ZK compilers?

https://governance.aave.com/t/bgd-aave-v3-zksync-activation-issue-report/18819
https://hackmd.io/@aztec-network/disclosure-of-recent-vulnerabilities
https://www.coindesk.com/markets/2019/02/05/zcash-team-reveals-it-fixed-a-catastrophic-coin-counterfeiting-bug

Testing Oracle (Ground Truth) Problem



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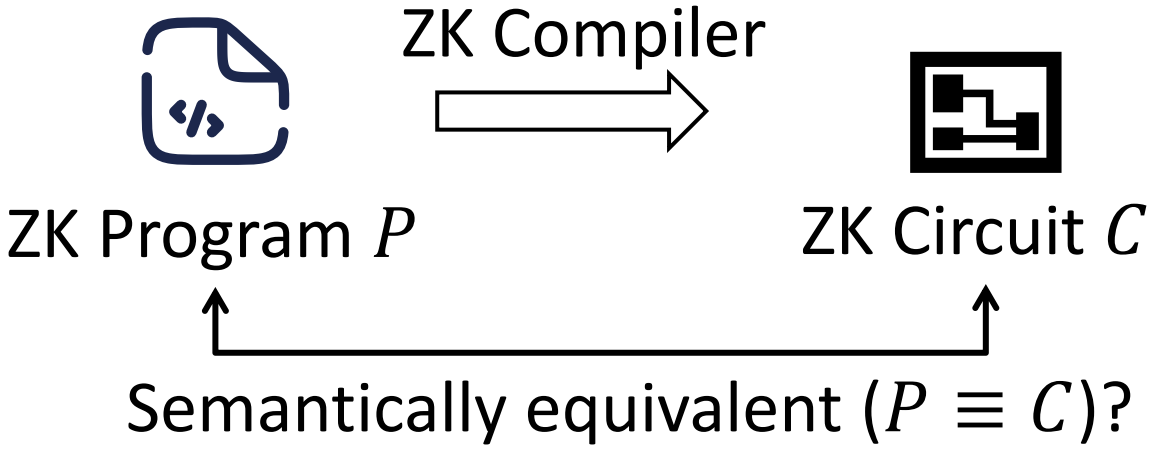


Hard!

Metamorphic Mutations

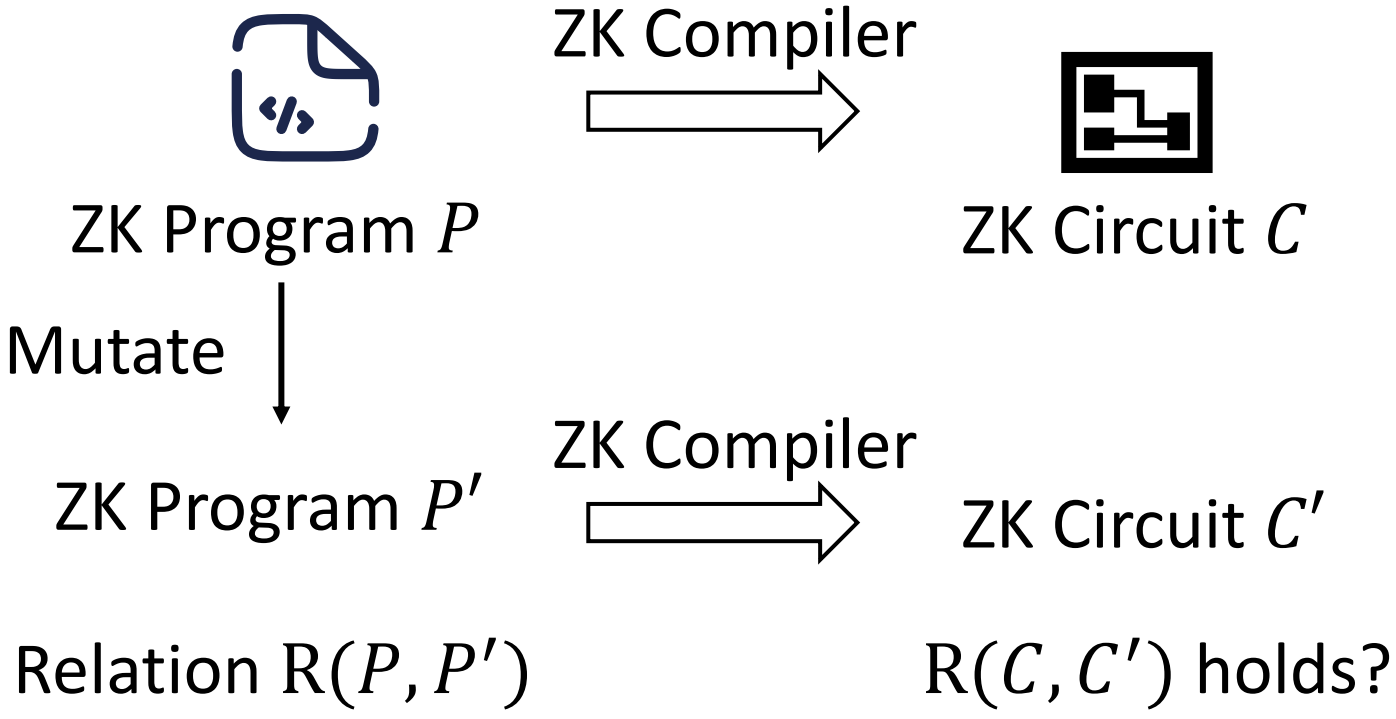
ZK Program P

Mutate

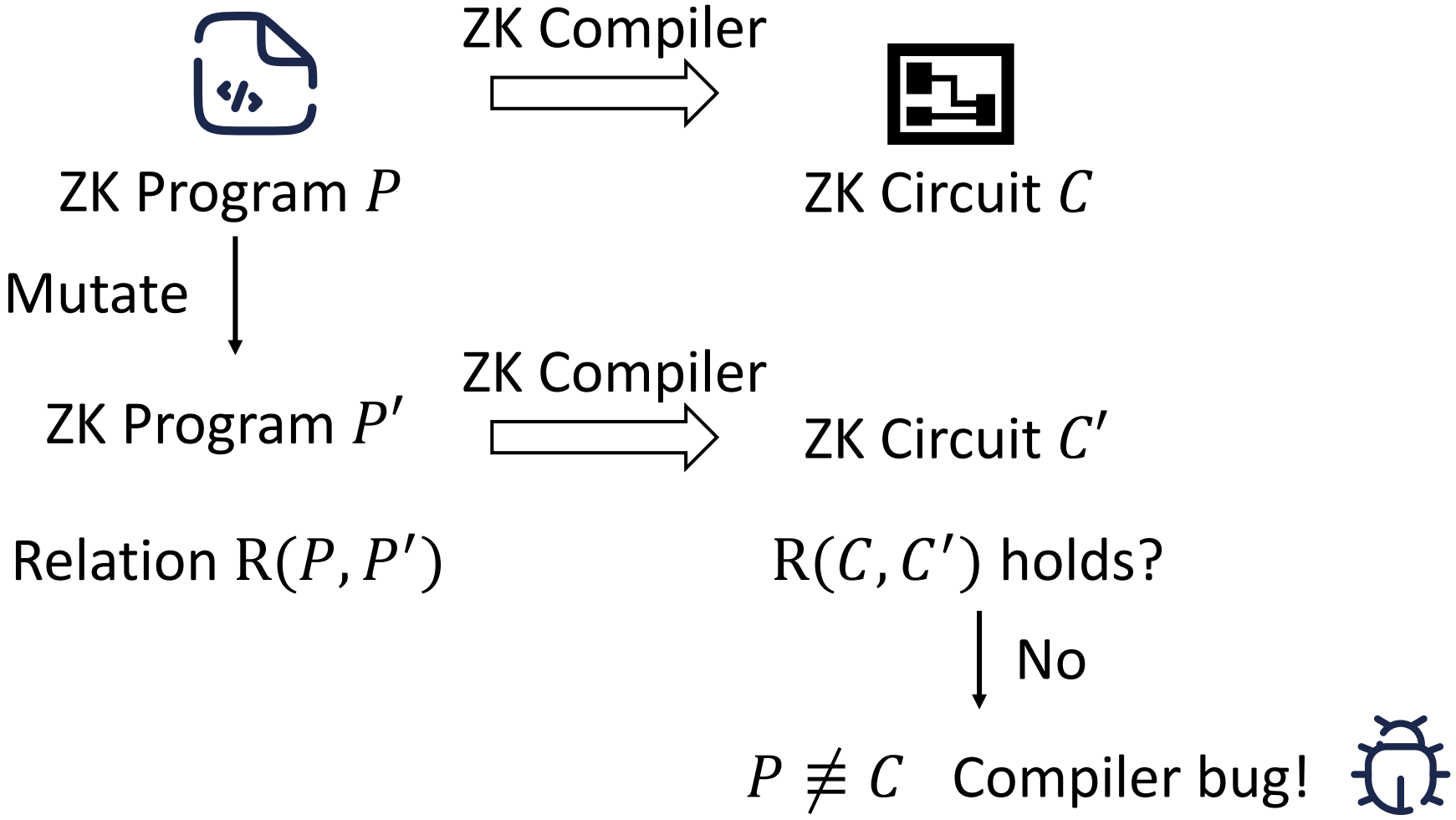
ZK Program P'

Relation $\mathrm{R}(P, P')$

Metamorphic Mutations



Metamorphic Mutations



MR_{SIM}: Satisfiability-Invariant Mutation

ZK Program P

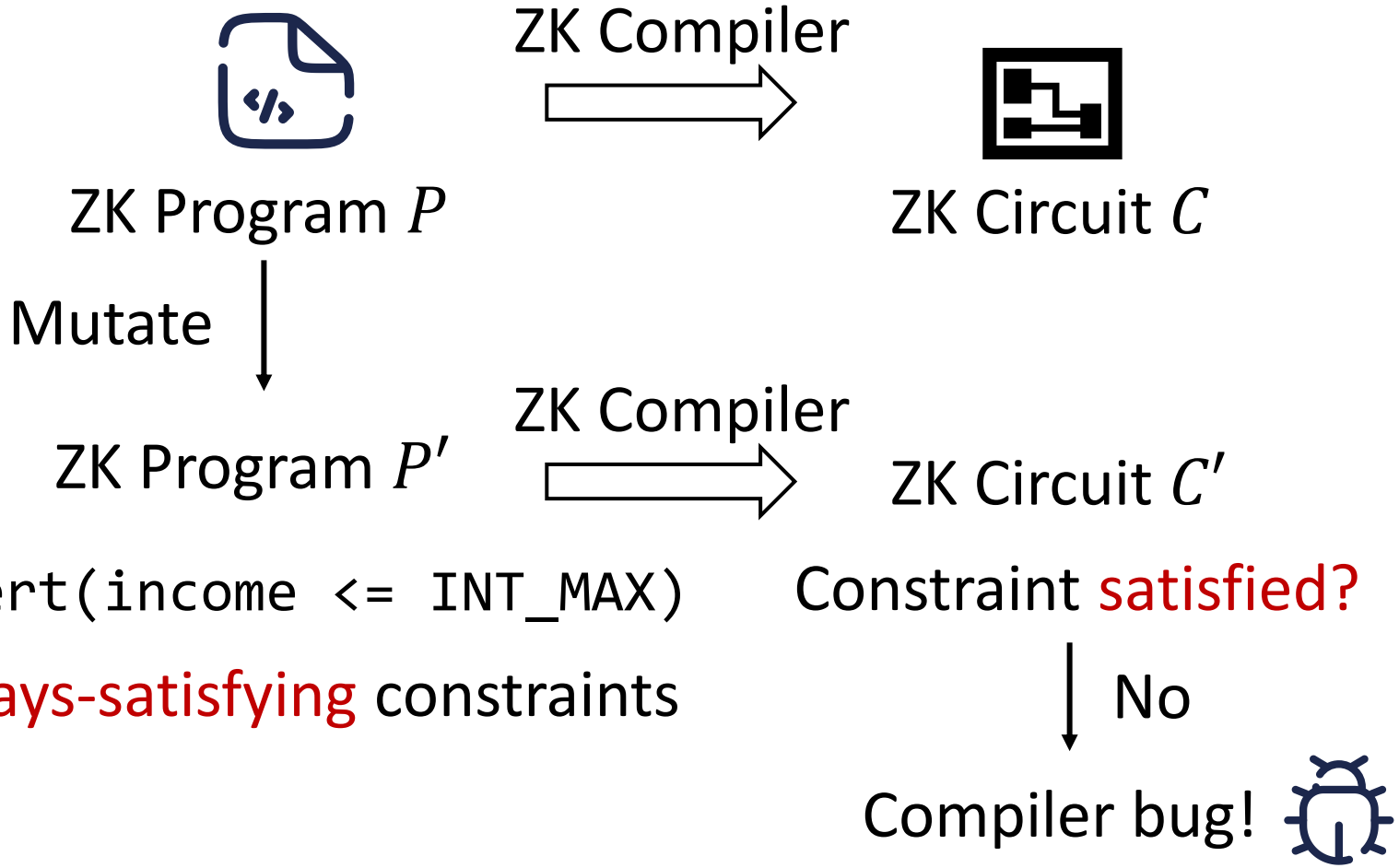
Mutate

ZK Program P'

```
assert(income <= INT_MAX)
```

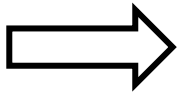
Always-satisfying constraints

MR_{SIM}: Satisfiability-Invariant Mutation



Implementation of MR_{SIM}

```
1  fn foo() {
2    let mut x = 81;
3    for i in 1..10
4      if x % i == 0 {
5        x += 1;
6      } else {
7        x -= 1;
8      }
9  }
```



```
1  fn foo() {
2    let mut x = 81;
3    for i in 1..10
4      if x % i == 0 {
5        x += 1;
6        assert(x <= INT_MAX) // C-MAX
7      } else {
8        x -= 1;
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10 }
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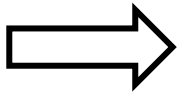

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7      } else {
8        x -= 1;
9        assert(x == x * 1)  // C-TAUT
10     }
11 }
```

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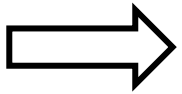

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7      } else {
8        x -= 1;
9        assert(x == x * 1)  // C-TAUT
10     }
11   //       C-EQ
12   assert(x == 76)
13 }
```

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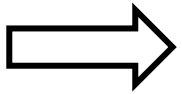

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7      } else {
8        x -= 1;
9        assert(x == x * 1)  // C-TAUT
10     }
11   //       C-EQ          C-NLT
12   assert(x == 76     !(x < 76))
13 }
```

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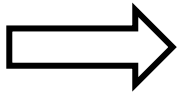
```



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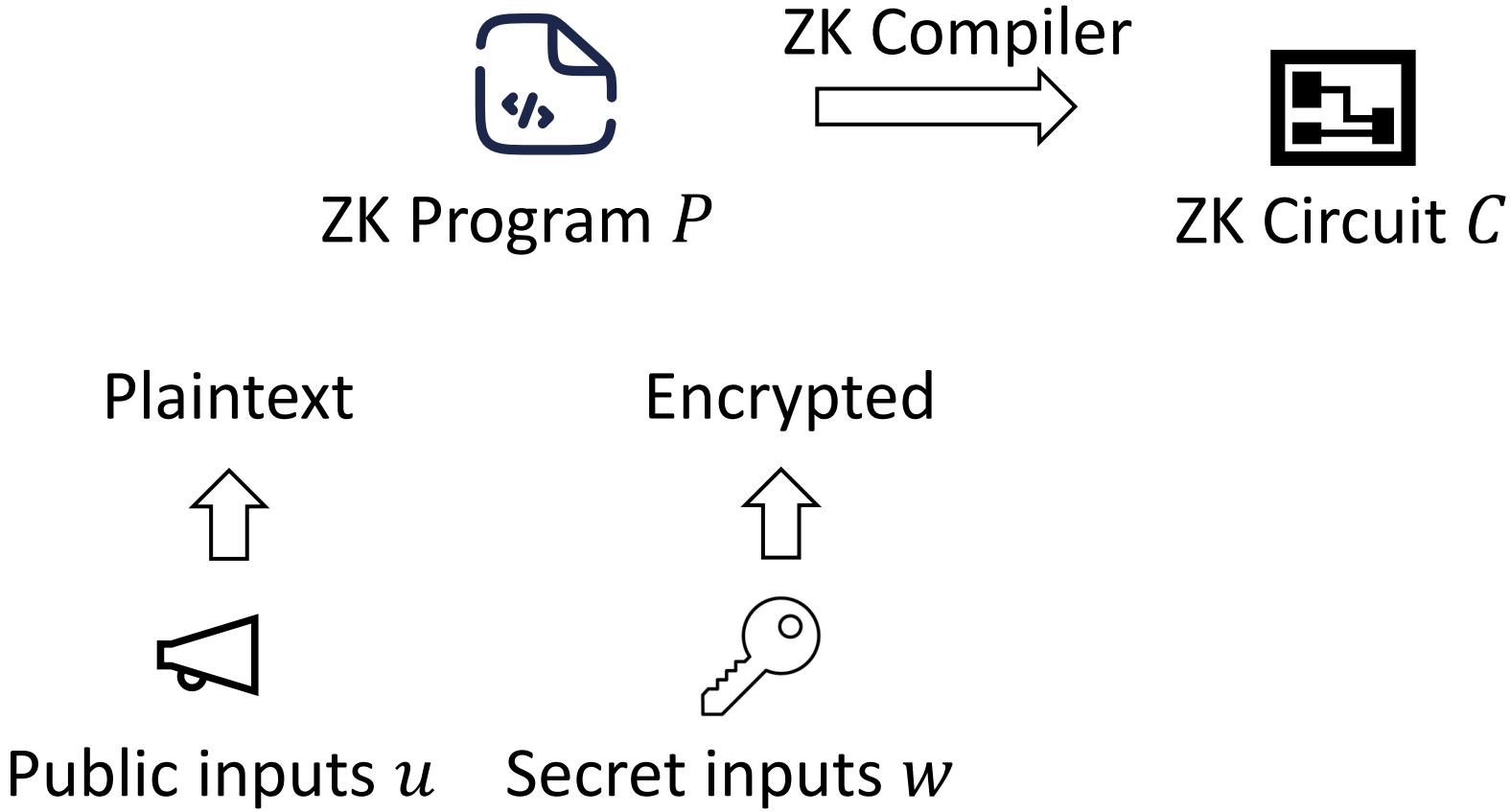
7      } else {
8        x -= 1;
9        assert(x == x * 1)  // C-TAUT
10     }
11   //       C-EQ  C-AND  C-NLT
12   assert(x == 76 && !(x < 76))
13 }
```

MR_{IVM}: Information Visibility Mutation



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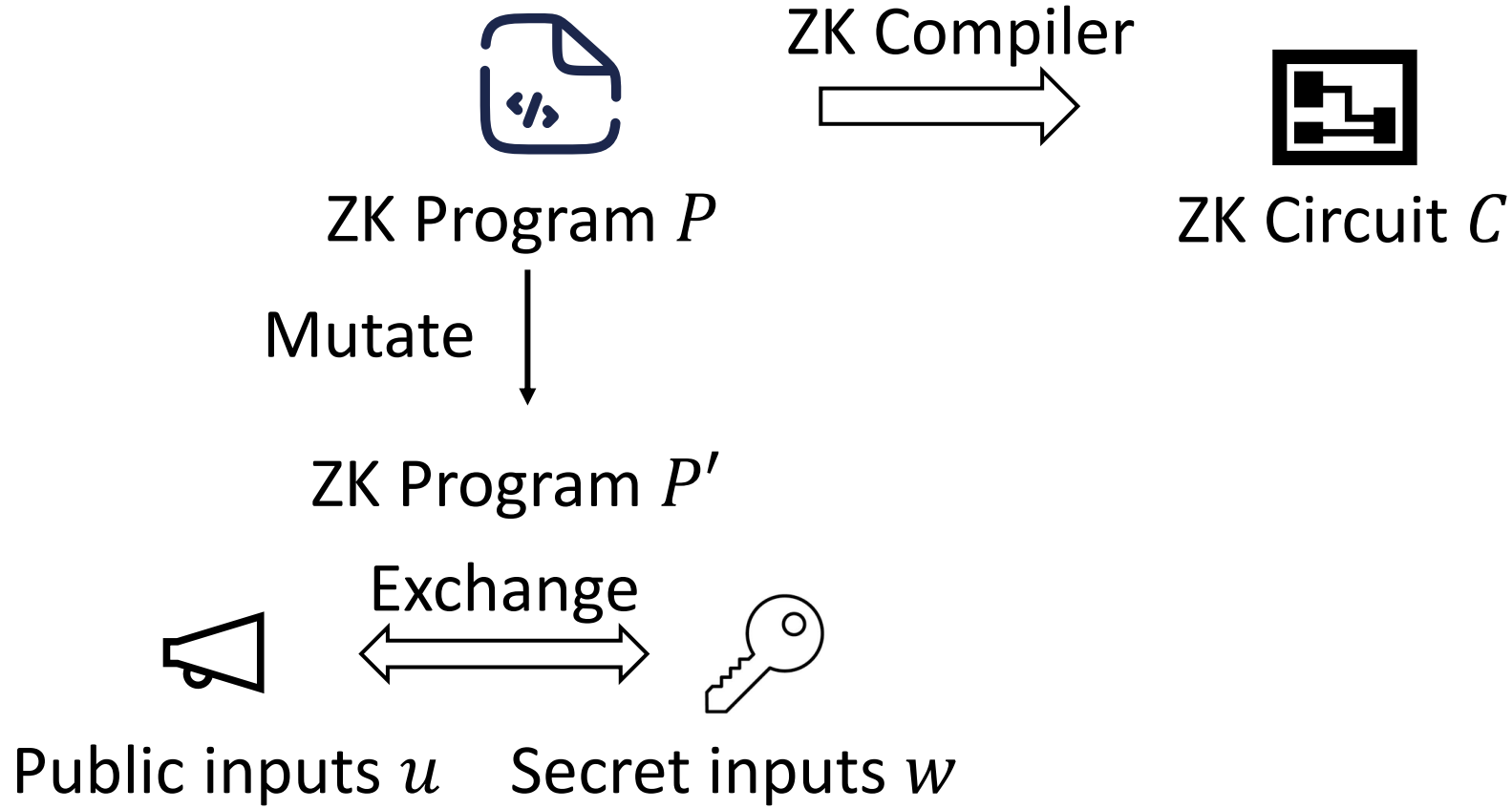

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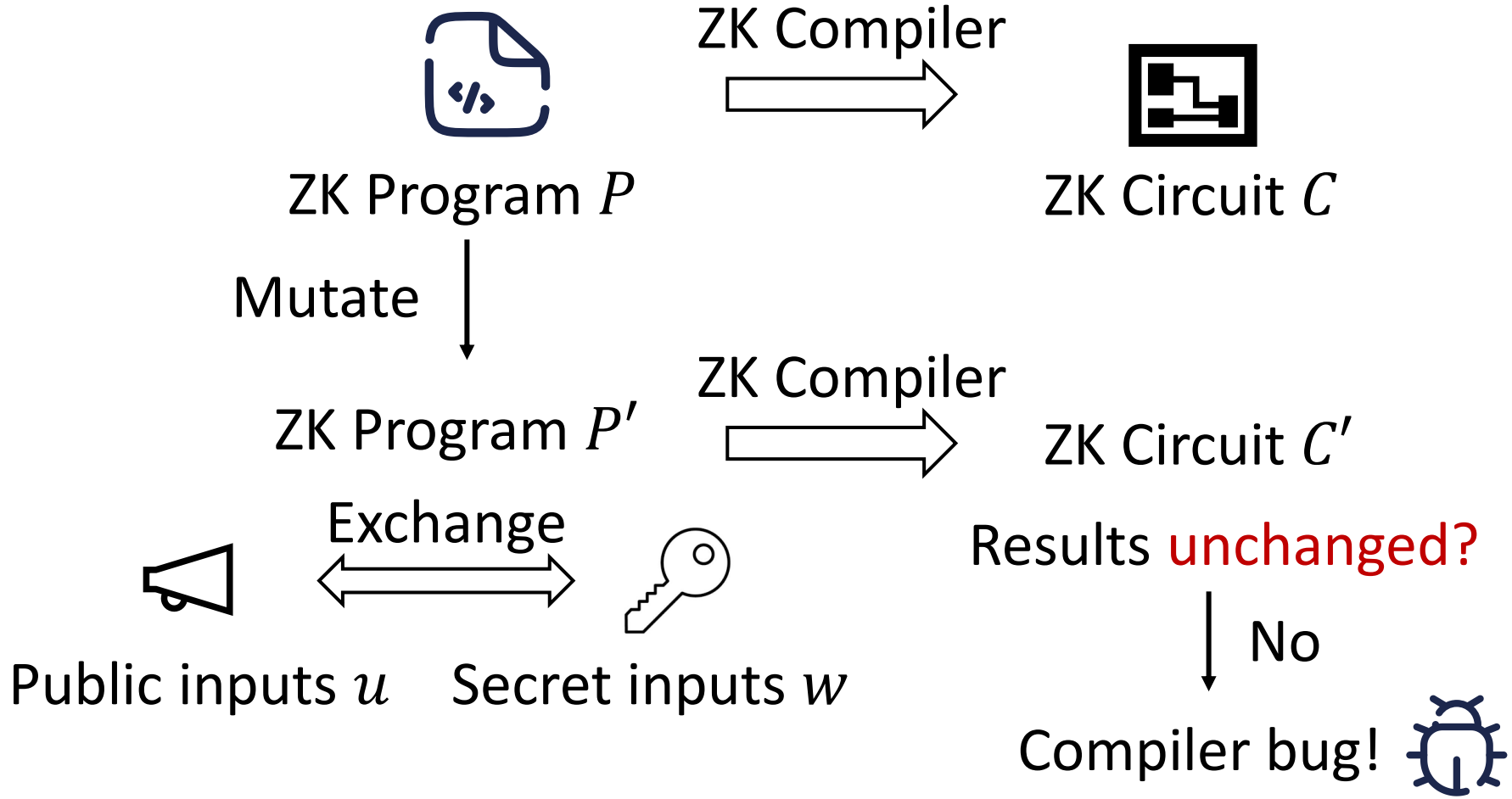

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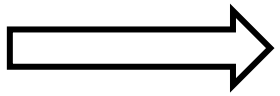

```
1 fn foo(public u) {
2   let mut x = 81;
3   for i in 1..10
4     if x % i == u { // 0 -> u
5       x += 1;
6     } else {
7       x -= 1;
8     }
9 }
```

Implementation of MR_{IVM}

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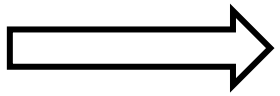

```
1  fn foo(public u, private w) {
2    let mut x = 81;
3    for i in 1..10
4      if x % i == u { // 0 -> u
5        x += 1;
6      } else {
7        x -= w;       // 1 -> w
8      }
9  }
```

Testing Target Selection

ZK Compilers	Blockchains
ZoKrates	polygon
Leo	Aleo
Noir	Aztec
CAIRO	STARKNET

Securing billions of dollars

Bug Findings

	ZoKrates	Noir	Cairo	Leo	Total
Total	7	7	5	2	21
#Confirmed	4	7	5	0	16
#Fixed	3	7	5	0	15

Infinite Withdrawal in ZoKrates

```
1 fn withdraw(account: &mut field, amount: field) {
2   let savings: field = read_savings(account);
3   assert(savings >= amount);
4   ... // Withdraw the money
5 }
```

Constraint always holds when `amount = MAX_FIELD`

Withdraw as much as you want!

Secret Backdoors in Noir

```
1  fn low_income(pwd, salary){
2    let m = 12;
3    let avg_salary = salary / m;
4
5    // Complex data flow
6    for ...
7    // Stealthily set m to 0
8
9    // Backdoor
10   if (pwd == MAGIC)
11     avg_salary = salary / m;
12
13   assert(avg_salary < 100);
14 }
```

⇦ Division-by-zero

Secret Backdoors in Noir

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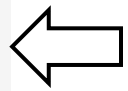
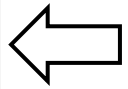
12
13   assert(avg_salary < 100);
14 }
```



avg_salary ← 0

Secret Backdoors in Noir

```
1  fn low_income(pwd, salary){
2    let m = 12;
3    let avg_salary = salary / m;
4
5    // Complex data flow
6    for ...
7    // Stealthily set m to 0
8
9    // Backdoor
10   if (pwd == MAGIC)
11     avg_salary = salary / m;
12
13   assert(avg_salary < 100);
14 }
```



0 < 100 Passed

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⇦ Backdoor

Input `pwd = MAGIC` and receive benefits for low-incomers!

Summary

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- Approach: two mutations:
  - Satisfiability-invariant mutation
  - Information visibility mutation
- Findings: 21 bugs on four mainstream ZK compilers

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Thanks for listening!