zkSNARKs for Virtual Machines are Non-Malleable

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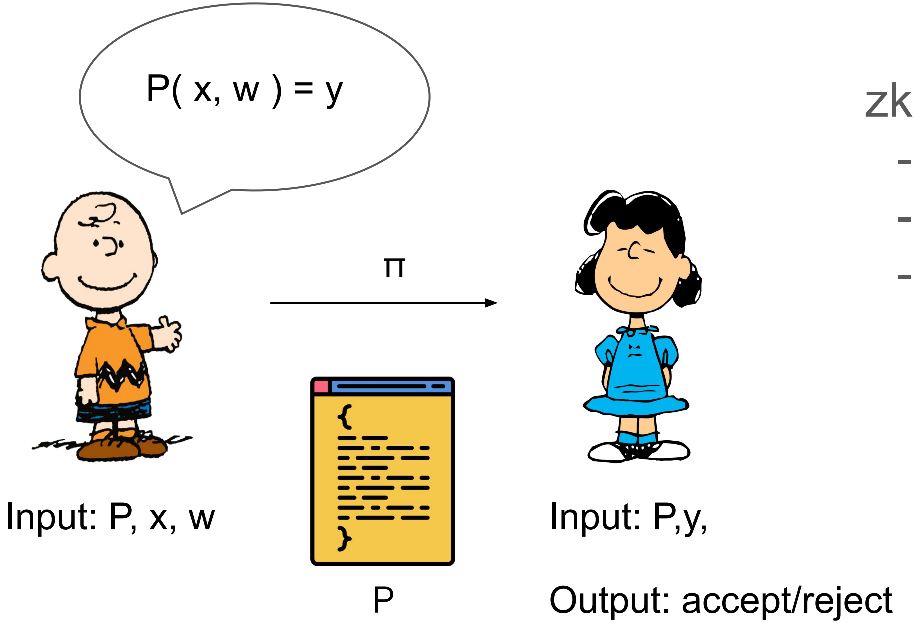
EURECOM
Sophia Antipolis

Proofs of program execution



P(x, w) = y

π

Input: P, x, w

P

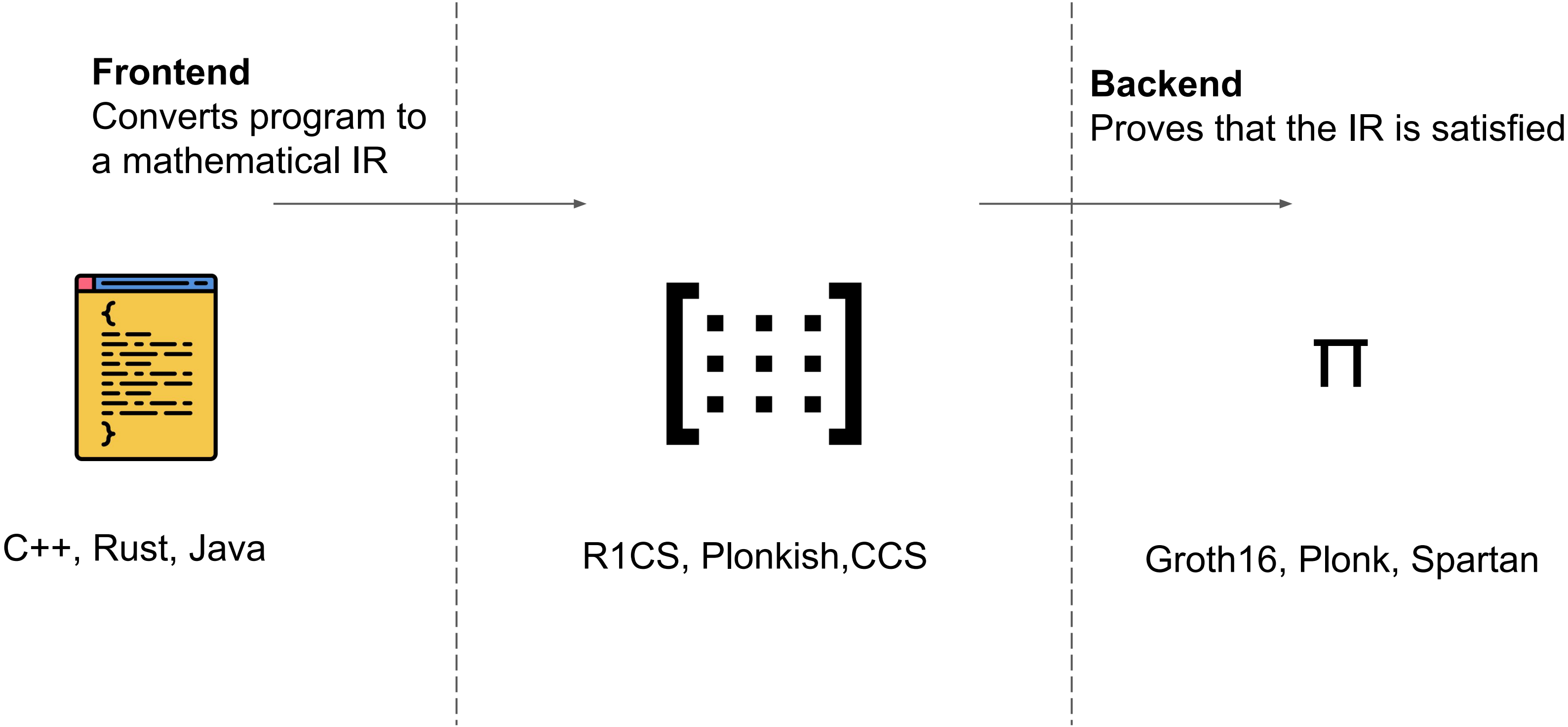
Input: P,y,

Output: accept/reject

zkSNARK

- Zero-knowledge
- Non-Interactive
- Succincts

zkSNARKs: frontends and backends



Frontend
Converts program to a mathematical IR

Backend
Proves that the IR is satisfied

C++, Rust, Java

R1CS, Plonkish,CCS

Groth16, Plonk, Spartan

The classical approach

Per-Program compilation
compiles each program into a new “circuit”

R1CS, Plonkish,CCS

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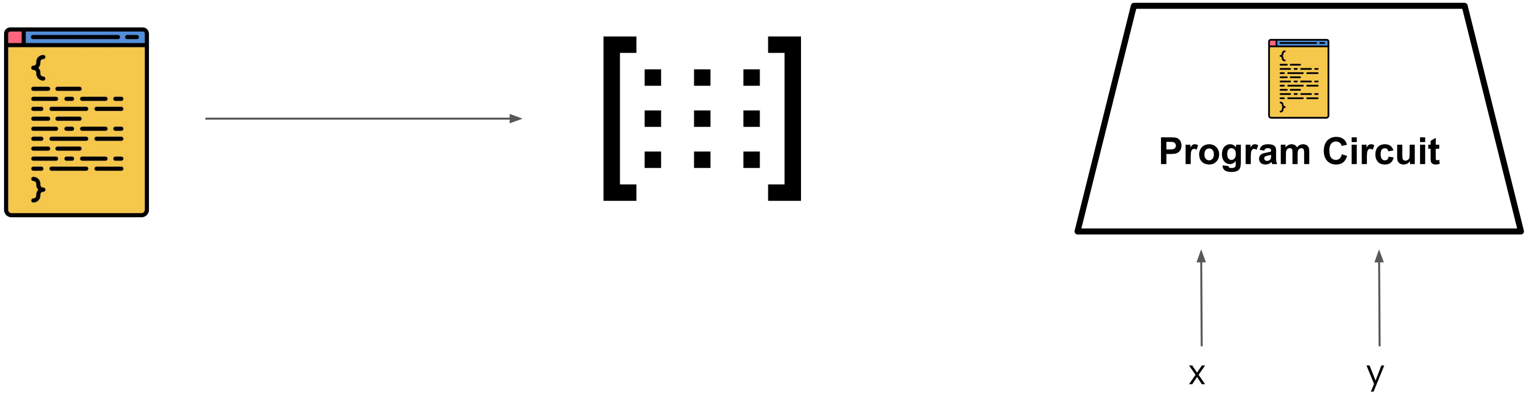
compiles each program into a new “circuit”



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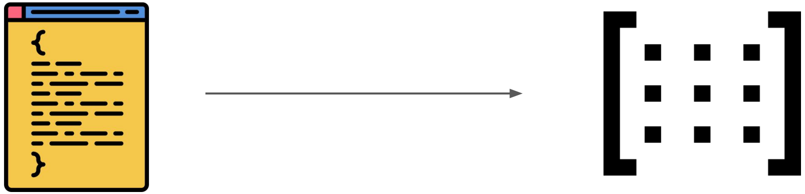
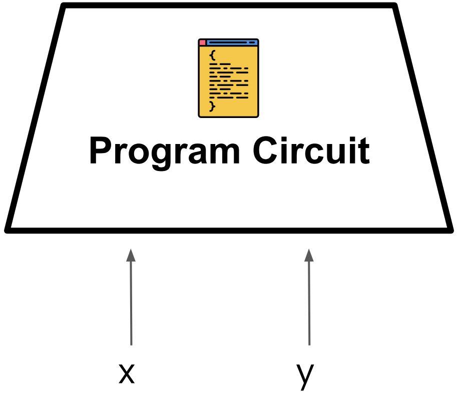


- Need to perform auditing and formal verification
- Ad-hoc languages and tooling

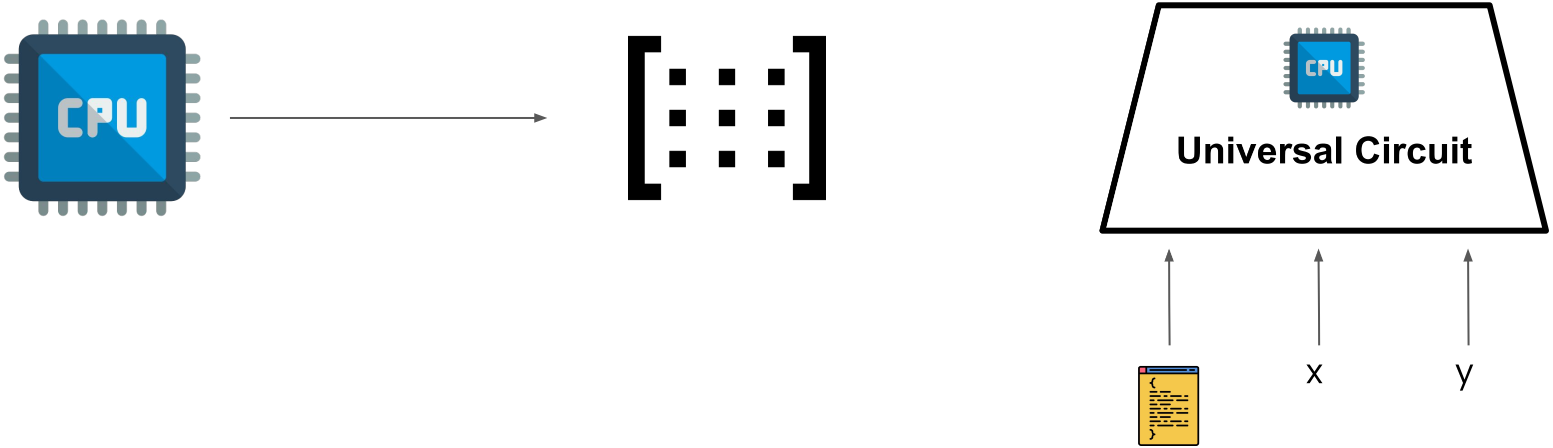


The zkVM approach

Per-Processor compilation
use a universal circuit that takes input (P,x) outputs y=P(x)

Frontend: a different approach

Per-Processor compilation
use a universal circuit that takes input (P,x) outputs y=P(x)



Universal Circuit

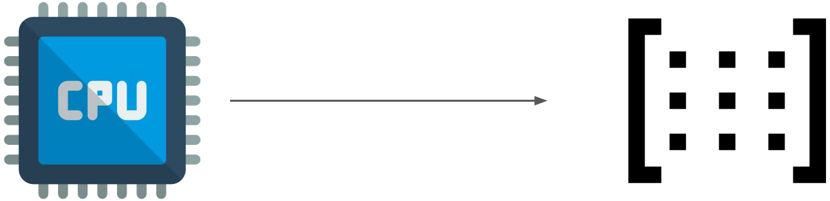
x

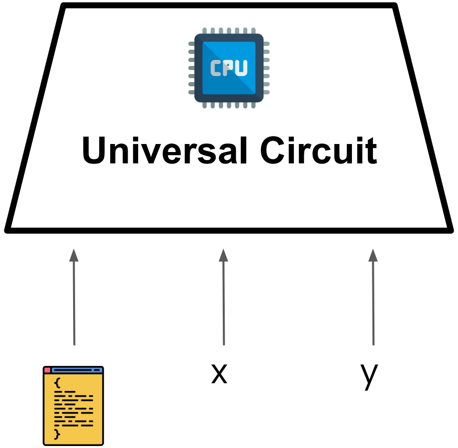
y

Frontend: a different approach

Per-Processor compilation

use a universal circuit that takes input (P,x) outputs y=P(x)





+ Auditing and formal verification on one circuit

+ Re-use existing languages and tooling

Frontend: a different approach

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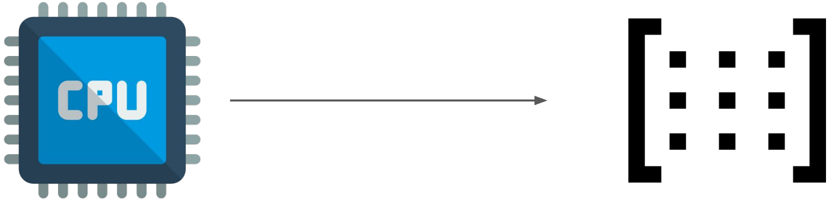

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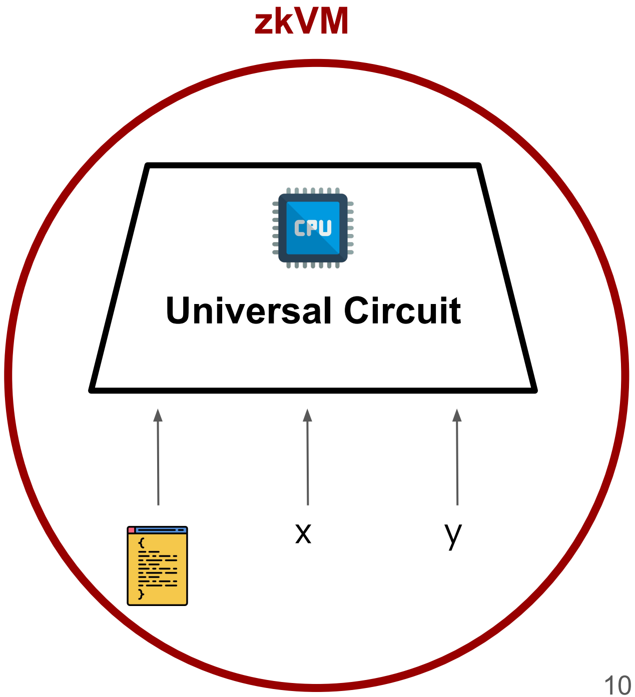

Applications & Use Cases

Generic

- Proof of solvency
- Image provenance
- Content moderation
- Fancy T-Shirt with a succinct proof of Fermat's last theorem (OR .. OR ..)

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Blockchain-related

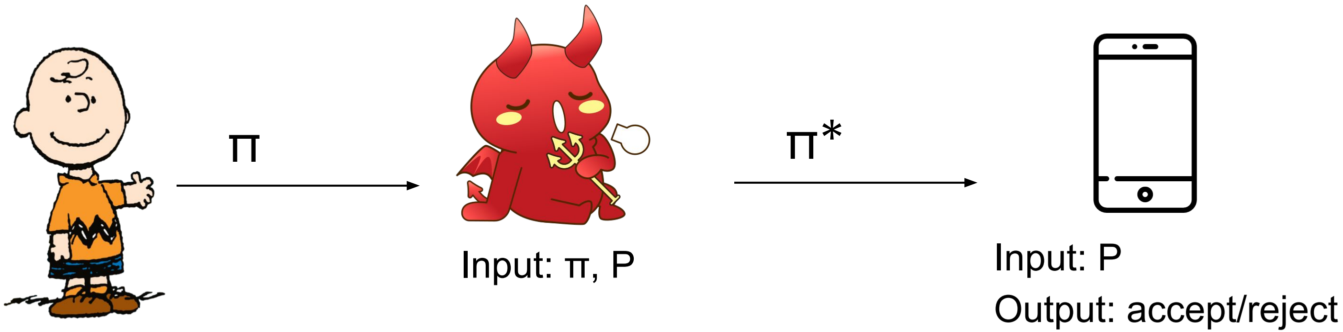
- Private transactions

- Private smart contracts

- ZK-Rollups

Can old proofs on-chain be useful to the adversary?

Security Question



π

π^*

Input: π, P

Input: P

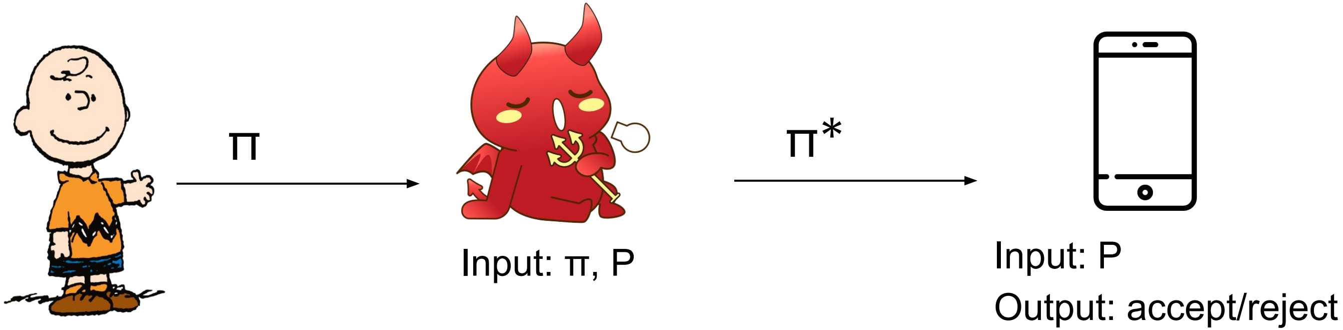
Output: accept/reject

Malleability attack

Modify an existing proof into a new proof

without knowing the witness

Security Question



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π^*

Input: π, P

Input: P

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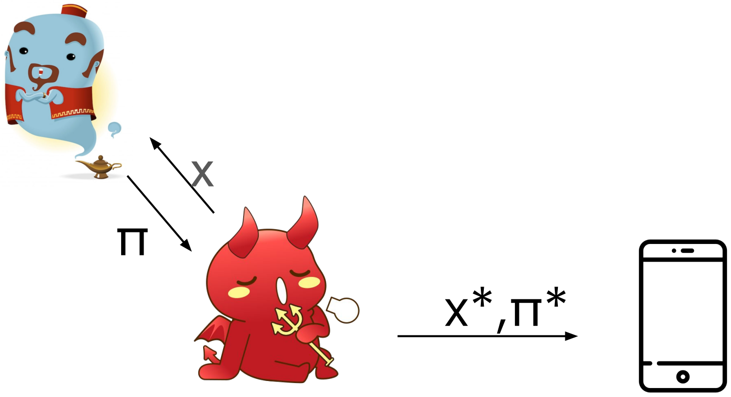
Malleability attack

Modify an existing proof into a new proof without knowing the witness

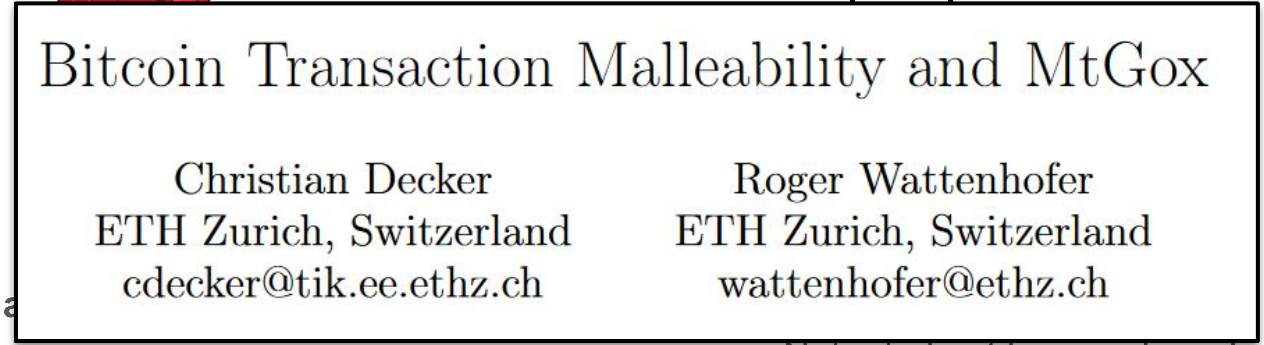
⚠ Not ruled out by zero-knowledge and knowledge soundness

Non-Malleability for zkSNARKS = Simulation-Extractability



- Adversary interacts with ZK simulator, and then forge a proof.
- We consider zkVMs that are indeed zero-knowledge 🙃.

Security Issues



Bitcoin Transaction Malleability and MtGox

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Malleability a

Modify an existing proof into a new proof without knowing the witness

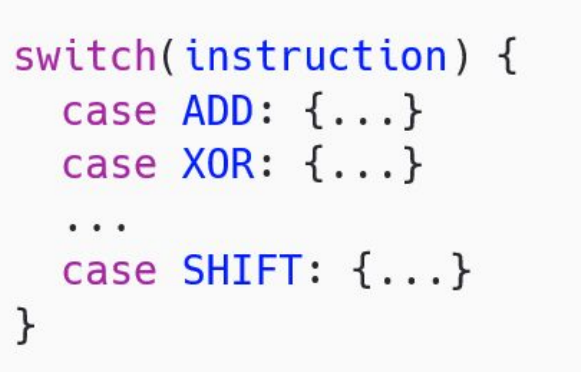
Not ruled out by zero-knowledge and knowledge soundness

Non-malleability of existing zkSNARKs

	[GOP+22]	[GKK+22]	[DG23]	[FFK+23]	[KPT23]	[Lib24]
Bulletproofs	✓		✓			
Spartan			✓			
Sonic		✓				
PLONK		✓		✓	✓	
Marlin		✓		✓	✓	
Lunar				✓	✓	
Basilisk				✓		
HyperPlonk						✓

The complexity of a zkVM

A universal circuit is large
It must be able to execute any operation at each step
e.g. RISC-V has 50 operations



```
switch(instruction) {
  case ADD: {...}
  case XOR: {...}
  ...
  case SHIFT: {...}
}
```

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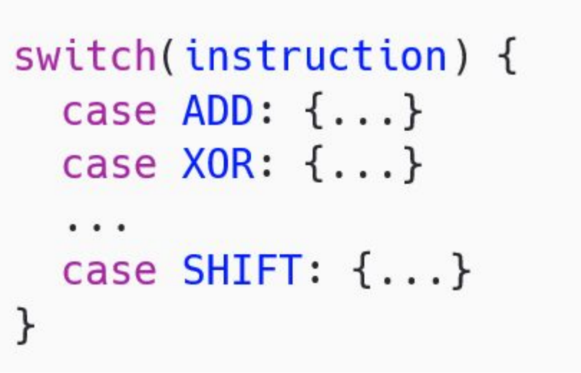

```
switch(instruction) {
  case ADD: {...}
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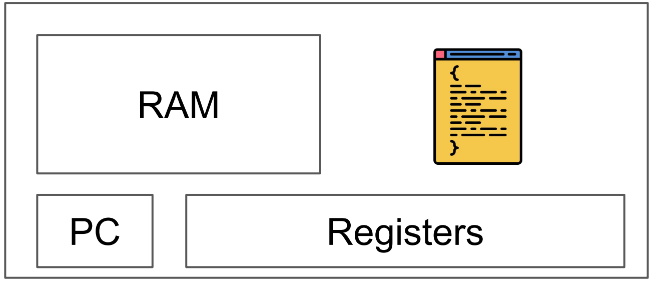
It's not only about instructions
The zkSNARK-Prover proves that:

- The memory is consistent throughout the entire computation
- The fetch and decode are correctly executed

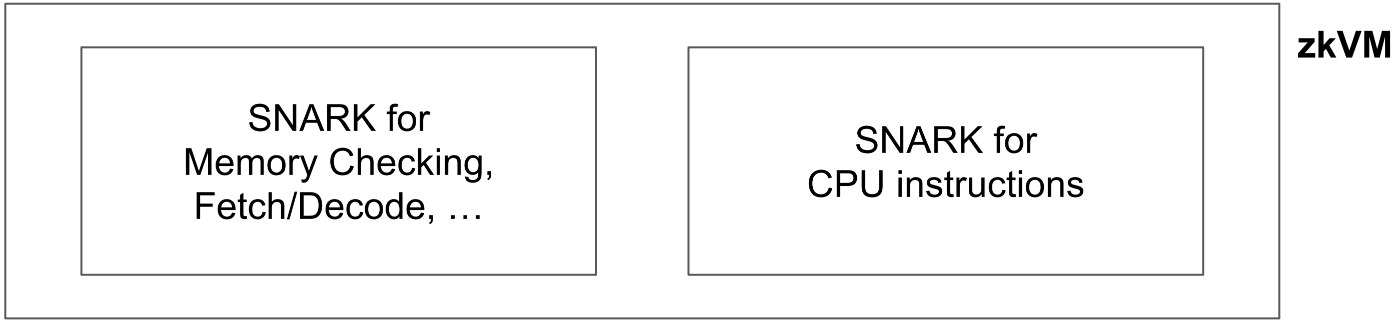


RAM

PC

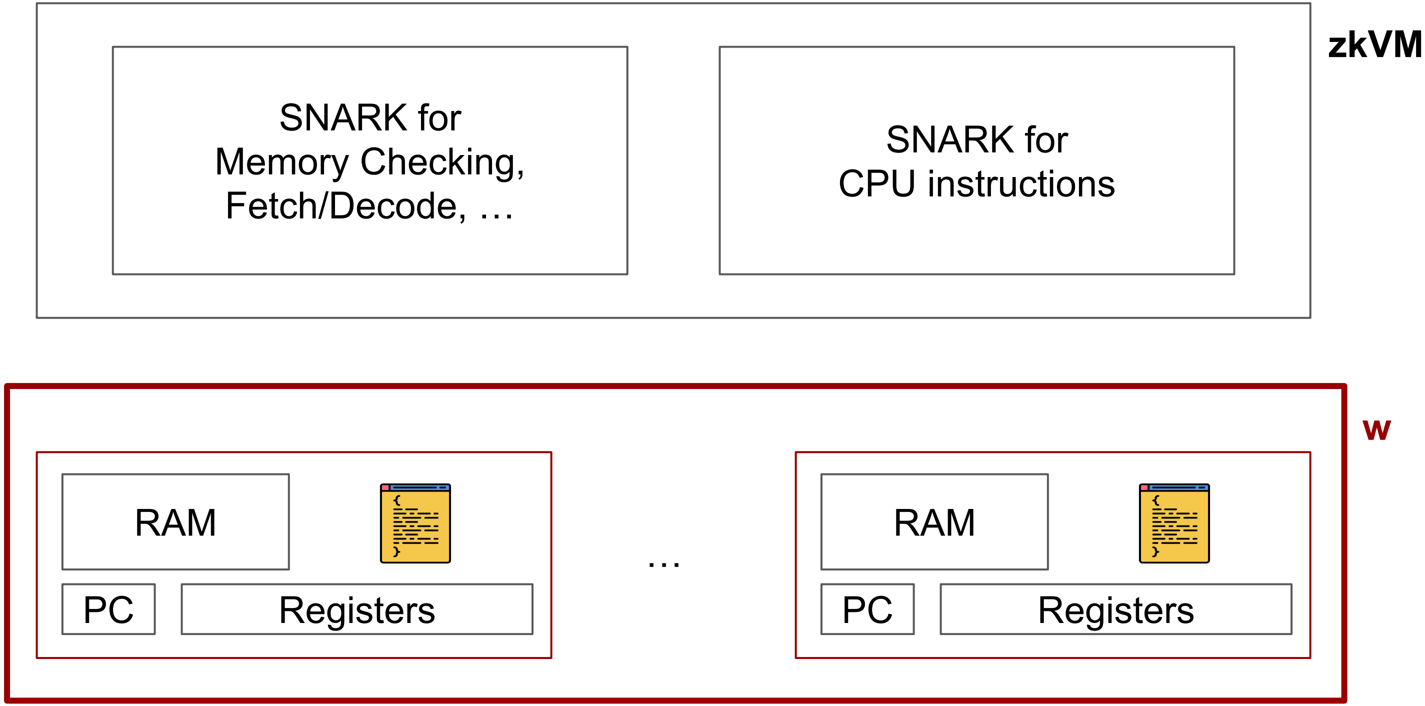
Registers

Joltish: a modular zkVM

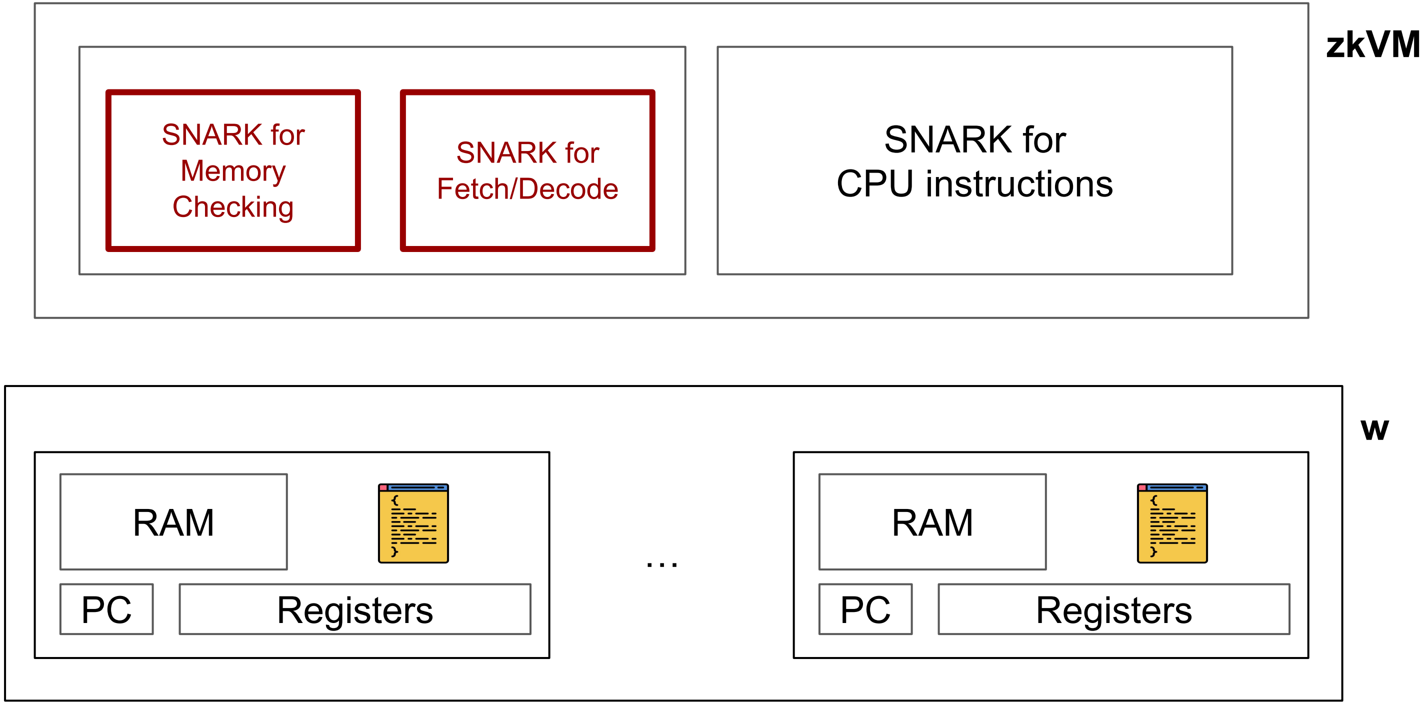


- Many zkVM's designs are modular (it's just natural)
- **Jolt** [AST'24] is the first zkVM based on *the lookup-singularity*
- Our Joltish: inspired by Jolt, but not quite Jolt

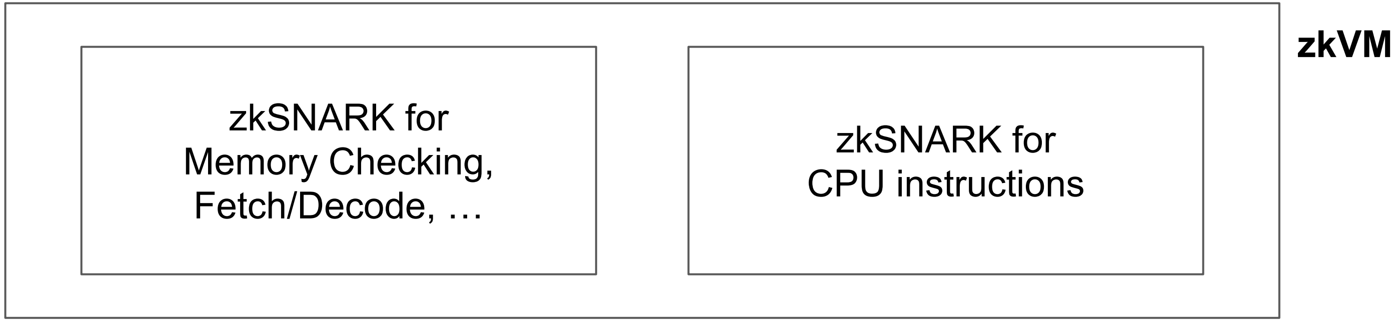
Joltish: a modular zkVM



Jolt~~ish~~: a modular zkVM



Joltish: a modular zkVM

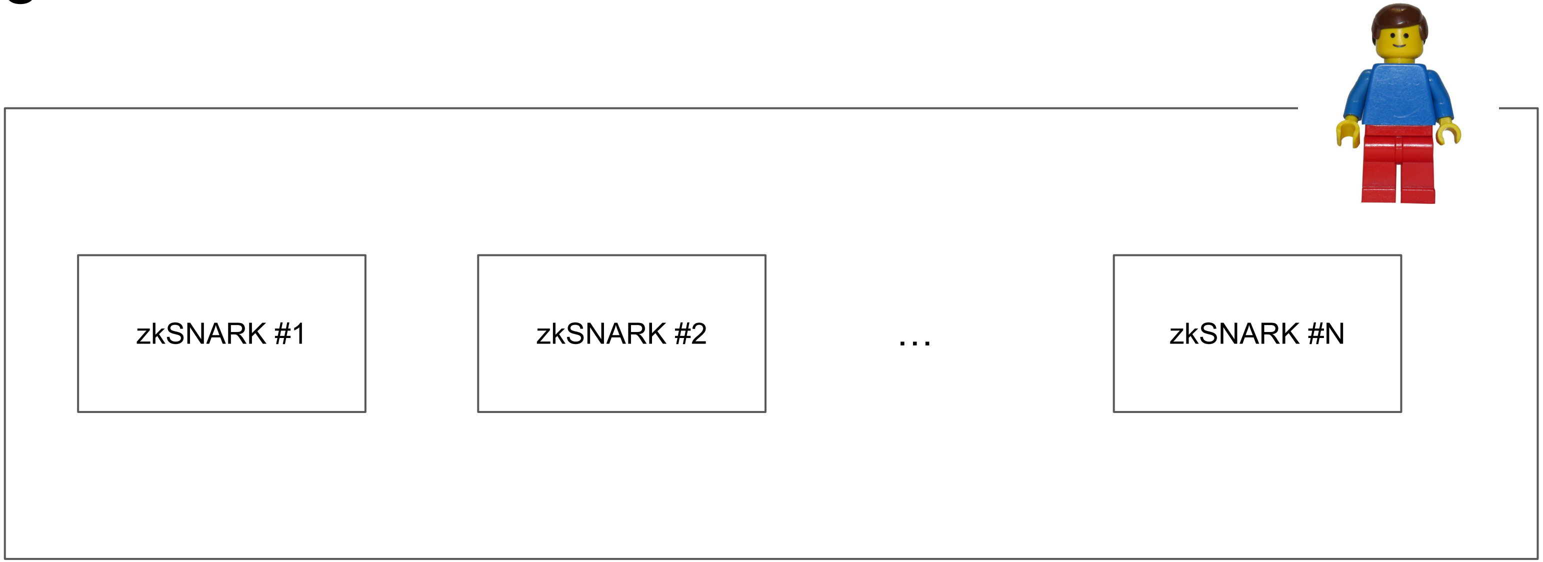

zkSNARK for Memory Checking, Fetch/Decode, …

zkSNARK for CPU instructions

zkVM

What are the conditions for the non-malleability of Joltish?

Lego-ish: a modular zkSNARK



zkSNARK #1

zkSNARK #2

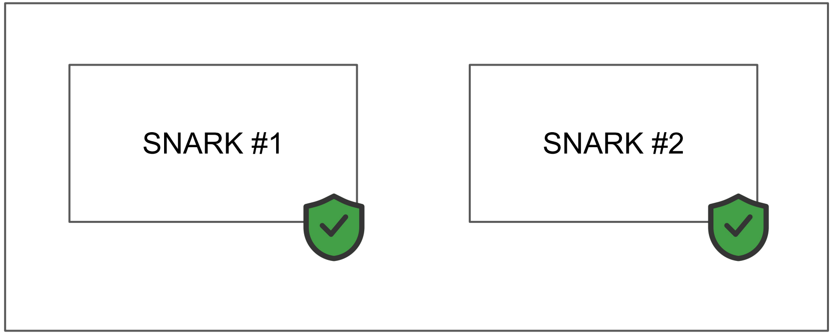
…

zkSNARK #N

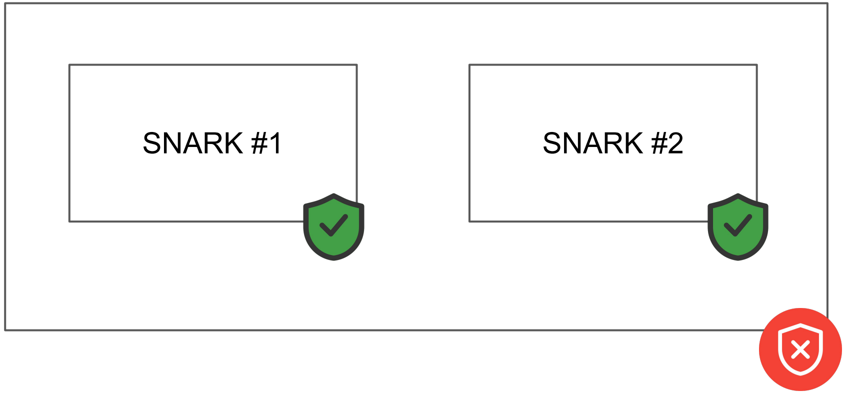
What are the conditions for the non-malleability of Joltish?

What are the conditions for the non-malleability of modular zkSNARKs?

Non-malleability challenges

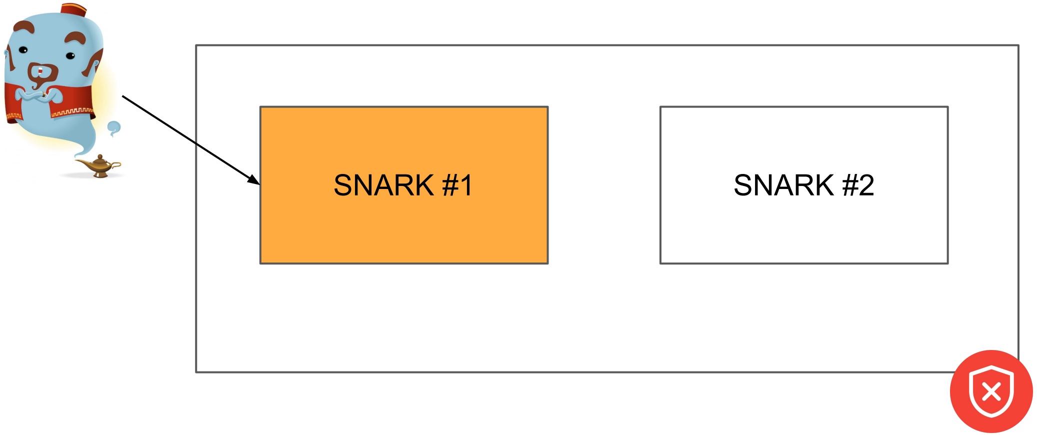


Non-malleability challenges



Copy & Paste attacks
Composition of non-malleable SNARK is not always secure

Non-malleability challenges



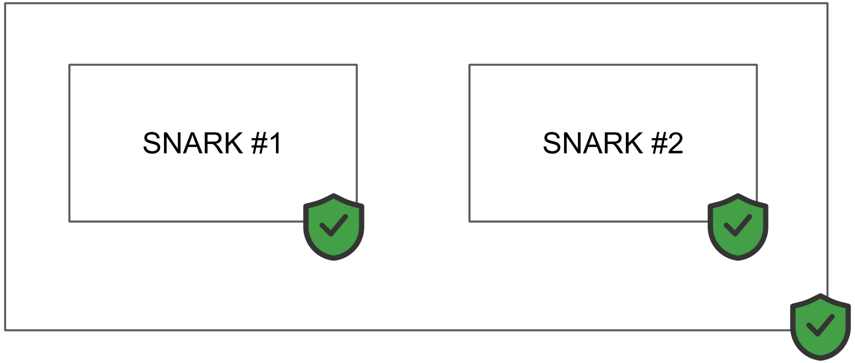
Copy & Paste attacks
Composition of non-malleable SNARK is not always safe!

Conjunction of Commit-and-Prove Relations

- A commit-and-prove relation (c, x ; w) in R iff
  - (1) P(x,w) = 1
  - (2) c = Commit(w)

- (Commit and Prove) Conjunction of R1 and R2 with shared witness
  - Instance (c, x1, x2)
  - Witness w
  - P1(x1, w) = 1 AND P2(x2, w) = 1 AND c = Commit(w)

Conjunction



R1(x1,w)=1 AND R2(x2,w)=1

Can we prove Non-Malleability for the conjunction with shared witness?

Yes! We give two (slightly different) Non-Malleable Compositions

Conjunction: First Case

Prover (x_1, x_2, w):

- commits w: as c = Commit(w)

- proves (c, x1; w) in R1 using zkSNARK #1

- proves that (c, x2; w) in R2 using zkSNARK #2

✓

Conjunction: First Construction

Prover (x_1, x_2, w):

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zkSNARK #1

zkSNARK #2

Trapdoorless zero-knowledge, Sim-Extractable

Conjunction: Secon

- ZK-sim for Conjunction: compute honest π1, simulate π2
- Reduction to KS of SNARK#1 does not need of simulated proofs
- π1 could be malleable => SoK: any change on π1 needs a new signature π2′

P(x_1, x_2, w):

- - commits w: as c

- proves (c, x1; w) in R1 using zkSNARK #1

- proves that (c, x2; w) in R2 using zkSNARK #2

and π2 is also a Signature-of-Knowledge for π1

SNARK #1

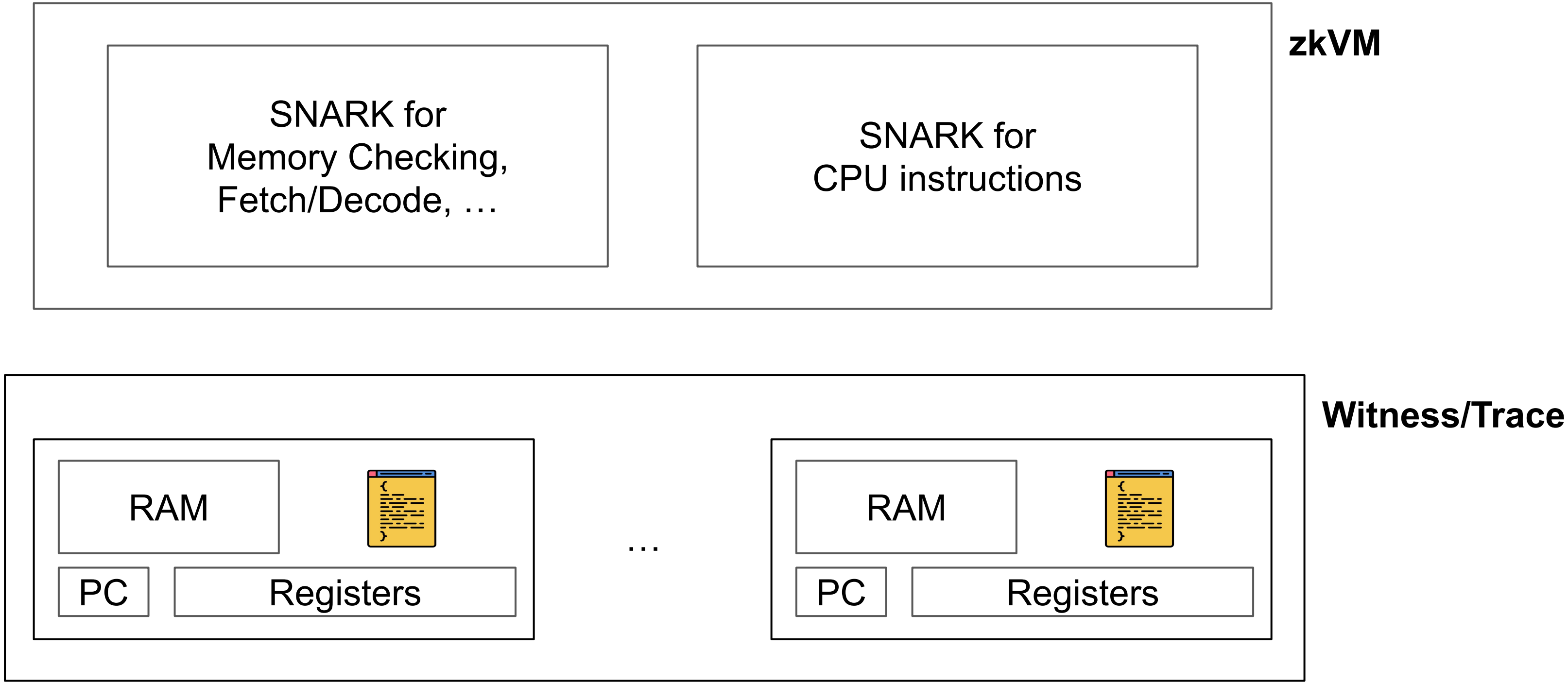
Witness-indistinguishability, knowledge-soundness,

efficient witness-computability *(easy to find w for x1)*

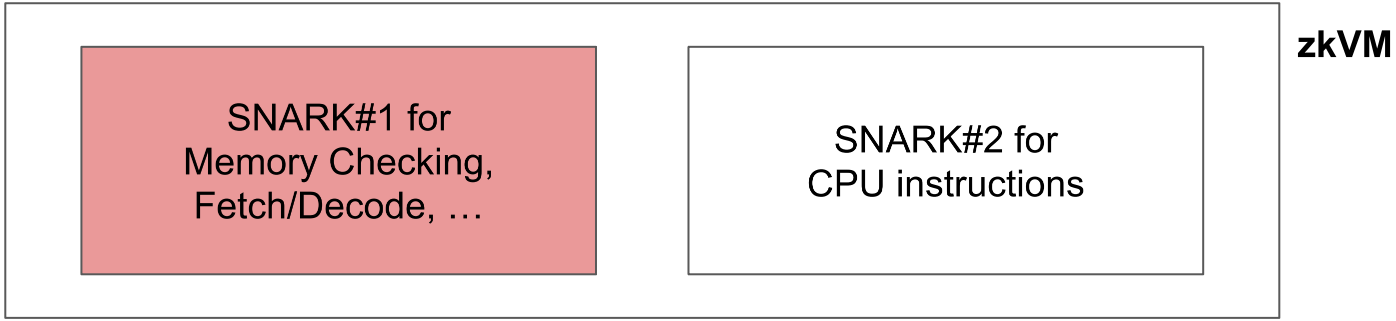
SNARK #2

Trapdoorless zero-knowledge, SoK (Sim-Extractable)

On the Non-Malleability of Joltish

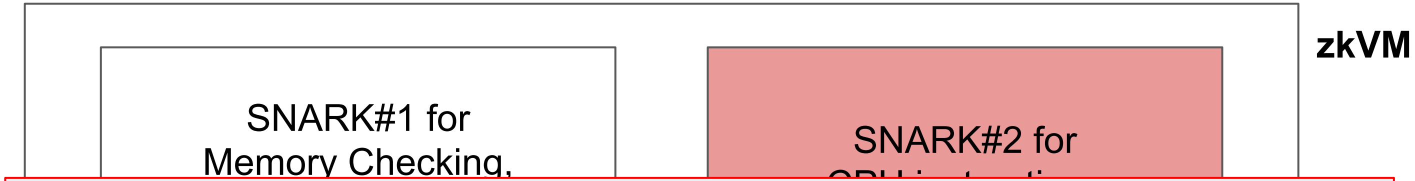


On the Non-Malleability of Joltish



- Knowledge-sound SNARK for Memory Checking, Fetch/Decode, …

On the Non-Malleability of Joltish

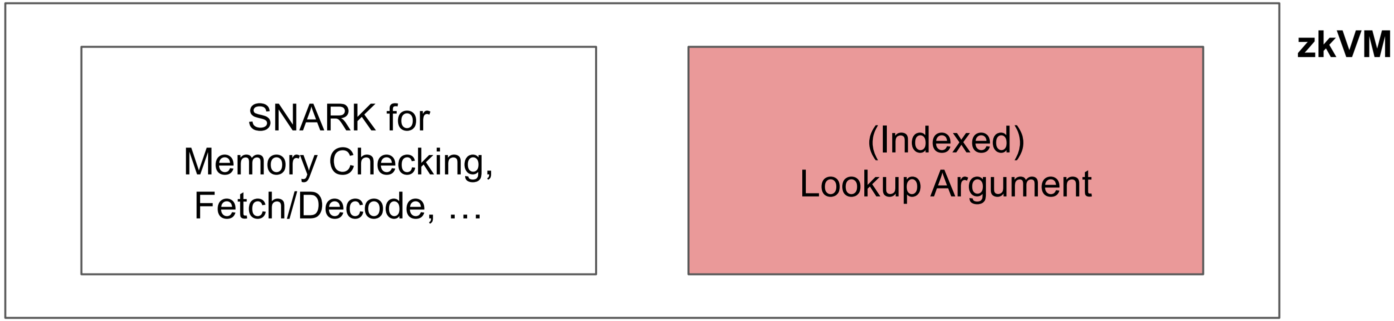


- Statement: (P,x,y) s.t. P(x)=y on RISC-V architecture.
- ZK-Simulator for (P,x,y) s.t. P(x)=y’≠ y on RISC-V architecture
  1) Hack the instructions set s.t. P(x)=y
  2) Run P(x)=y on hacked architecture to obtain program trace W
  3) W good trace for (P,x,y) for SNARK#1 => Run Prover#1
  4) W not good witness for P(x)=y for SNARK#2 => Simulated Proof

- K

- S

The Lookup Singularity based zkVM



- Knowledge-sound SNARK for Memory Checking, Fetch/Decode, …

- Sim-Ext ~~zkSNARK for CPU instructions~~ Lookup Argument

Lookup Arguments

- Lookup Arguments prove that committed vector F is sub-vector of big table T
  - |F| << |T|
  - prover complexity is proportional to |F|
- They can handle very big table:
  - as big as truth tables of all RISC-V instructions
- Lookup Argument in Jolt is Lasso [STW'24]

zk-Lasso

- Define a zero-knowledge version of Lasso
- Prove Sim-Extractability: based on the framework of [FaustKMV12]

  (trapdoorless ZK + Unique Response + Special Soundness => Sim Ext)

- We extend and improve over [Dao and Grubbs23]
  - (Lasso is based on Spartan)

Future Works

- Non-Malleability of ~~zk~~SNARKs: non-malleability w/o simulation extractability?
- Non-Malleability for composition of Reduction-of-Knowledge: very natural!
- Non-Malleability of other Lookup Arguments?

Thank you

Truth table and lookups

XOR(x,y)

x	**y**	**out**
00	00	00
00	01	01
00	10	10
00	11	11
	…	
11	10	01
11	11	00

Truth table and lookups

XOR(x,y)

x	**y**	**out**
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Checking that out = XOR(x,y) can be reduced to

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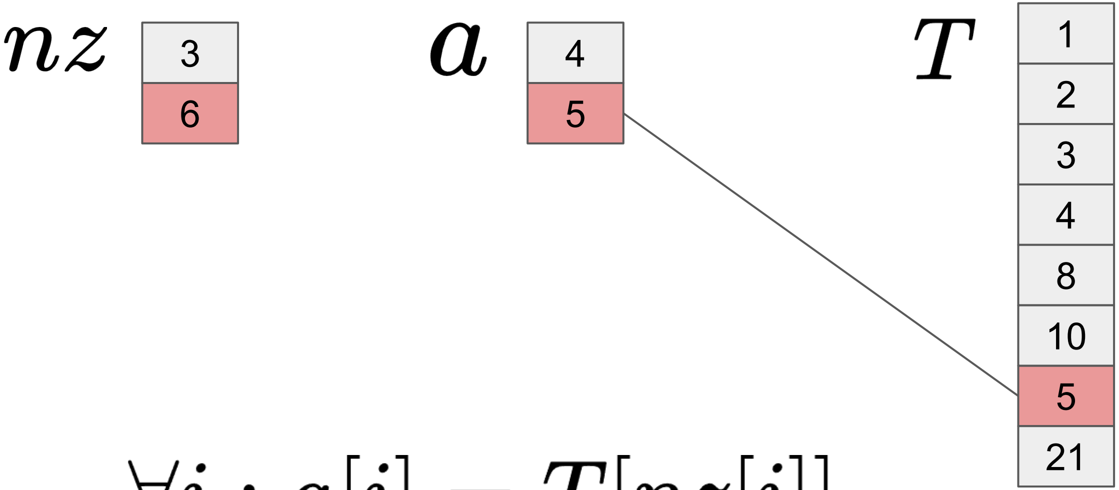
Lasso in a nutshell



$$\forall i : a[i] = T[nz[i]]$$

Lasso in a nutshell

0	0	0	1	0	0	0	0
0	0	0	0	0	0	1	0

M

1
2
3
4
8
10
5
21

T

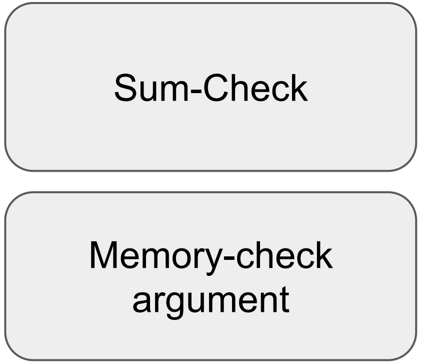
4
5

a

Lasso in a nutshell

+ Reduces the matrix-vector product to a Sum-Check
+ Performs a memory-checking argument
+ Supports gigantic tables as long as they are structured

- The scheme is not zero-knowledge



Sum-Check

Memory-check argument

Non-Malleability of Lasso

Reduce non-malleability to Special Soundness + k-ZK + k-UR

- The simulator can reprogram the RO only at the k-th round
- Proofs are unique after the k-th round
- Witness can be extracted from a sufficient number of proofs… or we can break dlog!
- Use rewinding to extract

References

[DG23] Quang Dao and Paul Grubbs. Spartan and bulletproofs are simulation-extractable (for free!). EUROCRYPT 2023

[FFK+23] Antonio Faonio, Dario Fiore, Markulf Kohlweiss, Luigi Russo, and Michal Zajac. From polynomial IOP and commitments to non-malleable zkSNARKs. TCC 2023

[GKK+22] Chaya Ganesh, Hamidreza Khoshakhlagh, Markulf Kohlweiss, Anca Nitulescu, and Michal Zajac. What makes fiat-shamir zksnarks (updatable SRS) simulation extractable? SCN 2022

[GOP+22] Chaya Ganesh, Claudio Orlandi, Mahak Pancholi, Akira Takahashi, and Daniel Tschudi. Fiat-shamir bulletproofs are non-malleable (in the algebraic group model). EUROCRYPT 2022

[KPT23] Markulf Kohlweiss, Mahak Pancholi, and Akira Takahashi. How to compile polynomial IOP into simulation-extractable SNARKs: A modular approach. TCC 2023

[Lib24] Benoit Libert. Simulation-Extractable KZG Polynomial Commitments and Applications to HyperPlonk. PKC 202

Additional notes

Our results on Legoish SNARKs

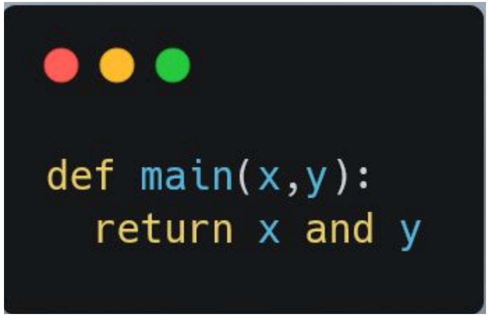
Conjunction (with shared witness)

- If two schemes are non-malleable then their composition is also non-malleable

- If the first scheme is knowledge-sound, witness-indistinguishable and witness-samplable, and the second one is a SoK, then their composition is non-malleable

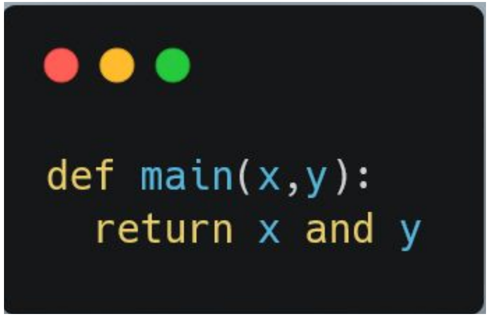
Similar results hold for **Functional composition**

From program to SNARK language



```
def main(x,y):
  return x and y
```

From program to SNARK language



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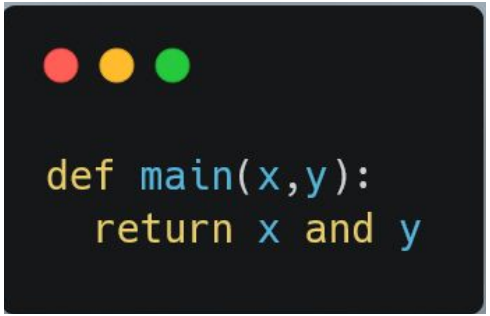
Polynomial Constraints

Check that:

- $x(x-1) = 0$
- $y(y-1) = 0$
- $x*y = out$

From program to SNARK language



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Polynomial Constraints

Check that:

- **$x(x-1) = 0$**
- **$y(y-1) = 0$**
- **$x^*y = out$**

Lookup Constraint

Check that **(x,y,out) belongs to the AND table**

zkSNARKs based on Lookup Singularity

Lookup Singularity

Transform arbitrary computer program into “circuits” that only perform lookups

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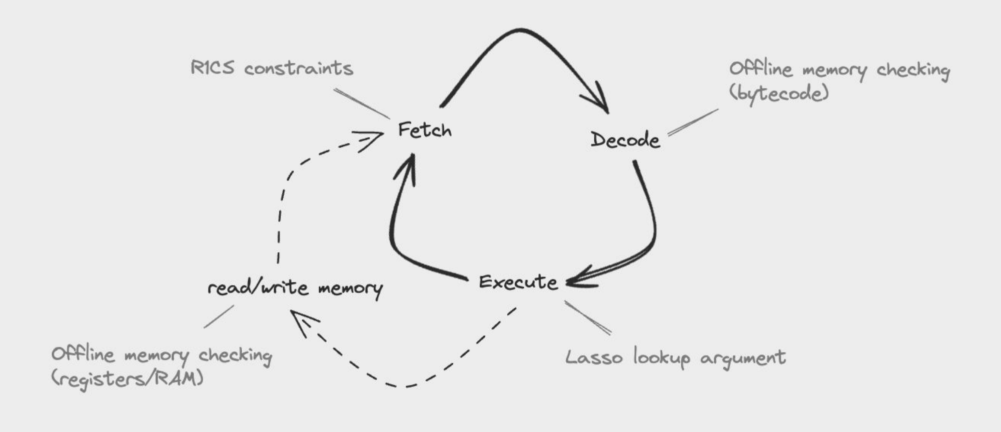
Lookup Singularity

Transform arbitrary computer program into “circuits” that only perform lookups

Jolt zkVM

- Repeatedly execute the fetch-decode-execute logic of its instruction set architecture (RISC-V)
- Perform reads and writes to RAM


R1CS constraints
Fetch
Decode
Offline memory checking (bytecode)
read/write memory
Execute
Offline memory checking (registers/RAM)
Lasso lookup argument

zkSNARKs based on Lookup Singularity

Lookup Singularity

Transform arbitrary computer program into “circuits” that only perform lookups

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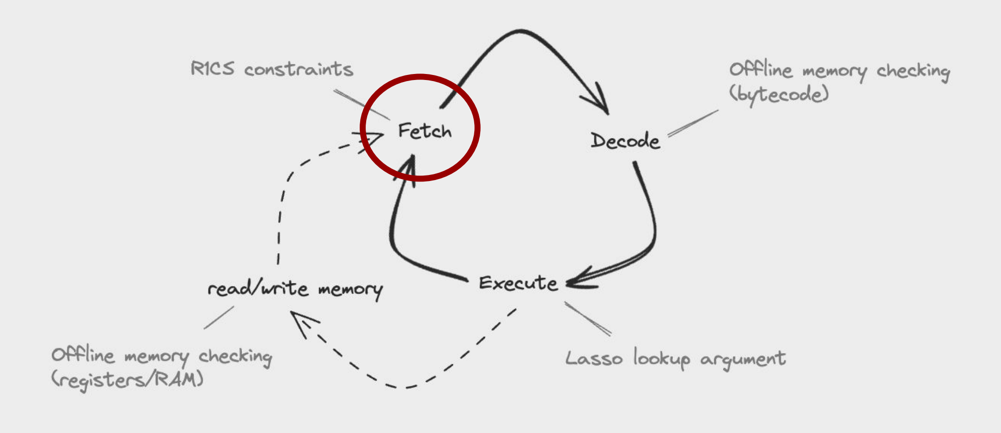


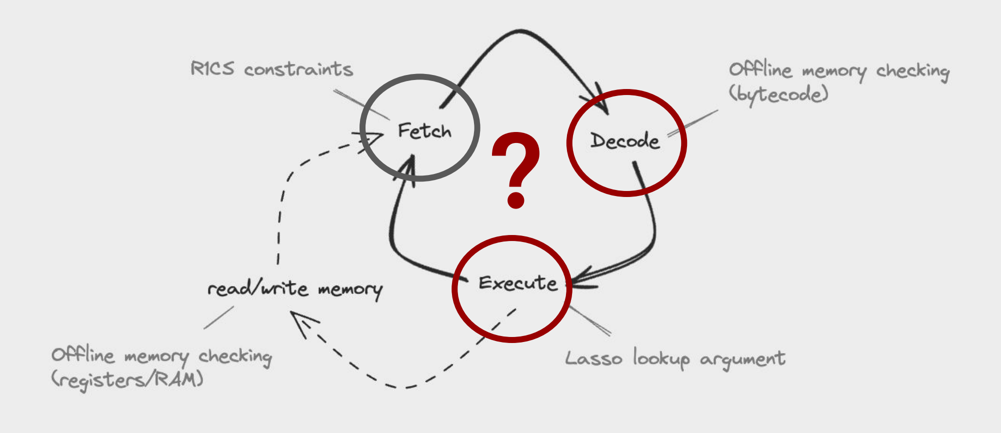
zkSNARKs based on Lookup Singularity

Lookup Singularity

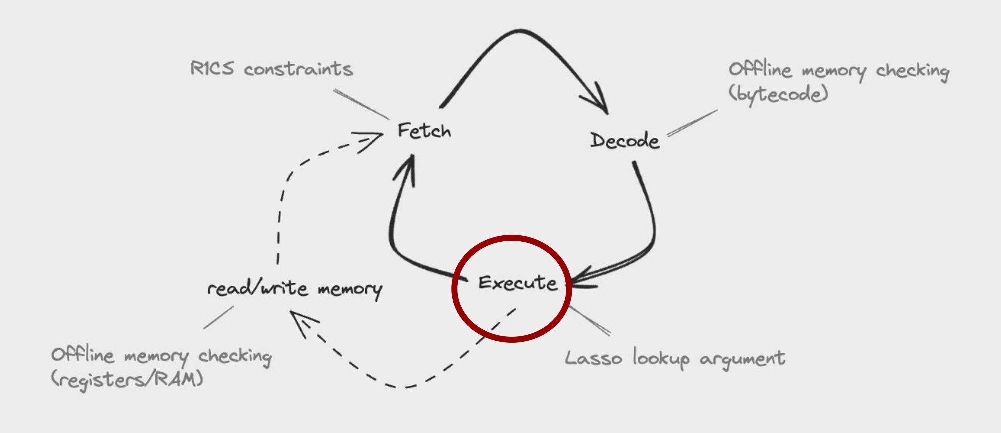
Transform arbitrary computer program into “circuits” that only perform lookups

Jolt zkVM

- Repeatedly execute the fetch-decode-execute logic of its instruction set architecture (RISC-V)
- Perform reads and writes to RAM


R1CS constraints
Fetch
Decode
Offline memory checking (bytecode)
?
Execute
read/write memory
Offline memory checking (registers/RAM)
Lasso lookup argument

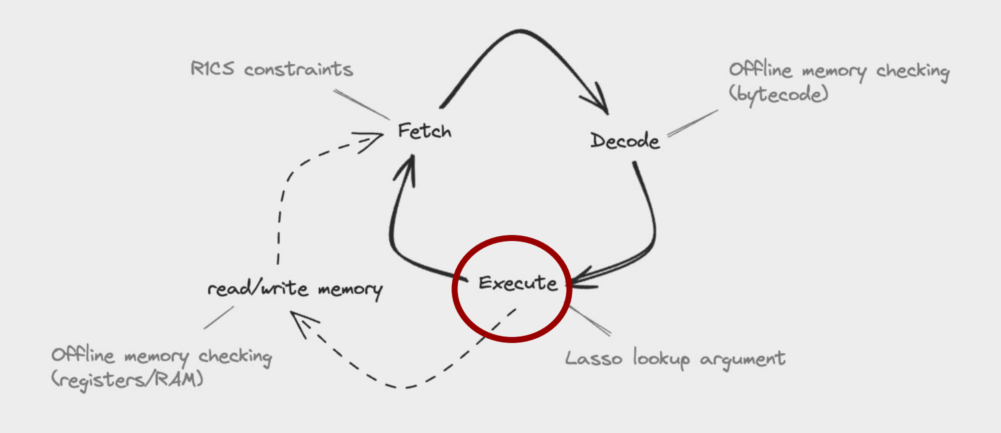
So what are our results?



So what are our results?

A zero-knowledge version of Lasso

- ○ Non-malleable under minimum assumptions (dlog+RO)
- ○ Comparably fast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Credits

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