zkSNARKs for Virtual Machines are Non-Malleable

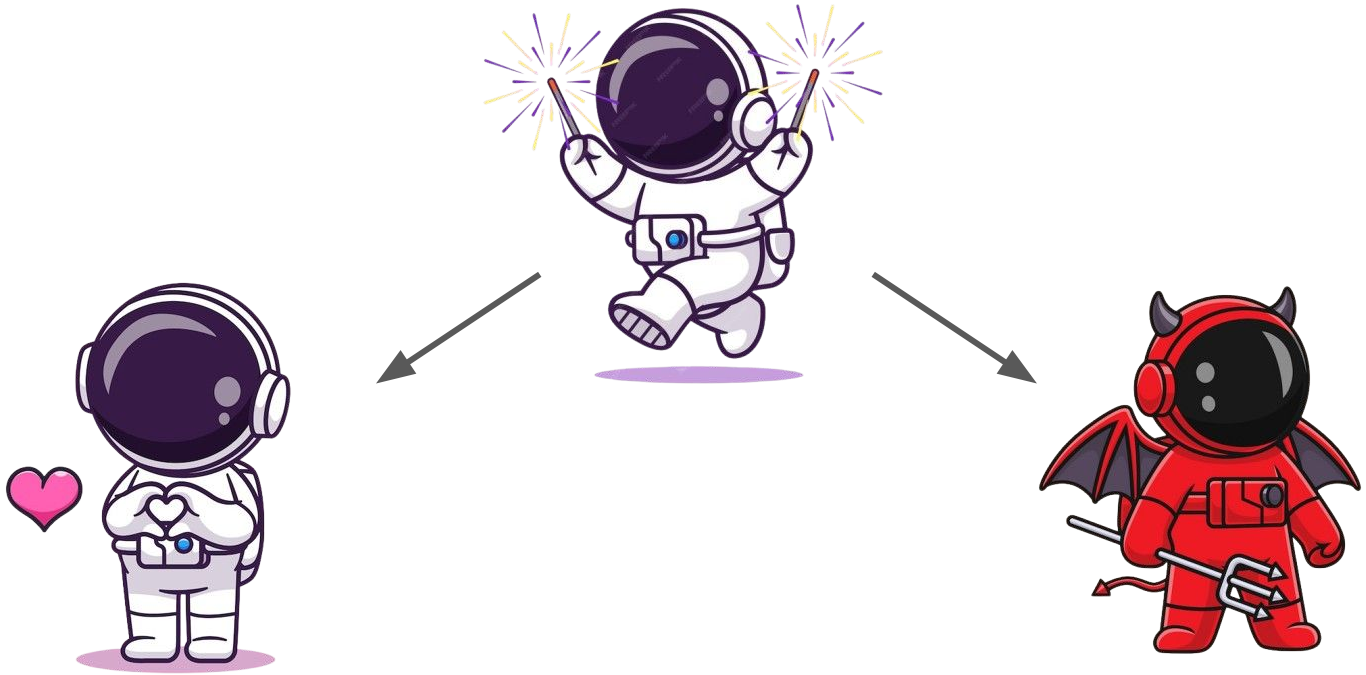
Matteo Campanelli, Antonio Faonio, **Luigi Russo**

Malleability in Cryptography

Métamorphose de Narcisse, Salvador Dalí (1937)

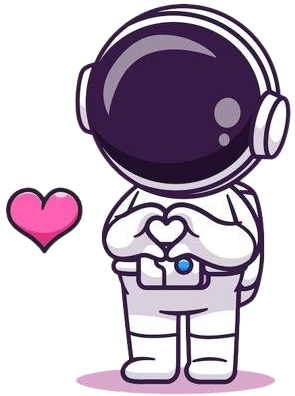
"Efficiently transforming a cryptographic object into a new valid one"

The double face of Malleability



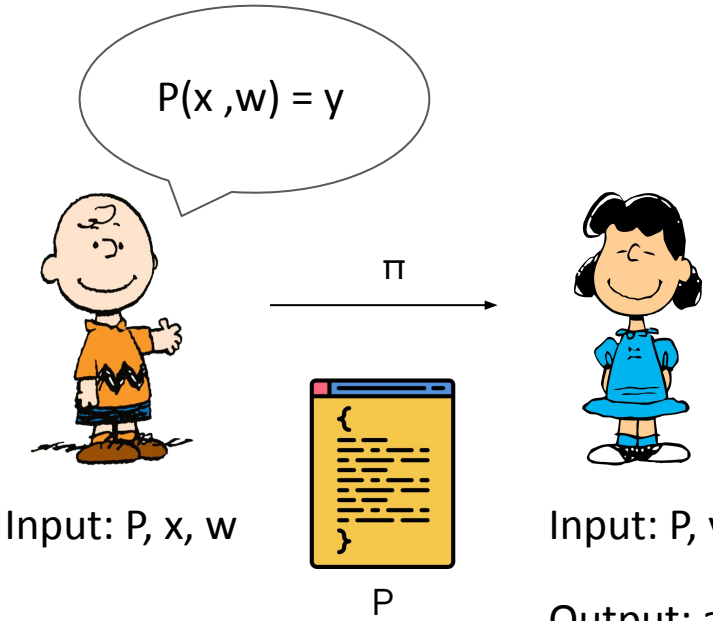
The double face of Malleability: (zk)SNARKs

The previous talk



This talk

Proofs of program execution



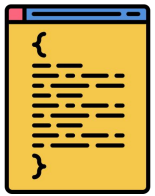
zkSNARK

- Zero-knowledge
- Non-Interactive
- Succinct
- Knowledge-sound

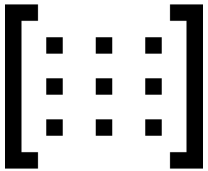
zkSNARKs: frontends and backends

Frontend
Converts program to a mathematical IR

Backend
Proves that the IR is satisfied



C++, Rust, Java



R1CS, Plonkish,CCS

Groth16, Plonk, Spartan

Frontend: zkVM

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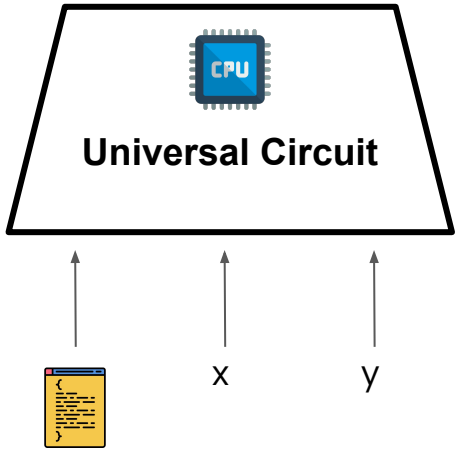
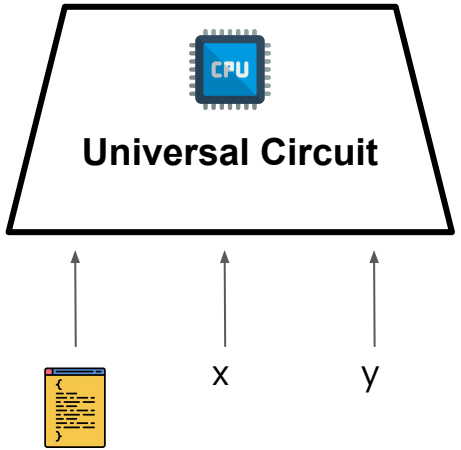


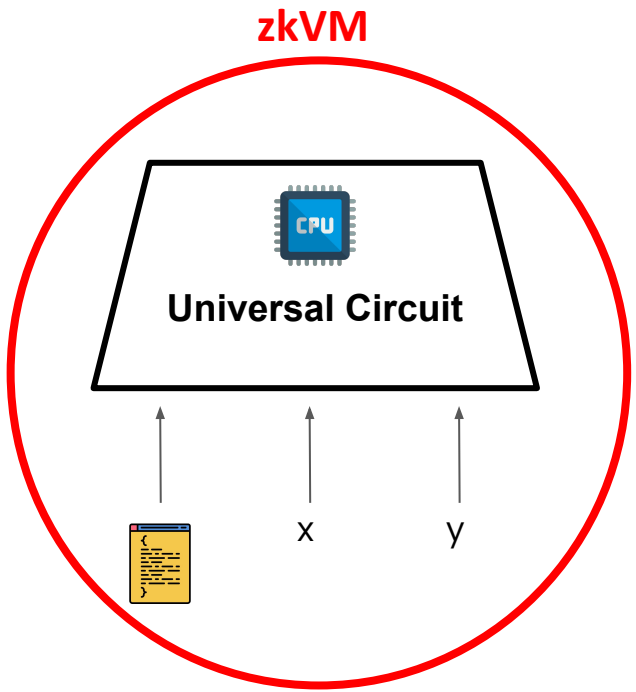
Frontend: zkVM



+ Auditing and formal verification on one circuit

+ Re-use existing languages and tooling

Frontend: zkVM



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Applications & Use Cases

Generic
- Proof of solvency
- Image provenance
- Content moderation

Blockchain-related
- Private transactions
- Private smart contracts
- ZK-Rollups

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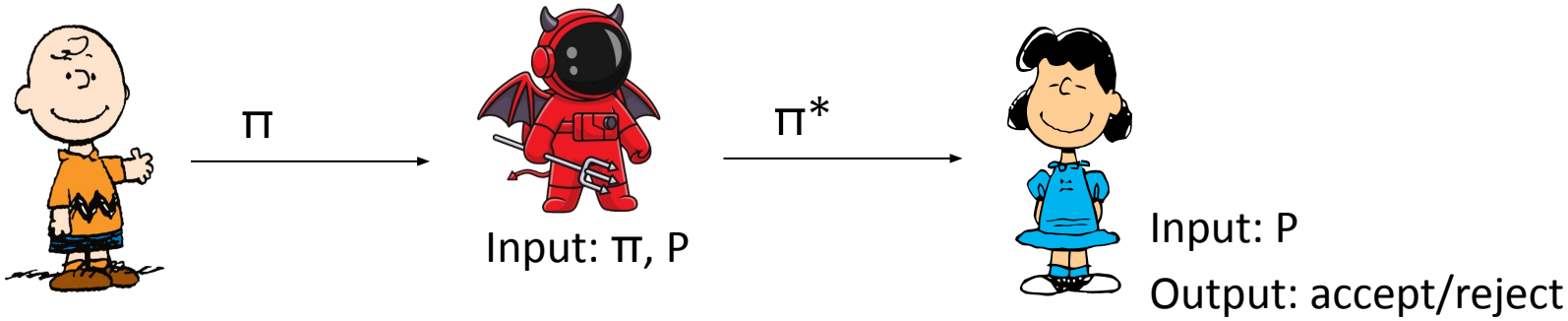
Can old proofs be useful to the adversary?

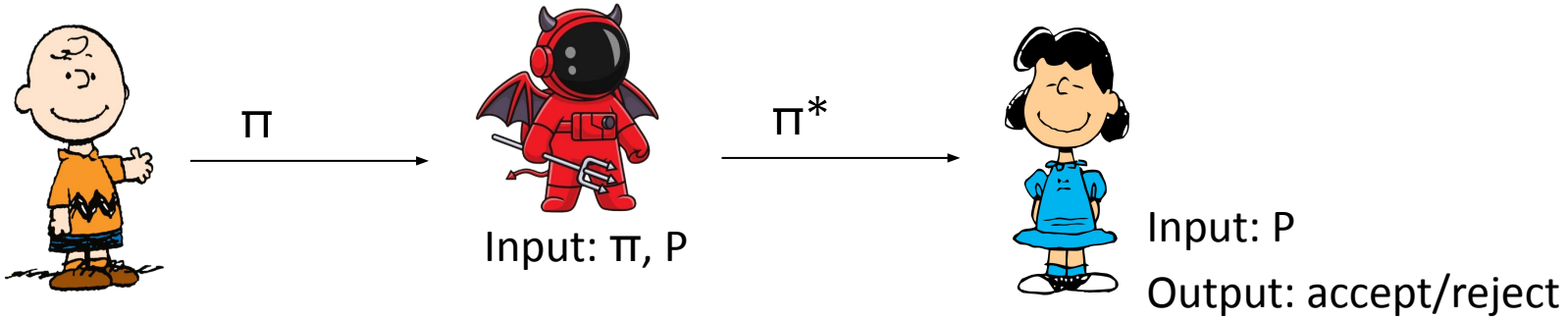
Malleability of zkSNARKs



Malleability attack

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

Malleability of zkSNARKs

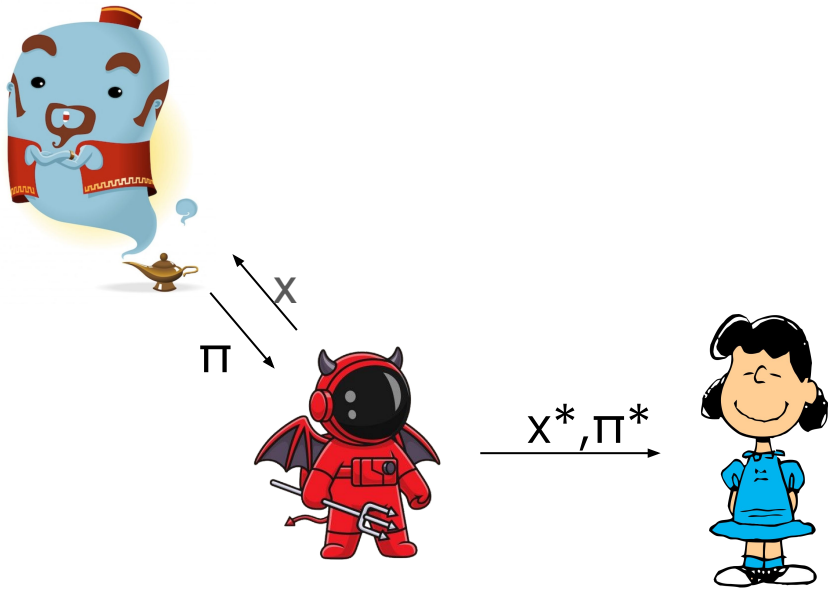


Malleability attack

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

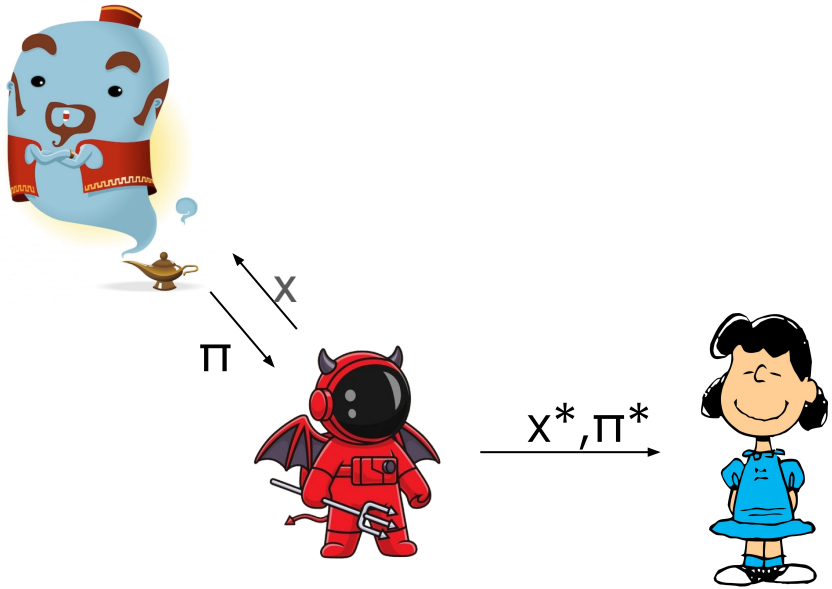
Not ruled out by zero-knowledge and knowledge soundness

Non-Malleability of zkSNARKs



Non-Malleability of zkSNARKs

= Simulation Extractability



Non-Malleability of existing zkSNARKs

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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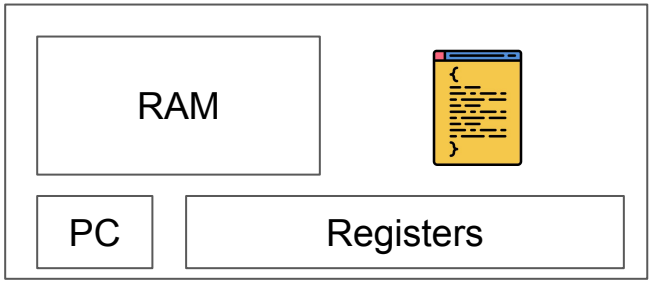
It's not only about instructions
The zkSNARK-Prover proves that:

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



Our Results

1. A “natural” (and truly zero-knowledge) zkVM, inspired by Jolt

2. A framework for the non-malleability of “composable” zkSNARKs

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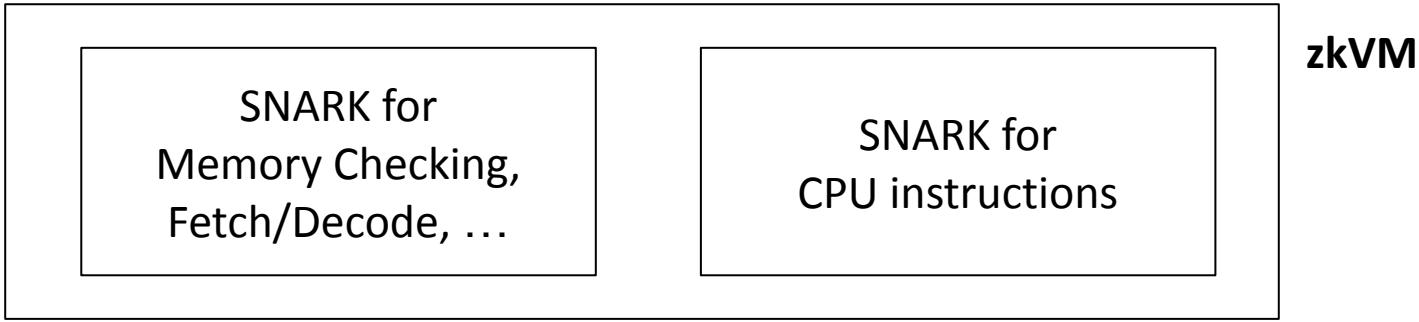
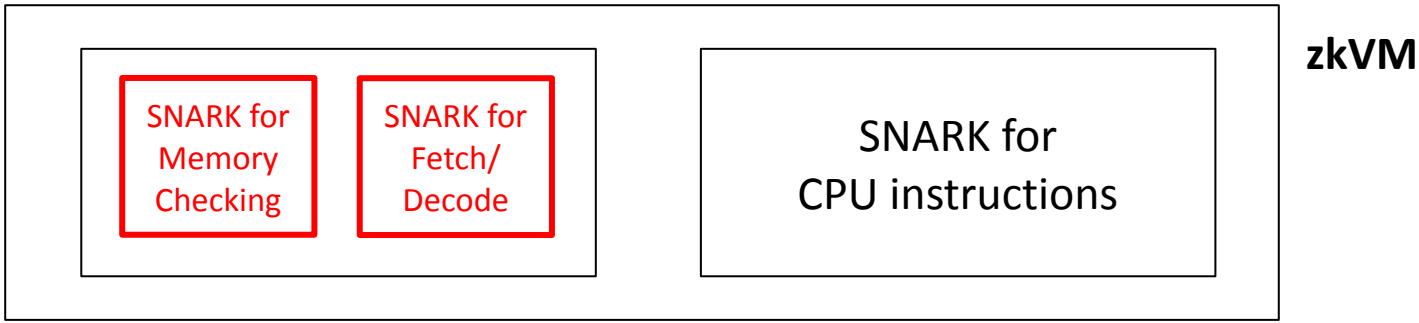
Joltish: a modular zkVM

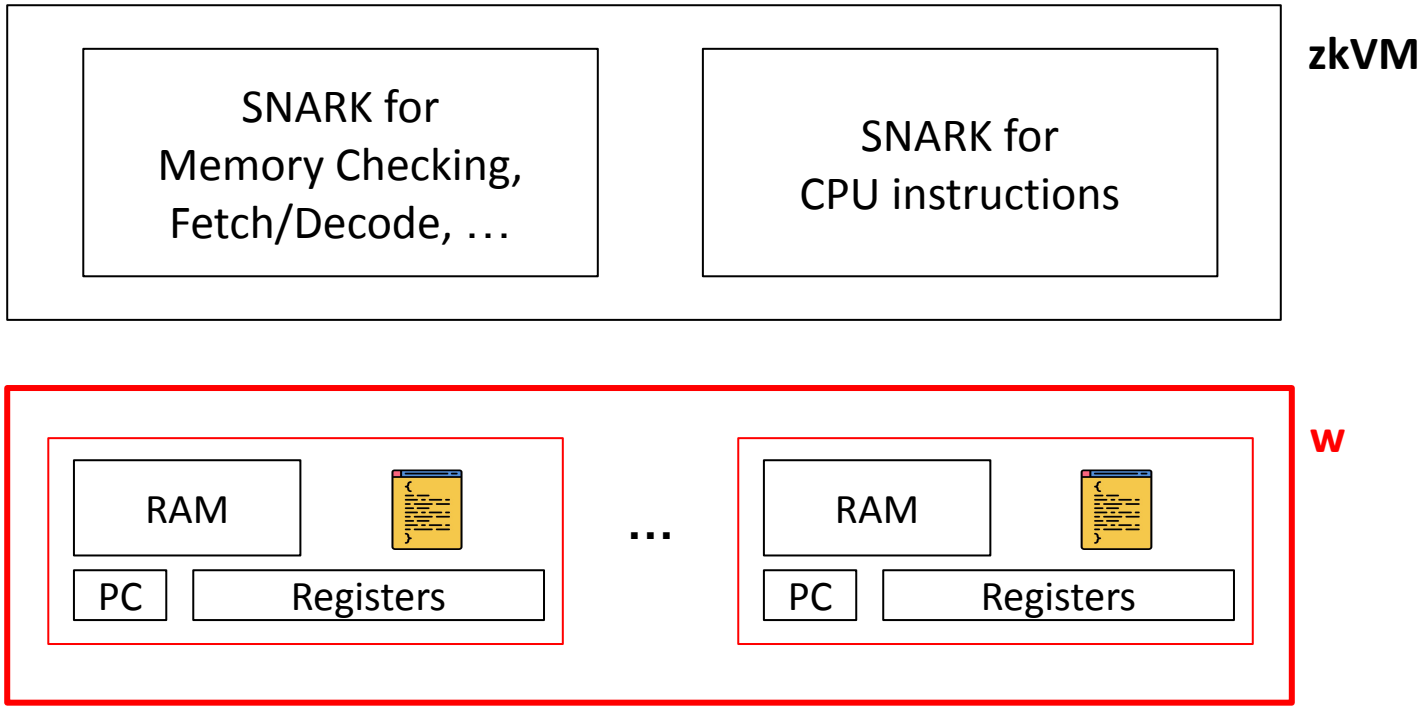


- Many zkVM's designs are modular (it's just natural)
- **Jolt** [AST24] is the first zkVM based on *the lookup-singularity*
- Our Joltish: inspired by Jolt, but not quite Jolt

zk Jolt from Joltish



Joltish: a modular zkVM



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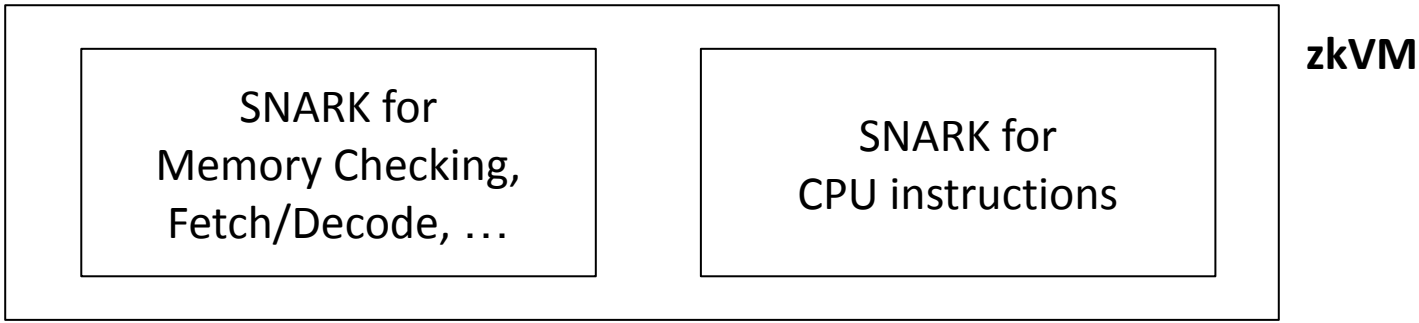
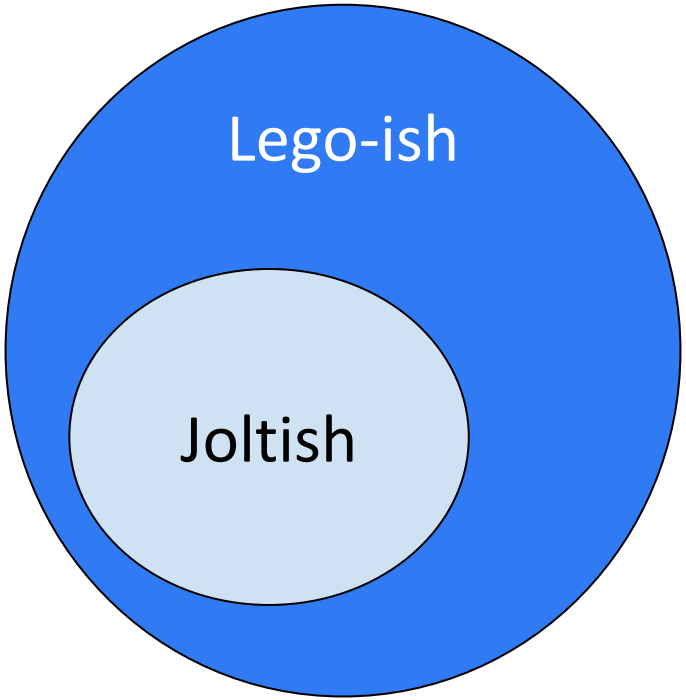
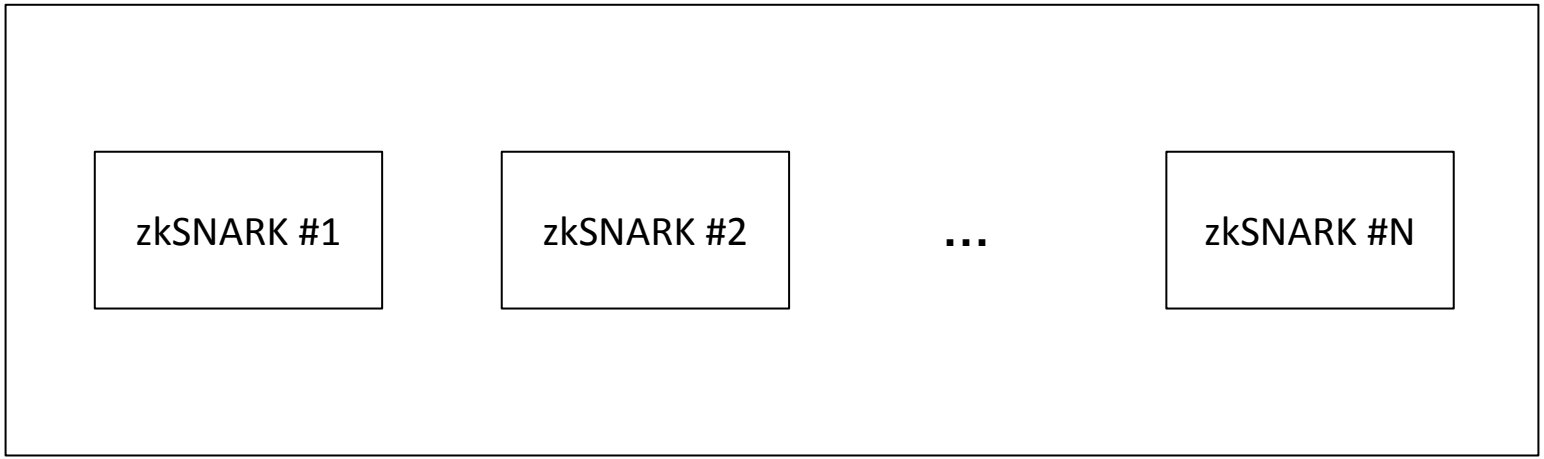


What are the conditions for the non-malleability of Joltish?

From *Joltish* to LEGO-ISH

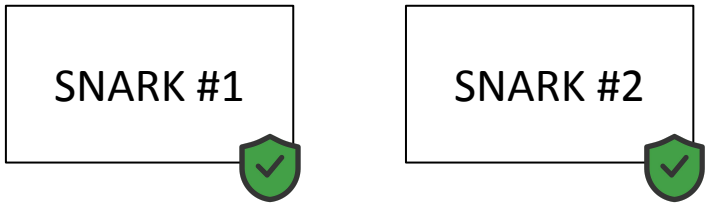


Lego-ish: a modular zkSNARK

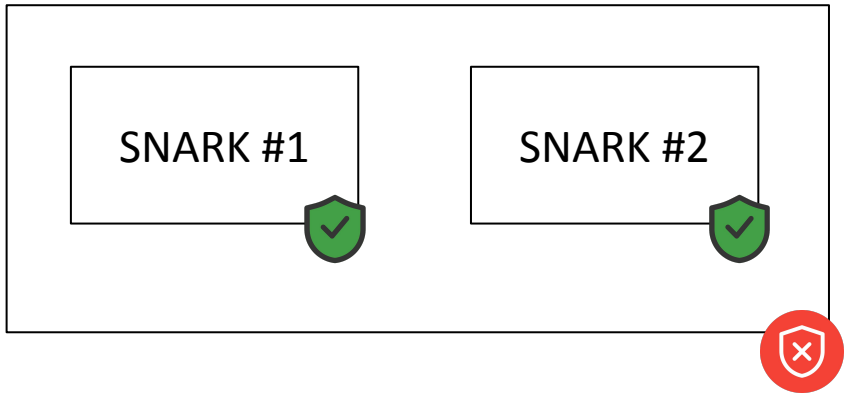


What are the conditions for the non-malleability of modular zkSNARKs?

Non-Malleability challenges



Non-Malleability challenges



Copy & Paste attacks
Composition of non-malleable SNARKs may be malleable

Our Results

1. A “natural” (and truly zero-knowledge) zkVM, inspired by Jolt

2. A framework for the non-malleability of “composable” zkSNARKs

Commit-and-Prove Relations

A commit-and-prove relation (c, x; w) in R iff:

- P(x,w) = 1
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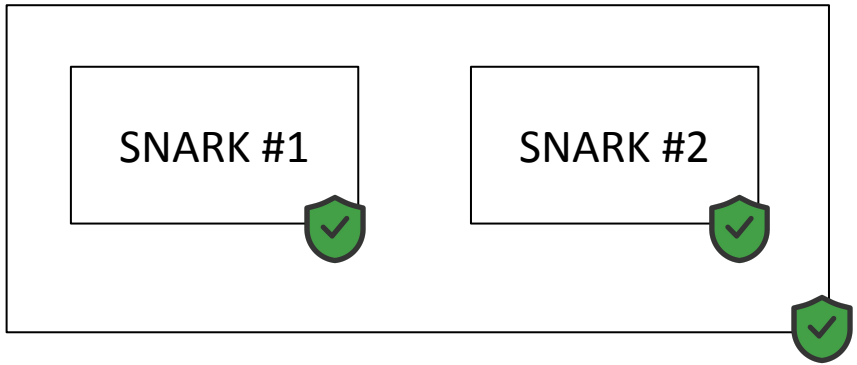
Conjunction of R_1 and R_2 with shared witness w:

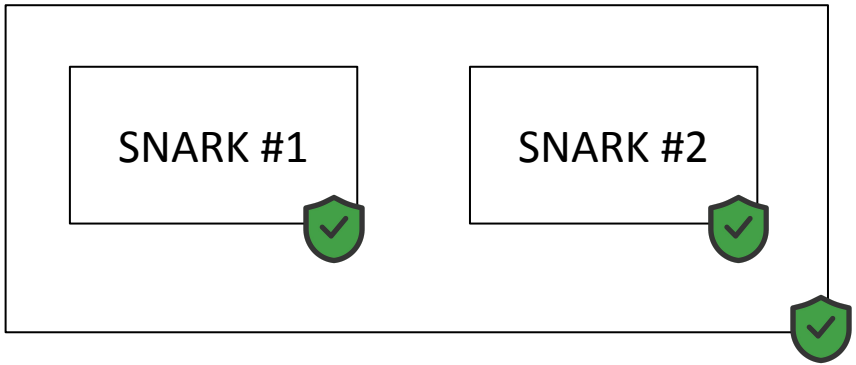
- Instance (c, x_1, x_2)
- P1(x_1, w) = 1 AND P2(x_2, w) = 1 AND c = Commit(w)

When is Conjunction Non-Malleable?



2 (slightly different) Non-Malleable Compositions

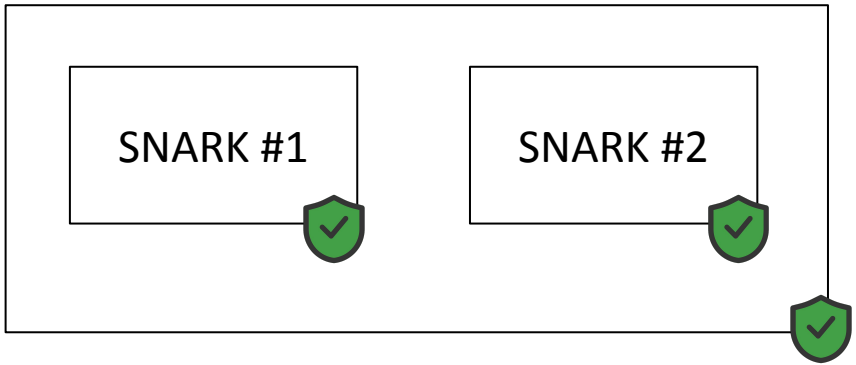
When is Conjunction Non-Malleable? **(1)**



If SNARK #1 AND SNARK #2 are **both**:

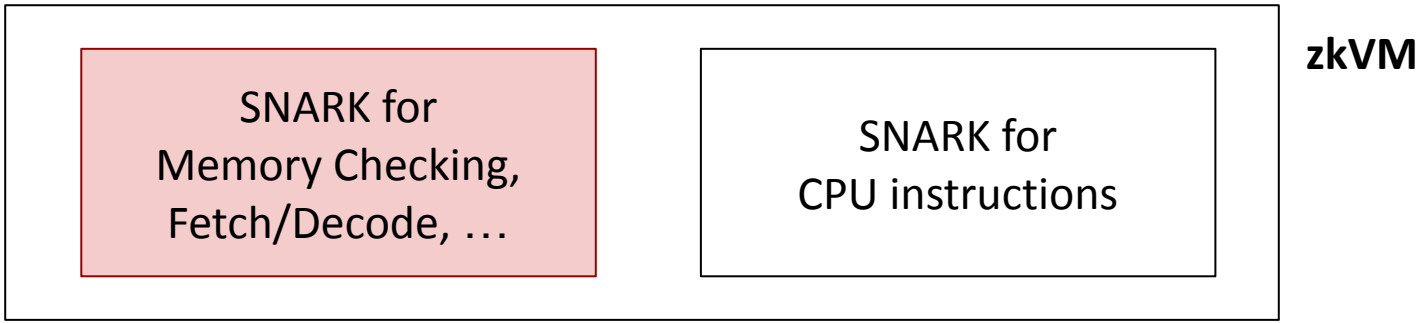
Trapdoorless zero-knowledge and non-malleable

When is Conjunction Non-Malleable? **(2)**



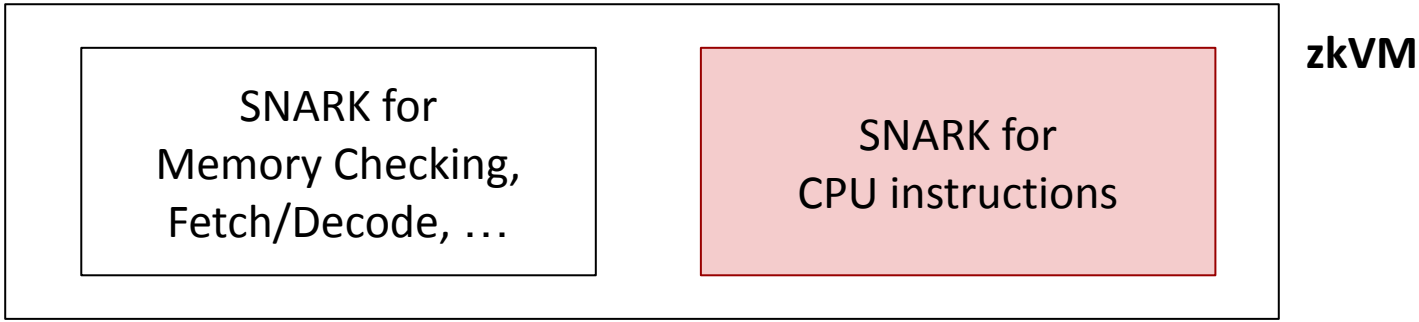
- SNARK #1 is witness-indistinguishable,
  efficient witness-computable (*easy to find w for x1*)
- SNARK #2 is Trapdoorless zero-knowledge, non-malleable SoK

On the Non-Malleability of Joltish



- Witness-indistinguishable SNARK for Memory Checking, Fetch/Decode, …

On the Non-Malleability of Joltish



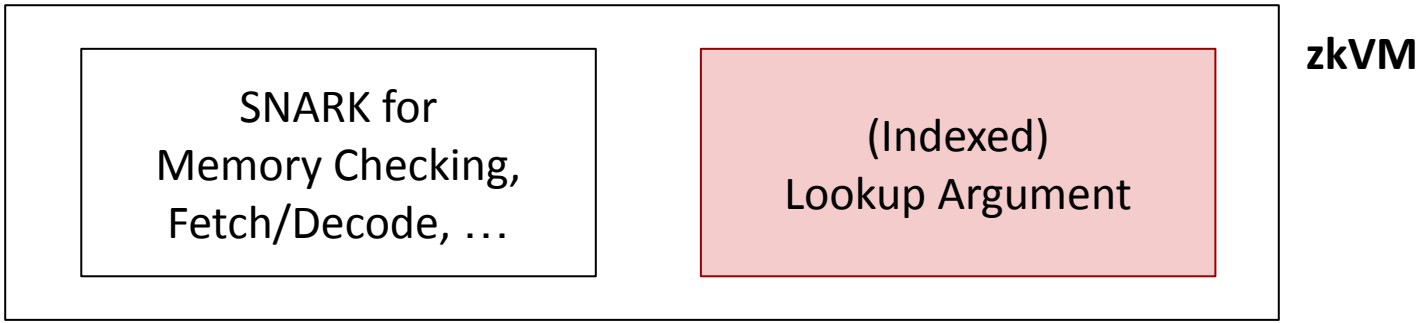
- Witness-indistinguishable SNARK for Memory Checking, Fetch/Decode, …

- Non-Malleable zkSNARK for CPU instructions

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

The Lookup Singularity based zkVM



- Witness-indistinguishable SNARK for Memory Checking, Fetch/Decode, …

- Non-Malleable 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|

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- Lookup Argument in Jolt is Lasso [STW24]
  - It can handle very big table as big as truth tables of all RISC-V instructions

zk-Lasso

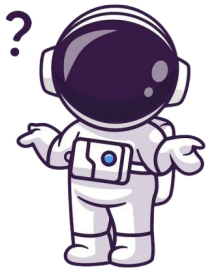
- Define a zero-knowledge version of Lasso
- Prove Sim-Extractability: based on the framework of [FKMV12]

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

- We extend and improve over [DG23]
  - (Lasso is based on Spartan)

Future Work

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



Thank you

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[FKMV12] Sebastian Faust, Markulf Kohlweiss, Giorgia Azzurra Marson, and Daniele Venturi. On the Non-malleability of the Fiat-Shamir Transform. INDOCRYPT 2012

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[STW24] Srinath Setty, Justin Thaler, Riad Wahby. Unlocking the lookup singularity with Lasso. EUROCRYPT 2024

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