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MIRAGE: Succinct Arguments for Randomized Algorithms with Applications to Universal zk-SNARKs

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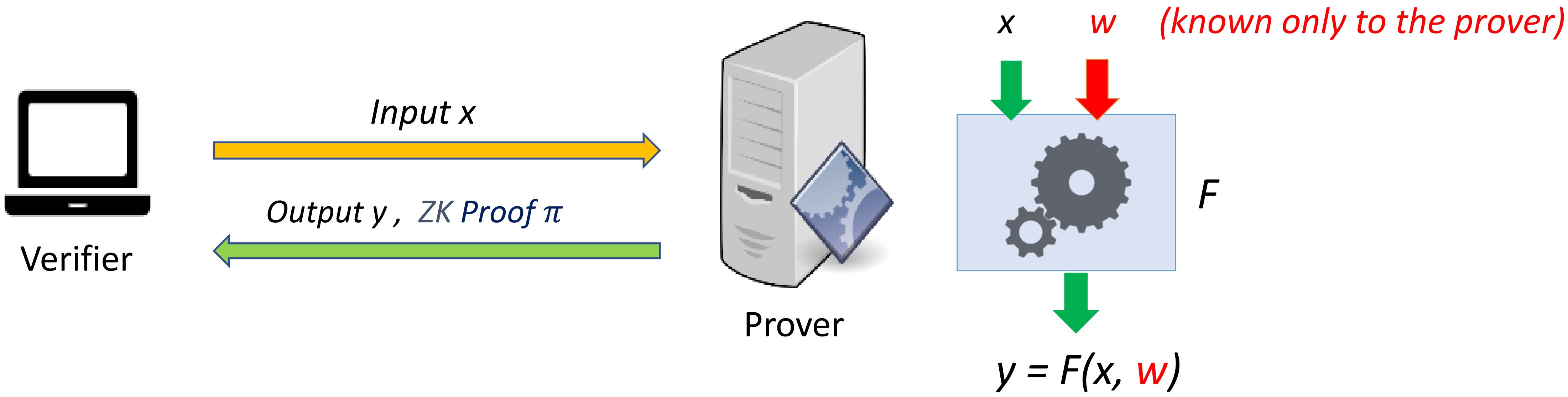
Zero-Knowledge Proofs [GMR85]



- The zero knowledge proof π should be convincing without leaking any information about w.

zk-SNARKs

- Zero knowledge succinct non-interactive arguments of knowledge
  - Main advantage: Very short proofs and fast verification
- In this talk, we consider QAP-based zk-SNARKs [GGPR13, PGHR13, Groth16], which provide succinct constant-size proofs.
  - This was attractive for many applications.

2013
PinocchioCoin [DFKP]

2014
CASH
ZeroCash [BCGGMTV]
ALITHEIA [ZPK]

2015

Mining Puzzles [MKKS]
VerDP [NFPH]

2016

PhotoProof [NT]
Cinderella [DFKP]
Hawk [KMSWP]

2017
Support for zk-SNARKs added for Ethereum

Challenges of zk-SNARKs in Practice

- Challenge 1: High proof computation cost
  - This led to several works on efficient circuit representations, SNARK-friendly cryptography, back end optimizations, distributed zk-SNARK proof computation, etc.
  - Examples include:

    Pantry [BFR+13], libsnark [BCTV14a], Scalable SNARKs [BCTV14b], TrueSet [KPP+14], Buffet[WSH+15], Ad-SNARK [BBFR15], Geppetto [CFH+15], C0C0 [KZM+16], [FFG+16], xJsnark [KPS18], DIZK [WZC+18]

- Challenge 2: Trusted setup per computation
  - The prover and verifier need access to a common reference string that is generated in a trusted manner.
  - If done insecurely, the prover can cheat.

ZK Proof Systems

Trusted setup per computation	[GGPR13], Pinocchio [PGHR13], [Groth16]	• Succinct proofs (128 to 288 bytes) • Efficient verification
No trusted setup	Ligero [AHIV17], zk-STARKs [BBHR18], Bulletproofs [BBBPWM18], Hyrax [WTSTW18], Aurora [BCRSVW18], Virgo [ZXZS20], ..	• The proof size and/or the verification effort are increased.

A middle ground?

Universal trusted Setup	**Approach 1: Universal Circuits** vnTinyRAM [BCTV14]	• Maintains succinct proofs and efficient verification • However, it has ***quasilinear*** circuits**.** • Very high proof computation cost.
	Approach 2: Universal Updatable CRS [GKMMM18], Sonic [MBKM19] Concurrent: PLONK [GWC19], MARLIN [CHMMVW19]	• In Sonic (unhelped) mode, proof is 1.1 KB. • Concurrent work: 448 bytes – 1 KB.

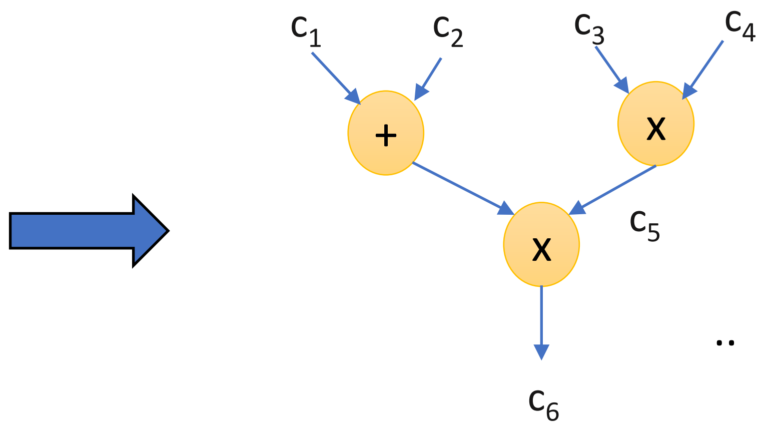
Our Contributions

- We address the previous two challenges via
  - Enabling randomized verification in zk-SNARK circuits.
  - Making universal circuits more efficient.

- In comparison with other universal ZK proof systems,
  - Universal circuit is linear instead of vnTinyRAM's quasilinear circuit.
  - Succinct proofs and efficient verification (Proof size = 160 bytes)
  - Proof size is 7x less than Sonic (unhelped), and 2.8x less than concurrent work.
  - Limitations:
    - CRS is not updatable
    - Proof computation overhead is high in comparison with per-circuit preprocessing zk-SNARKs

QAP-based zk-SNARK Circuits

```
int compute(int[] input, int[] witness){
     .
     .
     return result;
}
```



Constraints

$c_5 = c_3.c_4$

$c_6 = c_5.(c_1 + c_2)$

…

..

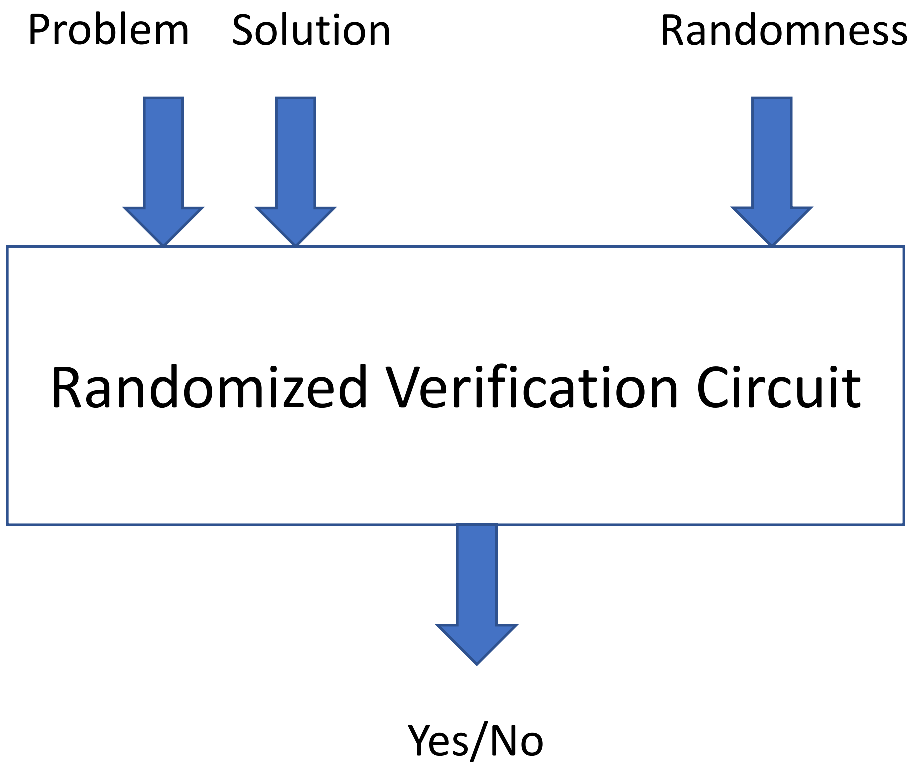
How to support randomized algorithms?

Why Randomized Algorithms?

- Many problems can be solved more efficiently using randomized algorithms. Examples include:
  - Polynomial identity testing
  - Primality testing

- In the case of universal zk-SNARK circuits, randomization can help with verifying permutations efficiently.

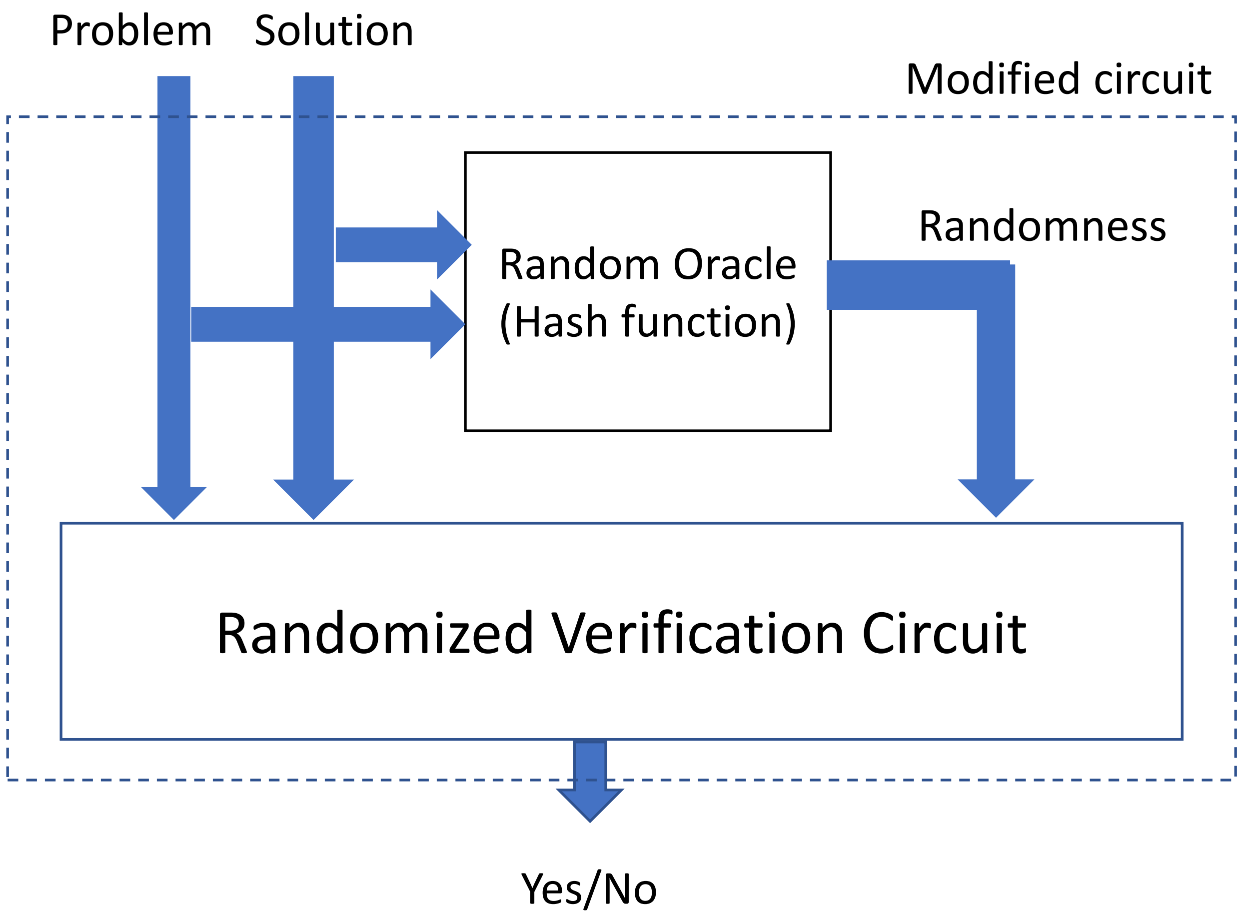
Randomized Verification in the Circuit



If we allow the prover to choose the randomness, or if the prover knows it before computing the solution, the prover can cheat.

Randomized Verification in the Circuit

- Naïve solution:



This solution will have a very high cost, due to calling the hash function in the circuit.

Question: Can we support randomized verification without having to pay this cost?

Randomized Verification in the Circuit

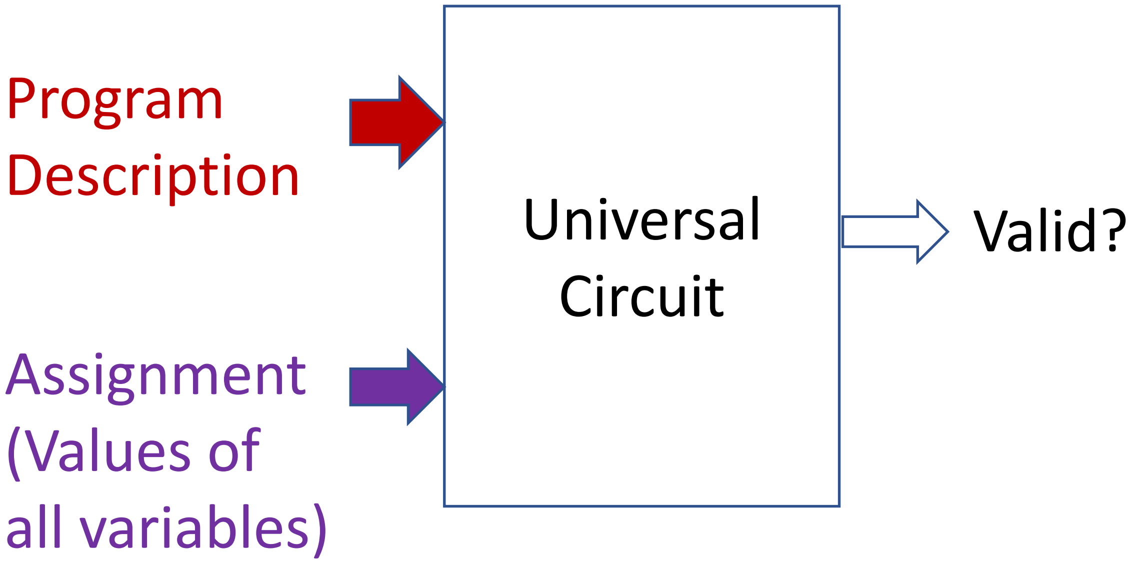
- We modify the Groth16 zk-SNARK protocol to support randomization
  - The prover adds **one group element** to the zk-SNARK proof. (Total proof size: 160 bytes)
  - The verifier will do **one extra pairing**, and apply hash function calls on part of the zk-SNARK proof.

- Intuition (simplified):
  - In a zk-SNARK protocol, the prover computes group elements as functions of all wires in the circuit.
  - These group elements can act as commitments.
  - We force the prover to do the computation of the proof over two stages.
  - We utilize the first part of the zk-SNARK proof to produce the randomness needed for the rest of the circuit.

How to make Universal Circuits more efficient?

Universal zk-SNARK Circuits

What is a universal circuit?



Example: A simple universal circuit that supports two multiplication operations and two addition operations.

MUL $(id_1, v_1), (id_2, v_2), (id_3, v_3)$

MUL $(id_4, v_4), (id_5, v_5), (id_6, v_6)$

ADD $(id_7, v_7), (id_8, v_8), (id_9, v_9)$

ADD $(id_{10}, v_{10}), (id_{11}, v_{11}), (id_{12}, v_{12})$

Universal zk-SNARK Circuits

The circuit must

1. Verify correctness

Example: assert ($v_1 * v_2 = v_3$)

2. Verify consistency

Example:

If ($id_1 = id_8$), assert ($v_1 = v_8$)

MUL	$(id_1, v_1), (id_2, v_2), (id_3, v_3)$
MUL	$(id_4, v_4), (id_5, v_5), (id_6, v_6)$
ADD	$(id_7, v_7), (id_8, v_8), (id_9, v_9)$
ADD	$(id_{10}, v_{10}), (id_{11}, v_{11}), (id_{12}, v_{12})$

To implement (2) efficiently, this requires checking permutations in the circuit.

Universal zk-SNARK Circuits

- To verify permutations, previous approaches, e.g., vnTinyRAM, use a permutation network. This has an O(n log n) overhead, where n is the number of operations.
- Using our modified zk-SNARK, we reduce this cost to O(n).
- We explore other issues related to universal circuit design in the paper.

Evaluation

- Comparison with custom zk-SNARK circuits and vnTinyRAM
  - We use vnTinyRAM results from [WSH+15]
- Scale of supported applications under nearly similar circuit costs:

		Universal circuit?	**Supported Scale**
Matrix multiplication $O(m^3)$ operations	Buffet, xJsnark	✗	m = 188
	vnTinyRAM	✓	m = 7
	MIRAGE	✓	m = 41
Merge sort O(m log m) operations	xJsnark	✗	m = 600
	vnTinyRAM	✓	m = 32
	MIRAGE	✓	m = 200

We reduce the gap between the universal circuit approaches and the custom circuits.

Evaluation

- Privacy-preserving smart contracts.
  - In HAWK [KMS+16], a trusted setup is needed per smart contract.
  - Instead, MIRAGE's universal circuit can be used.
    - Cryptographic keys will be generated once in a trusted manner.
    - For any new computation, a publicly verifiable custom verification key (32 bytes) will be pushed to the blockchain. (This does not require a trusted setup)

Needs a trusted setup per app

Auction (6 parties)	Universal Setup	Universal PK	Universal VK	Custom PK	Custom VK	Proof time	Proof size	Verification time
HAWK	✗	N/A		57.8 MB	3.9 KB	10.3 sec	128 B	1.5 ms
This work	✓	1.8 GB	473 KB	N/A		322 sec	160 B	2.1 ms

Cost of universality

Succinct proof and minimal verification overhead

Conclusions and Future Directions

- We presented MIRAGE, which enables
  - Verification of randomized algorithms in zk-SNARK circuits
  - Linear-sized universal circuits

- Future directions:
  - More optimization for universal circuits
  - Explore scalability options
  - Integrate randomization in zk-SNARK compilers (for non-universal circuits)

Thank you!

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