State of the STARK

Eli Ben-Sasson, Chief Scientist (East) | October 2018

Overview

What's a STARK?

STARK comparison to

- SNARKs (Zcash)
- Recursive SNARKs (Coda)
- Bulletproofs (Monero)

Benefits of STARK for scalability

Potential use-cases

Scalability, Privacy & Proofs

Proofs of Computational Integrity

INTEGRITY

The quality of being honest
(Dictionary)

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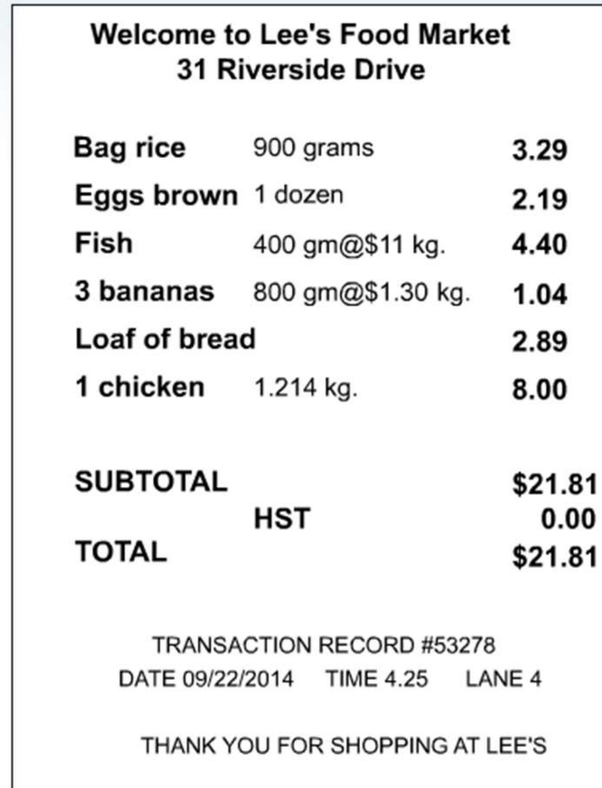
Grocery receipts are proofs of computational integrity

- Verification via naive re-execution of computation
- Proof is (i) deterministic, (ii) error free, (iii) one-shot (non-interactive)
- Modern CI proofs have (i) randomness, (ii) small error, (iii) interaction; in return, offer many benefits…


Welcome to Lee's Food Market
31 Riverside Drive

Bag rice	900 grams	3.29
Eggs brown	1 dozen	2.19
Fish	400 gm@$11 kg.	4.40
3 bananas	800 gm@$1.30 kg.	1.04
Loaf of bread		2.89
1 chicken	1.214 kg.	8.00
SUBTOTAL		$21.81
	HST	0.00
TOTAL		$21.81

TRANSACTION RECORD #53278
DATE 09/22/2014 TIME 4.25 LANE 4

THANK YOU FOR SHOPPING AT LEE'S

Modern proofs of Computational Integrity

Invented by Goldwasser, Micali, Rackoff in 1985:

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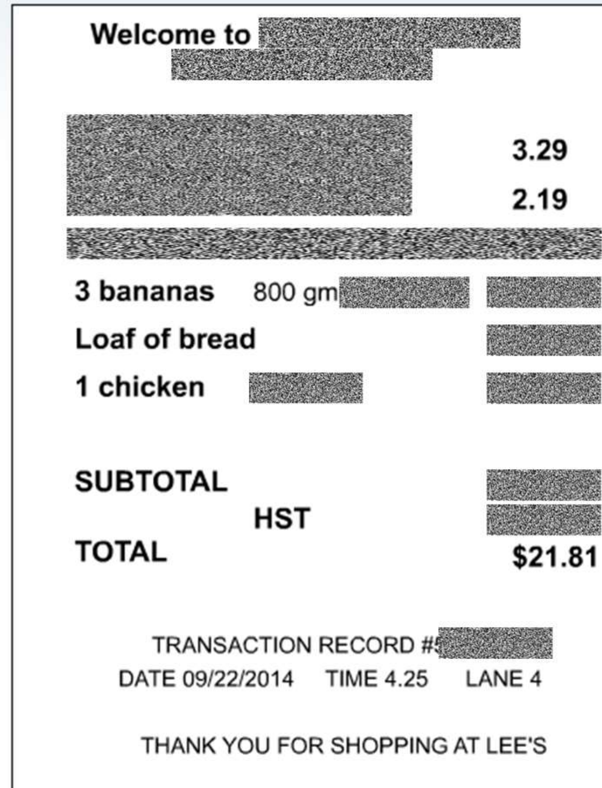

Welcome to [redacted]

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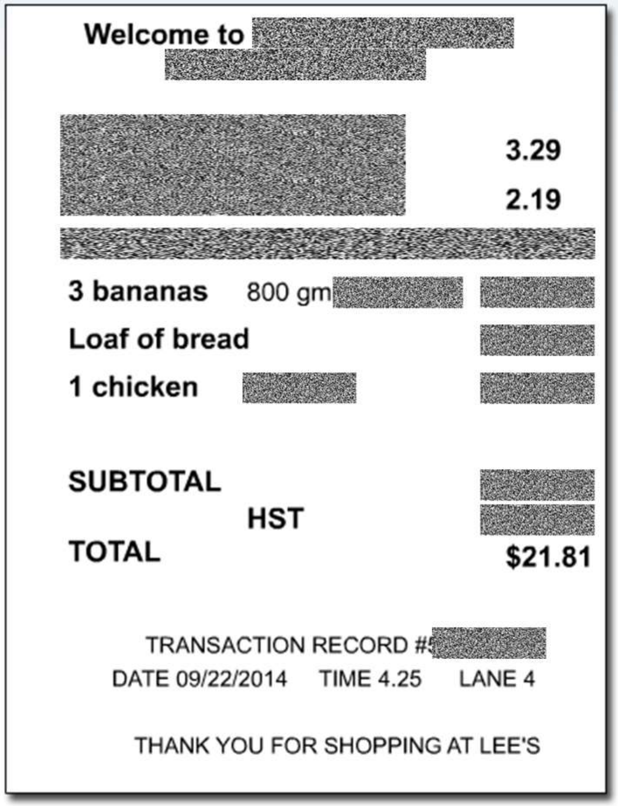
- **Zero knowledge (ZK):** private inputs are shielded
- **Scalability:** for computation lasting T cycles, proofs
  - generated in ~ T cycles (quasi-linear in T), and
  - verified exponentially faster than T (~ log T cycles)
- **Universality (Turing Completeness):** apply to any computation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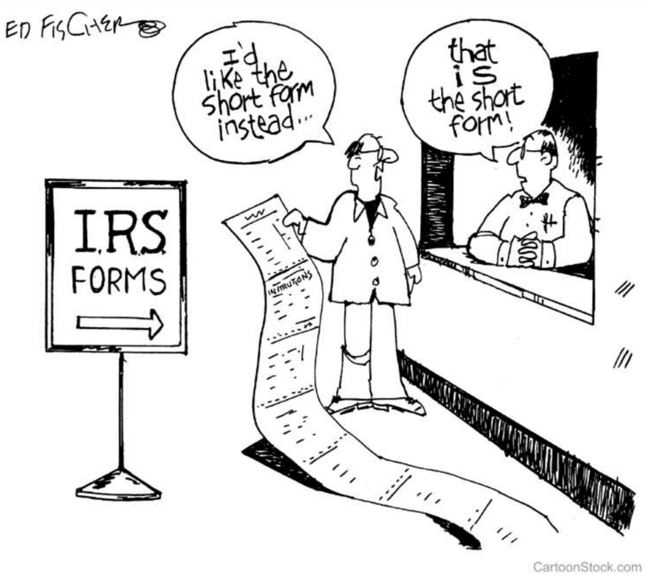

Examples of things one can prove:

- **Paid taxes on all my cryptocurrency tx's for 2017**
- **Control at least 10 ETH as of today**
- **Crypto exchange is in the black as of today (pf of solvency)**
- …

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ZK-STARK: core attributes

Many flavors of proof systems

Variety of theoretical constructions (past 30 yrs)

PCP based, linear PCPs, elliptic curve+pairing based succinct NIZKs, quadratic span/arithmetic programs (QAP/QSP), interactive oracle proofs (IOP), …

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Many flavors of proof systems

Variety of theoretical constructions (past 30 yrs)

…and implementations (past 5 yrs)

See zkp.science

PCP based, linear PCPs, elliptic curve+pairing based succinct NIZKs, quadratic span/arithmetic programs (QAP/QSP), interactive oracle proofs (IOP), …

Pinocchio, libsnark, zcash, pepper, ligero, bulletproofs, libstark, aurora, …

zk-STARK definition

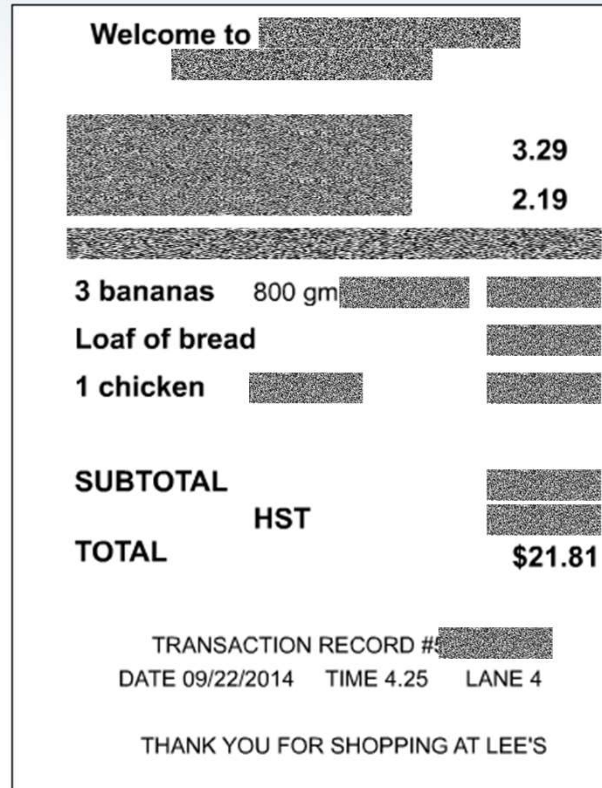
A proof system is a zk-STARK if it satisfies:

zk — **zero knowledge**: private inputs are shielded

S — **Scalable:** proofs for CI of computation lasting T cycles are
- generated in roughly T cycles (quasi-linear in T), and
- verified exponentially faster than T (roughly log T cycles)

T — **Transparent**: verifier messages are random coins; no trusted setup

AR K — **ARgument of Knowledge:** proof can be generated only by party knowing private input (formally: an efficient procedure can extract the secrets from a prover)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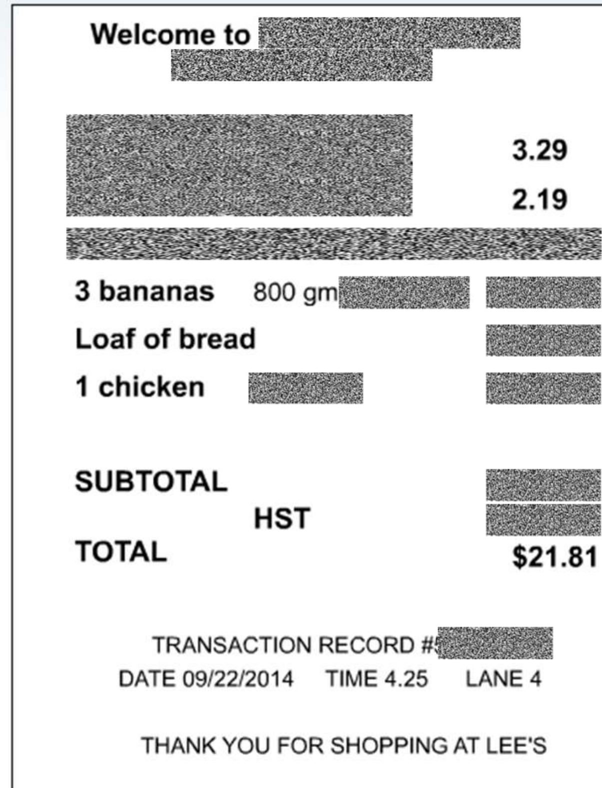
- STARKs may be interactive (use blockchain as source of transparent randomness), gives shorter & safer proofs
- 1st STARK: SCI-POC [BCG+16]; 1st zk-STARK: libstark [BBHR18]



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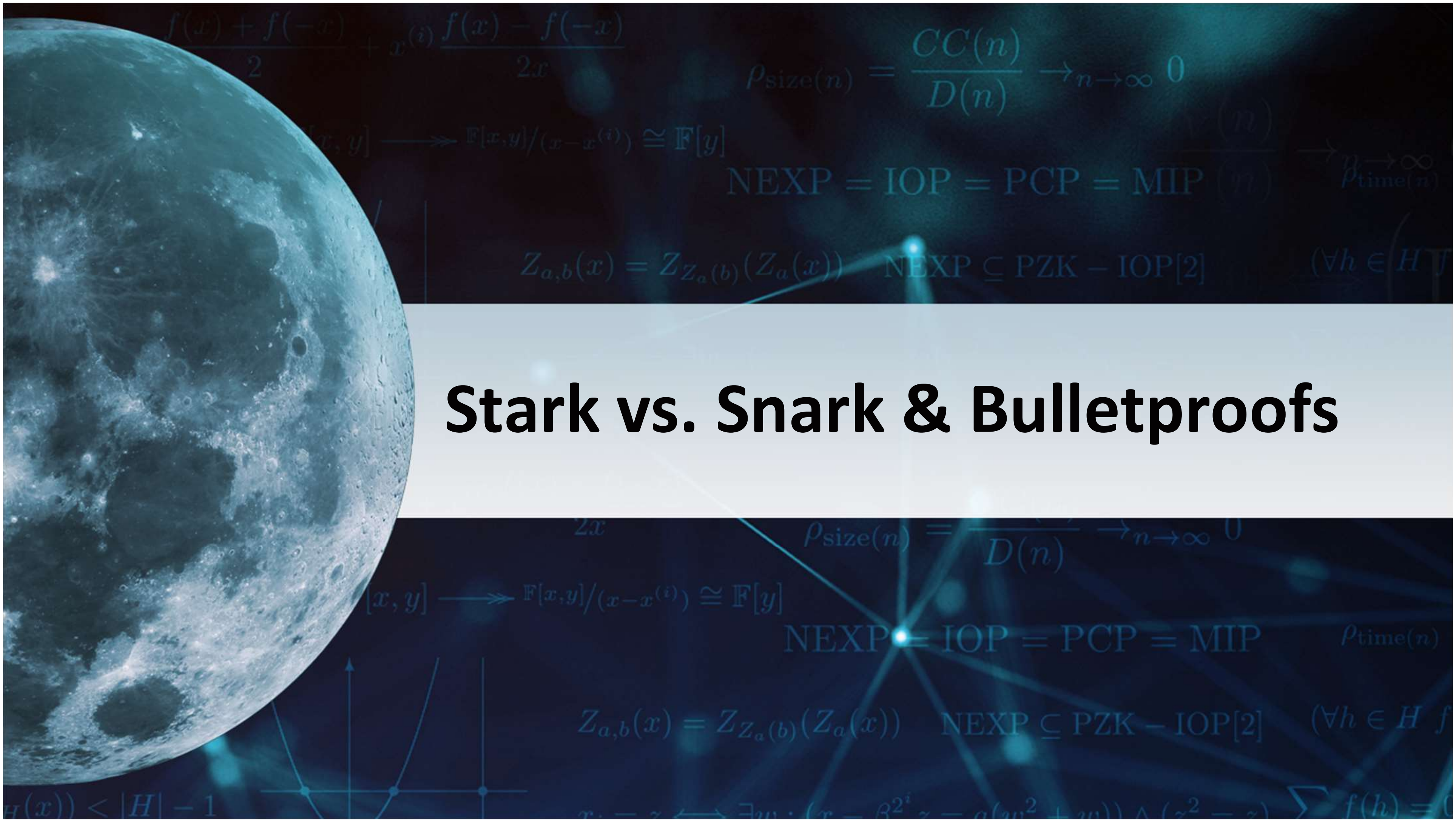
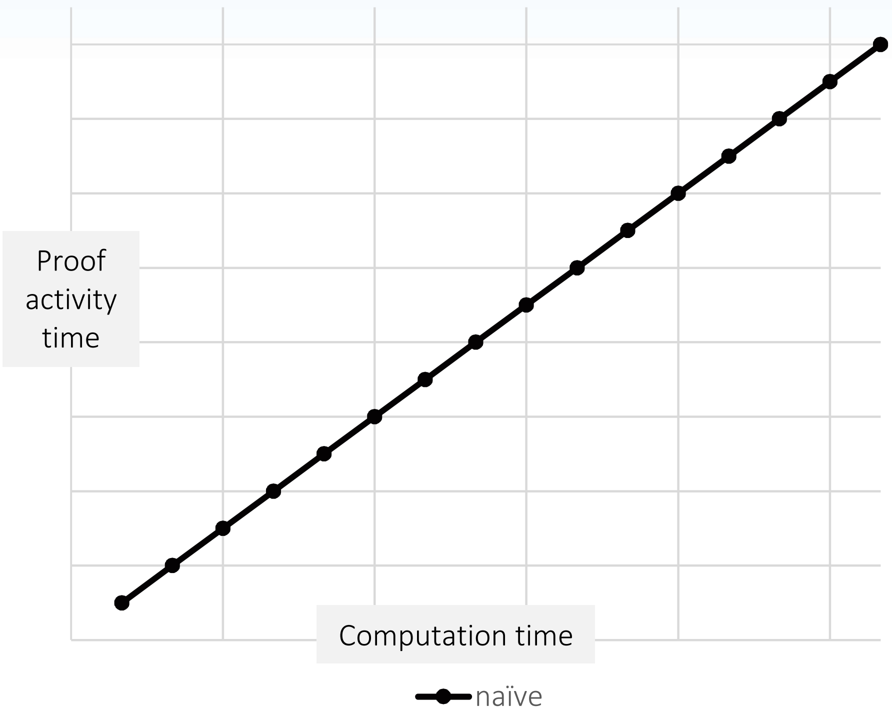

Stark vs. Snark & Bulletproofs

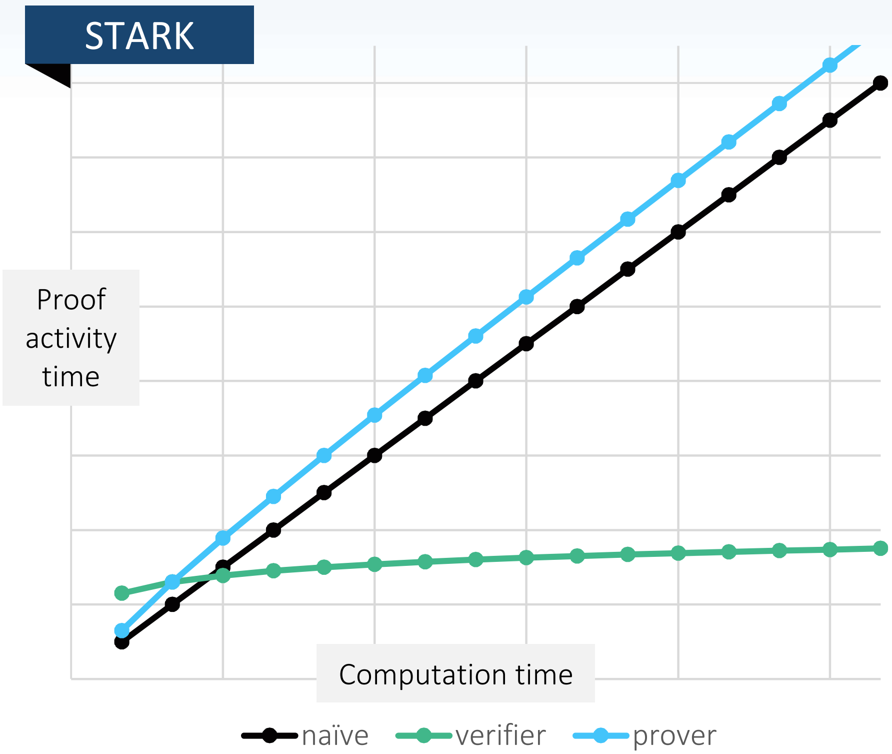
Scalability - Stark vs naive verification



Naive:

Verification = proving

Scalability - Stark vs naive verification



Naive:

Verification = proving

STARK:

Quasi-linear proving

Poly-logarithmic verification

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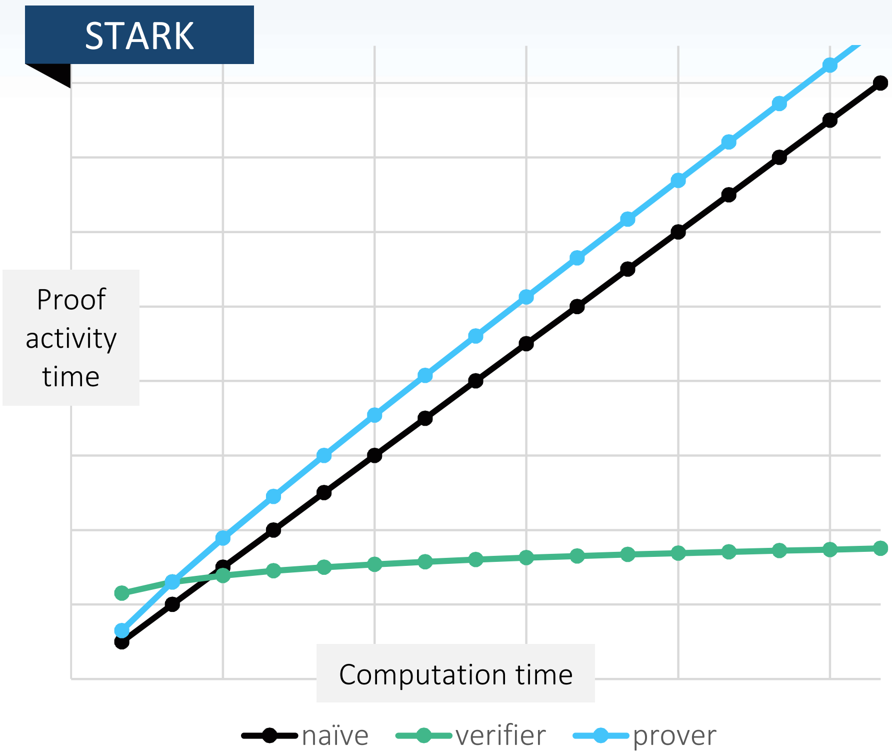
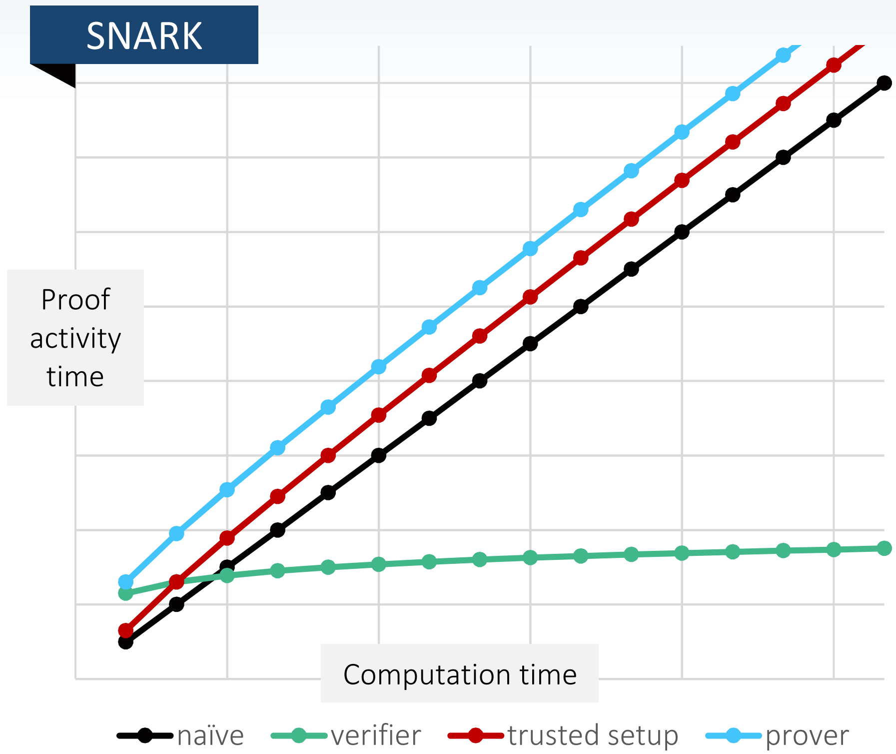
Scalability - Stark vs Snark (Zcash)





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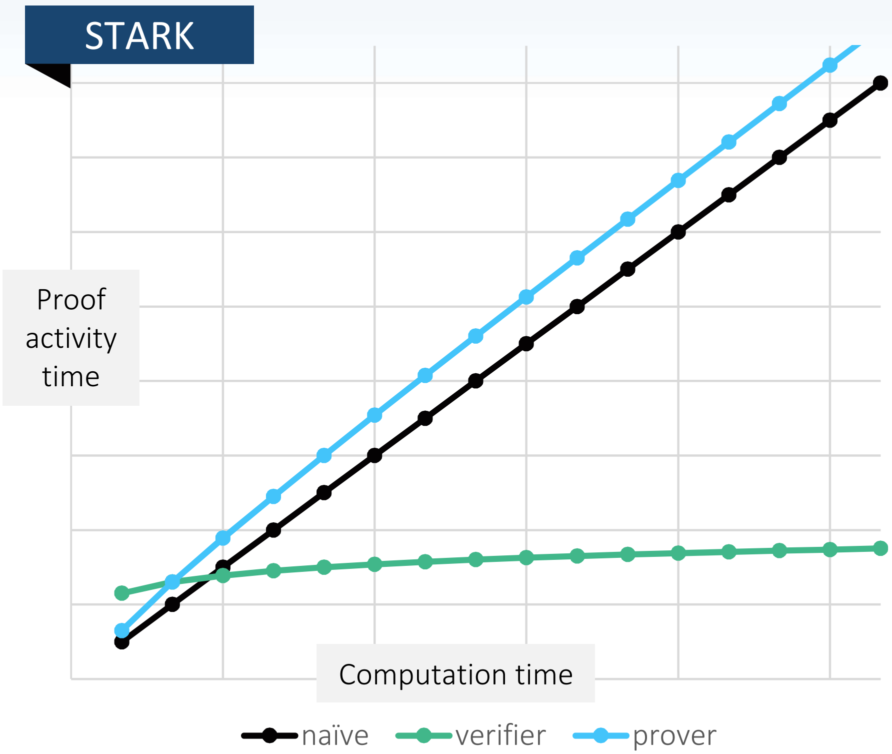

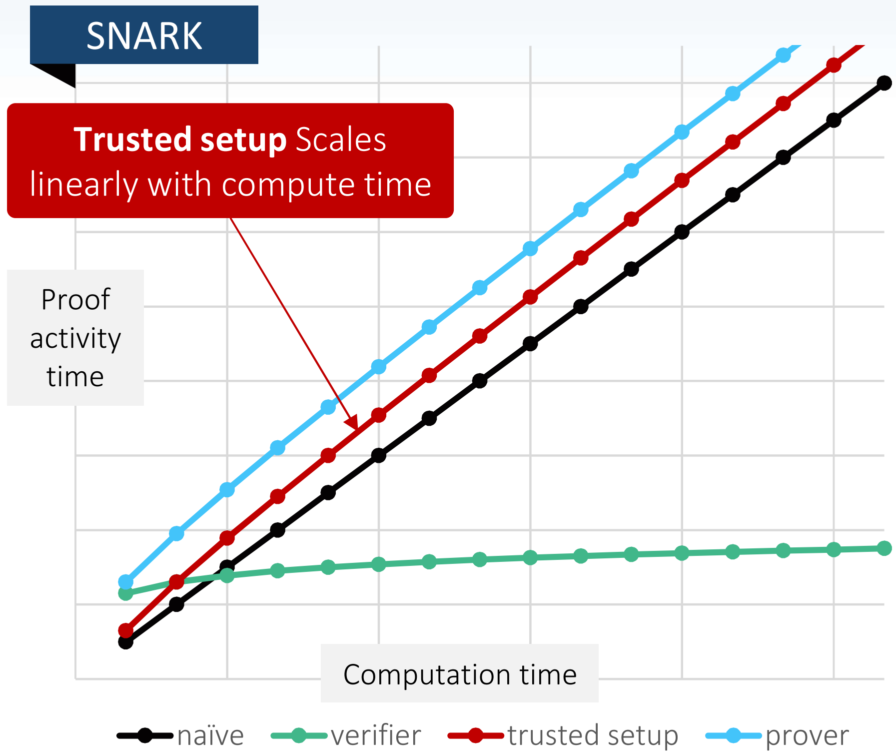

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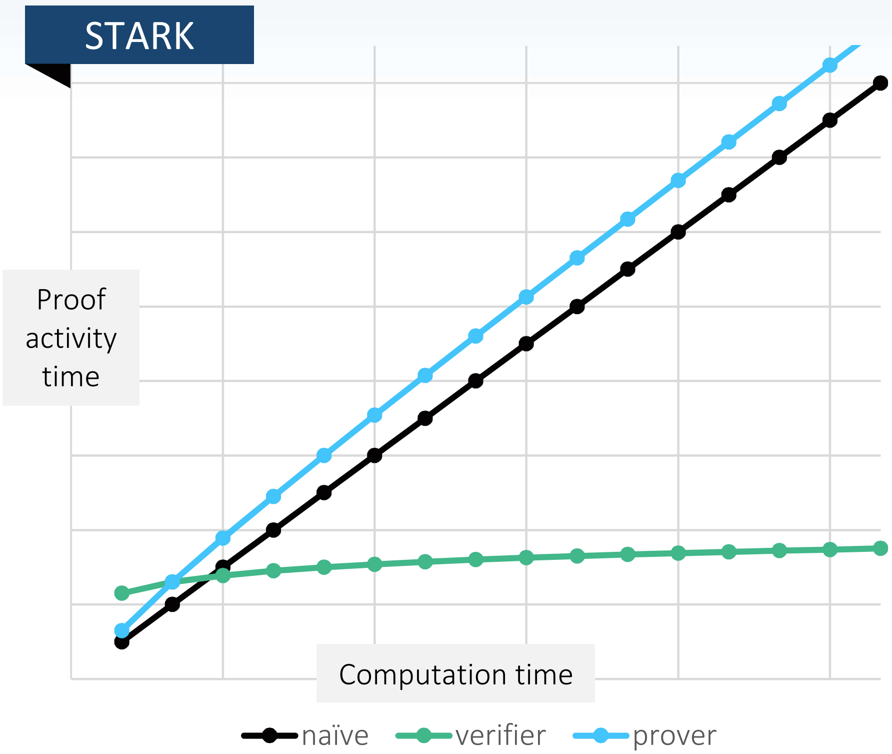
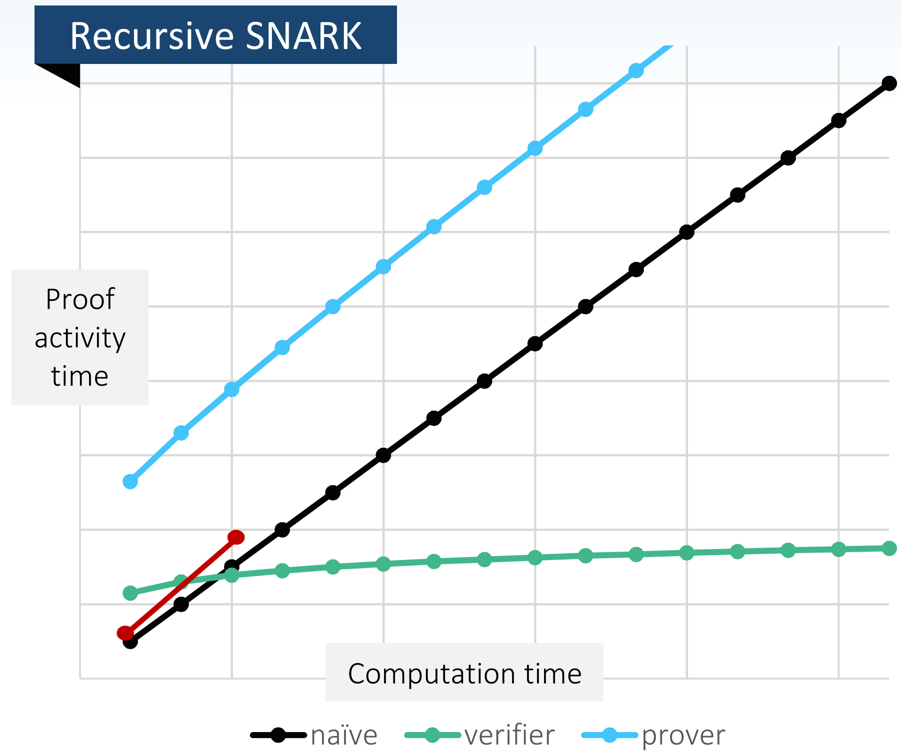
Scalability - Stark vs recursive Snark (Coda)





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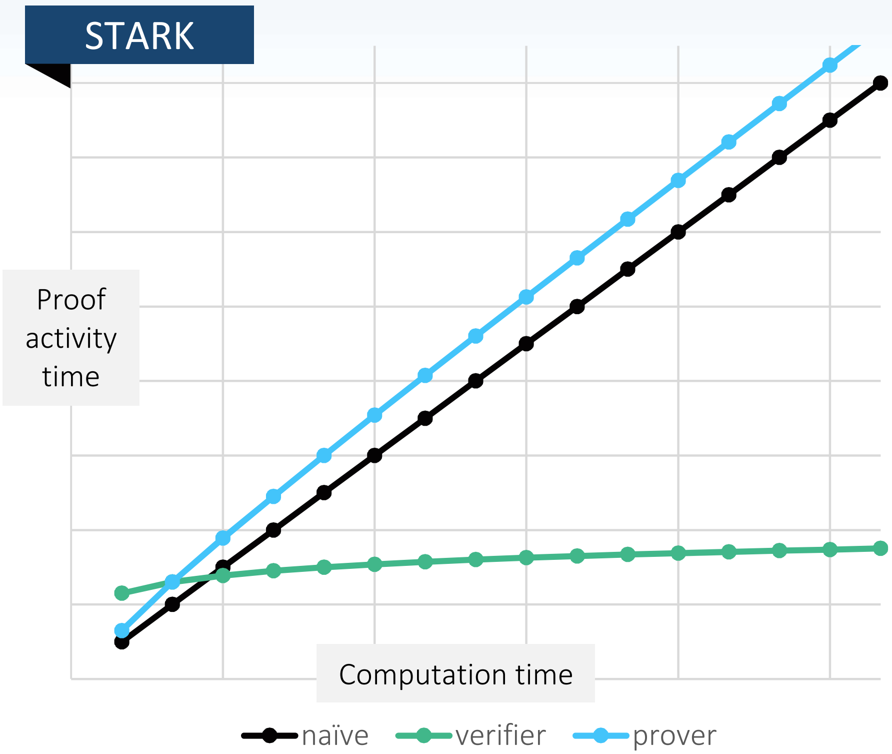

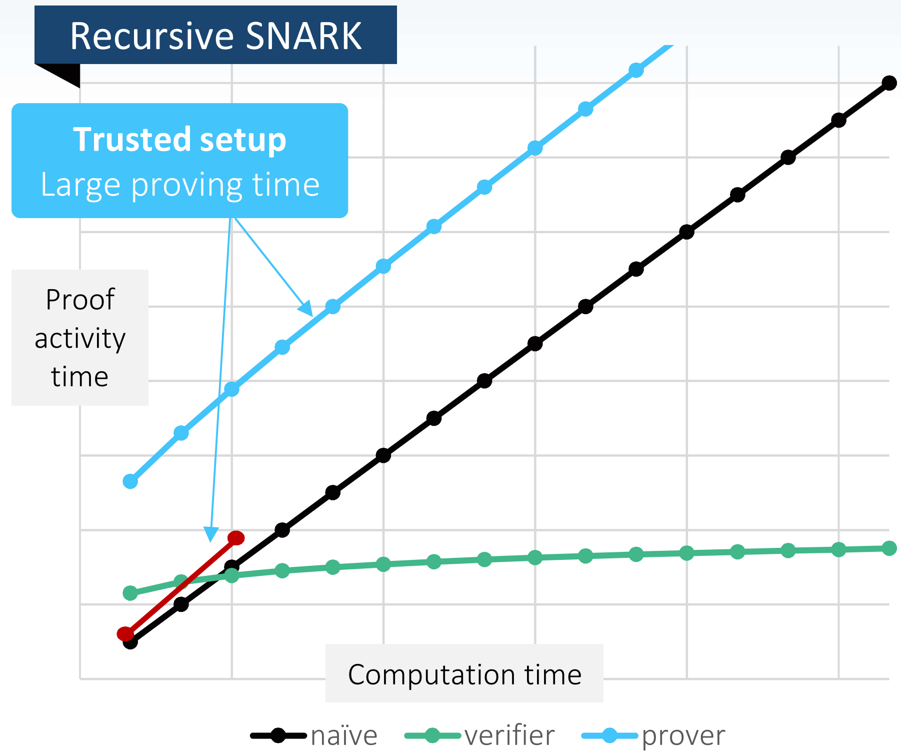

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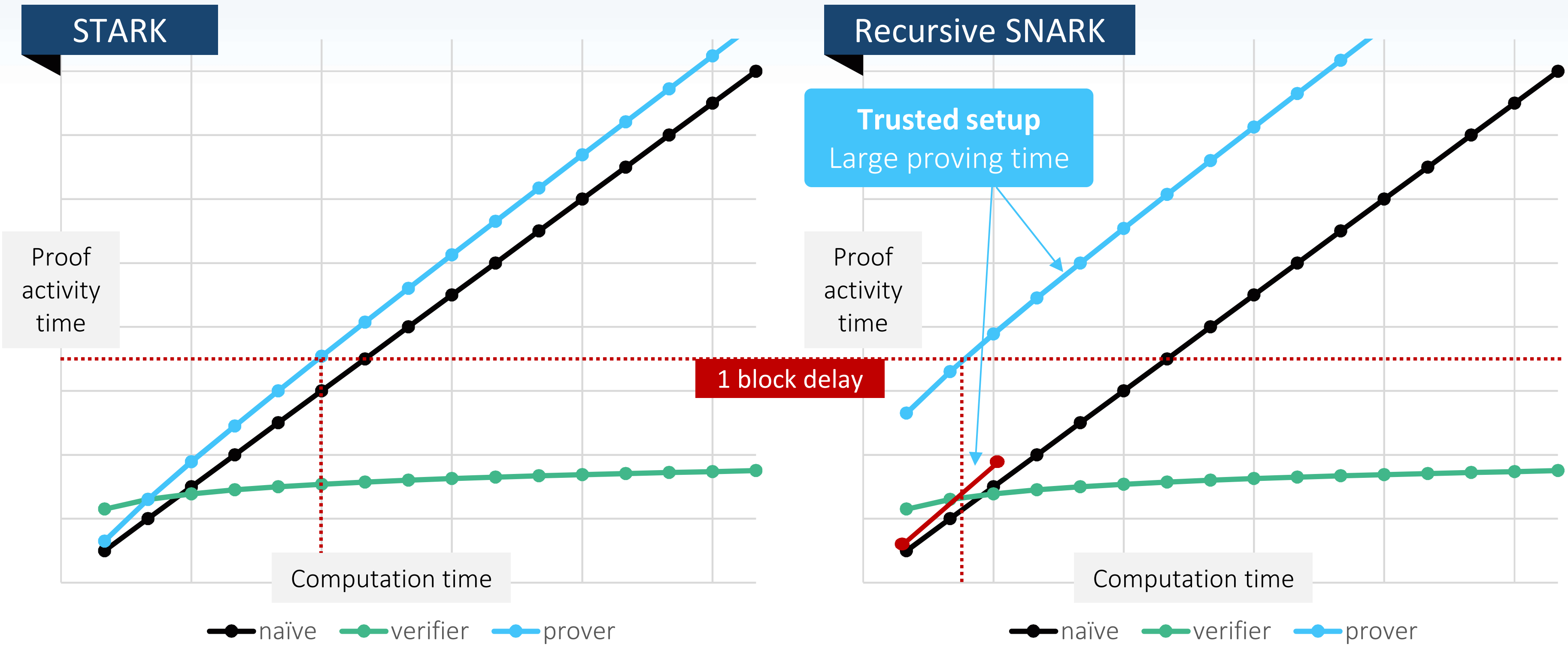
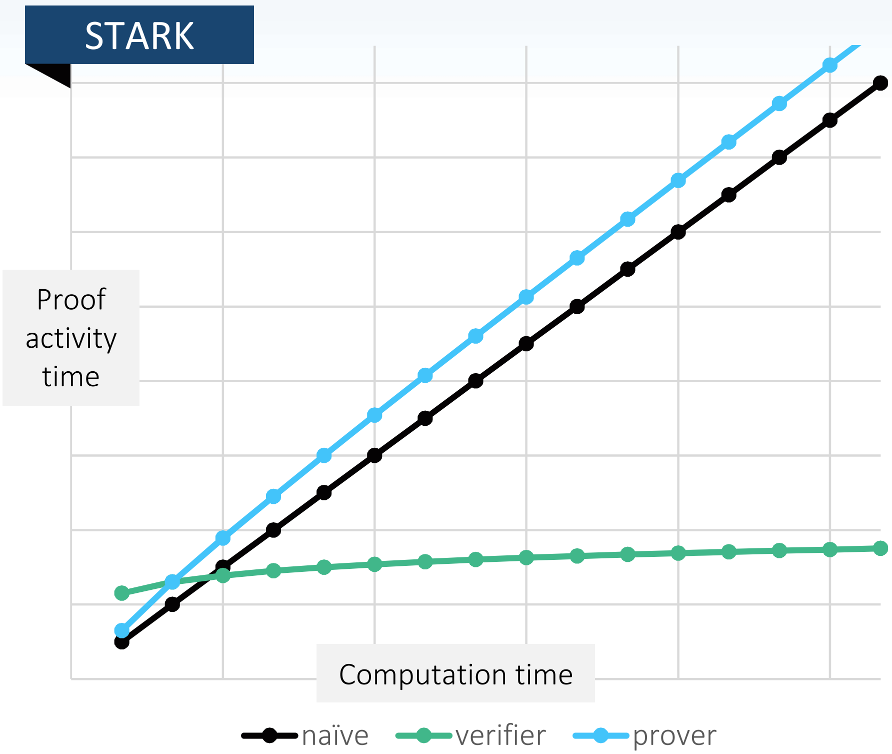
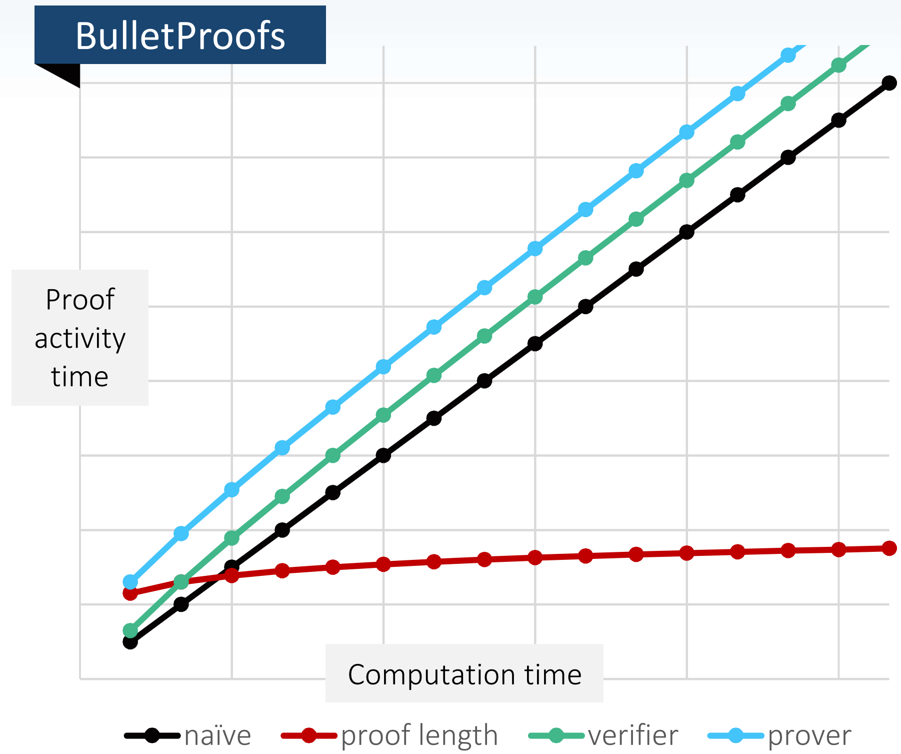


Stark vs BulletProofs (Monero)





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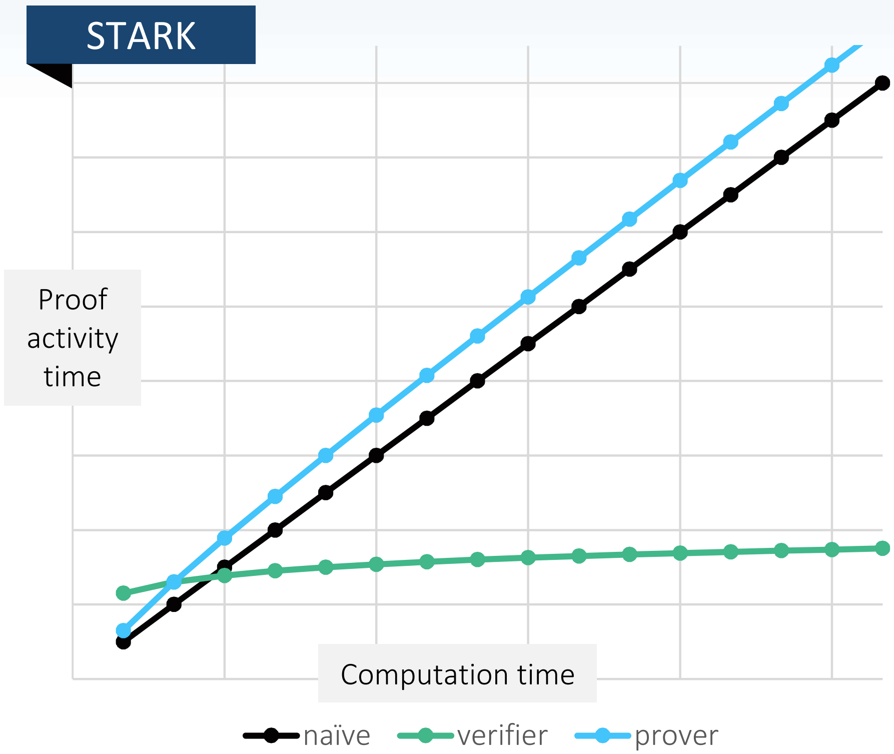

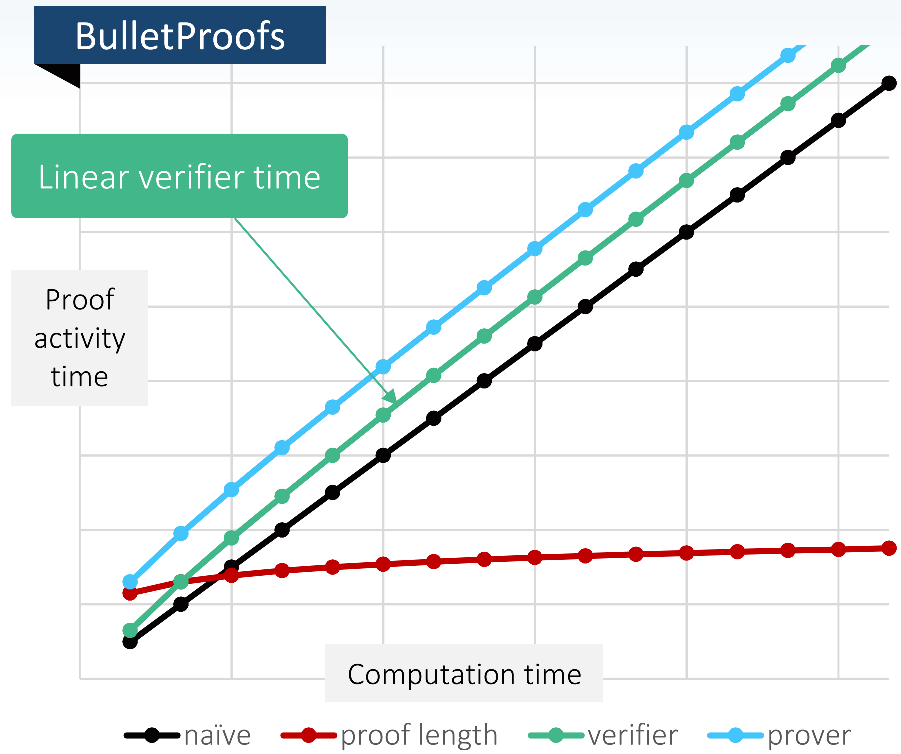

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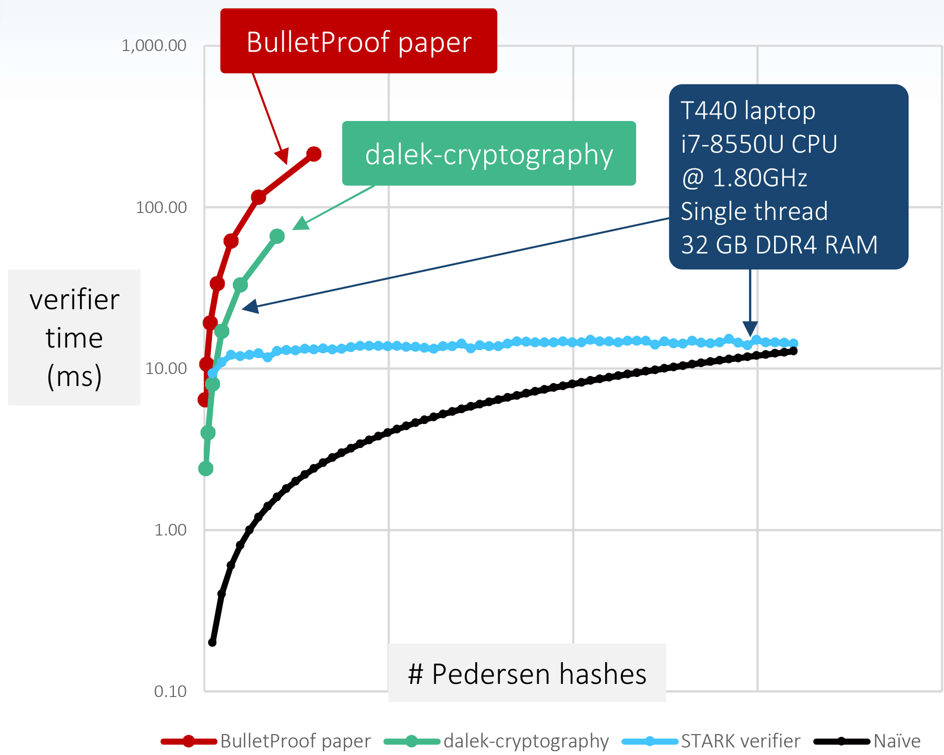
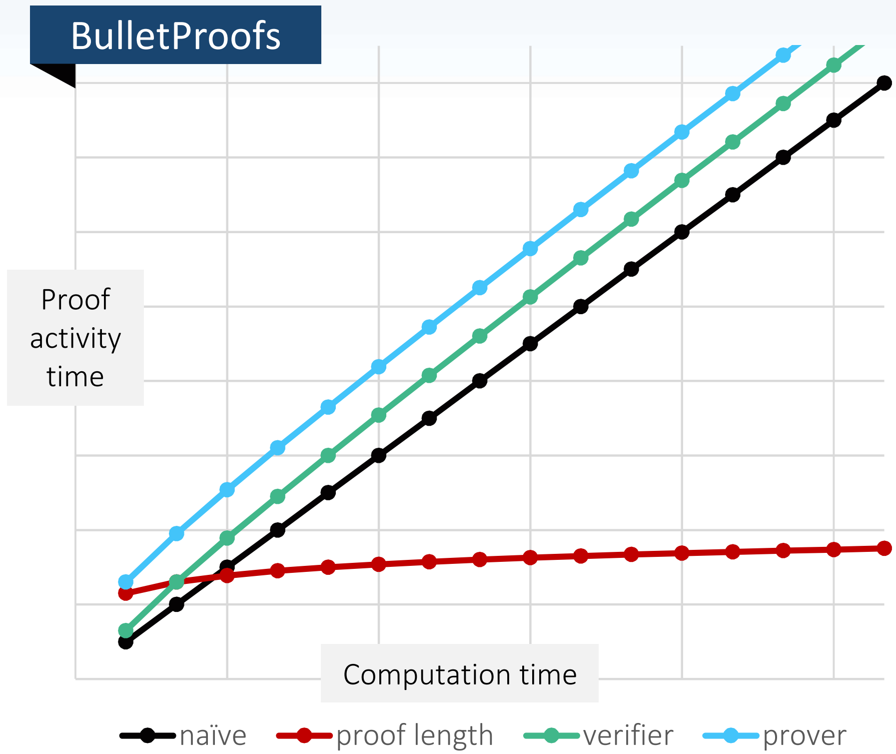
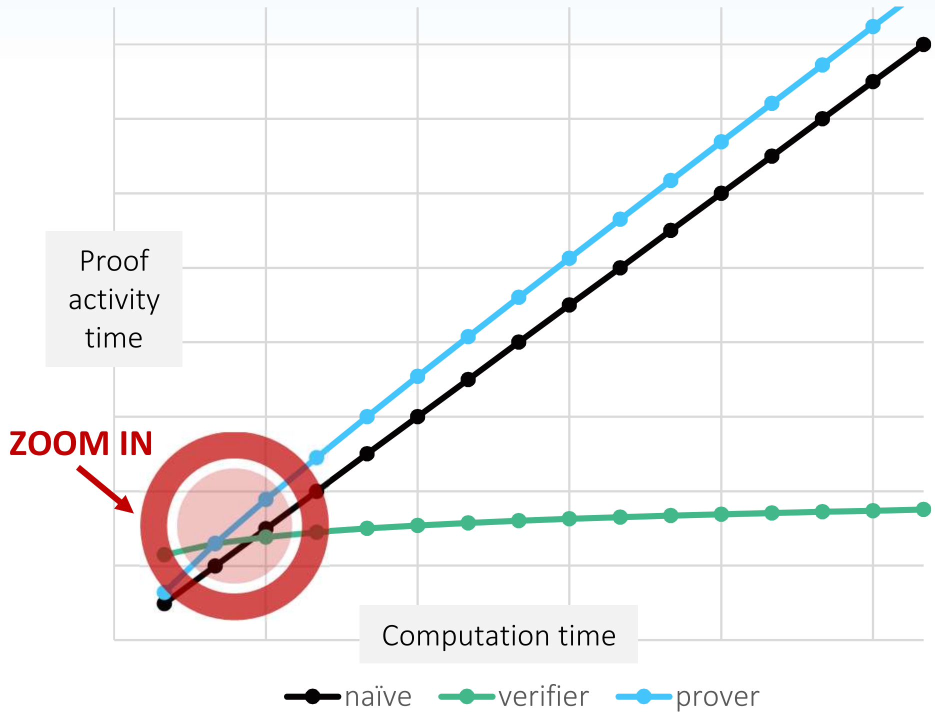
STARK vs BulletProofs verification measurements



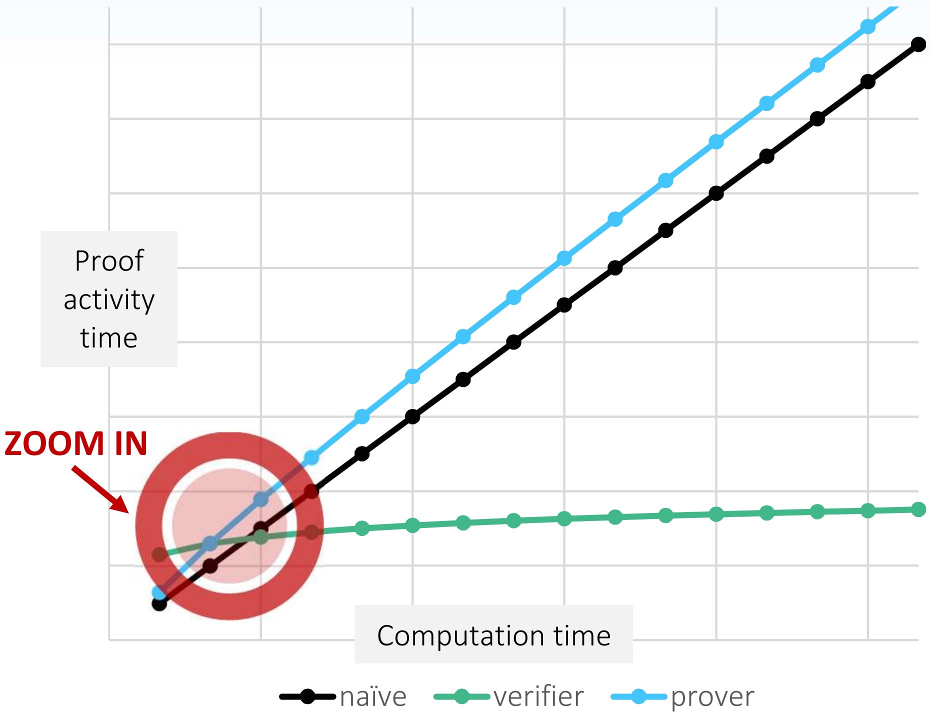


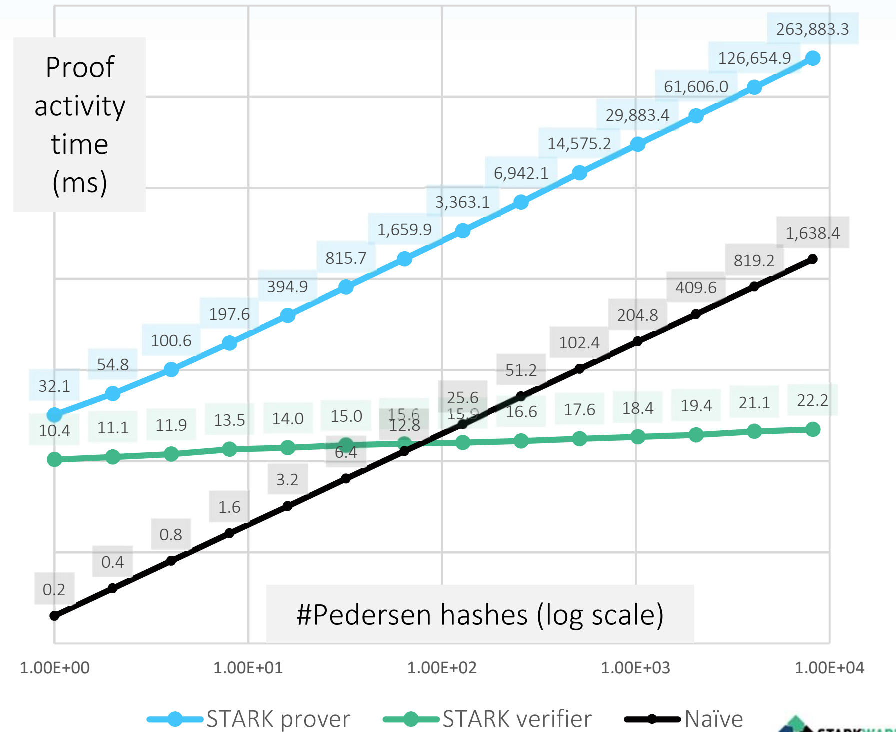
Scalability - Stark vs naive verification



Scalability - Stark vs naive verification

T440 laptop
i7-8550U CPU
@ 1.80GHz
Single thread
32 GB DDR4 RAM





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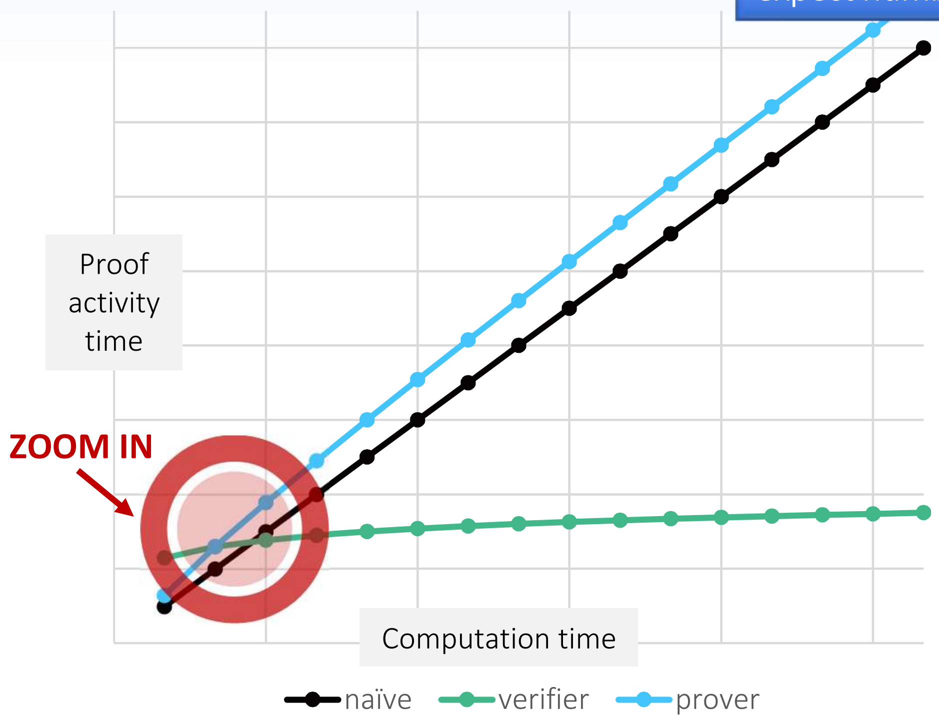
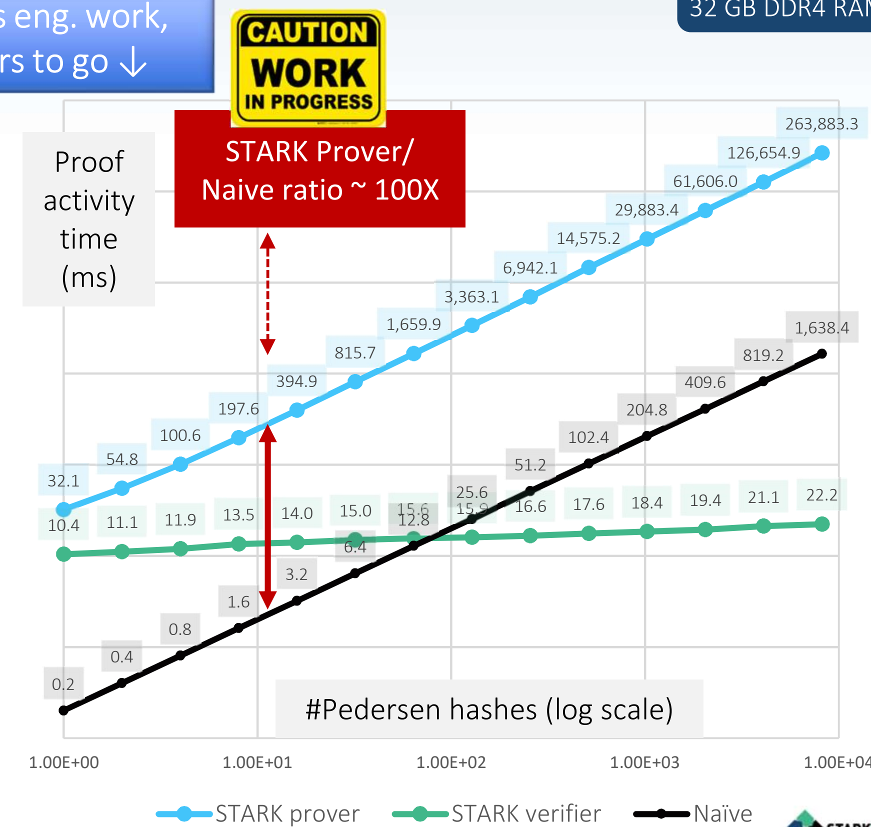
after 6 months eng. work, expect numbers to go ↓





Virtues of Transparency (no trusted setup)

- Eliminate single point of failure (trusted setup)
- Facilitates continuous deployment of minor upgrades
- Reduces trust assumption: nothing up your sleeve, no need to trust setup ceremony
- Additional virtues of reliance on symmetric cryptography
  - Post-quantum security
  - Faster proving and verification time
  - Simpler, more reliable trust assumptions (CRH/Fiat-Shamir)
  - Reliance on "old" peer-reviewed principles (PCP Theorem, interactive knowledge extractors, …)

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STARK for Scalability

Trust Assumptions	Crypto Assumptions	Quantum Safety
ZK-STARK	ZK-STARK	ZK-STARK
ZK-SNARK	ZK-SNARK	ZK-SNARK
Bulletproof	Bulletproof	Bulletproof

ZK-STARK **ZK-SNARK** **Bulletproof**

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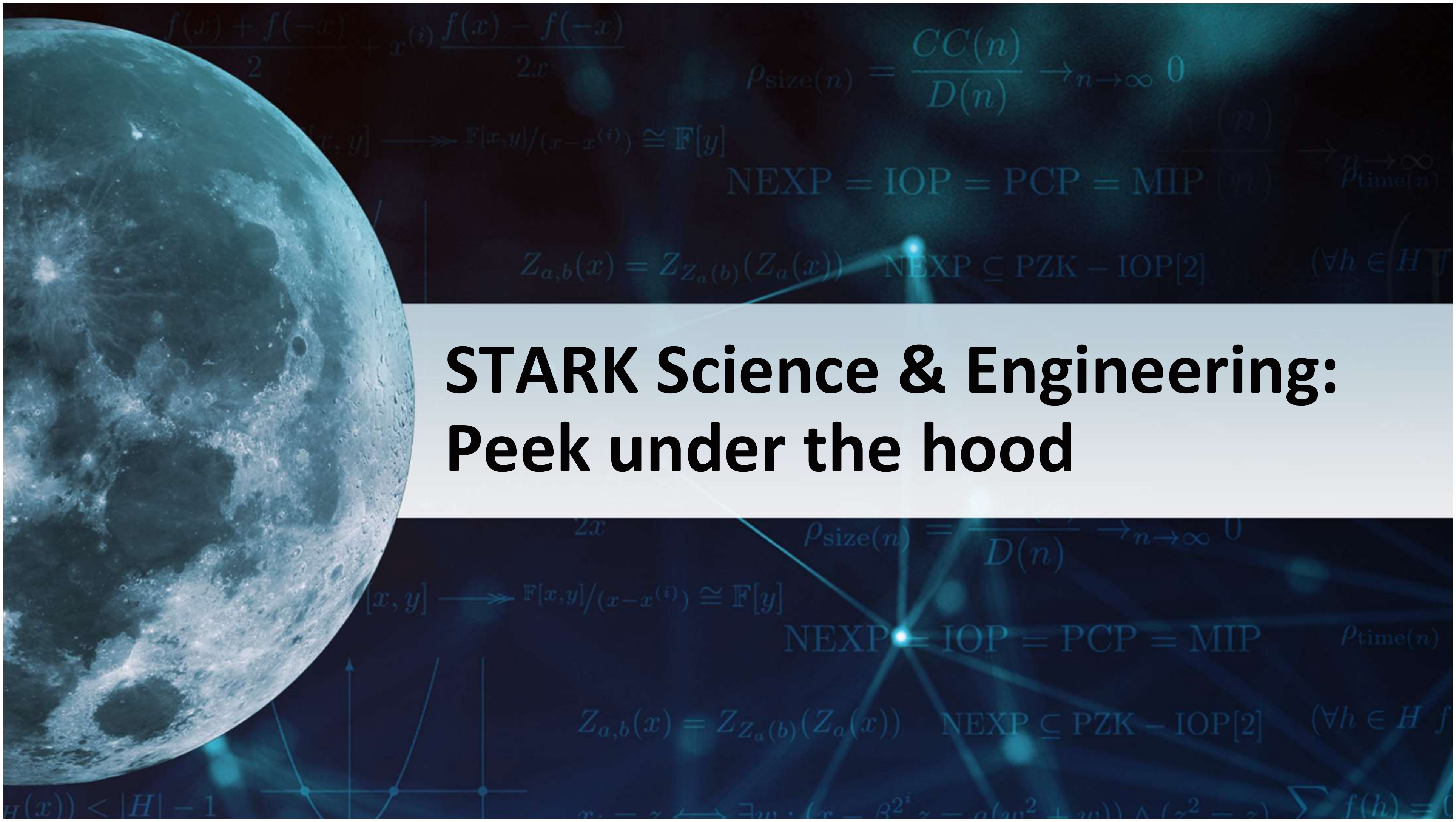
STARK for Scalability: Space

Runtime Comparison	ZK-STARK	ZK-SNARK	Bulletproof
1 Tx	~~500kb~~ ~~80kb~~ 45 kb (yet to identify lower bound)	Tx: 200 byte Key: 50 MB	1.5 kb
10K Tx	~~190kb~~ 135 k (yet to identify lower bound)	Tx: 200 byte Key: 500 GB	2.5 kb



STARK Science & Engineering: Peek under the hood

How to build efficient STARKs?

Convert computation to Algebraic Intermediate Representation (AIR)

- Generalization of R1CS constraints (used by SNARKs)
- State of computation is sequence of field elements
- Program expressed as set of polynomial relations over consecutive states
- Then apply more crypto+algebra …

Long term

tool-chain converting programs to AIRs

Mid term

domain specific languages for composing crypto-primitives

Short term

hand-optimize AIRs for specific computations

STARKWARE

Example: Pedersen Merkle path

Statement proved → Useful for.. → StarkWare's first major milestone → Let's examine the numbers

Statement proved:

I know a leaf in Merkle-tree of depth *d* with Merkle root *r*

Useful for..

- Shielded Txs (major component in Zcash Sapling circuit)
- Verifiable Delay Functions (VDFs)
- Scalability solutions (more on this later)

StarkWare's first major milestone:

implementing STARK for this

STARK measurements - Pedersen Merkle path

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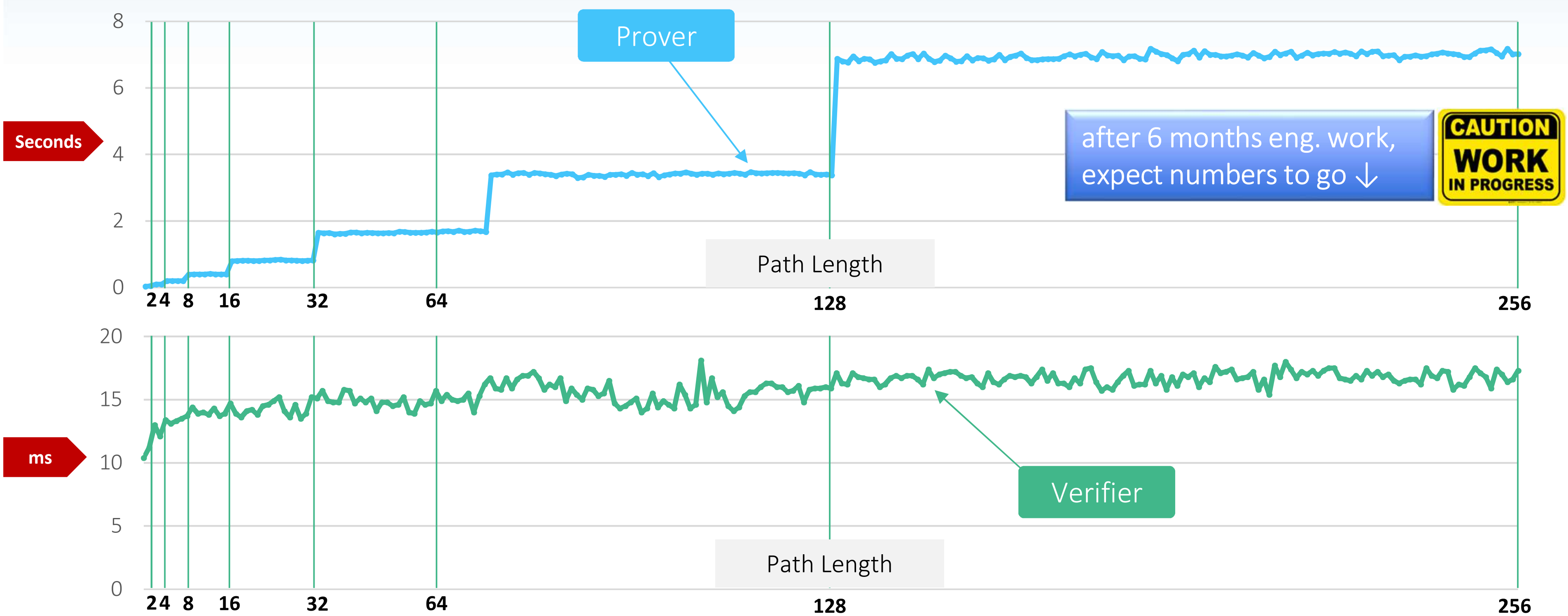

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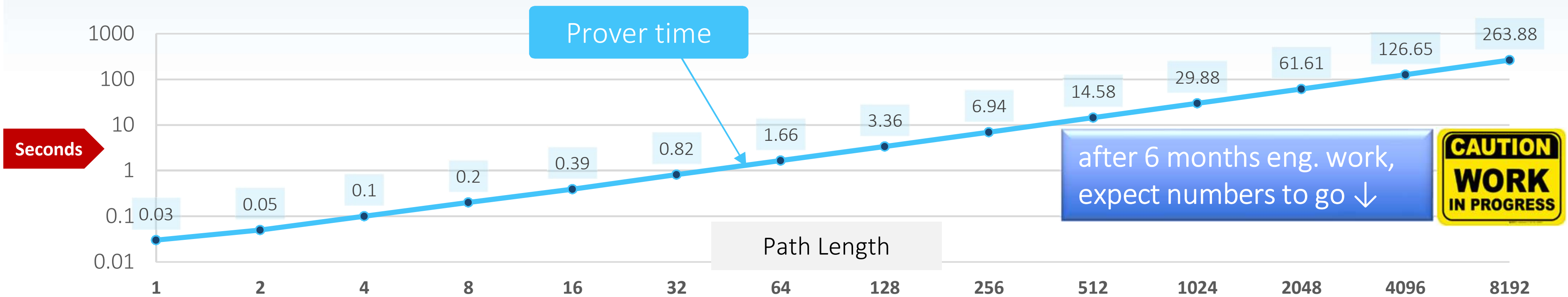

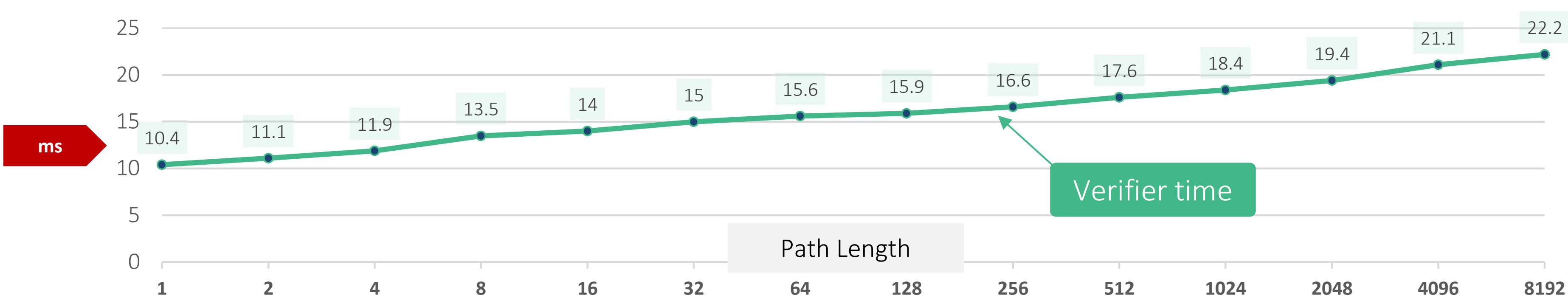

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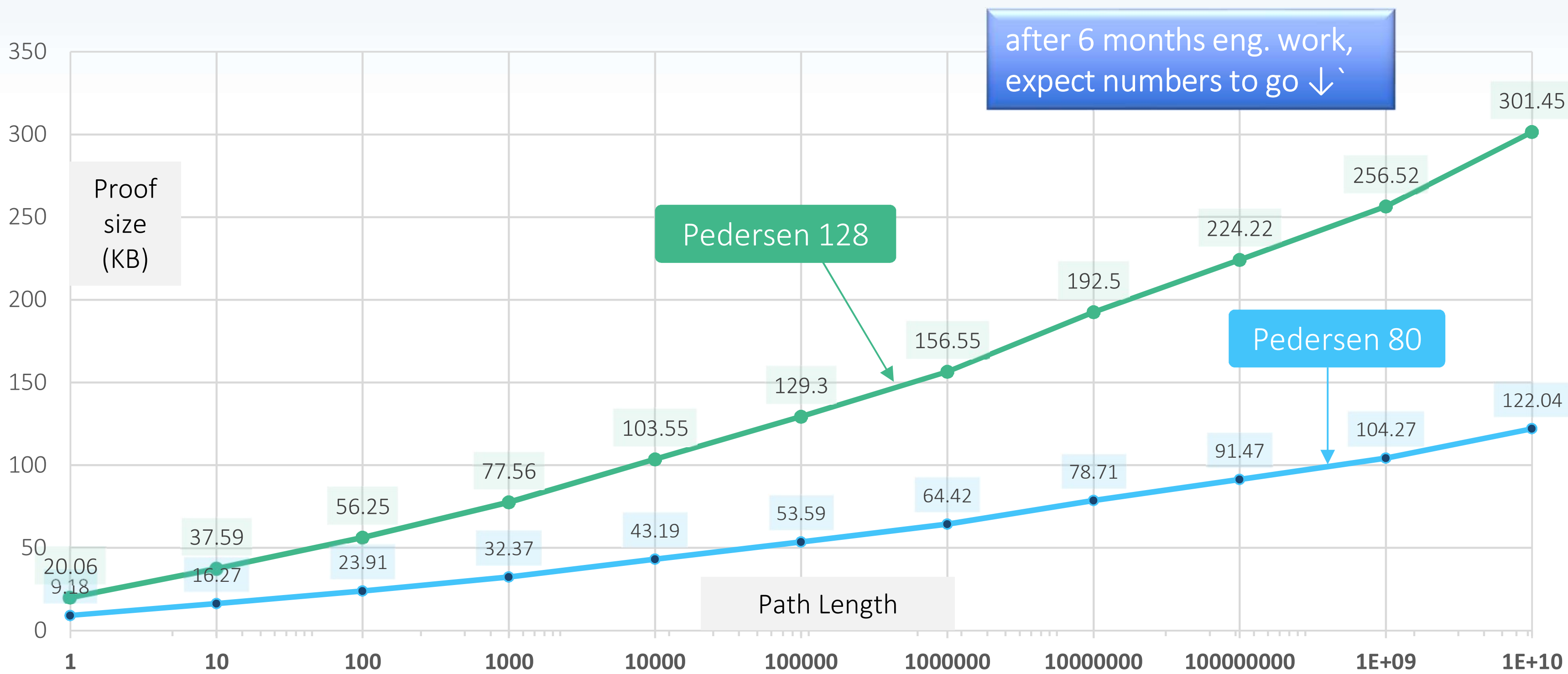
STARK measurements - Pedersen Merkle path

CAUTION WORK IN PROGRESS



STARK verifier complexity

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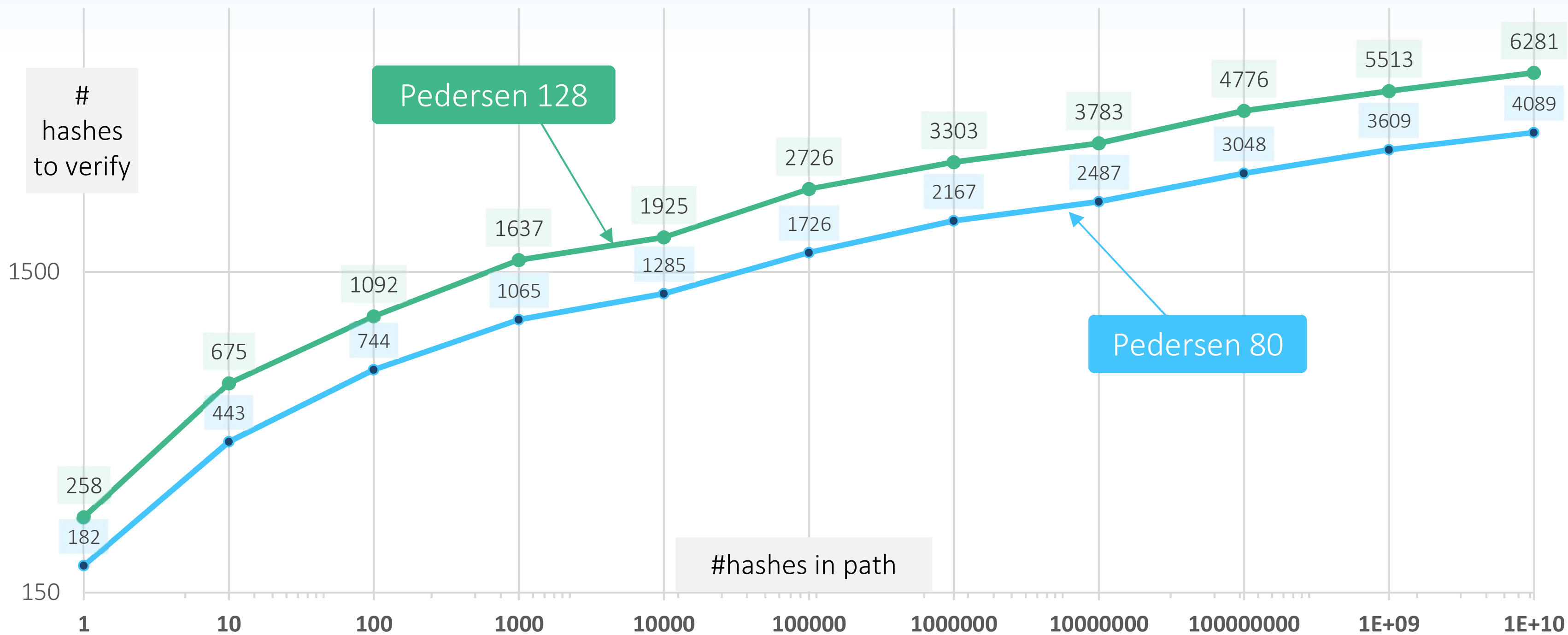

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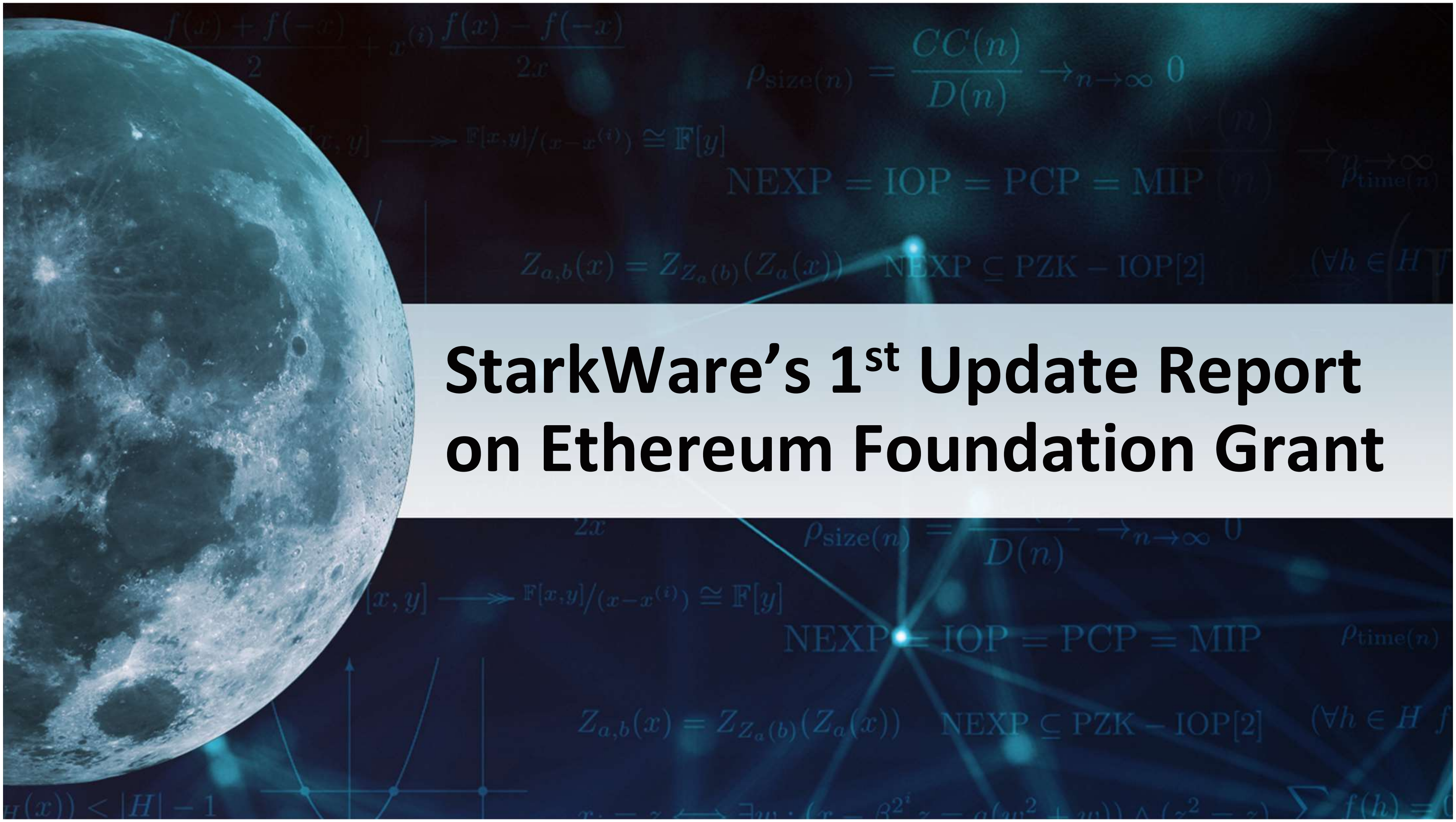


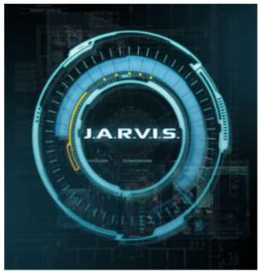
StarkWare's 1st Update Report on Ethereum Foundation Grant

1st T4T: Ethereum Foundation grant update

2-year performance and milestone-based grant

Requested Milestone: STARK proofs at rate of 100 hash/sec on quad-core

Latest: 100 Pedersens/3 sec on single thread of this laptop (1.8Ghz)



STARK-friendly hash functions

Defined complexity parameters of STARK friendly primitives

Designed by *Dr. Tomer Ashur & Siemen Dhooghe*, Scientific supervision by *Prof. Vincent Rijmen* (co-inventor of Rijndael/AES cypher standard), see [Tomer's blog]

- Rijndael/AES-based constructions (over binary fields)
- Jarvis - STARK-friendly cypher candidate
- Friday - STARK-friendly hash candidate, ~25X STARK-friendlier than Pedersen
- Next: expert+community review, including cypher-breaking competition

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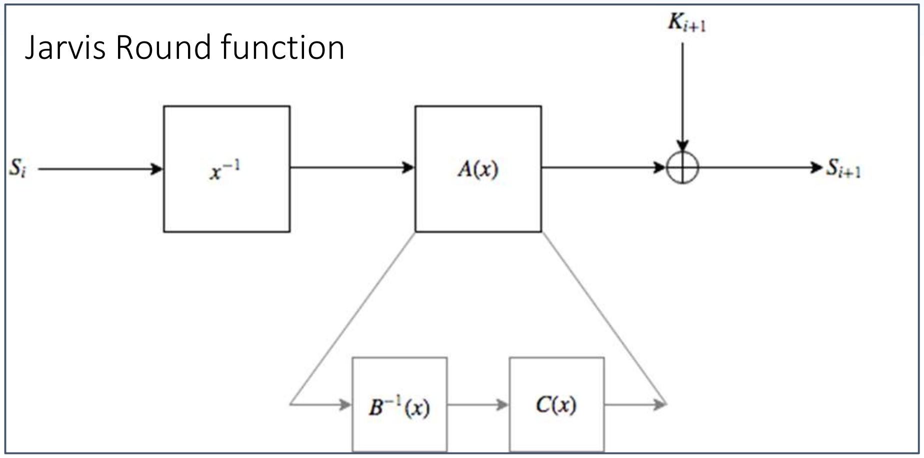
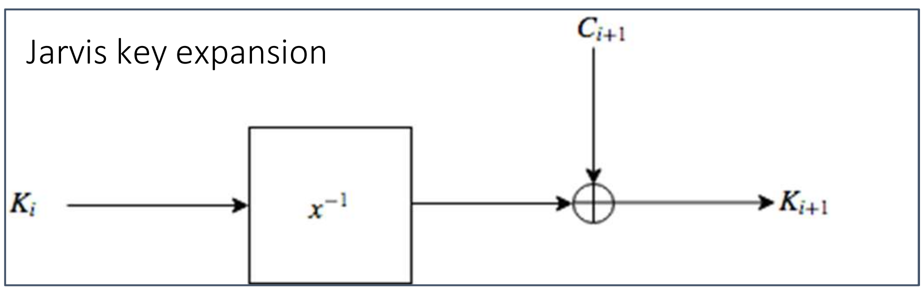
1st T4T: Ethereum Foundation grant update

Images from Dr. Tomer Ashur's blog:
www.esat.kuleuven.be/cosic/jarvis-and-friday-stark-friendly-cryptographic-primitives/





- Jarvis is a cypher, Friday is its hash (Miyaguchi-Perneel)
- Jarvis defined over GF(2^{2n}) for n-bit security
- # rounds TBD, between 6 to 10
- B(X), C(X): quartic linearized permutation polynomials
- Security relies on Rijndael-style analysis
- Jarvis is not prime-field friendly (not SNARK/BP friendly)

1st T4T: Ethereum Foundation grant update

[Images from Dr. Tomer Ashur's blog](www.esat.kuleuven.be/cosic/jarvis-and-friday-stark-friendly-cryptographic-primitives/):
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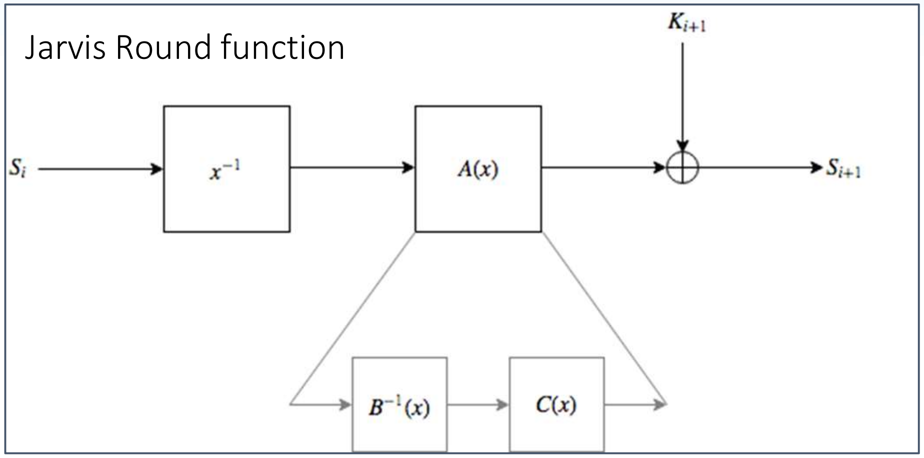
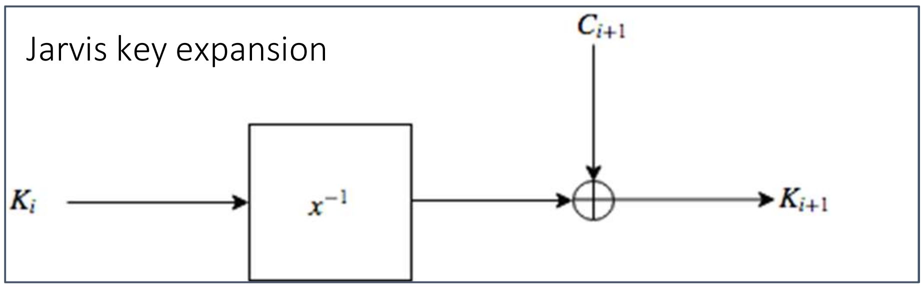
Jarvis Round function



Jarvis key expansion



To support STARK, Jarvis, Friday, need

- EVM opcodes for binary field +, *, /
- EVM opcodes for blake, Friday
- We'll submit an EIP request

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Convert computation to Algebraic Intermediate Representation (AIR)

Generalization of R1CS constraints (used by SNARKs)

State of computation is sequence of field elements

Algebraic Execution Trace (AET) captures computation:

	security	width	cycles	degree	w*c*d
SHA2	128	56	3762	11	2,317,392
Rijdael 160	80	68	58	8	31,552
Pedersen	128	4	256	2	2,048
MimC	128	1	70-80	3	210 - 240
Friday	128	5	6-10	2	60 - 100

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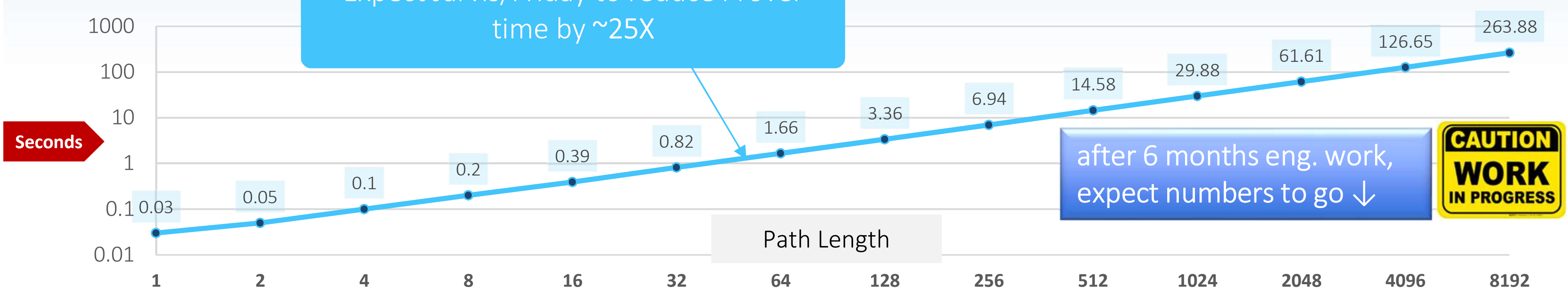
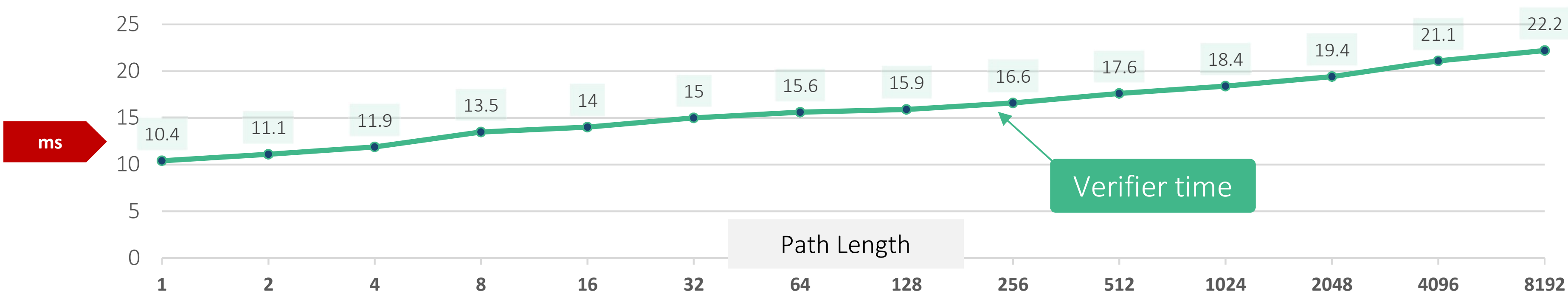
Single thread
32 GB DDR4 RAM

Expect Jarvis/Friday to reduce Prover time by ~25X





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STARK proof length estimates, repeated hash

CAUTION
WORK
IN PROGRESS

after 6 months eng. work, expect numbers to go ↓

STARKWARE


STARKWARE
Demo


STARKWARE
One more thing…


STARKWARE
Questions?

STARKWARE

STARK Use Cases

Avihu Levy, Head of Product | October 2018

Potential Uses

Scalability → Privacy → Bootstrap & Sync → STARK-based primitives → …

Scalability

- Infrastructure level (layer 1 / layer 2)
- Application level (STARK-powered dapp)

STARK-based primitives

- VDF
- Signature aggregation

Scalability

Complex computations

Batches of simple computations

Verifying 10K Txs costs only 3x of verifying single Tx!

Storage

What’s Done On-Chain Vs. Off-Chain?

Verifier

On Chain

Verifier

Prover

Off Chain

Native

Computation

Prover

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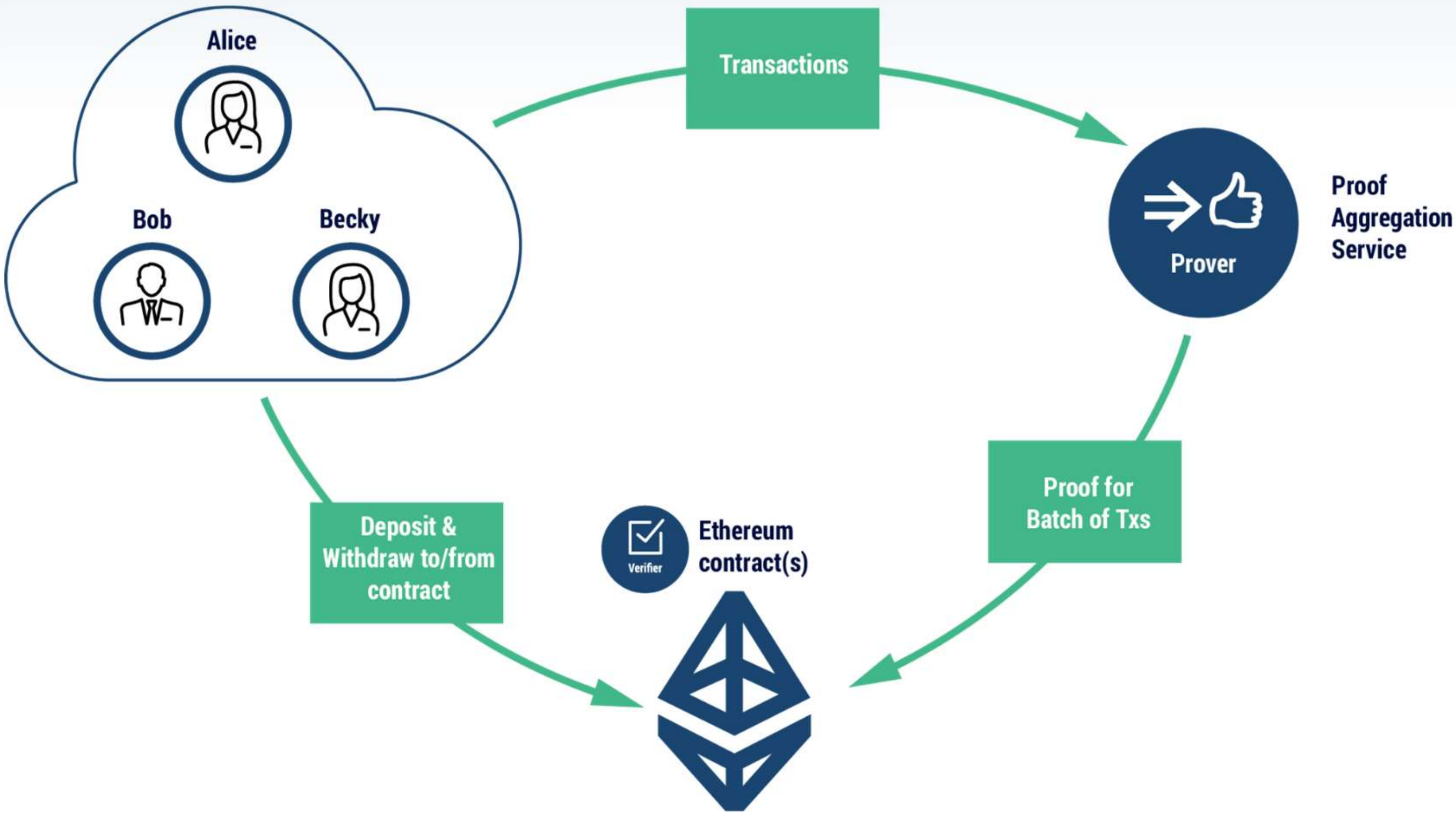
Scalability by batching



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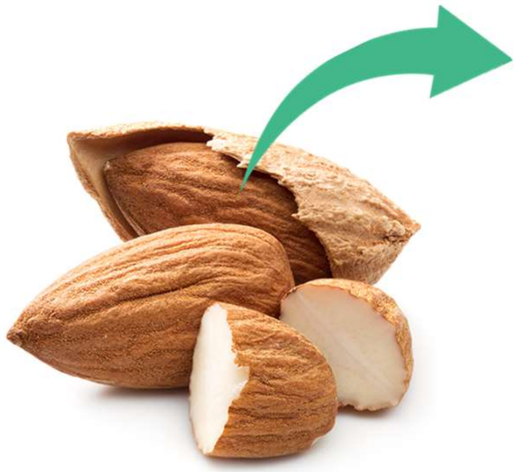
Payment Txs: In a Nutshell



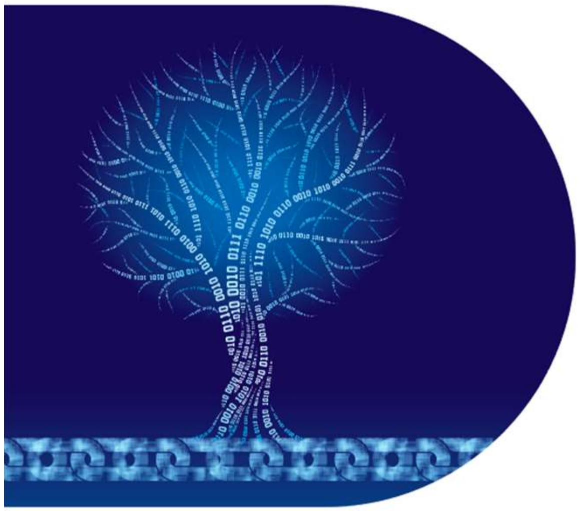
Increase the network throughput (e.g. of Ethereum)

Reduce Tx fees
(for native Ether and
ERC-20 tokens)

Significant saving
(> 10X)

**Users register to the contract,
and only then can interact with one another**

Payment Txs: How Is This Achieved?



No need to send and verify signatures

Covered by proof

Less transmission, less computation

State storage taken off chain, state root stored on-chain

Proof proves state changes

Centralization trade-off (unless done by miners)

Increasing network throughput by 1 OOM

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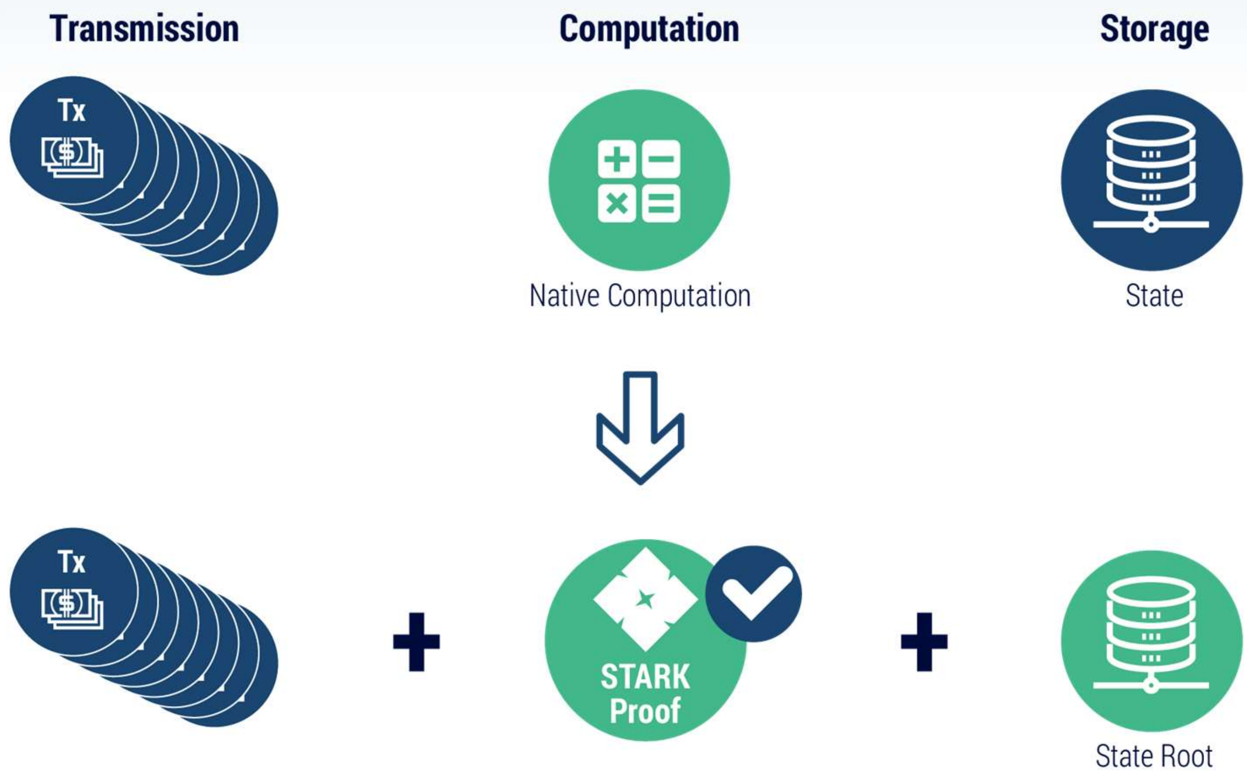
Scalability



DEX: In a Nutshell

Provide users with “best of all worlds”:

- Users keep custody of their funds
- Low latency
- At a negligible blockchain cost
- Breaking the gas-induced ceiling on volume/liquidity

Later add (cheap) transfers and shielded Txs through DEX

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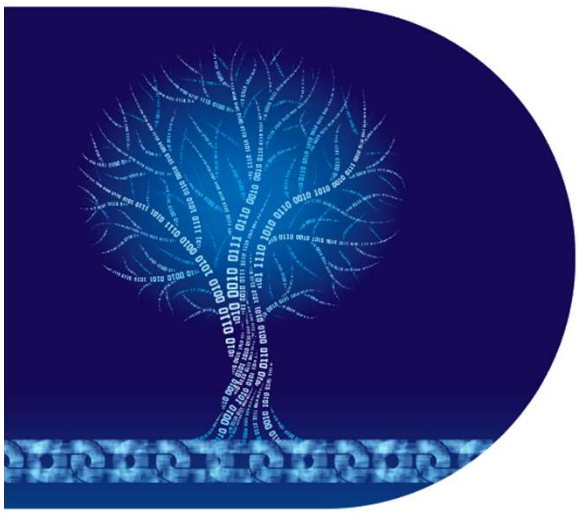
DEX: How Is This Achieved?



No need to send and verify maker/taker signatures

Covered by proof

Less transmission, less computation

Trader balances taken off chain, state root stored on-chain

Proof proves balance changes

Centralization not an issue in this case

lowering blockchain costs* by 1-2 OOM

*Blockchain costs are currently the dominant DEX costs

Overview

- What's a STARK?
- STARK comparison to
  - SNARKs (Zcash)
  - Recursive SNARKs (Coda)
  - Bulletproofs (Monero)
- Benefits of STARK for scalability
- Potential use-cases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Bootstrap & Sync

Problem:
new clients bootstrapping process is heavy, as well as keeping your client sync

$\Rightarrow$

Solution:
Download a state and a proof for the validity of the state, rather than download & recompute the whole history

Bootstrap & Sync

Block headers for light clients

E.g. (Ethereum):
~500 bytes header,
~3MB headers/day

Instead, a stark proof for block header having X work behind it since genesis/ last known checkpoint

Proof size ~100KB with 20 ms verification time

Full Clients

Prove that the state computed based on previous block state/ genesis block is valid

VDF

Problem:
randomness from block data is hard, if the block creator knows the output of the random function

⇒

Solution:
a function that take time to compute, so when fixing the input the output is unknown

We do want a fast verification of the output

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VDF