CS251 Fall 2023

(cs251.stanford.edu)

Privacy on the Blockchain

Dan Boneh

[project #4 posted]

The need for privacy in the financial system

Supply chain privacy:

- A manufacturer does not want to reveal how much it pays its supplier for parts.

Payment privacy:

- A company that pays its employees in crypto wants to keep list of employees and salaries private.
- Endusers need privacy for rent, donations, purchases

Business logic privacy: Can the code of a smart contract be private?

The need for privacy in the financial system

The bottom line:

Blockchains cannot reach their full potential without some form of private transactions

Types of Privacy

Pseudonymity: (weak privacy)

- Every user has a long-term consistent pseudonym (e.g. reddit)
  - Pros: reputation
  - Cons: link to real-world identity can leak over time

Full anonymity: User's transactions are unlinkable

- No one can tell if two transactions are from the same address

A difficult question: privacy from who?

No privacy:
Everyone can see all transactions

Privacy from the public:
Only a trusted operator can see transactions

Semi-full privacy:
only “local” law enforcement can see transactions

full privacy:
no one can see transactions

Negative aspects of complete privacy

How to prevent criminal activity?

The challenge:

- How to support positive applications of private payments, but prevent the negative ones?
- Can we ensure legal compliance while preserving privacy?
- Yes! The key technology: **zero knowledge proofs**

Are Bitcoin and Ethereum Private?

The base systems are definitely not …

Privacy in Ethereum?

- Every account balance is public
- For Dapps: code and internal state are public
- All account transactions are linked to account

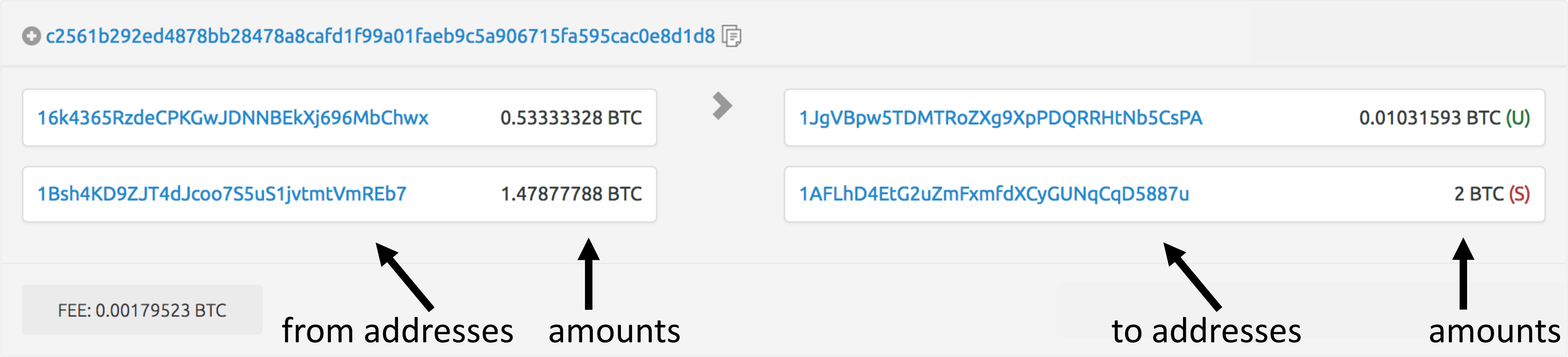
etherscan.io:

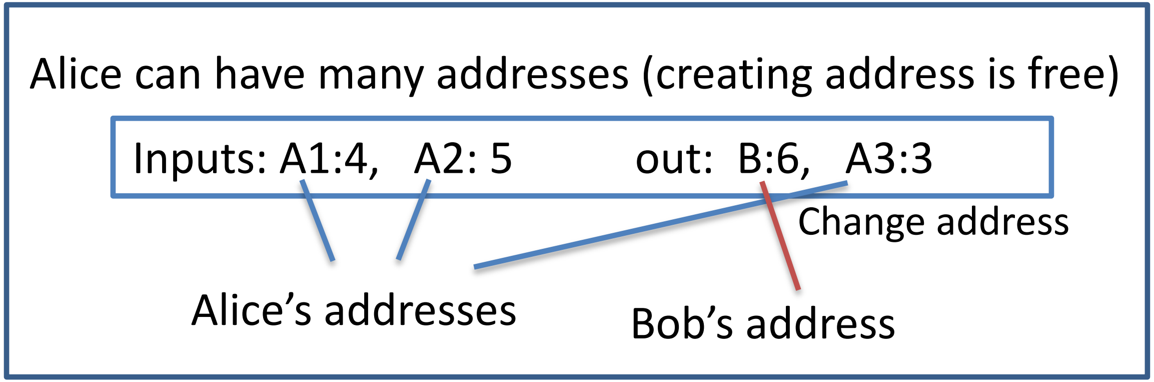
Address 0x1654b0c3f62902d7A86237…

Balance:	1.114479450024297906 Ether
Ether Value:	$4,286.34 (@ $3,846.05/ETH)

	Txn Hash	Method	Block
	0x0269eff8b4196558c07…	Set Approval For...	13426561
	0xa3dacb0e7c579a99cd…	Cancel Order_	13397993
	0x73785abcc7ccf030d6a…	Set Approval For...	13387834
	0x1463293c495069d61c…	Atomic Match_	13387703

Privacy in Bitcoin?





Transaction data can be used to link an address to a physical identity

(chainalysis)

Linking an addresses to an identity

inputs: A1: 4, A2: 5 outputs: B: 6, A3: 3

Alice buys a book from a merchant:

- Alice learns one of merchant's address (B)
- Merchant links three addresses to Alice (A1, A2, A3)

Alice uses an exchange (ETH ↔ USD)

- BSA: a US exchange must do KYC (know your customer)

  … collect and verify Alice's ID
- Exchange links Alice to her addresses (A1, A2, A3)

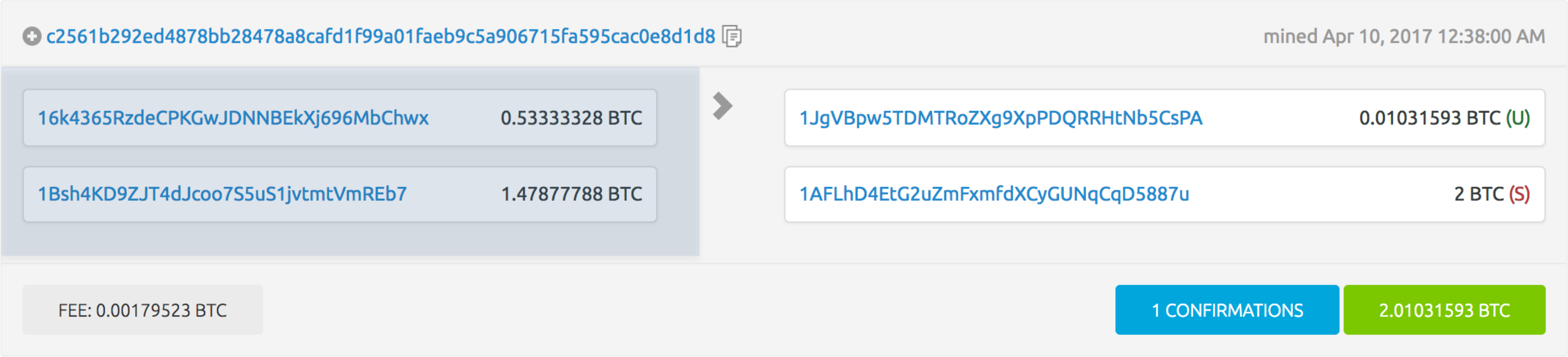
De-anonymization strategy: Idioms of use

A general strategy for de-anonymizing Bitcoin addresses

Heuristic 1:

Two addresses are input to a TX

$\Rightarrow$ both addresses are controlled by same entity



De-anonymization strategy: Idioms of use

Heuristic 2:

Change address is controlled by the same user as input address

Which is the change address?

- Heuristic: a new address that receives less than every input

c2561b292ed4878bb28478a8cafd1f99a01faeb9c5a906715fa595cac0e8d1d8 — mined Apr 10, 2017 12:38:00 AM

16k4365RzdeCPKGwJDNNBEkXj696MbChwx	0.53333328 BTC	>	1JgVBpw5TDMTRoZXg9XpPDQRRHtNb5CsPA	0.01031593 BTC (U)
1Bsh4KD9ZJT4dJcoo7S5uS1jvtmtVmREb7	1.47877788 BTC		1AFLhD4EtG2uZmFxmfdXCyGUNqCqD5887u	2 BTC (S)

FEE: 0.00179523 BTC

1 CONFIRMATIONS — 2.01031593 BTC

A Bitcoin experiment [Meiklejohn, et al.]

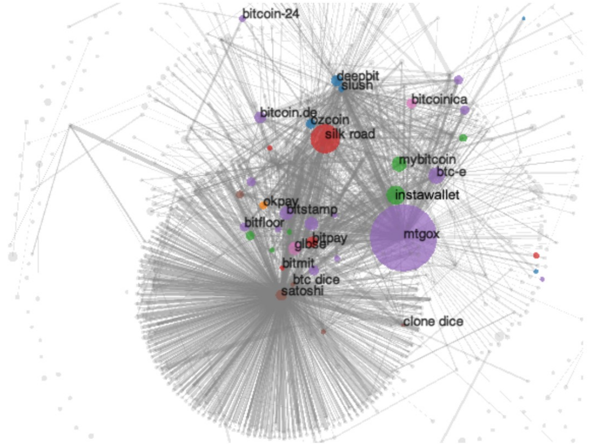
step 1: Heuristic 1 and 2 ⇒ 3.3M clusters

step 2: 1070 addresses identified by interacting with merchants

- Coinbase, Kraken, …

step 3: now 15% of all addresses identified

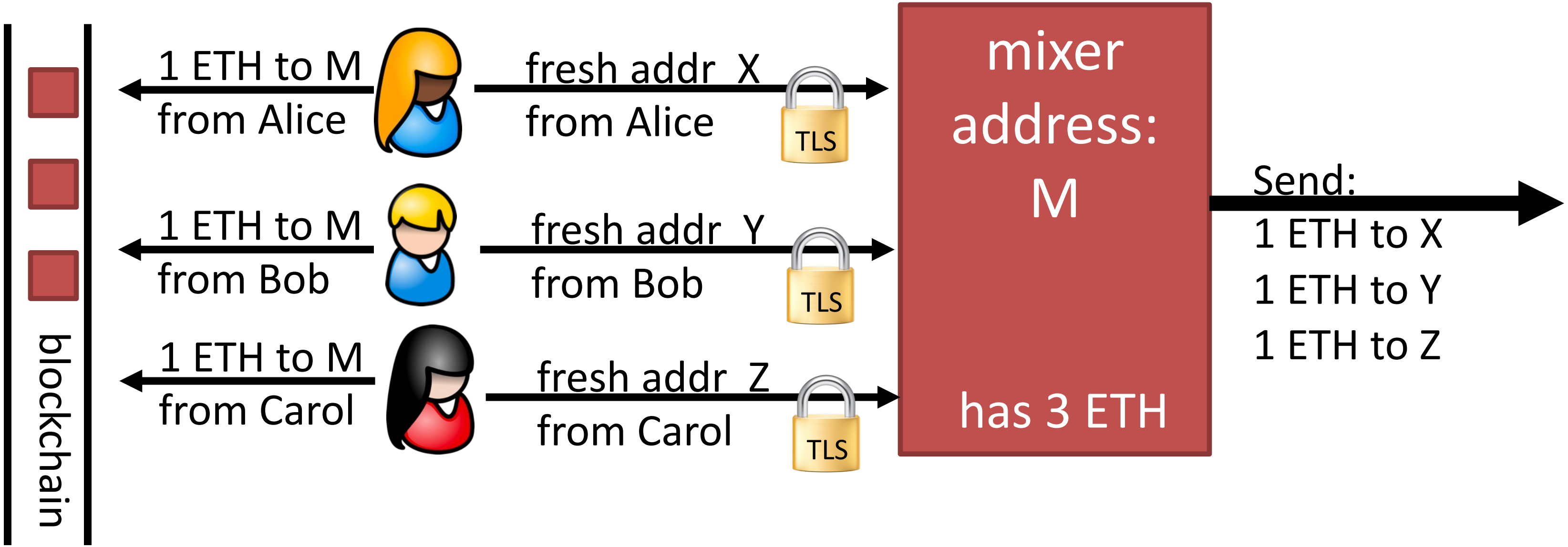
- Learn total assets for all clusters



Commercial efforts: Chainalysis, Elliptic, …

Private coins on a Public Blockchain

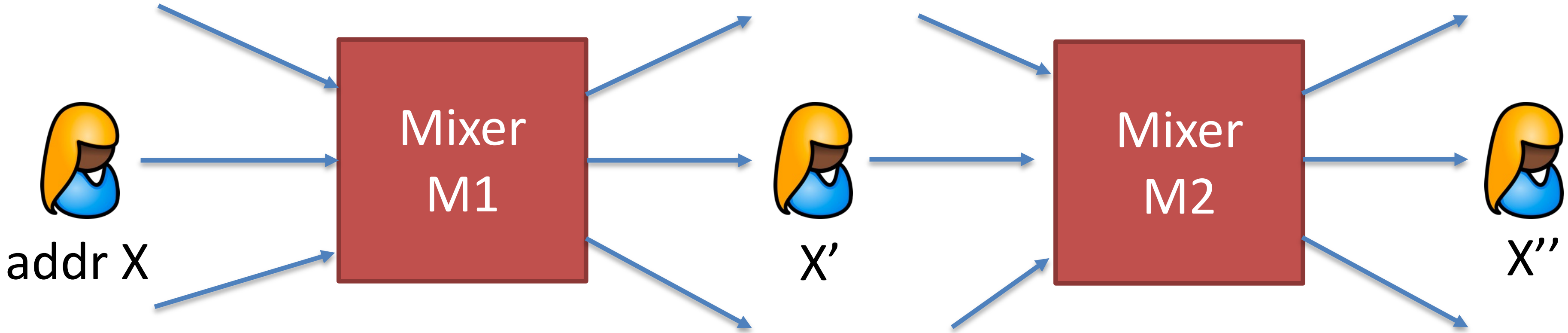
Attempt 1: simple mixing



Observer knows Y belongs to one of {Alice, Bob, Carol} but does not know which one
$\Longrightarrow$ anonymity set of size 3.

Problems: (i) mixer M knows shuffle, (ii) mixer can abscond with 3 ETH !!

Increasing the anonymity set



M1: mix n inputs from n users $\Rightarrow$ X’ has anonymity set size = n

M2: mix output from m mixers $\Rightarrow$ X’’ has anonymity set size = $n \times m$

Privacy: as long as one of M1 **or** M2 are honest

Secure mixing without a mixer?

Problem: Mixer can abscond with funds or reveal the shuffle.

Can we securely mix without a trusted mixer? Answer: yes!

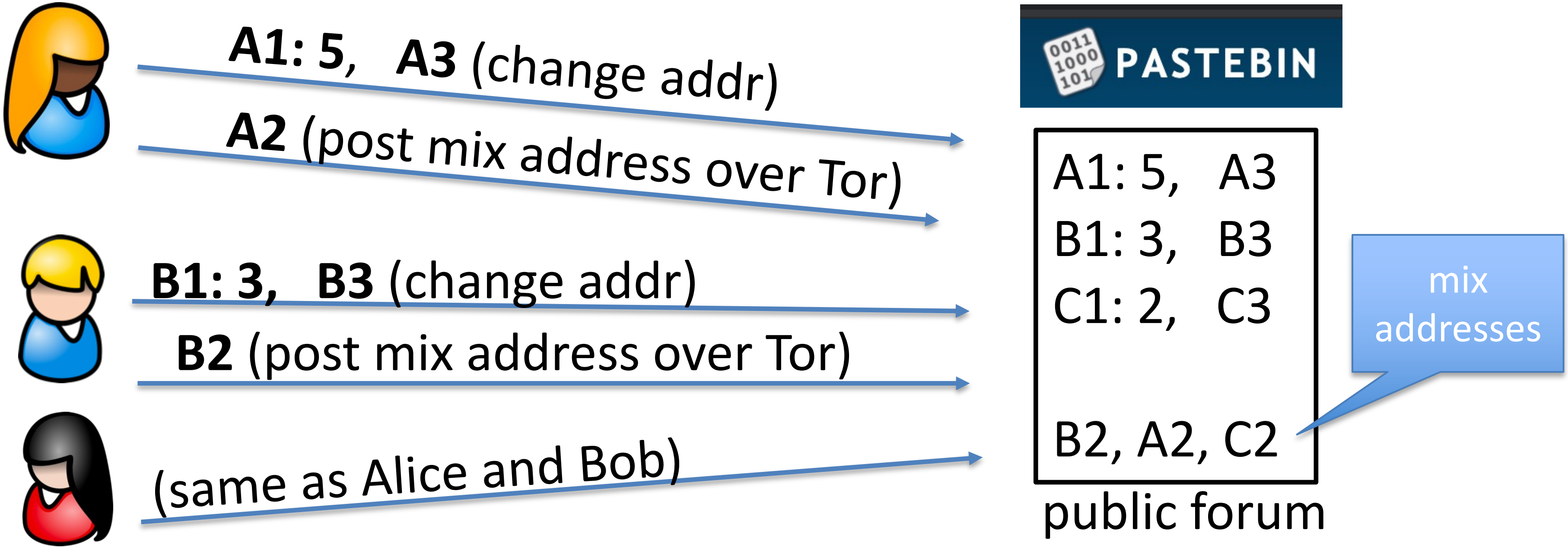
- on Bitcoin: **CoinJoin** (used by, e.g., Wasabi wallet)
- on Ethereum: **Tornado cash, Privacy Pools, …**

… a single mixer using ZK proofs – next lecture

CoinJoin: Bitcoin Mixing without Mixer

The setup: Alice, Bob, and Carol want to mix together.

Alice owns UTXO **A1:5**, Bob owns UTXO **B1:3**, Carol owns **C1:2**



CoinJoin: Bitcoin Mixing without Mixer

CoinJoin TX: all three prepare and sign the following Tx:

inputs (not private):	A1: 5, B1: 3, C1: 2
outputs (private):	**B2: 2, A2: 2, C2: 2**
outputs (not private):	A3: 3, B3: 1

mix addresses

Mixed UTXOs all have same value = min of inputs (2 in this case)

All three post sigs on Pastebin ⇒ one of them posts Tx on chain.

Coinjoin drawbacks

In practice: each CoinJoin Tx mixes about <u>40 inputs</u>

- Large Tx: 40 inputs, 80 outputs

All participants must sign CoinJoin Tx for it to be valid

$\Rightarrow$ ensures all of them approve the CoinJoin Tx

… but any one of them can disrupt the process

Beyond simple mixing

Private Tx on a public blockchain

Can we have private transactions on a public blockchain?

Naïve reasoning:

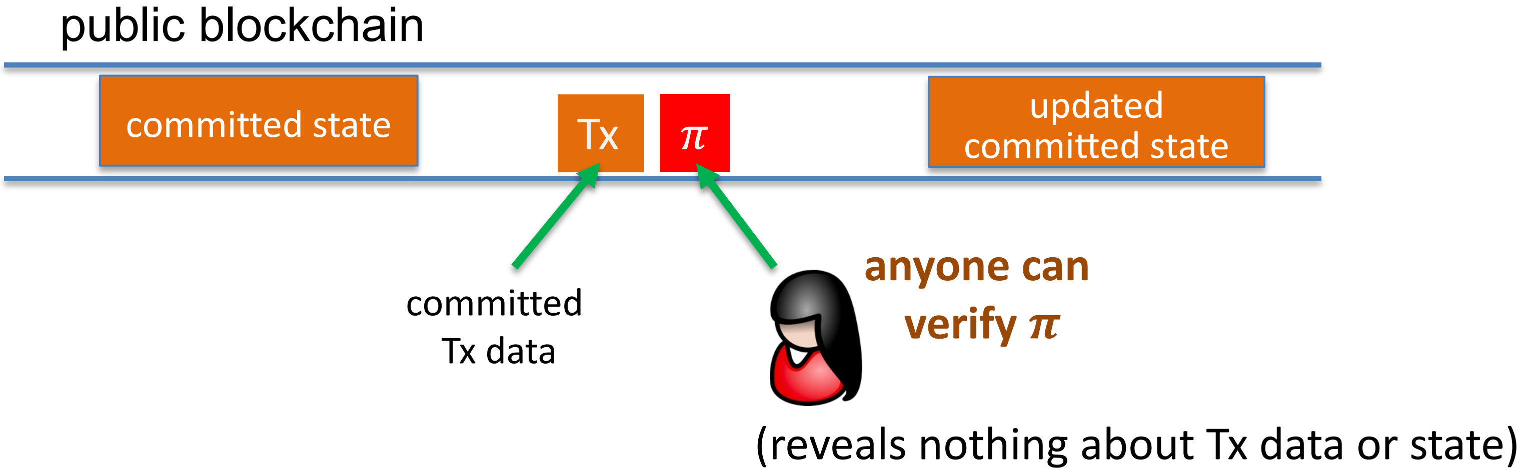
universal verifiability $\Rightarrow$ transaction data must be public

otherwise, how we can verify Tx ??

crypto magic $\Rightarrow$ private Tx on a publicly verifiable blockchain

Crypto tools: **commitments** and **zero knowledge proofs**

A paradigm for Private Tx



Committed data: short (hiding) commitment on chain

Proof π: succinct *zero-knowledge proof* that

(1) committed Tx data is consistent with committed current state, and
(2) committed updated state is correct

Review: cryptographic commitments

Cryptographic commitment: emulates an envelope

Many applications: e.g., a DAPP for a sealed bid auction

- Every participant **commits** to its bid,
- Once all bids are in, everyone opens their commitment

Cryptographic Commitments

Syntax: a commitment scheme is two algorithms

- **commit**(*msg*, *r*) $\rightarrow$ *com*

  $\underbrace{r}_{\text{secret randomness}}$ $\qquad$ $\underbrace{com}_{\text{commitment string}}$

- **verify**(*msg*, *com*, *r*) $\rightarrow$ accept or reject

  anyone can verify that commitment was opened correctly

Commitments: security properties

- **binding**: Bob cannot produce two valid openings for ***com***

  More precisely: no efficient adversary can produce

  com, (m_1, r_1), (m_2, r_2)

  such that verify(m_1, ***com***, r_1) = verify(m_2, ***com***, r_2) = accept

  and $m_1 \neq m_2$.

- **hiding**: ***com*** reveals nothing about committed data

  commit(m, r) → ***com***, and r is sampled uniformly in a set R,

  then ***com*** is statistically independent of m

Example: hash-based commitment

Fix a hash function $H: M \times R \rightarrow C$ (e.g., SHA256)

where H is collision resistant, and $|R| \gg |C|$

- commit($m \in M$, $r \leftarrow R$): **com** $= H(m, r)$
- verify(m, **com**, r): accept if **com** $= H(m, r)$

binding: follows from collision resistance of H

hiding: follows from a mild assumption on H

What is a zk-SNARK?

Succinct zero knowledge proofs:
an important tool for privacy on the blockchain

What is a zk-SNARK ? (intuition)

SNARK: a <u>succinct</u> proof that a certain statement is true

Example statement: "I know an m such that SHA256$(m) = 0$"

- **SNARK**: the proof is **"short"** and **"fast"** to verify

  [if m is 1GB then the trivial proof (the message m) is neither]

- **zk-SNARK**: the proof "reveals nothing" about m

Commercial interest in SNARKs

STARKWARE

Aztec

Matter Labs

ESPRESSO SYSTEMS

RISC Zero

Scroll

polygon

Aleo

SUPRA NATIONAL

INGONYAMA

Many more building applications that use SNARKs

Blockchain Applications I

Outsourcing computation: (no need for zero knowledge)

L1 chain quickly verifies the work of an off-chain service

To minimize gas: need a short proof, fast to verify

Examples:

- **Scalability:** proof-based Rollups (zkRollup)

  off-chain service processes a batch of Tx;

  L1 chain verifies a succinct proof that Tx were processed correctly

- **Bridging blockchains:** proof of consensus (zkBridge)

  Chain A produces a succinct proof about its state. Chain B verifies.

Blockchain Applications II

Some applications require zero knowledge (privacy):

- **Private Tx on a public blockchain**:
  - zk proof that a private Tx is valid (Tornado cash, Zcash, IronFish, Aleo)
- **Compliance:**
  - Proof that a private Tx is compliant with banking laws (Espresso)
  - Proof that an exchange is solvent in zero-knowledge (Raposa)

More on these blockchain applications in a minute

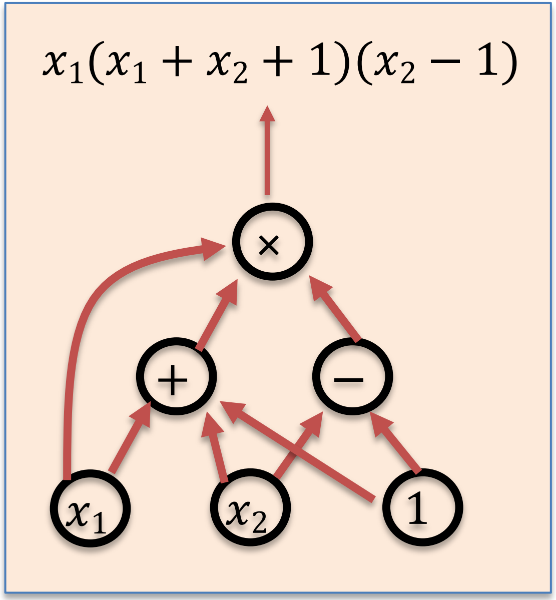
Many non-blockchain applications

Blockchains drive the development of SNARKs

… but **many** non-blockchain applications benefit

Arithmetic circuits

- Fix a finite field $\mathbb{F} = \{0, \ldots, p-1\}$ for some prime p>2.
- **Arithmetic circuit:** $C: \mathbb{F}^n \to \mathbb{F}$
  - directed acyclic graph (DAG) where
    internal nodes are labeled $+, -,$ or $\times$
    inputs are labeled $1, x_1, \ldots, x_n$
  - defines an n-variate polynomial
    with an evaluation recipe
- $|C| = \#$ gates in C



Interesting arithmetic circuits

<u>Examples</u>:

- $C_{hash}(h, \mathbf{m})$: outputs 0 if SHA256($\mathbf{m}$) = h , and ≠0 otherwise

  $C_{hash}(h, \mathbf{m}) = (h - \text{SHA256}(\mathbf{m}))$, $|C_{hash}| \approx$ 20K gates

- $C_{sig}(pk, m, \sigma)$: outputs 0 if σ is a valid ECDSA signature on m with respect to pk

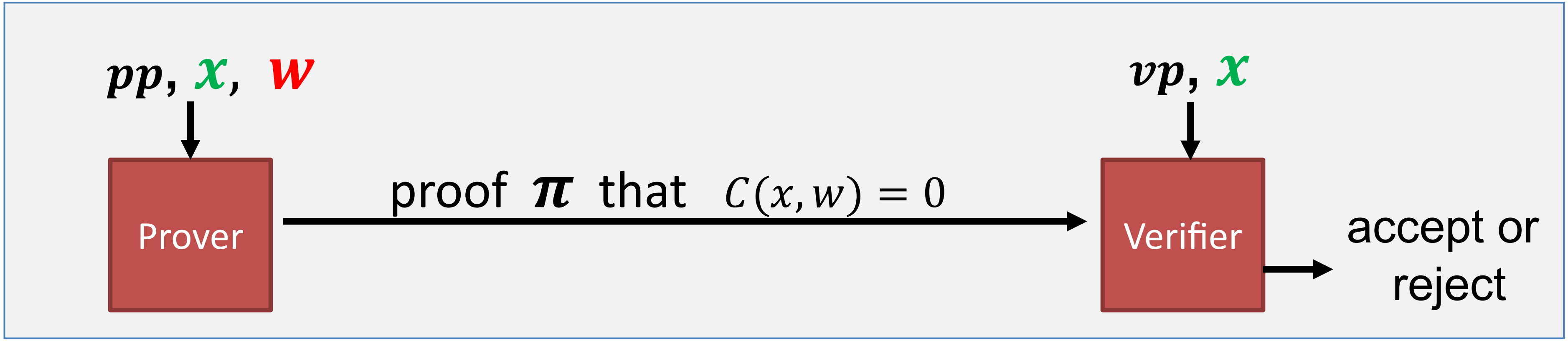
(preprocessing) NARK: Non-interactive ARgument of Knowledge

Public arithmetic circuit: $C(\,x,\; w\,) \rightarrow \mathbb{F}$

public statement in $\mathbb{F}^n$

secret witness in $\mathbb{F}^m$

Preprocessing (setup): $\mathbf{S}(C) \rightarrow$ public parameters $(\boldsymbol{pp}, \boldsymbol{vp})$



(preprocessing) NARK: Non-interactive ARgument of Knowledge

A **preprocessing NARK** is a triple (S, P, V):

- **S**(C) $\rightarrow$ public parameters (pp, vp) for prover and verifier
- **P**$(pp, \boldsymbol{x}, \boldsymbol{w})$ $\rightarrow$ proof π
- **V**$(vp, \boldsymbol{x}, \boldsymbol{\pi})$ $\rightarrow$ accept or reject

NARK: requirements (informal)

Prover P(pp, $\mathbf{x}$, $\mathbf{w}$) Verifier V (vp, $\mathbf{x}$, $\boldsymbol{\pi}$)

proof π $\longrightarrow$

accept or reject

Complete: $\forall x, w$: $C(\mathbf{x}, \mathbf{w}) = 0 \quad \Rightarrow \quad$ Pr[V(vp, x, P(pp, $\mathbf{x}$, $\mathbf{w}$)) = accept] = 1

knowledge sound: V accepts $\Rightarrow$ P "knows" $\mathbf{w}$ s.t. $C(\mathbf{x}, \mathbf{w}) = 0$

(an extractor E can extract a valid $\mathbf{w}$ from P)

Optional: **Zero knowledge**: $(C, pp, vp, \mathbf{x}, \pi)$ "reveal nothing" about $\mathbf{w}$

SNARK: a Succinct ARgument of Knowledge

A **succinct preprocessing NARK** is a triple (S, P, V):

- **S**(C) → public parameters (pp, vp) for prover and verifier

- **P**(pp, $\boldsymbol{x}$, $\boldsymbol{w}$) → **short** proof π ; $\boxed{\text{len}(\pi) = O_\lambda(\,\textbf{polylog}(|\boldsymbol{C}|))}$

- **V**(vp, $\boldsymbol{x}$, $\boldsymbol{\pi}$) **fast to verify** ; $\boxed{\text{time(V)} = O_\lambda(|x|,\ \textbf{polylog}(|\boldsymbol{C}|))}$

short "summary" of circuit

V has no time to read C !!

[for some SNARKs, $\text{len}(\pi) = \text{time}(V) = O_\lambda(1)$]

SNARK: a Succinct ARgument of Knowledge

SNARK: a NARC (complete and knowledge sound) that is **succinct**

zk-SNARK: a SNARK that is also **zero knowledge**

The trivial SNARK is not a SNARK

(a) Prover sends $\boldsymbol{w}$ to verifier,

(b) Verifier checks if $C(\boldsymbol{x}, \boldsymbol{w}) = 0$ and accepts if so.

<u>Problems with this</u>:

(1) $\boldsymbol{w}$ might be long: we want a "short" proof

(2) computing $C(\boldsymbol{x}, \boldsymbol{w})$ may be hard: we want a "fast" verifier

(3) $\boldsymbol{w}$ might be secret: prover might not want to reveal $\boldsymbol{w}$ to verifier

The SNARK zoo … next lecture

STARK	Bulletproofs	Groth16	Gemini
Plonky2	Halo2	Plonk	DARK
Breakdown	Nova	Marlin	Hyperplonk
Orion	Hyrax	Sonic	⋮
Spartan			

Open: one SNARK to rule them all

SNARKs in practice

DSL
program

Circom,
ZoKrates,
Leo,
Zinc,
Cairo,
Noir,
…

domain specific language

compiler →

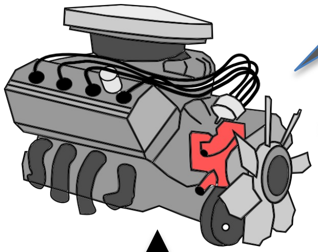
SNARK friendly format

circuit,
R1CS,
AIR,
…
EVM byte code

→

SNARK backend prover

heavy computation



→ π

↑
x, witness

END OF LECTURE

Next lecture:
more on zk-SNARKs and their applications