Monero Cross-Chain Traceability

Empirical Analysis of Privacy Implications from Currency Hard-Forks

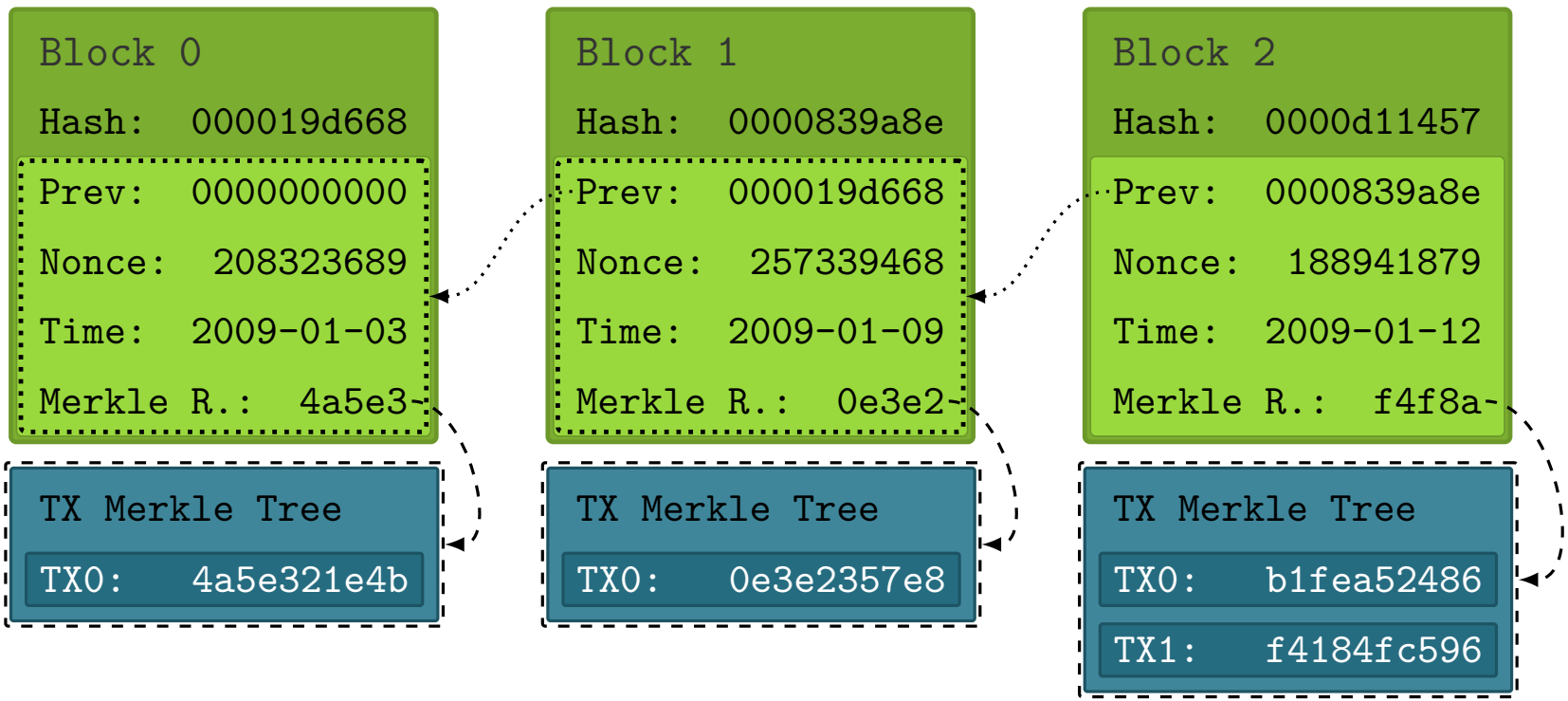
Abraham Hinteregger

November 13th, 2018

Cryptocurrencies

- [Nakamoto, 2008] laid the foundation of modern cryptocurrencies (scheme for trusted decentralized transactions)
- Transactions have inputs (references to previous outputs) and outputs
- Each output is issued to address of a user (public key)
- Recipient can spend outputs with private key

Blockchain


Block 0
Hash: 000019d668
Prev: 0000000000
Nonce: 208323689
Time: 2009-01-03
Merkle R.: 4a5e3-
TX Merkle Tree
TX0: 4a5e321e4b
Block 1
Hash: 0000839a8e
Prev: 000019d668
Nonce: 257339468
Time: 2009-01-09
Merkle R.: 0e3e2-
TX Merkle Tree
TX0: 0e3e2357e8
Block 2
Hash: 0000d11457
Prev: 0000839a8e
Nonce: 188941879
Time: 2009-01-12
Merkle R.: f4f8a-
TX Merkle Tree
TX0: b1fea52486
TX1: f4184fc596

Transaction

TX Hash: be83f7760b5f1a91

Version no: 1

#Inputs: 2

#Outputs: 2

TX Hash/Index: ba7521ec/2

Signature: 3045022100c...

TX Hash/Index: 888e0464/1

Signature: 30440220244...

Outputs:

0: Value: 1.99713455

Recipient addr: 126uLE1GDFxj

scriptPubKey: ...OP_CHECKSIG

1: Value: 6.00255800

Recipient addr: 16jaR3vF4TH3

scriptPubKey: ...OP_CHECKSIG

Monero

- Public nature of Bitcoin TX history prevents meaningful level of anonymity
- Monero (based on CryptoNote, [Van Saberhagen, 2013]) addresses this issue with the following methods:
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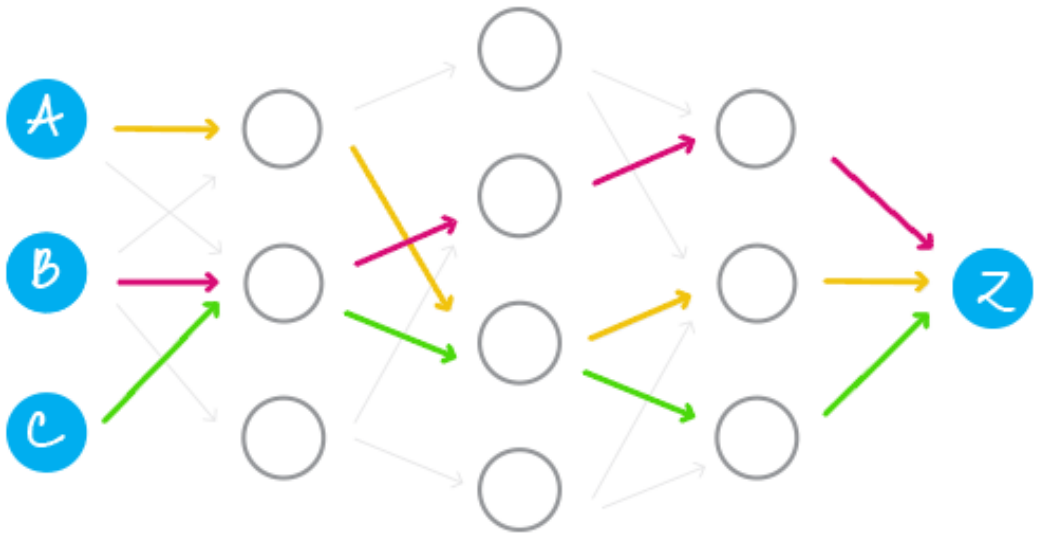

Source: `https://cryptonote.org/inside/`

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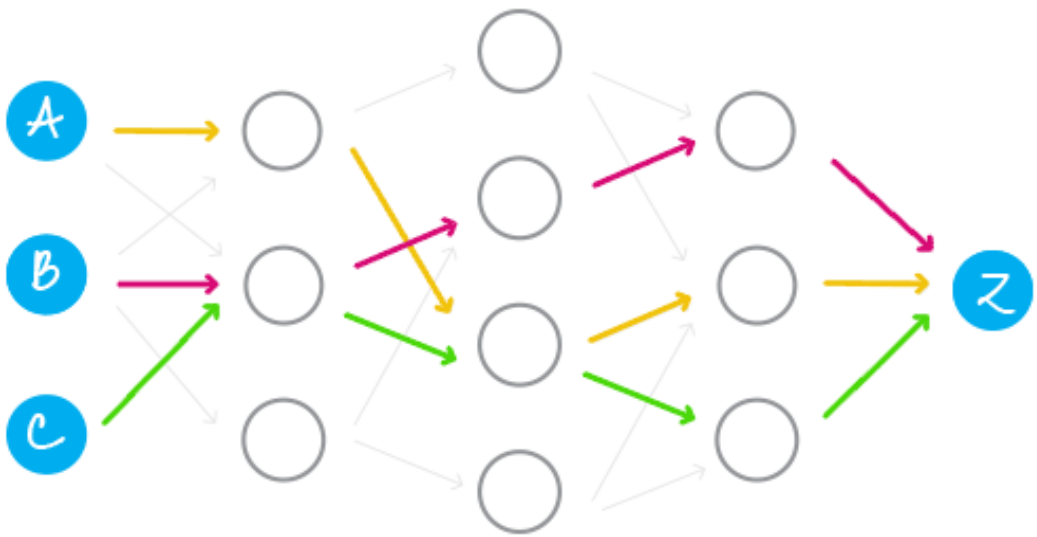

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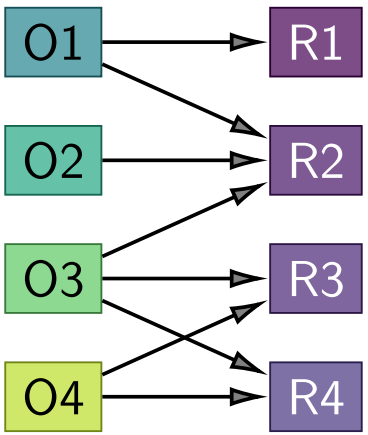
- Decoys are sampled from set of eligible outputs

Zero Mixin Removal & Intersection Removal



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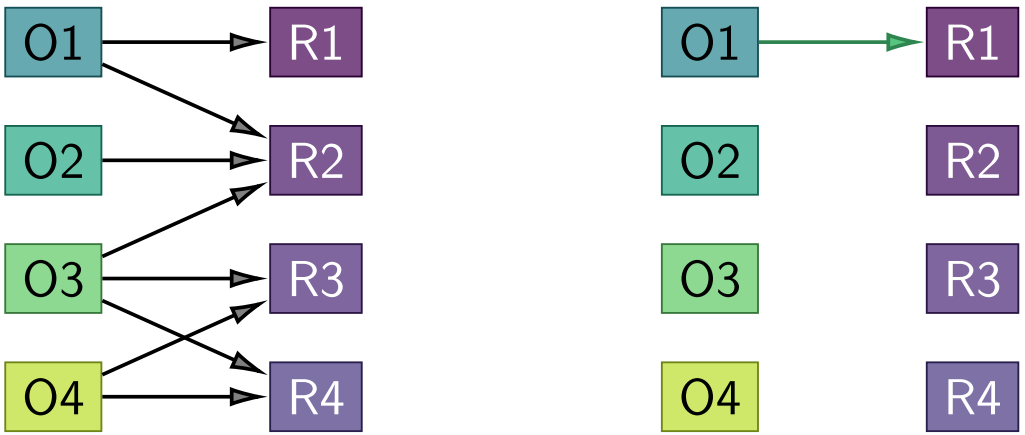

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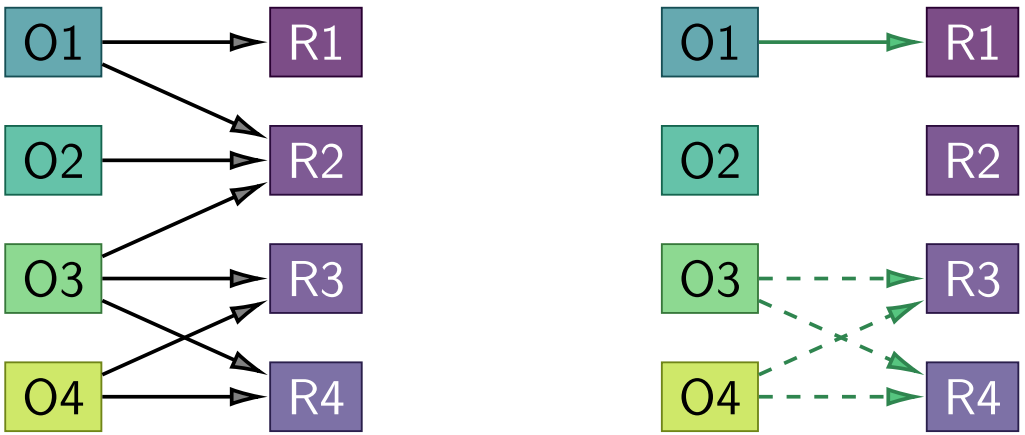

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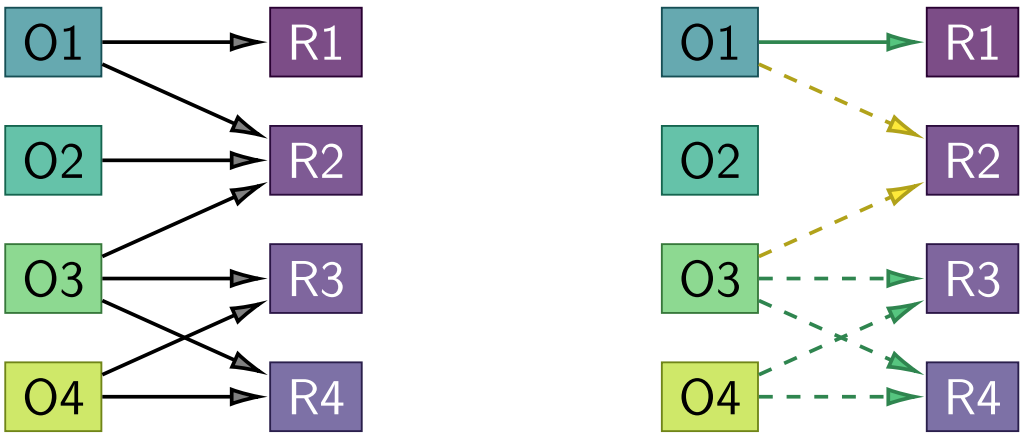

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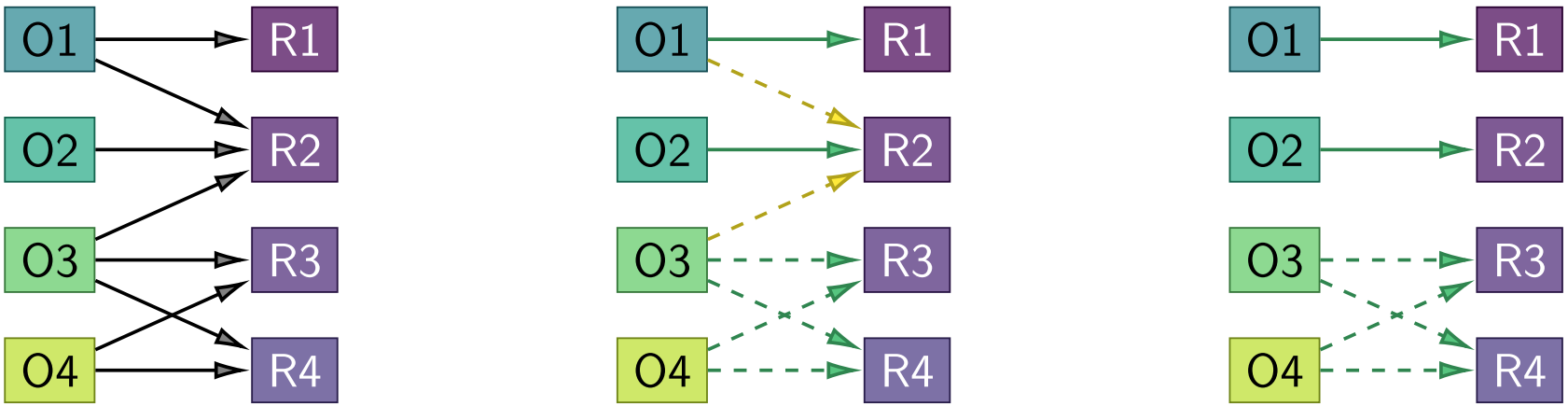

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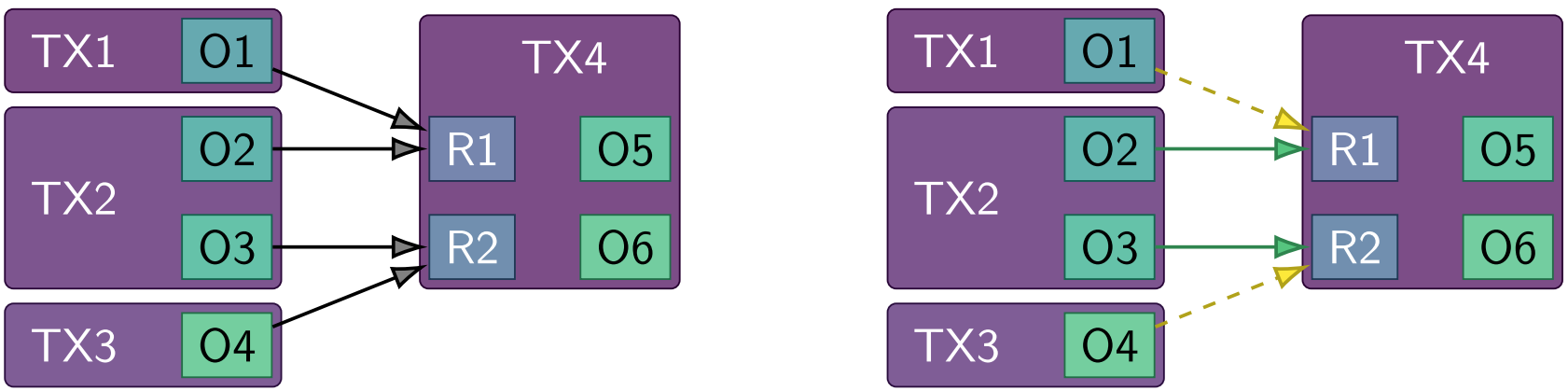

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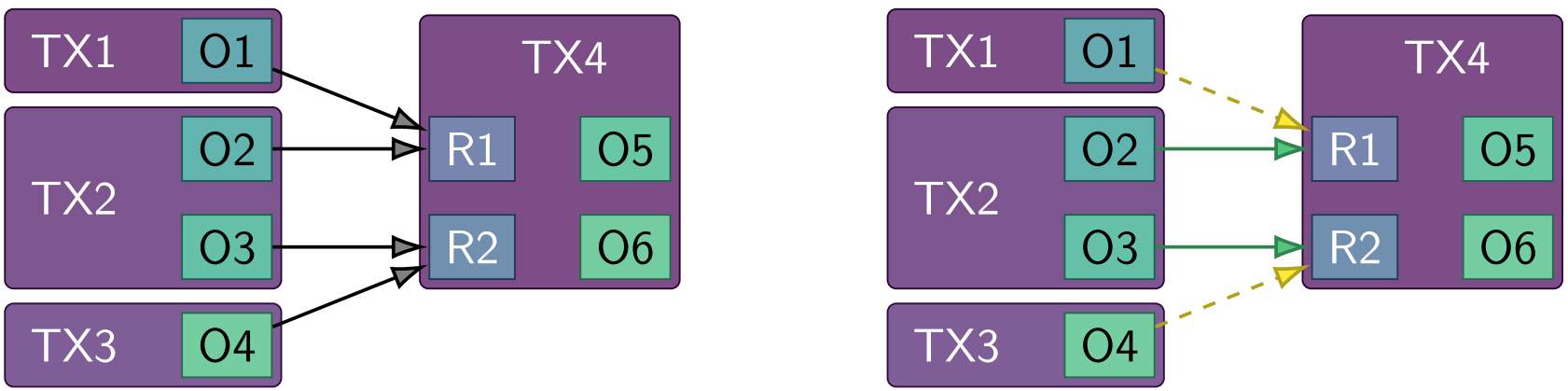

- TX4 has two inputs which reference a TXO from TX2
- OMH assumes that these outputs are real

Traceability Analysis

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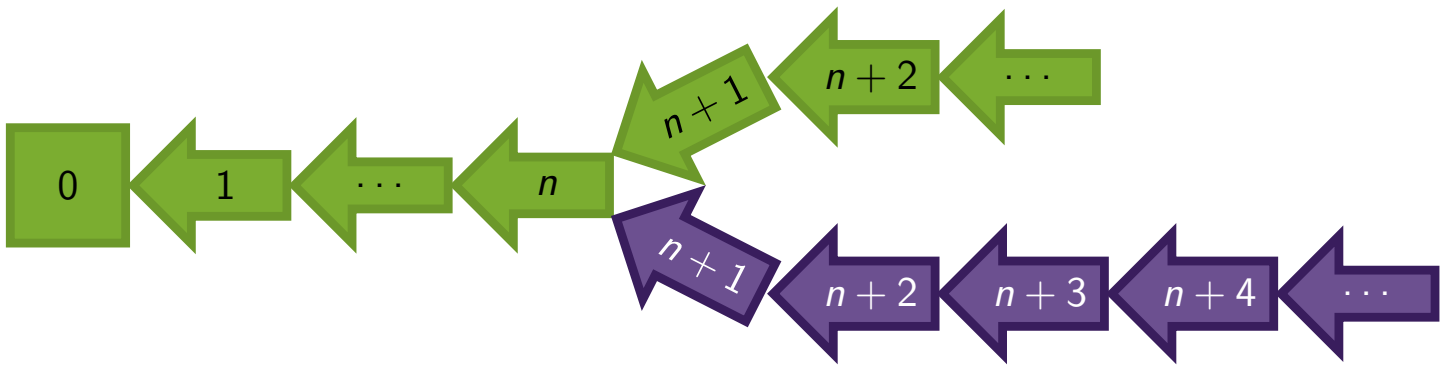
- Temporal distribution of decoys and spent outputs don't match
  - $\rightarrow$ Educated guessing based on output-age effective
- Transaction protocol has been updated since

Improvements to the protocol

- ZMR works like a chain reaction from an initial set of inputs without decoys.
  - Since 2016, the mandatory minimum ringsize has been increased
  - Minimum ringsizes + RingCT TX were effective
  - Ringsize $\equiv 11$ since last update
- Mixin sampling has been improved with different approaches
  - Triangular distribution
  - Recent zone: Force 25-50% recent outputs
  - Gamma distribution: Distribution based on empirical analysis

Currency hardforks

- A cryptocurrency can be forked, resulting in two currencies.
- A fork can either start a new blockchain or continue the existing chain.



- Pre-fork funds can be spent on both chains
- This can be exploited for linking/tracing analysis

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- Method to derive key image must be identical on all branches
- If two rings on two branches have the same key image, they spend the same TXO.

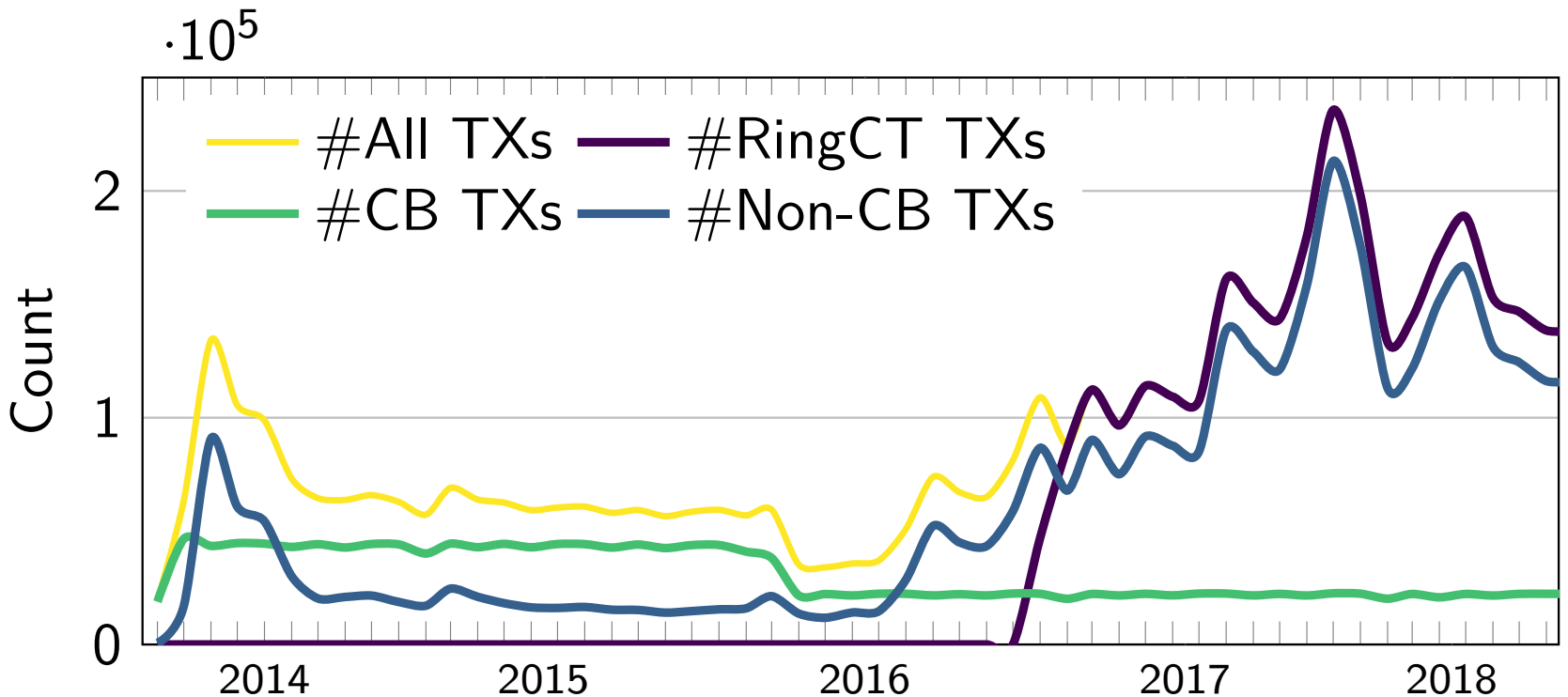
Contribution of this work

- Up to date evaluation of existing methods
  - Previous studies published shortly after introduction of RingCT
  - Changes to mixin sampling and ringsize in 09/2017 and 04/2018.
- Quantify impact on traceability from recent Monero hardforks
  - Monero Original: Continuation of Monero v6 (ASIC compatible)
  - MoneroV: Fork with some changes to emission curve

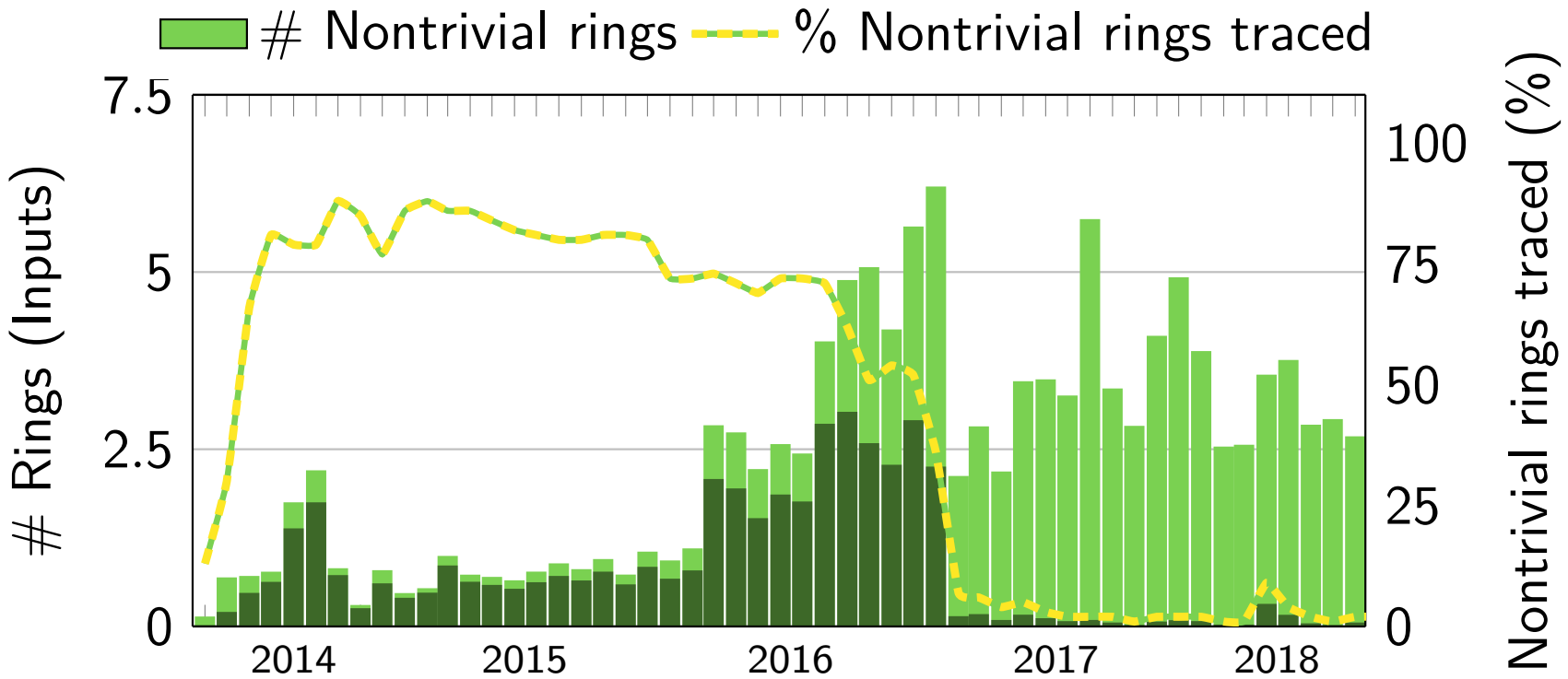
Dataset & Method

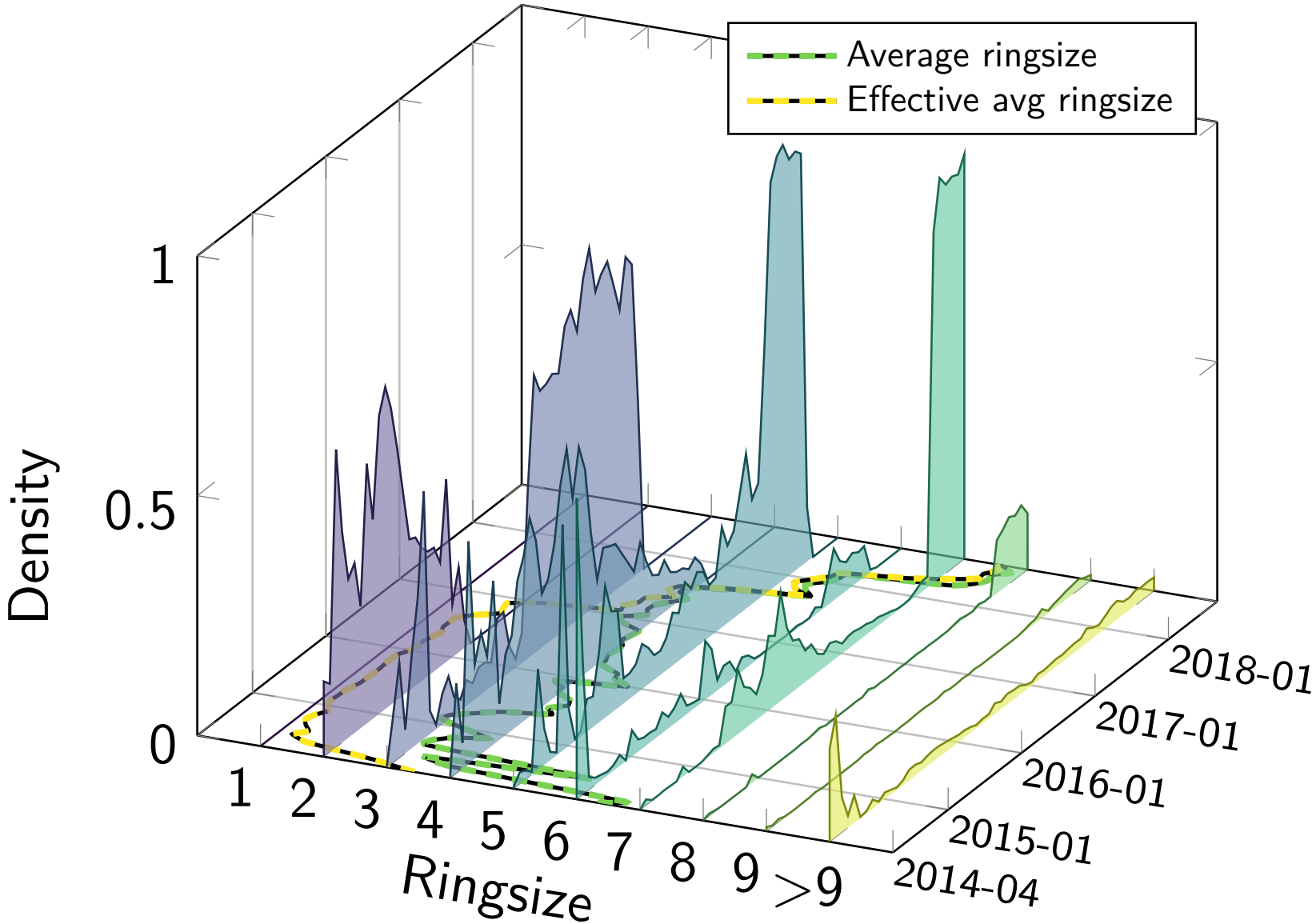
1. Exported Monero (XMR), MoneroV (XMV) and Monero Original (XMO) blockchain up to Aug. 31th, 2018.
2. Employed Zero Mixin Removal & Intersection Removal
3. Added fork data and applied cross chain analysis (+ZMR/IR)
4. Applied heuristics from [Kumar et al., 2017] and [Möser et al., 2018]:
   - Guess Newest Heuristic
   - Output Merging Heuristic
5. Evaluated accuracy with ground truth (where possible) with results from steps 3.

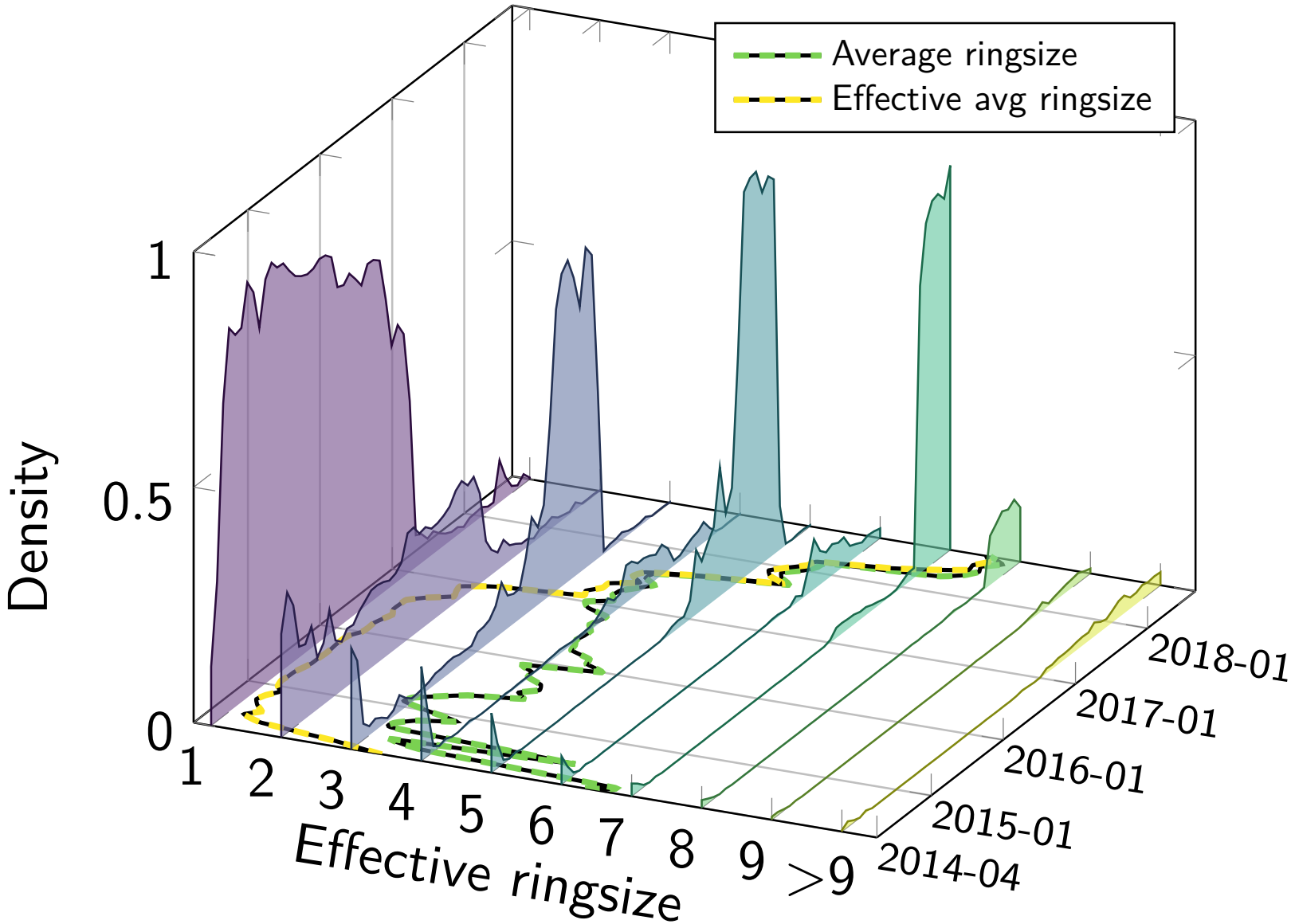
Monero Activity



Traced Inputs




Average ringsize
Effective avg ringsize
Density
1
0.5
0
1 2 3 4 5 6 7 8 9 >9
Ringsize
2014-04
2015-01
2016-01
2017-01
2018-01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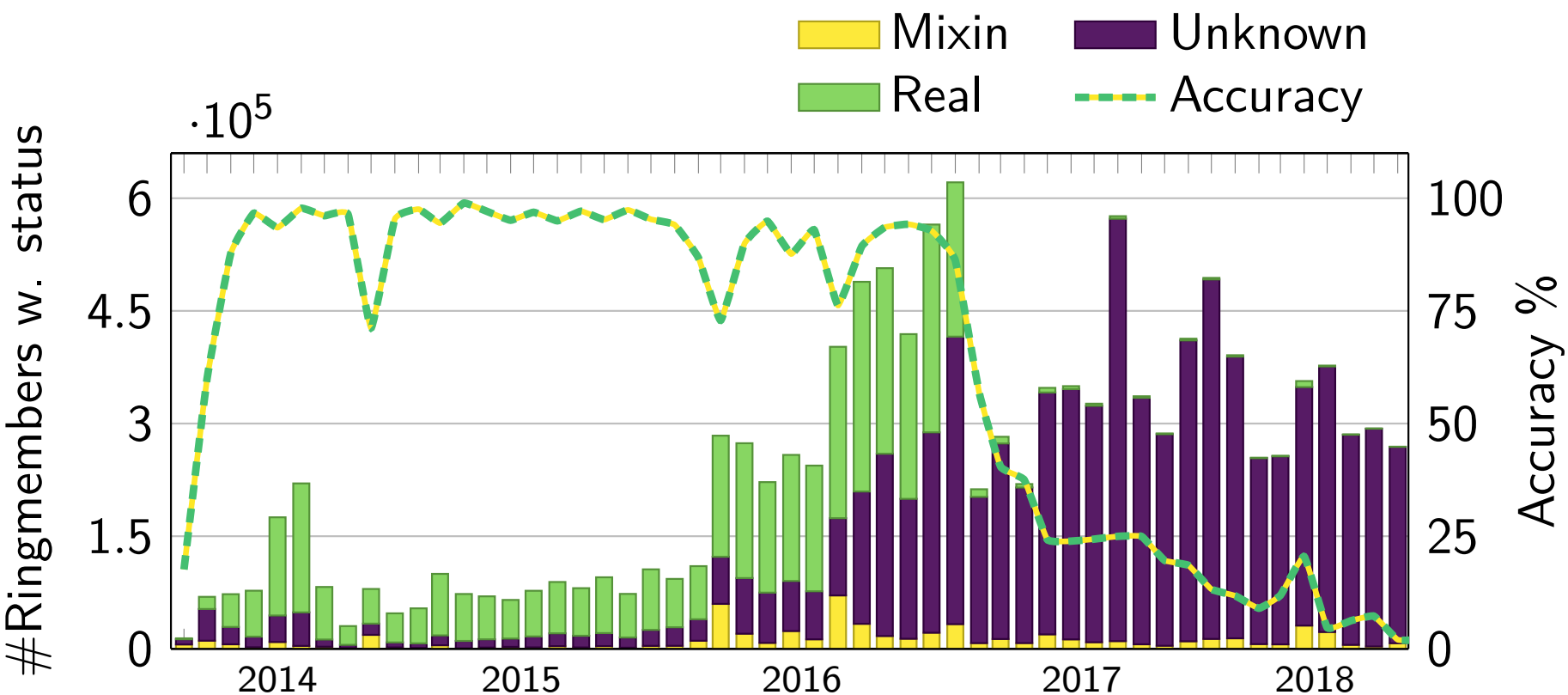
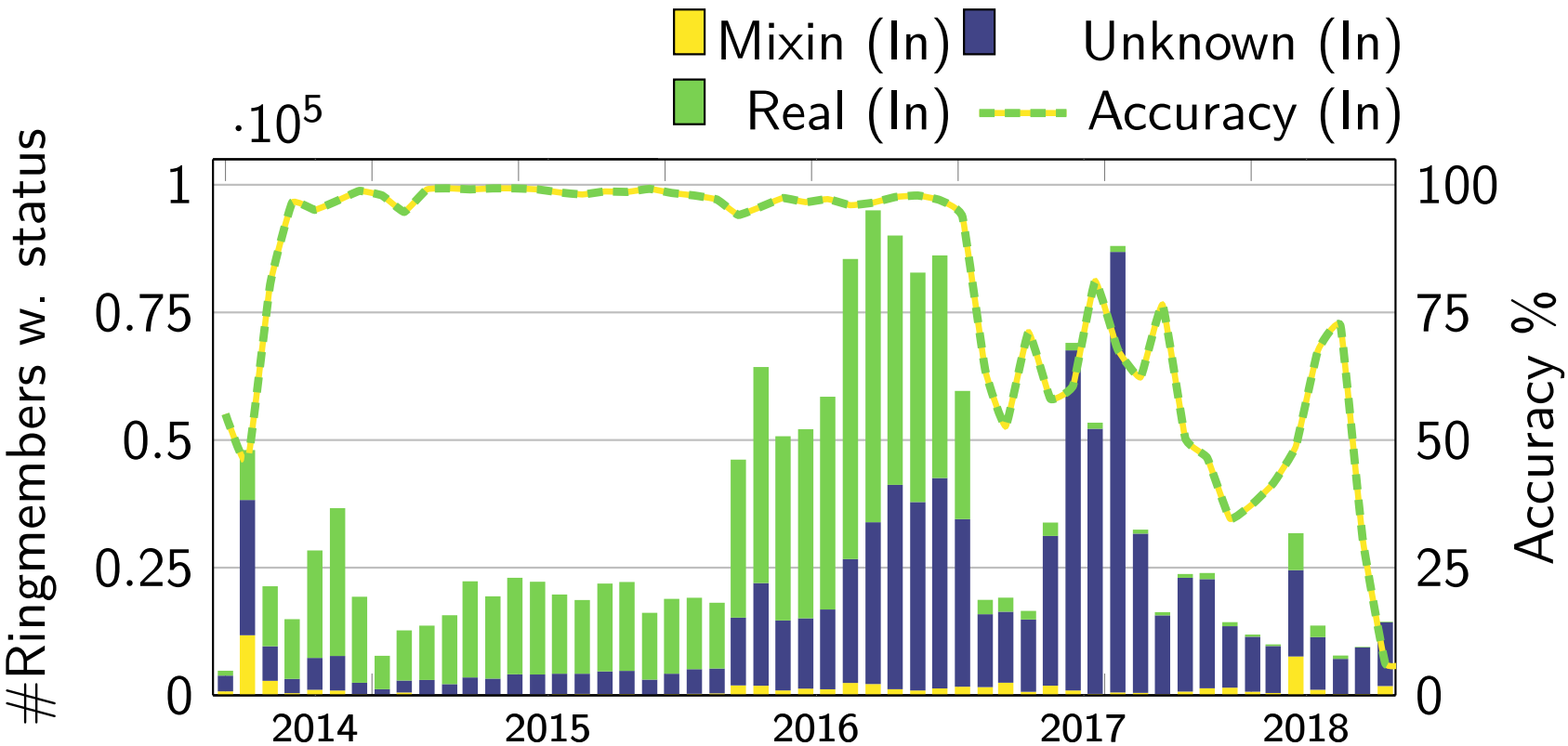
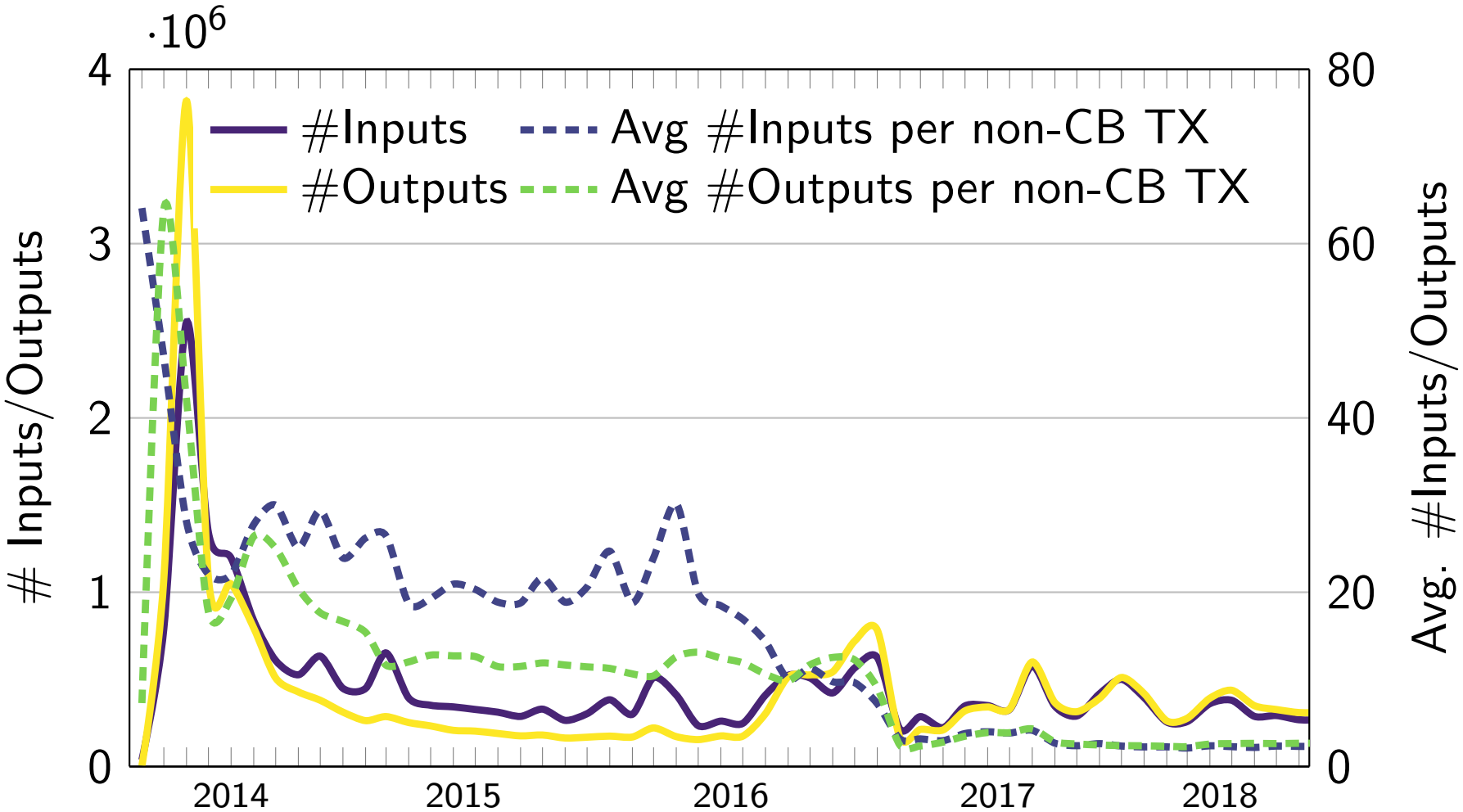
Guess Newest Heuristic



Output Merging Heuristic



Inputs/Outputs (per TX)



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  2. Mandatory ringsize of 7 enough to prevent chain reactions

References I


Kumar, A. et al. (2017).
A traceability analysis of Monero's blockchain.
In *European Symposium on Research in Comp. Sec.*, pages 153–173. Springer.


Möser, M. et al. (2018).
An Empirical Analysis of Traceability in the Monero Blockchain.
PoPET, 2018(3):143–163, DOI: 10.1515/popets-2018-0025, https://content.sciendo.com/view/journals/popets/2018/3/article-p143.xml.


Nakamoto, S. (2008).
Bitcoin: A peer-to-peer electronic cash system.

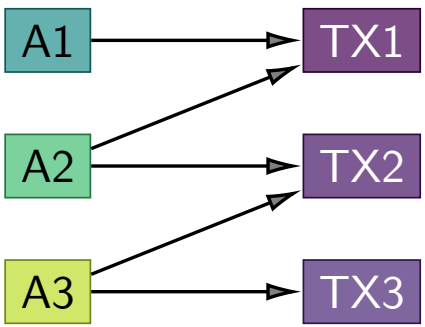
References II


Van Saberhagen, N. (2013).
Cryptonote v 2. 0.
https://cryptonote.org/whitepaper.pdf,
https://cryptonote.org/whitepaper.pdf.

Bitcoin analytics

- Analysis techniques impeded privacy of Bitcoin
- Sets of addresses belonging to a user can often be identified
  - Multi Input Heuristic
  - Change Heuristics
- Simplified transaction graph allows further analysis

Multiple Input Heuristic (MIH)



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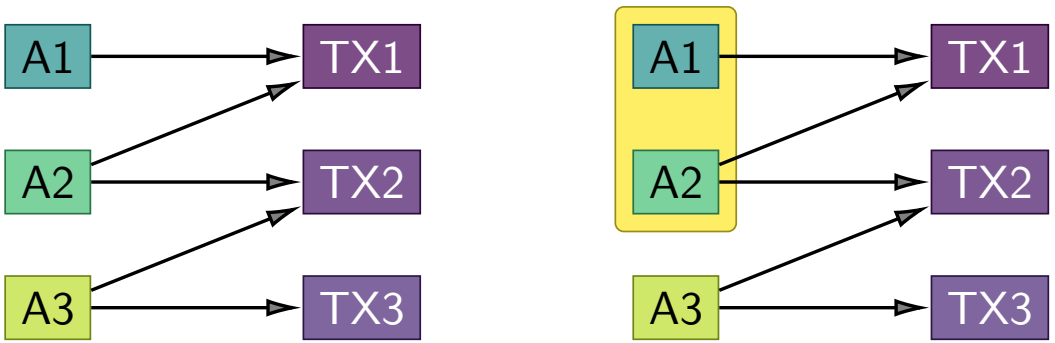

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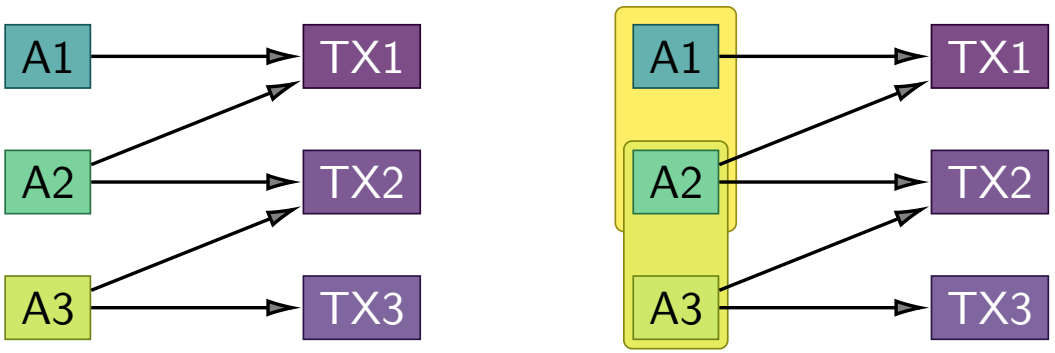

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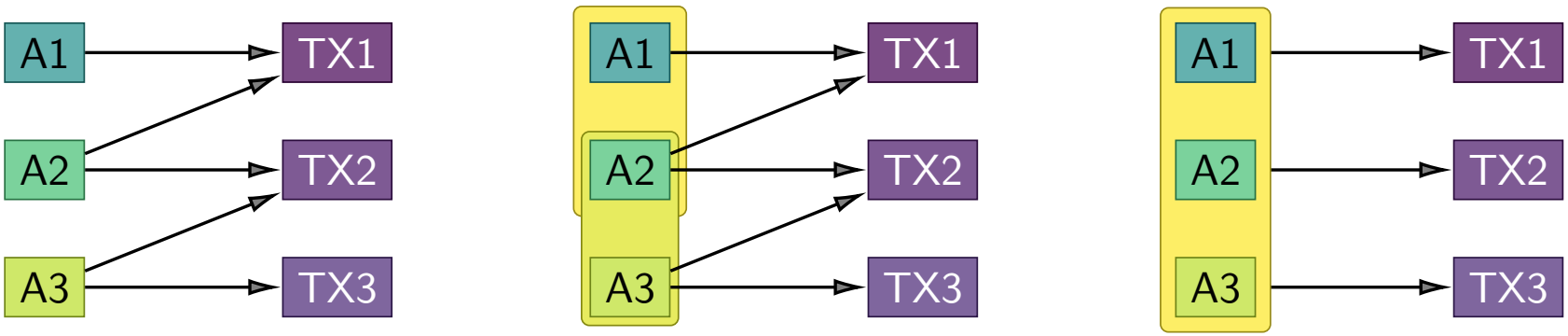

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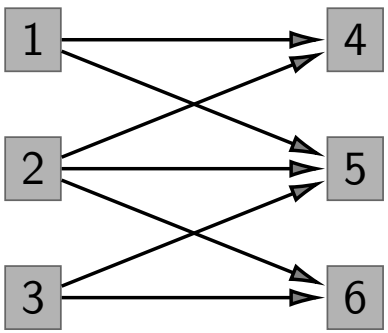

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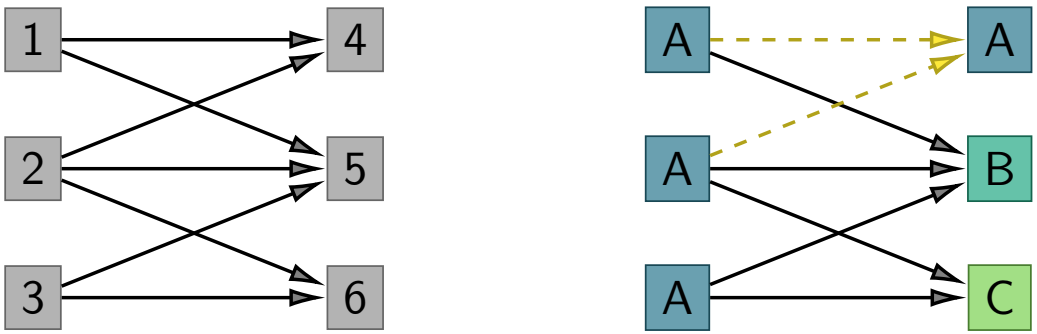

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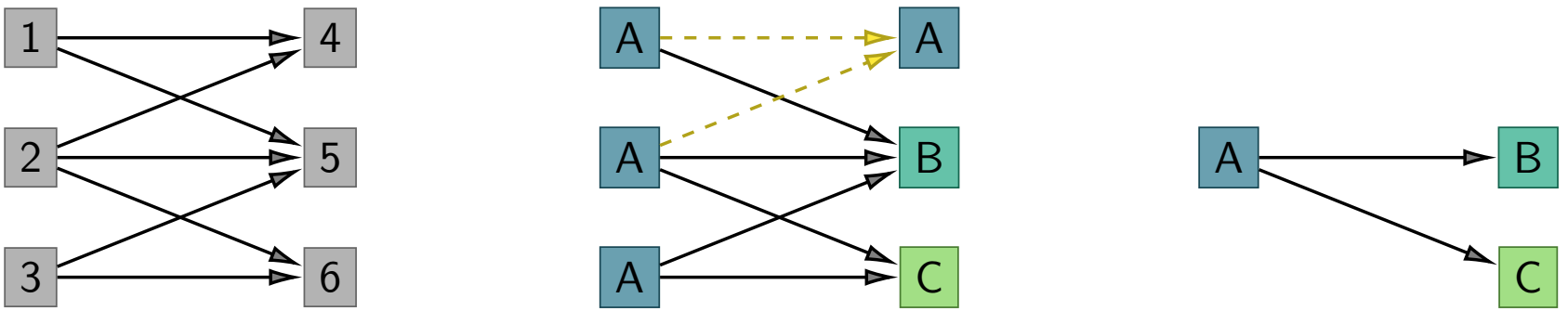

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- Simplify graph: Address graph $\Rightarrow$ Entity graph

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