An Empirical Analysis of Linkability in the Monero Blockchain

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Abstract

Monero is a privacy-centric cryptocurrency that allows users to obscure their transaction graph by including chaff coins, called “mixins,” along with the actual coins they spend. In this report, we empirically evaluate two weaknesses in Monero’s mixin sampling strategy. First, about 62% of transaction inputs with one or more mixins are vulnerable to “chain-reaction” analysis — that is, the real input can be deduced by elimination, e.g. because the mixins they include are spent by 0-mixin transactions. Second, Monero mixins are sampled in such a way that the mixins can be easily distinguished from the real coins by their age distribution; in short, the real input is usually the “newest” input. We estimate that this heuristic can be used to guess the real input with 80% accuracy over all transactions with 1 or more mixins. Our analysis uses only public blockchain data, in contrast to earlier attacks requiring active participation in the network [10, 7]. While the first weakness primarily affects Monero transactions made by older software versions (i.e., prior to RingCT), the second weakness is applicable to the newest versions as well. We propose and evaluate a countermeasure derived from blockchain data that can improve the privacy of future transactions.

Working paper disclaimer: This is a draft of work-in-progress. It has not yet been peer-reviewed, and contains preliminary results that may be subject to further revision.

Figure 1: Transactions and linkage in different cryptocurrencies. Consider a new transaction (the star) which spends an available coin (the second circle from the right). In Bitcoin (a), each transaction input explicitly identifies the coin being spent, thus forming a linkage graph. In Zcash (c), each transaction (c) also spends a unique coin, however a zero-knowledge proof conceals any information about which coin is spent [1]. The Cryptonote protocol (b) offers a middle ground, where each transaction input identifies a set of coins, including the real coin along with several chaff coins called “mixins.” However, due to a weaknesses in how mixins are sampled by client software, many mixins can ruled out by deduction (Section 3); furthermore, the real input is usually the “newest” one (Section 4).

1 Introduction

Monero is a leading privacy-centric cryptocurrency based on the Cryptonote protocol. As of April 2017 it is the sixth largest cryptocurrency by market capitalization. Whereas Bitcoin, the first and currently largest cryptocurrency, ex-

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Figure 2: Age distributions of Monero mixins. In each graph, the Y-axis is the number of TXOs, and the X-axis represents the time difference between input and referenced output in days. The left graph (a) shows the distribution of all transaction inputs from blocks 0.9M to 1.2M where at least 1000 possible TXOs are available to choose from. Graph (b) shows the age distribution among mixins that can be ruled out. Graph (c) shows that real TXOs (based on deducible transactions, see Section 3) typically conform to a highly-skewed distribution. The disparity between these distributions makes it possible to guess the real input with an estimated 80% accuracy.

Explicitly identifies which coin in the transaction graph is being spent, Cryptonote allows users to obscure the transaction graph by including chaff transaction inputs called “mixins.”

In this report, we evaluate the impact of two weaknesses of Monero’s mixin sampling strategy, which substantially undermine its privacy guarantees. Neither of these weaknesses is entirely new, having been discussed (but not addressed) by Monero developers since as early as 2015. Our work provides the first quantitative assessment of the severity of these weaknesses.

**Weakness 1. Many Monero transaction inputs contain deducible mixins, and can be linked to prior transactions via “chain-reaction” analysis.**

The Monero software allows users to configure the default number of mixins to include in each transaction. Most Monero transaction inputs (66.09% of all transaction inputs so far) do not contain any mixins at all, but instead explicitly identify the prior TXO they spend, much like ordinary Bitcoin transactions.

Not only do 0-mixin transactions provide no privacy to the users that created them, but also, more worryingly, they present a privacy hazard if other users include these provably-spent transaction outputs as mixins in other transactions too. When the Monero client chooses mixins, it does not take into account whether the potential mixins have already been spent. We find that among Monero transaction inputs with one or more mixins, 62% of these are deducible, i.e. they can be incontrovertibly linked to the prior TXO they spend.

**Weakness 2. Monero mixins are sampled from a distribution that does not resemble real transaction inputs, and thus the real inputs can usually be identified.**

The Monero client spends a coin, it samples mixins to include by choosing randomly from a triangular distribution over the ordered set of available TXOs with the same denomination as the coin being spent. However, when users spend coins, the coins they spend are not chosen randomly from the blockchain, but instead appear (based on our empirical observations) as though drawn from a highly skewed (e.g., exponential) distribution.

A prescient 2015 post from Monero forum user EbVedado0Anonimato describes this problem quite clearly:

> Actual usage is not random: the age of the outputs change the likelihood of it being used. Newer outputs tend to be used more frequently. You can check that in Bitcoin and probably on other coins.

In Figure 2, we show data from the Monero blockchain...
Table 1: Linkability of Monero transaction inputs with 1+ mixins (up to block 1236195). Deducible transaction inputs can be linked with complete certainty to the transaction output they spend (see Section 3). Among deducible transaction inputs, the real input is usually the “newest” one, i.e., the one with the smallest offset (see Section 4). Entries marked [Est.] are estimated by extrapolating from deducible transaction inputs, under the assumption that the spend-time distribution of deducible transactions is representative of the distribution overall.

|                  | Not deducible | Deducible     | Total       |
|------------------|---------------|---------------|-------------|
| Real input is not newest | 15.07% [Est.] | 286799 (4.60%) | 19.67% [Est.] |
| Real input is newest    | 22.61% [Est.] | 3597933 (57.72%) | 80.33% [Est.] |
| Total             | 2349224 (37.68%) | 3884732 (62.32%) | 6233956 (100%) |

Proposed countermeasures. We propose an improved mixin-sampling strategy that can mitigate this weakness for future transactions. Our solution is based on sampling mixins according to a model derived from the blockchain data. We provide evidence that the “spend-time” distribution of real transaction inputs is robust (i.e., changes little over time and across different software versions), and can be well approximated with a simple two-parameter model.
TXOs, including both the real TXO along with several chaff TXOs, called mixins. Instead of an ordinary digital signature, each Cryptonote transaction comes with a ring signature (a form of zero-knowledge proof) that is valid for one of the indicated TXOs, but that does not reveal any information about which one is real. To prevent double-spending, every input must provide a key image that is unique to the output being spent, and the network must check whether this key image has ever been revealed before.

Several cryptocurrencies are based on the Cryptonote protocol, including Monero, Boolberry, Dashcoin, Bytecoin, and more. We focus our empirical analysis on Monero, since it is currently the largest and most popular, e.g. it has the fifth largest market cap of all cryptocurrencies, of over $200M. However, we believe our results are applicable to other Cryptonote-based currencies as well.

Choosing Mixin Values. The Cryptonote protocol does not provide an explicit recommendation on how the “mixins” should be chosen. However, the original Cryptonote reference implementation included a “uniform” selection policy, which has been adopted (at least initially) by most implementations, including Monero. Since all the TXOs referenced in a transaction input must have the same denomination, the client software maintains a database of available TXOs, indexed by denomination. Mixins are sampled from this ordered list of available TXOs, disregarding any temporal information except for their relative order in the blockchain.

In principle, it is up to an individual user to decide on a policy for how to choose the mixins that are included along with a transaction. Since it is not a “consensus rule,” meaning that miners do not validate that any particular distribution is used, clients can individually tune their policies while using the same blockchain. The Monero command-line interface allows users to specify the number of mixins, with a default of 4.

Over the past several years, Monero’s mixin selection policy has undergone several changes, the major ones of which we describe below (the block heights reported correspond to the cutoffs we use in our subsequent analysis):

- **Prior to version 0.9.0. (January 1, 2016, Block 892866)**
  Prior to the Monero version 0.9.0 release (Hydrogen Helix), mixins were selected uniformly from among the set of all prior TXOs having the same denomination as the coin being spent. As a consequence, earlier outputs would be chosen more often than newer ones.

- **After version 0.9.0. (January 1, 2016, Block 892866)**
  The Monero version 0.9.0 release (Hydrogen Helix) introduced a new policy for selecting mixins, based on a triangular distribution. In contrast with a uniform distribution, the triangular distribution selection is skewed so as to favor using newer coins rather than old coins as mixins. Based on forum posts from the developers, we believe this choice was made under the cognizance that the actual inputs are also likely to be new. However, as can be clearly seen from the blockchain data, the triangular distribution is not adequately skewed enough, significantly less than the real distribution.

  This version also introduced a mandatory minimum number of 2 mixins per transaction input, as recommended by MRL-0001. This mandatory minimum was enforced after a “hard fork” flag day, which occurred at block 1009827 on March 23, 2016.

- **After version 0.10.0. (September 19, 2016)**
  The Monero version 0.10.0 release (Wolfram Warptangent) introduced a new RingCT feature, which allows users to conceal the denomination of their coins, avoiding the need to partition the available coins into different denominations. RingCT transactions were not considered valid until after a “hardfork” flag day, which occurred at block 1220516 on January 5, 2017.

  The RingCT feature does not inherently address the linkability concern. However, since RingCT transactions can only include other RingCT transaction outputs as mixins, and since RingCT was deployed after the 2-mixin minimum was established (in version 0.9.0), there are no 0-mixin RingCT inputs to cause a hazard.

- **After version 0.10.1 (December 13, 2016, Block 1201528)**
  The Monero version 0.10.1 release includes a change to the mixin selection policy: now, some mixins are chosen from among the “recent” TXOs (i.e., those created within the last 5 days, called the “recent zone”). Roughly, the policy is to ensure 25% of the inputs in a transaction are sampled from the recent zone.


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1See [https://cryptonote.org/coins](https://cryptonote.org/coins) for a list of Cryptonote-based currencies.
We used a dashed arrow, which node (running v0.10.2.1) to extract all relevant data into a graph database (9.7GB of data in total).

Transactions included in the blockchain are processed sequentially; we use subscript油漆 to indicate the elements of input/output vectors, e.g. tx.in denotes the first input of tx. Each Cryptonote transaction input contains a reference to one or more prior transaction outputs. We use array notation to denote the individual references of an input. We used a dashed arrow, \( \rightarrow \), to denote this relationship, e.g. \( \text{tx}_A.\text{out}_i \rightarrow \text{tx}_B.\text{in}_j[m] \) means that \( m \)'th reference of the \( j \)'th input of transaction \( \text{tx}_B \) is a reference to the \( i \)'th output of \( \text{tx}_B \). Although a Cryptonote transaction input may contain more than one reference, only one input is the real reference (known only to the sender), indicated by a solid arrow. Thus \( \text{tx}_A.\text{out} \leftarrow \text{tx}_B \) indicates that \( \text{tx}_A \) contain an output that is spent by one of the inputs in \( \text{tx}_B \).

Transactions included in the blockchain are processed in sequential order; we use \( \text{tx}_A < \text{tx}_B \) to indicate that \( \text{tx}_A \) occurs before \( \text{tx}_B \). Other properties of a transaction are defined as functions, and introduced as needed. For example, \( \text{time}(\text{tx}) \) refers to the timestamp of the block in which \( \text{tx} \) is committed.

Blockchain Analysis Infrastructure. We extracted relevant information from the Monero blockchain, up to block 1236196 (January 31, 2017) and stored it for further analysis in a graph database (9.7GB of data in total).

We chose Neo4j for its stability and expressive SQL-like query language Cypher. In the near future we will provide a reproducibility kit that includes the source code we used for data collection and analysis.

3 Deducible Monero Transactions

A significant number of Monero transactions do not contain any mixins at all, but instead explicitly identify the real TXO being spent (i.e., resembling Bitcoin transactions). Critically, at the beginning of Monero’s history, users were allowed to create zero-mixin transactions that do not contain any mixins at all. Figure 5 shows the fraction of transactions containing zero-mixin inputs over time. As of block 1236196, a total of 12148622 transaction inputs do not contain any mixins, accounting for 66.09% of all transaction inputs overall.

One might think at first that 0-mixin transactions are benign. Transactions with fewer mixins are smaller, and hence cost less in fees; they thus represent an economical choice for an individual who does not explicitly desire privacy for a particular transaction. However, it turns out that the presence of 0-mixin transactions is a hazard that reduces the unlinkability of other transactions, even those that include one or more mixins. For example, suppose a transaction output \( \text{tx}_A.\text{out}_i \) is spent by a 0-mixin transaction input \( \text{tx}_B.\text{in}_j \) (i.e., \( \text{tx}_A.\text{out}_i \leftrightarrow \text{tx}_B.\text{in}_j \) where \( |\text{tx}_B.\text{in}_j| = 1 \), from which we can conclude \( \text{tx}_A.\text{out}_i \leftarrow \text{tx}_B.\text{in}_j \)). Now, suppose \( \text{tx}_A.\text{out}_i \) is also included as a mixin in a second transaction with one mixin, \( \text{tx}_A.\text{out}_i \leftrightarrow \text{tx}_C.\text{in}_k[m] \), where \( |\text{tx}_C.\text{in}_k| = 2 \). Since we know that the given output was actually spent in \( \text{tx}_B \), we can deduce it is not spent by \( \text{tx}_C \) (i.e., \( \text{tx}_A.\text{out}_i \not\leftarrow \text{tx}_C \)).
Figure 5: Fraction of transaction inputs that can be deduced over time (averaged over intervals of 10,000 blocks)

MATCH (i:Input)-[:REFERENCES]->(o:UnknownSpend)
WITH i, COUNT(o) as cnt WHERE cnt = 1
MATCH (i)-[:REFERENCES]->(o:UnknownSpend)
REMOVE o:UnknownSpend
CREATE (i)-[:SPENDS]->(o)

Figure 6: A Neo4J Cypher Query for deducing Monero transaction inputs.

MATCH (i:Input)-[:REFERENCES]->(o:UnknownSpend)
WITH i, COUNT(o) as cnt WHERE cnt = 1
MATCH (i)-[:REFERENCES]->(o:UnknownSpend)
REMOVE o:UnknownSpend
CREATE (i)-[:SPENDS]->(o)

Implementation in Neo4j. In Figure 6 we show a Neo4J Cypher query that implements this algorithm. Initially, we import the Monero blockchain as a graph comprising two types of nodes, Inputs and Outputs, with directed edges of type REFERENCES between them. To each Output node we initially add an UnknownSpend label, indicating that we have not (yet) deduced whether this has been spent. The query proceeds by identifying each Input node i that references only a single UnknownSpend Output node o; for each such output, we create a SPENDS relation between i and o, and remove the UnknownSpend label for o. We then iteratively repeat this query until no new SPEND edges are created.

Results. In Table 2 we show the results from applying the query described above to Monero blockchain data. As it turns out, approximately 62% of Monero transaction inputs (with 1+ mixins) so far can be linked in this way.

In Figure 7 we show how the vulnerability of Monero transactions to deduction analysis varies with the number of mixins chosen, and in Figure 5 we show how this has evolved over time. We make two observations: first, transactions with more mixins are (as one would hope) significantly less likely to be deducible; and second, even among transactions with the same number of mixins, transactions made with later versions of the software are less vulnerable. This is because at later dates, the 0-mixin transaction outputs accounted for a smaller number of the available mixins to choose from. Surprisingly, we found tens of thousands of transactions with a large number (10+) of mixins (presumably indicating a high level of desired privacy) that are vulnerable under this analysis.

Comparison with related work on Monero linkability. We note that earlier reports from Monero Research Labs (MRL-0001 [10] and MRL-0004 [7]) have previously discussed concerns about such deduction, called a “chain-reaction,” based on similar insights as described above. However, our results paint a strikingly different picture than these.

First, the MRL reports suggested that the vulnerability would require the participation of an attacker, who must...
Table 2: Monero transaction inputs (with 1 or more mixins) where the real input can be deduced.

| Mixins | Prior to 0.9.0 | After 0.9.0, prior to 0.10.1 | After 0.10.1, prior to Feb 1, 2017 |
|--------|---------------|-----------------------------|-----------------------------------|
|        | Total          | Deducible (%)               | Total          | Deducible (%)               | Total          | Deducible (%)               |
| 1 mixins| 662011         | 566800 (85.62)              | 45777          | 39979 (87.33)              | 0              | – (–)                      |
| 2 mixins| 231855         | 189438 (81.71)              | 192578         | 1216993 (63.19)            | 713616         | 294702 (41.30)             |
| 3 mixins| 487121         | 368010 (75.55)              | 714907         | 484706 (67.80)             | 107695         | 52942 (49.16)              |
| 4 mixins| 191667         | 138555 (72.29)              | 403259         | 209658 (51.99)             | 106829         | 24980 (23.38)              |
| 5 mixins| 61068          | 25688 (42.06)               | 76588          | 44833 (58.54)              | 3883           | 817 (21.04)                |
| 6 mixins| 53820          | 32245 (59.91)               | 285833         | 152044 (53.19)             | 24695          | 6942 (28.11)               |
| 7 mixins| 3191           | 1529 (47.92)                | 5010           | 2190 (43.71)               | 1351           | 171 (12.66)                |
| 8 mixins| 2001           | 948 (47.38)                 | 5314           | 2253 (42.40)               | 1206           | 204 (16.92)                |
| 9 mixins| 1388           | 662 (47.69)                 | 3728           | 1284 (34.44)               | 246            | 43 (17.48)                 |
| 10+ mixins| 54126       | 10251 (18.94)               | 52332          | 14463 (27.64)              | 7661           | 1402 (18.30)               |
| Total   | 1748248        | 1334126 (76.31)             | 3518526        | 2168403 (61.63)            | 967182         | 382203 (39.52)             |
| Overall |               | (62.32)                     |                 |                             |                |                             |

at least must have owned some coins used in previous transactions (in their terms, even a “passive” attacker is one that owns prior coins and creates subsequent transactions):

... a malicious party with a large number of transaction outputs can cause a chain reaction in traceability by sacrificing their own anonymity.

(Mackenzie et al. [2])

Our results show this vulnerability is not hypothetical and does not require an active attack, but in fact leads to the linkability of most existing transactions to date.

Second, MRL-0001 [2] provided a simulation analysis predicting that the mandatory 2-mixin minimum (implemented in version 0.9) would “allow the system to recover from a passive attack quite quickly.” Our results (Figure 5) show that indeed the fraction of deducible inputs drops steadily after instituting the 2-mixin minimum (from 95% in March 2016 down to 20% in January 2017). However, a significant fraction still remain vulnerable.

In summary, while the MRL reports model a hypothetical “attack” scenario, our results show that this scenario has in fact occurred and we quantify the vulnerability of actual transactions. The earlier MRL reports did not contain an analysis of the blockchain data, and as a result their simulation results are based on unrealistically conservative estimates. For example, while MRL-0001 considered scenarios where the attacker owns up to 50% of the transactions, even at the time of its publication (September 2014, around block 250000) it could have been seen that around 80% of transaction inputs had zero-mixin.

Applicability to current and future transactions using RingCT. The weakness studied in this section is primarily a concern for transactions made in the past, as transactions using the new RingCT transaction option are generally immune. RingCT has been available to users since February 2017, and at the time of writing has already been widely deployed. RingCT transactions are now used by default for the vast majority of new transactions. The reason why these new transactions are immune is not because of the RingCT mechanism itself, but rather because RingCT was only deployed after the mandatory 2-mixin minimum was enforced. Therefore, RingCT transaction outputs cannot be spent by 0-mixin inputs.

4 Linking With Temporal Analysis

In the previous section, we showed that a majority of Monero transactions inputs can be linked with certainty through logical deduction. In this section, we investigate an entirely unrelated complementary weakness that allows to be linked statically.

4.1 The Guess-Newest Heuristic

Among all the prior outputs referenced by a Monero transaction input, the real one is usually the newest one (the
Figure 7: Transaction inputs are less likely to be deducible if they have more mixins and if they are found among later blocks in the Monero blockchain.

4.2 Monte Carlo Simulation

The weakness in Monero that leads to input deduction (Section 3) is not directly related to the weakness leading to the Guess-Newest heuristic. However, the effects are partially correlated, i.e., transactions where the real input is the “newest” are also more likely to be “deducible.”

To extrapolate from our deducible transactions dataset, we developed a Monte Carlo simulation based on the Monero client code and the blockchain dataset. For each iteration, we first sample a real output (as described below), and then follow the mixin sampling procedure.

Initially, we create a dataset of “spend time” distributions, i.e. the block timestamp difference between when a transaction output is created and when it is spent, i.e.

\[ \text{spendtime}(tx_B.in_j) = \text{time}(tx_B) - \text{time}(tx_A) \]

where \( tx_A \leftarrow tx_B \).

This dataset consists of all spend times of 0-mixin transaction inputs as well as deducible inputs.

For each trial in the simulation, we begin by sampling a spend time at random, weighted according to the relative frequency of denominations. Next, for the given denomination, we choose a spend time at random from the dataset, and then choose the offset. Note that while the spend time dataset is based on historic transactions, the resulting “offset” is relative to the head of the chain at our time of
Table 3: Percentage of deducible transaction inputs where the real input is the “newest” input.

|    | Prior to 0.9.0 |           | After 0.9.0, prior to 0.10.1 |           | After 0.10.1, prior to Feb 1, 2017 |
|----|---------------|-----------|-------------------------------|-----------|-----------------------------------|
|    | Deducible     | Newest (%)| Deducible                     | Newest (%)| Deducible                         |
| 1 mixins | 566800       | 550145 (97.06) | 39979                        | 33999 (85.04) | 0 NA (NA)                         |
| 2 mixins | 189438       | 177995 (93.96) | 121693                       | 1131586 (92.98) | 294702 283978 (96.36)             |
| 3 mixins | 368010       | 358330 (97.37) | 484706                       | 451565 (93.16) | 52942 49668 (93.82)               |
| 4 mixins | 138555       | 123905 (89.43) | 209658                       | 165006 (78.70) | 24980 16136 (64.60)               |
| 5 mixins | 25688        | 22881 (89.07)  | 44833                        | 42687 (95.21) | 817 442 (54.10)                   |
| 6 mixins | 32245        | 28635 (88.80)  | 152044                       | 124862 (82.12) | 6942 5842 (84.15)                |
| 7 mixins | 1529         | 1375 (89.93)   | 2190                         | 1417 (64.70)  | 171 96 (56.14)                    |
| 8 mixins | 948          | 850 (89.66)    | 2253                         | 1593 (70.71)  | 204 154 (75.49)                   |
| 9 mixins | 662          | 598 (90.33)    | 1284                         | 495 (38.55)   | 43 37 (86.05)                     |
| 10 mixins | 10251       | 9395 (91.65)   | 14463                        | 12957 (89.59) | 1402 1304 (93.01)               |
| Total | 1334126 | 1274109 (95.50) | 2168403                     | 1966167 (90.67) | 382203 357657 (93.58)          |
| Overall | (92.62) |                                      |                             |                             |                                   |

Figure 8: Estimated vulnerability to the Guess-First heuristic for varying sampling policies in Monero, based on Monte Carlo simulations (100k trials each).

writing. After sampling an output to be “spent,” we then simulate the Monero mixin-choosing procedure. In the Appendix, we provide the pseudocode for the sampling procedures used in our simulation. We note that our sampling procedures are simplified models, and in particular elide the handling of edge cases such as avoiding “locked” coins that have been recently mined, i.e. “coinbase outputs.”

In Figure 8 we show the results of simulating transactions using the sampling rules from the three main Monero versions (pre 0.9, 0.9, and 0.10.1), as applied to the blockchain at height 1236196 (Jan 31, 2017). We report our results in the form of the “effective linkability set,” which we define as the inverse of the probability of guessing the correct input reference. In the ideal case (i.e., when all input references are equally likely to be the real one), the linkability set for an input with $M$ mixins is $M + 1$.

For versions 0.9.0 and prior, even up to 4 mixins, our simulation suggests that the newest input can be guessed correctly 75% of the time. Across all versions, including more mixins does reduce the effectiveness of this heuristic, although the benefit of each additional mixin is significantly less than the ideal.

Each subsequent update to Monero’s mixin sampling procedure has improved the resistance of transactions to the Guess-First heuristic. We note that from developer discussions it appears that this concern has indeed been the motivation for such changes. In particular, the triangular distribution was adopted in place of the uniform distribution in Monero version 0.9 specifically because it chooses new mixins with higher probability than “old” mixins, and version 0.10.1 explicitly introduces a policy that often includes additional “recent” (within 5 days) mixins. However, we believe the magnitude of the problem has so far been underestimated, and even the most recent version only partially mitigates the problem. Under the current default behavior, i.e. 4 mixins and using the 0.10.1 sampling procedure, we estimate that the correct input ref-
Figure 9: Mixin offset distribution among RingCT transactions (Blocks 1220516 to 1236195).

The reference can be guessed with 45% probability (rather than the 20% ideal if all input references were equally likely).

Excluding all of the “deducible” inputs, the average number of mixins among the remaining inputs is 3.53. We therefore estimate that as a lower bound, based on the “0.10.1” line in Figure 8, that at least 60%. Extrapolating from this figure, we estimate that in total the Guess-Newest heuristic correctly identifies 80% of all Monero inputs (Table 1).

4.2.1 Extrapolation to Future Transactions (using RingCT)

As mentioned in Section 2, a new transaction format, called RingCT, has been available since January 5 2017. RingCT transaction inputs can only reference other RingCT transaction outputs. In Figure 9, we show the offset-distribution of all RingCT transactions inputs to date (up to block 1236195, approximately Jan 31, 2017). The characteristic pattern of a triangular distribution mixed with a more heavily left-skewed distribution is plainly visible, though not as pronounced.

Unlike the deducibility weakness, which appears to improve over time (see Figure 7), we hypothesize that the problem of sampling from the wrong distribution becomes worse over time, since the set of “old” mixins to choose from grows larger and larger as time goes on.

To validate this hypothesis, we used our simulation strategy to extrapolate the behavior of Monero version 0.10 with RingCT, out to six and twelve months. Our extrapolation is based on an assumption that the transaction rate of Monero remains constant; since RingCT’s activation, there have been an average of 8.29 RingCT transaction outputs per block. The results of our experiment (along with a comparison of the countermeasures proposed in the next section) are shown in Figure 11.

5 Improved Mixin Sampling

In this section we discuss a way to improve the sampling procedure. At a high level, the idea is to estimate the actual spend-time distribution, and then sample mixins according to this distribution.

Estimating the spend-time distribution. Monero core developer smooth justified the choice of the triangular distribution by the heuristic that this is the “lack of knowledge” distribution [4]. As we are now equipped with data from the Monero blockchain, we thus set about fitting a model to this data.

In Figure 10, we show the spend-time distributions from the Monero blockchain as well as the Bitcoin blockchain. For the Monero data, we split the data by 0-mixin transaction inputs as well as the 1+ mixin inputs, and divide between for which we can deduce the real input.

From this graph, we make the following qualitative observations:

- Observation 1: The spend-time distribution appears invariant with respect to time.
- Observation 2: The spend-time distribution appears the same for 0-mixin as well as 1+ mixin transactions.
- Observation 3: The spend-time distribution has a similar shape in Monero and in Bitcoin, although the spend time is different.

We heuristically determined that the spend time distributions, when plot on a log scale, are closely matched by the shape of a gamma distribution. We used R’s fitdistr function to fit a gamma distribution to the combined Monero data from deducible transaction inputs (in log seconds). The resulting best-fit distribution has shape parameter 19.28, and rate parameter 1.61. By inspection
Figure 10: Spend-time distributions in Bitcoin and in Monero (deducible transaction inputs), over multiple time intervals. A gamma distribution (black line) is fitted to the combined Monero data (shape=19.28, rate=1.61). (Figure 10), this appears to accurately fit the overall Monero spend-time distribution.

Sampling mixins according to the spend-time distribution. To make use of the spend-time distribution described above, we next need to identify a way of sampling transaction output indices that matches the ideal spend-time distribution as closely as possible. Our proposed mechanism is to first sample a target timestamp directly from the distribution, and then find the nearest block containing at least one RingCT output. From this block, we sample uniformly among the transaction outputs in that block. This procedure is defined Algorithm 1.

Evaluating our improved sampling strategy. To quantify the effectiveness of our new sampling scheme, we turn again to the Monte Carlo simulation described in the previous section. Figure 11 shows the effective linkability set under our proposed mixin sampling routine, extrapolated out six and twelve months.

Our scheme performs very close to ideal when applied to actual blockchain data, even for large numbers of mixins. At the default setting of 4 mixins, our method nearly doubles the effective linkability set; for large numbers of mixins, our improvement is nearly four times better. In our extrapolated dataset, our method performs slightly worse than ideal at 6 months and 12 months out, although still much better than the current method, and staying within 75% of the ideal.

Daemon privacy. In the Monero implementation, the wallet software runs as a separate process that communicates with the monerod full node. Only the wallet has access to the user’s keys, but it does not have access to the entire blockchain dataset. We note that the current Monero mixin sampling routines are designed in part to protect against eavesdropping from the Monero daemon: the wallet generates a list of output indices in sorted order (including the index of the actual output being spent) and requests all the corresponding public keys from the daemon. Our proposed solution requires searching the blockchain database for the nearest block matching a target timestamp. Thus to implement our proposal would require expanding the wallet so that it maintains a dataset of each block header, along with the number of RingCT outputs included in each block. In future work we plan to evaluate the overhead this would impose on the wallet software.

Algorithm 1: Our proposed mixin sampling scheme.

\[ \text{SAMPLEMIXINS}(\text{RealOut}, \text{NumMixins}) \]

\[ \text{MixinVector} := []; \]
\[ \text{while } |\text{MixinVector}| < \text{BaseReqMixCount} \text{ do} \]
\[ \quad t \leftarrow \text{Exp} (\text{GammaSample}(\text{shape}=19.28, \text{rate}=1.61)); \]
\[ \quad \text{if } t > \text{CurrentTime} \text{ then} \]
\[ \quad \quad \text{continue;} \]
\[ \quad \text{Let } B \text{ be the block containing at least one RingCT output, with timestamp closest to } \text{CurrentTime}-t; \]
\[ \quad \quad i \leftarrow \text{uniformly sampled output among the RingCT outputs in } B \text{ if } i \notin \text{MixinVector} \text{ and } i \neq \text{RealOut}.\text{idx} \text{ then} \]
\[ \quad \quad \quad \text{MixinVector.append}(i); \]
\[ \text{return sorted(MixinVector + [RealOut.idx]);} \]
6 Discussion and Recommendations

We have identified two weaknesses in Monero’s mixin selection policy, and shown that they pose a significant risk of linkability to early Monero transactions. In light of these findings, we make the following three recommendations to the Monero developer community:

Recommendation 1. The mixing sampling distribution should be modified to closer match the real distribution. We have provided evidence that the strategy by which Monero mixins are sampled results in a different time distribution than real spends, significantly undermining the unlinkability mechanism. To correct this problem, the mixins should ideally be sampled in such a way that the resulting time distributions match.

A report from Monero Research Labs cited the difficulty of frequently tuning parameters based on data collection (especially since the data collection mechanism itself becomes a potential target for an attacker hoping to alter the parameters) [7].

Fortunately, we provide preliminary evidence that the distribution of “spend-times” changes very little over time (and in fact is similar even in different cryptocurrencies). Hence we recommend a sampling procedure based on a model of spending times derived from blockchain data, as discussed in Section 5.

Recommendation 2: The Monero community should engage in further data-backed analysis of privacy claims. We have examined the vulnerability of Monero’s sampling strategies to simple linking techniques, using data from the publicly available blockchain dataset, and proposed a countermeasure that we show thwarts these techniques. However, there remain many possible analysis avenues, including network analysis, side channels, and more sophisticated statistical methods. These have been discussed informally within the community [7], but not yet substantiated with data. We suggest that future changes to the protocol should be validated with such analysis prior to deployment.

Recommendation 3: Monero users should be warned that their prior transactions are likely vulnerable to linking analysis. A significant fraction (62%) of Monero transactions with one or more mixins are deducible (i.e., contain only deducible mixins), and therefore can be conclusively linked. Furthermore, we estimate that among all transaction inputs so far, the “GuessNewest” heuristic can be used to identify the correct mixin with 80% accuracy.

Complementing this report, we have launched a block explorer website, http://monerolink.com, which displays the linkages between transactions inferred using our techniques. We recommend additionally developing a wallet tool that users can run locally to determine whether their previous transactions are vulnerable.

Ethics. We released an initial draft of this report to Monero core developers, and intend to support the development and evaluation of countermeasures. However, we believe it is in the best interests of Monero users that we publish this report immediately, without waiting for countermeasures to be deployed. One reason for our decision is that the data from the Monero blockchain is public and widely replicated, and thus delaying this report would not mitigate post-hoc analysis, which can be carried out at any future time. Second, countermeasures built into future versions of the Monero software would not affect the vulnerability of

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3 We do not plan to maintain this website for more than a year; we will therefore update the online version of this article to point to a snapshot on Internet Archive.
transactions occurring between the time of our publication and the deployment of such future versions.

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A Detailed Description of our Models of Monero Sampling Routines

In Algorithms 2, 3, 4 we give pseudocode for the mixin selection procedures used in our simulation (Section 4). The changes between each successive version are highlighted in blue. We note that these are simplified models of the mixin sampling behavior in the Monero client, in particular they elide over edge cases that avoid spending “locked” coins that have recently been mined. The full code listing of the Monero client can be found on the Monero git repository.

Algorithm 2: SAMPLEMIXINS(RealOut, NumMixins) [vPre0.9.0]
Let TopGIdx be the index of the most recent transaction output with denomination RealOut.amount;
BaseReqMixCount := ⌊(NumMixins + 1) × 1.5 + 1⌋;
while |MixinVector| < BaseReqMixCount do
        i ← UniformSelect(0, TopGIdx);
        if i /∈ MixinVector and i ≠ RealOut.idx then
                MixinVector.append(i);
Let FinalVector be a uniform random choice of NumMixins elements from MixinVector;
return sorted(FinalVector + [RealOut.idx]);

Algorithm 3: SAMPLEMIXINS(RealOut, NumMixins) [v0.9.0]
Let TopGIdx be the index of the most recent transaction output with denomination RealOut.amount;
BaseReqMixCount := ⌊(NumMixins + 1) × 1.5 + 1⌋;
MixinVector := [];
while |MixinVector| < BaseReqMixCount do
        i ← TriangleSelect(0, TopGIdx);
        if i /∈ MixinVector and i ≠ RealOut.idx then
                MixinVector.append(i);
Let RecentGIdx be the index of the most recent transaction output prior to 5 days ago with denomination RealOut.amount prior to 5 days ago;
BaseReqRecentCount := MAX(1, MIN(TopGIdx - RecentGIdx + 1, BaseReqMixCount × RecentRatio));
if RealOut.idx ≥ RecentGIdx then
        BaseReqRecentCount -= 1
MixinVector := [];
while |MixinVector| < BaseReqRecentCount do
        i ← UniformSelect(RecentGIdx, TopGIdx);
        if i /∈ MixinVector and i ≠ RealOut.idx then
                MixinVector.append(i);
        i ← TriangleSelect(0, TopGIdx);
        if i /∈ MixinVector and i ≠ RealOut.idx then
                MixinVector.append(i);
Let FinalVector be a uniform random choice of NumMixins elements from MixinVector;
return sorted(FinalVector + [RealOut.idx]);

Algorithm 4: SAMPLEMIXINS(RealOut, NumMixins) [v0.10.1]
Let TopGIdx be the index of the most recent transaction output with denomination RealOut.amount;
BaseReqMixCount := ⌊(NumMixins + 1) × 1.5 + 1⌋;
Let RecentGIdx be the index of the most recent transaction output prior to 5 days ago with denomination RealOut.amount prior to 5 days ago;
BaseReqRecentCount := MAX(1, MIN(TopGIdx - RecentGIdx + 1, BaseReqMixCount × RecentRatio));
if RealOut.idx ≥ RecentGIdx then
        BaseReqRecentCount -= 1
MixinVector := [];
while |MixinVector| < BaseReqRecentCount do
        i ← UniformSelect(RecentGIdx, TopGIdx);
        if i /∈ MixinVector and i ≠ RealOut.idx then
                MixinVector.append(i);
        i ← TriangleSelect(0, TopGIdx);
        if i /∈ MixinVector and i ≠ RealOut.idx then
                MixinVector.append(i);
Let FinalVector be a uniform random choice of NumMixins elements from MixinVector;
return sorted(FinalVector + [RealOut.idx]);