Surveying definitions of election verifiability

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Abstract

We explore definitions of verifiability by Juels et al. (2010), Cortier et al. (2014), and Kiayias et al. (2015). We discover that voting systems vulnerable to attacks can be proven to satisfy each of those definitions and conclude they are unsuitable for the analysis of voting systems. Our results will fuel the exploration for a new definition.

1 Introduction

Electronic voting systems for large-scale public elections place extensive trust in software and hardware. Unfortunately, instead of being trustworthy, many are vulnerable to attacks that could unduly influence election outcomes [KSRW04, WWH+10, JS12]. Trusting voting systems is unwise; proving that systems can detect undue influence is essential.

Election verifiability enables determination of whether a voting system is vulnerable to undue influence, regardless of whether system software and hardware are trustworthy [CRS05, Adi06, Dag07, Adi08, JCJ10]. Kremer et al. [KRS10] decompose election verifiability into aspects including:

- \textit{Individual verifiability:} voters can check that their own ballots are recorded.

- \textit{Universal verifiability:} anyone can check that the tally of recorded ballots is computed properly.

Definitions of universal verifiability seem to originate with Benaloh and Tuinstra [BT94], who define a correctness property asserting that every participant
is convinced that the tally is accurate with respect to votes cast, and with Cohen and Fischer [CF85], who define verifiability to mean that there exists a function that accepts the announced tally if and only if the announced tally corresponds to cast votes.

Juels et al. [JCJ10, §3] define properties they name correctness and verifiability to formalize election verifiability (we rename those properties JCJ-correctness and JCJ-verifiability to avoid ambiguity), Cortier et al. [CGGI14] directly formulate definitions of individual and universal verifiability, and Kiayias et al. [KZZ15] define a property they name E2E verifiability (E2E abbreviates “end-to-end”) to formalize individual and universal verifiability. We explore those definitions.

**Contribution.** We prove that definitions by Juels et al. and Cortier et al. do not detect new classes of collusion, biasing and malicious-key attacks. We also identify the definition by Kiayias et al. as not detecting some biasing attacks.

- **Collusion attacks.** A voting system’s tallying and verification algorithms might be designed such that they collude to accept illegitimate tallies. Examples of collusion attacks include vote stuffing, and announcing tallies that are independent of the election.

- **Biasing attacks.** A voting system’s verification algorithm might be designed to reject some legitimate tallies. Examples of biasing attacks include rejecting tallies in which a particular candidate does not win, and rejecting all tallies, even correct ones.

- **Malicious key attacks.** A voting system’s verification algorithm might be designed to accept some illegitimate tallies or reject some legitimate ones, in the presence of a maliciously generated key. Examples of malicious key attacks include accepting or rejecting all tallies, regardless of their legitimacy.

In complimentary work, Smyth [Smy20] shows insecure voting systems can be proven to satisfy global verifiability, an alternative, holistic notion of verifiability. Together, these works demonstrate the need for a new verifiability definition.

Our results are presented in the context of centralised, public-key based voting systems comprising of (at least) the following four steps: First, a tallier generates a key pair $PK_T, SK_T$. Secondly, each voter constructs and casts a ballot $b$ for their vote $\beta$. These ballots are recorded on a bulletin board $BB$. Thirdly, the tallier tallies the ballots recorded on the bulletin board, to derive tally $X$ and proof $P$ of correct tallying. Finally, voters and other interested parties verify the election to determine whether that tally corresponds to votes expressed by recorded ballots. Algorithms `Setup`, `Vote`, `Tally`, and `Verify` may be used in those steps.
2 Collusion attacks

Two examples of collusion attacks as follows:

- **Vote stuffing.** Tally behaves normally, but adds $\kappa$ votes for candidate $\beta$. Verify subtracts $\kappa$ votes from $\beta$, then proceeds with verification as normal. Elections thus verify as normal, except that candidate $\beta$ receives extra votes.

- **Backdoor tally replacement.** Tally and Verify behave normally, unless a backdoor value is posted on the bulletin board. For example, if $(SK_T, X^*)$ appears on the board, then Tally and Verify both ignore the correct tally and instead replace it with tally $X^*$. The tallier’s private key $SK_T$ is the backdoor here, it cannot appear on the bulletin board (except with negligible probability) unless the tallier is malicious.

Intuitively, vote stuffing and backdoor tally replacement attacks should be detected by universal verifiability, because that notion should require Verify to accept only those tallies that correspond to a correct tally of the bulletin board. (Voting stuffing attacks should also be detected by correctness, because it should require the tally produced by Tally to correspond to the votes encapsulated in ballots on the bulletin board.)

Elections are big business; history teaches us that malice is rife. Talliers can be incentivized to act in their own selfish interests, rather than serve democracy. They should never be trusted—that’s why verifiability emerged as an essential property of voting systems. Accordingly, we should anticipate talliers launching backdoor tally replacement attacks, even though a honest tallier would never relinquish their private key.

**Design guideline** (Soundness). *Verification must only accept tallies that correspond to votes expressed in collected ballots.*

We formalize a vote stuffing attack by modifying an election scheme $\Pi$ to derive a vote-stuffing election scheme $\text{Stuff}(\Pi, \beta, \kappa)$, which adds $\kappa$ votes for candidate $\beta$, wherein the modified scheme:

- Tallies ballots using $\Pi$’s tallying algorithm to compute tally $X$ and a proof, and announces tally $\text{Add}(X, \beta, \kappa)$ along with that proof.

- Verifies elections using $\Pi$’s verification algorithm with respect to tally $\text{Add}(X, \beta, -\kappa)$.

where $\text{Add}(X, \beta, \kappa) = (X[1], \ldots, X[\beta - 1], X[\beta] + \kappa, X[\beta + 1], \ldots, X[|X|])$ and $|X|$ denotes the length of vector $X$. (Note that Juels et al. define tally $X$ as a vector such that $X[j]$ is the number of votes for the $j$th candidate.) The definition of election verifiability by Juels et al. does not detect vote stuffing attacks:
**Proposition 1.** Given an election scheme $\Pi$ satisfying JCJ-correctness and JCJ-verifiability, and integers $\beta$ and $\kappa$, it holds that $\text{Stuff}(\Pi, \beta, \kappa)$ satisfies JCJ-correctness and JCJ-verifiability.

We state definitions by Juels et al. for an election scheme, JCJ-correctness, and JCJ-verifiability, along with a proof of Proposition 1 in Section 5.

We formalize a backdoor tally replacement attack by modifying an election scheme $\Pi$ to derive an election scheme $\text{Backdoor}(\Pi)$, where the modified scheme:

- Tallies ballots as follows: If there exists a unique $X^*$ such that $(SK_T, X^*) \in BB$, then announce tally $X^*$ and some arbitrary proof $\bot$, otherwise, announce a tally and proof computed using $\Pi$'s tallying algorithm.
- Verification proceeds as follows: If there exists a unique $X^*$ such that $(SK_T, X^*) \in BB$, then accept, otherwise, verify the election using $\Pi$'s verification algorithm.

The definition of election verifiability by Juels et al. does not detect backdoor tally replacement attacks:

**Proposition 2.** Given an election scheme $\Pi$ satisfying JCJ-correctness and JCJ-verifiability, it holds that $\text{Backdoor}(\Pi)$ satisfies JCJ-correctness and JCJ-verifiability, assuming the scheme does not leak the tallier’s private key. A proof appears in Section 5, where we also define key leakage.

Cortier et al. propose a definition similar to JCJ-verifiability and insist that election schemes must satisfy their notions of correctness and partial tallying. Vote stuffing attacks are detected by their notion of correctness, and $\text{Backdoor}(\Pi)$ does not satisfy their notion of partial tallying. Nonetheless, we formalize a further backdoor tally replacement attack by modifying $\text{Backdoor}$ to derive $\text{Backdoor}'$, which additionally checks whether the most significant bit of private key $SK_T$ is zero. The definition of election verifiability by Cortier et al. does not detect that backdoor tally replacement attack:

**Proposition 3.** Given an election scheme $\forall, \mathcal{R}, \rho, \Pi$ satisfying Cortier et al. verifiability, it holds that $\forall, \mathcal{R}, \rho, \text{Backdoor}'(\Pi)$ satisfies Cortier et al. verifiability, assuming the scheme does not leak the tallier’s private key and the most significant bit of an honestly generated private key is one.

We state definitions by Cortier et al. for an election scheme and verifiability, along with a proof of Proposition 3 in Section 6, where we also define key leakage for such schemes.

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1The pre-condition must also check that $SK_T$ is the private key corresponding to public key $PK_T$. We omit formalizing this detail, noting it is straightforward for encryption schemes such as El Gamal and RSA.
3 Biasing attacks

We derive the following three examples of biasing attacks from an election scheme \( \Pi \), by modifying verification:

- **Reject all.** Election scheme \( \operatorname{Reject}(\Pi) \) always rejects; no election will ever be considered valid.

- **Selective reject.** Let \( \varepsilon \) be a distinguished value that would not be posted on the bulletin board by honest voters. Election scheme \( \operatorname{Selective}(\Pi, \varepsilon) \) defines verification as follows: If \( \Pi \)'s verification algorithm accepts and \( \varepsilon \notin \BB \), then accept, otherwise, reject. Since elections are invalidated when \( \varepsilon \) appears on the bulletin board, some elections can be nullified.

- **Biased reject.** Let \( Z \) be a set of tallies. Election scheme \( \operatorname{Bias}(\Pi, Z) \) defines verification as follows: If \( \Pi \)'s verification algorithm accepts a tally in \( Z \), then accept, otherwise, reject. Elections are biased toward tallies in \( Z \), because verification only accepts such tallies.

Intuitively, these formalizations should not satisfy universal verifiability, because that notion should require \( \operatorname{Verify} \) to always accept tallies that correspond to a correct tally of the bulletin board.

**Design guideline** (Completeness). Verification must always accept tallies that correspond to votes expressed in collected ballots.

The definition of verifiability by Juels et al. does not detect any of the above three attacks, because that definition has no notion of completeness. For example, it is vulnerable to biased reject attacks:

**Proposition 4.** Given an election scheme \( \Pi \) satisfying JCJ-correctness and JCJ-verifiability, and given a set \( Z \), it holds that \( \operatorname{Bias}(\Pi, Z) \) satisfies JCJ-correctness and JCJ-verifiability.

A proof sketch appears in Section 5.

The definition of verifiability by Cortier et al. detects biased reject and reject all attacks, but does not detect selective reject attacks, because that definition's notion of completeness does not quantify over all bulletin boards:

**Proposition 5.** Given an election scheme \( \forall, \mathcal{R}, \rho, \Pi \) satisfying Cortier et al. verifiability and symbol \( \varepsilon \) that does not appear in the co-domain of \( \operatorname{Vote} \), it holds that \( \forall, \mathcal{R}, \rho, \operatorname{Selective}(\Pi, \varepsilon) \) satisfies Cortier et al. verifiability.

A proof sketch appears in Section 6.

The definition of verifiability by Kiayias et al. does not detect selective reject attacks either, because (like Juels et al.) the definition has no notion of completeness. Their notion of correctness rules out reject all and biased reject attacks. The ideas remain the same, so we omit formalized results.
4 Malicious key attacks

We derive the following two examples of malicious key attacks from an election scheme \( \Pi \), for which the most significant bit of honestly generated public keys is one:

- **Malicious key accept.** Let \( \text{Accept}(\Pi) \) be \( \Pi \) except, firstly, verification is defined as follows: If the most significant bit of the tallier’s public key is zero, then accept, otherwise, verify using \( \Pi \)’s verification algorithm. Secondly, other algorithms are the same except they remove the most significant bit of public keys when that bit is zero. Thus, elections verify as normal, except when a tallier announces a public key with a maliciously prepended zero.

- **Malicious key reject.** Let \( \text{Reject} \) be \( \text{Accept} \), except verification rejects when the most significant bit is zero.

Intuitively, these formalizations should not satisfy universal verifiability, because soundness and completeness should, respectively, preclude the former and latter class of attacks. Yet, the definitions of verifiability by Juels et al. and Cortier et al. do not detect the above attacks, because their definitions do not consider maliciously generated keys:

**Proposition 6.** Given an election scheme \( \Pi \) satisfying JCJ-correctness and JCJ-verifiability, it holds that both \( \text{Accept}(\Pi) \) and \( \text{Reject}(\Pi) \) satisfy JCJ-correctness and JCJ-verifiability, assuming the most significant bit of honestly generated public keys is one.

**Proposition 7.** Given an election scheme \( V, \ R, \ \rho, \ \Pi \) satisfying Cortier et al. verifiability, it holds that both \( V, \ R, \ \rho, \ \text{Accept}(\Pi) \) and \( V, \ R, \ \rho, \ \text{Reject}(\Pi) \) satisfy Cortier et al. verifiability, assuming the most significant bit of honestly generated public keys is one.

Proofs follow immediately from the definitions of verifiability by Juels et al. and Cortier et al., because those definitions consider only honestly generated keys: The former explicitly assumes keys pairs are generated by “a trusted third party [or] on an interactive computationally secure key-generation protocol.” The latter generates key pairs using algorithm \( \text{Setup} \) (cf. the opening lines of games in Definition 4). Maliciously generated keys are not considered.

5 Juels et al. definitions and related proofs

We state formal definitions of election schemes and verifiability by Juels et al., and prove that their security definition does not detect collusion nor biasing attacks.
5.1 Syntax

In addition to a tallier and voters, a registrar in possession of key pair $PK_R, SK_R$ is considered. That registrar generates voter-credential pairs $pk, sk$, before ballots are cast. Election schemes are defined as tuples $(Register, Vote, Tally, Verify)$ of probabilistic polynomial-time algorithms:

- **Register**, denoted $(pk, sk) \leftarrow Register(SK_R, i, k_1)$, is executed by the registrar. *Register* takes as input the private key $SK_R$ of the registrar, a voter’s identity $i$, and security parameter $k_1$. It outputs a credential pair $(pk, sk)$.

- **Vote**, denoted $b \leftarrow Vote(sk, PK_T, n_C, \beta, k_2)$, is executed by voters. *Vote* takes as input a voter’s private credential $sk$, the public key $PK_T$ of the tallier, the number of candidates $n_C$, the voter’s vote $\beta$, and security parameter $k_2$. It outputs a ballot $b$.

- **Tally**, denoted $(X, P) \leftarrow Tally(SK_T, BB, n_C, \{pk_i\}_{i=1}^{n_V}, k_3)$, is executed by the tallier. *Tally* takes as input the private key $SK_T$ of the tallier, the bulletin board $BB$, the number of candidates $n_C$, the set containing voters’ public credentials, and security parameter $k_3$. It outputs the tally $X$ and a proof $P$ that the tally is correct, where $X$ is a vector of length $n_C$ such that $X[j]$ indicates the number of votes for the $j$th candidate.

- **Verify**, denoted $v \leftarrow Verify(PK_R, PK_T, BB, n_C, X, P)$, can be executed by anyone to verify the election. *Verify* takes as input the public key $PK_R$ of the registrar, the public key $PK_T$ of the tallier, the bulletin board $BB$, the number of candidates $n_C$, and a candidate proof $P$ of correct tallying. It outputs a bit $v$, which is 1 if the tally successfully verifies and 0 on failure.

The above syntax fixes an apparent oversight in the original presentation: we supply the registrar’s public key as input to the verification algorithm, because that key would be required by *Verify* to check the signature on the electoral roll.

5.2 Security definitions

Juels et al. formalize correctness and verifiability to capture their notion of election verifiability. We rename those to **JCJ-correctness** and **JCJ-verifiability** to avoid ambiguity. For readability, the definitions we give below contain subtle differences from the original presentation. For example, we sometimes use for loops instead of pattern matching.

**JCJ-correctness** asserts that an adversary cannot modify or eliminate votes of honest voters, and stipulates that at most one ballot is tallied per voter. Intuitively, the security definition challenges the adversary to ensure that verification succeeds and the tally does not include some honest votes or contains

\[^2\text{Juels et al. do not explicitly name key generation algorithms. For consistency, readers may like to consider Setup generating tallier key pairs.}\]
too many votes. Our presentation of JCJ-correctness fixes apparent errors in the original: the adversary is given the credentials for corrupt voters and distinct security parameters are supplied to the Register and Vote algorithms. An implicit assumption is also omitted: \( \{\beta_i\}_{i \in V \setminus V'} \) is a multiset of valid votes, that is, for all \( \beta \in \{\beta_i\}_{i \in V \setminus V'} \) we have \( 1 \leq \beta \leq n_C \). Without this assumption the security definition cannot be satisfied by many election schemes, including the election scheme by Juels et al.

**Definition 1 (JCJ-correctness).** An election scheme \( \Pi = (\text{Register}, \text{Vote}, \text{Tally}, \text{Verify}) \) satisfies JCJ-correctness if for all probabilistic polynomial-time adversary \( A \), there exists a negligible function \( \mu \), such that for all positive integers \( n_C \) and \( n_V \), and security parameters \( k_1 \), \( k_2 \), and \( k_3 \), we have \( \text{Succ}(\text{Exp-JCJ-Cor}(\Pi, A, n_C, n_V, k_1, k_2, k_3)) \leq \mu(k_1, k_2, k_3) \), where:

\[
\text{Exp-JCJ-Cor}(\Pi, A, n_C, n_V, k_1, k_2, k_3) = \\
1 \ V \leftarrow \{1, \ldots, n_V\}; \\
2 \text{ for } i \in V \text{ do } (pk_i, sk_i) \leftarrow \text{Register}(SK_R, i, k_1); \\
3 \ V' \leftarrow A(\{pk_i\}_{i=1}^{n_V}); \\
4 \text{ for } i \in V \setminus V' \text{ do } \beta_i \leftarrow A(); \\
5 \ BB \leftarrow \{\text{Vote}(sk_i, PK_T, n_C, \beta_i, k_2)\}_{i \in V \setminus V'}; \\
6 \ (X, P) \leftarrow \text{Tally}(SK_T, BB, n_C, \{pk_i\}_{i=1}^{n_V}, k_3); \\
7 \ BB' \leftarrow BB \cup A(\text{BB}, \{(pk_i, sk_i)\}_{i \in V \setminus V'}); \\
8 \ (X', P') \leftarrow \text{Tally}(SK_T, BB, n_C, \{pk_i\}_{i=1}^{n_V}, k_3); \\
9 \text{ if } \text{Verify}(PK_R, PK_T, BB, n_C, X', P') = 1 \\
10 \quad \text{ then return 1; } \\
11 \text{ else } \\
12 \quad \text{ return 0; }
\]

and \( \langle X \rangle \) denotes the translation of tally \( X \) to multiset \( \bigcup_{1 \leq j \leq |X|} \{\underbrace{j, \ldots, j}_X \text{ times} \} \).

The JCJ-correctness definition implicitly assumes that the tally and associated proof are honestly computed using algorithm Tally. By comparison, the definition of JCJ-verifiability does not use this assumption, hence, JCJ-verifiability is intended to assert that voters and auditors can check whether votes have been recorded and tallied correctly. Intuitively, the adversary is assumed to control the tallier and voters, and the security definition challenges the adversary to concoct an election (that is, the adversary generates a bulletin board \( BB \), a tally \( X \), and a proof of tallying \( P \)) such that verification succeeds and tally \( X \) differs tally \( X' \) derived from honestly tallying the bulletin board \( BB \). It follows that there is at most one verifiable tally that can be derived.

**Definition 2 (JCJ-verifiability).** An election scheme \( \Pi = (\text{Register}, \text{Vote}, \text{Tally}, \text{Verify}) \) satisfies JCJ-verifiability if for all probabilistic polynomial-time adversary \( A \), there exists a negligible function \( \mu \), such that for all positive integers \( n_C \)
and \( n_V \), and security parameters \( k_1 \) and \( k_3 \), we have \( \text{Succ}(\text{Exp-JCJ-Ver}(\Pi, \mathcal{A}, n_C, n_V, k_1, k_2, k_3)) \leq \mu(k_1, k_2, k_3) \), where:

\[
\text{Exp-JCJ-Ver}(\Pi, \mathcal{A}, n_C, n_V, k_1, k_2, k_3) = \\
\begin{align*}
1 & \text{ for } 1 \leq i \leq n_V \text{ do } \langle pk_i, sk_i \rangle \leftarrow \text{Register}(SK_{\mathcal{R}}, i, k_1); \\
2 & \langle BB, X, P \rangle \leftarrow \mathcal{A}(SK_{\mathcal{T}}, \{\langle pk_i, sk_i \rangle \}_{i=1}^{n_V}); \\
3 & \langle X', P' \rangle \leftarrow \text{Tally}(SK_{\mathcal{T}}, BB, n_C, \{pk_i\}_{i=1}^{n_V}, k_3); \\
4 & \text{ if } \text{Verify}(PK_{\mathcal{R}}, PK_{\mathcal{T}}, BB, n_C, X, P) = 1 \land X \neq X' \text{ then } \\
5 & \quad \text{return } 1; \\
6 & \quad \text{else } \\
7 & \quad \text{return } 0;
\end{align*}
\]

5.3 Proof of Proposition 1

Suppose \( \Pi = (\text{Register}, \text{Vote}, \text{Tally}, \text{Verify}) \) is an election scheme satisfying JCJ-correctness and JCJ-verifiability. Further suppose \( \text{Stuff}(\Pi, \beta, \kappa) = (\text{Register}, \text{Vote}, \text{Tally}_{\mathcal{S}}, \text{Verify}_{\mathcal{S}}) \), for some integers \( \beta, \kappa \in \mathbb{N} \). We prove that \( \text{Stuff}(\Pi, \beta, \kappa) \) satisfies JCJ-correctness and JCJ-verifiability.

We show that \( \text{Stuff}(\Pi, \beta, \kappa) \) satisfies JCJ-correctness by contradiction. Suppose \( \text{Succ}(\text{Exp-JCJ-Cor}(\text{Stuff}(\Pi, \beta, \kappa), \mathcal{A}, n_C, n_V, k_1, k_2, k_3)) \) is non-negligible for some \( k_1, k_2, k_3, n_C, n_V, \mathcal{A} \). Hence, there exists an execution of the experiment \( \text{Exp-JCJ-Cor}(\text{Stuff}(\Pi, \beta, \kappa), \mathcal{A}, n_C, n_V, k_1, k_2, k_3) \) that satisfies

\[
\text{Verify}_{\mathcal{S}}(PK_{\mathcal{R}}, PK_{\mathcal{T}}, BB, n_C, X', P') = 1 \\
\quad \land \left( \{\beta_i\}_{i \in V \setminus V'} \not\subset \langle X' \rangle \lor |\langle X' \rangle| - |\langle X \rangle| > |V'| \right)
\]

with non-negligible probability, where \( \{\beta_i\}_{i \in V \setminus V'} \) is the set of honest voters, \( (X, P) \) is the tally of honest votes, \( (X', P') \) is the tally of all votes, \( V' \) is a set of corrupt voter identities, and \( BB \) is the bulletin board. Further suppose \( BB_0 \) is the bulletin board \( BB \) before adding adversarial ballots. By definition of \( \text{Tally}_{\mathcal{S}} \), there exist computations

\[
\langle Y, Q \rangle \leftarrow \text{Tally}(SK_{\mathcal{T}}, BB_0, n_C, \{pk_i\}_{i=1}^{n_V}, k_3)
\]

and

\[
\langle Y', Q' \rangle \leftarrow \text{Tally}(SK_{\mathcal{T}}, BB, n_C, \{pk_i\}_{i=1}^{n_V}, k_3)
\]

such that \( X = \text{Add}(Y, \beta, \kappa), X' = \text{Add}(Y', \beta, \kappa), \) and \( P' = Q' \). Since \( \kappa \in \mathbb{N} \), we have \( \langle Y' \rangle \subseteq \langle X' \rangle \). Moreover, \(|\langle X \rangle| = |\langle Y \rangle| + \kappa \) and \(|\langle X' \rangle| = |\langle Y' \rangle| + \kappa \), hence,

\[
|\langle Y' \rangle| - |\langle Y \rangle| = |\langle X' \rangle| - |\langle X \rangle|.
\]

By definition of \( \text{Verify}_{\mathcal{S}} \) and since \( Y' = \text{Add}(X', \beta, -\kappa) \), there exists a computation

\[
v \leftarrow \text{Verify}_0(PK_{\mathcal{R}}, PK_{\mathcal{T}}, BB, n_C, Y', Q')
\]
such that \( v = 1 \). It follows that

\[
\text{Verify}(PK_R, PK_T, BB, n_C, Y', Q') = 1 \\
\land (\{\beta_i\}_{1 \leq i \leq \nu} \not\subset \langle Y' \rangle \lor \|\langle Y' \rangle\| - \|\langle Y \rangle\| > |Y'|)
\]

with non-negligible probability and, furthermore, we have \( \text{Succ}(\text{Exp-JCJ-Cor}(\Pi, A, n_C, n_V, k_1, k_2, k_3)) \) is non-negligible, thereby deriving a contradiction.

We show that \( \text{Stuff}(\Pi, \beta, \kappa) \) satisfies JCJ-verifiability by contradiction. Suppose \( \text{Succ}(\text{Exp-JCJ-Ver}(\text{Stuff}(\Pi, \beta, \kappa), A, n_C, n_V, k_1, k_2, k_3)) \) is non-negligible for some \( k_1, k_3, n_C, n_V, \) and \( A \). Hence, there exists an execution of the experiment \( \text{Exp-JCJ-Ver}(\text{Stuff}(\Pi, \beta, \kappa), A, n_C, n_V, k_1, k_2, k_3) \) which satisfies

\[
\text{Verify}(PK_R, PK_T, BB, n_C, X, P) = 1 \land X \neq X'
\]

with non-negligible probability, where \((BB, X, P)\) is an election concocted by the adversary and \((X', P')\) is produced by tallying \( BB \). By definition of \( \text{Tally}_S \), there exists a computation

\[
(Y', Q') \leftarrow \text{Tally}(SK_T, BB, n_C, \{pk_i\}_{i=1}^{n_V}, k_3)
\]

such that \( X' = \text{Add}(Y', \beta, \kappa) \) and \( P' = Q' \). By definition of \( \text{Verify}_S \), there exists a computation

\[
v \leftarrow \text{Verify}(PK_R, PK_T, BB, n_C, \text{Add}(X, \beta, -\kappa), P)
\]

such that \( v = 1 \). Let the adversary \( B \) be defined as follows: given input \( K \) and \( S \), the adversary \( B \) computes

\[
(BB, X, P) \leftarrow A(K, S)
\]

and outputs \((BB, \text{Add}(X, \beta, -\kappa), P)\). We have an execution of the experiment \( \text{Exp-JCJ-Ver}(\text{Stuff}(\Pi, \beta, \kappa), B, n_C, n_V, k_1, k_2, k_3) \) that concocts the election \((BB, \text{Add}(X, \beta, -\kappa), P)\) and tallying \( BB \) produces \((Y', Q')\) such that

\[
\text{Verify}(PK_R, PK_T, BB, n_C, \text{Add}(X, \beta, -\kappa), P) = 1
\]

with non-negligible probability. Moreover, since \( X \neq X' \) and \( Y' = \text{Add}(X', \beta, -\kappa) \), we have \( \text{Add}(X, \beta, -\kappa) \neq Y' \) with non-negligible probability. It follows immediately that \( \text{Succ}(\text{Exp-JCJ-Cor}(\Pi, B, n_C, n_V, k_1, k_2, k_3)) \) is non-negligible, thus deriving a contradiction and concluding our proof.

\[\square\]

5.4 Proof of Proposition 2

We define key leakage before proving Proposition 2.

**Definition 3** (Key leakage). An election scheme \( \Pi = (\text{Register}, \text{Vote}, \text{Tally}, \text{Verify}) \) does not leak the tallier’s private key if for all positive integers \( n_C \) and \( n_V \), security parameters \( k_1 \) and \( k_3 \), and probabilistic polynomial-time adversary \( A \), we have \( \text{Succ}(\text{Exp-leak}(\Pi, A, k_1, k_3, n_C, n_V)) \) is negligible, where:
\textbf{Proof of Proposition 2.} Suppose \( \Pi = (\text{Register}, \text{Vote}, \text{Tally}, \text{Verify}) \) is an election scheme satisfying JCJ-correctness and JCJ-verifiability that does not leak the tallier’s private key, and \( \text{Backdoor}(\Pi) = (\text{Register}, \text{Vote}, \text{Tally}_{B}, \text{Verify}_{B}) \). Since \( \Pi \) does not leak the tallier’s private key, the experiment \( \text{Exp-JCJ-Cor}(\Pi, A, n_{C}, n_{V}, k_{1}, k_{2}, k_{3}) \) produces a bulletin board \( BB \) such that \( SK_{\tau} \in BB \) with non-negligible probability, for all \( k_{1}, k_{2}, k_{3}, n_{C}, n_{V} \) and \( A \). It follows that an execution of the experiment \( \text{Exp-JCJ-Cor}(\text{Backdoor}(\Pi), A, n_{C}, n_{V}, k_{1}, k_{2}, k_{3}) \) is an execution of the experiment \( \text{Exp-JCJ-Cor}(\Pi, A, n_{C}, n_{V}, k_{1}, k_{2}, k_{3}) \) with non-negligible probability and, hence, \( \text{Backdoor}(\Pi) \) satisfies JCJ-correctness.

We show that \( \text{Backdoor}(\Pi) \) satisfies JCJ-verifiability by contradiction. Suppose \( \text{Succ}(\text{Exp-JCJ-Ver}(\text{Backdoor}(\Pi), A, n_{C}, n_{V}, k_{1}, k_{2}, k_{3})) \) is non-negligible for some \( k_{1}, k_{3}, n_{C}, n_{V}, \) and \( A \). Hence, there exists an execution of the experiment \( \text{Exp-JCJ-Ver}(\text{Backdoor}(\Pi), A, n_{C}, n_{V}, k_{1}, k_{2}, k_{3}) \) which satisfies

\[
\text{Verify}(PK_{R}, PK_{\tau}, BB, n_{C}, X, P) = 1 \land X \neq X'
\]

with non-negligible probability, where \( (BB, X, P) \) is an election concocted by the adversary and \( (X', P') \) is produced by tallying \( BB \). If there is one and only one \( Y \) such that \( (SK_{\tau}, Y) \in BB \), then \( X' = Y \) by definition of \( \text{Tally} \) and \( X = Y \) by definition of \( \text{Verify} \), otherwise, the execution of the experiment \( \text{Exp-JCJ-Cor}(\text{Backdoor}(\Pi), A, n_{C}, n_{V}, k_{1}, k_{2}, k_{3}) \) is an execution of the experiment \( \text{Exp-JCJ-Cor}(\Pi, A, n_{C}, n_{V}, k_{1}, k_{2}, k_{3}) \) and, hence,

\[
\text{Succ}(\text{Exp-JCJ-Ver}(\text{Backdoor}(\Pi), A, n_{C}, n_{V}, k_{1}, k_{2}, k_{3})) = \text{Succ}(\text{Exp-JCJ-Ver}(\Pi, A, n_{C}, n_{V}, k_{1}, k_{2}, k_{3})).
\]

In both cases we derive a contradiction, thereby concluding our proof. \( \square \)

\section{5.5 Proof sketch of Proposition 4}

Suppose \( \Pi = (\text{Register}, \text{Vote}, \text{Tally}, \text{Verify}) \) is an election scheme satisfying JCJ-correctness and JCJ-verifiability. Further suppose \( \text{Bias}(\Pi, Z) = (\text{Register}, \text{Vote}, \text{Tally}, \text{Verify}_{R}) \), for some set of vectors \( Z \). By definition of \( \text{Verify}_{R} \), we have

\[
\text{Verify}_{R}(PK_{R}, PK_{\tau}, BB, n_{C}, X, P) = 1
\]

implies the existence of a computation

\[
v \leftarrow \text{Verify}(PK_{R}, PK_{\tau}, BB, n_{C}, X, P)
\]
such that \( v = 1 \) with non-negligible probability, for all \( PK_T, BB, n_C, X, \) and \( P \). It follows that

\[
\text{Succ}(\text{Exp-JCJ-Cor}(\text{Bias}(\Pi), A, n_C, n_V, k_1, k_2, k_3)) \\
\leq \text{Succ}(\text{Exp-JCJ-Cor}(\Pi, A, n_C, n_V, k_1, k_2, k_3))
\]

and

\[
\text{Succ}(\text{Exp-JCJ-Ver}(\text{Bias}(\Pi), A, n_C, n_V, k_1, k_2, k_3)) \\
\leq \text{Succ}(\text{Exp-JCJ-Ver}(\Pi, A, n_C, n_V, k_1, k_2, k_3))
\]

for all \( k_1, k_2, k_3, n_C, n_V, \) and \( A \). Hence, \( \text{Bias}(\Pi, Z) \) satisfies JCJ-correctness and JCJ-verifiability.

\[\square\]

6 Cortier et al. definitions and related proofs

We state definitions of election schemes and verifiability by Cortier et al., and prove their security definition does not detect selective reject nor backdoor tally replacement attacks.

6.1 Syntax

Election schemes are defined over a vote space \( V \), a result space \( R \), a result function \( \rho : V \times \cdots \times V \to R \), and a tuple \( (\text{Setup}, \text{Register}, \text{Vote}, \text{Validate}, \text{Box}, \text{VerifyVote}, \text{Tally}, \text{Verify}) \) of probabilistic polynomial-time algorithms:

- **Setup**, denoted \( (PK_T, SK_T) \leftarrow \text{Setup}(k) \), is executed by the tallier. **Setup** takes a security parameter \( k \) as input and outputs a key pair \( (PK_T, SK_T) \).

- **Register**, denoted \( (pk, sk) \leftarrow \text{Register}(PK_T, i, k) \), is executed by the registrar. **Register** takes as input the tallier’s public key \( PK_T \), a voter’s identity \( i \), and security parameter \( k \). It outputs a credential pair \( (pk, sk) \).

- **Vote**, denoted \( b \leftarrow \text{Vote}(i, pk, sk, PK_T, \beta) \), is executed by voters. **Vote** takes as input a voter’s identity \( i \) and credential pair \( (pk, sk) \), tallier’s public key \( PK_T \), and vote \( \beta \in V \). It outputs a ballot \( b \).

- **Validate**, denoted \( v \leftarrow \text{Validate}(PK_T, b) \), is executed by the bulletin board. **Validate** takes as input the tallier’s public key \( PK_T \) and ballot \( b \). It outputs a bit \( v \), which is 1 for a well-formed ballot and 0 otherwise.

- **Box**, denoted \( BB' \leftarrow \text{Box}(PK_T, BB, b) \), is executed by the bulletin board. **Box** takes as input the tallier’s public key \( PK_T \), bulletin board \( BB \), and ballot \( b \). It outputs an updated bulletin board \( BB' \).
• **VerifyVote**, denoted \( v \leftarrow \text{VerifyVote}(i, pk, sk, PK_T, BB, b) \), is executed by voters. VerifyVote takes as input a voter’s identity \( i \) and credential pair \((pk, sk)\), tallier’s public key \( PK_T \), bulletin board \( BB \), and ballot \( b \). It outputs a bit \( v \), which is 1 if ballot \( b \) has been recorded by bulletin board \( BB \) and 0 otherwise.

• **Tally**, denoted \((X, P) \leftarrow \text{Tally}(PK_T, SK_T, BB)\), is executed by the tallier. Tally takes as input the tallier’s key pair \((PK_T, SK_T)\) and the bulletin board \( BB \). It outputs the tally \( X \) and a proof \( P \) that the tally is correct.

• **Verify**, denoted \( v \leftarrow \text{Verify}(PK_T, BB, X, P) \), can be executed by anyone to verify the election. Verify takes as input the tallier’s public key \( PK_T \), the bulletin board \( BB \), a tally \( X \), and a proof \( P \) of correct tallying. It outputs a bit \( v \), which is 1 if the tally successfully verifies and 0 on failure.

Election schemes must satisfy the following properties:

**Cortier et al. correctness.** For all security parameters \( k \), integers \( n_V \) and votes \( \beta_1, \ldots, \beta_{n_V} \in V \), we have:

\[
\Pr\left[ (PK_T, SK_T) \leftarrow \text{Setup}(k); \\
\text{for } 1 \leq i \leq n_V \text{ do} \\
(\cdot) \leftarrow \text{Register}(PK_T, i, k); \\
b_i \leftarrow \text{Vote}(i, pk_i, sk_i, PK_T, \beta_i); \\
BB \leftarrow \{b_1, \ldots, b_{n_V}\}; \\
(X, P) \leftarrow \text{Tally}(PK_T, SK_T, BB); \\
X = \rho(\beta_1, \ldots, \beta_{n_V}) \land \text{Verify}(PK_T, BB, X, P) = 1 \land \\
\left( \bigwedge_{1 \leq i \leq n_V} \text{Validate}(PK_T, b_i) = 1 \land \text{VerifyVote}(i, pk_i, sk_i, PK_T, \{b_i\}, b_i) = 1 \land \text{Box}(PK_T, \emptyset, b_i) = \{b_i\} \right) = 1.
\]

**Cortier et al. partial tallying.** There exists a commutative binary operator \( \star : \mathbb{R} \times \mathbb{R} \rightarrow \mathbb{R} \) such that for all integers \( j \) and \( k \), and votes \( \alpha_1, \ldots, \alpha_j, \beta_1, \ldots, \beta_k \in V \), we have \( \rho(\alpha_1, \ldots, \alpha_j, \beta_1, \ldots, \beta_k) = \rho(\alpha_1, \ldots, \alpha_j) \star \rho(\beta_1, \ldots, \beta_k) \). Moreover, for all security parameters \( k \) and disjoint bulletin boards \( BB_1 \) and \( BB_2 \), there exists a negligible function \( \mu \) such that

\[
\Pr[(PK_T, SK_T) \leftarrow \text{Setup}(k); \\
(X_1, P_1) \leftarrow \text{Tally}(PK_T, SK_T, BB_1); \\
(X_2, P_2) \leftarrow \text{Tally}(PK_T, SK_T, BB_2); \\
(X, P) \leftarrow \text{Tally}(PK_T, SK_T, BB_1 \cup BB_2); \\
X \neq \perp \Rightarrow X = X_1 \star X_2] > 1 - \mu(k).
\]

For consistency and readability, our presentation of the above syntax and properties contain some minor differences from the original presentation. In addi-
tion, we fix an apparent oversight: we define the tallier’s public key and voter credentials.

6.2 Security definition

The definition of verifiability by Cortier et al. is captured by experiments similar to Exp-JCJ-Ver (Section 5.2).

Definition 4 (Cortier et al. verifiability). An election scheme $\mathcal{V}$, $\mathbb{R}$, $\rho$, $\Pi$ satisfies Cortier et al. verifiability if for all security parameters $k$ and probabilistic polynomial-time adversaries $A$, there exists a negligible function $\mu$ such that $\text{Succ}(\text{Exp-CGGI-Ver-b}(\mathcal{V}, \rho, \Pi, \star, A, k)) + \text{Succ}(\text{Exp-CGGI-Ver-g}(\mathcal{V}, \rho, \Pi, \star, A, k)) \leq \mu(k)$, where $\star$ is a commutative binary operator satisfying the partial tallying property and the aforementioned experiments are defined as follows:\(^4\)

\begin{verbatim}
Exp-CGGI-Ver-b(\mathcal{V}, \rho, \Pi, \star, A, k) =
    1 (PK_T, SK_T) ← Setup(k);
    2 Crpt ← ∅; Reg ← ∅; Rvld ← ∅;
    3 (BB, X, P) ← A_C,E,R(PK_T);
    4 if Verify(PK_T, BB, X, P) = 0 then return 0;
    5 if X = ⊥ then return 0;
    6 if $\exists (i_A^1, \beta_i^1, b_i^1), \ldots, (i_n^A, \beta_i^n_A, b_i^n_A) \in \text{Rvld} \setminus \text{Chck}$
        $\land \exists \beta_1^B, \ldots, \beta_n^B, 0 \leq n_B \leq |\text{Crpt}|$
        $\land X = \rho(\{\beta_i \mid (i, \beta, b) \in \text{Chck}\}) \star \rho({\beta_i^{A_i}}_{i=1}^n) \star \rho({\beta_i^B}^B_{i=1}^n)$
        then return 0;
    7 else return 1;
\end{verbatim}

\(^4\)Unfortunately, set $\text{Chck}$ is undefined in both experiments and set $\text{Reg}$ is undefined in the latter. Set $\text{Chck}$ should contain triples of voter identities, their votes, and ballots, for voters that “checked that their ballots will be counted [using mechanisms defined for individual verifiability],” but there is no notion of voters performing individual verifiability checks in either experiment. (Unavilable verifiability checks are performed.) Set $\text{Reg}$ is maintained by oracle $E$, yet “the adversary is not given...access to [this] oracle [in the latter experiment], since it controls the registrar and thus can register users arbitrarily, even with malicious credentials.” No alternative definition of set $\text{Reg}$ is given, hence, the set is undefined for oracles $C$ and $R$. Since our results are not reliant on set $\text{Chck}$ nor $\text{Reg}$, we will not second-guess the authors’ intention, and we leave undefined sets in experiments to signal that something is missing.
Exp-CGGI-Ver-g(\(V, \rho, \Pi, *, A, k\)) =

1. \((PK_T, SK_T) \leftarrow \text{Setup}(k);\)
2. \(BB \leftarrow \emptyset; \ Crpt \leftarrow \emptyset; \ Rvld \leftarrow \emptyset;\)
3. \((X, P) \leftarrow A_{B,C,R}(PK_T);\)
4. if \(\text{Verify}(PK_T, BB, X, P) = 0\) then return 0;
5. if \(X = \bot\) then return 0;
6. if \(\exists (i_A^1, \beta_A^1, b_A^1), \ldots, (i_{n_A}^A, \beta_{n_A}^A, b_{n_A}^A) \in \text{Rvld} \setminus \text{Chck}\)
   \(\land \exists \beta_B^1, \ldots, \beta_{n_B}^B, 0 \leq n_B \leq |\text{Crpt}|\)
   \(\land X = \rho(\{\beta \mid (i, \beta, b) \in \text{Chck}\}) \star \rho(\{\beta_A^1\}_{1=1}^{n_A}) \star \rho(\{\beta_B^1\}_{1=1}^{n_B})\) then
   return 0;
7. else
   return 1;

Oracle \(E\) is used to model \(A\) enrolling voters. On invocation \(E(i)\), oracle \(E\) does the following: Computes \((pk, sk) \leftarrow \text{Register}(PK_T, i, k)\), records \(i\) as being enrolled by updating Reg to be \(\text{Reg} \cup \{(i, pk, sk)\}\), and outputs \(pk\).

Oracle \(C\) is used to model \(A\) corrupting voters and learning their private credentials. On invocation \(C(\ell)\), if \((\ell, pk, sk) \in \text{Reg}\), then the oracle records that voter \(\ell\) is corrupted by updating \(\text{Crpt}\) to be \(\text{Crpt} \cup \{(\ell, pk)\}\) and outputs \(sk\).

Oracle \(R\) reveals ballots. On invocation \(R(i, \beta)\), if \(\beta \in \mathcal{V}\) and there exists \(pk\) and \(sk\) such that \((i, pk, sk) \in \text{Reg} \land (i, pk) \notin \text{Crpt}\), then oracle \(R\) does the following: Computes \(b \leftarrow \text{Vote}(i, pk, sk, PK_T, \beta)\), records \(b\) as being revealed by updating \(\text{Rvld}\) to be \((\text{Rvld} \setminus \{(i, \beta', b') \mid (i, \beta', b') \in \text{Rvld}\}) \cup \{(i, \beta, b)\}\), and outputs \(b\).

Oracle \(B\) controls the bulletin board. On invocation \(B(b)\), oracle \(B\) computes \(BB \leftarrow \text{Box}(PK_T, BB, b)\).

6.3 Proof of Proposition 3

We define key leakage for Cortier et al. election schemes before proving Proposition 3.

Definition 5. An election scheme \(\mathcal{V}, \mathcal{R}, \rho, \Pi = (\text{Setup}, \ldots)\) does not leak the tallyer’s private key if for security parameters \(k\) and probabilistic polynomial-time adversary \(A\), we have \(\text{Succ} (\text{Exp-leak}(\Pi, A, k))\) is negligible, where:

\[
\text{Exp-leak}(\Pi, A, k) =
\]

1. \((PK_T, SK_T) \leftarrow \text{Setup}(k);\)
2. \(SK'_T \leftarrow A(PK_T);\)
3. if \(SK'_T = SK_T\) then
   return 1;
4. else
   return 0;

Proof of Proposition 3. We first show that \(\mathcal{V}, \mathcal{R}, \rho, \text{Backdoor}'(\Pi)\) is an election scheme—i.e., it satisfies Cortier et al. correctness and partial tallying. Since \(\Pi\)
does not leak the tallier’s private key, it follows that schemes II and Backdoor’(II) are equivalent in the context of correctness (in particular, the tallier’s private key cannot appear on the bulletin board), hence, Backdoor’(II) satisfies correctness because II does. Moreover, since the most significant bit of an honestly generated private key is one, it follows that schemes II and Backdoor’(II) are equivalent in the context of partial tallying, hence, Backdoor’(II) satisfies partial tallying because II does. Next, we show that Cortier et al. verifiability is satisfied. Since II does not leak the tallier’s private key, experiments Exp-CGGI-Ver-b(V, ρ, Backdoor’(II), *, A, k) and Exp-CGGI-Ver-g(V, ρ, Backdoor’(II), *, A, k) produce bulletin boards that exclude the tallier’s private key with overwhelming probability, for all k and probabilistic polynomial-time adversary A. It follows that an execution of experiment Exp-CGGI-Ver-b(V, ρ, Backdoor’(II), *, A, k) is an execution of experiment Exp-CGGI-Ver-b(V, ρ, II, *, A, k) with non-negligible probability. Similarly, an execution of experiment Exp-CGGI-Ver-g(V, ρ, Backdoor’(II), *, A, k) is an execution of the experiment Exp-CGGI-Ver-g(V, ρ, II, *, A, k). Thus, Backdoor’(II) satisfies Cortier et al. verifiability. □

6.4 Proof sketch of Proposition 5

Suppose II = (Setup, …, Vote, …, Tally, Verify) and Selective(II, ε) = (Setup, …, Vote, …, Tally, VerifyR). We first show that V, R, ρ, Selective(II, ε) is an election scheme—i.e., it satisfies Cortier et al. correctness and partial tallying. Satisfaction of the latter is trivial, since we only modify Verify, and we proceed with a proof of the former: Since V, R, ρ, II satisfies Cortier et al. correctness and ε is not in Vote’s co-domain, we have for all key pairs (PK, SK) output by Setup, subsets BB of Vote’s co-domain and tallies (X, P) output by Tally that Verify(PK, BB, X, P) = 1 implies VerifyR(PK, BB, X, P) = 1. It follows that V, R, ρ, Selective(II, ε) satisfies Cortier et al. correctness. Next, we show that Cortier et al. verifiability is satisfied.

Let E hold in an execution of Exp-CGGI-Ver-b if ε ∈ BB, where BB is output by the adversary. By definition of Selective(II, ε), we have Pr[Exp-CGGI-Ver-b(V, ρ, Selective(II, ε), *, A, k) = 1 | E] = 0 and

\[ \Pr[\text{Exp-CGGI-Ver-b}(V, \rho, \text{Selective}(II, \varepsilon), *, A, k)] = \Pr[\text{Exp-CGGI-Ver-b}(V, \rho, II, *, A, k) = 1 | \neg E]. \]

It follows that

\[ \text{Succ}(\text{Exp-CGGI-Ver-b}(V, \rho, \text{Selective}(II, \varepsilon), *, A, k)) = \Pr[\text{Exp-CGGI-Ver-b}(V, \rho, II, *, A, k) = 1 | \neg E]. \]

Since

\[ \text{Succ}(\text{Exp-CGGI-Ver-b}(V, \rho, II, *, A, k)) = \Pr[\text{Exp-CGGI-Ver-b}(V, \rho, II, *, A, k) = 1 | E] + \Pr[\text{Exp-CGGI-Ver-b}(V, \rho, II, *, A, k) = 1 | \neg E], \]

16
we have
\[
\text{Succ}(\text{Exp-CGGL-Ver-b}(V, \rho, \text{Selective}(\Pi, \varepsilon), \star, A, k)) \\
\leq \text{Succ}(\text{Exp-CGGL-Ver-b}(V, \rho, \star, A, k)).
\]
Similarly, we derive
\[
\text{Succ}(\text{Exp-CGGL-Ver-g}(V, \rho, \text{Selective}(\Pi, \varepsilon), \star, A, k)) \\
\leq \text{Succ}(\text{Exp-CGGL-Ver-g}(V, \rho, \star, A, k)).
\]
Since \(V, R, \rho, \Pi\) satisfies Cortier et al. verifiability, we have \(V, R, \rho, \text{Selective}(\Pi, \varepsilon)\) satisfies Cortier et al. verifiability too.

7 Conclusion

We have seen that definitions of verifiability by Juels et al., Cortier et al. and Kiayias et al. do not detect some collusion, biasing and malicious-key attacks. Although a well-designed voting system would hopefully not exhibit vulnerabilities to these attacks, it is the job of security definitions to detect malicious systems, regardless of whether vulnerabilities are due to malice or error. So definitions of election verifiability should preclude them. Yet, the aforementioned definitions do not. Revisiting the security of previously-analysed voting systems in light of the attacks identified here is a possible direction for future work. Our findings have been reported to original authors Dario Catalano, Véronique Cortier, Markus Jakobsson, and David Galindo, and will fuel the exploration for a new definition of verifiability. In collaboration with Frink, we have developed one such definition.

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