TRIP: Trust-Limited Coercion-Resistant In-Person Voter Registration

Louis-Henri Merino*, Simone Colombo*, Rene Reyes†, Alaleh Azhir‡, Haoqian Zhang*, Jeff Allen*, Bernhard Tellenbach‡, Vero Estrada-Galíñanes*, Bryan Ford*

*EPFL †MIT ‡Armassuisse

Abstract—Remote electronic voting is convenient and flexible, but presents risks of coercion and vote buying. One promising mitigation strategy enables voters to give a coercer fake voting credentials, which silently cast votes that do not count. However, current proposals make problematic assumptions during credential issuance, such as relying on a trustworthy registrar, on trusted hardware, or on voters interacting with multiple registrars. We present TRIP, the first voter registration scheme that addresses these challenges by leveraging the physical security of in-person interaction. Voters use a kiosk in a privacy booth to print real and fake paper credentials, which appear indistinguishable to others. Voters learn the difference by observing the order of printing steps, and need not understand the technical details. We prove formally that TRIP satisfies coercion resistance and verifiability. In a user study with 150 participants, 83% successfully used TRIP.

1. Introduction

State-of-the-art online voting systems can ensure that each vote is verifiable and private, but leave unsolved challenges such as voter coercion and vote buying [60, 26, 13, 43, 23, 46]. Together with the attractive freedom and convenience of voting in any physical setting on any device, comes the risk that a coercer may control the voter’s physical setting and/or device [4, 28, 6, 43, 13]. Many reports show that voter coercion and vote buying remain widespread issues in democratic countries, which can reduce voter trust and participation [19, 35, 33, 31, 18]. Some systems allow a voter to override a coerced vote with a truthful vote cast later [37, 52, 5], but this defense is readily defeated by coercing a last-minute vote or stealing the voter’s credential.

The property of coercion resistance, as introduced by Juels, Catalano, and Jakobsson (JCJ), is achieved when coercers cannot determine whether voters have complied with their demands [43]. To resist coercion and vote buying, JCJ proposes creating fake voting credentials, which appear identical to real credentials, but which cast votes that do not count in the election. A voter under coercion may give (or sell) fake credentials to a coercer, while secretly using their real credential to cast their true vote at any time, either before or after coerced votes are cast.

Any remote voting system that offers protection against coercion critically depends on some trusted bootstrapping process, in which voters have an uncompromised interaction with the election authority: e.g., to establish their real and fake credentials. Most proposed voting schemes [66, 7, 12, 67, 52], including JCJ [43], merely assume that some abstract trusted registration process exists, without detailing how such registration is to be achieved, or is to be made secure and usable in practice.

Prior work addressing voter registration focuses on ensuring the integrity of the real credential but leaves design gaps. Civitas [23], for instance, distributes the issuance of the real credential across multiple registrars (e.g., online and in-person registration tellers). However, Civitas requires voters to possess private registration materials for authentication with each registrar, and assumes that voters will neither sell nor surrender these under coercion. Subsequent works on Civitas [56, 55, 30] realize this assumption with trusted hardware, e.g., smart cards. In Krivoruchko’s [46] work, the integrity of the real credential also relies on the voter having a trusted device during registration. Despite these strides, critical practical questions remain unanswered: What prevents a coercer from confiscating the voter’s trusted device, or imposing their own device on the voter just prior to registration?

We present Trust-limited Registration In-Person or TRIP, which, to our knowledge, is the first coercion-resistant registration scheme that ensures the integrity of voters’ real credential without requiring multiple registrars nor any trusted device during its issuance. We also design the essential TRIP components required to implement a concrete registration process, as corroborated by a user study detailed in a companion paper [53] and summarized in §7.

TRIP leverages an in-person process in which voters interact with only one registration authority, and are neither required nor permitted to have a trusted device during credential issuance. Voters use a kiosk in a privacy booth to create their real credential and any fake credentials, each on separate paper receipts. The voter learns in the privacy booth which credential is real, but cannot prove this to anyone after leaving. Voters under coercion need only conceal their real paper credential (and not an electronic device) from
the coercer at registration time.¹ This real credential may be used later to vote from any device the voter trusts—such as that of a trusted friend, if their own device(s) are under the coercer’s control. Moreover, real and fake credentials are usable across elections, amortizing the cost of in-person registration which can conveniently coincide with other infrequent in-person events such as passport issuance.

TRIP confronts three key practical security challenges. First, the credentialing process must be voter verifiable despite the voter being prohibited from bringing devices into the booth. For example, it must be detectable if a malicious kiosk issues a fake credential while claiming it is real. Second, real and fake credentials must be cryptographically indistinguishable after the voter leaves the booth. Third, all real (and fake) credentials must be securely—without relying on tamper-proof, non-transferable trusted hardware—and conveniently transferable to, verifiable by, and subsequently usable on any vote-casting device of the voter’s (or coercer’s) choosing.

To create voter-verifiable credentials, the voter and the kiosk carry out and print a transcript of an interactive Σ protocol, which in essence proves in zero knowledge that votes cast with this credential will be counted. The printing of real credentials follows the proper (commit, challenge, response) order for Σ protocols, and hence constrain the kiosk to produce a sound proof. The voter’s device checks this proof later during credential activation, so that voters can identify and report any kiosk misbehavior. The printing of fake credentials, however, follows a distinct (challenge, commit, response) order allowing the kiosk to lie: i.e., to print a proof transcript indistinguishable from a real one but embodying a false claim that votes cast with this (fake) credential will be counted. Because only the printing sequence differentiates sound proofs from unsound proofs, the voter can distinguish the real credential as it is printed

TRIP’s full process just as usable as a simplified one involving only real credentials. Participants who received security education could detect and report a misbehaving kiosk in 47% of cases, while 10% could do so without security education.

This paper makes the following primary contributions:

• The design of TRIP, the first coercion-resistant and verifiable voter registration scheme that maintains the integrity of voters’ real credentials with a single registrar and without relying on a trusted device during credentialing.

• The first use of paper transcripts of interactive zero-knowledge proof to achieve voter verifiability during registration, avoiding reliance on trusted hardware.

• A novel mechanical two-state receipt-envelope design that maintains confidentiality by selectively disclosing information only when needed.

• Security proofs demonstrating that TRIP satisfies verifiability and coercion-resistance properties.

2. Background

This section presents the motivations for secret ballots, highlights the drawbacks of existing “secret-ballot” electronic voting systems and introduces coercion-resistance.

2.1. Why Secret Ballots?

Throughout human history, vote-buying, voter intimidation and political violence have plagued democratic societies [34, 27, 68]. As far back as the Roman Empire, bribery was the norm at every political election and acts to intimidate voters were not uncommon [68]. More than a millennia later, many democratic societies are still plagued with voter intimidation and vote buying. Developing countries [19, 18] and those with a low democracy index [31, 33] are particularly vulnerable, but even those with a high index are not immune [36]. Examples include gangs, employers, domestic partners and political parties.

In the 1850s, Australia introduced the modern practice of casting secret ballots in a private, supervised polling environment with independent observers [34, 11]. This also marked the introduction of uniform, government-supplied ballots to prevent malicious tracing of ballots to voters [25]. The Australian secret ballot’s design emphasizes two key objectives: (1) ensuring voters cannot prove their vote to third parties, and (2) minimizing trust in government officials. TRIP’s goal is to achieve these same objectives for online voting registration.

Contrary to common assertions that publicly verifiable (e.g., blockchain-based) secret-ballot electronic voting systems improve voting security, they are actually quite susceptible to vote buying and coercion [26, 60]. In such systems, decentralized autonomous organizations can confirm how

¹Extreme coercion scenarios—where the voter is unable to hide even a paper credential from the coercer, or has no access to any device they trust to cast votes online outside the privacy booth—are beyond TRIP’s threat model, but could be addressed with a vote-delegation extension outlined in §B.
individuals voted and pay them accordingly [26]. Future ransomware might even extort votes, not just cryptocurrency, in exchange for unlocking ransomed data. Such attacks are globally scalable, are often hard to trace, and are difficult to deter even if traced due to jurisdictional boundaries.

2.2. Remote Electronic Voting Systems

Electronic voting systems promise convenience and a higher voter turnout [28], as well as unparalleled integrity in election results through end-to-end verifiability compared to their non-electronic counterparts [24, 23]. For example, voters might in principle cast their votes on a public ledger, whose final tally can then be verified by anyone, not just by designated observers. Each voter can also readily verify that their vote was recorded accurately. However, public voting exposes voters to peer pressure, vote buying, and coercion, which can reduce trust in the electoral process [18]. Electronic voting systems must then not only ensure integrity, but also protect against adversarial influence on voters’ choices.

Secret ballot electronic voting systems have been studied since the 1980s by Chaum [22], Benaloh [9], and others. Modern secret ballot electronic voting systems generally either have the client encrypt the ballots [65] or have voters use code voting [4]. A set of talliers, collectively trusted for vote confidentiality, tally the ballots and generate a correctness proof. These systems thus prevent an adversary from using the public ledger to verify how a particular voter voted. An adversary can, however, ask the voter to prove how they voted, as was often done before the introduction of the secret ballot (§2.1). As a result, despite their strong appeal, these systems do not yet offer the same level of voter protections as traditional in-person voting.

2.3. Evolution to Coercion-Resistance

Receipt-freeness. The notion of receipt-freeness [13, 57] informally requires that voters be incapable of proving how they voted [41]. Several voting schemes have focused on receipt-freeness [38, 58, 15, 44], but are nevertheless susceptible to at least one of the following attacks [43, 48]:
- Simulation: an adversary impersonates the voter by, for example, having the voter divulge their voting credential.
- Randomization: an adversary has the voter submit an invalid vote, which will not count in the final tally.
- Forced abstention: an adversary prevents the voter from casting a vote altogether.

Coercion-Resistance. JCJ proposes a stronger notion called coercion-resistance, where the coercer cannot determine whether a targeted voter followed their demands [43]. JCJ suggests the use of fake credentials, which appear to act ide ntically to a voter’s real credential but do not affect the election’s outcome. Voters can then give or sell fake credentials to a coercer, or cast votes under the coercer’s supervision using fake credentials, thereby pretending to comply with the coercer’s demands. Another common approach is deniable re-voting [52, 61, 5], where only the last vote cast using the voter’s voting credential counts in an election. However, this approach exposes the voter to last-minute coercion or to the theft of their (only) credential.

Voter Registration. JCJ assumes a trusted registrar and an untappable channel between the voter and the registrar. However, the specifics of this channel and the credentialing process—particularly their resilience against a powerful adversary’s interference—are left undefined. This ambiguity is particularly concerning when voters intend to cooperate with the adversary, e.g., by using the adversary’s device in return for financial gain. Moreover, for voters not under coercion, a trusted registrar should not be necessary, allowing them to verify the integrity of their real credential. TRIP addresses these concerns by defining a concrete voter registration process that satisfies coercion-resistance without relying on a trusted registrar. A comparison with key related works such as Civitas [23], and the work by Krivoruchko [46] is detailed in §9.

3. TRIP Design Overview

This section summarizes TRIP’s design, detailing its key properties, system and trust model, assumptions, and outlining a voter’s perspective on the registration process.

Preliminary. TRIP is a coercion-resistant registration scheme designed to take in an electoral roll and output a real and any potential fake credentials for each voter. This scheme is integratable into a broader electronic voting system that supports fake credentials and handles both ballot casting and tallying. We adopt the necessary elements commonly used in electronic voting schemes (e.g., actors, definitions) to show how TRIP fits into such a scheme and provide well-founded proofs. For simplicity, we generally ignore provisions pertaining to casting or tallying ballots.

Registration Workflow. The four steps in the registration process (Fig. 1), excluding Setup, are Check-In, Credentialing, Check-Out and Credential Activation. At check-in, prospective voters present traditional authentication documents, such as an ID, to a registration official to receive their check-in ticket. Voters then surrender their electronic devices to the registrar and enter a privacy booth. Inside, voters present their check-in ticket to a kiosk to obtain their electronic devices and proceed to check-out. At check-out, voters display a credential (real or fake) to the official and exit the registrar. Voters can now activate their credentials at any time and cast votes in elections.

3.1. System Properties

TRIP, as a voter registration scheme, aims to satisfy the following properties:
- Coercion-Resistance [43]: a (coercive) adversary cannot determine whether a targeted voter complied with the coercer’s demands, even if the voter is willing to comply.
- Individual Verifiability [14, 4]: a voter is convinced that a ballot confirmed as coming from the voter contains
The voter (1) authenticates themselves to an official at a check-in desk to obtain a check-in ticket (2) enters a supervised private environment to create a real and any potential fake credentials, (3) presents one of their credentials to an official at the check-out desk, and (4) activates their real and any fake credentials on a trusted device, which could belong to them or a trusted third party.

We assume each voter, also under coercion, can attend a registrar office during open enrollment (C1), conceal their real and any potential fake credentials; (2) envelope printers \( P = \{P_1, P_2, \ldots, P_{n_P}\} \), which issues the envelopes later used by voters during credentialing inside the privacy booth; and, (3) registration officials \( O = \{O_1, O_2, \ldots, O_{n_O}\} \), represented by their official supporting device (OSD), who authenticate voters and authorize their credentialing sessions.

**Authority.** The authority \( A = \{A_1, A_2, \ldots, A_{n_A}\} \) consists of \( n_A \) members who jointly process the ballots cast on the ledger to produce a publicly verifiable tally. Additionally, the authority is responsible for managing election logistics, setting policy, and is ultimately accountable to the voters.

**Voters.** The set of voters on some given electoral roll \( V = \{V_1, V_2, \ldots, V_{n_V}\} \) who obtain their credentials at the registrar, and then activate them on their voter supporting device (VSD) to cast (real or fake) ballots on the ledger. VSDs periodically monitor the ledger and inform voters of updates relevant to them, such as a completed registration.

### 3.3. Actor Assumptions

To ensure the integrity of voters’ credentials (I) and help them evade coercion (C), we present our actor assumptions.

**Ledger.** We assume the ledger is secure and ensures liveness (e.g., via Byzantine fault tolerant consensus to withstand compromised and unavailable nodes). We assume that mechanisms exist for the ledger to certify the bindings between public keys and actors (except for voters).

**Voters.** We assume that for the integrity of all voters’ real credentials, some percentage of voters can understand and visually follow the steps required to create their real credential and report any deviations or misbehavior (I1). We assume these voters pick envelopes in an unpredictable manner (I2). Finally, we assume most voters activate their credentials before the tallying phase (I3). We assume these voters pick envelopes in an unpredictable manner (I2). Finally, we assume most voters activate their credentials before the tallying phase (I3).

We assume each voter, also under coercion, can attend a registrar office during open enrollment\(^2\) (C1), conceal their real paper credential from their coercer (C2), after leaving the registrar’s office, access a trusted device, whether that

\(^2\) Similar to how some countries like Australia [1] mandate voting, countries could also mandate voter registration.
is their own or that of a trusted third party such as friend or family member, for credential activation and voting (C3), obtain an unsupervised, coercion-free moment, either alone with their trusted third party, for credential activation and voting (C4), and lie to a coercer about having complied with the coercer’s demands (C5). As per the JCJ voting scheme [43], we assume the vote-casting device can open an anonymous channel with the ledger for online voting (C6). Assumptions C3 and C4 seem essential in any online private-voting system. Assumptions C2-4 (inclusive) and C6 could be disregarded in the most extreme coercion scenarios in favor of stronger integrity assumptions via a vote-delegation extension discussed in §B.

Registrar. We assume that the details about the registration process are widely recognized (I4). In particular, the instructional video shown at the registrar is available online, and significant discrepancies between videos would be detected.

To maximize protection against coercion, we assume that the registrar protects voter privacy in the booth, and that the registrar does not collude with coercers (C7), e.g., by preventing a coercer from impersonating a targeted voter. This assumption mirrors the existing premise for in-person secret ballot voting. Furthermore, the registrar provides sufficient envelopes in each booth for upcoming registrations. We assume that manually counting the exact number of envelopes, without the aid of forbidden devices, is time-consuming enough to draw officials’ attention (C8). The thinness of envelopes (< 1mm) makes it practical for each booth to contain a stack of hundreds or even thousands.

3.4. Threat Model

One threat-modeling challenge that electronic voting systems encounter is that different threats pertain to different situations. Rather than using a single conceptual adversary, these systems [4, 47] typically establish distinct adversaries, each embodying unique assumptions and capabilities tailored to their particular situation. For example, most model separate (non-colluding) privacy and integrity adversaries, so that some system elements can be trusted for privacy more (or less) than they are trusted for integrity.

We build on this practice by further distinguishing between situations in which a voter is, or is not, under coercion. For the hopefully-common case of voters not under coercion, we minimize the extent to which uncoerced voters must trust the system either for privacy or integrity, i.e., we maximize the adversary’s control over system elements in these respects. For the hopefully-rare but important case of voters under coercion, we must consider the registrar to be trusted to ensure the voter’s privacy and not to collude with the voter’s coercer, at least by this (coerced) voter. Otherwise, the coercer would effectively control both the voter and the registrar, leaving no plausible basis to bootstrap any kind of security. This trust relationship is consistent with in-person voting, where voters rely on the election authority to provide them with a safe space to cast their ballots, but may also scrutinize the election process to ensure its integrity.

| Device | Ledger | Authority | OSD | Kiosk | Envelope Printers | VSD w/ Cred. |
|--------|--------|-----------|-----|-------|------------------|--------------|
| Adv    | Integrity | Coercion |
|        | No      | Yes       | Yes | Yes   | Yes              | Yes          |
|        | Yes     | Yes       | Yes | Yes   | No               | Yes          |

TABLE 1: Threat Model: This table depicts an adversary’s ability to compromise a device and the entity or credential it represents.

We now informally define three distinct, non-colluding adversaries: integrity I, privacy P and coercion C, and present in Table 1 which devices they may compromise. We assume that adversaries are computationally bounded and that the cryptographic primitives we use are secure.

- **Integrity.** I’s goal is to manipulate the outcome of a voting event without detection, e.g., pre-empt, alter or cancel votes. We assume a well-known, accurate electoral roll that I cannot alter. We also assume I cannot compromise the ledger nor the VSDs containing voters’ real credential.

- **Privacy.** P’s goal is to reveal a voter’s real vote. We assume that P cannot compromise VSDs containing voters’ real credential nor compromise all authority members. The former assumption is predicated on our focus on the registration process while the latter is common not only in electronic voting but also in other privacy-enhancing systems [63, 32].

- **Coercion.** C’s goal is to determine whether a targeted voter complied with their demands. For example, through undue influence or vote-buying, C can demand voters to reveal their real credential, cast C-intended ballots, or even refrain from voting. C may control a subset of voters, who comply with C’s demands. Similar to P, C may not compromise all authority members nor the VSD containing the voters’ real credential. In addition, C cannot compromise any of the registrar actors (kiosks, OSDs and envelope printers) nor monitor the actions of voters while they are inside the booth. Finally, C cannot prevent voters from registering.

3.5. Voter-Facing Design

We now describe registration from a voter’s perspective. **Instructional Video.** Upon arrival at the registrar, the voter first views an instructional video that illustrates registration from check-in to credential activation. This video introduces the concept of fake credentials, and depicts the differences between creating a real credential and a fake one.

**Check-In.** At check-in, the voter authenticates themselves to the official, who then gives the voter a check-in ticket containing a barcode, and the label “Check-In Ticket” (Fig. 3a).
Booth Entrance. Before entering the booth, the voter deposits any electronic devices in a lockable compartment, similar to those often found at a gym, museum, or embassy. Inside the booth, the voter finds a touchscreen kiosk with a built-in QR/Barcode reader, a receipt printer, a pen and a set of envelopes. Each envelope (Fig. 3b) is a hollow rectangle featuring a symbol, a QR code, a transparent window, and a designated area for voter markings. Once a voter is ready to initiate the credentialing procedure, the kiosk displays instructional screens to guide the voter through the process. The voter is then prompted to scan their check-in ticket.

Real Credential Creation. The voter creates their real credential in 4 steps. Once the voter has scanned their check-in ticket (Step 1), the kiosk prints a symbol and a QR code. The voter is then asked to confirm on-screen the symbol printed along with a QR code (Step 2). Upon confirmation, the voter selects an envelope with the same symbol from a set of envelopes and scans it (Step 3). The kiosk then finalizes the paper receipt containing three QR codes (Step 4, Fig. 3c). Finally, the voter tears the receipt from the printer and places it inside the envelope to complete their credential (Fig. 3d). To have the voter distinguish their real credential from fake credentials, the kiosk instructs the voter to use the provided pen to mark their real credential in some way the voter can remember in the designated area.

We refer to the state in which the receipt is fully inserted as the transport state. In this state, the middle QR code on the receipt remains visible for an official to scan, while keeping the (sensitive) information in the top and bottom QR codes hidden. Maintaining the confidentiality of sensitive information is solely to prevent the voter from experiencing the inconvenience of re-registration in the event of a leak.

Coercion & Vote Buying Education. The kiosk then educates the voter on coercion and vote buying and invites the voter to create a fake credential.

Fake Credential Creation. If the voter agrees to create a fake credential, this process happens in 2 steps. The voter picks and scans any envelope (Step 1) and the kiosk then prints the entire receipt containing three QR codes (Step 2). Similar to creating real credentials, the voter inserts the receipt into the envelope and marks the credential to distinguish it from their other credentials. The kiosk then invites the voter to create another fake credential and if the voter agrees, they repeat the two steps outlined above. The voter can create as many fake credentials as desired within reason. Once the voter has their credential(s), the kiosk reiterates key information and instructs them to present one of their credentials at the check-out desk. Upon leaving the booth, the voter retrieves any deposited electronic devices.

Check-Out. The voter now presents any one of their credentials (in its transport state) to the official, who then scans the check-out ticket visible through the credential’s transparent window. After scanning the credential, the official informs the voter that their visit to the registrar is now complete. The voter will subsequently receive a notification of their visit on their VSD or potentially via some out-of-band channel such as postal mail if no VSD is associated with the voter.

Activation. Whenever the voter obtains their own private (coercion-free) moment, the voter can activate their real credential. They may activate their fake credentials at any time, including under coercion, following exactly the same steps. Upon opening the voting application, VSD instructs the voter to lift the receipt one third of its length out of the envelope, placing the credential in the activate state.

We expect that registration officials will inquire if a voter spends an inordinate amount of time in a booth, thereby imposing an informal and nondeterministic upper bound on the number of fake credentials printed and resources consumed. An alternative solution is for the kiosk to impose a per-voter randomized maximum quota of time or fake credentials.

5We introduce symbols to enhance usability and meet voter assumptions (I1 and I2), as further discussed in §7.

6Under coercion, for example, a voter might mark a fake credential “real” for their coercer, but mark their real credential “REAL!”.

7We expect that registration officials will inquire if a voter spends an inordinate amount of time in a booth, thereby imposing an informal and nondeterministic upper bound on the number of fake credentials printed and resources consumed. An alternative solution is for the kiosk to impose a per-voter randomized maximum quota of time or fake credentials.
state (Fig. 3e). This state reveals, in order, the receipt’s top QR code outside the envelope, the envelope’s QR code, and the receipt’s bottom QR code inside the transparent window. The receipt’s middle QR code is no longer visible. The device then prompts the voter to scan the three visible QR codes to complete activation.

After activation, the voter can cast ballots in current or future elections until a policy-determined expiration date, after which the voter must re-register in person. VSD finally instructs the voter to discard the physical credential after which the voter must re-register in person. VSD finally instructs the voter to discard the physical credential.

4. TRIP Scheme

This section presents the TRIP scheme, which we formally describe in Fig. 4.

Notation. For a finite set $S$, $s \in S$ denotes that $s$ is sampled independently and uniformly at random from $S$. The symbol $\oplus$ represents exclusion from a collection of elements. We denote $a \leftrightarrow b$ as appending $b$ to $a$, $a \| b$ as concatenating $b$ with $a$, $x$ as a set of elements of type $x$, and $x[i]$ as the $i$th entry of the vector $x$. We use $\top$ and $\bot$ to indicate success and failure, respectively. Variables used throughout the TRIP scheme are summarized in Table 2.

Primitives. TRIP requires (1) the M-ElGamal scheme MEG defined in IJCI [43], (2) a distributed key generation scheme DKG, (3) a EUF-CMA signature scheme Sig, (4) a secure hash function $H$, (5) a message authentication code scheme MAC, and (6) an interactive zero-knowledge proof of equality of discrete logarithms ZKPoE. These primitives are defined in §D for completeness.

4.1. TRIP Functions

Setup. Setup (Fig. 9, §A) initializes the core system actors (Ledger, Authority, and Registrar). Prior works often include registration as part of a general setup process, but we separate it to delineate registration cleanly:

- The Ledger $L$ becomes accessible and made accessible to all (including third) parties. We denote $L_{R}, L_{E}, L_{V}$ the registration, envelope, and voting sub-ledgers, respectively.
- The authority members $A$ run DKG and outputs a private, public keypair for each authority member $(A_{i}^{PK}, A_{i}^{PK})$ and a collective public key $A_{pk}$ which is made available to all parties. $A_{pk}$ must be a generator of $G_{q}$.
- Each registrar actor (OSDs, kiosks & printers) generates their own private and public key pair using $\text{Sig.KGen}(1^{l})$. The registrar uses the electoral roll $V$ to populate $L_{E}$ with each voter’s unique identifier $V_{id}$. The printer issues at least $n_{E} > c[|V| + C|K|]$ envelopes $E^{9}$, where the

9For voters not under coercion, the paper credential can be made immaterial after activation with the help of the tallying scheme (§8).

9The more (fake) credentials in circulation, the less vote buying is a threat.

| Symbol | Description |
|--------|-------------|
| $G, q, g$ | A cyclic group $G$ of order $q$ with generator $g$ |
| $A, O, K, P, V$ | Authority, Officials, Envelope Printers, Electoral roll |
| $n_{A}, n_{O}, n_{K}, n_{P}$ | Number of Authorities, Officials, Envelops, Envelope printers |
| $L_{R}, L_{E}, L_{V}$ | Ledger and Registration, Envelope & Voting (sub-)ledgers |
| $C_{pk}, c_{pk}$ | Voter’s identifier, Public Credential, Public & Private Keys |
| $E, n_{E}, n_{C}$ | Envelope challenges and number of envelopes & credentials |
| $s, s_{rk}$ | MAC authorization tag, Official & kiosk shared secret key |
| $t_{in}, t_{out}, t_{c}, t_{r}$ | Check-In & Check-Out Tickets, Commit & Response Codes |

TABLE 2: Scheme Notations.

constant $c \geq 2$ represents the authority’s estimate of the number of envelopes each voter consumes and constant $C$ represents the minimum number of envelopes that must be present in each booth to satisfy assumption C8. Each envelope contains the printer’s public key $P_{i}^{pk}$, a cryptographic nonce $c \in Z_{q}$, and a signature on this nonce $\sigma_{p} \leftarrow \text{Sig.Sign}_{p}(H(e))$. For each envelope, the printer also publishes $(P_{i}^{pk}, H(e), \sigma_{p})$ to the ledger $L_{E}$. The officials $O$ and kiosks $K$ generate a shared secret key $s_{rk}$ to create and verify MAC authorization tags.

Check-In. Upon successful authentication at Check-In (Fig. 10, §A), the OSD issues the voter a check-in ticket, $t_{in}$, consisting of the voter’s identifier, $V_{id}$, and an authorization tag, $\tau_{r}$, on $V_{id}$. The kiosk validates the authorization tag, $\tau_{r}$, when the voter presents their ticket $t_{in}$.!

Real Credential. After verifying the authorization tag $\tau_{r}$, the kiosk issues the voter their real credential while proving its correctness (Fig. 5a). The kiosk first generates the voter’s real credential’s public and private keys $(c_{pk}, c_{pk})$ and M-ElGamal encrypts $c_{pk}$ using the authority’s public key $A_{pk}$ to obtain the voter’s public credential $c_{pc}$. To prove that $c_{pc}$

10If authorities underestimates the average consumption of envelopes, $P$ can issue additional envelopes. Unlike paper ballots, envelopes do not expire, allowing unused ones to be saved for future registrations.

11For usability, as discussed in §7, we use a barcode instead of a QR code, and due to storage constraints in a barcode, we use MAC instead of Sig.
encrpts \( c_{pk} \) without revealing the M-ElGamal randomness secret \( x \) (to later enable the construction of fake credentials), the prover, the voter, as the verifier, run an interactive zero-knowledge proof of equivalence of discrete logarithms: \( ^{12} \) ZKPoE \( \mathbb{E} C_{1}, C_{2}, X \{ x : C_{1} = g_{1}^{x} \land C_{2} = g_{2}^{y} \land X = X_{pk} \} \). The kiosk first computes the commits \( Y_{1} = g_{1}^{x} \), \( Y_{2} = g_{2}^{y} \), and \( Y_{3} = A_{pk}^{y} \) for \( y \leftrightarrow Z_{q} \) and prints the commit \( q_{c} \), containing the voter’s public credential \( c_{pc} \), the commits \( Y_{t} = (Y_{1}, Y_{2}, Y_{3}) \), and a signature \( \sigma_{kc} \), on \( \mathbb{V}_{id} \| c_{pc} \| Y_{c} \). The voter then supplies the kiosk with an envelope \( E_{i} \leftrightarrow E_{q} \) containing the challenge \( e \). The kiosk finally computes the response \( r = y - cx \), computes the signatures \( \sigma_{kt} \) and \( \sigma_{kr} \), and prints the check-out ticket \( t_{ot} \) and response \( q_{r} \).

At this stage, the voter observes that the process adheres to the \( \Sigma \)-protocol sequence: commit, challenge, response. If the voter detects and reports an anomaly, we expect the registrar or some other authority to direct the voter to another kiosk and inspect the one reported. The voter’s device later verifies the computational correctness.

Fake Credentials. To create a fake credential (Fig. 5b), the kiosk generates a new credential \( \tilde{c}_{pk} \) and falsely proves that the public credential \( c_{pc} \) encrypts \( \tilde{c}_{pk} \). The kiosk first derives the “new” M-ElGamal secret \( \tilde{X} \leftarrow C_{3}/\tilde{c}_{pk} \). Evidently, the kiosk has no knowledge of an \( \tilde{x} \) that satisfies \( \tilde{X} = \tilde{X}_{pk} \), requiring one to solve the discrete logarithm problem. Instead, the kiosk and the voter follow an incorrect proof construction sequence that violates soundness without affecting the correctness of the computations. In this sequence, the voter first supplies a new envelope \( E_{z} \leftrightarrow E_{q} \) to the kiosk, where \( e \) are the previously used envelopes/challenges. Then, the kiosk uses the new challenge \( e \) to compute a ZKP commit \( (Y_{1}, Y_{2}, Y_{3}) \leftarrow (g_{1}^{x} C_{1}, g_{2}^{y} C_{2}, A_{pk}^{y} \tilde{X}) \) for some \( y \leftrightarrow Z_{q} \) and the ZKP response \( r \leftrightarrow y \). The kiosk finishes by computing signatures \( \sigma_{kc} \) and \( \sigma_{kr} \), printing the commit \( \tilde{q}_{c} \), check-out \( t_{ot} \), and response \( q_{r} \) sequentially, where \( t_{ot} \) is identical (both in content and visually) to the one in the real credential process. The voter can repeat this process for any number of desired fake credentials (within reasonable limits mentioned in §3.5).

Check-Out. At check-out (Fig. 11, §A), the registration official uses their OSD to scan the credential displayed by the voter. This credential is shown in transport state (Fig. 3d), which reveals the contents of the check-out ticket \( t_{ot} \) but not the secrets to be used in activation.

The OSD first checks the credential’s authenticity by checking the kiosk’s public key \( K_{pk} \in K_{pk} \), and verifying the signature \( \sigma_{kt} \). OSD then provides their stamp of approval with a digital signature \( \sigma_{o} \) on the voter’s identifier \( V_{id} \), the voter’s public credential \( c_{pc} \) and the kiosk’s signature \( \sigma_{kc} \). Finally, OSD updates the ledger entry \( V_{id} \) with \( (c_{pc}, K_{pk}, \sigma_{kc}, O_{pk}, \sigma_{o}) \). Once updated, the ledger \( L \) performs the necessary checks and VSD notifies the voter about their recent registration with information on how to report any irregularities.

Activation. During activation (Fig. 12, §A), the voter uses their VSD to scan a credential in the activate state (Fig. 3e).
This reveals the commit \( q_e \), envelope \( e \), and response \( q_r \); the check-out ticket \( t_{\text{st}} \) is not visible. VSD then verifies the integrity of the credential by (1) verifying the signatures \( (\sigma_{k_e}, \sigma_{k_h}, \sigma_p) \), (2) deriving the ElGamal secret \( X \) and verifying the ZKP, (3) checking whether the public credential \( c_{\text{pc}} \) matches the public credential on the ledger \( c_{\text{pc}} \), and (4) checking that the challenge \( e \) has not been used via the ledger \( L_E \). Upon success, the device publishes the challenge \( e \) on \( L_E \) and stores the credential \( c_{\text{sk}} \) for future voting. The device publishes the envelope on the ledger for integrity, ensuring that the challenges are not re-used. Upon failure, VSD reports the offending actor based on the failure check, and instructs the voter to re-register.

5. Security Analysis

This section evaluates the resilience of TRIP against coercion, integrity and privacy adversaries (§3.4), focusing on its key properties of coercion-resistance and individual verifiability (§3.1). We presume that voters comply with our assumptions and defer discussion on human factors to §7.

Coercion. This section shows that \( C \) cannot determine whether the victim succumbed to the coercer’s demands, thereby rendering coercion meaningless. We prove that TRIP is coercion-resistant by showing that the difference between \( C \)’s winning probability in a real game (representing the adversary’s interactions with our system) and an ideal game (representing the desired level of coercion-resistance) is negligible. In both games, \( C \)’s goal is to determine whether the targeted voter evaded coercion and cast a real vote. Like the total number of votes cast in an election, we treat the total number of credentials created as public information: \( C \) could trivially win if it knew exactly how many (fake) credentials all other voters created. The adversary’s uncertainty about the target voter thus derives from the other honest voters, each of whom creates an unknown (to the adversary \( C \)) number of fake credentials, which we model as a probability distribution \(^{13} D^f \). To achieve statistical uncertainty also on the voting choice, we adopt the same approach for the content of the ballot with the distribution \( D^t \). This “anonymity among the honest voters” mimic the reasoning by which votes themselves are considered to be (statistically) protected once anonymized. We present the ideal game in Fig. 6 to highlight TRIP’s level of coercion-resistance and defer the proof to §E.1.

In this ideal game, adapted from JCJ [43], the coercer chooses the target voter \( j \) and \( n_C < n_V \) controlled voters who abide by the coercer’s demands. All voters obtain their real credential while honest voters also create and activate fake ones. The envelope ledger \( L_E \)’s content (line 21) releases to \( C \) the number of total credentials created during Activate. The distribution \( D^t \) reflects the statistical uncertainty pertaining to the number of fake credentials created

\(^{13}\) In practice, to artificially increase this uncertainty, envelope printers can post challenges on the ledger without printing a corresponding envelope and gradually release these values, similar to the JCJ option of voting authorities or third parties intentionally injecting fake votes to add noise.

**Table 3: Additional Variables for Proofs.**

| Notation | Description |
|----------|-------------|
| \( R \) | Registrar (combines kiosks, envelope printers and officials) |
| \( L_E, \lambda, \beta, \pi \) | Voting (sub-)ledger, Tally & Tally Proofs, (Adversarial) state |
| \( D^t, D^f \) | Probability distribution of fake credentials and votes |
| \( C, \lambda, \pi \) | Coercer, \( C \)-controlled voters, \( C \)-target voter, \( C \)-intended ballot |
| \( \beta, n_C, M \) | Target Vote, Target number of total credentials, Voting options |
| \( n_V, n_{C}, n_{\text{sd}} \) | Number of voters, controlled voters and voting options |

**Figure 6: Game C-Resist-TRIP-Ideal.** The TRIP ideal game for coercion-resistance, adapted from JCJ, to take into account the adversary’s probabilistic knowledge of honest voters’ fake credentials. Notations are defined in Table 2 and Table 3. TRIP API is defined in Fig. 13.
Theorem 1 (Coercion-resistance, informal). The TRIP registration scheme (within the JCJ remote electronic voting scheme [43]) is coercion-resistant under the decisional-Diffie-Hellman assumption in the random oracle model.

Integrity.

The adversary \( I \) seeks to undetectably influence the election’s result (§3.4). In a voter registration system that incorporates fake credentials, this boils down to covertly “stealing” a voter’s real credential to cast real votes—potentially by substituting the real credential with a fake one during issuance without the voter’s knowledge. Hence, the system must allow voters to verify that the credential presented by the registrar as “real” is truly real. We first illustrate that \( I \)’s winning probability under individual verifiability is small but not negligible. Subsequently, we show that our new iterative individual verifiability notion, which takes into account the registration of multiple voters instead of just one, achieves a negligible winning probability.

Our definition builds on the work of Bernhard et al. [14], which considers vote casting: a voter is convinced that their vote was cast as intended. Their definition is, however, unsuitable for a registration process as we aim to detect whether an adversary tampered with the construction of a voter’s credential. We present our definition of individual verifiability in Fig. 7a. For iterative individual verifiability (Fig. 7b), we draw inspiration from Ordinos [47], a tally-hiding focused electronic voting system that relies on the analysis of how the security of TRIP evolves under different configurations in §6. In Theorem 5 (§E.2), we prove that \( I \)’s advantage is negligible in the security parameter \( \lambda \), under the new definition of iterative individual verifiability (Fig. 7b), where \( \lambda \) represents the number of times that \( I \) must win the game IV to successfully win against I-IV. This game offers a more accurate representation of large-scale elections, where to influence the outcome, \( I \) needs to win not just against a single voter but many voters.

While voters can verify the integrity of their real credentials, the kiosks that issued it could potentially cast votes without voters’ consent. We suggest two solutions in §8.

Privacy. The goal of a privacy adversary \( P \) is to reveal the content of a voter’s real vote. We only provide an informal analysis as privacy is solely relevant to the ballot’s contents, but voting and tallying are out of scope. To win, \( P \) needs to (1) identify and (2) decrypt the ciphertext that encrypts the real vote. Given our threat model for \( P \) commonly used in e-voting (§3.4 & §2.2), \( P \) can complete the first objective by compromising the kiosk but fails to complete the second: it cannot compromise VSDs to view the plaintext vote nor compromise all talliers to decrypt the encrypted vote.

6. Real Credential Integrity Analysis

This section analyzes the advantage that the integrity adversary obtains by controlling (1) the setup of the booth and (2) the real credential creation process. In particular, the adversary can perform a one-time setup of the envelopes prior to the voter entering the booth to influence the distribution of ZKP challenges printed on the envelopes. The
adversary’s goal is to predict the challenge printed on the envelope that the voter picks; an incorrect guess exposes the adversary during credential activation (Fig. 12, line 7, §A).

In an illustrative but unrealistic scenario, the adversary issues two envelopes and decides between a single challenge for both or different challenges for each. With two unique challenges, the winning probability, i.e., the probability to correctly guess the challenge that the voter picks, is 0.5. With one challenge, the adversary wins if the voter creates only the real credential but gets exposed if the voter also creates a fake credential. This mirrors Benaloh’s work on vote casting verifiability [10], where the adversary’s chance of winning depends on the voter’s decision of whether to challenge the device or continue with the protocol. Although the adversary might win if the voter creates a single credential, it is improbable for this to occur for each voter, which motivates us to introduce the notion of iterative individual verifiability (Theorem 5), which accounts for the registration of multiple voters. The user study (§7) demonstrates the soundness of this notion: 76% of participants created at least one fake credential and 53% said they would create fake credentials if such a system were available today.

A single voter reporting suspicious behavior during credentialing (e.g., the kiosk refusing to proceed or urging the voter to continually select new envelopes) is enough to catch the kiosk in the act and have the authorities proceed with remediation measures, such as recalling previous registration sessions. To confirm the kiosk’s misconduct, the authorities challenge the device to reveal the random value $y$ used to calculate the ZKP commitments $C_1, C_2, C_3$ for this session, as printed on the receipt. If the kiosk refuses or if $y$ does not satisfy the equations in Fig. 5a, line 5, the authority has unequivocal proof of the kiosk’s misconduct.

In practice with many envelopes, the adversary’s optimal strategy (as detailed in §E.2) involves issuing identical envelopes containing the challenge they intend to use in the ZKP commitments (Fig. 5b, line 9) during the real credential creation session. This increases the probability that the voter picks an envelope with this challenge. However, as shown in Fig. 8a, after a certain number of identical (same challenge) envelopes, the adversary’s success rate starts to decline; the more envelopes with the same target challenge, the higher the likelihood that the voter selects it again during their fake credential creation process. The probabilities in Fig. 8a represent an upper bound as the adversary lacks prior knowledge of the voter’s intended number of credentials.

In Fig. 8b, we see that the adversary’s winning probability decreases with each registration as the adversary must win against each one. Failing to win against a single session makes the adversary detectable. Fig. 8 presents a case with a low number of envelopes $(n = 100)$. In reality TRIP requires hundreds, or even thousands of envelopes as to make them practically uncountable without a sufficient margin of error necessary for coercion-resistance (assumption C8 in §3.3).\textsuperscript{14}

7. User Study

This section presents a summary of the user study we conducted with TRIP [53]. This study evaluated whether ordinary voters can understand and use TRIP by conducting a study with 150 paid participants, recruited over 3 months at a suburban park of a major metropolitan city. Participants’ age ranges from 19 to 83, with a median and mean of 36.5 and 44, respectively. We do not include full details of this study, but briefly summarize its findings on two key questions: system usability and the rate at which participants identify and report a malicious kiosk.

Study Design. The study simulated voter registration according to §3.5, with variations for A/B testing: The 150 participants were randomly divided equally into 1 control and 4 experimental groups: (C) only real credential, (F) real and fake credentials, (M) group F with a misbehaving kiosk, (SF) group F with security education, (SM) group SF with a misbehaving kiosk. The control group only received a real credential known as the “voting credential”. In group F, participants experienced the anticipated voter registration process (§3.5): real and fake credentials and a well-intentioned kiosk. In group M, participants encountered a “malicious” kiosk, designed to trick them into creating a fake credential under the pretense of creating a real one. The difference between F and SF along with M and SM is that the participants in the latter groups were exposed to an instructional video that explicitly stated that the kiosk can, in the unlikely event, misbehave. This video includes the visual cues of a misbehaving kiosk that intends to violate ZKP soundness. After completing registration, each participant completed a survey asking them about their experience.

Evaluating Usability via Voting Process. After checkout, the study asked participants to cast a vote using their real credential. Out of the potential 120 participants capable of creating fake credentials, 92 did so, with 90% of them successfully casting a mock vote using their real credential. Once considering those requiring help during the study, either in the credentialing phase or during credential activation, TRIP exhibited an overall success rate of 83%.

\textsuperscript{14}To our knowledge, no study evaluates the error rate in paper counting. We draw a parallel with manual data entry, a similarly slow and labor-intensive process, identified to have a 1% error rate [49]. This rate equates to a margin of error of 10 envelopes in a set of a thousand, providing an ample buffer for coerced voters.
between group F and groups SF and SM suggests that the usability drop. The noticeable difference in SUS scores real and fake credentials compared to the control group suggests that TRIP is usable, and the slight increase in SUS score of participants who were exposed to both these studies and according to Bangor et al. [8], is SUS score of 70.4, which falls within the 57.8th percentile standard deviation of 12.5 [62]. TRIP (Group F) achieved a score from 446 studies of diverse systems is 68 with a Table 4 shows each group's SUS score. The average SUS Subjective assessment of the system’s appropriateness for its purpose. SUS consists of ten standardized statements, where participants rate their agreement with them from Strongly Agree to Strongly Disagree (a 5 point Likert Scale [51]). Table 4 shows each group’s SUS score. The average SUS score from 446 studies of diverse systems is 68 with a standard deviation of 12.5 [62]. TRIP (Group F) achieved a SUS score of 70.4, which falls within the 57.8th percentile of these studies and according to Bangor et al. [8], is “Acceptable” and earns an adjective rating of “Good”. This suggests that TRIP is usable, and the slight increase in the SUS score of participants who were exposed to both real and fake credentials compared to the control group only exposed to real credentials, defies the expectation of a usability drop. The noticeable difference in SUS scores between group F and groups SF and SM suggests that the participants perceived the system as less usable due to the exposure to a video on system misbehavior. However, it may be the exposure and detection of this misbehaving kiosk that brings down the SUS score the most since the difference is two times greater with SM than with SF. Such malicious behavior should (hopefully) not occur in practice. Malicious Kiosk Detection. Since TRIP assumes that a reasonable percentage of voters can detect and report a malicious kiosk (§3.3), the study estimated this reporting rate with ordinary people. As expected, no participant who interacted with an honest kiosk (Group C, F, and SF) reported any misbehavior to a facilitator. A small number of participants reported oddities with the kiosk in the survey, but their responses were related to confusion with the credentialing process. Participants in Group M and SM interacted with a misbehaving kiosk that instructs voters to scan an envelope after scanning their check-in ticket and removes any related material around the correct process. In group M, 10% and 20% of participants reported the kiosk’s misbehavior to the facilitator and on the survey, respectively. This discrepancy between the reporting rates may have been due to being uncomfortable in expressing their doubt, but the survey gave a medium to express such doubts, as shown in the non-security priming groups. In group SM, 47% of participants reported the misbehavior to the facilitator and an additional 10% reported it on the survey. In fact, the security education in group SM resulted in a statistically significant improvement over group M (chi-squared test, $p < 0.004$) but at the cost of a perceived decrease in system usability.

Preliminary Usability Studies. With approval from our institutional review board, we conducted two preliminary studies involving 77 participants: 41 from a university and 36 from a city (anonymized). These participants were divided into two groups that closely mirrored the F and SM groups from [53]. Their feedback led to two significant design enhancements: 1) replacing the check-in ticket’s QR code with a barcode to prevent confusion, as participants frequently mistook the check-in ticket’s QR code for the initial QR code printed by the kiosk during the real credential creation process; 2) including a symbol on the receipt to prompt participants to consider their envelope choice carefully, specifically to ensure they only select an envelope after the kiosk has printed the symbol and QR code.

7.1. Key Results

System Usability Scale. The companion paper’s study [53] evaluated usability with the commonly used System Usability Scale (SUS) [17] which measures an individual’s subjective assessment of the system’s appropriateness for its purpose. SUS consists of ten standardized statements, where participants rate their agreement with them from Strongly Disagree to Strongly Agree (a 5 point Likert Scale [51]). Table 4 shows each group’s SUS score. The average SUS score from 446 studies of diverse systems is 68 with a standard deviation of 12.5 [62]. TRIP (Group F) achieved a SUS score of 70.4, which falls within the 57.8th percentile of these studies and according to Bangor et al. [8], is “Acceptable” and earns an adjective rating of “Good”. This suggests that TRIP is usable, and the slight increase in the SUS score of participants who were exposed to both real and fake credentials compared to the control group only exposed to real credentials, defies the expectation of a usability drop. The noticeable difference in SUS scores between group F and groups SF and SM suggests that the participants perceived the system as less usable due to the

| Groups (Control) (F) Fake Creds. (M) Malicious Kiosk (S) & (F) (S) & (M) | Scales System Usability Scale |
|---|---|---|---|---|
| Overall | 69.6 | 70.4 | 69.9 | 67.3 | 62.7 |
| SD | 18.6 | 18.6 | 17.4 | 19.8 | 21.9 |
| N | 29 | 28 | 29 | 30 | 29 |
| Percentile | 55.1 | 57.8 | 56.1 | 47.8 | 35.0 |
| Usability | 69.5 | 69.8 | 68.4 | 67.7 | 62.5 |
| Learnability | 69.8 | 73.2 | 75.9 | 65.8 | 63.4 |

Reporting Malicious Kiosk Detection

| Facilitator | 0% | 0% | 10% | 0% | 47% |
| Survey | 10% | 7% | 20% | 7% | 57% |

TABLE 4: System Usability Scale & Malicious Kiosk Detection

The top half displays the System Usability Scale (SUS), including standard deviation (SD) and sample size (N). SUS has two subscales: Usability and Learnability. The Percentile Rank measures the group’s usability relative to 446 studies [62]. The bottom half presents the proportion of participants who reported the kiosk’s misbehavior to the facilitator or on the survey. Security priming significantly increases reporting rate (chi-squared $p = 0.004$) but at the cost of a perceived decrease in system usability.

8. Limitations and Future Work

This section discusses limitations and areas for future work. Mitigating Real Credential Exposure. The TRIP registrar, which has access to voters’ real credential due to its issuance role, may cast real votes without voter consent. One potential solution is for the kiosk to produce not the voting credential itself but a single-use token that the VSD “spends” at activation time to create a fresh voting credential. The voter would know if this token has been spent before activation, and if not, only the VSD holds the private key for vote casting. Another solution might involve the VSD alerting the voter when a vote is cast with their credential, and the vote was not cast with this VSD.

Ledger Flooding Attack. The JCJ scheme is susceptible to a straightforward yet powerful denial-of-service attack where anyone, not just eligible voters, can flood the ledger with arbitrary ballots, thereby indefinitely extending vote tallying time [45]. With TRIP, the ledger could be configured to accept only votes cast with a kiosk-issued credential. Moreover, this enables talliers to pre-process ballots (e.g., select only the first or last ballot cast with the same credential) before running expensive tallying operations.

Electoral Roll Integrity Dilemma. Practically all electronic voting systems rely on electoral rolls for bootstrapping. In reality, electoral rolls are not necessarily accurate, revealing instances of millions of ghost and duplicate voters [3].
For transparency some countries have made their electoral rolls publicly available [2]. However, the disclosure of such information could lead to coercion and vote-buying, such as preventing voters from registering to vote or targeting voters in swing districts. Companies [59] and political parties [64] have also used this information to influence voters. Unfortunately, addressing this problem is challenging, seemingly requiring yet another delicate balance between transparency and resistance to undue influence.

9. Related Work

Voter registration is pivotal in upholding election legitimacy [46], yet prevailing coercion-resistant works concentrate on vote tallying [23, 66, 7, 12, 67, 52]. Only a few works have endeavored to enhance voter registration, specifically regarding the integrity of the real credential, given JCJ’s assumption of a trusted registrar. Civitas [23], for instance, distributes this trust among several registrars, while Krivoruchko’s work [46] moves this trust to the voter’s trusted device. We assess TRIP against these prior works by evaluating how each maintains the real credential’s integrity while resisting coercion during the credentialing phase.

In the benchmark JCJ scheme [43], besides the untappable channel needed between the voter and the registrar—a necessity in all coercion-resistant schemes—the registrar is trusted to maintain the integrity of the real credential. With TRIP, the paper-based workflow inside a private booth during in-person registration represents a realization of the JCJ untappable channel without the need of a trusted device.

The Civitas scheme ensures the integrity of the real credential by requiring voters to acquire a share of their real credential from each registrar they interact with (online and in-person [23, 55]). However, this approach raises several concerns. First, a trusted device seems to be the only practical method for voters to acquire these shares and reconstruct the real credential, as confirmed by subsequent works on Civitas that employ smart cards [56, 55, 30, 29]. These smart cards are also meant to satisfy another Civitas’ assumption: voters will not be coerced into revealing their private registration materials. However, if a voter can be coerced during the voting phase, what prevents a coercer from coercing them during the registration phase, i.e., taking the voter’s smart card and allowing its use only under the coercer’s supervision? TRIP, in contrast, physically separates each credential, thereby enabling voters to hide their real credential from coercers. Moreover, voters who do not have a device they can access or trust, can instead trust a third party such as a friend or family member to activate their real credential and cast votes on their behalf. Replicating this feature with one smart card per credential would be more costly both financially and environmentally, especially since the coercer can demand a certain number of credentials from the voter prior to registration. In addition, to render vote-buying essentially non-existent, a saturation of (fake) credentials in public circulation is necessary. Finally, although the issuance of the real credential is split among several registrars, a coerced voter must pick a teller whom they trust will not reveal their share of the real credential to their coercer. Given that voters typically have little acquaintance with each teller, determining who to trust poses a challenge for coerced voters. In TRIP, coerced voters avoid such a predicament: they know they must either trust the kiosk (and realistically the registrar) not to collude with their coercer or else comply with the coercer’s demands—a binary choice.

In Krivoruchko’s work [46], voters must generate their real credential, encrypt it, and then provide the encrypted version to the registrar. This process ensures that the registrar never obtains the real credential, eliminating the need for them to prove its integrity. Nevertheless, this approach has two shortcomings with respect to coercion-resistance: First, it requires voters to possess a trusted device during registration, which must have always been out of the coercer’s reach. Second, the scheme lacks a mechanism that proves to the registrar that the voter’s device knows the real credential from the encrypted version it submits to the registrar. This measure is essential to prevent situations where voters may have sold their voting rights by providing the registrar with an encrypted version of a real credential which they cannot access, and which actually belongs to a third-party.

Prior work has used interactive Zero-Knowledge Proofs (ZKPs) for receipt-free, voter-verifiable voting with Direct Recording Electronic (DRE) machines [54, 20]. In particular, Moran and Noar’s approach [16] relied on the DRE machine to preserve an opaque shield over part of the receipt and asked voters to enter random words as a challenge. In contrast, TRIP uses interactive ZKPs for voter registration and simplifies the process for users with a design that involves selecting an envelope and scanning its QR code. In TRIP, we do not consider necessary to shield the printed commitment from the voter’s view: it is not only hard to interpret or compute cryptographic functions but also hard to find the envelope from a large set that contains the challenge that fits the coercer’s demands without a forbidden device.

10. Conclusion

In this paper, we presented TRIP, a voter registration scheme tailored for coercion-resistant online voting systems using fake credentials. TRIP empowers voters to verify the integrity of their real credential, while also protecting them against coercion. To assess TRIP, we undertook a comprehensive security analysis, proving that TRIP satisfies iterative individual verifiability and coercion-resistance. Moreover, we conducted two preliminary studies with 77 participants to validate and improve our design as well as summarized key results from our larger study on TRIP usability [53]. We also outlined some avenues for future work: developing an extension to mitigate the exposure of the real credential, enhancing the JCJ voting and tallying scheme given the TRIP registration scheme, and opening

15To our knowledge, only an interactive zero-knowledge proof, conducted in-person and offline with the voter’s device, would sufficiently prove that the voter’s device has the real credential and is not being aided by a third party over the Internet who actually possesses the real credential.
Pandora’s box on the issue of preserving the integrity of the electoral roll. Lastly, we compared TRIP with the few existing related works [23, 46].

11. Acknowledgments

The authors would like to thank the E-Voting Group at Bern University of Applied Sciences, especially Rolf Haenni and Eric Dubuis, for their valuable feedback. This project was supported in part by the Fulbright U.S. Student Program, the Swiss Government Excellence Scholarships for Foreign Scholars, the armasuisse Science and Technology, the AXA Research Fund, and the US ONR grant N000141912361.

References

[1] Failure to Vote. Western Australian Electoral Commission.
[2] Open Election Data Initiative.
[3] 85 million fake or duplicate names on electoral rolls: EC, 2015.
[4] Protocol of the Swiss Post Voting System: Computational Proof of Complete Verifiability and Privacy. Technical Report 1.0.0, 2021.
[5] Dirk Achenbach, Carmen Kempka, Bernhard Löwe, and Jörn Müller-Quade. Improved coercion-resistant electronic elections through deniable re-voting. USENIX Journal of Election Technology and Systems (JETS), August 2015.
[6] Ben Adida. Helios: Web-based Open-Audit Voting. In USENIX Security Symposium, volume 17, pages 335–348, 2008.
[7] Roberto Araújo, Sébastien Fouille, and Jacques Traoré. A Practical and Secure Coercion-Resistant Scheme for Internet Voting. In Towards Trustworthy Elections: New Directions in Electronic Voting, pages 330–342. Springer, Berlin, Heidelberg, 2010.
[8] Aaron Bangor, Philip Kortum, and James Miller. Determining what individual SUS scores mean: Adding an adjective rating scale. Journal of Usability Studies, 4(3):114–123, 2009.
[9] Josh Benaloh. Verifiable Secret-Ballot Elections. Ph.D. Thesis, 1987.
[10] Josh Benaloh. Ballot Casting Assurance via Voter-Initiated Poll Station Auditing. In 2007 USENIX/Accurate Electronic Voting Technology Workshop, Boston, MA, August 2007.
[11] Josh Benaloh. Rethinking Voter Coercion: The Realities Imposed by Technology. USENIX Journal of Election Technology and Systems, 1(1), 2013.
[12] Josh Benaloh, Tal Moran, Lee Naish, Kim Ramchen, and Vanessa Teague. Shuffle-Sum: Coercion-Resistant Verifiable Tallying for STV Voting. IEEE Transactions on Information Forensics and Security, 4(4):685–698, December 2009.
[13] Josh Benaloh and Dwight Tuinstra. Receipt-free-secret-ballot elections. In Proceedings of the 26th annual ACM symposium on Theory of Computing, STOC ’94, pages 544–553, May 1994.
[14] David Bernhard, Véronique Cortier, Pierrick Gaudry, Mathieu Turuani, and Bogdan Warinschi. Verifiability Analysis of CHVote, 2018.
[15] David Bernhard, Oksana Kulyk, and Melanie Volkamer. Security Proofs for Participation Privacy, Receipt-Freeness and Ballot Privacy for the Helios Voting Scheme. In Proceedings of the 12th International Conference on Availability, Reliability and Security, 2017.
[16] Matthew Bernhard, Allison McDonald, Henry Meng, Jensen Hwa, Nakul Bajaj, Kevin Chang, and J. Alex Halderman. Can Voters Detect Malicious Manipulation of Ballot Marking Devices? In 2020 IEEE Symposium on Security and Privacy, pages 679–694, May 2020.
[17] John Brooke. SUS: A ‘Quick and Dirty’ Usability Scale. In Usability Evaluation In Industry, CRC Press, 1996.
[18] Miguel Carreras and Yasemin Iregoğlu. Trust in elections, vote buying, and turnout in Latin America. Electoral Studies, 32(4), 2013.
[19] Eleno Castro and Randy Kotti. Saving Democracy: Reducing Gang Influence on Political Elections in El Salvador. Master’s thesis, 2022.
[20] David Chaum. Secret-ballot receipts: True voter-verifiable elections. IEEE Security & Privacy, 2(1):38–47, January 2004.
[21] David Chaum and Torben Pyrs Pedersen. Wallet Databases withObservers. In Advances in Cryptology — CRYPTO’ 92, pages 89–105, Berlin, Heidelberg, 1993.
[22] David L. Chaum. Untraceable electronic mail, return addresses, and digital pseudonyms. Communications of the ACM, 24(2):84–90, 1981.
[23] Michael R. Clarkson, Stephen Chong, and Andrew C. Myers. Civitas: Toward a Secure Voting System. In 2008 IEEE Symposium on Security and Privacy, pages 354–368, May 2008.
[24] Véronique Cortier, David Galindo, Ralf Küsters, Johannes Müller, and Tomas Trudering. SoK: Verifiability Notions for E-Voting Protocols. In 2016 IEEE Symposium on Security and Privacy, 2016.
[25] Malcolm Crook and Tom Crook. Reforming Voting Practices In a Global Age: The Making and Remaking of the Modern Secret Ballot in Britain, France and the United States c. 1600—c. 1950. Past & Present, (212):199–237, 2011.
[26] Philip Daian, Tyler Kell, Ian Miers, and Ari Juels. On-Chain Vote Buying and the Rise of Dark DAOs, July 2018.
[27] Jason Daley. Lessons in the Decline of Democracy From the Ruined Roman Republic. Smithsonian Magazine, November 2018.
[28] Piret Ehin, Mihkel Solvak, Jan Willimson, and Priit Vinkel. Internet voting in Estonia 2005–2019: Evidence from eleven elections. Government Information Quarterly, 39(4):101718, October 2022.
[29] Ehsan Estaji, Thomas Haines, Kristian Gjøsteen, Peter B. Rønn, Peter Y. A. Ryan, and Najmeh Soroush. Revisiting Practical and Usable Coercion-Resistant Remote E-Voting. In E-Vote-ID 2020: Electronic Voting, pages 50–66, 2020.
[30] Christian Feier, Stephan Neumann, and Melanie Volkamer. Coercion-Resistant Internet Voting in Practice. In Informatik 2014, 2014.
[31] Dragan Filipovich, Miguel Niño-Zarazúa, and Alina Santillán Hernández. Voter coercion and pro-poor redistribution in rural Mexico. July 2021.
[32] David Froelicher, Patricia Egger, João Sá Sousa, Jean Louis Raison, Zhichong Huang, Christian Vincent Mouchet, Bryan Ford, and Jean-Pierre Hubaux. UnLynx: A Decentralized System for Privacy-Conscious Data Sharing. In Proceedings on Privacy Enhancing Technologies, volume 4, pages 152–170, 2017.
[33] Timothy Frye, Ora John Reuter, and David Szakonyi. Hitting Them With Carrots: Voter Intimidation and Vote Buying in Russia. British Journal of Political Science, 49(3):857–881, July 2019.
[34] Livia Gershon. Why Do We Vote by Secret Ballot? In Democratic Theory: An Introduction. Routledge, 2020.
[35] Ezequiel Gonzalez-Ocantos, Chad Kiewiet de Jonge, Carlos Meléndez, David Nickerson, and Javier Osorio. Carrots and sticks: The Influence on Political Elections in El Salvador. Master’s thesis, 2022.
[36] John Brooke. SUS: A ‘Quick and Dirty’ Usability Scale. In Usability Evaluation In Industry, CRC Press, 1996.
[37] Miguel Carreras and Yasemin Iregoğlu. Trust in elections, vote buying, and turnout in Latin America. Electoral Studies, 32(4), 2013.
[38] Eleno Castro and Randy Kotti. Saving Democracy: Reducing Gang Influence on Political Elections in El Salvador. Master’s thesis, 2022.
[39] David Chaum. Secret-ballot receipts: True voter-verifiable elections. IEEE Security & Privacy, 2(1):38–47, January 2004.
[40] David Chaum and Torben Pyrs Pedersen. Wallet Databases with Observers. In Advances in Cryptology — CRYPTO’ 92, pages 89–105, Berlin, Heidelberg, 1993.
[41] David L. Chaum. Untraceable electronic mail, return addresses, and digital pseudonyms. Communications of the ACM, 24(2):84–90, 1981.
[42] Michael R. Clarkson, Stephen Chong, and Andrew C. Myers. Civitas: Toward a Secure Voting System. In 2008 IEEE Symposium on Security and Privacy, pages 354–368, May 2008.
Appendix A.

TRIP Formal Function Definitions

This section contains the formal definitions of the internal TRIP functions (Fig. 9, Fig. 10, Fig. 11 & Fig. 12).
Consequently, during tallying, votes cast by these well-identical as if the voter had only a single real credential. This ensures the rest of the registration process is fake the kiosk then follow the key—instead of a new credential’s public key. The voter and well-known entities. If a voter decides to delegate their vote provide the kiosks with the names and public keys of these collaborate between the registration and tallying schemes. elaborate how vote-delegation could work, which requires voters to trust the registrar (kiosk), foregoing their known entity like a political party. However, this approach requires voters to a coercer, who might conduct a search post-registration. The printer noise might expose the quantity of each voter, a random, minimum number of fake credentials. Side Channels

The printer noise might expose the quantity of credentials created. To mitigate this, we suggest minimizing printer sounds using a low-noise printer or by relocating voters to a separate room. Additionally, introducing a noise simulation device might help mask the origin of the sound.

Appendix D.

Cryptographic Primitives

This section presents the primitives used in TRIP.

Distributed Key Generation Scheme. TRIP uses a distributed key generation protocol DKG [32] that takes in a group parameter \((G, q, g)—a cyclic group \(G\) of order \(q\) with generator \(g\)—and the number of parties \(n\) and creates a private key and public key pair for each party \((p_{sk_i}^{pk}, p_{sk_i}^{pk})\) and a collective public key \(p_{sk}^{pk}\):

\[
\{p_{sk}^{pk}, p_{sk_i}^{pk}\}, p_{sk}^{pk} \leftarrow DKG(G, p, q, n),
\]

such that \(p_{sk_i}^{pk} = g_i^{r_i}\), where \(p_{sk_i}^{pk} \leftarrow \mathbb{Z}_q\) and \(p_{sk}^{pk} = p_{sk_i}^{pk} + p_{sk_i}^{pk} + \cdots + p_{sk_n}^{pk}\).

M-ElGamal Encryption Scheme. TRIP employs the modified ElGamal (M-ElGamal) encryption scheme as defined in JCI [43]. This scheme is parameterized by a cyclic group \(G\) of prime order \(q\) and two distinct, random generators \(g_1, g_2\); and consists of the following algorithms: EG.KGen\((G, q, g_1, g_2)\) which takes as input the group definition and outputs a public key \(pk\) along with two private keys \(sk_1, sk_2\) such that \(pk = g_1^{sk_1} g_2^{sk_2}\) where \(sk_1, sk_2 \leftarrow \mathbb{Z}_q\); a randomized encryption algorithm \(EG.Enc(k, m)\) which inputs a public key \(pk\) and a message \(m \in \mathbb{G}\) and outputs a ciphertext \(C = (C_1, C_2, C_3) = (g_1^r, g_2^r, pk^rm)\) for \(r \leftarrow \mathbb{Z}_q\); and, a deterministic decryption algorithm \(EG.Dec(sk_1, sk_2, C)\) which takes as input two private keys \(sk_1, sk_2\) and a ciphertext \(C\) and outputs a message \(m = C_3(C_1^{sk_1} C_2^{sk_2})^{-1}\).

Signature Scheme. TRIP uses a EUF-CMA signature scheme defined by the following three algorithms: a randomized key generation algorithm \(Sig.KGen(\lambda)\) which takes
as input the security parameter and outputs a signing key pair \((sk, pk)\); a signature algorithm \(\text{Sig.Sign}(sk, m)\) which inputs a private key and a message \(m \in \{0, 1\}^\ast\) and outputs a signature \(\sigma\); a signature verification algorithm \(\text{Sig.Vf}(pk, m, \sigma)\) which outputs \(\top\) if \(\sigma\) is a valid signature of \(m\) and \(\bot\) otherwise; and, an algorithm \(\text{Sig.PubKey}(sk)\) that takes as input a private key and outputs the corresponding public key \(pk\).

**Hash.** TRIP utilizes a cryptographic secure hash function \(H\), for which the output is \(2\lambda\), for security parameter \(\lambda\).

**Message Authentication Code.** TRIP uses a message authentication code scheme defined by the following two algorithms: a probabilistic signing algorithm \(\text{MAC.Sign}(k, m)\) which takes as input a (secret) key \(k\) and a message \(m\) and outputs an authorization tag \(\tau\); and a deterministic verification algorithm \(\text{MAC.Vf}(k, m, \tau)\) which takes as input the (secret) key \(k\), the message \(m\) and the authorization tag \(\tau\) and outputs either \(\top\) for accept or \(\bot\) for reject.

**Zero-Knowledge Proof of Equality.** TRIP employs an interactive zero-knowledge proof of equality of discrete logarithms \([21]\) ZKPoE so that a prover \(P\) can convince a verifier \(V\) that \(P\) knows \(x\), given messages \(y \equiv g_1^x \pmod{p}\) and \(z \equiv g_2^x \pmod{p}\) without revealing \(x\). In interactive zero knowledge proofs, the verifier \(V\) must provide the challenge only after the prover \(P\) has computed and provided the commit to \(V\).

**Appendix E. Security Proofs**

We prove that TRIP satisfies coercion-resistance and individual verifiability, according to our definitions in §5. Tables 2 and 3 show our notation and summarize our variables.

**TRIP API.** We first redefine the TRIP API (Fig. 13), where algorithms append to a ledger instead of submitting to it. Since the registrar is either all malicious (integrity, privacy) or all honest for coercion, we denote \(R\) to represent the kiosks, registration officials and the envelope printers.

**E.1. Coercion-Resistance**

In this section, we prove that TRIP is coercion-resistant.

**JCJ E-Voting Scheme.** To demonstrate the coercion-resistant properties of TRIP, we need voting and tallying protocols. To do so, we will adopt those relevant protocols from the JCJ e-voting scheme, but we first provide an overview of the complete JCJ scheme for the reader’s understanding. Their scheme comprises four distinct phases: Setup, Voter Registration, Voting, and Tallying. During the setup phase, the system actors, including the talliers, the registrar, and the ledger, are established. In voter registration, eligible voters undergo authentication, receive their real credentials, and have their encrypted real credentials published on the ledger. During the voting phase, voters use their device to cast their vote which creates a 2-tuple ballot, including a fresh encryption of their real credential and the actual vote. This ballot is then published on the ledger. In the presence of coercion, voters use any freshly generated credential. During the tallying phase, the talliers verifiable shuffle the encrypted real credentials published by the registrar, and the encrypted 2-tuple ballots cast by each voter. Talliers then determine the actual ballots by conducting privacy equivalence tests \([39]\) between each encrypted real credential published by the registrar and the first element of each 2-tuple ballot on the ledger. Finally, the talliers work together to decrypt the votes and uncover the actual results.

**Definition 3 (Coercion-resistance).** A scheme is coercion-resistant if for all PPT adversaries \(C\), all security parameters \(\lambda \in \mathbb{N}\), and all parameters \(\mathbb{V}, \mathbb{R}, \mathbb{A}, M, n_C\), the following holds:

\[
\text{Adv}^{\text{coer}}_{\text{C-Resist}}(\lambda, \cdot) = \left| \Pr_{C}^{\text{C-Resist}}(\cdot) - \Pr_{C}^{\text{C-Resist-Ideal}}(\cdot) \right| \leq \negl(\lambda),
\]

where the probability is computed over all the random coins used by the algorithms in the scheme.

We introduce the following three major changes from JCJ games to model TRIP’s behavior.

**Change #1: Voter Registration Algorithms.** To model information beyond the credential (e.g., proofs of correctness), we replace JCJ algorithms register and fakecred, respectively. We also employ Activate to model additional registration data on the ledger.

Figure 13: TRIP API.
(e.g., envelope challenges). In our C-Resist games, Activate consistently returns output as T since the registrar R is trusted.

**Change #2: Fake Credentials Issuance.** In contrast to the JCI game where \(C\) has no influence over the voter before the voting phase, TRIP allows \(C\) to interact with voters before registration. Specifically, \(C\) can demand voters to generate \(n_f \in \mathbb{N}\) fake credentials during registration. We use the probability distribution \(D^f\) to model the uncertainty around fake credentials created and activated by honest voters.

**Change #3: Ledger Entries.** While JCI uses a trusted registration algorithm to generate a voting roster with each voter’s public credential \(c_{pc}\), TRIP incorporates a more complex protocol to achieve individual verifiability. Specifically, during Activate, the envelope challenge is disclosed on the envelope ledger, permitting the adversary to discern the total number of fake credentials created. Additionally, the registration ledger includes digital signatures from both the kiosk and officials responsible for issuing the voter’s credential. Despite these additions, we show that \(C\)’s winning probability is negligibly affected, outside of the added probability distribution of fake credentials represented in the ideal game. Similar to JCI, the winning probability of the ideal game is \(\gg 0\) as coercion-resistance is bounded by the adversary’s uncertainty over the behavior of honest voters.

We present our formal definition for coercion-resistance under Definition 3, and use the ideal (C-Resist-Ideal) and real (C-Resist) games in figures 6 and 14, respectively. The coercer wins if they can correctly guess the bit \(b\), representing whether or not the targeted voter gives in to coercion. While C-Resist represents the coercive adversary \(C\), to prove security we must compare \(C\) with another adversary \(C'\) who plays C-Resist-Ideal, which embodies the security we want to achieve against coercion. We show that the difference between the real and ideal games is negligible.

**Proof:** We use three hybrid games to transition from the real to the ideal game, with each game involving a protocol change.

1. **Eliminate Voting Ledger View:** Eliminate \(C\)’s access to the TRIP voting ledger \(L_V\), as \(C\) is incapable of differentiating between a ledger filled with honest voter ballots and a randomly generated set of ballots, assuming the decisional-Diffie-Hellman assumption holds.

2. **Number of Fake Credentials:** \(C\)’s ability to demand voters to create a specific number of fake credentials is equal to that of an adversary \(C'\) who cannot demand voters to create a specific number of fake credentials, given the distribution of the honest voters’ fake credentials.

3. **Eliminate Registration Ledger View:** Eliminate \(C\)’s access to TRIP roster \(L_R\) by introducing a new ledger \(L_R^j\) where we can decouple \(V_i^{\text{real}}\) and \((c_{pc}, K, \sigma, R, \sigma_j)\) via semantic security: \(L_R: (V_i^{\text{real}}, c_{pc}, K, \sigma, R, \sigma_j) \& L_R^j: (c_{pc})\)

**Hybrid 1.** We replace Tally (Fig. 14, l. 27) with Ideal-Tally (Fig. 6, l. 20) by proving that \(C\) has no longer access to \(L_V\). We use a simulation-based approach to show that if an adversary with access to \(L_V\) has a non-negligible advantage over an adversary who does not have access to \(L_V\), then the decisional-Diffie-Hellman assumption is broken. The simulator gets as input a tuple of group elements that are either a Diffie-Hellman tuple or uniformly random and must output a guess. It interacts with \(C\), simulates the honest parties of the protocol, and makes a guess based on its output.

The simulator then proceeds as follows:

1. **Setup:** Choose two group elements \(x_1, x_2\) uniformly at random and broadcast the public key \((g_1, g_2, g_1^{x_1}, g_2^{x_2})\). Broadcast a list of candidate identifiers \(\{M_i\}_{i=1}^{n_M}\) where each identifier is a random group element.

2. **Coin Flip:** Flip the coin \(b\).

3. **Adversarial Corruption:** The adversary chooses the set \(V_C\) of controlled voters and a target voter \(j\). For each controlled voter and the target voter, the adversary chooses the number of fake credentials \(n_f\) to create. For the target voter, \(C\) sets the target vote \(\beta\). If the number of controlled voters is not equal to \(n_C\), or \(j\) is not an appropriate index then the simulator aborts.

4. **Registration:** For each voter \(i\), the simulator runs the TRIP registration process while acting as the registrar. The simulator first issues each voter their real credential \(c_{pc}\) along with their public credential \(c_{pc}\). The simulator then continues with generating fake credentials for each group of voters. For each controlled voter \(i\) in \(V_C\), the simulator issues \(n_f\) fake credentials as specified by the adversary. For the target voter, if \(b = 0\), the simulator generates \(n_f + 1\) fake credentials for the target voter; otherwise, it generates \(n_f\) fake credentials. For each uncontrolled honest voter, the simulator creates...
fake credentials, for which the amount is sampled from a probability distribution that models the adversary’s knowledge of the number of fake credentials that these voters intend to create. Finally, the simulator carries out check-out for all voters.

5) **Credential Release:** The simulator gives $C$ the real and fake credentials of voters in $V_C$. If $b = 0$, the simulator gives $C$ the target voter’s $n_i^f + 1$ fake credentials; otherwise, the simulator gives $C$ the voter’s real credential and $n_i^f$ fake credentials.

6) **Honest Ballot Posting:** For each honest voter $i$, the simulator samples a random vote $\beta_i \leftarrow \mathcal{D}_{n_V-n_C-n_M}$ and posts a ballot for this vote on the voting ledger $L_V$. The simulator forms the ballot using the input $(g_1, g_2, h_1, h_2)$ as follows. The simulator generates two random group elements $r_i, k_i$. Next, the simulator computes the encryption of the public credential $c^i$ as $E_1 = (h_1^r, h_2^r, h_1^{z r_i} h_2^{z r_i} c^i)$, and the encryption of the vote as $E_2 = (h_1^k, h_2^k, h_1^{z k} h_2^{z k} \beta_i)$. This way, if the input is Diffie-Hellman, the result is a valid encryption, whereas if the input is random, the ballot is random and contains no information about the vote or the credential used to cast it. The simulator then simulates the required NIZK proofs using standard techniques.

7) **Adversarial Ballot Posting:** The adversary now posts a set of ballots onto $L$.

8) **Decryption of Ballots:** The simulator can now check the NIZK proofs and discard the ballots with incorrect proofs. Then, since the simulator plays the role of the honest talliers, it can decrypt the ballots to prepare for the tallying process.

9) **Tallying Simulation:** This is carried out as in JCJ’s simulator [42]. Namely, the simulator eliminates duplicates, mixes, removes fake votes and finally decrypts the remaining real votes:

- **Duplicate elimination:** The simulator removes duplicates.
- **Mixing:** To simulate the MixNets from the real tally protocol, the simulator outputs an equal-length list of random ciphertexts.
- **Credential Validity:** The simulator now checks, for each ballot, whether it was cast with a valid credential. This check is possible since the simulator can decrypt all the entries in $L_R$ and $L_V$.
- **Output final count:** The simulator can then use the decrypted values to compute the final tally and output it.

10) **Output Guess:** The simulator uses $C$’s output to make its guess about whether the input was a DDH triplet or a random triplet.

If we can show that $C$ has a non-negligible advantage in the real game over hybrid 1, then this implies that the simulator can break the DDH assumption. The key to this argument lies in how the simulator constructs the ballots in Step 6. When the input is DDH, where $h_1 = g_1^k$ and $h_2 = g_2^k$, we have $E_1 = (g_1^{a_i^r}, g_2^{a_i^r}, \tilde{g}_1, \tilde{g}_2^{a_i^r} c^i)$ which is a valid M-ElGamal encryption. The same holds for $E_2$, but with $k_i$ instead of $r_i$. Thus, when the input is DDH, the view of $C$ corresponds to the actual game and the adversary receives the contents of $L_V$. However, if the input tuple is a random one, then $E_1$ and $E_2$ are not valid M-ElGamal encryptions, but just random tuples. In this scenario, the vote and credential are perfectly concealed, making it equivalent to denying the adversary access to the ledger. Hence, if the adversary $C$ holds a significant advantage in the real game, then the probability that the simulator correctly guesses will also be significant, leading to a contradiction.

**Hybrid 2.** In this Hybrid, we demonstrate that the adversary’s ability to demand a specific number of fake credentials from voters is lost, as compared to Hybrid 1. Text In C-Resist (Fig. 14, l. 16 and 20), the voter gives their credentials to the adversary while in C-Resist-Ideal, the adversary always gets the voter’s single real credential. (Fig. 6, l. 17).

First, we show that real and fake credentials are indistinguishable: both real and fake credentials contain a ZKP transcript, although the ZKP transcript for the fake credentials are simulated. The zero-knowledge property of the proof system implies indistinguishability.

Next, from hybrid 1, $C$ does not get access to $L_V$, thus $C$ cannot use any real or fake credentials to cast valid ballots, or see ballots cast with these. As a result, since real and fake credentials are indistinguishable, always giving the adversary the real credential gives them no advantage since the credentials cannot influence the tally outcome with it. Now the value of $b$ only determines whether or not the target voter casts a ballot.

For the same reason, $C$ can only use the $n_f$ fake credentials for determining whether the target voter cast a ballot or not and to influence the number of envelope challenges on $L_E$.

Yet, the signing key pair $(\tilde{c}_sk, \tilde{c}_pk)$ corresponding to each fake credential is sampled independently from the real pair $(c_sk, c_pk)$, and these cannot be used by the adversary or the target voter to cast a valid vote. Regarding the number of challenges on $L_E$, the only difference in the case where the target voter resists coercion is that they create an additional fake credential. As a result, the number of challenges will only differ by one. To detect this, the adversary needs to distinguish between the following distributions:

- Number of envelope challenges when target complies:
  \[ n_C + n_T + n_H + n_f + D_{fake}^{C} \]
- Number of envelope challenges when target resists:
  \[ n_C + n_T + n_H + n_f + D_{fake}^{C} + 1 \]

Since everything but $D_f^{C}$ is known to the adversary, this is equivalent to just distinguishing between $D_{fake}^{C}$ and $D_{fake}^{C} + 1$, so they get no advantage from requesting a certain number of fake credentials. Therefore, the adversary does not gain an advantage from specifying the number of fake credentials, since these fake credentials will not help them identify whether the voter gave them a real credential.

**Hybrid 3.** In this hybrid, we replace the TRIP roster $L_R$ initialized on the first line of Figure 14 with the JCJ Roster $L'_R$ from the Ideal Game in Figure 6.
To prove that the advantage of the adversary is negligible between these hybrids, we show that given a JCJ roster, a simulator can output a TRIP roster that is indistinguishable from a real one. This is possible due to the semantic security of m-ElGamal.

We describe the simulator: **Input:** JCJ roster \( L_R \), List of voter IDs \( V_{id} \)
1) Create a kiosk key pair \((k, K)\) and a registrar key pair \((r, R)\). If there are multiple kiosks and registrars, these keys contain all the individual keys.
2) Initialize \( L'_{R} \) to contain each \( V_{id} \) in a different entry, along with a random timestamp \( d \).
3) Apply a random permutation to the JCJ roster.
4) Append one entry \( V_e \) of the JCJ roster to each entry of \( L'_{R} \).
5) For each entry, add the necessary signatures. First, use \( k \) to simulate the kiosk signature \( \sigma_k = \text{Sign}_k(V_{id}'||d||V_e) \) and append \( K, \sigma_k \) to the entry. Then, use \( r \) to simulate the registrar’s check-out signature \( \sigma_r = \text{Sign}_r(V_{id}'||d||V_e||\sigma_k) \) and append \( R, \sigma_r \) to the entry.
6) Output \((K, R, L'_{R})\). Recall that we consider a single logical entity for all the registration actors.

As stated earlier, \( L'_{R} \) is indistinguishable from a real TRIP roster for the same list of voters due to the semantic security of m-ElGamal. If we start with a real TRIP roster, we could create intermediate rosters by swapping two encryptions at a time and updating the digital signatures until we get a random permutation. Each of these swaps will yield indistinguishable rosters by the semantic security of m-ElGamal. At the end, the distribution will be the same as that of our simulator.

Recall that the view of \( C \) is the list of valid verification keys for the kiosks and registrars, along with the TRIP roster. Since we have shown that the additional elements contained in the TRIP roster but not in the JCJ roster can be simulated, this means that the advantage of \( A \) is negligible.

With this, we have reached the Ideal JCJ game and have thus shown that the advantage of \( A \) in the C-Resist game is negligible over the advantage in C-Resist-Ideal.

---

### E.2. Individual Verifiability

Our definition of verifiability builds on the work of the Swiss Post E-Voting System [4] and CH-Vote [14]. As is traditional with individual verifiability, their focus is on “voter receiving conclusive evidence that the vote has been cast and recorded as intended” [14]. However, since TRIP is a registration scheme, we define individual verifiability as

\[
\text{the voter receiving conclusive evidence that their voting credential is real},
\]

a prerequisite to voting. In (Fig. 7a, §5), we introduced our individual verifiability game IV. In the IV game, the adversary has partial control over the Setup and Register functions. For Setup, only the ledger needs to be honest. For Register, as shown in Fig. 15, the adversary controls the creation of real and fake credentials, but **does not** control the number fake credentials, \( n_f \), that the voter decides to create, nor the Activate process.

During the execution of the Register function, the voter conducts several checks, some of which are under adversarial control. To formally prove verifiability, we make these checks explicit: the voter interacts with the potentially malicious kiosk and produces explicit checks, denoted as check. Furthermore, in §5, we defined an inefficient extractor that, given the ledger, can extract either the plain real credential or the unencrypted ballot, mirroring the approach of Bernhard et al. [14]. The adversary succeeds only if all checks pass while the real credential is incorrect, or if the ledger does not contain the correct adversarially-selected vote \( s \).

**Theorem 4** (Individual verifiability of TRIP). Under the discrete-logarithm assumption in the random oracle model, for a PPT adversary \( I \), the following holds:

\[
\text{Adv}^I_{\text{IV}} = \Pr[I^T = 1] \leq \frac{E[r]}{n_c} \cdot \left( \frac{n_c - E[r]}{n_c - 1} \right)^{n_f} + \text{negl}(\lambda),
\]

where the probability is computed over all the random coins that the algorithms use and \( E \) is the set of envelopes produced by the adversary available to the voter, \( n_c \) is the number of envelopes \( |E| \), \( E[r] \) is the number of envelopes in \( E \) that contain the challenge \( r \), which is the challenge that the adversary guesses as the one that the voter picks during the real credential process, and \( n_f \) is the number of fake credentials that the voter creates and activates.

**Proof.** We give a sketch of the proof. The adversary’s winning probability depends on correctly guessing (1) the challenge that the voter picks to create the real credential, and (2) the number of fake credentials that the voter decides to creates. Let \( E \) be set of envelopes produced by the adversary available to the voter, \( n_c \) the cardinality of \( |E| \), \( E[e] \) the number of envelopes that contain the same challenge \( e \) in \( E \), \( E \) be the event “the adversary correctly guesses the voter’s chosen challenge for the real credential”, \( r \) be the challenge that the adversary guesses, and let \( F \) be the event “the voter does not pick the same challenge twice”.

---

**Register** \( (L, A_{pk}, A_{sk}, R_{pk}, V_j) \)

1. \( c, \text{check}_1, st_x \rightarrow I(st_x, L, A_{pk}, R_{pk}) \)
2. \( e \rightarrow \{c\} \) % List of credentials
3. \( e \rightarrow \{c[e]\} \) % List of used challenges
4. \( n_f \rightarrow V() \) % Voter decides on # fake credentials
5. \( 5: \text{for } i \text{ to } n_f \text{ do} \)
6. \( \tilde{c}, st_x \rightarrow I(st_x, t_{ax}) \)
7. \( c \leftarrow \tilde{c}, e \leftarrow \tilde{c}[e] \)
8. \( \text{endfor} \)
9. \( c_o \leftarrow V() \)
10. \( L, \text{check}_2 \leftarrow I(st_x, L, c_o[t_{on}]) \)
11. \( \text{for } i \text{ to } n_f + 1 \text{ do} \)
12. \( L, \text{check}_3, i \leftarrow \text{Activate}(L, V, c_o) \)
13. \( \text{return } c \)

**Figure 15: Register function.**
Then the advantage of the integrity adversary \( I \) is

\[
\text{Adv}^\text{IV}_I = \Pr[I|\text{IV}^I = 1] = \Pr[E] \cdot \Pr[F] + \negl(\lambda)
\]

\[
= \frac{E[r]}{n_e} \cdot \Pr[F] + \negl(\lambda) \leq \frac{E[r]}{n_e} \cdot \left(\frac{n_e - E[r]}{n_f}\right)^{n_f} + \negl(\lambda),
\]

where the last inequality follows from the adversary’s optimal strategy to maximize \( \Pr[F] \). The optimal strategy involves duplicating envelopes with the same challenge \( r \), while ensuring the remaining envelopes contain unique challenges. As shown in §6, this increases the probability of a voter selecting the adversary’s chosen challenge \( r \) but, to the adversary’s disadvantage, this also increases the probability that a voter selects another envelope with the same challenge \( r \) during the creation of fake credentials. If the voter picks an envelope containing a different challenge than \( r \) for the real credential creation process, then Activate returns check = false as the ZKP verifier returns false (Fig. 12, line 7). If the voter leaves with two or more envelopes with the same challenge, then Activate returns check = false during the activation of the second envelope (Fig. 12, line 10). We derive the adversary’s winning probability with the best strategy as follows:

\[
\text{Adv}^\text{IV}_I = \Pr[I|\text{IV}^I = 1]
\]

\[
= \frac{E[r]}{n_e} \cdot \frac{n_e - E[r]}{n_e - 1} \cdot \frac{n_e - E[r]}{n_e - 2} \cdot \frac{n_e - 3}{n_e - 2} \cdot \cdots
\]

\[
= \frac{E[r]}{n_e} \cdot \frac{n_e - E[r]}{n_e - 1} \cdot \frac{n_e - E[r] - 1}{n_e - 2} \cdot \frac{n_e - E[r] - 1 - 1}{n_e - 3} \cdot \cdots
\]

\[
\leq \left(\frac{E[r]}{n_e} \cdot \frac{n_e - E[r]}{n_e - 1}\right) \cdot \prod_{i=1}^{n_f} \frac{n_e - E[r] - i + 1}{n_e - i}
\]

\[
= \frac{E[r]}{n_e} \cdot \left(\frac{n_e - E[r]}{n_f}\right)^{n_f}
\]

\[
\leq \frac{E[r]}{n_e} \cdot \left(\frac{n_e - E[r]}{n_f}\right)^{n_f} \cdot \left(\frac{n_e - 1}{n_f}\right)^{-n_f}
\]

\[
= \frac{E[r]}{n_e} \cdot \left(\frac{n_e - E[r]}{n_e - 1}\right)^{n_f}
\]

The inequality marked with (a) follows from the observation that if the number of fake credentials \( n_f \) is bigger than the remaining unique challenges \( n_e - E[r] \) the adversary loses because of the check in the Activate procedure. If \( n_f = 0 \), then the right hand side returns 1, leaving \( \frac{E[r]}{n_e} \). \( \square \)

Individual verifiability does not achieve a negligible advantage against the integrity adversary since we cannot use \( n_f \) as a security parameter (i.e., expect each voter to create 128 or 256 credentials). Many individual verifiability schemes [47] based on [10], have the same issue: they rely on the voter repeating a task multiple times to achieve negligibility as the audited ballot cannot be cast. Instead, we achieve negligible advantage when considering the combined probability across voter registration sessions. To this end, we introduce iterative individual verifiability in Fig. 7b, which is parametrized by a security parameter \( \lambda \), indicating the minimum number of votes that the adversary must change to sway the final outcome of an election.

**Theorem 5** (Iterative individual verifiability of TRIP). Assume that all the cryptographic primitives that TRIP uses are secure. Under the discrete-logarithm assumption in the random oracle model, for a PPT adversary \( I \), the following holds:

\[
\text{Adv}^\text{IV}_I = \Pr[I|\text{IV}^I = 1] \leq \negl(\lambda),
\]

where the probability is computed over all the random coins that the algorithms use.

**Proof.** We give a sketch of the proof. In order to win the IV game, the adversary \( I \) must win at least \( \lambda \) times the IV game of Fig. 7a. The theorem follows. \( \square \)