Finding Safety in Numbers
with Secure Allegation Escrows

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Abstract—For fear of retribution, the victim of a crime may be willing to report it only if other victims of the same perpetrator also step forward. Common examples include 1) identifying oneself as the victim of sexual harassment, especially by a person in a position of authority or 2) accusing an influential politician, an authoritarian government, or ones own employer of corruption. To handle such situations, legal literature has proposed the concept of an allegation escrow: a neutral third-party that collects allegations anonymously, matches them against each other, and de-anonymizes allegers only after de-anonymity thresholds (in terms of number of co-alleegers), pre-specified by the allegers, are reached.

An allegation escrow can be realized as a single trusted third party; however, this party must be trusted to keep the identity of the allegers and content of the allegations private. To address this problem, this paper introduces Secure Allegation Escrows (SAE, pronounced “say”). A SAE is a group of parties with independent interests and motives, acting jointly as an escrow for collecting allegations from individuals, matching the allegations, and de-anonymizing the allegations when designated thresholds are reached. By design, SAEs provide a very strong property: No less than a majority of parties constituting a SAE can de-anonymize or disclose the content of an allegation without a sufficient number of matching allegations (even in collusion with any number of other allegers). Once a sufficient number of matching allegations exist, the join escrow discloses the allegations with the allegers’ identities. We describe how SAEs may be implemented as a single trusted third party; particularly those involving sexual harassment, the survivor may not report the crime anticipating negative social consequences or further harassment by the perpetrator. In such situations, the victim (or the witness) may find it easier to act against the perpetrator if others also accuse the perpetrator of similar crimes. Examples of this abound, a notable example being the recent #MeToo movement [1], which led to many public allegations of sexual abuse in the US film industry and elsewhere, all triggered by the courage of an initial few.

An allegation escrow aids such collective allegations, by matching allegations against a common perpetrator confidentially. Technically, an allegation escrow allows a victim or witness of a crime to file a confidential allegation, which is to be released to a designated authority once a pre-defined number of matching allegations against the same party have been filed. The identities of the accusers and the accused, as well as the content of the allegation, remain confidential until the release condition holds.

Besides helping fearful victims to report crimes (safe in the knowledge that their allegation will be revealed only as part of a larger group), allegation escrows help improve reporting in cases where the victim is uncertain if the perpetrator’s actions constitute a crime. Escrowed allegations also enjoy higher credibility since, to all appearances, they are filed independently of each other (as opposed to public allegations, where the credibility of subsequent allegations may be questioned). In technical terms, allegation escrows have been shown to mitigate the first-mover disadvantage that perpetrators typically benefit from [2].

Project Callisto [3] is an allegation escrow system that has been deployed in 13 universities with over 100k students, to help report sexual assault on university campuses. A victim can instruct the system to release the allegation only when another allegation against the same person exists. Sexual assault survivors who visit the Callisto website of their university are 5 times more likely to report the crime than those who do not, and Callisto has reduced the average time taken by a student to report an assault from 11 to 4 months [2]. This makes a very strong case for the usefulness of allegation escrows.

However, existing allegation escrows such as Project Callisto are implemented as a single trusted third-party, similar to ombuds-offices in many organizations. Although technically simple and effective in many cases, the use of a single party may raise concerns about the escrow’s trustworthiness, impartiality and fallibility to influential perpetrators, thus driving away potential users. In the case of a university or corporate escrow (e.g. an ombuds-office), students or employees may be unsure that an allegation against a high-ranking official would be treated with integrity. A commercial escrow may raise concerns about its independence from funding sources and long-term security, just as a government-run escrow may raise concerns about its independence from high-ups in law enforcement and the judiciary. In all these cases, users may not trust the escrow enough to file allegations against people they deem to have the power to coerce or compromise the escrow. When they do file allegations, strong perpetrators may actually abuse their power to prematurely discover escrowed allegations, suppress and alter the allegations, or even seek retribution against the victims. Finally, even if one victim trusts an escrow, other victims of the same perpetrator may not, making it impossible for the escrow to match their allegations. This suggests the need for allegation escrows based on several independent parties, none of which in itself is a single point of coercion or attack by strong adversaries.

In this paper, we present a cryptographic design of such escrows.
A. Contributions

Our escrows, called SAEs (short for Secure Allegation Escrows), distribute client secrets—confidential allegations and identities of the allegor and accused—among several parties by threshold secret-sharing [36]. These parties, called escrows, act together and perform multi-party computations (MPCs) to provide the same functionality as a single-party allegation escrow, but compromising less than half of the escrows provides no information about escrowed allegations, accusers or the accused. The escrows can span diverse administrative, political and geographic domains, mitigating the chances of simultaneous attacks over a majority by the same adversary. To enable SAE, we make three key technical contributions.

First, SAE needs to provide a strong accountability property: Every filed allegation can be linked to a real-world (strong) identity, which is revealed to the concerned authority once the allegation has found enough matches. This discourages fake allegations and probing attacks all allegation escrows are susceptible to (see § II-A). Simultaneously providing accountability and privacy requires a non-trivial authentication protocol (see § IV-C). When filing an allegation, no minority of escrows learn the identity of the filing user. But when the allegation is to be revealed, a majority can determine the identity.

Second, we need to efficiently match allegations to each other, even when each escrow only has shares of the allegations, while providing accountability. For this, we use a novel construction of distributed (verifiable) pseudorandom functions (DVRFs) over shared secrets. This is necessary, since traditional Oblivious PRFs will not provide accountability (see § II-B).

Third, SAE allows each allegor to decide their reveal threshold; how many matching allegations must be available before their allegation may be revealed. A set of matching allegations, \( A \), is revealed if and only if all their thresholds are \( \leq |A| \). For instance, if three matching allegations with thresholds \( \{2,3,5\} \) are filed, no allegation should be revealed, since 5’s threshold isn’t met. But if another allegation with threshold 3 is filed, then the ones with thresholds \( \{2,3,3\} \) (but not 5) should be revealed. We design a novel bucketing algorithm to support reveal thresholds \( > 2 \) efficiently (see § IV-D2).

This flexibility is important since one size doesn’t fit all. In many cases of sexual misconduct, a small threshold is desired to maximize the probability of a match; indeed Project Callisto which always uses a threshold of two—where an allegation is revealed if another matching one is filed—has demonstrated real-world utility. However, when the perpetrator is powerful, such as an influential politician, allegors may need many more corroborators to get justice while avoiding adverse consequences for themselves. Similarly, when accusing one’s employer (or government) of misconduct or corruption, a person risks getting fired or persecuted. Having just 1 or 2 corroborators may not be much better than being alone. A threshold of 50 (or even 500 or 5000) could be more appropriate. SAE’s flexibility allows each allegor to tailor the reveal threshold to the semantics of their allegation.

We formally prove the end-to-end security of our SAE cryptographic design in the universal composability (UC) framework [10]. Specifically, we present an ideal functionality which, by definition, captures the expected security and accountability properties of a SAE, and then show that our cryptographic design realizes this functionality. We also implement a prototype of SAE to understand the latency and throughput of the system. We find that our design is efficient enough for typical use-conditions of allegation escrows.

To summarize, the contributions of our work are: 1) The concept of SAE, a distributed allegation escrow, that is robust to compromise or coercion of minority subsets of constituting parties. 2) A cryptographic realization of SAEs using verifiable secret sharing (VSS) and efficient multi-party computation (MPC) protocols. In particular, new protocols for user authentication, matching and bucketing allegations. 3) A formal security analysis of our cryptographic realization. 4) A prototype implementation and empirical evidence of reasonable performance in practice.

B. Related Work

Ayres and Unkovic [4] discuss the legal and social utility of allegation escrows in encouraging reporting of sexual misconduct. As discussed, Project Callisto [3] is a real deployment that uses a single trusted-party escrow for allegations of sexual misconduct, and has demonstrated the utility of such a system in university settings. WhoToo [31] is a recent work that proposes a secure allegation escrow for allegations of sexual misconduct. Like SAE, it distributes trust among multiple parties using MPC. SAE differs from WhoToo in two key ways. First, WhoToo forces all allegations to use a global pre-determined reveal threshold. As discussed above, this inflexibility limits its scope of application. To our knowledge, SAE is the first system to allow each allegation to have its own reveal threshold.

Second, if there are \( N \) allegations already in the system, to file the \( (N + 1) \)th allegation, WhoToo needs to perform \( O\left(\frac{N}{2}\right) \) cryptographic operations, including \( O\left(\frac{N}{2}\right) \) multi-party computations. SAE is more scalable. Its running time is \( O(1) \), independent of the number of pre-existing allegations. We compare the compute complexity in detail in section § IV-E. To obtain such efficiency, SAE sometimes reveals which allegations match which others, before their thresholds are met. Nevertheless, an adversary is unlikely to be able to exploit this (see § IV-D2).

Project Callisto has also developed a prototype cryptographic solution to distribute the trust assumptions [35], [34]. It uses a (potentially distributed) Oblivious PRF (OPRF) server. Allegors can query the server to learn the (deterministic) PRF of the accused’s identity, while the server just learns the allegor’s identity (not the accused’s). The allegor uploads the PRF to a database server, which compares them, in clear-text, to match allegations. Callisto’s security analysis is informal and has a weaker threat model that admits two attacks.

First, the OPRF server learns the allegor’s identity. If a perpetrator compromises this server and learns that one of their victims filed an allegation soon after the crime, they may be able to deduce the probable content of the allegation. By contrast, in SAE, no minority set of escrows learn the identity of any allegor until enough matches are found.

Second, it doesn’t hold allegors accountable, which allows the adversary to probe how many allegations exist against a given person. They may then guess who filed the allegation from context. To mount the attack, they query the OPRF server to learn the PRF of that person’s identity, and compromise the database server to learn how many previously filed allegations match this PRF. SAE prevents this attack by ensuring that if a PRF of an accused’s identity is computed, the identity of the allegor is irrevocably tied to the allegation. This enforces accountability and disincentivizes such attacks (see § II-A).
**Trusted Hardware.** In recent work, Harnik et al. [26] use a hardware-backed secure enclave (built on Intel SGX) to isolate a fully autonomous, single-party allegation escrow. The ideas can be combined with SAE to obtain a threat model stronger than either: SAE’s escrows can be hosted in SGX enclaves to provide a second line of defense even when the administrators of a majority of escrows are acting maliciously.

**Generic MPC and Covert Computation.** Generic black-box MPC can also be used to solve the problem. However, like WhoToo, it too incurs at least $O(N)$ cost per allegation, and doesn’t scale. Like covert computation [11, 38], SAE hides even the participation of a user in the protocol, revealing the result only if a pre-defined condition is met. However, black-box covert protocols don’t scale well to large numbers of users, and require users to be online for matching to occur.

### II. SAE Design

#### A. Requirements for Secure Allegation Escrow

A private allegation escrow system should provide the following security and privacy properties:
- **Allegation secrecy.** The escrow should hold each allegation secret until enough matches are found. An allegation should be released only as part of a group of matching allegations.
- **Alleger anonymity.** Similarly, the escrow should hold each alleger’s identity secret until enough matches are found.
- **Scalability.** The escrow should scale to many allegers and allegations. In section [IV-D] we discuss why scalability 1) helps avoid crippling DoS attacks, 2) increases probability of a correct match and, 3) enhances privacy by preventing timing side-channel attacks.
- **Accountability.** Each allegation is bound to a strong, real-world identity. Once a match is found, the real identities of the matched allegers are revealed to the designated authority. Accountability discourages fake/bogus allegations, and acknowledges that the primary source of authenticity of an allegation, escrowed or otherwise, is the human backing it.

All allegation escrows (not just SAEs) are fundamentally vulnerable to probing attacks where the adversary files fake probe allegations against itself in the hope of revealing other genuine allegations before sufficiently many genuine matching allegations have been filed. E.g. the adversary may be a guilty perpetrator seeking vengeance or a troll/journalist seeking a story. While the ultimate defense against such attacks lies in preventing this kind of abuse by non-technical means (e.g., by criminalizing probe allegations), SAEs aid such defenses through the property of accountability, which ensures that the real-world identities of all allegers, including fake allegers, are revealed to the designated authority after a match. For this to work, we assume the adversary is afraid of law and/or public perception.

Accountability doesn’t deter an adversary who knows their allegation (and hence identity) will never be revealed, perhaps because their reveal threshold is too high or their allegation is unlikely to match any others. We ensure a probe is useful for discovering the presence of only those allegations, that would be revealed at the same time as the probe itself (see [IV-D2]). Hence the probe is just as likely to be revealed as the victim allegation.

Additionally, allegation escrows are most useful in asymmetric situations, where individual allegers are at a disadvantage compared to the accused. Allegation escrows enable the allegers to build “strength in numbers” without fear of premature retaliation. However, the very information held by allegation escrows motivate powerful attacks against them, since the accused can gain by learning about allegers before a large enough group has formed. Thus, allegation escrows should expect to be a targeted. This leads to the following meta-property, that spans the previous properties.
- **Robustness.** The escrow should resist coercion and compromise attacks. It should continue to provide the properties above even if some constituent parts are compromised or willingly cooperate with the adversary.

#### B. Threat model and assumptions

A SAE adversary is interested in prematurely learning the identities of one or more allegers or discovering unrevealed allegations. For instance, the adversary may be a guilty perpetrator, interested in determining whether there is any allegation against them. Or, they may be journalists/trolls looking for a story against a famous person. To this end, an adversary may actively compromise some escrows into revealing information they hold and/or not following the SAE protocol correctly. By design, SAEs are robust to such attacks on up to half the escrows simultaneously: allegation secrecy, alleger anonymity, scalability and accountability hold even if the adversary learns all cryptographic and allegation-related material possessed by up to half the escrows, and causes them to behave arbitrarily. Moreover, we expect the compromised escrows to be maliciously but cautious; i.e., we expect the SAE protocol to catch any malicious behaviour, ensuring that the compromised nodes continue to follow protocol (say, to avoid detection and removal by the honest majority) and SAE remains live—it continues to offer the expected functionality.

We make the standard assumption that the adversary cannot break cryptography. Technically, the adversary is a probabilistic polynomial time (PPT) algorithm with respect to a chosen security parameter $\lambda$. We assume, as usual, that uncompromised parties (escrows and allegers) keep their long-term secrets safe.

For alleger anonymity, we assume that allegers do not reveal any information beyond that explicitly mentioned in our protocols. For example, they should hide their IP addresses using standard network anonymity solutions like Tor [19]. To ensure the time of allegation filing doesn’t reveal extra information, honest escrows regularly file ‘garbage’ allegations at random times. These are indistinguishable from genuine allegations, and hence serve to hide them. SAE’s scalability ensures that this doesn’t hurt performance significantly.

#### C. Protocol Overview

Figure 1 shows high-level protocol flow for the SAE protocol. We describe the individual protocols for each of these stages in [IV].

**Registration.** SAE uses real-world (strong) identities to ensure accountability. Prior to registering with SAE, a user proves their real identity to a certifying authority (CA) and gets its signature on their public key. The CA may be the user’s employer or university registering all its employees and students into the system, or even an independent entity verifying physical identities like passports.

To register with a SAE, the user authenticates to all escrows using the CA certificate. The escrows and the user then run a cryptographic
protocol during which the user gets authentication tokens (in particular, MACs) on a fixed number \( l \) of fresh public keys. Each of these \( l \) keys can be used once to file an allegation. Importantly, the escrows only learn individual *shares* of these keys, but neither the full keys, nor the MACs on them. This prevents the escrows from learning the identity of a user when the user files an allegation later, but allows a majority of escrows to reconstruct the identity (by pooling their shares of the public key) when an allegation has to be revealed.

For their own benefit, users should register ahead of time, even when they see no need to file an allegation. This prevents timing correlation channels. For example, if an accused is expecting an allegation due to a recent incident, and colludes with a escrow, then the act of registration by the potential alleger may provide a strong hint of a pending allegation. Ahead of time registration removes this channel of inference and could be enforced, for instance, by a company asking its employees to register with an allegation escrow service as soon as they join the company.

**Allegation filing.** When the user wants to file an allegation, they contact the escrows, providing one of the \( l \) public keys and the MAC on it, which the escrows can verify. The verification tells each escrow that this user has registered before, but doesn’t reveal the identity of the user, since no escrow has seen these in cleartext before. After this, the user provides the allegation’s text along with some meta-data in a specific cryptographic form, and a *reveal threshold*—the minimum number of allegations that must match before this one is revealed.

**Matching, thresholding and revelation.** The material provided with each allegation is fed into a novel matching and bucketing algorithm. This algorithm matches allegations to each other. As soon as a set \( A \) of matching allegations, each with a reveal threshold \( \leq |A| \) (the size of \( A \)), is found, they are revealed to a designated authority for further action. The revelation contains the real identities of the allegers and the full texts of their allegations. The designated authority can then take appropriate action.

### III. Threshold Cryptographic Tools

In this section, we present threshold cryptographic protocols that we use in SAE. We first describe the necessary threshold primitives, and then design the required distributed versions of the signing and private matching protocols.

#### A. Multi-Party Computation

An MPC protocol enables a set of parties \( \{P_1, P_2, \ldots, P_n\} \) to jointly compute a function on their private inputs in a privacy-preserving manner [31, 12, 7, 25]. More formally, every party \( P_i \) holds a secret input value \( x_i \), and \( P_1, \ldots, P_n \) agree on some function \( f \) that takes \( n \) inputs and provide \( y = f(x_1, \ldots, x_n) \) to a recipient while making sure that the following two conditions are satisfied: (i) **Correctness:** the correct value of \( y \) is computed; (ii) **Secrecy:** the output \( y \) is the only new information that is released to the recipient.

An \( (n,f) \) Shamir secret sharing [36] allows a dealer to distribute shares of a secret among \( n \) parties \( \{P_1, \ldots, P_n\} \) such that any number set of \( \leq f \) shares reveals no information about the secret itself, while an arbitrary subset of shares larger than \( f \) allows full reconstruction of the shared secret. Since in some secret sharing applications the dealer may benefit from behaving maliciously, parties also require a mechanism to confirm that each \( f + 1 \) subset of shares combine to form the same value. To solve this problem, Chor et al. [13]
introduced verifiability in secret sharing, which led to the concept of 

\textit{verifiable secret sharing (VSS)} \cite{23, 20, 24, 6}.

In our construction we use the MPC protocol by Gennaro et al. \cite{23}. It uses VSS, where Pedersen commitments \cite{23} on the Shamir shares are provided to all parties. It works on secrets in a prime-order ring $\mathbb{Z}_q$ and a multiplicative group $G$ of order $q$ of size linear in the security parameter $\lambda$.

\section{MPC Tools and Notation}

\textbf{VSS and MPC Notation.} We denote the $n$ shares of a secret value $s$ by the set $[s] = \{[s]_1, \ldots, [s]_n\}$, where $[s]_j$ represents the VSS share of party $P_j$. In SAEs, we use $n = 2f + 1$.

As the employed VSS protocol is additively homomorphic, operations $[[x_1 + x_2]]_j = [[x_1]]_j + [[x_2]]_j$, and $[[c \cdot x]]_j = [c] [[x]]_j$ for a known constant $c \in \mathbb{Z}_q$ can be computed by each $P_j$ locally using her shares $[[x_1]]_j, [[x_2]]_j$. The computation of $[[x]]_j$ from given $[[x]]_j, [[y]]_j$ is an interactive process and requires cooperation from $2f + 1$ parties \cite{24}. This protocol has identifiable abort \cite{27} and can identify which the non-cooperating parties (if any) are; thus, a malicious-but-cautious party will always cooperate. We formalize identifiable abort as $\text{IdentifiableAbort}(i)$, where $i$ indicates that $P_i$ either offered wrong or no input.

Given threshold addition and multiplication, we can efficiently perform some additional operations. In the following, we list the employed VSS and MPC operations. These functions are cooperatively called by each escrow with their share of the inputs. When enough escrows cooperate, the functions return their values.

- $\text{VSS}(x)$: Verifiably secret share $x$ among all the escrows such that $f+1$ of them can reconstruct $x$, but no fewer can \cite{24}. In SAE, $f = \lceil (n+1)/2 \rceil$.
- $\text{COMBINE SHARES}([x])$: Broadcast $[x]$; gather shares from other $\geq f + 1$ parties, and reconstruct the secret $x \in \mathbb{Z}_q$ if at least $f + 1$ honest shares are available.
- $\text{RANDOM COIN TOSSED}(j)$: Return a share $[r]_j$ of $r \in \mathbb{Z}_q$ chosen uniformly at random using distributed key generation \cite{23, 29}.
- $\text{PUBLIC EXPONENTIATE}(g, [x], \text{recipients})$: Compute $g^x$, where $x$ is secret-shared and $g \in G$ or $g \in G_\ell$ are publicly known generators of bilinear groups (see \appendix{A}). The result is revealed as clear-text only to recipients, which is a set of parties. In our protocol, recipients is either a given client or the set of all the escrows. This operation can be done efficiently with interaction since the result is revealed in the clear, not in secret shared form.
- $\text{DVRF}([[SK]], [x], \text{flag proof, recipients})$: Return the VRF $F_{SK}(x)$ to recipients (see \appendix{F}). If flag proof is true, also return the proof $\pi_{SK}(x)$, along with the VRF.
- $\text{VERIFY VRF}(PK, \pi, x)$: Verify that $\pi = \pi_{SK}(x)$, where $SK$ is the secret key of the VRF (see \appendix{F}) corresponding to $PK$. Unlike above, this function can be executed locally by each escrow without interaction.

\section{Distributed Verifiable Pseudorandom Functions (DVRFs)}

\textbf{VRFs.} A verifiable pseudo-random function is a pseudo-random function $F_{SK}(x)$, along with a proof function $\pi_{SK}(x)$. A PPT adversary cannot distinguish $F_{SK}(x)$ from a random function if it doesn’t have access to $SK$ or $\pi_{SK}(x)$. However, given $\pi_{SK}(x)$ and a public key $PK$, a PPT can verify that $F_{SK}(x)$ was computed correctly. The formal definition of VRFs is given in \appendix{A}.

In SAE, we need to compute VRFs in a multi-party computation where both the key and the input values are available in a secret shared form. Any VRF scheme can be transformed using general purpose MPC to work with shared key and shared input tags. However, keeping efficiency and practicality in mind, we choose a VRF construction by Dodis and Yampolskiy from \cite{19}.

In this construction, if a Decisional Bilinear Diffie Hellman Inversion (q-DBDHI) assumption holds in a bilinear group $G$ with generator $g$ (see \appendix{A}), then $F_{SK}(x) = e(g, g)^{1/(x+SK)}$ (1) is a PRF. When coupled with a proof $\pi_{SK}(x) = g^{1/(x+SK)}$, it is a VRF. Here, $SK$ is a private key chosen randomly from $\mathbb{Z}_q$, and $PK = g^{SK}$. To verify whether $y = F_{SK}(x)$, we can test whether $e(g^y, PK, \pi) = e(g, g)$ and whether $y = e(g, \pi)$.

\textbf{Distributed Input VRF.} We need a distributed protocol for computing a VRF. However, we could use distributed VRF (DVRF) schemes in \cite{9, 32, 8} as, in SAE, the VRF computing parties (the escrows) know the input only in a secret-shared form (this will become clear in \appendix{IV}). So, we design a DVRF with secret-shared (or distributed) input messages. Our construction may be of independent interest to other distributed security systems.

A set of $2f + 1$ escrows can efficiently compute $F_{SK}(x)$ or $\pi_{SK}(x)$ if each has a share of $x$ and $SK$ as shown in Algorithm 1. Here the result is sent only to recipients (either all-escrows or the given client). If flag proof is false, DVRF computes $F_{SK}(x) = e(g, g)^{1/(x+SK)}$. Else, it computes $\pi_{SK}(x) = g^{1/(x+SK)}$. $g \in G$ is a group generator. Given $\pi_{SK}(x)$, the recipient can compute $F_{SK}(x) = e(\pi_{SK}(x), g)$. If an escrow refuses to cooperate, the other escrows can determine the identity of the corrupted escrow.

\begin{algorithm}
\caption{Efficient MPC algorithm to compute DVRFs.}
\begin{algorithmic}
\Function{DVRF}{$[SK], [x], \text{flag proof, recipients}$}
\State $[t_1] \leftarrow [SK] + [x]$
\State $[\text{blind}] \leftarrow \text{RANDOM COIN TOSSED}()$
\State $[[t_2], \text{Identifiable Abort}(i)] \leftarrow [[t_1] * \text{[blind]}$
\State $\exp \leftarrow \text{COMBINE SHARES}([t_2])$
\If {flag proof = True}
\State $\text{PUBLIC EXPONENTIATE}(g, \exp, \text{recipients})$
\Else
\State $\text{PUBLIC EXPONENTIATE}(e(g, g), \exp, \text{recipients})$
\EndIf
\EndFunction
\end{algorithmic}
\end{algorithm}

Algorithm 1 first inverts $[[x]] + [[SK]]$ which takes two multiplications, and then exponentiates it. The only values available in clear-text (i.e., not information-theoretically hidden by the secret sharing) are $t_2$ and the final output. $t_2$ is uniformly distributed and independent of the input, since it is blinded. Hence this algorithm does not reveal any information about the inputs beyond what is revealed by the output.
IV. SAE Construction

In this section, we present the detailed cryptographic protocols we use to implement a secure allegation escrow. A formal summary of the protocol is given in Figure 8.

A. Format of an Allegation

An allegation escrow must have some mechanism to determine whether or not two allegations match. To allow this, along with free-form text describing their allegation, allegers provide structured meta-data describing the allegation. Escrows deem that two allegations match if their meta-data are identical. Although simple, this mechanism is quite effective—it is also used in Callisto [3], a deployed (non-cryptographic) escrow. Matching should be unambiguous, since false positive matches can cause allegations to be revealed prematurely. Unlike more sophisticated matching criteria, equality tests are simple and robust.

Allegation meta-data is a formatted string containing specific fields. For instance, it could contain: 1) identity of the accused and, 2) the type and intensity of a crime. The identity can be specified either as a name or as a unique identifier, if available. In an institutional setting for instance, the user could select from a drop-down list of other employees/students in that institute. The ‘type and intensity’ of crime is selected from a drop-down list containing entries like ‘sexual harassment’, ‘sexual assault’, ‘petty theft’, ‘fraud (< $10^3)’, ‘fraud (≥ $10^3, < $10^6)’, ‘fraud (≥ $10^6)’ and ‘racial discrimination by a person in power’.

Along with the meta-data and free-form text, the user also submits a reveal threshold—the lowest number of matching allegations that must be revealed along with this (or before) this one. Unlike prior work [35], [26], [31], which only supports a single matching threshold throughout the system, we allow the user to pick a threshold to their own satisfaction with each allegation.

B. Initialization

All escrows register with a standard PKI. They use this to form secure, two-way authenticated TLS links between every pair of escrows. These are used for all inter-escrow communication. During both registration and filing, the user and escrows use a session ID to ensure all escrows are talking to the same user.

The escrows use RANDOMCOINTOSS() to generate individual shares of private DVRF keys that are later used to 1) register and authenticate users $SK_i$, 2) reveal user identities when required $SK_R$ and 3) match allegations in each bucket $i$, $SK_i$. Since there are infinitely many buckets $i \in 0,1,...$, $SK_i$ is generated lazily when required. How these keys are used will be explained later. The public component of $SK_i$, $PK_i$ is also generated using PUBLICEXponentiate and publicly published. All shares use a fixed recombination threshold of $f+1\leq|\frac{n}{2}|$, so all the escrows must cooperate to perform operations with these keys, and any minority can be compromised by an adversary without violating any of SAE’s properties.

C. User Registration, Allegation Filing and Revelation

Registration. The user first obtains a certificate of real identity (e.g., their passport/employee ID) from an appropriate certificate authority (e.g., their employer). This authority is trusted to verify the identity of the user in the real world, denoted as $ID$. During registration, user forms a two-way authenticated TLS link with each escrow using this certificate, and non-repudiable signs all communication during registration.

The user generates $l$ random one-time public-private key pairs and secret shares the public parts, $pk_1,...,pk_l$ among the escrows. Each of these can be used to file one allegation later.

Using the MPC protocol for DVRF, the escrows compute a MAC on each of these public keys $pk_i$, as $(FSK_i(H_2(pk_i)), \pi_{SK_i}(H_2(pk_i)))$ using their secret-shared private DVRF key generated at initialization. $SK_i$, $H_2$ is a collision resistant hash function from the set of public keys to $\mathbb{Z}_q$. Each escrow learns only its share of the public key and its share of the computed MAC, while the registering user (and not any of the escrows) learns the full MAC.

The escrows also compute a PRF $FSK_{SK_R}(H_2(pk_i))$ using a different private key $SK_R$. Individual escrows learn the PRF, but nothing else. Each escrow stores the association between the user’s real-world identity and $FSK_{SK_R}(H_2(pk_i))$ in a local map. This association is used when revealing allegations later.

At the end of the registration, every escrow knows the real user, but knows only one share of each of the public keys $pk_i$, the user provided and one share of the MAC computed on it. Consequently, when presented with one of these public keys and its MAC later, no minority of escrows can link the key back to a specific registered user.

Allegation filing. A registered alleger files an allegation by connecting to the escrows over an anonymous communication channel which is modelled by the functionality $F_{anon}$ (e.g., see [5]) It anonymously delivers messages to users in the network. The escrows’ identities are authenticated with standard PKI.

During the filing, the alleger chooses a random public key $pk$ from the set previously registered and submits 1) $pk$, 2) $\pi_{SK_i}(pk)$, the escrows’ MAC on it, 3) the allegation’s full text encrypted with a fresh symmetric key $SK_R$. Individual escrows learn the PRF, but nothing else. Each escrow stores the association between the user’s real-world identity and $FSK_{SK_R}(H_2(pk_i))$ in a local map. The escrows’ identities are authenticated with standard PKI.

Since no escrow has seen the whole public key $pk$ or the entire MAC on it before, no escrow can link it back to any specific user. However, all escrows can locally verify with VERIFYVRF that the MAC on the public key is legitimate, and hence, that the public key comes from a user who has previously registered. This verification only requires local computation by each escrow and no MPC, which improves efficiency.

Note that no escrow has enough information to reconstruct the allegation, its meta-data or the identity of the alleger. A majority must cooperate to reconstruct any of these. This ensures the properties of allegation secrecy and alleger anonymity (11), even if a minority of the escrows cooperate with the adversary.

Allegation revelation. Allegations are matched using a dedicated algorithm by the escrows. The algorithm is described in [14]. Once a majority of escrows determine that a set $A$ of matching allegations can be revealed, i.e., they all have thresholds $\leq|A|$, the
escrows combine their shares to decode the symmetric keys used to encrypt the texts of the allegations in \( A \). These texts are provided to a designated authority for further action.

Along with the allegation texts, the escrows also reveal the real-world identities of the allegers who filed \( A \). To obtain the identity of an alleger, the escrows compute the PRF \( F_{SK_{\text{alleger}}}(pk) \) (using DVRF, the algorithm described in \( \text{III-C} \)), on the public key \( pk \) the alleger used to file the allegation. Recall that the escrows also computed this PRF when the alleger registered and mapped the PRF to the victim’s identity in a local store. Hence, to discover the user’s identity, they merely need to look up the PRF in the store. This search is done in clear-text locally by each individual escrow and is efficient.

Providing the real-world identities of the matched allegers to the designated authority allows the authority to reach out to the allegers and also provides the accountability property from \( \text{II-A} \).

**Registered public keys must not be used twice.** As just described, after an allegation filed with public key \( pk \) has been matched and revealed, the escrows map \( pk \) to the strong identity of the individual. Consequently, the key \( pk \) should not be used to file a second allegation unless the alleger wishes to de-anonymize itself to the escrows. To allow users to file multiple allegations anonymously, a user registers \( l \) different keys during a single registration. This can be repeated periodically, allowing for \( l \) allegation filings for every user within each period. For instance, every participating individual may register 10 public keys every year, thus allowing every user 10 allegation filings every year.

### D. Matching and Thresholding

Now, we discuss how the escrows match allegations to each other and reveal sets of matching allegations when thresholds are met.

1) **Matching protocol**: We describe a simple MPC protocol that matches two allegations when their meta-data hashes are equal. We start by noting that, by design, our matching protocol does not allow any minority set of escrows to match two allegations on their own. Recall that each escrow receives only a share of the (collision-resistant) hash of the meta-data, \( H_1(m) \), of each allegation. The shares are randomized, so a minority of escrows cannot check the equality of \( H_1(m) \) and \( H_1(m') \) using the shares alone. This property is important, else, an adversary who corrupts a minority of escrows can probe existing allegations to discover if an allegation against a specific individual exists. They can do this without any honest parties being aware of such probing.

To compare a set of allegations for equality, all the escrows participate in DVRF (see \( \text{III-C} \) to compute a pseudo-random function \( F_{SK}(H_1(m)) \) for all allegations in the set. The resulting PRF is revealed in the clear to all escrows, but \( SK \) and \( H_1(m) \) aren’t. \( SK \) is a shared secret specially generated for each set of allegations being compared. The sets are determined by the thresholding protocol described below.

Since the PRF is bijective when the range of \( H_1(\cdot) \in \mathbb{Z}_q \), \( H_1(m) \) and \( H_1(m') \) are equal if and only if \( F_{SK}(H_1(m)) = F_{SK}(H_1(m')) \). Hence, each escrow can locally determine which allegations match which others (note, \( H_1 \) is collision-resistant). Further, \( F_{SK}(\cdot) \) is a PRF whose secret-key is not used for any other purpose, so no additional information about \( m \) is revealed. Thus all pairs that match in a set of \( n \) allegations can be computed efficiently in linear-time (constant time per allegation).

**Algorithm 2** Rules for the secure thresholding algorithm BUCKETING, whose interface is described in \( \text{IV-D} \). It reveals a set of allegations if and only if all of their thresholds are satisfied by that set.

Apply the following rules repeatedly (in any order) till no further rules apply. Rules 2, 3 and 4 only apply to collections that haven’t been revealed.

1) When an allegation with threshold \( t \) is filed, it forms a singleton collection and is added to bucket \( t - 1 \) (since \( t - 1 \) other allegations must match the allegation before it is revealed).

2) If \( Min(A) \) is the smallest bucket occupied by a collection \( A \) and every allegation in \( A \) has a threshold \( < Min(A) + |A| \), \( A \) is copied to bucket \( Min(A) - 1 \). Note that \( A \) still occupies the buckets it used to occupy. Copying merely adds the collection to a new bucket.

3) When two collections overlap and occupy the same bucket, and their allegations are found to match (\( \text{IV-D} \)), they coalesce into one collection.

4) When a collection reaches bucket 0, all of its allegations are revealed as described in \( \text{IV-C} \).

5) If a collection \( A \) is revealed, we make sure it occupies buckets \( 1, \ldots, |A| \), even as \( A \) grows. This enables future matching allegations to be revealed.

2) **Bucketing Protocol for Reveal Thresholds \( > 2 \)**: The above matching protocol is secure when the reveal thresholds equal 2. Supporting higher thresholds securely and scalably requires more work. A collection \( A \) of matching allegations should be revealed when every allegation in \( A \) has a reveal threshold no more than the size of \( A \) (written \( |A| \)). One way to find such collections would be to run the above matching protocol on the set of all allegations irrespective of their thresholds and then locally determine whether an appropriate set \( A \) exists. However, this design is susceptible to a probing attack where an adversary interested in probing for the existence of a specific allegation, files the same allegation with a very high threshold. By corrupting just one of the escrows, the adversary could then compare this allegation to all other allegations in the system, without any risk that its own false allegation would ever be revealed (since the probe allegation has a very high threshold). To deter such attacks, we control which allegations can be compared to each other. We ensure that if two allegations can ever be compared by a minority of escrows, then they will be revealed at the same time, if at all. That is, two allegations can be compared by a minority only if they are waiting for the same number of matching allegations. Now, if the adversary tries to probe with a fake allegation, the fake allegation (and hence the adversary’s real-world identity) is exactly as likely to be revealed as the allegers’ actual matching allegation.

Thus, to just learn the number of allegations against a person, the adversary must risk leaving a non-repudiable paper trail. Additionally, if the adversary is a guilty party seeking to determine the number of escrowed allegations against them, they risk precipitating the revelation of an honest allegation, which may have otherwise remained escrowed forever. We assume the adversary won’t take such risks.

Note, the above attack only works for threshold \( > 2 \). If an honest allegers’ threshold is 2, SAE doesn’t admit any attacks not present

\(^3\)Note, that we just use a PRF and not the verifiability property of our VRF here.
in a single trusted-party implementation, even if the adversary is willing to risk filing a probe allegation. Prior work on single trusted-party based allegation escrows only supports thresholds of 2, and still demonstrates social utility in allegations of sexual misconduct.

It is possible to use generic MPC to avoid such probing attacks. However, the time taken to process one allegation would then increase with the number of allegations already present in the system. By simply filing many ‘junk’ allegations, an adversary can slow down the system till it is no longer useful. Hence scalability is crucial; our matching/bucketing protocol does only a constant amount of work per allegation.

To keep track of how many matches each allegation needs, each escrow independently maintains buckets numbered 0, 1, 2, 3, ..., An allegation is in the \( i\)th bucket only if it is waiting for \( i \) more allegations. An allegation may be present in more than one bucket. Bucket 0 contains a list of allegations that have been revealed.

**Algorithm 2** controls which allegation occupies which buckets.

Only allegations within a bucket may be compared to each other. To ensure this, each bucket \( i \) is associated with an independently chosen secret key \( SK_i \), which is shared among the escrows \( SK_i \) is generated lazily when bucket \( i \) is first used. When an allegation is added to bucket \( i \), the escrow computes \( F_{SK_i}(H(m)) \) for that allegation using DURF (see [III-C]). Any escrow can use this to locally compare any two allegations in bucket \( i \). Since, by design, \( SK_i \neq SK_j \) if \( i \neq j \), \( H(m) \) and \( H(m') \) cannot be compared using \( F_{SK_i}(H(m)) \) and \( F_{SK_j}(H(m')) \) when \( i \neq j \). Allegations that are known to match each other, either directly because they are in the same bucket or indirectly by transitivity, are said to belong to the same ‘collection’. When allegations from two different collections are found to match, the collections coalesce into one. The resulting collection spans the union of buckets spanned by the parent collections and contains the union of allegations. Every allegation belongs to exactly one collection at any given time. To copy all allegations in a collection into a new bucket, the PRF for only one allegation’s meta-data needs to be computed, since all allegations in a collection have identical meta-data.

This algorithm trivially satisfies the property that, once two allegations are known to be equal to each other, they belong to the same collection and are revealed together (if at all). This deters the probing attacks described above that motivated this elaborate mechanism. We also prove that the thresholding algorithm is ‘correct’:

**Theorem 1 (Correctness).** Algorithm 2 reveals a collection if and only if the thresholds of all allegations in it are satisfied.

**Proof:** Let \( Max(A) \) and \( Min(A) \) be the largest and smallest buckets occupied by collection \( A \). We begin by proving that the following three properties hold whenever all five rules of Algorithm 2 have been applied to saturation (meaning no further rule applies), (1) every collection spans a contiguous range of buckets, (2) every collection \( A \) spans \( |A| \) buckets, i.e., \( |A| = Max(A) - Min(A) = Span(A) \), (3) every allocation in a collection \( A \) has a threshold \( \leq |A| + Min(A) \) and hence can be revealed if \( Min(A) \) more matches are available.

The first property can be proved as an invariant that is trivially maintained by rules 2, 4 and 5 with rule 1 as the base case. Now, two collections coalesce only if they share a bucket (and hence their allegations may be compared). Since the union of contiguous, overlapping segments is contiguous, rule 3 also maintains the invariant.

To prove the second property, note that in any collection \( A \), all allegations have a threshold \( \leq Max(A) \) by definition. If \( Span(A) < |A|, Max(A) = (Max(A) - Min(A)) + Min(A) < |A| + Min(A) \), since \( Max(A) - Min(A) = Span(A) \). Hence rule 2 can be applied repeatedly until \( Span(A) \) increases to equal \( |A| \). Hence \( Span(A) \geq |A| \). We now prove that \( Span(A) \leq |A| \) is an invariant with rule 1 as the base case. Rules 4 and 5 trivially maintain the invariant. Rule 2 would not apply if it causes the invariant to be broken, as there is at least one allocation with threshold \( Max(A) \) if \( A \) is not yet revealed (which is when rule 2 applies). The threshold condition for this allocation will not be met if \( Span(A) > |A| \), as it implies the threshold \( t = Max(A) = Min(A) + Span(A) \geq Min(A) + |A| \). Applying Rule 3 to create \( C \) out of \( A \) and \( B \), maintains the invariant. \( |C| \) spans a union of the parent’s buckets, hence \( Span(C) \leq Span(A) + Span(B) \leq |A| + |B| = |C| \) because \( A \) and \( B \) are disjoint. Hence the invariant is maintained.

The third property is explicitly maintained as an invariant by rule 2 and is trivially satisfied by rules 1 and 5. Rule 3 is applicable in two ways. First, when a new allocation arrives in between an older collection, the property is not broken. Second, if two existing collections, \( A \) and \( B \), coalesce into \( C \) by rule 3, one is ‘above’ another. Let \( Min(B) = Max(A) \), without loss of generality. Then, \( Min(C) = Min(A) \), hence allegations in \( A \) satisfy the property. The drop in \( Min \) for allegations in \( B \) is \( Min(B) - Min(C) = Max(A) - Min(A) = Span(A) \leq |A| \) (we proved above that all rules maintain \( Span(A) \leq |A| \) as an invariant). This drop in \( Min \) is compensated by a corresponding increase in size of the collection by \( |A| \).

We now use these properties to prove correctness. The third property implies that when a collection \( A \) is revealed, the threshold condition is satisfied for all revealed allegations, since \( Min(A) = 0 \). To prove the other direction, let there be \( n \) matching allegations such that all their thresholds are \( \leq n \). Assume for contradiction that they are not revealed. This means that they all belong to buckets \( 1, \ldots, n - 1 \). By the pigeonhole principle, there will be one bucket with multiple allegations which will start coalescing with rules 2 and 3. If the process stops with a collection of size \( k < n \), \( n - k \) buckets will be left with \( n - k \) allegations, because property 2 ensures the size of a collection equals its span. Again, by the pigeonhole principle, the coalescing process starts. This continues till there is only one collection with \( n \) allegations that spans buckets \( 0, \ldots, n - 1 \) and all \( n \) allegations get revealed. Hence, a set of \( n \) matching allegations are revealed if and only if all their thresholds are \( \leq n \).

**BUCKETING(buckets): Interface to the Algorithm** The real protocol (Figure 2) and ideal protocol (Figure 3) interface the bucketing algorithm with the BUCKETING function. It takes as input the set of buckets, \( \text{buckets} \). Each bucket \( i \), (denoted as \( \text{buckets}[i] \)) is a set of tuples \((id,M)\) describing the allegations in that bucket. \( id \) is a unique allegation identifier and \( M \) is a representation of the meta-data which can be compared for equality to determine which allegations matches which others within a bucket.

The function BUCKETING returns a task \( T \) if more rules apply in Algorithm 2. Else it returns \( \bot \). Task \( T \) instructs the caller to move an allocation \( T.ID \) to a bucket \( T.i \). For ease of exposition, when a collection is added to a new bucket, BUCKETING produces one
We formalize the functionalities very well and doesn’t increase with the number of users as well as E. Computation Cost are defined in § of its threshold. Revealing an allegation requires one more PRF itself, require any PRF computation. The cost to move a collection of shared secrets. However, the number of such computations scales escrows, since they involve multiplication and exponentiation over the VRF/PRF computations that require interaction between the F.

# Identity Verification and Filing IV -D2. Every identity is only allowed to register a fixed number authentifications do not cause MPC operations. Further, each user authentication. Since authentication is a local computation, failed to process a user request doesn’t increase with the number of users as well.

### Escrow Initialization

Every escrow executes:

1. \([SK_i] \leftarrow \text{RANDOMCOINTOS}(\) \(\)\)
2. \([SK_i] \leftarrow \text{RANDOMCOINTOS}(\) \(\)\)
3. \(PK_i \leftarrow \text{PUBLICEXPO}\) (\(\) \(\)\)
4. \([SK_i] \leftarrow \text{RANDOMCOINTOS}(\) \(\)\) \((\) \(\)\) \(\)\)

\#\(SK_i\) is generated lazily when required.

### Client Initialization and Registration

The client uses ID, a certificate previously obtained from a CA, to authenticate to the escrows. The escrow’s identities are managed with PKI. The secure authenticated channel is idealized using \(F_{\text{auth}}\). Client signs all messages with ID. The client executes:

1. \((pk, sk) \leftarrow \text{Gen}(\) \(\)\) \(\) \(\)\) \(\) \(\)\) # Signing key-pair
2. Broadcast (“Register”, ID) idealized using \(F_B\)
3. \(VSS(H_2(pk))\) among the escrows

Every escrow executes:

4. \(\bot \leftarrow \text{DVRF}(\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)True, client
5. \(R \leftarrow \text{DVRF}(\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)False, all-escrows
6. \(\text{identities}[R] \leftarrow \text{ID}\)

The client executes:

7. Receive \(\pi_{SK_i}(H_2(pk))\) from escrows’ DVRF call in step 4.
8. Store \((pk, sk)\) and \(\pi_{SK_i}(H_2(pk))\) for future use.

### Allegation Filing

With allegation text \(a\), \(m = H_2(\text{meta-data})\), reveal threshold \(t\), fresh symmetric encryption key \(k\) and, \((pk, sk, \pi_{SK_i}(H_2(pk)))\) during registration, the client connects to each escrow over an anonymous communication channel, idealized using functionality \(F_{\text{escrow}}\). It signs all communication with \(sk\), which escrows verify before accepting the input. The escrows process allegations serially. They identify an allegation by the \(pk\) used to file it.

The client executes:

1. Broadcast (“File”, \(pk\), \(t\)) idealized using \(F_B\)
2. Broadcast \((\pi_{SK_i}(H_2(pk)), \text{Enc}(a))\), idealized using \(F_B\)
3. \(VSS(m), VSS(k)\) among the escrows

Every escrow executes:

# Identity Verification and Filing

4. If \(\text{VERIFY}_VRF(F_{PK_j}, \pi_{SK_i}(H_2(pk)), H_2(pk))\) fails, abort.
5. If \(\text{allegations}[pk]\) exists, abort.
6. \(\text{allegations}[pk] \leftarrow (t.pk, \text{Enc}(a), \{[m], \{k\}\})\)
7. \(M \leftarrow \text{DVRF}(\{SK_i\}, \{m\}, \{k\})\), False, all-escrows
8. \(\text{buckets}[t-1] \leftarrow \text{buckets}[t-1] \cup \{(pk, M)\}\)

# Revealing Allegations

16. For \(\text{buckets}[0] = \ldots\)
17. \(\text{buckets}[0] \leftarrow \text{buckets}[0]\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\) \(\) \(\)\)...
To model security and privacy we use the UC framework, which allows SAE to compose with other cryptographic schemes while maintaining security.

### V. Security Analysis

 attackers can be ensured by filing allegations against random strings. Decoy allegations won’t slow down the system since SAE is scalable.

#### Attacker Model

Agents (allegers and escrows) in our system are interactive Turing machines that communicate with an ideal functionality \(F_{SAE}\). The adversary \(A\) is a PPT machine with access to an interface corrupt(). It takes an agent identifier and returns the internal state of the agent to the adversary. All subsequent incoming and outgoing communication of the agent is then routed through \(A\). The adversary is \(f-bounded\), and can corrupt a minority \(f < n/2\) of escrows and any number of allegations. For formal security, we consider the static corruption model; i.e., the adversary commits to the identifiers of the agents it wishes to corrupt ahead of time\(^5\).

#### Communication Model

We assume the network to be bounded-synchronous \([24]\) such that the protocol execution occurs in discrete rounds. The agents are aware of the current round, and if a message is created at round \(i\), it is delivered at the beginning of round \((i+1)\). Our model assumes that computation is instantaneous. In practice, this is justified by setting a maximum publicly known time bound on message transmission. If no message is delivered by beginning of the next round, then the message is set to be \(\perp\). For an example of the corresponding ideal functionality \(F_{syn}\), we refer the reader to \([10], [30]\).

The attacker model assumes that computation is instantaneous. In practice, this is the same as black-box MPC. Further, it allows users to file allegations (amortized), including for identity verification. Note that, WhoToo’s per-allegation complexity is \(O(N)\), and hence \(O(N^2)\) complexity for \(N\) allegations.

#### 2) Larger Allegation Pool

To maximize the probability that a matching allegation will be found, we must allow a large set of allegations to be used to file the same escrow. This allows large pools of allegations to be matched with each other. Scalability is essential to enable this.

#### 3) Avoid Timing Side-Channels

If somebody commits a crime and learns (through a compromised escrow) that an allegation was filed two days later, when filings are otherwise rare, they may reasonably conclude that their victim filed the allegation. We excluded such side-channels in the threat model. To realize this, honest escrows (and other external well-wishers) can regularly file decoy allegations. Since SAE maintains anonymity and privacy, the adversary cannot distinguish decoys from real allegations. Those filing decoy allegations must register their separate (real) identities for doing so, and enter a contractual obligation to ensure no decoy ever gets revealed. This can be ensured by filing allegations against random strings. Decoy allegations won’t slow down the system since SAE is scalable.

### V. Security Analysis

To model security and privacy we use the UC framework, which allows SAE to compose with other cryptographic schemes while maintaining security.

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\(^5\)The static adversary is a standard assumption employed by most practically relevant MPC systems today. [15]
Initialization
1. registered ← {}, allegations ← {}, buckets ← {}, unique ← {}

Registration Invoked by client with identity ID
1. Send ("Register", ID) to all escrows
2. If received ⊥ from escrow i, then IdentifiableAbort(i)
3. registered ← registered ∪ {ID}

Allegation Filing Invoked by client with identity ID, allegation a, reveal-threshold t, and metadata m
1. If ID ∈ registered, then Abort
2. registered ← registered ∖ {ID}
3. Send ("File", UNIQUE(ID), t) to all escrows.
4. If received ⊥ from escrow i, then IdentifiableAbort(i)
5. allegations[ID] ← (t, m, a)
6. buckets[t − 1] ← buckets[t − 1] ∪ {ID, m}
7. Send (t − 1, UNIQUE(ID), UNIQUE((t − 1, m))) to all escrows

# Matching and Bucketing
8. T ← Bucketing(buckets)
9. While T ̸= ⊥
10. # Move allocation T.ID to bucket T.i
11. If received ⊥ from escrow i, then IdentifiableAbort(i)
12. m′ ← allegations[T.ID] ∖ m
13. buckets[T.i] ← buckets[T.i] ∪ {T.ID, m′}
14. Send (T.i, UNIQUE(T.ID), UNIQUE((T.i, m′))) to all escrows
15. Task ← Bucketing(buckets)

# Reveal Allegations
16. For each (ID, M) in buckets[0]
17. buckets[0] ← buckets[0] ∖ {ID, M}
18. If received ⊥ from escrow i, then IdentifiableAbort(i)
19. (t, m, a) ← allegations[ID]
20. Send (t, m, a, ID) to all escrows

function UNIQUE(x) begin
1. if x is in unique
2. return unique[x]
3. end if
4. unique[x] ← |unique|
5. return unique[x]
end function

Bucketing Algorithm. To scalably and efficiently implement reveal thresholds, we propose a bucketing protocol (see Section IV-D2) that divides allegations into buckets. All escrows know which allegations within a bucket match each other. This makes the ideal functionality admit a somewhat surprising attack: If an adversary files an allegation, it learns whether other matching allegations exist in the same bucket in which the adversary’s allegation is placed. These attacks are consistent with our threat model, which allows for probing attacks by adversaries. As explained in Section IV-D2, the buckets in which an allegation is placed are carefully chosen to disincentivize these attacks by relying on our accountability property (see Section II-A). Note, Bucketing is a local and non-cryptographic algorithm. It merely determines what information can be revealed to the adversary, and hence can be called from the ideal functionality.

Discussion. F_{SAE} satisfies the allegation secrecy, allegor anonymity and accountability properties described in Section IV relative to our threat model. Accountability is ensured since, if a user files an allegation, F_{SAE} reveals their real identity (ID) as soon as their threshold is met. Note that we already proved the bucketing protocol correct. Allegation secrecy and allegor anonymity are ensured because F_{SAE} reveals information about an allegation only in the following scenarios: (1) F_{SAE} reveals a user’s identity then they register into the system (step 6). This is harmless since users register irrespective of whether or not they currently intend to file an allegation. (2) As the bucketing protocol progresses, F_{SAE} reveals which allegations match which others (step 14); we discussed why this information doesn’t violate our properties above. (3) It reveals the threshold of an allegation when it is filed (step 9), hiding which isn’t part of our threat model. (4) Finally it reveals the entire allegation when its threshold is met and is ready to be revealed (step 20), always in the IV-D2 Theorem 1.

Figure 2 presents the pseudocode for our cryptographic protocol. We prove UC-security in the (F_{B}, F_{anon}, F_{syn})-hybrid model. Theorem 2 holds for any UC-secure realization (as defined in Definition 1) of F_{B}, F_{anon}, and F_{syn}. We provide a proof sketch of Theorem 2 in Appendix C.

Theorem 2 (UC-Security). Let VSS be a secure verifiable secret sharing scheme, RANDOMCOIN TOSS() be a secure DKG protocol, let (DVRF, VERIFYVRF) be a secure distributed input DVRF protocol, let H_{1} and H_{2} be collision resistant hash functions, let (E, D) be a non-committing symmetric encryption scheme, and the employed signature scheme is strongly existentially unforgeable. Then the SAE protocol UC-realizes the ideal functionality F_{SAE} defined in Figure 4 in the (F_{B}, F_{anon}, F_{syn})-hybrid model.

VI. IMPLEMENTATION AND EVALUATION

Implementation. We build our prototype in Java, with our own implementation of the GRR MPC protocol [23]. We use SCAPI [37] version 2.3 for establishing communication channels and its bindings to OpenSSL [21] version 1.1, which use for hashing, symmetric encryption and public-key encryption. We use the Java bindings to the Pairing Based Cryptography library, jPBC [16] version 2.0 for pairing based cryptography primitives. For operations in Z_q, we use Java BigInteger. To maintain each escrow’s persistent state, we use a MySQL database to achieve security, scalability and, security. To demonstrate scalability, we pre-populate the database with one million allegations from one million distinct users. Since
our computational complexity per allegation/registration does not depend on the number of pre-existing allegations/registrations, this imposes a negligible overhead on the protocol.

We now evaluate our implementation to show that SAEs are fast enough for practical use.

**Latency and throughput.** We first measure the latency and throughput of user-SAE interaction in a realistic setting. We set up to 9 escrows on Amazon AWS cloud servers, chosen to maximize geographical extent. In an experiment involving $n$ escrows, the escrows run on servers in the first $n$ of Virginia, Frankfurt, Sydney, N. California, Singapore, Sao Paulo, London, Seoul, and Mumbai. Each escrow runs on a M4.large AWS instance. At the time of the experiments, this provided 2 vCPUs, 8GB of RAM, and ‘moderate’ network performance. Each server runs up to 60 threads, the maximum supported on the machines; each thread handles one concurrent client request. Note that the SAE registration is embarrassingly parallel with respect to client requests—cost is dominated by network latencies and MPC computation, which require no syncing across client requests; such synchronization is needed only storing registered identities to database. Allegation filing must be done serially one-by-one. We use up to 60 client replicas, all hosted on a single c4.4xlarge instance of AWS in Virginia. At the time of our experiments, this provides 16 vCPUs, 30GB RAM and ‘High’ network performance.

**Latency:** Figure 5(top) shows the average latency for registering a new key as the number of escrows varies, in two configurations: When the escrows are lightly loaded (no concurrent requests) and when they are heavily loaded (60 concurrent clients). Latency is the time between when a user sends its request, to when it gets the SAE’s MACs on its keys. There are three notable aspects here. First, as expected, the latency increases with the number of escrows (since the MPC becomes more complex). Second, increasing the number of concurrent clients does not increase the latency significantly. This suggests that the cost is dominated by the number of escrows and inter-escrow network latencies. Finally, even though the absolute latency numbers might look high (of the order of 10s of seconds), they are acceptable since user interaction with SAEs is relatively infrequent. In particular, users register new keys once every few months, so such latencies seem quite practical. Latency is not a concern for filing an allegation, since the user does not expect any response from the escrows. The cost of matching and bucketing is better captured in terms of throughput.

**Throughput:** Next, we measure the throughput of SAE in terms of the number of key registrations and allegation filings it can handle per second. For registration, we use 60 concurrent clients. Figure 5 (bottom) shows the throughput as a function of the number of escrows. Allegations are filed serially. As expected, the throughput number decreases with increasing number of escrows.

For allegation filing, each client repeatedly files allegations with thresholds varying between 2 and 20, chosen from a truncated exponential distribution with mean 5. When a threshold of $t$ is chosen, $t$ matching allegations are created with 50% probability, and $t−1$ matching allegations are created the rest of the time. These, respectively, represent the cases where the allegation is eventually revealed and the worst-case (for performance) when the allegation is not actually revealed.

We believe that these throughputs are acceptable for SAE, since user operations are expected to be very infrequent. Moreover, each escrow can be separately replicated on several servers to get proportionally higher throughput.

**Impact of network latency.** The primary source of user-perceived latency is inter-escrow network latency. To test this, we emulate a network with Linux qdiscs to get predictable performance on a single Amazon AWS c4.4xlarge instance. The escrow servers and our client occupy one core each. Every pair of escrow servers is given an emulated 100 Mbps link and 1 bandwidth × delay worth of buffer (the recommended buffer size for TCP to obtain full link utilization and minimal delay). We vary the latency of the emulated network links and
A. Deployment Considerations

Client Software. Users need client software to participate in the protocol. It would be convenient if this software were part of a web-page. However, it is challenging to access anonymity services like ToR from within a browser (which suggests interesting future work). If users were required to download special software instead, we expose other security concerns. The very act of downloading the software could indicate an intent to file an allegation, and not all users will use an anonymity service like ToR to do so. To prevent this channel of inference, the client software should be bundled with other commonly used software. Alternatively, we can produce cover traffic by making a fraction of all visitors of a popular web-page (e.g. organization's home page) download the software.

Practical Security. Like all software, SAE will have security vulnerabilities; there is no use in encrypting secrets codes a buffer-overflow attack leaks the secret keys. In addition to careful code audits, we could make multiple implementations that use independent hardware/software stacks and compare their outputs to see if they are identical. If not, we halt the system until a security expert can find and fix the bug. This forces an attacker to find the same vulnerability on different hardware/software stacks, which is much more difficult. Such a heavy-handed approach is prudent here since security is much more important than performance and availability.

Non-technical considerations. Since SAE handles sensitive information, its social design requires considerable thought. While a full analysis is out-of-scope for this primarily technical paper, we discuss some issues here. When thresholds for a set of allegations are met, to whom should they be revealed? To avoid centralization, we could reveal them to the allegers themselves. They can then coordinate to whom should they be revealed? To avoid centralization, we could provide cover traffic by making a fraction of all visitors of a popular web-page (e.g. organization’s home page) download the software. SAE forces creators to create a paper-trail while filing an allegation to discourage fake/probe allegations. We need effective legal mechanisms to make this a significant deterrent. For more discussion of other social issues, we refer the reader to prior social-science work [4], [2].

B. Future Work

Withdrawing/modifying allegations. A user can readily update allegation free-form text by sharing a new value. However, SAE cannot always let them withdraw an allegation or modify its metadata/reveal threshold. Since an allegation’s threshold could be met as soon as it is filed, allegers should only file one if they are comfortable with it being revealed. Nevertheless, allegers may want to modify one. For example if an allegation hasn’t been revealed in several months/year, they may want to either withdraw it or reduce its reveal threshold. In SAE, this is hard, since for thresholds > 2, escrows may know that two allegations match even before they are revealed. An adversary can use this to probe for allegations; if they can withdraw their probe allegation, they can delete the paper trail that disincentivizes such probes (see §V-D2).

Note, if an allegation isn’t yet known match any another, we can allow it to be withdrawn. To do so, we must pick a new secret key for the bucket it is in and recompute all PRFs with this new key. Since this is computationally expensive, we can limit the overhead by recomputing PRFs at-most once per week. Users are notified that withdrawal can take up to one week, which is acceptable in this context. Fully supporting allegation withdrawal and modification is interesting future work.

Other matching criteria. SAE matches allegations based on exact string equality. Could we support other criteria? For instance, some allegers may be victims of the crime and others may be witnesses. Can we support different thresholds based on type of allegers? Could we match on multiple fields, e.g. ‘match only if at least two of (name/phone number/email address/employee id) match’, ‘match against this accused person only if the crime happened within this time-frame/physical coordinates’, or ‘match only against allegations filed in the last year’. In applications where some ambiguity is acceptable, it would be interesting to match based on softer criteria provided by machine learning. E.g. based on a person’s picture, or a textual description. Note, these more complex criteria break transitivity. That is ‘A matches B’ and ‘B matches C’ doesn’t imply ‘A matches C’. Future work would need to define what it means for the thresholds for a group of allegations to be satisfied.

Identity Management. To enable real-world identities, allocation escrows require a robust public-key infrastructure (PKI), for which users should validate their identity with a trusted authority. If a user registers immediately before filing an allegation, then this act reveals an intent to file an allegation. Hence the PKI must be established beforehand. SAE requires a pre-registration step in addition to PKI, which is acceptable in many cases since a new PKI must be established anyway; most organizations either don’t have one for their employees/students, or the ones they have aren’t very robust. For instance, some administrators may have access to employee logsins/emails. Nevertheless, it is interesting future work to explore how to effectively exploit a pre-existing PKI to avoid a separate pre-registration for the escrow system. For instance, if each person had a certificate, they could secret share their identity and prove in zero-knowledge that they own the secret-shared identity. Prior work demonstrates how to do this while being backwards compatible with X.509 certificates [17] and email services [39]. Future work must establish that this is practical and efficient. Additionally, many organizations use multi-factor authentication. Exploiting this additional layer of security is also interesting future work.

VIII. Conclusion

We have presented SAE, a robust system that implements an allegation escrow with strong cryptographic security guarantees, and
showed that it is practical. SAE keeps allegations and the identities of allegers and the accused confidential until alleger-specified match-thresholds are reached. The system’s security and privacy guarantees provably hold as long as a majority of the escrow parties are uncorrupted. Our empirical evaluation suggests that SAEs are efficient enough to be used in practice, and scales well to large numbers of users and allegations.

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A. Bilinear Pairings

Let $G_1, G_2, G_T$ be multiplicative, cyclic groups of prime order $q$. Let $g_1, g_2$ be generators of $G_1, G_2$ respectively. A map $e : G_1 \times G_2 \rightarrow G_T$ is called bilinear if it has the following properties. (1) Non-degenerate: $e(g_1, g_2) \neq 1$. (2) Bilinear: For all $u \in G_1, v \in G_2, x, y \in \mathbb{Z}$, $e(u^x, v^y) = e(u, v)^{xy}$. (3) Computable: There is an efficient algorithm to compute $e(u, v)$ for all $u \in G_1, v \in G_2$. For ease of exposition, we assume that the pairing employed is symmetric, i.e., $G_1 = G_2 = G$. Unless mentioned otherwise, $g \in G$ is a publicly known generator.

B. Verifiable Pseudorandom Functions (VRFs)

VRFs cannot be distinguished from a random function by a computationally bounded adversary that does not have access to the proof. For our purposes, we adopt the following formal definition of a VRF from [19]. Let $A_1 : \mathbb{N} \rightarrow \mathbb{N} \cup \{s\}$ and $A_2 : \mathbb{N} \rightarrow \mathbb{N}$ be functions computable in $\text{poly}(k)$ time $^2$ $F_{\cdot}(\cdot) : \{0,1\}^{\text{poly}(\lambda)} \rightarrow \{0,1\}^{\text{poly}(\lambda)}$ is a family of VRFs if there exists a PPT (probabilistic polynomial time computable) algorithm $\text{GEN}$ and deterministic algorithms $\text{PROVE}$ and $\text{VER}$ such that $\text{GEN}(\lambda)$ outputs a pair of keys $(SK, PK)$; $\text{PROVE}_{PK}(x)$ computes $F_{SK}(x)$, $\pi_{SK}(x)$, where $\pi_{SK}(x)$ is a proof of correctness; and $\text{VER}_{PK}(x, y, \pi)$ verifies that $y = F_{SK}(x)$. They satisfy the following properties:

1) Uniqueness: No values $(PK, x, y_1, y_2, \pi_1, \pi_2)$ satisfy $\text{VER}_{PK}(x, y_1, \pi_1) = 1 = \text{VER}_{PK}(x, y_2, \pi_2)$ when $y_1 \neq y_2$.
2) Provable: If $(y, \pi) = \text{PROVE}_{SK}(x)$, then $\text{VER}_{PK}(x, y, \pi) = 1$ and
3) Pseudorandomness: For any PPT algorithm $A = (A_1, A_2)$ that does not query its oracle on $x$, the following holds

$$\Pr \left[ b = b' \mid (SK, PK) \leftarrow \text{GEN}(\lambda), (x, st) \leftarrow A_1^{\text{PROVE}_{PK}(\cdot)}(PK), y_0 \leftarrow F_{SK}(x), y_1 \leftarrow \{0,1\}^{\text{poly}(\lambda)}, b = \{0,1\}, b' = A_2^{\text{PROVE}_{PK}(\cdot)}(y_0, st) \right] \leq \frac{1}{2} + \eta(\lambda)$$

where $\eta(\cdot)$ is a negligible function. Further, it satisfies the following unpredictability property.

For any PPT algorithm $A$, who does not query its oracle on $x$, the following holds:

$$\Pr \left[ y = F_{SK}(x) \mid (PK, SK) \leftarrow \text{GEN}(\lambda); (x, y) \leftarrow A^{\text{PROVE}_{PK}(\cdot)}(PK) \right] \leq \text{negl}(k)$$

C. Postponed Security Analysis

Definition 2. [14]. A symmetric encryption scheme $(E, D)$ is non-committing if there exist two PPT algorithms $(A_1, A_2)$ s.t. $(e, k)$ and $(e', k')$ are computationally indistinguishable when $e' \leftarrow A_1(1^\lambda)$.

*Except when $a_1$ takes the value $*$, which means the VRF is defined for inputs of all length.

$k' \leftarrow A_2(e', M)$, $k \leftarrow K$ and $c \leftarrow E(k, M)$ for all $M \in \mathcal{M}$ where $K, \mathcal{M}, \mathcal{C}$ denote key, message and ciphertext spaces respectively.

We refer [14] for a simple construction.

Proof Sketch for Proof Theorem 2. Our proof strategy consists of the description of a simulator $S$ that handles users corrupted by the attacker and simulates the real world execution protocol while interacting with the ideal functionality $\mathcal{F}_{SAE}$.

The simulator $S$ spawns honest users at adversarial will and impersonates them until the environment $E$ makes a corruption query on one of the users: At this point $S$ hands over to $A$ the internal state of the target user and routes all of the subsequent communications to $A$, who can reply arbitrarily. For operations exclusively among corrupted users, the environment does not expect any interaction with the simulator. Similarly, interactions exclusively among honest nodes happen through secure channels and therefore the attacker does not gather any additional information other than the fact that the interactions took place. For simplicity, we omit these operations in the description of our simulator. The simulator simulates the following honest nodes: 1) the honest escrows, 2) the honest users, 3) the CA for users’ real identities. Next, we describe how the simulator behaves at various points of the protocol.

At several points in the SAE protocol, DKG is required. namely, $SK_I$ used to compute MACs on identities, $SK_H$ used for revealing user identity and $SK_T$ for each $i$th bucket used for thresholding.

To simulate this with a minority of stochastically corrupted escrows, $S$ chooses a random key pair, performs DKG simulation [23] Theorem 1, and sends the the public key to the corrupted escrows. As this simulation is exactly the distribution in the real protocol [23] Theorem 1, and hence is indistinguishable from it. Notice that the simulator knows all the DKG secret keys here. It participates in computing $PK_I$ from $SK_I$. The simulator also generates the public-private key pairs for all the honest users and generates certificates for them from the CA.

For alligation filing and registration, we consider two cases depending on whether or not the allegor is honest.

Case 1: Honest allegor, corrupted minority of escrows

When an honest allegor registers, $\mathcal{F}_{SAE}$ sends (“Register”, ID) to the the simulator. The simulator proves the honest allegor’s identity to the corrupted escrows. This is possible because it simulates the CA and can generate arbitrary certificates. Then it generates $l$ new public keys $pk_1, \ldots, pk_l$ (note, figure 2 shows only $l=1$ for notational simplicity) and secret shares them among the escrows and participates in the distributed computation of $\pi_{SK_I}(H_2(pk_i))$ and $F_{SK_H}(H_2(pk_i))$ as described in [14] (note, the simulator knows $SK_I$ and $SK_H$). If the adversary refuses to participate in this computation, the simulator sends $\bot$ to $\mathcal{F}_{SAE}$ from a corrupted escrow’s channel and aborts. Else it sends $\bot$. As in the real protocol, the adversary obtains $F_{SK_H}(pk_i)$, but not $\pi_{SK_I}(pk_i)$. So far, this is exactly what happens in the real protocol, except that DKG and the honest parties’ private keys are chosen by the simulator, but from the same distribution. Hence it is indistinguishable from the real execution.

When an honest allegor files an allegation, $\mathcal{F}_{SAE}$ sends (“File”, UID, t) to the simulator. The simulator chooses a random key pair $(sk, pk) \leftarrow \text{Gen}(1^\beta)$, generates a MAC $\pi_{SK_I}(H_2(pk))$ on

\[\text{Henceforth, whenever the adversary makes the } r^{th} \text{ escrow fail, the simulator sends } \bot \text{ from that escrow’s channel. But we omit this detail for clarity.}\]
it and sends ("File", pk,t) and (πSAE(H2(pk)), C) to the corrupted escrows signed using sk, where the C is a random non-committing encryption ciphertext. The simulator generates a random meta-data m = H1(meta-data) and symmetric key k, and distributes a minority of shares among the corrupted escrows as VSS(m) and VSS(k), signed with sk. The distribution of meta-data doesn’t matter since it is information theoretically hidden from the adversary. Since the adversary has not seen the honest alleger’s public key before, the simulator can choose a random one. FSAE now moves to matching and thresholding, returning (i, UID, Um) each time an allegation identified by UID is added to bucket i. Let pk be the public key the simulator chose for UID (in the dishonest alleger case discussed below, the adversary provides pk, corresponding to which FSAE provides UID).

At this point, the real protocol would be computing FSAE(allegations[pk], m). The simulator can control the value of this result. If Um matches any other allegations in bucket i, the simulator produces the value it previously returned for that allegation in bucket i. Else it produces a fresh random value. This works because H1 is collision resistant, H1(m) = H1(m’) iff m = m’ for a computationally bounded adversary. Since F is a PRF, the adversary cannot distinguish between its output and truly random numbers. Note all matching allegations have the same (hash of) meta-data m by definition. If at any point, the adversary refuses to cooperate in distributed-input DPRF computation, the protocol is aborted, and the simulator sends ⊥ to FSAE, which also halts execution. Else it sends OK each time to move the protocol forward.

To reveal identity in the real protocol, the escrows compute FSKR(H2(pk)), where pk was the public key used during allegation. To simulate this, the simulator picks pk random from the set of unrevealed public keys it chose when ID was registered. It simulates the other escrows’ behavior such that, if the adversary cooperates, it gets FSKR(H2(pk)). Note, the simulator knows SKR. The simulator sends shares of the (non-committing) symmetric encryption key from honest escrows such that the ciphertext C open to a to the corrupted escrows. Allegation reveal now succeeds.

**Case 2: Corrupted alleger, corrupted minority of escrows**

During registration, the adversary provides a proof of ID from a CA to the simulator. It also sends the honest escrows’ shares of hashes of l public keys H2(pk1),...,H2(pk) to the simulator. If the proof of ID is invalid, or the shares are incorrect (i.e. VSS verification fails), the simulator sends ⊥ to adversary. Else, it sends ("Register", ID) to FSAE from the corrupted alleger’s ID. Note, the simulator has a majority of shares of H2(pk) and hence can reconstruct them. It also knows the secret keys SK1 and SKR. Hence it can participate in the computation of πSAE(H2(pk)) and FSKR(H2(pk)) on the l public keys to produce the correct result. If the adversary refuses to participate in the computation, it sends ⊥ to FSAE.

When filing an allegation, the allegor sends (t, pk, πSAE(H2(pk)), EncC(a)) to the simulator for broadcasting. It secret shares the key k and a collision-resistant hash of the meta-data, m. The simulator verifies that pk has not been used before and verifies the MAC on it. If the check fails, the simulator sends ⊥ from the honest escrows to the corrupted alleger. If verification succeeds, the simulator determines the ID with which pk was registered (since it has all the registered keys), and connects to FSAE from ID’s channel. It then invokes registration with FSAE with (File,m,a,t), which responds with (File,C)

Now the bucketing algorithm takes place, the simulation process for which is identical to the honest alleger case. FSAE returns matching allegations for various buckets, and we simulate for the corrupted escrows, a pseudo-random function on the meta-data. This is possible since we know, for the relevant buckets, meta-data of which allegations match.

When an allegation filed by a corrupted party is to be revealed, FSAE sends ("Reveal", C, t) to the simulator. The simulator cooperates in computing πSAE(pk), where pk is the corresponding key used to file the allegation identified by C. If the adversary refuses to cooperate, the simulator sends ⊥ to FSAE. Else, it sends OK, and cooperates to reveal a, which it knows. ■

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8The simulator knows (m,a) since it has a majority of the necessary shares. Again, if the shares are invalid, it sends ⊥ to the adversary as verifiable secret-sharing is used.