Formal Analysis of Session-Handling in Secure Messaging: Lifting Security from Sessions to Conversations

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Abstract

The building blocks for secure messaging apps, such as Signal's X3DH and Double Ratchet (DR) protocols, have received a lot of attention from the research community. They have notably been proved to meet strong security properties even in the case of compromise such as Forward Secrecy (FS) and Post-Compromise Security (PCS). However, there is a lack of formal study of these properties at the application level. Whereas the research works have studied such properties in the context of a single ratcheting chain, a conversation between two persons in a messaging application can in fact be the result of merging multiple ratcheting chains.

In this work, we initiate the formal analysis of secure messaging taking the session-handling layer into account, and apply our approach to Sesame, Signal's session management. We first experimentally show practical scenarios in which PCS can be violated in Signal by a clone attacker, despite its use of the Double Ratchet. We identify exactly how this is enabled by Signal's session-handling layer. We then design a formal model of the session-handling layer of Signal that is tractable for automated verification with the Tamarin prover, and use this model to rediscover the PCS violation and propose two provably secure fixes to offer stronger guarantees.

1 Introduction

Modern secure messaging apps use intricate cryptographic building blocks to achieve stronger security guarantees. For instance, the Double Ratchet (DR) protocol is a core component of the Signal protocol library, and is used by many secure messaging apps including WhatsApp, the Signal App, and Facebook Secret Conversations.

There is a rich line of research formally analyzing and proving the strong security properties of the Double Ratchet and its variants, e.g., [1, 2, 4, 9–11, 19, 25]. This includes, for example, proving that the DR achieves Forward Secrecy (FS) and modern properties like Post-Compromise Security (PCS): even after a full compromise of a party's device state, attackers are locked out of the conversation again if the victim can exchange a few messages with their partner without the attacker interfering [12]. Over time, these models have been improved in terms of precision, granularity, and threat models, getting closer to real-world DR implementations.

While these are important results, they focus on a specific building block only, and not on the security guarantees that users actually get when using a messaging app. In particular, while the Extended Triple-Diffie-Hellman (X3DH) handshake and the Double Ratchet (DR) have been extensively formally studied, there has been no formal analysis that includes other layers, such as the session-handling. In fact, several application-level behaviors of messaging apps were discovered that seem to offer to their end users lower security guarantees compared to what might be expected from using X3DH and DR protocols, such as [13, 31].

In this work we initiate the formal study of the session-handling layer of secure messaging apps, picking Signal's Sesame protocol as a first case study. This is technically challenging, as we would ideally like to model the entirety of the session handling layer with a detailed model of the X3DH and DR protocols. However, the fact is that state-of-the-art formal approaches struggle to deal with X3DH and DR accurately

even without any additional mechanisms. To make any analysis tractable, we have to devise a reasonable abstraction of the session-handling layer and its underlying building blocks.

We first motivate our work by experimentally showing two scenarios in which Signal Android app v5.40.4 (May 2022) does not achieve PCS despite using the DR protocol. Our core experimental observation that we strive to formalize is that while a single DR session preserves PCS, this does not propagate to the higher level of the conversation between two end users, because conversations are invisible constructed from possibly multiple concurrent sessions that have their own ratcheting chains. Thus, our work ranges from the applied (real-world experiments on the current Signal app with a clone attacker) to the foundational (first formal modeling of session-handling layer for secure messaging, and automated analysis).

Contributions Our main contributions are the following:

- We first show the real-world impact of the session-handling layer: we showcase two practical scenarios in which current the current Signal app does not achieve PCS, despite using the DR protocol, against a clone attacker.
  - Our experiments show how guarantees proven for the underlying building blocks (e.g., in [1, 9, 24]) do not transfer to the application level.
  - We analyze the root causes and determine they derive from design decisions in the session-handling layer of the Signal app: the Sesame protocol.
- We initiate the formal study of security properties of secure messaging that take the session-handling layer into account.
  - We create the first formal model of Signal that includes an abstraction of its Sesame session-handling layer and the underlying ratcheting mechanisms. Notably, we introduce the notion of conversation-based Post-Compromise Security (PCS), which lifts the classical PCS property to the conversation level.
  - Automated analysis of this model using the TAMARIN prover automatically discovers the scenario in which PCS is violated at the session handling-layer despite using the DR protocol.
  - We show that protection against a clone attacker at the session-handling layer of Signal can be improved by a simple fix, and use our model to formally prove that the fix restores conversation-based PCS.
  - Additionally, we propose and prove a fix that enables clone detection.

We provide our models publicly for inspection and reproduction [14]: they are notably intended for developing refined Sesame models or as a starting point to model the session-handling of other apps.

Outline We introduce the required background on Signal and its core mechanisms in Section 2. We then detail two scenarios in which PCS is violated, and their experimental set-up in Section 3. We follow up by proposing our fixes in Section 4. In Section 5 we develop our formal model of Signal's session-handling layer. We then use this model to automatically detect property violations, and to prove that our fix works. We finally summarize our findings and provide an outlook in Section 6. In addition, we provide a third scenario that violates PCS in Appendix A.1 (recently independently reported in [18]), and discuss some additional practical concerns in Appendix A.2.

Related work The notion of PCS was introduced and formalized in [12]. Since then, the Double Ratchet (DR) and Extended Triple Diffie-Hellman (X3DH) protocols have received multiple increasingly fine-grained analyses [1, 2, 4, 9, 11, 19], and are still subject to active study. In particular, recent studies have proposed post-quantum secure versions of the X3DH key exchange protocol [6, 7, 16, 22]. Similar to our approach, some of the previous analysis relied on formal analysis tools [3, 25]. However, these focused on the two underlying DR and X3DH protocols, not Sesame. To the best of our knowledge, we are the first to formally analyze the final security provided by the combination of Sesame and the underlying layers.

In [31], the authors show an attack on Sesame that allows the registration of an attacker's device capable of sending and receiving messages. In another work [8] is proposed an alternative to Sesame that opens only a single channel between two users, while hiding the number of partner's devices. From the experimental point of view, the concrete security of Signal under cloning was studied in [13]. Interestingly, we show that compared to their experiment on Signal Android app version v4.47.7 (August 2019), some security guarantees of Signal were lost compared to version v5.40.4 (May 2022). Previous work on clone detection

propose mechanisms that use *third*-parties [32] or *counters*, *hashing*, and *commitments* [29] to flag the attacker.

The most recent related work is [18] that proposes a new mechanism to provide improve Signal's PCS guarantees. We notably independently rediscovered the same Signal PCS violation, which we describe in Appendix A.1. Overall, their work is orthogonal to ours: they consider a PCS property against a fully active attacker while our attacker is inactive during the small healing time-frame and otherwise active. They also only consider a single DR session, while we put the focus on multiple parallel DR sessions.

2 Background

2.1 Security properties of messaging protocols

In the following, we give an overview of two security properties achieved by the core Signal protocol DR, namely *forward secrecy* and *post-compromise security*. While both capture session security guarantees with respect to a compromise, the former talks about previous sessions and the latter about future ones, as shown in Fig. 1.

Forward Secrecy (FS)   FS is the security guarantee that compromise of a session does not impact the security of previous sessions of the protocol [5]. In other words, despite revealing the current session's state (e.g. identity key and session key) to an attacker, previous message keys cannot be computed.

In reality, there are subtle variants of FS. One main form relates to the compromise of long-term keys such as identity keys and an attacker that can at least observe all network traffic. To achieve this variant of FS, parties can use asymmetric cryptography to derive the session keys from ephemeral asymmetric keys such that each key is independent of the previous, while the identity keys are used for authentication. In practice this is usually realized using ephemeral Diffie-Hellman keys or KEMs, but needs a back-and-forth roundtrip to offer protection. In contrast, if keys were decrypted from network traffic using identity keys, this form of FS would not be met, as they would for example in basic key transport protocols.

A second form of FS involves attackers that can only reveal session/message keys, and can be achieved without roundtrips. This can be achieved by encrypting each with a different key, i.e., an attacker knowing the key of message i, cannot compute the previous message keys $[0, i-1]$. Instead of encrypting the messages with the session key, the latter can be used as an input to a key derivation function KDF (i.e., a one-way function), which outputs a new message key and the forwarded session secret. In the literature, FS can also be achieved using time-based methods [17] or puncturable encryption [15, 20, 21].

Post-Compromise Security (PCS)   PCS is the guarantee a party A has, that security of their conversation with partner B can be recovered (healed) after the compromise of the latter [12]. In other words, leaking the partner's keys does not mean that all future communication can be decrypted. To restore security, the parties need a *healing* phase, during which the attacker does not interfere with the honest communication. Depending on the type of compromise, a protocol offers two levels of PCS a) via *weak* or partial compromise of ephemeral secrets (*session* keys) or b) via *full* compromise of the state (both *long-term* and *session* keys).

Weak-PCS is achieved when the attacker leaks session-specific keys, but has only temporary access to the long-term secrets e.g., if the identity keys are stored encrypted in an external device. This means that the protocol can use the long-term secret (or a token derived from it) to evolve old corrupted session keys and lock the attacker out. More specifically, the parties can compute the session key *sk* for run i of the protocol as $sk_i = KDF(sk_{i-1}, token)$. If the session key is forwarded this way, the attacker cannot compute future keys without knowing the token, hence security is restored.

In the full compromise case, the attacker knows all the keys at the time of compromise, therefore the parties need to incorporate new ephemeral secrets in the derivation of the session key. This can be done using asymmetric cryptography [19, 23, 24], such that enough entropy is introduced in the session key during the healing phase, e.g., using the Diffie-Hellman output as the token. Having been passive in the healing phase, the attacker cannot compute the new key.

2.2 Double Ratchet

Signal's Double Ratchet (DR) is a widely used protocol to exchange messages between two parties which guarantees strong security properties such as forward secrecy and post-compromise security. The protocol is
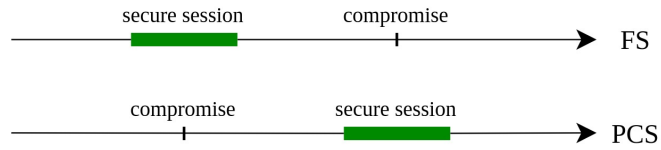
Figure 1: Forward Secrecy (FS) and Post-Compromise Security (PCS).

constructed by two parts: a symmetric and an asymmetric ratchet, the latter also referred as the Diffie-Hellman (DH) ratchet. As a prerequisite, DR expects the parties to authenticate one another and establish a shared key before the start of the protocol, e.g., Signal uses the Extended Triple Diffie-Hellman (X3DH) protocol [26].

DR is constructed from a hierarchy of three types of keys: a root key which is the shared key between the parties at the start of the protocol, chain keys derived from the root key, and message keys derived from the chain keys. When the parties switch their roles, say from sender to receiver they perform the asymmetric step, and when they maintain the same role they perform the symmetric step. We will shortly summarize both ratchets below, and refer the reader to the documentation [30] for more details.

Asymmetric Ratchet   The core idea of this step is to introduce ephemeral DH keys into the root key, thus achieving PCS. Consider a party A switching roles, say from receiver to sender. They generate a DH key pair (a, g^a), and get their partners public key g^b. Then, A computes the current root key rk_i and sending chain key ck_0 using a KDF with input the old key and the DH output, i.e., $rk_i, ck_0 = \texttt{KDF}(rk_{i-1}, g^{ab})$. The initial sending chain ck_0 serves as input for the symmetric ratchet to derive the actual message keys. A will keep performing the symmetric ratchet, i.e., send messages sequentially, until interrupted by an incoming message, signaling role switch with the partner.

Symmetric Ratchet   The symmetric step forwards the chain key, using a KDF function, to derive new keys for each message, thus providing forward secrecy, Resuming the previous example, A can now compute any message key mk_i from the chain key, specifically, $ck_i, mk_i = \texttt{KDF}(ck_{i-1})$. Then, A uses mk_i to encrypt a message and along with the ciphertext sends their public DH key g^a. Upon receiving this message, the partner will compute the same steps and be able to decrypt.

2.3   Sesame: Signal's session management

Sesame is a session management protocol responsible for managing sessions and multiple devices for the libsignal library. The protocol enables a user to link several devices to their account and handles the synchronization of messages sent and received with the devices of their partners. The core idea is to create a session between the sending device and every other device of both parties, i.e., a message sent from user A to B is encrypted for every device of B and all other linked devices of A. This means that Sesame has to manage a local database containing the records of each partner's device and their respective open sessions. To maintain the device list, Sesame depends on the Signal server to inform it of any new or removed devices. In addition, Sesame uses a mailbox server to store the messages sent to devices until they can retrieve them, enabling asynchronous communication.

Additionally, Sesame is designed to handle multiple sessions between two devices. According to the specification, this is done to facilitate the convergence to a single session in those cases when two devices are desynchronized. These cases include: a) parties starting a session simultaneously and hence resulting in different derived keys, b) one of the parties restoring an old backup, or c) losing their local state. Sesame keeps a list of multiple sessions per device, and upon receiving a message encrypted from any of them, promotes it as the new *active* session, thus making both parties agree on the current state.

Initialize Session   Sesame uses a key agreement protocol (i.e., X3DH in Signal) to initialize the sessions between the sending device and all the receiving devices. To enable this, X3DH needs at least two types of keys: an identity key and an ephemeral key, called a pre-key bundle. The idea is to use the keys of both parties in an intricate key derivation algorithm, in which only the two involved participants can derive a common secret [26]. In the implementation of Sesame, the identity key pair is assigned per user account, and the ephemeral keys are generated per device and signed by the identity key. This allows for both user

authentication and uniqueness of session keys among the devices of the same account. When a device wants to start a new conversation, they receive from the server an updated list of all the devices and per device pre-keys of the intended recipient. The user will start a new session for each of the devices and store the session keys indexed per user, device and a session identifier.

Multiple Sessions   Sesame manages a local list of sessions between two devices, where only one is the current *active* session and the others are stale sessions kept for synchronization or out-of-order messages. A session is defined by the completion of a key exchange resulting in a new shared key. This means that the secrets (root, chain, and message keys) derived for each session are independent of another. When a message is received in Sesame from any of the sessions, that session will be marked as the current active session. The reactivation of older sessions, enables a) the decryption of messages without loss, and b) agreement on a common session even when the parties are momentarily desynchronized.

Retry Message   Another feature of Sesame is to keep a record of sent messages until the sender receives a valid receipt message. This means that if the partner cannot decrypt any message, they can send an *unencrypted* retry request indexed by the message identifier. Upon receiving the request, the sender encrypts the message with a new key derived from either: a) the current active session (in case it is different from the one used to encrypt the message previously), or b) establish a new session with the device.

Session Reset and Expiration   Sesame also suggests a session expiration policy, however the implemented mechanism differs from the specification. In the design of Sesame, it is suggested to delete old sessions depending on their creation timestamp. In practice the app limits the of number sessions (40 sessions) that are maintained at any time in a FIFO fashion i.e. anytime it creates a new session it removes the last one in the pile from the list. In addition, previous versions of the Signal app used to offer a session reset which is not included in the specification. The idea is that the users can trigger the creation of new sessions themselves directly from the user interface. However, this was deprecated in Signalapp version v5.25.0[1]. Instead, the conversation is automatically reset every one hour when the two parties need to establish a new session. This means the keys used in the conversation are replaced every hour by freshly computed ones. In theory this could yield increased security for the protocol, however as we will see later, this is not the case in practice.

3   Concrete Signal scenarios violating PCS

In this section, we show two real-world scenarios in which a clone attacker can violate PCS for Signal, which are consequences of the current design of Signal's session-handling layer Sesame. In our scenarios, we consider a so-called *clone* attacker. The clone compromises the full state of a party, including session specific keys and long-term identity keys. However, it is limited in using the user interface of the app, instead of performing complex operations with the compromised secrets. In practical terms, this can be an attacker gaining temporary access to a device and duplicating its contents to run a parallel app instance. Notably, the clone does not need to have any knowledge of intricate attack vectors or the inner workings of the protocols. Our experiments were performed on the Signal Android app version v5.40.4 (May 2022).

Intuitively, we consider the following scenario in attacking the conversation between A and B: At some point during the message exchange between the honest parties, we compromise A's device, effectively cloning it. We then have A and B continue their conversation without the attacker being online, i.e., the *healing* phase. From the analyses of the DR protocol, we expect that this heals the conversation. We then re-activate the clone. The expected behavior now is that the clone should be locked out of the conversation of A and B.

From a high level point of view, we found the following scenarios that violate this expectation:

1. if an old clone and the honest partner are online, decryption failures on the clone side trigger retry messages, that result in a new session agreement and the honest partner resending previous messages to the clone (Section 3.1), and
2. after a time-triggered reset (creating a new session), a clone can still re-enable an old session (Section 3.2).

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[1]Signal's Session Reset Deprecation: link.

We did find a third scenario in which PCS is violated: old receiver chains that are still stored can be prolongated by a clone. We describe this scenario in Appendix A.1, since (a) it exploits the DR implementation, and is not linked to Sesame's design, and (b) it was independently reported in recent work [18].

Interestingly, a clone that simply uses the unmodified Signal app is enough to perform these scenarios. In the following, we show how we were able to exploit emulated clones to produce the attacks on the deployed Signal app, and explain the attacks using Signal's log as well as the Sesame/Signal specifications and its open source code.

Experimental setup   We conducted a series of experiments on the Signal application to find potential weaknesses introduced by Sesame. First, we created two legitimate accounts in the deployed messaging app (version 5.40.4). To register the users, we modeled two android devices (Android Api 10.0) using the Genymotion emulator (version 3.2.1). After the two honest parties started a conversation together, we investigate the consequences of a compromise. Our threat model allows for an attacker to fully compromise the state of a party and run another instance of the app with the cloned state. To mimic this, we used the cloning feature of the emulator, which allows to fully duplicate an entire virtual machine. We then explore the behaviors of the multiple parties by exchanging messages between them, triggering different behaviors (such as message resend, session reset, etc) potentially leading to violations of properties such as PCS.

To precisely identify the causes of the observed behaviors we downloaded the debug logs provided by the app.[2] From these logs, we can extract the following information:
1. Which chain keys are used for encryption (unique public identifier of the chain key for logging purpose)?
2. When do parties send retry requests?
3. When did the parties initialize a new session?

This allowed us to deduce which actions were triggered to allow messages to be received without any error in the user interface, which should have otherwise been protected by PCS. In addition, since Signal's library is open source, we cross-checked with the implementation and pinpointed the exact parts of the code that enabled the scenarios.

Notation   The experiments are conducted between 3 agents: two honest parties A and B, and A's clone (A_{clone}). When a message is sent from A to B we use the notation $A \rightarrow B$ and vice versa. To denote that the parties are exchanging roles between sending and receiving we use $A \leftrightarrow B$, which means $A \rightarrow B$ and $B \rightarrow A$. Repetition of the message exchange n times is expressed as $(A \leftrightarrow B)^n$.

3.1   Abusing the Retry feature

In this scenario, we investigate whether a compromised party can recover the security of the conversation once all chain keys known by the attacker are deleted from the app's local memory. The experiment considers two parties A and B having a conversation, until A is cloned (i.e., the attacker has an identical copy of the messaging app). The honest parties continue the conversation without interference; in terms of the underlying DR, this should enable healing. Once the clone's machine goes online, they check if the clone receives past messages or can inject new ones in the conversation.

Concretely, we have A and B exchange more than 5 messages in the conversation after the clone to represent healing, and we check if the clone can still inject their own messages in the conversation. We need 5 or more messages, because, as shown in Appendix A.1, the conversation does not heal due to Signal storing at any time the latest 5 receiver chains, which can be extended by the clone.

In this experiment, we noticed that B was able to receive all the messages sent from the clone, as long as the two are online at the same time. This means that PCS is not guaranteed, since the clone can continue the conversation even after 5 consecutive healings. We will now see how A_{Clone} and B resynchronize, abusing the retry feature of Sesame.

Concrete steps   The steps to reproduce the scenario are the following:
1. A and B exchange 4 messages: $(A \leftrightarrow B)^4$.
2. Duplicate A's machine and send clone offline.
3. A and B exchange 6 more messages: $(A \leftrightarrow B)^6$.
4. A goes offline, and clone goes online.

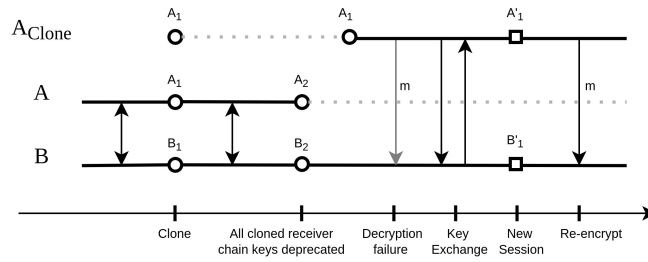[2]Logs are found in the user interface under Settings/Help/Debug Log.

Figure 2: Abusing the retry option upon decryption error on Signal. After parties A and B exchange messages, A at state $\circ A_1$ is cloned. The clone goes offline (denoted by the dotted line) and the parties exchange messages to heal their session to $\circ A_2$. A goes offline, while the clone encrypts a message m with the old session state $\circ A_1$. B cannot decrypt the message, so they initiate a new session marked, respectively, as $\square B_1'$ and $\square A_1'$. B can decrypt the message received in the last step.

5. Clone sends 4 consecutive messages to B $(A_{Clone} \to B)^4$
6. B can decrypt the messages sent by the clone.
 Fig. 2 illustrates the scenario described above.

Analysis   The experiment shows that the clone can insert their own messages despite the honest parties having deleted all the compromised chain keys from memory. This is due to Sesame's feature of retrying to send a message. Basically, once B receives the clone's messages sent in step 5), it realizes that it cannot decrypt them and sends a retry receipt. Once the clone processes the message, it will initiate a new X3DH key exchange with B and re-encrypt the messages using the new session's keys. Now, B can derive the new session keys and decrypt the messages.

We verified with the app's logs that the clone received the retry receipt from B, followed by fetching keys from the server and starting a new session. Also, on the receiver's side in B's logs, we can observe the successful decryption in the newly created session. The retry mechanism is described in the Signal documentation[3] and implementation[4]. We thus showed how the retry option of the session management breaks the PCS guarantee offered by the underlying protocol DR, by allowing a clone to continue the conversation with A's partner despite the healing phase. In fact, not only can the clone inject messages, but also have a conversation in parallel to A, as we will show in the next scenario.

3.2   Abusing session reactivation

As the conversation evolves, Signal automatically resets sessions every hour, i.e., the parties generate new secrets and deprecate the old ones. One would assume that this increases the security of the conversation, and potentially prevents the scenario from Section 3.1. However, Sesame allows for older sessions to be reinstated as the main sending session, i.e., the parties will encrypt messages using the latest state of these sessions. The following example gives an intuition on why this seemingly small feature can break the PCS security.

Example: Consider the clone of a compromised party as described in Appendix A.1 and Section 3.1. The two honest parties resetting the session means that all compromised session secrets are replaced by new ones. From the DR design, this implies that the attacker has no knowledge of the current session keys and should be locked out of the conversation. However, due to the time-based reset, once the clone goes online they will start a new session with the partner as well and can continue the conversation. In addition, Sesame stores previous sessions and promotes any old session as the current active, upon receiving a message from it. Assume now that the honest party also sends a message from their session. Upon receiving the message, the partner will switch to the session that it can be decrypted with and reply to the honest party using the keys stored there. As a result, the victim can also continue the conversation, despite the clone doing the same in parallel in another session.

Concrete steps   The steps for this scenario are:

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[3] Sesame's retry option documentation: link.
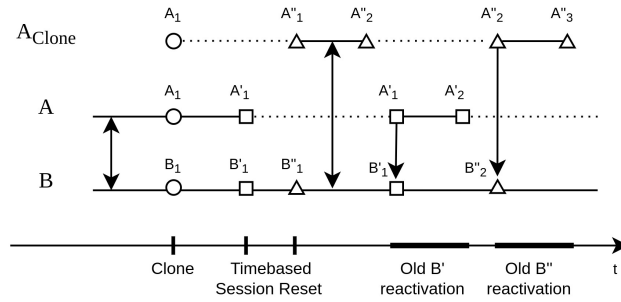[4] Sesame's retry option implementation: link.

Figure 3: Abusing session reactivation, making it possible for A and its clone to have parallel sessions with B. A and B exchange messages, until A at state $\circ A_1$ is cloned. The clone goes offline (denoted by the dotted line) and the parties exchange messages until session reset at $\square A'_1$. A goes offline, and when the clone sends a message, the automatic reset starts a new session $\triangle A''_1$ and respectively for $\triangle B''_1$ for B. Now, when A sends a message, B reactivates $\square B'_1$, and $\triangle B''_2$ for when the clone does.

1. A and B exchange 4 messages: $(A \leftrightarrow B)^4$.
2. Duplicate A's machine and send clone offline.
3. Signal resets the session after 1 hour.
4. A and B exchange 6 more messages: $(A \leftrightarrow B)^6$.
5. A goes offline, and clone goes online.
6. Clone sends 4 consecutive messages to B $(A_{Clone} \rightarrow B)^4$
7. B can decrypt the messages sent by the clone and continue the conversation.
8. Clone goes offline, A online. A encrypts 4 messages to B $(A \rightarrow B)^4$.
9. B can decrypt the messages sent by A.

Fig. 3 shows the scenario described above.

Analysis   The experiment shows that indeed A and their clone can have parallel conversations with B, without the conversation ever healing or any of the agents receiving any notification or sign of compromise in the user interface. The parties exchange 6 messages in step 4) in order to delete any old stored keys. The previous scenario is excluded, since the time-based reset makes it impossible for the clone to use the old compromised session. Instead, they are forced by the app to start a new session with B and encrypt their messages with correct keys. This means that B has no reason to issue a retry request. Note that the clone interacts only with the user interface, therefore it strictly follows the Signal protocol. The same logic follows for the real A at step 8), where they send messages with keys B is able to compute, hence no decryption error is thrown in the app (no need for retry option).

There are two mechanisms intertwined here:
- The reset session between the attacker and A allows for the compromise to continuity.
- The session switching allows for a compromise and honest session to exist in parallel without any detection.

We could confirm from the logs that a new session was indeed established between the clone and B at step 6. And from the logs, we confirmed that when receiving a message from an old session, B would log that they "decrypted with previous session state", which is also visible in the implementation [5]. We thus saw the old session reactivation at step 8). This could go on like this with B alternating between the compromised and the honest session, where the latest one used to receive is promoted to be the current active one [6]. The victim can never heal in this case, since on every automatic reset both of them are forced by the app to start two new parallel sessions with B.

Existing mitigation   There is currently a bound on the number of sessions stored (40 sessions). We would expect this bound to lock the attacker out at some point. However, this is not the case for two reasons.

First, consider the case of a full compromise of both the identity key and the session states, which corresponds to our previous experiment. Let us assume that the clone stays offline for more than 40 hours,

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[5]Sesame's Previous Session Decryption: link.
[6]Sesame's Session Reactivation: link.

which is the lifetime of a session before it is deleted[7]. A and B can then delete enough sessions so that old ones cannot be reactivated. However, because the clone knows the identity key, it will automatically start a new session with B when going back online.

Second, let us consider a weaker threat model where the bound would intuitively be enough: the case of a partial compromise, where only one session was compromised and the attacker cannot initiate new sessions with B. Then, it seems that the bound would still not be enough, as an attacker could regularly send messages to B, so that even if no reset goes through, the compromised session is regularly promoted and stays at the top of the stored session list, and is thus never dropped. This could be circumvented if the implementation followed the session's expiration policy (see Section 2.3). Note that to carry out this experiment, we would however deviate from an attacker that simply uses the official Signal app.

4   Improving Sesame's PCS guarantees

Experimental summary   Currently, Signal's session-handling layer allows the following scenarios in which PCS is violated:

1. After a compromise, the cloned device can initiate new sessions with the partner. The creation of this new session may either follow a session reset from a timeout as in Section 3.2, or from a retry receipt Section 3.1.
2. When there are both a malicious session and a valid session running in parallel, the compromise will continue undetected, as we showed in Section 3.2.

Threat model systematization   Our aim is to propose provable fixes in the later sections. We thus need to clarify the set of relevant threat models, as summarized in Fig. 4.

The threat model considered in Sesame's specs, which we will refer to as threat model $\mathcal{A}_{\text{Signal}}$, is defined as a passive attacker that has fully compromised the device's state. Its claims of security against a passive attacker are derived from the underlying protocols it manages the sessions for, namely DR and X3DH. A passive attacker is an eavesdropper that does not interfere with the protocol flow or the agents in any way.

In the literature however, it is shown that DR is resilient to a stronger adversary that not only has total control over the network but can drop, inject and manipulate any message actively. In an ideal world, we would be able to lift the guarantees from the literature over the DR to Signal, even in this stronger active attacker threat model. We will refer to an active attacker that can fully compromised the state of an agent as the threat model $\mathcal{A}_{\text{Ideal}}$, the ideal goal. However, Signal has no mechanism to achieve this, since it would require to refresh the identity keys of compromised agents, which is currently treated as a new registered user. Achieving PCS for $\mathcal{A}_{\text{Ideal}}$ would then require significant new developments to the standard.

However, there are two interesting weakening of $\mathcal{A}_{\text{Ideal}}$:

1. Our experiment threat model $\mathcal{A}_{\text{Experiment}}$: an attacker that can compromise fully the user, but then strictly follows the protocol and the features from the app.
2. Our formal analysis threat model $\mathcal{A}_{\text{Formal}}$: an active attacker that can however only compromise a single session and not the identity keys.

$\mathcal{A}_{\text{Experiment}}$ has already been considered in a previous work, which proved that Signal could achieve PCS for this threat model. This is not the case anymore as shown in Section 3. In addition to losing PCS in $\mathcal{A}_{\text{Experiment}}$, we also demonstrate in our formal analysis that PCS is in fact lost by design in Sesame for $\mathcal{A}_{\text{Formal}}$. This in turn makes it impossible to achieve PCS for $\mathcal{A}_{\text{Ideal}}$ even with new mechanisms for identity key revocation. Further, achieving PCS at $\mathcal{A}_{\text{Ideal}}$ with a key revocation implies to be able to know when we need to revoke keys: there is the need for clone detection at the lower levels.

Fixes overview   To restore the Sesame PCS in $\mathcal{A}_{\text{Formal}}$, our first fix specifies that an outdated session must only be allowed to receive older messages, and never re-enabled to send new ones. Moreover, our second fix specifies that receiving a message on an outdated session should trigger a warning message, sent to both the current and the outdated session, thus enabling for clone detection on the other end. Our first solution is a minimal fix to restore PCS that does not break the current functionalities and ensures that no messages are lost. Our second fix requires adding messages to the protocol flow, and is thus slightly more complex to implement.

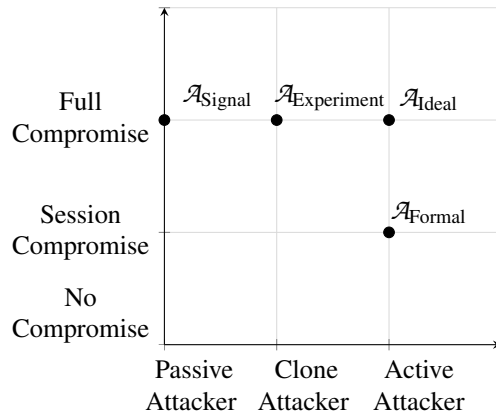[7]Number of stored sessions in Signal: link.

Figure 4: Signal's threat models categorized by attacker capabilities and level of compromise. The four threat models are: the threat model from Signal's specification ($\mathcal{A}_{\text{Signal}}$), the DR's literature threat model ($\mathcal{A}_{\text{Ideal}}$), the experiment model in this work ($\mathcal{A}_{\text{Experiment}}$), and the formal analysis model ($\mathcal{A}_{\text{Formal}}$). Full compromise means session and long-term keys compromise.

In the following, we first precisely describe our fixes, and then show how we prove their security using the TAMARIN prover. From a high level point of view, we provide four distinct security results:

- We prove that when restricted to a single session between two parties, a model of the Double Ratchet with idealized cryptography does provide PCS. This also leads to a clear formalization of the best PCS guarantees that the Double Ratchet can provide.
- We show that when multiple sessions are allowed in parallel, our model is expressive enough that the scenario of Section 3 is automatically found in TAMARIN.
- We prove that when implementing our first fix, we restore PCS between two parties.
- And finally, we prove that the clone detection fix is sound: it does not raise false positives and cannot be triggered without an actual compromise.

4.1 Description of fixes

PCS fix As we have seen, PCS is lost because healing one session does not heal others. Subsequently, we should make sure that after the current active sessions have been healed from a compromise, older sessions cannot be used again. A first idea would be to instantly fully deprecate older sessions and keys whenever we create a new one. However, this results in messages being lost because the parties are unable to decrypt out of order messages. Thus, we instead suggest that:

- sessions must never become active again and used to send messages after they became inactive;
- inactive sessions can still be used to receive messages.

The solution is simple, practical, and preserves the current level of usability with minimal changes to the code. As we will formally prove later, it allows lifting the precise PCS guarantees provided by a single session to multiple sessions.

With respect to the specification, our fix is obtained by removing item 4 of section 3.4 from [27]), which says that upon decryption of a message "if the relevant session is not active it is activated". This step of the algorithm is responsible for promoting an old session as the current active one.

The issue of Clone detection With our previous fix implemented, we restore PCS in $\mathcal{A}_{\text{Formal}}$, but a clone in $\mathcal{A}_{\text{Experiment}}$ may never be detected. Indeed, whenever either the clone or the honest party go online, they can trigger the creation of a fresh session and become the current active session with their partner. This results in the inactive party to simply not receive any message as long as it does not go online. We thus propose a mechanism that allows the detection of such behaviors. In particular, assuming that A is talking to B, and A_{Clone} is a clone of A, we need to detect the following two situations:

- *A* and *B* share an active session, and *B* receives a message from A_{Clone} in a deprecated session.
- A_{Clone} and *B* share an active session, and *B* receives a message from *A* in a deprecated session.

It is impossible for *B* to distinguish whether the received message is from a clone or the honest party. However, *B* can notify their partner that they received a message from a deprecated session and include in

this warning message some information about that session. This way, the responsibility falls on to the victim *A* to decide whether this warning message implies the existence of a clone or not. To cover the two previously described situations, we need to make sure that *A* receives the warning message in either case, therefore *B* needs to encrypt it for both the outdated and the active session.

There is a core difficulty for the clone detection mechanism: the mechanism should not be activated during the normal operations of the protocol, i.e. only a cloning behavior should result in a detection. Otherwise, an external attacker can trigger false positives and carry out e.g. denial of service attacks. This property has been called the *soundness* of clone detection in [29].

Clone detection fix We make three additions to the current flow. First, we specify that when a new root key rk is computed, both parties derive a root key identifier $\mathsf{pk}(\mathsf{rk})$ and a warning key $\mathsf{wk} = \mathsf{KDF}(\textit{"warning"}, \mathsf{rk})$ and store them in memory. Then, when *B* with a current active session root key rk_a receives a message inside an inactive session with root key rk_i, *B* sends to the other party the pair of ciphertext $(\mathsf{enc}(\mathsf{pk}(\mathsf{rk}_a), \mathsf{wk}_i), \mathsf{enc}(\mathsf{pk}(\mathsf{rk}_i), \mathsf{wk}_a))$. Finally, whenever a party receives a warning message that decrypts to $\mathsf{pk}(\mathsf{rk}_x)$, if this identifier is stored in the memory, the warning is ignored, and if this identifier corresponds to a root key never computed by the other party, the compromise error is raised.

5   Formal Analysis of Secure Messaging with Session-Handling

In this section, we describe our multiple formal models and give the intuition behind their security proofs. To perform the analysis we rely on the TAMARIN prover, which we introduce in the following along with its way to model security properties. We summarize our security analysis in Table 1 and show the results obtained using the TAMARIN prover in Table 2.

5.1   Tamarin

The TAMARIN prover is a tool for formally modeling and analyzing complex cryptographic protocols [28]. TAMARIN works within the symbolic model, meaning that messages are expressed as terms built from variables, constants and function symbols. Rules allow modeling the possible protocol steps, or protocol actions, that can be executed by the multiple parties in parallel, and thus model network inputs, outputs and computations.

Rules can be labeled with so-called events. The semantics of the rules together with the labels yield the set of possible executions, i.e., possible behaviors of the protocol sessions in the presence of the adversary. The security properties are then modeled as guarded first-order logic formulas, and can refer to the events occurring in a specific trace, e.g.,

$$\forall \textit{ userId}, \textit{key}, i. \ \mathtt{ReceivedPayload}(\textit{userId}, \textit{key}) \ @i$$
$$\Rightarrow \neg\exists \ j. \ \mathtt{K}(\textit{key}) \ @j$$

Here `ReceivedPayload` is the event raised whenever the user identified by *userId* receives a payload encrypted with *key*, and *K* is a builtin TAMARIN event that models that the attacker knows or can compute the argument. Intuitively, this property states that if a user has received a payload at some timepoint *i* inside a trace, there is no point *j* in the trace where the attacker can compute the decryption key. In other terms, this is the secrecy of the keys.

The tool has a built-in attacker, the so-called Dolev-Yao attacker, which has control over the network and can inject, drop and manipulate any traffic. Furthermore, TAMARIN allows the user to add custom equational theories to model additional attacker capabilities or data structures.

Given a protocol model, a specification of the attacker and a security property, the tool returns either a proof that the property holds for all traces of the protocol, a counterexample, or it does not terminate (the underlying problem is undecidable). In case of termination, the user can inspect the proof steps or the graphical representation of the counterexample in the interactive mode. Moreover, the user can guide the tool in proof finding, by writing and proving helper lemmas such as invariants of the protocol.

5.2   Formal model with Session Handling

We first systematize here the points that should ideally be taken into account to perform a formal analysis of Signal, or any similar application. This corresponds to an ideal goal, that we found is currently out of reach

for existing automated analysis tools such as Proverif or Tamarin. We thus introduce several simplifications and abstractions in order to perform a first formal analysis of the core mechanism that we aim to improve here, the multiple session management.

Ideal Goal and limitations   In an ideal world, to study the PCS guarantees of Signal a formal model should capture:

- a model of the X3DH and the DR protocols, including publication of Diffie-Hellman share bundles signed with identity keys on the server;
- capture the multiple session managements as well as new device registration;
- allow for compromises of all different materials, chain keys, root keys and identity keys.

Verifying such a model is currently out of our reach and its analysis would probably need to rely on modular result. For instance, the latest Signal analysis using Proverif only considers the X3DH protocol followed by only three message exchange in the DR [25]. To make this first study of the multiple session management tractable, we thus performed several simplifications and abstractions. As we will see when discussing the proofs, they required significant human intervention, even with the following abstractions. We estimate the human effort to be in the order of a month.

Atomic operations   To tame the complexity, we abstracted away the initialization of the sessions, replacing the X3DH protocol by a single step creating a new session between two given parties. The intuition is that at our higher level, if X3DH is secure and was successfully completed, then it should be equivalent to instantiating a fresh shared secret between the two parties. We also simplified the asymmetric ratchet step of the double ratchet, by collapsing the sending and the receiving steps into a single rule, which instantly provide the two parties with a new shared secret value to rely on. This is in fact a simplification needed to capture the PCS property: in our context, healing means that an asymmetric ratchet was fully completed and that the attacker did not interfere with its execution. As such, the PCS property considers the asymmetric ratchet, which is the healing step, as an atomic step that the attacker cannot interfere with. If the attacker can interfere and for instance block the execution of a healing, PCS cannot even be expressed in a meaningful fashion. The difficulty of formally verifying PCS against active adversary is also discussed in [18]: instead of seeing the asynchronous ratchet as an atomic step that the attacker cannot interfere with, they choose to base their security definition on an additional recurring authentication mechanism running in parallel that the attacker must try to cheat.

As a consequence of the two previous simplifications, notice that our model does not need to explicitly capture Diffie-Hellman exponentiations, as we directly model the resulting fresh secret. This significantly reduces the complexity of the symbolic analysis, and may be one of the core points that makes the analysis tractable.

Multiple devices   We considered that device registration is a separate operation and that it was reasonable to not include it in the model. With respect to Sesame and our observed PCS violations, we showed in the experiments that the attacks were indeed possible even with a single device registered.

Possible compromise scenarios   Each possible compromise adds a layer of complexity to the PCS proof, as it introduces new cases in which the attacker may break the security. In our models, we do not capture the fact that the attacker can compromise the long term identity keys of a party, similarly to [18]. This is meaningful because long term identity keys can be stored in a more secure way, and one first needs to consider PCS against only chain and root key compromise before hoping to achieve it against stronger attackers.

Our formal model and fixes in fact pave the way to aiming for PCS against such strongest forms of compromise: if we have PCS when everything but the long term keys are compromised, we force the attacker to use the identity keys to sign new pre-key bundles in order to maintain the compromise, and simple mechanisms could be set into motion on the honest devices to detect those malicious bundles.

Final Protocol Model   Our formal model allows performing the following actions in an atomic fashion:

Initialization - Instantiates a new session with a fresh shared root key between two participants. This corresponds to reaching the final state of the X3DH in a single step.

Send Message - Symmetric ratchet performed on the sender side.

Receive Message - Symmetric ratchet on the receiver side.

Skip Message - Skip a message and ratchet forward to receive a later one.

Asymmetric Ratchet - In a single step swap sender and receiver roles, giving them a new fresh shared root key.

Every initialization leads to the creation of a fresh session between the two parties, each party creating a fresh identifier sid_A and sid_B to identify this new session. In our core model, the number of parties, the number of possible sessions between two parties, as well as the number of ratchets (symmetric and asymmetric) within a given session are all unbounded. By adding restrictions on how parallel sessions are managed, this first model can then be used to instantiate multiple variants of Sesame.

Threat Model The attacker has full control over the network, can manipulate and build new messages, but the cryptography is assumed to be perfect. That is, the attacker can see the encrypted sent messages, but can only decrypt them if it knows the secret key.

In addition, we also consider that the attacker can at any time compromise the currently stored keys of a party, e.g. learn their sending/receiving keys or root keys. An important point is that due to skipped messages, a receiving key can be compromised at any time in the future even after asymmetric ratchets. This corresponds to the behavior of storing old receiving chain keys.

As a consequence of this threat model, remark that if the attacker knows the current key, it can then decide to trigger an asymmetric step either with the receiver or the sender, which locks out the other party.

Session-based PCS We first define here the classical PCS property, which considers the security of each session individually, and thus effectively reasons only about a single ratchet chain. Intuitively, whenever inside a session there was a heal and a message sent afterwards, the attacker cannot learn this message unless it compromises one of the party again. Conversely, the only way that the attacker can decrypt a message is to perform a compromise after the latest heal.

We raise the following events to express the session-based PCS property:

- the event $\text{Sent}(\text{sid}_a, A, B, \text{sck})$ whenever the agent A over its session sid_A sends to agent B a message encrypted with the encryption key sck;
- the events $\text{Heal}(\text{sid}_A, A, B)$ and $\text{Heal}(sid_B, B, A)$ when the two parties perform an asymmetric ratchet, and thus heal their session;
- and raise $\text{Compromise}(A, B)$ whenever the attacker chooses to compromise the cryptographic material of a session of A talking to B.

Capturing this PCS notion formally using TAMARIN's first-order logic language, is as follows:

$$\forall A, B, \text{sid}_A, \text{sck}, i, j, k.$$
$$\text{Sent}(\text{sid}_A, A, B, \text{sck})@i \;\&\; \text{K}(\text{sck})@j \;\&$$
$$\text{Heal}(\text{sid}_A, A, B)@k \;\&\; k < i$$
$$\Rightarrow \left(\begin{array}{l} \exists l. \, \text{Compromise}(A, B)@l \;\&\; k < l \\ \| \; \exists l. \, \text{Compromise}(B, A)@l \;\&\; k < l \end{array} \right)$$

This means that if we are in a situation where A sends a message to B using sck key, $\text{Sent}(\text{sid}_A, A, B, \text{sck})@i$, and A healed before sending this message, $\text{Heal}(\text{sid}_A, A, B)@k \;\&\; k < i$, and the attacker knows the key $\text{K}(\text{sck})@j$, then the attacker must have compromised the keys of A talking to B after the heal $\text{Compromise}(A, B)@l \;\&\; k < l$, or the keys of B talking to A.

Conversation-based PCS One of the core insights in our formalization is that the app user does not (cannot) observe PCS per session: messaging apps invisibly merge different sessions with the same peer into a single displayed conversation. This is also ultimately the reason why the PCS properties proven for the DR do not seem to hold at the session-handling layer. Instead, at the session-handling layer or higher, we need to use a different technical definition of PCS that considers the conversation between two agents instead of sessions. This effectively encodes that from the user's point of view, multiple sessions are invisibly merged into a single conversation. Indeed, in all our experiments, the classical per session PCS holds, but the intuitive notion of PCS over the full conversation shown to the user at the higher level does not. To express this new goal, we drop the session identifier from the send and heal event. If there is any healing phase during the conversation, that is, over any of the involved sessions, then any message sent afterwards should be secret

Mechanism	Source	Threat Model	PCS	Clone Detection
Double Ratchet	[1]	$\mathcal{A}_{\text{Formal}}$	✓ [1, 4, 9, 11]	Implicit
Old Sesame	v4.47.0	$\mathcal{A}_{\text{Experiment}}$	✓ [13]	✗
Sesame (currently deployed)	v5.40.4	$\mathcal{A}_{\text{Signal}}$	✓	✗
		$\mathcal{A}_{\text{Experiment}}$	✗ [Section 3, Appendix A.1]	✗
		$\mathcal{A}_{\text{Formal}}$	✗ [Section 5, TAMARIN]	✗
Sesame with sequential sessions	This work	$\mathcal{A}_{\text{Formal}}$	✓	Implicit
Sesame, sequential sessions + warning message	This work	$\mathcal{A}_{\text{Formal}}$	✓	✓

Table 1: Security Analysis Summary

Summary of our results, both experimental and using the TAMARIN prover. We report on the security of a single session Double Ratchet, on the older version Sesame studied in a previous work, on the currently deployed Sesame mechanism, and on our two proposed incremental fixes.

Mechanism	Source	Property	Result	Run Time (s)	Helper Lemmas
Double Ratchet (Sesame with single session)	[1]	PCS	✓	25	24
Sesame (currently deployed)	v5.40.4	PCS	✗	2	0
Sesame with sequential sessions	This work	PCS	✓	36	27
Sesame, sequential sessions + warning message	This work	Clone Detection	✓	31	23

Table 2: TAMARIN Formal Analysis Summary

Results obtained with the TAMARIN prover. Our proofs are obtained by using a so-called oracle to guide TAMARIN's proof search, as well as some manually stored proof. We describe the run time needed for TAMARIN to find the proof automatically and verify the manual proofs for each lemma. When running the models we did not include the supplementary proofs, such as forward secrecy. The models were run on a Intel(R) Xeon(R) CPU E5-4650L 2.60GHz server with 756GB of RAM, and 4 threads per TAMARIN call. In addition we give the number of helper lemmas needed to prove the property, which are intermediate lemmas manually specified to prove the protocol.

unless there is a new compromise. This yields the following instantiation of conversation-based PCS:

$$
\begin{aligned}
&\forall\, A, B, \mathsf{sck}, i, j, k. \\
&\quad \texttt{Sent}(A, B, \mathsf{sck})@i \,\&\, \texttt{K}(\mathsf{sck})@j \,\& \\
&\quad \texttt{Heal}(A, B)@k \,\&\, k < i \\
&\quad \Rightarrow \left(
\begin{array}{l}
\exists\, l.\, \texttt{Compromise}(A, B)@l \,\&\, k < l \\
\parallel \exists\, l.\, \texttt{Compromise}(B, A)@l \,\&\, k < l
\end{array}
\right)
\end{aligned}
$$

While at first glance this property may seem slightly simpler than the session-based property, its proof obligation is in fact more complex: because the sending and healing are no longer bound to the same specific session, this property depends on the scope of healing in relation to messages sent in *any* session of the sender. As we will see later, our proof of conversation-based PCS requires us to first prove that session-based PCS holds.

In addition to these two PCS properties, we also model the forward secrecy (FS) properties, which essentially state that the attacker can only learn messages after it compromised a session. FS is in fact often an intermediate step towards proving PCS. We only discuss the more interesting PCS proofs in the following discussions but note that we in all cases also proved the corresponding FS property.

5.3 Single session PCS

We start by proving that if we enforce that two given parties will always use the same session, PCS is obtained. While this is of course not a reasonable assumption, this is in fact an intermediate step over which we build the proofs for the real use cases. In this case, session-based PCS and conversation-based PCS collapse.

Proof   To perform the PCS proof, it is necessary to answer the question: how could the attacker learn some key sck. From an intuitive level, the following scenarios are possible:
- the current state of either the sender or the receiver was compromised,
- the sender or the receiver was compromised previously, but still on the same chain, and the attacker just has to ratchet forward the key to compute sck,
- the sender or the receiver was compromised even before the last asymmetric ratchet, the attacker then became active, performed an asymmetric ratchet with the sender, and since then the sender is in fact talking to the attacker.

A core difficulty of the proof is that we model an unbounded number of asymmetric or symmetric ratchet steps for each session. An attacker may know a sending key because it knew a previous sending key, or a previous root key, and so on. While the PCS property concerns the sent messages and the sender chain keys, we see here that the property is in fact interdependent between receiver and sender keys. We must then consider all the possible keys the attacker can learn or compute instead of only considering the sender chain key, and reason by induction. Namely, with respect to PCS, we must consider that the attacker may know a sending key (case 1), a receiver key (case 2), or a root key (case 3), each of them being possible either because another case happened previously, or because there was a compromise.

This is in fact a generic *observation* relative to Tamarin proofs. While we want to prove by induction a formula $P_1 \Rightarrow Q$, we see that we in fact also need to prove $P_2 \Rightarrow Q$ and $P_3 \Rightarrow Q$. However, we crucially cannot prove each of those formulas separately due to their interdependence, and we must prove instead in one big induction $\bigwedge_{1 \leq i \leq 3}(P_i \Rightarrow Q)$, or equivalently $(P_1 \vee P_2 \vee P_3) \Rightarrow Q$.

In our case, we have to prove the following property, corresponding to a strengthening of the original PCS property:

$$
\begin{aligned}
&\forall\, A,B,\mathsf{rk},\mathsf{rck},\mathsf{sck},i,j,k. \\
&\quad ((\mathtt{Sent}(A,B,\mathsf{sck})@i \;\&\; \mathtt{K}(\mathsf{sck})@j \;\& \\
&\quad\; \mathtt{Heal}(A,B)@k \;\&\; k < i) &&\textit{case} 1 \\
&\quad \vee \\
&\quad (\; \mathtt{Root}(A,B,\mathsf{rk})@i \;\&\; \mathtt{K}(\mathsf{rk})@j \;\& \\
&\quad\; \mathtt{Heal}(A,B)@k \;\&\; k < i) &&\textit{case} 2 \\
&\quad \vee \\
&\quad (\; \mathtt{Received}(A,B,\mathsf{rck})@i \;\&\; \mathtt{K}(\mathsf{rck})@j \;\& \\
&\quad\; \mathtt{Heal}(A,B)@k \;\&\; k < i)\;) &&\textit{case} 3 \\
&\quad\Rightarrow \left(\begin{array}{l} \exists\, l.\, \mathtt{Compromise}(A,B)@l \;\&\; k < l \\ \vee\, \exists\, l.\, \mathtt{Compromise}(B,A)@l \;\&\; k < l \end{array} \right) &&\textit{implied}
\end{aligned}
$$

Proving this strengthened induction proved to be too difficult for TAMARIN's current automated heuristics, and we had to perform it in the interactive mode. However, we relied on TAMARIN automation to prove many structural properties over the protocol, without which we would have not been able to complete the proof. To give an example of such a structural property, consider the following formula:

$$
\begin{aligned}
&\forall\, A_1,B_1,A_2,B_2,\mathsf{rck},i,j,k. \\
&\quad \mathtt{Received}(A_1,B_1,\mathsf{rck})@i \;\&\; \mathtt{Sent}(B_2,A_2,\mathsf{rck})@j \\
&\quad\Rightarrow A_1 = A_2 \;\&\; B_1 = B_2
\end{aligned}
$$

This formula states that if a receiver and a sender are both agreeing on some secret key rck , then they are necessarily talking to each other, i.e. $A_1 = A_2$ and $B_1 = B_2$. This is for instance needed when trying to prove the previous induction, in the reasoning how the attacker can obtain the receiving chain rck (case 3). Proving this lemma helps TAMARIN in deducing that compromise of any other party, other than A or B, does not result in knowing rck, since the receiving chain key is unique per pair of user.

Overall, the proof required 24 such structural helper lemmas, which are proved automatically by TAMARIN with an oracle. The strengthened PCS with 718 proof steps, had to be selected manually out of the available proof steps.

5.4   Conversation-based PCS

We model the current design of Sesame by allowing in the previous model any number of sessions between A and B to run in parallel. Over this model, we will first describe how TAMARIN rediscovers the scenario trace corresponding to the one described in Section 3.2. Then, we will present how to model our fix over this model and the corresponding security proof.

Conversation-based PCS violation We observe on this model that if we consider the full conversation between two parties, then PCS is lost. This suggests that our model is general enough to capture the experimentally found scenario. However, we proved previously that for a single session, we have PCS between two agents. The session-based PCS property still holds for this new model with multiple sessions, and is essentially a proof that multiple sessions of the DR do not share any cryptographic material and are independent. Interestingly, we could in this setting mostly reuse the proof made in the single session case to prove the session-based PCS.

Modeling the fix To introduce a notion of active and inactive session, we specify that whenever a new session is created for a party, all sending actions and asymmetric ratcheting that would use a previous session are forbidden. To do so, we rely on so-called restrictions: they are expressed in TAMARIN in the same language as the security properties, but are used to forbid certain executions.

For instance, we can model that we have an event $\texttt{NewSession}(A, \mathsf{sid})$ raised by party A whenever they create a new session with identifier sid, and that in addition to the $\texttt{Sent}$ event there is also a $\texttt{SentSID}(\mathsf{sid})$ event raised whenever A uses sid to send a message. Then, a core feature of our fix is modeled by adding the following restriction:

$$\neg(\exists A, \mathsf{sid}_1, \mathsf{sid}_2, i, j, k.$$
$$\texttt{NewSession}(A, \mathsf{sid}_1)@i \;\&\; \texttt{NewSession}(A, \mathsf{sid}_2)@j \;\&\;$$
$$\texttt{SentSID}(\mathsf{sid}_1)@k \;\&\; i < j < k)$$

This restriction expresses that for any execution, A cannot send a message from session sid_1, once it has created a new session sid_2. This ensures the deprecation of an old session sid_1, once it is replaced by newer one sid_2.

Proof To prove the conversation-based PCS between A and B, we then rely on:
- the previous per session proof of PCS,
- the restrictions modeling our fix.

Essentially, if our fix is correct, the restrictions will forbid all attacks arising from lifting the per session PCS to the conversation-based PCS property. We were indeed able to carry out this proof in TAMARIN. This proof required 4 additional structural helper lemmas, and the conversation-based PCS took 146 steps by reusing all the previous proofs.

5.5 Proof for the clone detection fix

With the first fix, we restore the conversation PCS against the $\mathcal{A}_{\text{Formal}}$ threat model. However, to also add some security in the case of $\mathcal{A}_{\text{Experiment}}$, we also model a clone detection fix that would detect whenever an attacker is initiating new sessions with a compromise identity key.

Modeling the fix To model the fix, we enrich the state of the sessions with the warning and identifier root keys, as well as the current session identifier, and modify the receive message action so that whenever a message is received over a deprecated session, it sends out the two corresponding root key warnings.

We then added the **warning process** action to the protocol, where a party can receive over its current active session a warning. This rule executed by agent A decrypts a warning message of the usage of a session with root key identifier pk_{ro} and then raises the event $\texttt{Report}(A, \mathrm{pk}_{ro})$. By having each root key creation also raise the event $\texttt{Rk}(A, rk)$, we express the actual processing of the report by adding the restriction:

$$\forall A, rk, i.$$
$$\texttt{Report}(A, \mathrm{pk}(rk))@i$$
$$\Rightarrow \neg(\exists j. \texttt{Rk}(A, rk)@j \;\&\; j < i)$$

This enforces the soundness of clone detection: A reports an error for some root key identifier only if the corresponding root key was never computed by A.

Proof   Our goal is to prove that the attacker cannot trigger a false positive of our mechanisms, that is, a report can only be raised if there was a compromise of some agent. An interesting point of the PCS proof is that the attacker is able to compute a root key of *A* only if it compromised *B* or *A*. So, any warning message received by *A* is either:

- from a honest conversation, in which case *A* will recognize the root key,
- from the attacker, in which case there must have been a compromise.

This mean that proving the clone detection fix is equivalent to proving the following two cases: a) honest warning messages do not trigger the error message, and b) the attacker needs to compromise one of the agent to compute a valid warning message. The first case is straightforward, and the second has mostly been done in the previous PCS proofs.

Following this idea, we were able to prove that our fix is sound. The proof effort involved the previous PCS proof, two new helper lemmas proved in 429 steps and 14 steps respectively, and the final proof done in 115 steps.

6   Conclusion

Our experimental result based on multiple PCS violations on the application level illustrated the need to consider PCS not at the per-session level but at the conversation level.

We introduced the first formal model that includes the multiple session management layer of a secure messaging protocol, taking Signal as a first case study. We used this model to show how at the conversation level PCS is violated by design, and use our model to prove the correctness of our two proposed improvements.

As a future direction, our models could be more precise, covering more high-level features like the addition of new devices, or more low level features like a more precise DR. It is however likely that this can only be achieved by improving existing verification tools to make such more detailed models tractable.

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A Appendix

A.1 Additional PCS violation: Abusing stored receiver chains

We describe here the PCS violation we found that is independent of the multiple sessions layer, and was independently discovered recently by [18].

This scenario also considers if PCS is achieved in practice by the Signal app. In previous work [13], its authors showed that Signal (app version v4.47.7) was able to protect past messages and lock an attacker out of the conversation. The experiment considers two parties A and B having a conversation, until A is cloned (i.e., the attacker has an identical copy of the messaging app). The honest parties continue the conversation, and once the clone's machine goes online, they check if the clone receives past messages or can inject new ones in the conversation. We performed a slight variation of their experiment, where in addition the parties go offline in order to prevent any other mechanisms from being triggered. Thus, we focus solely on PCS, and disregard any features that may also come into play, such as message re-encryption.

The main goal of the experiment is to check whether a fully compromised honest user can recover the security of a session and make it impossible for its clone to inject their own messages. This should be achieved by the DR protocol, since exchange of messages with the partner introduces new entropy in the key derivation. In particular, once the session keys (root, sender, and receiver chain) are ratcheted forward, the attacker should not be able to recompute them.

Although we expected the same experiment results as in [13], we noticed an unexpected decrease in the security of Signal. On the positive side, the clone is not able to decrypt past messages exchanged between the honest parties during the healing phase i.e., when the clone is offline. However, future communication between the clone and the honest party are not blocked anymore: the clone can send messages that the partner is able to decrypt without any error or notification shown in the user interface.

Concrete steps We now outline the explicit steps we followed to conduct the scenario:
1. A and B exchange 4 messages: $(A \leftrightarrow B)^4$.
2. Duplicate A's machine and send clone offline.
3. A and B exchange 4 more messages: $(A \leftrightarrow B)^4$.
4. A and B go offline, and clone goes online.
5. Clone sends 4 consecutive messages to B $(A_{Clone} \rightarrow B)^4$
6. Clone goes offline, and B online. B can decrypt the messages sent by the clone.
We show this attack in Fig. 5.

Analysis The intuition behind the scenario is that B can forward a key from a past state, that they should have otherwise deleted. Notice that the clone blindly follows the protocol and acts as an honest user. This means that they use only the local state to compute the next message key. In addition, since A and B's devices are offline at the time, the clone has no external input on the progress of the conversation. On the receiver
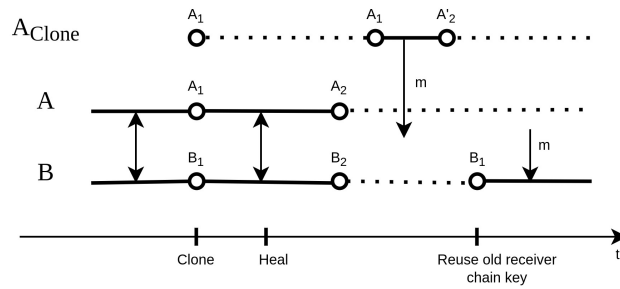
Figure 5: Abusing stored receiver chain keys on Signal. In the first phase, honest parties A and B exchange messages until A is cloned. The clone goes offline (denoted by the dotted line) and the parties exchange messages to heal their session. A and B go offline, and the clone encrypts a message m with the old session state A_1. When, B goes online they can decrypt the message by using the old receiver chain stored at state B_1.

side, the fact that B is able to compute the session key means they can go back to a previous receiver chain and compute the next message key.

We checked the debug logs on the machines of the agents to confirm the mechanism that allowed this behavior. We then found that the chain key being used to encrypt the clone's messages was the same as the one A had used to encrypt their messages at the time of cloning. In addition, we cross-checked with the implementation of Signal and found that the scenario is indeed possible. In fact, Signal allows for the parties to store up to 5 receiver chain keys at any time [8].

In theory, it should be impossible to extend those receiver chains, as only the actually skipped messages before the corresponding asymmetric ratchet should have been stored. However, the compromised key is still stored in the receiver's state, and the clone can actually extend older chains and use it to send an arbitrary number of messages impersonating A. This behavior is in contradiction with PCS, as after the asymmetric ratchet the old compromised material should be useless except for skipped messages.

A.2 Clone detection fix discussion

Memory usage A downside of our clone detection mechanism is that it requires devices to store a long list of warning root keys in order to correctly report compromises without false positives (soundness of the clone detection). However, in the full compromise setting, it can be argued that our clone detection mechanism is stronger than needed: our PCS fix quickly heals all honestly established sessions, and we may not care about detecting low impact compromise of those sessions. If we only care about detecting the case where the attacker is using the compromised identity key to initiate a fresh session, our clone detection mechanism can be adapted so that instead of deriving warning keys from each root key, we only derive warning keys from the first root key of the session. This solution would then be such that:

- the memory usage is strongly reduced;
- cloned sessions are detected.

Device Reset There are side cases where we are fully resetting the state of a device, either to a clean blank state or to a backup, for instance after the original device was lost or there was a state loss. In such cases, our clone detection mechanism could yield false reports:

- after restoring a backup, the user may receive a report over a root key computed after the point of the backup;
- after a full reset, the user may receive a report over a root key corresponding to the older identity key.

To mitigate those false reports, a simple solution is to specify that a device that performed a backup restore or a reset should ignore any clone detection reports it obtains from a partner that just came online for the first time since the reset. However, this may lead to an attacker exploiting this small time-frame to avoid detection, and this mechanism may still let some false positive report be produced in some edge cases.

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[8] Signal's stored receiver chains: link.

A.3 Security Parameters in Signal

Signal is deployed with a specific set of parameters that directly affect the security of the protocol. The following is a list of some interesting parameters:

1. 25000 forward jumps - Signal allows for the message keys to be forwarded 25000 steps ahead and stored locally. A message with any counter smaller than the parameter, results in the partner storing all keys up to the message counter. This means that even if the honest parties heal from the compromise, the attacker can still encrypt messages using the skipped message keys.

2. Reset every 1 hour - The parties perform a new handshake every one hour and thus refreshing their conversation secrets. This means that an attacker cannot be locked out of a conversation, since both them and the victim are forced by the app to reset their sessions with the partner.

3. 5 stored chains - The 5 latest receiver and sender chains are stored at any time on the device. As we have shown, this allows an attacker to extend any of these chains with an arbitrary number of new messages.

4. 40 sessions stored - Signal stores 40 sessions per device. As we showed, a compromise in any of them allows the attacker to continue the conversation in that session without being detected from the honest parties.