

Security Notions for Bidirectional Channels

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Abstract. This paper closes a definitional gap in the context of modeling cryptographic two-party channels. We note that, while most security models for channels consider exclusively unidirectional communication, real-world protocols like TLS and SSH are rather used for bidirectional interaction. The motivational question behind this paper is: Can analyses conducted with the unidirectional setting in mind—including the current ones for TLS and SSH—also vouch for security in the case of bidirectional channel usage? And, in the first place, what does security in the bidirectional setting actually mean?

After developing confidentiality and integrity notions for bidirectional channels, we analyze a standard way of combining two unidirectional channels to realize one bidirectional channel. Although it turns out that this construction is, in general, not as secure as commonly believed, we confirm that for many practical schemes security is provided also in the bidirectional sense.

Keywords: cryptographic channels, bidirectional communication, security models, TLS

1 Introduction

Cryptographic Channels. Today cryptography plays a fundamental role in our interconnected world. One of the most widely-deployed applications of cryptography is to establish secure connections over the Internet, allowing secure transmission of data between two endpoints over an unprotected network. These processes require an initial key exchange step with which the two endpoints share a secret, and a subsequent secure channel which uses the secret to protect the actual communication. In this work we focus on the second cryptographic component, a secure channel. Suppose that two parties, Alice and Bob, wish to exchange messages reliably and securely. While reliability comes by default from TCP/IP, security needs to be added using a cryptographic channel like the Transport Layer Security (TLS) protocol [DR08].

Security: State of the Art. Several research efforts have been devoted to channel security, the result being a generally undisputed understanding of which properties a cryptographic channel should provide. The main features offered by cryptographic channels are data confidentiality and integrity—ensuring that only the intended recipient obtains the transmitted messages and that received messages truly originate from the alleged sender, respectively. Confidentiality and integrity are usually, but not necessarily, required simultaneously. Beyond these two, in most situations it is desired that out-of-order delivery and replays of messages also be detected. Bellare, Kohno, and Namprempre [BKN02] were the first to identify the above security goals as the target of a cryptographic channel, and introduced the notion of stateful authenticated encryption (stateful AE) as the ideal primitive that meets them all. They then used the stateful AE security model as a reference to analyze the Secure Shell (SSH) Binary Packet protocol [YL06]. Later work by the same and other authors [KPB03,PRS11,JKSS12,KPW13,BMM⁺15], particularly in the context of analyzing the TLS Record Protocol [DR08], either confirms or refines the stateful AE notion. All in all, it is common to consider stateful AE as a reasonable approximation of a secure channel.

We note, however, that although stateful AE is understood as the target of *bidirectional* channel protocols, the notion is rather an approximation of a *unidirectional* channel. Indeed, stateful AE and its follow-ups all consider a restricted scenario where Alice sends messages but never receives and, conversely, Bob receives messages but never sends. As a consequence, existing work assessing the cryptographic security of prominent protocols like TLS and SSH (as done in the above-mentioned papers) only accounts for the much simpler scenario in which the communication takes place *in one direction*, from the sender to the receiver. However, in practice, secure channels are most often used to communicate *in both directions*. Thus, there is an evident gap between the security that cryptographic channels are designed to offer in

theory and the actual security that cryptographic channels should achieve in practice. Filling this gap is one of the main goals of this paper.

Towards Defining Bidirectional Security. Our first objective is to understand the security that channels should target to protect bidirectional communication. Intuitively, we expect from a bidirectional channel that confidentiality and integrity of data be ensured for each of the communication directions.

A first attempt to define bidirectional security may be to require that (unidirectional) security holds in each direction independently of the other direction. According to this notion, a bidirectional channel would be deemed secure if ‘it behaves as a secure unidirectional channel’ when used to protect either direction, from Alice to Bob (\rightarrow) or from Bob to Alice (\leftarrow). Adopting such a notion would immediately allow to extend the existing analyses of the SSH and TLS channel protocols to the bidirectional case. This notion is, however, completely flawed. Indeed, we can design bidirectional channels that achieve the strongest confidentiality and integrity properties as long as the communication is restricted to one direction while becoming immediately vulnerable as soon as a second communication direction is available. We present one such scheme in Figure 9 (in Appendix B).

As a second attempt we may try to repair the notion above by requiring that (unidirectional) security holds in each direction *even if both directions are available simultaneously*. That is, according to this stronger notion a bidirectional channel would be declared as secure if each direction enjoys (unidirectional) security against adversaries attacking that specific direction. Let us validate this notion against a widely-deployed channel design that realizes a bidirectional channel by running two unidirectional channels in opposite directions. We name this construction the *canonic composition* of unidirectional channel, where ‘canonic’ indicates that it follows a common design of real-world channel protocols (including TLS and SSH) that combines two independent unidirectional channels to realize a bidirectional channel. For reference, we give the details of the canonic composition in Figure 5 (see Section 5), however, for now an intuitive understanding is sufficient. Assume that the two unidirectional channels offer confidentiality against active adversaries (a.k.a. indistinguishability against chosen-ciphertext attacks, IND-CCA). Then their canonic composition would be considered a confidential bidirectional channel according to our second-attempt notion. However, the latter notion misses an important point: it ignores the possibility that attacking one direction may indirectly harm the other direction. We clarify this with a practical example.

Consider an instant messaging service that allows registered users, after authenticating with a password, to chat with any other user of the service. Alice and Bob engage in a conversation and, since they care about confidentiality, they run the service over a bidirectional cryptographic channel that offers confidentiality against active attacks. If Alice and Bob follow the canonic composition paradigm and communicate using two independent, IND-CCA-secure channels, do they achieve the desired level of security? They do not, even if the underlying unidirectional channels are secure against active attacks. Indeed, assume the channel is such that the adversary is able to inject ciphertexts that decrypt to messages of its choice.¹ Under this condition, here is how the adversary proceeds. It delivers in the $B \rightarrow A$ direction a ciphertext that Alice decrypts to ‘please authenticate’; Alice answers by sending her password over the $A \rightarrow B$ channel; as Alice’s message comes unexpected and Bob cannot make sense out of it, he puts the password on public display; the adversary learns it from there. See Figure 1 for an illustration of the attack.

Intuitively, a bidirectional channel with confidentiality against *active* adversaries should prevent this attack from working (more precisely: it does not have to identify and report the attack but ensure that any information that Bob recovers under attack and potentially makes public be independent of what Alice sent). Evidently, the canonic composition falls short in providing this kind of protection.

As the described attack involves tampering with ciphertexts, one could come to the conclusion that requiring the unidirectional channels to provide integrity in addition to confidentiality would solve the problem. Is this change sufficient? Is it necessary? We do not question that demanding integrity protection from a cryptographic channel is a good idea in general. However, making integrity a necessary part of the model also obstructs the view on the core of its security properties.

In this work we propose a security model for bidirectional communication that naturally extends the idea of ensuring ‘unidirectional security’ in the two directions but also captures the intuition that

¹ This assumption does not contradict a pure confidentiality notion: IND-CCA security only requires that the outputs of the decryption algorithm in case of an active attack be *independent* of the encrypted messages. For a concrete example, see the proof of Theorem 5 (on page 13).

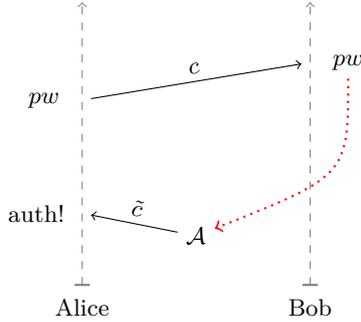


Fig. 1. A confidentiality attack against the canonic composition of two IND-CCA-secure unidirectional channels. In the figure time evolves bottom-up (dashed lines).

attacking one direction may affect the other direction. The two naive notions presented above fail because they both consider a bidirectional channel as ‘built’ from unidirectional channels. Our model instead sees a bidirectional channel ‘as a whole’. After defining appropriate notions of confidentiality and integrity for bidirectional channels we will formally recast the attack from Figure 1. Using our framework, it will be evident that adding integrity to the unidirectional components does prevent the attack. However, requiring integrity is not necessary, in general, to achieve bidirectional confidentiality.

Contribution and Organization In the first part of the paper we develop security notions for bidirectional channels. Following a long tradition (e.g., [KPB03,PRS11,JKSS12,KPW13,BMM⁺15]) our definitions are game based. In Section 3 we introduce a joint syntax for unidirectional and bidirectional channels. For bidirectional channels we then propose two flavors of integrity, INT-2PTXT and INT-2CTXT, as well as two flavors of confidentiality, IND-2CPA and IND-2CCA, in Section 4. Our models generalize the confidentiality and integrity notions for unidirectional channels by BKN [BKN02] (the latter we denote in the rest of the paper with INT-1PTXT, INT-1CTXT, IND-1CPA and IND-1CCA to avoid confusion with the bidirectional setting; for reference, we reproduce details of the four BKN models in Appendix A). In Section 4 we also study the relations among the newly defined notions and show that standard implications also hold in the bidirectional setting. Most notably, we prove a generalized version of the classic result that ciphertext integrity leverages confidentiality against passive attacks to confidentiality against active attacks, shortly $\text{IND-2CPA} + \text{INT-2CTXT} \implies \text{IND-2CCA}$. This result can be seen as a benchmark for the soundness of our notions. In the second part of the paper, in Section 5, we apply our model to scrutinize the canonic composition, an important real-world channel design that realizes a bidirectional channel from two unidirectional channels. More specifically, we study how security scales from the unidirectional components to the composed bidirectional channel. We particularly prove that the resulting bidirectional channel inherits both plaintext integrity and ciphertext integrity of its building blocks. We also prove that confidentiality against passive attacks can be lifted. Somewhat unexpectedly, the same does not hold for confidentiality against chosen-ciphertext attacks. We show this by giving an explicit counter example (which formalizes the confidentiality attack from Figure 1).

Further Related Work. It is fair to say that the seminal work of Bellare, Kohno, and Namprempre [BKN02] is considered as a reference for channel models in the game-based tradition. Black *et al.* [KPB03] extend the notions from [BKN02] to capture further confidentiality and authenticity goals, e.g., for protecting against combinations of packet loss, replay, and reordering attacks. Boldyreva *et al.* [BDPS12] refine the model of [BKN02] and pioneer the study of symmetric encryption in the presence of ciphertext fragmentation where the decryption processes ciphertexts in a byte-by-byte fashion. In different work [BDPS14] the same authors extend the security model of [BKN02] to allow for multiple decryption errors which occur in some implementations. More recently, Fischlin *et al.* [FGMP15] introduce security notions for channels that transport a stream of bytes rather than a sequence of (atomic) messages. The security models of [BKN02] and their numerous successors have been employed to prove the security of the full TLS suite (key exchange and channel protocol) and other protocols, e.g., in [KPW13,JKSS12].

An approach towards cryptographic channels from the perspective of composability with other primitives is pursued in [CK01,CK02,MRT12]. For instance, Canetti and Krawczyk [CK02] consider channels in the UC framework. In their model, users communicate over a bidirectional link and the only information the adversary sees is the length of the messages. Prior work [CK01] by the same authors has a slightly more restricted model but receives a closer look by Namprempre [Nam02] who characterizes (game-based) notions that suffice to achieve a UC secure channel as per [CK01]. Recent works by Maurer *et al.* [MRT12,BMM⁺15] consider cryptographic channels, from the point of view of Constructive Cryptography, as a unidirectional primitive.

2 Notation

Our security definitions are based on games played between a challenger and an adversary. These games are expressed using program code and terminate when a ‘Stop’ instruction is executed; the argument of the latter is the output of the game. We write $\Pr[G \Rightarrow 1]$ for the probability that game G terminates by running into a ‘Stop with 1’ instruction.

In game definitions, we distinguish the following operators for assigning values to variables: We use symbol ‘ \leftarrow ’ when the assigned value results from a constant expression (including the output of a deterministic algorithm), and we write ‘ \leftarrow_{\S} ’ when the value is either sampled uniformly at random from a finite set or is the output of a randomized algorithm.

We use bracket notation to denote associative arrays (a data structure that implements a ‘dictionary’). For instance, for an associative array A the instruction $A[7] \leftarrow 3$ assigns value 3 to memory position 7, and expression $A[2] = 5$ tests whether the value at position 2 is equal to 5. Associative arrays can be indexed with elements from arbitrary sets.

We denote the Boolean constants True and False with T and F, respectively. We sometimes use the ternary operator known from the C programming language: If C is a Boolean condition and e_1, e_2 are arbitrary expressions, the expression “ $C ? e_1 : e_2$ ” evaluates to e_1 if $C = T$ and to e_2 if $C = F$.

If A, B are sets, with $A \cup B$ we denote their disjoint union.

3 Cryptographic Channels

We give a syntax definition that covers both unidirectional and bidirectional channels. Security notions for unidirectional channels are standard and reproduced in Appendix A. Security notions for bidirectional channels, and the relations among them, are studied in Section 4.

Our concept of cryptographic channel assumes two participants that we routinely refer to as Alice (A) and Bob (B). In the unidirectional setting, Alice invokes the *send* algorithm to transform messages into ciphertexts and Bob invokes the *receive* algorithm to translate ciphertexts back into messages. In the bidirectional setting, both parties can send and receive. In our formalization, the send and receive algorithms also take associated data [Rog02] that is assumed to match on both sides. Further, we assume both participants keep state between invocations of their algorithms.

Definition 1 (Syntax of channels). A (cryptographic) channel $\text{Ch} = (\text{init}, \text{snd}, \text{rcv})$ for associated data space \mathcal{AD} and message space \mathcal{M} consists of a key space \mathcal{K} , a ciphertext space \mathcal{C} , a state space \mathcal{S} , a distinguished rejection symbol $\perp \notin (\mathcal{M} \cup \mathcal{S})$, and three efficient deterministic algorithms as follows:

- The initialization algorithm takes a key $K \in \mathcal{K}$ and outputs initial states $st_A, st_B \in \mathcal{S}$. We write $(st_A, st_B) \leftarrow \text{init}(K)$. Overloading notation, we sometimes write $(st_A, st_B) \leftarrow_{\S} \text{init}$ as an abbreviation for $K \leftarrow_{\S} \mathcal{K}$ followed by $(st_A, st_B) \leftarrow \text{init}(K)$, i.e., the initialization of a channel with a uniform (but anonymous) key.
- The sending algorithm takes a state $st \in \mathcal{S}$, associated data $ad \in \mathcal{AD}$, and a message $m \in \mathcal{M}$, and outputs an updated state $st' \in \mathcal{S}$ together with a ciphertext $c \in \mathcal{C}$. We write $(st', c) \leftarrow \text{snd}(st, ad, m)$.
- The receiving algorithm takes a state $st \in \mathcal{S}$, associated data $ad \in \mathcal{AD}$, and a ciphertext $c \in \mathcal{C}$, and outputs an updated state $st' \in \mathcal{S}$ or \perp , and a message $m \in \mathcal{M}$ or \perp . We write $(st', m) \leftarrow \text{rcv}(st, ad, c)$. If $st' = \perp$ or $m = \perp$ we say the channel rejects. To ease notation, we require $st' = \perp$ iff $m = \perp$.

The `rcv` algorithm uses symbol ‘ \perp ’ as an explicit error indicator. Note that since $\perp \notin \mathcal{S}$, once `rcv` outputs $st' = \perp$ our syntax does not allow any further invocation of the `snd` and `rcv` algorithms on input ‘state’ st' . This reflects the reasonable behavior of (cryptographic) applications which, upon being notified of an error, erase all current state information and refuse to process all further ciphertexts.

We proceed with definitions of correctness. Naturally, unidirectional and bidirectional channels offer different guarantees. We start with unidirectional communication.

Correctness of unidirectional channels. Cryptographic unidirectional channels were first studied by BKN [BKN02], and the following definitions are in line with their work. For unidirectional channels we require that if Alice invokes the `snd` algorithm on a sequence of messages, the resulting ciphertexts are transmitted to Bob without modification (and without changing their order), and Bob plugs the ciphertexts into his `rcv` algorithm, then Bob recovers the messages that Alice sent. Formally we require that for all sequences $ad_1, \dots, ad_l \in \mathcal{AD}$ of associated data strings and all sequences $m_1, \dots, m_l \in \mathcal{M}$ of messages, if $K \in \mathcal{K}$ and $\text{init}(K)$ outputs (st_A^0, st_B^0) , and if c_1, \dots, c_l and st_A^1, \dots, st_A^l and st_B^1, \dots, st_B^l and m'_1, \dots, m'_l are such that $(st_A^i, c_i) = \text{snd}(st_A^{i-1}, ad_i, m_i)$ and $(st_B^i, m'_i) = \text{rcv}(st_B^{i-1}, ad_i, c_i)$ for all i , then Bob’s `rcv` invocations do not reject and he obtains $(m'_1, \dots, m'_l) = (m_1, \dots, m_l)$. A different way to formalize exactly the same is via the `FUNC1` game in Figure 2 (left). Here, an adversary \mathcal{A} schedules any number of send operations for Alice and receive operations for Bob and it wins (lines 14,15,16) if it delivers associated data and ciphertexts in the right order and without modification, but either the channel rejects or Bob recovers a wrong message. Game-internal variables $s, r, h, AD-C, M$ keep track of this winning condition: s and r are `send` and `receive` counters, h is a Boolean flag that indicates whether Bob is still honest (or ‘clean’, i.e., was not yet exposed to a manipulated or out-of-order ciphertext), and $M, AD-C$ are associative arrays storing `messages`, `associated data`, and `ciphertexts`. Observe that once Bob is flagged as exposed (line 19), the adversary cannot win the game any more, meaning no particular behavior of the channel is expected from this moment on.

For any adversary \mathcal{A} playing in the described game we define its advantage as $\mathbf{Adv}^{\text{func1}}(\mathcal{A}) = \Pr[\text{FUNC}^1(\mathcal{A}) \Rightarrow 1]$, where the probability is over the choice of $K \in \mathcal{K}$ and over \mathcal{A} ’s randomness. Throughout this paper we require perfect correctness, i.e., $\mathbf{Adv}^{\text{func1}}(\mathcal{A}) = 0$ for all \mathcal{A} . Under this condition the two above correctness definitions for unidirectional channels are equivalent.

Correctness of bidirectional channels. We define the functionality of bidirectional channels by extending the game based approach from above. The corresponding game `FUNC2` is in Figure 2 (right). The working principles of `FUNC1` and `FUNC2` are quite similar. Besides the fact that in the bidirectional case Alice and Bob have independent send and receive counters, and flags indicating their honesty, the main difference is the update logic of the latter: Recall that in the unidirectional case Bob’s h -flag was cleared when he was exposed to an associated data field or ciphertext that was manipulated by the adversary. In the bidirectional case, Bob’s h -flag is cleared in addition when receiving an (authentic) ciphertext that Alice crafted after her own h -flag was cleared. (The h -flag of Alice is managed correspondingly.) This behavior is implemented, somewhat indirectly, in the `FUNC2` game via the conditional execution of lines 39–41.

For any adversary \mathcal{A} playing in the described game we define its advantage as $\mathbf{Adv}^{\text{func2}}(\mathcal{A}) = \Pr[\text{FUNC}^2(\mathcal{A}) \Rightarrow 1]$, where the probability is over the choice of $K \in \mathcal{K}$ and over \mathcal{A} ’s randomness. Again we require perfect correctness, i.e., $\mathbf{Adv}^{\text{func2}}(\mathcal{A}) = 0$ for all \mathcal{A} .

We finally note that, in line with intuition, constructions of bidirectional channels in particular also serve as unidirectional channels: Alice would only send but never receive (although she could) and Bob would only receive but never send (although he could). In this sense, observe that bidirectional correctness implies unidirectional correctness. (This immediately follows from the specifications of the `FUNC` games: in `FUNC2` the `rcv` oracle of Alice would never be invoked, so her h_A flag remains set throughout the game and lines 39–41 are always executed for her, just as in `FUNC1`.)

4 Security of Bidirectional Channels

We give game based security definitions for bidirectional channels by defining two flavors of integrity protection and two flavors of indistinguishability. (See Appendix A on notions for unidirectional channels.) Our notions and naming conventions extend the ones from BKN [BKN02].

<p>Game $\text{FUNC}^1(\mathcal{A})$</p> <p>00 $s \leftarrow 0$ 01 $r \leftarrow 0$ 02 $h \leftarrow \text{T}$ 03 $AD-C \leftarrow \emptyset; M \leftarrow \emptyset$ 04 $(st_A, st_B) \leftarrow_s \text{init}$ 05 $\mathcal{A}^{\text{snd,rcv}}$ 06 Stop with 0</p> <p>Oracle $\text{snd}(ad, m)$</p> <p>07 $(st_A, c) \leftarrow \text{snd}(st_A, ad, m)$ 08 $AD-C[s] \leftarrow (ad, c)$ 09 $M[s] \leftarrow m$ 10 $s \leftarrow s + 1$ 11 Return c</p> <p>Oracle $\text{rcv}(ad, c)$</p> <p>12 $(st_B, m) \leftarrow \text{rcv}(st_B, ad, c)$ 13 If $\neg h$: Return m 14 If $r < s \wedge (ad, c) = AD-C[r]$: 15 If $m = \perp \vee m \neq M[r]$: 16 Stop with 1 17 $r \leftarrow r + 1$ 18 Else: 19 $h \leftarrow \text{F}$ 20 Return m</p>	<p>Game $\text{FUNC}^2(\mathcal{A})$</p> <p>30 $s_A \leftarrow 0; s_B \leftarrow 0$ 31 $r_A \leftarrow 0; r_B \leftarrow 0$ 32 $h_A \leftarrow \text{T}; h_B \leftarrow \text{T}$ 33 $AD-C \leftarrow \emptyset; M \leftarrow \emptyset$ 34 $(st_A, st_B) \leftarrow_s \text{init}$ 35 $\mathcal{A}^{\text{snd,rcv}}$ 36 Stop with 0</p> <p>Oracle $\text{snd}(u, ad, m)$</p> <p>37 $(st_u, c) \leftarrow \text{snd}(st_u, ad, m)$ 38 If h_u: 39 $AD-C[u, s_u] \leftarrow (ad, c)$ 40 $M[u, s_u] \leftarrow m$ 41 $s_u \leftarrow s_u + 1$ 42 Return c</p> <p>Oracle $\text{rcv}(u, ad, c)$</p> <p>43 $v \leftarrow \{A, B\} \setminus \{u\}$ 44 $(st_u, m) \leftarrow \text{rcv}(st_u, ad, c)$ 45 If $\neg h_u$: Return m 46 If $r_u < s_v \wedge (ad, c) = AD-C[v, r_u]$: 47 If $m = \perp \vee m \neq M[v, r_u]$: 48 Stop with 1 49 $r_u \leftarrow r_u + 1$ 50 Else: 51 $h_u \leftarrow \text{F}$ 52 Return m</p>
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Fig. 2. Functionality game for unidirectional (left) and bidirectional (right) channels. We assume that once an oracle query for a participant results in the participant’s state being set to \perp , then no further query for that participant is accepted. We further assume $u \in \{A, B\}$, $ad \in \mathcal{AD}$, $m \in \mathcal{M}$, and $c \in \mathcal{C}$ for all such values provided by the adversary.

4.1 Integrity

The first type of integrity that we formalize is INT-2PTXT which ensures the (bidirectional) integrity of plaintexts. The corresponding security experiment is in Figure 3 (left). Plaintext integrity means that the adversary cannot arrange that messages (plaintexts) recovered by the receiving algorithm differ from those priorly fed into the peer’s sending algorithm. In the game this is tracked via the send and receive counters s_A, s_B, r_A, r_B , and the associative array $AD-M$. The test that the recovered messages are the right ones (and also the provided associated data strings are consistent) is in line 13; in case the requirement is violated, the adversary wins (line 16). If the receive algorithm detects a manipulation and decides to torn down the channel, this is explicitly communicated to the adversary (line 12). Unless the adversary manages to let one party accept a forged message, the game terminates indicating a loss (line 05).

The second notion of integrity is INT-2CTXT which ensures the (bidirectional) integrity of ciphertexts. The notion is similar to INT-2PTXT, but the focus is on preventing manipulations of ciphertexts rather than manipulations of messages. The corresponding security experiment is in Figure 3 (right), and the relevant changes are in lines 37 and 43.

We define the INT-2PTXT advantage of an adversary \mathcal{A} as $\text{Adv}^{\text{int-2ptxt}}(\mathcal{A}) = \Pr[\text{INT}^{\text{2ptxt}}(\mathcal{A}) \Rightarrow 1]$ and we define its INT-2CTXT advantage as $\text{Adv}^{\text{int-2ctxt}}(\mathcal{A}) = \Pr[\text{INT}^{\text{2ctxt}}(\mathcal{A}) \Rightarrow 1]$. The probabilities are over the choice of $K \in \mathcal{K}$ and over \mathcal{A} ’s randomness. Intuitively, a bidirectional channel offers plaintext integrity if $\text{Adv}^{\text{int-2ptxt}}(\mathcal{A})$ is small for all efficient adversaries \mathcal{A} ; similarly, it offers ciphertext integrity if $\text{Adv}^{\text{int-2ctxt}}(\mathcal{A})$ is small for all efficient \mathcal{A} .

<p>Game $\text{INT}^{2\text{ptxt}}(\mathcal{A})$</p> <p>00 $s_A \leftarrow 0; s_B \leftarrow 0$ 01 $r_A \leftarrow 0; r_B \leftarrow 0$ 02 $AD-M \leftarrow \emptyset$ 03 $(st_A, st_B) \leftarrow_{\mathcal{S}} \text{init}$ 04 $\mathcal{A}^{\text{snd,rcv}}$ 05 Stop with 0</p> <p>Oracle $\text{snd}(u, ad, m)$</p> <p>06 $(st_u, c) \leftarrow \text{snd}(st_u, ad, m)$ 07 $AD-M[u, s_u] \leftarrow (ad, m)$ 08 $s_u \leftarrow s_u + 1$ 09 Return c</p> <p>Oracle $\text{rcv}(u, ad, c)$</p> <p>10 $v \leftarrow \{A, B\} \setminus \{u\}$ 11 $(st_u, m) \leftarrow \text{rcv}(st_u, ad, c)$ 12 If $(st_u, m) = (\perp, \perp)$: Return \perp 13 If $r_u < s_u \wedge (ad, m) = AD-M[v, r_u]$: 14 $r_u \leftarrow r_u + 1$ 15 Else: 16 Stop with 1 17 Return m</p>	<p>Game $\text{INT}^{2\text{ctxt}}(\mathcal{A})$</p> <p>30 $s_A \leftarrow 0; s_B \leftarrow 0$ 31 $r_A \leftarrow 0; r_B \leftarrow 0$ 32 $AD-C \leftarrow \emptyset$ 33 $(st_A, st_B) \leftarrow_{\mathcal{S}} \text{init}$ 34 $\mathcal{A}^{\text{snd,rcv}}$ 35 Stop with 0</p> <p>Oracle $\text{snd}(u, ad, m)$</p> <p>36 $(st_u, c) \leftarrow \text{snd}(st_u, ad, m)$ 37 $AD-C[u, s_u] \leftarrow (ad, c)$ 38 $s_u \leftarrow s_u + 1$ 39 Return c</p> <p>Oracle $\text{rcv}(u, ad, c)$</p> <p>40 $v \leftarrow \{A, B\} \setminus \{u\}$ 41 $(st_u, m) \leftarrow \text{rcv}(st_u, ad, c)$ 42 If $(st_u, m) = (\perp, \perp)$: Return \perp 43 If $r_u < s_u \wedge (ad, c) = AD-C[v, r_u]$: 44 $r_u \leftarrow r_u + 1$ 45 Else: 46 Stop with 1 47 Return m</p>
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Fig. 3. Games for plaintext integrity (left) and ciphertext integrity (right) for bidirectional channels. We assume that once an oracle query for a participant results in the participant’s state being set to \perp , then no further query for that participant is accepted. We further assume $u \in \{A, B\}$, $ad \in \mathcal{AD}$, $m \in \mathcal{M}$, and $c \in \mathcal{C}$ for all such values provided by the adversary.

4.2 Confidentiality

We define two confidentiality notions for bidirectional channels: The first, IND-2CPA, models (passive) chosen-plaintext attacks and the second, IND-2CCA, models (active) chosen-ciphertext attacks. For both we give game based definitions based on indistinguishability. We start with discussing the second notion.

Consider the game for IND-2CCA in Figure 4 (right). The counters s_A, s_B, r_A, r_B , the Boolean flags h_A, h_B , and the associative array $AD-C$ have the same function as in games FUNC^2 and $\text{INT}^{2\text{ctxt}}$. In particular, the h -flags indicate whether non-authentic ciphertexts have been delivered to the respective participant. Parties are initially considered clean or honest (line 32), but when the adversary delivers a counterfeit ciphertext they are flagged as unclean (line 48). From that moment on, ciphertexts created by the affected participant are considered poisoned and their delivery to the peer renders also the latter unclean. As in Figure 2, this logic is implemented by the conditional execution of lines 39,40. Concerning line 49, observe that as long as a participant is clean, the message m recovered in line 43 is equal to the peer’s message m^b (from line 37), by the functionality of the channel. Also the adversary knows this, so to disallow trivial attacks, instead of letting the oracle return m , for honest participants the rcv oracle returns the suppression symbol \diamond .

Consider next the game for IND-2CPA in Figure 4 (left). The chosen-plaintext setting assumes a passive adversary, i.e., one where participants remain clean. Correspondingly, the game for IND-2CPA is the simplified version of the game for IND-2CCA where $h_A = h_B = \text{T}$ is assumed throughout the execution and the game is aborted if this assumption is violated (line 16).

We define the IND-2CPA advantage of an adversary \mathcal{A} as $\text{Adv}^{\text{ind-2cpa}}(\mathcal{A}) = |\Pr[\text{IND}^{2\text{cpa},1}(\mathcal{A}) \Rightarrow 1] - \Pr[\text{IND}^{2\text{cpa},0}(\mathcal{A}) \Rightarrow 1]|$ and we define its IND-2CCA advantage as $\text{Adv}^{\text{ind-2cca}}(\mathcal{A}) = |\Pr[\text{IND}^{2\text{cca},1}(\mathcal{A}) \Rightarrow 1] - \Pr[\text{IND}^{2\text{cca},0}(\mathcal{A}) \Rightarrow 1]|$. The probabilities are over the choice of $K \in \mathcal{K}$ and over \mathcal{A} ’s randomness. Intuitively, a bidirectional channel offers confidentiality against passive attacks if $\text{Adv}^{\text{ind-2cpa}}(\mathcal{A})$ is small for all efficient adversaries \mathcal{A} ; similarly, it offers confidentiality against active attacks if $\text{Adv}^{\text{ind-2cca}}(\mathcal{A})$ is small for all efficient \mathcal{A} .

We conclude this section with two technical notes on our definitions.

Note 1. For unidirectional channels, BKN [BKN02] give confidentiality definitions considering passive (CPA) and active (CCA) attacks where the difference between then CPA and CCA security games is

<p>Game $\text{IND}^{2\text{cpa},b}(\mathcal{A})$</p> <p>00 $s_A \leftarrow 0; s_B \leftarrow 0$ 01 $r_A \leftarrow 0; r_B \leftarrow 0$ 02 $AD-C \leftarrow \emptyset$ 03 $(st_A, st_B) \leftarrow_{\mathcal{S}} \text{init}$ 04 $b' \leftarrow_{\mathcal{S}} \mathcal{A}^{\text{snd,rcv}}$ 05 Stop with b'</p> <p>Oracle $\text{snd}(u, ad, m^0, m^1)$ 06 $(st_u, c) \leftarrow \text{snd}(st_u, ad, m^b)$ 07 $AD-C[u, s_u] \leftarrow (ad, c)$ 08 $s_u \leftarrow s_u + 1$ 09 Return c</p> <p>Oracle $\text{rcv}(u, ad, c)$ 10 $v \leftarrow \{A, B\} \setminus \{u\}$ 11 $(st_u, m) \leftarrow \text{rcv}(st_u, ad, c)$ 12 If $(st_u, m) = (\perp, \perp)$: Return \perp 13 If $r_u < s_v \wedge (ad, c) = AD-C[v, r_u]$: 14 $r_u \leftarrow r_u + 1$ 15 Else: 16 Stop with 0 17 Return \diamond</p>	<p>Game $\text{IND}^{2\text{cca},b}(\mathcal{A})$</p> <p>30 $s_A \leftarrow 0; s_B \leftarrow 0$ 31 $r_A \leftarrow 0; r_B \leftarrow 0$ 32 $h_A \leftarrow \text{T}; h_B \leftarrow \text{T}$ 33 $AD-C \leftarrow \emptyset$ 34 $(st_A, st_B) \leftarrow_{\mathcal{S}} \text{init}$ 35 $b' \leftarrow_{\mathcal{S}} \mathcal{A}^{\text{snd,rcv}}$ 36 Stop with b'</p> <p>Oracle $\text{snd}(u, ad, m^0, m^1)$ 37 $(st_u, c) \leftarrow \text{snd}(st_u, ad, m^b)$ 38 If h_u: 39 $AD-C[u, s_u] \leftarrow (ad, c)$ 40 $s_u \leftarrow s_u + 1$ 41 Return c</p> <p>Oracle $\text{rcv}(u, ad, c)$ 42 $v \leftarrow \{A, B\} \setminus \{u\}$ 43 $(st_u, m) \leftarrow \text{rcv}(st_u, ad, c)$ 44 If $(st_u, m) = (\perp, \perp)$: Return \perp 45 If $r_u < s_v \wedge (ad, c) = AD-C[v, r_u]$: 46 $r_u \leftarrow r_u + 1$ 47 Else: 48 $h_u \leftarrow \text{F}$ 49 Return $h_u ? \diamond : m$</p>
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Fig. 4. Games for confidentiality of bidirectional channels against chosen-plaintext (left) and chosen-ciphertext (right) attacks. We assume that once an oracle query for a participant results in the participant's state being set to \perp , then no further query for that participant is accepted. We further assume $u \in \{A, B\}$, $ad \in \mathcal{AD}$, $m^0, m^1 \in \mathcal{M}$, and $c \in \mathcal{C}$ for all such values provided by the adversary.

precisely the existence of a rcv oracle. This is in line with security definitions for many other encryption primitives (e.g., public key encryption). Our formalizations for bidirectional channels, however, equip the adversary also in the CPA case with a rcv oracle. This discrepancy comes from the fact that in unidirectional channels (and similarly public key encryption), if ciphertexts are delivered faithfully, the messages obtained by invoking the rcv algorithm are known a priori, namely by the requirement of (perfect) correctness. That is, in these cases the rcv oracle is redundant and can be removed without loss of generality. In contrast, in the setting of bidirectional channels where participants are both senders and receivers, the rcv oracle cannot be removed from the IND-2CPA game as it allows the adversary to advance the state of participants in a more general way.

The following simple example illustrates why the rcv oracle is indispensable for properly modeling the security of bidirectional channels against passive adversaries: Assume a channel construction in which the first rcv invocation of each participant flips an internal bit in the participant's state that makes all later snd invocations of the participant append vital key material to its ciphertext output. Such a scheme is clearly not secure against passive adversaries, but in a confidentiality model that lacks a rcv oracle the corresponding attack could not be expressed.

Note 2. We comment on a further restriction one might want to impose on the $\text{IND}^{2\text{cpa}}$ and $\text{IND}^{2\text{cca}}$ experiments. Most security definitions for stateless or stateful encryption, AEAD, etc. require that the snd oracle aborts if the lengths of m^0 and m^1 do not match (technically, a line saying “If $|m^0| \neq |m^1|$: Stop with 0” would be inserted before lines 06 and 37). This is because most practical encryption schemes do not hide the length of the encrypted message, so if these lines are not added, the indistinguishability games could be won by submitting m^0, m^1 of different lengths. Observe that our understanding of channels assumes an arbitrary abstract message space \mathcal{M} (see Definition 1) which is not required to be a set of strings. As at our level of generality expressions like $|m|$ are not even defined, we did not add them to the games. Clearly, in the moment a specific message space is assumed, e.g., $\mathcal{M} = \{0, 1\}^*$, the corresponding restrictions could, and likely should, be added. As no formal argument in this paper

depends on the presence or absence of such a length check, all claims we make can be adapted to versions of the security notions that have length checks.

4.3 Relations Among Notions

We defined two notions of integrity and two notions of confidentiality. In the following we clarify on three relations between these notions, where the first two are immediate.

$\text{INT-2CTXT} \implies \text{INT-2PTXT}$. The security requirement that ciphertexts are delivered without modification is stronger than the requirement that plaintexts are. The argument is standard and leverages on the correctness definition of channels (see Figure 2): Correctness precisely says that if ciphertexts are delivered faithfully, then also messages are transported without modification. That is, whenever the condition in line 43 in Figure 3 is fulfilled, then the condition in line 13 would be fulfilled in particular. We conclude that if no adversary succeeds in reaching line 46 of $\text{INT}^{2\text{ctxt}}$, then also no adversary succeeds in reaching line 16 of $\text{INT}^{2\text{ptxt}}$.

Standard arguments further show that the $\text{INT-2CTXT} \implies \text{INT-2PTXT}$ implication is strict. Observe that if we would relax our syntax and correctness definitions towards allowing randomized `rcv` algorithms and small correctness errors, the named implication would *not* hold.

$\text{IND-2CCA} \implies \text{IND-2CPA}$. Also this implication is standard, but the argument does not build on the perfect correctness of the channel. Here the observation is simply that IND-2CPA adversaries are more restricted than IND-2CCA adversaries. In particular, any adversary for game $\text{IND}^{2\text{cpa}}$ that is run in $\text{IND}^{2\text{cca}}$ would achieve at least the same advantage.

$\text{IND-2CPA} + \text{INT-2CTXT} \implies \text{IND-2CCA}$. A channel that simultaneously is confidential against passive adversaries (eavesdroppers) and detects all modifications of ciphertexts, also provides confidentiality against active adversaries. This statement makes intuition formal: the INT-2CTXT notion degrades active adversaries (that in principle could manipulate ciphertexts on the wire) to passive observers, and for the latter the IND-2CPA notion ensures nothing is learned about transmitted messages. Corresponding results are well-known for stateless encryption [BN00] and unidirectional stateful encryption [BKN02].

As the current implication does not follow as directly as the relations above, we give a formal proof. Note that, as the claim is in line with intuition, the proof also serves as confirmation that our definitions of integrity and confidentiality are well chosen.

Theorem 1 ($\text{IND-2CPA} + \text{INT-2CTXT} \implies \text{IND-2CCA}$). *Let Ch be a bidirectional channel that offers indistinguishability under chosen-plaintext attacks (IND-2CPA) and integrity of ciphertexts (INT-2CTXT). Then Ch also offers indistinguishability under chosen-ciphertext attacks (IND-2CCA). More precisely, for every adversary \mathcal{A} there exist adversaries \mathcal{B} and \mathcal{C} such that*

$$\text{Adv}^{\text{ind-2cca}}(\mathcal{A}) \leq 2 \cdot \text{Adv}^{\text{int-2ctxt}}(\mathcal{B}) + \text{Adv}^{\text{ind-2cpa}}(\mathcal{C}) .$$

The running times of \mathcal{B}, \mathcal{C} are about that of \mathcal{A} , and the three adversaries also pose the same number of `snd` and `rcv` queries.

Proof. For $b \in \{0, 1\}$ let $G^{0,b}$ denote the $\text{IND}^{2\text{cca},b}(\mathcal{A})$ game (from Figure 4) for channel Ch against adversary \mathcal{A} , and let $\Pr[G^{0,b}]$ be a shortcut for the probability $\Pr[G^{0,b} \Rightarrow 1]$. We proceed via game hopping. Let $G^{1,b}$ be the game derived from $G^{0,b}$ by replacing the instruction of line 48 with ‘Stop with 0’. The newly added instruction forces termination of the game if the condition of line 45 is not satisfied, i.e., if \mathcal{A} causes participant u to accept a pair (ad, c) that deviates from the sequence of associated data and ciphertexts sent by its peer v . For $b \in \{0, 1\}$ let bad^b denote the event that, during an execution of either $G^{0,b}$ or $G^{1,b}$, the adversary’s query does not fulfill the condition of line 45. As the two games $G^{0,b}$ and $G^{1,b}$ execute exactly the same instructions as long as the event bad^b does not occur, we have $\Pr[G^{0,b} \wedge \neg bad^b] = \Pr[G^{1,b} \wedge \neg bad^b]$, and thus $|\Pr[G^{0,b}] - \Pr[G^{1,b}]| \leq \Pr[bad^b]$.

Now we build two INT adversaries, \mathcal{B}^0 and \mathcal{B}^1 , whose advantages are related to the probability that \mathcal{A} triggers events bad^0 and bad^1 , respectively. For $b \in \{0, 1\}$, adversary \mathcal{B}^b emulates the left-or-right oracle of the IND game using the `snd` oracle provided to it by the INT game. More specifically, whenever \mathcal{A} poses a query `snd`(u, ad, m^0, m^1) then \mathcal{B}^b asks `snd`(u, ad, m^b) to its own oracle and forwards the answer to \mathcal{A} ;

similarly, \mathcal{B}^b forwards to its own rcv oracle any query $\text{rcv}(u, ad, c)$ that \mathcal{A} poses, and releases the oracle answer only if the condition of line 45 is not fulfilled, otherwise it gives back the suppression symbol \diamond . Observe that \mathcal{B}^b performs a perfect simulation of the games (both $G^{0,b}$ and $G^{1,b}$) as long as event bad^b does not occur; however, if bad^b happens then \mathcal{B}^b breaks ciphertext integrity of Ch (indeed, the event would trigger line 46 from Figure 3), thus $\Pr[bad^b] \leq \mathbf{Adv}^{\text{int-2ctxt}}(\mathcal{B}^b)$. Consider now an adversary \mathcal{B} which tosses a coin $d \in \{0, 1\}$ and then runs \mathcal{B}^0 or \mathcal{B}^1 according to the outcome. By construction, \mathcal{B} 's advantage is the average of \mathcal{B}^0 and \mathcal{B}^1 's advantages: $\mathbf{Adv}^{\text{int-2ctxt}}(\mathcal{B}) \geq \Pr[bad^0 \wedge d = 0] + \Pr[bad^1 \wedge d = 1] = \frac{1}{2} \cdot \Pr[bad^0] + \frac{1}{2} \cdot \Pr[bad^1]$. We can now derive the following bound for \mathcal{A} 's advantage in the original game:

$$\begin{aligned} \mathbf{Adv}^{\text{ind-2cca}}(\mathcal{A}) &= |\Pr[G^{0,1}] - \Pr[G^{0,0}]| \\ &\leq |\Pr[G^{0,1}] - \Pr[G^{1,1}]| + |\Pr[G^{1,1}] - \Pr[G^{1,0}]| + |\Pr[G^{1,0}] - \Pr[G^{0,0}]| \\ &\leq \Pr[bad^1] + |\Pr[G^{1,1}] - \Pr[G^{1,0}]| + \Pr[bad^0] \\ &\leq 2 \cdot \mathbf{Adv}^{\text{int-2ctxt}}(\mathcal{B}) + |\Pr[G^{1,1}] - \Pr[G^{1,0}]| . \end{aligned}$$

It remains to prove that chosen-plaintext power suffices to perform a faithful simulation of game $G^{1,b}$. To this end we construct an adversary \mathcal{C} that emulates game $G^{1,b}$ using the oracles provided by the IND-2CPA game. Briefly, \mathcal{C} relays \mathcal{A} 's sending queries to its left-or-right oracle (the snd oracle is essentially the same in the IND-2CPA game and the IND-2CCA game) and registers sent pairs (ad, c) as entries of an associative array $AD-C$ corresponding to each sending query. Answering \mathcal{A} 's queries to rcv is in principle more challenging, since the IND-2CPA game provides \mathcal{C} with a receiving oracle that expects 'in-sync' queries (i.e., queries (u, ad, c) that match the sequence $AD-C$ that u 's peer sent) while the IND-2CCA game also allows \mathcal{A} to submit 'out-of-sync' queries and see the corresponding output of rcv on those. However, in game $G^{1,b}$ it is easy to predict the answers of the rcv oracle. Indeed, in game $G^{1,b}$ we can assume wlog that \mathcal{A} does not trigger event bad^b , or equivalently that all out-of-sync queries will cause algorithm rcv to reject. Given this, \mathcal{C} simply answers in-sync queries with the suppression symbol \diamond , while it answers out-of-sync queries by returning \perp . To detect out-of-sync queries, \mathcal{C} keeps for each user u a Boolean h_u (as in the IND-2CCA experiment) and sets it to $h_u \leftarrow \text{F}$ when the first query (u, ad, c) is made such that (ad, c) does not match the correspondingly sent pair. Clearly \mathcal{C} provides a sound simulation of game $G^{1,b}$. This leads to the desired inequality:

$$\begin{aligned} \mathbf{Adv}^{\text{ind-2cca}}(\mathcal{A}) &\leq 2 \cdot \mathbf{Adv}^{\text{int-2ctxt}}(\mathcal{B}) + |\Pr[G^{1,1}] - \Pr[G^{1,0}]| \\ &\leq 2 \cdot \mathbf{Adv}^{\text{int-2ctxt}}(\mathcal{B}) + \mathbf{Adv}^{\text{ind-2cpa}}(\mathcal{C}) . \end{aligned}$$

□

5 The Canonic Composition

We study a classical construction paradigm that realizes a bidirectional channel by running two independent instances of a unidirectional channel in opposite directions. Due to its widespread deployment we call this paradigm the *canonic composition* (of two unidirectional channels). As anticipated in the introduction, existing security analyses of real-world channel protocols like SSH and TLS consider the security of these channels when used exclusively in one direction [BKN02,JKSS12,KPW13]. With other words, all established results hold only for the unidirectional components of the channel, considered in isolation. We complete the picture by studying how the security of the whole (bidirectional) channel scales in terms of the security of the underlying (unidirectional) building blocks.

5.1 The Construction

Let $\text{Ch} = (\text{init}, \text{snd}, \text{rcv})$ be a unidirectional channel for associated data space \mathcal{AD} and message space \mathcal{M} , with key space \mathcal{K} , ciphertext space \mathcal{C} , and state space \mathcal{S} . The canonic composition paradigm employs two independent instances of Ch: one protects the communication in the direction from Alice to Bob (\rightarrow) using a key K^{\rightarrow} , the other protects the direction from Bob to Alice (\leftarrow) using a key K^{\leftarrow} .

Let $\text{Ch}^* = (\text{init}^*, \text{snd}^*, \text{rcv}^*)$ denote the bidirectional channel obtained from Ch by applying the transform specified in Figure 5; we have $\mathcal{K}^* = \mathcal{K} \times \mathcal{K}$, $\mathcal{C}^* = \mathcal{C}$, and $\mathcal{S}^* = \mathcal{S} \times \mathcal{S}$. Each instance of Ch^* is keyed with a key of the form $K = (K^\rightarrow, K^\leftarrow)$. The idea is that Alice uses K^\rightarrow to send and Bob uses the same key to receive; similarly, Bob uses K^\leftarrow to send and Alice uses it to receive. To this end, the initialization algorithm init^* prepares initial states for Alice and Bob by running init twice, on input keys K^\rightarrow and K^\leftarrow , obtaining state pairs $(st_S^\rightarrow, st_R^\rightarrow)$ and $(st_S^\leftarrow, st_R^\leftarrow)$; it then sets Alice and Bob's initial states to $st_A = (st_S^\rightarrow, st_R^\leftarrow)$ and $st_B = (st_S^\leftarrow, st_R^\rightarrow)$. When a party wishes to send a message m , it extracts from its state $st = (st_S, st_R)$ the part st_S dedicated to sending and invokes (unidirectional) algorithm snd on input st_S and m . Similarly, for processing a ciphertext c the party extracts part st_R from its state and invokes rcv on input st_R and c , in order to recover m . Importantly, if the latter operation rejects (this is indicated by $st_R = \perp$), the rcv^* algorithm also sets $st \leftarrow \perp$.

Proc $\text{init}^*(K)$	Proc $\text{snd}^*(st, ad, m)$	Proc $\text{rcv}^*(st, ad, c)$
00 $(K^\rightarrow, K^\leftarrow) \leftarrow K$	06 $(st_S, st_R) \leftarrow st$	10 $(st_S, st_R) \leftarrow st$
01 $(st_S^\rightarrow, st_R^\rightarrow) \leftarrow \text{init}(K^\rightarrow)$	07 $(st_S, c) \leftarrow \text{snd}(st_S, ad, m)$	11 $(st_R, m) \leftarrow \text{rcv}(st_R, ad, c)$
02 $(st_S^\leftarrow, st_R^\leftarrow) \leftarrow \text{init}(K^\leftarrow)$	08 $st \leftarrow (st_S, st_R)$	12 If $st_R \neq \perp$:
03 $st_A \leftarrow (st_S^\rightarrow, st_R^\leftarrow)$	09 Return (st, c)	13 $st \leftarrow (st_S, st_R)$
04 $st_B \leftarrow (st_S^\leftarrow, st_R^\rightarrow)$		14 Else:
05 Return (st_A, st_B)		15 $st \leftarrow \perp$
		16 Return (st, m)

Fig. 5. A bidirectional channel $\text{Ch}^* = (\text{init}^*, \text{snd}^*, \text{rcv}^*)$ built from a unidirectional channel $\text{Ch} = (\text{init}, \text{snd}, \text{rcv})$ using the **canonic composition** paradigm.

5.2 Security Analysis

We investigate the relation between the security of the unidirectional components Ch and the bidirectional result Ch^* . (Recall that we reproduce definitions of integrity and confidentiality of unidirectional channels in Appendix A; in particular we define the notions INT-1PTXT, INT-1CTXT, IND-1CPA, IND-1CCA.) Concretely, we study whether strong enough security assumptions on Ch suffice to obtain security for Ch^* . As we prove, channel Ch^* inherits both plaintext integrity and ciphertext integrity from Ch . Informally, we have:

$$\begin{array}{l} \overbrace{\text{INT-1PTXT}}^{\text{direction } \rightarrow} + \overbrace{\text{INT-1PTXT}}^{\text{direction } \leftarrow} \implies \overbrace{\text{INT-2PTXT}}^{\text{directions } \leftrightarrow} \\ \text{INT-1CTXT} + \text{INT-1CTXT} \implies \text{INT-2CTXT} \end{array}$$

Moreover, if Ch offers confidentiality against passive attacks (IND-CPA), then so does Ch^* :

$$\overbrace{\text{IND-1CPA}}^{\text{direction } \rightarrow} + \overbrace{\text{IND-1CPA}}^{\text{direction } \leftarrow} \implies \overbrace{\text{IND-2CPA}}^{\text{directions } \leftrightarrow}$$

Perhaps surprisingly, the analogous implication does not hold for confidentiality against *active* attacks (IND-CCA). Indeed, we anticipated in the introduction (see Figure 1) that indistinguishability against chosen-ciphertext attacks cannot be generically lifted from the unidirectional building block Ch to the result Ch^* of the canonic composition:

$$\overbrace{\text{IND-1CCA}}^{\text{direction } \rightarrow} + \overbrace{\text{IND-1CCA}}^{\text{direction } \leftarrow} \not\implies \overbrace{\text{IND-2CCA}}^{\text{directions } \leftrightarrow}$$

In the rest of this section we provide formal statements and proofs for all the above (informal) security implications and separations.

Theorem 2 (Integrity of plaintexts). *If Ch offers integrity of plaintexts (INT-1PTXT) then Ch^* offers integrity of plaintexts (INT-2PTXT). More precisely, for every adversary \mathcal{A} against Ch^* there exists an adversary \mathcal{B} against Ch such that*

$$\mathbf{Adv}^{\text{int-2ptxt}}(\mathcal{A}) \leq 2 \cdot \mathbf{Adv}^{\text{int-1ptxt}}(\mathcal{B}) .$$

The running time of \mathcal{B} is about that of \mathcal{A} , and the two adversaries pose the same number of snd and rcv queries.

Proof. As we formalize in the course of the proof, any integrity violation (in the bidirectional sense) of Ch^* immediately translates to an integrity violation (in the unidirectional sense) of an instantiation of Ch , either in the direction from Alice to Bob (\rightarrow) or in the direction from Bob to Alice (\leftarrow). Let G^0 denote $\text{INT}^{2\text{ptxt}}(\mathcal{A})$ game (from Figure 3) for channel Ch^* and let $\Pr[G^0]$ be a shortcut for the probability $\Pr[G^0(\mathcal{A}) \Rightarrow 1]$. Let bad^{\rightarrow} be the event that \mathcal{A} causes termination of game G^0 with output 1 with a query $\text{rcv}(B, ad, c)$, i.e., a winning termination of the game due to a receiving query to Bob. Intuitively, in this case \mathcal{A} wins when attacking the Alice-to-Bob direction. Analogously, let bad^{\leftarrow} denote the event that \mathcal{A} wins the integrity game when attacking the opposite direction, i.e., with a receiving query to Alice. We proceed by game hopping. In the first hop we modify G^0 by forcing termination of the game with output 0 (making \mathcal{A} lose the game) whenever event bad^{\rightarrow} occurs, and denote the resulting game by G^1 . The new game prevents \mathcal{A} from winning when attacking the direction \rightarrow . Similarly, define game G^2 as the modification of G^1 with forced termination with output 0 if the event bad^{\leftarrow} is triggered. The latter game also prevents the adversary from attacking the direction \leftarrow , leaving it no chance to win. By definition, games G^0 and G^1 execute precisely the same instructions as long as event bad^{\rightarrow} does not occur. Analogously, G^1 and G^2 behave identically until event bad^{\leftarrow} . We thus derive the inequalities $|\Pr[G^0] - \Pr[G^1]| \leq \Pr[bad^{\rightarrow}]$ and $|\Pr[G^1] - \Pr[G^2]| \leq \Pr[bad^{\leftarrow}]$. Finally, since $\Pr[G^2] = 0$ we obtain the following bound for \mathcal{A} 's advantage in the original game:

$$\begin{aligned} \mathbf{Adv}^{\text{int-2ptxt}}(\mathcal{A}) &\leq |\Pr[G^0] - \Pr[G^1]| + |\Pr[G^1] - \Pr[G^2]| + |\Pr[G^2]| \\ &\leq \Pr[bad^{\rightarrow}] + \Pr[bad^{\leftarrow}] + 0 . \end{aligned}$$

It remains to bound the probabilities of events bad^{\rightarrow} and bad^{\leftarrow} . In what follows we construct an adversary $\mathcal{B}^{\rightarrow}$, which runs \mathcal{A} internally, and show that $\mathcal{B}^{\rightarrow}$ breaks the INT-1PTXT property of channel Ch as soon as \mathcal{A} provokes event bad^{\rightarrow} . Briefly, $\mathcal{B}^{\rightarrow}$ answers \mathcal{A} 's sending queries from Bob and \mathcal{A} 's receiving queries to Alice (i.e., in the \leftarrow direction) by picking a key $\tilde{K} \leftarrow_{\$} \mathcal{K}$, initializing fresh states $(\widetilde{st}_S, \widetilde{st}_R) \leftarrow \text{init}(\tilde{K})$, and running its own instance of channel Ch in the direction from Bob to Alice, and it answers \mathcal{A} 's sending queries of the form $\text{snd}(A, ad, m)$, respectively, receiving queries $\text{rcv}(B, ad, c)$, by posing corresponding queries $\text{snd}(ad, m)$ and $\text{rcv}(ad, c)$ to the oracles provided by the INT-1PTXT game. Now, observe that if \mathcal{A} triggers event bad^{\rightarrow} then in the INT-1PTXT game (from Figure 7), line 14 would be executed, thus causing $\mathcal{B}^{\rightarrow}$ to win the integrity game against the unidirectional channel Ch . Using a similar argument in the opposite direction we obtain a reduction \mathcal{B}^{\leftarrow} that wins the INT-1PTXT game as soon as event bad^{\leftarrow} happens. Finally, let \mathcal{B} be an adversary that tosses a coin $d \in \{0, 1\}$ uniformly at random and runs $\mathcal{B}^{\rightarrow}$ if $d = 0$ and \mathcal{B}^{\leftarrow} if $d = 1$. By construction we have $\mathbf{Adv}^{\text{ind-1cpa}}(\mathcal{B}) \geq \frac{1}{2} \cdot \mathbf{Adv}^{\text{ind-1cpa}}(\mathcal{B}^{\rightarrow}) + \frac{1}{2} \cdot \mathbf{Adv}^{\text{ind-1cpa}}(\mathcal{B}^{\leftarrow})$, from which the claimed inequality follows. \square

The above proof strategy is easily adapted to show that also the ciphertext integrity of channel Ch can be lifted to that of bidirectional channel Ch^* . We thus omit an explicit proof and just give the theorem statement.

Theorem 3 (Integrity of ciphertexts). *If Ch offers integrity of ciphertexts (INT-1CTXT) then Ch^* offers integrity of ciphertexts (INT-2CTXT). More precisely, for every adversary \mathcal{A} against Ch^* there exists an adversary \mathcal{B} against Ch such that*

$$\mathbf{Adv}^{\text{int-2ctxt}}(\mathcal{A}) \leq 2 \cdot \mathbf{Adv}^{\text{int-1ctxt}}(\mathcal{B}) .$$

The running time of \mathcal{B} is about that of \mathcal{A} , and the two adversaries pose the same number of snd and rcv queries.

We proceed with the last implication, which considers confidentiality against passive adversaries.

Theorem 4 (Confidentiality against passive adversaries). *If Ch offers indistinguishability against chosen-plaintext attacks (IND-1CPA) then Ch^* offers indistinguishability against chosen-plaintext attacks (IND-2CPA). More precisely, for every adversary \mathcal{A} against Ch^* there exists an adversary \mathcal{B} against Ch such that*

$$\mathbf{Adv}^{\text{ind-2cpa}}(\mathcal{A}) \leq 2 \cdot \mathbf{Adv}^{\text{ind-1cpa}}(\mathcal{B}) .$$

The running time of \mathcal{B} is about that of \mathcal{A} , and the two adversaries pose the same number of snd and rcv queries.

Proof. We prove the theorem statement with an argument similar to the one used in the proof of Theorem 2: if the adversary \mathcal{A} asks only in-sync queries (i.e., never triggers line 16 from Figure 4) then, by looking at each communication direction individually, \mathcal{A} 's queries are also considered in-sync according to the unidirectional IND-1CPA game (i.e., none of these queries trigger line 14 from Figure 8 on page 17). To formalize this intuition we define some intermediate games. The first game, that we denote by $G^{0,0}$, is the game $\text{IND}^{2\text{cpa},0}(\mathcal{A})$ from Figure 4. As in the previous proofs, we use the shortcut $\Pr[G^{0,0}]$ for the probability $\Pr[G^{0,0} \Rightarrow 1]$. Now define $G^{0,1}$ from $G^{0,0}$ by modifying the left-or-right oracle as follows: Whenever \mathcal{A} poses a query $\text{snd}(A, ad, m^0, m^1)$, invoke algorithm snd on message m^0 (as in the original game); if the query is $\text{snd}(B, ad, m^0, m^1)$, invoke algorithm snd on message m^1 . In other words, $G^{0,1}$ selects the 'left' message if the sender is Alice while it sends the 'right' message if the sender is Bob. Finally, define $G^{1,1}$ from game $G^{0,1}$ by letting the left-or-right oracle always select message m^1 . Note that $G^{1,1} = \text{IND}^{2\text{cpa},1}(\mathcal{A})$. Given the games we can bound \mathcal{A} 's advantage in the original game as follows:

$$\mathbf{Adv}^{\text{ind-2cpa}}(\mathcal{A}) \leq |\Pr[G^{1,1}] - \Pr[G^{0,1}]| + |\Pr[G^{0,1}] - \Pr[G^{0,0}]| .$$

We show next that the difference in probability between games $G^{1,1}$ and $G^{0,1}$, and between games $G^{0,1}$ and $G^{0,0}$, can be upper bounded by the IND-1CPA advantage of two adversaries $\mathcal{B}^{\rightarrow}$ and \mathcal{B}^{\leftarrow} against the unidirectional channel Ch . Note that either of the above combinations of games fixes one of the two selection bits. For instance, both games $G^{1,1}$ and $G^{0,1}$ make Bob send the 'left' message. This combination of games implicitly defines a new indistinguishability game $G^{b,1}$ where \mathcal{A} has to tell apart $G^{1,1}$ and $G^{0,1}$. In fact, the latter observation is the basic working principle of the reduction $\mathcal{B}^{\rightarrow}$, which answers \mathcal{A} 's queries in the direction ' \rightarrow ' using the oracles provided by the IND-1CPA game (defined in Figure 8 on page 17) against channel Ch , and answers the queries in the direction ' \leftarrow ' by running an independent instance of channel Ch . It is immediate to see that $\mathcal{B}^{\rightarrow}$ provides a perfect simulation of game $G^{b,1}$. To bound \mathcal{A} 's distinguishing advantage in game $G^{b,1}$ with $\mathcal{B}^{\rightarrow}$'s advantage it suffices to show that if all of \mathcal{A} 's queries are in-sync, i.e., do not cause premature termination of the game, then the corresponding queries that $\mathcal{B}^{\rightarrow}$ poses in the outer IND-1CPA game are in-sync, too. Let $q = (u, ad, c)$ be any of \mathcal{A} 's receiving queries and suppose that q does not trigger the execution of instruction 16 (in Figure 4). If $u = B$ there is nothing to show: $\mathcal{B}^{\rightarrow}$ answers the query on its own by invoking algorithm rcv (recall that $\mathcal{B}^{\rightarrow}$ runs an independent instance of Ch , so in particular it is in control of the states st_A and st_B for this instance). In the opposite case, i.e., $u = A$, $\mathcal{B}^{\rightarrow}$ asks a query $\text{rcv}(ad, c)$ to its own receiving oracle, and this may in principle cause abrupt termination of the game. However, by inspection of the IND-1CPA game it is immediate to see that this is not the case, as any out-of-sync query would also be considered out-of-sync in the IND-2CPA game from Figure 4. This allows us to derive the bound $|\Pr[G^{1,1}] - \Pr[G^{0,1}]| \leq \mathbf{Adv}^{\text{ind-1cpa}}(\mathcal{B}^{\rightarrow})$. Using a similar strategy we can construct a reduction \mathcal{B}^{\leftarrow} which, symmetrically to $\mathcal{B}^{\rightarrow}$, emulates game $G^{0,b}$ using the oracles provided by the IND-1CPA game and maintaining its own instance of the unidirectional channel Ch in the direction Alice-to-Bob (\rightarrow), and attacks the unidirectional channel Ch in the Bob-to-Alice direction (\leftarrow). This leads us to a second inequality: $|\Pr[G^{0,1}] - \Pr[G^{0,0}]| \leq \mathbf{Adv}^{\text{ind-1cpa}}(\mathcal{B}^{\leftarrow})$. Now consider an IND-adversary \mathcal{B} which tosses a coin $d \in \{0, 1\}$ uniformly at random and runs $\mathcal{B}^{\rightarrow}$ if $d = 0$ and \mathcal{B}^{\leftarrow} if $d = 1$. We obtain $\mathbf{Adv}^{\text{ind-1cpa}}(\mathcal{B}) \geq \frac{1}{2} \cdot \mathbf{Adv}^{\text{ind-1cpa}}(\mathcal{B}^{\rightarrow}) + \frac{1}{2} \cdot \mathbf{Adv}^{\text{ind-1cpa}}(\mathcal{B}^{\leftarrow})$, which implies the claimed bound. \square

To prove the next theorem we revisit the attack from Figure 1 in light of our formalisms, showing a successful chosen-ciphertext attack (IND-2CCA) against the canonic composition of two instances of a unidirectional channel which is indistinguishable against chosen-ciphertext attacks (IND-1CCA).

Theorem 5 (No confidentiality against active adversaries). *If IND-1CCA-secure unidirectional channels exist, then there exists one such channel Ch such that its canonic composition Ch^* is not IND-2CCA secure. More precisely, there exists an efficient adversary \mathcal{A} that breaks the confidentiality of Ch^* achieving $\mathbf{Adv}^{\text{ind-2cca}}(\mathcal{A}) = 1$.*

Proof. We prove the statement in two steps. We first argue that an IND-1CCA secure unidirectional channel Ch exists where the rcv algorithm never rejects an incoming ciphertext but always outputs a message. We then show that the canonic composition Ch^* of two instances of Ch is not IND-2CCA secure.

Let Ch' be any IND-1CCA secure unidirectional channel. Construct $\text{Ch} = (\text{snd}, \text{rcv})$ from $\text{Ch}' = (\text{snd}', \text{rcv}')$ by having snd and snd' be the same algorithms, and having rcv such that (1) when rcv' outputs a message m then also rcv outputs m , and (2) when rcv' rejects then rcv switches to a mode where on each invocation it outputs an a priori fixed message $\tilde{m} \in \mathcal{M}$. Clearly, if Ch' is IND-1CCA secure, then so is Ch . (Of course Ch does not offer any reasonable kind of integrity, but this does not contradict its IND-1CCA security.)

Consider now the canonic composition Ch^* of two instances of Ch . We describe an adversary \mathcal{A} against the IND-2CCA security of Ch^* that achieves an advantage of 1. As the attack does not rely on the associated data input of the snd and rcv algorithms, for simplicity, in the following we do not annotate it. Adversary \mathcal{A} fixes an arbitrary ciphertext \tilde{c} and two messages $m^0 \neq m^1$. It then poses three queries: (1) a query (A, \tilde{c}) to rcv , which makes Alice output some message (that plays no further role in the attack), (2) a query (A, m^0, m^1) to snd , which makes Alice produce a ciphertext c for either m^0 or m^1 , and (3) a query (B, c) to rcv , which asks Bob for a decryption of c . Adversary \mathcal{A} outputs $b' = 1$ if Bob answers with m^1 ; otherwise it outputs $b' = 0$. See Figure 6 for an illustration of the attack.

We analyze \mathcal{A} 's advantage as follows: By the rules of the IND-2CCA experiment (see Figure 4), query (1) is identified as active (Alice receives although nothing has been sent by Bob; formally, $r_A < s_B$ is not satisfied, see line 45) and, thus, $h_A \leftarrow \mathbb{F}$ is set in line 48. Also query (3) is identified as active (because $r_B < s_A$ is not satisfied), thus $h_B \leftarrow \mathbb{F}$ and the oracle returns c 's decryption m^b , which allows recovering b with probability 1. \square

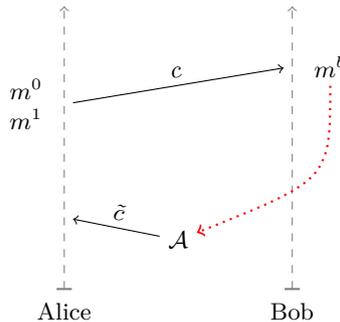


Fig. 6. An IND-2CCA attack against a bidirectional channel Ch^* obtained from an IND-1CCA-secure unidirectional channel Ch (as in the proof of Theorem 5) via the canonic composition paradigm. In the figure time evolves bottom-up (dashed lines).

Although in Theorem 5 we show a negative result, it does not say that all real-world channels designed following the canonic composition paradigm, like TLS and SSH, are actually insecure. Indeed, security analyses for the latter show that the unidirectional components of the SSH and the TLS channels meet the strong notion of stateful authenticated encryption (essentially that of a unidirectional channel, see Appendix A) [Kra01,BKN02,PRS11,BMM⁺15], thus providing confidentiality against chosen-plaintext attacks as well as integrity of ciphertexts. Using our formalisms from Section 4 we conclude that the TLS and SSH bidirectional channel protocols fulfill the requirements of Theorem 1 and, thus, *do* achieve the strongest security notions proposed in this paper.

The following corollary combines the results of Theorems 1, 3, and 4, and confirms the bidirectional security of the canonic composition of two unidirectional channels—given the unidirectional channels are sufficiently secure.

Corollary 1 (Security of the Canonic Composition). *If Ch offers unidirectional integrity of ciphertexts (INT-1CTXT) and indistinguishability against chosen-plaintext attacks (IND-1CPA) then Ch^* offers bidirectional integrity of ciphertexts (INT-2CTXT) as well as bidirectional indistinguishability against chosen-ciphertext attacks (IND-2CCA).*

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A Unidirectional Channels

In the cryptographic literature, secure channels are often modeled as stateful encryption primitives (as in [Nam02,BKN02,KPB03], to just name a few). Importantly for this paper, these channel models consider a restricted scenario in which one party only sends and the other only receives, thus providing a *unidirectional* channel. Our syntax in Definition 1 contains that of stateful (authenticated) encryption as a special case. For completeness, in this section we reproduce some established security definitions for unidirectional channels. Precisely, we translate the ideas of BKN [BKN02] to our notation.

We indicate unidirectional flavors of security notions by prefixing their name with a “1”, obtaining integrity of plaintexts (INT-1PTXT), integrity of ciphertexts (INT-1CTXT), indistinguishability against chosen-plaintext attacks (IND-1CPA), and indistinguishability against chosen-ciphertext attacks (IND-1CCA).

Consider the integrity games in Figure 7. We define the INT-1PTXT advantage of an adversary \mathcal{A} as $\mathbf{Adv}^{\text{int-1ptxt}}(\mathcal{A}) = \Pr[\text{INT}^{\text{1ptxt}}(\mathcal{A}) \Rightarrow 1]$ and we define its INT-1CTXT advantage as $\mathbf{Adv}^{\text{int-1ctxt}}(\mathcal{A}) = \Pr[\text{INT}^{\text{1ctxt}}(\mathcal{A}) \Rightarrow 1]$. The probabilities are over the choice of $K \in \mathcal{K}$ and over \mathcal{A} ’s randomness. Intuitively, a unidirectional channel offers plaintext integrity if $\mathbf{Adv}^{\text{int-1ptxt}}(\mathcal{A})$ is small for all efficient adversaries \mathcal{A} ; similarly, it offers ciphertext integrity if $\mathbf{Adv}^{\text{int-1ctxt}}(\mathcal{A})$ is small for all efficient \mathcal{A} .

Consider next the confidentiality games in Figure 8. We define the IND-1CPA advantage of an adversary \mathcal{A} as $\mathbf{Adv}^{\text{ind-1cpa}}(\mathcal{A}) = |\Pr[\text{IND}^{\text{1cpa},1}(\mathcal{A}) \Rightarrow 1] - \Pr[\text{IND}^{\text{1cpa},0}(\mathcal{A}) \Rightarrow 1]|$ and we define its IND-1CCA advantage as $\mathbf{Adv}^{\text{ind-1cca}}(\mathcal{A}) = |\Pr[\text{IND}^{\text{1cca},1}(\mathcal{A}) \Rightarrow 1] - \Pr[\text{IND}^{\text{1cca},0}(\mathcal{A}) \Rightarrow 1]|$. The probabilities are over the choice of $K \in \mathcal{K}$ and over \mathcal{A} ’s randomness. Intuitively, a unidirectional channel offers confidentiality against passive attacks if $\mathbf{Adv}^{\text{ind-1cpa}}(\mathcal{A})$ is small for all efficient adversaries \mathcal{A} ; similarly, it offers confidentiality against active attacks if $\mathbf{Adv}^{\text{ind-1cca}}(\mathcal{A})$ is small for all efficient \mathcal{A} .

<p>Game INT^{1ptxt}(\mathcal{A})</p> <p>00 $s \leftarrow 0; r \leftarrow 0$</p> <p>01 $AD\text{-}M \leftarrow \emptyset$</p> <p>02 $(st_S, st_R) \leftarrow_s \text{init}$</p> <p>03 $\mathcal{A}^{\text{snd,rcv}}$</p> <p>04 Stop with 0</p> <p>Oracle $\text{snd}(ad, m)$</p> <p>05 $(st_S, c) \leftarrow \text{snd}(st_S, ad, m)$</p> <p>06 $AD\text{-}M[s] \leftarrow (ad, m)$</p> <p>07 $s \leftarrow s + 1$</p> <p>08 Return c</p> <p>Oracle $\text{rcv}(ad, c)$</p> <p>09 $(st_R, m) \leftarrow \text{rcv}(st_R, ad, c)$</p> <p>10 If $(st_R, m) = (\perp, \perp)$: Return \perp</p> <p>11 If $r < s \wedge (ad, m) = AD\text{-}M[r]$:</p> <p>12 $r \leftarrow r + 1$</p> <p>13 Else:</p> <p>14 Stop with 1</p> <p>15 Return m</p>	<p>Game INT^{1ctxt}(\mathcal{A})</p> <p>30 $s \leftarrow 0; r \leftarrow 0$</p> <p>31 $AD\text{-}C \leftarrow \emptyset$</p> <p>32 $(st_S, st_R) \leftarrow_s \text{init}$</p> <p>33 $\mathcal{A}^{\text{snd,rcv}}$</p> <p>34 Stop with 0</p> <p>Oracle $\text{snd}(ad, m)$</p> <p>35 $(st_S, c) \leftarrow \text{snd}(st_S, ad, m)$</p> <p>36 $AD\text{-}C[s] \leftarrow (ad, c)$</p> <p>37 $s \leftarrow s + 1$</p> <p>38 Return c</p> <p>Oracle $\text{rcv}(ad, c)$</p> <p>39 $(st_R, m) \leftarrow \text{rcv}(st_R, ad, c)$</p> <p>40 If $(st_R, m) = (\perp, \perp)$: Return \perp</p> <p>41 If $r < s \wedge (ad, c) = AD\text{-}C[r]$:</p> <p>42 $r \leftarrow r + 1$</p> <p>43 Else:</p> <p>44 Stop with 1</p> <p>45 Return m</p>
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Fig. 7. Games for plaintext integrity (left) and ciphertext integrity (right) for unidirectional channels.

<p>Game $\text{IND}^{\text{1cpa},b}(\mathcal{A})$</p> <p>00 $s \leftarrow 0; r \leftarrow 0$ 01 $AD-C \leftarrow \emptyset$ 02 $(st_S, st_R) \leftarrow_{\mathcal{S}} \text{init}$ 03 $b' \leftarrow_{\mathcal{S}} \mathcal{A}^{\text{snd,rcv}}$ 04 Stop with b'</p> <p>Oracle $\text{snd}(ad, m^0, m^1)$</p> <p>05 $(st_S, c) \leftarrow \text{snd}(st_S, ad, m^b)$ 06 $AD-C[s] \leftarrow (ad, c)$ 07 $s \leftarrow s + 1$ 08 Return c</p> <p>Oracle $\text{rcv}(ad, c)$</p> <p>09 $(st_R, m) \leftarrow \text{rcv}(st_R, ad, c)$ 10 If $(st_R, m) = (\perp, \perp)$: Return \perp 11 If $r < s \wedge (ad, c) = AD-C[r]$: 12 $r \leftarrow r + 1$ 13 Else: 14 Stop with 0 15 Return \diamond</p>	<p>Game $\text{IND}^{\text{1cca},b}(\mathcal{A})$</p> <p>30 $s \leftarrow 0; r \leftarrow 0; h \leftarrow \text{T}$ 31 $AD-C \leftarrow \emptyset$ 32 $(st_S, st_R) \leftarrow_{\mathcal{S}} \text{init}$ 33 $b' \leftarrow_{\mathcal{S}} \mathcal{A}^{\text{snd,rcv}}$ 34 Stop with b'</p> <p>Oracle $\text{snd}(ad, m^0, m^1)$</p> <p>35 $(st_S, c) \leftarrow \text{snd}(st_S, ad, m^b)$ 36 If h: 37 $AD-C[s] \leftarrow (ad, c)$ 38 $s \leftarrow s + 1$ 39 Return c</p> <p>Oracle $\text{rcv}(ad, c)$</p> <p>40 $(st_R, m) \leftarrow \text{rcv}(st_R, ad, c)$ 41 If $(st_R, m) = (\perp, \perp)$: Return \perp 42 If $r < s \wedge (ad, c) = AD-C[r]$: 43 $r \leftarrow r + 1$ 44 Else: 45 $h \leftarrow \text{F}$ 46 Return $h ? \diamond : m$</p>
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Fig. 8. Games for confidentiality of unidirectional channels against chosen-plaintext (left) and chosen-ciphertext (right) attacks. Note the rcv oracle of game IND^{1cpa} is redundant and could be removed.

B Unidirectional Security $\not\Rightarrow$ Bidirectional Security

Let Ch be a unidirectional channel with key space \mathcal{K} , let $K^{\rightarrow}, K^{\leftarrow} \in \mathcal{K}$, and let Ch^* be the bidirectional channel obtained from Ch as specified in Figure 9. Notice that if we restrict the attention to the (traditional) unidirectional case by letting Alice only send and Bob only receive, channel Ch^* inherits the same level of confidentiality of its underlying building block Ch . However, in a bidirectional setting this channel is blatantly insecure against passive attacks (IND-2CPA), even in case Ch provides security against active attacks (IND-1CCA).

<p>Proc $\text{init}^*(K)$</p> <p>00 $(K^{\rightarrow}, K^{\leftarrow}) \leftarrow K$ 01 $(st_S^{\rightarrow}, st_R^{\rightarrow}) \leftarrow \text{init}(K^{\rightarrow})$ 02 $(st_S^{\leftarrow}, st_R^{\leftarrow}) \leftarrow \text{init}(K^{\leftarrow})$ 03 $st_A \leftarrow (K^{\leftarrow}, st_S^{\rightarrow}, st_R^{\leftarrow})$ 04 $st_B \leftarrow (K^{\rightarrow}, st_S^{\leftarrow}, st_R^{\rightarrow})$ 05 Return (st_A, st_B)</p>	<p>Proc $\text{snd}^*(st, ad, m)$</p> <p>06 $(k, st_S, st_R) \leftarrow st$ 07 $(st_S, c) \leftarrow \text{snd}(st_S, k \parallel ad, m)$ 08 $st \leftarrow (k, st_S, st_R)$ 09 $c \leftarrow (k, c)$ 10 Return (st, c)</p>	<p>Proc $\text{rcv}^*(st, ad, c)$</p> <p>11 $(k, st_S, st_R) \leftarrow st$ 12 $(k', c) \leftarrow c$ 13 $(st_R, m) \leftarrow \text{rcv}(st_R, k' \parallel ad, c)$ 14 If $st_R \neq \perp$: 15 $st \leftarrow (k, st_S, st_R)$ 16 Else: 17 $st \leftarrow \perp$ 18 Return (st, m)</p>
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Fig. 9. A bidirectional channel $\text{Ch}^* = (\text{init}^*, \text{snd}^*, \text{rcv}^*)$ built from two instances of a unidirectional channel $\text{Ch} = (\text{init}, \text{snd}, \text{rcv})$. We have $\mathcal{K}^* = \mathcal{K} \times \mathcal{K}$, $\mathcal{S}^* = \mathcal{K} \times \mathcal{S} \times \mathcal{S}$, $\mathcal{C}^* = \mathcal{K} \times \mathcal{C}$, and $AD = \mathcal{K} \times AD^*$. The constructed channel falls prey to a purely passive (IND-2CPA) attack, even if Ch is secure against active adversaries (IND-1CCA).