On Symmetric Encryption with Distinguishable Decryption Failures

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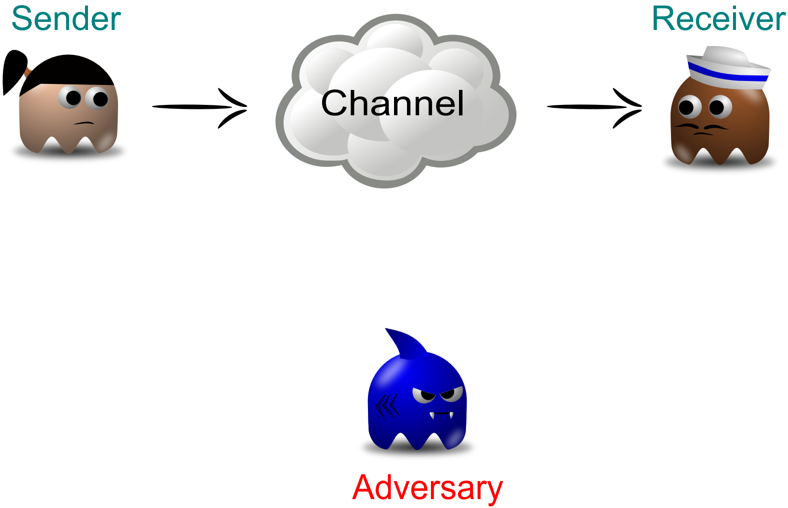
Outline

Attacks Based on Decryption Failures



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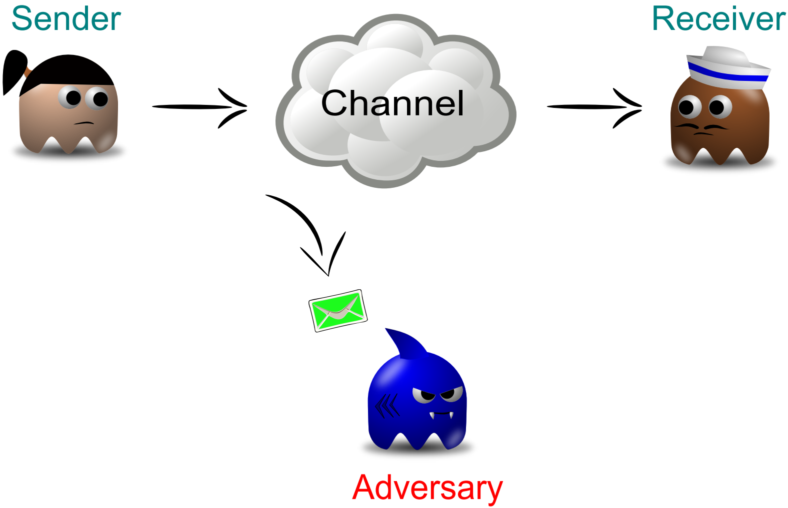

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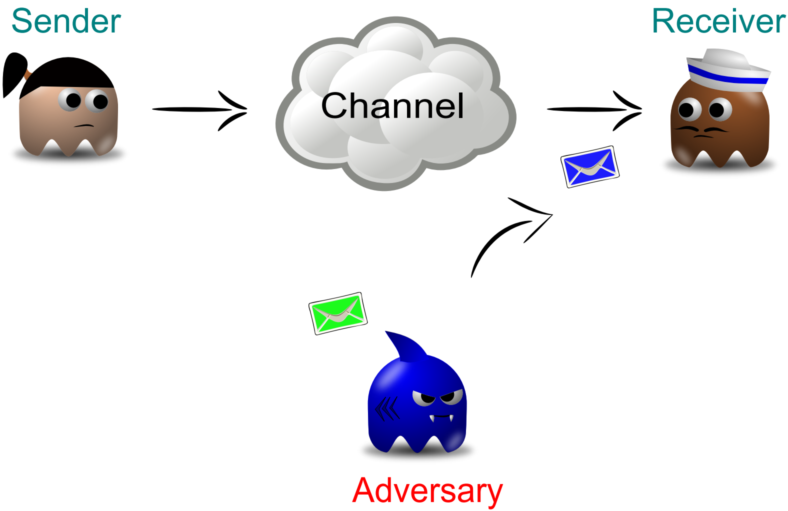

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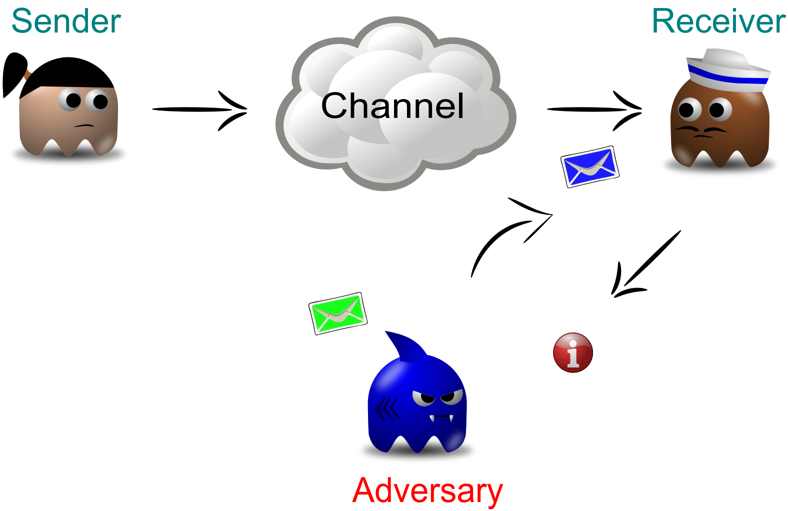

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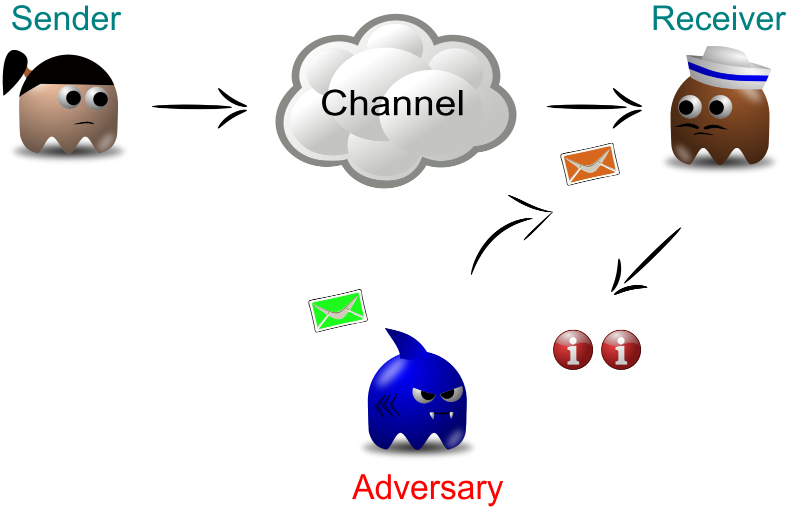

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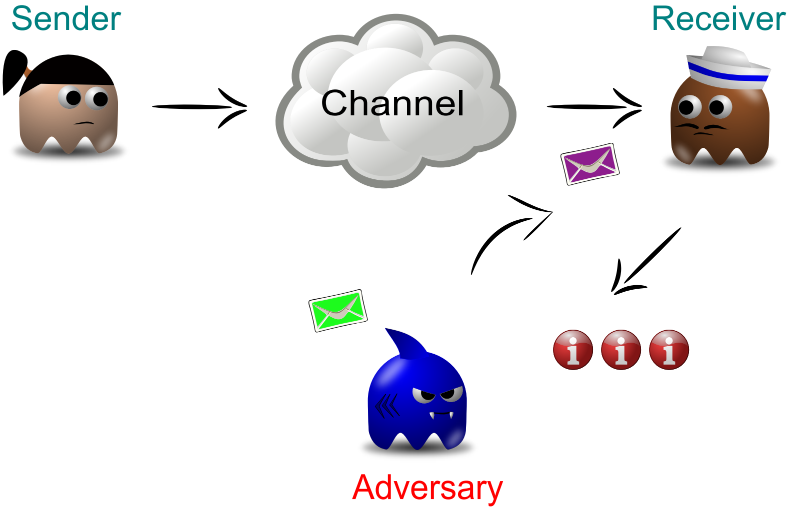

Attacks Based on Decryption Failures

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- The decryption algorithm can have **multiple checks** that may cause it to fail. Knowledge of which check failed may convey more information to the adversary.
- Distinguishable decryption failures enabled attacks against TLS **[CHVV 03]**, DTLS **[AP 12]**, and IPsec **[DP 10]**.

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- Distinguishable decryption failures enabled attacks against TLS **[CHVV 03]**, DTLS **[AP 12]**, and IPsec **[DP 10]**.

- **GAP:** In IND-CCA the adversary only learns whether a ciphetext is valid or not (distinct decryption failures always return $\perp$).

A Common Response

- *"This is a flaw in the implementation. It can be easily fixed by ensuring that errors are not distinguishable."*
- But errors are useful for troubleshooting; moreover side-channels due to timing or interaction with other protocols (e.g. IPsec) are hard to prevent.

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- But errors are useful for troubleshooting; moreover side-channels due to timing or interaction with other protocols (e.g. IPsec) are hard to prevent.

- On the other hand it is easy to model distinguishable decryption failures – **multiple-error schemes**.

$$\mathcal{D} : \mathcal{K} \times \mathcal{C} \to \mathcal{M} \cup \mathcal{S}_\perp$$

where $\mathcal{S}_\perp = \{\perp_1, \perp_2, \ldots, \perp_n\}$

- How does this affect the theory of symmetric encryption?

Revisiting Classic Relations

- The following relation is attributed to Bellare and Namprempre **[BN00]**, and to Katz and Yung **[KY00]**.

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- This relation provides a simple technique for realizing IND-CCA secure schemes in the symmetric setting.

- Furthermore INT-CTXT $+$ IND-CPA has become the target security notion for **authenticated encryption**, since INT-CTXT $\Rightarrow$ INT-PTXT.

Revisiting Classic Relations

- In their work on SSH, Bellare, Kohno, and Namprempre **[BKN04]** extended this relation to the stateful setting.

$$\text{IND-CPA} \wedge \text{INT-sfCTXT} \Rightarrow \text{IND-sfCCA}$$

- INT-sfCTXT and IND-sfCCA are strengthened variations, which additionally capture replay and reordering attacks.

- Any encryption scheme which satisfies these notions must be stateful – hence the name.

Classic Relations in the Multiple-Error Setting

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Theorem

If pseudorandom functions exist, then there exists a multiple-error encryption scheme that is both IND-CPA and INT-CTXT secure, but not IND-CCA secure.

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- A similar separation holds for the **stateful setting**:

$$\text{IND-CPA} \wedge \text{INT-sfCTXT} \not\Rightarrow \text{IND-sfCCA}$$

- As we shall see, **it is possible to define ciphertext integrity in two ways**, both separations allow the stronger variant.

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New Relations in the Multiple-Error Setting

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$$\text{IND-CVA} \wedge \text{INT-CTXT} \Rightarrow \text{IND-CCA}$$

- Informally, IND-CVA is described as the IND-CPA game with additional access to a **ciphertext validity oracle** which returns decryption errors but no plaintext.

- The **stronger variant** of ciphertext integrity is **required**.

- Similar relations can be obtained for IND-sfCCA, IND$-CCA, and IND$-sfCCA.

Defining Ciphertext Integrity

INT-CTXT* (weaker variant):

$\mathbf{Exp}_{\mathcal{SE}}^{\text{int-ctxt}*}(\mathcal{A})$	$\text{Enc}(m)$	$\text{Try}^*(c)$
$K \leftarrow \mathcal{K}$ $\mathtt{C} \leftarrow \emptyset, \text{win} \leftarrow 0$ $\mathcal{A}^{\text{Enc}(\cdot),\text{Try}^*(\cdot)}$ **return** win	$c \leftarrow \mathcal{E}_K(m)$ $\mathtt{C} \leftarrow \mathtt{C} \cup c$ **return** c	$m \leftarrow \mathcal{D}_K(c)$ **if** $c \notin \mathtt{C}$ **and** $m \in \mathcal{M}$ **then** win $\leftarrow \mathtt{true}$ **if** $m \in \mathcal{M}$ **then** $m \leftarrow \mathtt{valid}$ **else** $m \leftarrow \mathtt{invalid}$ **return** m

- Try queries reveal only whether a ciphertext is **valid** or **not**.

Defining Ciphertext Integrity

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$\mathtt{C} \leftarrow \emptyset, \mathrm{win} \leftarrow 0$	$\mathtt{C} \leftarrow \mathtt{C} \cup c$	**if** $c \notin \mathtt{C}$ **and** $m \in \mathcal{M}$
$\mathcal{A}^{\mathrm{Enc}(\cdot),\mathrm{Try}(\cdot)}$	**return** c	**then** $\mathrm{win} \leftarrow \mathtt{true}$
return win		**if** $m \in \mathcal{M}$ **then** $m \leftarrow \mathtt{valid}$
		return m

- Try queries reveal either that a ciphertext is **valid** or the **error** that it generates.

Ciphertext Integrity

- Obviously INT-CTXT $\Rightarrow$ INT-CTXT*, but is the converse true?

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Ciphertext Integrity

- Obviously INT-CTXT $\Rightarrow$ INT-CTXT*, but is the converse true? NO
- The new relations required strong ciphertext integrity, is this necessary or is it just an artefact of the proof? NECESSARY
- Both questions are settled through the following non-trivial separation.

Theorem

Given a scheme with a sufficiently large message space that is both IND-CVA and INT-CTXT, we can construct a multiple-error scheme that is both IND-CVA and INT-CTXT* but not IND-CCA.*

$$\textit{IND-CVA} \wedge \textit{INT-CTXT*} \not\Rightarrow \textit{IND-CCA}$$

IND-CCA3

- Rogaway and Shrimpton **[RS06]** introduced a notion that captures concisely the goal for authenticated encryption:

$$\text{IND-CCA3} \Leftrightarrow \text{IND-CPA} \wedge \text{INT-CTXT}.$$

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- For all adversaries $\mathcal{A}$:

$$\Pr\left[\mathcal{A}^{\mathcal{E}_K(\cdot),\mathcal{D}_K(\cdot)} = 1\right] - \Pr\left[\mathcal{A}^{\mathcal{E}_K(\$|\cdot|),\perp(\cdot)} = 1\right] \leq \epsilon.$$

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- **Can we extend** this notion to the multiple-error setting? **What security** would it guarantee?

IND-CCA3 in the Multiple-Error Setting

- There exists a $\perp_0 \in \mathcal{S}_\perp$ such that for all adversaries $\mathcal{A}$:

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- IND-CCA3 provides the following security guarantees:

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Informally INV-ERR says that all invalid ciphertexts that an adversary can come up with, will generate the **same error**.

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- It can further be shown that:

$$\text{IND-CCA3} \Rightarrow \text{IND-CVA} \wedge \text{INT-CTXT} \Rightarrow \text{IND-CCA}.$$

  Hence IND-CCA3 still constitutes a **good notion for authenticated encryption**, albeit perhaps it is too strong.

Authenticated Encryption Through Generic Composition

- In **[BN00]** Encrypt-then-MAC emerges as the preferred generic composition for realizing authenticated encryption.

- Krawczyk **[Kra01]** however, showed that MAC-then-Encrypt is also IND-CCA secure when encryption is instantiated with CBC mode or CTR mode.

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- Krawczyk **[Kra01]** however, showed that MAC-then-Encrypt is also IND-CCA secure when encryption is instantiated with CBC mode or CTR mode.
- Hence, when encryption is instantiated with CBC mode or CTR mode, the question as to which generic composition is better remains open.
- Nonetheless practical cryptosystems (using CBC and CTR) based on EtM have proved to be less vulnerable to attack than ones based on MtE.

Re-examining Generic Compositions

- Re-examining generic compositions in the light of distinguishable decryption failures, provides new formal evidence to support this observation.

- We consider an Encode-then-Encrypt-then-MAC (EEM) composition – to account for the pre-processing that is common in practical schemes.

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- We consider an Encode-then-Encrypt-then-MAC (EEM) composition – to account for the pre-processing that is common in practical schemes.

Theorem

For any multiple-error encoding scheme, any IND-CPA multiple-error encryption scheme, and any UF-CMA MAC, the EEM composition yields an IND-CCA3 secure scheme.

Re-examining Generic Compositions

- This theorem says that EEM is a **robust composition**, since security holds even when decryption failures are distinguishable, and without assuming anything about the error behaviour of the encoding or encryption components.

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- It may seem unfair that we do not consider multiple-error MACs. This is justified as follows:
  - Most MACs verify the tag by recomputing the tag and comparing – only one test condition.
  - When this is implemented badly (the keyczar library example) it results in the MAC itself not being secure.

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- **Preventive Approach:** Assign distinct error messages to the distinct checks made during decryption $\Rightarrow$ achieve security that is **less implementation-dependent**.
- **A Posteriori Analysis:** Alternatively the multiple-error setting can be used to model realizations of cryptographic protocols and analyze the **security of the implementation**.