Quantum non-malleability and authentication – Information theoretic security + ~~sneak preview~~ teaser

based on arXiv:1610.04214 and arXiv:1709.06539

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Joint work with Gorjan Alagic, NIST and University of Maryland,
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Quantum Innovators, IQC, University of Waterloo

20.09.2017

Motivation: a classical story...

Crypto for bank transfers

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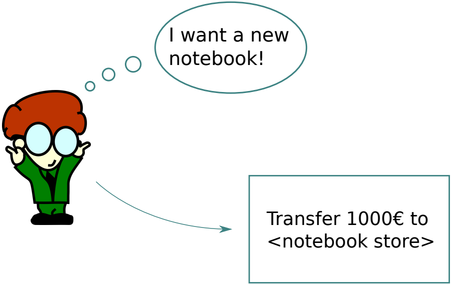

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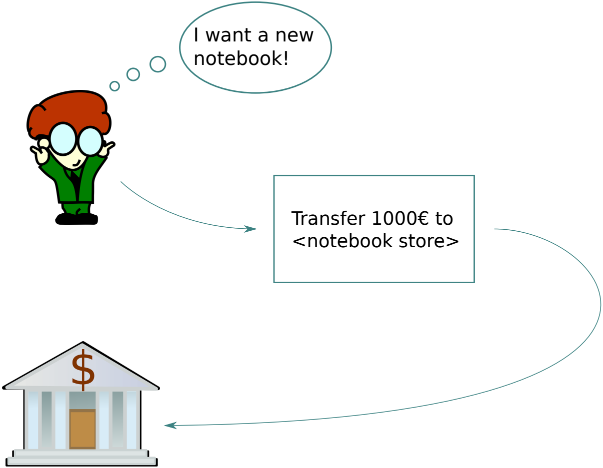

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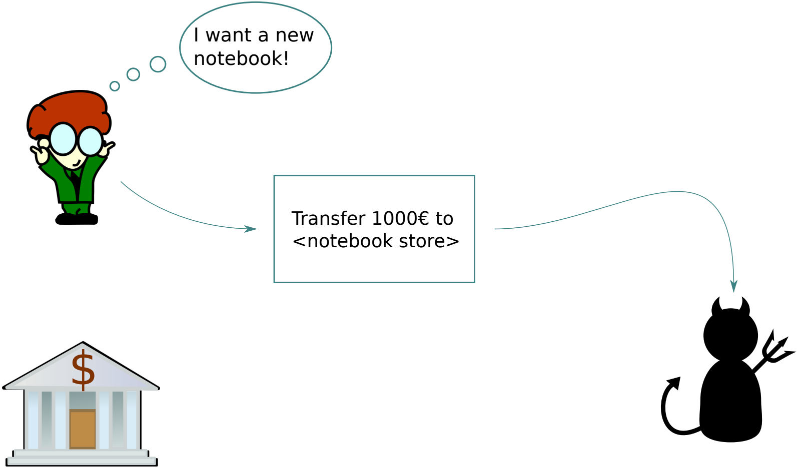

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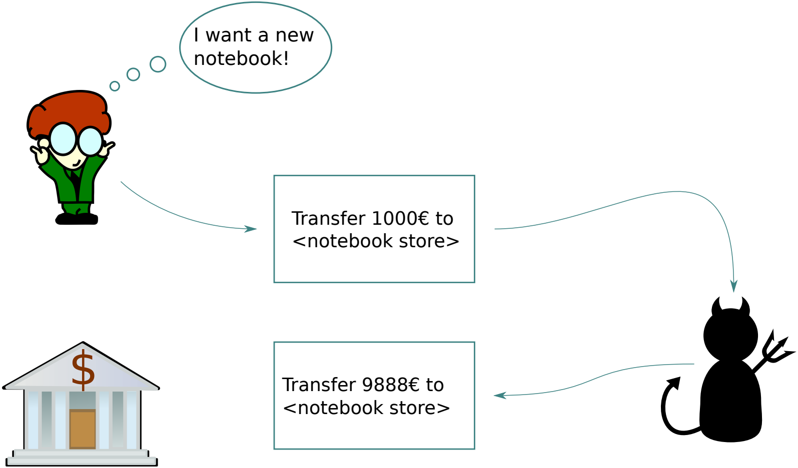

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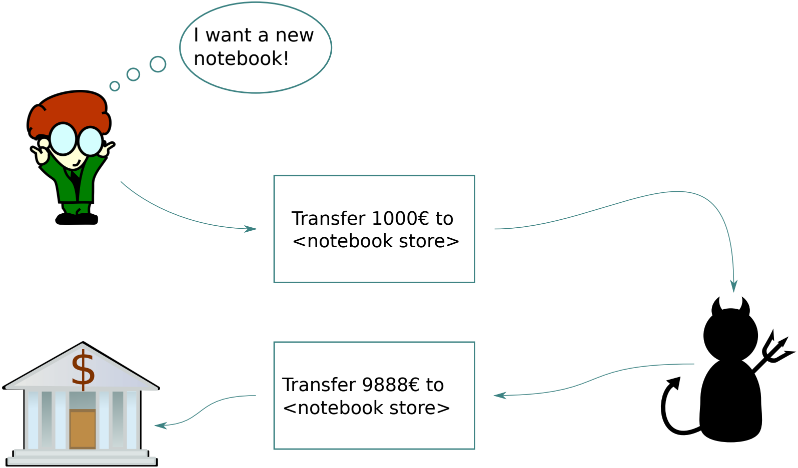

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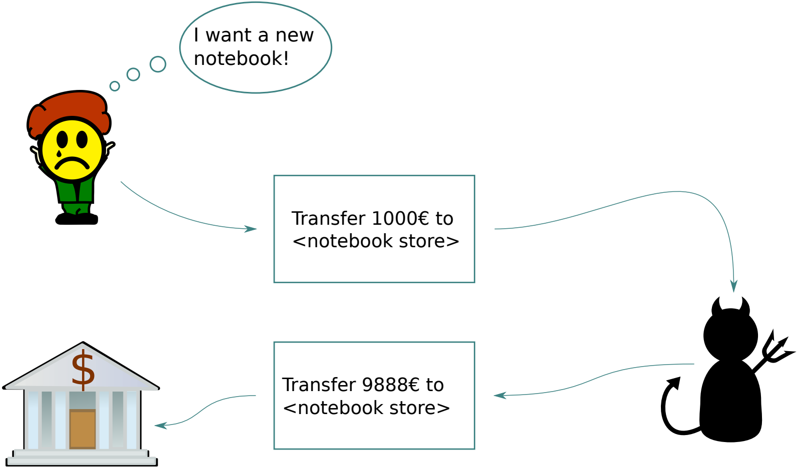

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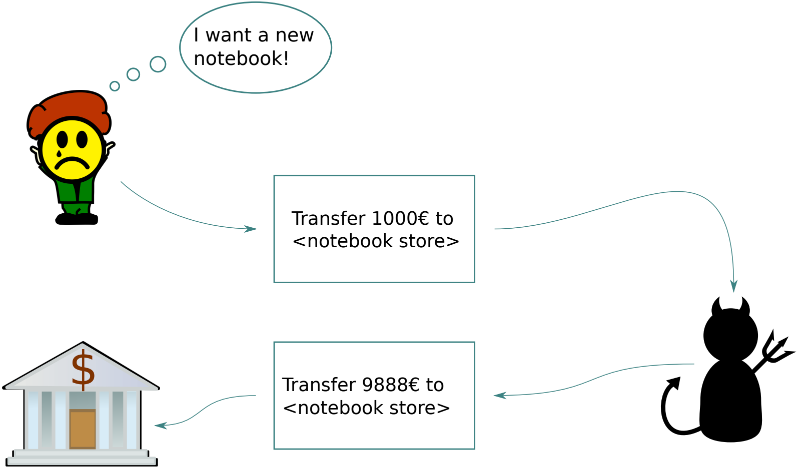

- What cryptographic security notions would fix this problem?

Non-malleability

- One solution is non-malleable encryption:

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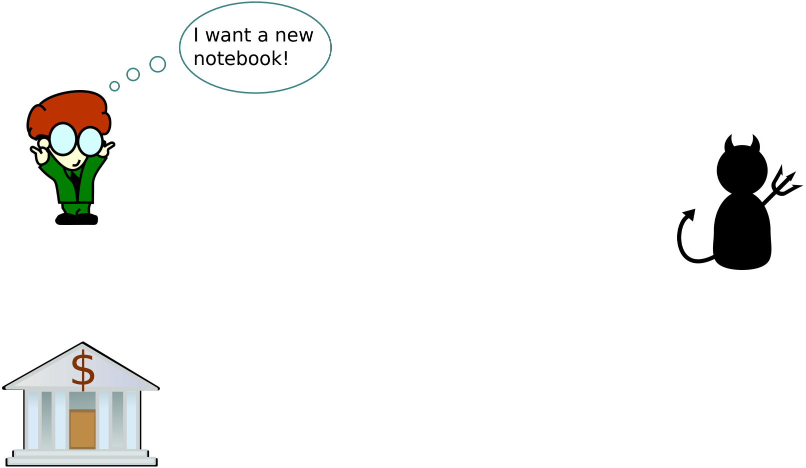

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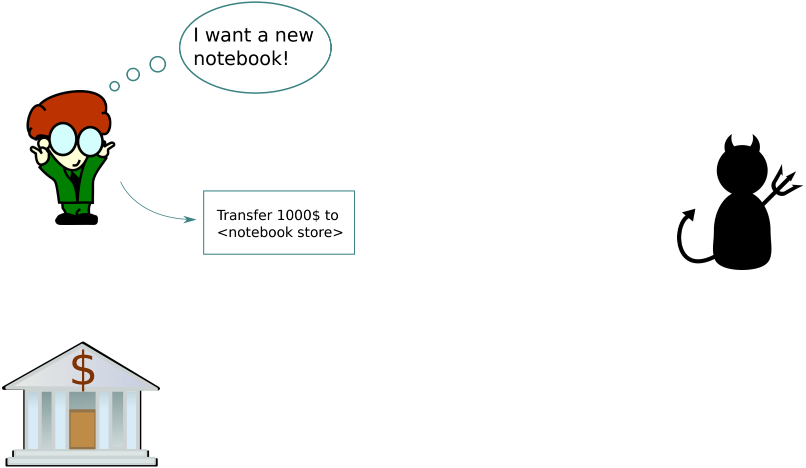

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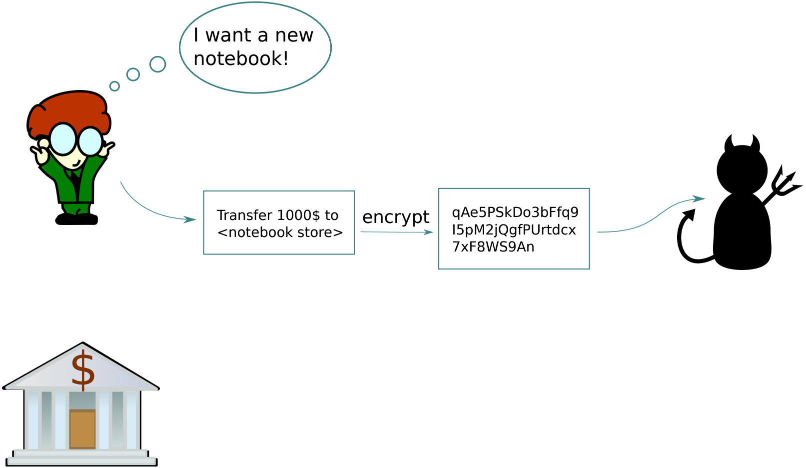

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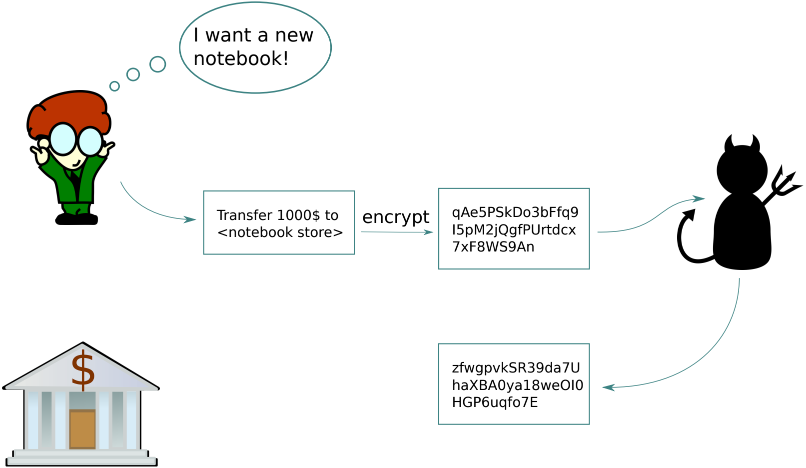

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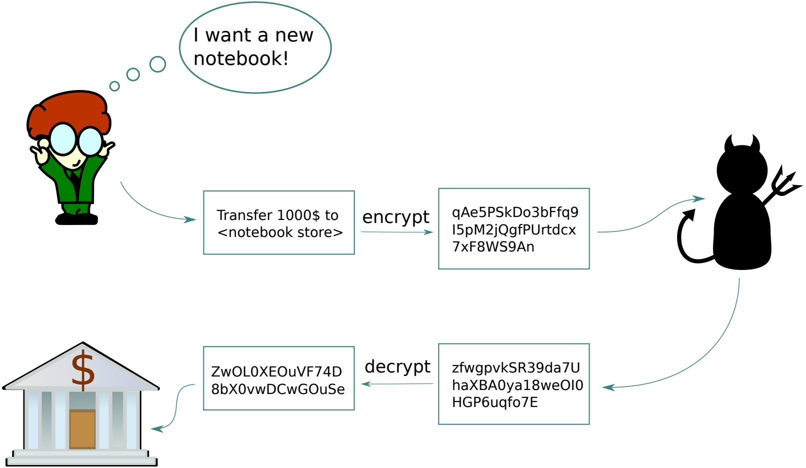

Outline

Non-malleability

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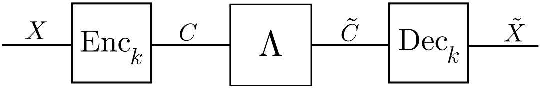
- Information theoretic definition using entropy:
  (X, C), $(\tilde{X}, \tilde{C})$ two plaintext ciphertext pairs, $C \neq \tilde{C}$

def: scheme is NM if $I(\tilde{X} : \tilde{C}|XC) = 0$ (Hanaoka et al. '02)

- Classical NM:



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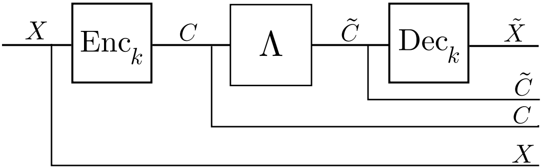

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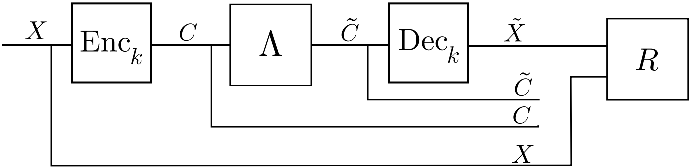

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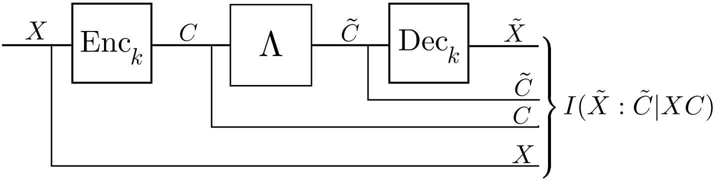

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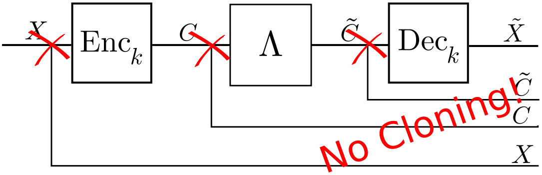

X
Enc_k
C
Λ
$\tilde{C}$
Dec_k
$\tilde{X}$
$\tilde{C}$
C
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No Cloning!

Quantum symmetric key encryption

def: Quantum encryption scheme: $(\mathrm{Enc}_k, \mathrm{Dec}_k)$

- classical uniformly random key k
- encryption map $(\mathrm{Enc}_k)_{A \to C}$, decryption map $(\mathrm{Dec}_k)_{C \to \bar{A}}$

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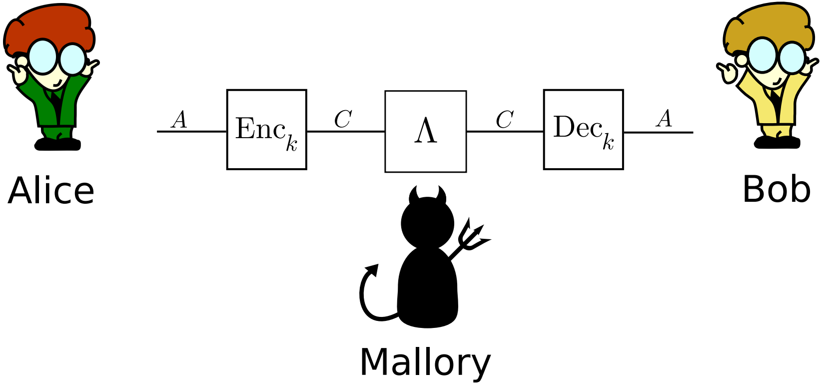
- correctness: $\mathrm{Dec}_k \circ \mathrm{Enc}_k = \mathrm{id}_A$
- average encryption map: $\mathrm{Enc}_K = \mathbb{E}_k \mathrm{Enc}_k$

Setup for q-non-malleability

- Recall: classical non-malleability setup



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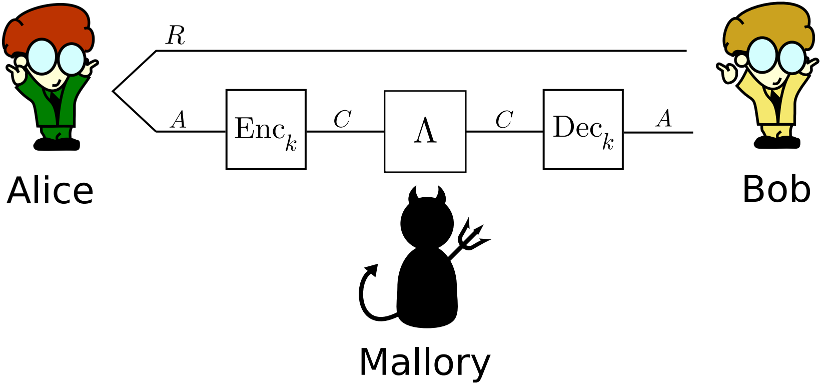

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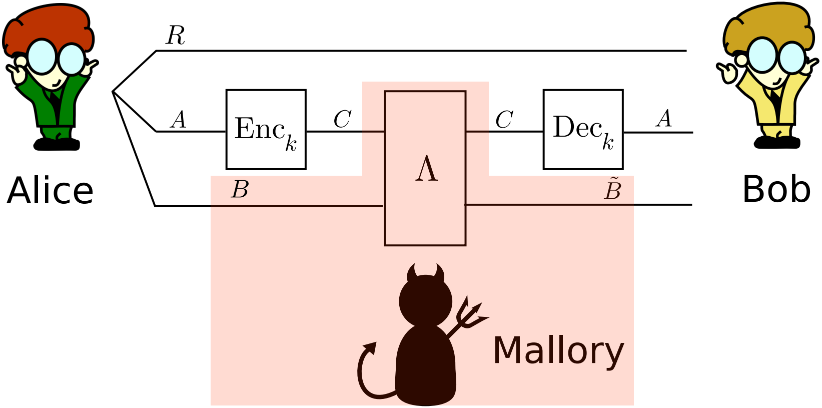

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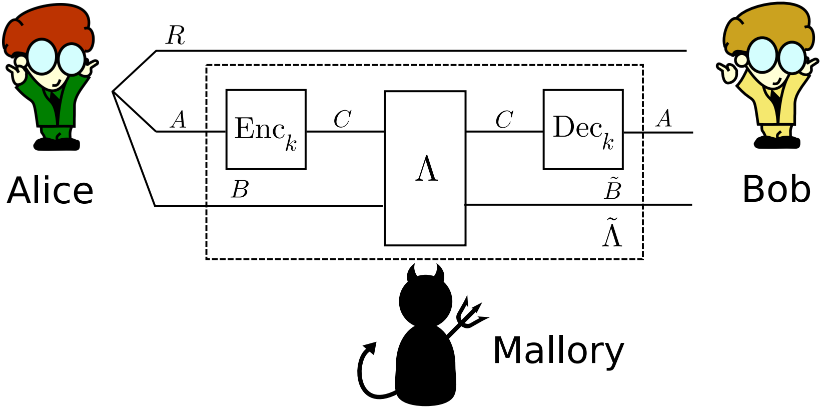
def: effective map on plaintexts and side info
$\tilde{\Lambda} = \mathbb{E}_k[\mathrm{Dec}_k \circ \Lambda \circ \mathrm{Enc}_k]$



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- example:

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- definition:

$$\begin{aligned} p_{=}(\Lambda_{CB\to C\tilde{B}}, \rho) =& \mathrm{tr}\left[(\phi^+_{CC'} \otimes \mathbb{1}_{\tilde{B}})\Lambda_{CB\to C\tilde{B}}(\phi^+_{CC'} \otimes \rho_B)\right] \\ =& F(\mathrm{tr}_{\tilde{B}}\Lambda_{CB\to C\tilde{B}}(\phi^+_{CC'} \otimes \rho_B), \phi^+_{CC'})^2 \end{aligned}$$

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- "probability of Λ acting as the identity on C"

$\Rightarrow$ $p_=(\Lambda) = p$ for the example if $\mathrm{tr}(U_C) = 0$.

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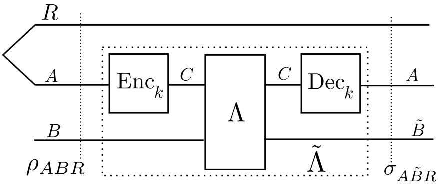
A scheme $\Pi = (\mathrm{Enc}_k, \mathrm{Dec}_k)$ *is non-malleable, if for all states* ρ_{ABR} *and all attacks* $\Lambda_{CB \to C\tilde{B}}$,

$$I(AR : \tilde{B})_\sigma \leq I(AR : B)_\rho$$

with $\sigma_{A\tilde{B}R} = \tilde{\Lambda}_{AB \to A\tilde{B}}(\rho_{ABR})$.



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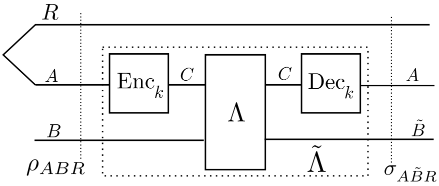

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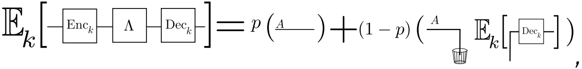
Comparison to previous definition

Definition (ABW-NM, Ambainis, Bouda, Winter '09)

Let $\Pi = (\mathrm{Enc}_k, \mathrm{Dec}_k)$ *be a quantum encryption scheme.* Π *is ABW-NM if*



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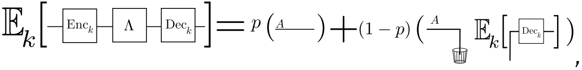

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Theorem (Alagic, CM)

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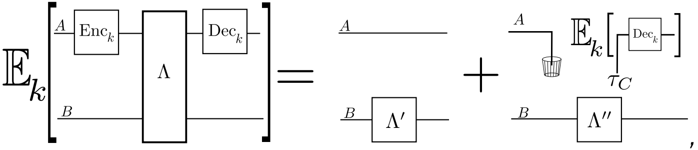

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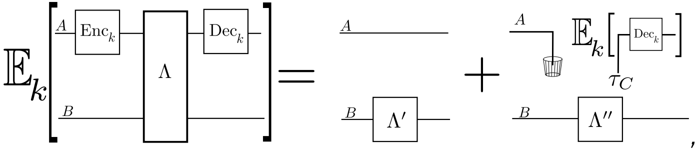

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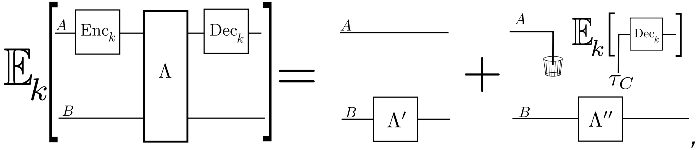

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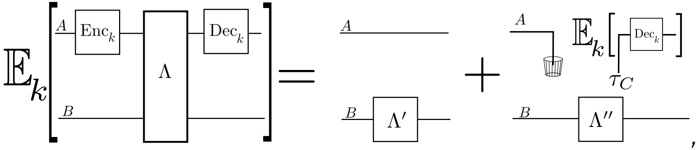

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\end{aligned}$$

$\Rightarrow$ Ciphertext non-malleability!

Improvements

The new definition

... allows adversaries with side information

... prevents plaintext injection attack

... provides *ciphertext* non-malleability

while ABW-NM does not.

More Properties

$$\begin{aligned}\Lambda'_{B\to\tilde{B}} =& \langle\phi+|_{CC'}\,\Lambda_{CB\to C\tilde{B}}(\phi^+_{CC'}\otimes(\cdot)_B)\left|\phi^+\right\rangle_{CC'}\\ \Lambda''_{B\to\tilde{B}} =& \mathrm{tr}_C\Lambda(\tau_C\otimes(\cdot)_B)-\Lambda'\end{aligned}$$

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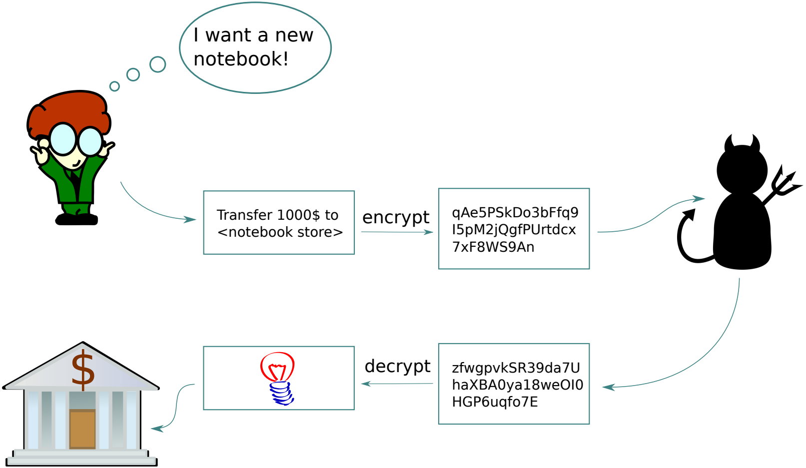
- non-unitary schemes are interesting, e.g. for authentication.
- qNM serves as primitive for quantum authentication schemes $\Rightarrow$ second part of the talk

Summary non-malleability

	ABW-NM	qNM
assumes secrecy	✓	✗
implies secrecy	✗	✓
secure against plaintext injection	✗	✓
primitive for authentication	✗	✓

Authentication

Authentication



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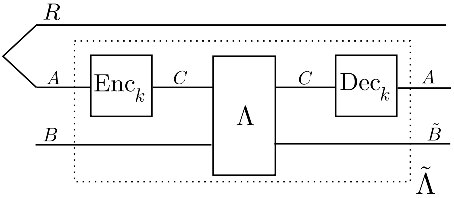
Definition (GYZ Authentication; Garg, Yuen and Zhandry)

$\Pi = (\mathrm{Enc}_k, \mathrm{Dec}_k)$ *is* ε*-GYZ-authenticating if, for any attack* $\Lambda_{CB \to CB'}$, *there exists* $\Lambda^{acc}_{B \to \tilde{B}}$ *such that for all* ρ_{AB}

$$\mathbb{E}_k \left[\left\| \Pi_{acc} \left[\mathrm{Dec}_k \circ \Lambda \circ \mathrm{Enc}_k(\rho_{AB}) \right] \Pi_{acc} - \left(\mathrm{id}_A \otimes \Lambda^{acc} \right)(\rho_{AB}) \right\|_1 \right] \leq \varepsilon$$

with $\Pi_{acc} = \mathbb{1} - \perp$.



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- Independently proven by Portmann '16
- advantages: shorter keys, nice constructions (Clifford group)

Proof sketch

want to ”decouple the adversary”

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consider pure states and attack isometries (Stinespring)

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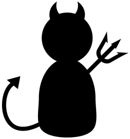
Use "swap trick" $\mathrm{tr} A_X B_X = \mathrm{tr} S_{XX'} A_X \otimes B_{X'}$ and Schur's lemma for $U \mapsto U\otimes U$

Authentication from NM: Intuition

I want a new notebook!

Transfer 1000$ to <notebook store>



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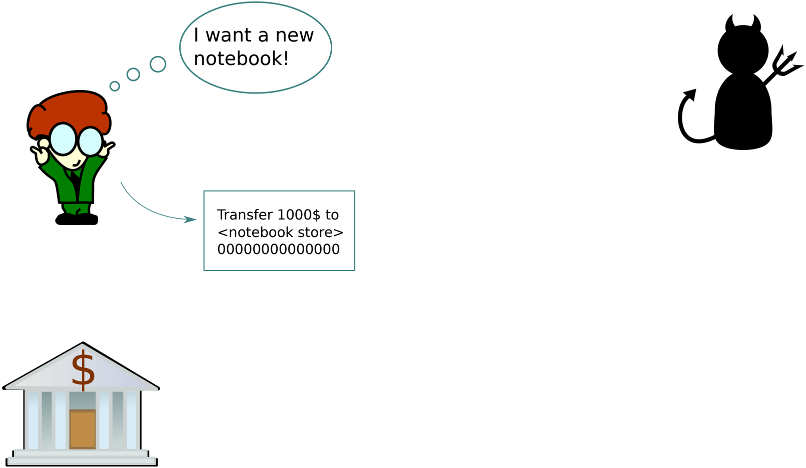

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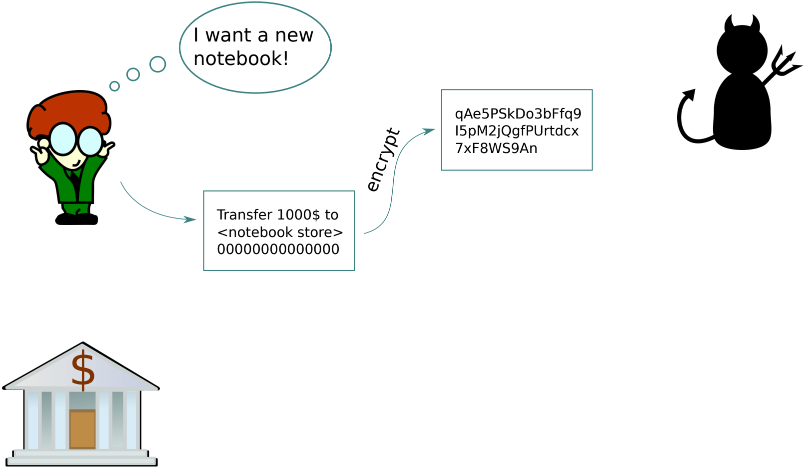

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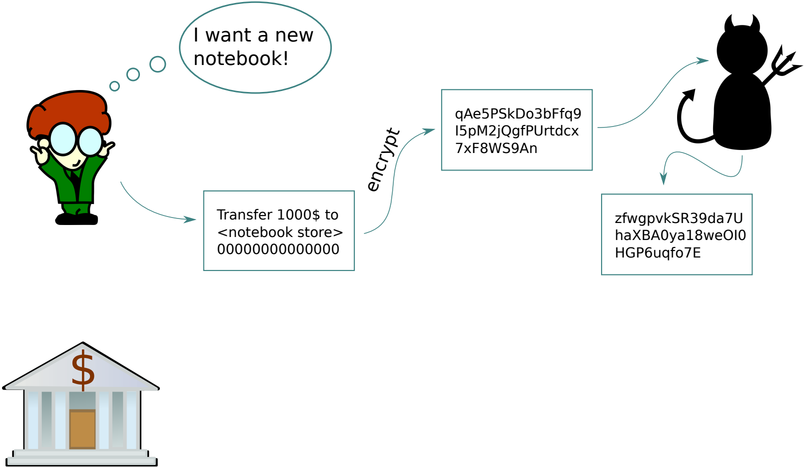

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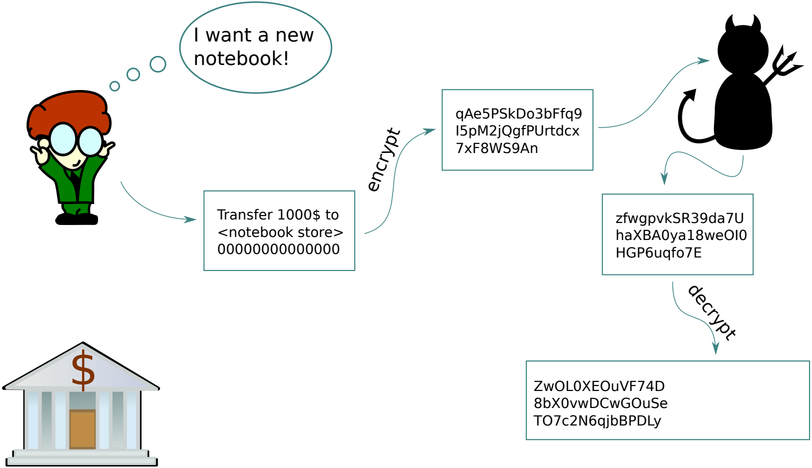

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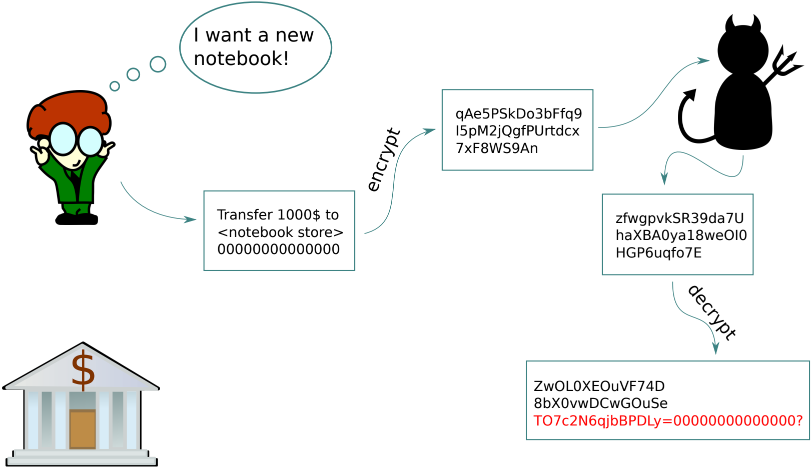

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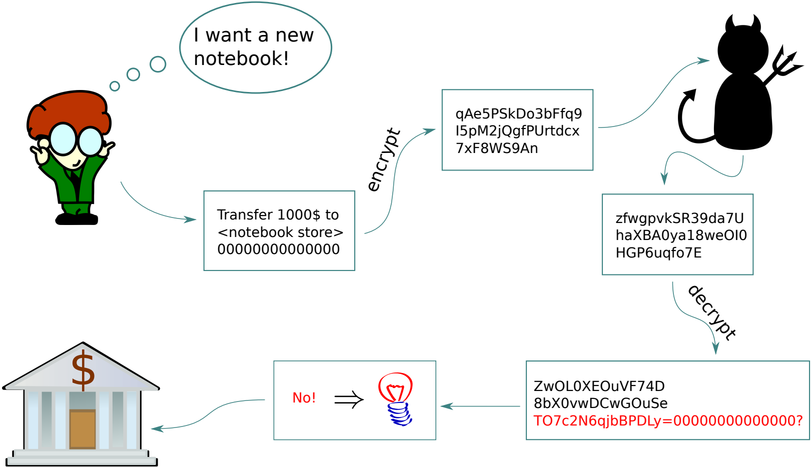

Authentication from qNM

Theorem (Alagic, CM)

Adding a constant tag to a quantum message and encrypting it with an qNM scheme achieves DNS-authentication

Summary authentication

- ✓ DNS authentication from qNM schemes via tagging
- ✓ GYZ authentication from 2-designs instead of 8-designs

Teaser: Unforgeable quantum encryption

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- quantum case: Alagic, Broadbent, Fefferman, Gagliardoni, Schaffner, St. Jules '16

CPA-ciphertext unforgeability

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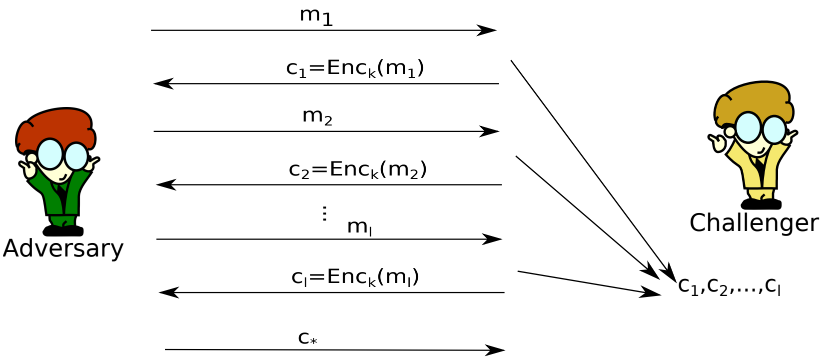

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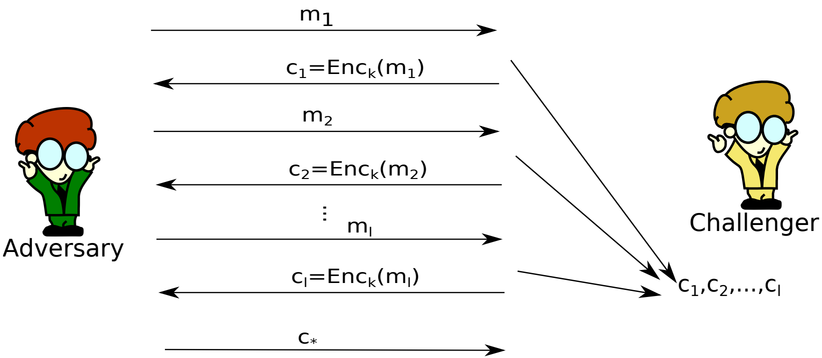

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- No-cloning problem 2.0!

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expect Quantum ciphertext authentication to imply IND-CPA

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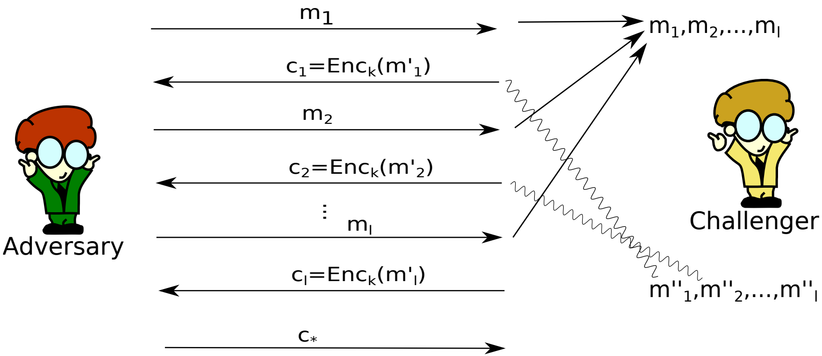

- Adversary wins if $m_* = \mathrm{Dec}_k(c_*) \neq \perp$ and measurement $|\phi\rangle\langle\phi|^+_{m_* m''_i}$ vs $\mathbb{1} - |\phi\rangle\langle\phi|^+_{m_* m''_i}$ yields the second outcome for all i

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- Asymptotic setting, exponential message space dimension
- Gentle measurment lemma $\Rightarrow$ negligible disturbance!
- problem only arises in plaintext unforgeability scenario

What more

- Enc_k is invertible on its image with CPTP inverse Dec_k

$\Rightarrow$ $\mathrm{Enc}_k(X) = U_k(X \otimes \sigma_k)U_k^\dagger$

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- use to define quantum ciphertext unforgeability (QUF)
- works for small message sizes (no disturbance problem)
- same techniques: quantum indistinguishability under adaptive chosen ciphertext attacks, quantum authenticated encryption

Open questions

- Q quantum non-malleability with high probability?
- Q How powerful is QUF? It does not consider side information with forgery...
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Thanks!