Limited-Quantum-Storage Cryptography

From Theory to Practice

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Contributors and Outline

(in order of appearance)

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2004

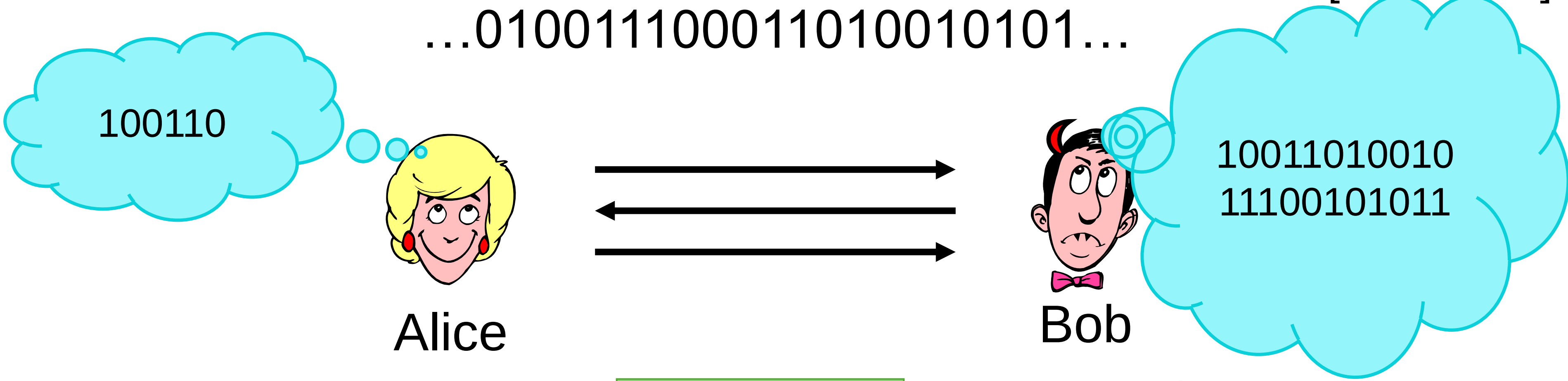
- Bounded Quantum Storage
- The Protocol
- Noisy Quantum Storage
- Secure Identification
- Composability
- Practical Problems

2009

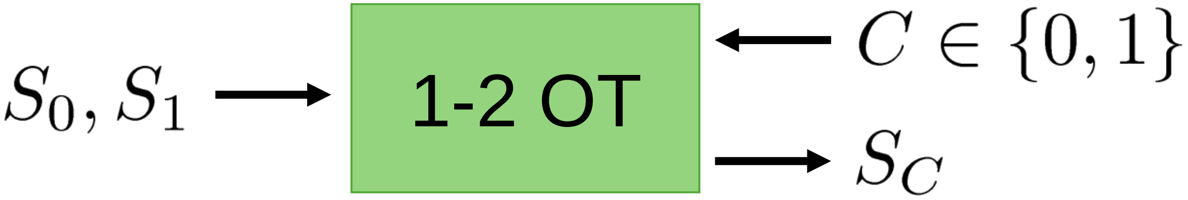
201?

Inspiration: Classical Bounded-Storage

[Maurer 90]



- goal:



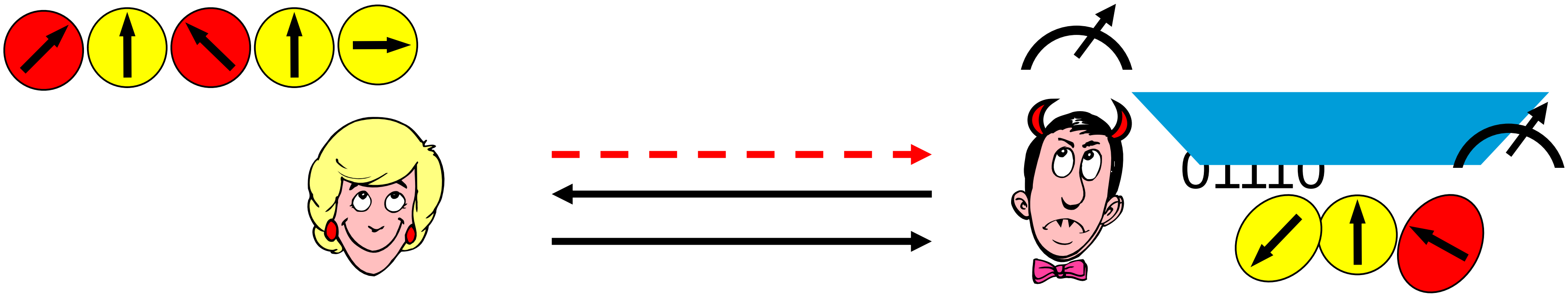
$S_0, S_1 \rightarrow$ 1-2 OT $\leftarrow C \in \{0,1\}$

1-2 OT $\rightarrow S_C$

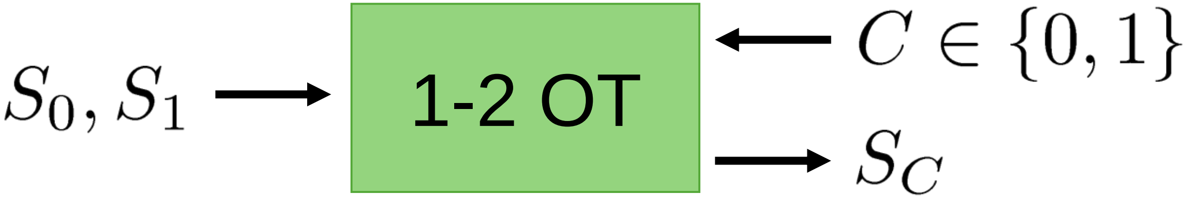
- honest player‘s memory: n
- dishonest player‘s memory: $\leq$ O(**n**^{2})
- information-theoretic security, no time-restrictions
- tight bound [Dziembowski Maurer 04],
relies on the difficulty of storing classical information

Bounded-Quantum-Storage Model

[Damgaard Fehr Salvail Schaffner 05, dito with Renner 07]



- goal:


S_0, S_1

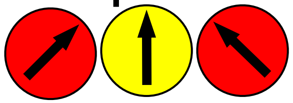
1-2 OT

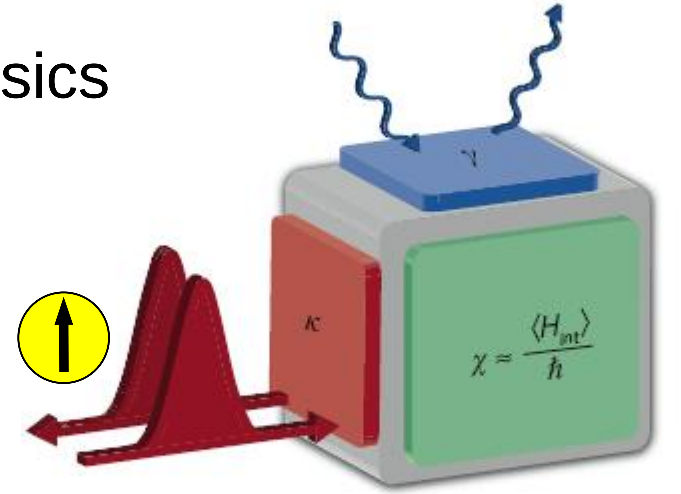
$C \in \{0,1\}$

S_C

- information-theoretic security, no running time-restrictions
- honest player‘s quantum memory: 0
- security as long as
  dishonest player‘s quantum memory: $\leq$ n/4
- relies on technical difficulty of storing quantum information

Storing Photonic Quantum Information

- major research field in quantum physics
- light - ‘flying media’ 
- matter - ‘stationary media’
- goal: light–matter interaction



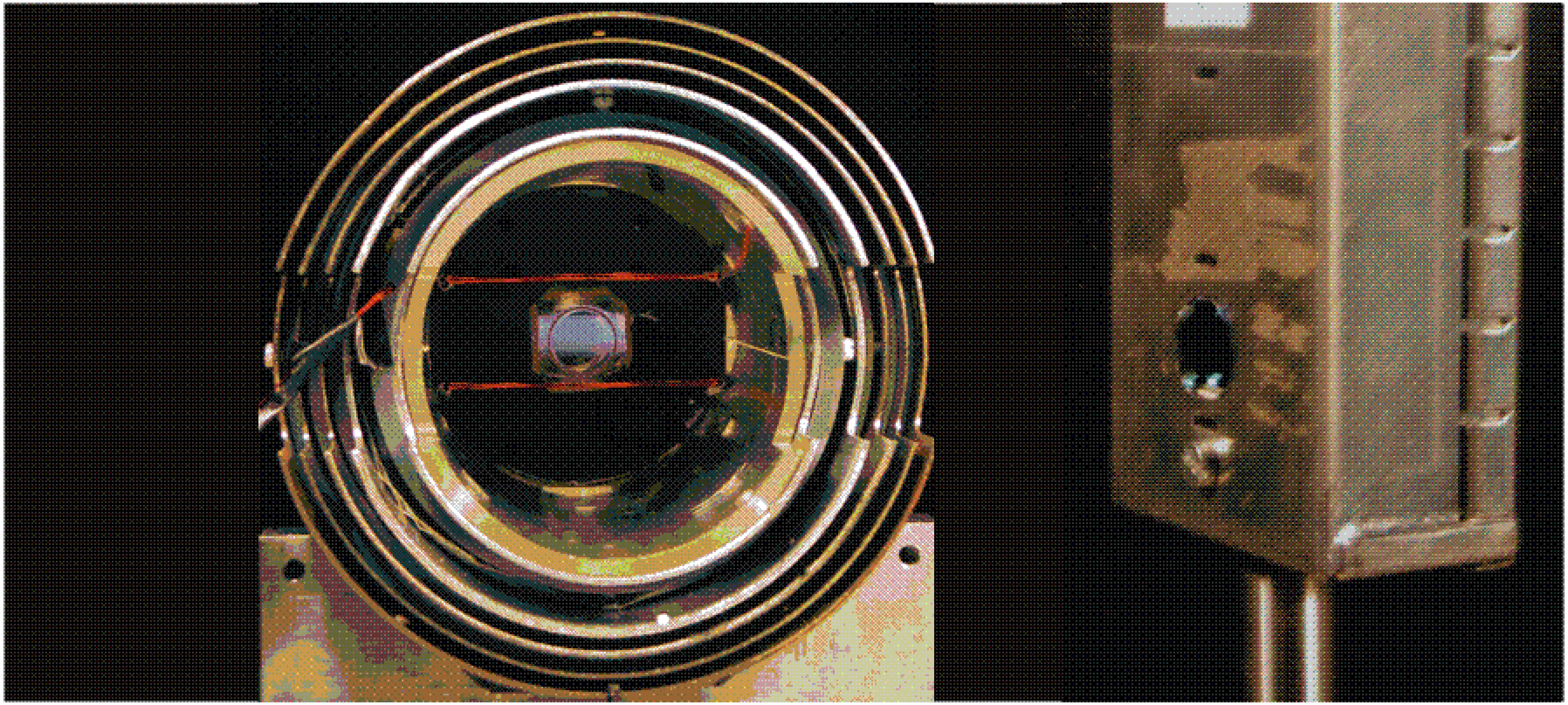
“The Quantum Internet” [Kimble 08]

- early stage: only special purpose experiments
- despite the efforts:
  - storage times of only microseconds
  - low success probabilities
- **storing quantum information is difficult**, i.e. limited quantum-storage is realistic assumption

Storing Photonic Quantum Information

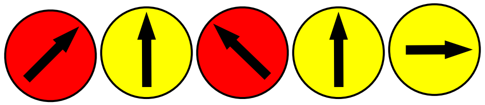
[physics group of Eugene Polzik, Copenhagen (DK)]

- 70% fidelity, few milliseconds, …



The Protocol

[Wiesner ~70, Bennett Brassard Crepeau Skubiszewska 92]



$|X_1\rangle_{\Theta_1} \ldots |X_n\rangle_{\Theta_n}$ $\dashrightarrow$

$\Theta \in_R \{+,\times\}^n$

$X \in_R \{0,1\}^n$

$\Theta' \in_R \{+,\times\}^n$

$\rightsquigarrow X' \in \{0,1\}^n$

$\xrightarrow{\Theta}$

$\xleftarrow{\mathcal{I}_0, \mathcal{I}_1}$

$\mathcal{I}_C := \{i : \Theta_i = \Theta'_i\}$

$\mathcal{I}_{1-C} := \{i : \Theta_i \neq \Theta'_i\}$

$X_0 := X|_{\mathcal{I}_0}, X_1 := X|_{\mathcal{I}_1}$

$F_0, F_1 \in_R \mathcal{F}$

$\xrightarrow{F_0, F_1}$

$M_0 := S_0 \oplus F_0(X_0)$

$M_1 := S_1 \oplus F_1(X_1)$

$S_C := M_C \oplus F_C(X'_C)$

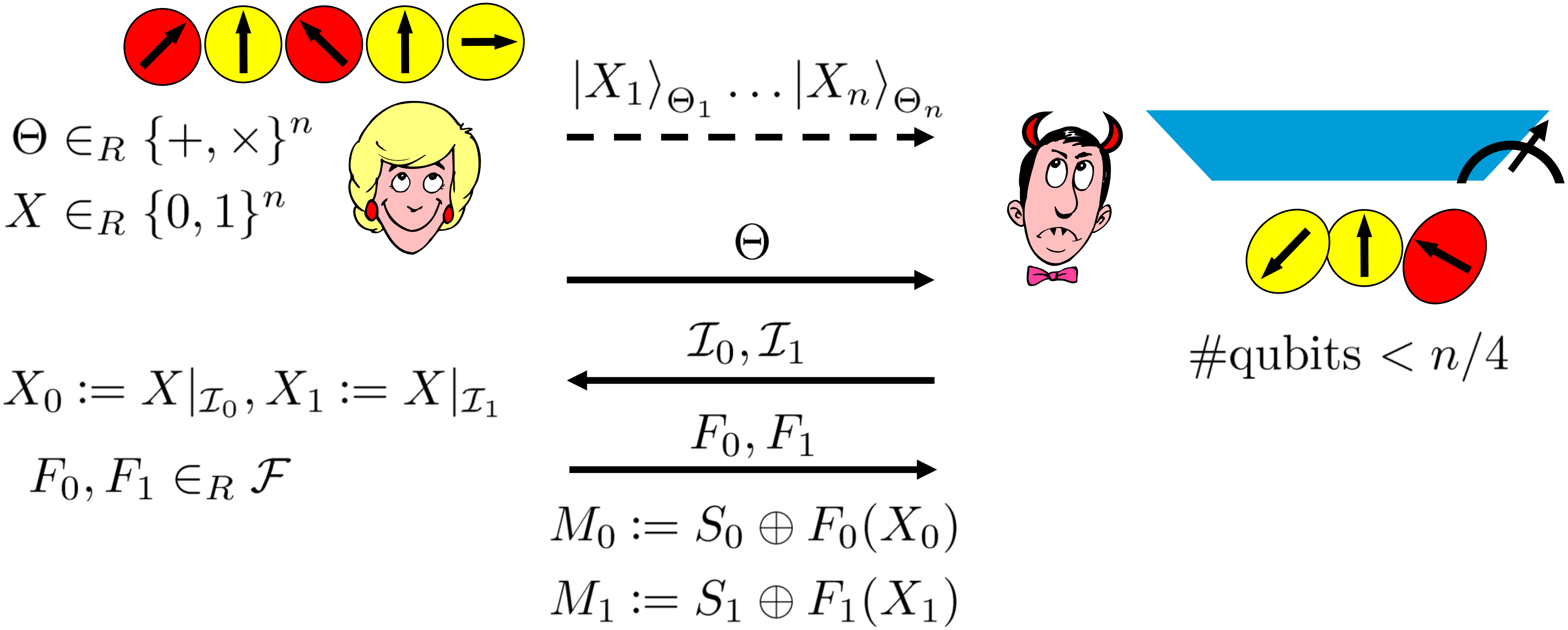
- goal: $S_0, S_1 \longrightarrow \boxed{\text{1-2 OT}} \longleftarrow C \in \{0,1\}$, $\boxed{\text{1-2 OT}} \longrightarrow S_C$

✓ correct

✓ secure against cheating Alice

Dishonest Bob with Bounded Q Storage

[Damgaard Fehr Renner Salvail Schaffner 07]



$\Theta \in_R \{+,\times\}^n$

$X \in_R \{0,1\}^n$

$|X_1\rangle_{\Theta_1} \dots |X_n\rangle_{\Theta_n}$

Θ

$\mathcal{I}_0, \mathcal{I}_1$

$X_0 := X|_{\mathcal{I}_0}, X_1 := X|_{\mathcal{I}_1}$

F_0, F_1

$F_0, F_1 \in_R \mathcal{F}$

$M_0 := S_0 \oplus F_0(X_0)$

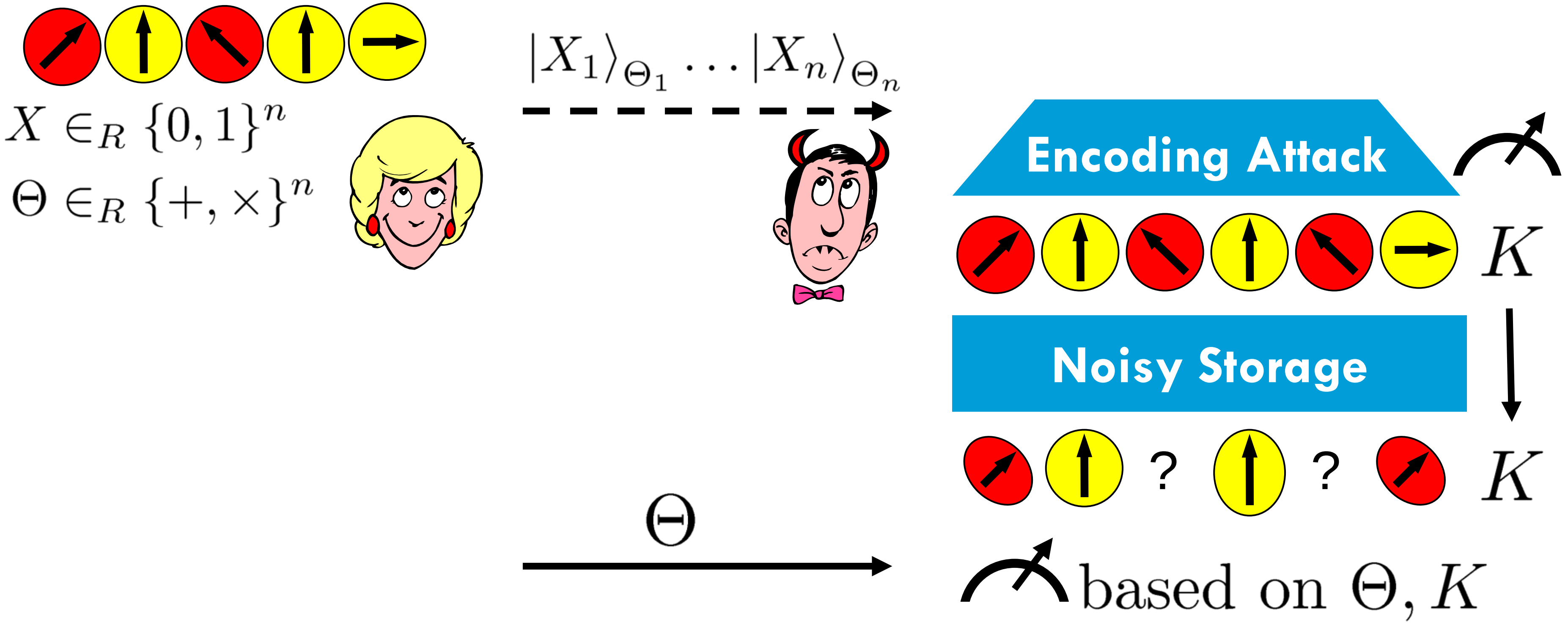
$M_1 := S_1 \oplus F_1(X_1)$

$\#\text{qubits} < n/4$

- purification argument (as in QKD)
- entropic uncertainty relation: $H_{\min}^{\varepsilon}(X|\Theta) \geq n/2$
- privacy amplification against quantum adversaries [Renner Koenig 07]

Noisy-Quantum-Storage Model

[Wehner Schaffner Terhal 08, König Wehner Wullschleger 09]



$X \in_R \{0,1\}^n$

$\Theta \in_R \{+,\times\}^n$

$|X_1\rangle_{\Theta_1} \dots |X_n\rangle_{\Theta_n}$

Encoding Attack

K

Noisy Storage

? ?

K

Θ

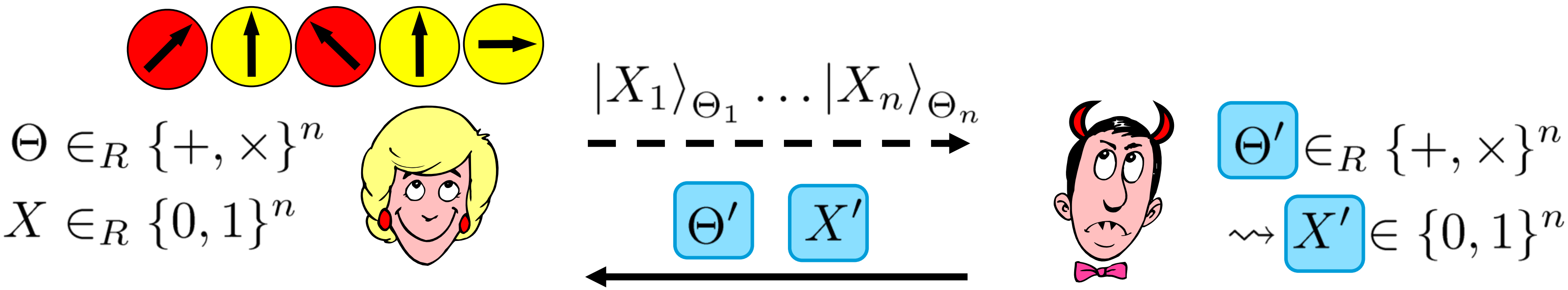
based on Θ, K

- more realistic limitation on quantum storage capabilities
- first step: individual-storage attacks
- recent result: general attacks
- related to classical capacities of quantum channels

Combining Security Assumptions

[Damgaard Fehr Lunemann Salvail Schaffner 09]

- two-party cryptography in the plain quantum model is impossible [Lo 96]
- security can be based on
  - difficulty of storing quantum information
  - computational assumptions
- can be combined!
- idea from [BBCS92]: commit to bases and outcomes



$\Theta \in_R \{+,\times\}^n$

$X \in_R \{0,1\}^n$

$|X_1\rangle_{\Theta_1} \cdots |X_n\rangle_{\Theta_n}$

$\boxed{\Theta'}$ $\boxed{X'}$

$\boxed{\Theta'} \in_R \{+,\times\}^n$

$\rightsquigarrow \boxed{X'} \in \{0,1\}^n$

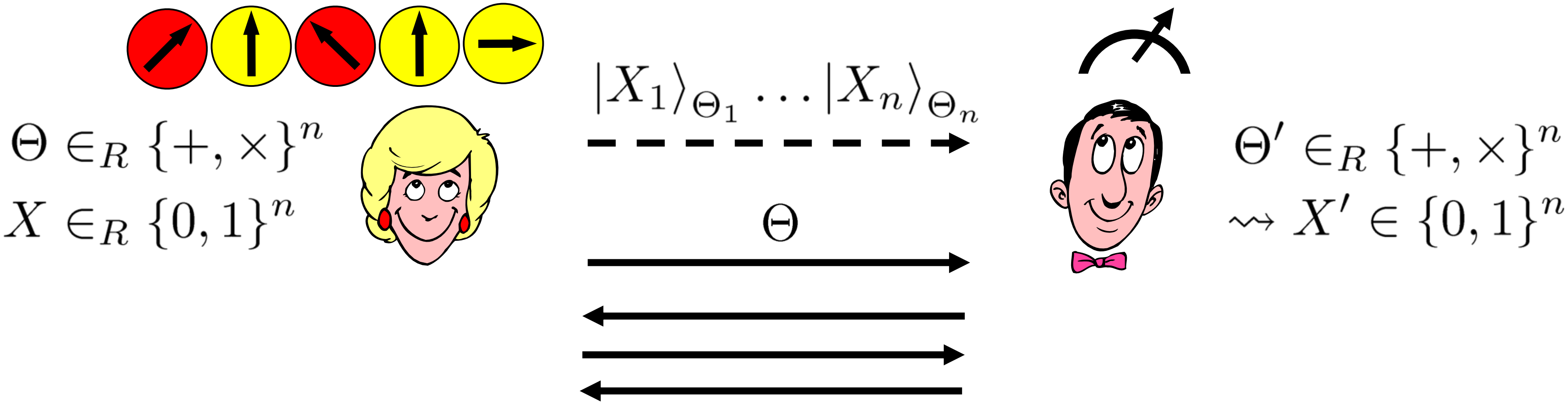
- forces adversary to have almost no quantum memory

Outline

- ✓ Bounded Quantum Storage
- ✓ The Protocol
- ✓ Noisy Quantum Storage
- Secure Identification
- Composability
- Practical Problems
- Future

Secure Identification

[Damgaard Fehr Salvail Schaffner 07]



$\Theta \in_R \{+,\times\}^n$

$X \in_R \{0,1\}^n$

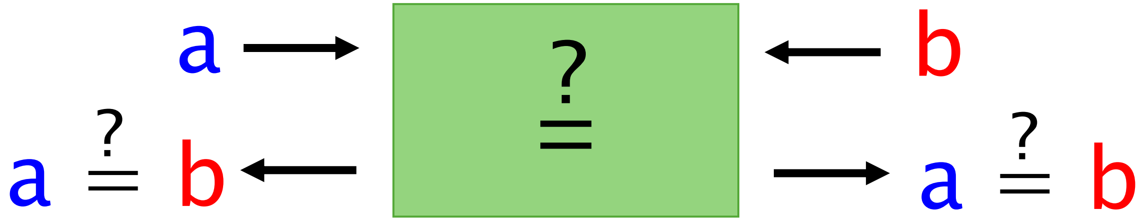
$|X_1\rangle_{\Theta_1} \dots |X_n\rangle_{\Theta_n}$

Θ

$\Theta' \in_R \{+,\times\}^n$

$\rightsquigarrow X' \in \{0,1\}^n$

- goal:



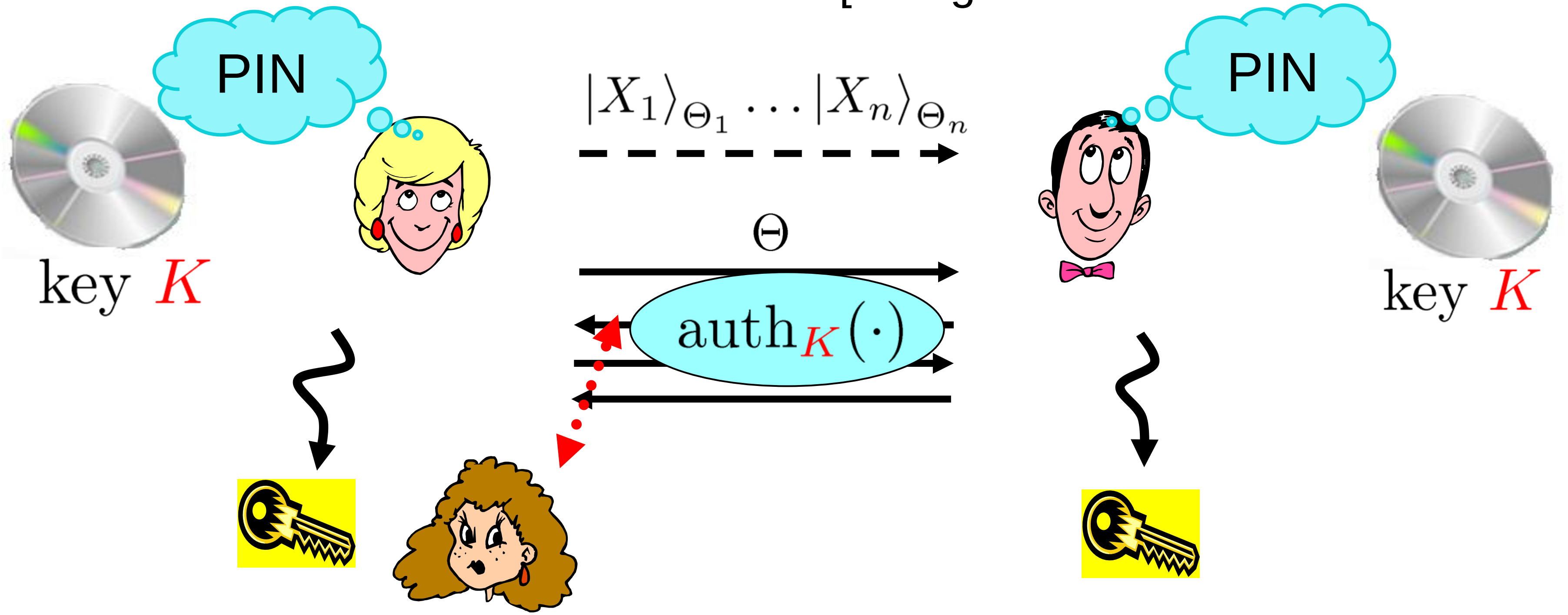
$a \rightarrow \boxed{\overset{?}{=}} \leftarrow b$

$a \overset{?}{=} b \leftarrow \qquad \rightarrow a \overset{?}{=} b$

- 3 classical messages, much more efficient than relying on reduction to 1-2 OT
- secure against adversaries with quant memory < const n
- can be made secure against man-in-the middle attacks

Man-In-The-Middle Security and QKD

[Damgaard Fehr Salvail Schaffner 07]

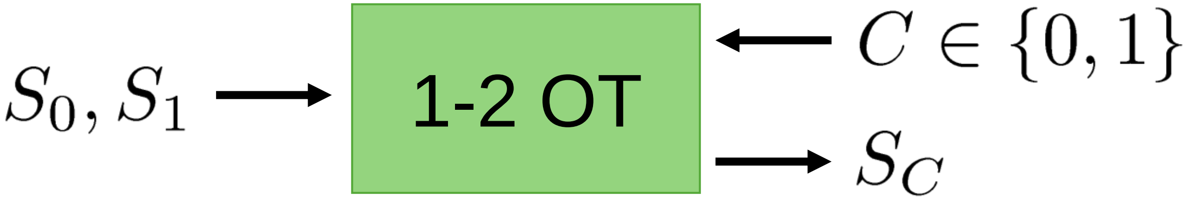


- non-trivial extension is also secure against man-in-the middle attacks (while preserving original security)
- QKD: key K can be reused, even if scheme is disrupted, i.e. q-memory bounded Eve cannot make honest players run out of auth key.

Composable Security Definitions

[Wehner Wullschleger 08, Fehr Schaffner 09, Unruh 09]

- goal:



$S_0, S_1 \rightarrow$ 1-2 OT $\leftarrow C \in \{0,1\}$

$\rightarrow S_C$

- want to use primitive in an classical outer protocol
  - or compose it with other quantum protocols
- subtle in the quantum domain, quantum information cannot be copied and carried through to the end
- need the right security definitions!
- general frameworks: [Ben-Or Mayers 02], [Unruh 04]
- simulation-based definitions allow for sequential composition

Practical Problems

[Wehner Curty Lo Schaffner 09]

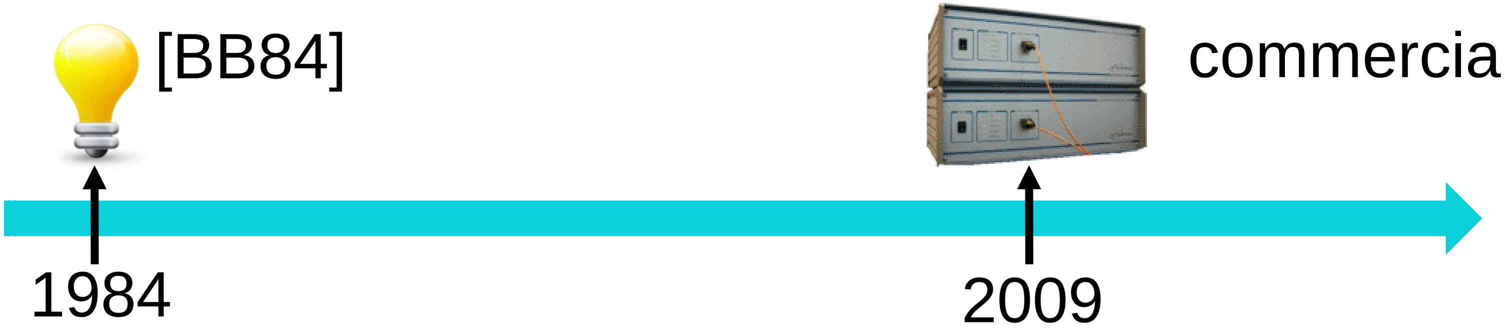
- imperfections similar to QKD:
  - approximation to single-photon sources (weak coherent pulses or parametric-down-conversion)
  - erasures in the channel
  - bit errors in the channel
  - dark counts
  - ...

– no trusted peer

+ shorter distances

- solutions: adapted security analyses, error-correction
- computational efficiency of classical post-processing
- physical size of devices

Similarities to QKD



- QKD know-how is now available
- similar technology can be used for limited-quantum-storage applications!
- but with different parameter ranges (e.g. shorter distances)
- big potential:

Practical Quantum Crypto

Limited-Q-Storage Crypto:

- identification
- comparison

other difficulties in doing quantum comp

QKD

Near and Far Future

Technology:

- harvest QKD knowledge
- conduct experiments
- check assumptions
- miniaturize devices

Theory:

- find more direct protocols
- continuous variables

- more realistic models for the difficulty of storing quantum information
- exploit other difficulties in doing quantum computation

win-win situation:

either large-scale quantum computing is possible or the reason why not can be exploited for cryptography