# Password-authenticated protocols

*A survey*

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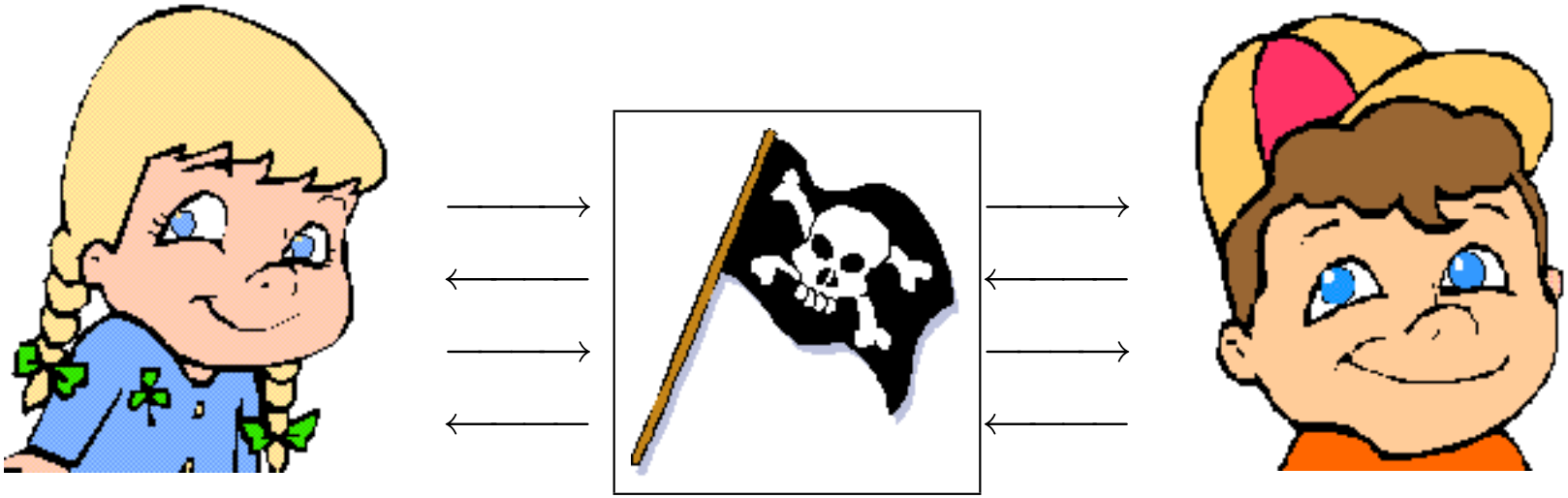
# Interaction context

A pool of $n$ participants ($n \geq 2$) try to commonly establish a symmetric session key, in the presence of an adversary.



The adversary tries to defeat the process: failure on the agreement, leakage of information, ...

# Security Goals

**Definition (Privacy)**

No one except the legitimate players can obtain the established key.

Key Exchange or KE. For a group of players, one talks about GKE (Group Key Exchange)

**Definition (Authentication)**

No one can prevent a terminating protocol to run normally, in particular no one can make a player believe there is a legitimate participant to talk with, if it is not the case.

Authenticated Key Exchange or AKE. In case of groups: GAKE.

# Several kinds of adversaries

**Definition (Passive adversary)**

Can only eavesdrop the communications.

Such an adversary threats the *privacy* only.

**Definition (Active adversary)**

Can eavesdrop and modify the communictaions.

Such an adversary can threat both *authentication* and *privacy*.

# How authentication can be achieved

## 4 possibilities

- high-entropy asymmetric secrets (public keys) – [DH76]
- high-entropy common secrets (symmetric keys) – [Yao86]
- low-entropy common secrets (passwords)
- low-entropy asymmetric secrets (*verifier-based passwords*)
- hybrid cases: client holds a password, server holds a public key

$\Rightarrow$ Scenario pwAKE (*Password-Authenticated Key Exchange*) or pwGAKE (*pw Group AKE*)

# Dictionary attacks (I)

A password is chosen in a small *dictionary* of size $N$; this provides the adversary the ability to make an exhaustive search.

1. A passive adversary can intercept communications (*transcripts*) and may try to test all the passwords one by one.
   - *off-line dictionary attacks*: no restriction can be made on the adversarial computing power.
2. An active adversary can additionally try to guess the password and use it to impersonate a player.
   - *on-line guessing attacks*: easy to detect.

# Dictionary attacks (II)

## What is impossible...

*Completely* prevent on-line attacks: any adversary can win after $N$ attempts.

In practice, the impact of such attacks is *limited* using operational methods (counter, delay,...).

## What can be (hopefully) achieved

Limit the adversary to on-line attacks only: this means off-line attacks must be made impossible.

A passive eavesdropping reveals nothing (in the sense of Shannon).
An active attempt reveals nothing except... password's (in)validity.

# Indistinguishability approach

Initially: scenario AKE [BR93a], then pwAKE [BPR00]

## *Queries* capturing adversarial capabilities

- Execute($\mathcal{U}$): returns a *transcript* of an honest execution
- Send($m, U$): sends the message $m$ to player $U$,
- Reveal($U$): returns session key hold by player $U$
- Corrupt($U$): returns the password used by $U$
- Test$^b$($U$): returns the key $sk$ if $b = 1$, or a random if $b = 0$.

$\mathrm{Adv}^{\mathrm{ake}}(\mathcal{A})$ = advantage of $\mathcal{A}$ in passing the Test (guessing $b$)

## Definition

Semantic security of $sk$: if $\mathrm{Adv}^{\mathrm{ake}}(\mathcal{A}) - \frac{\text{Nb of Send}}{N} \approx \varepsilon$

# Security = key indistinguishability

## Find-then-Guess (FtG)

- Many Reveal-queries
- Only one Test$^b$-query
- $\mathcal{A}$ searches for bit $b$

## Real-or-Random (RoR)

- No Reveal-query
- Many Test-queries...
- ...with the same bit $b$ !

## Theorem (Comparison FtG *vs.* RoR [AFP05])

*For any protocol $\mathcal{P}$ for authenticated key exchange, one has:*

$$\mathsf{Adv}_{\mathcal{P}}^{\mathsf{ror-ake}}(t) \leq q_{test}\mathsf{Adv}_{\mathcal{P}}^{\mathsf{ftg-ake}}(t) \leq 2\mathsf{Adv}_{\mathcal{P}}^{\mathsf{ror-ake}}(t)$$

# The security bound

## Meaning of the result

Upper-bounding the advantage by $q_{send}/N$ means:

- The adversary cannot eliminate more than one password in an active attack.
- passive attacks are useless: the number of eavesdropped transcripts does not appear.

Strictly speaking, the important quantity is the number of sessions initiated by the adversary, rather than the number of messages... (in particular for group protocols)

# *Forward-secrecy* and *known-key attacks*

## Forward-secrecy

The session key remains secure if $\pi$ is revealed after the execution

Using the Corrupt-query

## Known-key attacks

The session and $\pi$ remain secure if previous keys are exposed

Using the Reveal-query

## Theorem

- *[GL01] guarantees forward-security and known-key attacks resistance.*
- *[KOY02] adds forward-secrecy which was missing in [KOY01]*

# Multiparty simulation: classical case [Bea91, MR91, C00]

Modeling Key Exchange [BCK98, Sho99]: emulate a TTP (*trusted third party*). Extended to passwords by Boyko *et al* [BMP00].

## Ideal world

- $\mathcal{A}$ initiates the game
- TTP chooses *sk*
- $A$ and $B$ do not communicate
- $\mathcal{A}$ can "test" a $\pi$

## Real world

- No TTP, $A$ and $B$ hold $\pi$
- $A$ and $B$ communicate
- $\mathcal{A}$ wins with proba $1/N$

## Definition (Security)

Any real adversary can be emulated in the ideal world, the output distributions being $\varepsilon$-indistinguishable [C00].

# Multiparty simulation: adapting th case

Definition proposed by Goldreich-Lindell [GL01]. Distributions are not indistinguishable anymore.

## Ideal world

- $A, B$: password $\pi$
- $A, B \rightarrow$ TTP: $\pi$
- TTP$\rightarrow A, B$: uniform key *sk*
- $\mathcal{A}$ can *abort*

## Real world

- No TTP, $A$ and $B$ hold $\pi$
- $A$ and $B$ communicate only *via* $\mathcal{A}$
- $\mathcal{A}$ wins with proba $1/N$

## Definition (Security: adapted to passwords)

$\Rightarrow$ **($\mathcal{A}$ passive) :** Output distributions are $\varepsilon$-indistinguishable

$\Rightarrow$ **($\mathcal{A}$ active) :** Output distributions can be distinguished only with probability $O(1/N) + \varepsilon$

# Universal composition [C01]

In the Key Exchange setting, it is important to consider the notion of universal composition [CK02].

**How to manage the following?**

- passwords are not uniformly distributed,
- password distribution can be unknown,
- a password can be used in several protocols,
- passwords can be correlated.

- Universal composition is welcome !!
- A definition involving "true" indistinguishability [BMP00] is better for protocol composition (rather than [GL01]).

# Cryptographic assumptions

## Definition

Diffie-Hellman problems [DH76, Bon98]

- CDH : given $(g^x, g^y)$, find $g^{xy}$
- DDH : given $(g^x, g^y, g^z)$, decide if $z = xy$

## *Chosen-basis* variants [AP05a, AP05b]

- C-CDH : given $(X, A, B)$, choose $Y$, then find $\mathbf{CDH}(X, Y)$ and $\mathbf{CDH}(X/A, Y/B)$
- C-DDH : given $(X, A, B)$, choose $Y$, then decide $r = x$ or $r = y$ on input: $(Y^r, (X/A)^x, \mathbf{CDH}(X/A, Y)^x, (X/B)^y, \mathbf{CDH}(X/B, Y)^y)$

# Group Diffie-Hellman problems

## Definition

Group Diffie-Hellman problems Let $I = \{1, \ldots, n\}$ and $x_1, \ldots, x_n$ random. Given some values $g^{\widehat{}}\{\prod_{j \in J} x_j\}$, for some proper subsets $J$ of $I$,

- G-CDH : find $g^{x_1 \cdots x_n}$
- G-DDH : decide if $r = x_1 \cdots x_n$ on input $g^r$

## Theorem

*Reduction GDH to DH [BCP02b] If the collection of subsets $J$ for which the exponentiations $\prod_J x_j$ are known, is "well formed" the GCDH and GDDH problems can be reduced to CDH and DDH, respectively.*

# Standards models

These models do not need a random oracle and so can be more reasonably instanciated.

**2 cases :**

- the "plain" model [GL01]: no *setup* assumption, only a password is given
- the standard model with CRS (*Common Random String*): there might be a public key in the CRS...

# Ideal models

**The *Random Oracle Model* (ROM) [BR93a]**

Function providing a fixed-length output, that is purely random for each new input.

There exists schemes secure in ROM and totally breakable for any instanciation of the function [CGH98].

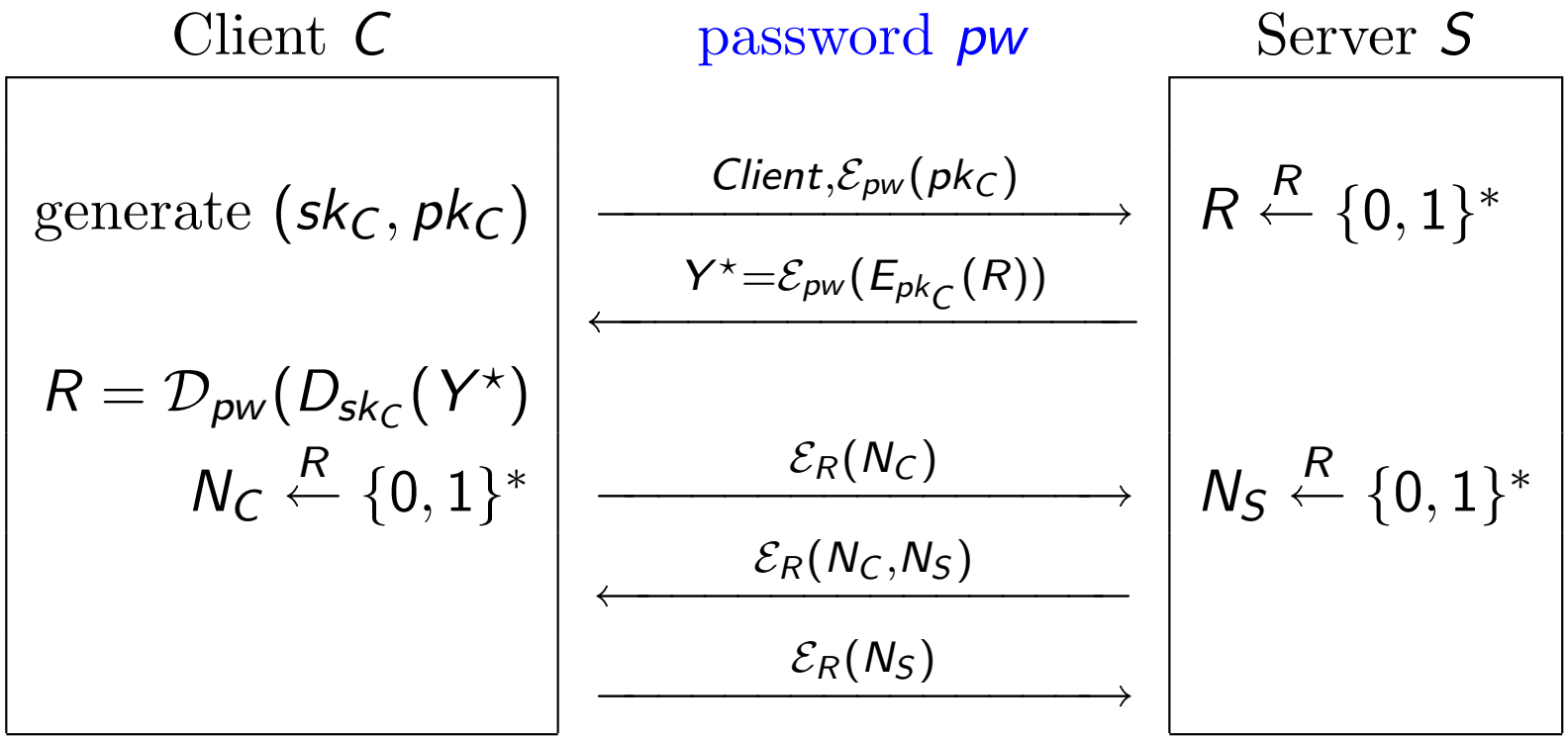
**The *Ideal Cipher Model* (ICM) [BPR00]**

Family of permutations (with their inverses) indexed by keys, where all permutations are perfectly independant and random.

This model is (strictly?) stronger than ROM.

# EKE: Encrypted Key Exchange ( [BM92])

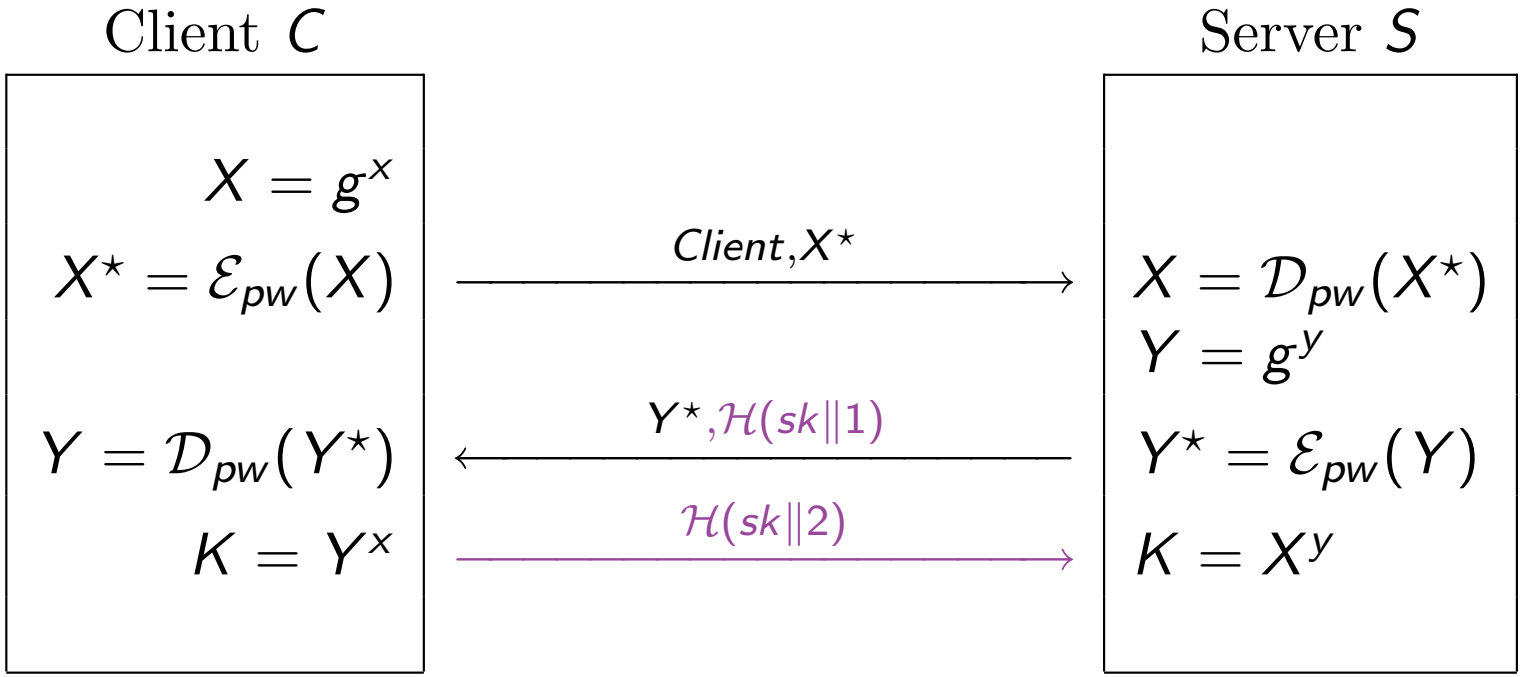
Encryption: symmetric $(\mathcal{E}, \mathcal{D})$, asymmetric $(E, D)$




Session key: $R$

# EKE2: Encrypted Key Exchange revisited ( [BPR00])

Group $G$, password $pw$




Session key: $sk = \mathcal{H}(C, S, X, Y, K)$ for pwKE

Clé $sk' = \mathcal{H}(sk\|0)$ for pwAKE

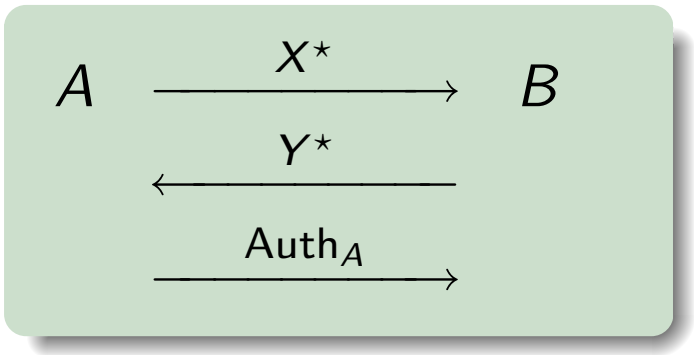
# History of EKE protocols

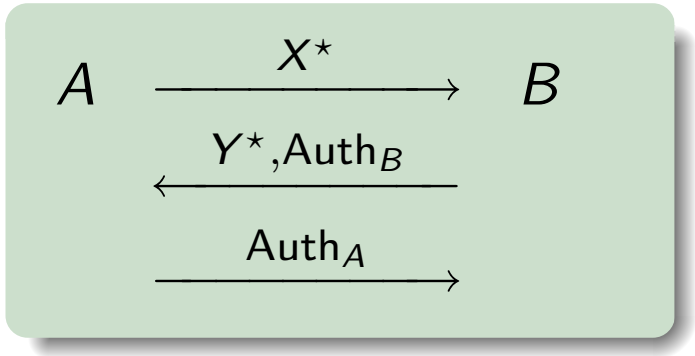
## Protocols derived from the previous one

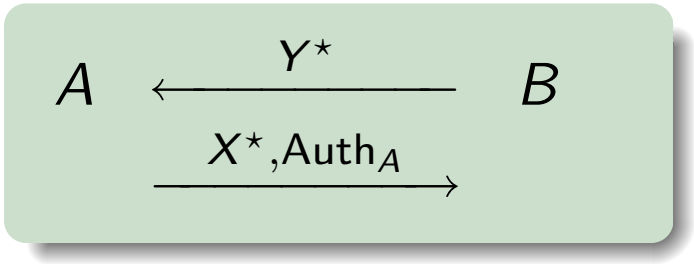
- Generic framework (AuthA) [BR00]: heuristic security
- Protocol EKE2 [BPR00]: directly derived from AuthA
  - formel modal (*queries* + indistinguishability )
  - security proof in the ideal cipher model (ICM)
- Protocol PAK [BMP00]: instanciation of AuthA
  - formal model (multiparty simulatability)
  - security under the random oracle (ROM); but intricate proof

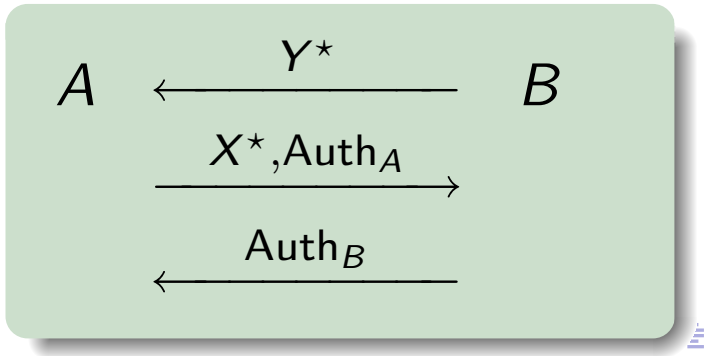
# Protocols AuthA for 2 parties ( [BR00], IEEE P1363)

Unilateral or bilateral ("mutual") authentication
Protocol initiated either by $A$, or by $B$



# Instanciations and applications of AuthA

## How to implement an ideal cipher $X^\star = \mathcal{E}_{pw}(X)$?

- PAK [BMP00]: multiplicative mask $X^\star = X \cdot \mathcal{H}(pw, \dots)$. Needs a full-domain hash function.
- SPAKE [AP05a]: algebraic version: $X^\star = X \times U^{pw}$. More flexibility.

## How to adapt these protocols?

- Protocol OEKE (*One-Encryption Key Exchange*): $X$ in clear
  - security proof in ICM [BCP03]
  - security proof in ROM [BCP04]
- SOKE [ABCM+06]: a version of SPAKE especially designed for TLS [BESW01]

# pwGAKE: security model

$n$ players share a password, and want to build a common session key.

**"Semantic security" model proposed in 2002 [BCP02]**

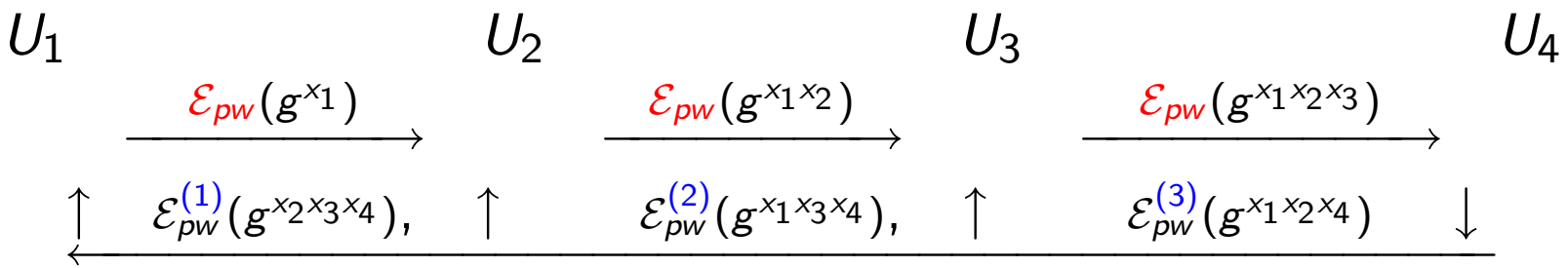
- Derived from the models for GAKE [BCPQ01], and pwAKE [BPR00]
- Can be adapted to "Find-then-Guess" or "Real-or-Random" definitions

$\Rightarrow$ Difficulties : the number of messages that are exchanged during an execution increases, thus making difficult to prevent information leakage

# pwGAKE: existing protocols

## Proposed protocols

- Protocol GEKE (*Group Encrypted Key Exchange*): everything is encrypted under $pw$ – proof in the ICM model [BCP02]
- Protocol GOKE (*Group Open Key Exchange*): partially encrypted – proof in the ROM model [BCP05] + dynamicity, adapted for ad-hoc modes of IEEE 802.11




+ 1 authentication round in the case of GOKE

# Constant-round pwGAKE

## History of Burmester-Desmedt [BD94]

- A protocol for KE [BD94] and AKE [KY03], independent of the number of players
- Tentative to convert it into *password-based* [DB06]
- Dictionary attacks, repaired scheme and security proof (ICM model) [ABCP06]

- Each player picks $x_i$ and broadcasts: $\mathcal{E}_{pw}(g^{x_i})$
- Each $U_i$ then broadcasts: $\mathcal{E}_{pw}(\Gamma_i/\Gamma_{i+1})$, with $\Gamma_k = g^{x_{k-1}x_k}$

## Not so simple!

The naive approach does not work: the product of plaintexts in the $2^{\text{nd}}$ round is 1 $\Longrightarrow$ *dictionary attack*

# Conclusion

- Multiplicity of possible scenarii, definitions, assumptions
- Multiplicity of proposed protocols (attacks. . . )
- Formalization appears, inspired from other primitives
- Unifying the treatment of the problem

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