One-Round Key Exchange with Strong Security: An Efficient and Generic Construction in the Standard Model

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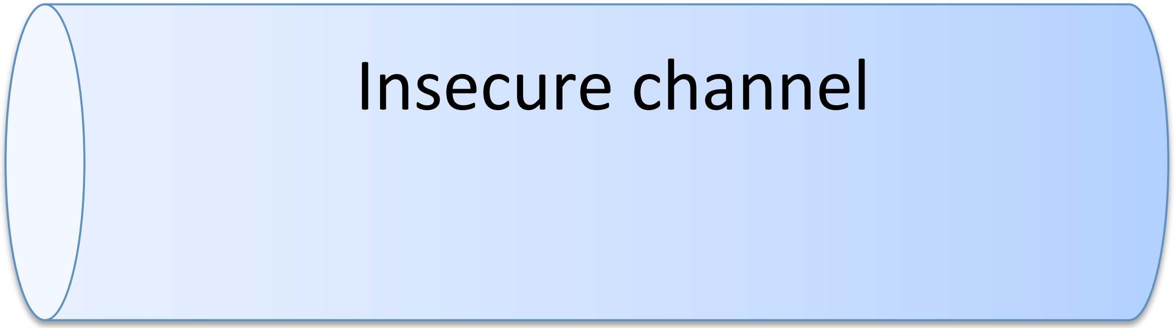
Horst Görtz Institute for IT-Security

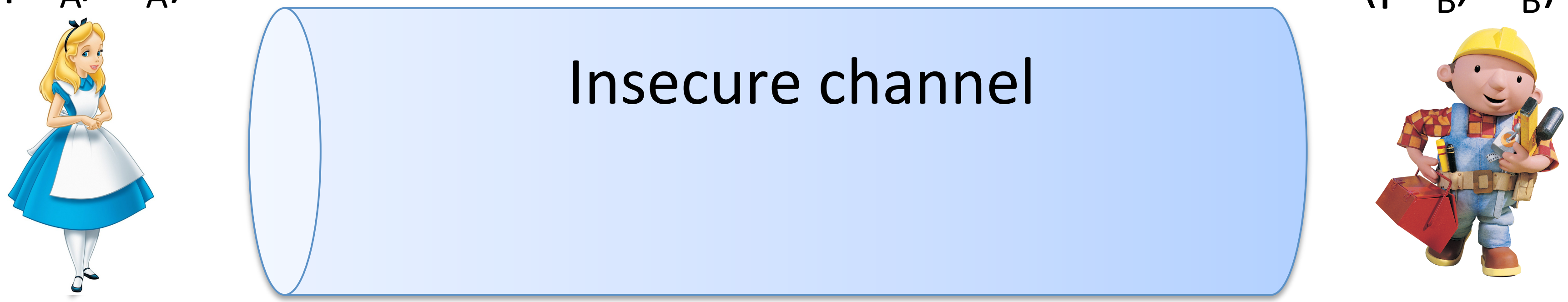
Public-Key Authenticated Key Exchange

Alice



Bob

Public-Key Authenticated Key Exchange



Public-Key Authenticated Key Exchange

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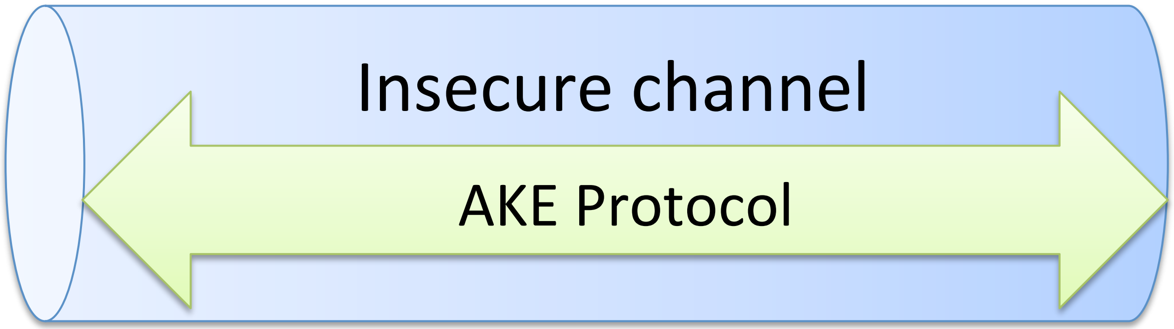
(pk_A, sk_A)

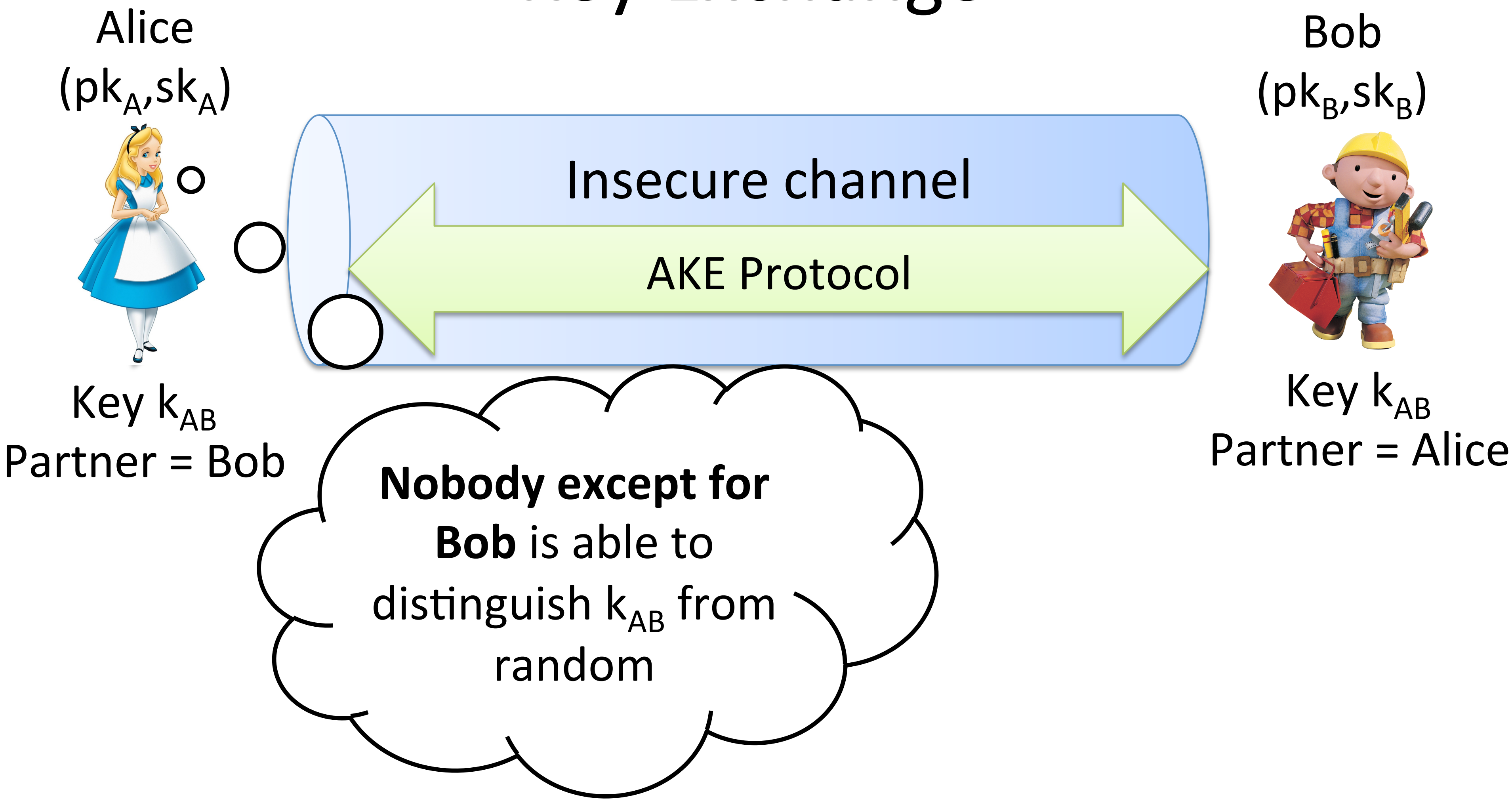
Key k_{AB}



Bob
(pk_B, sk_B)

Key k_{AB}

Public-Key Authenticated Key Exchange



One-Round Key Exchange (ORKE)

(pk_A, sk_A)

(pk_B, sk_B)

$m_A = f(pk_B, sk_A, r_A)$ →

← $m_B = f(pk_A, sk_B, r_B)$

$$KDF(pk_B, sk_A, r_{A,} m_B) = k_{AB} = KDF(pk_A, sk_B, r_{B,} m_A)$$

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(pk_A, sk_A)

Possibly sent **simultaneously**
(or ***precomputed)***

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(pk_B, sk_B)

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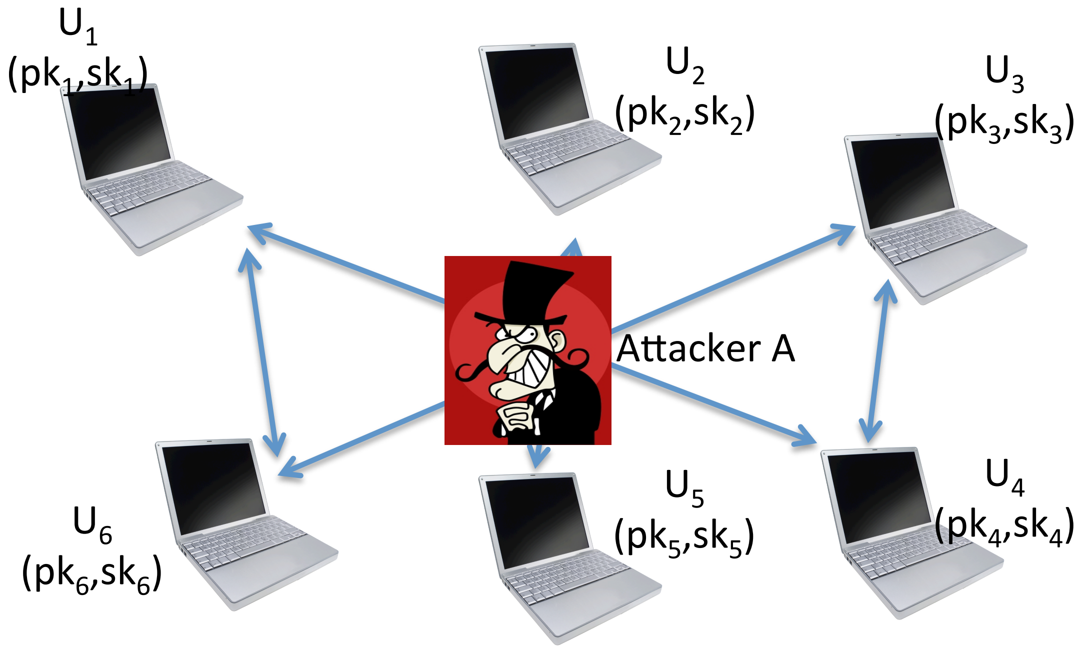
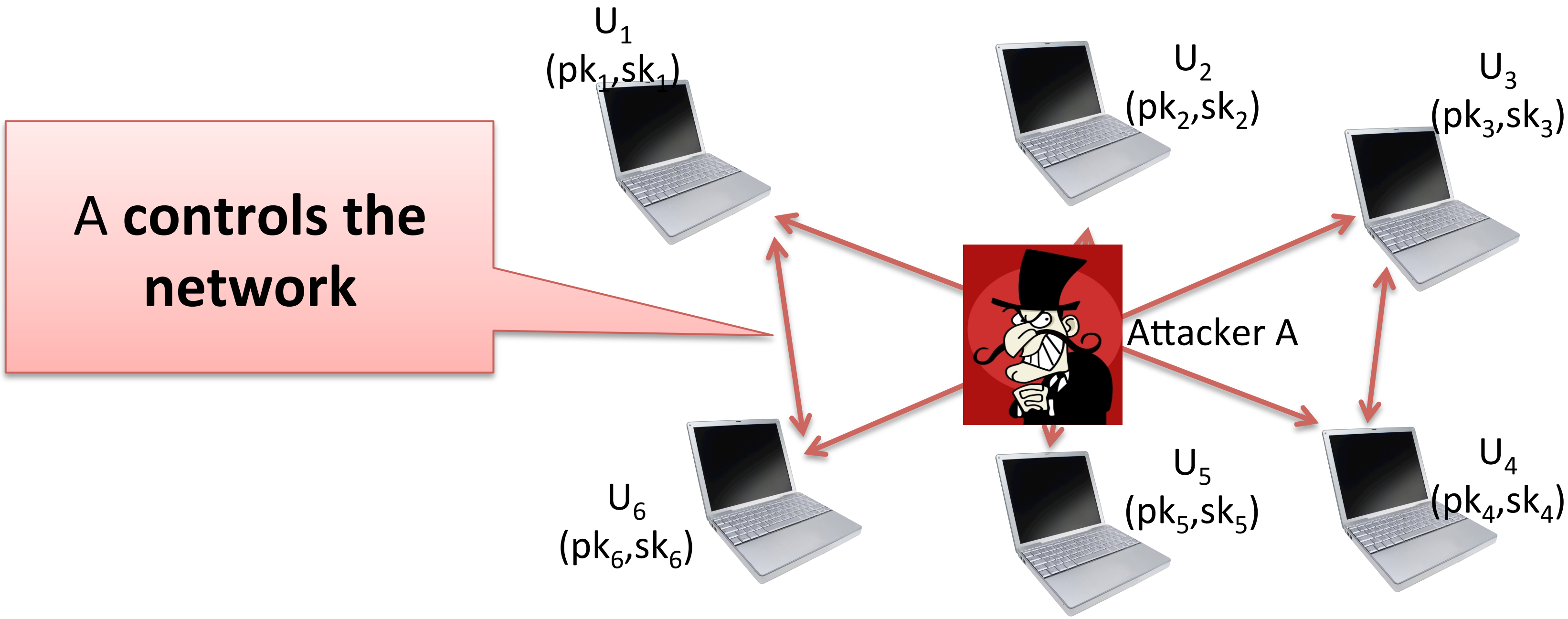
- **Simple** design and implementation
- **Quick** key establishment in at most one RTT

Security Analysis of AKE Protocols



- Provide A with "execution environment" that formalizes A's capabilities

Security Analysis of AKE Protocols



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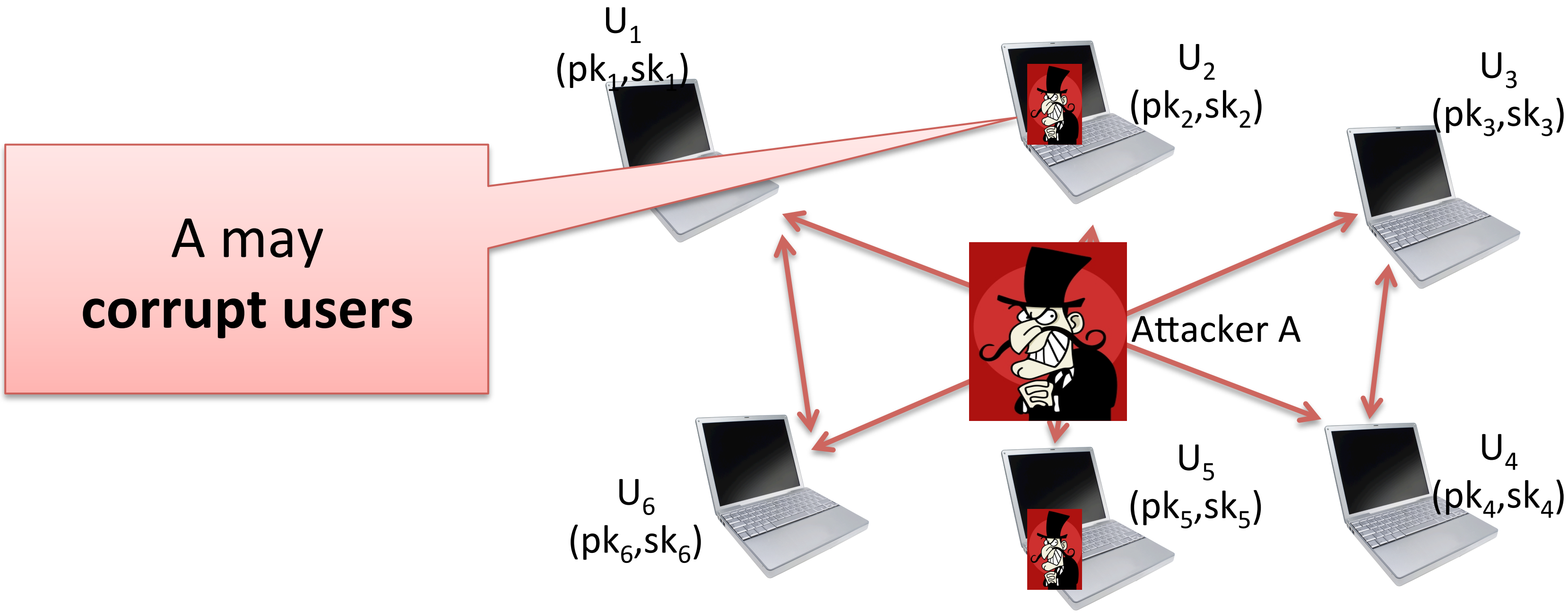

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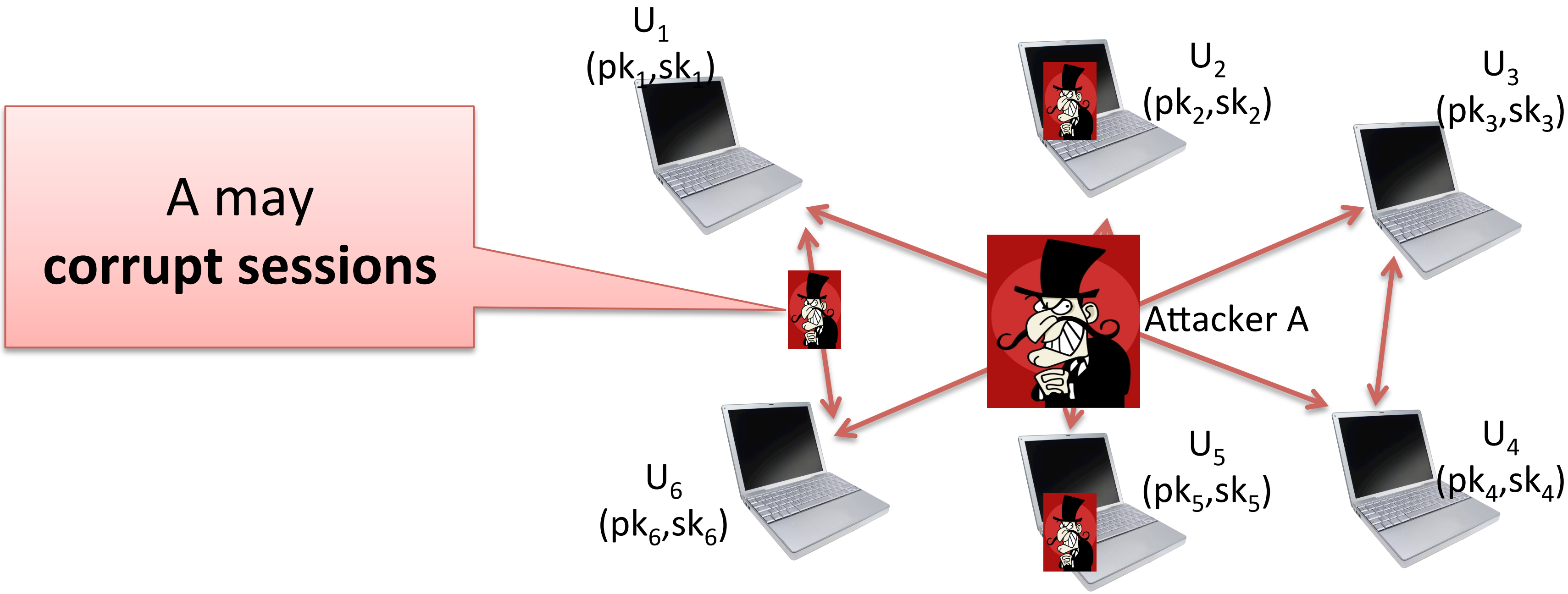

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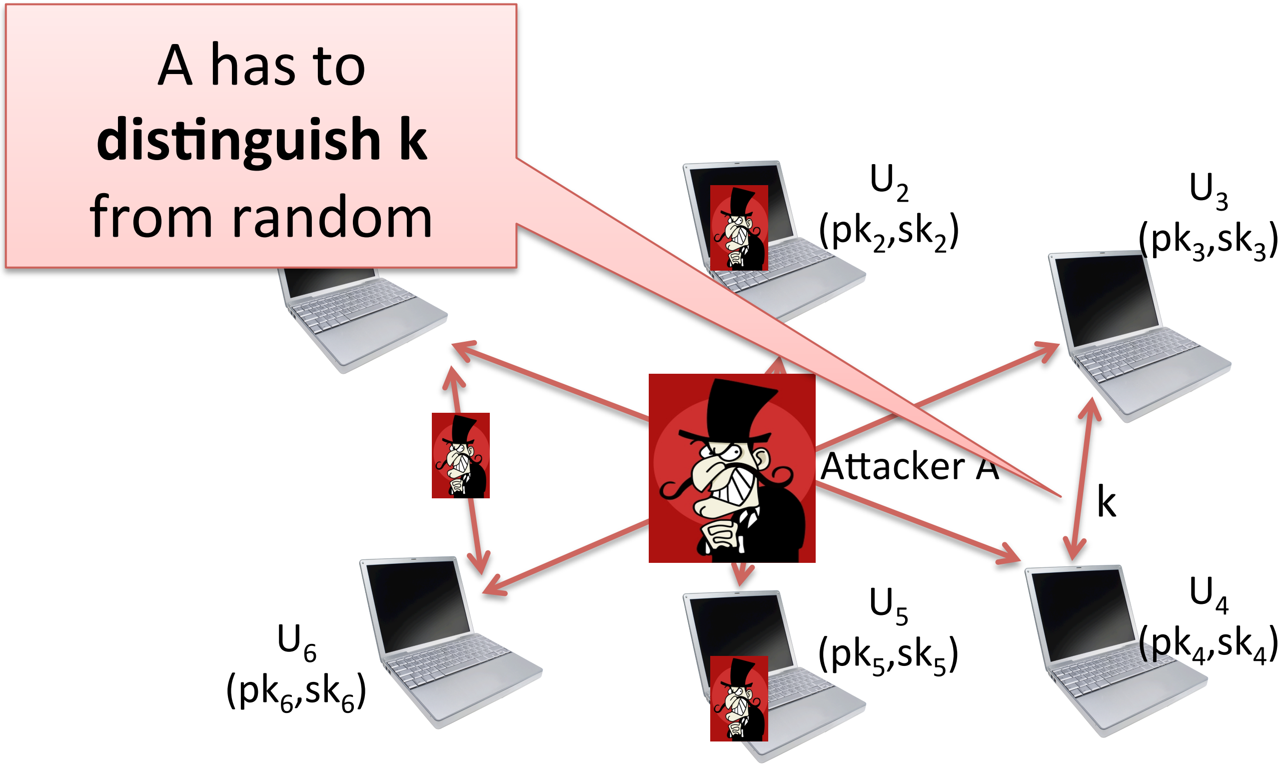
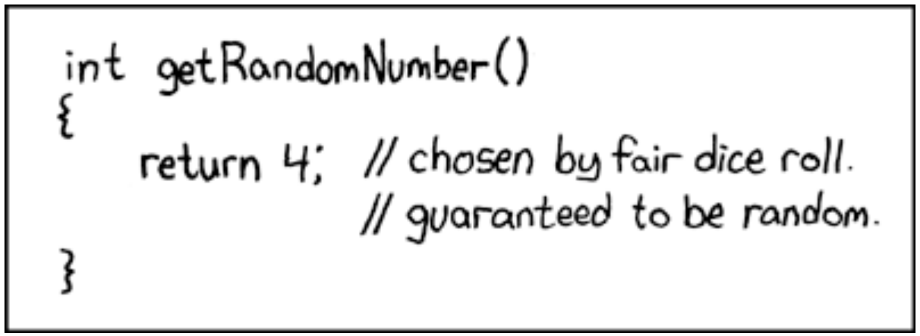


- Provide A with “execution environment” that formalizes A’s capabilities

Weak Randomness in Practice

Many examples for the **difficulty in practice**:

- Debian OpenSSL PRNG Bug (2006-2008)
- Weak RSA public keys
  - Lenstra et al. (Crypto 2012)
  - Heninger et al. (USENIX Security 2012)
  - Bernstein et al. (Asiacrypt 2013)
- Cold boot attacks
  - Halderman et al. (USENIX Security 2008)



https://xkcd.com/221/

“eCK Security”

[LLM07]

Key k_{AB} is indistinguishable even if **the attacker learns the randomness**

(pk_A, sk_A)

(pk_B, sk_B)

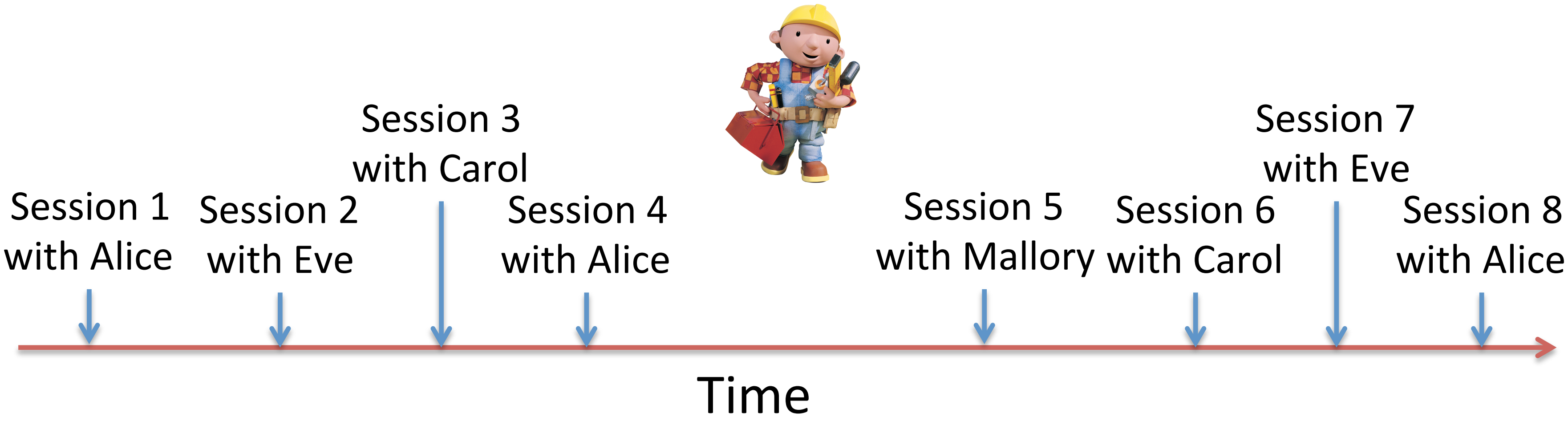
$m_A = f(pk_B, sk_A, \mathbf{r_A})$ →

$m_B = f(pk_A, sk_B, \mathbf{r_B})$ ←

$g(pk_B, sk_A, \mathbf{r_A}, m_B) = k_{AB} = g(pk_A, sk_B, \mathbf{r_B}, m_A)$

Forward Security (PFS)

(Diffie, van Oorschot, Wiener, DESI 1992)



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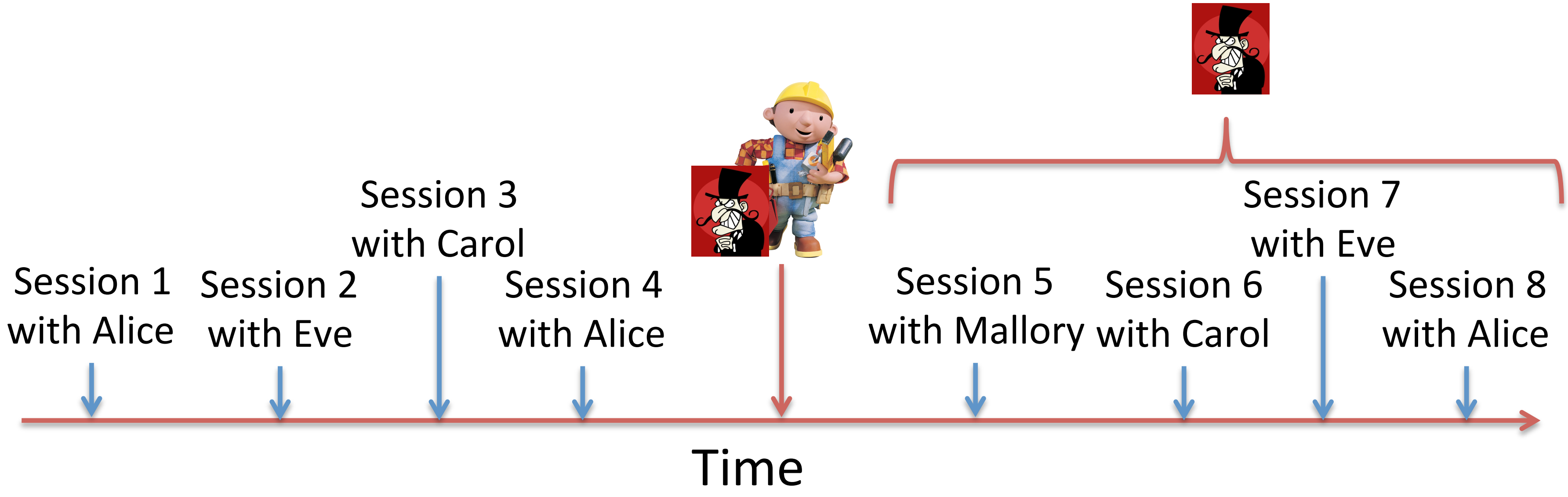

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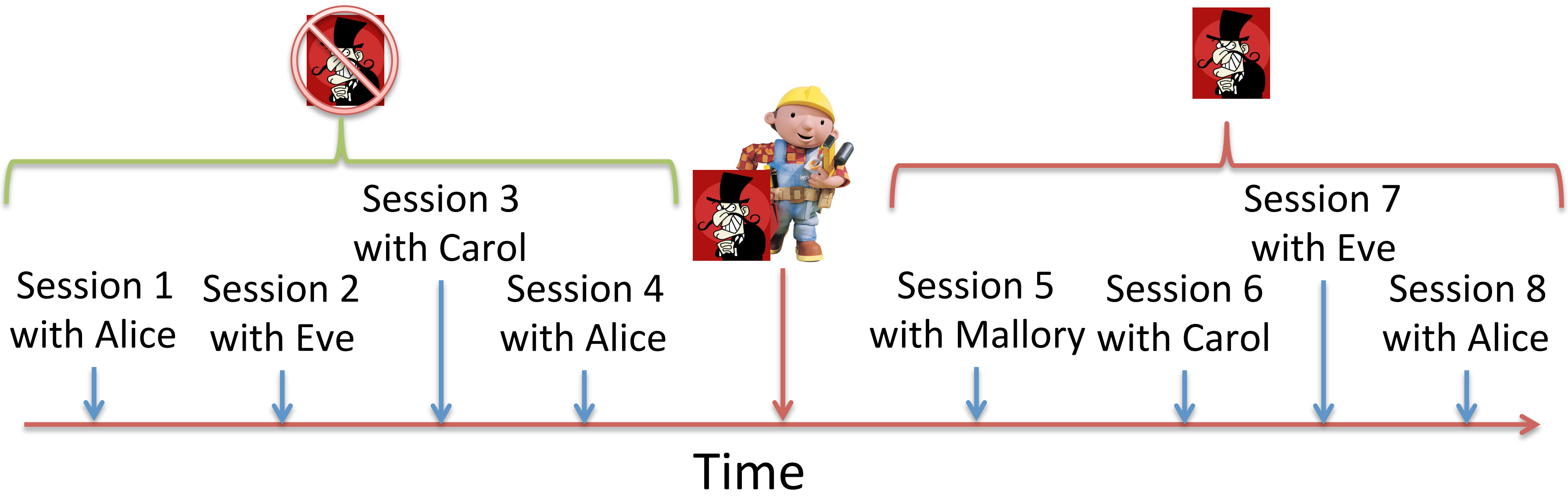

"Corruption of the long-term secret should not compromise sessions that were established **before** the corruption"

- Put forward by large Internet companies since 2011 (Google)
- Design goal of modern protocols like TLS 1.3, TextSecure, ...

The Difficulty of
Forward Security in the eCK Model

Forward security:
key-indistinguishability is based on
secret ephemeral randomness

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Forward security:
key-indistinguishability is based on **secret ephemeral randomness**

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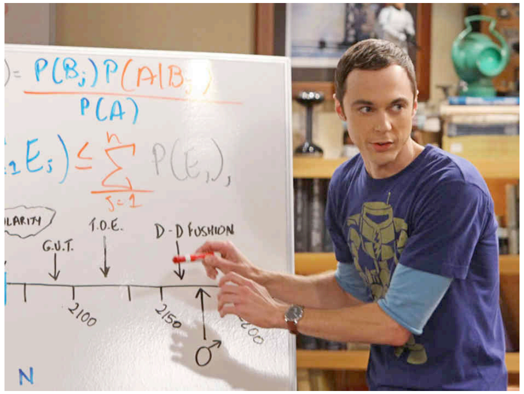
Session keys must depend on **both long-term and ephemeral** secrets, such that **corruption of either (but not both)** does not corrupt the security of session keys

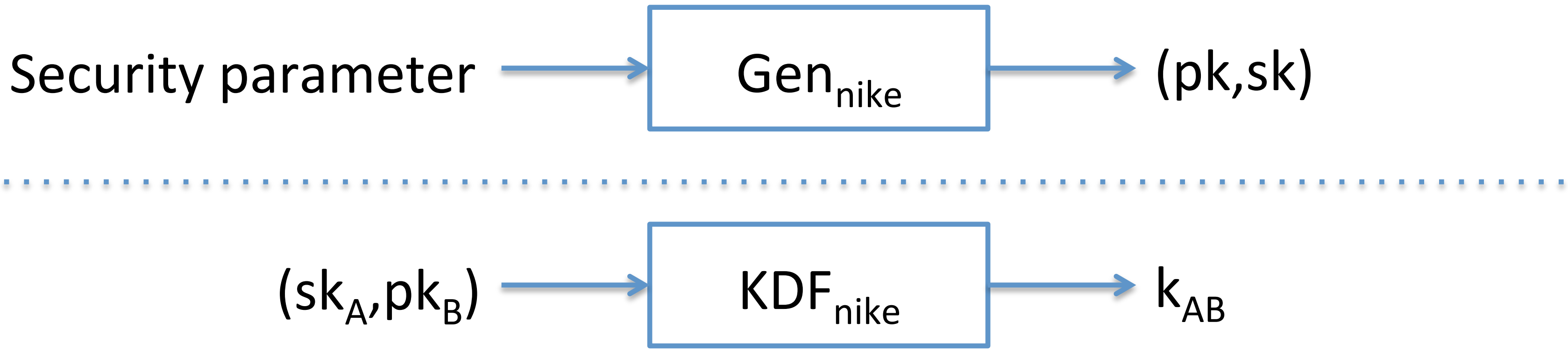
Contributions



- eCK-PFS secure key exchange
  - One-round (ORKE)
  - First from **generic assumptions**
    - Signature scheme
    - Pseudorandom function
    - Non-interactive key exchange
    - **First not based on discrete log** type assumption
  - Without Random Oracles
  - Relatively **efficient**
  - **Simple** construction and proof

Non-Interactive Key Exchange (NIKE)

(Diffie, Hellman `76; Freire, Hofheinz, Kiltz, Paterson, PKC `13)



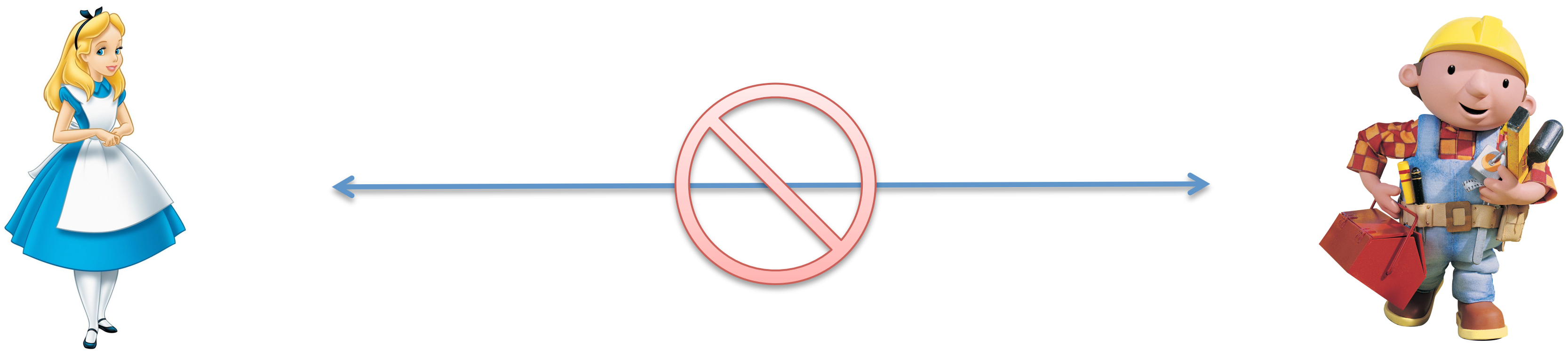
Non-Interactive Key Exchange (NIKE)

(Diffie, Hellman `76; Freire, Hofheinz, Kiltz, Paterson, PKC `13)

Security parameter → Gen_{nike} → (pk,sk)

(sk_A, pk_B) → KDF_{nike} → k_{AB}

(pk_A, sk_A) (pk_B, sk_B)



$\text{KDF}_{nike}(pk_B, sk_A) \;=\; k_{AB} \;=\; \text{KDF}_{nike}(pk_A, sk_B)$

Our Protocol

$pk_A := (pk_{A,sig}, pk_{A,nike})$

$pk_B := (pk_{B,sig}, pk_{B,nike})$

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$pk_A := (pk_{A,sig}, pk_{A,nike})$ $pk_B := (pk_{B,sig}, pk_{B,nike})$

$(pk'_A, sk'_A) \leftarrow NIKEGen(1^k, r_A)$ $(pk'_B, sk'_B) \leftarrow NIKEGen(1^k, r_B)$

$m_A = (pk'_A, sig_A(pk'_A))$ →

$m_B = (pk'_B, sig_B(pk'_B))$ ←

$KDF_{orke}(pk_B, sk_A, m_B, r_A) = k_{AB} = KDF_{orke}(pk_A, sk_B, m_A, r_B)$

Our Protocol

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$(pk'_A, sk'_A) \leftarrow \text{NIKEGen}(1^k, r_A)$ $(pk'_B, sk'_B) \leftarrow \text{NIKEGen}(1^k, r_B)$

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$$KDF_{orke}(pk_B, sk_A, m_B, r_A) \;=\; k_{AB} \;=\; KDF_{orke}(pk_A, sk_B, m_A, r_B)$$

Similar to **signed Diffie-Hellman**, but

- **NIKE instead of DH**
- more **complex key derivation**

Idea of KDF_{orke}

Alice **essentially** computes:

$KDF_{orke}(pk_B, sk_A, pk_B', sk_A') :=$

$KDF_{nike}(pk_B, sk_A) \oplus KDF_{nike}(pk_B', sk_A') \oplus KDF_{nike}(pk_B, sk_A') \oplus KDF_{nike}(pk_B', sk_A)$

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- Adversary learns Randomness(A) and Randomness(B)

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- Adversary learns Randomness(A) and Randomness(B)
- Adversary learns SecretKey(A) and SecretKey(B)
- Adversary learns SecretKey(A) and Randomness(B)
- Adversary learns Randomness(A) SecretKey(B)

Adversary may learn **all non-trivial** combinations of randomness / long-term secret, **even from the "target-session"**

The "real" KDF_{orke}

Input: $(pk_B, sk_A, (pk_B', sig_B), (pk_A', sig_A))$

- $T := sort((pk_B', sig_B), (pk_A', sig_A))$
- $k_1 := PRF(KDF_{nike}(pk_B, sk_A), T)$
- $k_2 := PRF(KDF_{nike}(pk_B, sk_A'), T)$
- $k_3 := PRF(KDF_{nike}(pk_B', sk_A), T)$
- $k_4 := KDF_{nike}(pk_B', sk_A')$
- $k := k_1 \oplus k_2 \oplus k_3 \oplus k_4$

Output k

Generic Construction

- Building blocks of the ORKE protocol:
  - Non-interactive key exchange
  - Signature scheme
  - Pseudorandom function

  Standard security definitions

- Instantiable with **any concrete construction**
  - From different assumptions, like
    - **Discrete log** type, with/without pairing
    - **Factoring-**related
    - Possibly **post-quantum**?

Summary

- eCK-PFS secure construction of ORKE
  - **Simple** and **natural** construction and proof
  - **Generic**, based on **standard primitives**
    - Gives rise to **first ORKE not based on DL**
  - Relatively **efficiently instantiable**
    - Instantiations in ROM: very efficient
    - Instantiations without ROM: not horrible

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Thank you!

Comparison with other protocols

	Standard Model	PFS	weak PFS	KCI	exp. per party	pairing evaluations	Security model
$\mathcal{TS}1$ [21]	✗	✗	✗	✗	1	-	BR^1
$\mathcal{TS}3$ [21]	✓	✓	✓	✗	3	-	BR^1
MQV	✗	✗	✓	✗	1	-	CK
HMQV	✗	✗	✓	✓	2	-	CK
KEA	✗	✗	✓	✓	2	-	CK
P1 [6]	✓	✗	✗	✓	8	2	CK
P2 [6]	✓	✗	✓	✓	10	2	CK
NAXOS	✗	✗	✓	✓	4	-	eCK
Okamoto	✓ $+\pi$PRF	✗	✓	✓	8	-	eCK
NAXOS^2_{pfs}	✗	✓	✓	✓	4	-	$eCK\text{-}PFS$
ORKE^3	✗ (NIKE)	✓	✓	✓	5	-	$eCK\text{-}PFS$
ORKE^4	✓	✓	✓	✓	16	12	$eCK\text{-}PFS$