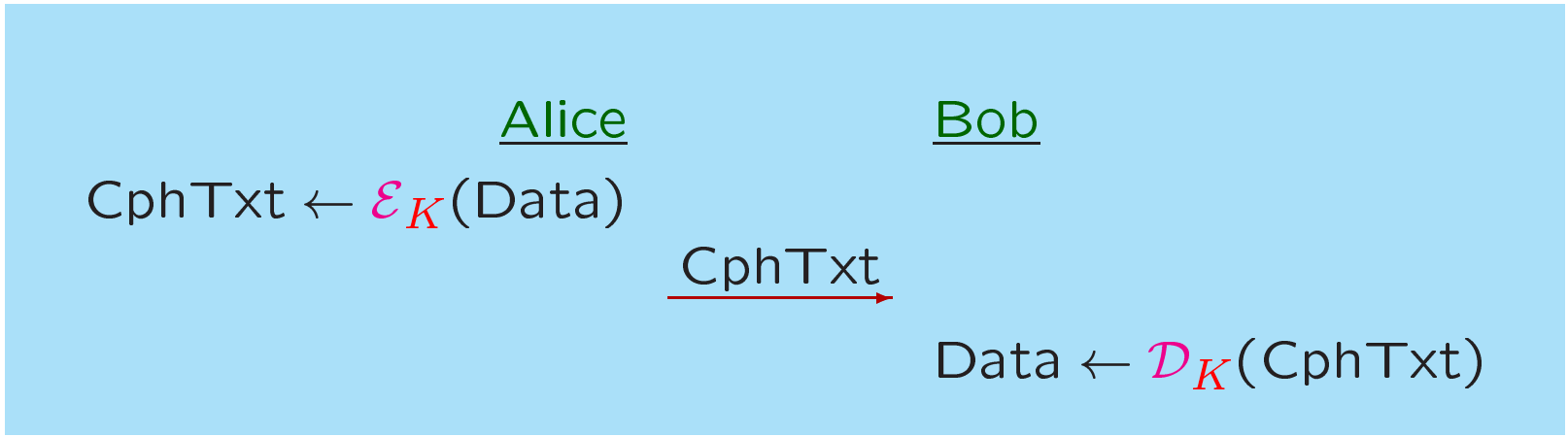
The Challenge of
Session-Key Distribution Protocols

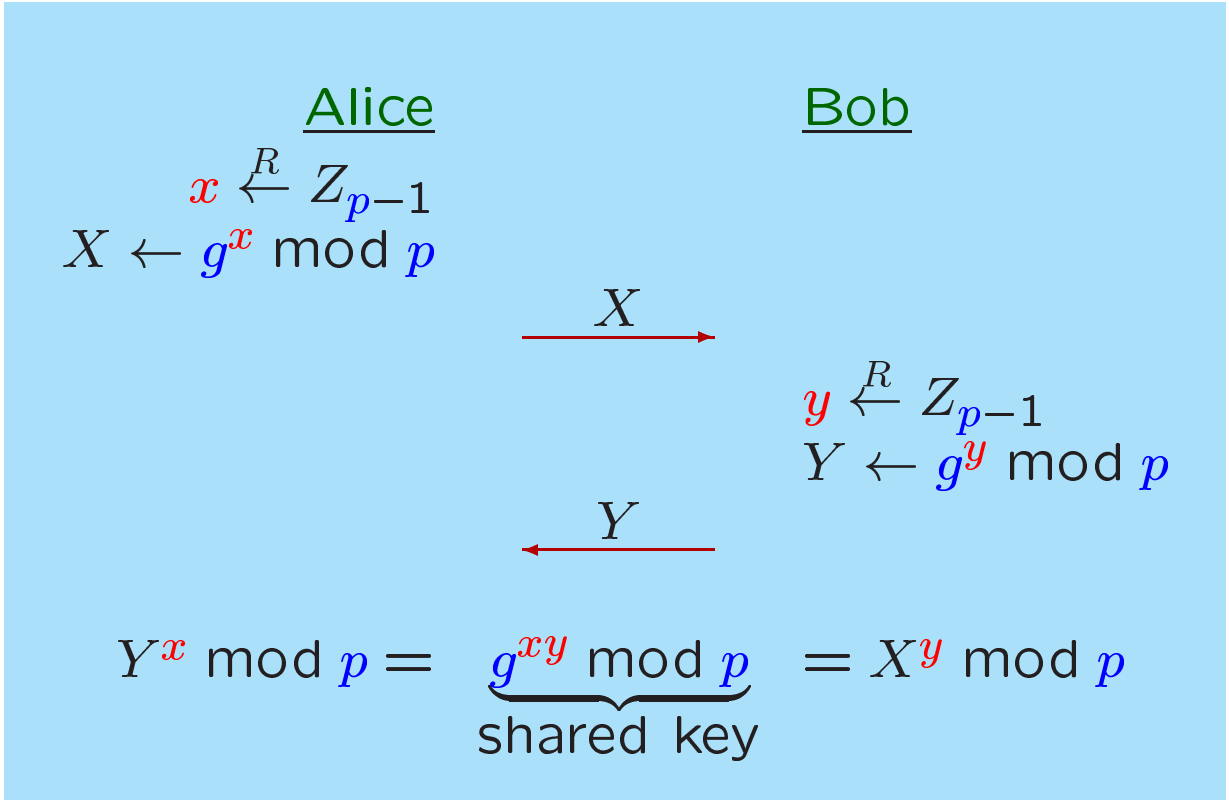
Mihir Bellare
University of California at San Diego

In practice, bulk data encryption or authentication is typically based on possession of a shared key K—



But how are Alice and Bob to obtain the shared key?

Diffie-Hellman Secret-Key Exchange Protocol

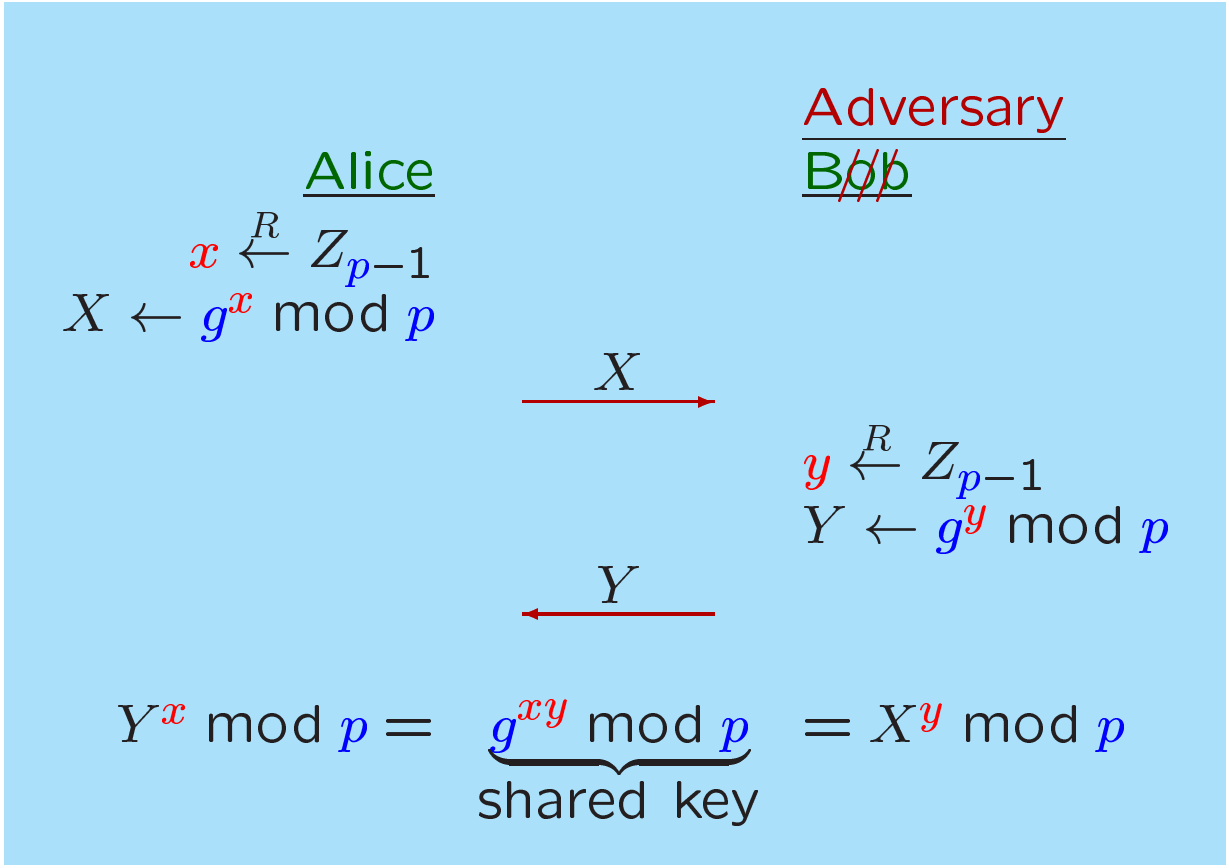


Publicly known:

- p – Prime number
- g – Generator of $Z_p{}^*$

Diffie-Hellman Secret-Key Exchange Protocol

Does not provide Authenticity



Publicly known:

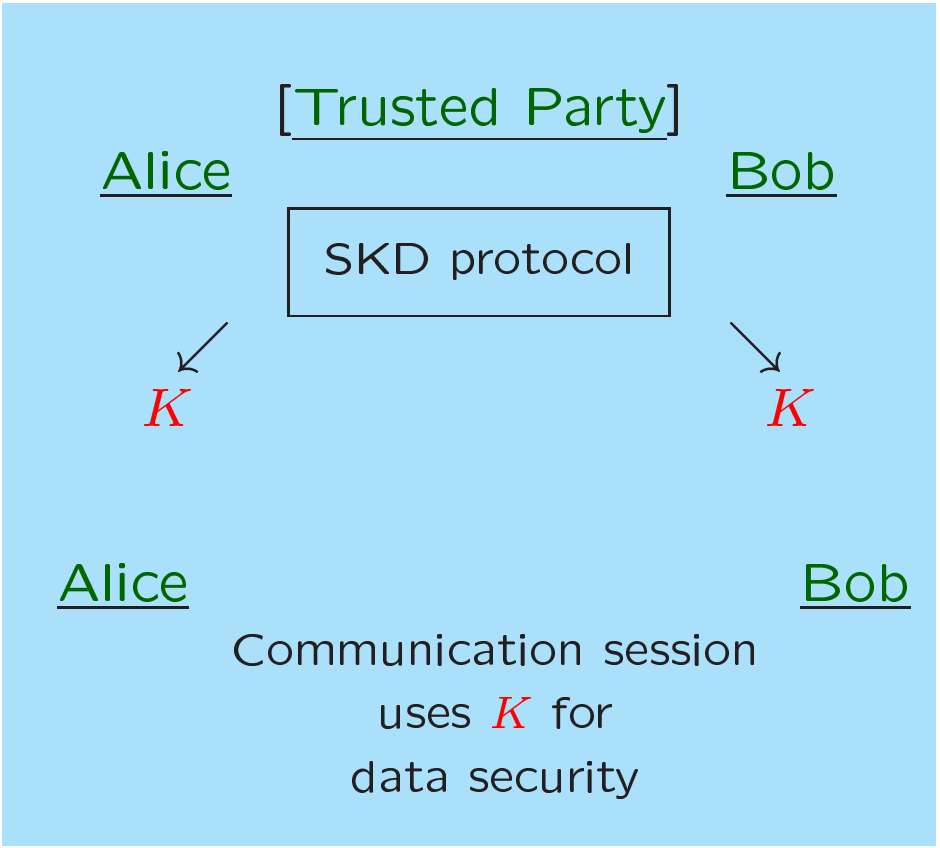
- p – Prime number
- g – Generator of $Z_p{}^*$

This protocol is only secure against passive (ie. eavesdropping) adversaries.

The **Session-Key Distribution (SKD)** problem

Premise: Existence of authentic long-lived (LL) keys based on which authentication is possible.

Goal: Parties wish to interact so as to come into possession of an authentic shared key to be used in a subsequent communication session.



Focus: The design and analysis of SKD protocols

De-coupling: No assumptions should be made about how K is used in the communication session.

The **Three-Party Model**

LL-keys and trust assumptions:

- There is a trusted authentication server S
- A shares a key (password) a with S
- B shares a key (password) b with S

SKD protocol problem: A, B, S interact to get a session key K

Example systems: Needham-Schroeder, Kerberos

Example protocol:

$$
\begin{array}{ll}
A \to S: & A, B, N_A \\
S \to A: & \{\, N_A, B, K, \{\, K, A \,\}_b \,\}_a \\
A \to B: & \{\, K, A \,\}_b \\
B \to A: & \{\, N_B \,\}_K \\
A \to B: & \{\, N_B - 1 \,\}_K
\end{array}
$$

The **Two-Party, Asymmetric Model**

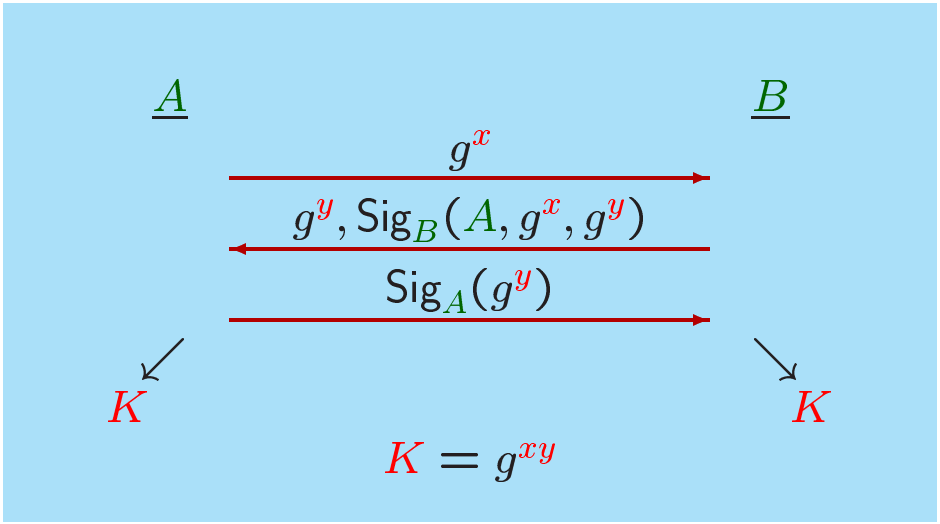
LL-keys and trust assumptions:

- There is a public-key infrastructure
- A has pk_B, the public key of B, and its certificate
- B has pk_A, the public key of A, and its certificate

SKD protocol problem: A, B interact to get a session key K

Example systems: SSL, TLS

Example protocol:

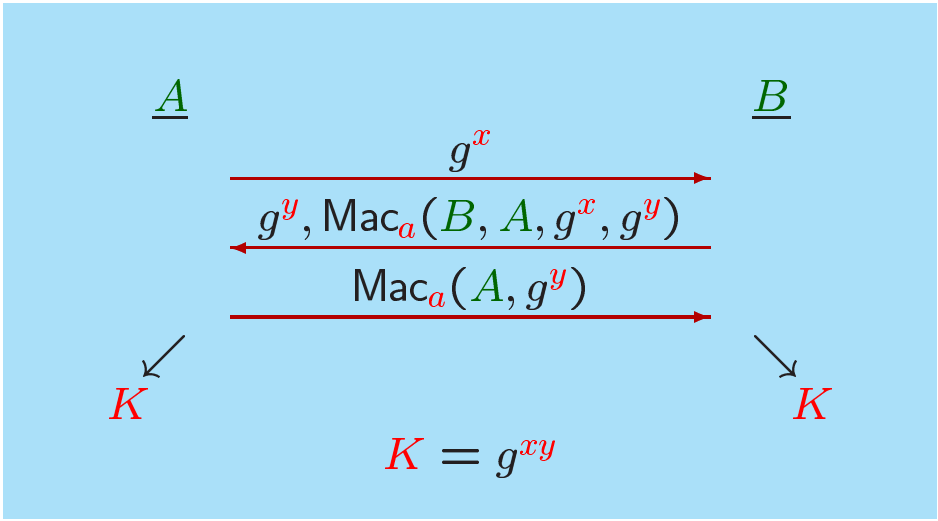


The **Two-Party, Symmetric Model**

LL-keys and trust assumptions: A and B share a key (password) a

SKD protocol problem: A, B interact to get a session key K

Example protocol:



Usage of Session-Key Distribution Protocols

Across technologies

- End to end Internet communication
- Smart Card authentication
- Wireless
- Hand-held devices
- ⋮

Across Applications

- Electronic payments
- Electronic banking
- Access control
- ⋮

Security goals for SKD:

A continually rising bar

- Authentication (unilateral or mutual)
- Freshness and secrecy of session key
- Resistance to known-key attacks
- Forward secrecy of session key
- Resistance to dictionary attacks
- Anonymity of mobile users
- ⋮

Implementation constraints:

Many possible kinds

- Processor speed
- Memory
- Power
- Bandwidth
- ⋮

Security: An elusive goal

SKD protocols are easy to propose but hard to get right.
The area is notorious for broken protocols.
Attacks sometimes take years to discover, by which time the protocols are deployed.

The world of SKD

More protocols for SKD are proposed every year than for all other cryptographic problems combined.

The bulk of proposed protocols are extraordinarily poor, typically designed by non-cryptographers and appearing in IEEE journals.

Attacks on these protocols fuel the production of more literature.

Two main approaches to the security analysis of SKD protocols

Formal methods: From the security community

- Initiated by Burrows, Abadi, Needham (BAN90)
- Often successful at finding bugs
- Some approaches can be automated
- Model primitives as ideal objects, but it is not clear what this means
- No rigorous proofs of security

References: Survey articles by Meadows 92, Rubin and Honeyman 93.

Provable security: From the cryptographic community.

- Initiated by Bellare, Rogaway (BeRo93)
- Based on computational complexity theory and the GM approach
- Definitions of security for both primitives and goals
- Helps find bugs
- Security of (secure) SKD protocols is proved

Provable-Security in SKD protocol analysis

Definitional approaches:

- Direct (BeRo93, BeRo95, BlJoMe97, BlMe97, BePoRo00)
- Simulation-based (BeCaKr98, Sh99, BoMaPa00)

Trust models treated:

- Two-party, symmetric (BeRo93)
- Two-party, asymmetric (BlJoMe97, BlMe97, BePoRo00)
- Three party (BeRo95, ShRu96)

Security goals treated:

- Authentication, freshness and secrecy of session keys, known key attacks (BeRo93, BeRo95, ...)
- Forward secrecy (BePoRo00)
- Dictionary attacks (HaKr98, BePoRo00, BoMaPa00)

Efficient, Provably-Secure SKD protocols

are available for the following problems:

- Two-party, symmetric SKD (BeRo93)
- Three party session key distribution (BeRo95)

and, most importantly in current climate, also for

Two-party, asymmetric SKD with forward secrecy and security against dictionary attack (BePoRo00, BoMaPa00)

Note: The analyses for the last use the random oracle model.

Where we are in SKD

Successes: Provable-security has been very successful, especially for treating the basic goals of SKD.

Getting harder: As more and more goals are added, the complexity of definitions and proofs increases.

Some directions for the future

Coming together: Try to combine the provable security and formal methods approaches (Mitchell et al, Abadi, Abadi-Rogaway)

Take responsibility for your protocols: The burden of proof is on the protocol proposer, NOT the attacker. Stop proposing un-analyzed protocols!

Plan for this talk

- [x] Introduction: Trust models, approaches, state of the art
- [ ] Example protocols and security goals
- [ ] How provable-security works

Needham-Schroeder 78

Three party model: S is a trusted server; A shares a key a with S; B shares a key b with S.

Notation:

$\{ X \}_{\text{key}} \stackrel{\text{def}}{=}$ Encryption of X under key

$N_{\text{party}} =$ Nonce chosen by party

Protocol:

$A \to S$:	A, B, N_A	Distribution phase
$S \to A$:	$\{ N_A, B, K, \{ K, A \}_b \}_a$	
$A \to B$:	$\{ K, A \}_b$	
$B \to A$:	$\{ N_B \}_K$	Freshness / Replay check
$A \to B$:	$\{ N_B - 1 \}_K$	

Session key: The distributed session key K is chosen by S.

Denning-Sacco 81: Known-key attack on NS

If a session key K is revealed to Adversary after the session is over then later, a compromised session can be created.

Adversary has a record of the full conversation—

$$
\begin{array}{ll}
A \to S: & A, B, N_A \\
S \to A: & \{N_A, B, K, \{K, A\}_b\}_a \\
A \to B: & \{K, A\}_b \\
B \to A: & \{N_B\}_K \\
A \to B: & \{N_B - 1\}_K
\end{array}
$$

Now K is leaked. So Adversary does the following—

$$
\begin{array}{ll}
\text{Adversary} \to B: & \{K, A\}_b \\
B \to \not{A}\ \text{Adversary}: & \{\overline{N}_B\}_K \\
\text{Adversary} \to B: & \{\overline{N}_B - 1\}_K
\end{array}
$$

Now B might encrypt a message under K and send it to A. But Adversary can read it.

Goal for secure session-key distribution

Security against known-key attacks: Adversary should not be able to obtain session key of one session even if it knows session keys of other sessions.

Rationale: No assumptions should be made about how a communication session uses its session key.

Confusion about primitives

Second flow of NS:

$$S \to A: \quad \{N_A, B, K, \{K, A\}_b\}_a$$

where $\{X\}_{\text{key}} \stackrel{\text{def}}{=}$ "Encryption" of X under key

How do we instantiate $\{\cdot\}_{\text{key}}$?

CBC encryption is not good enough because here encryption is used to provide authenticity.

The **Modern cryptography** view of primitives

Encryption: $\mathsf{Enc}_{\mathsf{key}[1]}(\mathsf{Data})$

Provides privacy
Instantiations: CBC, CTR,
and other modes of operation

MAC: $\mathsf{Data}, \mathsf{Mac}_{\mathsf{key}[2]}(\mathsf{Data})$

Provides authenticity
Instantiations: CBC-MAC,
HMAC, UMAC

Key Separation: Encryption and MAC functions use different keys, but they can be derived from a single higher level key.

Second flow of NS, done right:

$$S \to A: \quad \underbrace{C_A, \mathsf{Mac}_{a[2]}(B, N_A, C_A)}_{\text{for } A} \; , \; \underbrace{C_B, \mathsf{Mac}_{b[2]}(A, N_A, C_B)}_{\text{for } B}$$

where

$$\begin{aligned} C_A &= \mathsf{Enc}_{a[1]}(K) \\ C_B &= \mathsf{Enc}_{b[1]}(K) \end{aligned}$$

Benefits of separating encryption and authentication

- Modular and flexible software design
- Easier to understand rationale for flows
- Facilitates security analysis
- Improves performance

Quality of secrecy of session key

Last two flows of NS:

$B \rightarrow A$: $\{N_B\}_K$
$A \rightarrow B$: $\{N_B - 1\}_K$

This reveals information about K which can result in the insecurity of a communication session using K.

BeRo93: New goal for secure session-key distribution

Semantic security of session key: Adversary should be unable to compute any partial information about K.

Rationale: No assumptions should be made about how a communication session uses its session key. Without semantic security, some usages will be insecure.

Remark: This rules out "key confirmation". But that can be done differently.

A provably-secure three-party SKD protocol (BeRo95)

$$
\begin{aligned}
A \to B\text{:} \quad & R_A \\
B \to S\text{:} \quad & R_A, R_B \\
S \to A\text{:} \quad & \underbrace{\mathsf{Enc}_{a[1]}(K)}_{C_A}, \mathsf{Mac}_{a[2]}(A, B, R_A, C_A) \\
S \to B\text{:} \quad & \underbrace{\mathsf{Enc}_{b[1]}(K)}_{C_B}, \mathsf{Mac}_{b[2]}(A, B, R_B, C_B)
\end{aligned}
$$

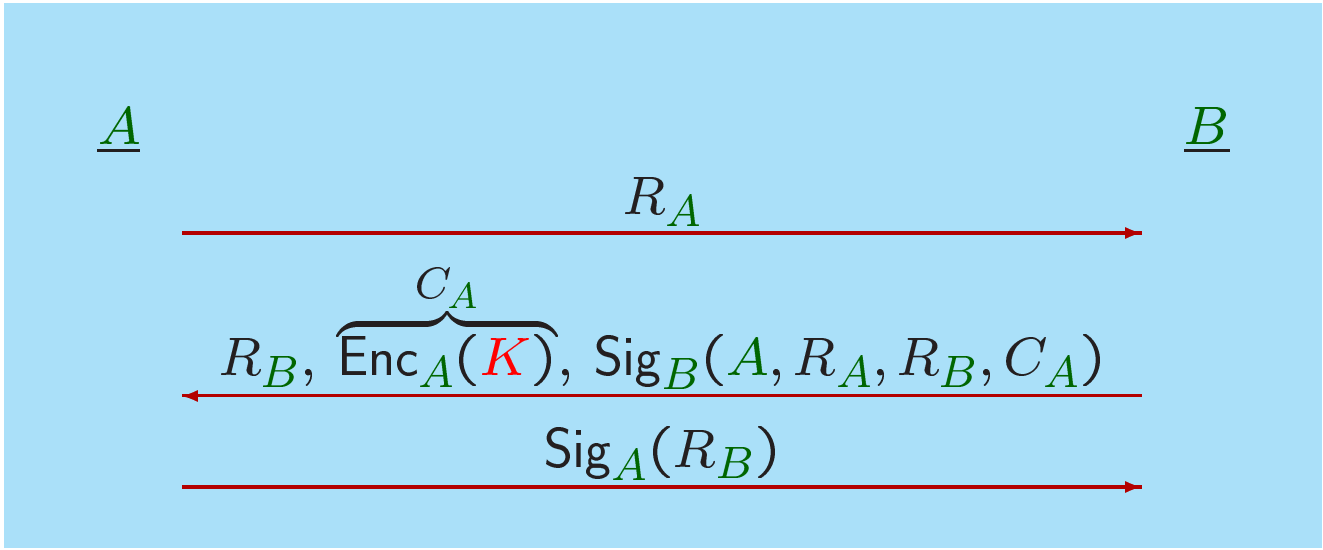
Easy to understand!

Provably provides security against known-key attacks and semantic security of session key assuming the encryption and MAC functions meet normal, well-understood security goals.

A provably-secure two-party, asymmetric SKD protocol

Adapted from BeRo93

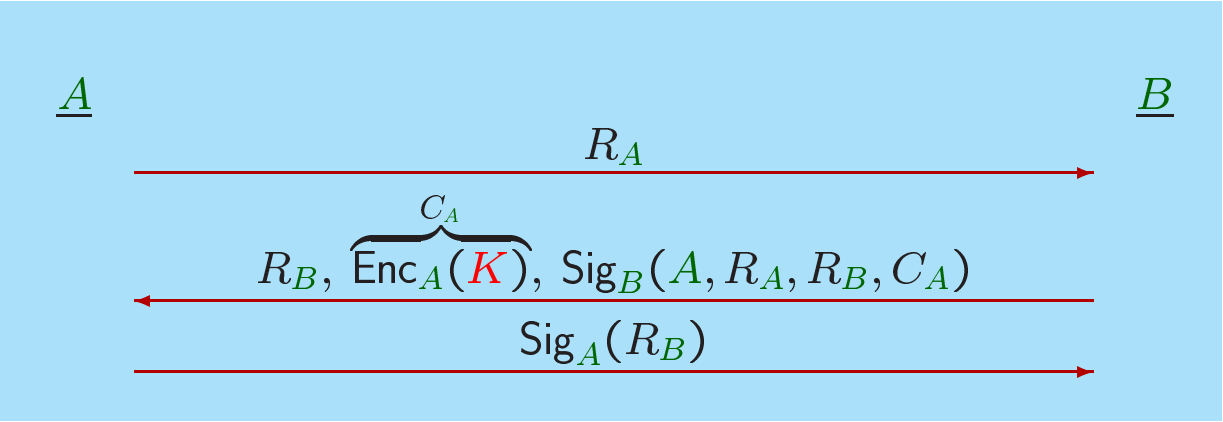
Two-party, asymmetric model: A has pk_B and B has pk_A



Provably provides security against known-key attacks and semantic security of session key assuming the public-key encryption and signature functions meet normal, well-understood security goals.

Raising the bar: Forward secrecy

August 15: Adversary captures the following transcript:



August 15: Adversary captures $C = \mathsf{Enc}_K(\text{Data})$

September 15: Adversary breaks into A's computer and obtains its LL secret key sk_A

September 15: Adversary can obtain

$$K = \mathsf{Dec}_A(C_A) \text{ and}$$
$$\text{Data} = \mathsf{Dec}_K(C).$$

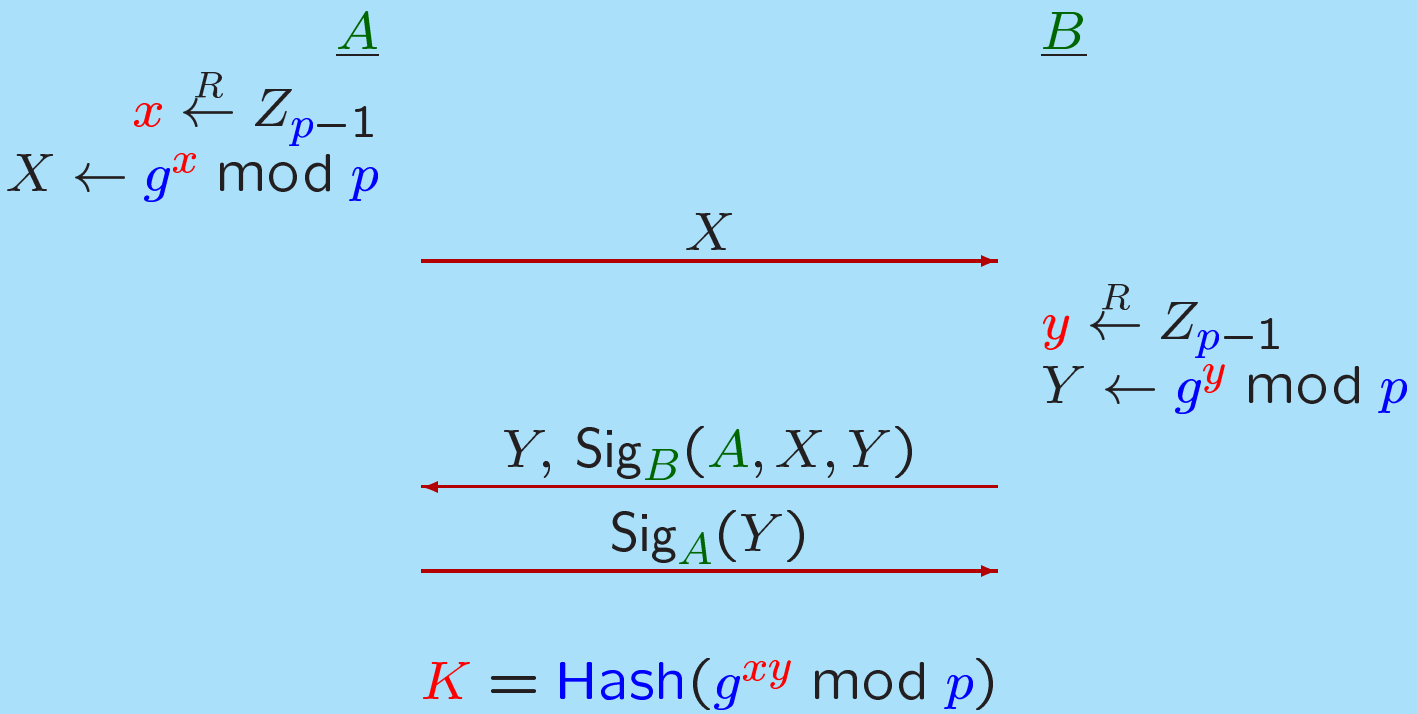
Gü89, DiVaWi92: New goal for SKD

Forward secrecy: Adversary should be unable to compute (any partial information about) K, even if it obtains the LL secret key of either party after the execution of the protocol distributing K has completed.

Rationale: In practice, computer systems are less secure than protocols, and forward secrecy mitigates the damage caused by key compromise due to break-ins.

SKD Protocol providing forward secrecy

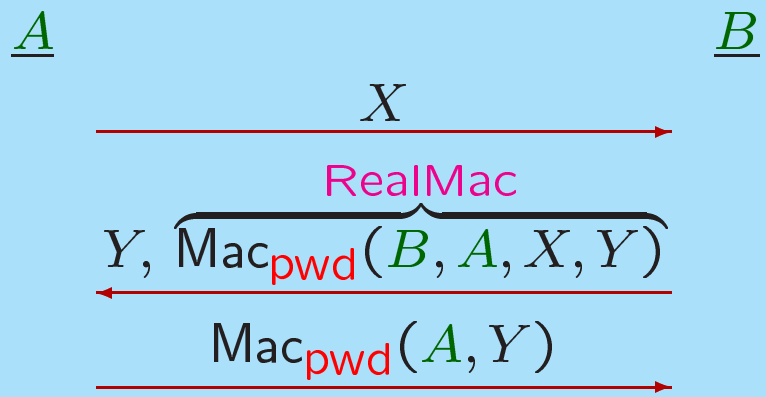
Variant of the STS protocol of DiVaWi92



Raising the bar further: Dictionary attacks

Client A has a short password pwd $\in$ Dictionary which is known to server B

Adversary captures the following transcript:



Dictionary attack:

For all CandidatePwd $\in$ Dictionary do

CandidateMac $\leftarrow$ $\mathsf{Mac}_{\mathsf{CandidatePwd}}(B, A, X, Y)$

If CandidateMac $=$ RealMac then return CandidatePwd

Another new goal for secure session-key distribution

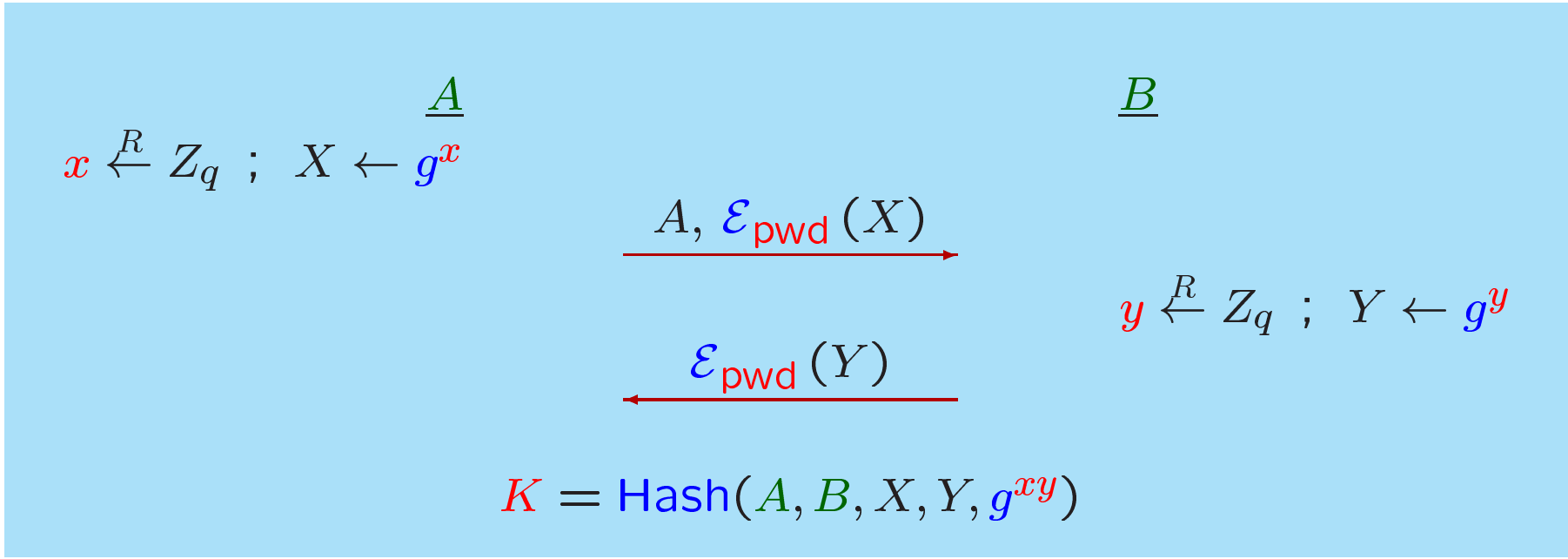
Security against dictionary attack: The number of candidate passwords that can be eliminated by off-line search is at most the number of protocol transcripts possessed by the adversary.

Rationale: This is the best possible security in the face of the existing practice of using poorly chosen passwords.

Lots of protocols:

- Bellovin and Merritt 92, 93 — EKE
- Ja96, Ja97, Lu97, MaSw99, Wu98, HaKr98, BePoRo00, BoMaPa00

SKD Protocol providing forward secrecy and security against dictionary attacks (BePoRo00)



Publicly known: Prime number q ; Generator g of a group G of order q ; Ideal cipher $\mathcal{E}$; Random oracle hash function Hash.

This protocol provably provides security against known-key attacks, semantic security of session key, forward secrecy and security against dictionary attacks in the random oracle model, assuming the Diffie-Hellman problem is hard in G.

Plan for this talk

- [x] Introduction: Trust models, approaches, state of the art
- [x] Example protocols and security goals
- [ ] How provable-security works

Two kinds of attacks on SKD protocols:

- Arising from weaknesses in the underlying primitives
  Example: break block cipher; MAC forgery
- Arising from flaws in SKD protocol design
  Example: known-key attack on NS

Goal of provable-security: **Prove** the absence of attacks arising from protocol flaws.

Assume: Absence of attacks on the underlying primitives.

Methodology of provable security

Model	–	What the adversary can do
Definition	–	When is the adversary successful
Proof	–	If the adversary succeeds we can break the underlying primitives

Based on clear, standard and well-understood cryptographic properties of the underlying primitives.

Sources of definitional ideas in SKD

Basic model and definitional ideas from Bellare-Rogaway 93–

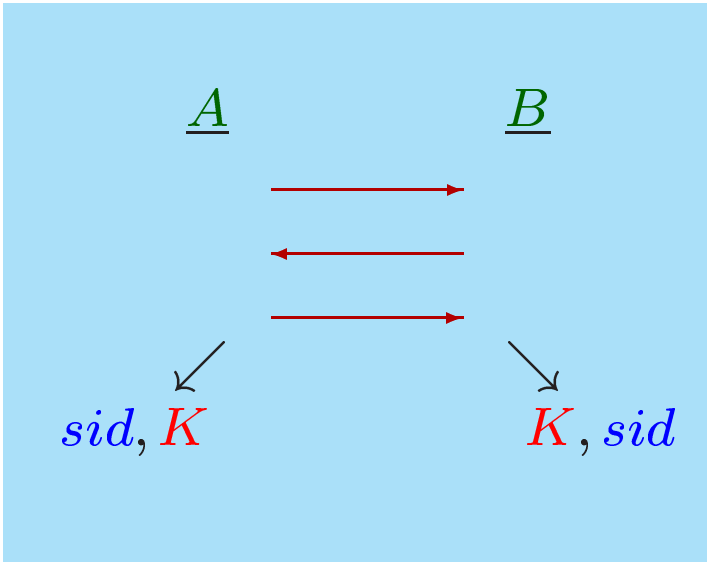
- Instances of parties
- Adversary communicating with its instance oracles via queries
- Adversary in control of all communication
- Freshness via partnering
- Semantic security of session keys

Some variations following Bellare-Pointcheval-Rogaway 00–

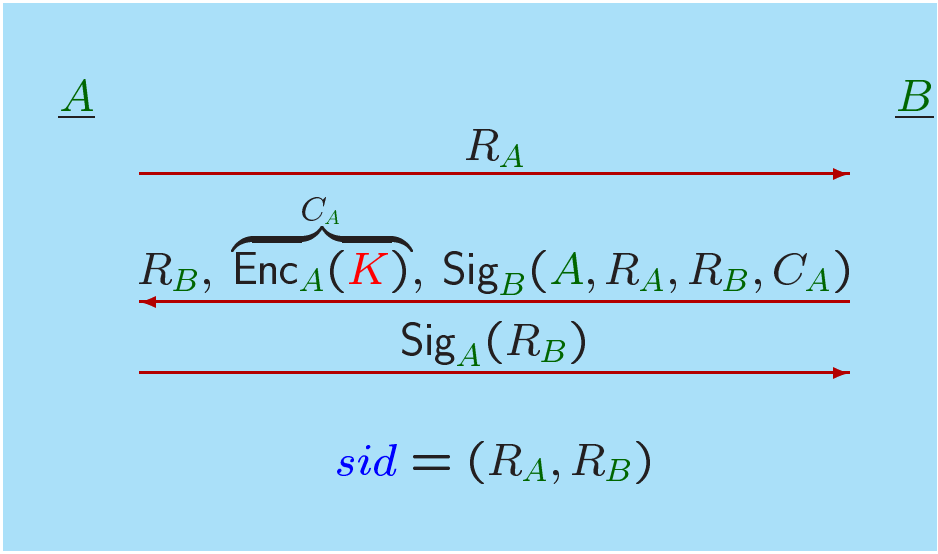
- Partnering via session ids
- Fixing some oversights: timing of the test query
- Extensions to forward secrecy and dictionary attacks

We will treat **two-party, asymmetric SKD**

Canonical Protocol



Example Protocol



Fix Π — Protocol description function / syntax which specifies all the software: The LL-key generation algorithm ; The underlying primitives ; The instructions for computing and verifying flows and for computing K, sid.

The question: Is Π secure?

Instances of parties

Instances of A – $A_1, A_2, A_3, \ldots$ – Each holds sk_A, pk_B
Instances of B – $B_1, B_2, B_3, \ldots$ – Each holds sk_B, pk_A

Instances run SKD protocol Π and are the endpoints of sessions
Many instances may be active concurrently

Session IDs pair-up instances: If A_i has sid then

- A_j cannot have the same session ID ($j \neq i$)
- There is at most one B_j —called A_i's partner— with this sid
- A_i, B_j have the same session key K

The **experiment** of executing Π with Adversary

Fix protocol description Π and adversary algorithm Adversary.

– Run key generation algorithm to get public/secret keys for A, B.
– Give sk_A, pk_B to $A_1, A_2, \ldots$
– Give sk_B, pk_A to $B_1, B_2, \ldots$
– Give pk_A, pk_B to Adversary

Adversary interacts with instances via oracle queries.

Send queries: Adversary controls communication between instances

- send(A_i, R) – String R, chosen by Adversary, is sent to A_i
- A_i runs Π to compute the reply and returns it to Adversary

  Example: R_B, $\underbrace{\mathrm{Enc}_A(K)}_{C_A}$, $\mathrm{Sig}_B(A, R_A, R_B, C_A)$

- ⋮

When an instance accepts, the session id is returned to the Adversary.

The **experiment** of executing Π with Adversary, continued

Reveal queries: To model known-key attacks

- reveal(A_i) – Adversary asks for A_i's session key
- If A_i has accepted then its session key is returned to Adversary

Test queries: To model semantic-security of session key

- test(A_i) – Adversary claims it can predict A_i's session key
- Flip a coin and return TestKey to Adversary where
  - If coin $= 0$ then TestKey $= K$
  - If coin $= 1$ then TestKey is a random string
- Adversary outputs a guess as to value of coin

The test query is allowed only if A_i is fresh, meaning Adversary does not already know its session key, meaning

- No reveal(A_i) query was made
- No reveal(B_j) query was made where B_j is A_i's partner

Definitions of security for SKD protocol Π

1. Authenticity: Adversary should be unable to disrupt the session-id based partnering.

> The probability of the following event is negligible: There exist distinct i, j such that
> - Either A_i and A_j output the same session ID
> - or B_i and B_j output the same session ID

2. Semantic security of session key: Adversary should be unable to distinguish the real session key of a fresh instance from a random string.

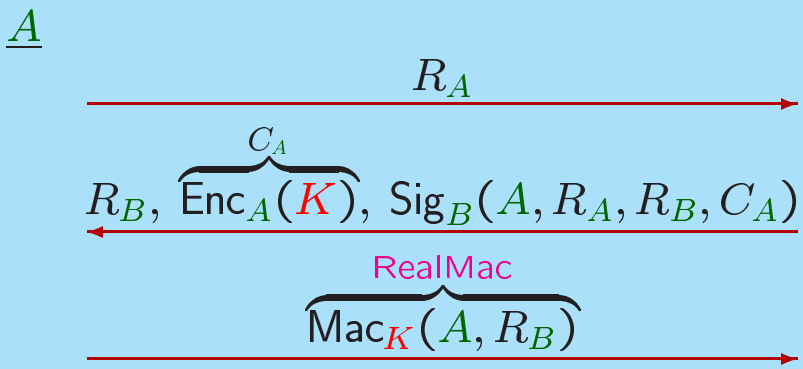
> The excess over 1/2 of the probability that Adversary returns the correct value of coin in its answer to its test query is negligible.

These conditions must hold for all probabilistic, polynomial time Adversary algorithms.

How the model helps find bugs

New protocol: Replaced signature on last flow of previous protocol with a MAC to improve performance.

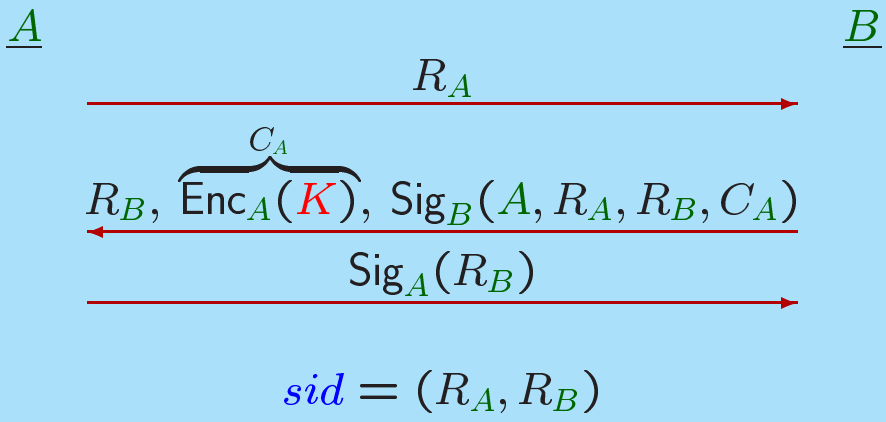
This protocol is insecure.



Adversary can attack the semantic security of the session key via–

- Obtain a transcript between A_1, B_1 via send queries
- Query test(A_1) to get back a test key TestKey
- If $\mathsf{Mac}_{\mathsf{TestKey}}(A, R_B) =$ RealMac
  then TestKey $= K$ else TestKey is random

Security of the basic two-party protocol



Theorem: The protocol Π above satisfies authenticity and semantic security of session keys assuming the signature scheme meets the notion of unforgeability under chosen-message attack and the encryption scheme meets the notion of indistinguishability under chosen plaintext attack.

Reductionist approach to prove the security theorem

Given Adversary violating one of the security properties of the SKD protocol, construct a forger Forger and an eavesdropper Eve such that

- Either Forger breaks the signature scheme, or
- Eve breaks the encryption scheme

The new adversary algorithms will run Adversary, simulate the instance oracles, and finally use the success of Adversary to win their own games.

A flexible framework

To model extra security goals, we enhance adversary capabilities by adding new kinds of oracle queries, and then make new definitions.

Corrupt queries: To model forward secrecy

- corrupt(A) – Adversary corrupts party A
- Adversary gets back sk_A

Forward secrecy is captured by semantic security of session keys in face of extended adversary capabilities and new notion of freshness.

Execute queries: To model dictionary attacks

- execute(A_i, B_j) – Adversary requests transcript
- Adversary gets back a transcript of a full interaction

Security against dictionary attacks is captured via the concrete security statement of the theorem.

Last words

The provable-security approach has been successful in delivering improved security guarantees for session-key distribution protocols.

We now have provably-secure and efficient SKD protocols achieving not just basic goals like semantic security of session keys but also forward secrecy and security against dictionary attacks.

Many challenges remain in the design and analysis of session-key distribution protocols.