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Modelling the Security of Key Exchange

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Outline

Diffie–Hellman key exchange

$$\begin{array}{ccc}
\textbf{A} & & \textbf{B} \\
r_A \in_R \mathbb{Z}_q & & \\
t_A = g^{r_A} & & \\
& \xrightarrow{\quad t_A \quad} & \\
& & r_B \in_R \mathbb{Z}_q \\
& & t_B = g^{x_B} \\
& \xleftarrow{\quad t_B \quad} & \\
Z_{AB} = t_B^{r_A} & & Z_{BA} = t_A^{r_B}
\end{array}$$

— r_A and r_B are *ephemeral secrets*

— Z_{AB} is the *shared secret*

HMQV protocol

A		B
$r_A \in_R \mathbb{Z}_q$		
$t_A = g^{r_A}$	$\xrightarrow{t_A}$	$r_B \in_R \mathbb{Z}_q$
		$t_B = g^{r_B}$
	$\xleftarrow{t_B}$	
$S_A = r_A + dx_A \bmod q$		$S_B = r_B + ex_B \bmod q$
$Z_{AB} = (t_B y_B^e)^{S_A}$		$Z_{BA} = (t_A y_A^d)^{S_B}$

- r_A and r_B are *ephemeral secrets*
- x_A and x_B are *long-term secrets*
- $y_A = g^{x_A}$ and $y_B = g^{x_B}$ are *public keys*
- $d = H(t_A, ID_B)$, $e = H(t_B, ID_A)$

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NAXOS protocol

A		**B**
$r_A \in_R \mathbb{Z}_q$ $h_A = H_1(x_A, r_A)$ $t_A = g^{h_A}$	$\xrightarrow{t_A}$	
		$r_B \in_R \mathbb{Z}_q$ $h_B = H_1(x_B, r_B)$ $t_B = g^{h_B}$
	$\xleftarrow{t_B}$	
$K_{AB} =$ $H_2(t_B^{x_A}, y_B^{h_A}, t_B^{h_A}, ID_A, ID_B)$		$K_{AB} =$ $H_2(y_A^{h_B}, t_A^{x_B}, t_A^{h_B}, ID_A, ID_B)$

— r_A and r_B are *ephemeral secrets*

— x_A and x_B are *long-term secrets*

— $y_A = g^{x_A}$ and $y_B = g^{x_B}$ are *public keys*

— K_{AB} is the *session key*

Jeong–Katz–Lee protocol TS3

$$
\begin{array}{ccc}
\textbf{A} & & \textbf{B} \\
r_A \in_R \mathbb{Z}_q & & \\
t_A = g^{r_A} & \xrightarrow{t_A,\ \mathrm{MAC}_{K_M}(ID_A, ID_B, t_A)} & r_B \in_R \mathbb{Z}_q \\
& & t_B = g^{r_B} \\
Z_{AB} = t_B^{r_A} & \xleftarrow{t_B,\ \mathrm{MAC}_{K_M}(ID_B, ID_A, t_B)} & Z_{BA} = t_A^{r_B}
\end{array}
$$

- r_A and r_B are *ephemeral secrets*
- x_A and x_B are *long-term secrets*
- $y_A = g^{x_A}$ and $y_B = g^{x_B}$ are *public keys*
- K_M is MAC key derived from static Diffie–Hellman $g^{x_A x_B}$

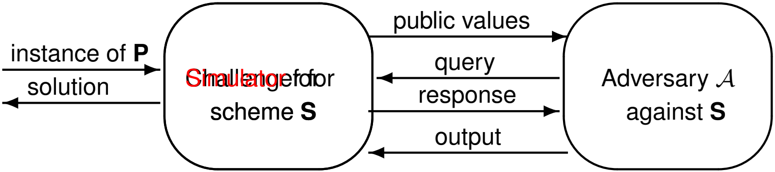
Need for formal modelling

- History of failed protocol designs in 1980s and 1990s
- What is a valid attack?
- Obtain proofs of security
- Analysis of real world protocols

Security games

- Adversary is an efficient probabilistic algorithm
- Challenger presents to the adversary $\mathcal{A}$ any elements required by the model.
- Adversary's queries must be answered by the challenger as if the adversary is interacting with the protocol
- The game ends when the adversary halts its computations and gives its output
- A winning condition at the end of the game decides whether or not the adversary has won the game
- Security is defined based on the success of the adversary in the security game

Security game for scheme S



- A successful adversary $\mathcal{A}$ against scheme **S** can be used to construct a solution to an instance of problem **P**
- We *reduce* the security of scheme **S** to the difficulty of problem **P**

Main elements in reductionist security analysis

- The security definition, including the specification of the challenger and a winning condition
- the specification of the protocol to be analysed
- a theorem and its proof bounding the probability that an adversary can win the security game in terms of some computational assumptions

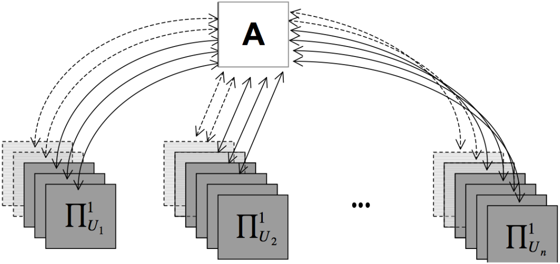
Game hopping

- A proof technique suitable for reductionist security proofs
- Security game *evolves* by changing rules for challenger
- Start with normal security game
- Each hop defines new game with quantifiable difference in adversary advantage
- End with game where adversary has zero advantage
- Typical game hops are:
  - changing distributions which the adversary cannot distinguish
  - aborting game if a certain event occurs

Bellare and Rogaway's security model

- First computational model, ACM CCS 1993
- Adversary controls the security game by querying a set of *sessions* at a party
- A session Π_U^s represents the actions of party U in the protocol run indexed by integer s
- Long-term keys are initialised using a key generation algorithm

— The adversary A is computationally bounded to probabilistic polynomial time



Adversarial queries in BR model

Query	Inputs	Outputs
send	session + input message	output message
reveal	session	accepted session key
corrupt	party	long-term key
test	fresh session	session key / random

— To win the security game the adversary must correctly decide the bit used in the answer to the test query

Freshness

— The test query may only be used for a *fresh* session

— An session is said to be *fresh* when:

- it has accepted a session key, and
- neither itself nor its *partner* have had a corrupt or reveal query

— The way of defining partners has varied in different models

— Original BR93 model defines partners to be sessions with *matching conversations*

BR model versions

Model	Setting	Partnering mechanism
BR93	2-party shared key	Matching conversations
BR95	Server-based	Partner function
SR96	Smart card	Partner function
BWM97	Public key	Matching conversations
BWJM97	Key agreement	Matching conversations
BPR00	Password-based	Session identifiers

Which elements are available to the adversary?

- Different models allow different combinations

Actor	owner of the test session
Peer	(intended) partner of the test session
✓	element is available (leaked or chosen)
(✓)	element may be available
$\mathcal{F}$	a (restricted) function of the element is available

- Table shows only test session
- Usually all elements are available for non-test sessions

Which elements are available to the adversary?

— BR model

	Before test session	After test session
Actor long-term		
Actor ephemeral		
Peer long-term		
Peer ephemeral	(✓)	

For some protocols (such as HMQV) an active adversary can choose ephemeral key of peer session

Modelling forward secrecy

- A protocol provides forward secrecy if adversary cannot distinguish session key from a random string even given the long-term keys after test session is complete
- Allow adversary to obtain long-term keys, *after* test session is complete
- Widely seen as desirable real-world property today
- Introduces *timing* into the model

Which elements are available to the adversary?

- BPR00 model with forward secrecy

	Before test session	After test session
Actor long-term		✓
Actor ephemeral		
Peer long-term		✓
Peer ephemeral	(✓)	

- Which protocols provide forward secrecy?

Canetti–Krawczyk (CK01) model

- Similar basic idea to Bellare–Rogaway models
- Two main motivations:
  - build secure channels for sessions
  - a modular design approach using *authenticators*
- Allows *session state* to be revealed

HMQV model

- Enhancement of CK01 model used to analyse HMQV protocol
- Session state query reveals ephemeral private key
- Key compromise impersonation (KCI) attacks are captured by allowing adversary to obtain private key of the owner of the test session

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Which elements are available to the adversary?

— HMQV model capturing KCI attack

	Before test session	After test session
Actor long-term	✓	✓
Actor ephemeral		
Peer long-term		
Peer ephemeral	(✓)	

— Which protocols provide KCI resistance?

Common elements of all models

- Adversary controls network
- Some mechanism identifies partners of sessions
- Adversary can obtain session key from sessions other than test session and its partner (if it exists)
- Adversary wins by distinguishing session key of test session from random string

The eCK model

- Proposed at Provsec 2007 by LaMacchia, Lauter and Mityagin, now widely referred to as eCK model
- Tackles directly some limitations in the CK and BR models. Specific advantages are:
  - the adversary can obtain ephemeral secrets which belong to the test session;
  - the adversary can obtain the long-term key of the test session and of its partner even before the session is completed.

Which elements are available to the adversary?

— eCK model

	Before test session	After test session
Actor long-term	✓	✓
Actor ephemeral		
Peer long-term		
Peer ephemeral	✓	✓

or

Actor long-term		
Actor ephemeral	✓	✓
Peer long-term		
Peer ephemeral	✓	✓

or . . .

Which elements are available to the adversary?

— eCK model if adversary is passive in test session

	Before test session	After test session
Actor long-term	✓	✓
Actor ephemeral		
Peer long-term	✓	✓
Peer ephemeral		

or

Actor long-term		
Actor ephemeral	✓	✓
Peer long-term	✓	✓
Peer ephemeral		

— NAXOS protocol is secure in eCK model

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Strong and weak forward secrecy

Strong forward secrecy (sFS)

— Adversary takes an active part in the session under attack

— Victim executes session with the adversary

Weak forward secrecy (wFS)

— Adversary is prevented from taking an active part in the session under attack

— Victim executes the session with a legitimate party

— eCK model *cannot* capture strong forward secrecy since it does not consider timing

Which elements are available to the adversary?

— eCK-PFS (Cremers–Feltz, 2012)

	Before test session	After test session
Actor long-term	✓	✓
Actor ephemeral		
Peer long-term		✓
Peer ephemeral	✓	✓

or,

	Before test session	After test session
Actor long-term	✓	✓
Actor ephemeral		
Peer long-term	✓	✓
Peer ephemeral		

or . . .

Leakage resilient key exchange

- Aims to capture side channel attacks
- Adversary gets access to a chosen function of the long-term secret with some restrictions
  - Leakage can be continuous or bounded
  - Leakage can be restricted to before the test session occurs
- First results by Moriyama and Okamoto, 2011 – assume *before-the-fact* leakage
- ASB 2015 achieve *continuous, after the fact leakage* (CAFL) security in an eCK type model

Which elements are available to the adversary?

— Leakage resilient model (CAFL-eCK)

	Before test session	After test session
Actor long-term	✓	✓
Actor ephemeral		
Peer long-term	$\mathcal{F}$	$\mathcal{F}$
Peer ephemeral	✓	✓

or

Actor long-term	$\mathcal{F}$	$\mathcal{F}$
Actor ephemeral	✓	✓
Peer long-term	✓	✓
Peer ephemeral		

or . . .

— $\mathcal{F}$ is restricted function of long-term secret

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Post-compromise security

- Analysed by Cohn-Gordon, Cremers and Garratt, IEEE Security and Privacy 2016
- Adversary can obtain (partial) information about long-term key *before* test session
- Models temporary loss of long-term secrets

Which elements are available to the adversary?

- Post-compromise security - weak compromise

	Before test session	After test session
Actor long-term	✓	✓
Actor ephemeral		
Peer long-term	$\mathcal{F}$	
Peer ephemeral	✓	✓

- $\mathcal{F}$ is interface to long-term secret, for example *HSM*
- $\mathcal{F}$ queries can be added to adversary queries for test session before completed
- Seems similar to CAFL-eCK but restrictions on $\mathcal{F}$ are different

Which elements are available to the adversary?

— Post-compromise security - full compromise

	Before test session	After test session
Actor long-term	✓	✓
Actor ephemeral		
Peer long-term	✓ then ✘	✓
Peer ephemeral		

— Can only be satisfied using *stateful* protocols

— Long-term keys evolve over time (ratcheting)

Which elements are available to the adversary?

— Mass surveillance model?

	Before test session	After test session
Actor long-term		✓
Actor ephemeral		✓
Peer long-term		✓
Peer ephemeral		✓

— Adversary is passive before test session

— Adversary can learn secrets after test session

— No stateless protocol is secure in this model

Which elements are available to the adversary?

— Weaker mass surveillance model?

	Before test session	After test session
Actor long-term		
Actor ephemeral		✓
Peer long-term		
Peer ephemeral		✓

— Adversary is passive before test session

— Adversary can learn secrets after test session

— No TLS 1.2 or TLS 1.3 variant is secure in this model

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Current and future challenges

- Is indistinguishability the right definition for real-world key exchange?
- Security against ephemeral key leakage for real-world protocols
- Post-quantum security
- Taming complexity … with automation?
- Classifying and unifying models … stateful protocols, functional security, …
- More real-world protocols: DTLS, ZRTP, …
- Modelling humans
- All of the above in the group setting

Key References

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