When One Key is Not Enough

Multi-Stage Key Exchange and the Case of Google's QUIC Protocol

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published in ACM CCS 2014

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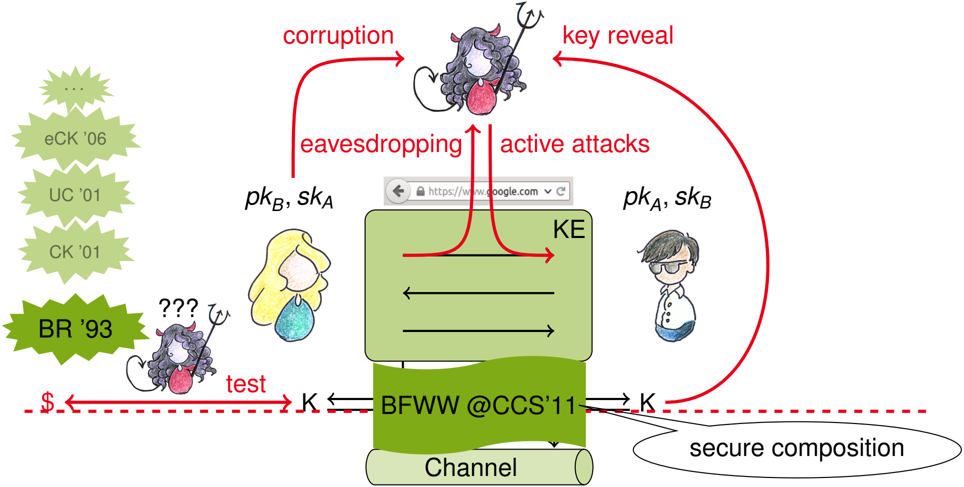
Key Exchange

so far…



corruption

key reveal

eavesdropping

active attacks

pk_B, sk_A

pk_A, sk_B

https://www.google.com

KE

…

eCK ’06

UC ’01

CK ’01

BR ’93

???

test

\$

K

BFWW @CCS’11

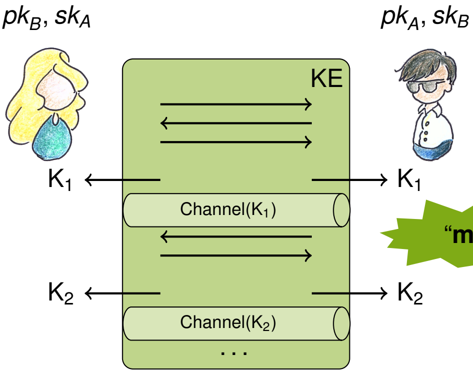
K

secure composition

Channel

drawings by *Giorgia Azzurra Marson*

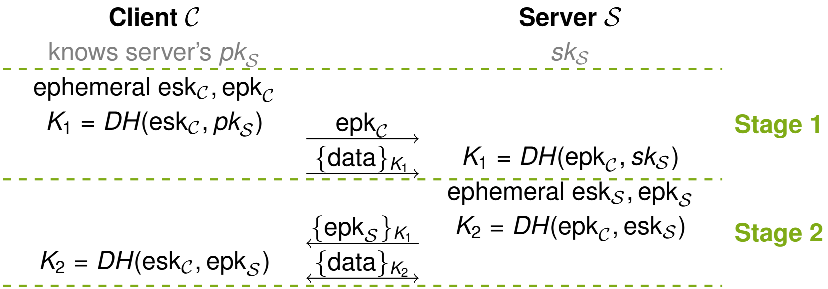
But what if. . . ?



- key exchange establishes more than one key?
- . . . even uses the intermediary keys within the key exchange or channel?
- not covered by KE models so far

Should we care?

- **QUIC** (“Quick UDP Internet Connections”, Google 2013)
  - “low-latency transport protocol with security equivalent to TLS”
  - Diffie–Hellman-based key exchange
  - aims at 0-RTT, i.e., immediately encrypts under intermediate key K_1
  - later rekeys to forward-secret K_2
  - intermediate key K_1 used to establish K_2 (i.e., in KE part)



Client $\mathcal{C}$ | **Server $\mathcal{S}$**

knows server's $pk_{\mathcal{S}}$ | $sk_{\mathcal{S}}$

ephemeral $\text{esk}_{\mathcal{C}}, \text{epk}_{\mathcal{C}}$

$K_1 = DH(\text{esk}_{\mathcal{C}}, pk_{\mathcal{S}})$ $\xrightarrow{\text{epk}_{\mathcal{C}}}$

$\xrightarrow{\{\text{data}\}_{K_1}}$ $K_1 = DH(\text{epk}_{\mathcal{C}}, sk_{\mathcal{S}})$

Stage 1

ephemeral $\text{esk}_{\mathcal{S}}, \text{epk}_{\mathcal{S}}$

$\xleftarrow{\{\text{epk}_{\mathcal{S}}\}_{K_1}}$ $K_2 = DH(\text{epk}_{\mathcal{C}}, \text{esk}_{\mathcal{S}})$

$K_2 = DH(\text{esk}_{\mathcal{C}}, \text{epk}_{\mathcal{S}})$ $\xleftrightarrow{\{\text{data}\}_{K_2}}$

Stage 2

Should we care?

- **TLS with session resumption**
  - client and server already established session and hold master key
  - client resumes session later
  - new session key is derived using (old) master key and fresh nonces

  - can also be though of as a *multi-stage* key exchange (keeps state)

  - related: TLS renegotiation considered as phases (GKS @ CCS'13)
    but renegotiation is new key exchange, not reusing the master key

Should we care?

- **TLS version 1.3**

```
ClientHello
ClientKeyShare            -------->          ServerHello
                                          ServerKeyShare
                                          {Certificate*}
                                                  {...*}
                          <--------           {Finished}
{...*}
{Finished}                -------->
[Application Data]        <------->   [Application Data]

              Figure 1.  Message flow for a full handshake
```

—IETF draft-ietf-tls-tls13-04 (work in progress)

- handshake messages are protected with intermediate keys
- application data is protected with final keys

Outline

- A **Model** for Multi-Stage Key Exchange
- What about **Composition**?
- Google's **QUIC** Protocol

Model for Multi-Stage Key Exchange

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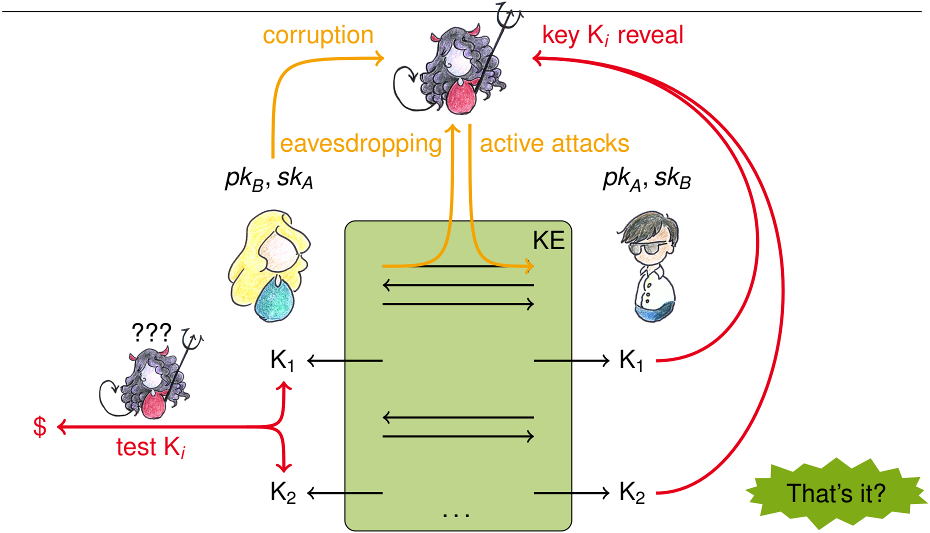
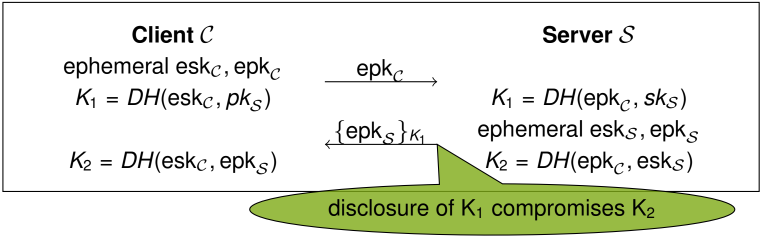


Model for Multi-Stage Key Exchange

Security aspects to consider

- **(Session-)Key Dependence**
  - multi-stage $\Rightarrow$ derived keys might build upon each other
  - we have to disallow trivial reveal queries

ex: QUIC



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$K_2 = DH(\mathsf{esk}_{\mathcal{C}}, \mathsf{epk}_{\mathcal{S}})$

$\xrightarrow{\mathsf{epk}_{\mathcal{C}}}$

$\xleftarrow{\{\mathsf{epk}_{\mathcal{S}}\}_{K_1}}$

Server $\mathcal{S}$

$K_1 = DH(\mathsf{epk}_{\mathcal{C}}, sk_{\mathcal{S}})$

ephemeral $\mathsf{esk}_{\mathcal{S}}, \mathsf{epk}_{\mathcal{S}}$

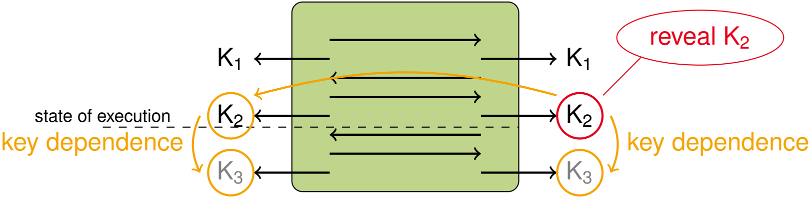
$K_2 = DH(\mathsf{epk}_{\mathcal{C}}, \mathsf{esk}_{\mathcal{S}})$

disclosure of K_1 compromises K_2

Model for Multi-Stage Key Exchange

Security aspects to consider

- **(Session-)Key Dependence**
  - multi-stage ⇒ derived keys might build upon each other
  - we have to disallow trivial reveal queries
  - **key-dependent**: disclosure of K_i before acceptance of K_{i+1} *may compromise* K_{i+1}
  - **key-independent**: disclosure of K_i before acceptance of K_{i+1} *without harm*



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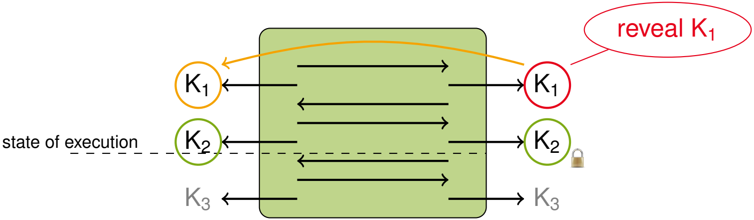

Model for Multi-Stage Key Exchange

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Wait a second. . .

- key independence says: keys can be revealed at any time
- . . . so K_i can't contribute to K_{i+1}
- doesn't this mean we run a KE from scratch for each K_i?

No. see TLS: K_{i+1} depends on master key, not K_i ⇒ (session-)key independent

Model for Multi-Stage Key Exchange

Security aspects to consider (cont'd)

- **Forward Secrecy**
  - multi-stage ⇒ forward secrecy might kick in only at some stage j
  - has to be considered in case of corruptions
  - **non-forward-secret**: all session keys compromised by corruption
  - **stage-j-forward-secret**: accepted keys at stages $i \geq j$ remain secure
    ex: QUIC aims at stage-2 forward secrecy
- **Unilateral Authentication**
  - (independent of multi-stage setting)
  - distinguish one side authenticated vs. both sides authenticated
  - **unilateral authentication**: only one side authenticated (here: responder)
  - **mutual authentication**: both sides authenticated

Model for Multi-Stage Key Exchange

Let's talk about security...
For clarity we define two notions: **Match**- and **Multi-Stage** security (as BFWW'11)

Match-Security

- ensures that session identifiers effectively match partnered sessions
  - sessions with same identifier (for some stage *i*) hold the same key (at *i*)
  - sessions are partnered with the intended (authenticated) participant
    unilateral case here: responder-only authentication
  - at most two sessions share a session identifier at any stage

Model for Multi-Stage Key Exchange

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Multi-Stage Security

- Bellare–Rogaway-like key secrecy in the multi-stage setting
- adversary has to distinguish real from random keys
- adversary must not reveal *and* test same key (in single or partnered sessions)

- **Flavors**

	key-dependent	or	key-independent
+	non-forward-secret	or	stage-j-forward-secret
+	unilateral authentication	or	mutual authentication

Model for Multi-Stage Key Exchange

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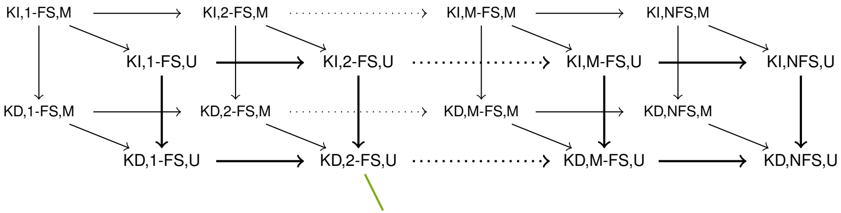
Multi-Stage Security Flavors

- key dependence, forward secrecy, unilateral authentication are **orthogonal**
- in principle one can think of any combination

- combinations form an ordered **hierarchy**



KI,1-FS,M KI,2-FS,M KI,M-FS,M KI,NFS,M

KI,1-FS,U KI,2-FS,U KI,M-FS,U KI,NFS,U

KD,1-FS,M KD,2-FS,M KD,M-FS,M KD,NFS,M

KD,1-FS,U KD,2-FS,U KD,M-FS,U KD,NFS,U

key-dependent (KD), stage-2-forward-secret (2-FS), unilateral authentication (U)

Model for Multi-Stage Key Exchange

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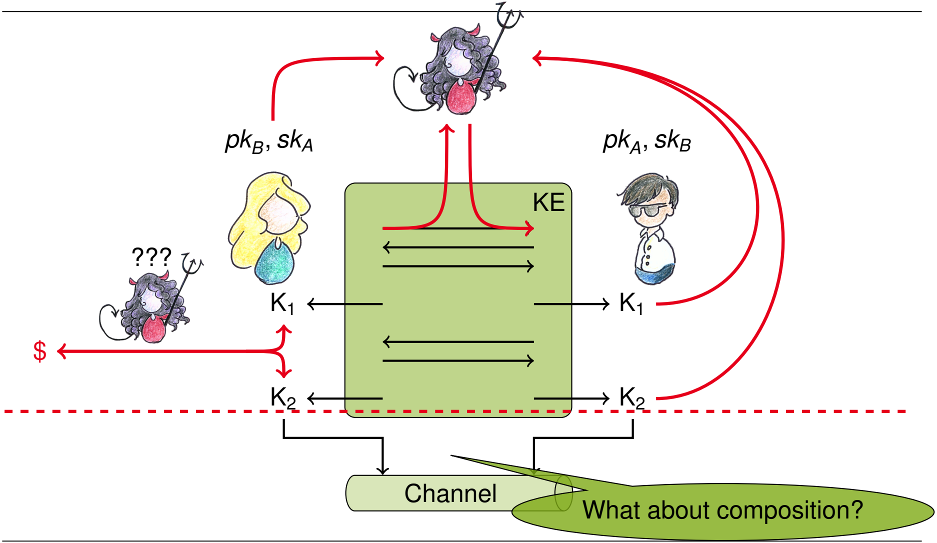


Composition

recap: BR-secure KE + symmetric-key protocol = secure composition (BFWW'11)
can we have the same for multi-stage key exchange?

Goal

- secure multi-stage key exchange KE (with some properties. . .)
- + symmetric-key protocol Π using keys of stage i
- = secure composition $\mathsf{KE}_i; \Pi$

What's a *secure* (multi-stage) composition?

- combine games G_{KE} (for KE) and G_{Π} (for Π) to composed game $G_{\mathsf{KE}_i;\Pi}$
- $G_{\mathsf{KE}_i;\Pi}$: for every $\mathsf{K}_i \leftarrow G_{\mathsf{KE}}$ at stage i, spawn Π with K_i
- adversary $\mathcal{A}$'s task: break the protocol security in subgame G_{Π}
- allow Reveal for all stages $i' \neq i$ in $G_{\mathsf{KE}_i;\Pi}$

Composition

Our Composition Result

Take

- secure multi-stage key exchange protocol
  - key-independent
  - stage-*j*-forward-secret
  - mutual authentication (extension to unilateral case possible)
  - efficient session matching (BFWW'11)
- symmetric-key protocol
  - secure w.r.t. some security notion

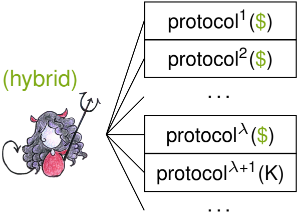
session partnering deducible from adversary communication

Then composition is secure for forward-secret stages ($i \geq j$).

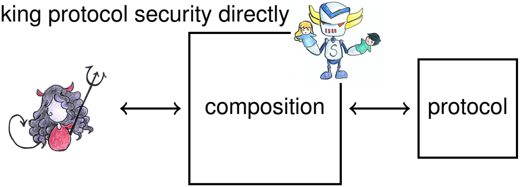
Composition

Proof idea (similar to BR-secure composition)

1. key replacement
   - gradually replace session keys K_i by random values (hybrid)
   - $\mathcal{A}$ distinguishes ⇒ we break Multi-Stage security



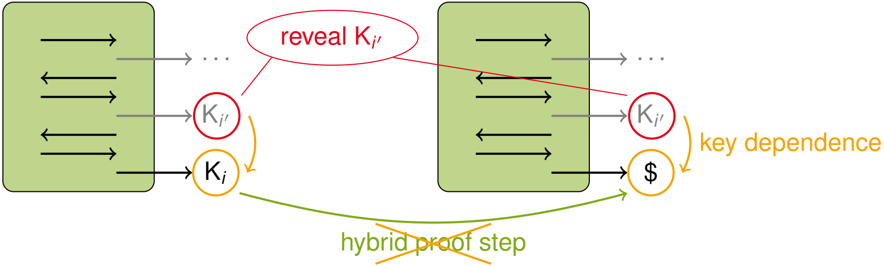
2. reduction to protocol security
   - all keys random ⇒ independent of KE
   - breaking is equivalent to breaking protocol security directly



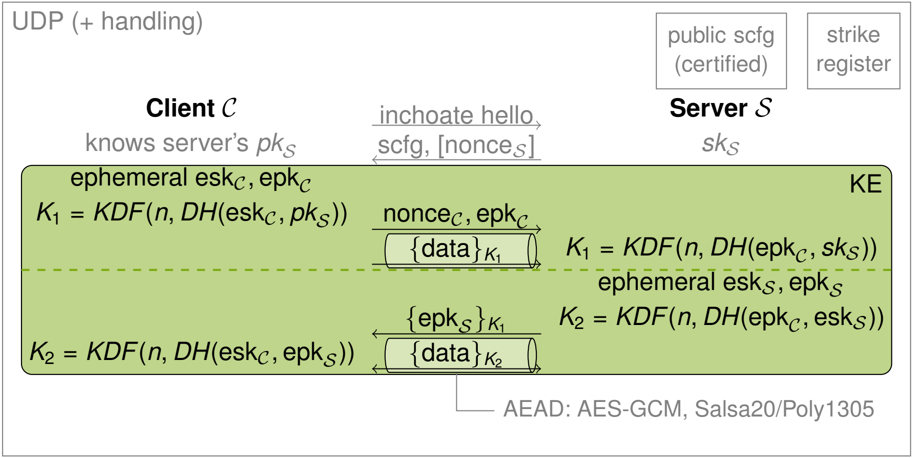
Composition

Proof ingredient example: key independence

- guarantees that compromising (reveal) $\mathsf{K}_{i'}$ ($i' < i$) doesn't affect stage-i keys
- otherwise replacing K_i with random key can be inconsistent



Google's Quick UDP Internet Connections



UDP (+ handling)

public scfg (certified)

strike register

Client $\mathcal{C}$

knows server's $pk_{\mathcal{S}}$

$\xrightarrow{\text{inchoate hello}}$

$\xleftarrow{\text{scfg, [nonce}_{\mathcal{S}}\text{]}}$

Server $\mathcal{S}$

$sk_{\mathcal{S}}$

KE

ephemeral $\text{esk}_{\mathcal{C}}, \text{epk}_{\mathcal{C}}$

$K_1 = KDF(n, DH(\text{esk}_{\mathcal{C}}, pk_{\mathcal{S}}))$

$\xrightarrow{\text{nonce}_{\mathcal{C}}, \text{epk}_{\mathcal{C}}}$

$\{\text{data}\}_{K_1}$

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$K_2 = KDF(n, DH(\text{epk}_{\mathcal{C}}, \text{esk}_{\mathcal{S}}))$

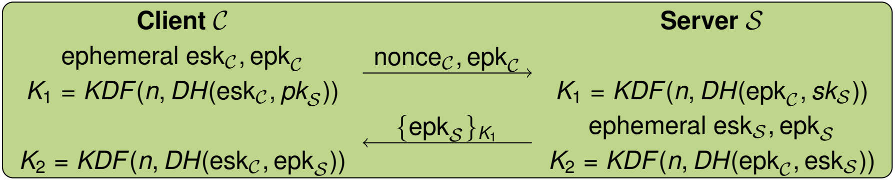
$\xleftarrow{\{\text{epk}_{\mathcal{S}}\}_{K_1}}$

$K_2 = KDF(n, DH(\text{esk}_{\mathcal{C}}, \text{epk}_{\mathcal{S}}))$

$\{\text{data}\}_{K_2}$

AEAD: AES-GCM, Salsa20/Poly1305

Google's QUIC



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Our (Multi-Stage) Security Result for QUIC's 0-RTT Key Exchange

- key-dependent
- stage-2-forward-secret
- (responder-authenticated) unilateral

assuming

- Gap-Diffie-Hellman is hard
- authenticated channel for 2nd message $\{\text{epk}_{\mathcal{S}}\}_{K_1}$
- (HMAC-based) key derivation function: extraction, expansion = random oracles

Google's QUIC

What about Composition?

- requirements:
  - key independence
  - stage-*j* forward secrecy
  - mutual authentication

What about Composition?

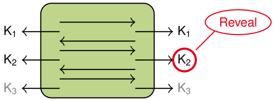
- what QUIC achieves:
  - key independence ✗
  - stage-2 forward secrecy ✓
  - unilateral authentication (✓)
- i.e., QUIC's key exchange as is doesn't allow to apply our composition result
- **but** QUIC can be easily turned into a key-independent variant **QUIC*i***:
  - TLS-like idea: keep some (master) secret not exposed in session keys
  - let an additional secret value from KDF in stage 1 enter KDF in stage 2
- QUIC*i* + composition result ⇒ (forward-)secret channels from stage 2

Summary

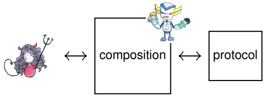
So far, KE models could not capture protocols that establish more than one key.

We

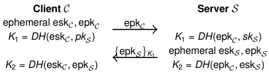
- propose a model for multi-stage key exchange



- give composition results under certain conditions (session-key independence matters!)



- show that QUIC's key exchange is multi-stage secure (key-dependent, stage-2-forward-secret, unilateral) for our composition technique: add key independence



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Thank You!