CSE 3400 - Introduction to Computer & Network Security (aka: Introduction to Cybersecurity)

Lecture 9
Shared Key Protocols – Part II

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From Textbook Slides by Prof. Amir Herzberg

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Outline

- ❑ Handshake protocol extensions.
- ❑ Key distribution centers.
- ❑ Improving resilience to key exposure.

Handshake Protocols Extensions

Authenticated Request-Response Protocols

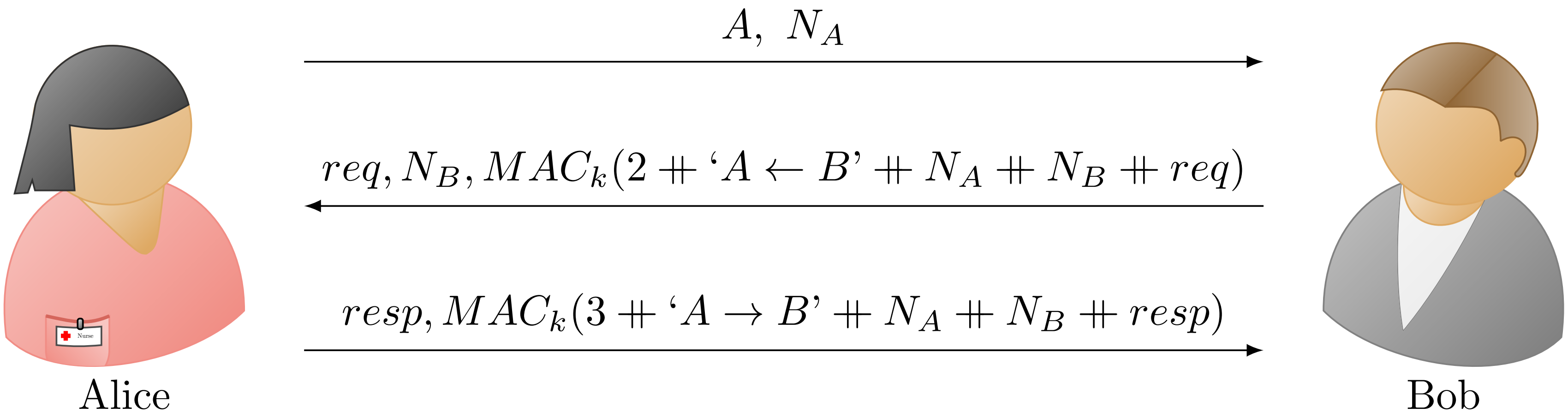
- Beside authenticating entities, these protocols authenticate the exchange of a request and a response between the entities.
- Required properties:
  - **Request authentication.**
    - The request was indeed sent by the peer.
  - **Response authentication**
    - The response was indeed sent by the peer.
  - **No replay.**
    - Every request/response was received at most the number of times it was sent by the peer.

Authenticated Request-Response Protocols

- Five variants:
  - 2PP-RR
  - 2RT-2PP
  - Counter-based-RR
  - Time-based-RR.
  - Key-exchange.

2PP-RR

- A three-flow nonce-based protocol.
- Significant drawback:
  - The request is sent by the responder and the initiator sends the response.
  - So initiator must wait for a request rather than sending it!!



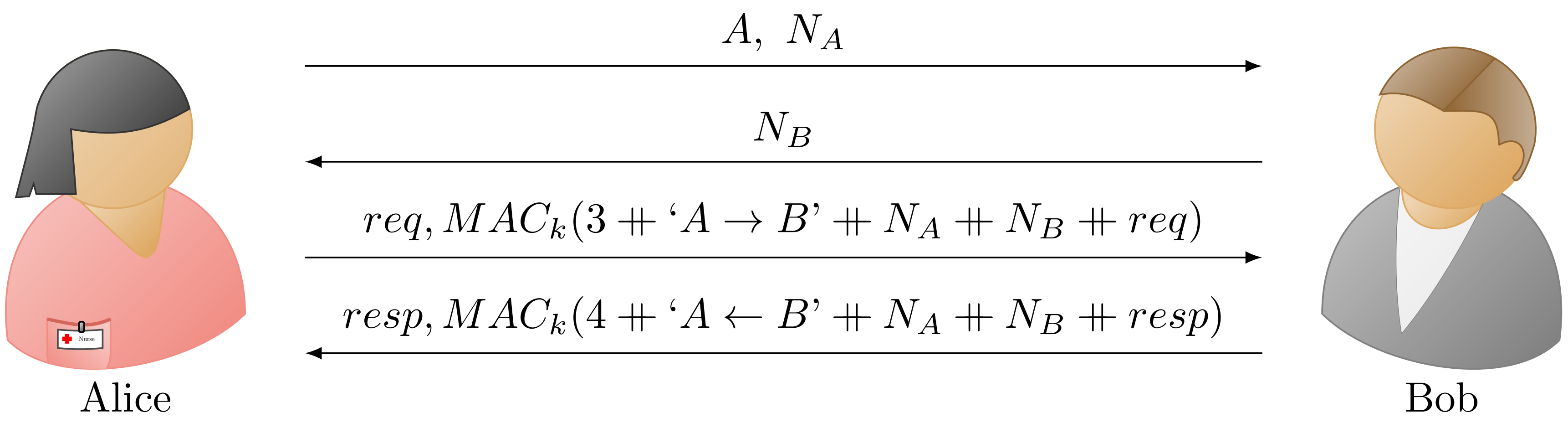
$A,\ N_A$

$req, N_B, MAC_k(2 \mathbin{+\!\!+} \text{`}A \leftarrow B\text{'} \mathbin{+\!\!+} N_A \mathbin{+\!\!+} N_B \mathbin{+\!\!+} req)$

$resp, MAC_k(3 \mathbin{+\!\!+} \text{`}A \rightarrow B\text{'} \mathbin{+\!\!+} N_A \mathbin{+\!\!+} N_B \mathbin{+\!\!+} resp)$

2RT-2PP

- A four-flow nonce-based protocol.
- Mainly fixes the drawback of 2PP-RR (see previous slide).



$A,\ N_A$

N_B

$req, MAC_k(3 \mathbin{+\!\!+} \text{‘}A \rightarrow B\text{’} \mathbin{+\!\!+} N_A \mathbin{+\!\!+} N_B \mathbin{+\!\!+} req)$

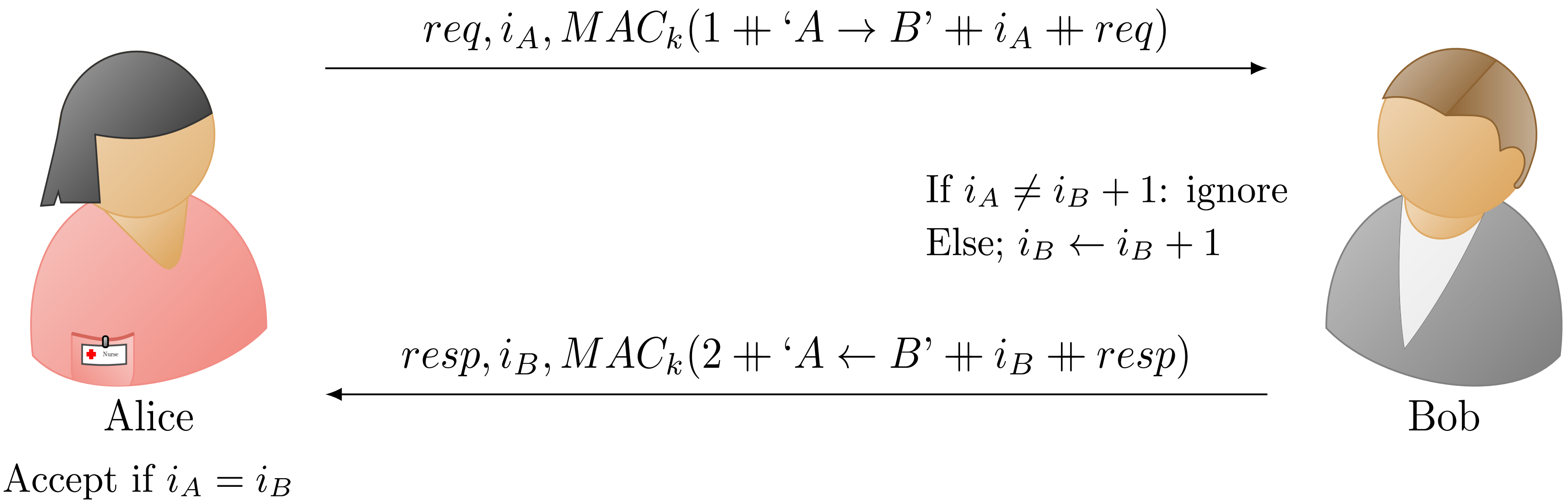
$resp, MAC_k(4 \mathbin{+\!\!+} \text{‘}A \leftarrow B\text{’} \mathbin{+\!\!+} N_A \mathbin{+\!\!+} N_B \mathbin{+\!\!+} resp)$

Alice

Bob

Counter-Based Authenticated RR

- **Simple stateful (counter) solution, requiring only one round:**
  - Unidirectional (run once for each direction if both are needed).
  - Parties maintain synchronized counter i of requests (and responses) to avoid replay attacks.
  - Recipient (e.g., Bob) validates counter received is $i + 1$
  - Both parties must remember counter



$req, i_A, MAC_k(1 \mathbin{+\!\!+} \text{‘}A \rightarrow B\text{’} \mathbin{+\!\!+} i_A \mathbin{+\!\!+} req)$

If $i_A \neq i_B + 1$: ignore
Else; $i_B \leftarrow i_B + 1$

$resp, i_B, MAC_k(2 \mathbin{+\!\!+} \text{‘}A \leftarrow B\text{’} \mathbin{+\!\!+} i_B \mathbin{+\!\!+} resp)$

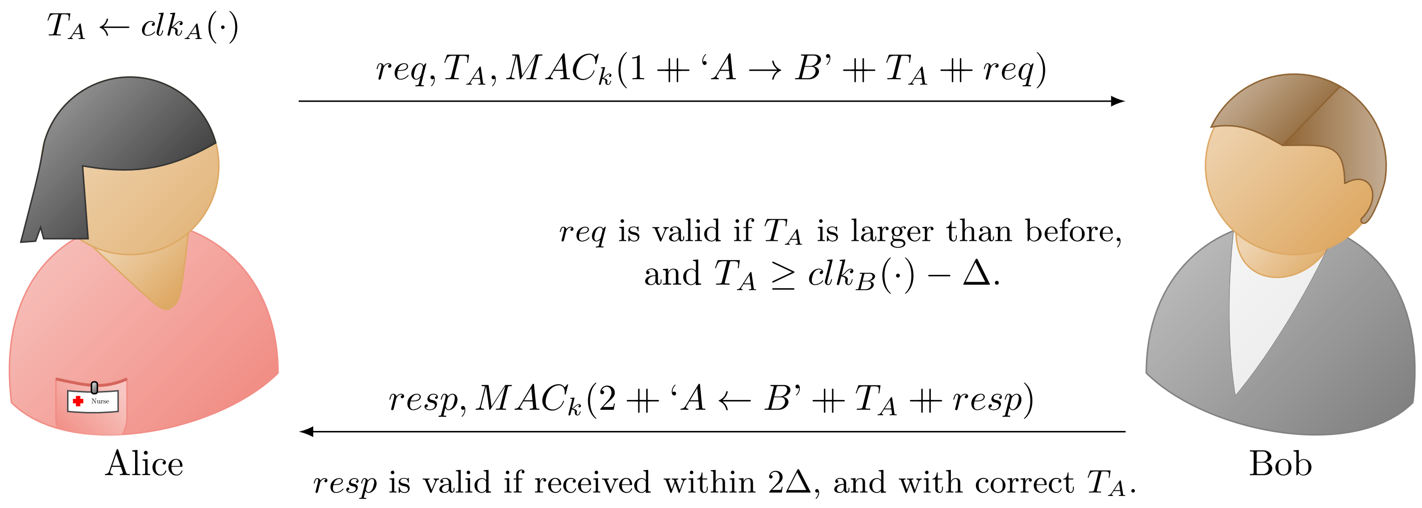
Alice

Accept if $i_A = i_B$

Bob

Time-Based Authenticated RR

- **Simple stateful (time) solution, requiring only one round:**
  - Use local clocks T_A, T_B instead of counters with two assumptions: bounded delays and bounded clock skews.
  - Responder (Bob):
    - Rejects request if: $T_B > T_A + \Delta$ where $\Delta \equiv \Delta_{skew} + \Delta_{delay}$
    - Or if he received larger T_A already
    - Maintains last T_A received, until $T_A + \Delta$
  - Initiator (Alice) does not need **any** state, when can Bob discard his?



$T_A \leftarrow clk_A(\cdot)$

$req, T_A, MAC_k(1 + + \text{`}A \rightarrow B\text{'} + + T_A + + req)$

req is valid if T_A is larger than before, and $T_A \geq clk_B(\cdot) - \Delta$.

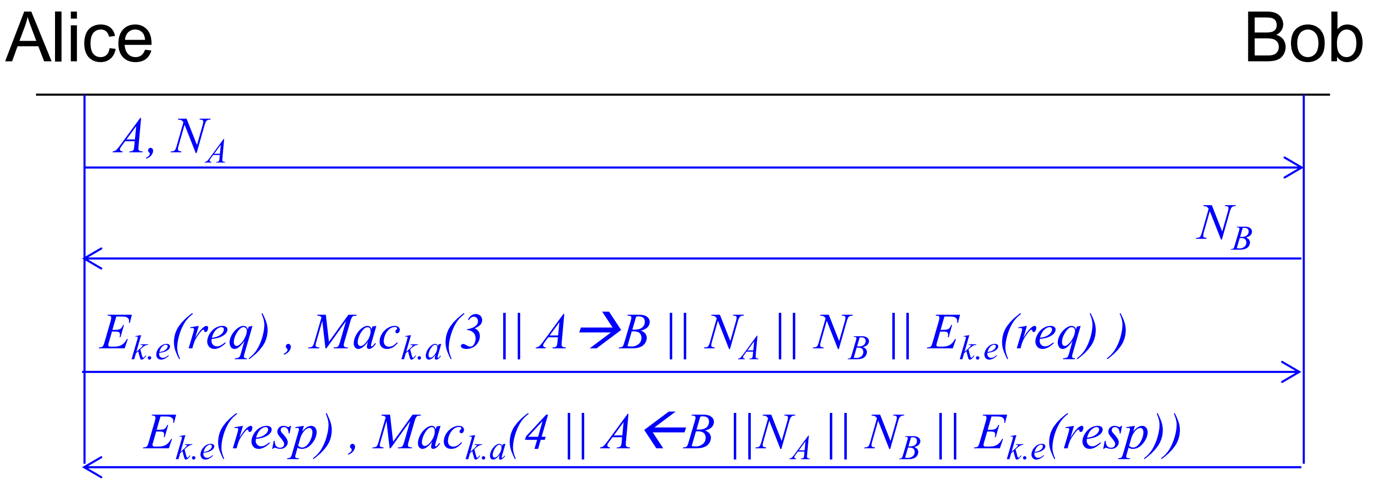
$resp, MAC_k(2 + + \text{`}A \leftarrow B\text{'} + + T_A + + resp)$

resp is valid if received within 2Δ, and with correct T_A.

Remember T_A

2RT-2PP with Confidentiality

- **Secure connection: authentication, freshness, secrecy**
  - Independent keys: for encryption $k.e$, for authentication: $k.a$
  - How can we derive them both from a single key k ?
  - $k.e = PRP_k(\text{“Encrypt”}), k.a = PRP_k(\text{“MAC”})$
  - Hmm… same key encrypts all messages, in all sessions ☹
- Can we improve security, by changing keys, e.g., btw sessions ?



Alice

Bob

A, N_A

N_B

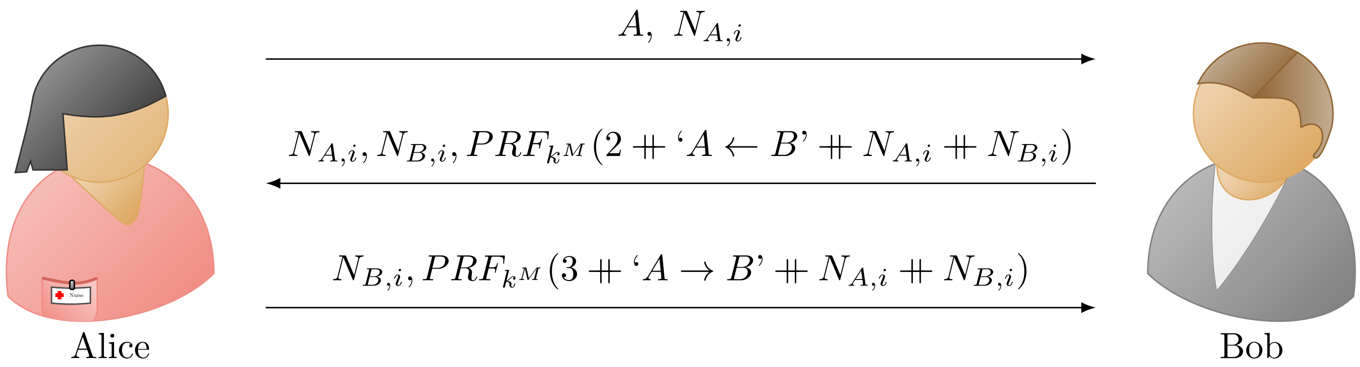
$E_{k.e}(req)\ ,\ Mac_{k.a}(3\ ||\ A \rightarrow B\ ||\ N_A\ ||\ N_B\ ||\ E_{k.e}(req)\ )$

$E_{k.e}(resp)\ ,\ Mac_{k.a}(4\ ||\ A \leftarrow B\ ||N_A\ ||\ N_B\ ||\ E_{k.e}(resp))$

2PP Key Exchange Protocol

- Independent session keys, e.g. $k{=}PRF_{MK}(N_A,N_B)$
- Or, `directly' for authentication and for encryption:
  $k.e{=}PRF_{MK}(\text{“}Encrypt\text{”}, N_A,N_B)$, $k.a{=}PRF_{MK}(\text{“}MAC\text{”}, N_A,N_B)$
- Improves security:
  - Exposure of session key does not expose (long-term) ‘master key’ MK
  - And does not expose keys of other sessions
  - Limited amount of ciphertext exposed with each session key k
- Later: reduce risk also from exposure of Master Key MK

Why a PRF is used instead of the MAC as before?



$A,\ N_{A,i}$

$N_{A,i}, N_{B,i}, PRF_{k^M}(2 \mathbin{+\!\!+} \text{‘}A \leftarrow B\text{’} \mathbin{+\!\!+} N_{A,i} \mathbin{+\!\!+} N_{B,i})$

$N_{B,i}, PRF_{k^M}(3 \mathbin{+\!\!+} \text{‘}A \rightarrow B\text{’} \mathbin{+\!\!+} N_{A,i} \mathbin{+\!\!+} N_{B,i})$

$k_i^S = PRF_{k^M}(N_{A,i} \mathbin{+\!\!+} N_{B,i})$ $\qquad$ $k_i^S = PRF_{k^M}(N_{A,i} \mathbin{+\!\!+} N_{B,i})$

Key Distribution Centers (KDCs)

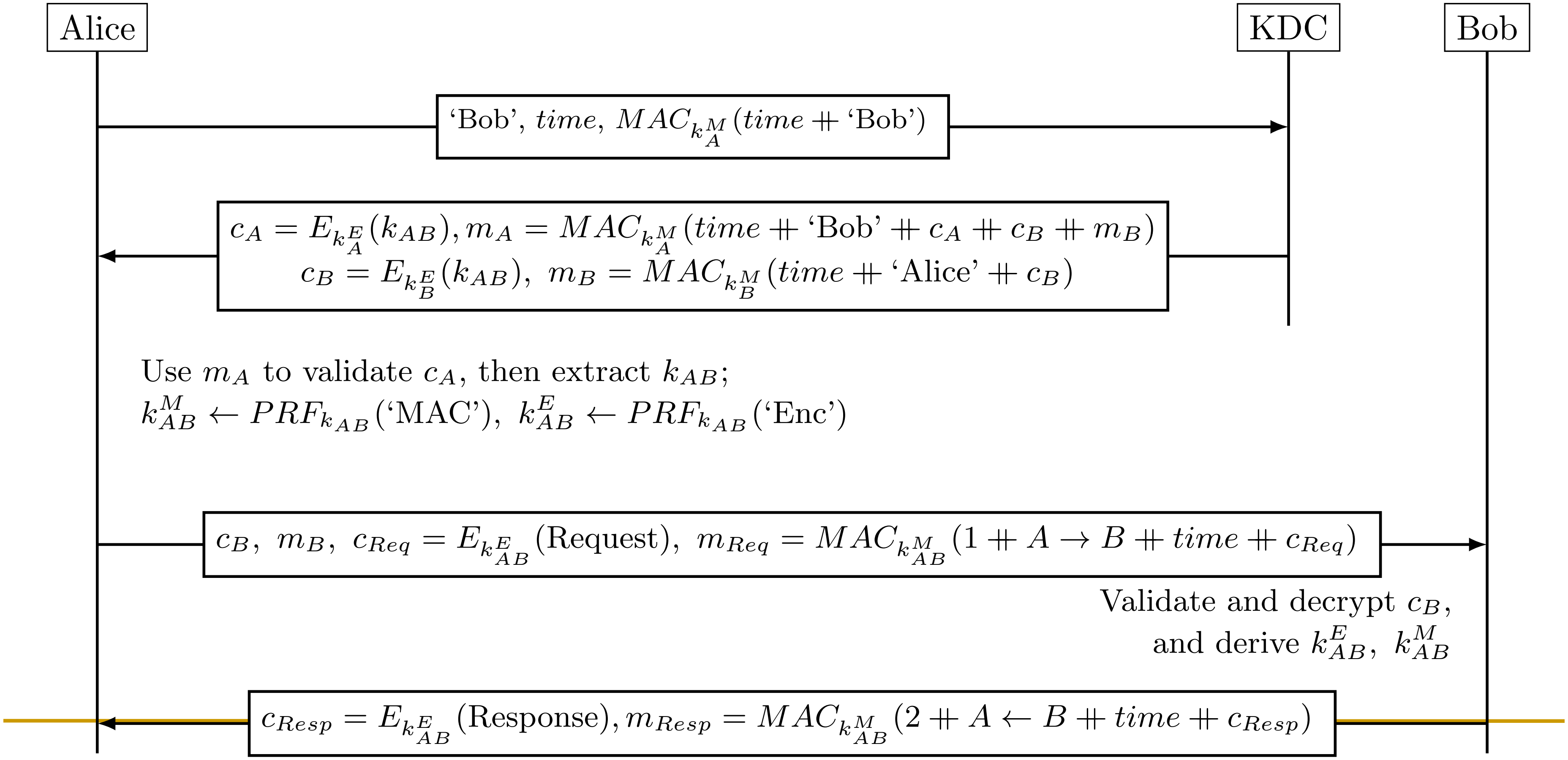
Establish a shared key between two or more entities, usually with the help of a trusted third party referred to as KDC

Key Distribution Center (KDC)

- Will focus on three party protocols; Alice, Bob, and KDC.
- KDC: shares keys with all parties (k_A, k_B…)
- Goal: help parties (A, B) establish k_{AB}
- We will study two protocols; simplified versions of:
  - The Kerberos protocol (secure) widely used in computer networks.
  - The GSM protocol (insecure) used by cellular networks.

The Kerberos KDC Protocol

- KDC shares keys k_A^E (enc.), k_A^M (MAC) with Alice and k_B^E, k_B^M with Bob
- Goal: Alice and Bob share k_{AB}, then derive: k_{AB}^E, k_{AB}^M
- KDC performs access control as well; controlling whom Alice can contact.



'Bob', $time$, $MAC_{k_A^M}(time \mathbin{+\!\!+} \text{'Bob'})$

$c_A = E_{k_A^E}(k_{AB}), m_A = MAC_{k_A^M}(time \mathbin{+\!\!+} \text{'Bob'} \mathbin{+\!\!+} c_A \mathbin{+\!\!+} c_B \mathbin{+\!\!+} m_B)$
$c_B = E_{k_B^E}(k_{AB}),\ m_B = MAC_{k_B^M}(time \mathbin{+\!\!+} \text{'Alice'} \mathbin{+\!\!+} c_B)$

Use m_A to validate c_A, then extract k_{AB};
$k_{AB}^M \leftarrow PRF_{k_{AB}}(\text{'MAC'}),\ k_{AB}^E \leftarrow PRF_{k_{AB}}(\text{'Enc'})$

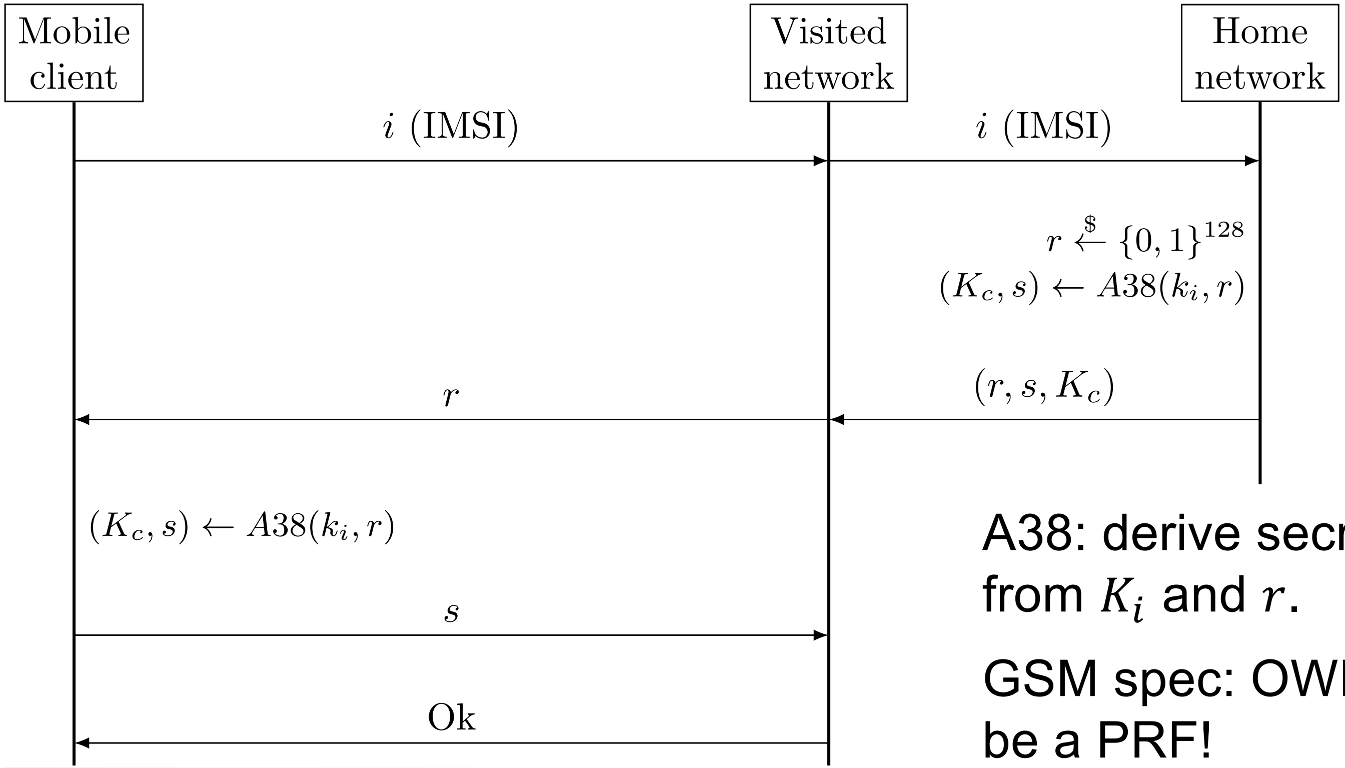
$c_B,\ m_B,\ c_{Req} = E_{k_{AB}^E}(\text{Request}),\ m_{Req} = MAC_{k_{AB}^M}(1 \mathbin{+\!\!+} A \rightarrow B \mathbin{+\!\!+} time \mathbin{+\!\!+} c_{Req})$

Validate and decrypt c_B,
and derive $k_{AB}^E,\ k_{AB}^M$

$c_{Resp} = E_{k_{AB}^E}(\text{Response}), m_{Resp} = MAC_{k_{AB}^M}(2 \mathbin{+\!\!+} A \leftarrow B \mathbin{+\!\!+} time \mathbin{+\!\!+} c_{Resp})$

The GSM Handshake Protocol

- Mobile client
  - Identified by i (IMSI: International Mobile Subscriber Identifier)
- Visited network (aka Base station); not fully trusted !
- Home network; trusted, shares key k_i with client i



Mobile client

Visited network

Home network

i (IMSI)

i (IMSI)

$r \xleftarrow{\$} \{0,1\}^{128}$

$(K_c, s) \leftarrow A38(k_i, r)$

r

(r, s, K_c)

$(K_c, s) \leftarrow A38(k_i, r)$

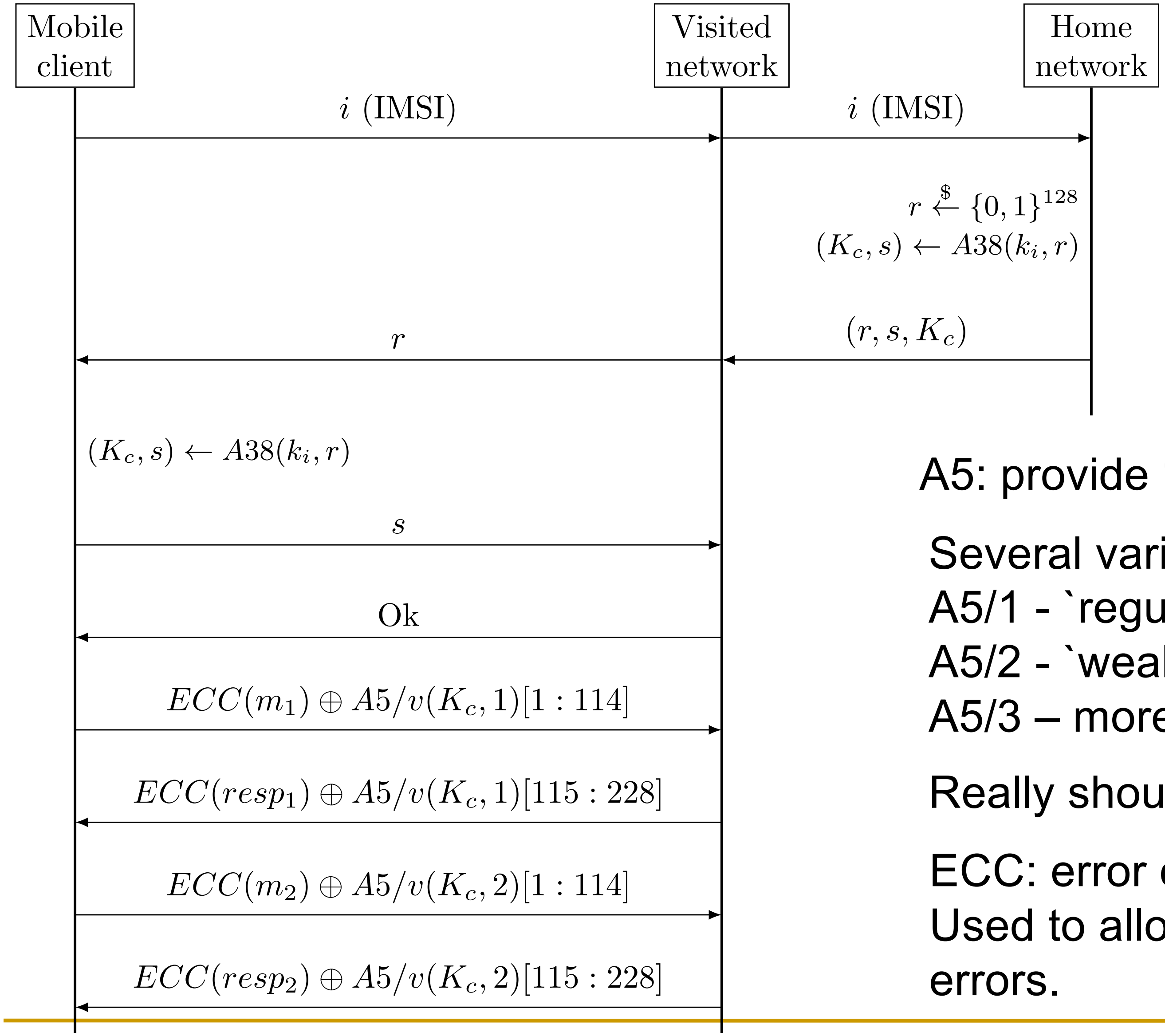
s

Ok

A38: derive secret, random K_c, s , from K_i and r.

GSM spec: OWF, but really should be a PRF!

Example – Sending two messages



Mobile client

Visited network

Home network

i (IMSI)

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$r \xleftarrow{\$} \{0,1\}^{128}$

$(K_c, s) \leftarrow A38(k_i, r)$

r

(r, s, K_c)

$(K_c, s) \leftarrow A38(k_i, r)$

s

Ok

$ECC(m_1) \oplus A5/v(K_c, 1)[1:114]$

$ECC(resp_1) \oplus A5/v(K_c, 1)[115:228]$

$ECC(m_2) \oplus A5/v(K_c, 2)[1:114]$

$ECC(resp_2) \oplus A5/v(K_c, 2)[115:228]$

Kc is the session key
s is called a secret authenticator

A5: provide ‘pad’ for encryption

Several variants:
A5/1 - `regular’
A5/2 - `weak’
A5/3 – more secure

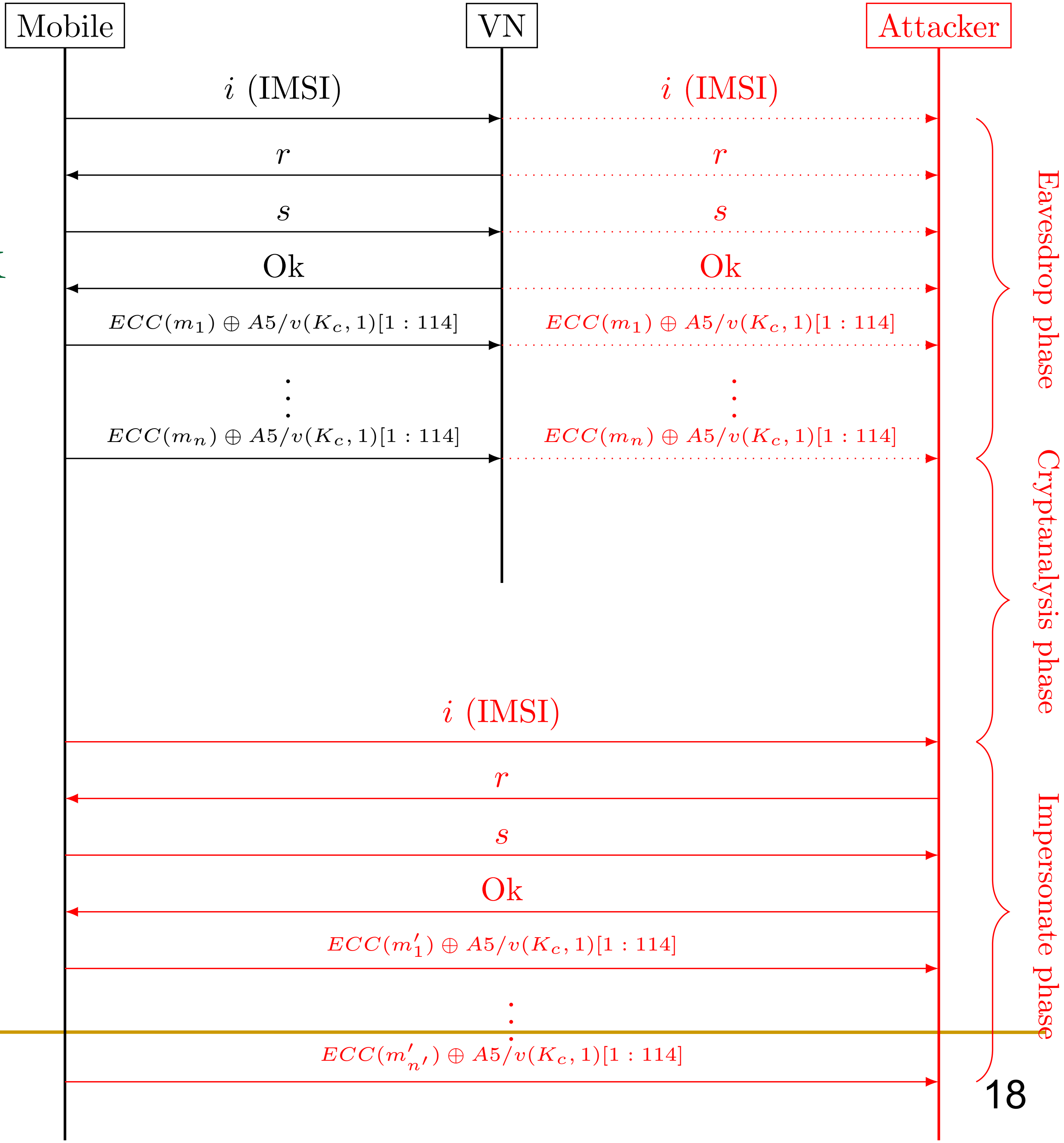
Really should be a PRF!

ECC: error correcting code. Used to allow recovery from errors.

Attacks on GSM

- We will explore two such attacks:
  - Visited network impersonation replay attack.
  - Downgrade attack.

Visited-network Impersonation Attack


Mobile
VN
Attacker
i (IMSI)
r
s
Ok
$ECC(m_1) \oplus A5/v(K_c, 1)[1:114]$
$ECC(m_n) \oplus A5/v(K_c, 1)[1:114]$
i (IMSI)
r
s
Ok
$ECC(m_1) \oplus A5/v(K_c, 1)[1:114]$
$ECC(m_n) \oplus A5/v(K_c, 1)[1:114]$
Eavesdrop phase
Cryptanalysis phase
i (IMSI)
r
s
Ok
$ECC(m'_1) \oplus A5/v(K_c, 1)[1:114]$
$ECC(m'_{n'}) \oplus A5/v(K_c, 1)[1:114]$
Impersonate phase

Note: does NOT Impersonate **mobile,** only Visited network.

In the cryptanalysis phase, the attacker will try to obtain Kc based on the cyphertexts it collected in the eavesdropping phase (recall A5/1 and A5/2 are not secure)

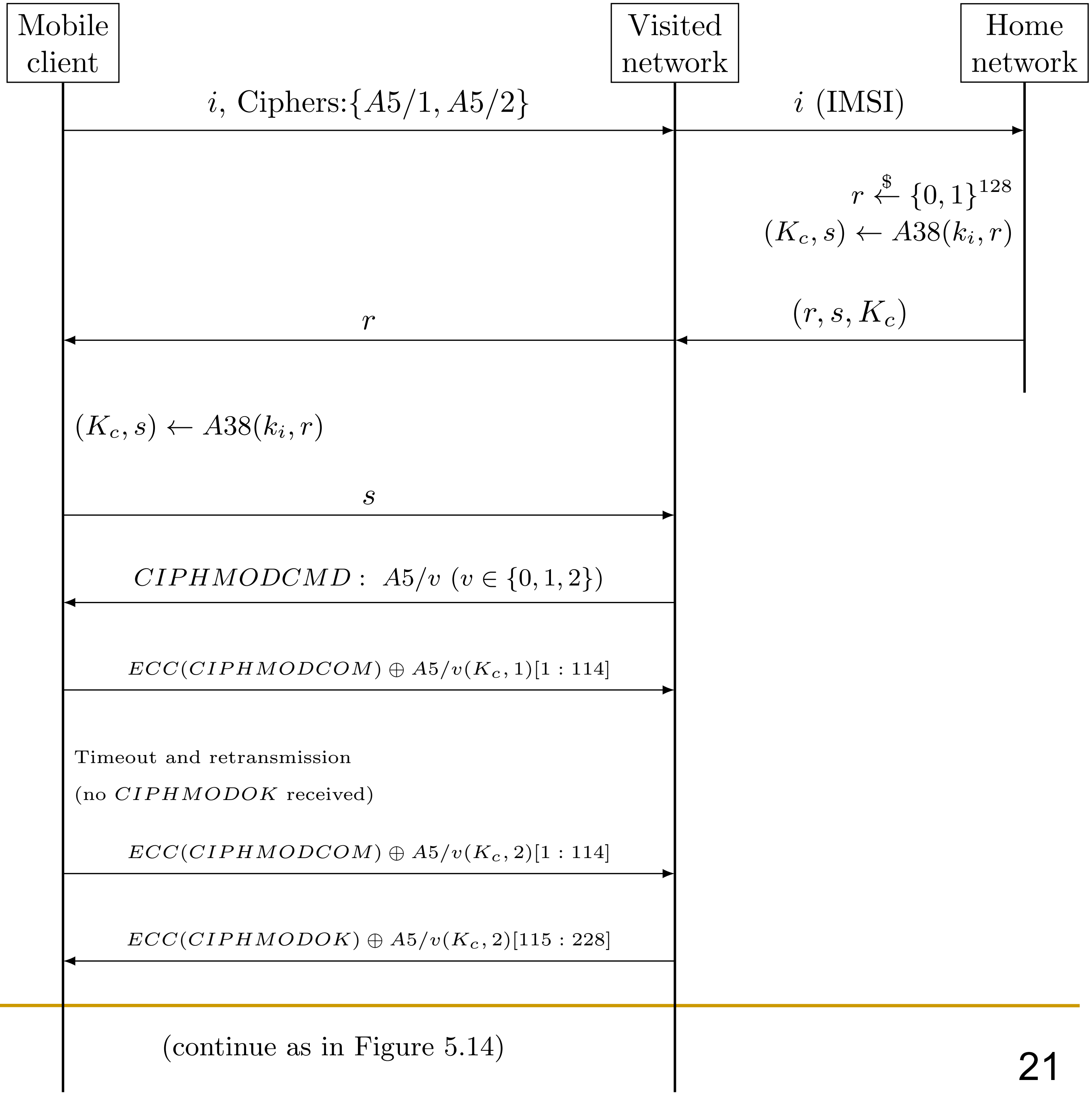
GSM Ciphersuites Downgrade Attack

- A ciphersuite is the set of cryptographic schemes used in a protocol execution.
- Ciphersuite negotiation:
  - Mobile sends list of cipher-suites it supports
  - Visited-network selects best one that it also supports
- GSM encryption algorithms E_k:
  - A5/0: none, A5/1: broken, A5/2: useless (break with only 1sec), A5/3: ‘other’
- A MitM attacker may trick these parties to use a weak suite although the parties can support a stronger one.
- Let’s first see how ciphersuite negotiation happened in GSM.

Cipher mode messages, negotiation

- Mobile sends list of supported ciphers
- VN sends choice in: CIPHMOD**CMD**
  - **Cipher Mode Command**
- Mobile confirms by sending encrypted: CIPHMOD**COM: cipher mode complete**
  - If not received (in few msecs), VN disconnects
- VN Acks: CIPHMOD**OK: cipher mode Ok**
  - If not received, mobile resends CIPHMOD**COM**

GSM Handshake, With Cipher-negotiation.

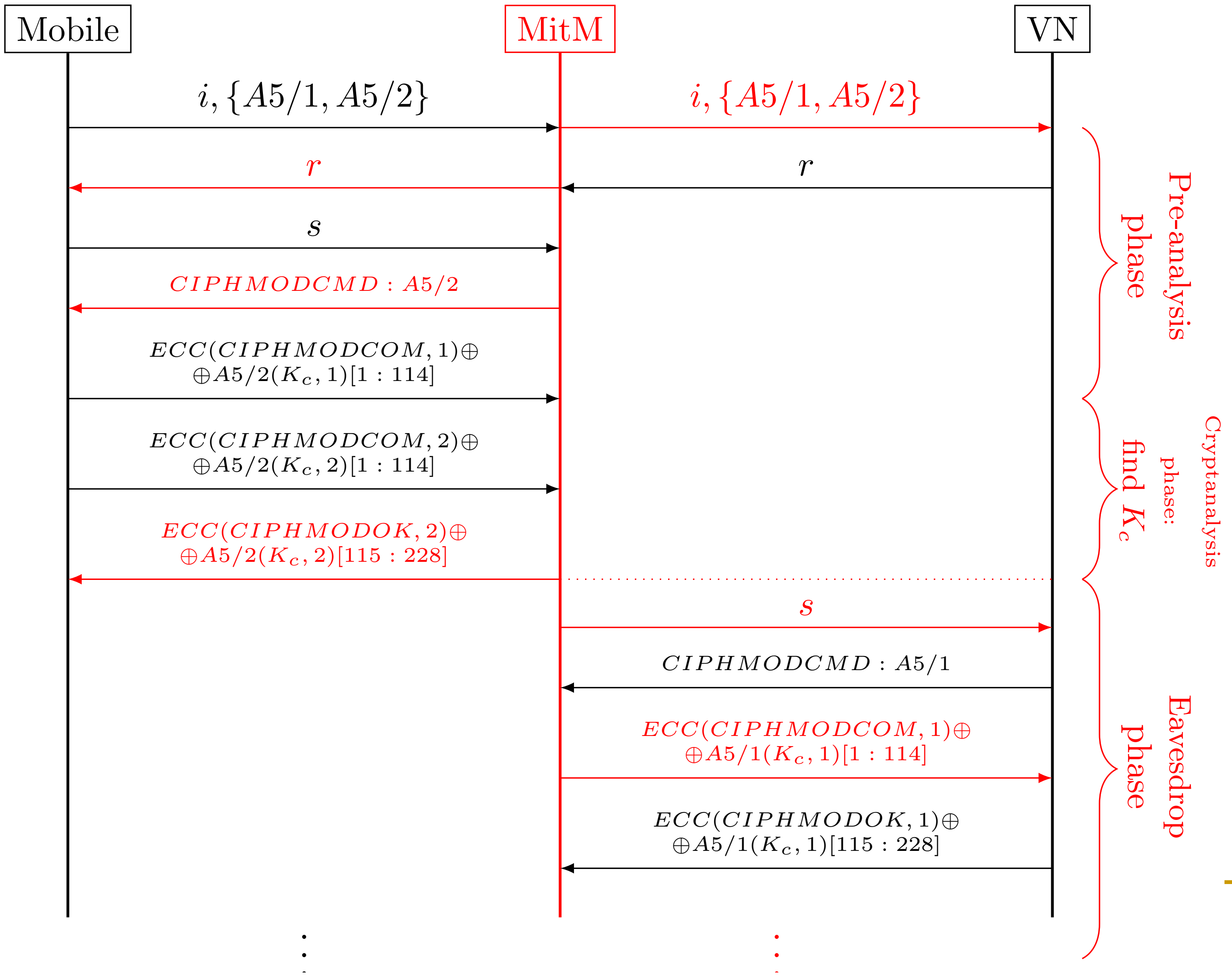

Mobile client
Visited network
Home network
i, Ciphers:$\{A5/1, A5/2\}$
i (IMSI)
$r \overset{\$}{\leftarrow} \{0,1\}^{128}$
$(K_c, s) \leftarrow A38(k_i, r)$
r
(r, s, K_c)
$(K_c, s) \leftarrow A38(k_i, r)$
s
$CIPHMODCMD: \ A5/v \ (v \in \{0,1,2\})$
$ECC(CIPHMODCOM) \oplus A5/v(K_c, 1)[1:114]$
Timeout and retransmission
(no $CIPHMODOK$ received)
$ECC(CIPHMODCOM) \oplus A5/v(K_c, 2)[1:114]$
$ECC(CIPHMODOK) \oplus A5/v(K_c, 2)[115:228]$
(continue as in Figure 5.14)

GSM ciphersuite facts: for fun and profit

- GSM uses same K_c for all ciphers
- CTO attack on A5/2 requires 900 bits, 1 sec
  - If ciphertext is after GSM's ECC, of course
  - Lots of redundancy
- Visited networks don't downgrade to A5/2
- Mobile encrypts, sends CIPHMOD**COM**
  - Resends (in few msecs) if no CIPHMOD**OK**
  - New encryption each time (counter)
  - 456bit message (after ECC)
- Allow 12s delay for the s message

Real Downgrade Attack

Works even if VN insists to use A5/1; attacker tricks client to use A5/2. That suffices, since GSM uses same key for all cryptosystems!



Mobile

MitM

VN

$i, \{A5/1, A5/2\}$

$i, \{A5/1, A5/2\}$

r

r

s

$CIPHMODCMD : A5/2$

$ECC(CIPHMODCOM, 1) \oplus$
$\oplus A5/2(K_c, 1)[1 : 114]$

$ECC(CIPHMODCOM, 2) \oplus$
$\oplus A5/2(K_c, 2)[1 : 114]$

$ECC(CIPHMODOK, 2) \oplus$
$\oplus A5/2(K_c, 2)[115 : 228]$

s

$CIPHMODCMD : A5/1$

$ECC(CIPHMODCOM, 1) \oplus$
$\oplus A5/1(K_c, 1)[1 : 114]$

$ECC(CIPHMODOK, 1) \oplus$
$\oplus A5/1(K_c, 1)[115 : 228]$

Pre-analysis phase

Cryptanalysis phase: find K_c

Eavesdrop phase

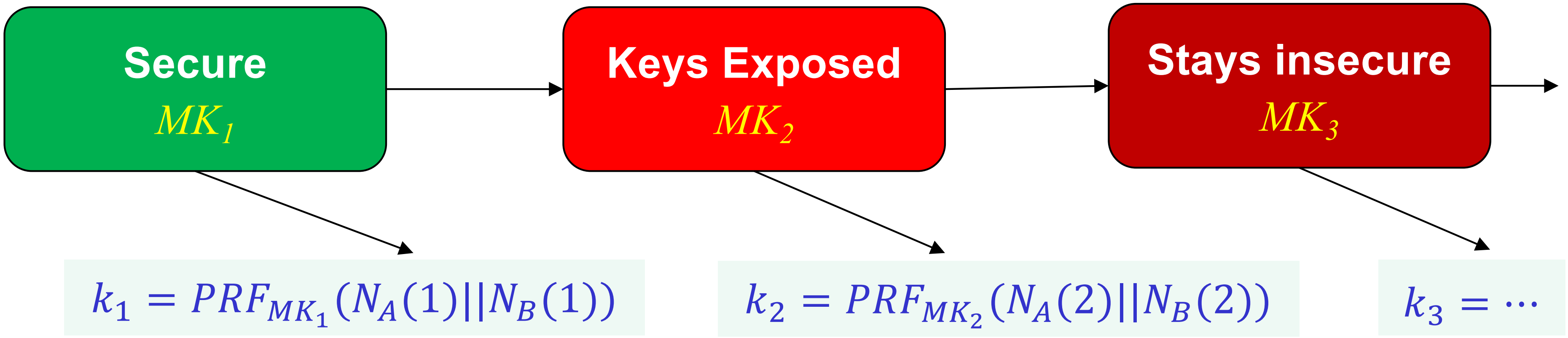
The 12 sec delay allows that!

Retransmissions of CIPHERMODCOM provides the attacker with more than 900 bits of ciphertext!

Improving Resiliency to Key Exposure

Forward Secrecy I

- **So far:** session key $k_i \not\Rightarrow k_j$ (expose no other keys)
  - And master key was fixed for all sessions
- Idea: we can do better!
  - Change the master key each session: $MK_1, MK_2, \ldots$
- Forward Secrecy (FS): master key $MK_i \not\Rightarrow k_j (j < i)$
  - I.e., MK_i (and k_i) don't expose keys, communication of previous sessions $(j < i)$



$k_1 = PRF_{MK_1}(N_A(1)||N_B(1))$

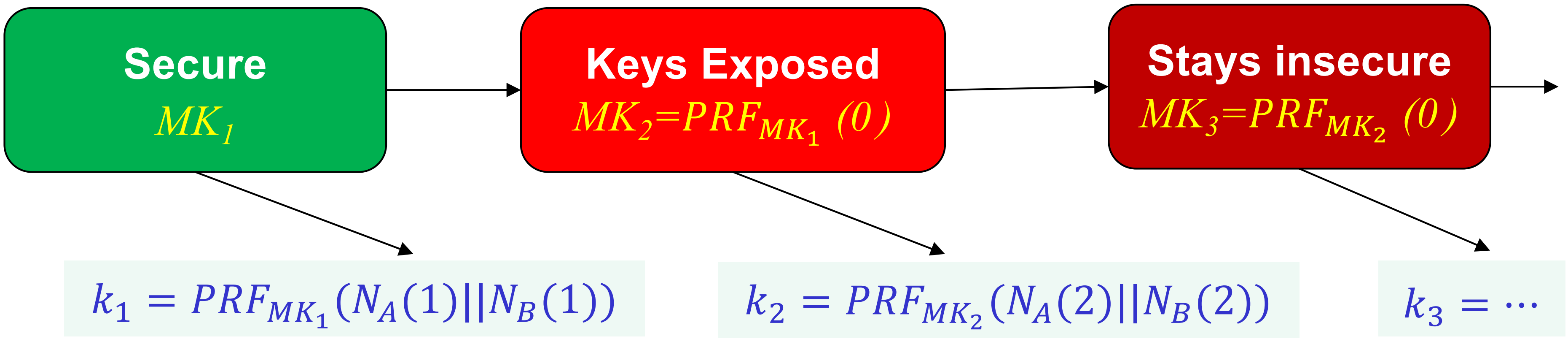
$k_2 = PRF_{MK_2}(N_A(2)||N_B(2))$

$k_3 = \cdots$

Forward Secrecy II

- Forward Secrecy (FS): master key $MK_j \nRightarrow k_i (j > i)$
  - Session i is secret even if any state of later sessions is exposed.
  - Uni-directional: $MK_i \rightarrow MK_{i+1}$, but $MK_{i+1} \not\rightarrow MK_i$
  - **How?** Solution: PRF!

$$MK_i = PRF_{MK_{i-1}}(0)$$



Secure

MK_1

Keys Exposed

$MK_2 = PRF_{MK_1}(0)$

Stays insecure

$MK_3 = PRF_{MK_2}(0)$

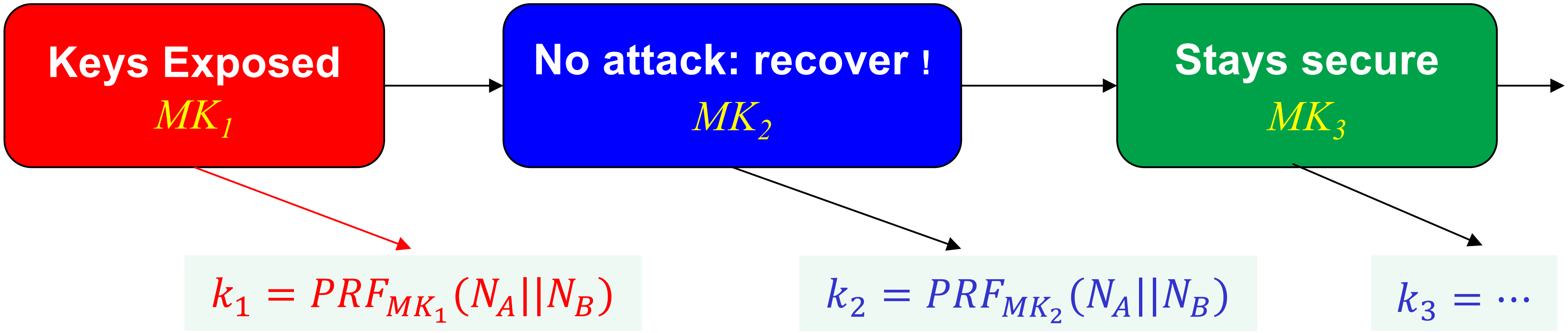
$k_1 = PRF_{MK_1}(N_A(1)||N_B(1))$

$k_2 = PRF_{MK_2}(N_A(2)||N_B(2))$

$k_3 = \cdots$

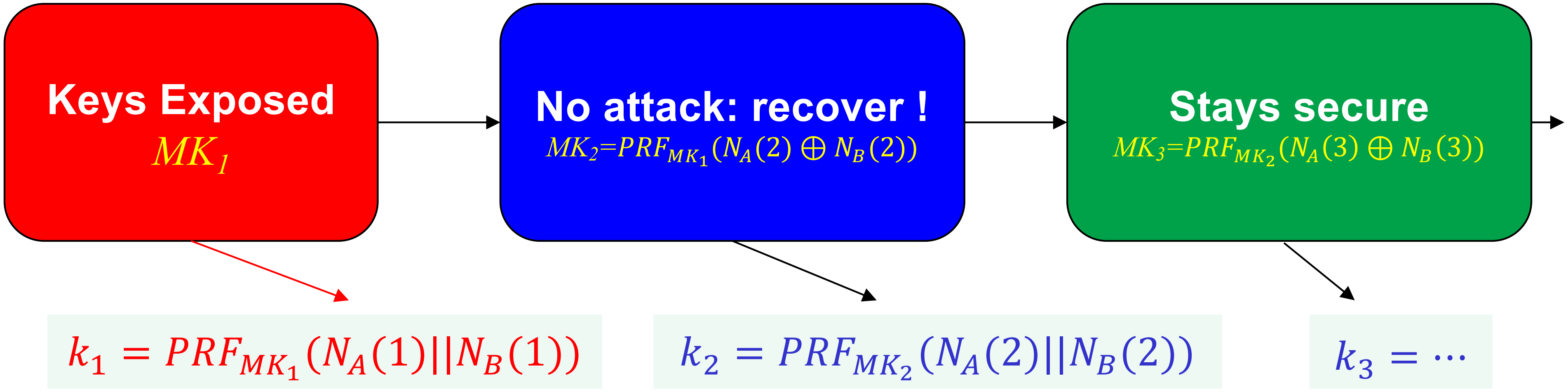
Recover Security

- Can we also **recover** security?
  - MK_{i_R-1} exposed, yet MK_{i_R}, $MK_{i_{R+1}}$ … secure ?
  - Idea: assume **no attack** during 'recovery session' i_R



Recover Security (RS)

- Recover security: key setup protocols where a single session without eavesdropping or other attacks, suffices to recover security from previous key exposures.
- That is, session i is secure if it's keys are not given to attacker, and either session $i-1$ is secure, or there is no attack during session i
- How? The RS-Ratchet Protocol:
  - Let $N_A(i), N_B(i)$ denote session's i nonces
  - Then: $MK_i = PRF_{MK_{i-1}}(N_A(i) \oplus N_B(i))$



Keys Exposed MK_1

No attack: recover ! $MK_2 = PRF_{MK_1}(N_A(2) \oplus N_B(2))$

Stays secure $MK_3 = PRF_{MK_2}(N_A(3) \oplus N_B(3))$

$k_1 = PRF_{MK_1}(N_A(1) || N_B(1))$

$k_2 = PRF_{MK_2}(N_A(2) || N_B(2))$

$k_3 = \cdots$

Covered Material From the Textbook

- Chapter 5
    - Sections 5.3 – 5.7 (except 5.7.3)

Thank You!