Cryptographic protocols

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Context

Applications exchanging sensitive data over a public network:

- eBanking,
- eCommerce,
- eVoting,
- ePassports,
- Mobile phones,
- . . .

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A malicious agent can:

- record, alter, delete, insert, redirect, reorder, and reuse past or current messages, and inject new messages
  $\longrightarrow$ the network is the attacker
- control dishonest participants

More complex systems needed...

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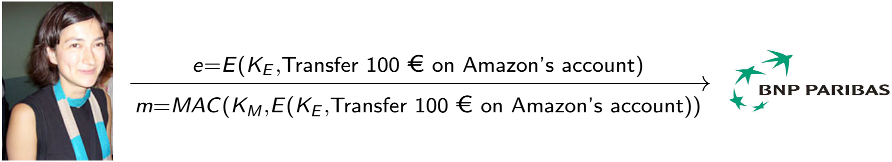
$$\xrightarrow[m=MAC(K_M,E(K_E,\text{Transfer 100 € on Amazon's account}))]{e=E(K_E,\text{Transfer 100 € on Amazon's account})}$$

BNP PARIBAS

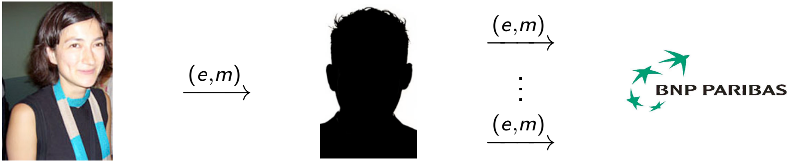
More complex systems needed...



e=$E(K_E$,Transfer 100 € on Amazon's account)

m=$MAC(K_M$,$E(K_E$,Transfer 100 € on Amazon's account))

Replay attack



(e,m)

(e,m)

$\vdots$

(e,m)

… to achieve more complex properties

- Confidentiality: Some information should never be revealed to unauthorised entities.
- Integrity: Data should not be altered in an unauthorised manner since the time it was created, transmitted or stored by an authorised source.
- Authentication: Ability to know with certainty the identity of an communicating entity.
- Anonymity: The identity of the author of an action (*e.g.* sending a message) should not be revealed.
- Unlinkability: An attacker should not be able to deduce whether different services are delivered to the same user
- Non-repudiation: The author of an action should not be able to deny having triggered this action.
- . . .

Cryptographic protocols

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Programs relying on cryptographic primitives and whose goal is the establishment of "secure" communications.

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Programs relying on cryptographic primitives and whose goal is the establishment of “secure” communications.

But!

Many exploitable errors are due not to design errors in the primitives, but to the way they are used, *i.e.* bad protocol design and buggy or not careful enough implementation

Numerous deployed protocols are flawed!!!

Needham-Schroeder protocol - G. Lowe, "An attack on the Needham-Schroeder public-key authentication protocol"

Kerberos protocol - I. Cervesato, A. D. Jaggard, A. Scedrov, J. Tsay, and C. Walstad, "Breaking and fixing public-key kerberos"

Single-Sign-On protocol - A. Armando, R. Carbone, L. Compagna, J. Cuellar, and M. L. Tobarra, "Formal analysis of SAML 2.0 web browser single sign-on: breaking the SAML-based single sign-on for google apps"

PKCS#11 API - M. Bortolozzo, M. Centenaro, R. Focardi, and G. Steel, "Attacking and fixing PKCS#11 security tokens"

BAC protocol - T. Chothia, and V. Smirnov, "A traceability attack against e-passports"

AKA protocol - M. Arapinis, L. Mancini, E. Ritter, and M. Ryan, "New privacy issues in mobile telephony: fix and verification"

...

Logical attacks

Many of these attacks do not even break the crypto primitives!!

Example of a logical attack

Assume a commutative symmetric encryption scheme

$$\{\{m\}_{k_1}\}_{k_2} = \{\{m\}_{k_2}\}_{k_1}$$

where $\{m\}_k$ denotes the encryption of message m under the key k
Example: RSA

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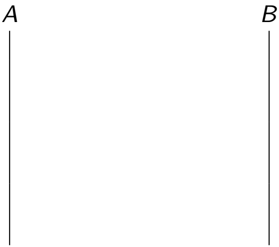

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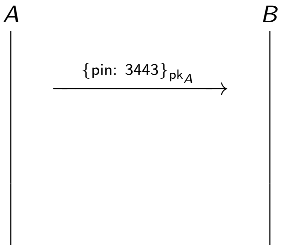

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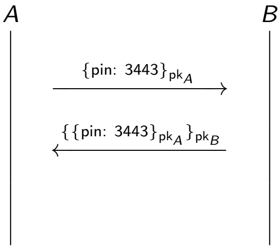

A

B

$\{\text{pin: } 3443\}_{\text{pk}_A}$

$\{\{\text{pin: } 3443\}_{\text{pk}_A}\}_{\text{pk}_B}$

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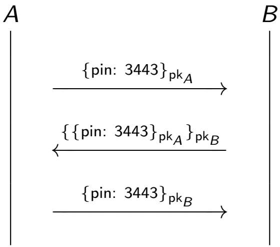

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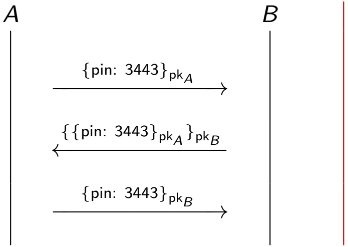

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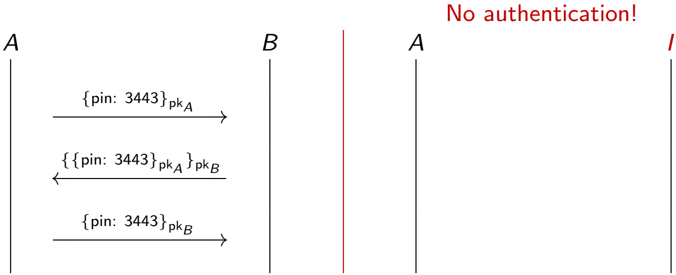
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B
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$\{\text{pin: }3443\}_{\text{pk}_B}$
A
I

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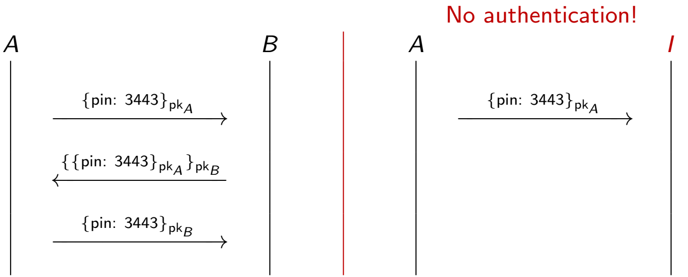

No authentication!

A B

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$\{\{\text{pin: } 3443\}_{\text{pk}_A}\}_{\text{pk}_B}$

$\{\text{pin: } 3443\}_{\text{pk}_B}$

A I

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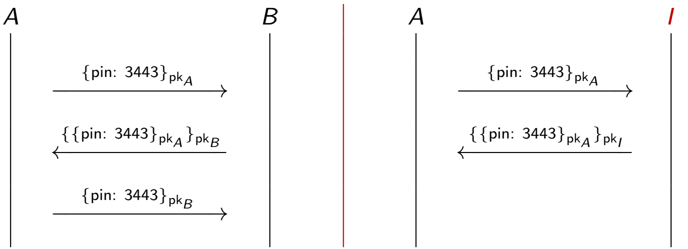

No authentication!

A B

$\{\text{pin: } 3443\}_{\text{pk}_A}$

$\{\{\text{pin: } 3443\}_{\text{pk}_A}\}_{\text{pk}_B}$

$\{\text{pin: } 3443\}_{\text{pk}_B}$

A I

$\{\text{pin: } 3443\}_{\text{pk}_A}$

$\{\{\text{pin: } 3443\}_{\text{pk}_A}\}_{\text{pk}_I}$

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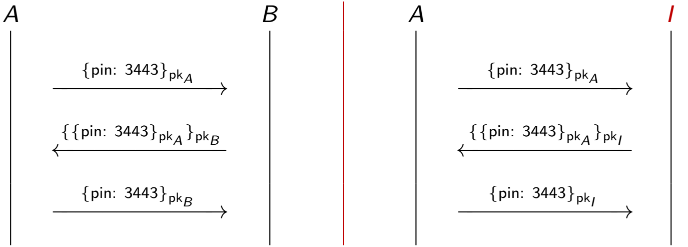

A B

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$\{\{\text{pin: } 3443\}_{\text{pk}_A}\}_{\text{pk}_B}$

$\{\text{pin: } 3443\}_{\text{pk}_B}$

A I

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Needham-Schroeder Public Key (NSPK)

NSPK: authentication and key agreement protocol

[N. Roger, M. Schroeder, Michael. “Using encryption for authentication in large networks of computers”. Communications of the ACM (December 1978)]

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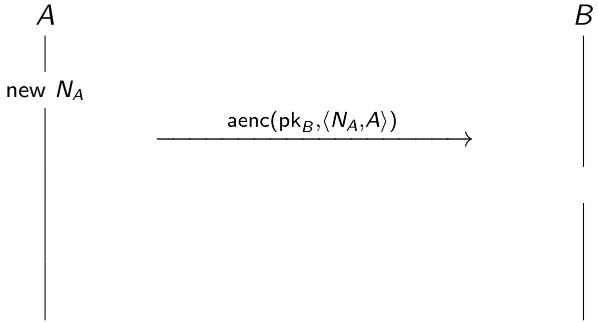

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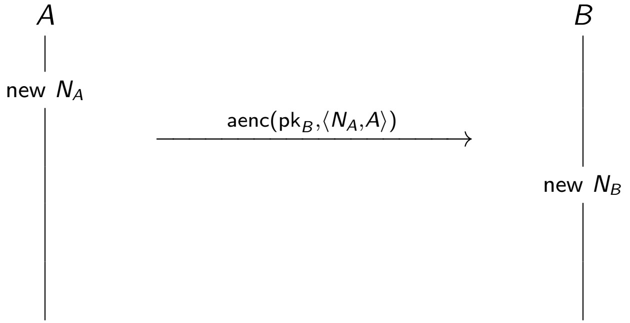

A

B

new N_A

$\mathsf{aenc}(\mathsf{pk}_B, \langle N_A, A \rangle)$

new N_B

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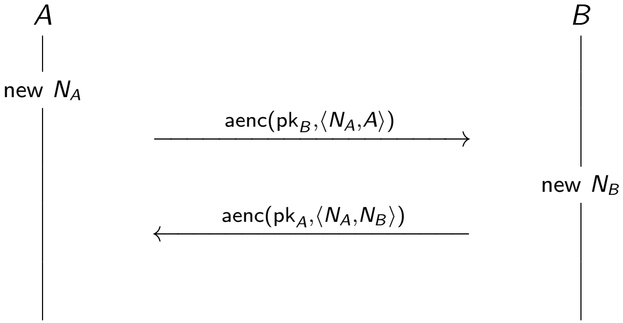

A
B
new N_A
$\mathsf{aenc}(\mathsf{pk}_B, \langle N_A, A\rangle)$
new N_B
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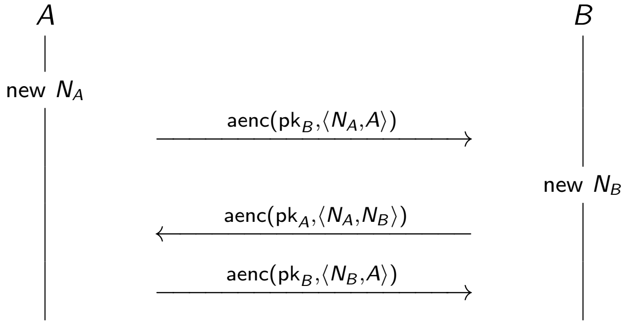
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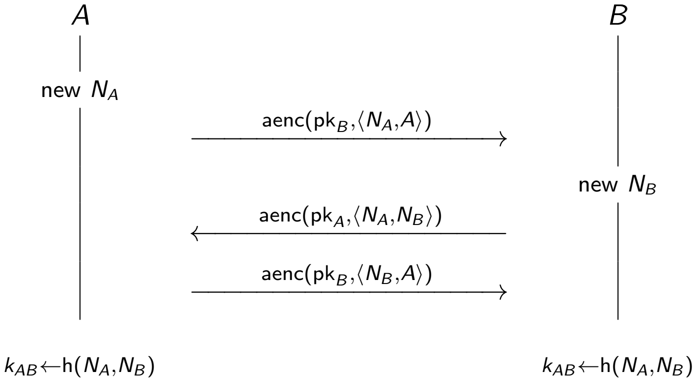

A B

new N_A

$\mathsf{aenc}(\mathsf{pk}_B, \langle N_A, A\rangle)$

new N_B

$\mathsf{aenc}(\mathsf{pk}_A, \langle N_A, N_B\rangle)$

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$k_{AB} \leftarrow \mathsf{h}(N_A, N_B)$ $k_{AB} \leftarrow \mathsf{h}(N_A, N_B)$

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NSPK: security requirements

- Authentication: if Alice has completed the protocol, apparently with Bob, then Bob must also have completed the protocol with Alice.
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- Confidentiality: Messages sent encrypted with the agreed key ($k \leftarrow \mathrm{h}(N_A, NB)$) remain secret.

NSPK: Lowe's attack on authentication

Attack found 17 years after the publication of the NS protocol!!

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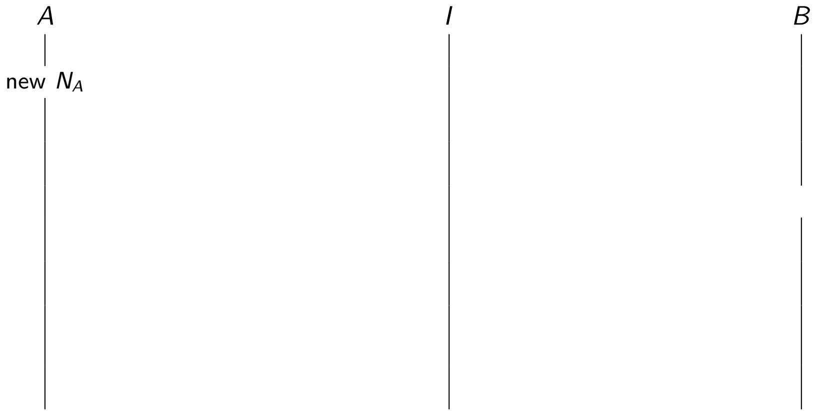

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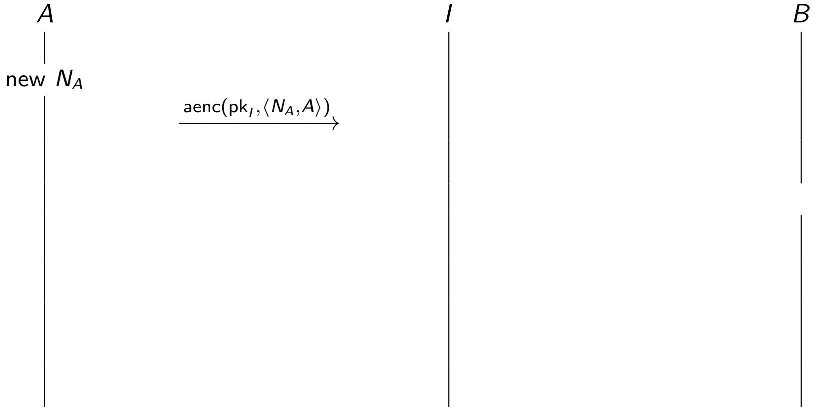

A
I
B
new N_A
$\xrightarrow{\text{aenc}(\text{pk}_I, \langle N_A, A\rangle)}$

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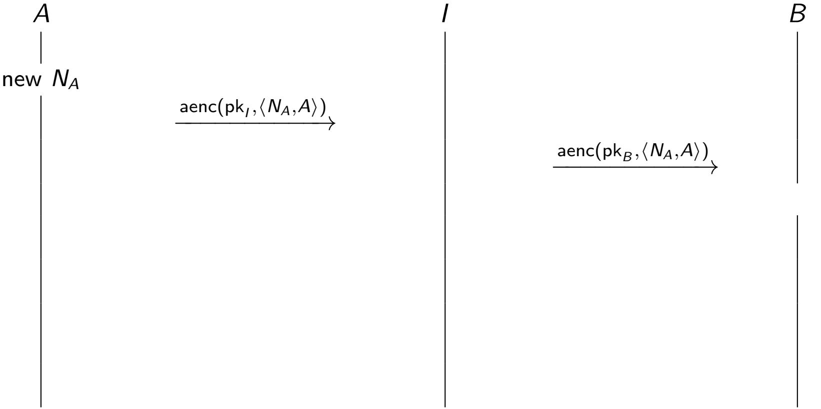
A
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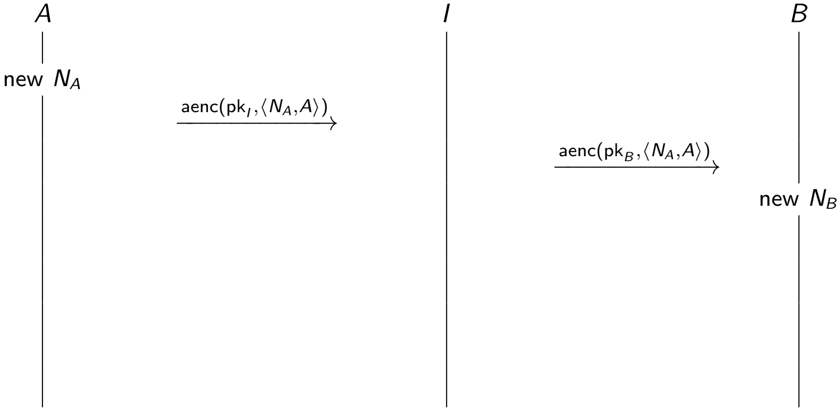

A I B

new N_A

$\mathsf{aenc}(\mathsf{pk}_I, \langle N_A, A\rangle)$

$\mathsf{aenc}(\mathsf{pk}_B, \langle N_A, A\rangle)$

new N_B

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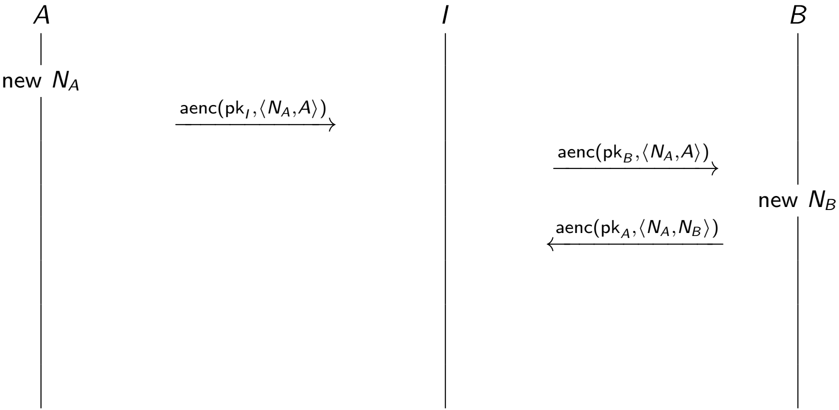

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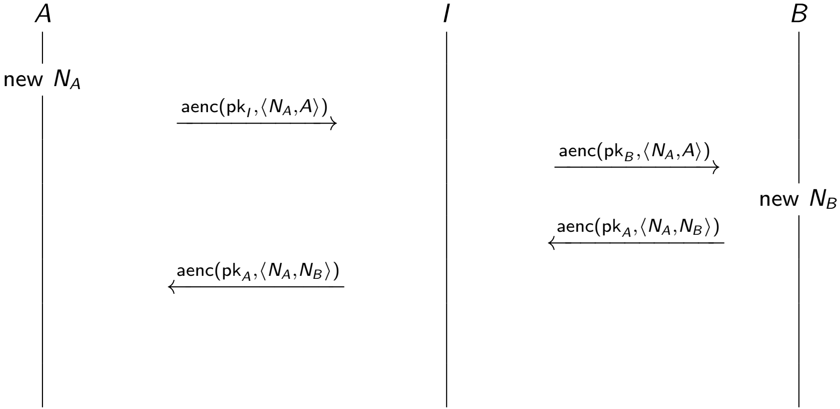
A
I
B
new N_A
$\mathrm{aenc}(\mathrm{pk}_I, \langle N_A, A \rangle)$
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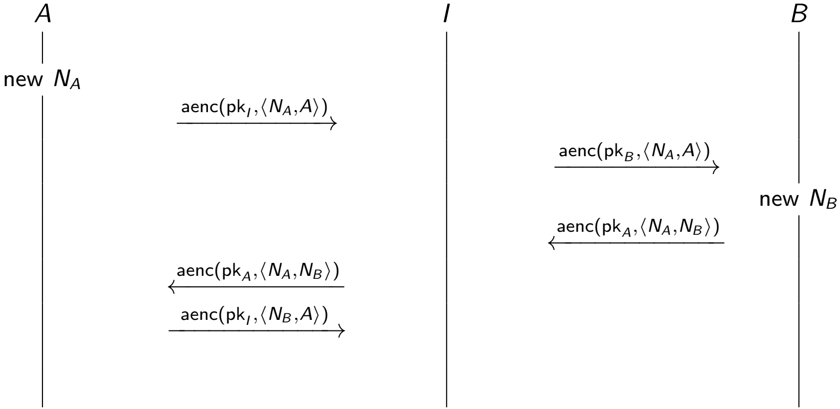

A

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B

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new N_B

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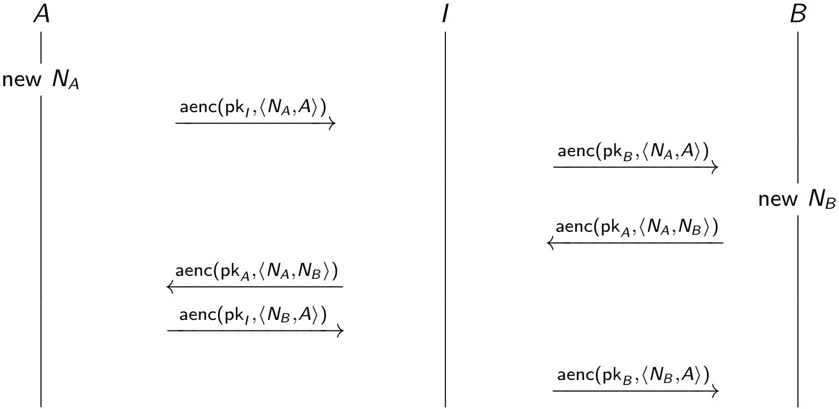

A I B

new N_A

$\mathsf{aenc}(\mathsf{pk}_I, \langle N_A, A\rangle)$

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new N_B

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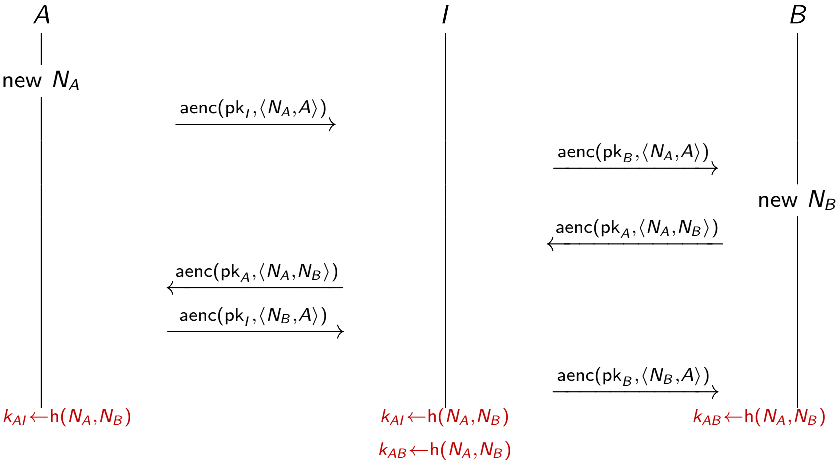

A I B

new N_A

$\mathrm{aenc}(\mathrm{pk}_I, \langle N_A, A \rangle)$

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new N_B

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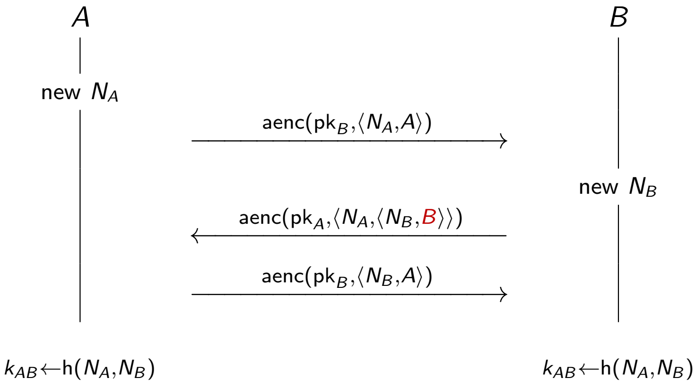
NSPK: Lowe's fix



A

B

new N_A

$\mathsf{aenc}(\mathsf{pk}_B, \langle N_A, A\rangle)$

new N_B

$\mathsf{aenc}(\mathsf{pk}_A, \langle N_A, \langle N_B, B\rangle\rangle)$

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Public Key Kerberos PKINIT-26 (very abstract)

Goals: client authentication, key agreement, TGT delivery

- $\{m\}^s_k$: message m symmetrically encrypted under key k
- $\{m\}^a_k$: message m asymmetrically encrypted under key k
- $[m]_k$: message m digitally signed with key k
- t_C, t_K: timestamps
- $TGT = \{AK, C, t_K\}^s_{k_T}$

Public Key Kerberos PKINIT-26 (very abstract)

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C

KAS

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C
KAS
new n_1, n_2

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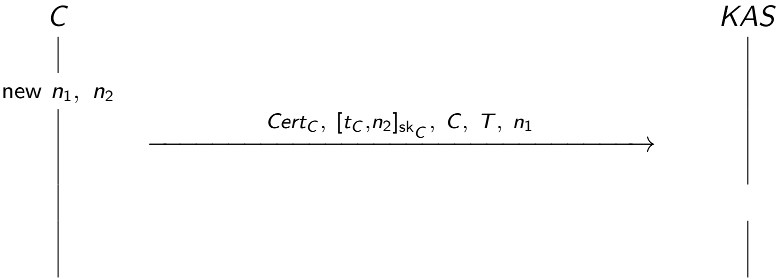
Public Key Kerberos PKINIT-26 (very abstract)

Goals: client authentication, key agreement, TGT delivery



C

KAS

new n_1, n_2

$Cert_C, [t_C, n_2]_{sk_C}, C, T, n_1$

- $\{m\}^s_k$: message m symmetrically encrypted under key k
- $\{m\}^a_k$: message m asymmetrically encrypted under key k
- $[m]_k$: message m digitally signed with key k
- t_C, t_K: timestamps
- $TGT = \{AK, C, t_K\}^s_{k_T}$

Public Key Kerberos PKINIT-26 (very abstract)

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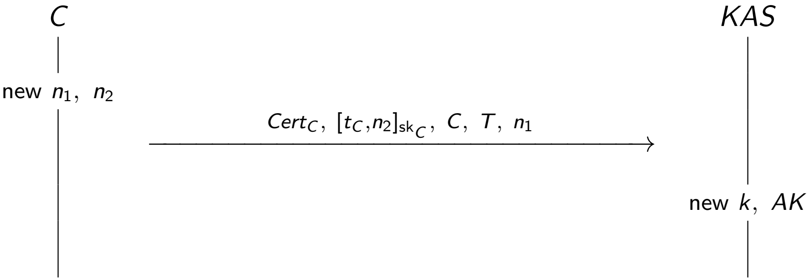

C

KAS

new $n_1, \ n_2$

$Cert_C, \ [t_C, n_2]_{\mathrm{sk}_C}, \ C, \ T, \ n_1$

new $k, \ AK$

- $\{m\}^s_k$: message m symmetrically encrypted under key k
- $\{m\}^a_k$: message m asymmetrically encrypted under key k
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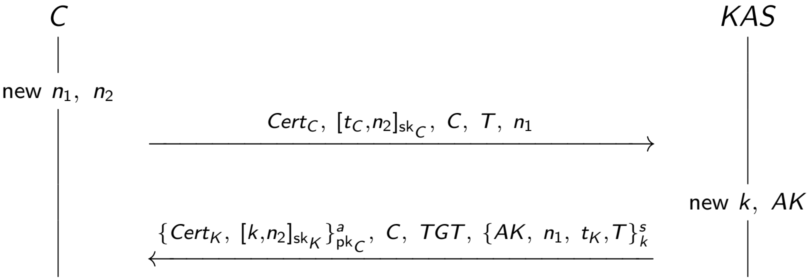

C

KAS

new $n_1,\ n_2$

$Cert_C,\ [t_C, n_2]_{sk_C},\ C,\ T,\ n_1$

new $k,\ AK$

$\{Cert_K,\ [k, n_2]_{sk_K}\}^a_{pk_C},\ C,\ TGT,\ \{AK,\ n_1,\ t_K, T\}^s_k$

- $\{m\}^s_k$: message m symmetrically encrypted under key k
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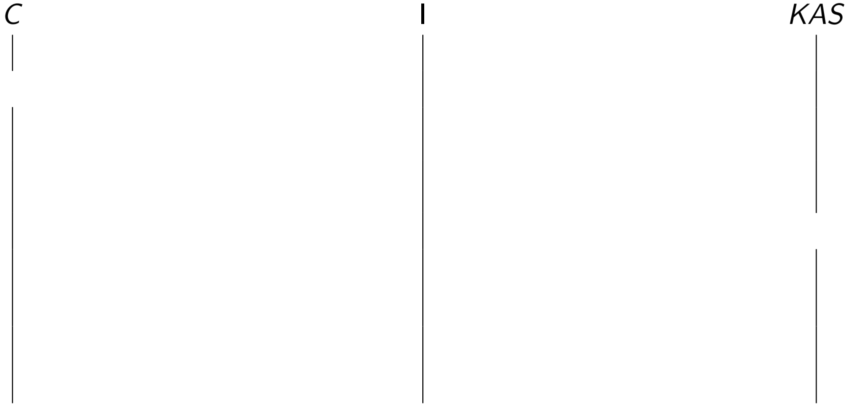
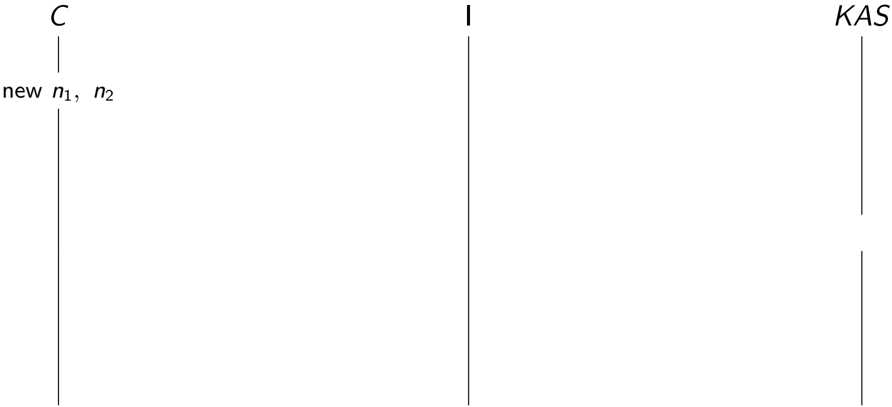
PKINIT-26: attack



C I *KAS*

[I. Cervesato, A. D. Jaggard, A. Scedrov, J. Tsay, C. Walstad. “Breaking and Fixing Public-Key Kerberos”. (ASIAN’06)]

PKINIT-26: attack



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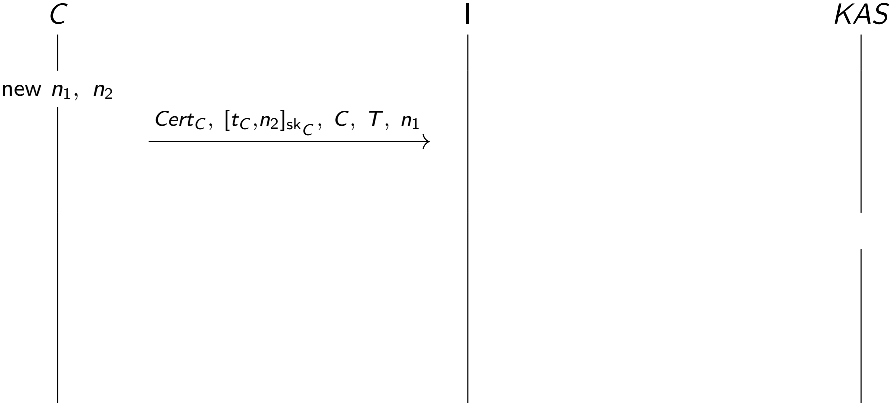

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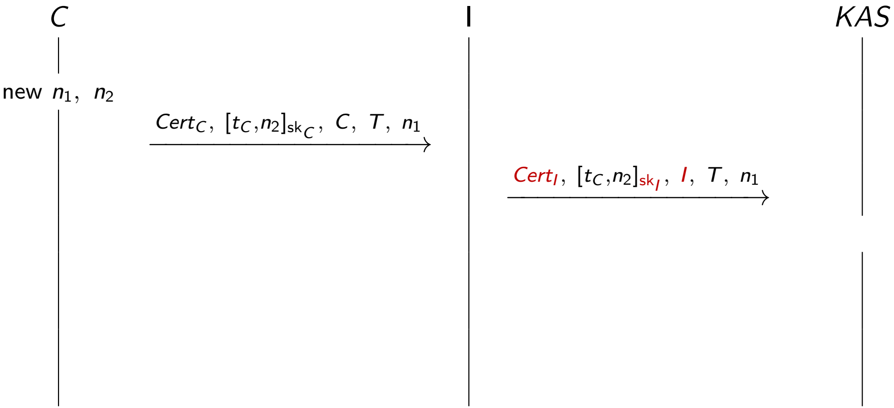


C

I

KAS

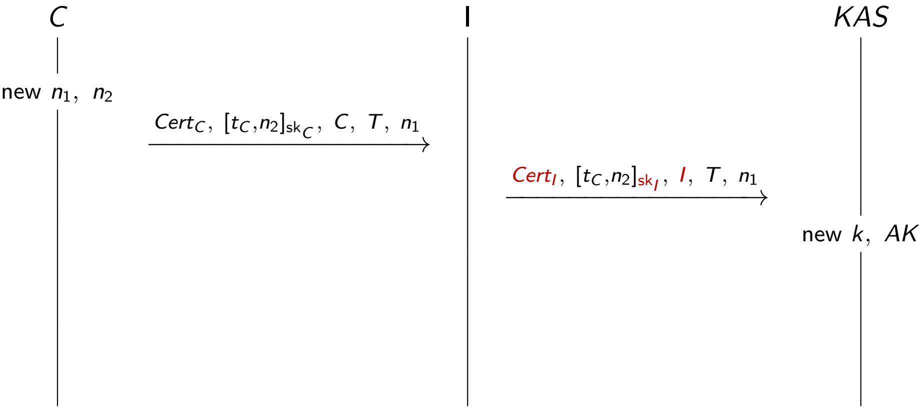
new n_1, n_2

$Cert_C$, $[t_C, n_2]_{\mathsf{sk}_C}$, C, T, n_1

$Cert_I$, $[t_C, n_2]_{\mathsf{sk}_I}$, I, T, n_1

[I. Cervesato, A. D. Jaggard, A. Scedrov, J. Tsay, C. Walstad. "Breaking and Fixing Public-Key Kerberos". (ASIAN'06)]

PKINIT-26: attack


C
I
KAS
new n_1, n_2
$Cert_C$, $[t_C, n_2]_{\mathsf{sk}_C}$, C, T, n_1
$Cert_I$, $[t_C, n_2]_{\mathsf{sk}_I}$, I, T, n_1
new k, AK

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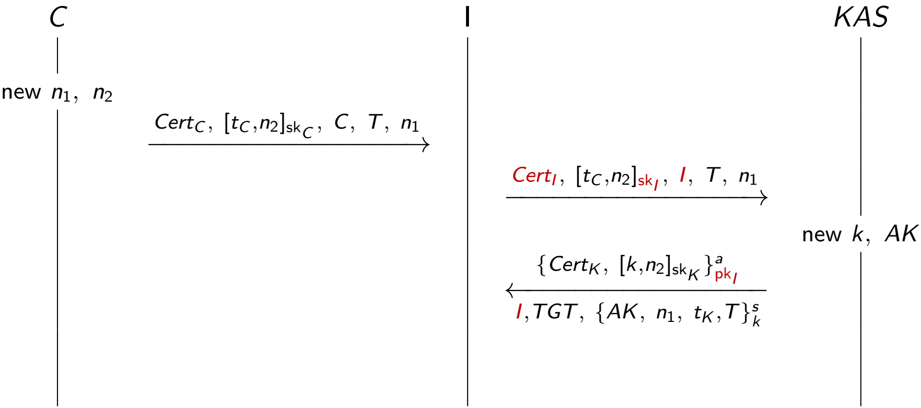
PKINIT-26: attack



C

I

KAS

new $n_1,\ n_2$

$Cert_C,\ [t_C, n_2]_{\mathsf{sk}_C},\ C,\ T,\ n_1$

$Cert_I,\ [t_C, n_2]_{\mathsf{sk}_I},\ I,\ T,\ n_1$

new $k,\ AK$

$\{Cert_K,\ [k, n_2]_{\mathsf{sk}_K}\}^a_{\mathsf{pk}_I}$

$I, TGT,\ \{AK,\ n_1,\ t_K, T\}^s_k$

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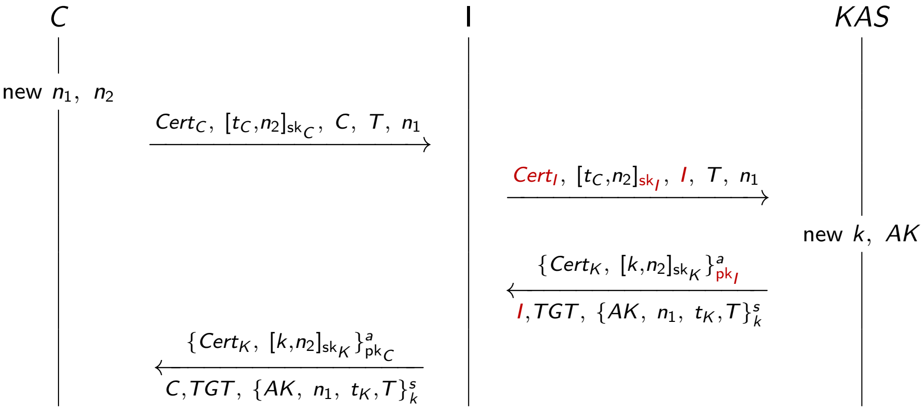
PKINIT-26: attack



C

I

KAS

new $n_1, \ n_2$

$Cert_C, \ [t_C, n_2]_{\mathrm{sk}_C}, \ C, \ T, \ n_1$

$Cert_I, \ [t_C, n_2]_{\mathrm{sk}_I}, \ I, \ T, \ n_1$

new $k, \ AK$

$\{Cert_K, \ [k, n_2]_{\mathrm{sk}_K}\}^a_{\mathrm{pk}_I}$

$I, TGT, \ \{AK, \ n_1, \ t_K, T\}^s_k$

$\{Cert_K, \ [k, n_2]_{\mathrm{sk}_K}\}^a_{\mathrm{pk}_C}$

$C, TGT, \ \{AK, \ n_1, \ t_K, T\}^s_k$

[I. Cervesato, A. D. Jaggard, A. Scedrov, J. Tsay, C. Walstad. “Breaking and Fixing Public-Key Kerberos”. (ASIAN’06)]