Control Flow Analysis for process algebras with applications to security

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Outline

1. Background on security protocols
2. CFA and security protocols
3. Possible further directions of investigation
4. Conclusions

Security protocols: why?

- There are many cryptographic primitives
- How can we use them to secure applications?
- It is a difficult task, even if cryptography is "perfect"

Security protocols

- A security protocol is a distributed algorithm. It consists of a set of rules (conventions) that determine the exchange of messages between two or more principals.
- Since principals communicate over channels an untrusted network, security protocols ensure that communication is not abused

Security protocols (cont.)

> *Security protocols are three-line programs that people still manage to get wrong.*
>
> *Roger M. Needham*

We focus in particular on authentication protocols

Problem: how to establish a virtual trusted channel:

- negotiate parameters of channel
- ensure that channel is still trusted

Security protocols (cont.)

Main characters:

- generic principals (aka agents, parties...): A (Alice), B (Bob)
- a trusted server: S (Sam)
- the **Dolev-Yao** attacker: C (Charlie) or M (Mallory - Malicious) or E (Eve - Evil) (it can eavesdrop, replay, encrypt, decrypt, generate and inject messages.)

A protocol involves a sequence of message exchanges of the form:

$$A \rightarrow B : Msg$$

meaning that a principal A sends the message Msg to principal B
$C(A)$ stands for C acting as A

Security protocols (cont.)

- Is cryptography enough?
- Attacks can be successful even without attacking the crypto-keys.

Wolf-in-the-middle attack: the wolf does not have the key

1. Little Red Riding Hood → Grandma

The wolf does not need the key:
grandma opens the door

1′ Wolf(Little Red Riding Hood) → Grandma

2. Grandma → Little Red Riding Hood

2′. Wolf(Grandma) → Little Red Riding Hood

Little Red Riding Hood believes grandma
opens the door

Bank transfer protocol

Example (Naive version)

$Alice \rightarrow Bob@Bank$: Transfer 100 euros to account X
$Bob@Bank \rightarrow Alice$: Tranfer just carried out

- How does Bob know that he is really speaking with Alice?
- How does Bob know Alice just said it?
- Bad guys like Charlie can be around

Bank transfer protocol (cont.)

Example (Easy attack)

$Alice \rightarrow Charlie(Bob@Bank)$: Transfer 100 euros to account X
$Charlie(Bob@Bank) \rightarrow Bob@Bank$: Transfer 200 euros to account X
$Bob@Bank \rightarrow Alice$: Tranfer just carried out

- Charlie can intercept and alter the message of Alice

$C(B)$ stands for C pretending to be B.

Bank transfer protocol (cont.)

Example

Cryptographic protection

$$Alice \rightarrow Charlie(Bob@Bank) : \{\text{Transfer 100 euros to account X}\}_K$$

...

- The attacker can intercept the message of Alice, but cannot alter it

Bank transfer protocol (cont.)

Example (Cryptography may not be not enough: reflection attack)

$$\begin{array}{l} Alice \rightarrow Charlie(Bob@Bank) : \{\text{Transfer 100 euros to account X}\}_K \\ Charlie(Bob@Bank) \rightarrow Alice : \{\text{Transfer 100 euros to account X}\}_K \end{array}$$

- The attacker can intercept the message of Alice, and just use it again
- Alice does not realise the received message is the one she generated

Bank transfer protocol (cont.)

Example (Possible fix)

$Alice \rightarrow Bob@Bank$: {I am Alice, Transfer 100 euros to account X}$_K$
$Bob@Bank \rightarrow Alice$: Tranfer just carried out

Bank transfer protocol (cont.)

Example (Replay attack)

$$\begin{array}{l} \mathit{Alice} \rightarrow \mathit{Bob@Bank} : \{\text{I am Alice, Transfer 100 euros to account X}\}_K \\ \mathit{Charlie} \rightarrow \mathit{Bob@Bank} : \{\text{I am Alice, Transfer 100 euros to account X}\}_K \end{array}$$

- The attacker can intercept the message of Alice, and just use it again
- Bob does not realize the received message is an old one: he has no way to verify the freshness of the message

Bank transfer protocol (cont.)

Example (Fixed protocol)

$Bob@Bank \rightarrow Alice : N_B$
$Alice \rightarrow Bob@Bank : \{\text{I am Alice, Transfer 100 euros to account X}, N_B\}_K$
...

- Use a nonce, a randomly generated number used only once.
- Principals do not see each other: their trust is based on the presence of expected and known terms in received messages.
- Bob can verify that the message is an answer to his request

This protocol is secure. It guarantees the secrecy and authenticity of the message

Security protocols (cont.)

- Is cryptography enough?
- Attacks can be successful even without attacking the crypto-keys.
- Cryptography translates a communication security problem into a key management problem; therefore, it can enhance security but it is not a substitute for security

Formal techniques can help

Protocols can be specified by using process calculi

- Process calculi are mathematically rigorous languages with well defined semantics, for formally modelling concurrent and distributed systems
- Protocol agents are modelled as models of processes
- Protocols evolution is described in terms of transitions systems, graphs whose states are process calculi terms
- BUT
- Transition systems are usually huge and their exploration can be computationally demanding
- Static techniques (CFA, TS, AI) provide approximate answers just looking at the system description.

Static vs dynamic techniques

STATIC	*DYNAMIC*
approximate	precise
terminates	may not terminate
"low" complexity	"high" complexity
"cheap" tools	"expensive" tools

SOUNDNESS

P has the static property implies P has the dynamic property

CFA applied to cryptographic protocols*

- **Control Flow Analysis** (CFA) soundly over-approximates the behaviour of protocols described in the process algebra LySa
- It tracks message flow for protocol, in the presence of a Dolev-Yao attacker
- The CFA addresses message authenticity: it verifies that a message encrypted by principal A (origin) and intended for B (destination) does indeed come from A and reaches B only
- If messages end up in a wrong place then there may be a problem

* C. Bodei and M. Buchholtz and P. Degano and F. Nielson and H. Riis Nielson (2005) Static Validation of Security Protocols, *Information and Computation* 13(3), pp. 347-390.

The Nature of Approximation

Block 1

If no violation of the message authentication property is detected, then no violation will ever arise at run time

Block 2

The existence of violations at static time does not necessarily imply their existence at run time

- BUT, the existence of static violations is a warning bell and should be further investigated

LySA model

- Typically, protocols are described by narrations and a textual description but details may be imprecise
- Protocol narrations can be made systematically translated into the process calculus called LySA
- LySA is inspired by the Spi-calculus but processes:
  - communicate through a global network
  - match values on input and decryption
  - use symmetric key cryptography

LySa Syntax

Expressions

$E ::=$	n	name ($n \in \mathcal{N}$)
	x	variable ($x \in \mathcal{X}$)
	$\{E_1, \cdots, E_k\}_{E_0}$	encryption

Processes

$P ::=$	$\langle E_1, \cdots, E_k \rangle .\, P$	output
	$(E_1, \cdots, E_j; x_{j+1}, \cdots, x_k).\, P$	input (with matching)
	decrypt E as $\{E_1, \cdots, E_j; x_{j+1}, \cdots, x_k\}_{E_0}$ in P	decryption (with matching)
	$P_1 \mid P_2$	parallel composition
	$(\nu\, n)P$	introduce new name n
	$!\, P$	replication
	0	terminated process

LySA features: decryptions on the fly

- No channels: communication is on a single global network.
- Decryptions are embedded inside inputs and performed on the fly when receiving the corresponding outputs. The output

$$\langle A, N_A, \{B, K_{AB}\}_{K_{AS}} \rangle$$

matches the input, including the embedded encryption

$$(A, x_N, \{B, x_K\}_{K_{AS}})$$

and the variables x_N and x_K are bound to N_A and to K_{AB}

LySA features: message authentication

To track message origin and destination, encryption terms and pattern terms are labelled:

$$\{E_1, \cdots, E_k\}^{\ell}_{E_0}[\text{dest } \mathcal{L}] \quad \text{and as} \quad \{M_1, \cdots, M_k\}^{\ell'}_{E'_0}[\text{orig } \mathcal{L}']$$

A decryption made in ℓ' with required **origin** in [orig $\mathcal{L}'$] matches an encryption in ℓ with required **destination** in [dest $\mathcal{L}$] if

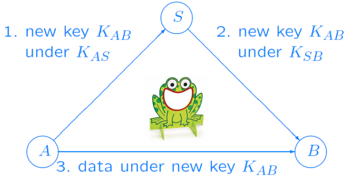
$$\ell \in \mathcal{L}' \wedge \ell' \in \mathcal{L}$$

Encoding a Protocol in LySa

Example

A key exchange inspired protocol by the Wide Mouthed Frog

$$\begin{array}{lll} 1. & A \rightarrow S: & A, B, \{K_{AB}\}_{K_{AS}} \\ 2. & S \rightarrow B: & A, \{K_{AB}\}_{K_{BS}} \\ 3. & A \rightarrow B: & \{m_1, \cdots, m_k\}_{K_{AB}} \end{array}$$



Encoding a protocol in LySa

Example (Wide Mouthed Frog)

$$\begin{array}{lll} 1. & A \rightarrow S: & A, B, \{K_{AB}\}_{K_{AS}} \\ 2. & S \rightarrow B: & A, \{K_{AB}\}_{K_{BS}} \\ 3. & A \rightarrow B: & \{m_1, \cdots, m_k\}_{K_{AB}} \end{array}$$

New names are modelled with restriction

$$(\nu\, K_{AB})\langle \qquad A, B, \{K_{AB}\}_{K_{AS}}\rangle.$$

$$|$$

Encoding a protocol in LySa

Example (Wide Mouthed Frog)

$$\begin{array}{lll} 1. & A \rightarrow S: & A, B, \{K_{AB}\}_{K_{AS}} \\ 2. & S \rightarrow B: & A, \{K_{AB}\}_{K_{BS}} \\ 3. & A \rightarrow B: & \{m_1, \cdots, m_k\}_{K_{AB}} \end{array}$$

Sender and receiver names are put at the beginning of the message

$$(\nu\, K_{AB})\langle A, S, A, B, \{K_{AB}\}_{K_{AS}}\rangle.$$

$$|$$

Encoding a protocol in LySa

Example (Wide Mouthed Frog)

$$\begin{array}{lll} 1. & A \to S: & A, B, \{K_{AB}\}_{K_{AS}} \\ 2. & S \to B: & A, \{K_{AB}\}_{K_{BS}} \\ 3. & A \to B: & \{m_1, \cdots, m_k\}_{K_{AB}} \end{array}$$

Agents are represented as parallel process (parallel composition is $|$)

$$(\nu\, K_{AB})\langle A, S, A, B, \{K_{AB}\}_{K_{AS}}\rangle.$$

$$|$$

$$(A, S, A; x_B, x)$$

Encoding a protocol in LySA

Example (Wide Mouthed Frog)

$$\begin{array}{lll} 1. & A \to S : & A, B, \{K_{AB}\}_{K_{AS}} \\ 2. & S \to B : & A, \{K_{AB}\}_{K_{BS}} \\ 3. & A \to B : & \{m_1, \cdots, m_k\}_{K_{AB}} \end{array}$$

Decryption is applied to the value received in x

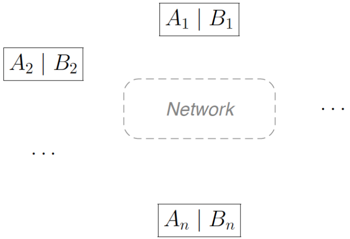
$$(\nu\, K_{AB})\langle A, S, A, B, \{K_{AB}\}_{K_{AS}}\rangle.$$

$$|$$

$$(A, S, A; x_B, x).\text{decrypt } x \text{ as } \{; x^K\}_{K_{AS}} \text{ in } \ldots$$

Protocol encoding: multiple instances

Protocols are played by several principals able to play both the initiator role A_i and the responder one B_i, plus a server S, if any



Adding annotations

Example (Wide Mouthed Frog)

$$
\begin{array}{lll}
1. & A \to S: & A, B, \{K_{AB}\}_{K_{AS}} \\
2. & S \to B: & A, \{K_{AB}\}_{K_{BS}} \\
3. & A \to B: & \{m_1, \cdots, m_k\}_{K_{AB}}
\end{array}
$$

Encryptions and decryptions come with labels

$$(\nu\, K_{AB})\langle A, S, A, B, \{K_{AB}\}^{A}_{K_{AS}}\rangle.$$

$$\mid$$

$$(A, S, A; x_B, x).\text{decrypt } x \text{ as } \{; x^K\}^{S}_{K_{AS}} \text{ in } \ldots$$

Adding annotations (cont.)

Example (Wide Mouthed Frog)

$$\begin{array}{lll} 1. & A \rightarrow S: & A, B, \{K_{AB}\}_{K_{AS}} \\ 2. & S \rightarrow B: & A, \{K_{AB}\}_{K_{BS}} \\ 3. & A \rightarrow B: & \{m_1, \cdots, m_k\}_{K_{AB}} \end{array}$$

Encryptions and decryptions come with annotations on the required destination and origin

$$(\nu\, K_{AB})\langle A, S, A, B, \{K_{AB}\}^{A}_{K_{AS}}[\text{dest } S]\rangle.$$

$$|$$

$$(A, S, A; x_B, x).\text{decrypt } x \text{ as } \{; x^K\}^{S}_{K_{AS}}[\text{orig } A] \text{ in } \ldots$$

Semantics

- Standard reduction semantics $P \rightarrow P'$
- Standard semantics ignores origin and destination annotations
- We can also make a reference monitor semantics $P \rightarrow_{\mathsf{RM}} P'$
- The reference monitor gets stuck when annotations are violated
- The reference monitor aborts the execution of P

whenever $P \rightarrow^* Q \rightarrow Q'$

but $P \rightarrow^*_{\mathsf{RM}} Q \not\rightarrow_{\mathsf{RM}} Q'$

Communication Rule

(Binary Com)

$$\frac{[\![E_1]\!] = [\![E_1']\!]}{\langle E_1, E_2\rangle.P \;\mid\; (E_1'; x_2).Q \rightarrow P \;\mid\; Q[E_2/x_2]}$$

$$(\nu\, K_{AS})(\langle A, S, A, B, \{K_{AB}\}_{K_{AS}}\rangle.\, A' \mid$$
$$(A, S, A;\; x_B, x).\,\text{decrypt } x \text{ as } \{; x^K\}_{K_{AS}} \text{ in } B')$$
$$\rightarrow$$
$$(\nu\, K_{AS})(A' \mid \text{decrypt } \{K_{AB}\}_{K_{AS}} \text{ as } \{; x^K\}_{K_{AS}} \text{ in } B')$$

Decryption Rule

(Binary Dec)

$$\frac{[\![E_0]\!] = [\![E_0']\!] \wedge [\![E_1]\!] = [\![E_1']\!] \wedge (cond)}{\text{decrypt } \{E_1, E_2\}^{\ell}_{E_0}[\text{dest } \mathcal{L}] \text{ as } \{E_1;\, x_2\}^{\ell'}_{E_0'}\ [\text{orig } \mathcal{L}'] \text{ in } P \to P \mid Q[E_2/x_2]}$$

$$(\nu\, K_{AS})(\langle A, S, A, B, \{K_{AB}\}^{A}_{K_{AS}}[\text{dest } S]\rangle .\, A' \mid$$
$$(A, S, A;\, x_B, x).\, \text{decrypt } x \text{ as } \{;\, x^K\}^{S}_{K_{AS}}[\text{orig } S] \text{ in } B')$$
$$\rightarrow$$
$$(\nu\, K_{AS})(A' \mid \text{decrypt } \{K_{AB}\}^{A}_{K_{AS}}[\text{dest } S] \text{ as } \{;\, x^K\}^{S}_{K_{AS}}[\text{orig } A] \text{ in } B')$$
$$\rightarrow$$
$$(\nu\, K_{AS})A' \mid B'[K_{AB}/x^K]$$

$$(cond) \quad \text{RM}(\ell, \mathcal{L}', \ell', \mathcal{L}) = (\ell \in \mathcal{L}' \wedge \ell' \in \mathcal{L})$$

The Analysis

Control Flow Analysis calculates (an over-approximation) to

- the messages on the network $\kappa \in \mathcal{P}(\mathcal{V}^*)$
- the values of the variables $\rho : \mathcal{X} \rightarrow \mathcal{P}(\mathcal{V})$

where $\mathcal{V}$ is the set of values (variable-free terms).

For example:

$$
\begin{array}{ll}
\langle A, S, A, B, \{K_{AB}\}^{A}_{K_{AS}}[\text{dest } S]\rangle & \in \kappa \\
\{K_{AB}\}^{A}_{K_A}[\text{dest } S] & \in \rho(x) \\
K_{AB} & \in \rho(x^K)
\end{array}
$$

The Error Component

- the possible mismatches of origin and destination: ψ

$$(A, B) \in \psi$$

reads

> "Something encrypted at A may *unintentionally* be decrypted at B."

E.g. if also $\langle A \rightarrow S, A, B, \{K\}_{K_A}^{A'}[\mathrm{dest}\ S]\rangle \in \kappa$ then

$$(A', S) \in \psi$$

because the expected origin was A

The Analysis

The analysis is specified as a Flow Logic with judgements

$$(\rho, \kappa) \models P : \psi$$

and auxiliary judgements for terms:

$$\rho \models E : \vartheta$$

where $\vartheta \in \mathcal{P}(\mathcal{V})$ is the values that E may evaluate to

Judgements for terms

$$\frac{\lfloor n \rfloor \in \vartheta}{\rho \models n : \vartheta}$$

$$\frac{\rho(\lfloor x \rfloor) \subseteq \vartheta}{\rho \models x : \vartheta}$$

encryption

$$\frac{\begin{array}{c} \wedge_{i=0}^{k}\, \rho \models E_i : \vartheta_i \,\wedge \\ \forall V_0, V_1, \cdots, V_k : \wedge_{i=0}^{k}\, V_i \in \vartheta_i \;\Rightarrow\; \{V_1, \cdots, V_k\}^{\ell}{}_{V_0}[\text{dest } \mathcal{L}] \in \vartheta \end{array}}{\rho \models \{E_1, \cdots, E_k\}^{\ell}_{E_0}[\text{dest } \mathcal{L}] : \vartheta}$$

For instance, if $E = \{A, x^K\}^{S}_{K_B}[\text{dest } B]$ and $K \in \rho(x^K)$, then

$$\{A, K\}^{S}_{K_B}[\text{dest } B] \in \vartheta$$

Judgement for Output

(of binary terms)

binary output

$$\frac{\begin{array}{c}\rho \models E_1 : \vartheta_1 \wedge \rho \models E_2 : \vartheta_2 \\ \forall V_0, V_1 : V_0 \in \vartheta_0 \wedge V_1 \in \vartheta_1 \Rightarrow \ \langle V_1, V_2 \rangle \in \vartheta \ \wedge \\ (\rho, \kappa) \models P : \psi\end{array}}{(\rho, \kappa) \models \langle E_1, E_2 \rangle.P : \psi}$$

- Analyse the expressions E_1, E_2
- ϑ includes the pairs of the values possibly bound to E_1, E_2
- Analyse the continuation

Judgement for Input

(of binary terms)

binary input

$\rho \models E_1 : \vartheta_1 \wedge$	evaluate subterms
$\forall \langle V_1, V_2 \rangle \in \vartheta :$	for all output tuples
$\quad V_1 \text{ E } \vartheta_1 \Rightarrow$	if values match
$\qquad V_2 \in \rho(x_2) \wedge$	x_2 has the value V_2
$(\rho, \kappa) \models P : \psi$	analyse the continuation

$$\frac{\rho \models E_1 : \vartheta_1 \wedge \forall \langle V_1, V_2 \rangle \in \vartheta : V_1 \text{ E } \vartheta_1 \Rightarrow V_2 \in \rho(x_2) \wedge (\rho, \kappa) \models P : \psi}{(\rho, \kappa) \models (E_1; x).P : \psi}$$

Judgement for Decryption

(of binary terms)

binary decryption

$$\frac{\begin{array}{ll}
\rho \models E : \vartheta \wedge & \text{evaluate terms} \\
\rho \models E_0 : \vartheta_0 \wedge \rho \models E_1 : \vartheta_1 \wedge & \text{and subterms} \\
\forall\, \{V_1, V_2\}^{\ell}{}_{V_0}[\mathsf{dest}\ \mathcal{L}] \in \vartheta : & \text{for all encrypted terms} \\
\quad V_0 \mathrel{\mathsf{E}} \vartheta_0 \wedge V_1 \mathrel{\mathsf{E}} \vartheta_1 \Rightarrow & \text{if values match} \\
\quad\quad V_2 \in \rho(x_2) \wedge & x_2 \text{ has the value } V_2 \\
\quad\quad \ell' \notin \mathcal{L} \vee \ell \notin \mathcal{L}' \Rightarrow (\ell, \ell') \in \psi \wedge & \text{check annotations} \\
\quad\quad (\rho, \kappa) \models P : \psi & \text{analyse the continuation}
\end{array}}{(\rho, \kappa) \models \mathsf{decrypt}\ E\ \mathsf{as}\ \{E_1; x_2\}^{\ell'}_{E_0}\ [\mathsf{orig}\ \mathcal{L}']\ \mathsf{in}\ P : \psi}$$

Formal results

- **Correctness**: the analysis is sound w.r.t. the semantics

Theorem

(Subject Reduction)

If $(\rho, \kappa) \models P : \psi$ *and* $P \to Q$ *then also* $(\rho, \kappa) \models Q : \psi$

Theorem

($\psi = \emptyset$ *means we're happy)*

If $(\rho, \kappa) \models P : \emptyset$ *then the reference monitor cannot abort the execution of* P.

- **Existence of solutions**: valid estimates are a Moore family

LySA: The Dolev-Yao attacker

The attacker is not specified at the calculus level. It is specified at analysis level (using ρ and κ) with a logic formula.

- The attacker knowledge is kept in a special variable $z_\bullet$
- The attacker inputs are labelled $Z_\bullet$
- The attacker has a special crypto-point called $\ell_\bullet$

E.g., its intercepting and injecting capabilities are written as

- $\forall \langle V_1, \cdots, V_k \rangle \in \kappa : \wedge_{i=1}^{k} V_i \in \rho(z_\bullet)$
- $\forall V_1, \cdots, V_k : \wedge_{i=1}^{k} V_i \in \rho(z_\bullet) \Rightarrow \langle V_1, \cdots, V_k \rangle \in \kappa$

Validating Authentication

Definition

P guarantees dynamic authentication if $P \mid Q$ cannot abort regardless of the choice of the attacker Q.

Definition

P guarantees static authentication if $(\rho, \kappa) \models P : \emptyset$ and $(\rho, \kappa, \emptyset)$ satisfies the formula describing the attacker.

Theorem

If P guarantees static authentication then P guarantees dynamic authentication.

Implementation

- Transform the analysis into (an extension of) Horn clauses.
- Calculate the solution using the Succinct Solver.
- Main challenge:
  - The analysis is specified using the infinite universe of terms.
  - Use an encoding of terms in tree grammars where terms are represented as a finite number of production rules.
- Runs in polynomial time in the size of the process P.

Example Revisited

Example

$$
\begin{array}{ll}
A \rightarrow S: & A, B, \{K_{AB}\}_{K_{AS}} \\
S \rightarrow B: & A, \{K_{AB}\}_{K_B} \\
A \rightarrow B: & \{m_1, \cdots, m_k\}_{K_{AB}}
\end{array}
$$

The analysis of n instances of the protocol gives

$$\psi = \{ \ (A_i, B_j), (A_i, \ell_\bullet), (\ell_\bullet, B_j) \mid 1 \leq i, j \leq n\}$$

If messages end up in a wrong place then there may be a problem

An attack

Investigating because of the warning bell

Example (protocol and protocol attack)

1.	$A \to S :$	$A, B, \{K_{AB}\}_{K_{AS}}$		1.	$A \to S :$	$A, B, \{K_{AB}\}_{K_{AS}}$
2.	$S \to B :$	$A, \{K_{AB}\}_{K_{BS}}$		2.	$S \to M(B) :$	$A, \{K_{AB}\}_{K_{BS}}$
3.	$A \to B :$	$\{m_1, \cdots, m_k\}_{K_{AB}}$		$2'$.	$M(S) \to B :$	$C, \{K_{AB}\}_{K_{BS}}$
				3.	$A \to B :$	$\{m_1, \cdots, m_k\}_{K_{AB}}$

B believes that K_{AB} comes from C

Other attacks

$$\begin{array}{ll} A \rightarrow M_S: & A, B, \{K\}_{K_A} \\ M_A \rightarrow S: & A, B', \{K\}_{K_A} \\ S \rightarrow B': & \{A, K\}_{K_{B'}} \\ A \rightarrow M_B: & \{m_1 \cdots m_k\}_K \\ M_A \rightarrow B': & \{m_1 \cdots m_k\}_K \end{array}$$

$$\begin{array}{ll} A \rightarrow M_S: & A, B, \{K\}_{K_A} \\ M_S \rightarrow S: & A, M, \{K\}_{K_A} \\ S \rightarrow M: & \{A, K\}_{K_M} \\ A \rightarrow M_B: & \{m_1 \cdots m_k\}_K \end{array}$$

$$\begin{array}{ll} A \rightarrow M_S: & A, B, \{K\}_{K_A} \\ M_S \rightarrow S: & A, M, \{K\}_{K_A} \\ S \rightarrow M: & \{A, K\}_{K_M} \\ M_A \rightarrow S: & A, B, \{K\}_{K_A} \\ S \rightarrow B: & \{A, K\}_{K_B} \\ M \rightarrow B: & \{m_1 \cdots m_k\}_K \end{array}$$

General Considerations

The presented analysis identifies a number of authentication flaws in symmetric key protocols such as Needham-Schroeder, Otway-Rees, Yahalom and Andrew Secure RPC.
The same approach is valid also for

- other cryptographic features, such as asymmetric cryptography (by extending the calculus)
- other security properties (by checking other annotations)
- other calculi

Other protocols and other paradigms

- Multi-factor authentication
- Internet of Things

Considerations on DY attacker*

- It has total control over all channels
  - this is not always realistic
  - attacking a channel has a cost (cheap or in terms of risk)
- It cannot compromise endpoints
  - browser, PC, smartphones
  - nonetheless this can happen (e.g. malware)

* Slides on multi-factor authentication are inspired by the ones of G. Costa

Multi-factor authentication

IDEA: increase the cost by increasing the factors that need to be compromised for carrying out the attack

Typical context: e-banking (a user must be authenticated by her/his bank)

Authentication factors

Authentication Factor: something that identifies who holds the control, e.g. credit card

Three types of AF

- what you know, e.g. a password, or a pin code;
- what you have, e.g. an access card or physical token
- what you are, e.g. a biometric measurement

Authenticator: device used for attesting control over one or more AF, e.g. a sw or hw keyboard

Evidence: generated by an authenticator, an information to demonstrate control over an AF, e.g. ID + ccv

Secure element

- Some authenticators are designed for be resistant against tampering, for example, SIM, Smartcard, OTP generators
- Virtually never this happens if the authenticator is software: the execution platform is untrusted

Attacker model revised

- Device Thief: can steal physical objects at owner
- Authenticator Duplicator: can duplicate an authenticator (except secure elements)
- Shoulder Surfer: can spy on the activity user
- Eavesdropping software: can spy the input of data by the user (e.g. keylogger)
- Social Engineer: can induce a user misinformed to use an authenticator in incorrect way
- Man in the Browser: has control of user browser (if the endpoint is a PC)
- Man in the Mobile: has control of the user smartphone

Stronger attackers are obtained for composition

Authentication with a card reader

Example

$$
\begin{array}{ll}
Alice \rightarrow Bank : & \{usr, h(psw)\}_{K_B} \\
Bank \rightarrow Alice : & \{N_B\}_{K_A} \\
Alice \rightarrow CReader : & N_B, pin \\
CReader \rightarrow Alice : & [N_B]_{K_{BC}} \\
Alice \rightarrow Bank : & [N_B]_{K_{BC}}
\end{array}
$$

A shoulder surfer can compromise knowldege factors, but cannot compromise possesion factors

Attack

Possible ways to attack the factors of possession, with e.g. a social engineer

- DT (subtracts CReader from Alice)
- (deceives Alice who uses CReader badly)
- (create a copy of CReader)
- But CReader is a secure element

Attack

Example

$$
\begin{array}{ll}
Charlie \rightarrow Bank: & \{usr, h(psw)\}_{K_B} \\
Bank \rightarrow Charlie: & \{N_B\}_{K_A} \\
Charlie \rightarrow Alice: & \{N_B\}_{K_A} \\
Alice \rightarrow CReader: & N_B, pin \\
CReader \rightarrow Alice: & [N_B]_{K_{BC}} \\
Alice \rightarrow Charlie: & [N_B]_{K_{BC}} \\
Charlie \rightarrow Bank: & [N_B]_{K_{BC}}
\end{array}
$$

Possible countermeasure: tell Alice

Example

$$
\begin{array}{ll}
Charlie \rightarrow Bank : & \{usr, h(psw)\}_{K_B} \\
Bank \rightarrow Charlie : & \{N_B, Op\}_{K_A} \\
Charlie \rightarrow Alice : & \{N_B, Op\}_{K_A} \\
Alice \ldots. &
\end{array}
$$

Alice can refuse to perform Op

IoT Challenges

Designing & implementing IoT systems is hard

- Smart objects are heterogeneous
  - Many hw, sw, protocols, etc.
- Cyber-physical and dynamic systems
- Security & privacy
  - Highly critical but difficult to achieve
  - Devices (Things) have limited computational capabilities and are battery powered

CFA for Internet of Things*

The process algebra IoT-LySa extends LySa

- Network of nodes
- Sensors & actuators
- Group communication
- Local communication à la Linda

Tracking data analysis to predict

- Interaction among nodes
- How data flow in the network and are manipulated, also related to security issues

* C. Bodei, P. Degano, G-L. Ferrari, L. Galletta. Tracing where IoT data are collected and aggregated. Logical Methods in Computer Science 13(3:5), pp. 1-38, 2017.

Tracking data analysis for security properties

A Control Flow Analysis (CFA) to safely approximate

- Interactions among nodes
- How data spread from sensors to network
- How data are manipulated

Verification based on the analysis results

- Checking whether classified data reach untrusted nodes
- Checking whether data come from untrusted sources
- ...

Conclusions

- Security protocols can achieve properties that cryptographic primitives alone cannot offer, e.g. authentication, secrecy, ...
- Even three lines show how difficult the art of correct design is
- Formal models of protocols and of their properties is required, to provide a mathematically sound basis for reasoning
- However, formal analysis of protocols is non trivial (even assuming perfect cryptography)
- New paradigms come with new security challenges

Thanks

THANK YOU FOR YOUR ATTENTION