Control Flow Analysis for Security Protocols

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Approach

- Define a protocol (using a process calculus)
- Define a Dolev-Yao style attacker
- Track message flow for protocol and attacker using *control flow analysis*
- If messages end up in a wrong place then there may be a problem
  - Attacker can alter message flow arbitrarily
  - Focus on encryption and decryption

Making Narrations Precise

- Typically, protocols are described by narrations and a textual description *but details may be imprecise*
- We make systematic translations of the protocol narrations into a 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

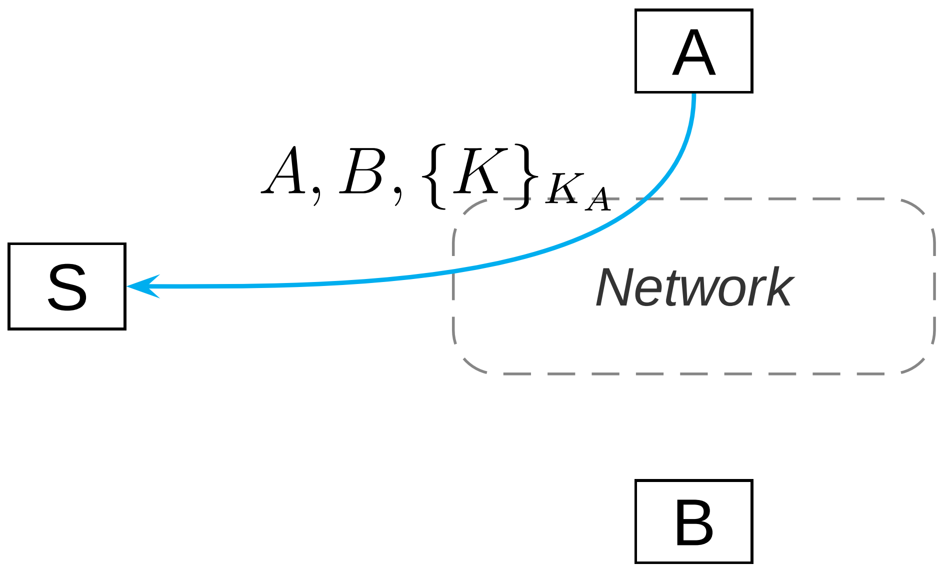
LySa Syntax

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

Encoding a Protocol in LySa

A key exchange inspired protocol by the Wide Mouthed Frog:

$$
\begin{array}{lll}
1. & A \rightarrow S: & A, B, \{K\}_{K_A} \\
2. & S \rightarrow B: & A, \{K\}_{K_B} \\
3. & A \rightarrow B: & \{m_1, \cdots, m_k\}_K
\end{array}
$$



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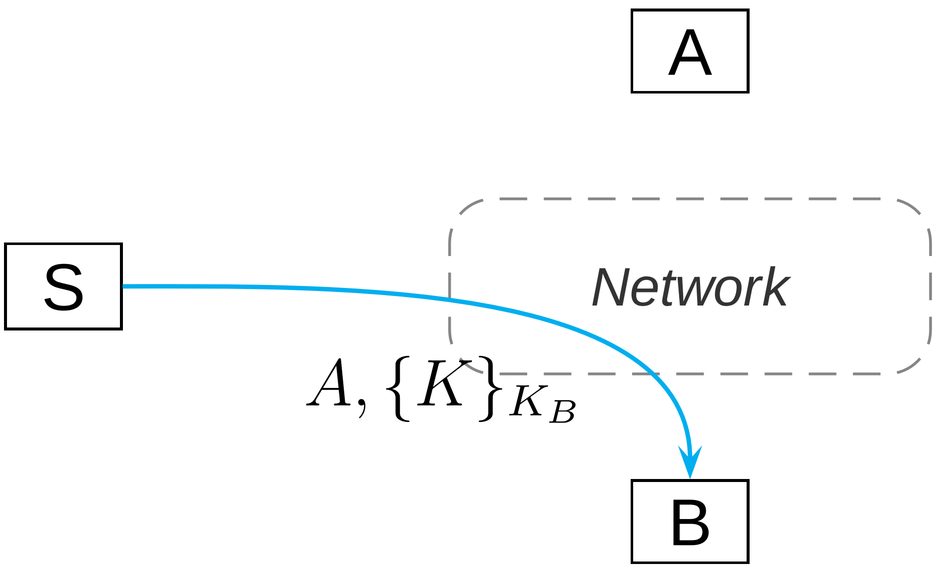

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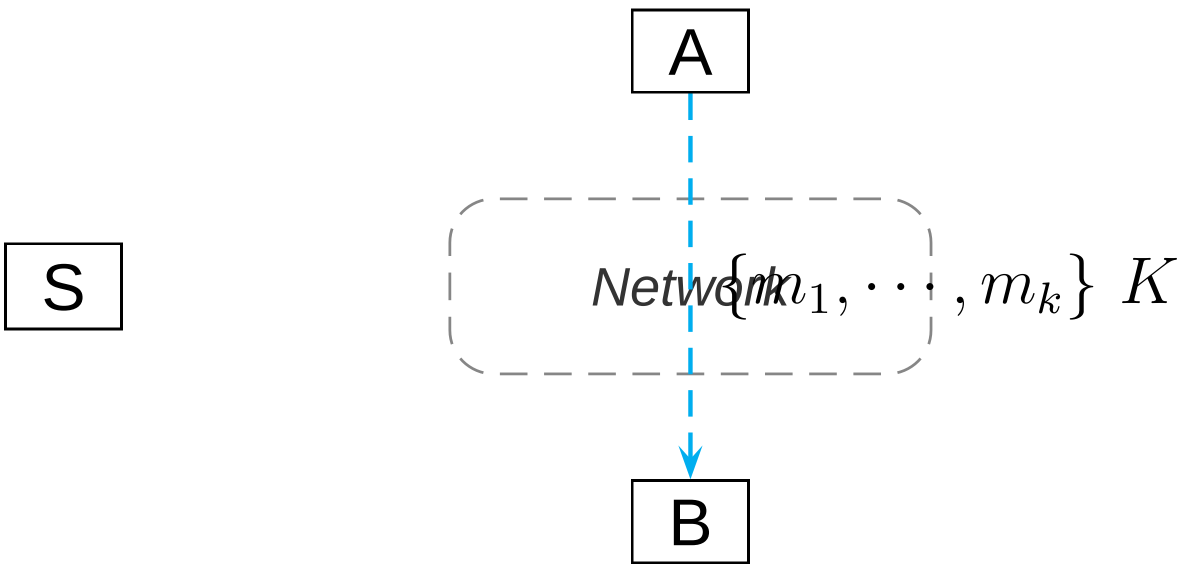

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$$(\nu\, K)\langle \qquad A, B, \{K\}_{K_A}\rangle.$$

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$$(\nu\, K)\langle A, S, A, B, \{K\}_{K_A}\rangle.$$

$$|$$

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

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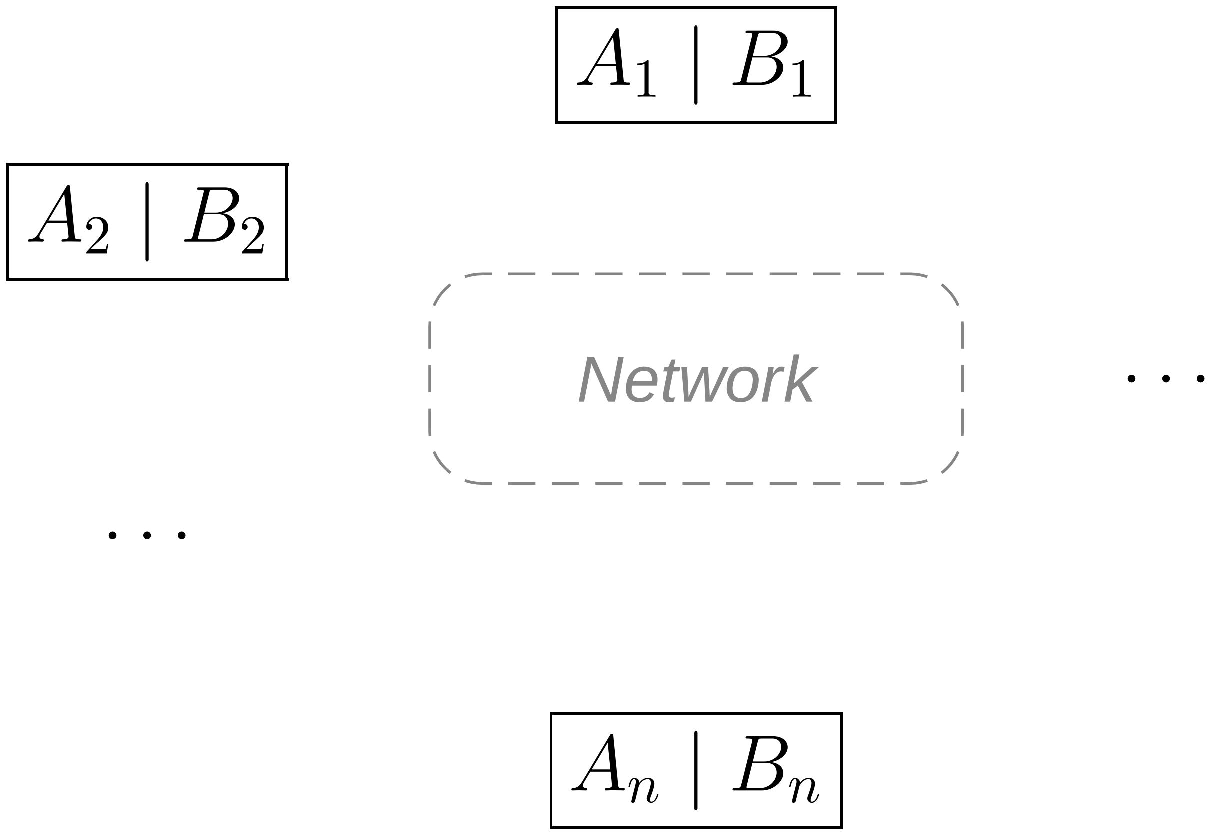
$(A, S, A; x_B, x)$. decrypt x as $\{; x^K\}_{K_A}$ in $\ldots$

Multiple Instances



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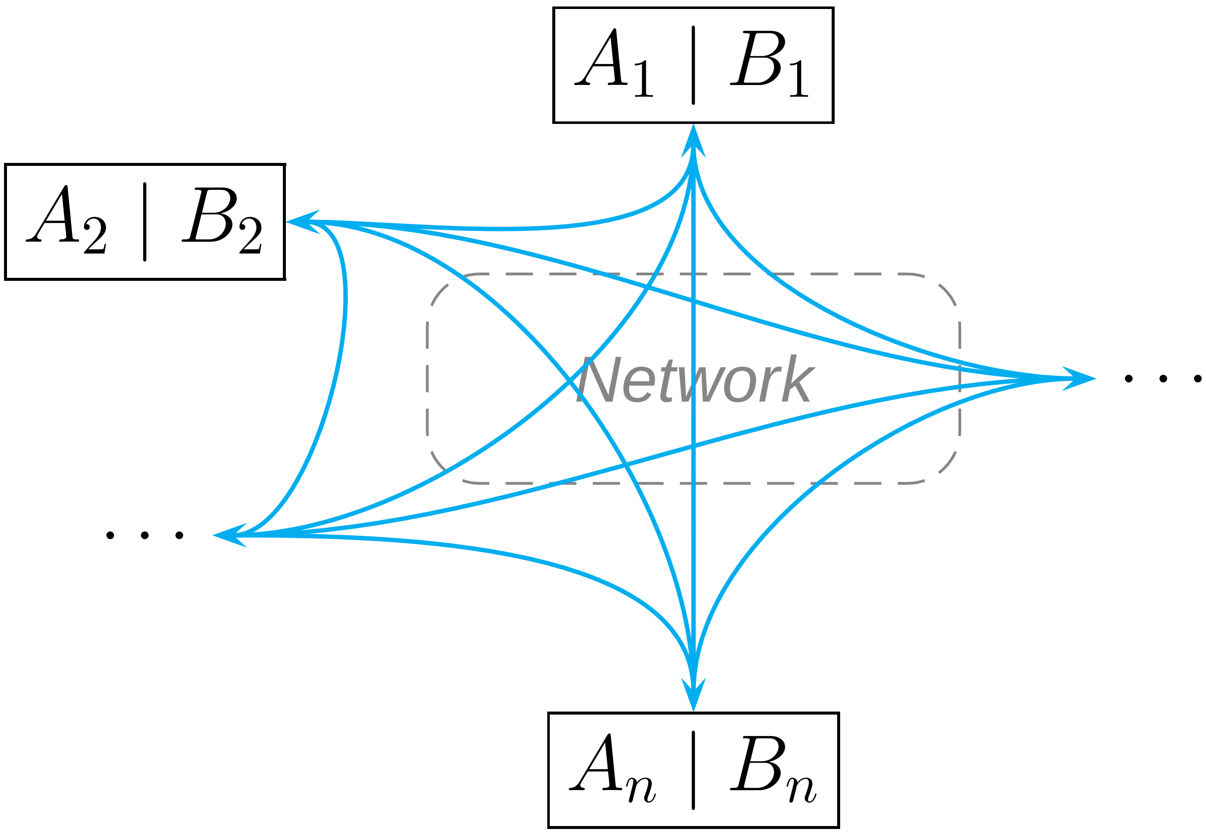

Adding Annotation

$$
\begin{array}{lll}
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$$
\begin{array}{l}
(\nu\, K)\langle A, S, A, B, \{K\}_{K_A} \qquad\qquad \rangle. \\
| \\
(A, S, A; x_B, x).\ \text{decrypt } x \text{ as } \{; x^K\}_{K_A} \qquad\qquad \text{in } \ldots
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$$(\nu\, K)\langle A, S, A, B, \{K\}^{A}_{K_A}[\mathsf{dest}\ S]\rangle.$$

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

Semantics

- Standard *reduction semantics* $P \to P'$
- The standard semantics ignores annotations

- We can also make a *reference monitor semantics* $P \to_{\mathsf{RM}} P'$
- The reference monitor gets stuck when annotations are violated

- The reference monitor *aborts* the execution of P

whenever $\quad P \to^* Q \to Q'$

but $\quad P \to^*_{\mathsf{RM}} Q \not\to_{\mathsf{RM}} Q'$

The Analysis

We make a *control flow analysis* that calculates (an over-approximation) to

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

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

For example:

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

The Error Component

The *error component* ψ collects pairs of crypto-points where the assertions in annotations may be violated. For example,

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

reads

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

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 $\vartheta \in \mathcal{P}(\mathcal{V})$ approximates the set of values that E may evaluate to

Judgement for Decryption

(of binary terms)

$\rho \models E : \vartheta \wedge$	evaluate terms
$\rho \models E_0 : \vartheta_0 \wedge \rho \models E_1 : \vartheta_1 \wedge$	and subterms
$\forall \{V_1, V_2\}^{\ell}_{V_0} [\text{dest } \mathcal{L}] \in \vartheta :$	for all encrypted term
$\quad V_0 \text{ E } \vartheta_0 \wedge V_1 \text{ E } \vartheta_1 \Rightarrow$	if values match
$\quad\quad V_2 \in \rho(x) \wedge$	x has the value V_2
$\quad\quad \ell' \notin \mathcal{L} \vee \ell \notin \mathcal{L}' \Rightarrow (\ell, \ell') \in \psi \wedge$	check annotations
$\quad\quad (\rho, \kappa) \models P : \psi$	analyse the rest

$$\overline{(\rho, \kappa) \models \text{decrypt } E \text{ as } \{E_1; x\}^{\ell'}_{E_0} \; [\text{orig } \mathcal{L}'] \text{ in } P : \psi}$$

Correctness of the Analysis

Theorem (subject reduction)

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

In fact, this holds for the standard semantics as well as the reference monitor semantics.

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

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

The Attacker

- Dolev-Yao style attacker that can receive, send, encrypt, decrypt, etc.
- Specified at analysis level (using ρ and κ)
- The knowledge is kept in a special variable $z_\bullet$
- For example, *receive* is written as

  $$\forall \langle V_1, \cdots, V_k \rangle \in \kappa : \wedge_{i=1}^{k} V_i \in \rho(z_\bullet)$$
- There exists a process – a “hardest attacker” – which has the capabilities of this formula
- The formula also checks annotations
- The attacker has a special crypto-point called $\ell_\bullet$

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.

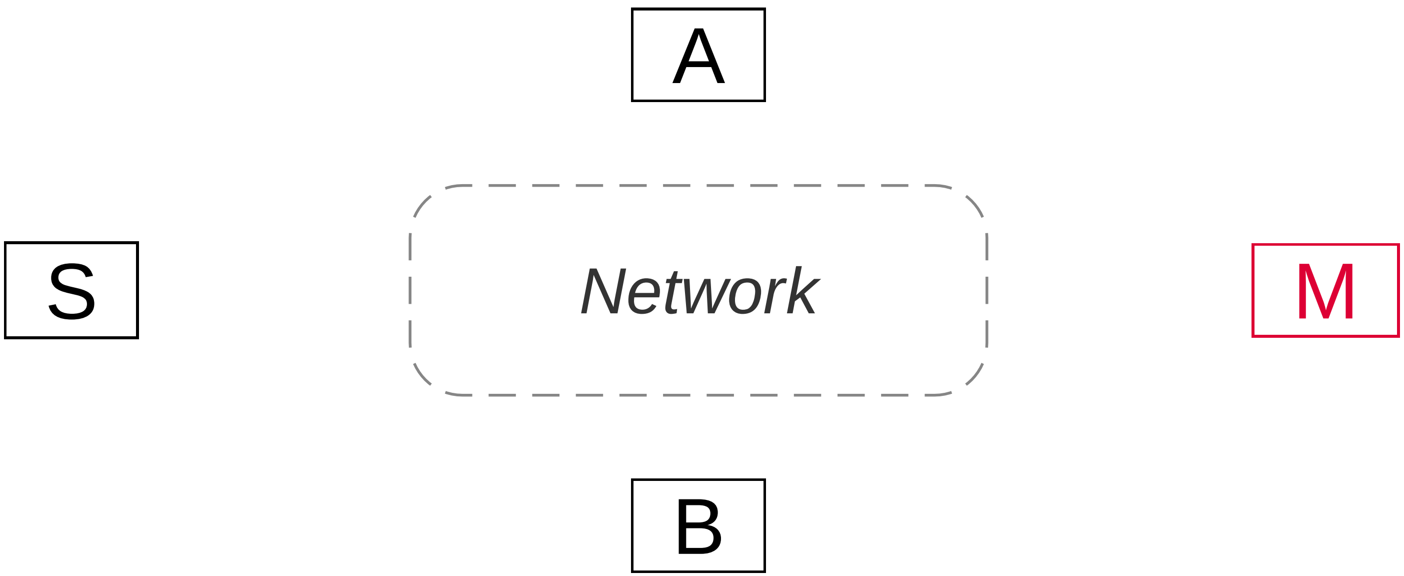
Example Revisited

$$\begin{aligned} A \rightarrow S: &\quad A, B, \{K\}_{K_A} \\ S \rightarrow B: &\quad A, \{K\}_{K_B} \\ A \rightarrow B: &\quad \{m_1, \cdots, m_k\}_K \end{aligned}$$

The analysis of n instances of the protocol gives

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

An Attack



Flawed protocol inspired by "Wide Mouthed Frog"

1. $A \rightarrow S: \quad A, B, \{K\}_{K_A}$
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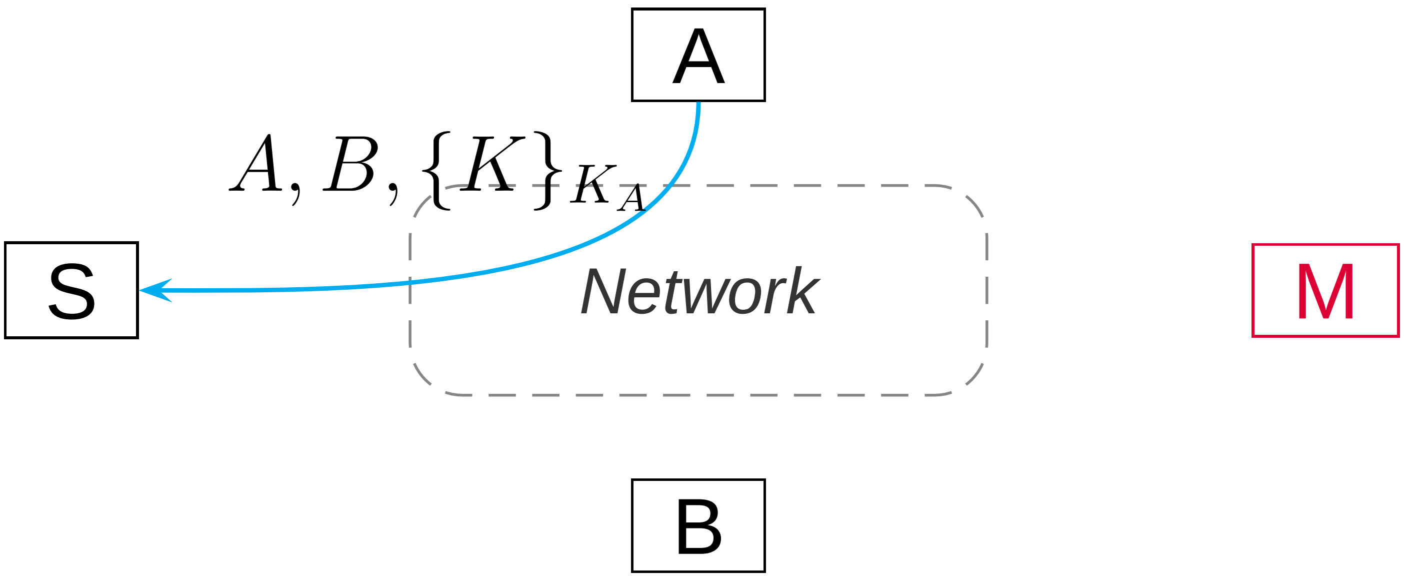

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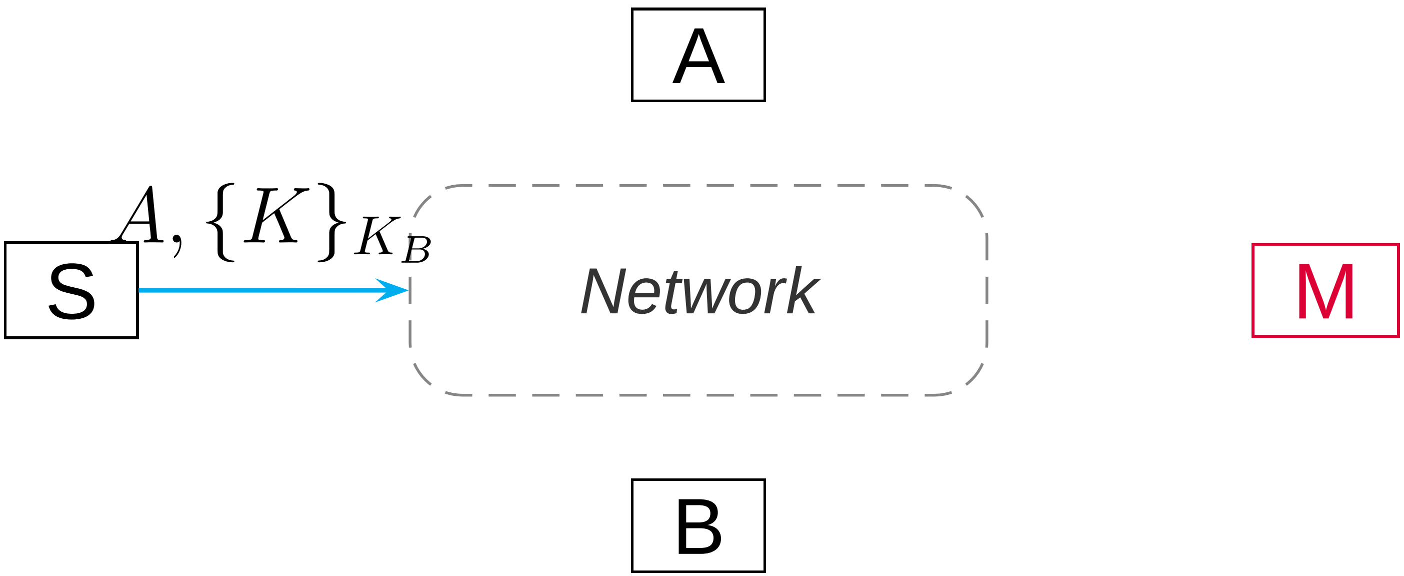

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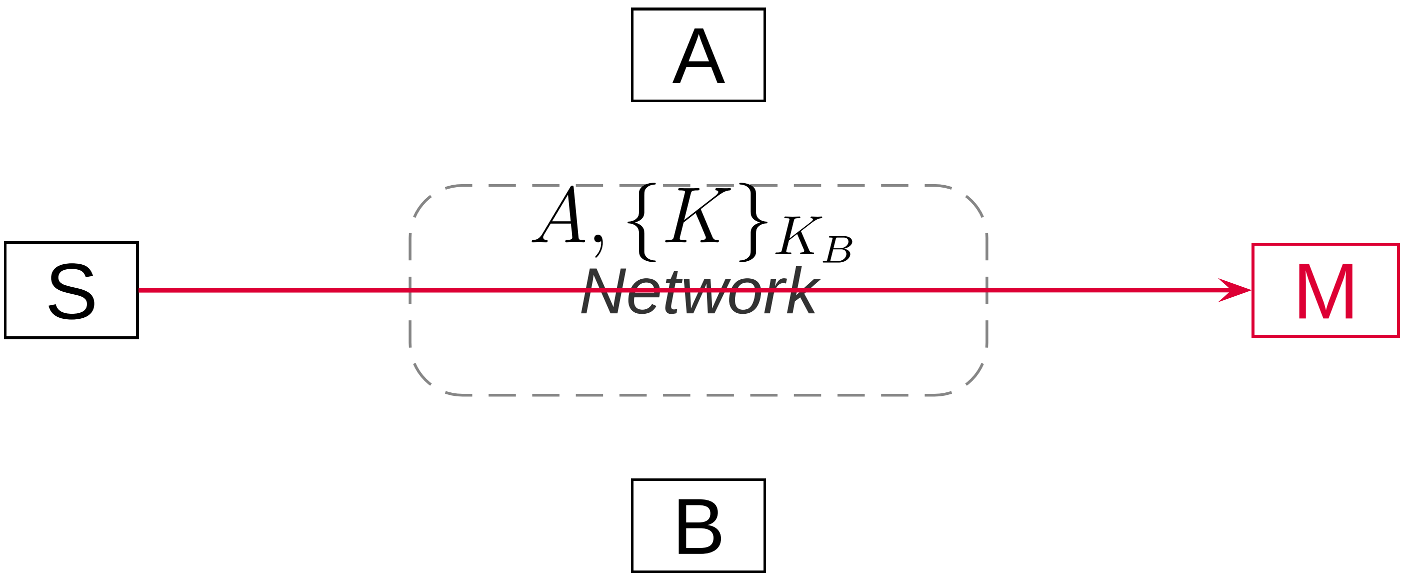

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2. & S \rightarrow B: & A, \{K\}_{K_B} & S \rightarrow M(B): & A, \{K\}_{K_B} \\
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\end{array}
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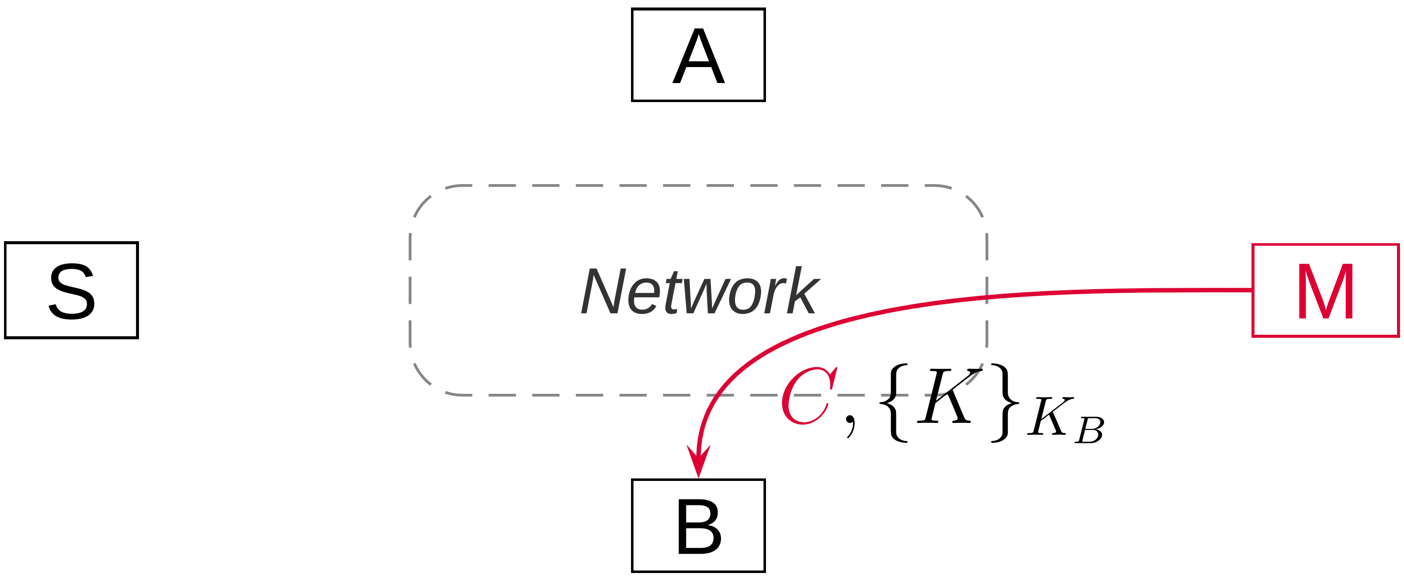
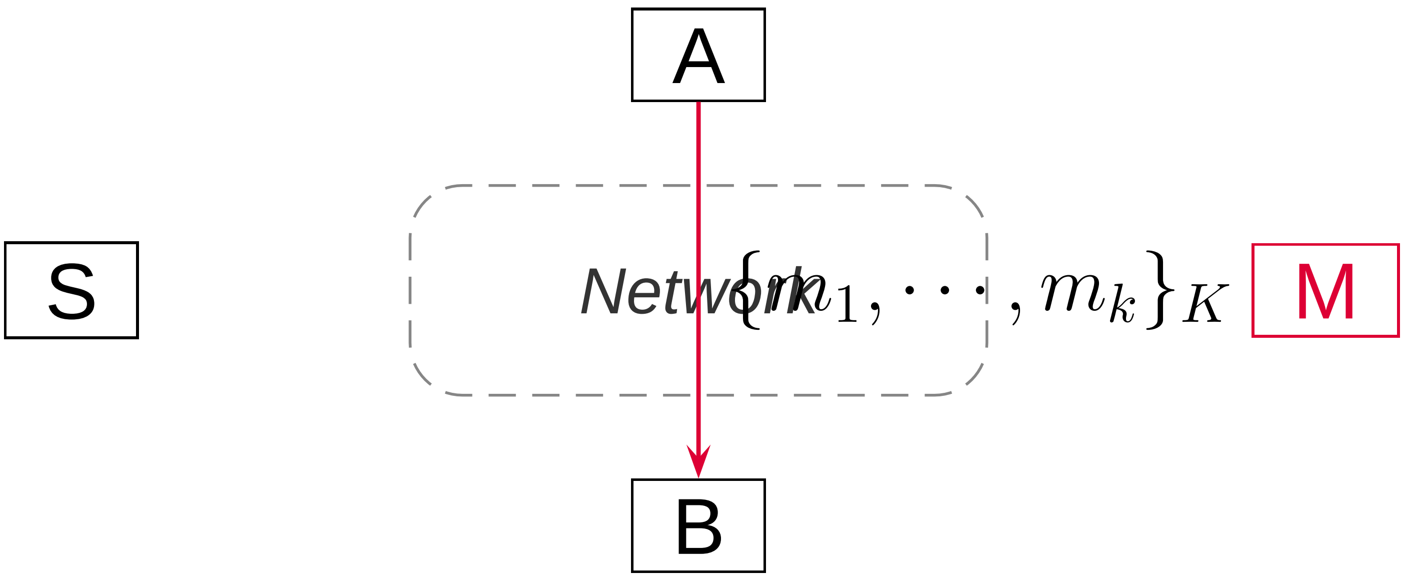
An Attack



Flawed protocol inspired by "Wide Mouthed Frog"

1.	$A \to S :$	$A, B, \{K\}_{K_A}$	$A \to S :$	$A, B, \{K\}_{K_A}$
2.	$S \to B :$	$A, \{K\}_{K_B}$	$S \to M(B) :$	$A, \{K\}_{K_B}$
3.	$A \to B :$	$\{m_1, \cdots, m_k\}_K$	$M(S) \to B :$	$C, \{K\}_{K_B}$

An Attack



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2.	$S \to B:$	$A, \{K\}_{K_B}$	$S \to M(B):$	$A, \{K\}_{K_B}$
3.	$A \to B:$	$\{m_1, \cdots, m_k\}_K$	$M(S) \to B:$	$C, \{K\}_{K_B}$
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Example Revisited

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The analysis of n instances of the protocol gives

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Analysis of Standard Protocols

Our analysis identifis a number of authentication flaws in symmetric key protocols such as Needham-Schroeder, Otway-Rees, Yahalom and Andrew Secure RPC. It shows that

- many classical problems occur precisely because some crucial distinctions (between identities and roles) are not sufficiently clear.
- Many protocols become insecure when old session keys are compromised.

General Considerations (1)

- The analysis identifies the well-known attacks on the protocols we have considered
- When well-known amendments are performed the analysis reports that there are no attacks
- Very few false positives
- Polynomial time validation procedure
- Improve the precision of the analysis

General Considerations (2)

The same approach is valid also for

- Other cryptographic features, such as asymmetric cryptography
- Other security properties (by checking other annotations): e.g. on freshness and type flaws, ...
- Other calculi: variations of LySa, Beta Binders, ...

Asymmetric Cryptography

$E ::=$	$n / (m^+, m-)$ key/key pair
$\{E_1, \cdots, E_k\}_{E_0}$	symm. encryption
$\{\!\mid E_1, \cdots, E_k \mid\!\}_{E_0}$	asymm. encryption
$P ::=$	...
$\langle E_1, \cdots, E_k \rangle . P$	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

symm. decryption (with matching)

decrypt E as $\{\!\mid E_1, \cdots, E_j; x_{j+1}, \cdots, x_k \mid\!\}_{E_0}$ in P

asymm. decryption (with matching)

$(\nu n)/(\nu m^+, m^-)P$	key/key pair creation

Considerations

- Our CFA (and the related tool) is able to deal with asymmetric cryptography
- The analysis identifies the well-known attacks on the protocols considered (e.g. Lowe's one on Needham Schroeder PK)
- The analysis discover an undocumented flow in the Beller-Chang-Jacobi MSR protocol

Some References (1)

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Some References (2)

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