AUTOMATIC VERIFICATION OF CRYPTOGRAPHIC PROTOCOLS

Privacy-type properties

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Context

Most communications take place over a public network

It is important to ensure their security

Cryptographic protocols

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- small programs designed to secure communication (e.g. secrecy)
- use cryptographic primitives (e.g. encryption, signature)

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- Reliable cryptography
- Correct protocol specification
- Implementation satisfying the specification

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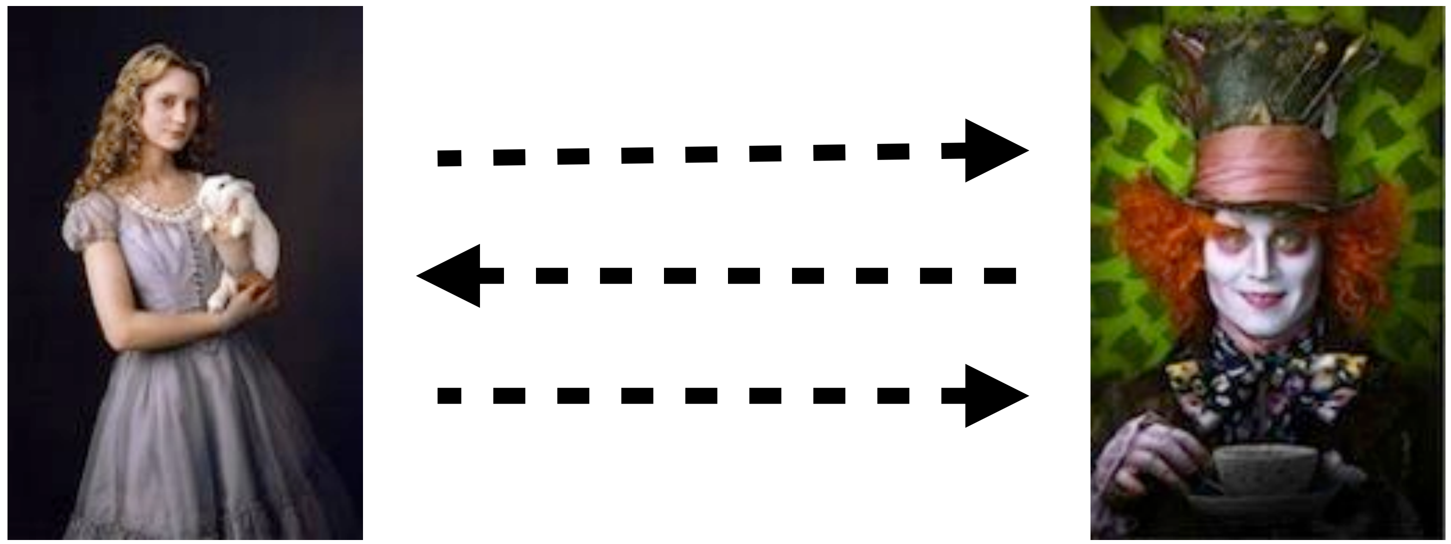
Symbolic model

Alice

Bob

Symbolic model



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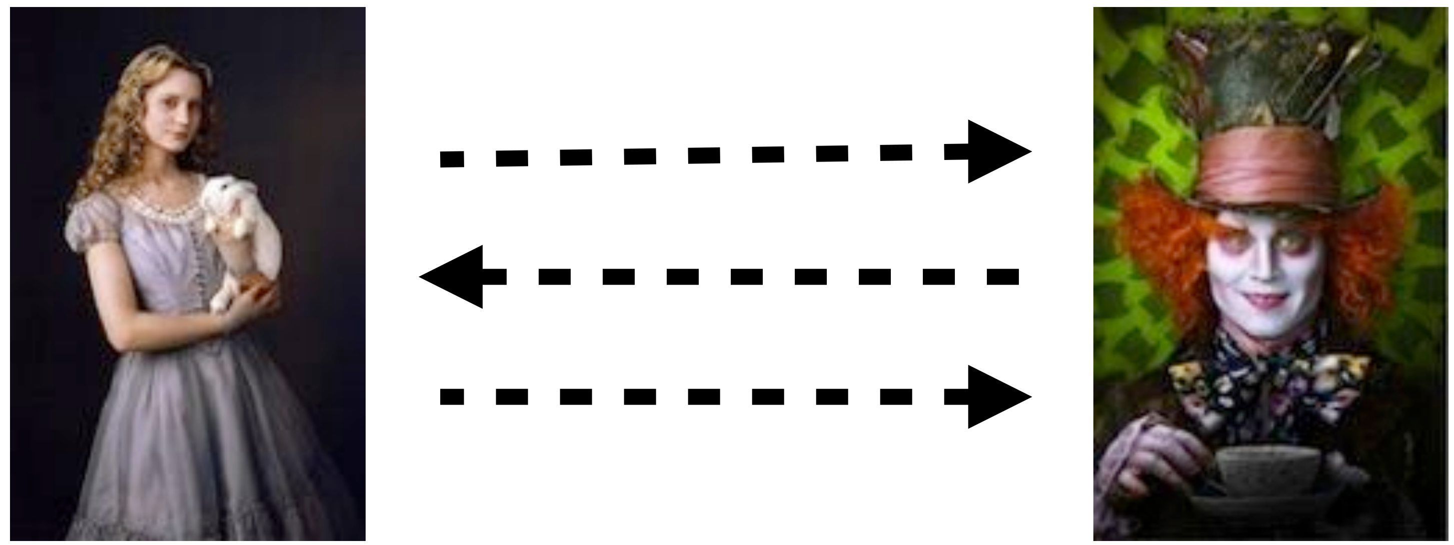

Alice Bob

- We assume perfect cryptographic primitives
- Messages are represented by terms

$$\{N\}_{\mathsf{pk}(k)} \qquad \langle N, M\rangle \qquad \mathsf{adec}(\{N\}_{\mathsf{pk}(k)}, k)$$

Symbolic model

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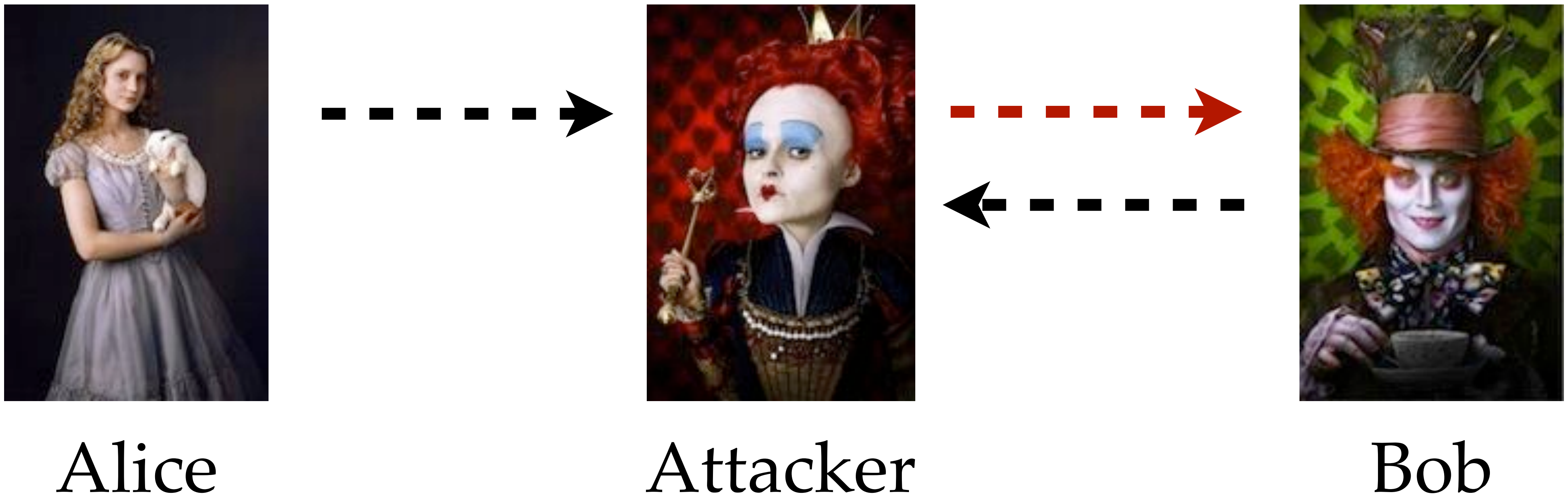

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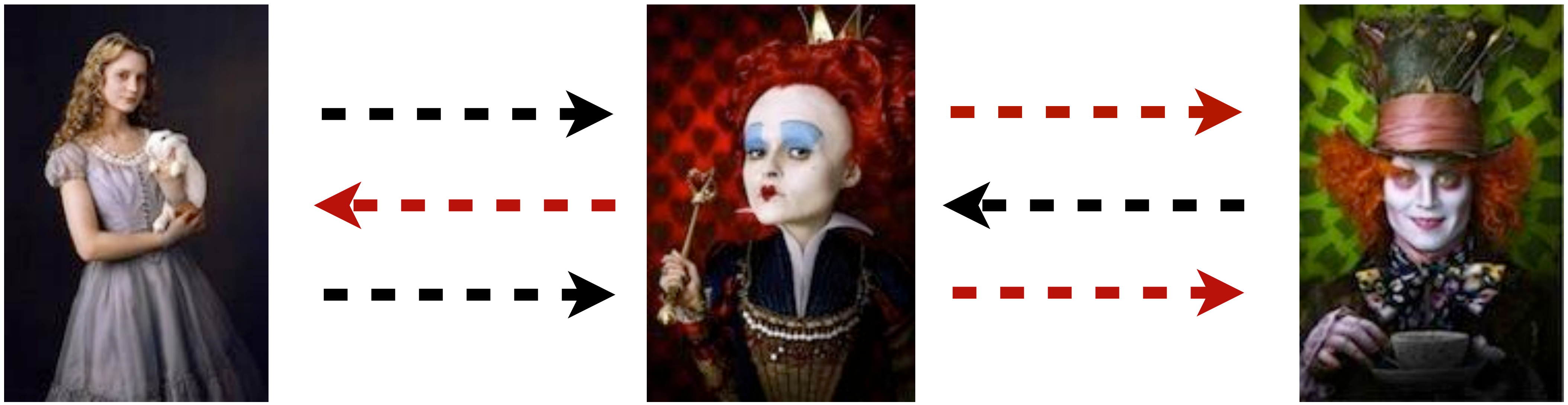

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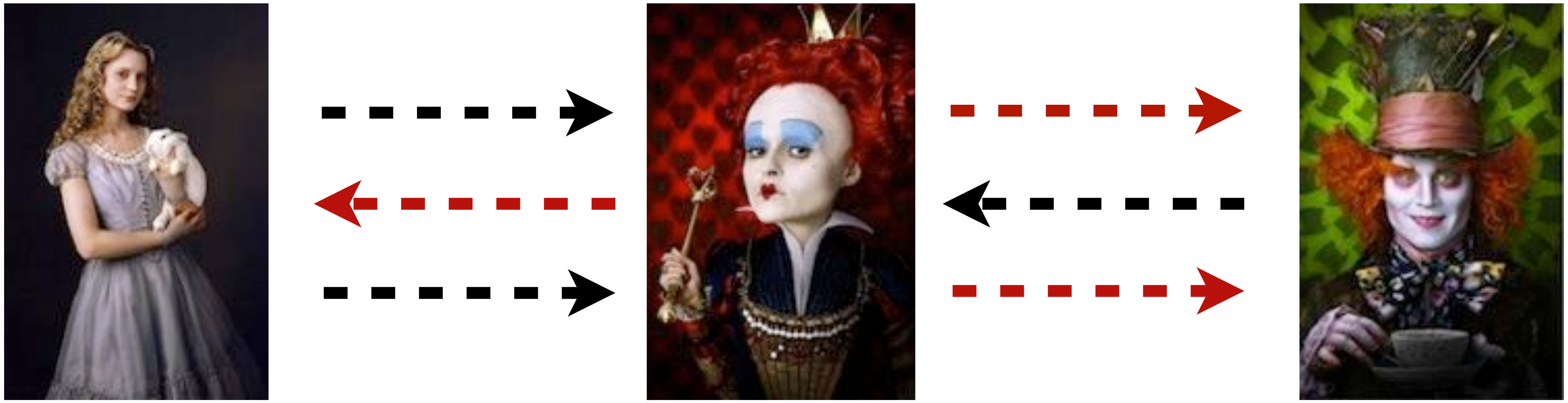


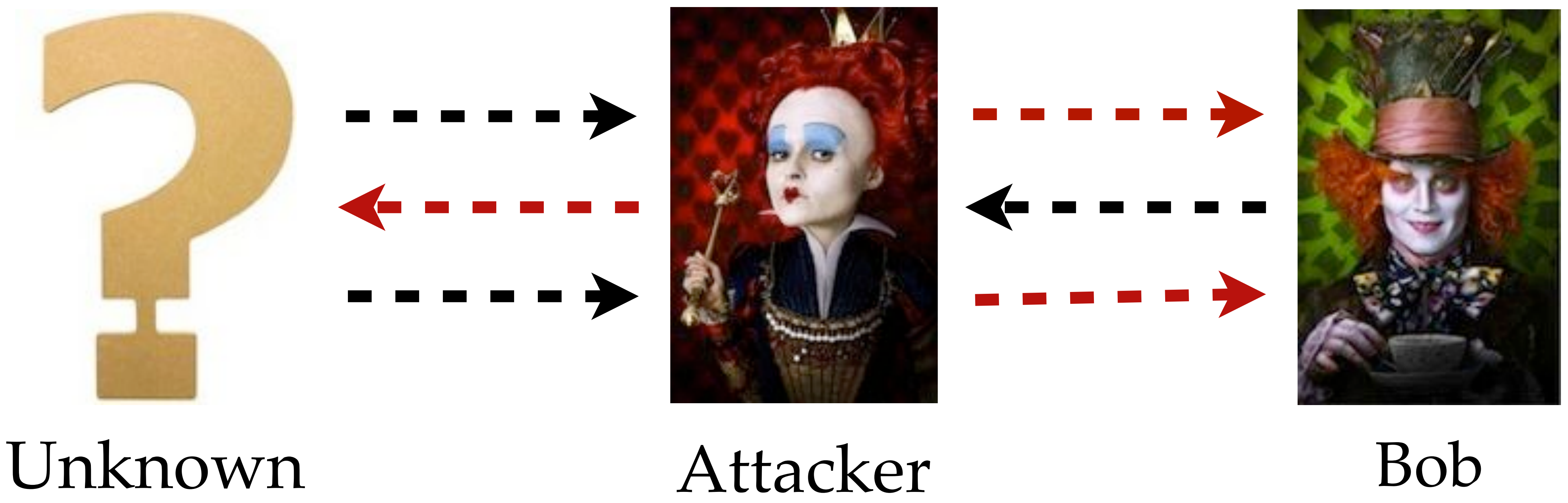
Alice Attacker Bob

Security properties:

- Reachability properties
- Equivalence properties

Security properties

Equivalence properties: anonymity



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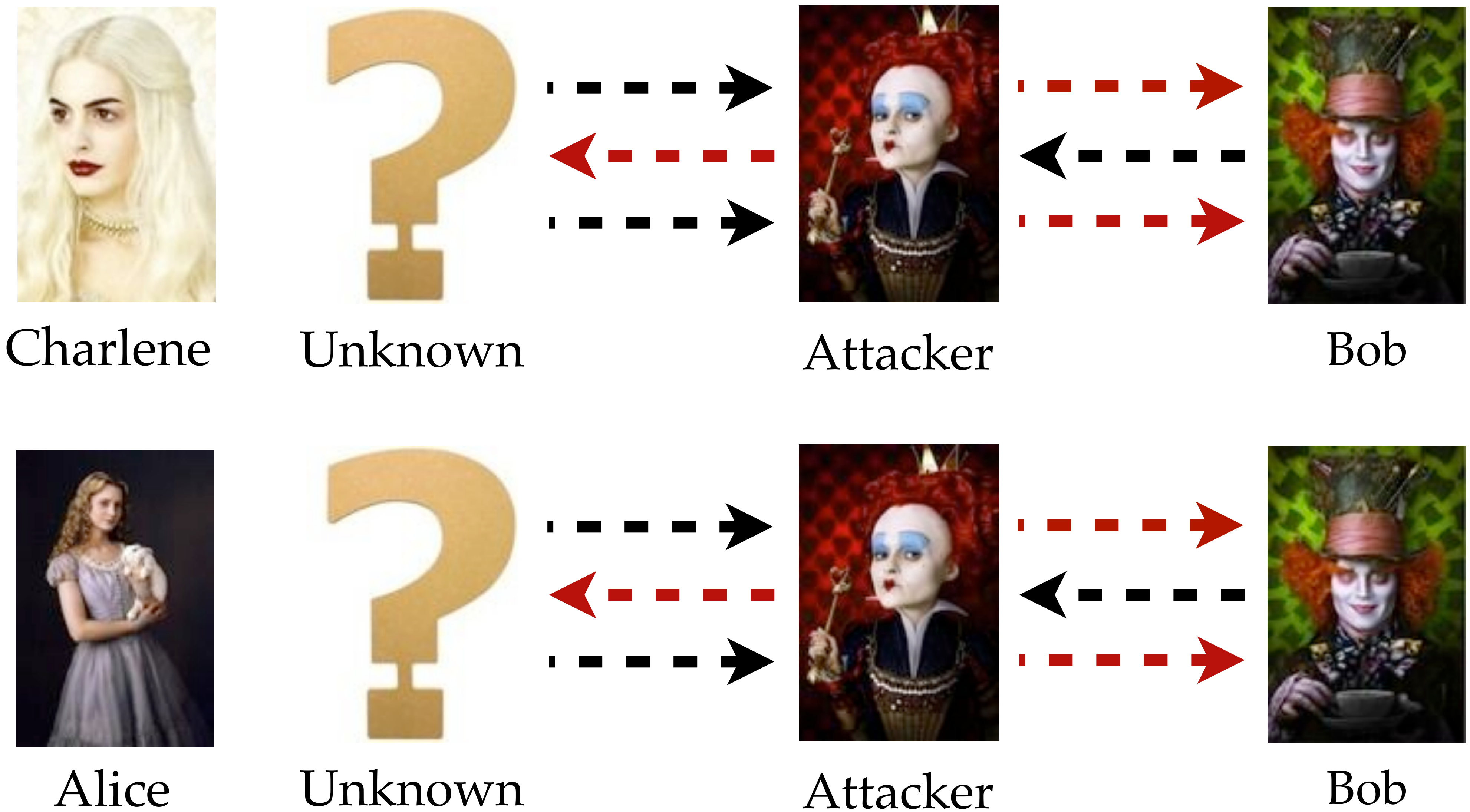

Security properties

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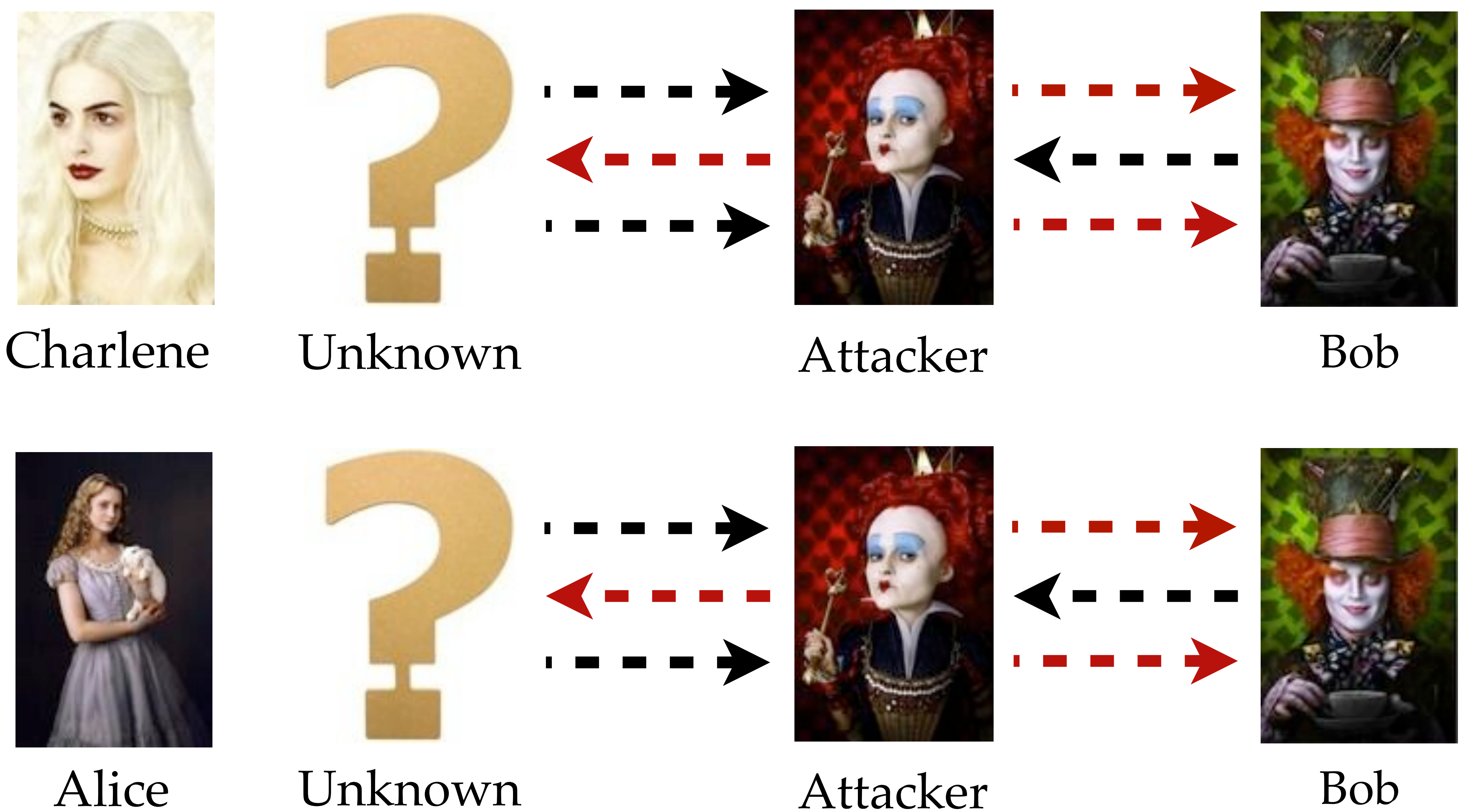
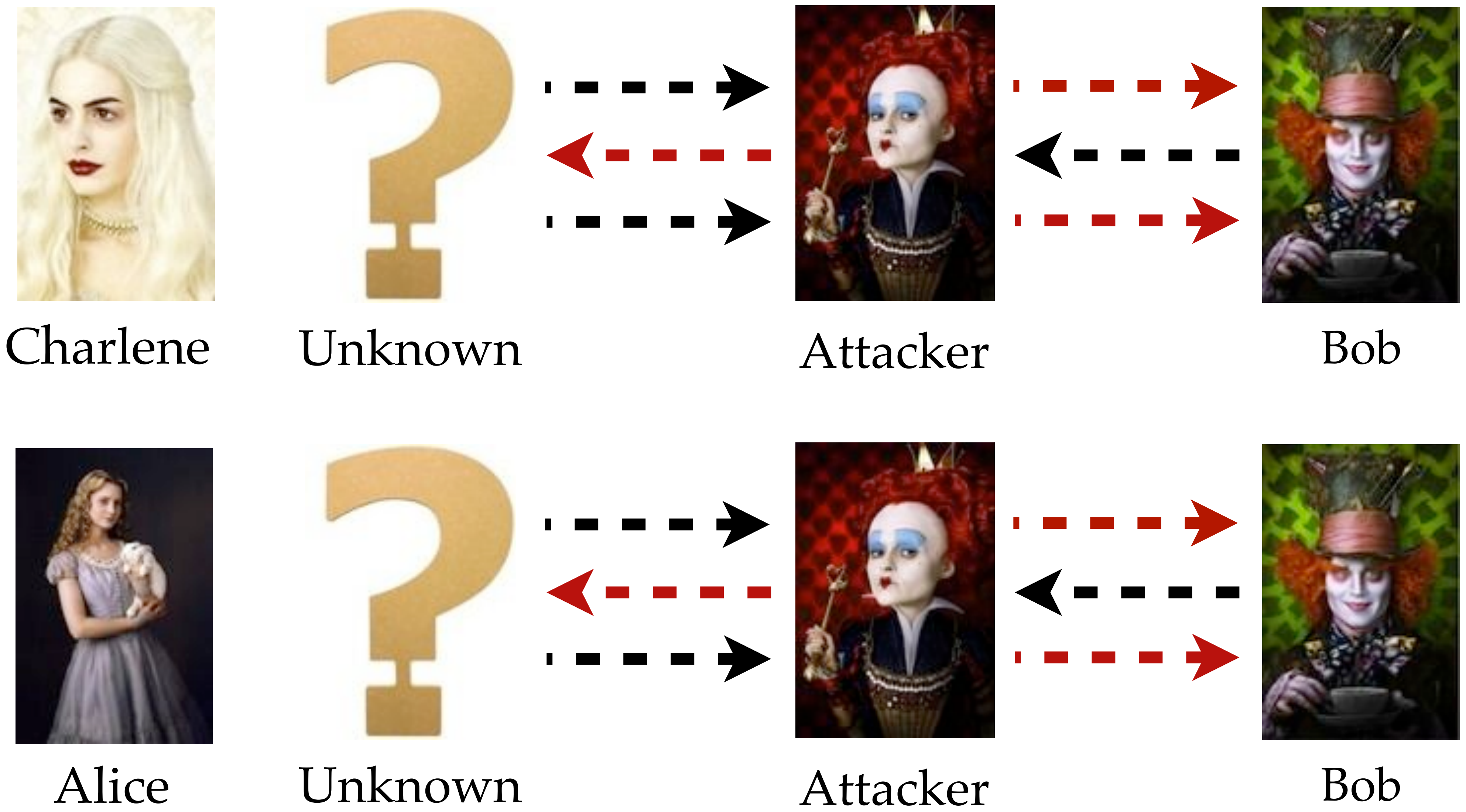


Can the intruder distinguish the two situations ?

Security properties

Equivalence properties: anonymity



Trace equivalence

Examples

Private authentication protocol

Examples

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$\{\langle N_a, \mathsf{pk}(k_A)\rangle\}_{\mathsf{pk}(k_B)}$

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$\mathsf{pk}(k_A)$?

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Examples

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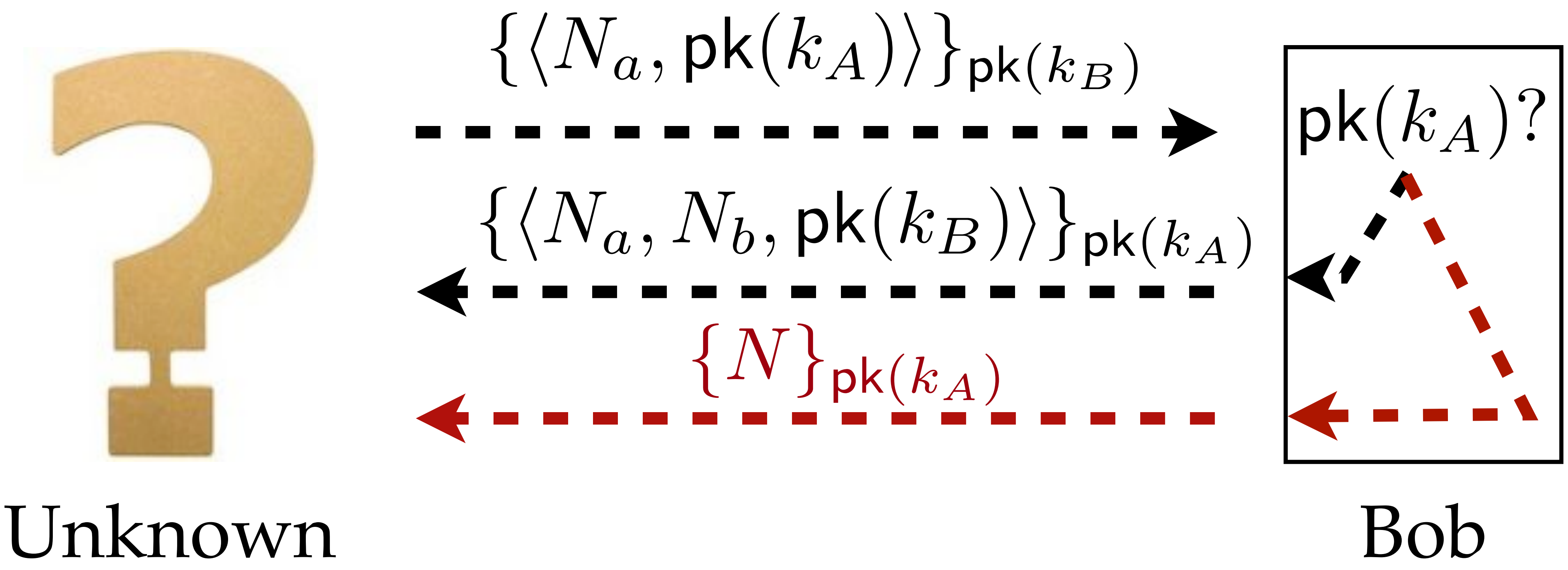

Automatic tools

- For reachability properties

  Avispa, CSP/FDR, ProVerif, Scyther, Maude-NPA, ...

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  • **ProVerif:** Bruno Blanchet. *An Efficient Cryptographic Protocol Verifier Based on Prolog Rules.*
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> Do not handle private authentication protocol and e-passport protocol

My contributions

- Relations between different notions of equivalences
- Algorithms to prove equivalence
  - ✓Extension of ProVerif
  - ✓New decision procedure for trace equivalence (else branches)
  - ✓New automatic tool : APTE
- Composition result for trace equivalence
  - ✓Application on the e-passport protocol

Outline

1. Proving more equivalence with ProVerif

2. Decision procedure for trace equivalence

3. Composing trace equivalence

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Proverif

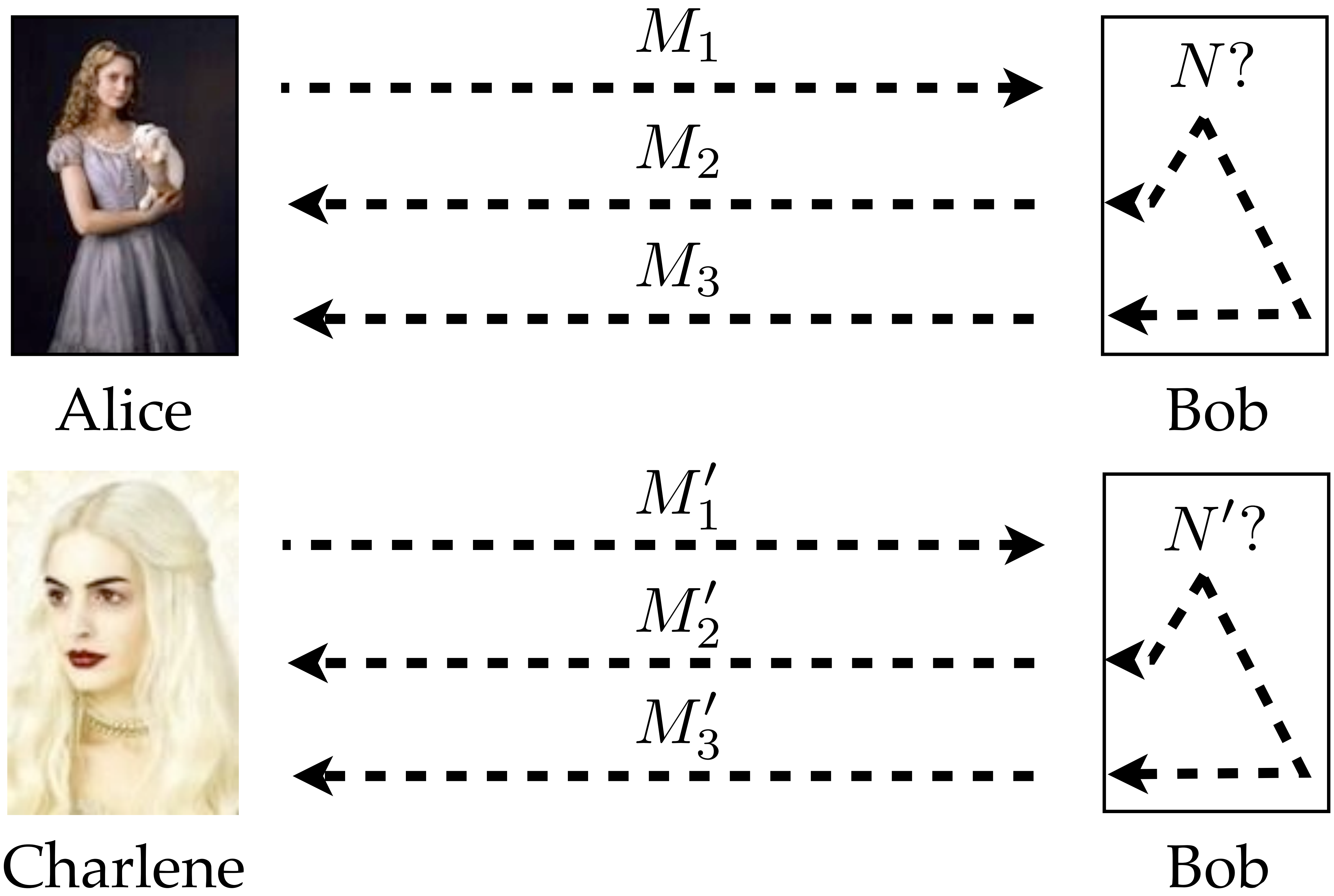
ProVerif was first an analyzer for reachability properties based on Horn clauses.

- Handle reachability and equivalence properties
- Cryptographic primitives described by equational theory and/or rewriting rules
- Handle processes with replication
- Possible false attack
- Does not always terminate

Processes

$$
\begin{aligned}
P, Q := \quad & 0 \\
& \mathsf{in}(c, x); P \\
& \mathsf{out}(c, M); P \\
& P \mid Q \\
& !\, P \\
& \mathsf{new}\ a; P \\
& \mathsf{let}\ x = D\ \mathsf{in}\ P\ \mathsf{else}\ Q
\end{aligned}
$$

Biprocesses



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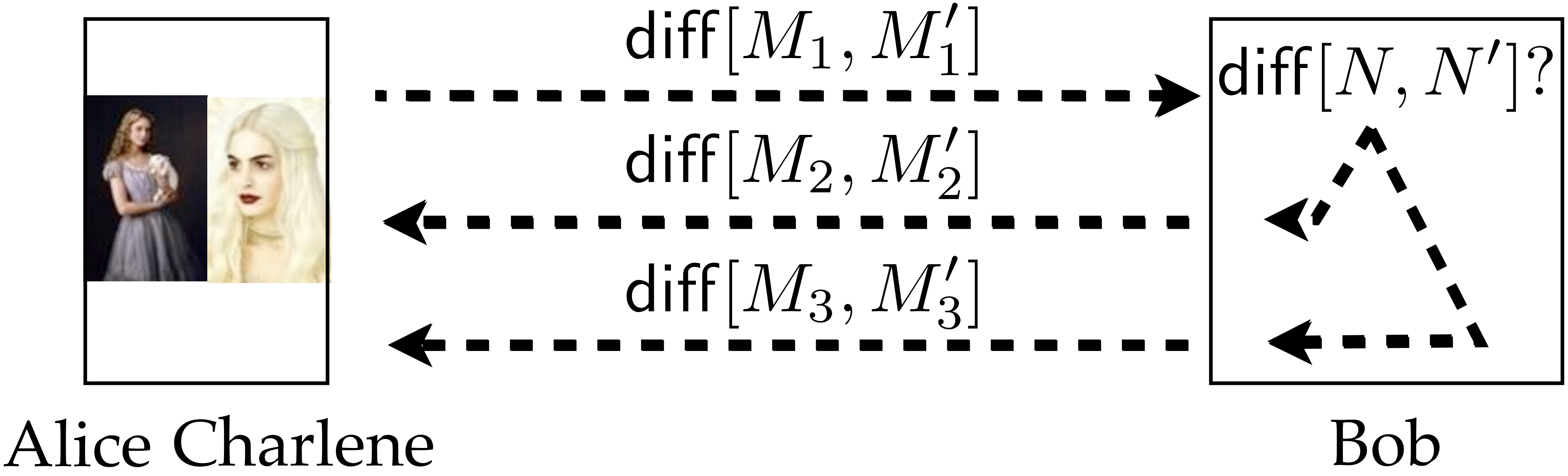

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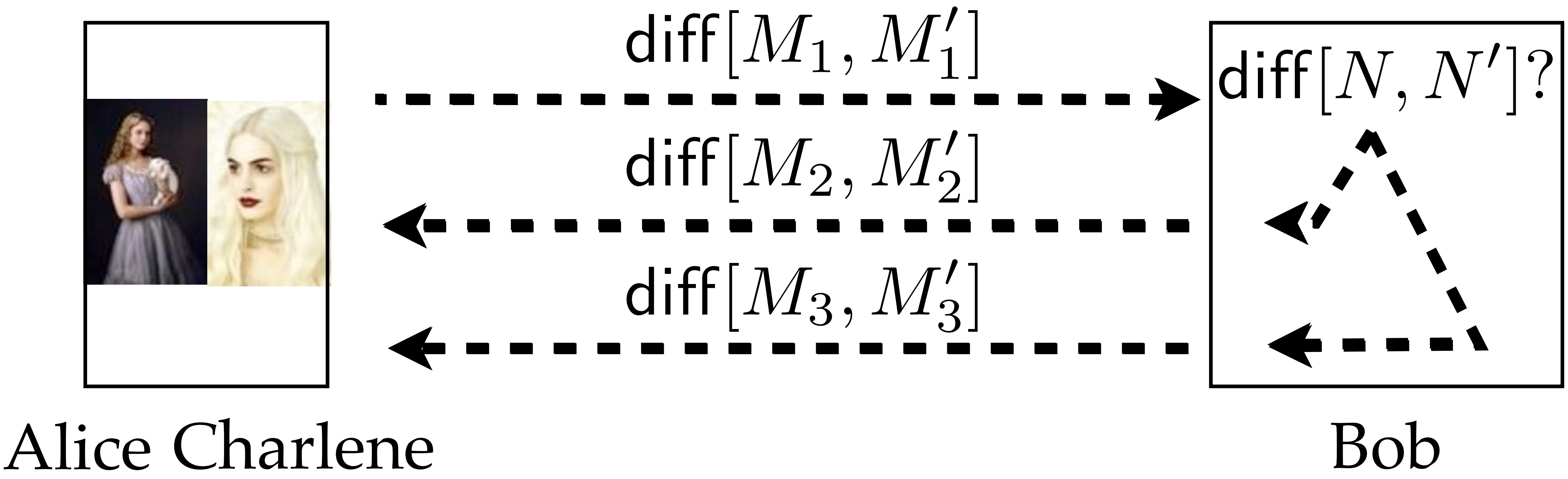

Equivalence too strong: possible false attack

Motivation

The private authentication protocol

Alice

Attacker

Bob

Charlene

Attacker

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Motivation

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$\{\langle N_a, \mathsf{pk}(k_A)\rangle\}_{\mathsf{pk}(k_B)}$

$\{\langle x, y\rangle\}_{\mathsf{pk}(k_B)}$

Alice

$\mathsf{pk}(k_A) = y$

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$\{\langle x, N_b, \mathsf{pk}(k_B)\rangle\}_y$

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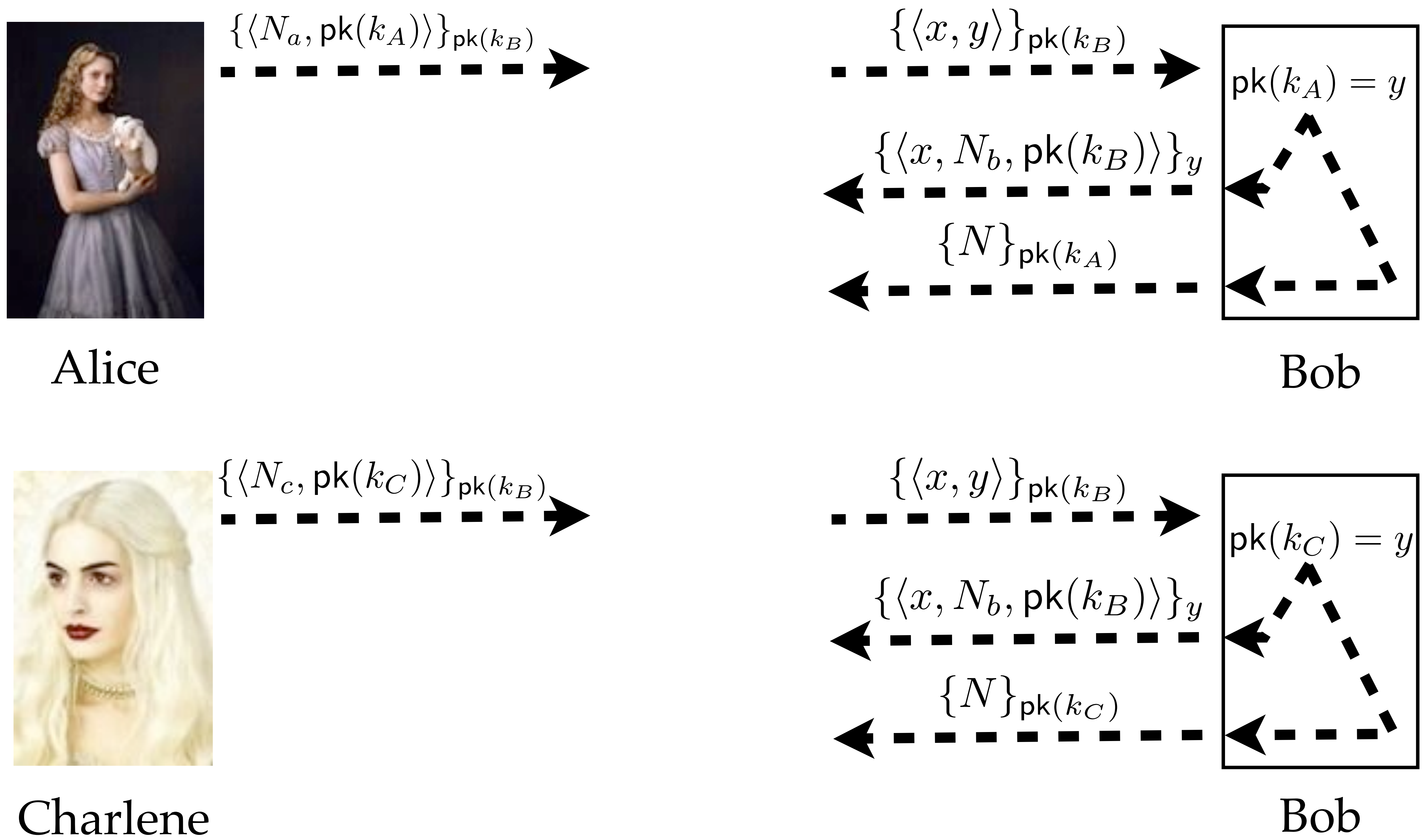

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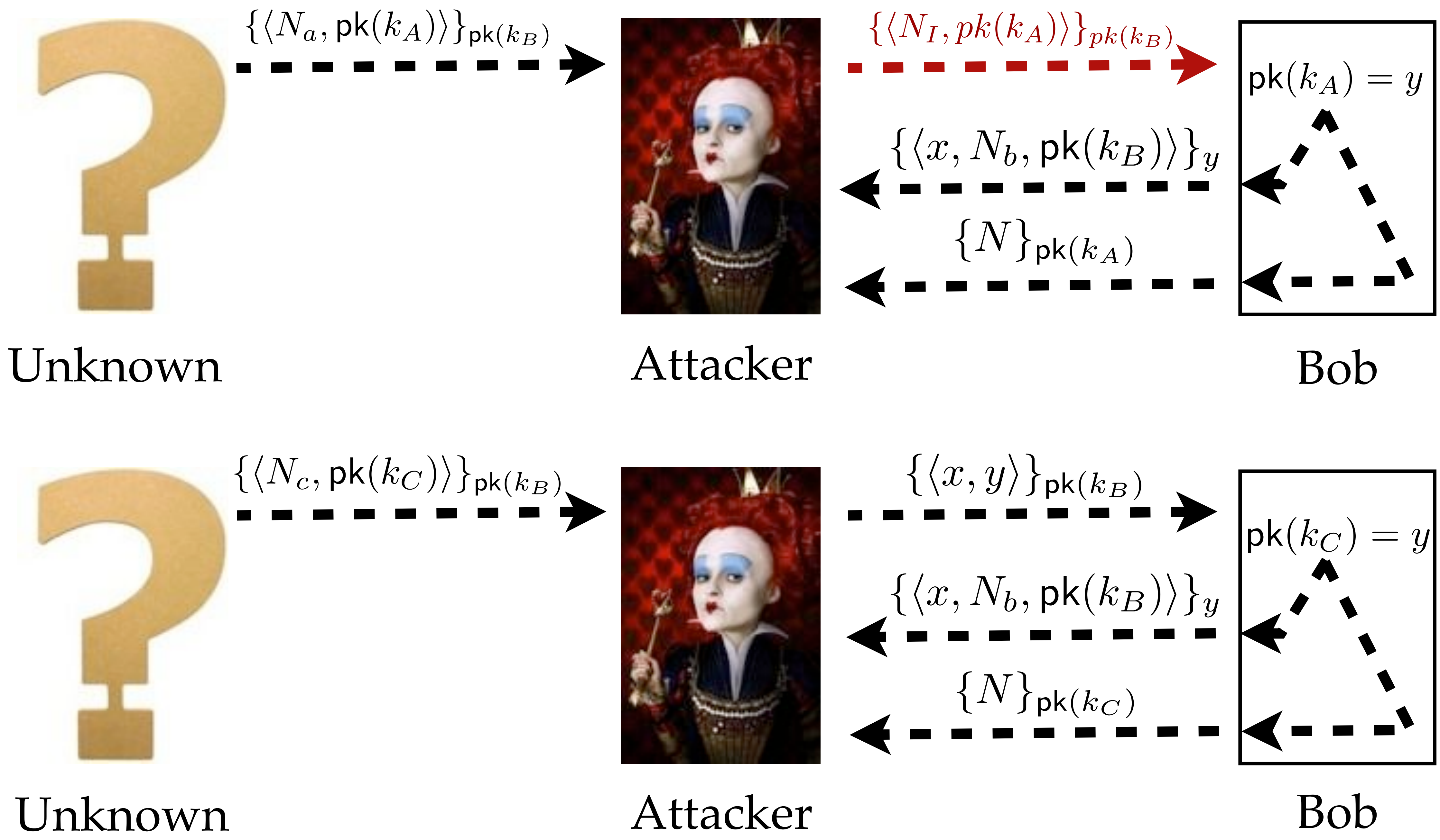

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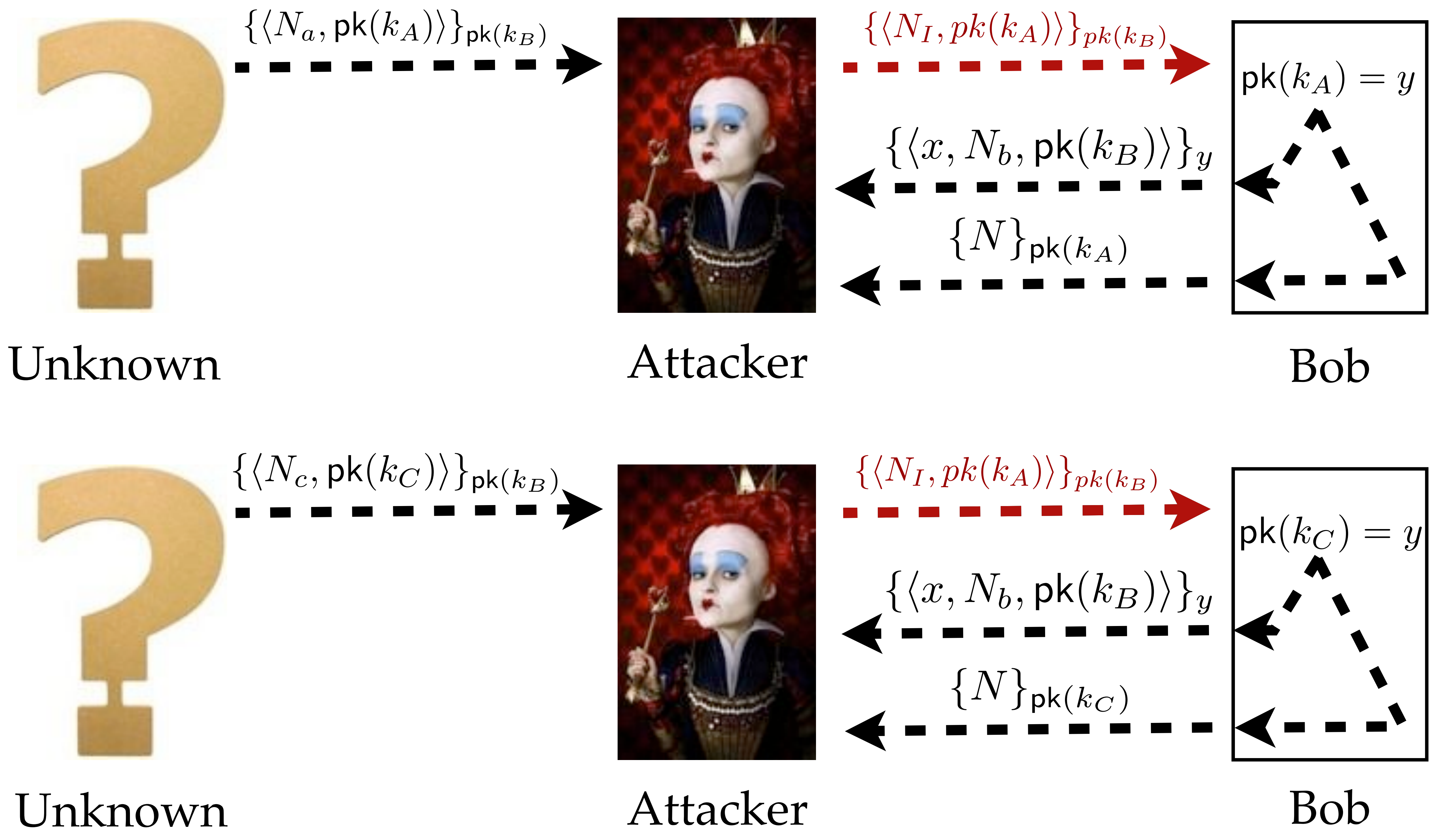

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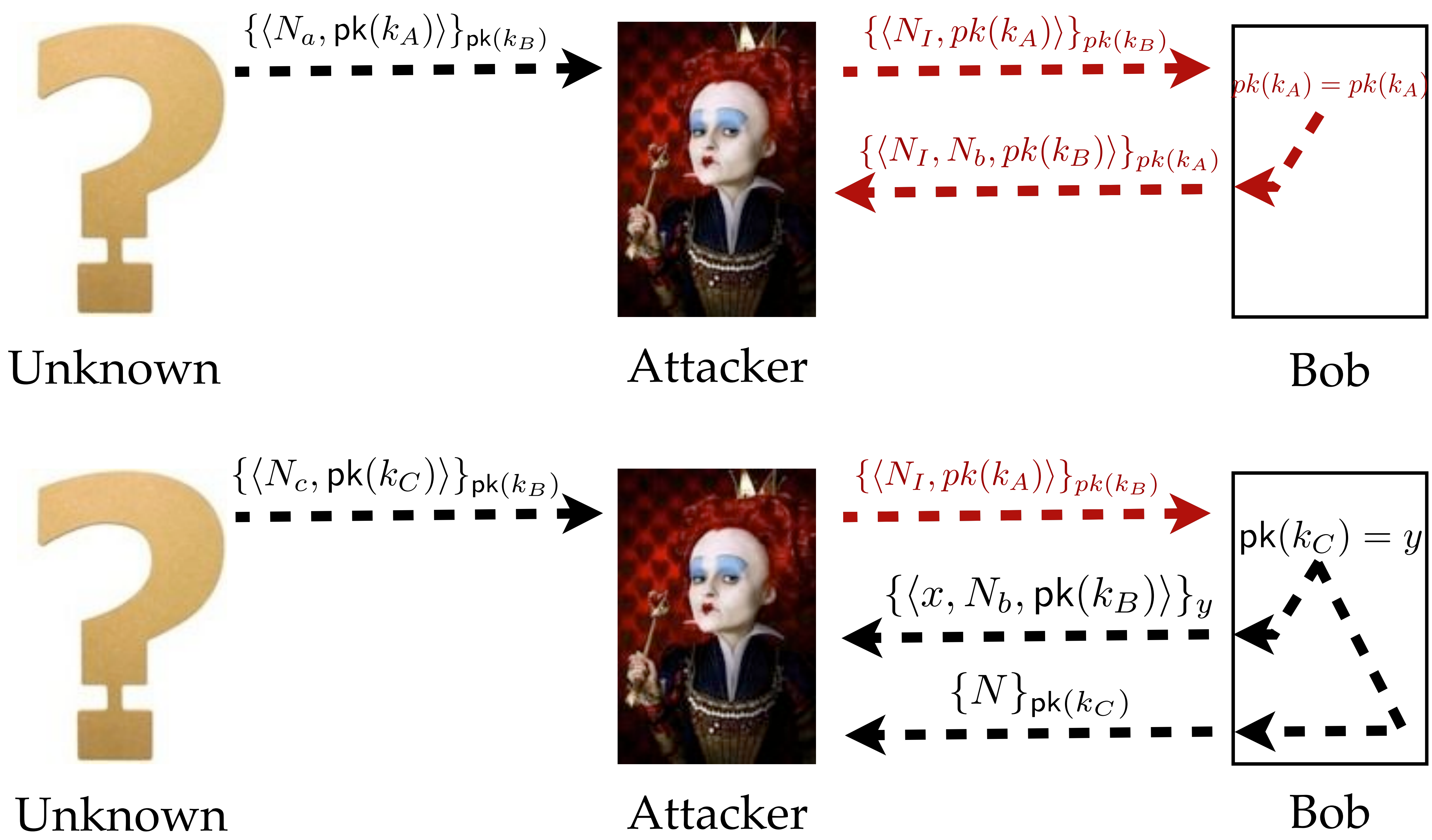

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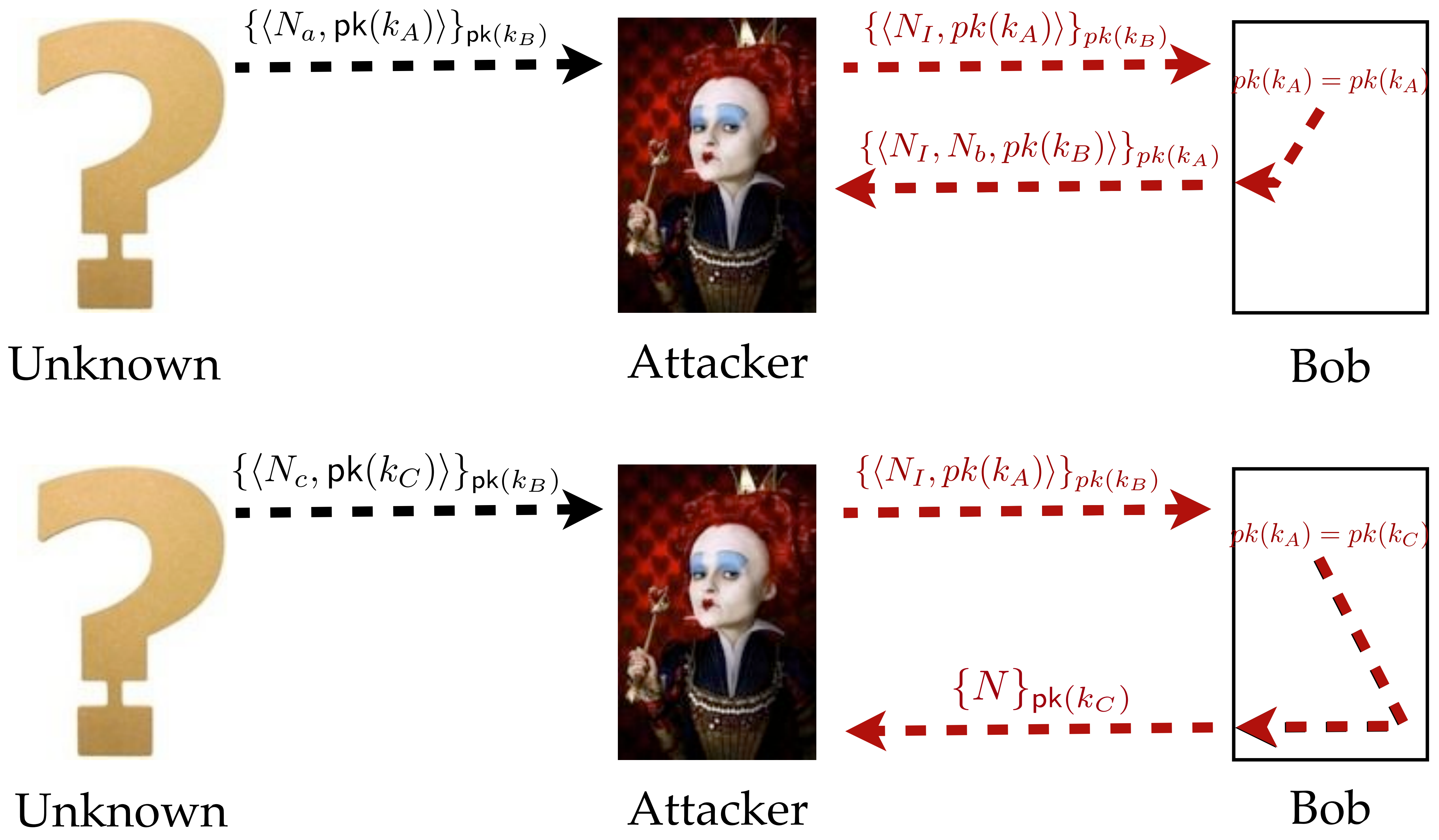

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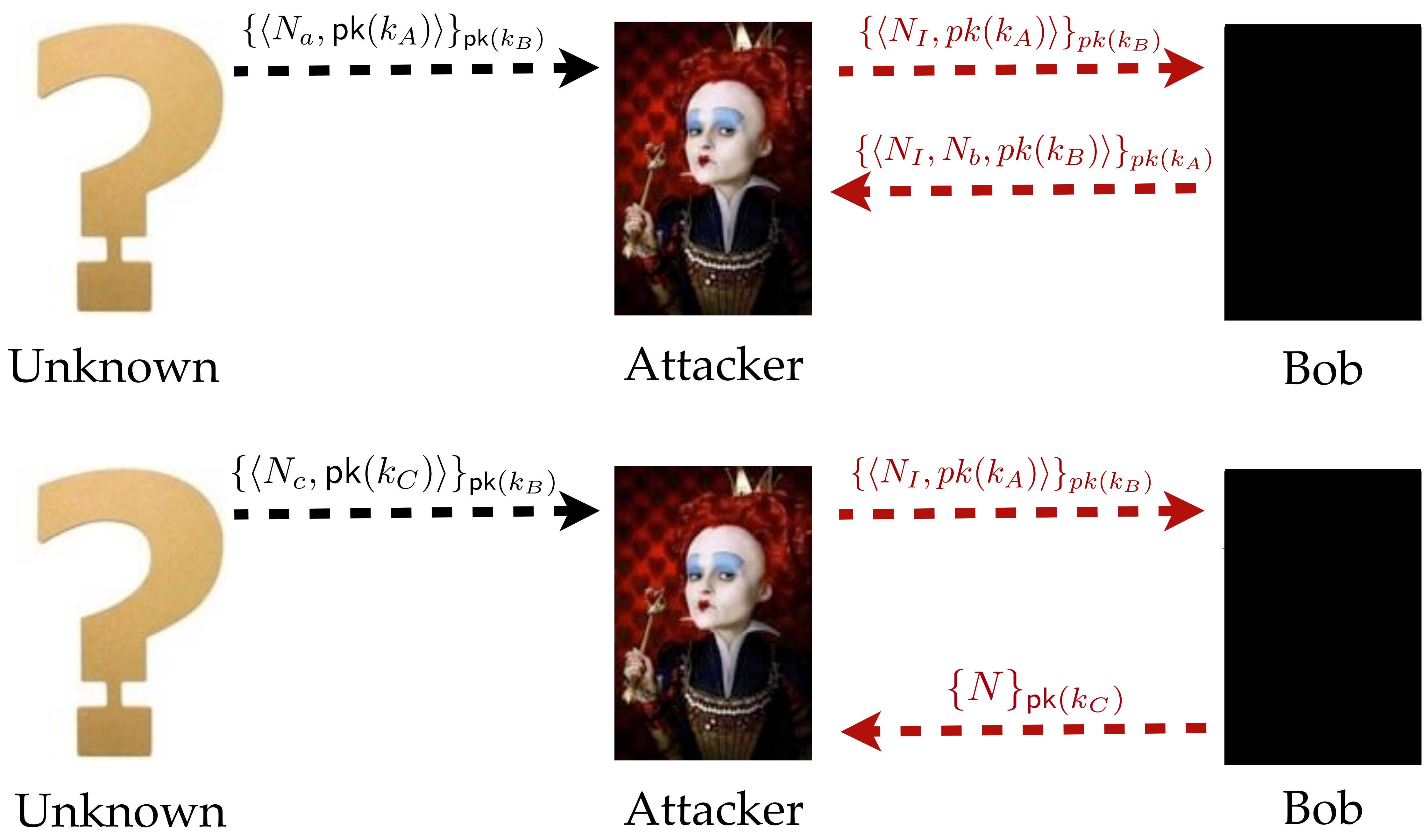

Contribution

Introduction of destructors with tests between terms

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The *If-then-else* destructor:

$$\mathsf{ifthenelse}(x, x, z, t) \rightarrow z$$

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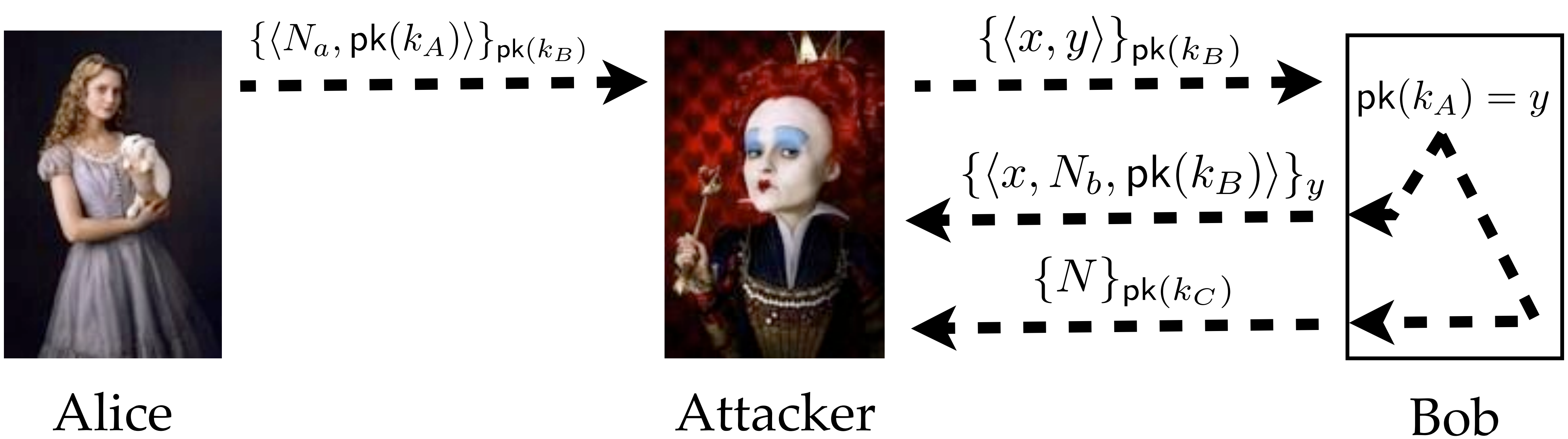

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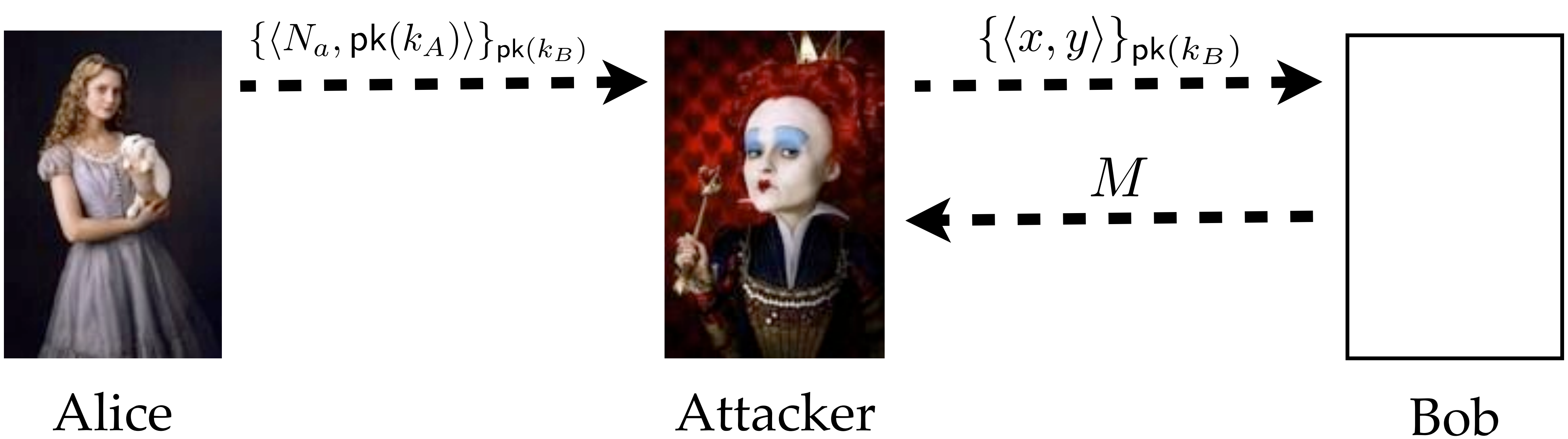

$$M = \mathsf{ifthenelse}(y, \mathsf{pk}(k_A), \{x, N_b, \mathsf{pk}(k_B)\}_y, \{N\}_{\mathsf{pk}(k_A)})$$

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Automatic transformation: *simpl*

For all processes P, $simpl(P) \approx P$

Implementation

Beta release:

ProVerif version 1.87beta

http://prosecco.gforge.inria.fr/personal/bblanche/proverif/

Content:

- Rewrite rules with tests
- Automatic transformation of biprocesses
- Equivalence between processes with different control structures

Results:

- Prove anonymity for private authentication protocol (unbounded number of sessions)

Outline

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2. Decision procedure for trace equivalence
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Constraint systems

One constraint system = several traces

Alice

Attacker

Bob

$\mathsf{pk}(k_A), \mathsf{pk}(k_B), \mathsf{pk}(k_C), N_I$

Constraint systems

One constraint system = several traces

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$$\mathsf{pk}(k_A), \mathsf{pk}(k_B), \mathsf{pk}(k_C), N_I, \{\langle N_a, \mathsf{pk}(k_A)\rangle\}_{\mathsf{pk}(k_B)} \vdash \{\langle x, y\rangle\}_{\mathsf{pk}(k_B)}$$

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$y = \mathsf{pk}(k_A)$

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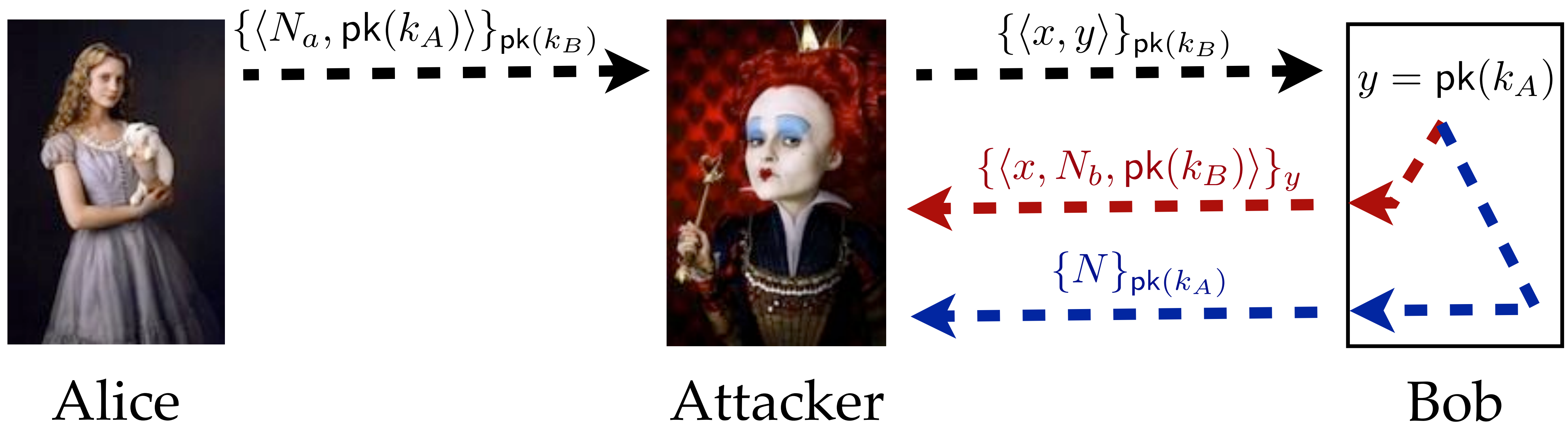

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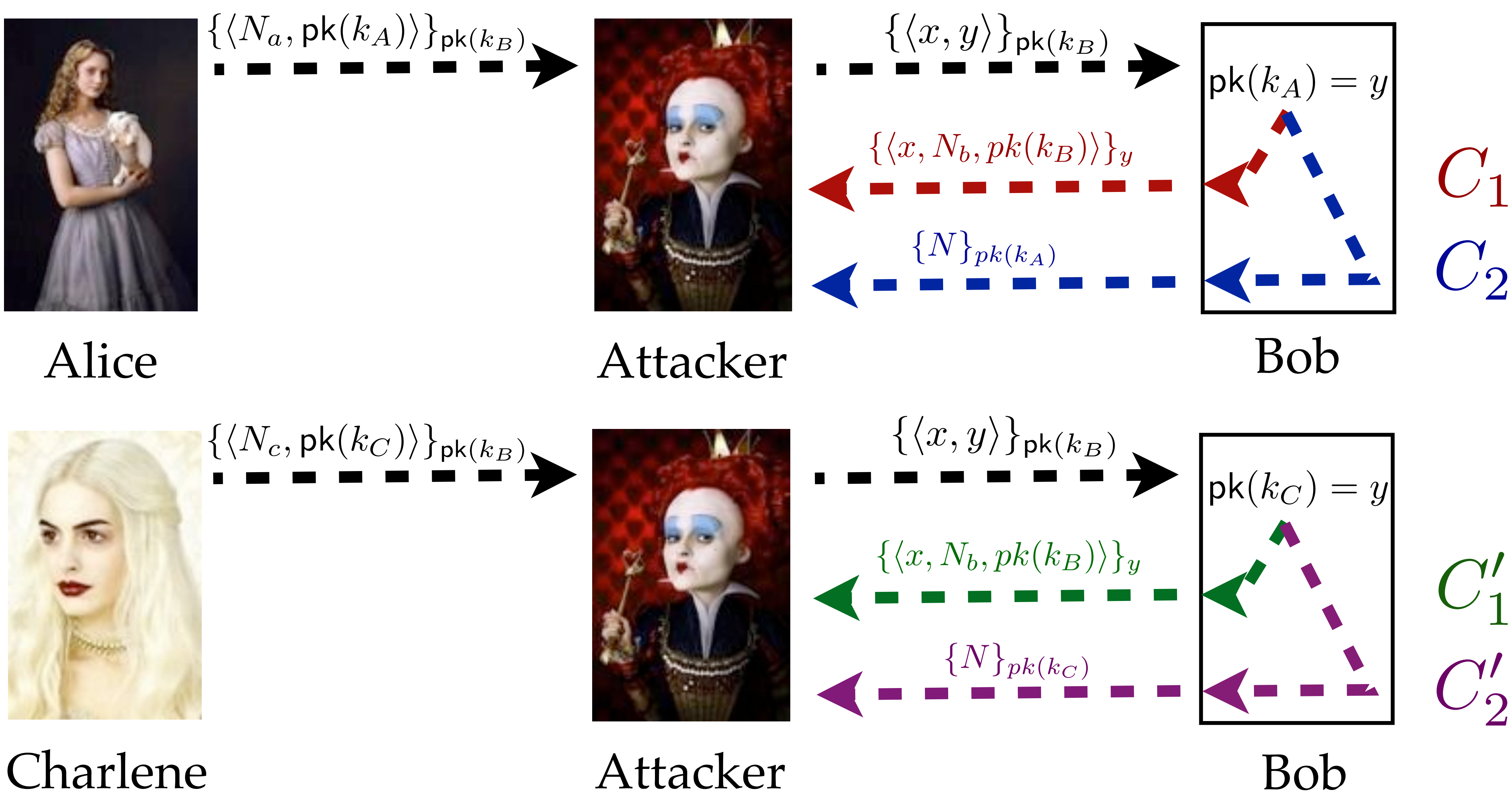
$$y \neq \mathsf{pk}(k_A)$$

Sets of constraint systems



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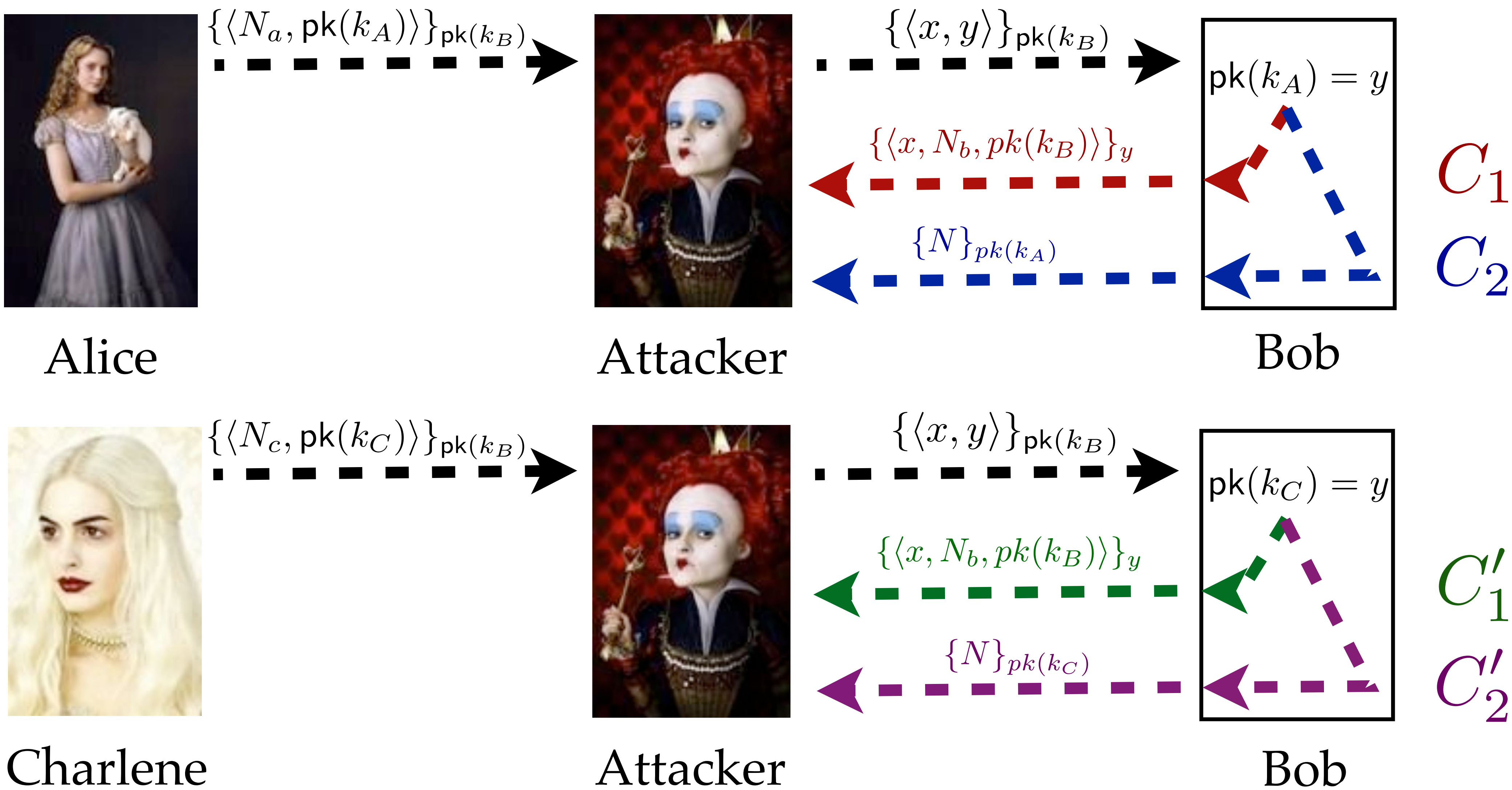
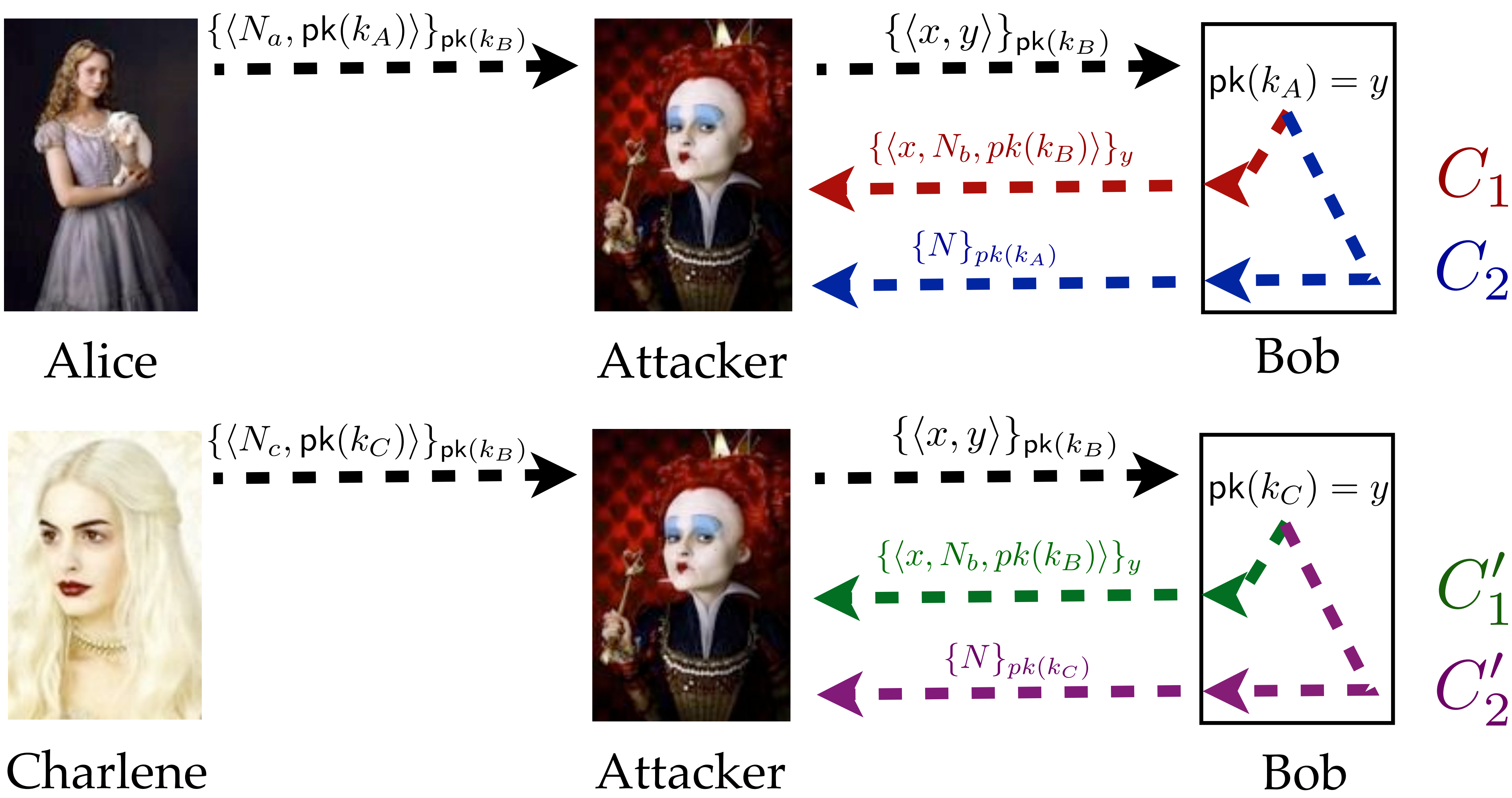


$$\{C_1;\ C_2\} \approx \{C'_1;\ C'_2\}$$

Sets of constraint systems



Symbolic equivalence between sets of constraint systems

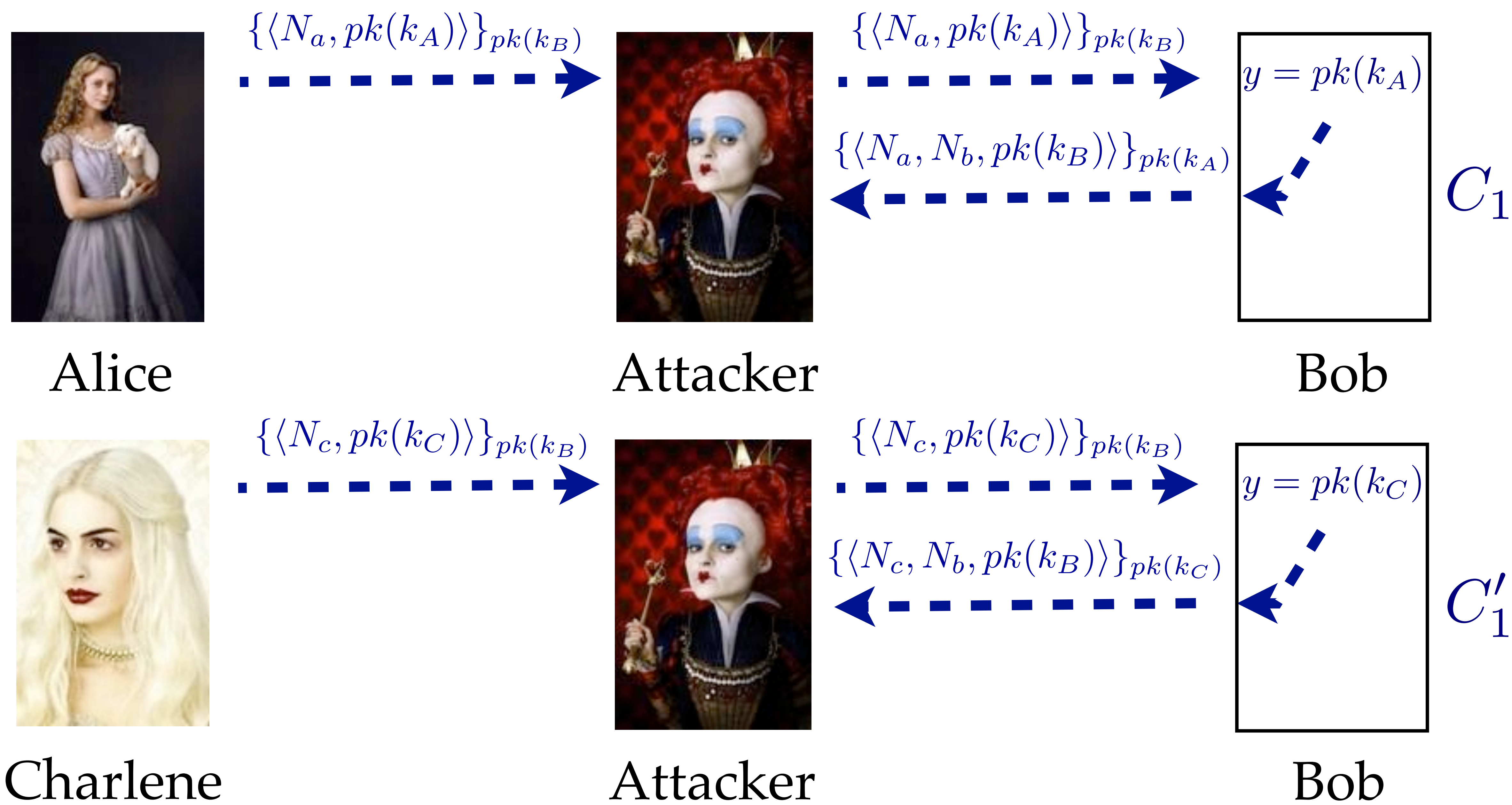
Previous works

1. M. Baudet. *Sécurité des protocoles cryptographiques : aspects logiques et calculatoires*. Phd thesis (2007)
2. Y. Chevalier and M. Rusinowitch. *Decidability of equivalence of symbolic derivations*. JAR (2012)
3. A. Tiu and J. E. Dawson. *Automating open bisimulation checking for the spi calculus*. CSF (2010)

- Do not handle set of constraint systems
- Do not handle inequations
- Do not handle non-deterministic processes

Sets of constraint systems

Why are they necessary ?



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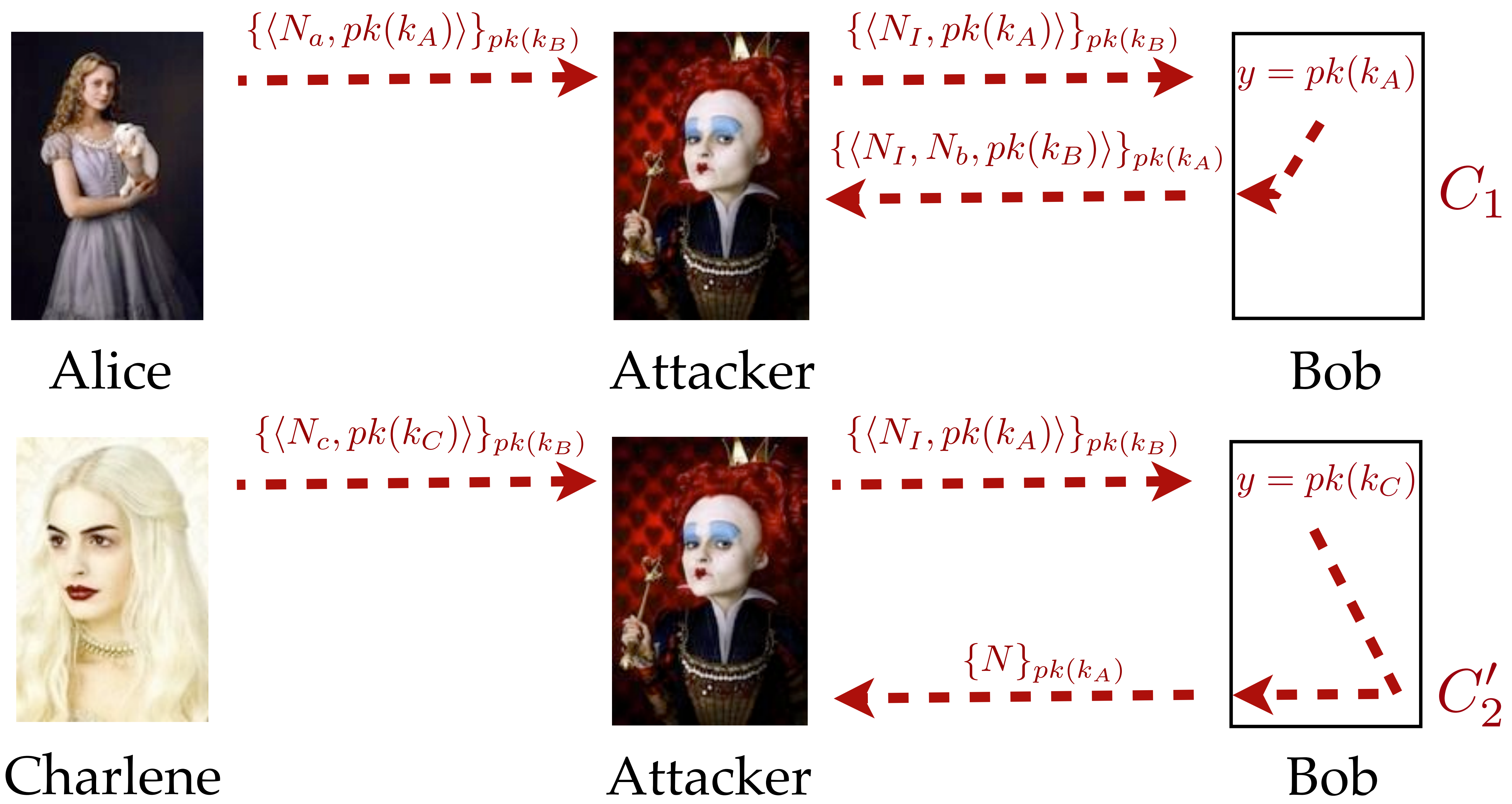

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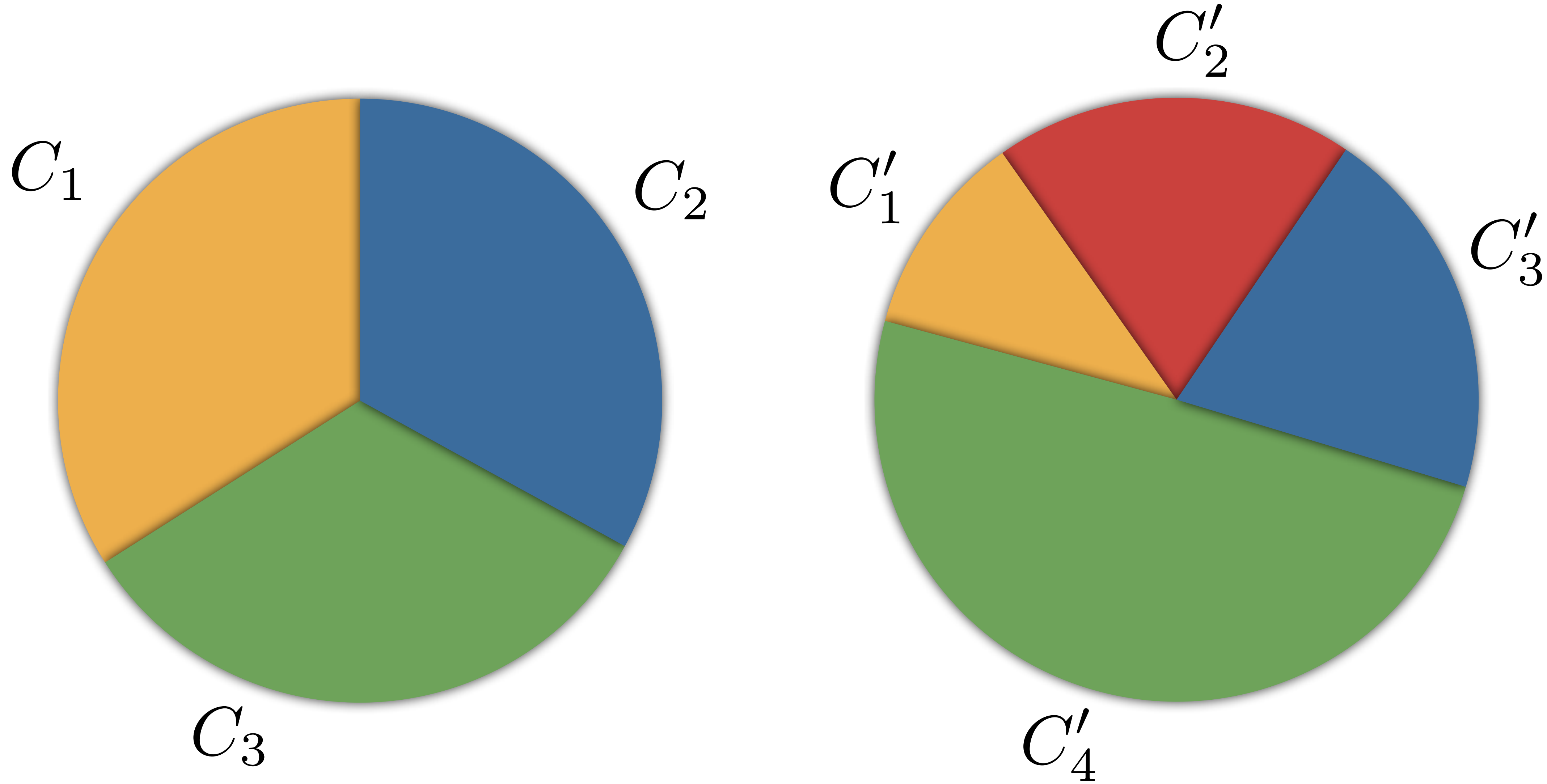
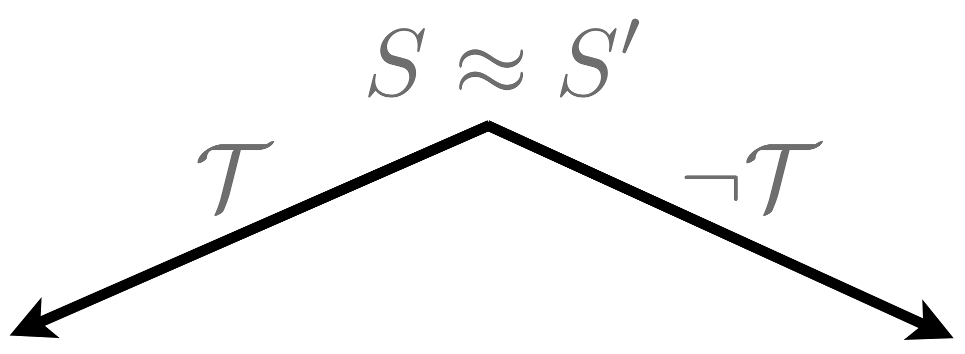


$S = \{C_1; C_2; C_3\}$ $\qquad$ $S' = \{C'_1; C'_2; C'_3; C'_4\}$

The Algorithm



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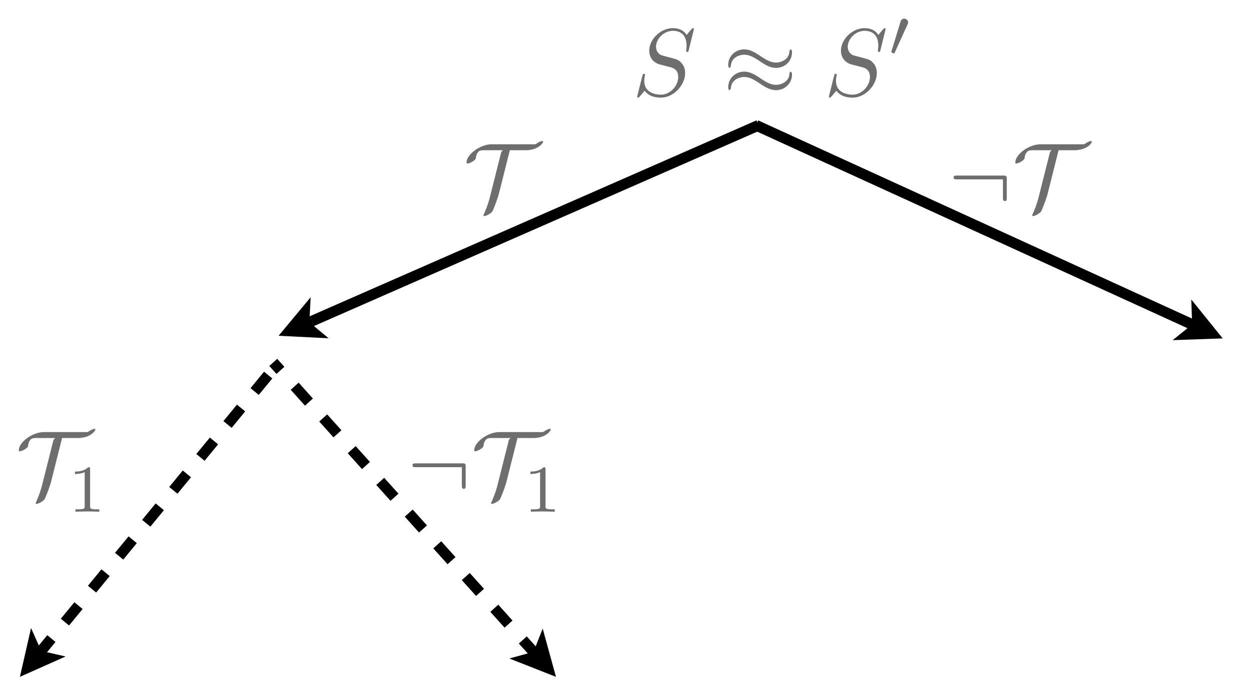

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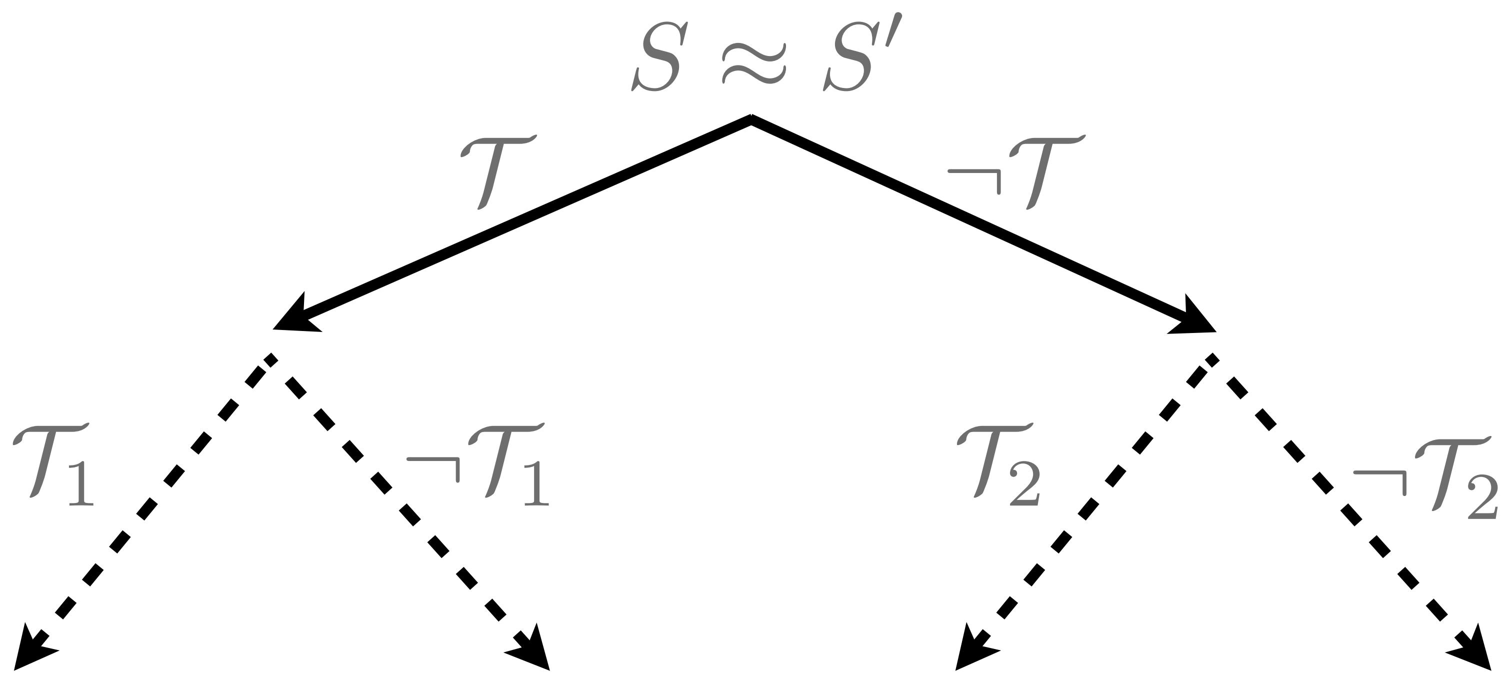

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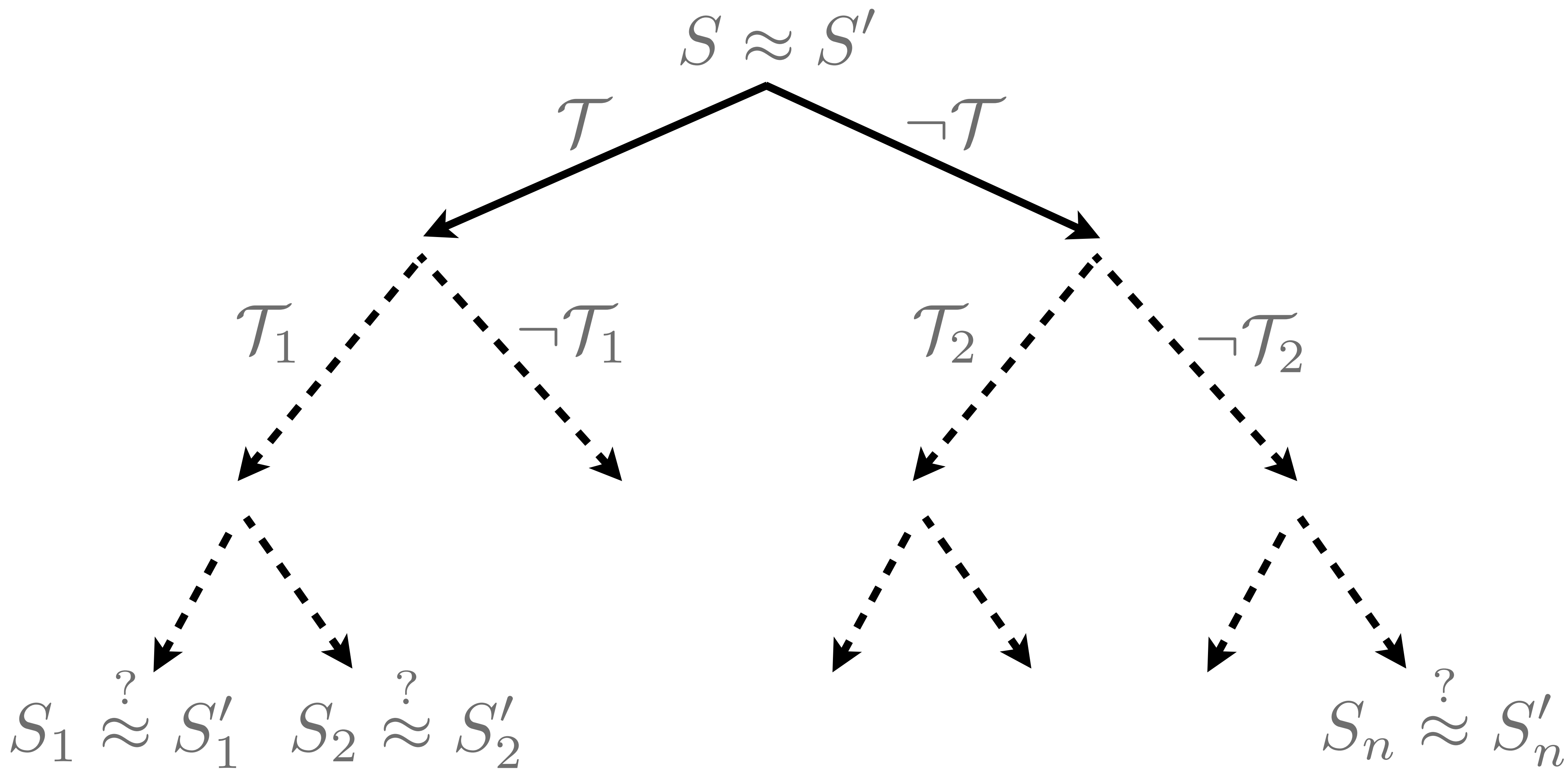

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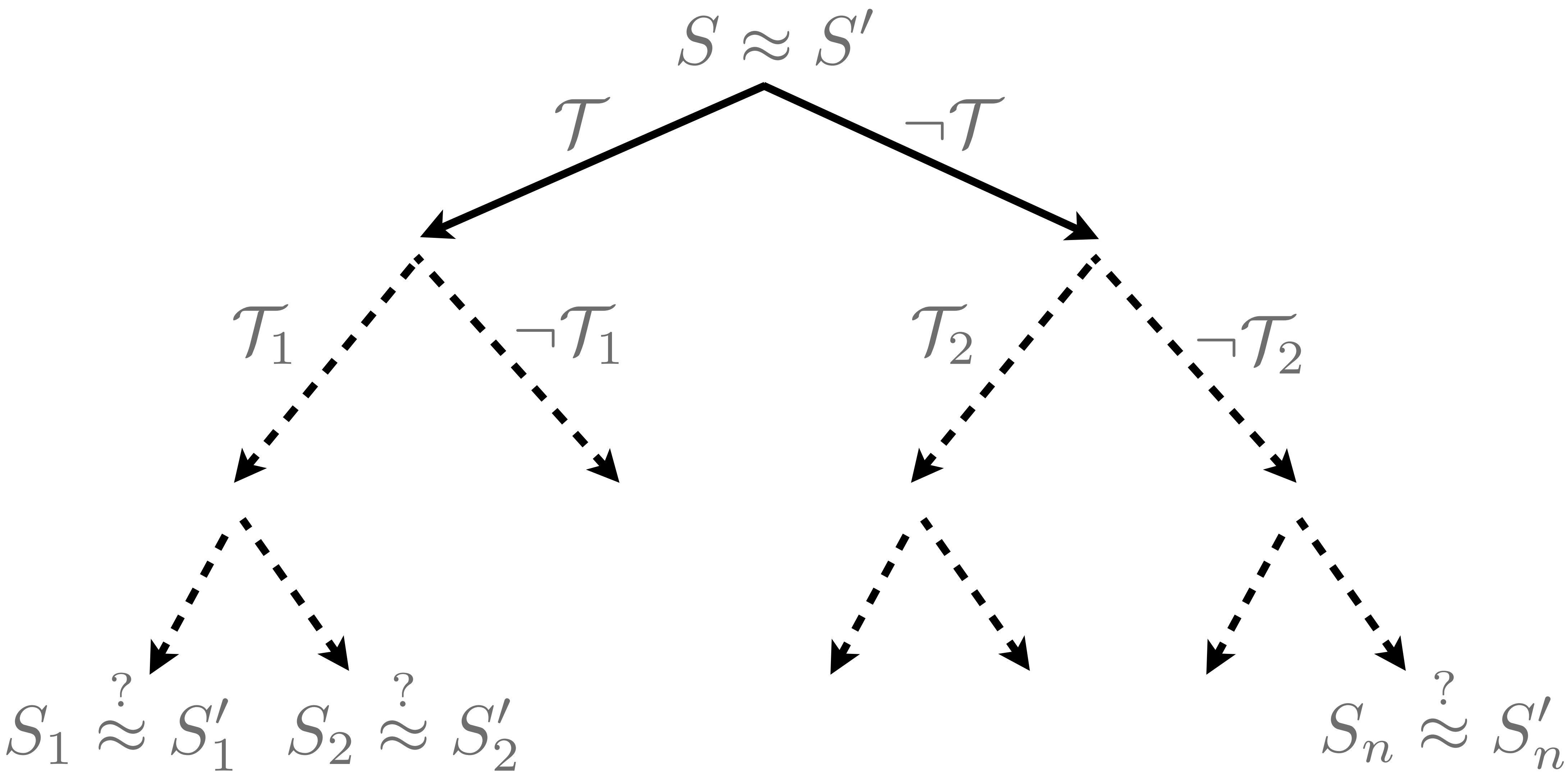

The symbolic equivalence is syntactically decided on each leaf

The Algorithm

Example of a rule

$$\begin{cases} \dots \\ T \vdash_X f(u_1, u_2) \\ \dots \end{cases}$$

The Algorithm

Example of a rule

$$\text{Test } \mathcal{T} = \exists X_1, X_2 \text{ s.t. } X = f(X_1, X_2)$$

$$\begin{cases} \dots \\ T \vdash_X f(u_1, u_2) \\ \dots \end{cases}$$

The Algorithm

Example of a rule

Test $\mathcal{T} = \exists X_1, X_2 \text{ s.t. } X = f(X_1, X_2)$

$$\begin{cases} \ldots \\ T \vdash_X f(u_1, u_2) \\ \ldots \end{cases}$$

$$\xrightarrow{\mathcal{T}}$$

$$\begin{cases} \ldots \\ T \vdash_{X_1} u_1 \\ T \vdash_{X_2} u_2 \\ X = f(X_1, X_2) \\ \ldots \end{cases}$$

The Algorithm

Example of a rule

Test $\mathcal{T} = \exists X_1, X_2 \text{ s.t. } X = f(X_1, X_2)$

$$\begin{cases} \ldots \\ T \vdash_X f(u_1, u_2) \\ \ldots \end{cases}$$

$\mathcal{T}$ $\neg\mathcal{T}$

$$\begin{cases} \ldots \\ T \vdash_{X_1} u_1 \\ T \vdash_{X_2} u_2 \\ X = f(X_1, X_2) \\ \ldots \end{cases} \qquad \begin{cases} \ldots \\ T \vdash_X f(u_1, u_2) \\ \mathsf{Top}(X) \neq f \\ \ldots \end{cases}$$

Termination difficulties

$$\begin{cases} T \vdash_X x \\ T \vdash_Y f(x, y) \end{cases}$$

$$\begin{cases} T' \vdash_X f(x', y') \\ T' \vdash_Y x' \end{cases}$$

Termination difficulties

$$\begin{cases} T \vdash_X x \\ T \vdash_Y f(x, y) \end{cases} \qquad \begin{cases} T' \vdash_X f(x', y') \\ T' \vdash_Y x' \end{cases}$$

$$\Big\downarrow \; X = f(X_1, X_2)$$

Termination difficulties

$$\begin{cases} T \vdash_X x \\ T \vdash_Y f(x, y) \end{cases} \qquad \begin{cases} T' \vdash_X f(x', y') \\ T' \vdash_Y x' \end{cases}$$

$$\Big\downarrow \; X = f(X_1, X_2)$$

$$\begin{cases} T \vdash_{X_1} x_1 \\ T \vdash_{X_2} x_2 \\ T \vdash_Y f(f(x_1, x_2), y) \end{cases} \qquad \begin{cases} T' \vdash_{X_1} x' \\ T' \vdash_{X_2} y' \\ T' \vdash_Y x' \end{cases}$$

Termination difficulties

$$\begin{cases} T \vdash_X x \\ T \vdash_Y f(x, y) \end{cases} \qquad \begin{cases} T' \vdash_X f(x', y') \\ T' \vdash_Y x' \end{cases}$$

$$\Big\downarrow \; X = f(X_1, X_2)$$

$$\begin{cases} T \vdash_{X_1} x_1 \\ T \vdash_{X_2} x_2 \\ T \vdash_Y f(f(x_1, x_2), y) \end{cases} \qquad \begin{cases} T' \vdash_{X_1} x' \\ T' \vdash_{X_2} y' \\ T' \vdash_Y x' \end{cases}$$

$$\Big\downarrow \; Y = f(Y_1, Y_2)$$

Termination difficulties

$$\begin{cases} T \vdash_X x \\ T \vdash_Y f(x, y) \end{cases} \qquad \begin{cases} T' \vdash_X f(x', y') \\ T' \vdash_Y x' \end{cases}$$

$$\downarrow \; X = f(X_1, X_2)$$

$$\begin{cases} T \vdash_{X_1} x_1 \\ T \vdash_{X_2} x_2 \\ T \vdash_Y f(f(x_1, x_2), y) \end{cases} \qquad \begin{cases} T' \vdash_{X_1} x' \\ T' \vdash_{X_2} y' \\ T' \vdash_Y x' \end{cases}$$

$$\downarrow \; Y = f(Y_1, Y_2)$$

$$\begin{cases} T \vdash_{X_1} x_1 \\ T \vdash_{X_2} x_2 \\ T \vdash_{Y_1} f(x_1, x_2) \\ T \vdash_{Y_2} y \end{cases} \qquad \begin{cases} T' \vdash_{X_1} f(x'_1, x'_2) \\ T' \vdash_{X_2} y' \\ T' \vdash_{Y_1} x'_1 \\ T' \vdash_{Y_2} x'_2 \end{cases}$$

Termination difficulties

$$\begin{cases} T \vdash_X x \\ T \vdash_Y f(x, y) \end{cases} \qquad \begin{cases} T' \vdash_X f(x', y') \\ T' \vdash_Y x' \end{cases}$$

$$\Big\downarrow \; X = f(X_1, X_2)$$

$$\begin{cases} T \vdash_{X_1} x_1 \\ T \vdash_{X_2} x_2 \\ T \vdash_Y f(f(x_1, x_2), y) \end{cases} \qquad \begin{cases} T' \vdash_{X_1} x' \\ T' \vdash_{X_2} y' \\ T' \vdash_Y x' \end{cases}$$

$$\Big\downarrow \; Y = f(Y_1, Y_2)$$

$$\begin{cases} T \vdash_{X_1} x_1 \\ T \vdash_{X_2} x_2 \\ T \vdash_{Y_1} f(x_1, x_2) \\ T \vdash_{Y_2} y \end{cases} \qquad \begin{cases} T' \vdash_{X_1} f(x'_1, x'_2) \\ T' \vdash_{X_2} y' \\ T' \vdash_{Y_1} x'_1 \\ T' \vdash_{Y_2} x'_2 \end{cases}$$

Results

Decision procedure for proving trace equivalence for bounded number of sessions.

Class of accepted processes:

- Non-deterministic (e.g. private channel) with else-branches
- Classic cryptographic primitives (symmetric and asymmetric encryption, signature, pairing, hash)

Include:

- E-passport protocols
- Private authentication protocols

Implementation

Alpha version:

APTE: Algorithm for Proving Trace Equivalence

Content:

- Front-end similar to ProVerif
- Handle equivalence between processes without replication
- Display witness of non-equivalence
- Handle equivalences between sequences of messages
- Handle reachability properties for processes without replication

Outline

1. Proving more equivalence with ProVerif
2. Decision procedure for trace equivalence
3. Composing trace equivalence

Motivation

Concrete example: e-passport protocols

- Basic Access Control (BAC) : establishes session keys between a reader and a passport
- Passive Authentication (PA)
- Active Authentication (AA)

Protocols are verified in isolation

Possible problems:

- Protocols may share some keys
- Protocols may share some cryptographic primitives
- Tools may not be able to prove the security property

Result

Verifying **S** on **P**

and

Verifying **S** on **Q**

↓ under conditions

Verifying **S** on **P** and **Q** running in parallel

where

- **P** and **Q** may share secrets and cryptographic primitives
- **S** is a security property

Conditions of the result

- The shared secret keys are not revealed
- The protocols **P** and **Q** are tagged
- The public keys are revealed at the beginning

Conclusion

- Relations between different notions of equivalences

- Algorithms to prove equivalence

  - Extension of ProVerif for proving more equivalence
  - New decision procedure for trace equivalence (else branches)
  - New automatic tool : APTE

  ✓ Anonymity for the private authentication protocol
  ✓ Unlinkability for the e-passport protocol

- Composition result for trace equivalence

  Application on the e-passport protocol

Future Works

- Improve the algorithms
  - Prove unlinkability of the e-passport protocol with ProVerif for unbounded number of sessions
  - Add cryptographic primitives in APTE (e.g. blind signature, xor, re-encryption)
- Optimize the implementation of APTE
  - Distributed implementation
  - Interleaving problem
  - Simplify the strategy on the rules
- Sequential composition for trace equivalence