Theorem-proving Privacy and Anonymity

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References

- Simulation-based proof method of privacy/anonymity
  - Y. Kawabe, K. Mano, H. Sakurada and Y. Tsukada
    Theorem-proving anonymity of infinite state systems
    Information Processing Letters, vol. 101, No.1, 2007
  - Y. Kawabe, K. Mano, H. Sakurada and Y. Tsukada
    Backward simulations for anonymity
    WITS '06 (Full version: submitted for journal publication)
  - I. Hasuo and Y. Kawabe
    Probabilistic anonymity via coalgebraic simulations
    Submitted for publication

Online *privacy*
Online *anonymity*

is attracting *growing*

- Threats
  - ISPs in EU are forced to keep logs of your web access
- Public concerns
  - You don't care?
- Research interest
  - See *Anonymity Bibliography*
    http://freehaven.net/anonbib/
  - No decisive definition for "privacy", "anonymity", etc.

Overview of this talk

A formal definition of anonymity which is based on **traces**

[ESORICS '96, Schneider & Sidiropoulos]

Proving trace inclusion by simulation
[Lynch & Vaandrager]

- **Simulation-based proof method for trace anonymity**
- **Theorem-proving anonymity**

Contents

- A method to prove anonymity (=privacy)

  - Formalization of anonymity

    & anonymous simulation technique
  - Theorem-proving anonymity/privacy
    - Crowds protocol

What is anonymity?

- Nobody can know “who it is”.
- Key notion: Principle of confusion

Who?

What is anon

Adversary's viewpoint

This person looks like Kawabe … but his face is hidden. This person might not be Kawabe.

- Nobody can know "who i
- Key notion: Principle of confusion

Who?

What is anon

"who i

e of confusion

The guys on this photo are too small ! I cannot recognize Kawabe!

Adversary's viewpoint

This person looks like Kawabe … but his face is hidden. This person might not be Kawabe.

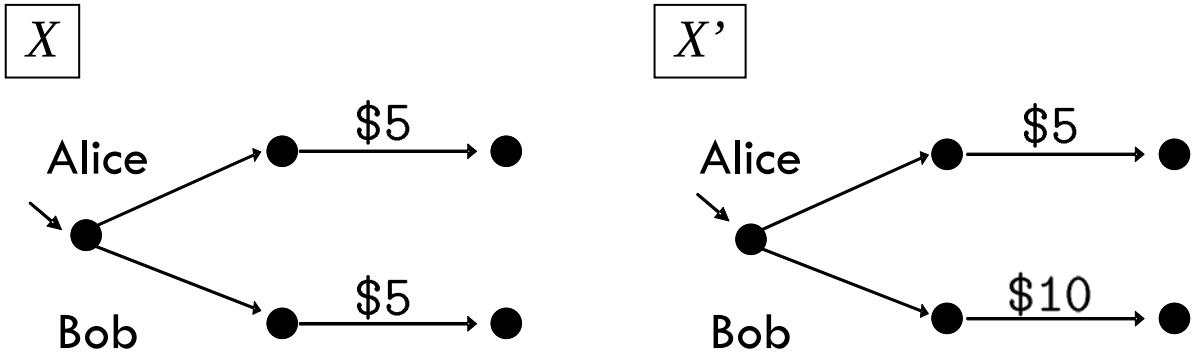
Releasing sea turtles

Who?

Can you find me?

“Trace” anonymity [Schneider&Sidiropoulos, ESORICS’96]

- Anonymous donation as an example



“Trace” anonymity [Schneider&Sidiropoulos, ESORICS’96]

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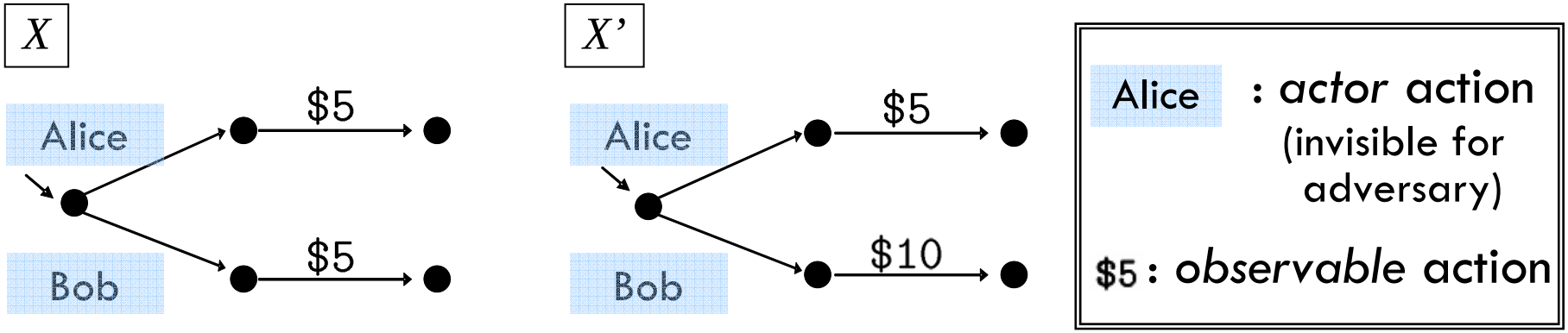
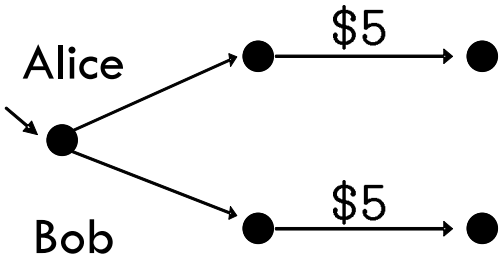


Are these protocols anonymous?

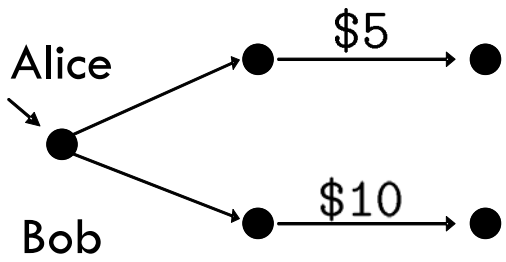
"Trace" anonymity [Schneider&Sidiropoulos, ESORICS'96]

- Anonymous donation as an example

X ***Anonymous!***



X' ***Not anonymous!***



"Trace" anonymity [Schneider&Sidiropoulos, ESORICS'96]

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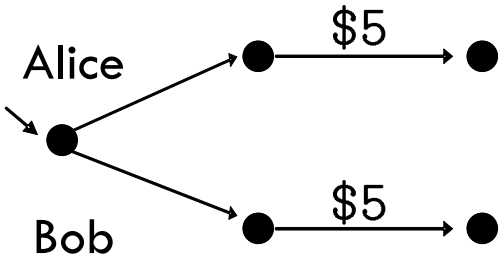
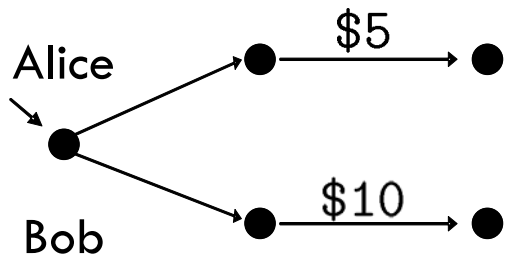


$$traces(X) = \left\{ \begin{array}{l} Alice.\$5 \\ Bob.\$5 \end{array} \right\}$$

X' ***Not anonymous!***



$$traces(X') = \left\{ \begin{array}{l} Alice.\$5 \\ Bob.\$10 \end{array} \right\}$$

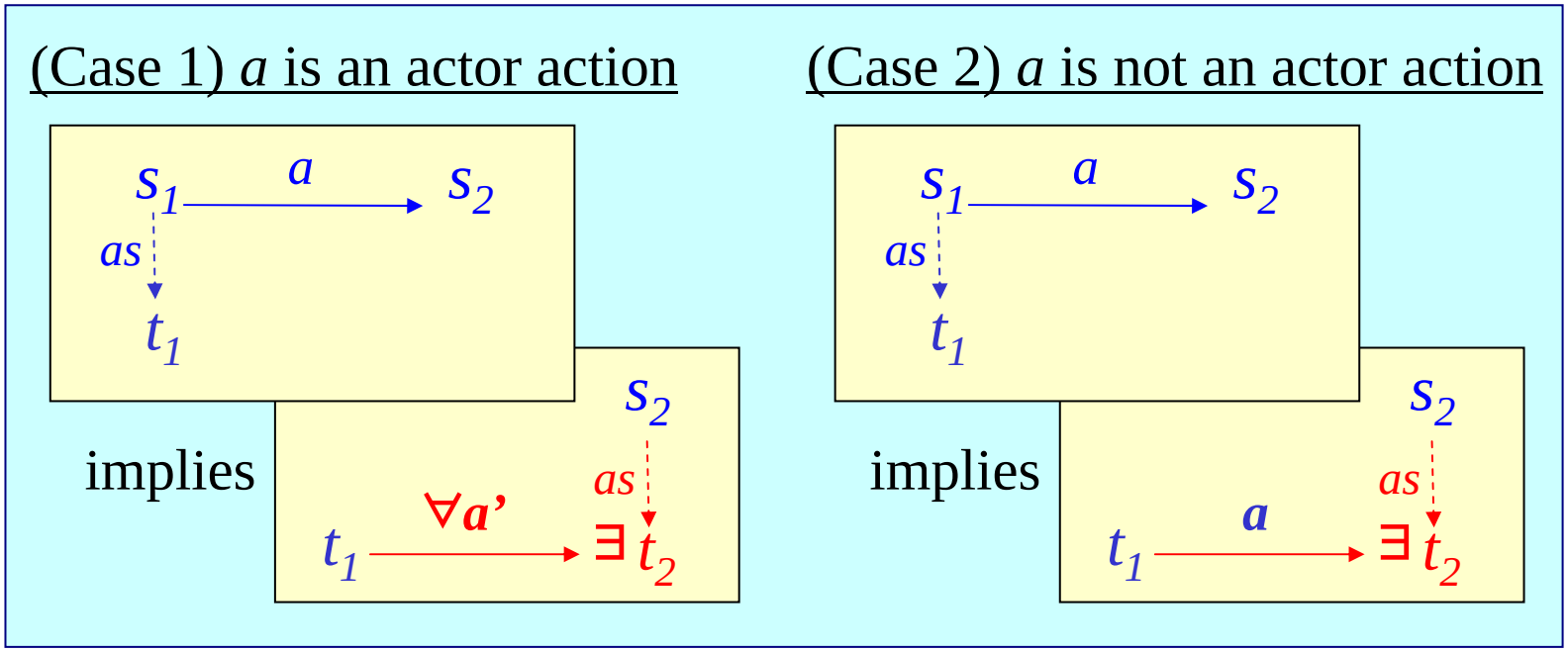
Observation $\vec{o}, \vec{o'}$ can be attributed to anybody (confusion!)

Definition (Trace anonymity)

X is anonymous $\Leftrightarrow \forall \vec{o}, \vec{o'}\ .\ \vec{o} \cdot \text{Alice} \cdot \vec{o'} \in traces(X)$
$\Longrightarrow \vec{o} \cdot \text{Bob} \cdot \vec{o'} \in traces(X),$
$\vec{o} \cdot \text{Chris} \cdot \vec{o'} \in traces(X), \ldots$

How to prove anonymity?
--- Find an anonymous simulation!

- Binary relation as over $states(X)$
  1. Initial state condition: $as(s, s)$ for any $s \in start(X)$
  2. Step correspondence condition:

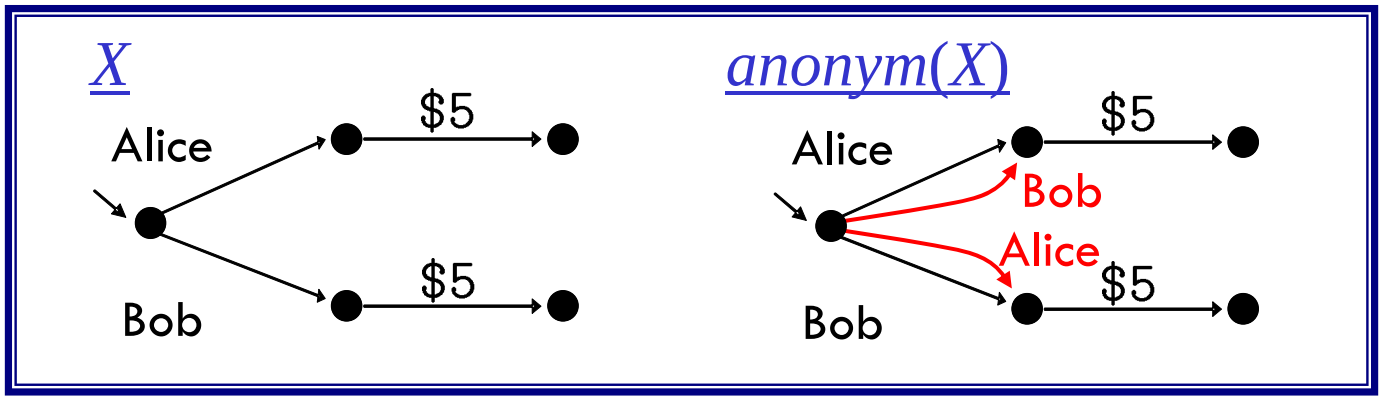


Soundness of the technique

- An anonymous simulation is a simulation from $anonym(X)$ to X.

  [Thm] $\exists$ simulation from X to $Y \Rightarrow traces(X) \subseteq traces(Y)$.

  [Lynch and Vaandrager, Inform.&Comput. 1995]



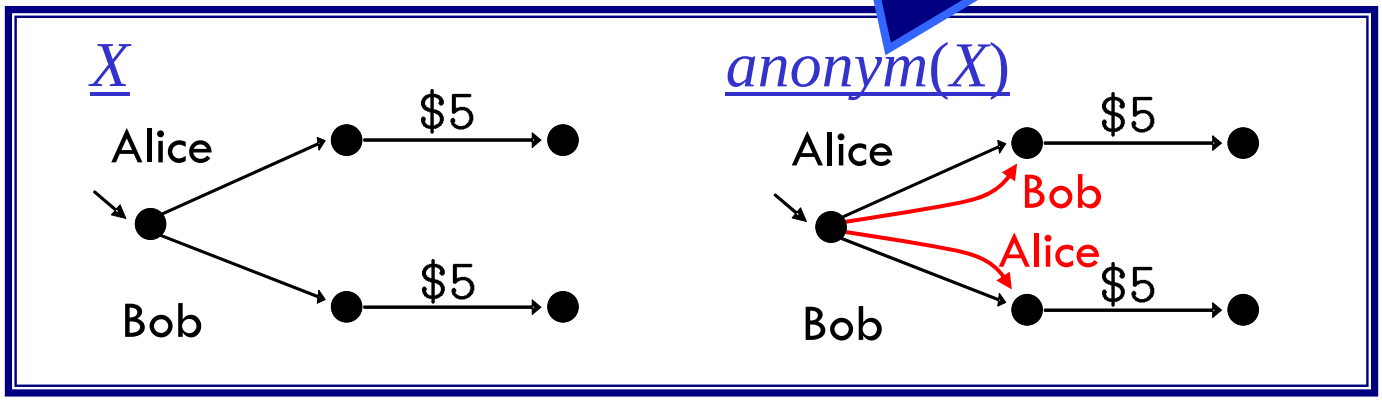
Soundness of the technique

- An anonymous simulation is a simulation from $anonym(X)$ to X.

  [Thm] ∃ simulation from X to Y.

  [Lynch and Vaandrager

"anonymized" version of X (trivially anonymous)

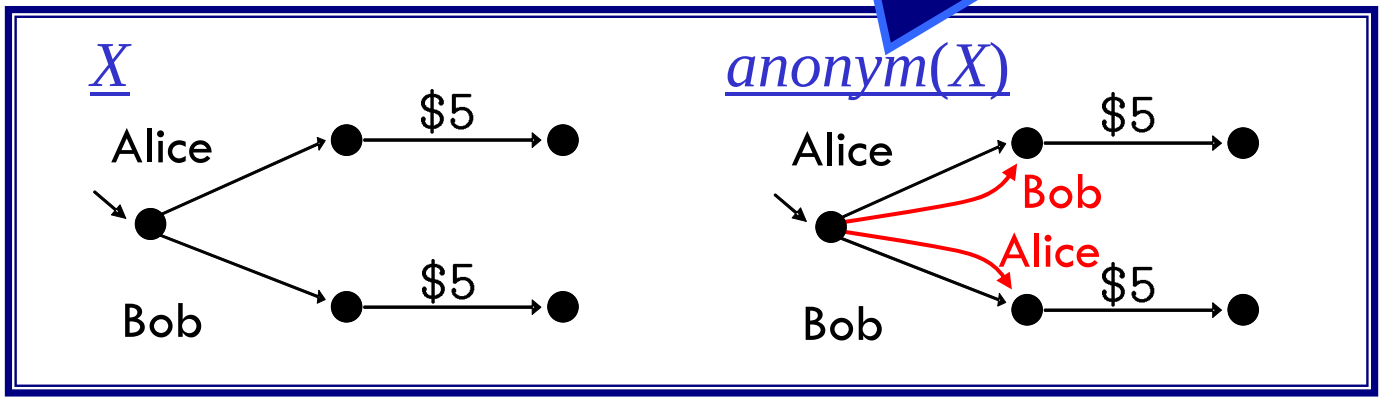


Soundness of the technique

- An anonymous simulation is a simulation from $anonym(X)$ to X.

[Thm] ∃ simulation from X to $anonym(X)$ [Lynch and Vaandrager Y).

"anonymized" version of X (trivially anonymous)



$traces(X) \subseteq traces(anonym(X))$ is trivial.

$\Rightarrow traces(X) = traces(anonym(X))$ holds!

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  - Theorem-proving anonymity/privacy
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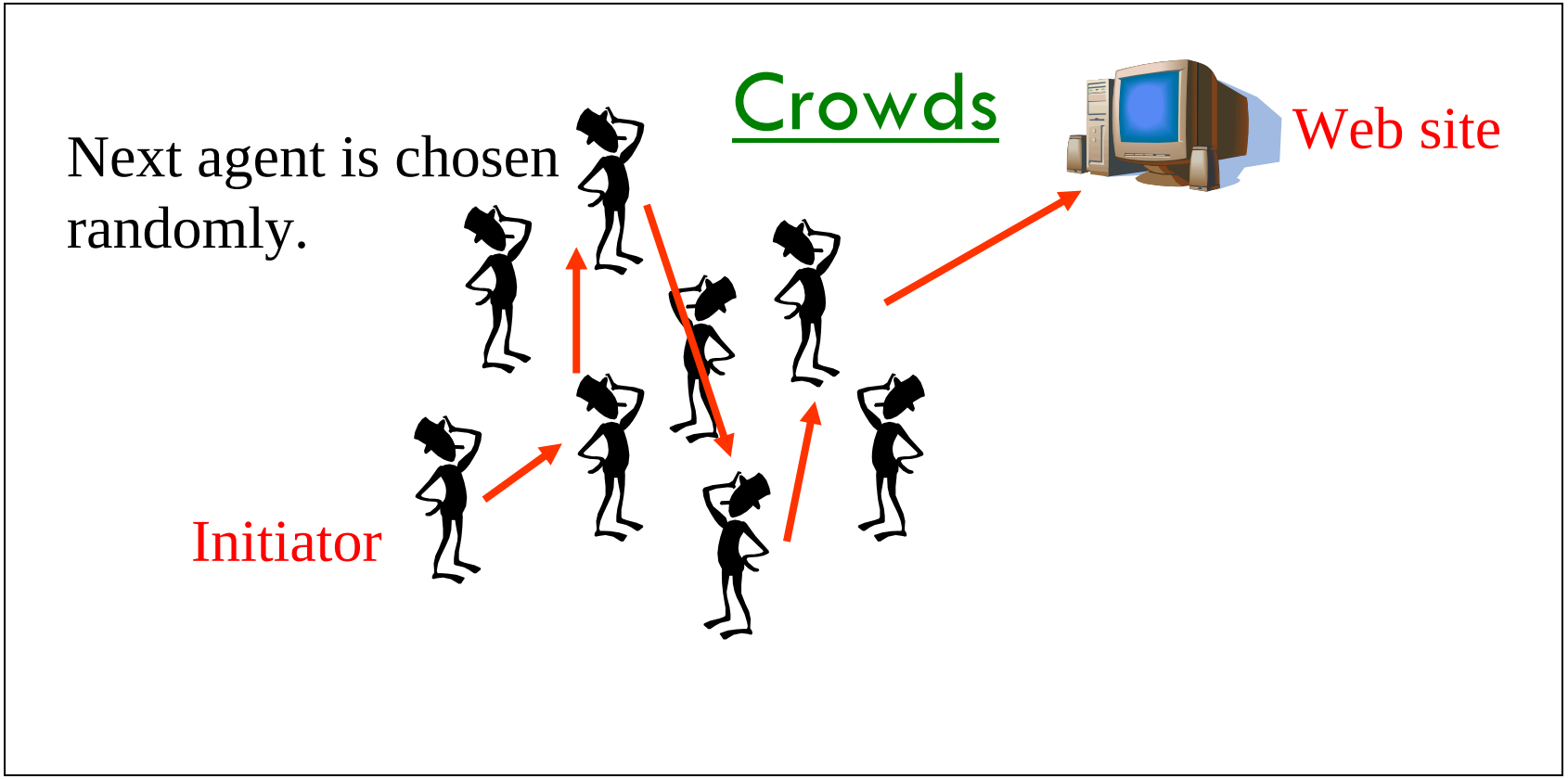
An example: Crowds
[Reiter & Rubin, ACM Trans. 1998]

- Comm. system for anonymous web access



An example: Crowds
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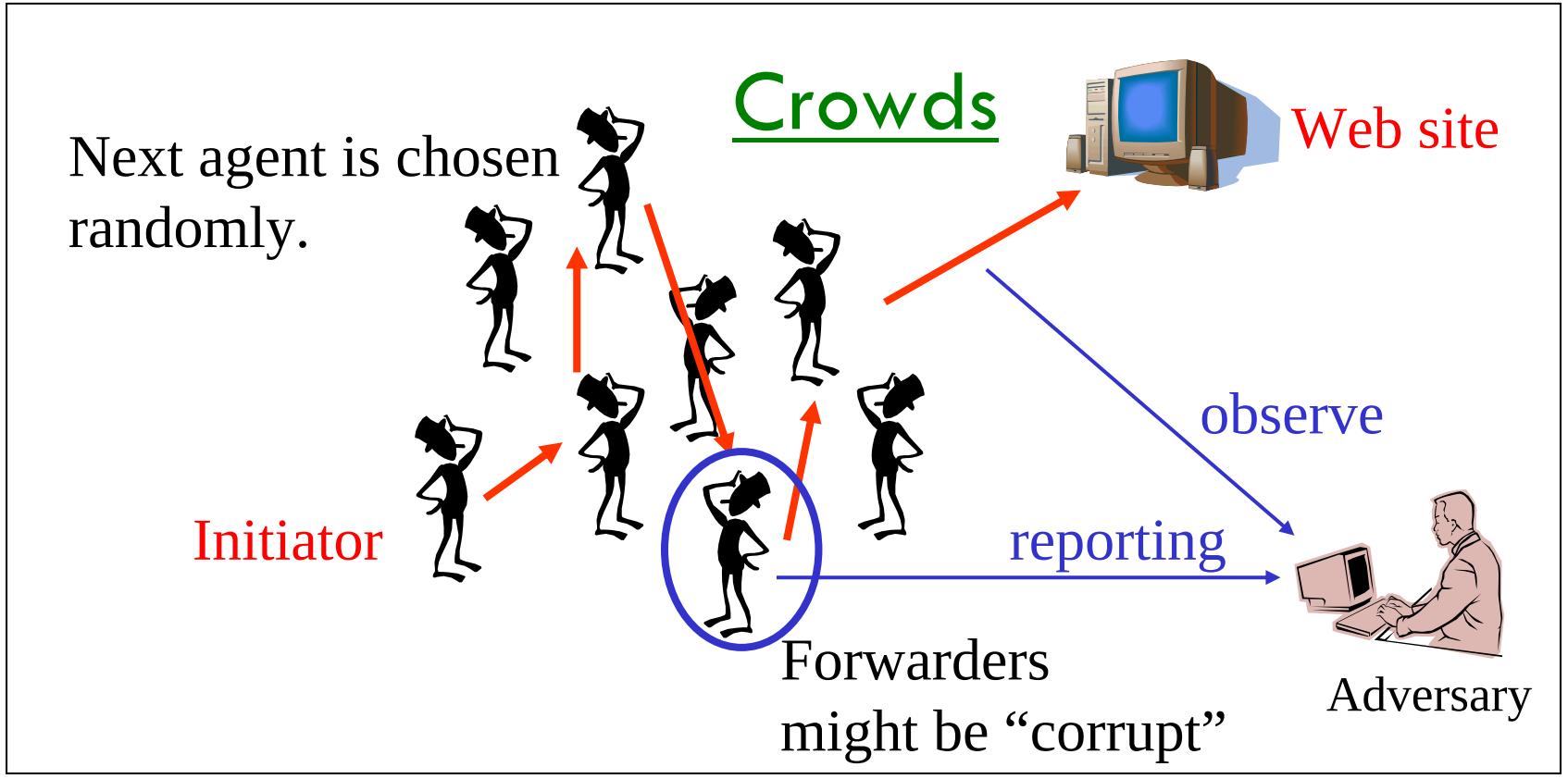


Anonymous = the adversary cannot know the initiator.

Theorem-proving anonymity of the Crowds example

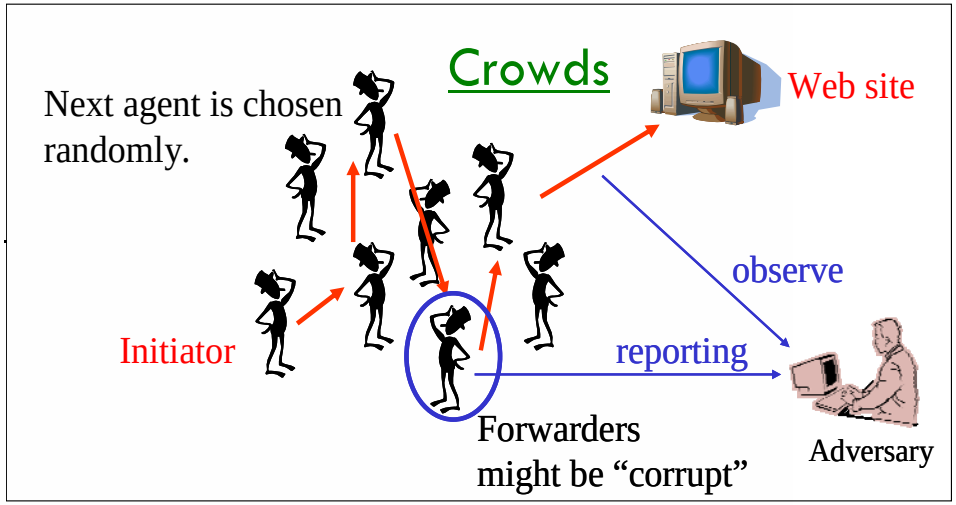
- Steps
  - Specify the system in IOA language which is a formal specification language based I/O-automaton
  - Translate the specification into LP's language --- first-order logic formulae --- with IOA-Toolkit
  - Prove anonymity with Larch Prover by proving there is an anonymous simulation

IOA language

- Formal specification language based on I/O-automaton
  - I/O-automaton (N. Lynch): formal system to describe and analyze distributed algorithms
- Formalization of distributed algorithms in IOA
  - Actions: precondition-effect style (i.e. if ~ then ~)
  - Data: (many-sorted) equational theory
    - LSL (Larch Specification Language)

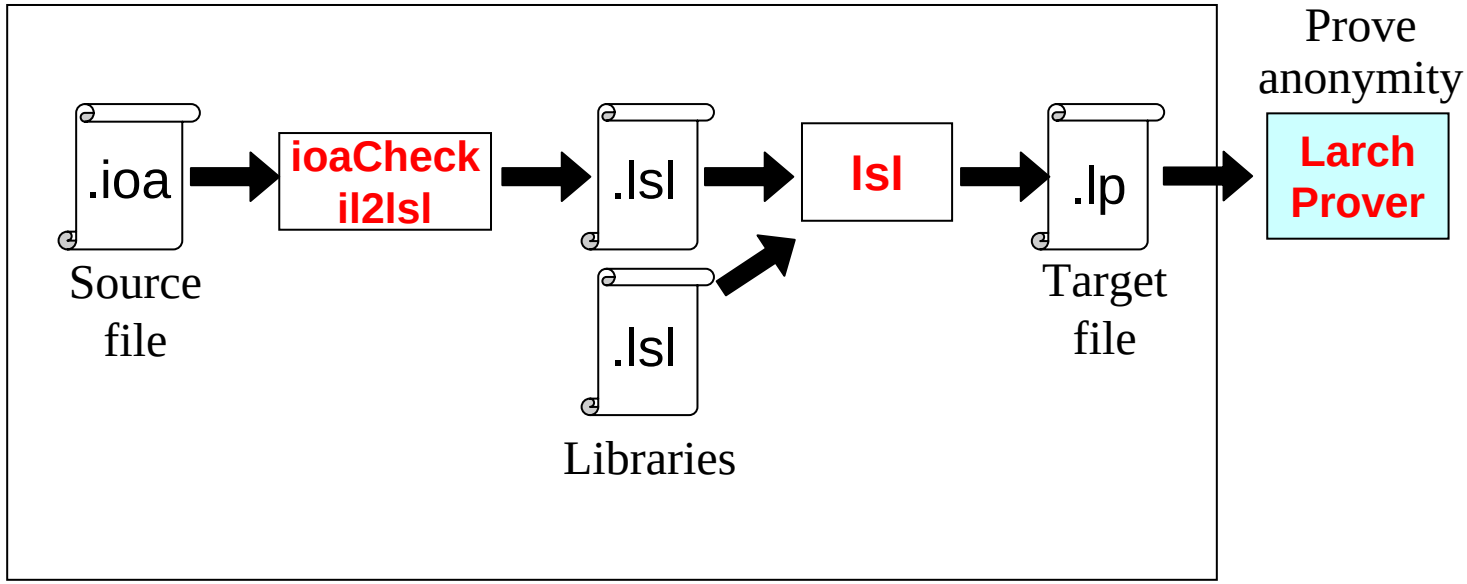
Specification of Crowds

```
uses crowdsDatatype

automaton crowds
  signature
    output   start(i:ID)
    internal pass(i:ID, j:ID)
    output   source(i:ID, j:ID)
    output   out(i:ID)

  states
    pc:        PC := init,
    mesIsAt:   ID,
    mesIsFrom: ID,
    corrp:     Array[ID, Bool]

  transitions
    output start(i)        % actor action that represents who is the starter
      pre pc = init
      eff pc := shuffle;
          mesIsAt := i;
          mesIsFrom := i

    internal pass(i, j)
      pre pc = shuffle
          /\ i = mesIsAt
      eff mesIsFrom := i;
          mesIsAt := j

    output source(i, j)
      pre pc = shuffle
          /\ i = mesIsFrom
          /\ j = mesIsAt
          /\ corrp[j]
      eff do nothing

    output out(i)
      pre pc = shuffle
          /\ i = mesIsAt
      eff pc := terminate
```



IOA-Toolkit

- Collection of formal verification tools for distributed systems



Compiling .ioa into .lp with IOA-Toolkit

Theorem-proving anonymity

- Introducing a candidate relation

```
assert
 as(s, s')
   <=> (s.pc = s'.pc
        /\ (s.corrp[s.mesIsAt] <=> s'.corrp[s'.mesIsAt]))
..
```

- Proving that as is an anonymous simulation

```
% --- start state condition
prove start(s:States[crowds]) => as(s, s)
qed
```

Initial state condition

```
% --- step correspondence
prove
  (reachable(s1)
   /\ reachable(s1')
   /\ as(s1, s1')
   /\ enabled(s1, a)
   /\ effect(s1, a) = s2
   /\ a = start(i)
   /\ s1.corrp[i])
   => (\A i':ID (\E s':States[crowds] (\E i'':ID (\E s2':States[crowds]
          (   enabled(s1', start(i'))
           /\ effect(s1', start(i')) = s'
           /\ enabled(s', pass(i', i''))
           /\ effect(s', pass(i', i'')) = s2'
           /\ as(s2, s2'))))))
..
```

Step correspondence condition
(for actor actions)

Conclusion

- A technique to theorem-prove anonymity of security protocols
  - Simulation technique for trace-based anonymity
- Example
  - Crowds

Coming soon with theorem provers

Ongoing work

- Simulation-based proof techniques for probabilistic anonymity
  - Conditional anonymity (with Ichiro Hasuo)
    - With coalgebras, our method is extended.
  - Probable innocence (with Hideki Sakurada and Ichiro Hasuo)
- Verifying anonymity for protocols in the presence of intruders

Questions?