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# Theorem-proving Privacy and Anonymity

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# References

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- 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*

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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

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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

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- A method to prove anonymity (=privacy)

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



# What is anonymity?

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



Who?



# What is anonymity?

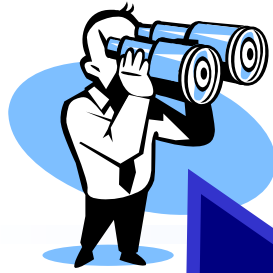
## Adversary's viewpoint

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

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



Who?



# What is an adversary's viewpoint?

## Adversary's viewpoint

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

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

“who is this?”  
state of confusion



Releasing sea turtles



Who?

Can you find me?



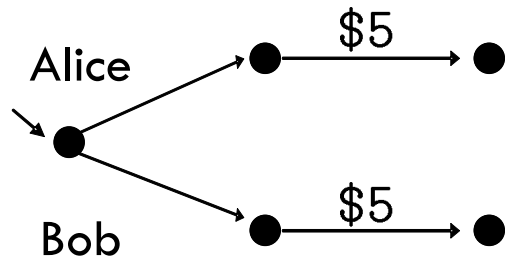
# “Trace” anonymity

[Schneider&Sidiropoulos, ESORICS’96]

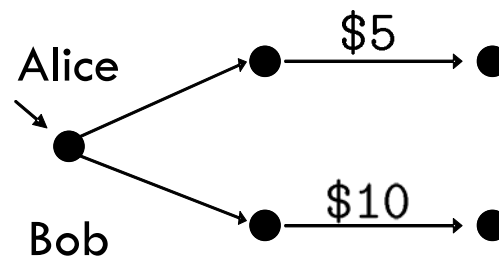
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- **Anonymous donation** as an example

$X$



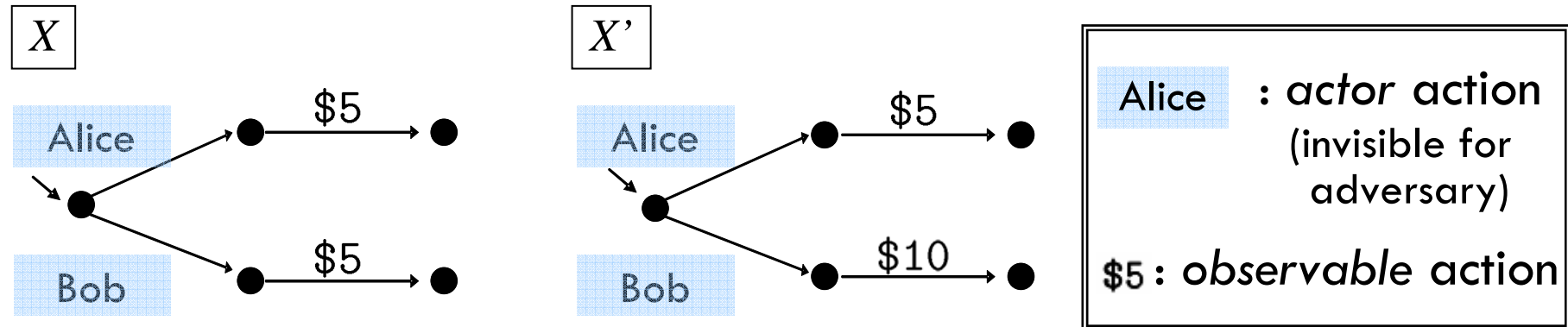
$X'$



# “Trace” anonymity

[Schneider&Sidiropoulos, ESORICS’96]

- **Anonymous donation** as an example



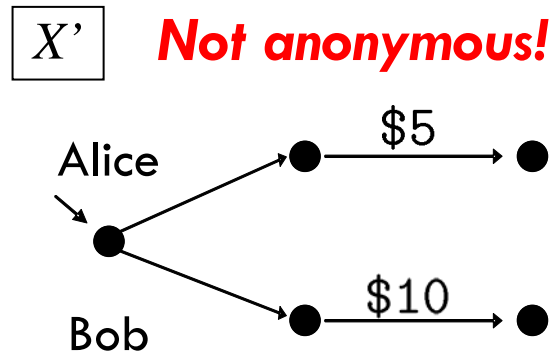
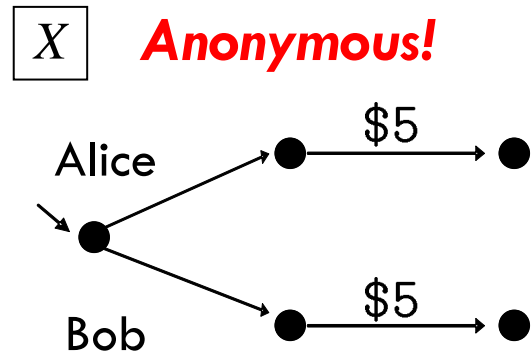
*Are these protocols anonymous?*

# “Trace” anonymity

[Schneider&Sidiropoulos, ESORICS’96]

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- **Anonymous donation** as an example

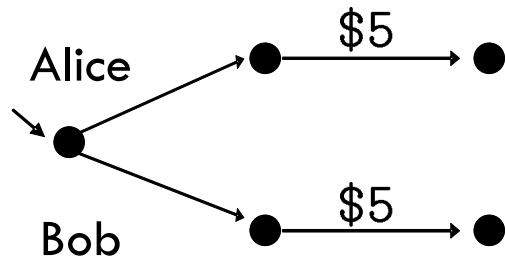


# “Trace” anonymity

[Schneider&Sidiropoulos, ESORICS'96]

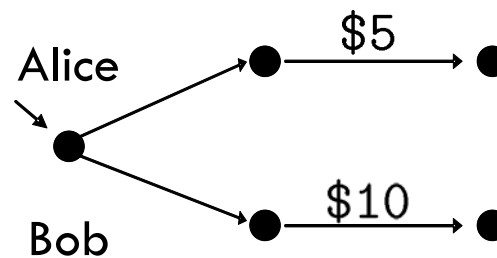
- Anonymous donation as an example

$X$  **Anonymous!**



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

$X'$  **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!**)

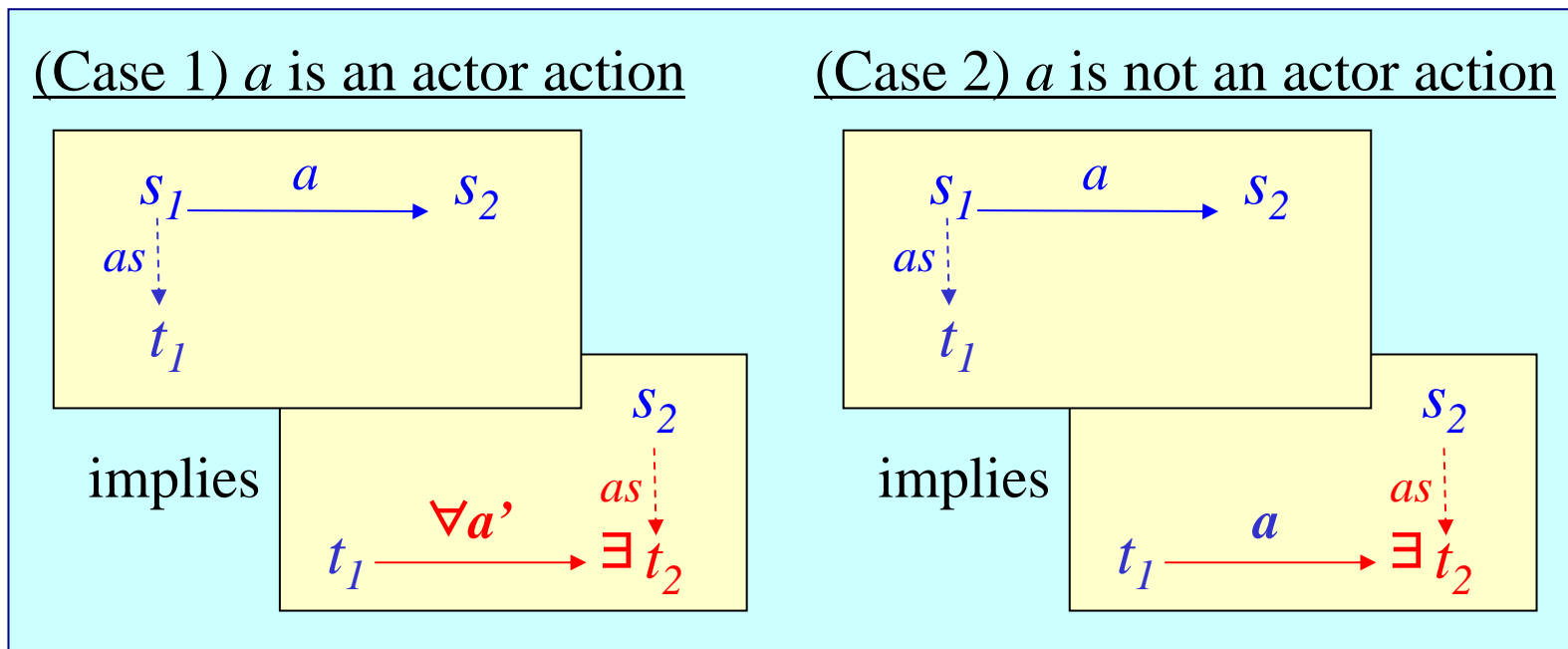
Definition (Trace anonymity)

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

# 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:**

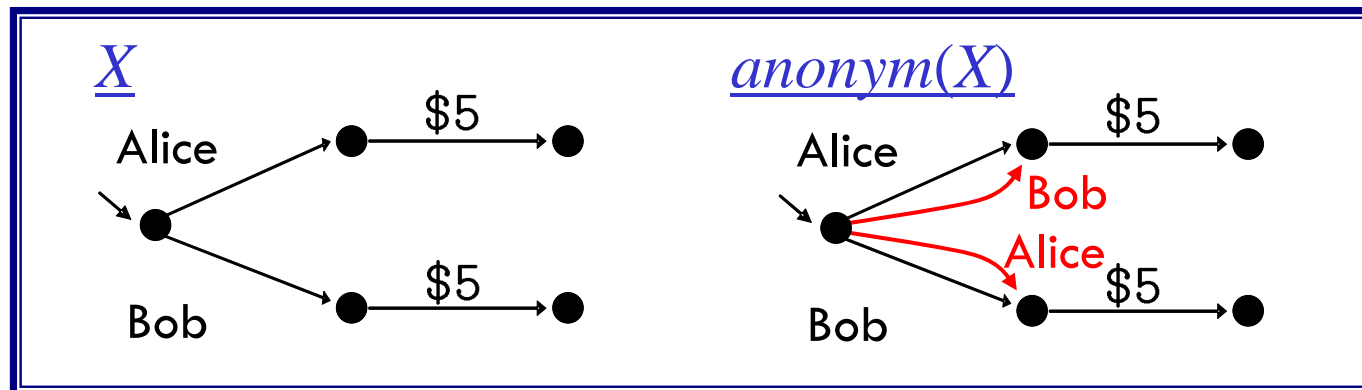


# Soundness of the technique

- An anonymous simulation is a **simulation from  $\text{anonym}(X)$  to  $X$** .

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

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



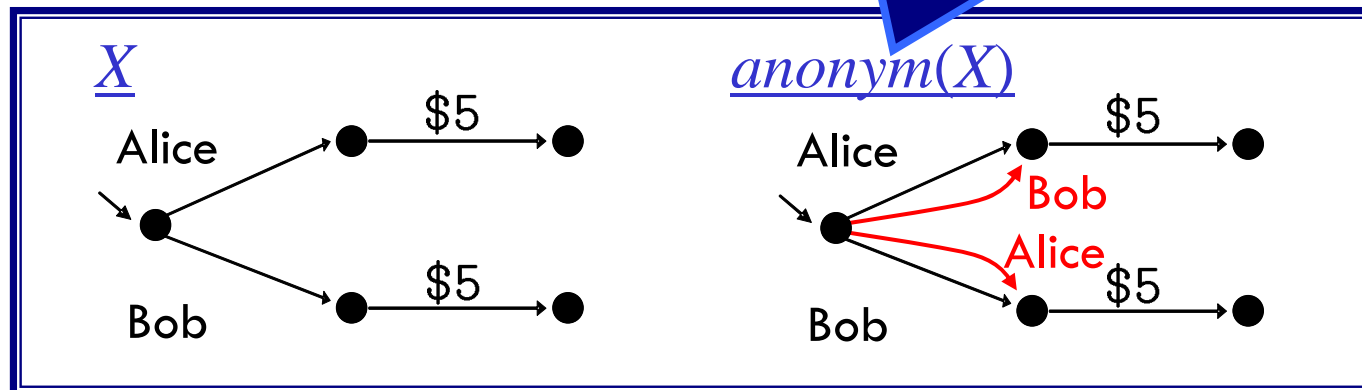
# Soundness of the technique

- An anonymous simulation is a **simulation from  $\text{anonym}(X)$  to  $X$** .

[Thm]  $\exists$  simulation from  $X$  to

[Lynch and Vaandrager

“anonymized” version  
of  $X$   
(trivially anonymous)



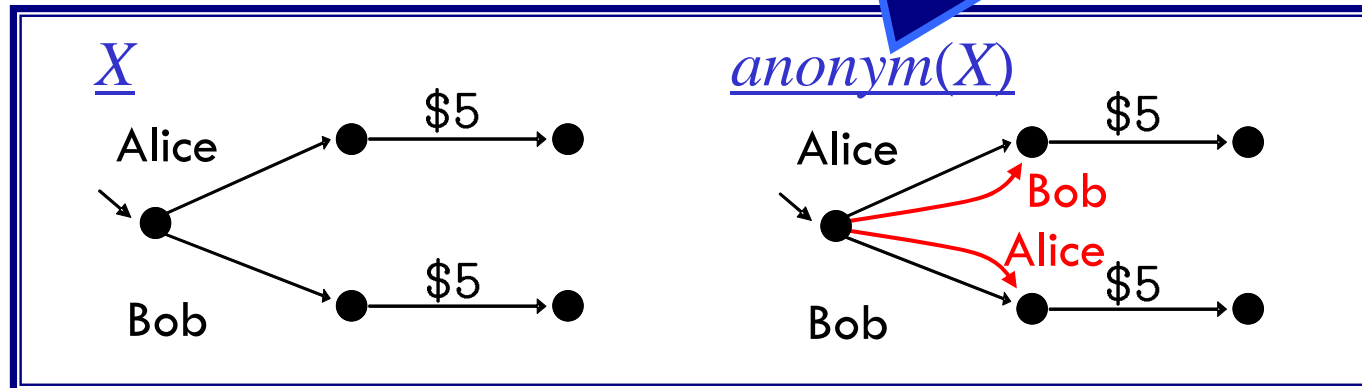
# Soundness of the technique

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

[Thm]  $\exists$  simulation from  $X$  to

[Lynch and Vaandrager

“anonymized” version  
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$traces(X) \subseteq traces(anonym(X))$  is trivial.

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



# Contents

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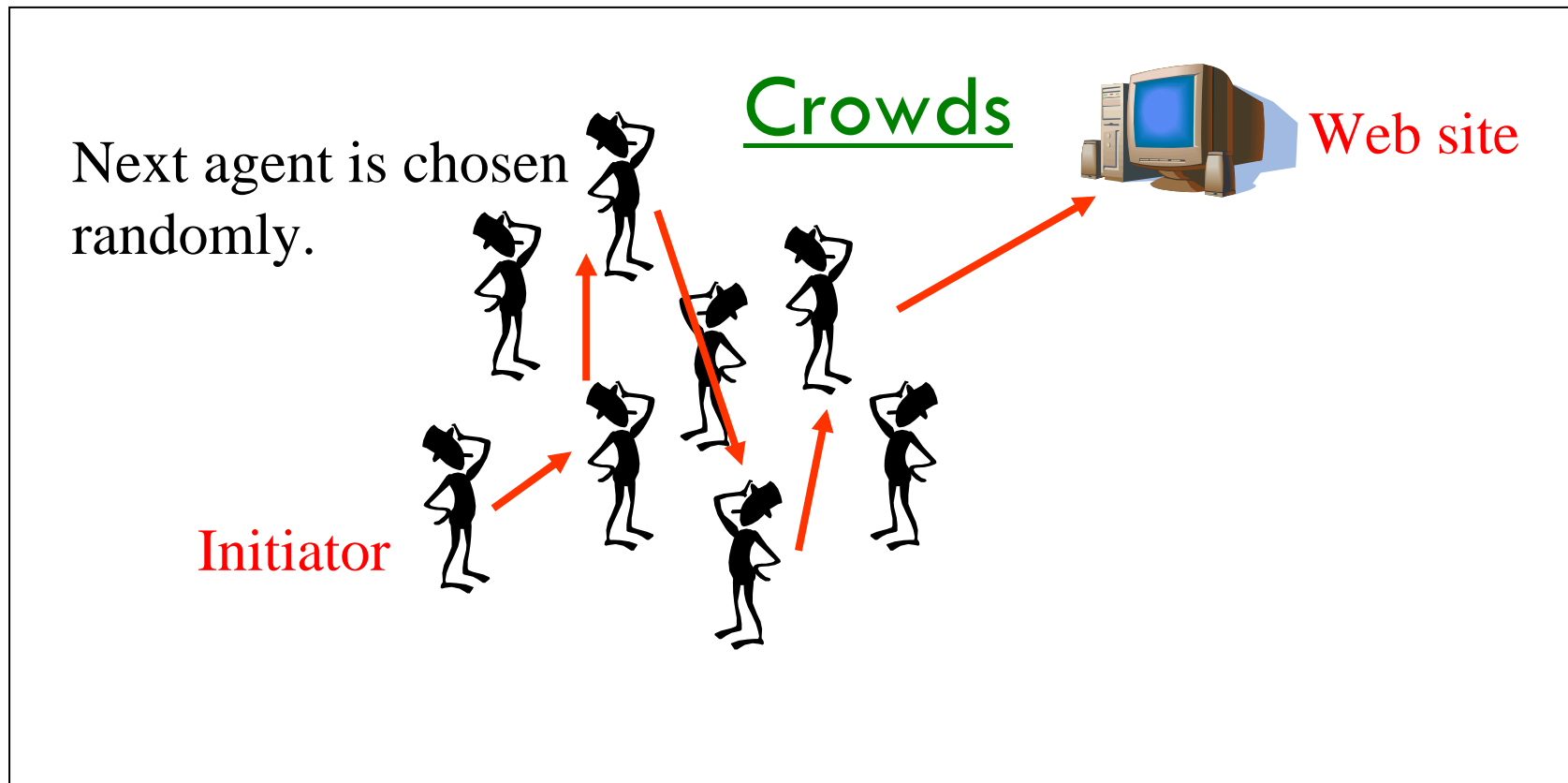
- A method to prove anonymity (=privacy)

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& anonymous simulation technique
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# An example: Crowds

[Reiter & Rubin, ACM Trans. 1998]

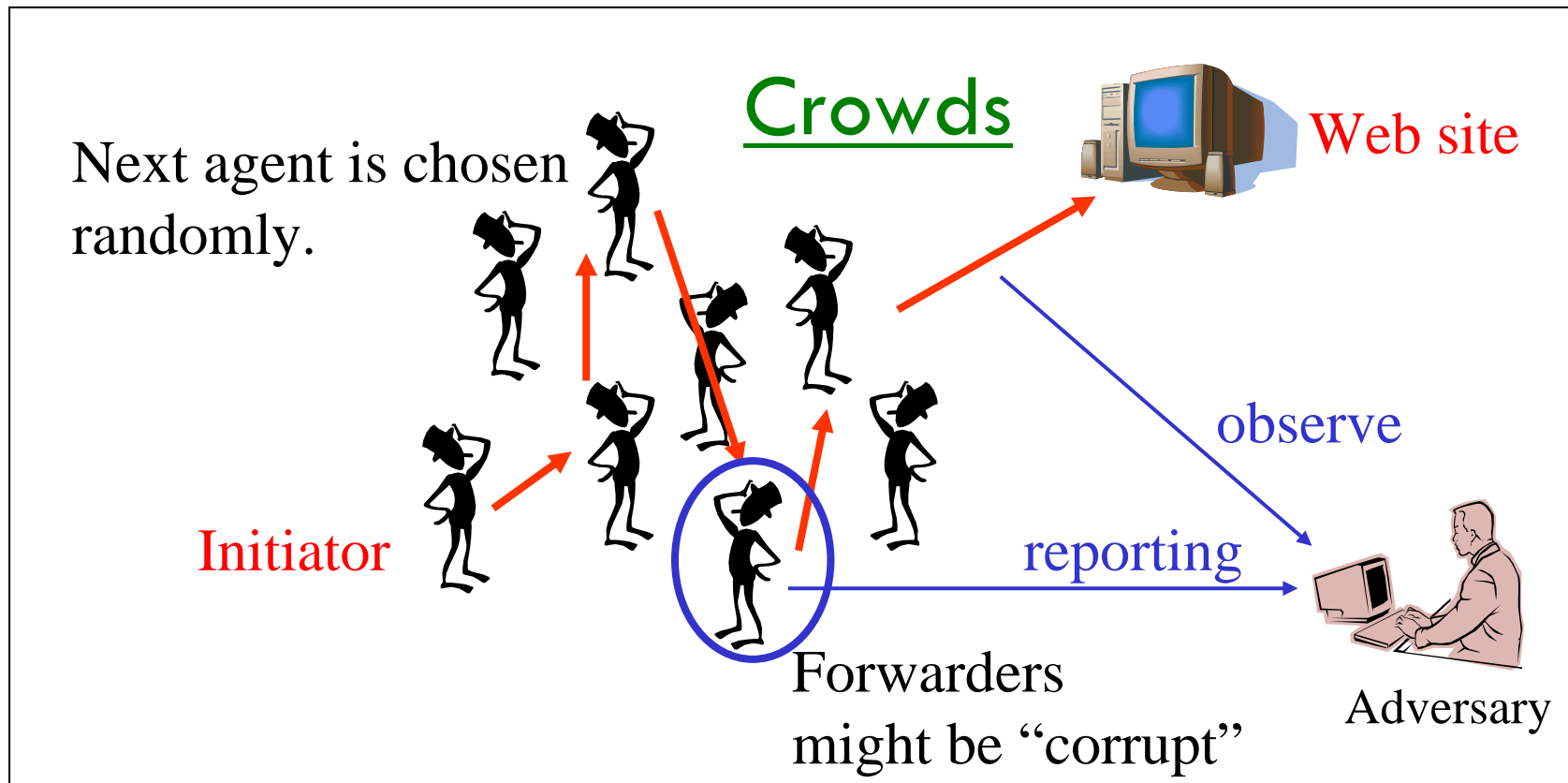
- Comm. system for anonymous web access



# An example: Crowds

[Reiter & Rubin, ACM Trans. 1998]

- Comm. system for anonymous web access



**Anonymous = the adversary cannot know the initiator.**

# Theorem-proving anonymity of the Crowds example

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- 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

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- 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  $\sim$  then  $\sim$ )
  - 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]
```

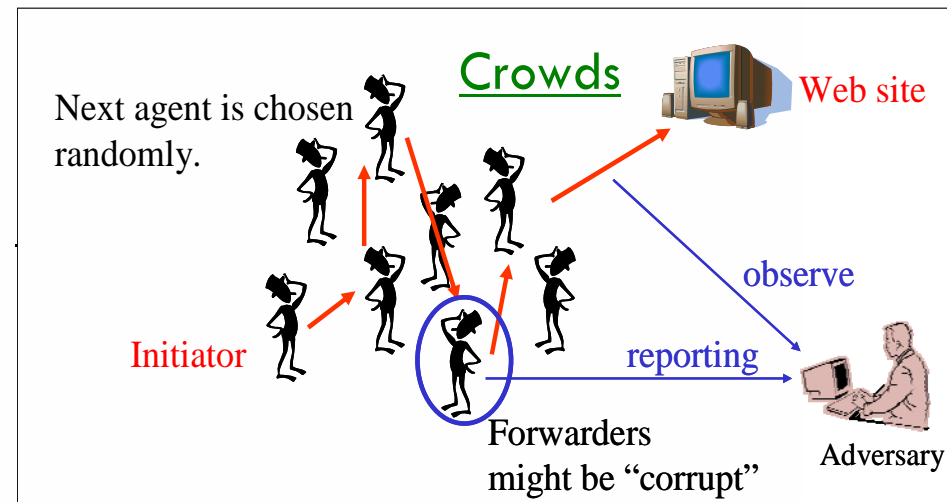
transitions

```
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
```

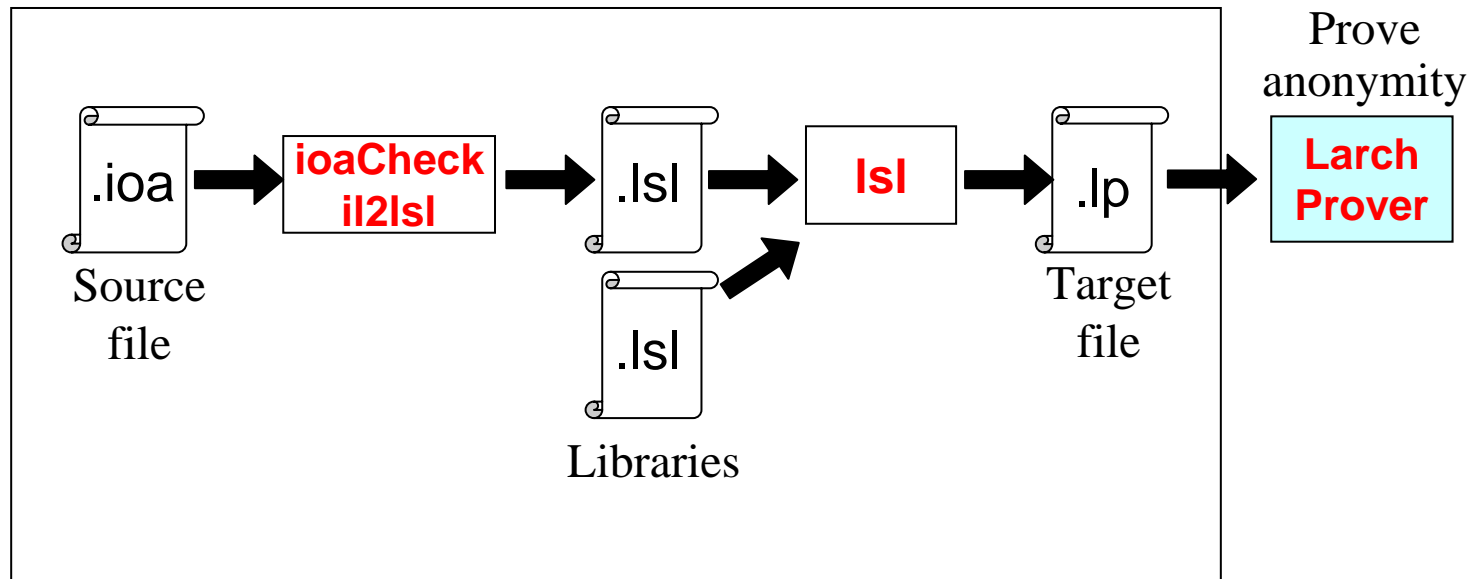
```
output source(i, j)
  pre pc = shuffle
  ^ i = mesIsFrom
  ^ j = mesIsAt
  ^ corrp[j]
  eff do nothing
```

```
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

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

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Coming soon with  
theorem provers

# Ongoing work

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- 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?