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School of Electronics
and Computer Science

Trust in Crowds

Probabilistic Behaviour in Anonymity Protocols

Vladimiro Sassone
University of Southampton

TGC 2010
München 2010.2.24

(based on joint work with S. Hamadou & E. ElSalamouny)

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Introduction

Anonymity in Social Networks

Social Networks: very easy to collect private and sensitive information about individuals.

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Introduction

Anonymity in Social Networks

<u>Social Networks:</u> very easy to collect private and sensitive information about individuals.

Introduction

Anonymity in Web Transactions

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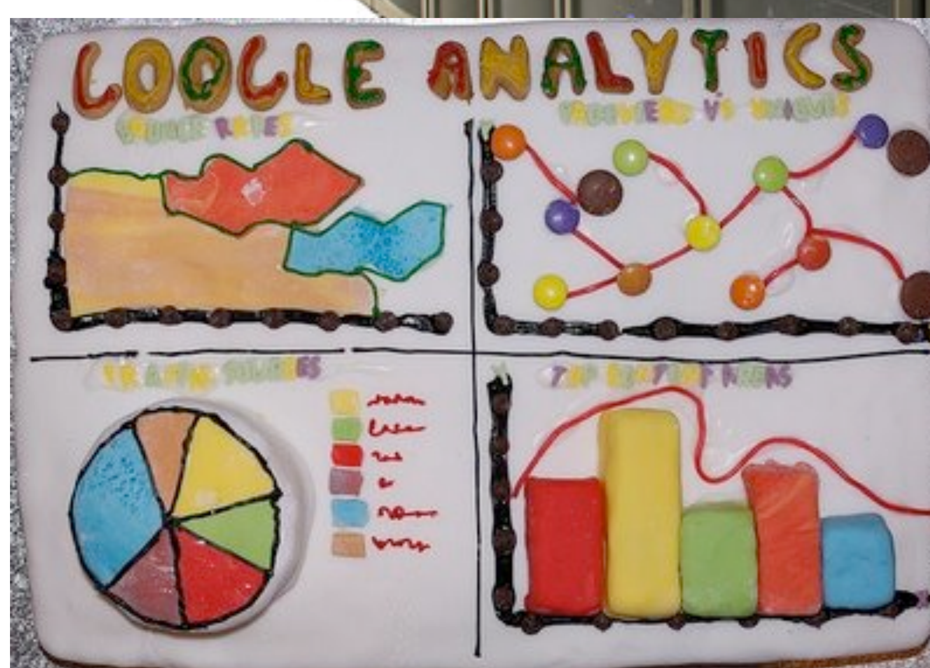
Google is watching you!



Introduction
Anonymity in Web Transactions

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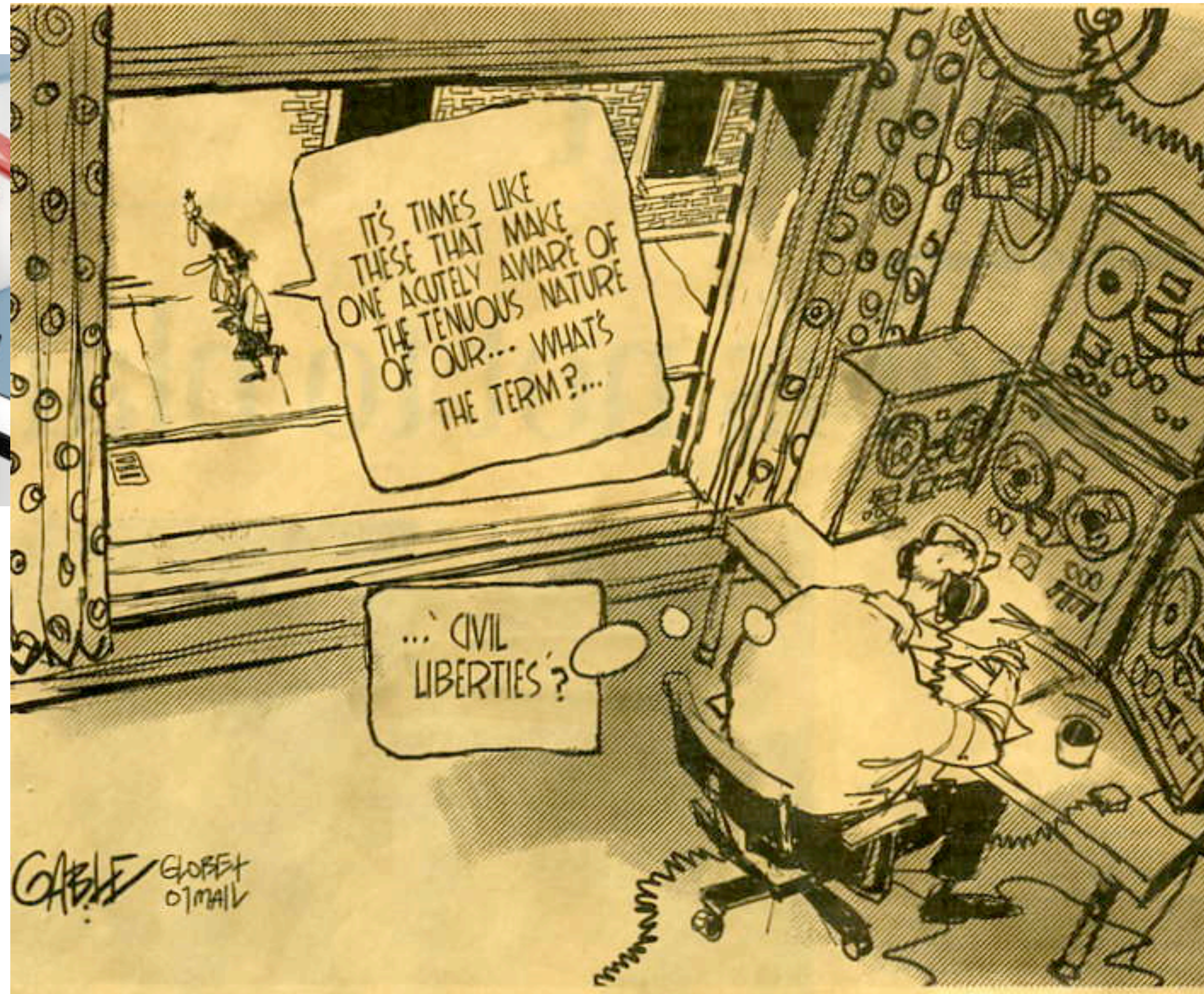

Introduction

Data Confidentiality

Introduction
Data Confidentiality

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...of course, but also...

Introduction
Data Confidentiality

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...of course, but also...

deduce high input from low output, in the fashion of information flow

Introduction

Anonymity Protocols (in general)

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- Aims at obfuscating the link between private input (anonymous actions) and public (observable) output
- Attacker tries to infer the hidden info from his observation of the protocol

This presentation

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Trust in the Crowds anonymity protocol

- Extend the Crowds protocol to a scenario where:
  - Each principal may suddenly become corrupt.
  - Principal behaviour is influenced by a trust relationship.
- Work:
  - Study the impact of these assumptions on the protocol.
  - Establish necessary and sufficient criteria for choosing a policy able to achieve a desired level of privacy.

Crowds
The protocol

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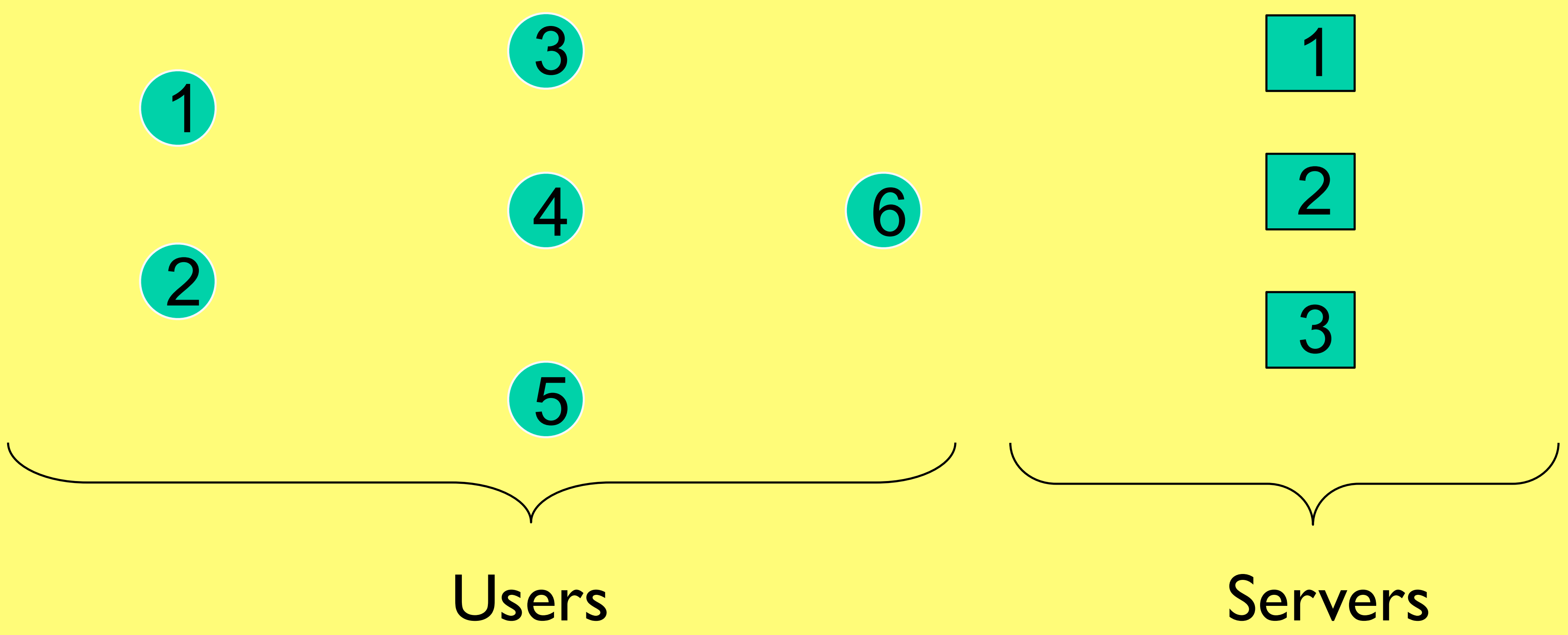
- **Crowds** [Reiter and Rubin 1998]: allows internet users to perform anonymous web transactions.



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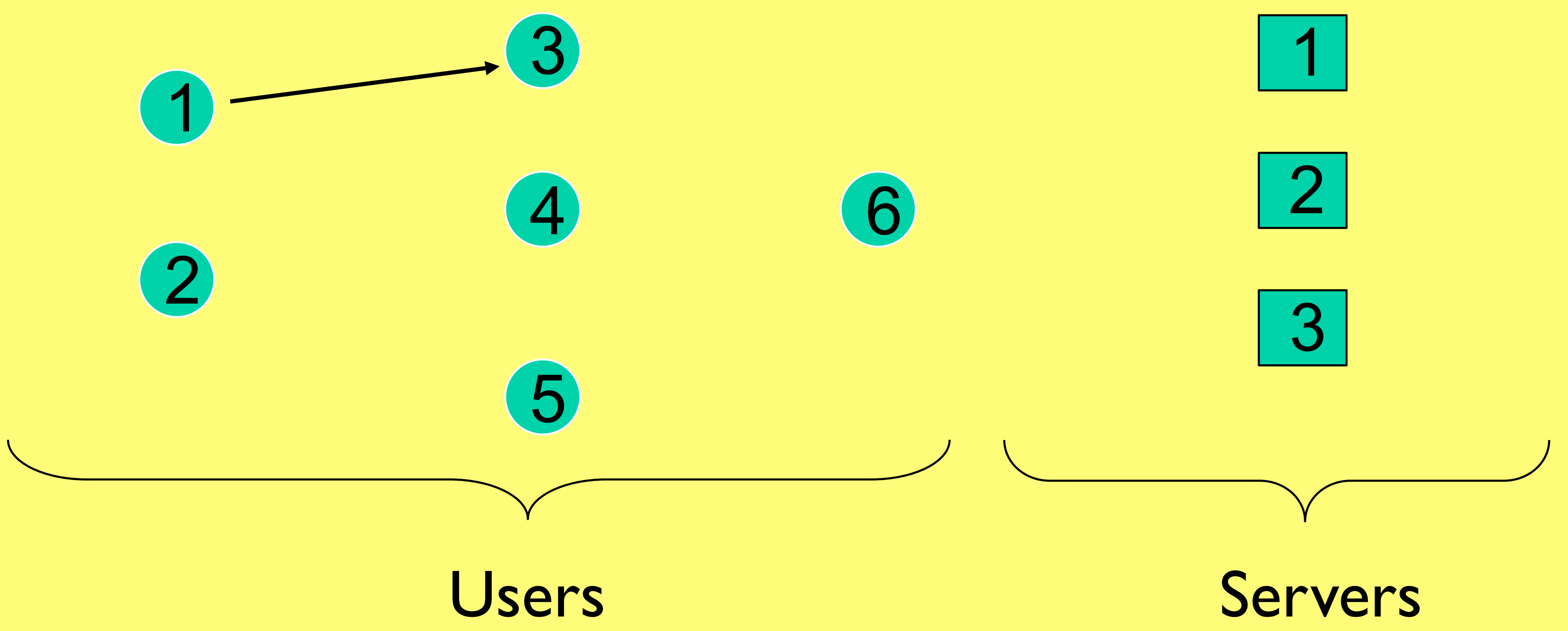

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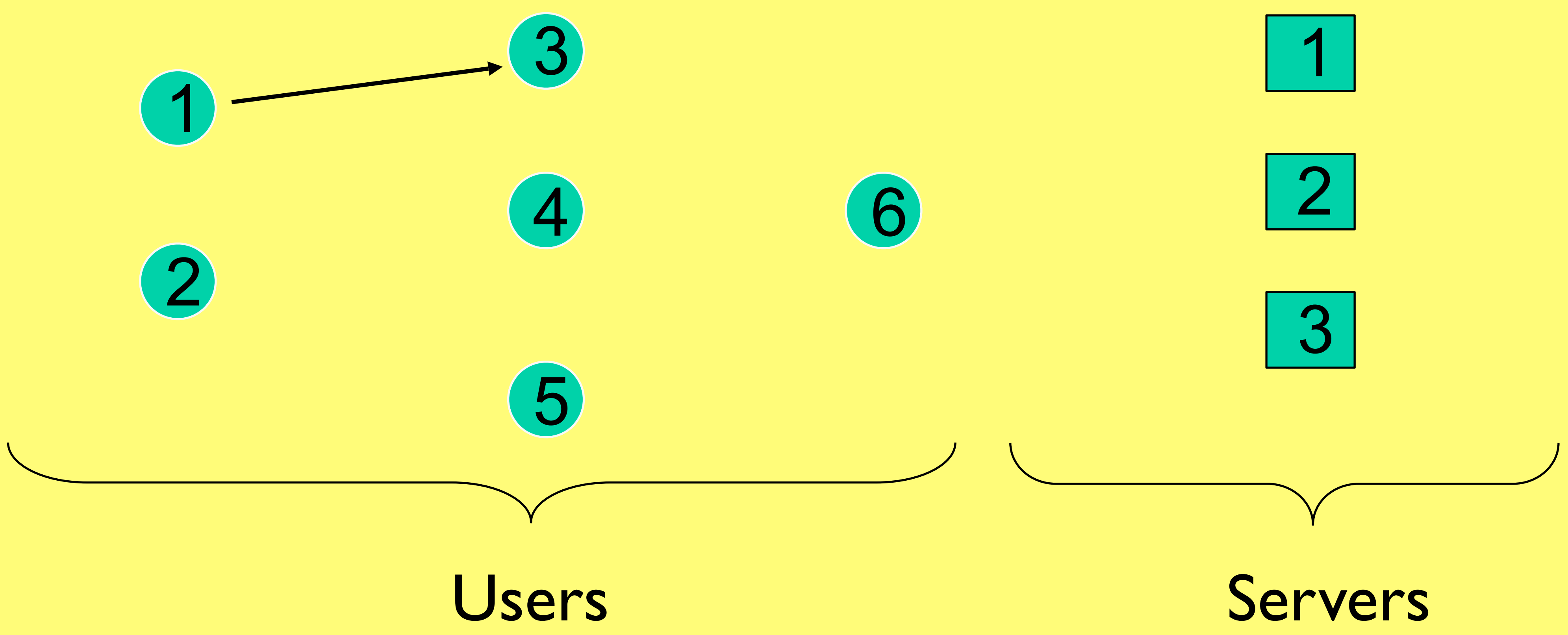
Flips a biased coin p_f



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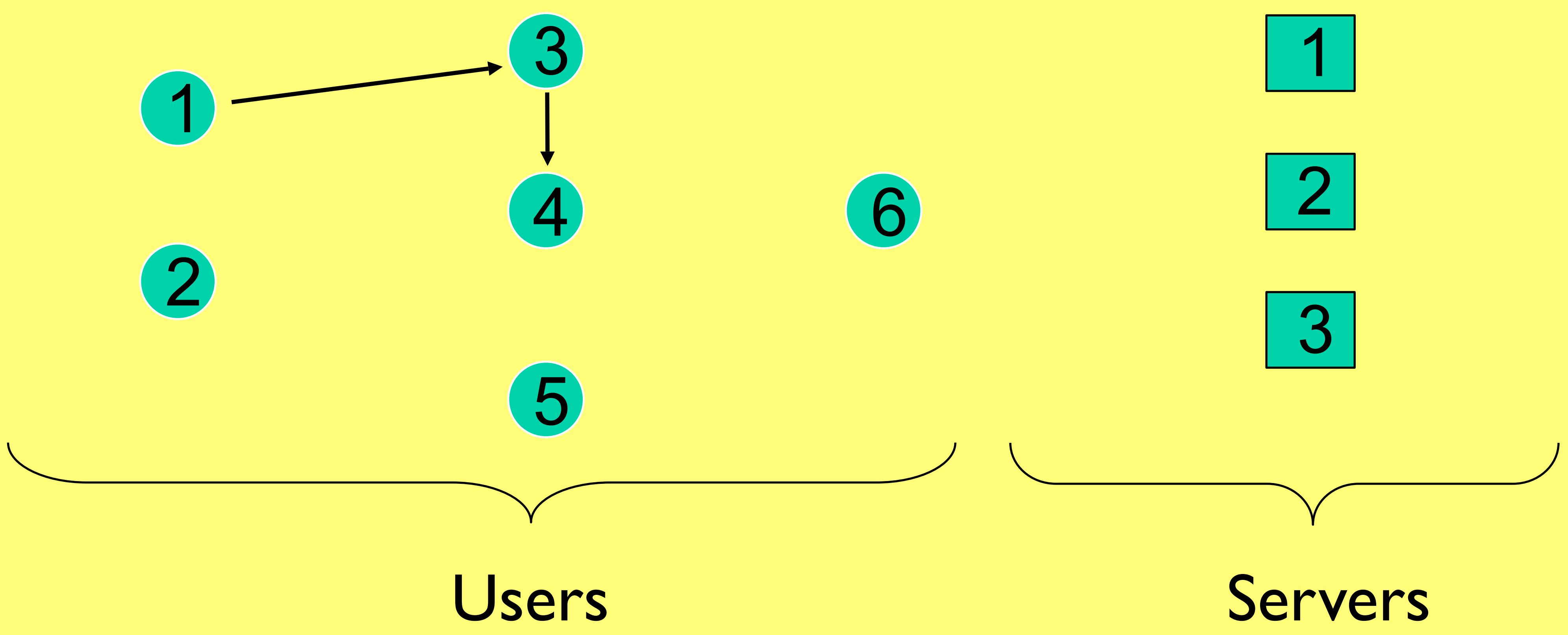

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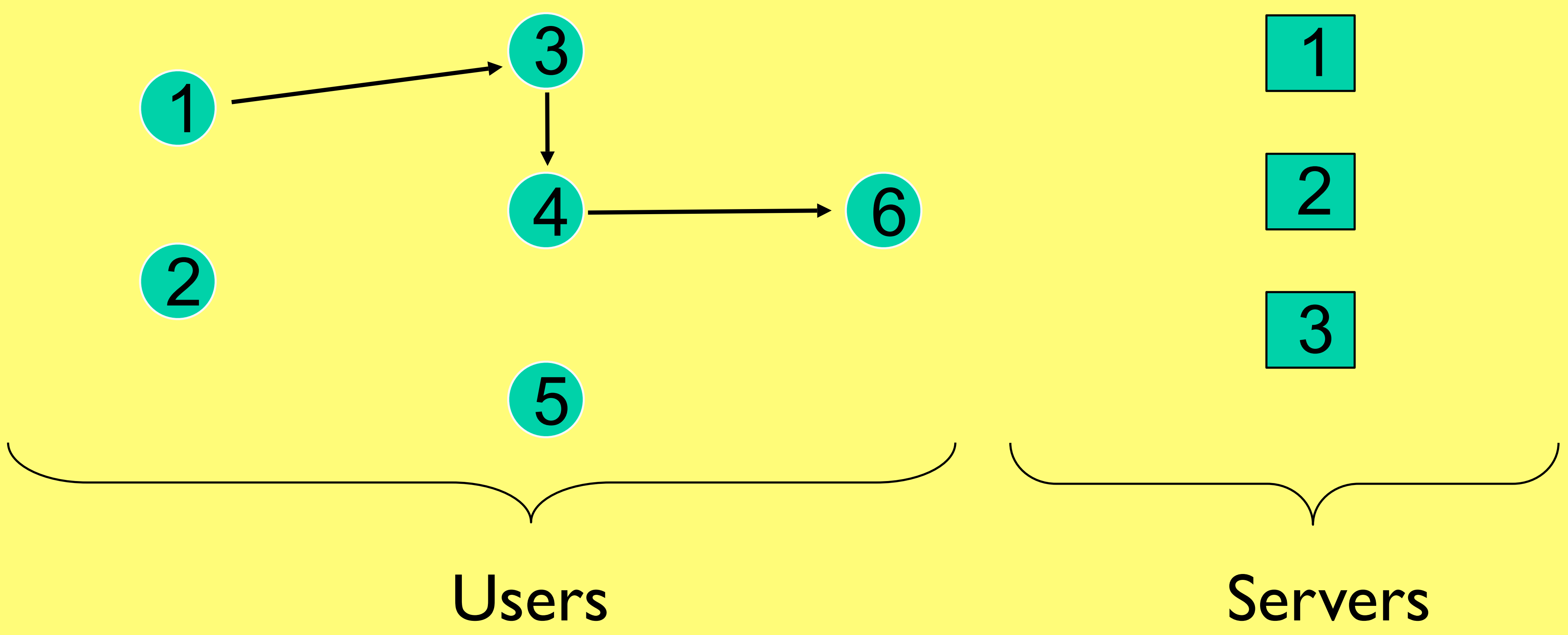

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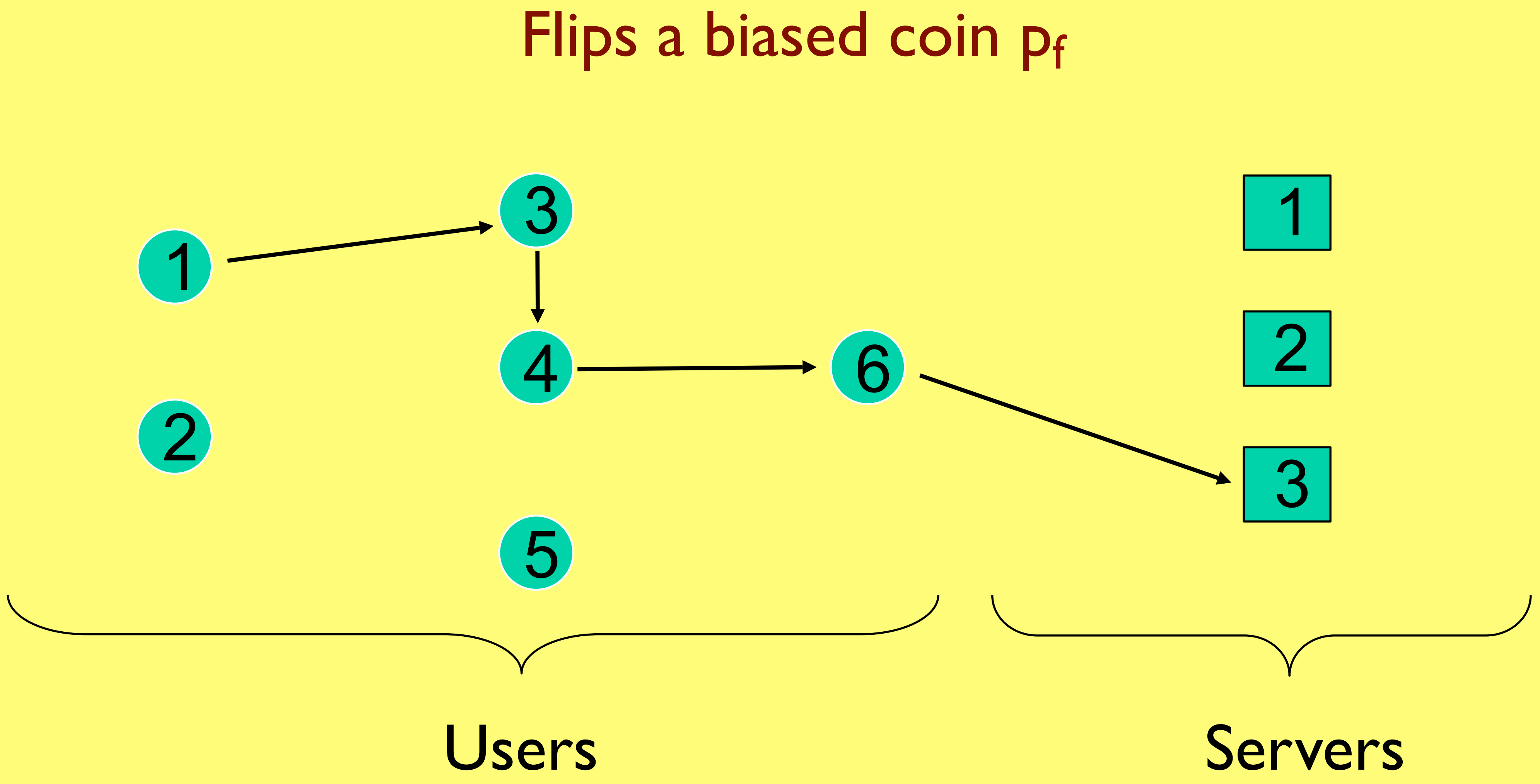

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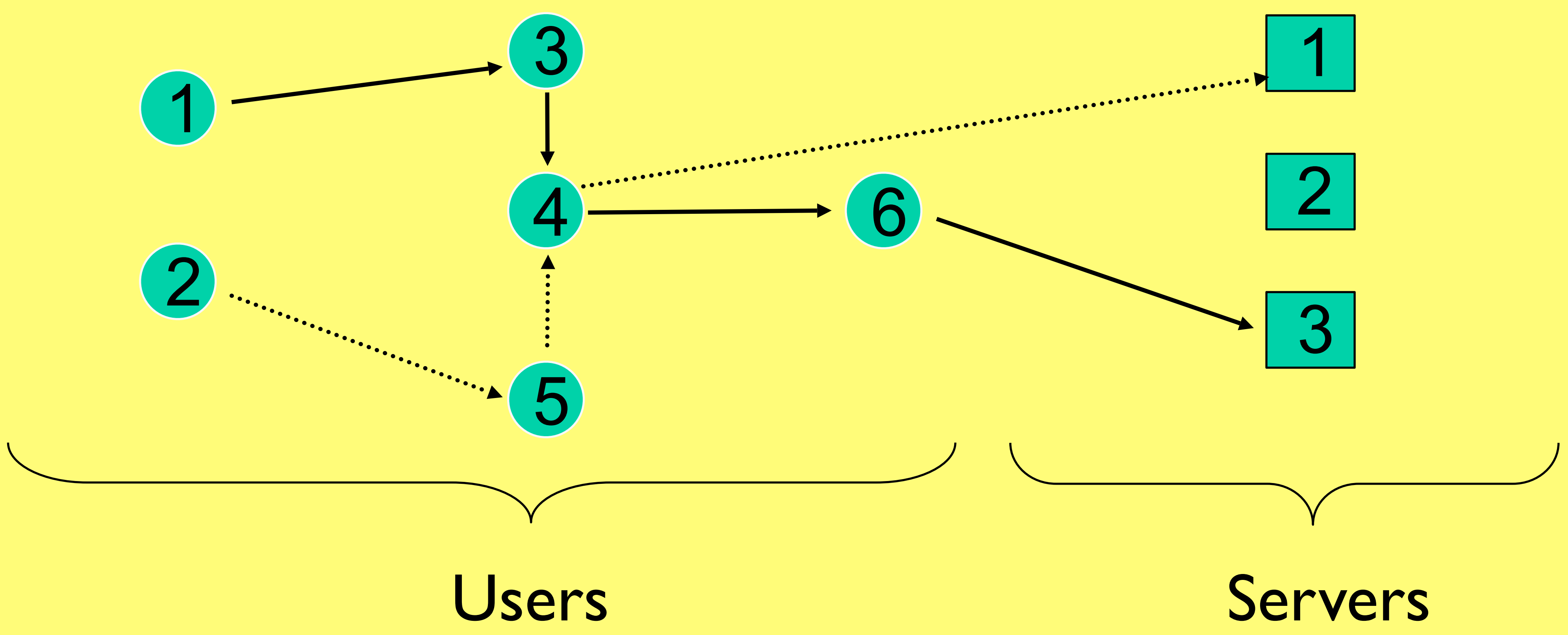

Probable Innocence

Informal definition

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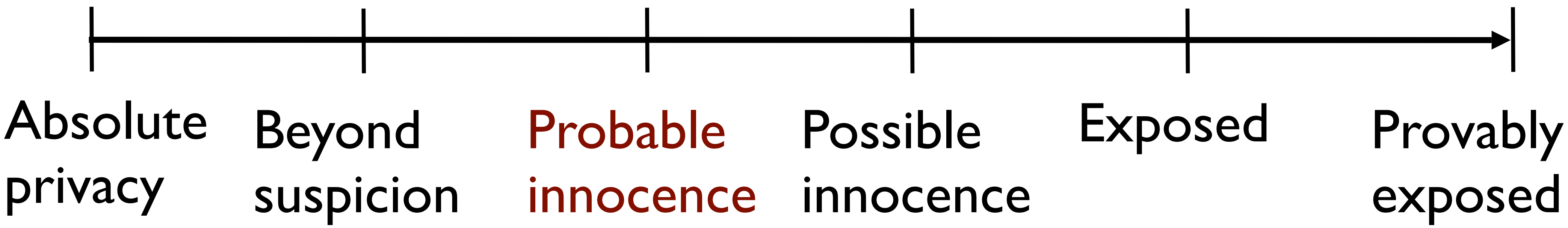

"A sender is <u>probably innocent</u> if, from the attacker's point of view, the sender appears no more likely to be the originator than to not be the originator"

Probable Innocence

Formal definition

- **Members:** m members participating in the protocol
  - n honest members
  - c=(m-n) corrupt members or collaborating attackers
- **Anonymous events:** a random variable A distributed over $\{a_1, a_2 \ldots, a_n\}$, where a_i indicates that the honest user i is the initiator of the message.
- **Observable events:** a random variable O distributed over $\{o_1, o_2 \ldots, o_n\}$, where o_i indicates that user i is honest and forwards the message to a corrupted user. In this case we say that user i is detected.

Probable Innocence

Formal definition

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Definition [Reiter and Ruben, 98]:

a protocol satisfies probable innocence if

$$\forall i \; p(o_i \mid a_i) \leq 1/2$$

Probable Innocence

Formal definition

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Probable Innocence

Formal definition

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Wrong

Definition [Halpern and O'Neill, 05]:

$$\forall i \; p(a_i \mid o_i) \leq 1/2$$

Right

Probable Innocence

Formal definition

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Proposition: if the a priori distribution is uniform then

$$\forall i \; p(o_i \mid a_i) = p(a_i \mid o_i)$$

Proof: by Bayes theorem we have

$$p(o_j \mid a_i) p(a_i) = p(a_i \mid o_j) p(o_j)$$

If A is uniformly distributed then (in Crowds) O is uniformly distributed too. Hence $p(a_i) = p(o_j) = 1/n$

Probable Innocence

Extended

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Definition:

a protocol satisfies α-probable innocence ($0 \leq \alpha \leq 1$) if

$$\forall i \; p(a_i \mid o_i) \leq \alpha$$

Proposition:

a protocol satisfies α-probable innocence if and only if

$$1 + n(1-\alpha)/p_f \leq m$$

Overview

Trust in Crowds

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- Extend the Crowds protocol to a more realistic scenario:
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  - The forwarding process is governed by a policy $q_i \in [0,1]$ which together with the forwarding factor p_f determines the probability that each member i is chosen as a forwarder.
- Results:
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observe this is at meta-level, a parameter of the analysis

Can be established experimentally, eg by the "*blender*" using Bayesian method, eg the Beta trust model

- Results:
  - Analyse the impact of such probabilistic behaviour of principals.
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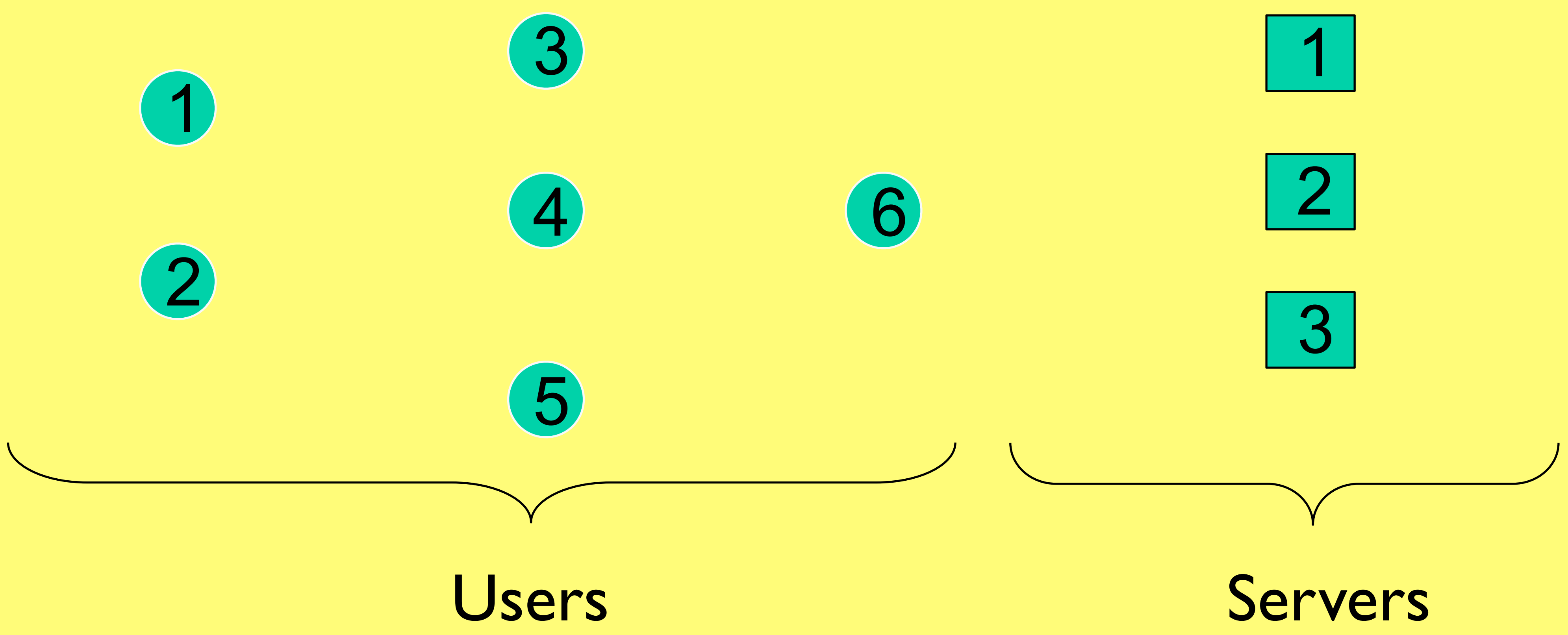
tCrowds

The extended protocol

- **tCrowds** [here and now]: allows users anonymous web transactions in the presence of probabilistic principals' behaviours.



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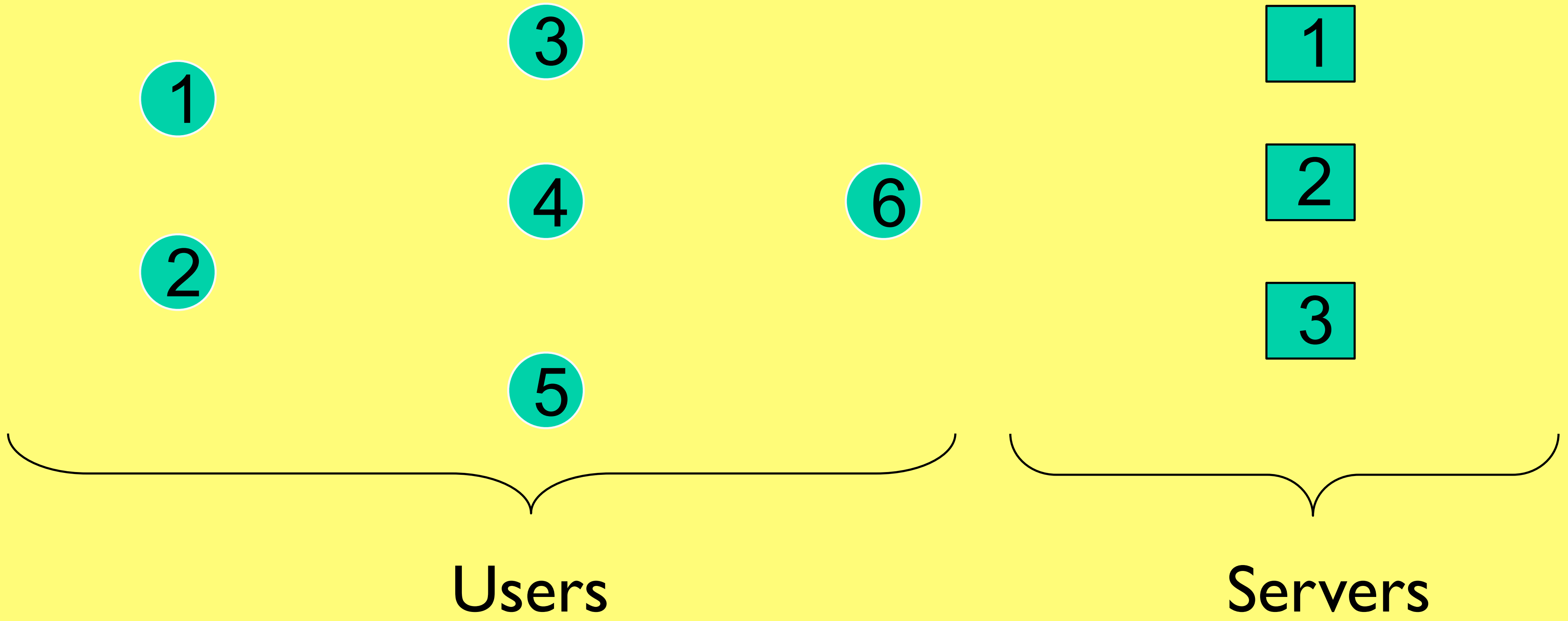

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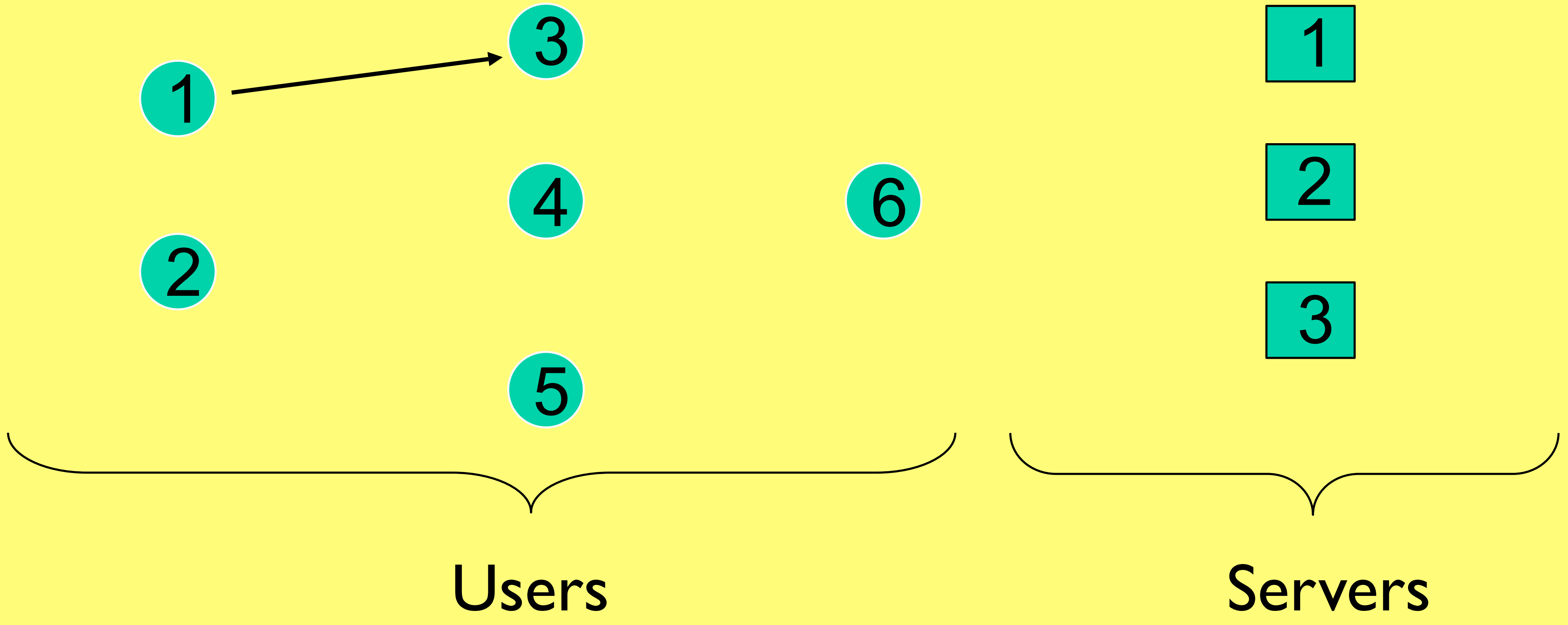

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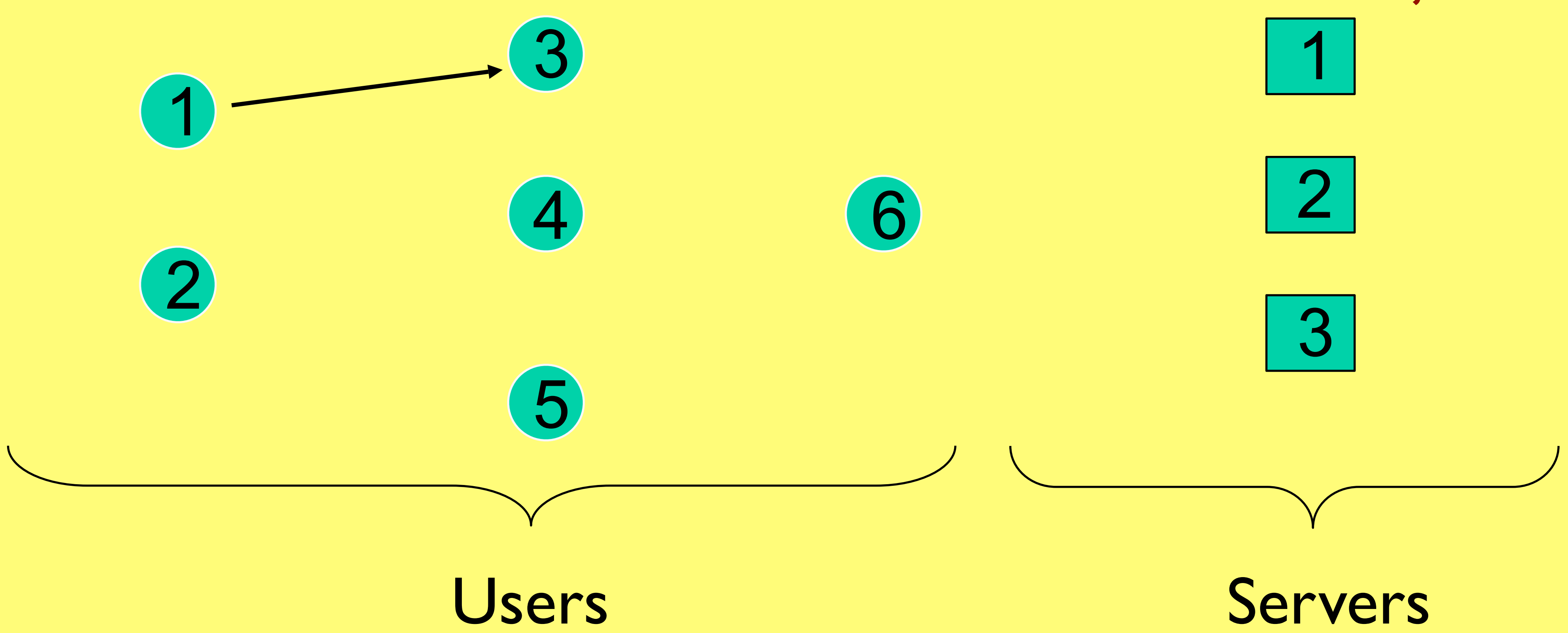
Forwards to j with prob $p_f \cdot q_j$



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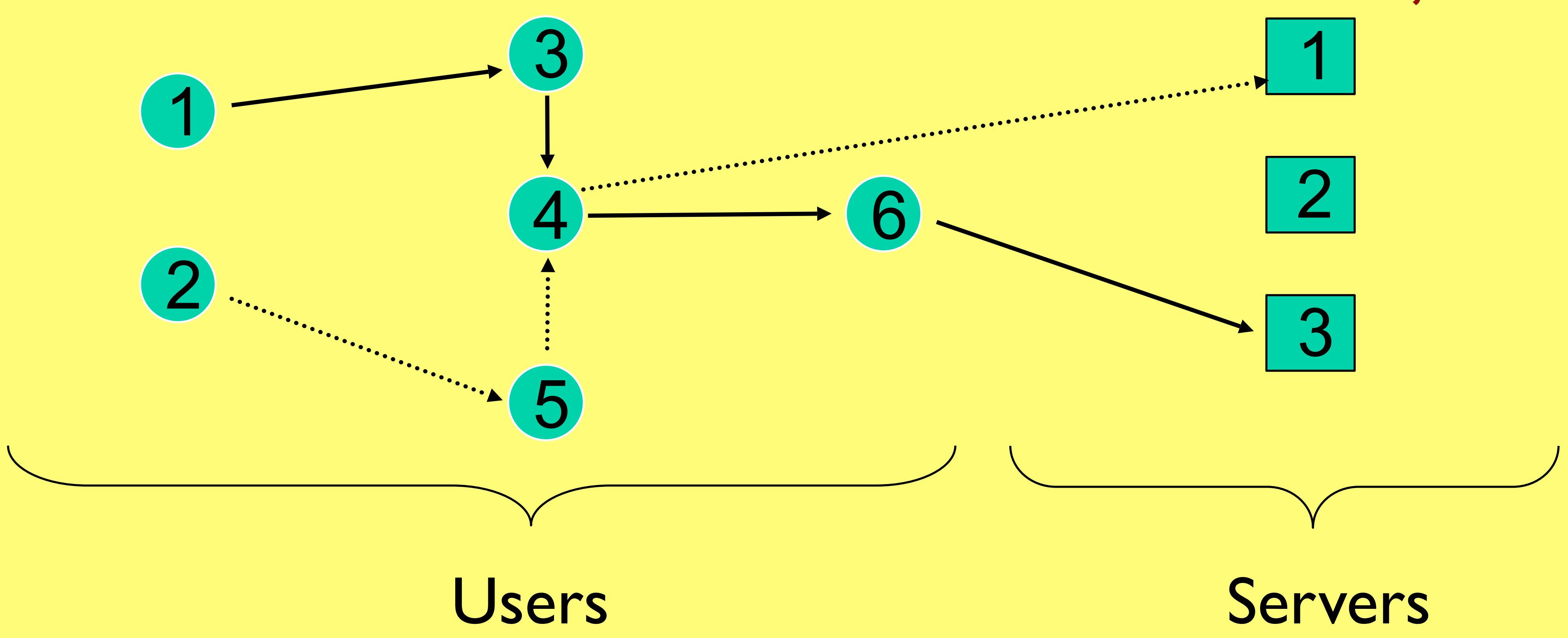

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The exter

observe we assume transactions are short, otherwise users could become corrupt whilst answer from server travels back.

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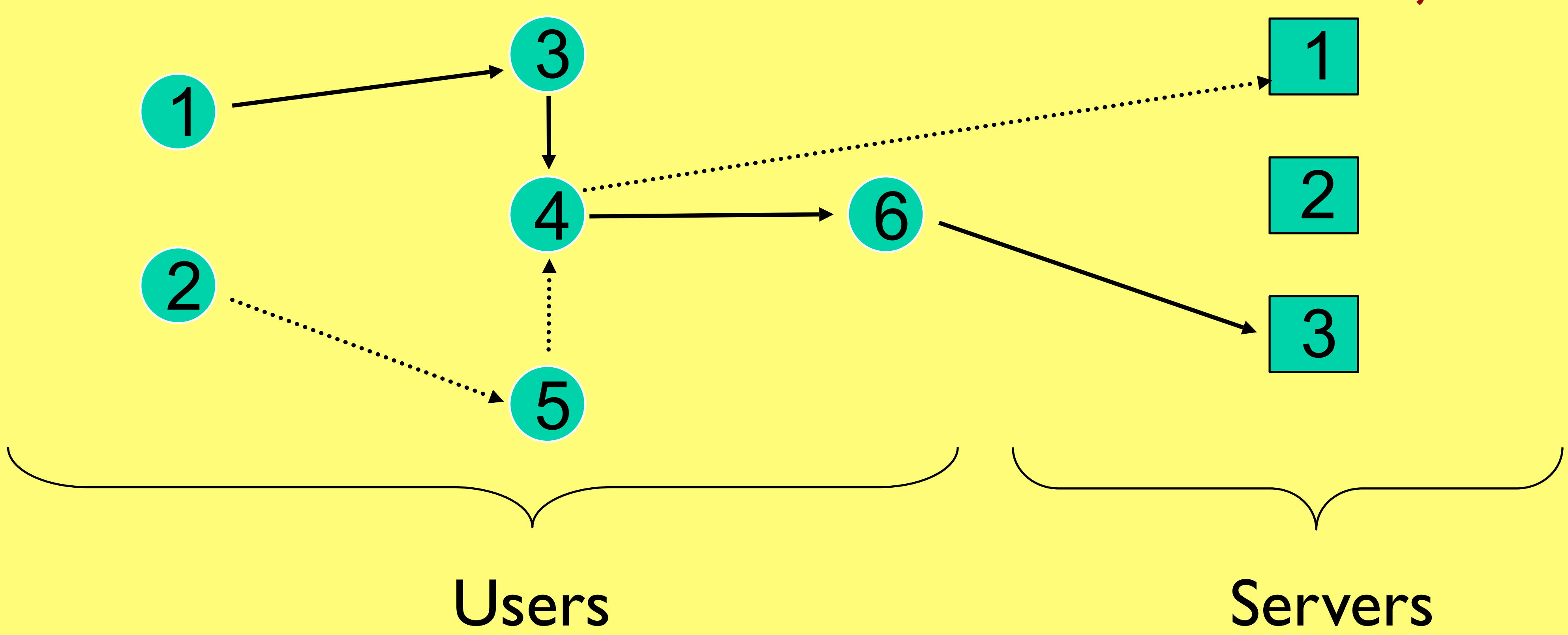

tCrowds

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The exten…

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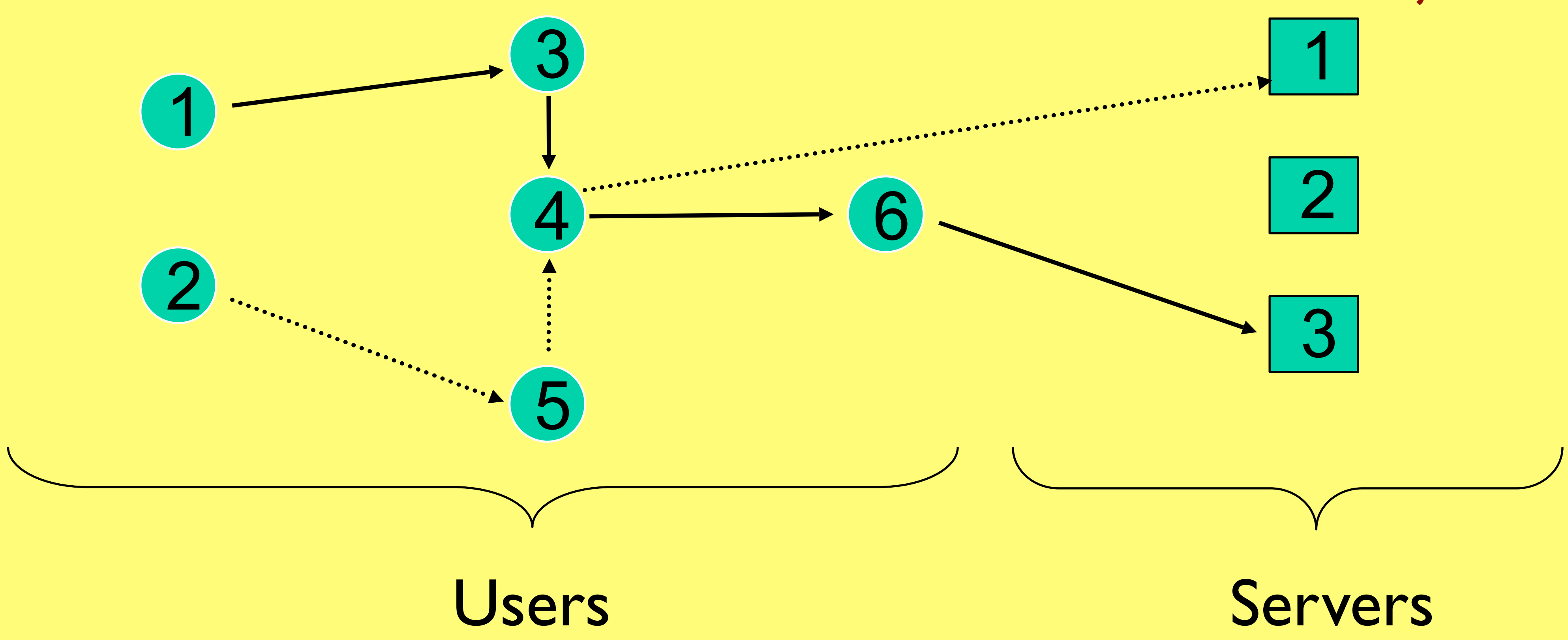
- tCrow… …web transactions in the presence of… …haviours.

extension to the general case is work in progress

Initiator selects j with prob q_j

Deliv… …p_f
Forwards to j with prob $p_f \cdot q_j$



Probable Innocence, again

- Need to compute

$$P\left(a_i \mid o_i\right) = \frac{P(a_i, o_i)}{P(o_i)}$$

- Start with:

Probable Innocence, again

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- Need to compute

$$P(a_i \mid o_i) = \frac{P(a_i, o_i)}{P(o_i)}$$

- Start with:

$$P(o_i, H_k) = \begin{cases} \frac{1}{n}(1 - t_i) & k = 0 \\ \frac{1}{n} t_i (1 - T) & k = 1 \\ \frac{1}{n} S\, T^{k-2}\, q_i t_i\, (1 - T) \cdot p_f^{k-1} & k \geq 2 \end{cases}$$

$$\text{with } S = \sum_{j=1}^{n} t_j \qquad T = \sum_{j=1}^{n} q_j t_j$$

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1st attacker at position k

Probable Innocence, again

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1st attacker at position k

prob to pick a honest principal

Probable Innocence, again

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- Need to compute

$$P\left(a_i \mid o_i\right) = \frac{P(a_i, o_i)}{P(o_i)}$$

- Continue with:

$$\begin{aligned}
P(o_i) &= \sum_{k=0}^{\infty} P(o_i, H_k) \\
&= \frac{1}{n}(1 - t_i) + \frac{1}{n} t_i (1 - T) \\
&\quad + \sum_{k=2}^{\infty} \frac{1}{n} S\, T^{k-2} \cdot q_i t_i \,(1 - T)\, p_f^{k-1} \\
&= \frac{1}{n}\left(1 - t_i T + S\, p_f q_i t_i \left(\frac{1 - T}{1 - p_f T}\right)\right)
\end{aligned}$$

Probable Innocence, again

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observe this is 0 iff T=1 and t_i=1
i is undetectable

Probable Innocence, again

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- Need to compute

$$P\left(a_i \mid o_i\right) = \frac{P(a_i, o_i)}{P(o_i)}$$

- Similarly:

$$\begin{aligned} P(a_i, o_i) &= \sum_{k=0}^{\infty} P(a_i, H_k, o_i) \\ &= \frac{1}{n}(1 - t_i) + \frac{1}{n} t_i (1 - T) \\ &\quad + \sum_{k=2}^{\infty} \frac{1}{n} t_i T^{k-2} \cdot q_i t_i \left(1 - T\right) p_f^{k-1} \\ &= \frac{1}{n}\left(1 - t_i T + p_f q_i t_i^2 \left(\frac{1 - T}{1 - p_f T}\right)\right) \end{aligned}$$

Probable Innocence, again

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- Need to compute

$$P(a_i \mid o_i) = \frac{P(a_i, o_i)}{P(o_i)}$$

- And therefore:

$$P(a_i \mid o_i) = \frac{1 - t_i T + p_f q_i t_i^2 \left(\frac{1-T}{1-p_f T}\right)}{1 - t_i T + S\, p_f q_i t_i \left(\frac{1-T}{1-p_f T}\right)}$$

- Observe that if i is detectable, this quantity is positive: ie, it can always be caught when is the initiator: Crowds never achieves "*absolute privacy*"

Probable Innocence, again

- Need to compute

$$P(a_i \mid o_i) = \frac{P(a_i, o_i)}{\ldots}$$

also observe that when T = 1- c/n and S = n - c, which characterise the (standard) Crowds, then this formula simplifies to the standard one.

- And there

$$P(a_i \mid o_i) = \frac{1 - t_i T + p_f q_i t_i^2 \left(\frac{1-T}{1-p_f T} \right)}{1 - t_i T + S\, p_f q_i t_i \left(\frac{1-T}{1-p_f T} \right)}$$

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Provably exposed principals

Proposition: *(Provably Exposed Principals)*

For all users s.t. $p(o_i) \neq 0$, we have $p(a_i \mid o_i) = 1$ iff one of the following holds.

1. $p_f = 0$
2. $t_i = 0$
3. $q_i = 0$
4. $T = 1$
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Provably exposed principals

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all paths $\# \leq 2$

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all paths # ≤ 2 (→ 1)

i is corrupt! (→ 2)

i never picked as forwarder (→ 3)

Provably exposed principals

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all paths # ≤ 2

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all participants are honest!

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all paths $\# \leq 2$

i is corrupt!

i never picked as forwarder

all participants are honest!

all but i are corrupt!

On Forwarding

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Theorem: *(Monotonicity in forwarding)*

$p(a_i \mid o_i)$ is a decreasing function of p_f

Corollary: *(Anonymity range)*

$$\forall i.\ P(a_i \mid o_i) \geq 1 - \frac{q_i t_i \sum_{j \neq i}^{n} t_j}{1 - t_i \sum_{j \neq i}^{n} q_j t_j + q_i t_i \sum_{j \neq i}^{n} t_j}$$

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tells us that high values of p_f enhance privacy. Yet, they slow the protocol down

tells us that $p_f = 1$ minimises $p(a_i \mid o_i)$. But then the message never reaches...

On Trust Values

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Theorem: *(α-Probable Innocence)*

For all α∈ [0,1], the extended protocol guarantees α-probable innocence to all its participants if

$$\forall i.\ \frac{q_i t_i \sum_{j\neq i}^{n} t_j}{1 - t_i \sum_{j\neq i}^{n} q_j t_j + q_i t_i \sum_{j\neq i}^{n} t_j} \geq 1 - \alpha$$

On Trust Values

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Theorem: *(α-Probable Innocence)*

For all α∈ [0,1], the extended protocol guarantees α-probable innocence to all its participants if

$$\forall i.\ \frac{q_i t_i \sum_{j\neq i}^{n} t_j}{1 - t_i \sum_{j\neq i}^{n} q_j t_j + q_i t_i \sum_{j\neq i}^{n} t_j} \geq 1 - \alpha$$

observe that this provides a *system of linear inequalities* that can be solved in q_i to try and achieve α-*probable innocence*

“Social” & “Rational” Policies

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Achieving α-Probable Innocence

Maintain the lower bound on $p(a_i \mid o_i)=1$ below α by manipulating the forwarding distribution (*social policy*), or by excluding untrustworthy participants (*rational policy*).

Example: Suppose $t_1 = 0.70, \quad t_2 = 0.97, \quad t_3 = 0.99$
For $\alpha=1/2$ the system admits two solutions, eg

$$q_1 = 0.4575, \quad q_2 = 0.2620, \quad q_3 = 0.2805 \ .$$

Observe how user 1 is helped (at the others’ risk!) to offset its higher tendency to corruption. Indeed, probable innocence in (standard) Crowds cannot be achieved.

The alternative, is for 2 and 3 to exclude 1 and yield higher overall security.

Conclusion & Further Work

- We have extended *Crowds* to take into account that principals are not usually either honest or malicious, but are liable to become *corrupt* (and again uncorrupt). Ours is the first attempt to cope with such probabilistic behaviour.

- Our forwarding policies can be used to make the protocol more secure (either *socially* or *rationally*) once an estimation of trust is available. A lot more work on integrating trust estimation is to be done.

- A deeper analysis of trust is likely to be possible on advanced anonymity protocols such as *Tarzan* and *ToR*.

- We are in the process of complete this analysis by *dropping* the hypothesis of short transactions.

Related Work

Crowds & External knowledge

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- Real world: attackers usually gather additional information correlated to the anonymous agents before attacking the protocol.

- Example: two agents voting by "yes" or "no" and the result of the vote is {yes, no}
  - Agents used different colours but the adversary does not know the correlation between the colors and the agents:

    {yes, no} ≡ {yes, no}

  - The adversary knows the correlation: {yes, no} ≠ {yes, no}

Related Work

Crowds & External knowledge

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analysis of the impact of attackers' extra knowledge on the security of information hiding protocols.

in *FAST 2009* with C. Palamidessi

Related Work

Crowds & Beliefs & Vulnerability

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- Open problem: measure and account for the accuracy of the adversary extra knowledge.
- Integrate the notion of adversary's beliefs:
  - Assume both actual a priori distribution of the hidden input and its correlation to the extra information unknown to adversary.
  - Generalise the approach to information flow systems.
- Results:
  - New metric for quantitative information flow based on the concept of vulnerability that takes into account the adversary's beliefs.
  - Model allows to identify the levels of accuracy for the adversary's beliefs which are compatible with the security of a given program or protocol.

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in *IEEE Symp on Security & Privacy 2010*
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