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Anonymity and one-way authentication in key exchange protocols

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Outline

Key exchange in Tor

Security goals

Security model

Protocols

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Key exchange in Tor

Tor circuit establishment

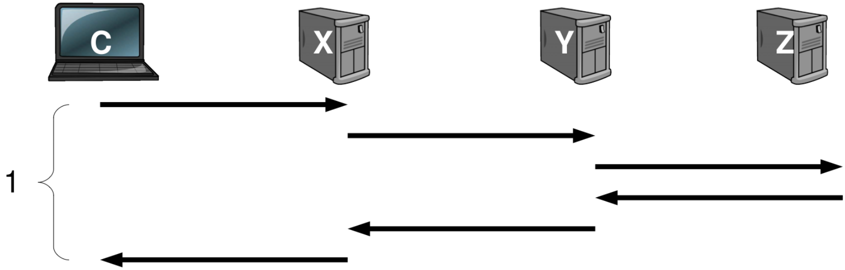
To establish a Tor **circuit**, a client Alice does the following:

1. Alice picks a Tor node X and establishes an encrypted authenticated channel with X
2. Alice picks a second Tor node Y and establishes an encrypted authenticated channel with Y, **tunnelled via** X
3. Alice picks a third Tor node Z and establishes an encrypted authenticated channel with Z, **tunnelled via** Y

$\vdots$

k. Alice relays her communication through nodes X, Y, Z, ..., W, with the final **exit node** W relaying communication to/from the destination address.

Tor circuit establishment



Øverlier and Syverson, PET 2007.

Tor authentication protocol (TAP)

A trusted PKI allows Alice to determine node n's public encryption key pk_n

1. Alice picks $x \stackrel{\$}{\leftarrow} \mathbb{Z}_q$
2. Alice sends $c \leftarrow \mathsf{Enc}_{pk_B}(g^x)$ to Bob.
3. Bob computes $m \leftarrow \mathsf{Dec}_{sk_B}(c)$, range checks m, picks $y \stackrel{\$}{\leftarrow} \mathbb{Z}_q$, and sends $a \leftarrow g^y$ and $b \leftarrow f(m^y)$ to Alice
4. Alice range checks a and that $b = f(a^x)$
5. Shared session key: $a^x = m^y$

Security of TAP

- Assume Π is an IND-CPA-secure, reaction-resistant encryption scheme and CDH in $\mathcal{G}$ is hard.
- TAP is secure:[2]
  - There exists no p.p.t. algorithm M such that, for a random output (pk, sk) of Π.KeyGen and a random exponent x, $M(pk, g, \mathsf{Enc}_{pk}(g^x)) = (a, a^x)$ for some a with non-negligible probability.

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- Non-standard security definition.
  - Customized to protocol construction.
  - Key recovery, not session key indistinguishability.

[2] Goldberg, PET 2006.

"Fourth protocol" of Øverlier and Syverson (PET 2007)

	Client $\hat{A}$		**Server** $\hat{B}$ long-term private key b, public key $B = g^b$
1.	select sid		
2.	$x \stackrel{\$}{\leftarrow} \mathbb{Z}_q$		
3.	$X \leftarrow g^x$	$\stackrel{X, sid}{\longrightarrow}$	$y \stackrel{\$}{\leftarrow} \mathbb{Z}_q$
4.			$Y \leftarrow g^y$
5.	$k \leftarrow (BY)^x$	$\stackrel{Y, sid}{\longleftarrow}$	$k \leftarrow X^{b+y}$

Proposed for, but never used, in Tor circuit establishment.

Insecurity of Øverlier and Syverson's "fourth protocol"

	Client $\hat{A}$		**Attacker** $\hat{M}$ Bob's public key $B = g^b$
1.	select sid		
2.	$x \xleftarrow{\$} \mathbb{Z}_q$		
3.	$X \leftarrow g^x$	$\xrightarrow{X, sid}$	$r \xleftarrow{\$} \mathbb{Z}_q$
4.		$\xleftarrow{Y', sid}$	$Y' \leftarrow B^{-1} g^r = g^{r-b}$
5.	$k \leftarrow (BY')^x = g^{(b+r-b)x} = g^{rx}$		$k \leftarrow X^r = g^{rx}$

Security goals

One-way authenticated key exchange

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One-way $\neq$ one-flow:

- **One-flow** AKE establishes a session key with a single message from the client to the server.
- **One-way** AKE gives server-to-client authentication but not client-to-server authentication

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One-way AKE as either:

- Restriction of standard two-way AKE to one-way setting
- Extension of public-key encryption to include forward secrecy

Secrecy without authentication?

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- A server provides the same level/type of service to each unauthenticated client:
  - Medical advice to anonymous patients the same whether request came encrypted or not.
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$$\text{secrecy} \leq \text{authentication}$$

But...

- Doctors required to preserve patient–doctor confidentiality even with unauthenticated patients $\Longrightarrow$ **exclusivity**.
- ISPs may eavesdrop on search engine queries/responses for marketing purposes.

Anonymity properties[3]

- **Anonymity**: party is not identifiable (within a set of parties)

[3] Pfitzmann and Hansen. http://dud.inf.tu-dresden.de/Anon_Terminology.shtml

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Related properties:

- **Identity hiding**: identity of a party never communicated in the clear but eventually made known to peer
- **Deniability**: identity of a party not necessarily kept secret, but party's participation in a session cannot be conclusively proven

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Security model

Session execution

- Parties have long-term (static) and session-specific (ephemeral) key pairs and certificates associated to long-term keys
- Parties assign a locally unique session identifier Ψ to each session
- Parties output a tuple $(sk, pid, \vec{v})$ for each session, where
  - sk is a session key
  - pid is a party identifier or the anonymous symbol $\circledast$
  - $\vec{v} = (\vec{v}_1, \vec{v}_2, \dots)$ is a vector of vectors of public values

Adversary powers

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- EstablishCertificate

One-way AKE security

- $\mathsf{Test}(P, \Psi) \to sk$:
  1. Stop if $\Psi.sk = \perp$ or $\Psi.pid = \circledast$.
  2. Choose $b \xleftarrow{\$} \{0, 1\}$
  3. If $b = 1$: return $\Psi.sk$
  4. If $b = 0$: return random key of same length

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- Ψ is **one-way-AKE-fresh** if both:
  1. for every $\vec{v}_j$ in $\Psi.\vec{v}$, there is at least one element $X \in \vec{v}_j$ where adversary is not a partner to X
  2. no $\mathsf{SessionKeyReveal}^P(\Psi')$ at $P = \Psi.pid$ where $\Psi'.\vec{v} = \Psi.\vec{v}$

One-way AKE security

- $\mathsf{Test}(P, \Psi) \to sk$:
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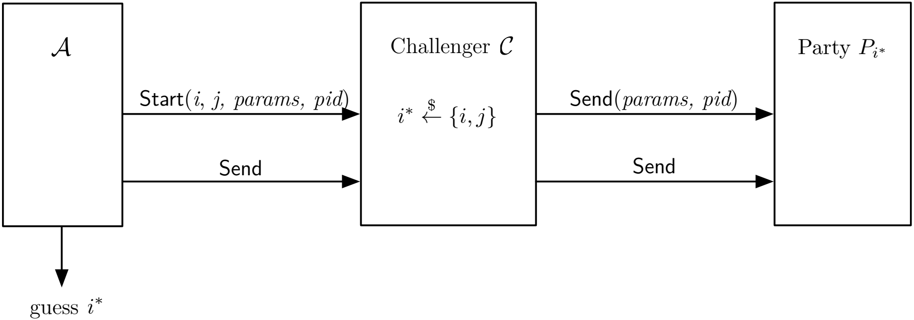
- **Forward secrecy?**

One-way anonymity

Guess which of two parties is participating in the key exchange.



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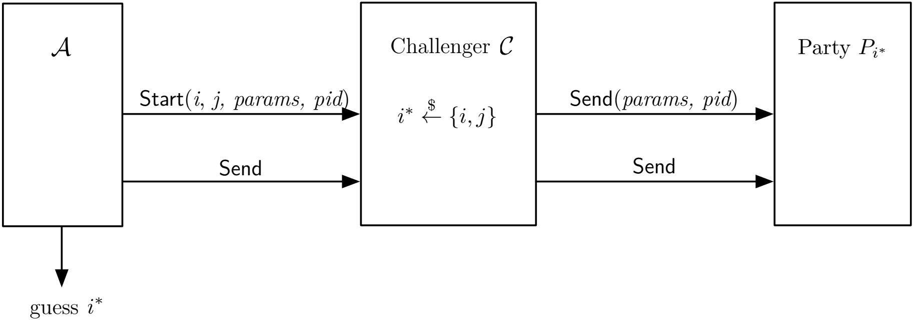

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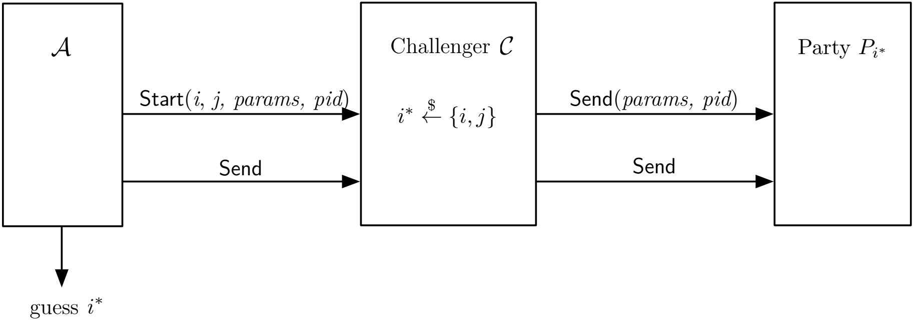
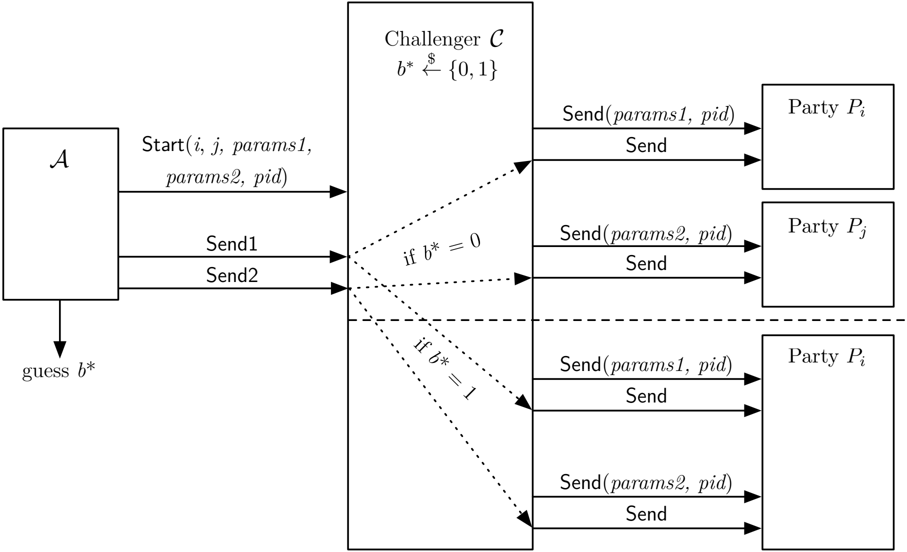


- **Goal:** Guess i^* with non-negligible advantage.
- Can issue RevealNext, Partner, and SessionKeyReveal to challenger
- Can't issue queries related to challenge session to original parties

Unlinkability

Determine whether two items of interest are related or not.



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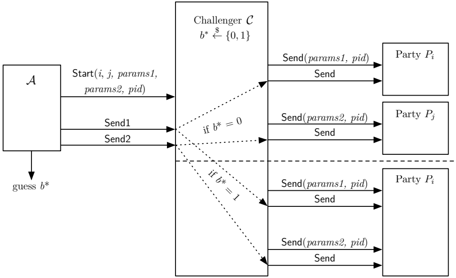

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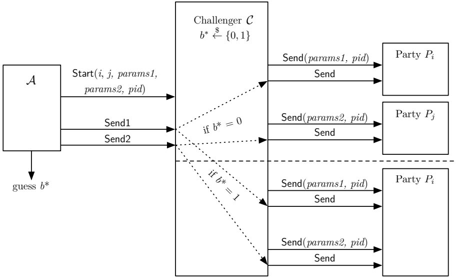

- **Goal:** Guess b^* with non-negligible advantage.
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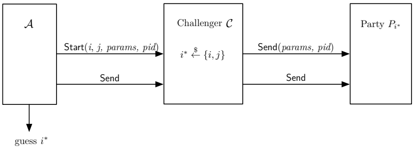

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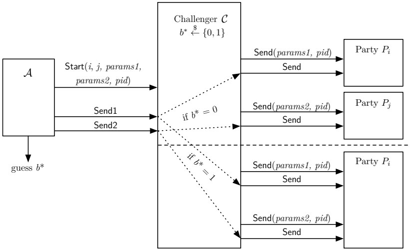
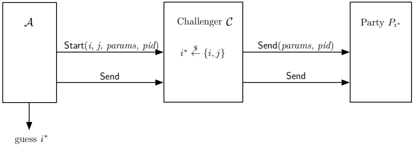
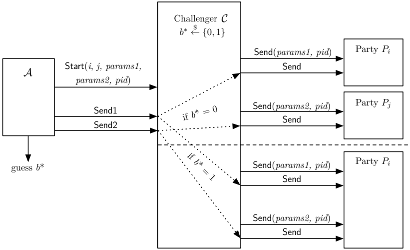


One-way anonymity = Unlinkability





Equivalence of anonymity and unlinkability

One-way anonymity $\implies$ unlinkability:

- Adversary starts unlinkability game with parties P_i and P_j

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One-way anonymity $\Longrightarrow$ unlinkability:

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- Simulator creates two sessions using anonymity challenger:
  1. One session with P_i
  2. One session with anonymity challenger for P_i and P_j

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- Adversary starts unlinkability game with parties P_i and P_j
- Simulator creates two sessions using anonymity challenger:
  1. One session with P_i
  2. One session with anonymity challenger for P_i and P_j
- If anonymity challenger uses P_i: unlinkability simulator uses P_i and P_i
- If anonymity challenger uses P_j: unlinkability simulator uses P_i and P_j

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- If anonymity challenger uses P_i: unlinkability simulator uses P_i and P_i
- If anonymity challenger uses P_j: unlinkability simulator uses P_i and P_j
- Unlinkability adversary guesses b

$\implies$ one-way anonymity simulator guesses $\begin{cases} i, & \text{if } b = 0 \\ j, & \text{if } b = 1 \end{cases}$

Equivalence of anonymity and unlinkability

Unlinkability $\implies$ one-way anonymity:

- Adversary starts one-way anonymity game with parties P_i and P_j
- Simulator uses unlinkability challenger for P_i and P_j:
  1. Adversary's queries are relayed to unlinkability challenger's second party
- If unlinkability challenger uses P_i: anonymity simulator uses P_i
- If unlinkability challenger uses P_j: anonymity simulator uses P_j
- Anonymity adversary guesses i'

$$\implies \text{ unlinkability simulator guesses } \begin{cases} 1, & \text{if } i' = i \\ 0, & \text{if } i' = j \end{cases}$$

Protocols

One-way-authenticated TLS

Session key security

- Mutually authenticated:
  - Jonsson and Kaliski (CRYPTO 2002): RSA encryption security
  - Morrissey, Smart, Warinschi (ASIACRYPT 2008): truncated TLS
  - Gajek et al. (ProvSec 2008): UC security of TLS_DHE
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- One-way authenticated:
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  - Gajek et al. (ProvSec 2008): UC security of TLS_DHE
  - TLS_RSA and TLS_DHE could be proven secure in our model, although neither with forward secrecy

One-way-authenticated TLS

Anonymity

Lots of values in TLS could leak identifying information:

- ClientHello: supported TLS versions, cipher suites, algorithms, extensions
- ClientHello.client_random.gmt_unix_time: current time in seconds
- ServerHello.session_id: many clients abort if they receive a session identifier that already exists in its cache

Proposed protocol: `ntor`

	Client $\hat{A}$		Server $\hat{B}$ long-term private key b, public key $B = g^b$
1.	$x \xleftarrow{\$} \mathbb{Z}_q$		
2.	$X \leftarrow g^x$		
3.	$\Psi_a \leftarrow \mathtt{H}_{sid}(X)$	$\xrightarrow{X, \Psi_a}$	$y \xleftarrow{\$} \mathbb{Z}_q$
4.			$Y \leftarrow g^y$
5.			$\Psi_b \leftarrow \mathtt{H}_{sid}(Y)$
6.			$(sk', sk) \leftarrow \mathtt{H}(X^y, X^b, \hat{B}, X, Y)$
7.		$\xleftarrow{Y, t_b, \Psi_b}$	$t_b \leftarrow \mathtt{H}_{mac}(sk', \hat{B}, Y, X)$
8.	$(sk', sk) \leftarrow \mathtt{H}(Y^x, B^x, \hat{B}, X, Y)$		
9.	verify t_b		
10.	output $(sk, \hat{B}, \vec{v} = (X, (Y, B)))$		output $(sk, \circledast, \vec{v} = (X, (Y, B)))$

Analysis of `ntor`

- **One-way AKE security**: If $\mathtt{H}$ and $\mathtt{H}_{mac}$ are random oracles and $\mathtt{H}_{sid}$ is collision-resistant, and the gap Diffie–Hellman assumption holds.
- **One-way anonymity**: Unconditionally.

[4] Backes, Kate, Mohammadi. http://www.infsec.cs.uni-saarland.de/~mohammadi/paper/owake.pdf

Analysis of ntor

- **One-way AKE security**: If H and H_{mac} are random oracles and H_{sid} is collision-resistant, and the gap Diffie–Hellman assumption holds.
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Protocol	Efficiency (client)		Efficiency (server)		authentication	security
	Off-line	On-line	Off-line	On-line		
DH	1	1	1	1	none	insecure
Signed-DH	1	1+sigver	1	1+sign	one-way	no FS
ØS	1	1	1	1	one-way	insecure
MQV	1	1.17 (1.5)	1	1.17 (1.5)	mutual	non-tight
UM	1	2	1	2	mutual	limited
ntor	1	2	1	1.33	one-way	tight
Ace[4]	2	1.08 (1.17)	1	1.08 (1.17)	one-way	tight

[4] Backes, Kate, Mohammadi. http://www.infsec.cs.uni-saarland.de/~mohammadi/paper/owake.pdf

Conclusions

Summary

- Insecurity of previously proposed protocol of Øverlier and Syverson
- **Security definitions** for
  - one-way AKE
  - anonymity
  - unlinkability
- **Equivalence** of anonymity and unlinkability
- **New protocol** `ntor` with security arguments

Open questions

- Most appropriate protocol for deployment?
- Impact of weak randomness on anonymity?
- Equivalence or inequivalence of anonymity and unlinkability in other settings?
- Pseudonymity in AKE: is it just mutual AKE with throw-away credentials?
- One-way AKE as public-key encryption with forward secrecy?