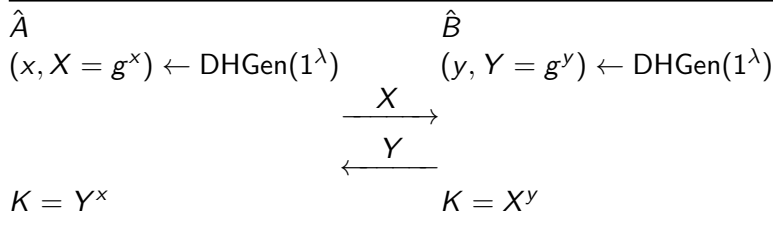






# Key Exchange Protocols

## Diffie-Hellman key exchange



- Allow two users to agree keying material without an existing shared secret;

# Key Exchange Protocols

KEA+: two way authenticated key exchange

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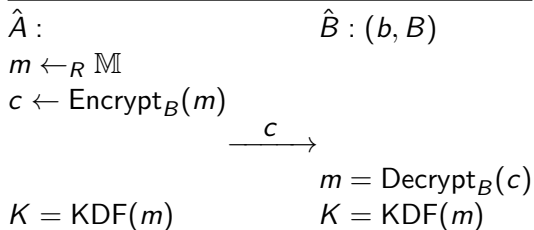
$\hat{A} : (a, A = g^a)$ $(x, X = g^x) \leftarrow \text{DHGen}(1^\lambda)$	$\hat{B} : (b, B = g^b)$ $(y, Y = g^y) \leftarrow \text{DHGen}(1^\lambda)$
$\xrightarrow{X}$ $\xleftarrow{Y}$	
$K = \text{KDF}(Y^a   B^x   \hat{A}   \hat{B})$	$K = \text{KDF}(A^y   X^b   \hat{A}   \hat{B})$

---

- Static (authenticated) keys:  $(a, A), (b, B)$
- Ephemeral keys:  $(x, X), (y, Y)$
- KDF: Key derivation function.

# Key transport

## Key Encapsulation Mechanism (KEM)



- One-way authentication and one-way anonymity
- No forward secrecy





## The Tor anonymity network

- Allows for improved privacy for Internet connections web browsing



- Run through a series of volunteer relays
- Increased interest following YOU-KNOW-WHO revelations



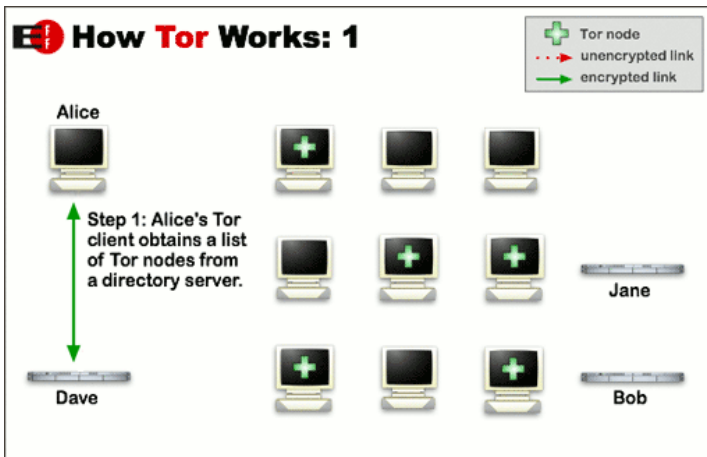


Figure source: torproject.org



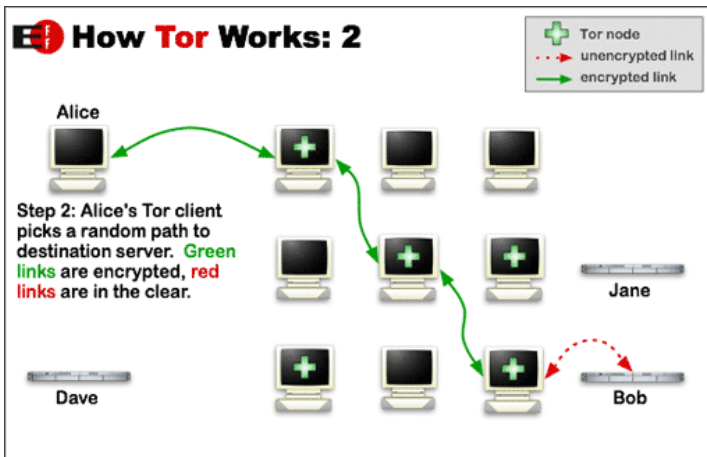


Figure source: torproject.org



## Tor handshake

- The clients need to remain anonymous;
- The servers need to be authenticated;
- Originally uses Tor Authentication Protocol (TAP);
- Current best practice: ntor protocol;



## ntor protocol

---


$$\hat{A} : \\ (x, X) \leftarrow \text{DHGen}(1^\lambda)$$

$$\xrightarrow{X}$$

$$\hat{B} : (b, B) \\ (y, Y) \leftarrow \text{DHGen}(1^\lambda)$$

$$s_1 = X^y | X^b$$

$$(vk, K) = H_1(s_1 | \hat{B} | X | Y)$$

$$auth = H_2(vk | \hat{B} | Y | X)$$

$$\xleftarrow{Y, auth}$$

$$s_1 = Y^x | B^x$$

$$(vk, K) = H_1(s_1 | \hat{B} | X | Y)$$

$$\text{ensure } auth = H_2(vk | \hat{B} | Y | X)$$


---





## A need for quantum-safe handshake

- If you send something now
  - Encrypted with an algorithm that's later broken
  - And someone has stored your message
  - They can decrypt it
- Encryption needs to take into account the lifetime for which your data might remain sensitive
- Attacker who doesn't actively get involved at the time of the interaction, but passively records traffic for later analysis
- Fits known attacker pattern





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$\hat{A} :$   
 $(x, X) \leftarrow \text{DHGen}(1^\lambda)$   
 $(pk_N, sk_N) \leftarrow \text{NTRUGen}(1^\lambda)$

$\hat{B} : (b, B)$   
 $(y, Y) \leftarrow \text{DHGen}(1^\lambda)$

$\xrightarrow{X, pk_N}$

$s_1 = X^y | X^b$   
 $s_2 \leftarrow_R \mathbb{M}$   
 $c \leftarrow \text{NTRUEnc}(s_2, pk_N)$   
 $(vk, K) = H(s_1 | \hat{B} | X | Y | s_2 | pk_N)$   
 $auth = H_{\text{mac}}(vk | \hat{B} | Y | X | c | pk_N)$

$\xleftarrow{Y, c, auth}$

$s_1 = Y^x | B^x$   
 $s_2 = \text{NTRUDec}(c, sk_N)$   
 $(vk, K) = H(s_1 | \hat{B} | X | Y | s_2 | pk_N)$   
 ensure  $auth = H_{\text{mac}}(vk | \hat{B} | Y | X | c | pk_N)$



$$\hat{A} :$$

$$(x, X) \leftarrow \text{DHGen}(1^\lambda)$$

$$(pk_N, sk_N) \leftarrow \text{NTRUGen}(1^\lambda)$$

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$$s_1 = Y^x | B^x$$

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$$\text{ensure } auth = \text{H}_{\text{mac}}(vk | \hat{B} | Y | X | c | pk_N)$$





## ntrutor protocol

- Efficiency
- Provable security
  - eCK model with extension to passive quantum attackers
  - multi CCA model
- Forward secrecy
- Reuse existing design as much as possible
- Easy to migrate to
- Add no identifiers



	TAP	ntor	ntrutor
client → server bytes	186	84	693
server → client bytes	148	64	673
client computation (stage 1)	280 $\mu$ s	84 $\mu$ s	272 $\mu$ s
server computation	771 $\mu$ s	263 $\mu$ s	307 $\mu$ s
client computation (stage 2)	251 $\mu$ s	180 $\mu$ s	223 $\mu$ s
total computation time	1302 $\mu$ s	527 $\mu$ s	802 $\mu$ s
% client	40.8%	50.1%	61.7%

Table : Performance comparison of TAP, ntor, and ntrutor



- We have a prototype implementation as a proof of concept
- Available on github:  
<https://github.com/NTRUOpenSourceProject/ntru-tor>
- But this can't simply be implemented as written
  - Tor packets are limited to 512 bytes
  - Tor handshake messages are limited to one packet
- Solutions:
  - Change one of the above
  - Both have been discussed within the Tor project in other contexts









