Secure Messaging Protocols

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Offensive Technologies – Guest Lecture

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Disclaimer

These slides are optimized for didactic purposes. Primitives and protocols have been simplified, sometimes to the point where technically they are incorrect (and most likely insecure).

Outline

History (1/3)

- 1991: Phil Zimmermann creates Pretty Good Privacy (PGP)
  - February 1993: US starts criminal investigation for "munitions export without a license"
  - 1995: PGP source code published as a physical book
    - US first amendment protects export of books
  - 1996: Criminal investigation was dropped, no charges were filed
- 2004: Nikita Borisov, Ian Goldberg and Eric Brewer create OTR
  - "Off-the-Record Communication, or, Why Not To Use PGP"
  - Has forward secrecy
  - Has deniability
  - Requires both parties online for setting up

History (2/3)

- 2011: Gary Belvin introduces SecureSMS; “OTR for SMS”
- 2012: SCIMP (Silent Circle instant messaging protocol)
  - By Vinnie Moscaritolo, Gary Belvin and Phil Zimmermann
  - SecureSMS for XMPP
  - I formally verified its security with ProVerif
- February 2014: Open Whisper Systems releases TextSecure v2
  - Asynchronous: allows offline initial user message
  - Later renamed to Signal
- May 2014: SC updates to SCIMP v2
  - Asynchronous: allows offline initial user message
- August 2015: SC releases code for SCIMP v2
  - Adds more inconsistencies between code and documentation
  - I find and report many security bugs in the code
- September 2015: SC discontinues SCIMP, switches to Signal based protocol

History (3/3)

- February 2014: Facebook (now Meta) acquires WhatsApp
- April 2014: Signal announces partnership with WhatsApp
- April 2016: WhatsApp completes integration of Signal protocol
- November 2016: Trevor Perrin and Moxie Marlinspike release official specification for the Signal protocol
- September 2023: Signal gets post-quantum confidentiality

Security and Privacy features

- Confidentiality
- Integrity
- Availability
- (Key) Authentication
- Forward Secrecy
- Post-Compromise Security (PCS)
- Deniability vs. Non-repudiation
- Transport Privacy

Trust Establishment

- Opportunistic encryption
- Public Key Infrastructure (PKI)
- Web-of-Trust (WoT)
- Trust-On-First-Use (TOFU)
- Fingerprint verification
  - Socialist Millionaire Protocol (SMP)
  - Short Authentication String (SAS)
  - Safety Numbers
- Key directory
- Key transparency
- Blockchain(?)

Miscellaneous

- User experience
- Multi-device
- Group chat
- File transfer
- Video-chat
- Backups
- (Formal) verification
- Implementation security
- Audits

Apps and protocols

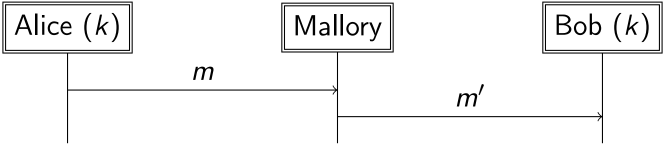
- Briar
- Discord (Dave)
- Dust
- Facebook Messenger
- Google Allo
- Google Chat
- Google Messages
- iMessage
- irc
- LINE
- Matrix (Olm/Megolm)
- Mattermost
- Pond
- QQ Mobile
- Rocket.Chat
- Session
- SimpleX
- Skype
- Slack
- SnapChat
- Teams
- Telegram (MTProto)
- Threema
- Viber
- WeChat
- WhatsApp
- Wickr
- Wire
- X
- XMPP (OMEMO)
- Zoom
- Zulip
- . . .

many use the Signal protocol or a variant

Attacker model

End-to-End security (E2E, sometimes E2EE for encryption)

- all messages are handed to the adversary for delivery.[1]



Alice (k)

Mallory

Bob (k)

Mallory has full control over all messages

- she may learn, change, inject, drop, reorder, and replay all messages

Kerckhoffs principle

- Mallory knows everything except the key

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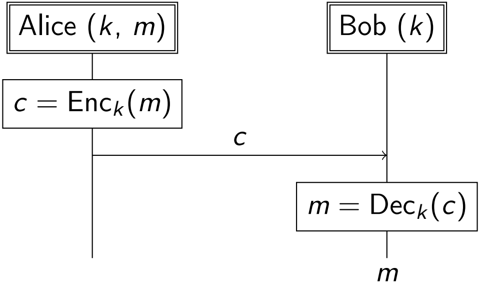
[1] For simplicity, I will omit Mallory from most diagrams for now.

Encryption



Alice (k, m)

Bob (k)

$c = \mathrm{Enc}_k(m)$

c

$m = \mathrm{Dec}_k(c)$

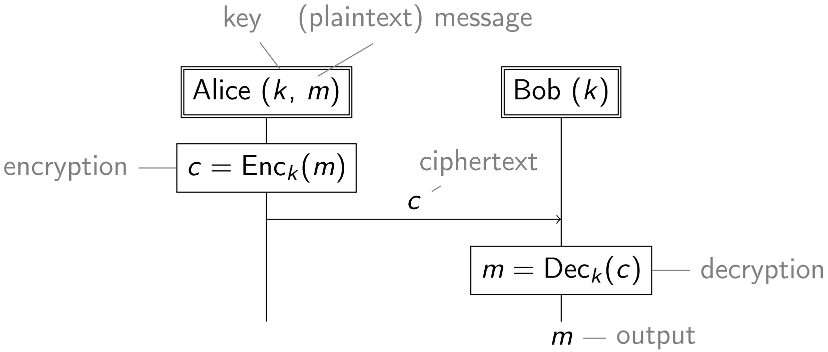
m

Provides confidentiality: Mallory learns nothing[2] about m

---

[2] almost nothing: I will not formalize this today

Encryption



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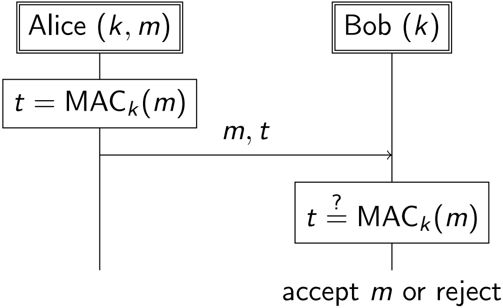
Message Authentication Code (MAC)



Alice (k, m)

Bob (k)

$t = \mathrm{MAC}_k(m)$

m, t

$t \overset{?}{=} \mathrm{MAC}_k(m)$

accept m or reject

Provides integrity: Mallory cannot[3] change m

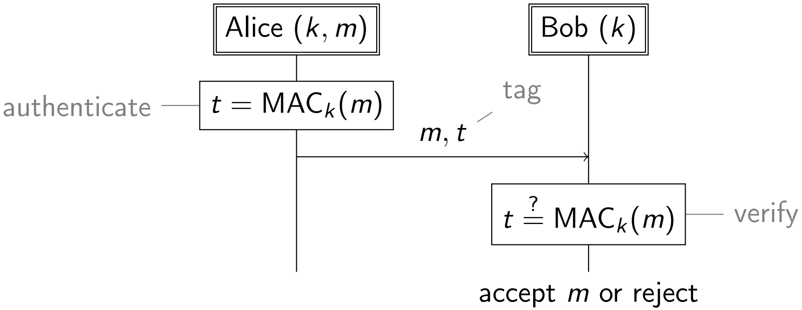
Provides authenticity: Bob knows m was sent by Alice

- *implicit*: Bob assumes only Alice knows k

---

[3] almost cannot: again we omit the details

Message Authentication Code (MAC)



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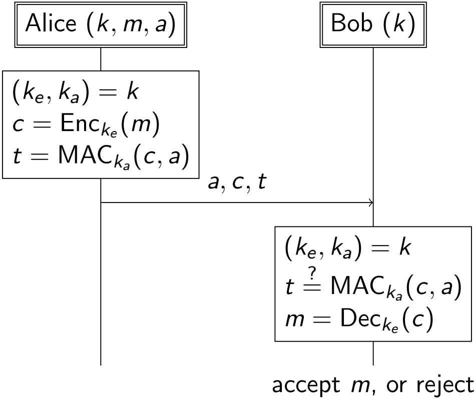
Authenticated Encryption



Alice (k, m, a)

Bob (k)

$(k_e, k_a) = k$
$c = \mathrm{Enc}_{k_e}(m)$
$t = \mathrm{MAC}_{k_a}(c, a)$

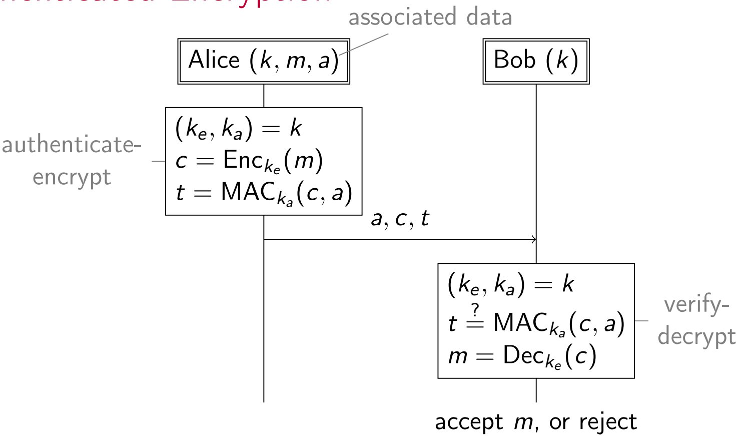
a, c, t

$(k_e, k_a) = k$
$t \overset{?}{=} \mathrm{MAC}_{k_a}(c, a)$
$m = \mathrm{Dec}_{k_e}(c)$

accept m, or reject

- Real-world AE often differs from encrypt-then-MAC
- Simplified notation:
  - $c = \mathrm{AEAD}_k(m, a)$ c includes the tag
  - $c = \mathrm{AEnc}_k(m)$ no a
  - $m = \mathrm{VDec}_k(c, a)$ $m = \perp$ on rejection

Authenticated Encryption



associated data

Alice (k, m, a)

Bob (k)

authenticate-encrypt

$(k_e, k_a) = k$
$c = \mathrm{Enc}_{k_e}(m)$
$t = \mathrm{MAC}_{k_a}(c, a)$

a, c, t

$(k_e, k_a) = k$
$t \overset{?}{=} \mathrm{MAC}_{k_a}(c, a)$
$m = \mathrm{Dec}_{k_e}(c)$

verify-decrypt

accept m, or reject

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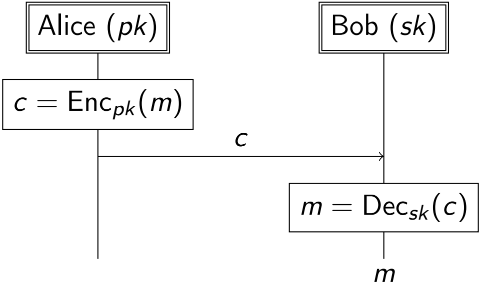
Symmetric Cryptography

Strong assumption:

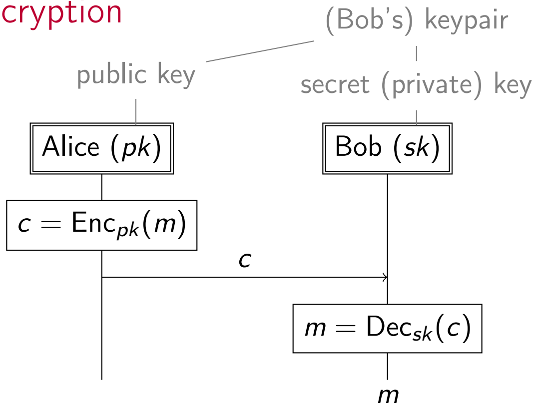
- Alice and Bob have *the same* secret key k

Public Key Encryption



- Provides confidentiality
- Bob publishes *pk*, keeps *sk* secret
  - Anyone can encrypt, but only Bob can decrypt

Public Key Encryption



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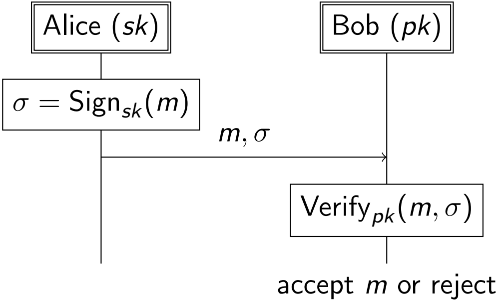
Digital Signatures



Alice (sk)

Bob (pk)

$\sigma = \mathsf{Sign}_{sk}(m)$

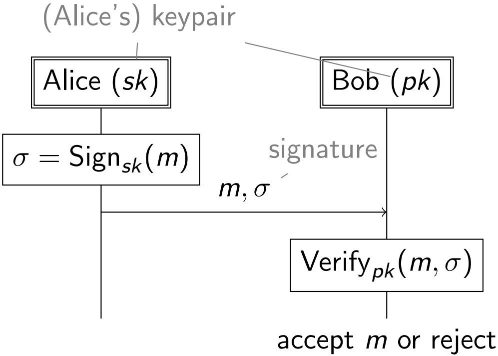
m, σ

$\mathsf{Verify}_{pk}(m, \sigma)$

accept m or reject

- Provides integrity and authentication
- Alice publishes pk, keeps sk secret
  - Only Alice can sign, but anyone can verify
  - Provides non-repudiation: (m, σ) is proof *for anyone* that Alice sent m

Digital Signatures



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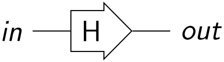
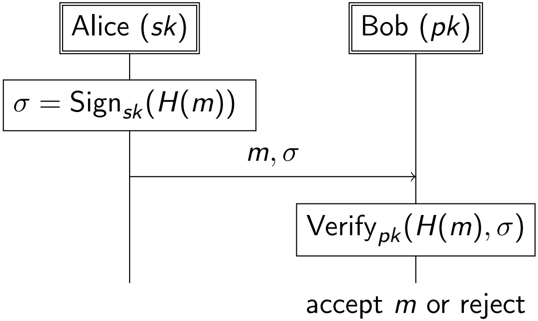
Cryptographic Hash



- Let H be a hash function: $out = H(in)$
    - large input
    - small output (digest)
- Security
    - the output "seems random" different ways to formalize this
    - Mallory cannot compute *out* without knowing *in*
    - Mallory cannot compute *in* when given *out*
- Note there is no key involved
    - Mallory can compute H on inputs of her choice

Digital signatures with hashes



Alice (sk)

Bob (pk)

$\sigma = \mathsf{Sign}_{sk}(H(m))$

m, σ

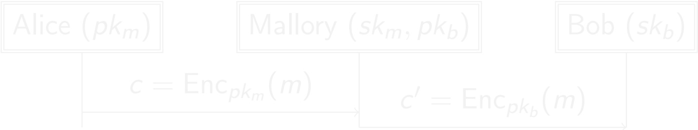
$\mathsf{Verify}_{pk}(H(m), \sigma)$

accept m or reject

Public Key Cryptography

- No large messages
  - PKE has limited size of messages
  - PKE is relatively slow
- How does Alice know that *pk* belongs to Bob?

Mallory-in-the-Middle (MitM) attack:



Alice (pk_m)

Mallory (sk_m, pk_b)

Bob (sk_b)

$c = \mathrm{Enc}_{pk_m}(m)$

$c' = \mathrm{Enc}_{pk_b}(m)$

Public Key Cryptography

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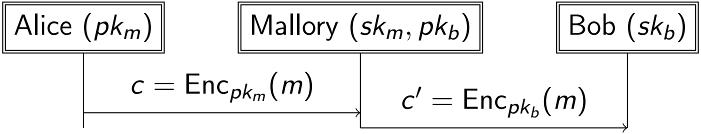

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Mallory (sk_m, pk_b)

Bob (sk_b)

$c = \mathsf{Enc}_{pk_m}(m)$

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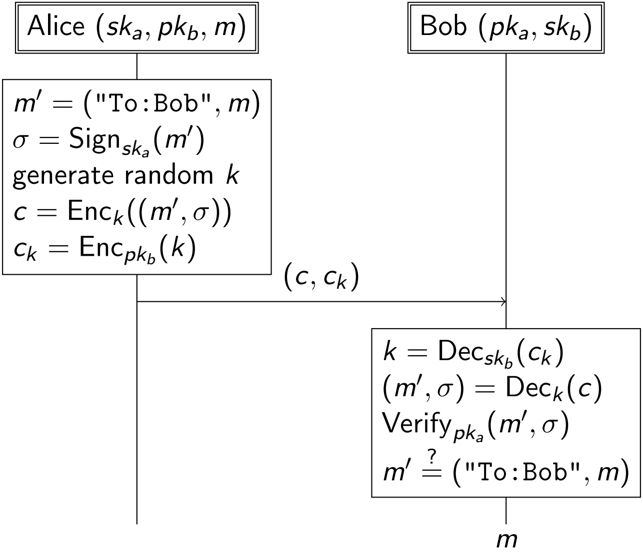
PKC: key/user authentication

- Not just an issue for secure messaging protocols
- SSH uses Trust On First Use (TOFU)
  - asks user to verify public key fingerprint (its hash) on first login
    - how to verify this, the protocol does not say
  - once accepted, it will silently keep accepting until the key changes
- TLS uses certificates and a PKI
  - you connect to a server
  - server presents a certificate: “this public key belongs to this website”
  - the certificate is signed by an authority
  - you as a user trust the authority (right?)
- PGP, OTR, SCIMP and Signal all use different methods

Pretty Good Privacy



Alice (sk_a, pk_b, m)

Bob (pk_a, sk_b)

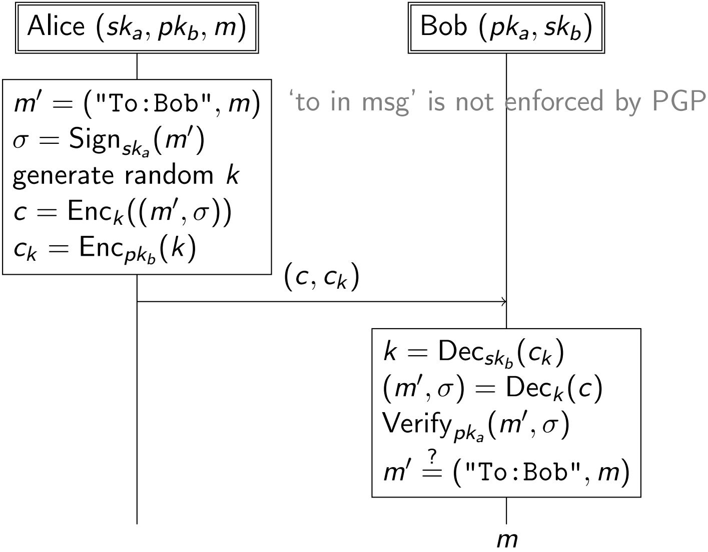
$m' = (\texttt{"To:Bob"}, m)$
$\sigma = \mathsf{Sign}_{sk_a}(m')$
generate random k
$c = \mathsf{Enc}_k((m', \sigma))$
$c_k = \mathsf{Enc}_{pk_b}(k)$

(c, c_k)

$k = \mathsf{Dec}_{sk_b}(c_k)$
$(m', \sigma) = \mathsf{Dec}_k(c)$
$\mathsf{Verify}_{pk_a}(m', \sigma)$
$m' \overset{?}{=} (\texttt{"To:Bob"}, m)$

m

Pretty Good Privacy



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generate random k
$c = \mathsf{Enc}_k((m', \sigma))$
$c_k = \mathsf{Enc}_{pk_b}(k)$

'to in msg' is not enforced by PGP

(c, c_k)

$k = \mathsf{Dec}_{sk_b}(c_k)$
$(m', \sigma) = \mathsf{Dec}_k(c)$
$\mathsf{Verify}_{pk_a}(m', \sigma)$
$m' \overset{?}{=} (\texttt{"To:Bob"}, m)$

m

PGP: key authentication

- PGP uses the Web of Trust (WoT)
- You meet in person, then sign each others key
  - yes there are (were?) key signing parties!
- Everyone publishes the signed keys
- If you get a key you don't know, you check if it's signed by someone you trust

Everyone loves this system and it scales great in practice!

PGP

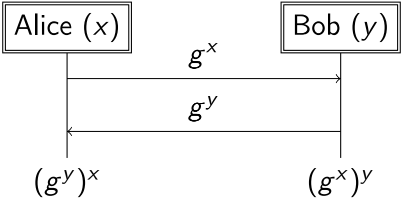
- PGP uses hybrid encryption
    - faster + larger messages
- PGP has many options
    - I am 80% sure the above is the sign-and-encrypt option
    - Without recipient ID, Bob could re-encrypt to others
        - not part of the PGP specification
    - Complexity leads to bad user experience, which leads to loss of security
- Two major issues
    - If a private key leaks, all messages leak (past and future)
    - Bob can publish (m, σ) as evidence that Alice said m

Off-the-Record (OTR)

Design philosophy: A secure online conversation should be more like a private in-person conversation

- Forward secrecy
  - leaking long-term keys should not reveal information about old messages
  - "key erasure property"
- Deniability (informal)
  - leaking a secure online conversation should not leak any more information than leaking a plain-text conversation
    - has many subtly different *mathematical* formalizations
    - unclear if this affects *legal* deniability

Diffie-Hellman Key Exchange



Alice (x)

Bob (y)

g^x

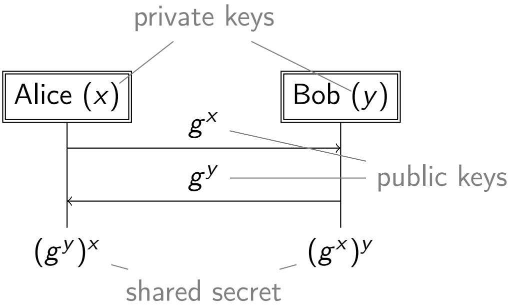
g^y

$(g^y)^x$

$(g^x)^y$

- correct: $g^{xy} = g^{yx}$
- security: follows from the Diffie-Hellman assumption:
    - Given g^x and g^y, it's hard to compute g^{xy}

Diffie-Hellman Key Exchange



private keys

Alice (x)

Bob (y)

g^x

g^y

public keys

$(g^y)^x$

$(g^x)^y$

shared secret

- correct: $g^{xy} = g^{yx}$
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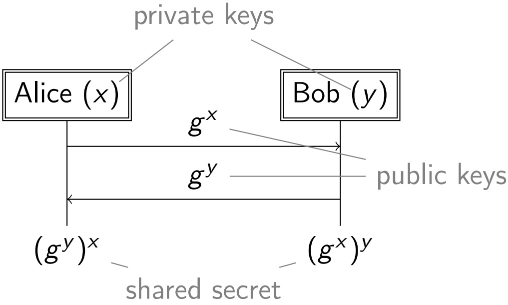
Diffie-Hellman Key Exchange



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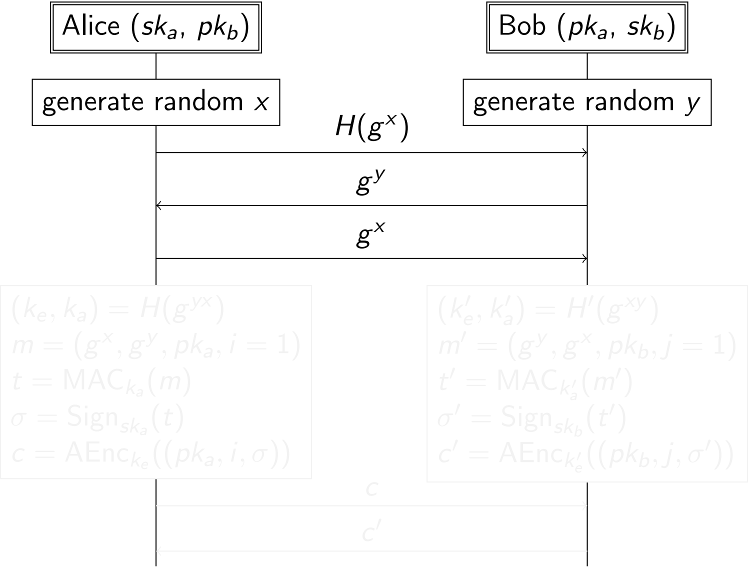
OTR: Authenticated Key Exchange



Alice (sk_a, pk_b)

Bob (pk_a, sk_b)

generate random x

generate random y

$H(g^x)$

g^y

g^x

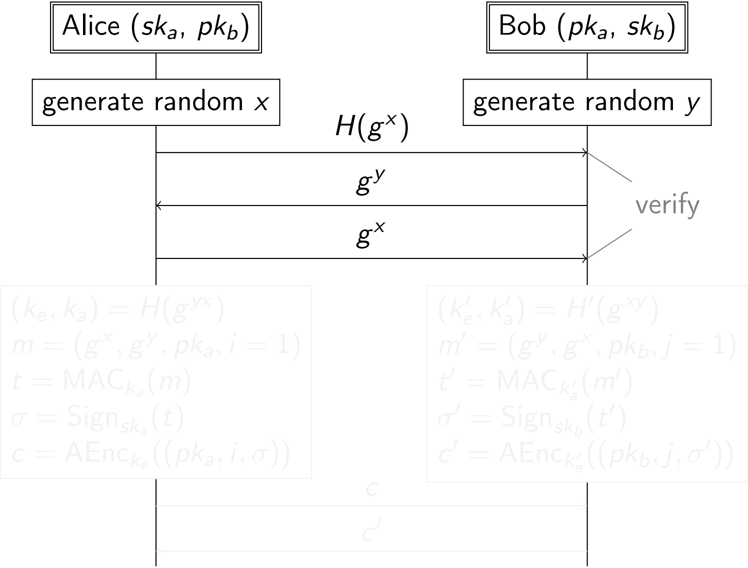
$(k_e, k_a) = H(g^{yx})$
$m = (g^x, g^y, pk_a, i = 1)$
$t = \mathrm{MAC}_{k_a}(m)$
$\sigma = \mathrm{Sign}_{sk_a}(t)$
$c = \mathrm{AEnc}_{k_e}((pk_a, i, \sigma))$

$(k'_e, k'_a) = H'(g^{xy})$
$m' = (g^y, g^x, pk_b, j = 1)$
$t' = \mathrm{MAC}_{k'_a}(m')$
$\sigma' = \mathrm{Sign}_{sk_b}(t')$
$c' = \mathrm{AEnc}_{k'_e}((pk_b, j, \sigma'))$

c

c'

OTR: Authenticated Key Exchange



Alice $(sk_a,\ pk_b)$

Bob $(pk_a,\ sk_b)$

generate random x

generate random y

$H(g^x)$

g^y

g^x

verify

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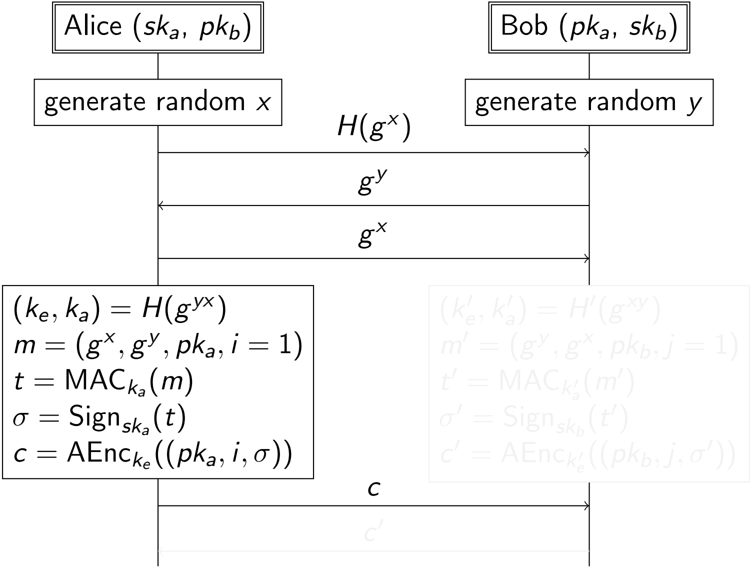

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\end{aligned}
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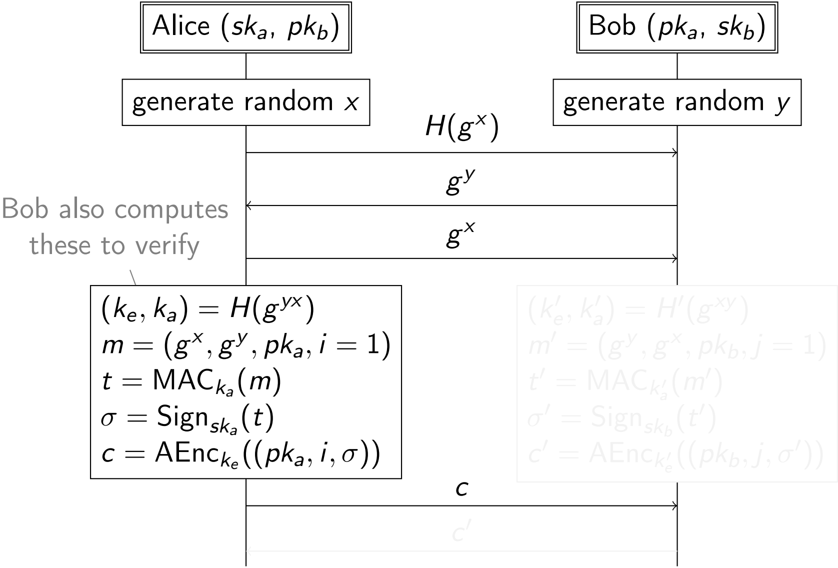
OTR: Authenticated Key Exchange



Alice $(sk_a,\ pk_b)$

Bob $(pk_a,\ sk_b)$

generate random x

generate random y

$H(g^x)$

g^y

g^x

Bob also computes these to verify

$$(k_e, k_a) = H(g^{yx})$$
$$m = (g^x, g^y, pk_a, i = 1)$$
$$t = \mathrm{MAC}_{k_a}(m)$$
$$\sigma = \mathrm{Sign}_{sk_a}(t)$$
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$$(k'_e, k'_a) = H'(g^{xy})$$
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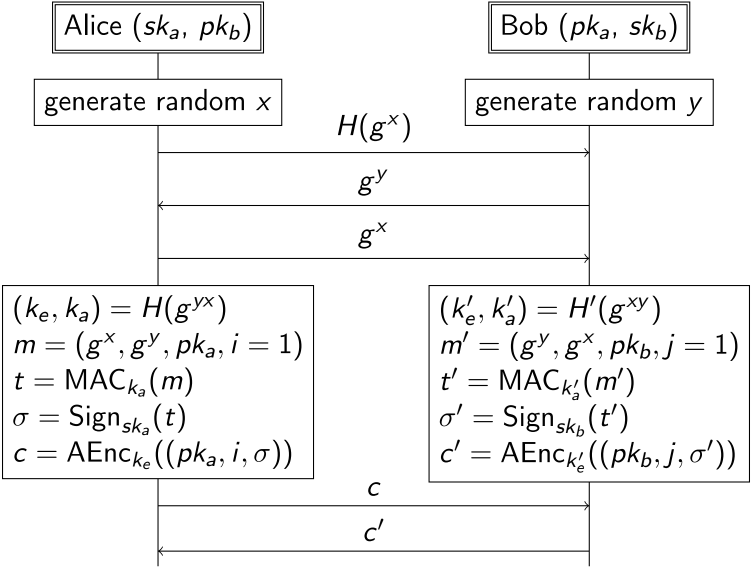
c

c'

OTR: Authenticated Key Exchange



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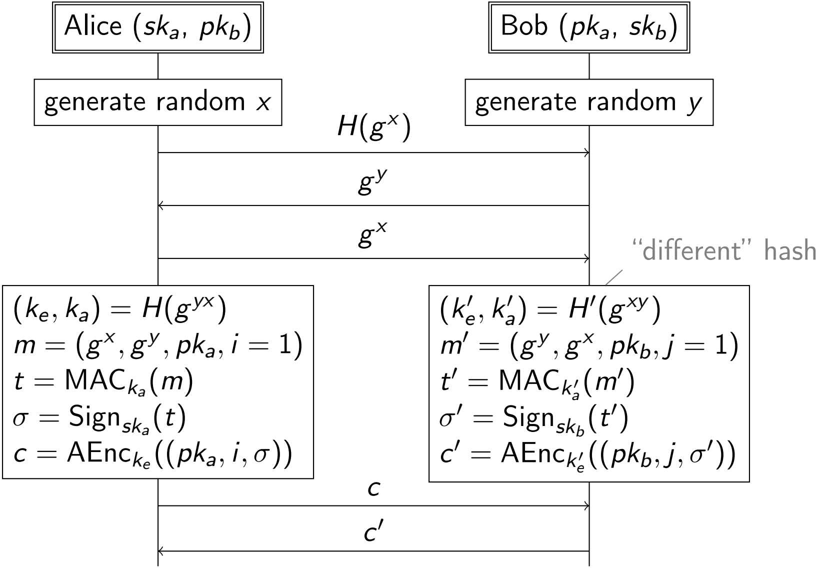


Alice (sk_a, pk_b)

Bob (pk_a, sk_b)

generate random x

generate random y

$H(g^x)$

g^y

g^x

“different” hash

$$\begin{aligned}(k_e, k_a) &= H(g^{yx})\\ m &= (g^x, g^y, pk_a, i = 1)\\ t &= \mathrm{MAC}_{k_a}(m)\\ \sigma &= \mathrm{Sign}_{sk_a}(t)\\ c &= \mathrm{AEnc}_{k_e}((pk_a, i, \sigma))\end{aligned}$$

$$\begin{aligned}(k'_e, k'_a) &= H'(g^{xy})\\ m' &= (g^y, g^x, pk_b, j = 1)\\ t' &= \mathrm{MAC}_{k'_a}(m')\\ \sigma' &= \mathrm{Sign}_{sk_b}(t')\\ c' &= \mathrm{AEnc}_{k'_e}((pk_b, j, \sigma'))\end{aligned}$$

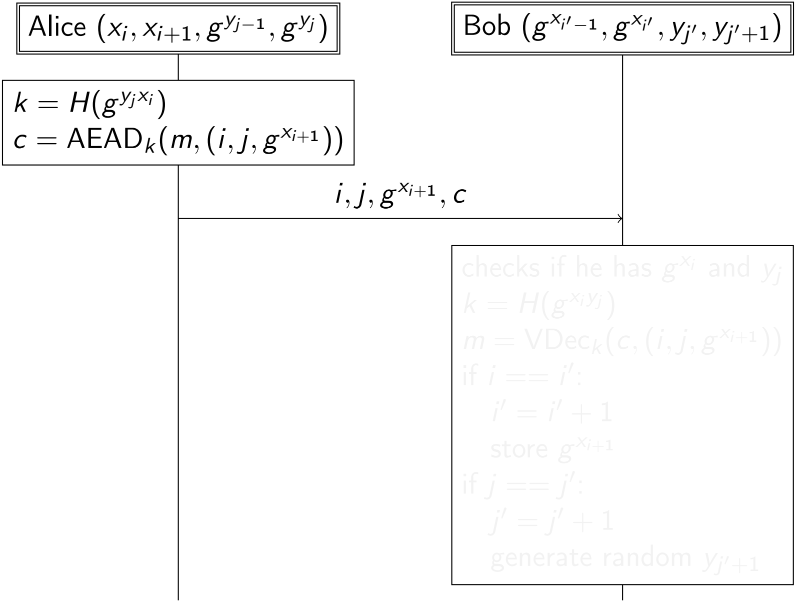
c

c'

OTR

- Deniability:
  - Parties only ever sign public values (g^x, g^y, pk)
    - No proof of conversation contents
  - Parties only ever sign *their own* public key
    - No proof of intent to communicate with other party
- Forward secrecy:
  - Securely delete x once we are done with it
    - (x, g^x) is called an ephemeral keypair
  - No information left on the device to recompute k_e
  - Discard k_e once we are done with it
    - . . . but when is that?

OTR: Sending Data Message



Alice $(x_i, x_{i+1}, g^{y_{j-1}}, g^{y_j})$

Bob $(g^{x_{i'-1}}, g^{x_{i'}}, y_{j'}, y_{j'+1})$

$k = H(g^{y_j x_i})$
$c = \mathrm{AEAD}_k(m, (i, j, g^{x_{i+1}}))$

$i, j, g^{x_{i+1}}, c$

```
checks if he has $g^{x_i}$ and $y_j$
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if $i == i'$:
    $i' = i' + 1$
    store $g^{x_{i+1}}$
if $j == j'$:
    $j' = j' + 1$
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```
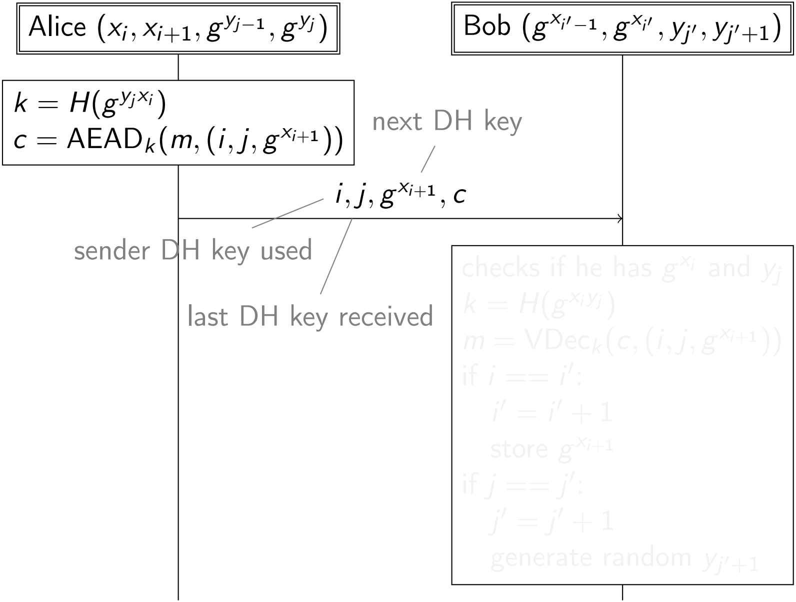

OTR: Sending Data Message



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$i, j, g^{x_{i+1}}, c$

next DH key

sender DH key used

last DH key received

```
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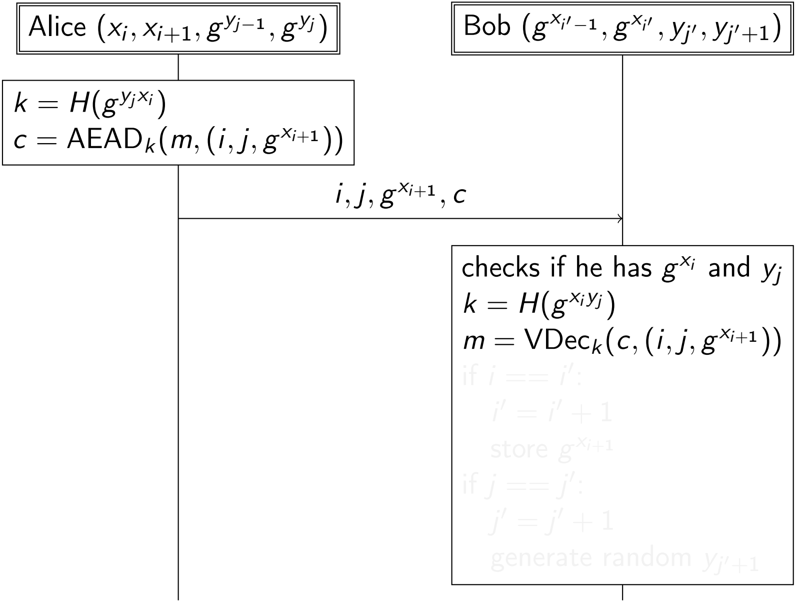

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$c = \text{AEAD}_k(m, (i, j, g^{x_{i+1}}))$

$i, j, g^{x_{i+1}}, c$

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$k = H(g^{x_i y_j})$

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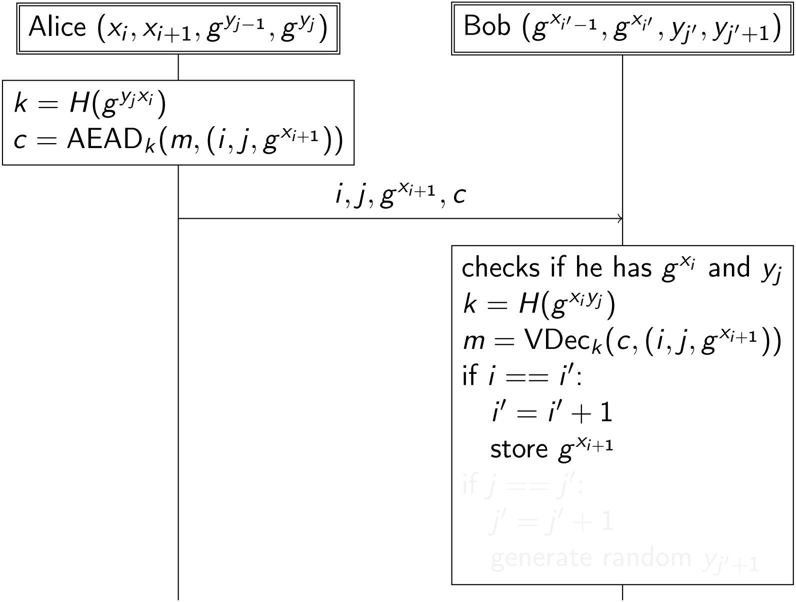

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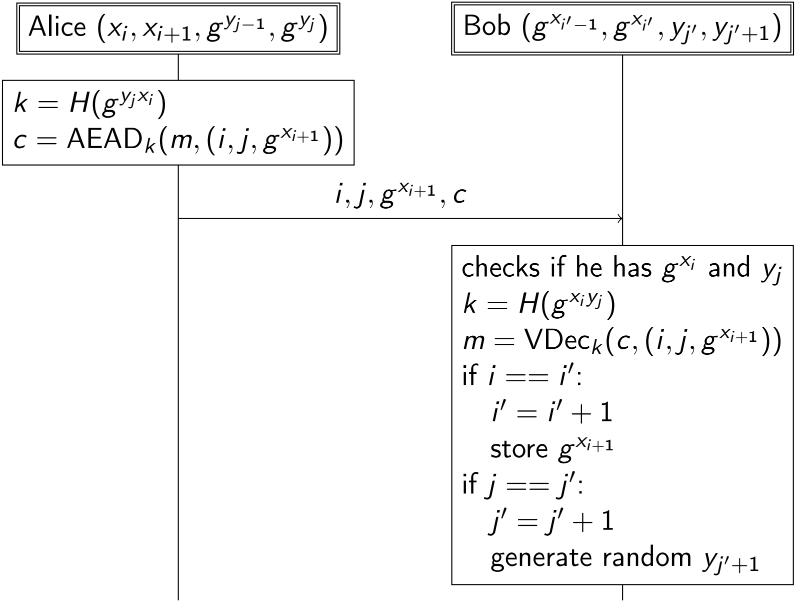

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```

OTR

- Forward Secrecy:
  - with every *reply* we remove an old key
  - old keys cannot be derived from previous ones
  - one-sided conversations don't move forward
    - could be fixed with heartbeat messages
- Post Compromise Security:
  - if Mallory steals your keys she can read your messages
  - once you generated a new DH key, she no longer has access
  - (this is not true if she actively maintains a MitM attack)
- Can handle missing a message, however
  - cannot handle out of order messages
    - storing old keys would compromise FS

OTR: key authentication

Option 1:

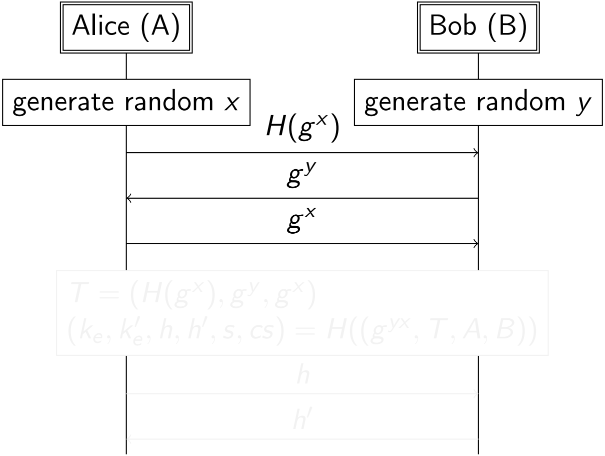
- Users can see the used public key fingerprints
- Verify these out-of-band

Option 2:

- Users are assumed to share some secret that Mallory doesn't know
- Hashes used public keys and the secret together
- Compare if they are the same using a zero-knowledge protocol
- this all happens in-band!

Usability studies show issues with both

SCIMP: Key Exchange



Alice (A)

Bob (B)

generate random x

generate random y

$H(g^x)$

g^y

g^x

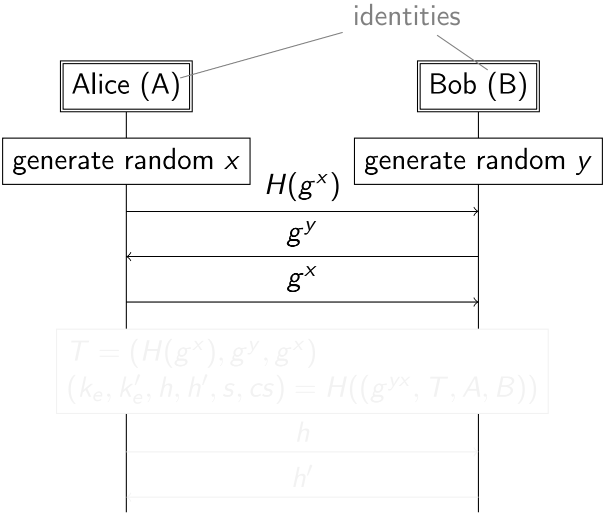
$T = (H(g^x), g^y, g^x)$

$(k_e, k'_e, h, h', s, cs) = H((g^{yx}, T, A, B))$

h

h'

SCIMP: Key Exchange



identities

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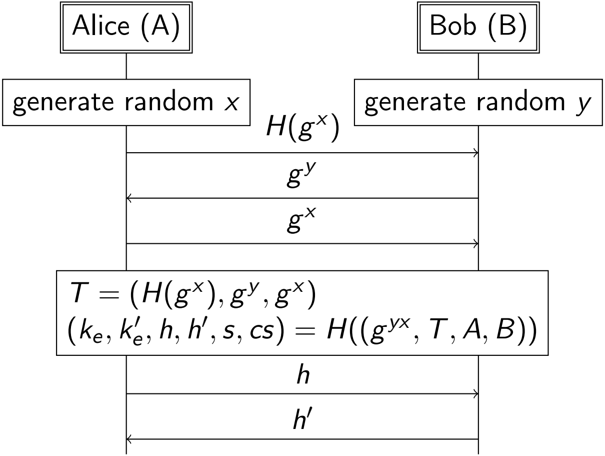

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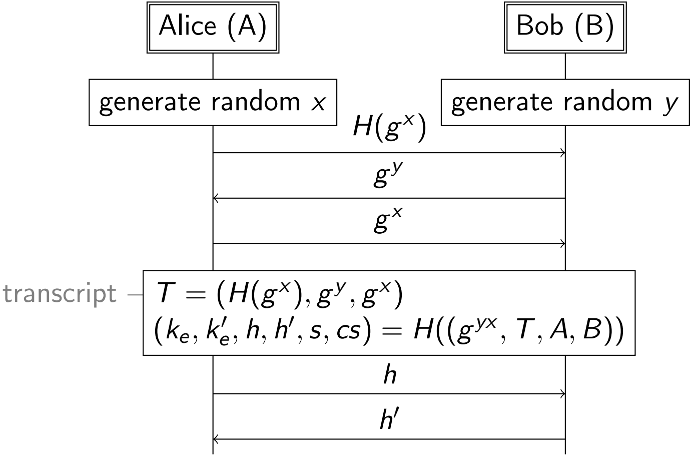

Alice (A)

Bob (B)

generate random x

generate random y

$H(g^x)$

g^y

g^x

transcript

$T = (H(g^x), g^y, g^x)$

$(k_e, k_e', h, h', s, cs) = H((g^{yx}, T, A, B))$

h

h'

SCIMP: (key) authentication

- There are no public keys, so key authentication is impossible
- In fact, the key exchange is **unauthenticated**
- To authenticate the (already established) session:
  - s is the "short authentication string"
  - Alice and Bob **must** compare s out-of-band
- But it also means we have good deniability

SCIMP Symmetric Ratchet

- symmetric key ratchet: $k_{e,i+1} = H(k_{e,i})$
- Send index i alongside ciphertext
- For example, Bob
  - has $k_{e,1}$, gets $i = 1$ (in order)
  - decrypts with $k_{e,1}$
  - computes $k_{e,2} = H(k_{e,1})$
  - deletes $k_{e,1}$
  - gets $i = 4$
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  - decrypts with $k_{e,4}$, then deletes $k_{e,4}$
  - stores $k_{e,2}$, $k_{e,3}$, and $k_{e,5}$
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  - $k_{e,2}$ threatens forward secrecy of msgs ≥ 2

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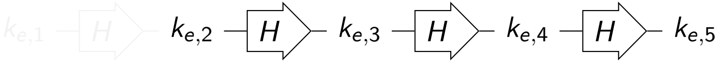

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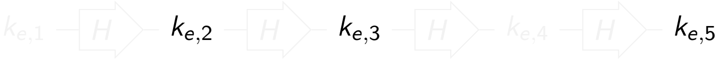

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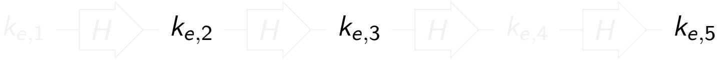

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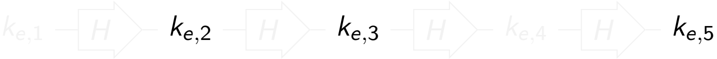

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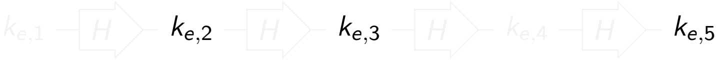

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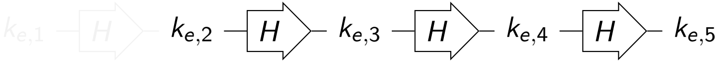

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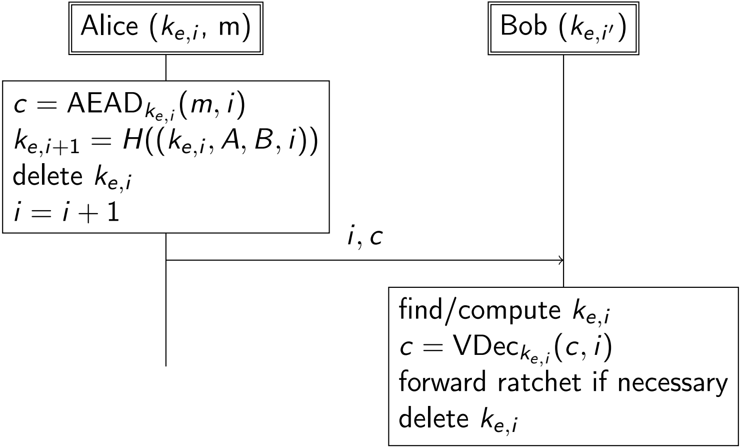
SCIMP: Sending Data Messages



Alice ($k_{e,i}$, m)

$c = \mathrm{AEAD}_{k_{e,i}}(m, i)$
$k_{e,i+1} = H((k_{e,i}, A, B, i))$
delete $k_{e,i}$
$i = i + 1$

i, c

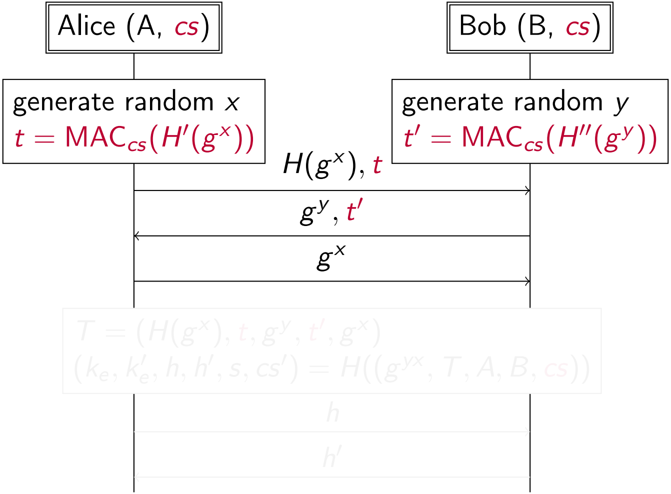
Bob ($k_{e,i'}$)

find/compute $k_{e,i}$
$c = \mathrm{VDec}_{k_{e,i}}(c, i)$
forward ratchet if necessary
delete $k_{e,i}$

SCIMP

- Forward secrecy
  - We forward the ratchet on each *sent* message
  - But stealing old keys also leaks newer keys
  - If a key is to old ($>$ 32 hashes old) it is removed

SCIMP: Rekeying



Alice (A, cs)

Bob (B, cs)

generate random x

$t = \mathrm{MAC}_{cs}(H'(g^x))$

generate random y

$t' = \mathrm{MAC}_{cs}(H''(g^y))$

$H(g^x), t$

g^y, t'

g^x

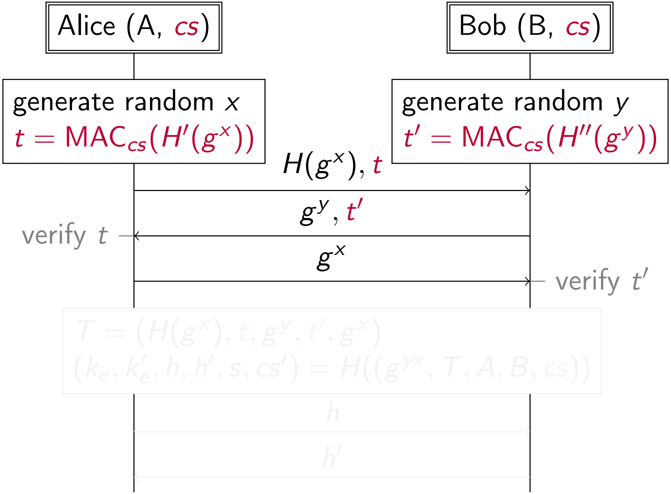
$T = (H(g^x), t, g^y, t', g^x)$

$(k_e, k'_e, h, h', s, cs') = H((g^{yx}, T, A, B, cs))$

h

h'

SCIMP: Rekeying



Alice (A, cs)

Bob (B, cs)

generate random x
$t = \mathrm{MAC}_{cs}(H'(g^x))$

generate random y
$t' = \mathrm{MAC}_{cs}(H''(g^y))$

$H(g^x), t$

g^y, t'

verify t

g^x

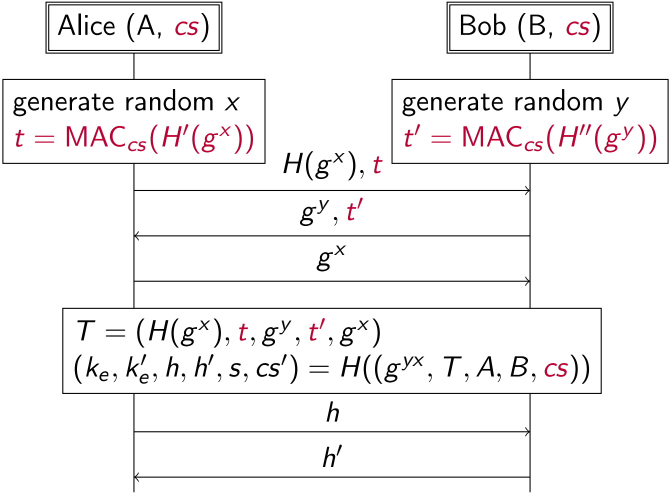
verify t'

$T = (H(g^x), t, g^y, t', g^x)$
$(k_e, k'_e, h, h', s, cs') = H((g^{yx}, T, A, B, cs))$

h

h'

SCIMP: Rekeying



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$t' = \mathrm{MAC}_{cs}(H''(g^y))$

$H(g^x), t$

g^y, t'

g^x

$T = (H(g^x), t, g^y, t', g^x)$

$(k_e, k'_e, h, h', s, cs') = H((g^{yx}, T, A, B, cs))$

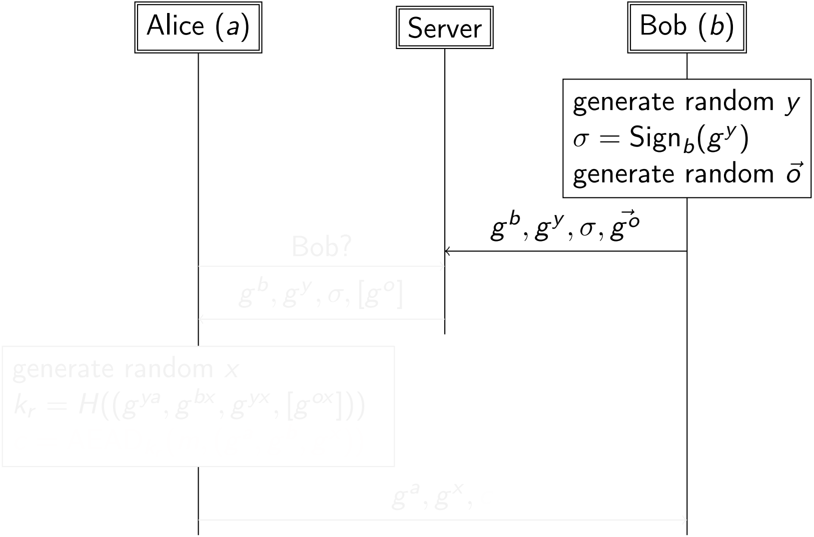
h

h'

SCIMP

- Future secrecy
  - rekeying mixes in new ephemeral keys
- Unspecified when rekeying should happen
- Store oldest unused receive key
  - in case out-of-order messages arrive
  - compromise between usability and forward secrecy
- On invalid t: all state is deleted
  - no longer authenticated!
  - Mallory can easily desynchronize

Signal: X3DH



Alice (a)

Server

Bob (b)

generate random y
$\sigma = \mathrm{Sign}_b(g^y)$
generate random $\vec{o}$

$g^b, g^y, \sigma, g^{\vec{o}}$

Bob?

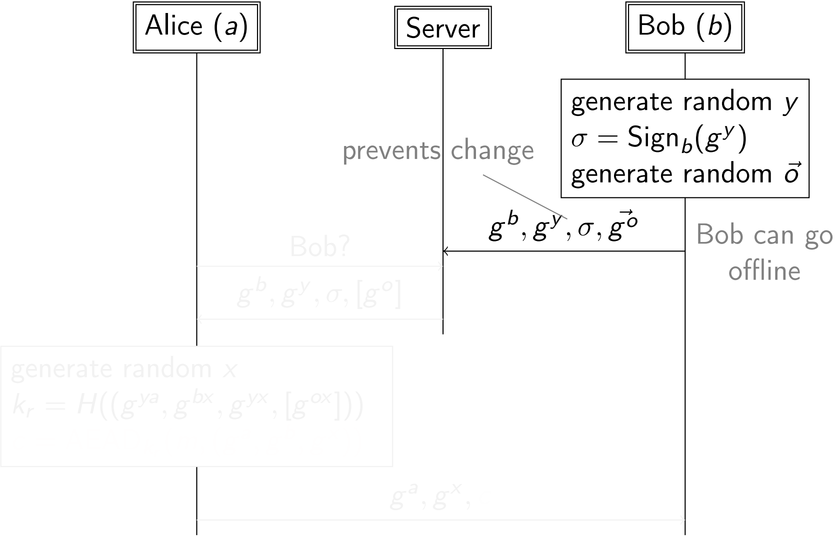
$g^b, g^y, \sigma, [g^o]$

generate random x
$k_r = H((g^{ya}, g^{bx}, g^{yx}, [g^{ox}]))$
$c = \mathrm{AEAD}_{k_r}(m, (g^a, g^b, g^x))$

g^a, g^x, c

Signal: X3DH

b is a DH *and* a sign key
generally **not** recommended



Alice (a)

Server

Bob (b)

generate random y
$\sigma = \text{Sign}_b(g^y)$
generate random $\vec{o}$

prevents change

$g^b, g^y, \sigma, g^{\vec{o}}$

Bob can go offline

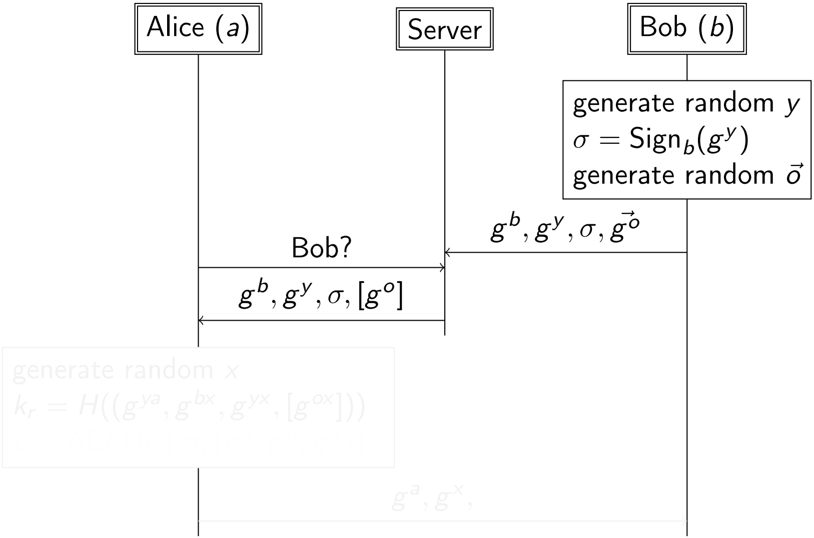
Bob?

$g^b, g^y, \sigma, [g^o]$

generate random x
$k_r = H((g^{ya}, g^{bx}, g^{yx}, [g^{ox}]))$
$c = \text{AEAD}_{k_r}(m, (g^a, g^b, g^x))$

g^a, g^x, c

Signal: X3DH



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Server

Bob (b)

generate random y
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generate random $\vec{o}$

$g^b, g^y, \sigma, g^{\vec{o}}$

Bob?

$g^b, g^y, \sigma, [g^o]$

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$k_r = H((g^{ya}, g^{bx}, g^{yx}, [g^{ox}]))$
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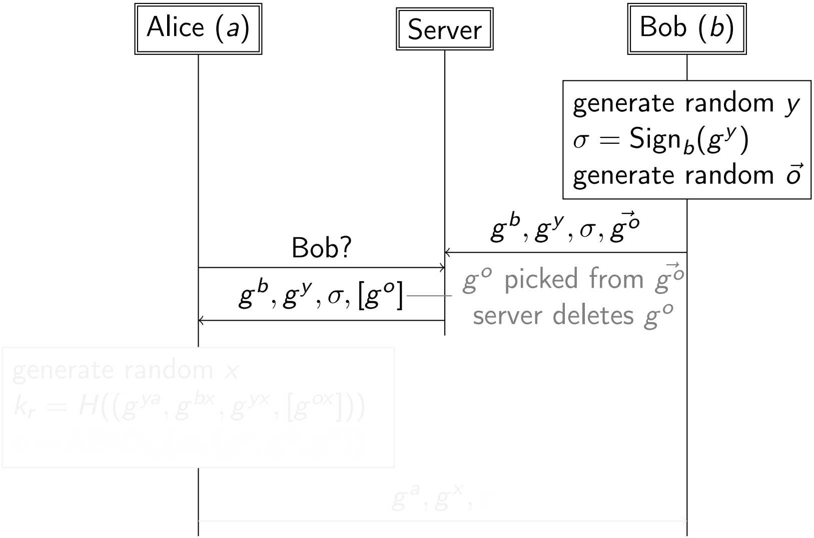
g^a, g^x, c

Signal: X3DH



Alice (a)

Server

Bob (b)

generate random y
$\sigma = \text{Sign}_b(g^y)$
generate random $\vec{o}$

$g^b, g^y, \sigma, g^{\vec{o}}$

Bob?

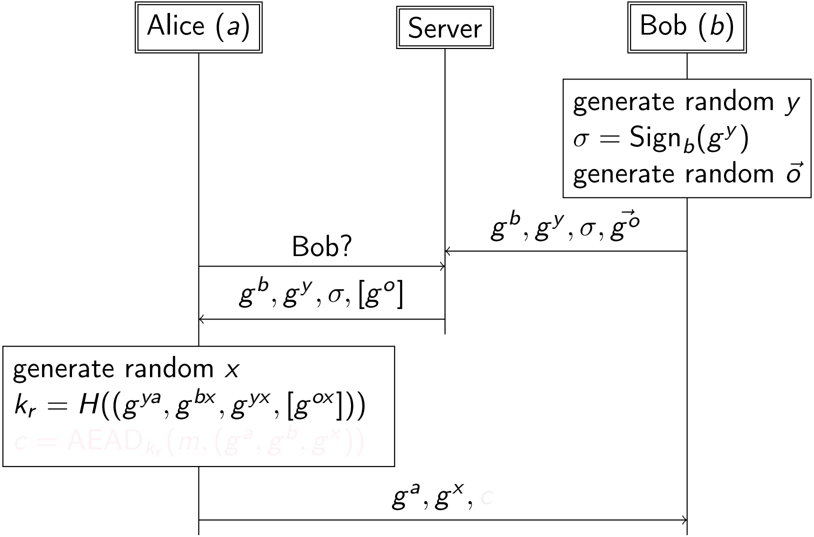
$g^b, g^y, \sigma, [g^o]$

g^o picked from $g^{\vec{o}}$
server deletes g^o

generate random x
$k_r = H((g^{ya}, g^{bx}, g^{yx}, [g^{ox}]))$
$c = \text{AEAD}_{k_r}(m, (g^a, g^b, g^x))$

g^a, g^x, c

Signal: X3DH



Alice (a)

Server

Bob (b)

generate random y
$\sigma = \text{Sign}_b(g^y)$
generate random $\vec{o}$

$g^b, g^y, \sigma, g^{\vec{o}}$

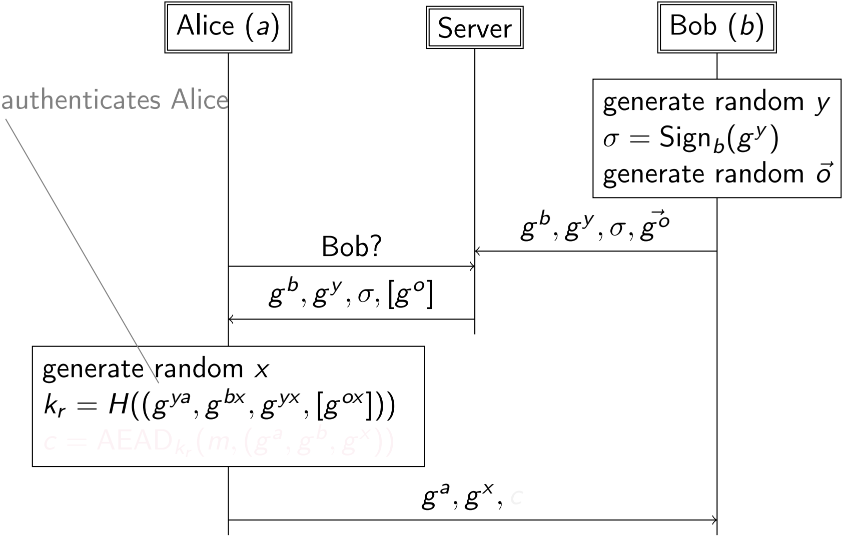
Bob?

$g^b, g^y, \sigma, [g^o]$

generate random x
$k_r = H((g^{ya}, g^{bx}, g^{yx}, [g^{ox}]))$
$c = \text{AEAD}_{k_r}(m, (g^a, g^b, g^x))$

g^a, g^x, c

Signal: X3DH



Alice (a)

Server

Bob (b)

generate random y
$\sigma = \text{Sign}_b(g^y)$
generate random $\vec{o}$

$g^b, g^y, \sigma, g^{\vec{o}}$

Bob?

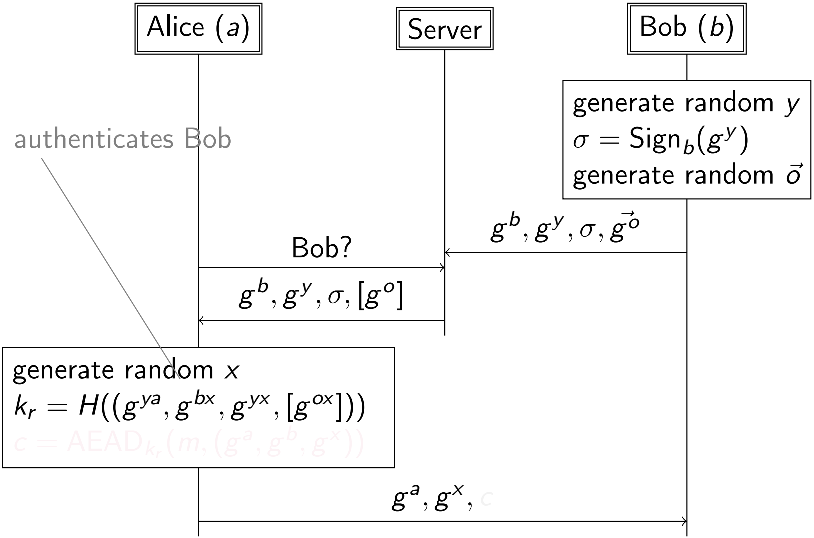
$g^b, g^y, \sigma, [g^o]$

authenticates Alice

generate random x
$k_r = H((g^{ya}, g^{bx}, g^{yx}, [g^{ox}]))$
$c = \text{AEAD}_{k_r}(m, (g^a, g^b, g^x))$

g^a, g^x, c

Signal: X3DH



Alice (a)

Server

Bob (b)

generate random y
$\sigma = \mathrm{Sign}_b(g^y)$
generate random $\vec{o}$

$g^b, g^y, \sigma, g^{\vec{o}}$

authenticates Bob

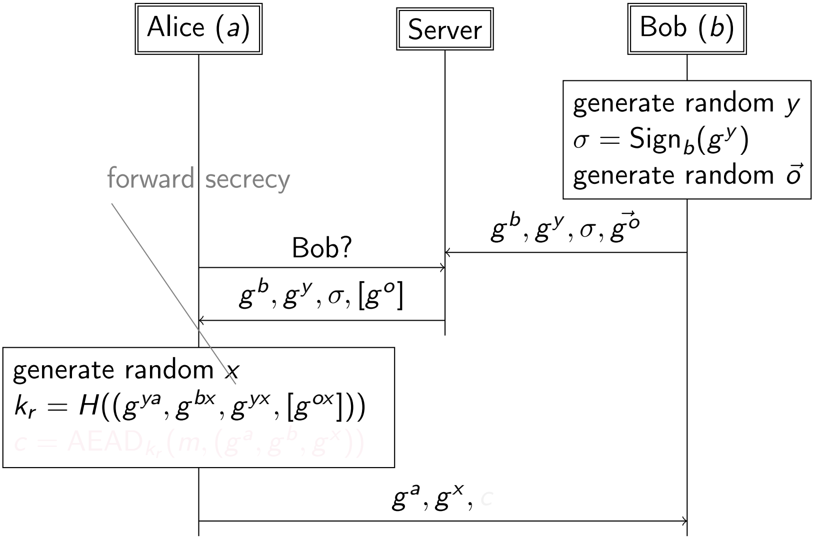
Bob?

$g^b, g^y, \sigma, [g^o]$

generate random x
$k_r = H((g^{ya}, g^{bx}, g^{yx}, [g^{ox}]))$
$c = \mathrm{AEAD}_{k_r}(m, (g^a, g^b, g^x))$

g^a, g^x, c

Signal: X3DH



Alice (a)

Server

Bob (b)

generate random y
$\sigma = \mathrm{Sign}_b(g^y)$
generate random $\vec{o}$

$g^b, g^y, \sigma, g^{\vec{o}}$

forward secrecy

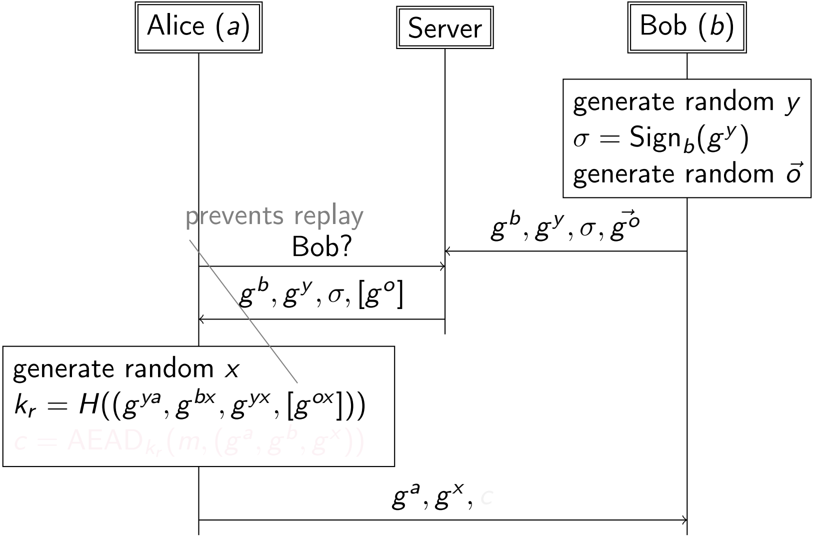
Bob?

$g^b, g^y, \sigma, [g^o]$

generate random x
$k_r = H((g^{ya}, g^{bx}, g^{yx}, [g^{ox}]))$
$c = \mathrm{AEAD}_{k_r}(m, (g^a, g^b, g^x))$

g^a, g^x, c

Signal: X3DH



Alice (a)

Server

Bob (b)

generate random y
$\sigma = \mathrm{Sign}_b(g^y)$
generate random $\vec{o}$

$g^b, g^y, \sigma, g^{\vec{o}}$

prevents replay

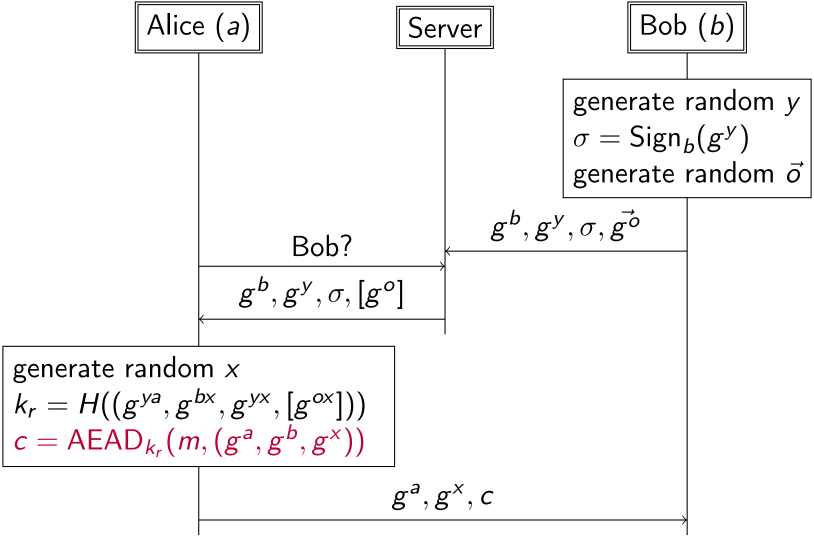
Bob?

$g^b, g^y, \sigma, [g^o]$

generate random x
$k_r = H((g^{ya}, g^{bx}, g^{yx}, [g^{ox}]))$
$c = \mathrm{AEAD}_{k_r}(m, (g^a, g^b, g^x))$

g^a, g^x, c

Signal: X3DH



Alice (a)

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Bob (b)

generate random y
$\sigma = \mathrm{Sign}_b(g^y)$
generate random $\vec{o}$

$g^b, g^y, \sigma, g^{\vec{o}}$

Bob?

$g^b, g^y, \sigma, [g^o]$

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$k_r = H((g^{ya}, g^{bx}, g^{yx}, [g^{ox}]))$
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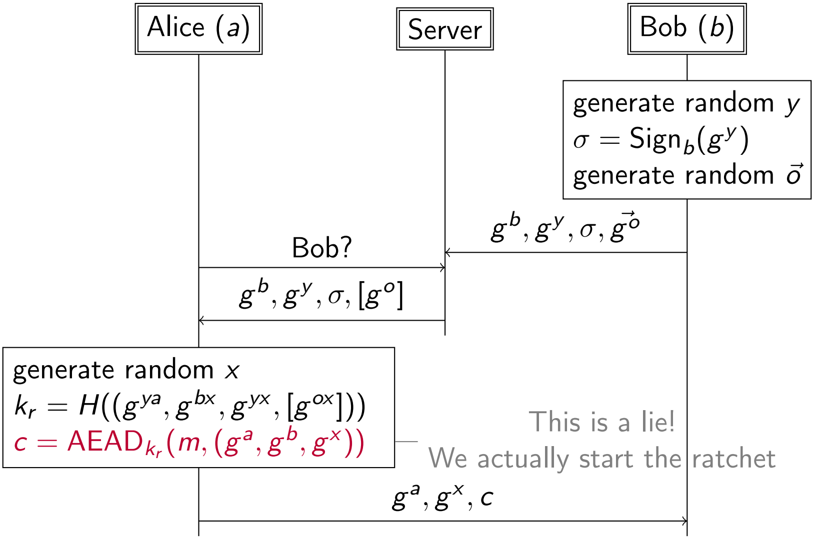
g^a, g^x, c

Signal: X3DH



Alice (a)

Server

Bob (b)

generate random y
$\sigma = \text{Sign}_b(g^y)$
generate random $\vec{o}$

$g^b, g^y, \sigma, g^{\vec{o}}$

Bob?

$g^b, g^y, \sigma, [g^o]$

generate random x
$k_r = H((g^{ya}, g^{bx}, g^{yx}, [g^{ox}]))$
$c = \text{AEAD}_{k_r}(m, (g^a, g^b, g^x))$

This is a lie!
We actually start the ratchet

g^a, g^x, c

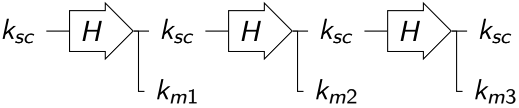
Signal: X3DH

- Asynchronous
  - Bob's handshake is independent of who wants to contact him
  - Bob does not have to be online
- All messages are delivered via the server
  - Mallory may control the server
- Alice encrypts a data message with her first message(!)

Signal: Double Ratchet

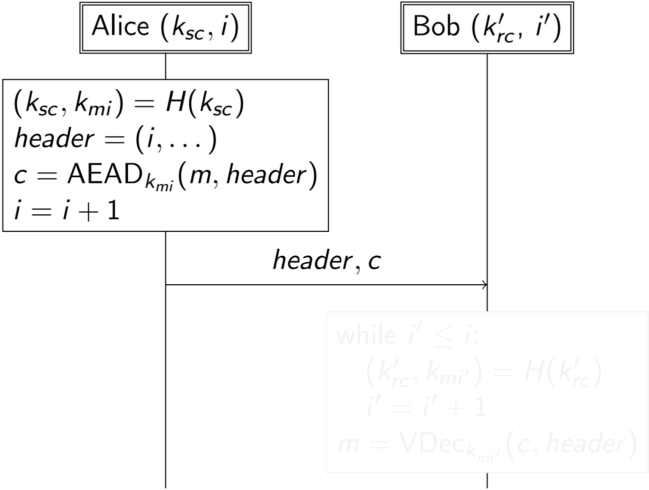
- Combine
    - the symmetrical ratchet (from SCIMP)
        - but split the chain key from the message key
    - the Diffie-Hellman ratchet (from OTR)
        - but require storage of fewer DH keys

Signal: Symmetric Ratchet



- Parties only ever store a single k_{sc}
- $(k_{sc}, k_{mi}) = H(k_{sc})$
- If Bob has $i = 0$ and receives $i = 3$
  - he iterates H three times
    - he overwrites k_{sc} with the new value
    - he stores k_{m1}, k_{m2}
    - he uses k_{m3} to decrypt
  - old k_m does not impact other keys
    - thus it does not threaten forward secrecy of other keys

Signal: Symmetric Ratchet



Alice (k_{sc}, i)

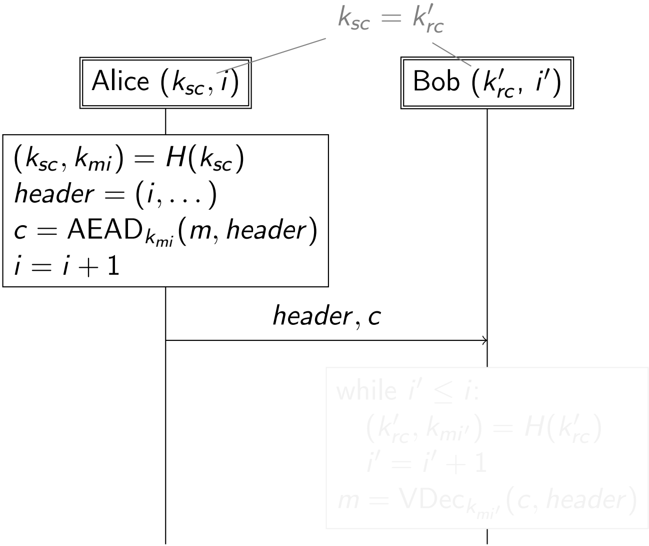
Bob $(k'_{rc},\ i')$

$(k_{sc}, k_{mi}) = H(k_{sc})$
$header = (i, \ldots)$
$c = \text{AEAD}_{k_{mi}}(m, header)$
$i = i + 1$

$header, c$

```
while $i' \leq i$:
    $(k'_{rc}, k_{mi'}) = H(k'_{rc})$
    $i' = i' + 1$
$m = \text{VDec}_{k_{mi'}}(c, header)$
```

Signal: Symmetric Ratchet



$k_{sc} = k'_{rc}$

Alice (k_{sc}, i)

Bob $(k'_{rc},\ i')$

$(k_{sc}, k_{mi}) = H(k_{sc})$
$header = (i, \dots)$
$c = \mathrm{AEAD}_{k_{mi}}(m, header)$
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while $i' \leq i$:
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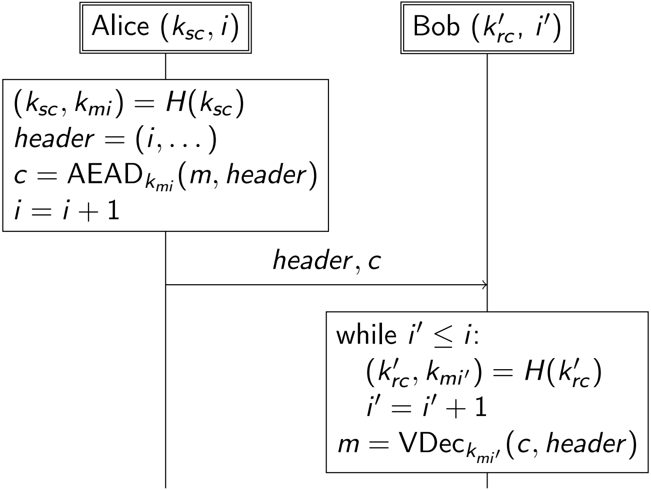
Signal: Symmetric Ratchet



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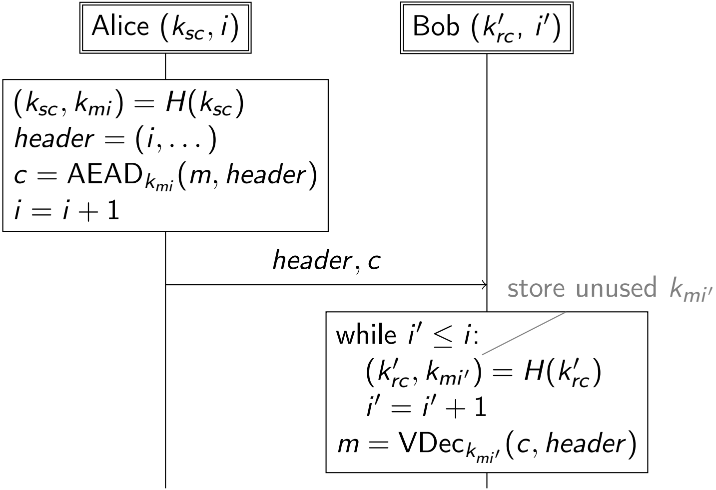
```

Signal: Symmetric Ratchet



Alice (k_{sc}, i)

Bob (k'_{rc}, i')

```
$(k_{sc}, k_{mi}) = H(k_{sc})$
$header = (i, \dots)$
$c = \mathrm{AEAD}_{k_{mi}}(m, header)$
$i = i + 1$
```

$header, c$

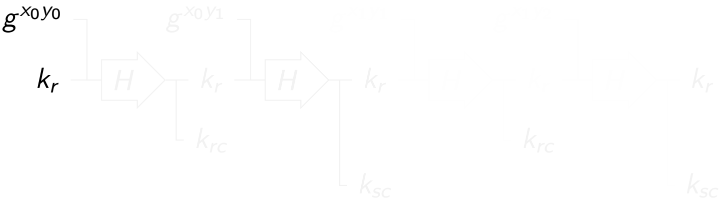
store unused $k_{mi'}$

```
while $i' \leq i$:
    $(k'_{rc}, k_{mi'}) = H(k'_{rc})$
    $i' = i' + 1$
$m = \mathrm{VDec}_{k_{mi'}}(c, header)$
```

Signal: Diffie-Hellman Ratchet

- Bob has k_r, y_0
- Alice sends a new g^{x_0}:
  - Bob computes $(g^{x_0})^{y_0}$
  - Bob ratchets: next receiving chain key k_{rc}
  - Bob generates new random y_1 and computes $g^{x_0 y_1}$
  - Bob ratchets: next sending chain key k_{sc}
  - Bob sends g^{y_1} to Alice
- When Alice sends g^{x_1}, Bob ratchets again (twice)
- Old values are deleted

Signal: Diffie-Hellman Ratchet



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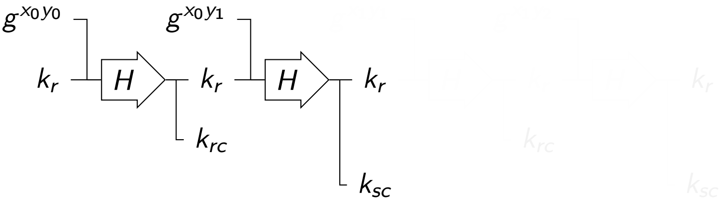
Signal: Diffie-Hellman Ratchet



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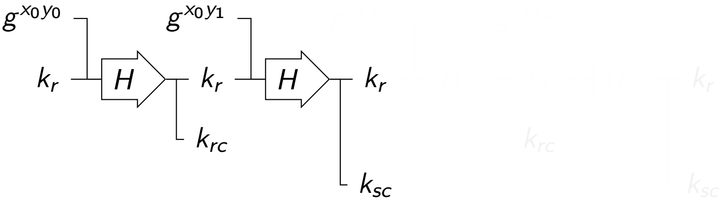
Signal: Diffie-Hellman Ratchet



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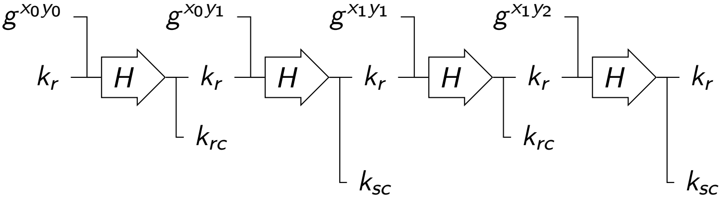
Signal: Diffie-Hellman Ratchet



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  - Bob ratchets: next sending chain key k_{sc}
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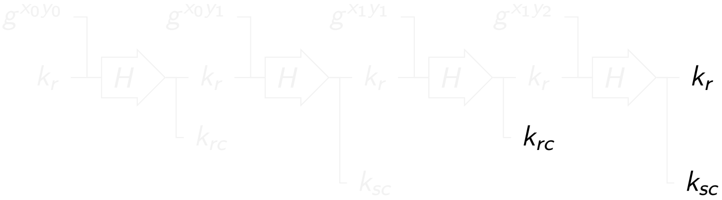
- Old values are deleted

Signal: Diffie-Hellman Ratchet



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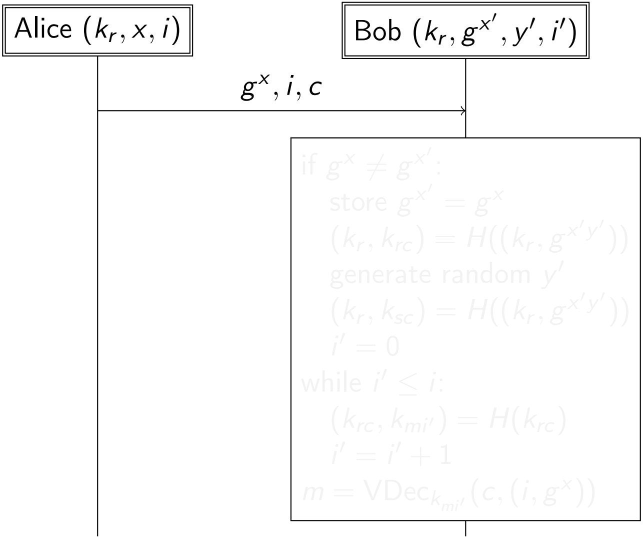
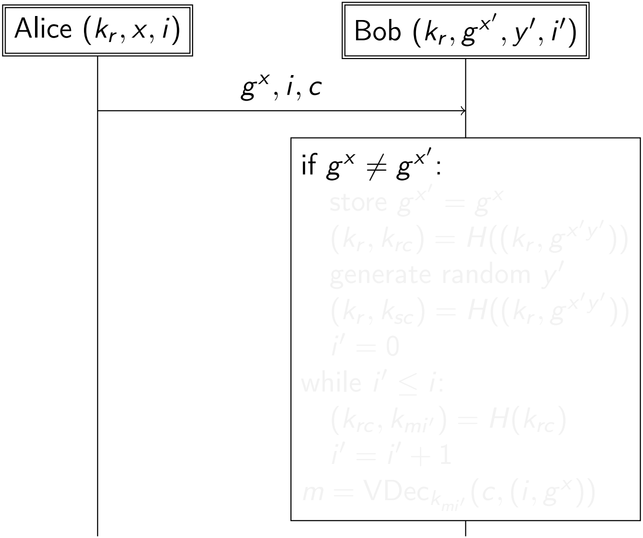
Signal: Diffie-Hellman ratchet



```
if $g^x \neq g^{x'}$:
    store $g^{x'} = g^x$
    $(k_r, k_{rc}) = H((k_r, g^{x'y'}))$
    generate random $y'$
    $(k_r, k_{sc}) = H((k_r, g^{x'y'}))$
    $i' = 0$
while $i' \leq i$:
    $(k_{rc}, k_{mi'}) = H(k_{rc})$
    $i' = i' + 1$
$m = \mathrm{VDec}_{k_{mi'}}(c, (i, g^x))$
```

Signal: Diffie-Hellman ratchet



Alice (k_r, x, i)

Bob ($k_r, g^{x'}, y', i'$)

g^x, i, c

```
if $g^x \neq g^{x'}$:
    store $g^{x'} = g^x$
    $(k_r, k_{rc}) = H((k_r, g^{x'y'}))$
    generate random $y'$
    $(k_r, k_{sc}) = H((k_r, g^{x'y'}))$
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while $i' \leq i$:
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    $i' = i' + 1$
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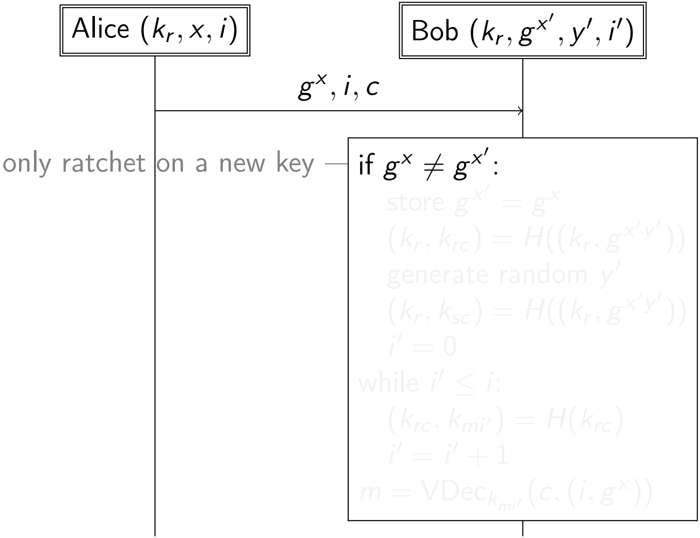
```

Signal: Diffie-Hellman ratchet



Alice (k_r, x, i)

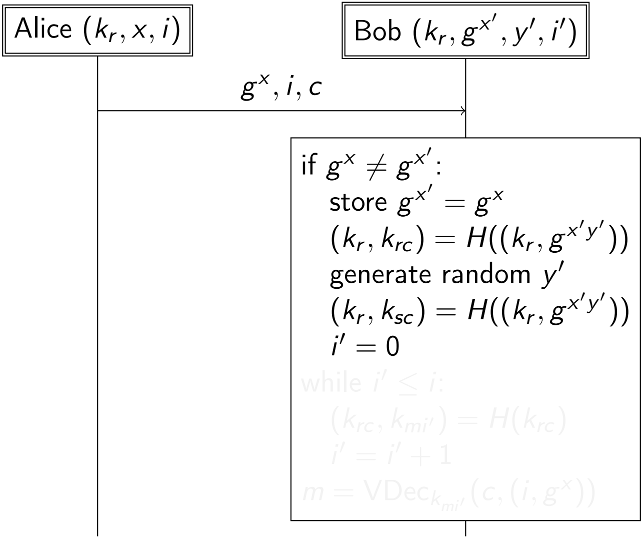
Bob $(k_r, g^{x'}, y', i')$

g^x, i, c

only ratchet on a new key

```
if $g^x \neq g^{x'}$:
    store $g^{x'} = g^x$
    $(k_r, k_{rc}) = H((k_r, g^{x'y'}))$
    generate random $y'$
    $(k_r, k_{sc}) = H((k_r, g^{x'y'}))$
    $i' = 0$
while $i' \leq i$:
    $(k_{rc}, k_{mi'}) = H(k_{rc})$
    $i' = i' + 1$
$m = \text{VDec}_{k_{mi'}}(c, (i, g^x))$
```

Signal: Diffie-Hellman ratchet



Alice (k_r, x, i)

Bob $(k_r, g^{x'}, y', i')$

g^x, i, c

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    store $g^{x'} = g^x$
    $(k_r, k_{rc}) = H((k_r, g^{x'y'}))$
    generate random $y'$
    $(k_r, k_{sc}) = H((k_r, g^{x'y'}))$
    $i' = 0$
while $i' \leq i$:
    $(k_{rc}, k_{mi'}) = H(k_{rc})$
    $i' = i' + 1$
$m = \mathrm{VDec}_{k_{mi'}}(c, (i, g^x))$
```
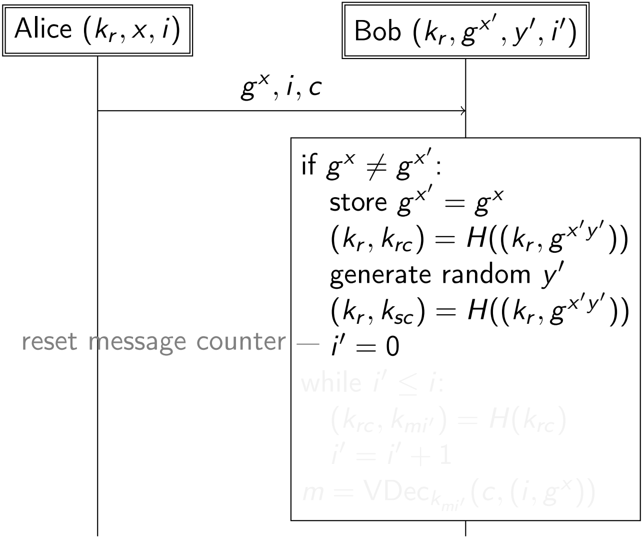

Signal: Diffie-Hellman ratchet



Alice (k_r, x, i)

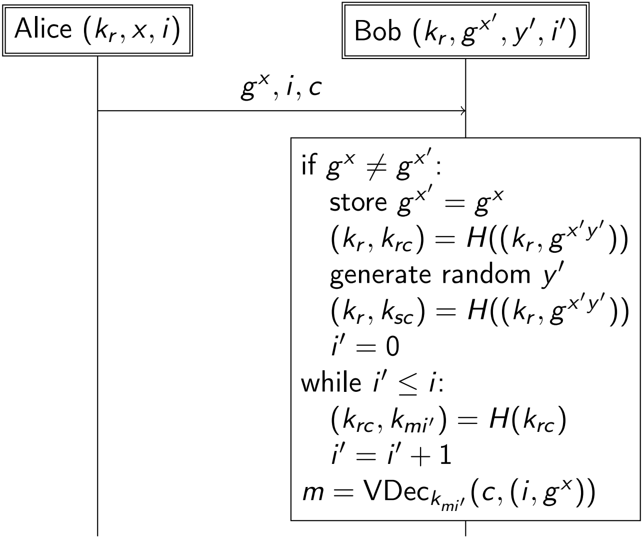
Bob $(k_r, g^{x'}, y', i')$

g^x, i, c

```
if $g^x \neq g^{x'}$:
    store $g^{x'} = g^x$
    $(k_r, k_{rc}) = H((k_r, g^{x'y'}))$
    generate random $y'$
    $(k_r, k_{sc}) = H((k_r, g^{x'y'}))$
    $i' = 0$
while $i' \le i$:
    $(k_{rc}, k_{mi'}) = H(k_{rc})$
    $i' = i' + 1$
$m = \mathrm{VDec}_{k_{mi'}}(c, (i, g^x))$
```

reset message counter — $i' = 0$

Signal: Diffie-Hellman ratchet



Alice (k_r, x, i)

Bob $(k_r, g^{x'}, y', i')$

g^x, i, c

```
if $g^x \neq g^{x'}$:
    store $g^{x'} = g^x$
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$m = \mathrm{VDec}_{k_{mi'}}(c, (i, g^x))$
```
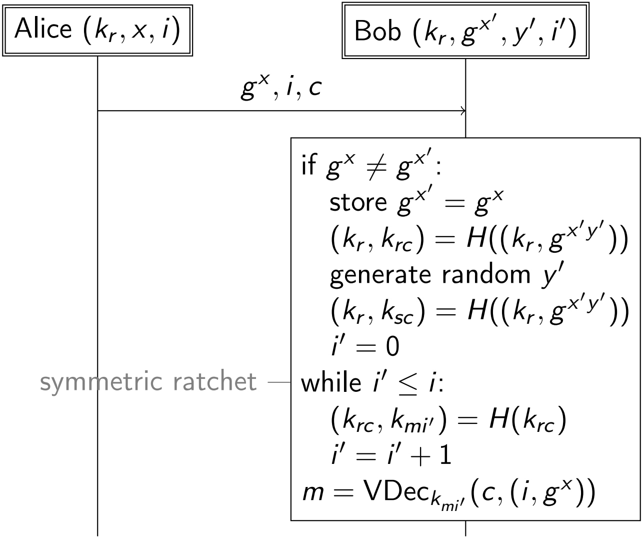

Signal: Diffie-Hellman ratchet



Alice (k_r, x, i)

Bob ($k_r, g^{x'}, y', i'$)

g^x, i, c

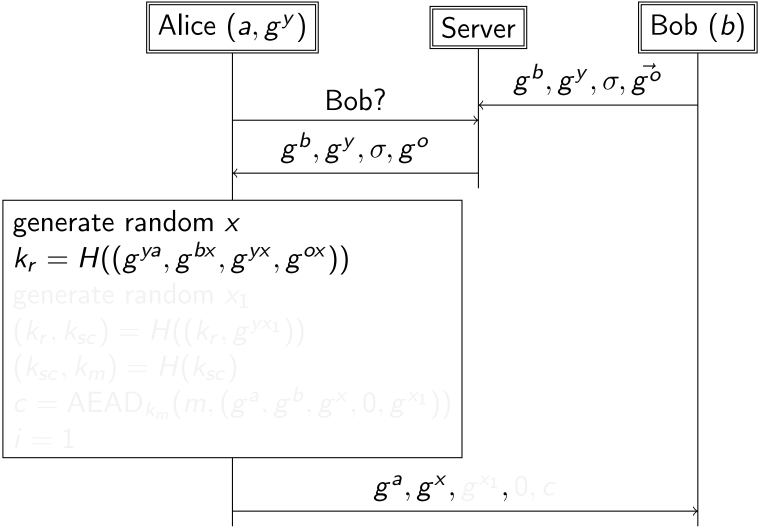
symmetric ratchet

```
if $g^x \neq g^{x'}$:
    store $g^{x'} = g^x$
    $(k_r, k_{rc}) = H((k_r, g^{x'y'}))$
    generate random $y'$
    $(k_r, k_{sc}) = H((k_r, g^{x'y'}))$
    $i' = 0$
while $i' \leq i$:
    $(k_{rc}, k_{mi'}) = H(k_{rc})$
    $i' = i' + 1$
$m = \mathrm{VDec}_{k_{mi'}}(c, (i, g^x))$
```

Signal: Diffie-Hellman ratchet

- Compare against OTR:
  - Bob uses g^x immediately
  - Bob verifies authenticity of g^x through associated data: $\mathrm{VDec}_{k_{mi}}(\cdot, (i, g^x, \dots))$
    - but k_{mi} is derived from g^x(!)
    - this turns out to be secure in this context, but this is not at all obvious (to me)
  - store only one g^x and one y per peer
- What if you missed a message before ratcheting?
  - header includes a value i_p: the total number of messages sent with the previous send chain key
  - compute all missed $k_{mi'}$ before starting the DH ratchet

Signal: X3DH + ratchet start



Alice (a, g^y)

Server

Bob (b)

$g^b, g^y, \sigma, g^{\vec{o}}$

Bob?

g^b, g^y, σ, g^o

generate random x

$k_r = H((g^{ya}, g^{bx}, g^{yx}, g^{ox}))$

generate random x_1

$(k_r, k_{sc}) = H((k_r, g^{yx_1}))$

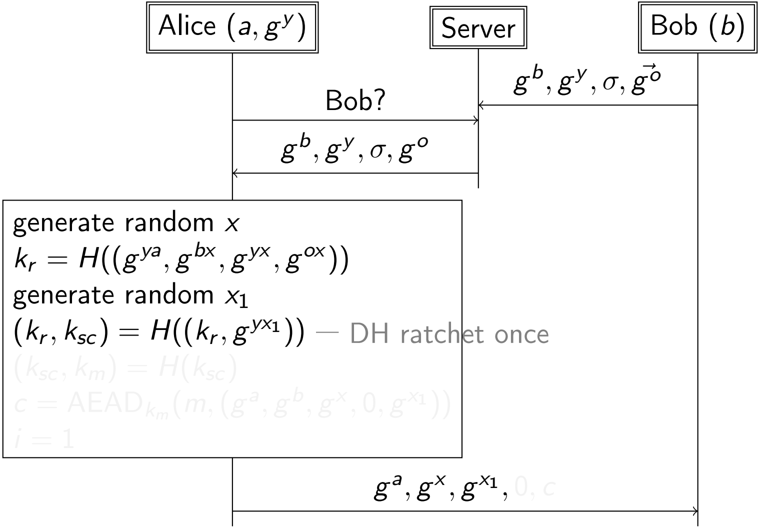
$(k_{sc}, k_m) = H(k_{sc})$

$c = \mathrm{AEAD}_{k_m}(m, (g^a, g^b, g^x, 0, g^{x_1}))$

$i = 1$

$g^a, g^x, g^{x_1}, 0, c$

Signal: X3DH + ratchet start



Alice (a, g^y)

Server

Bob (b)

$g^b, g^y, \sigma, \vec{g^o}$

Bob?

g^b, g^y, σ, g^o

generate random x

$k_r = H((g^{ya}, g^{bx}, g^{yx}, g^{ox}))$

generate random x_1

$(k_r, k_{sc}) = H((k_r, g^{yx_1}))$ — DH ratchet once

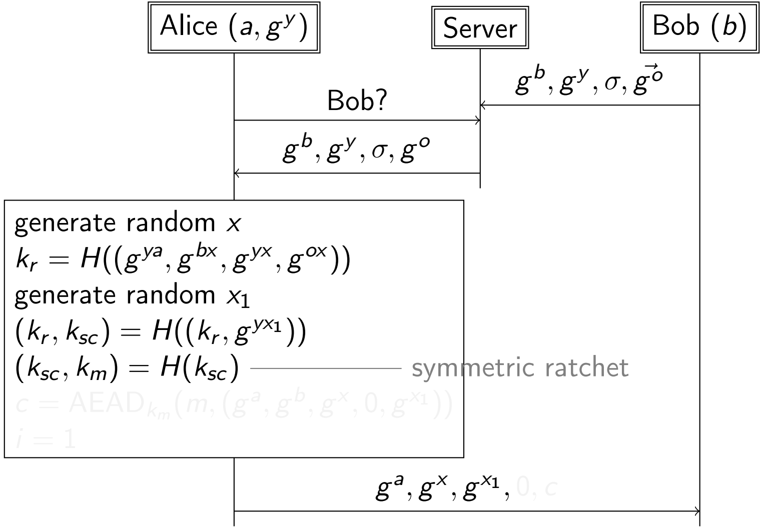
$(k_{sc}, k_m) = H(k_{sc})$

$c = \mathrm{AEAD}_{k_m}(m, (g^a, g^b, g^x, 0, g^{x_1}))$

$i = 1$

$g^a, g^x, g^{x_1}, 0, c$

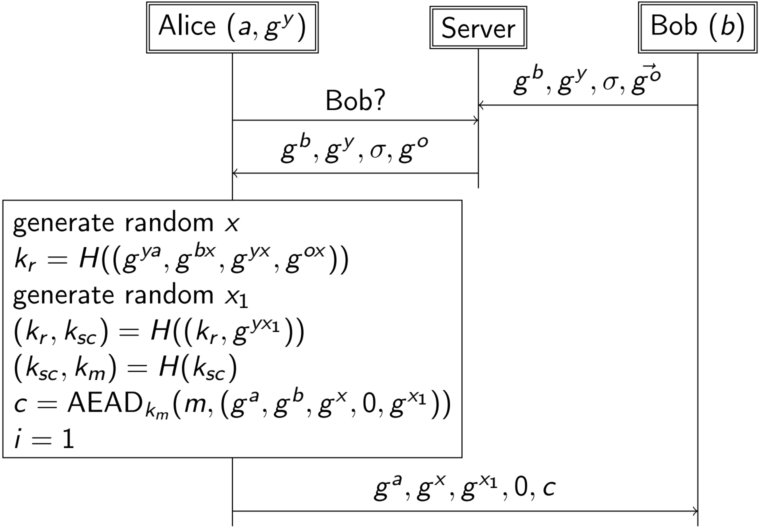
Signal: X3DH + ratchet start



generate random x
$k_r = H((g^{ya}, g^{bx}, g^{yx}, g^{ox}))$
generate random x_1
$(k_r, k_{sc}) = H((k_r, g^{yx_1}))$
$(k_{sc}, k_m) = H(k_{sc})$ — symmetric ratchet
$c = \text{AEAD}_{k_m}(m, (g^a, g^b, g^x, 0, g^{x_1}))$
$i = 1$

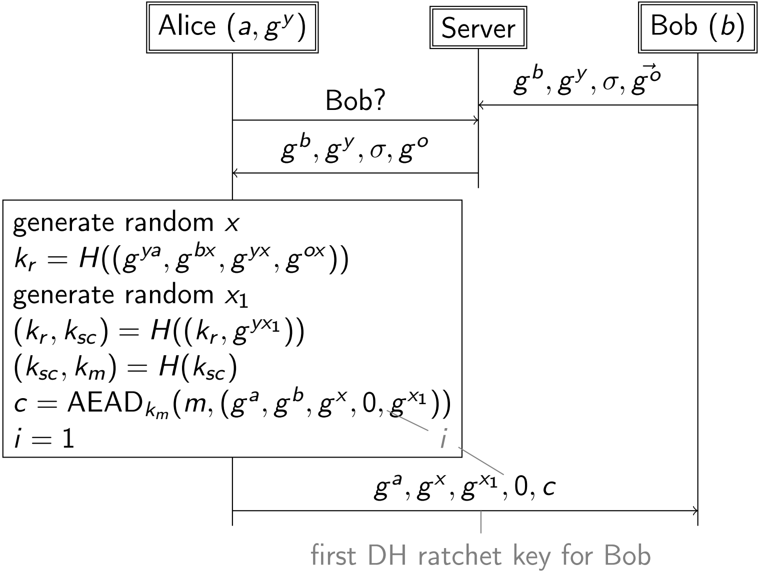
$g^a, g^x, g^{x_1}, 0, c$

Signal: X3DH + ratchet start



generate random x
$k_r = H((g^{ya}, g^{bx}, g^{yx}, g^{ox}))$
generate random x_1
$(k_r, k_{sc}) = H((k_r, g^{yx_1}))$
$(k_{sc}, k_m) = H(k_{sc})$
$c = \text{AEAD}_{k_m}(m, (g^a, g^b, g^x, 0, g^{x_1}))$
$i = 1$

Signal: X3DH + ratchet start



Alice (a, g^y)

Server

Bob (b)

$g^b, g^y, \sigma, g^{\vec{o}}$

Bob?

g^b, g^y, σ, g^o

generate random x

$k_r = H((g^{ya}, g^{bx}, g^{yx}, g^{ox}))$

generate random x_1

$(k_r, k_{sc}) = H((k_r, g^{yx_1}))$

$(k_{sc}, k_m) = H(k_{sc})$

$c = \mathrm{AEAD}_{k_m}(m, (g^a, g^b, g^x, 0, g^{x_1}))$

$i = 1$

i

$g^a, g^x, g^{x_1}, 0, c$

first DH ratchet key for Bob

Signal: key authentication

Safety numbers:

- these are hashes of the public key (+ some other values)
- users should compare these out-of-band

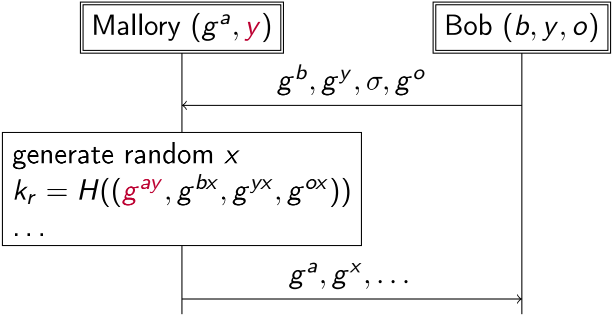
Signal Protocol

What security is not provided by this protocol?

- Mallory can block all messages
- Server may send the wrong g^b:
  - MitM, if Alice and Bob don't check the safety number
- If there's no g^o in original message (server ran out or is malicious)
  - Messages can be replayed to Bob
  - Reduced forward secrecy, until Bob refreshes g^y
- Key Compromise Impersonation
- Unknown Key Share

Signal: Key Compromise Impersonation

- Expected: If Mallory steals b, she can impersonate Bob to others
- KCI attack: If Mallory steals y (a key from Bob), she can impersonate others to Bob



Mallory (g^a, y)

Bob (b, y, o)

g^b, g^y, σ, g^o

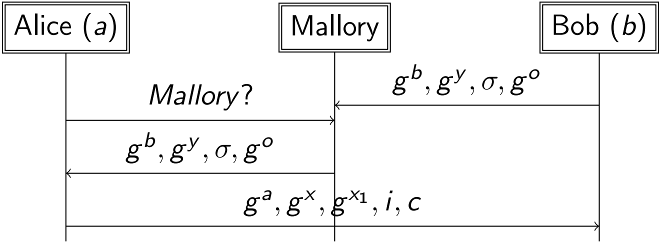
generate random x

$k_r = H((g^{ay}, g^{bx}, g^{yx}, g^{ox}))$

$\ldots$

$g^a, g^x, \ldots$

Signal: Unknown Key Share



- Alice thinks she is talking to Mallory
- Mallory substituted her own keys with those of Bob
- Alice is actually talking to Bob

Signal: multiple devices

Setup

- Desktop displays QR
  - address
  - ephemeral public key
- Phone scans QR, encrypts to device's ephemeral key
  - identity key pair
  - account info
  - linking token
- Desktop registers with server as new device

Sending messages

- Encrypt the message to each device of the user
- Encrypt the message to each other device of yourself

Phishing

- Mallory sends device link QR, disguised as group invite QR
- user scans and doesn't read the pop-up message
- Mallory can now read along and/or impersonate

Signal: multiple devices

Setup

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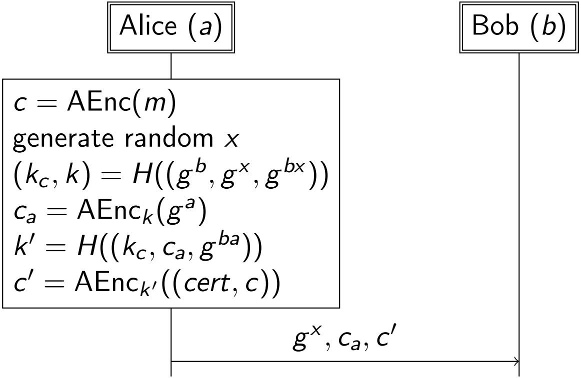
Signal: sealed sender

Hide sender from metadata



Alice (a)

Bob (b)

$c = \mathrm{AEnc}(m)$

generate random x

$(k_c, k) = H((g^b, g^x, g^{bx}))$

$c_a = \mathrm{AEnc}_k(g^a)$

$k' = H((k_c, c_a, g^{ba}))$

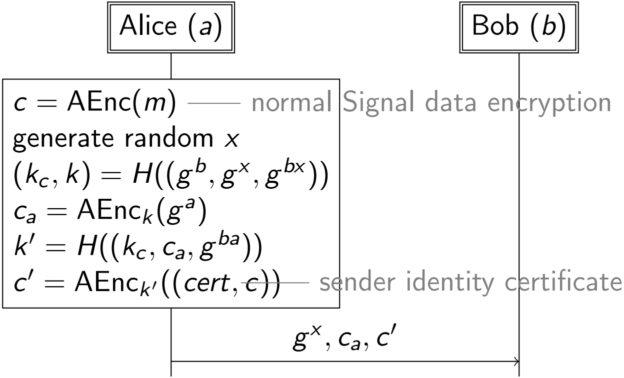
$c' = \mathrm{AEnc}_{k'}((cert, c))$

g^x, c_a, c'

- Delivered to server over one-way authenticated channel
- Cautious senders should use TOR/VPN to hide their ip address

Signal: sealed sender

Hide sender from metadata



Alice (a)

Bob (b)

$c = \mathrm{AEnc}(m)$ — normal Signal data encryption

generate random x

$(k_c, k) = H((g^b, g^x, g^{bx}))$

$c_a = \mathrm{AEnc}_k(g^a)$

$k' = H((k_c, c_a, g^{ba}))$

$c' = \mathrm{AEnc}_{k'}((cert, c))$ — sender identity certificate

g^x, c_a, c'

- Delivered to server over one-way authenticated channel
- Cautious senders should use TOR/VPN to hide their ip address

Signal: attachments

- generate a random key k
- encrypt the file using k
- upload the encrypted file to the file server
- send k and address to recipient *over a pairwise Signal session*
- only need to re-encrypt k and address for other recipients

~~Signal~~ WhatsApp: groups

Each group member:

- generates a sending chain key k_{sc}
- generates an ephemeral signing key pair (sk, pk)
- sends k_{sc}, pk to each group member *over a pairwise Signal session*
- if anyone leaves the group: delete k_{sc} (and sk?)

For each message m

- ratchet forward: $(k_{sc}, k_m) = H(k_{sc})$
- encrypt: $c = \mathrm{Enc}_{k_m}(m)$
- authenticate: $\sigma = \mathrm{Sign}_{sk}(c)$
- send (c, σ) to the server
- server forward (c, σ) to all group members

References

- 2015, Unger et al. SoK: Secure Messaging `https://doi.org/10.1109/SP.2015.22`
- PGP: RFC 9580
- OTR: `https://otr.cypherpunks.ca/Protocol-v3-4.0.0.html`
- SCIMP: `https://ia.cr/2016/703`
- Signal: `https://signal.org/docs/`

Slides will be made available on my website zeroknowledge.me

Public Key Authenticated Encryption?

How not to do it:

- Sign-then-encrypt
  - $\sigma = \mathsf{Sign}_{sk_a}(m)$
  - $c = \mathsf{Enc}_{pk_b}((m, \sigma))$
  - Did Alice intend the message to be delivered to Bob?
- Encrypt-then-sign
  - $c = \mathsf{Enc}_{pk_b}(m)$
  - $\sigma = \mathsf{Sign}_{sk_a}(c)$
  - Did Alice generate the original ciphertext?
- PGP usability problems lead security problems
  - user responsible for key management
  - user can arbitrarily combine encryption and signing

How to do it:

- use `crypto_box` from NaCl
- use age `age-encryption.org`