CS489/698 Privacy, Cryptography, Network and Data Security

Secure Messaging

Spring 2024, Monday/Wednesday 11:30am-12:50pm

Today

- Secure Messaging Goals
- PGP
  - PGP Keys
  - Problems with PGP
- OTR
- Signal

Secure Messaging Goals

Secure Messaging Goals

- **Confidentiality:** Only Alice and Bob can read the message
- **Integrity:** Bob knows Mallory has not tampered with the message (and that it has not been corrupted)
- **Authentication:** Bob knows Alice wrote the message
  - Non-repudiation?

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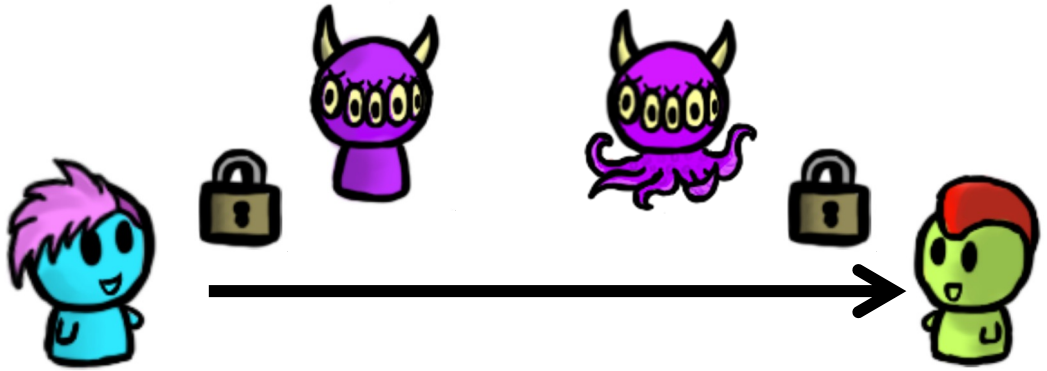

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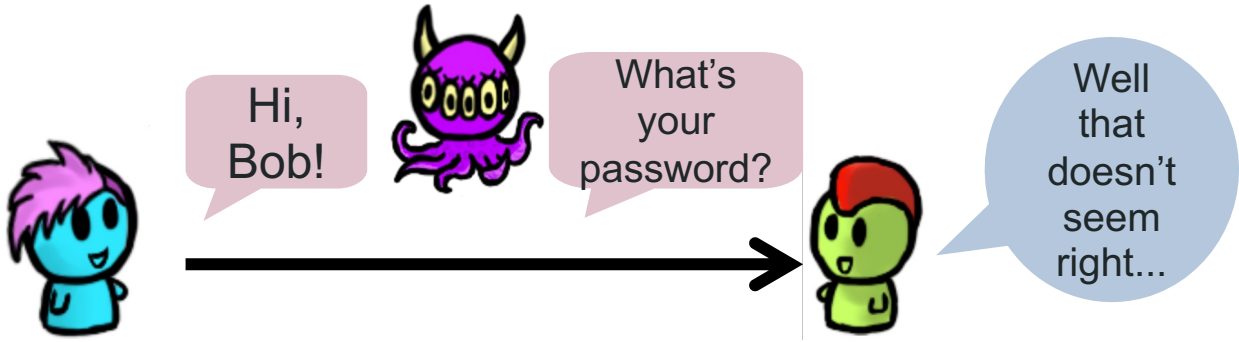

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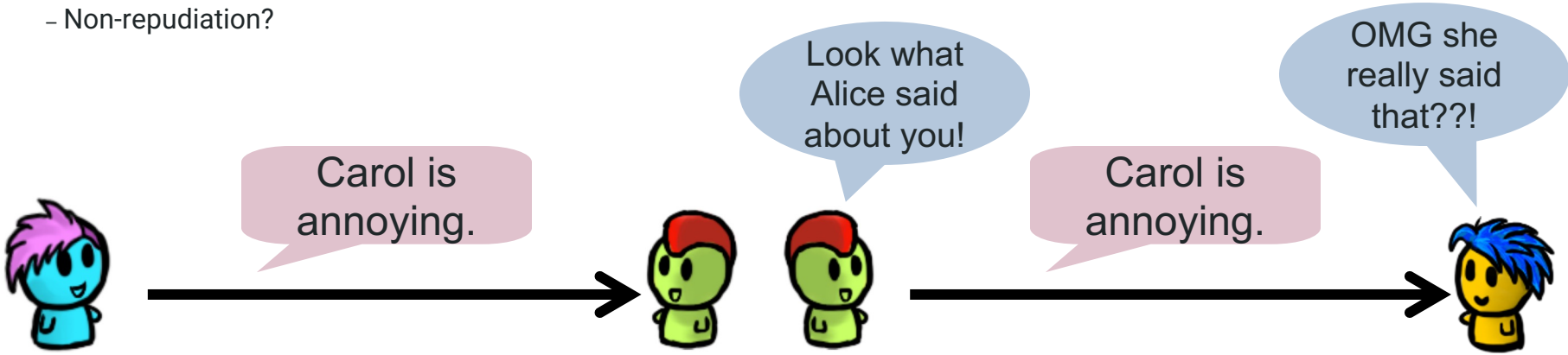


Pretty Good Privacy

PGP

- Public-key (actually hybrid) encryption tool
- Used for encrypted email (and other uses)
- Originally made by Phil Zimmermann in 1991
  - He got in a lot of trouble for it, since cryptography was highly controlled at the time
  - https://www.philzimmermann.com/EN/essays/WhyIWrotePGP.html

PGP

- PGP: Pretty Good Privacy (original program)
- OpenPGP: Open standard (RFC 4880)
- GPG/GnuPG: GNU Privacy Guard (a popular OpenPGP program)
- Many people just say “PGP” for all of the above
- Today, there are many programs which implement OpenPGP
  - GNU Privacy Guard (gpg), Thunderbird, Evolution, Mailvelope, OpenKeychain, PGPro, Delta Chat, Proton Mail, ...

PGP

Message

PGP

Message

hash(Message) = h

PGP

Message

hash(Message) = h

sign(h , ) = sig

PGP

sig

Message

PGP

sig | Message

SK = secret key (random)

PGP

sig | Message

SK = secret key (random)

enc(sig | Message , SK)

(symmetric encryption)

PGP

enc(sig | Message , SK)

(symmetric encryption) =

C1

PGP

C1

SK

PGP

C1

enc(SK , ) = C2

(public key encryption)

PGP

C1

enc(SK , ) = C2

C2 C1

PGP

C2

C1

PGP

C2 C1

PGP

(public key crypto)

PGP

C2 C1

dec(C2 , ) = SK

(public key crypto)

C1 SK

PGP

C1

SK

PGP

C1

SK

dec(C1 , SK)

(symmetric encryption)

PGP

C1

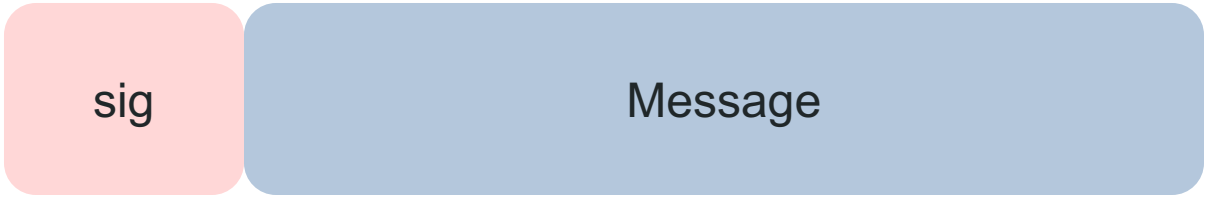
SK

dec(C1 , SK)

(symmetric encryption) =

sig | Message

PGP



PGP

sig | Message

verify(sig , Message , )

Encrypted Messaging Goals and PGP

- Confidentiality
- Integrity
- Authentication
  - Non-repudiation?

Encrypted Messaging Goals and PGP

- Confidentiality

- Integrity

- Authentication

– Non-repudiability?

Encrypted Messaging Goals and PGP

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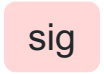

- Authentication

– Non-repudiability?

Encrypted Messaging Goals and PGP

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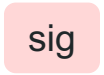
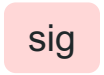


- Authentication



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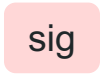

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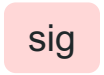

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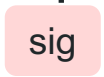

PGP Keys

PGP Keys

Each person has at least 2 keypairs:

- One for signatures
  - Public key used to verify
  - Private key used to sign
- One for encryption
  - Public key used to encrypt
  - Private key used to decrypt

```
pub   rsa4096 2023-01-27 [SC] [expires: 2023-02-26]
      EF22E516EA9C43B7A67E4FB41CD25603C14C0D05
uid           [ultimate] Alice <alice@example.com>
sub   rsa4096 2023-01-27 [E] [expires: 2023-02-26]
```

Obtaining Keys

- How does Alice get Bob's public key?
  - Download from Bob's website
  - Download from a keyserver
  - Bob sends it via email
  - Other channel
- How does Alice know it's Bob's **authentic** key?

Verifying Public Keys

- Alice and Bob would rather not have to trust CAs
- They can compare keys (in-person, through a secure channel, etc.)
- But keys are big and unwieldy!

-----BEGIN PGP PUBLIC KEY BLOCK-----

mQINBGPUBx4BEADa3JsMGX9GKriACgI1vvokxOc8ltbHSl7aYYMZu5UzgCxYy29n
7YDGDiwN23ibyi8Gf36HNJ6mQuzgUBJ7T54ed8pEf1rtMWL+7OoMNRNaFX6vosT5
3pFn+CiRY5avIGPkut8YdYrkaLixshjakYehmwwWVcVMBBGfrP3pR93dKWbET2EN
RMDSVBO6AzPnjedZmGpJUqp8UPxEP8JoTCn0xAv4ugjM6VE6xxb/Cj15I/5PsIhx
76LPqSsPUwRzKQ9stP8YjTX+Ol91+GNqLhtdmy5yXPD9F/NO+fhQVwvUZ0oJ544a
KeFDQ/G9GKJfJzTlhvQn9BdkZpff5Kjzun0+4HNk0msB5S8BItdPpuc3qs+rkL6W
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FCUH/aoRjZQV/Xi5laQHg+cbEtLRACdkaAHNNjxGDXkzjbuYzjtv3hPMvNiBF897
PvihCO2w4pXBQ7rpxzn6OvU1iawfrmdZQA2tRZOSN2Cpti3KJ0OzKzfGT0VFRaVq
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uynR6zO+rVcwAKz3g/aK5kknPG/Or4KdEhsmOKuPgATSduGo96t299dRqQARAQAB
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fI11i44fYII2ZxWWVr2vQ6T9oELTyCjJTeGxaot0thOxxQ3pdXavxuYdG84zZyMd
i96dvg==
=tJAW
-----END PGP PUBLIC KEY BLOCK-----

Fingerprints

- Hash the key to get the key **fingerprint**
- Instead compare the fingerprints
- Much shorter:
  - EF22 E516 EA9C 43B7 A67E 4FB4 1CD2 5603 C14C 0D05
- Remember: With a good hash function, no two key fingerprints should collide
- (What if you only use part of the fingerprint?)

Verifying Public Keys

- Alice and Bob have verified each other. Great!
- But verifying is hard
  - Inconvenient if possible at all
  - Bob and Carol may not know each other well
- What if Bob and Carol can’t verify each other?
- (Would it help if Carol has verified Alice?)

Signing Keys

- Once Alice has verified Bob's key, she uses her certification key to sign Bob's key
  - (By default, certification key == signature key)
- This is effectively the same as Alice signing a message saying "I have verified that the key with [Bob's fingerprint] belongs to Bob"
- Bob can attach Alice's signature to the key he has published somewhere
- (Are there any issues with doing this?)

Web of Trust

- Now Alice can act as an introducer for Bob
- If Carol can't verify Bob herself, but she has already verified Alice (and she trusts Alice to introduce other people):
  - She downloads Bob's key
  - She sees Alice's signature on it
  - She is able to use Bob's key without verifying it herself
- This is called the Web of Trust

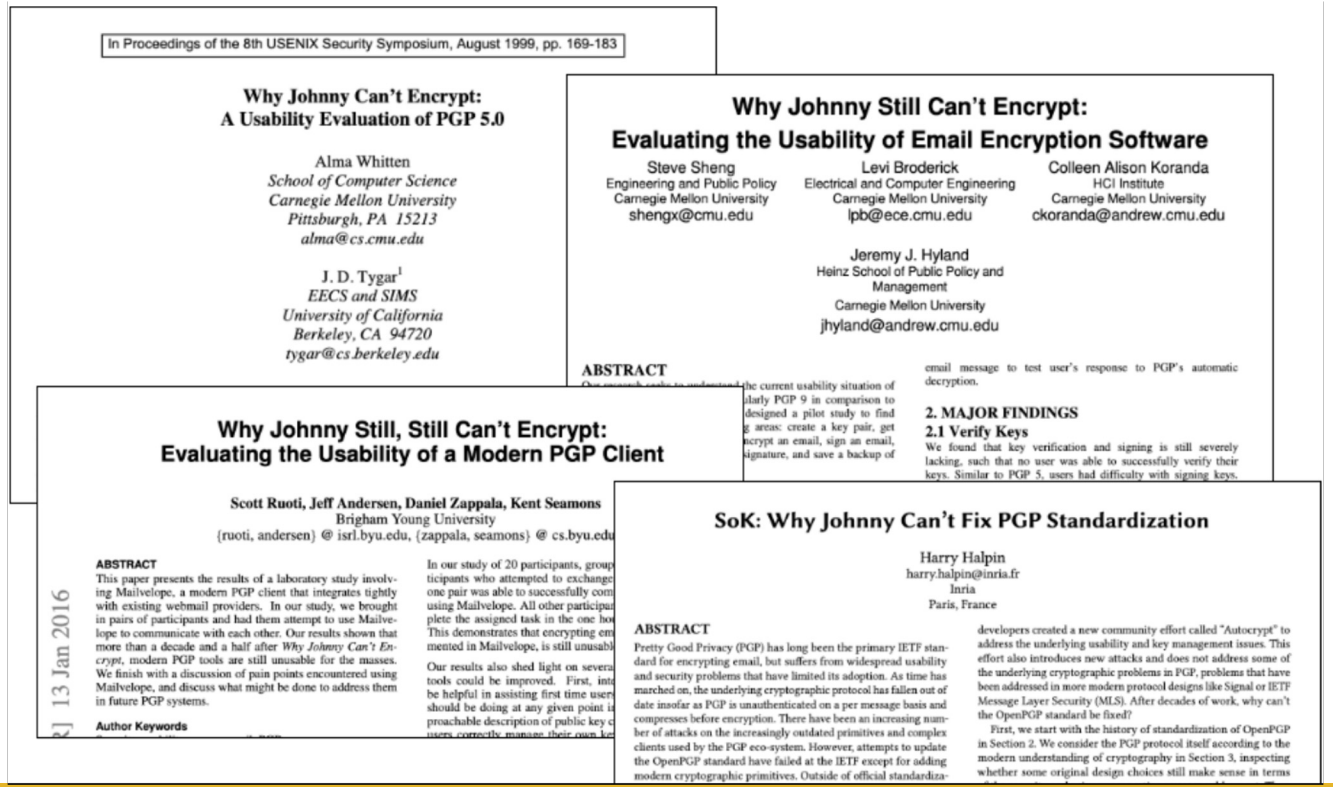
Awesome!

- If Alice and Bob want to have a private conversation:
  - They create their keys
  - They exchange their keys (possibly relying on the WoT)
  - They send signed and encrypted messages back and forth
- Pretty Good, right?

Problems with PGP

Problem #1: Usability

- Hard to use
- Low adoption



In Proceedings of the 8th USENIX Security Symposium, August 1999, pp. 169-183

Why Johnny Can't Encrypt:
A Usability Evaluation of PGP 5.0

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Why Johnny Still Can't Encrypt:
Evaluating the Usability of Email Encryption Software

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ABSTRACT

2. MAJOR FINDINGS
2.1 Verify Keys

Why Johnny Still, Still Can't Encrypt:
Evaluating the Usability of a Modern PGP Client

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ABSTRACT

Author Keywords

13 Jan 2016

SoK: Why Johnny Can't Fix PGP Standardization

Harry Halpin
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Inria
Paris, France

ABSTRACT

Problem #1: Usability

- https://moxie.org/2015/02/24/gpg-and-me.html

–"When I receive a *GPG encrypted* email from a stranger, though, I immediately get the feeling that I don't want to read it. [...] Eventually I realized that when I receive a GPG encrypted email, it simply means that the email was written by *someone who would voluntarily use GPG.*"

https://xkcd.com/1181/

Problem #1: Usability

- Usability is a security parameter
  - If it's hard to use, people will not use it
  - If it's hard to use **properly**, people will use it, but in insecure ways

Problem #2: Lack of Forward Secrecy

- Alice sends many encrypted messages to Bob
  - Possibly over the course of months, years
- Suppose Eve saves all of them
  - Not so unreasonable if Eve runs the email server
- What if Eve steals Bob's private key?
  - She can decrypt all messages sent to him. Past, present, and future...

Problem #3: Non-repudiation

- Why non-repudiation?
- Good for contracts, not private emails
- Casual conversations are "off-the-record"
  - Alice and Bob talk in private
  - No one else can hear
  - No one else knows what they say
  - No one can prove what was said
    - Not even Alice or Bob

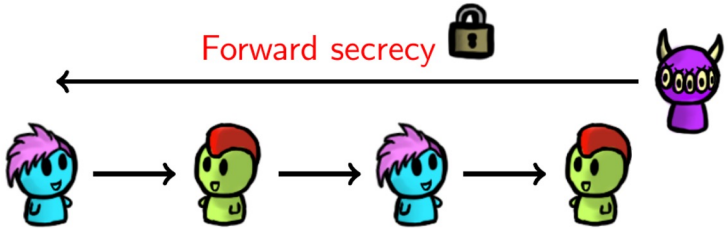
Off-The-Record (OTR) Messaging

OTR

- Messaging (XMPP) extension for encryption with:
  - Forward secrecy
  - Post-compromise security
  - Deniability

Goals of Off-The-Record Messaging

- **(Perfect) Forward secrecy: a key compromise does not reveal past communication**
- Post-compromise security ~~Backward secrecy~~ ~~Future secrecy~~ ~~Self-healing~~: a key compromise does not reveal future communication
- Repudiation (deniable authentication): authenticated communication, but a participant cannot prove *to a third party* that another participant said something



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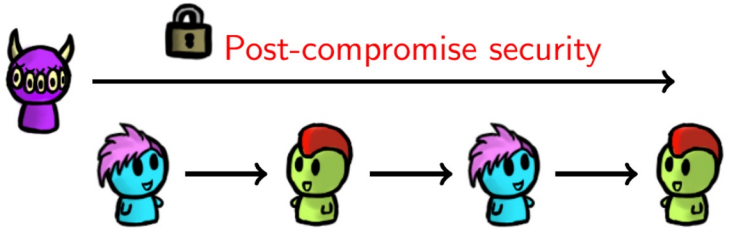

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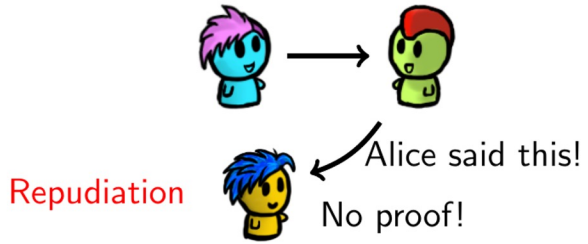

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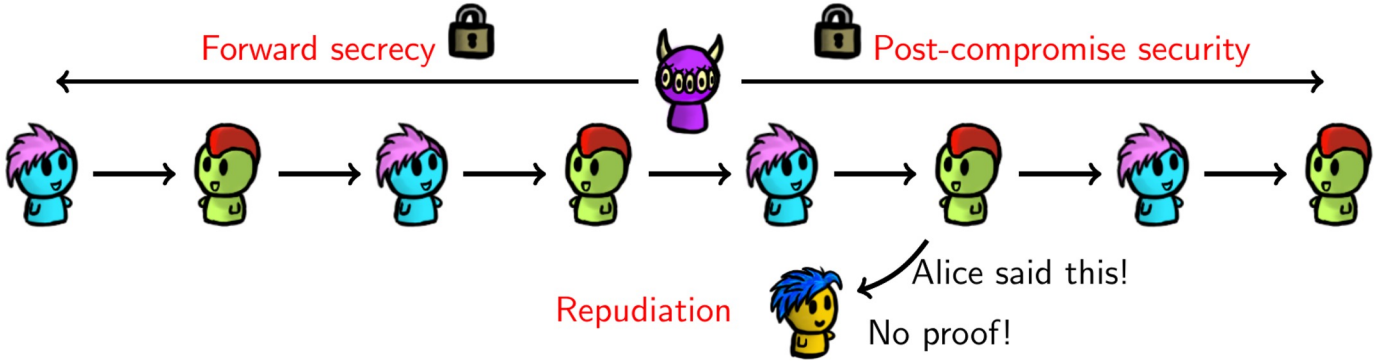


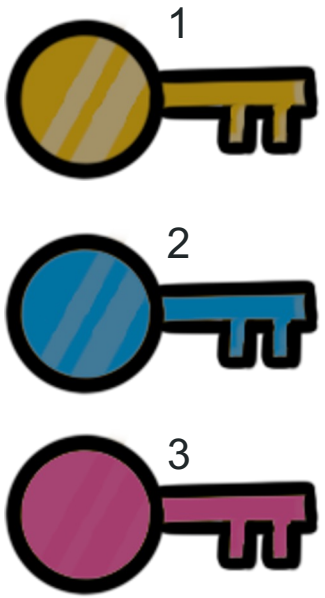
Forward Secrecy

- **Key compromise doesn't reveal past messages**

  Q: How can we accomplish that?

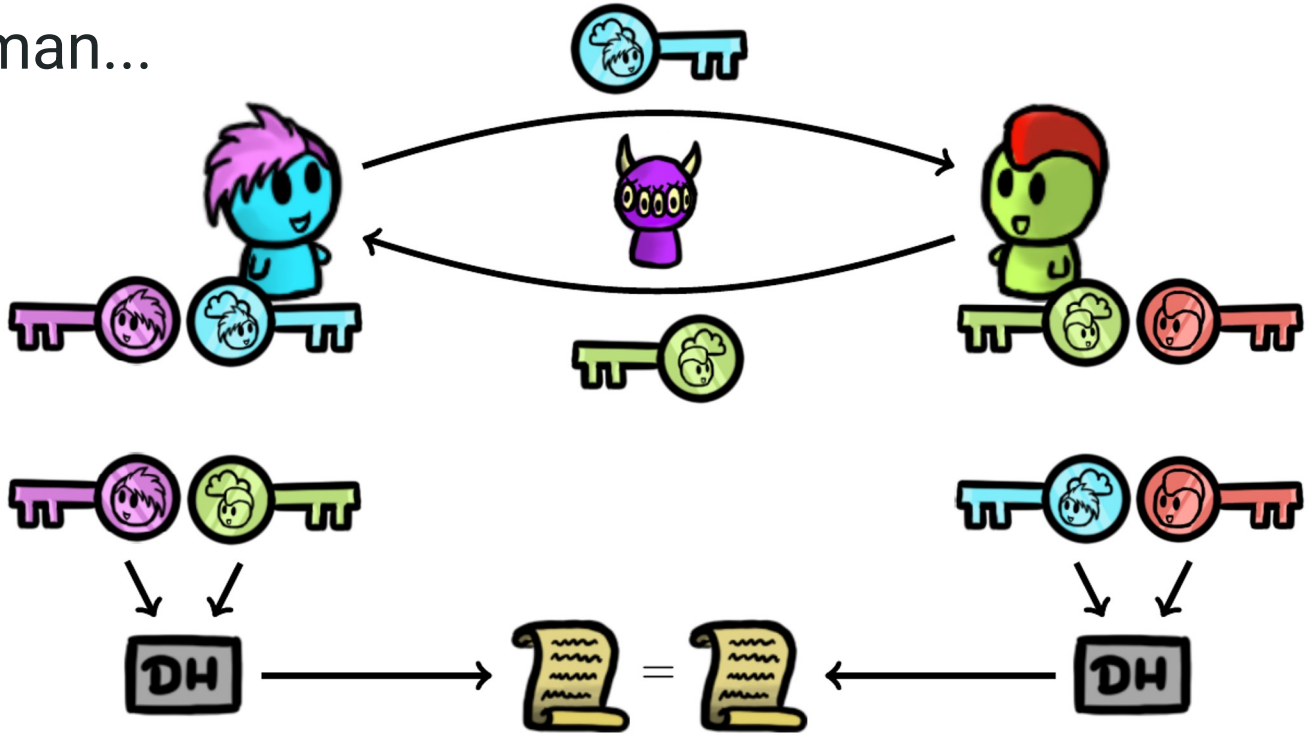
  Change the key!

  Old keys must be securely deleted



Forward Secrecy (one approach)

- Recall Diffie-Hellman...

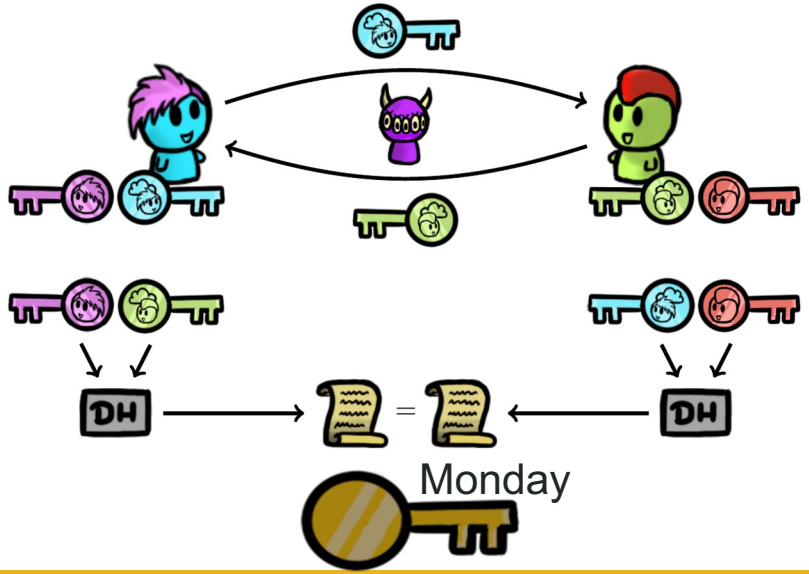


Forward Secrecy (one approach)

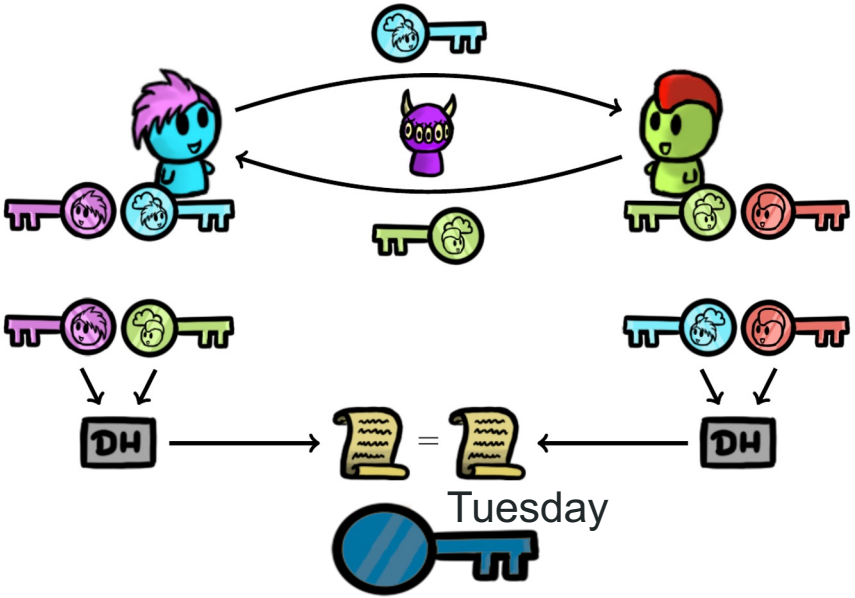
- Alice and Bob have ephemeral (temporary) “sessions”
- Alice produces ephemeral DH keys (a, g^a)
  - She signs the public key with her long-term key A
- Bob produces ephemeral DH keys (b, g^b)
  - He signs the public key with his long-term key B
- Alice and Bob use shared secret g^{ab}
- They make new keys later

Forward Secrecy (one approach)

- Alice and Bob talk on Monday...

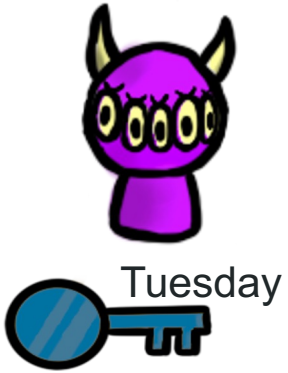


- Alice and Bob talk on Tuesday...



Forward Secrecy (one approach)

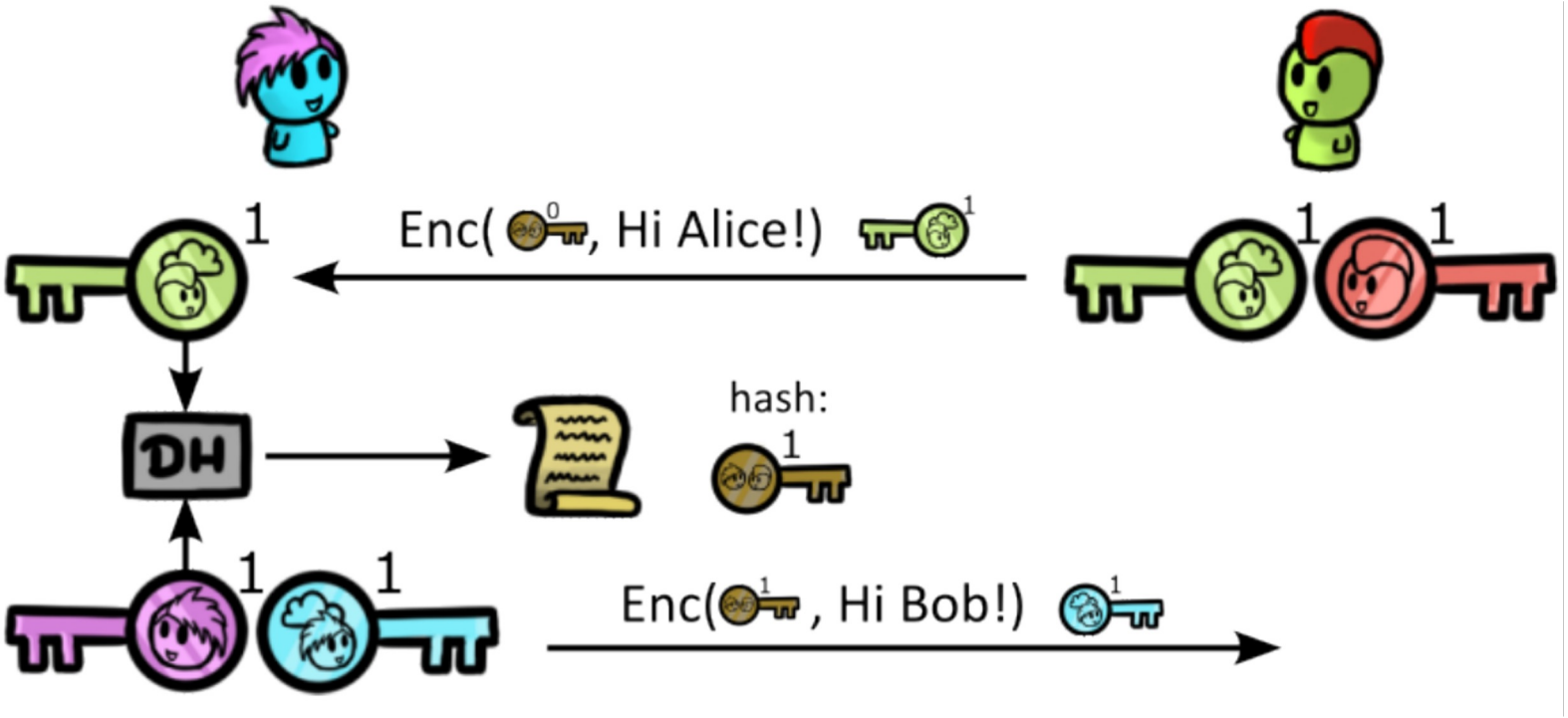
- Eve can compromise a session but not everything
- Problems?
  - Alice can’t start a session unless Bob is online
  - Eve can still compromise a whole session
  - We’ll see other ideas later



Forward Secrecy in OTR

- What if we make the sessions as short as possible?
- What if new sessions don’t have to be negotiated interactively?

Forward Secrecy in OTR



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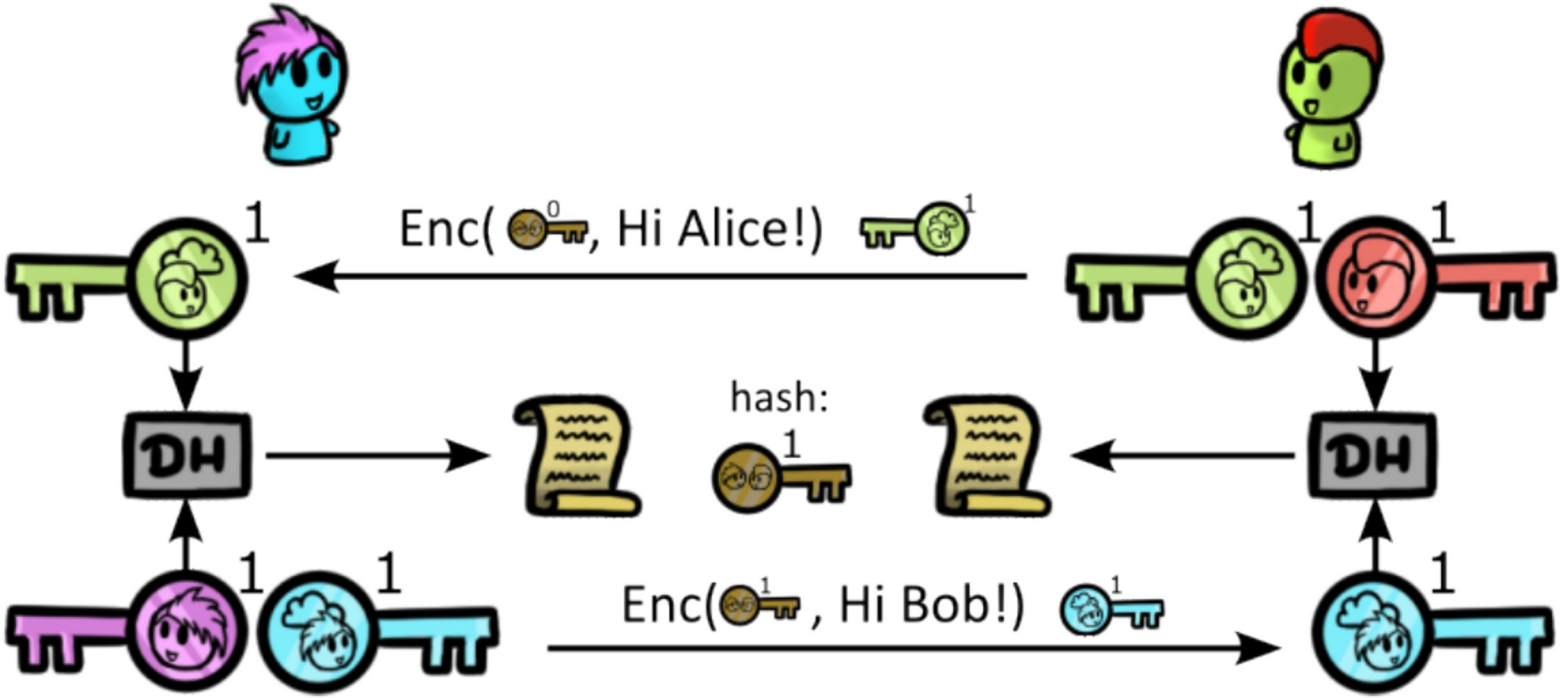

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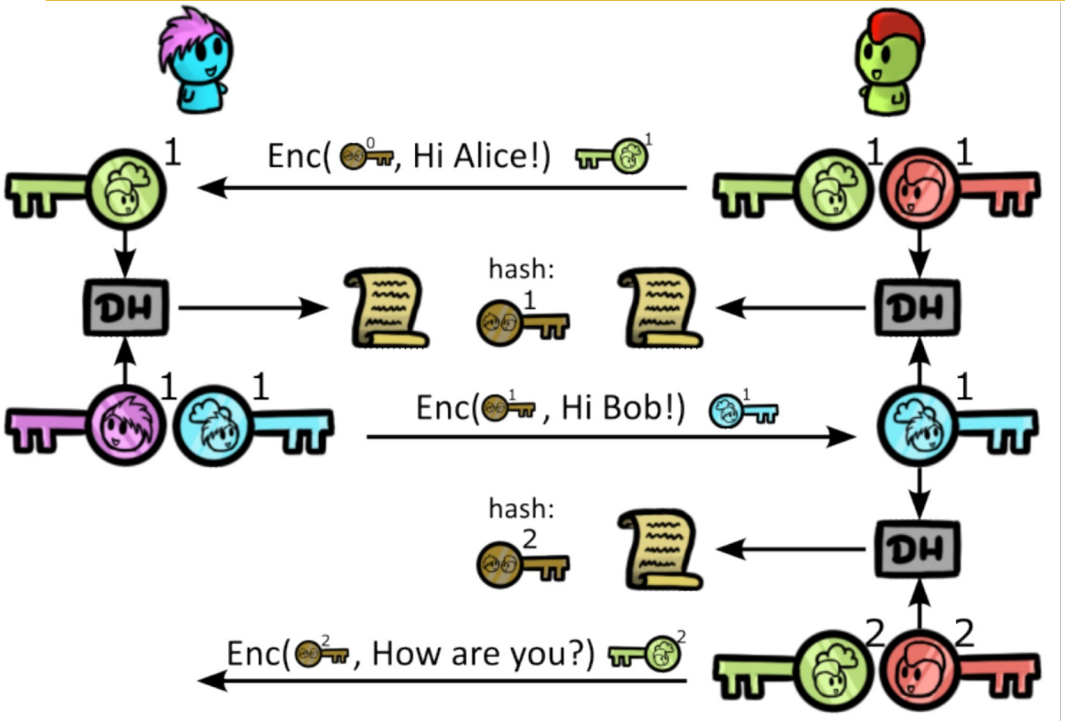
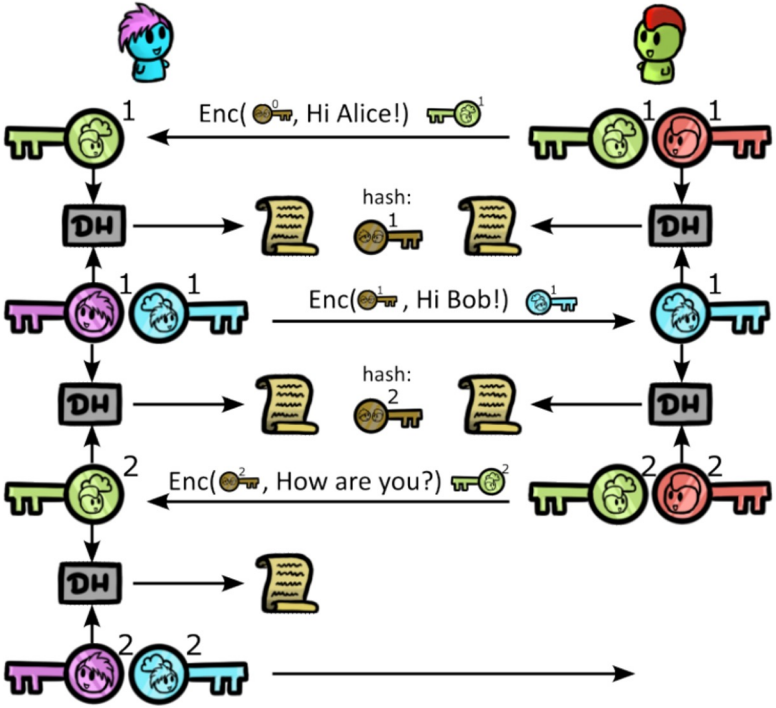


Forward Secrecy in OTR

- Alice and Bob automatically create new sessions as they reply to each other
- Also provides post-compromise security
- Awesome! :)
- This is a “ratchet”: You can’t go backwards



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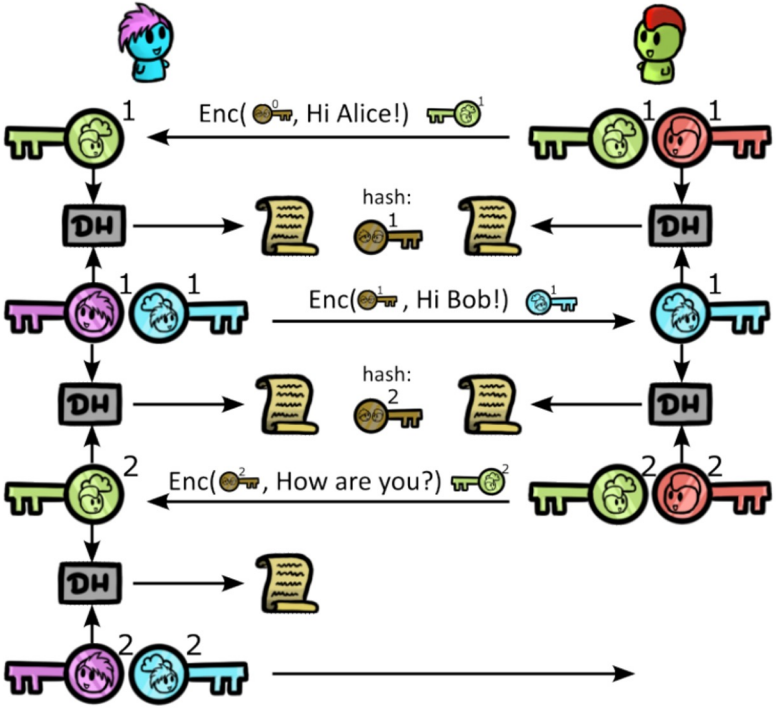
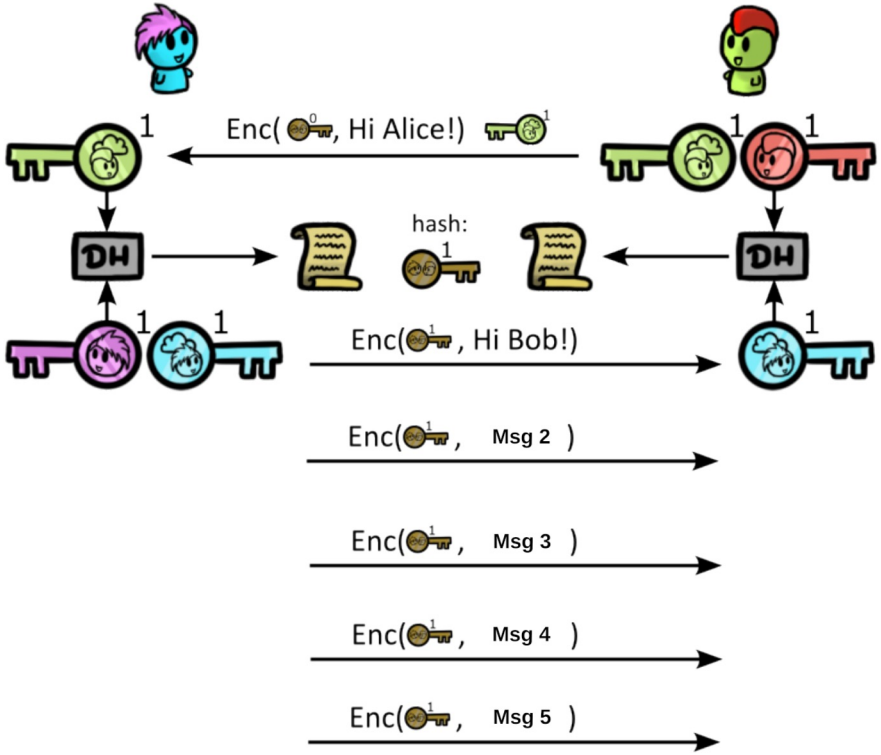


Forward Secrecy in OTR

- One problem...
  - Session keys only roll forward when sender changes
  - What if Alice sends Bob many messages in a row?
  - (We'll see Signal improve upon this later)



Deniable Authentication in OTR

- PGP uses signatures for authentication...
- ...but they also provide non-repudiation

Q: How can we get authentication without non-repudiation?

Deniable Authentication in OTR

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Q: How can we get authentication without non-repudiation?

A: With a MAC!

  - Alice and Bob similarly negotiate DH authentication key

Recall...

- Why are MACs deniable?
  - Only Alice and Bob know K
- Alice sends Bob a message MACed with K
- Bob knows it was Alice because:
  - Only Alice or Bob could have produced this MAC
  - Bob did not produce the MAC
- Why doesn't this argument work for Carol?

Signal

Signal

- Mobile app with companion desktop (Electron) client
  - OTR was less mobile-friendly
- Encryption protocol based on OTR
  - Double Ratchet Algorithm builds on OTR DH ratchet
  - Deniability ideas from OTR
- Protocol also used in other apps like WhatsApp, OMEMO extension for XMPP, etc.

Double Ratchet Algorithm

- Uses two ratchets:
  - KDF chain
  - Diffie-Hellman sessions (like OTR)
- Originally called Axolotl ratchet for its “self-healing” property (from the DH ratchet)

“Axolotl” is a Nahuatl word. (pronunciation)

Photo: th1098

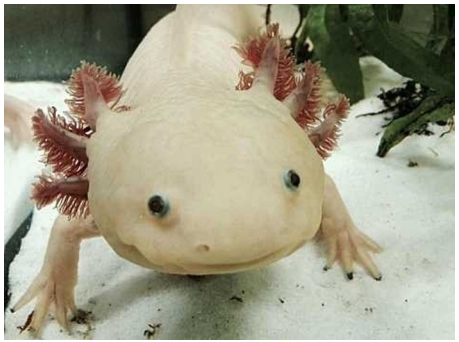

Illustration: ArmandoAre1

Forward Secrecy (another approach)

- What if instead of session keys, we had a new key for *each message*?
- We can do this deterministically
- Simplified ratchet:
  - $K_{n+1} = H(K_n)$
- What happens if Eve compromises a key?

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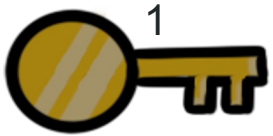

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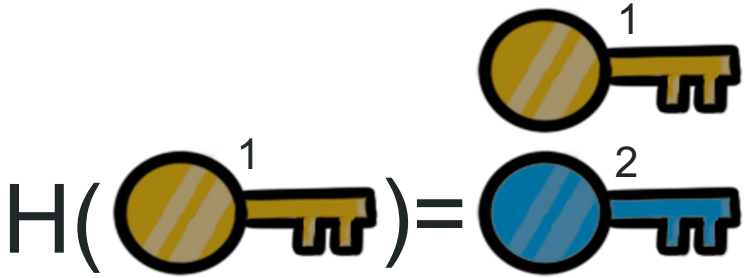

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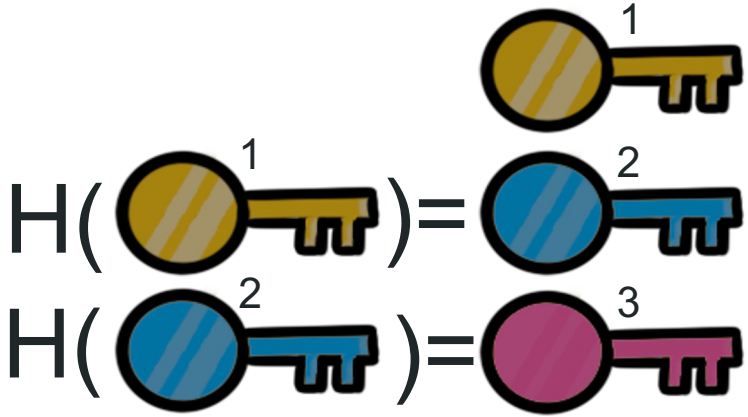
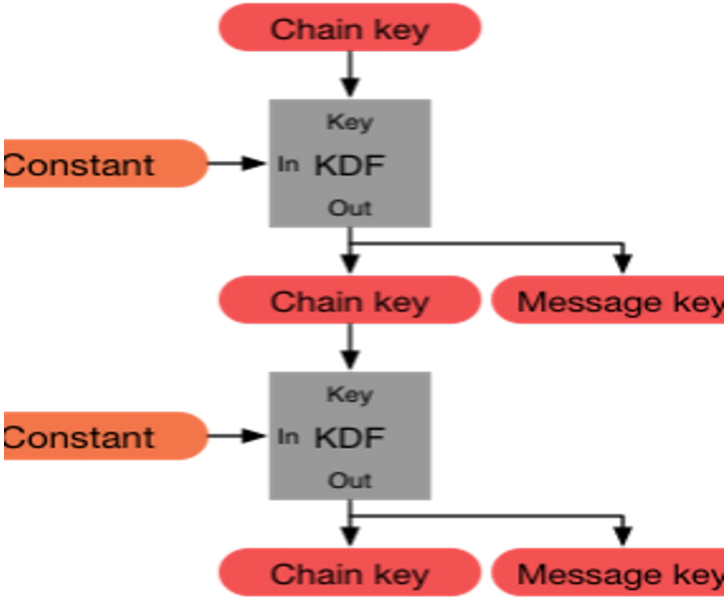


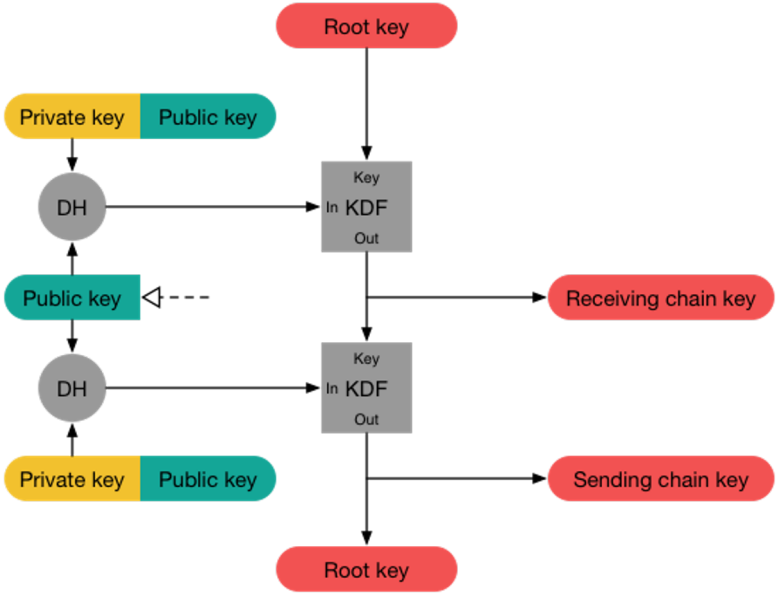
KDF Ratchet

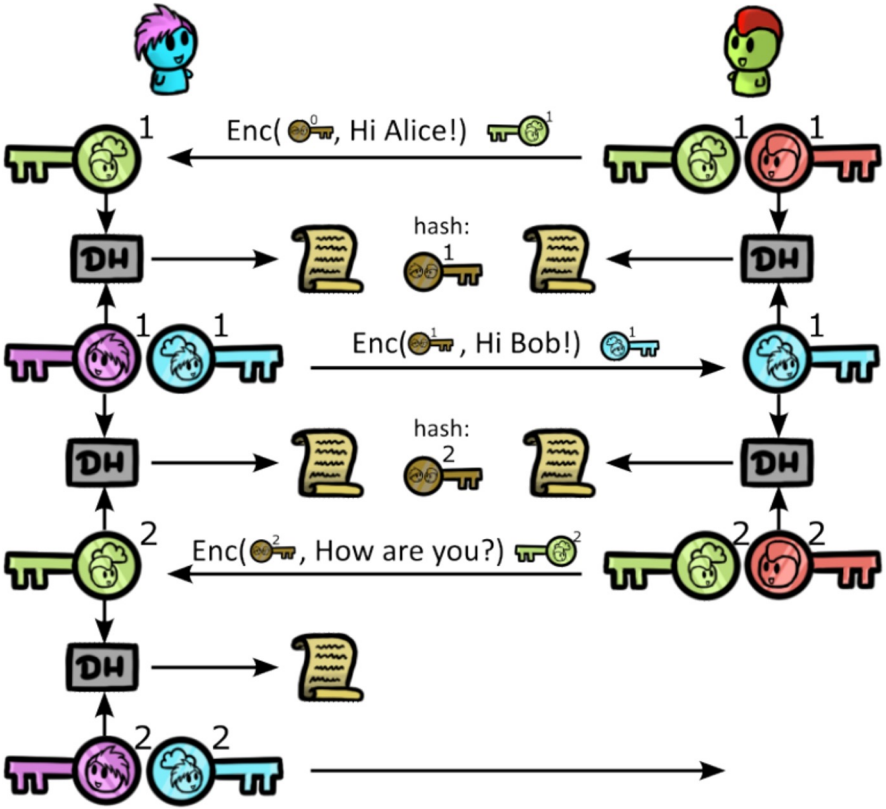
- KDF = Key Derivation Function
  - (think hashing – it only goes one way)
- Outputs message key
  - **Used to encrypt a single message**
- Outputs chain key
  - Used to derive future keys
- Why separate chain & message keys?
  - What if messages are out-of-order?

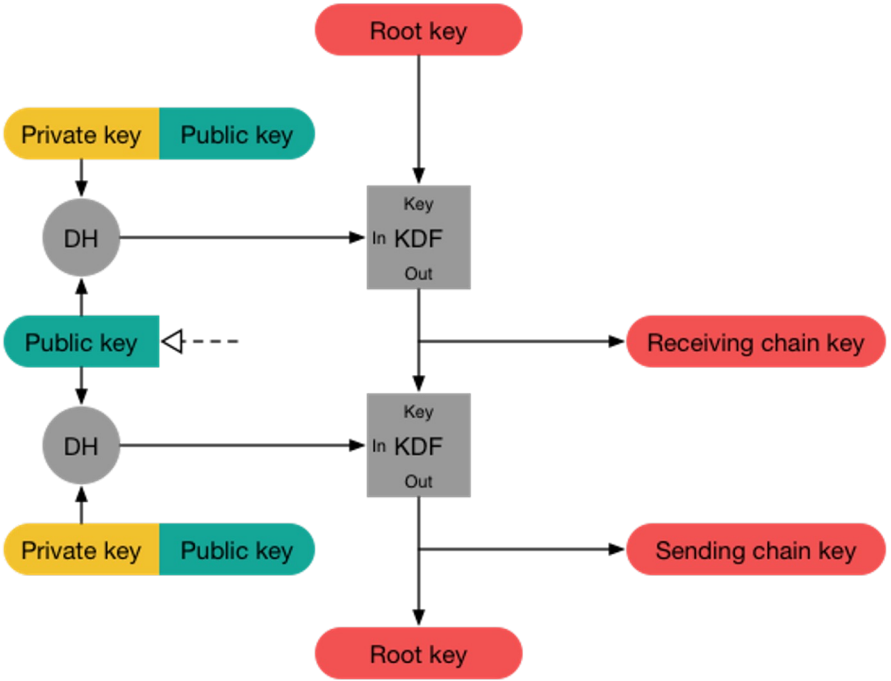


DH Ratchet

- Like OTR
- Outputs Receiving and Sending chain keys
  - These are used for KDF ratchet (previous slide)




Enc(, Hi Alice!)
hash:
DH
Enc(, Hi Bob!)
hash:
DH
Enc(, How are you?)
DH


Root key
Private key
Public key
DH
Key In KDF Out
Public key
Receiving chain key
DH
Key In KDF Out
Private key
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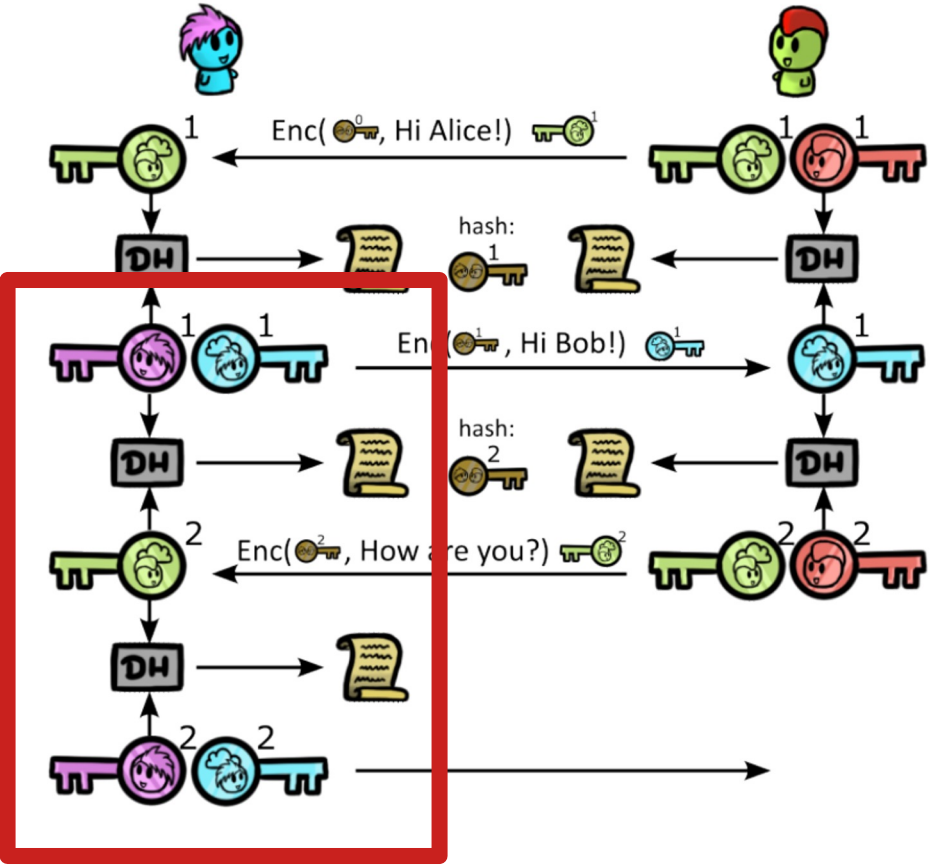
Root key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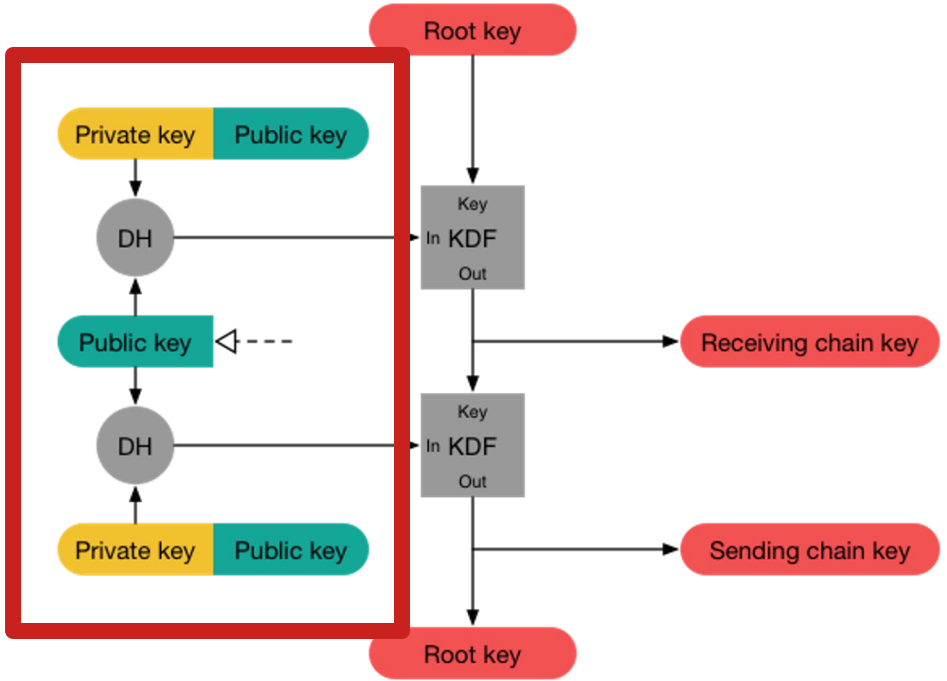

Root key
Private key
Public key
DH
Key
In KDF
Out
Public key
Receiving chain key
DH
Key
In KDF
Out
Private key
Public key
Sending chain key
Root key

Brace Yourselves!!!

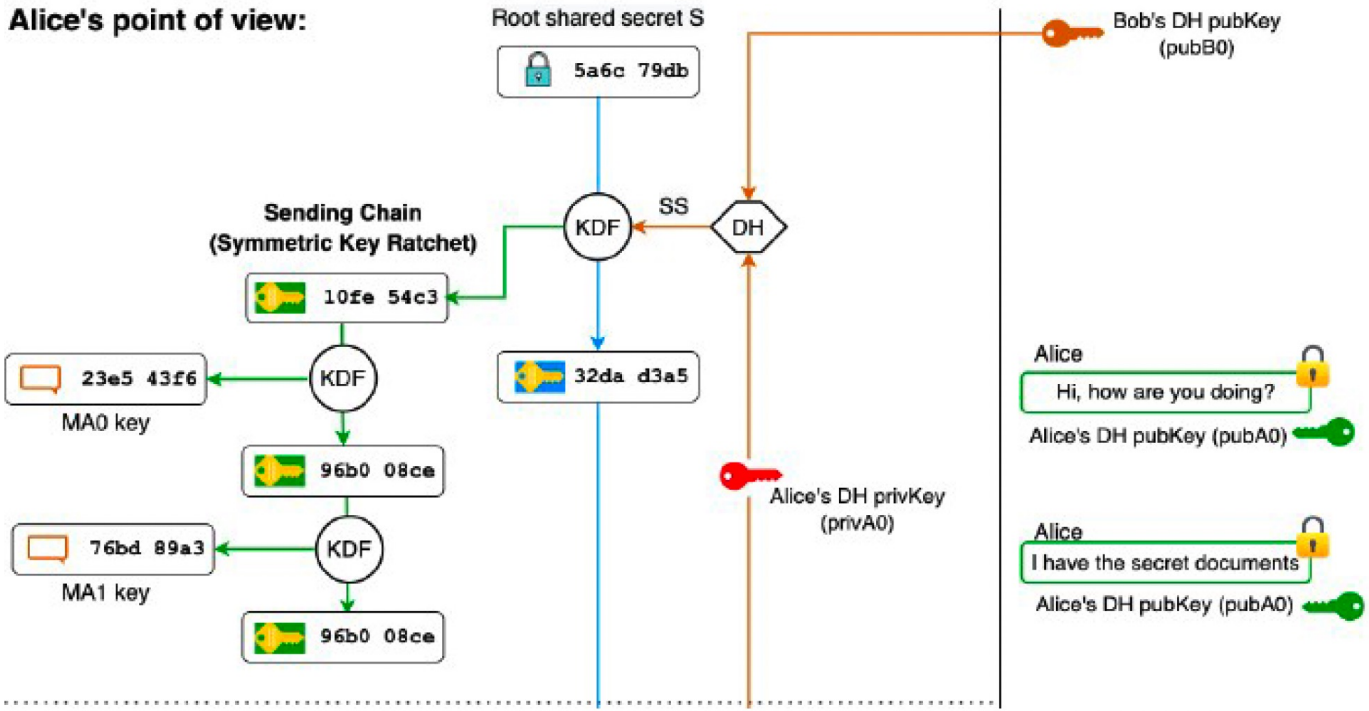
- We're about to put the two ratchets together
- It's going to be complicated
  - But it will be okay ☺

Photo: David J. Stang

Photo: ZeWrestler

Double Ratchet Algorithm

- Alice -> Bob
- Alice and Bob do **DH** and get Alice's sending chain/Bob's receiving chain
- Alice **derives a key** with her sending chain
- Alice uses this **MA0** key to encrypt her message to Bob



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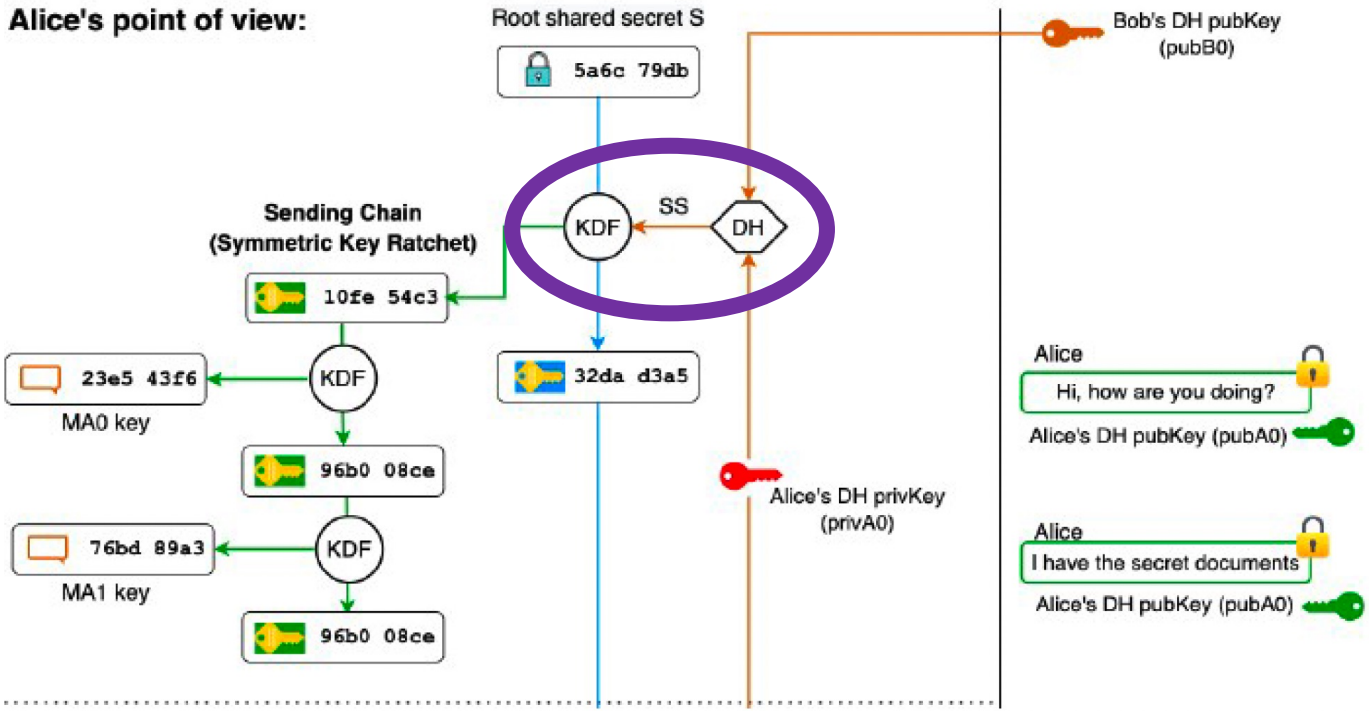

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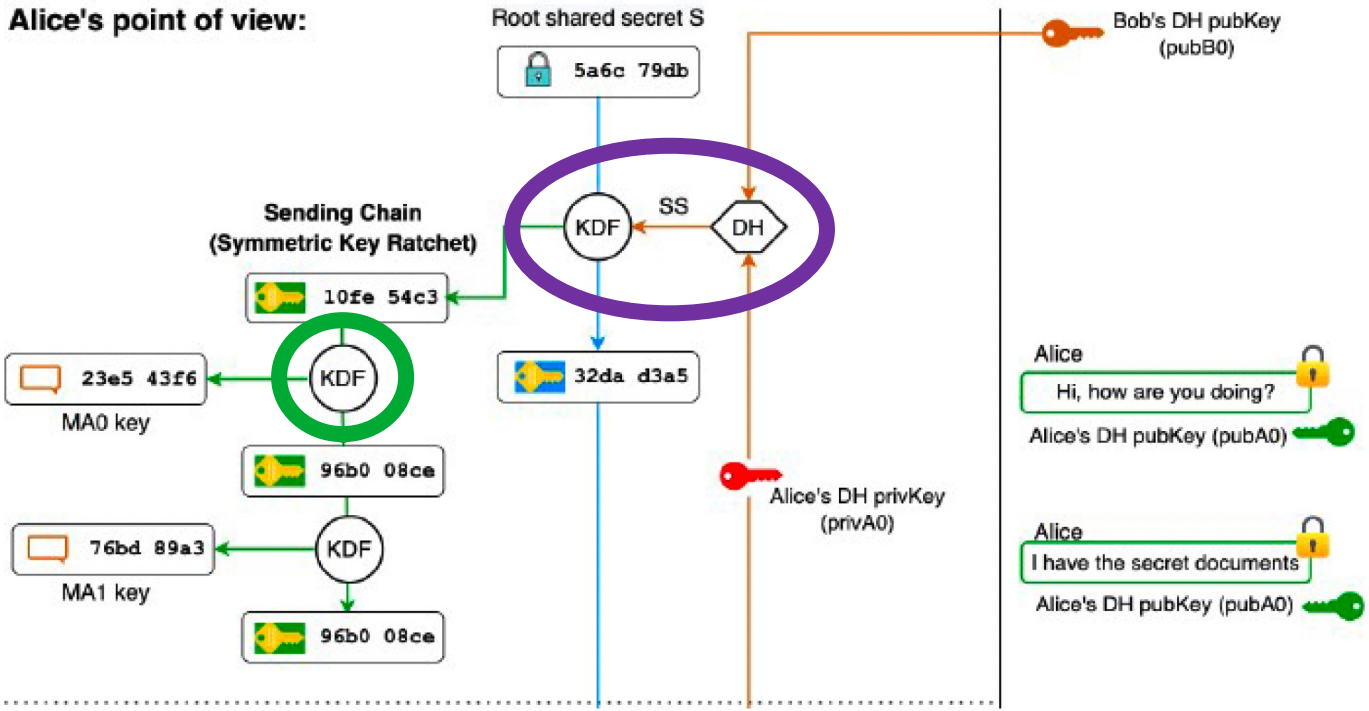

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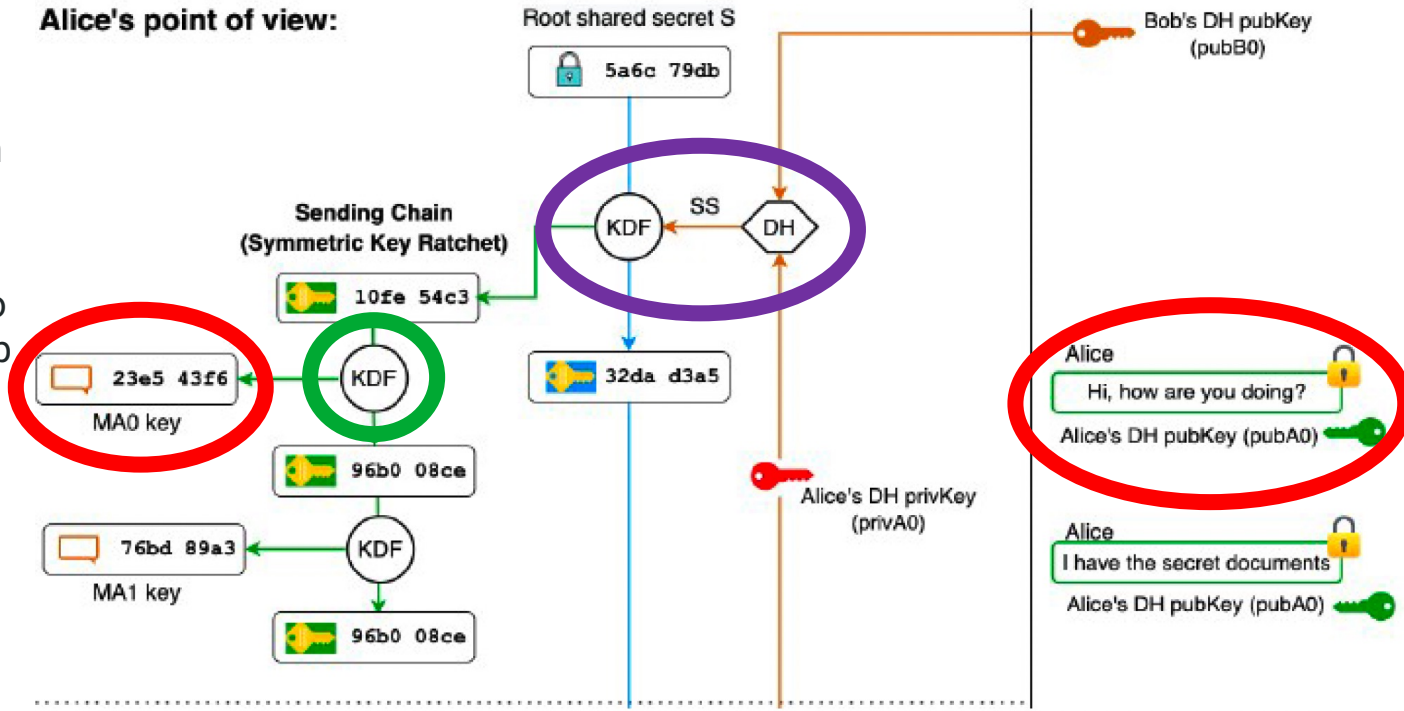
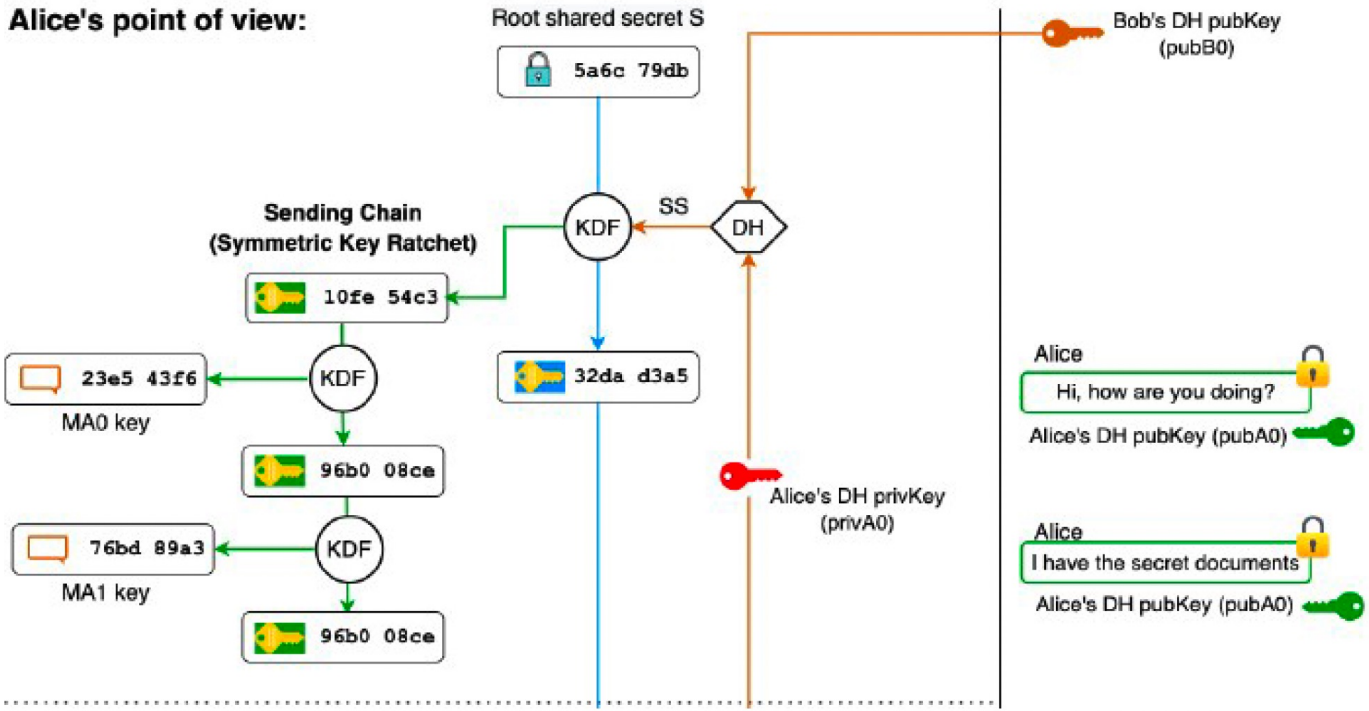


Double Ratchet Algorithm

- Alice -> Bob **(again)**
- **No new DH until Bob replies**
- Alice **derives another key** with her sending chain
- Alice uses **MA1** key to encrypt her message to Bob



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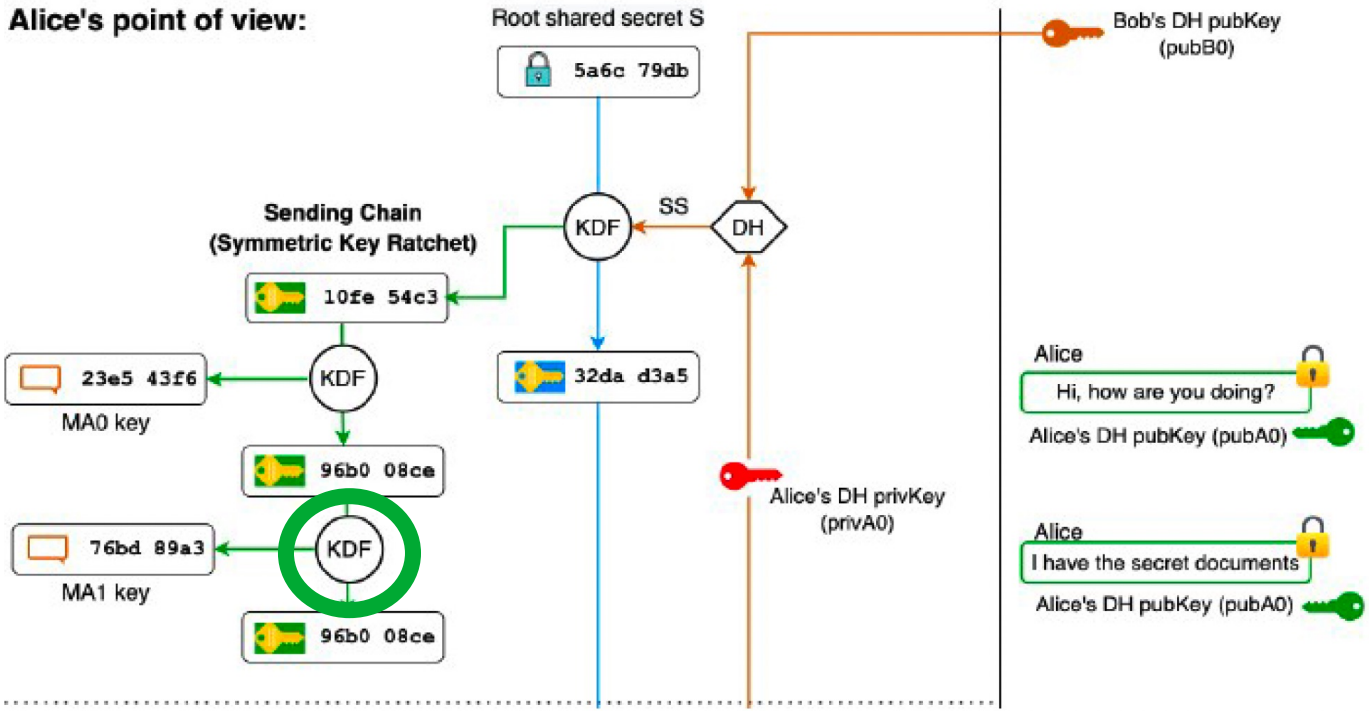

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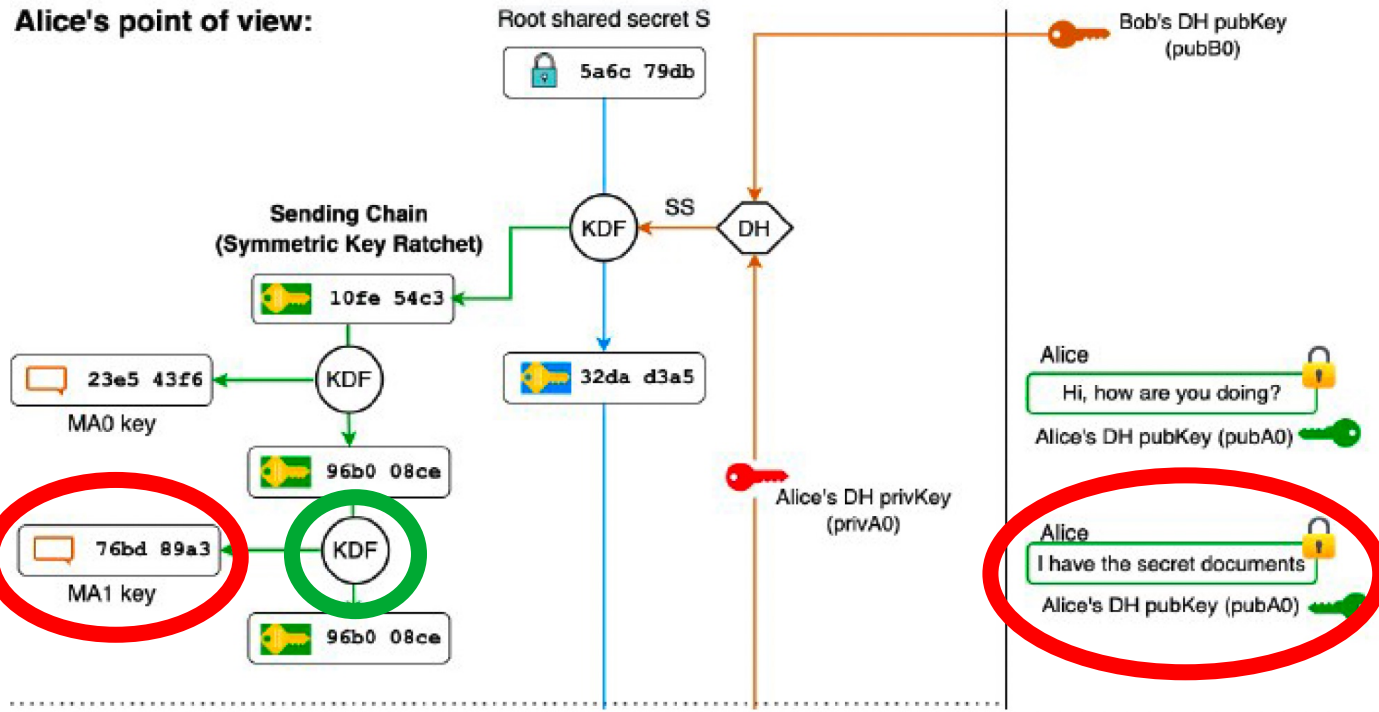

Double Ratchet

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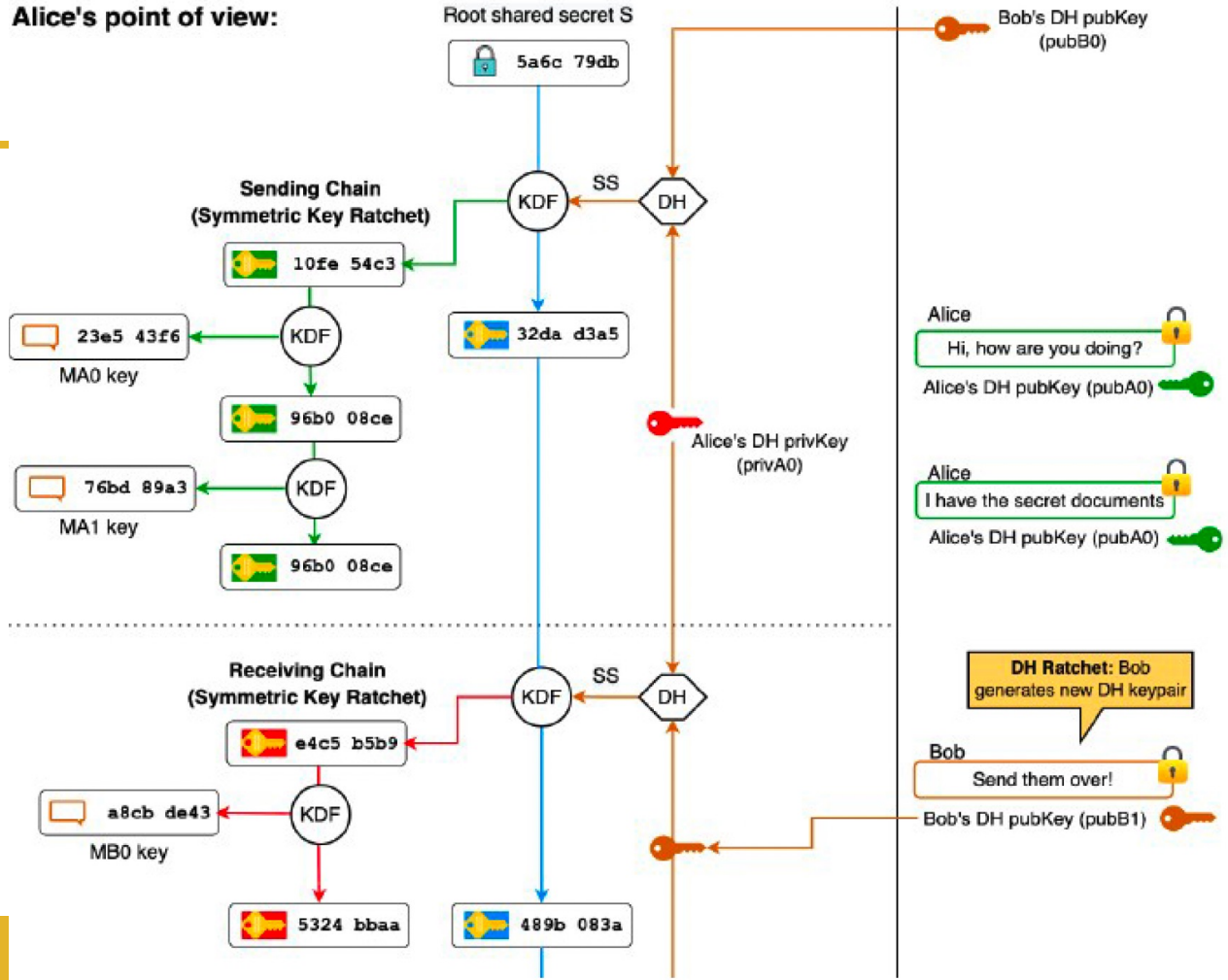
- Alice uses **MB0** key to decrypt a message from Bob



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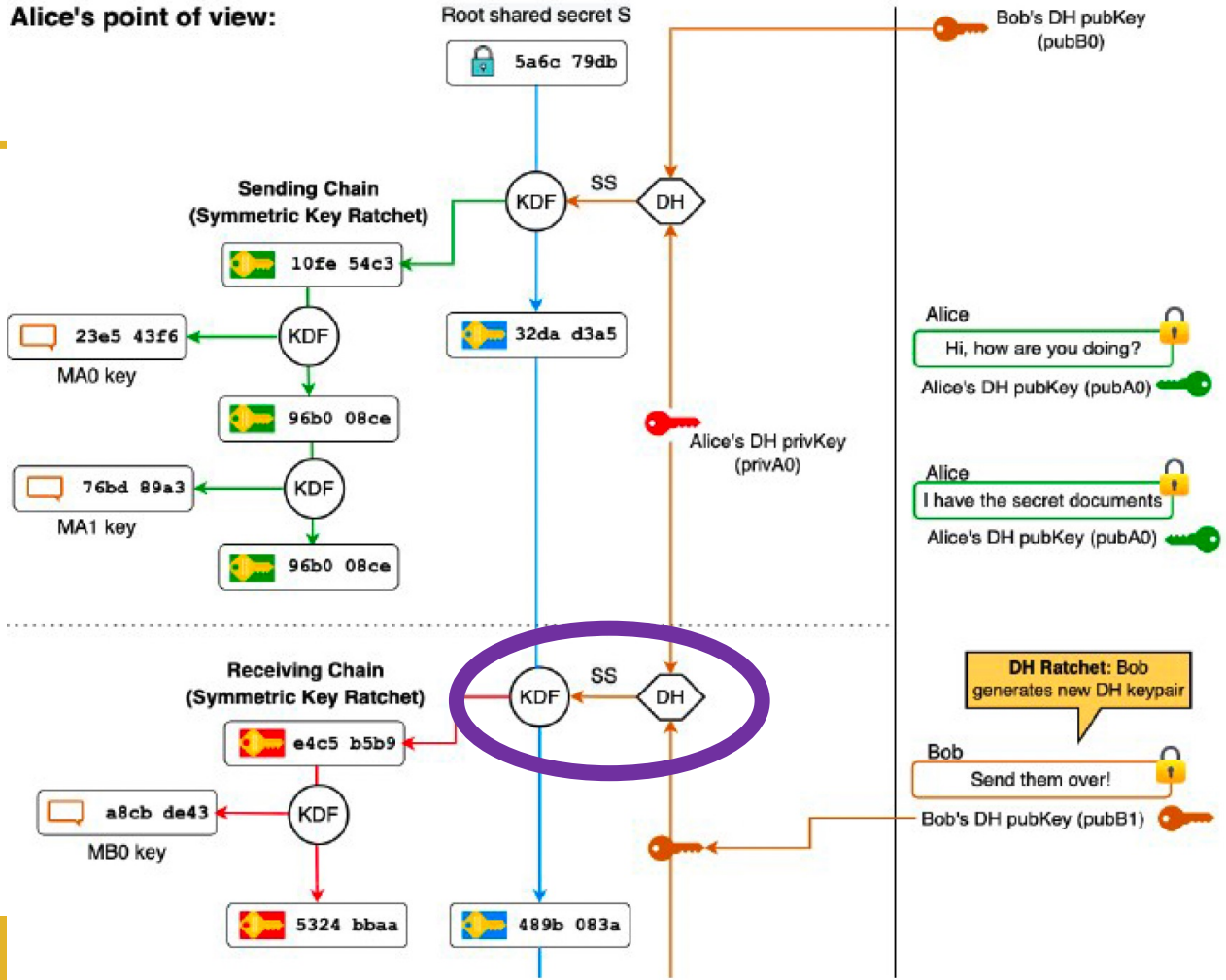

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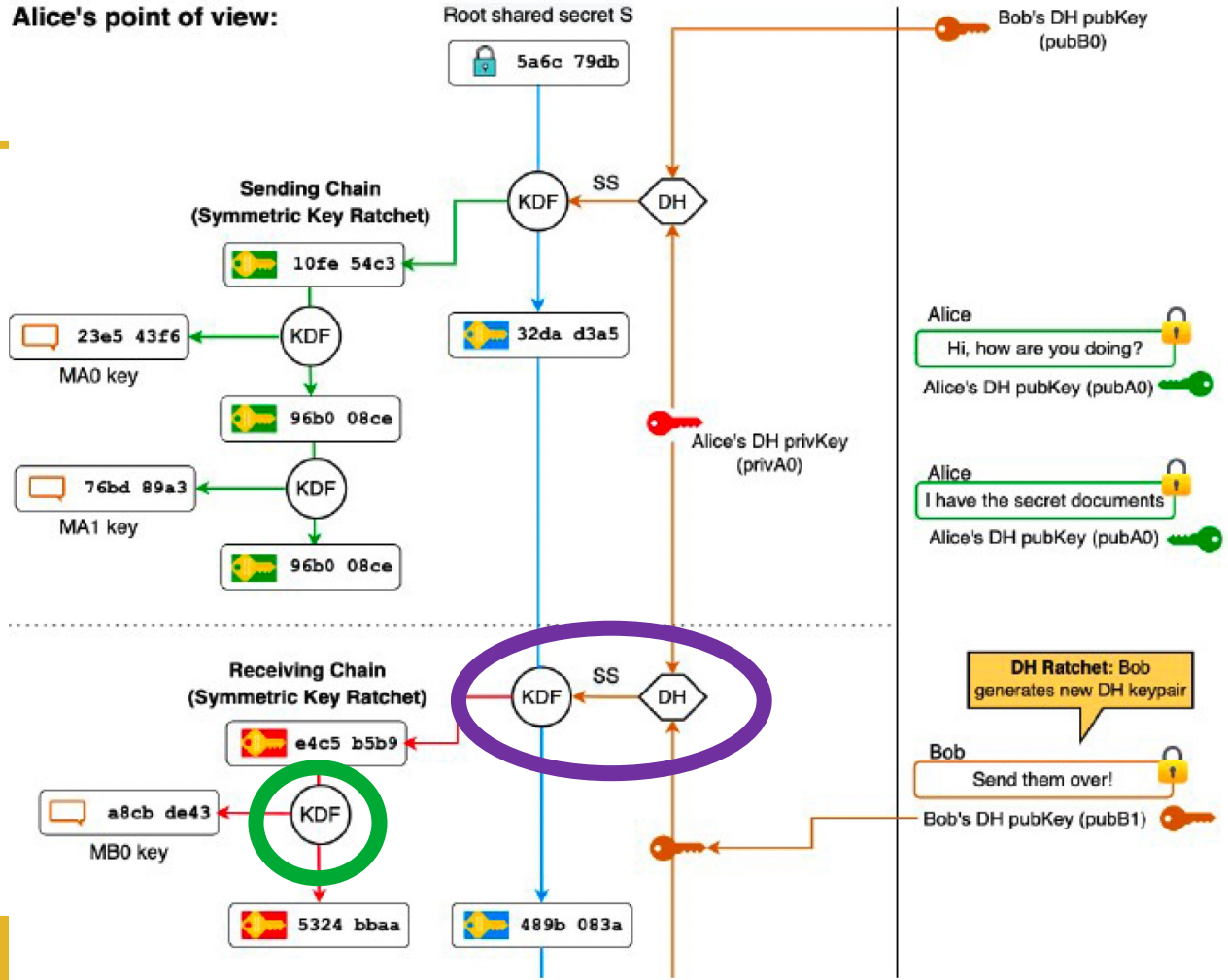

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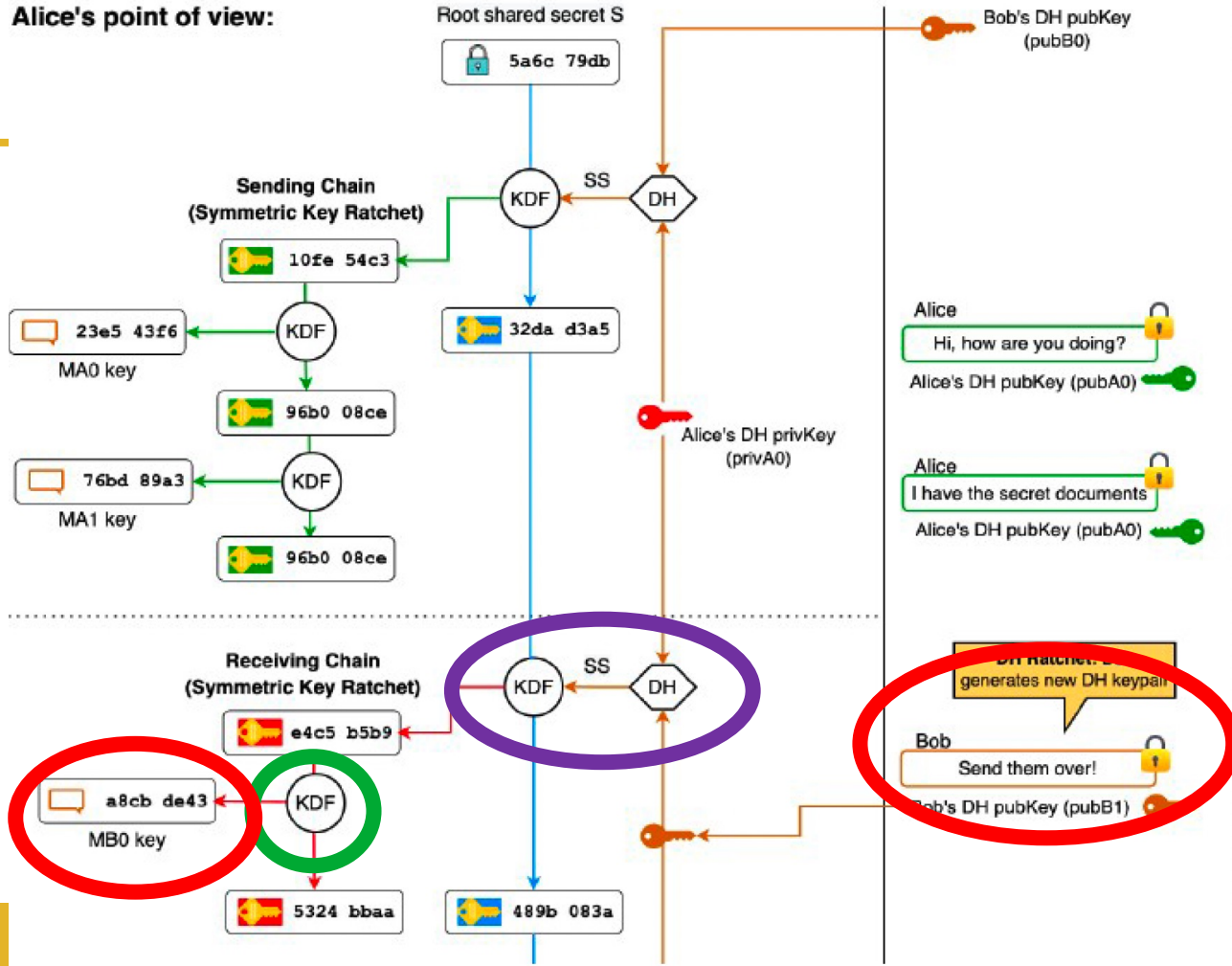


Let’s take a breath

- Here are some more pictures of axolotls

Photo: LeDameBucolique

Photo: uthlas

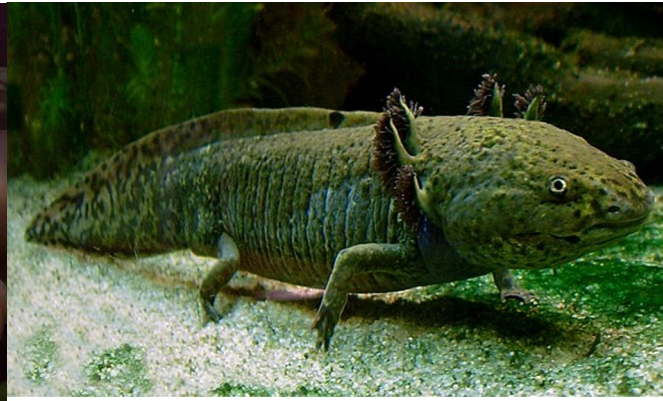


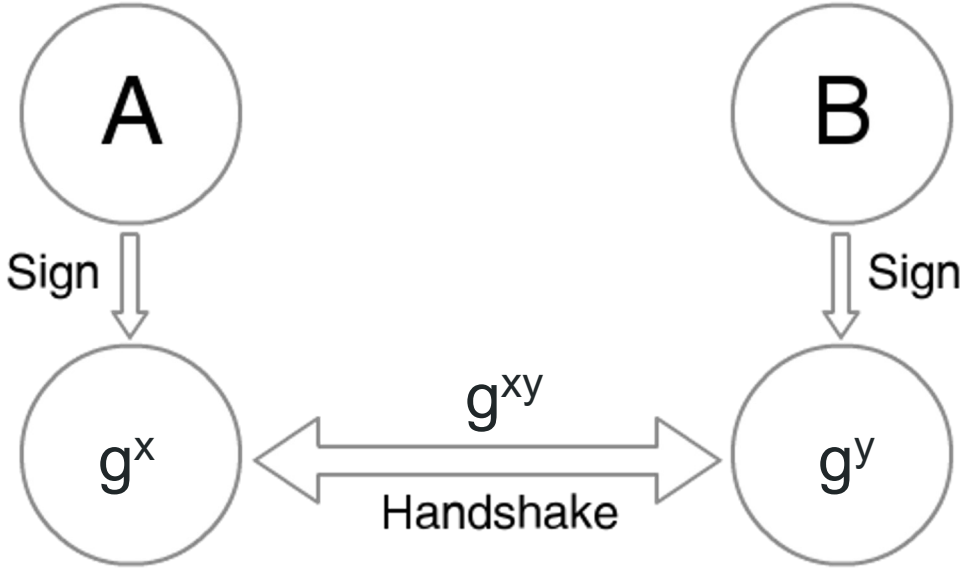
Photo: LoKiLeCh

Deniability in Signal

- Alice and Bob use MACs (like in OTR)
- But what if they can make it even more deniable?

Deniability in OTR

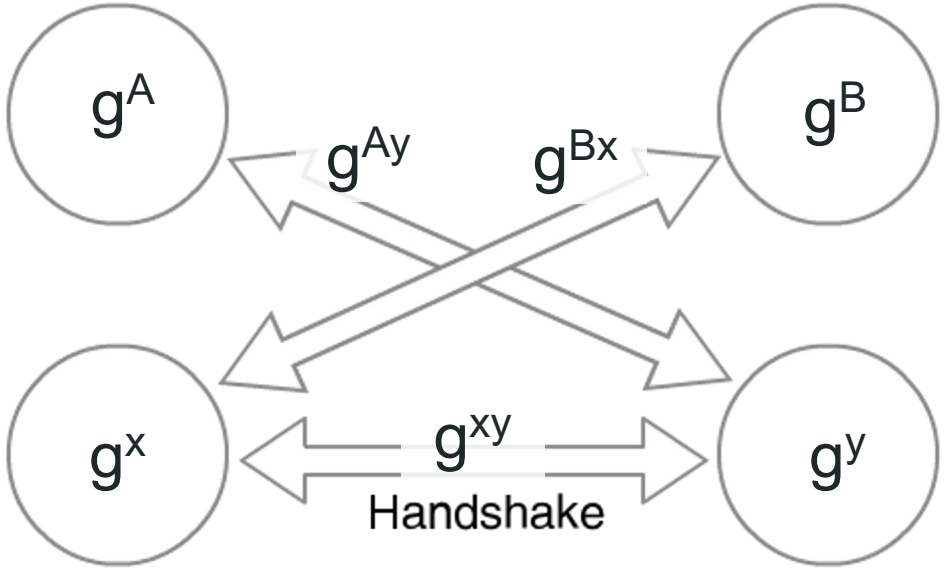
- DH(x,y) can only be created by Alice or Bob
  - A: long-term (Alice)
  - B: long-term (Bob)
  - x: ephemeral (Alice)
  - y: ephemeral (Bob)



Deniability in Signal: 3DH

- DH(A,y) || DH(x,B) || DH(x,y) can be created by anyone
- But if Alice knows x, only Bob could know y
- Why?

https://signal.org/blog/simplifying-otr-deniability/



That’s more theoretical

- Signal actually uses a more complicated eXtended Triple Diffie-Hellman (X3DH) key agreement protocol which involves some signatures
- X3DH is useful for enabling asynchronous communication
  - More mobile-friendly
- We won’t talk about it, but it’s well-documented here: https://signal.org/docs/specifications/x3dh/

Quick Recap

- **PGP**
  - No forward secrecy
  - Non-repudiable (not off-the-record)
- **OTR**
  - Forward secrecy through DH ratchet ☺
  - Deniable ☺
- **Signal**
  - DH ratchet provides forward secrecy *and* post-compromise security based on replies
  - KDF ratchet provides only forward secrecy, but for *every message*
  - Deniable ☺