# CS489/698 Privacy, Cryptography, Network and Data Security

## Network Anonymity

Fall 2024, Tuesday/Thursday 02:30pm-03:50pm

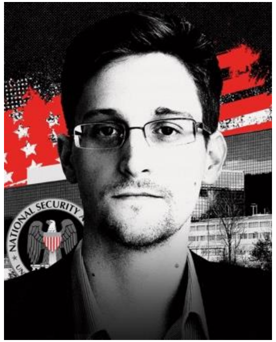
# Recall a Little Bit About Privacy

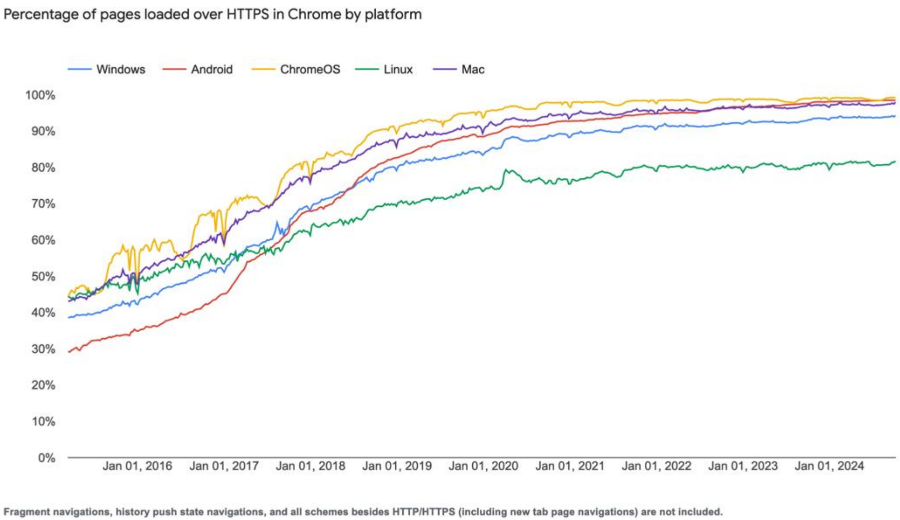
Two “types” of information that could be privacy-sensitive:

- Data: refers to contents of messages, contents of a database...
  - Data streams headers (e.g., source and destination IP)
  - Body (may or may not be encrypted)
- Meta-data: any other information that is not data
  - When communication occurs
  - Who communicates
  - How often do they communicate
  - …

# Encryption on the Internet

- When the Internet was designed, the main concern was reliability
  - The data should get transmitted successfully
  - SSL used only for the financial transactions
- Big change in the mid-2010s
  - Encryption at scale
  - HTTPS become ubiquitous





# Encryption on the Internet

- You certainly use encryption on the Internet
  - SSL used only for the financial transactions
- You may also be familiar with “end-to-end” encrypted messaging apps
  - e.g., iMessage, WhatsApp, Signal
  - Even the servers facilitating the communication cannot read the contents of the messages

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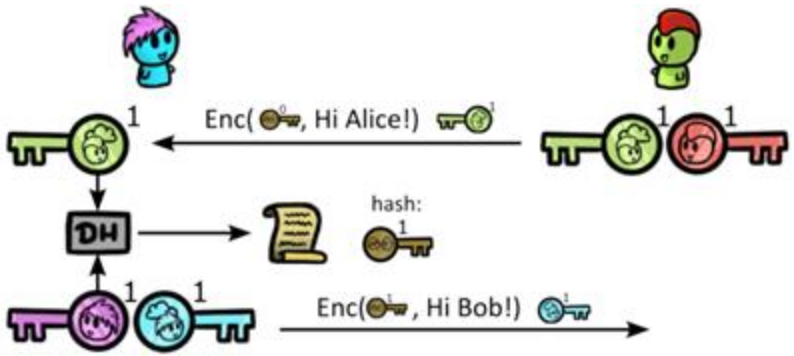
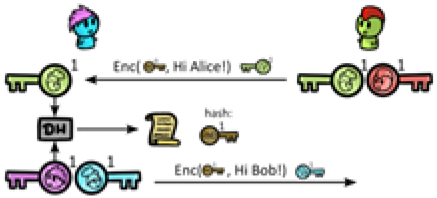
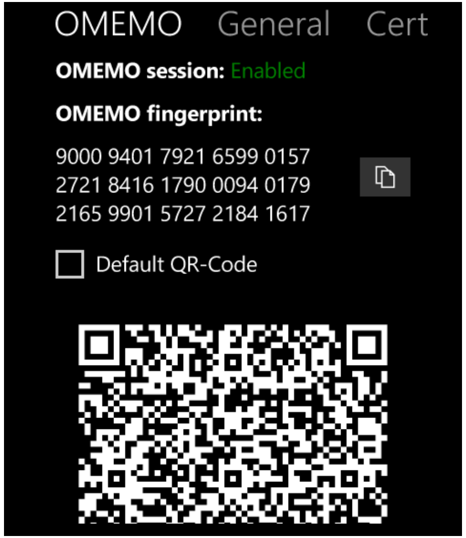


# How do we Trust these Keys?




- You Manual Verification – OMEMO: QR Codes

XMPP



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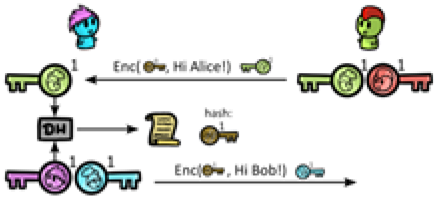
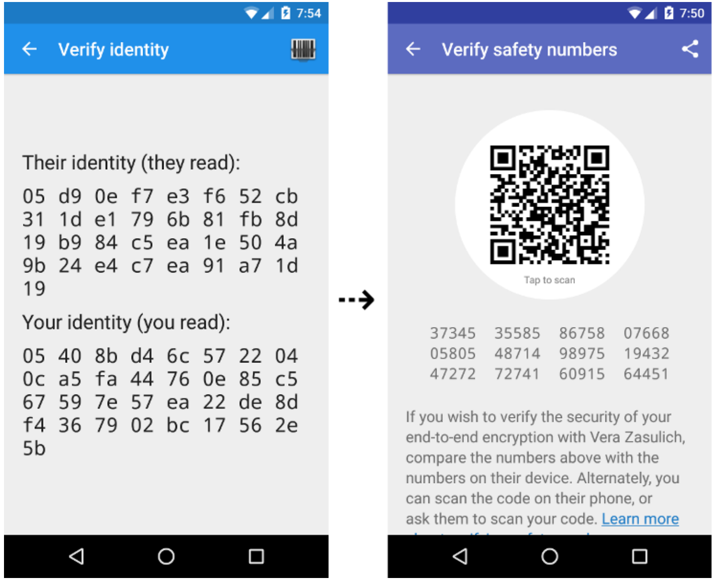
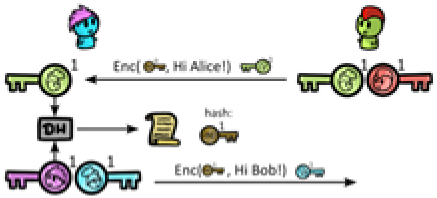



- You Manual Verification – Signal: Safety number

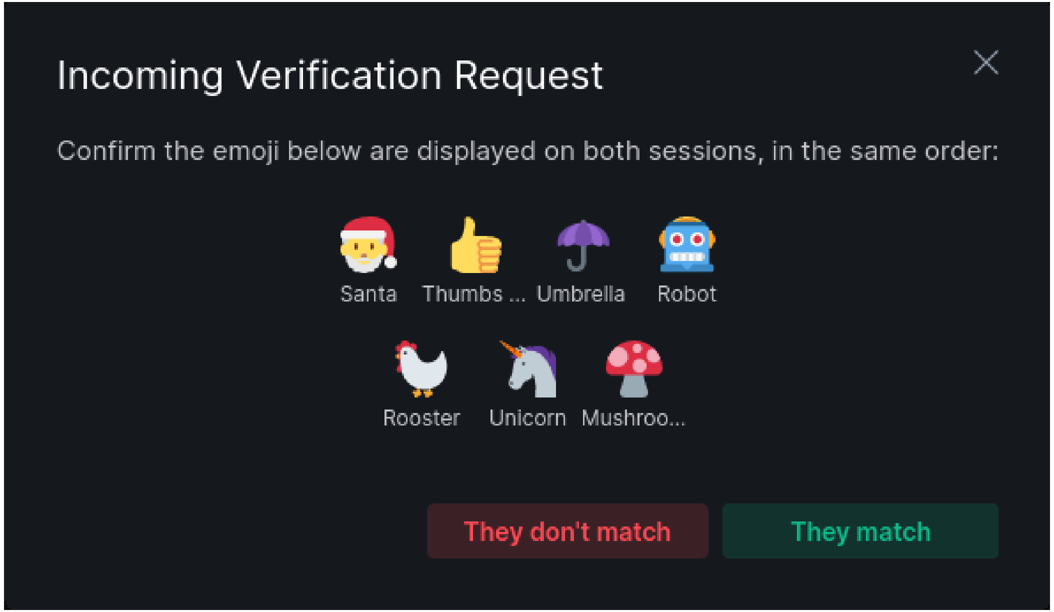
Signal






# How do we Trust these Keys?

- You Manual Verification – Matrix: Emoji



# Metadata

- Protecting data with encryption is necessary for security and privacy, but not sufficient
- Just knowing who your friends are gives a lot of information about you
  - This can be a big problem in some countries

"We kill people based on metadata"
— Gen. Michael Hayden, former director of NSA and CIA

# Anonymous Versus Confidential Communication

- Confidential communication encrypts **payload** (contents – HTTP/HTML, email, etc.)
- Parts of the communication that are not encrypted
  - Sometimes called meta-data
  - Network addresses (necessary for routing the message)
    - Email address, IP addresses (TCP ports)
      - Consider personal information
    - Your email provider likely knows “who” you are by your email address
    - Your ISP likely knows “who” you are by your IP address
  - Length (encryption does not hide the length – except minimally)
  - Timing

# Protecting metadata from whom

- That is, what is the threat model? Who might be adversarial?

- ASes the network traffic passes through
  - Note that this could include governments
  - In the extreme, a global adversary

- The servers facilitating the communications
  - Even if they're compelled by law or force

- Sometimes even the person you're talking to
  - More limited in what we can protect

# A Simple Linkage Attack Based on Length

- You record your sibling's wedding, encrypt the recording and upload it to an anonymous storage server
- The file is 15,837,448,756 bytes large
- Two weeks later you download it again
- Eve is observing the network traffic to and from the anonymous storage server

**Q:** Can Eve determine that both access were by the same person?

**A:** Well enough

# PETs to Control Data Leakage and Meta-data

- Anonymity in communication (privacy as masks): how to hide who communicates with whom.
  - Tor
  - Remailers (Mixes)

**Today:** the meta-data of communication

E.g., Who communicates with whom, how often, from where…

# Tor

# Onion routing

- This new technology was onion routing (Syverson, Goldschlag, and Reed, 1997), and its successor, Tor (Dingledine, Mathewson, Syverson, 2004)

# Why Tor?

Tor is a successful privacy enhancing technology that works at the transport layer with **≈2 million** daily users

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**Q:** Why do we need Tor when we have TLS?

**A:** TLS **protects data**, but…We also **want to protect metadata** about the communication: e.g., IP addresses, browser fingerprints.

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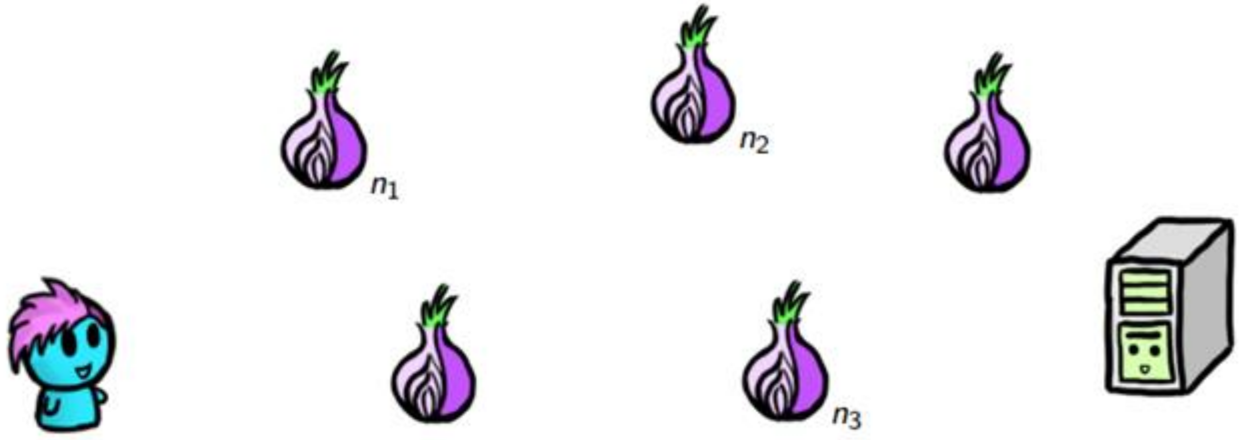
Tor makes internet browsing unlinkably anonymous. But Tor does not (and cannot) hide the existence of the transaction (website visit) altogether

# Tor: Building a Circuit (I)

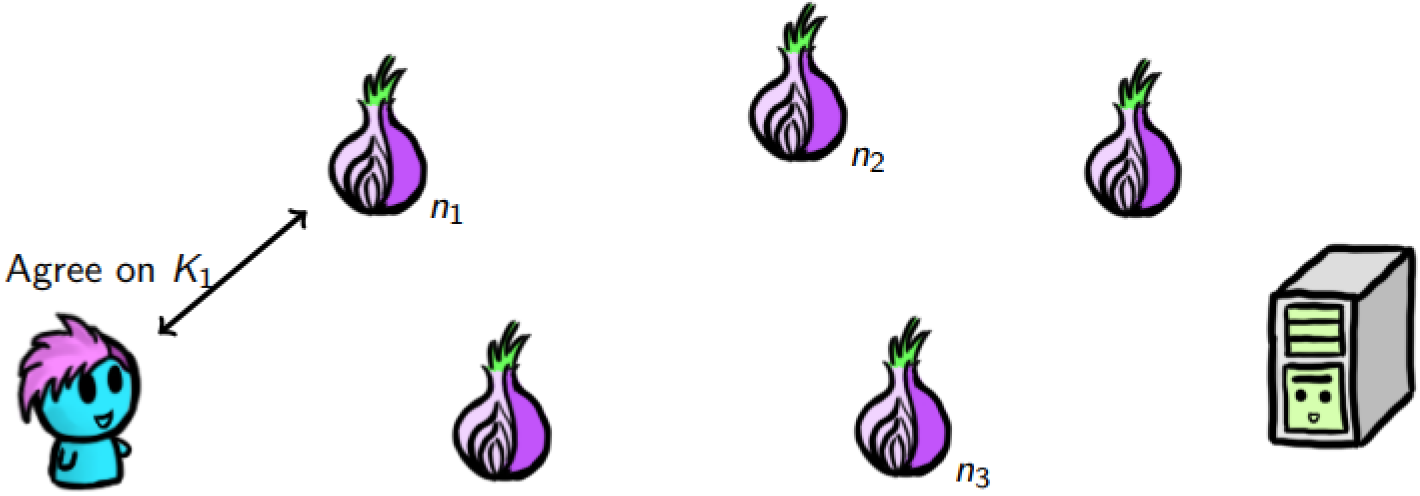
**Goal:** Alice wants to connect to a server without revealing her IP address




Alice has a global view of available Onion Routers (and their verification keys!)

# Tor: Building a Circuit (II)

Alice picks Tor nodes ($n_1$) and uses PKC to establish an encrypted communication channel to it (much like TLS)



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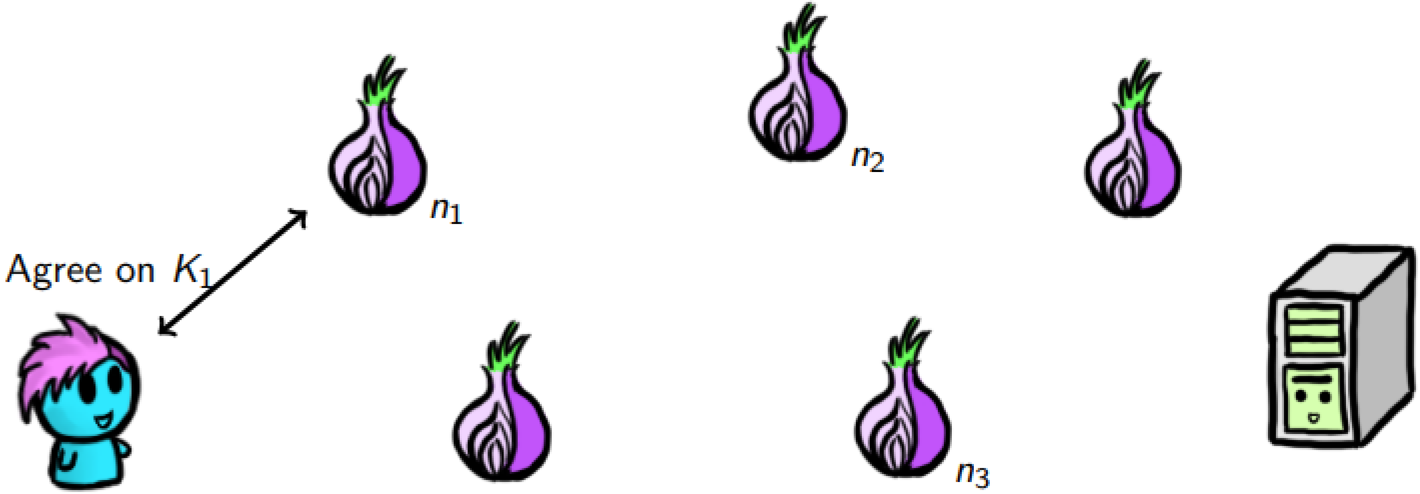
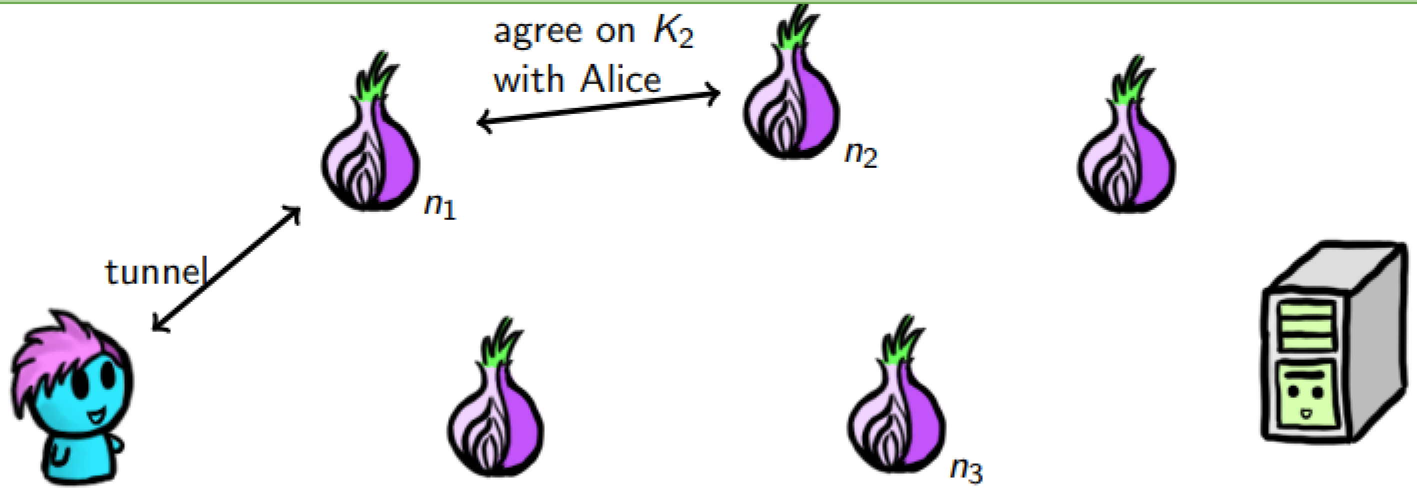



The result is a secret key $K_1$ shared by Alice and $n_1$

# Tor: Building a Circuit (III)

Alice tells $n_1$ to contact a second node ($n_2$), and establishes a new encrypted comm.channel to $n_2$, tunneled within the previous one to $n_1$



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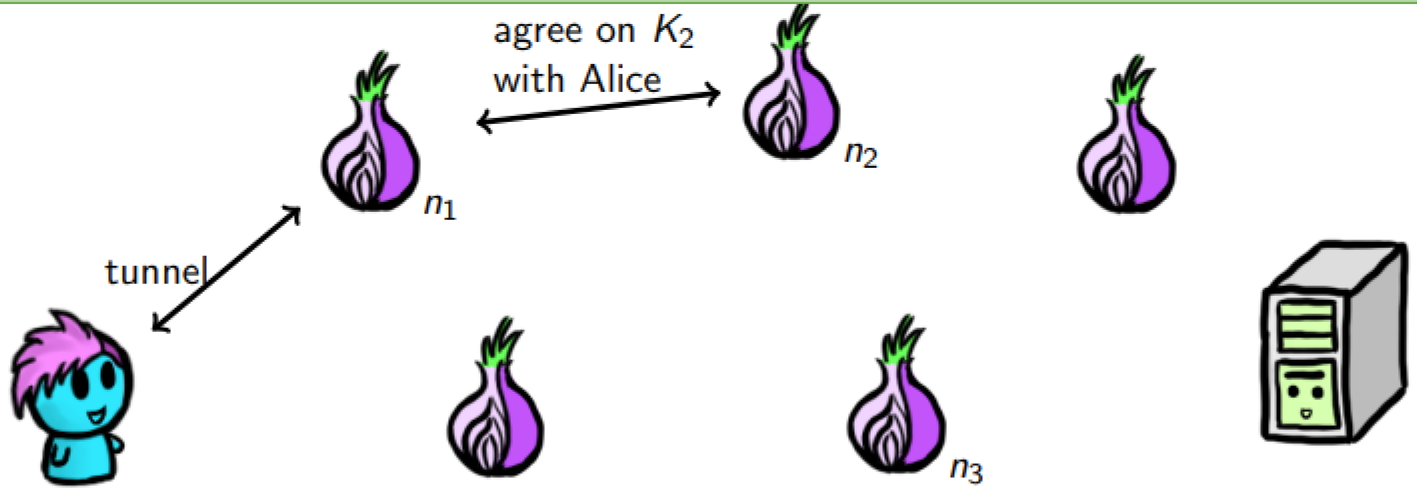
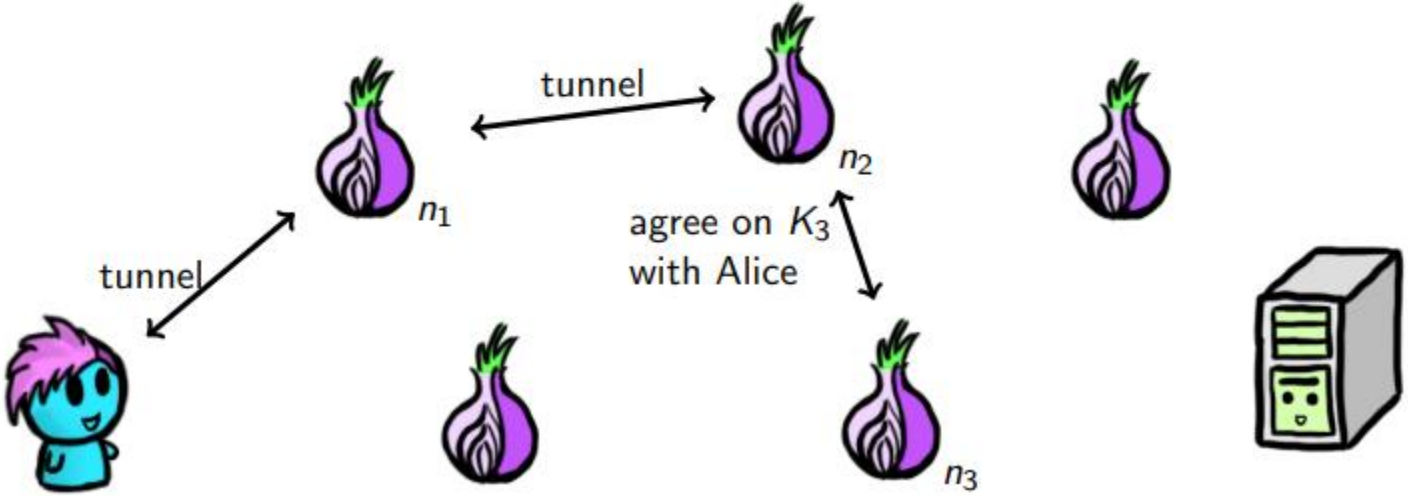



The result is a DH secret key $K_2$ shared between Alice and $n_2$, which is unknown to $n_1$

# Tor: Building a Circuit (IV)

Alice tells $n_2$ to contact a third node ($n_3$), establishes a new encrypted communication channel to $n_3$, tunneled within the previous one to $n_2$



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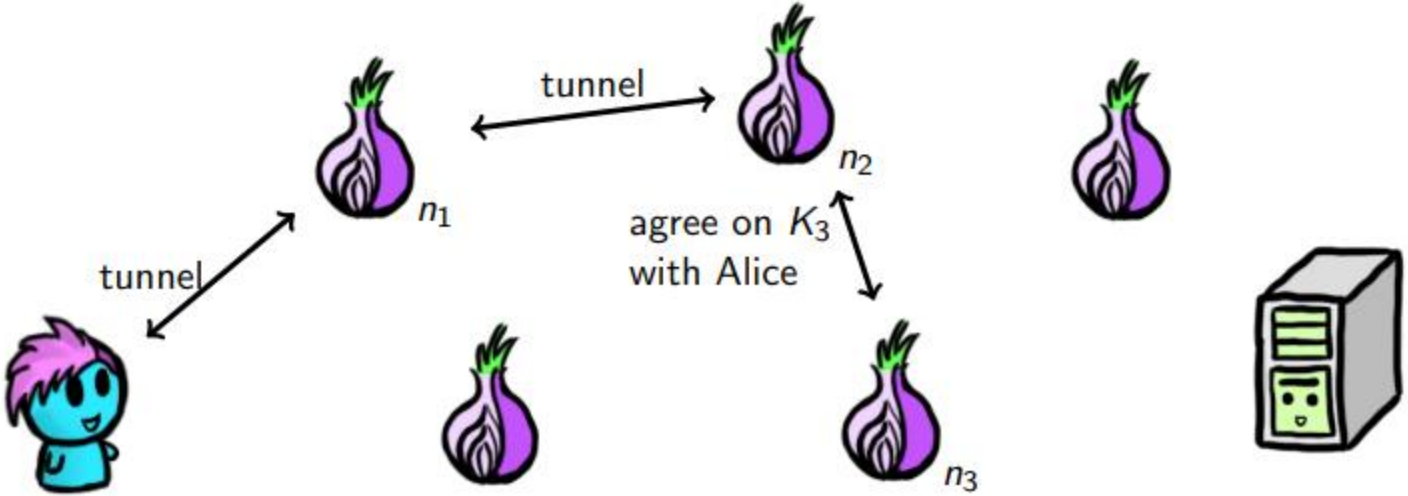


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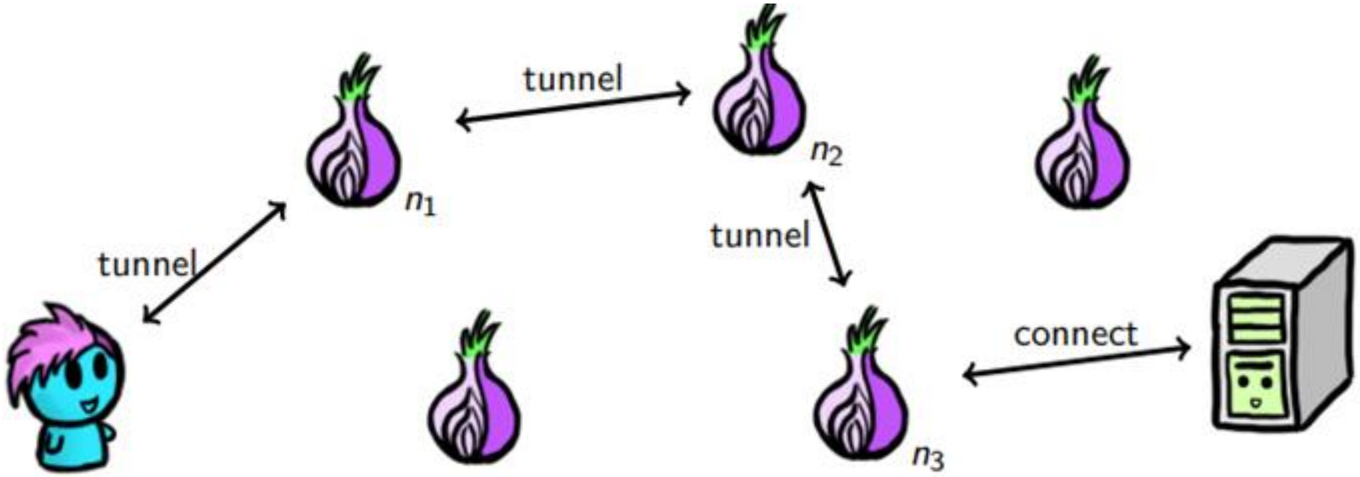
# Tor: Building a Circuit (V)

... And so on, for as many steps as she likes (usually 3) ...



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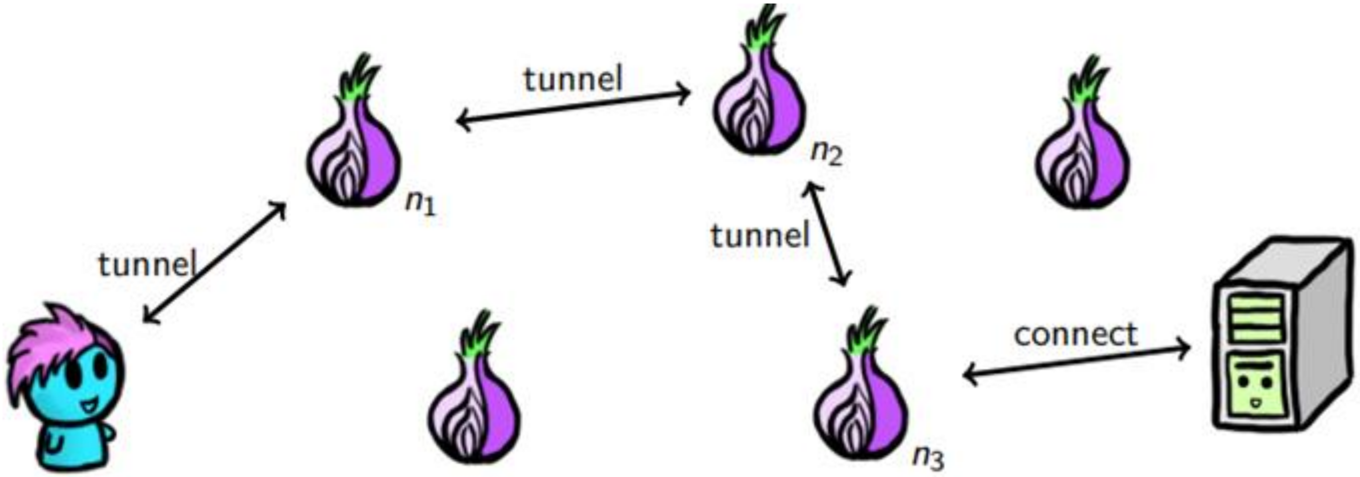
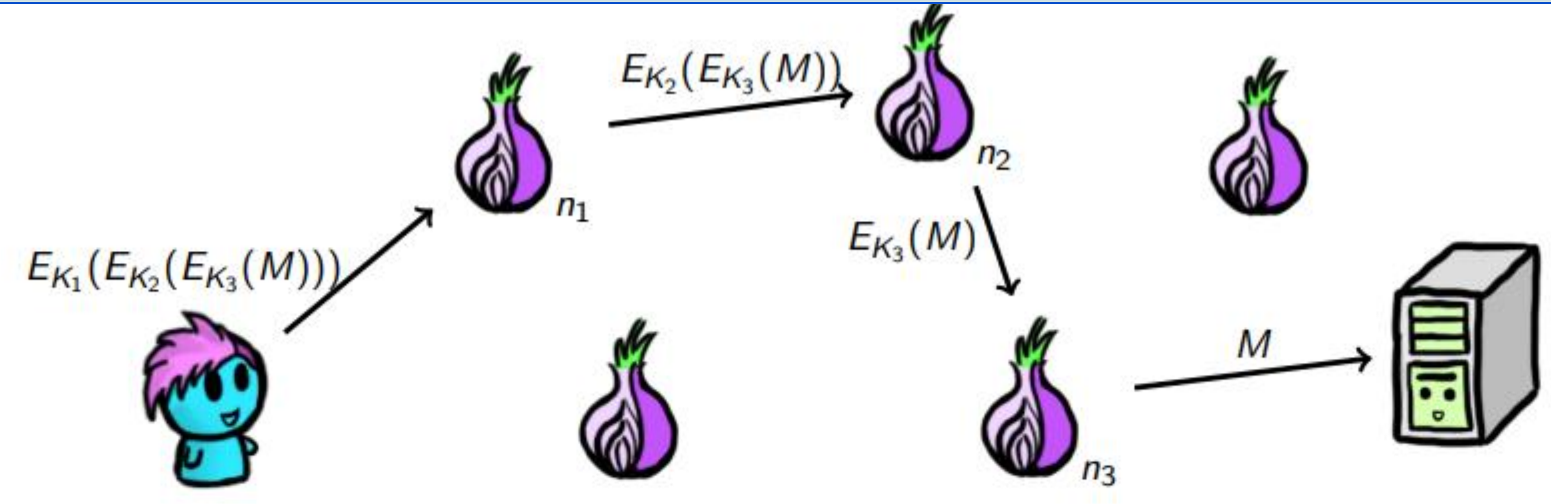



Alice tells the last node (within the layers of tunnels) to connect to the website

# Sending Messages with Tor

Alice encrypts her message “like an onion”; each node peels a layer off and forwards it to the next step



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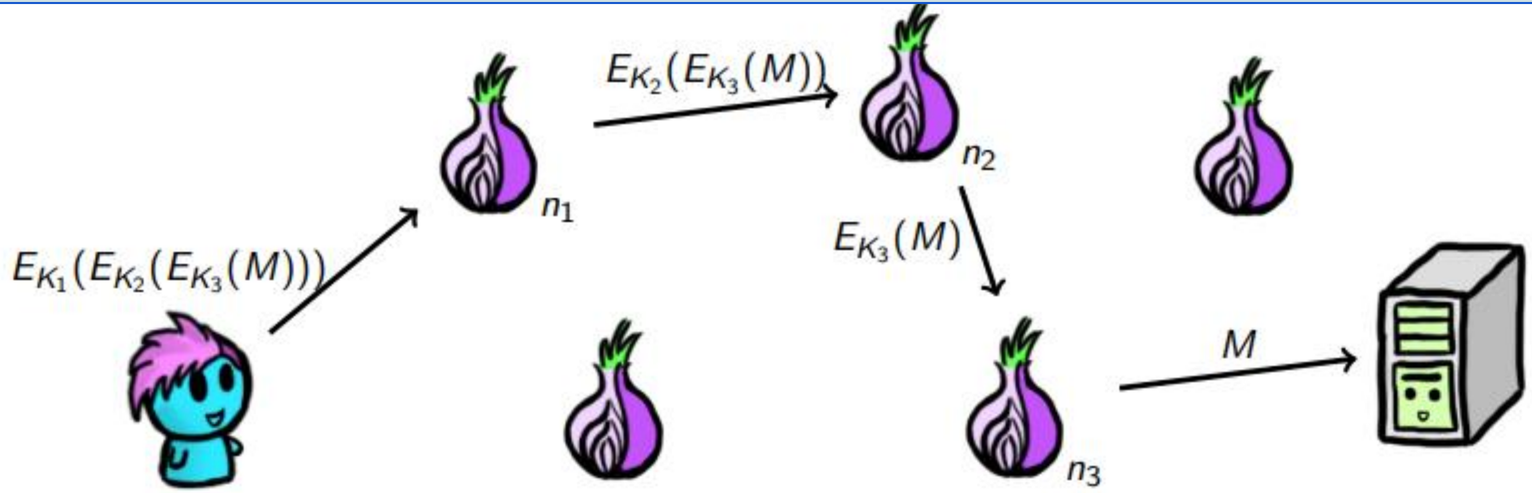
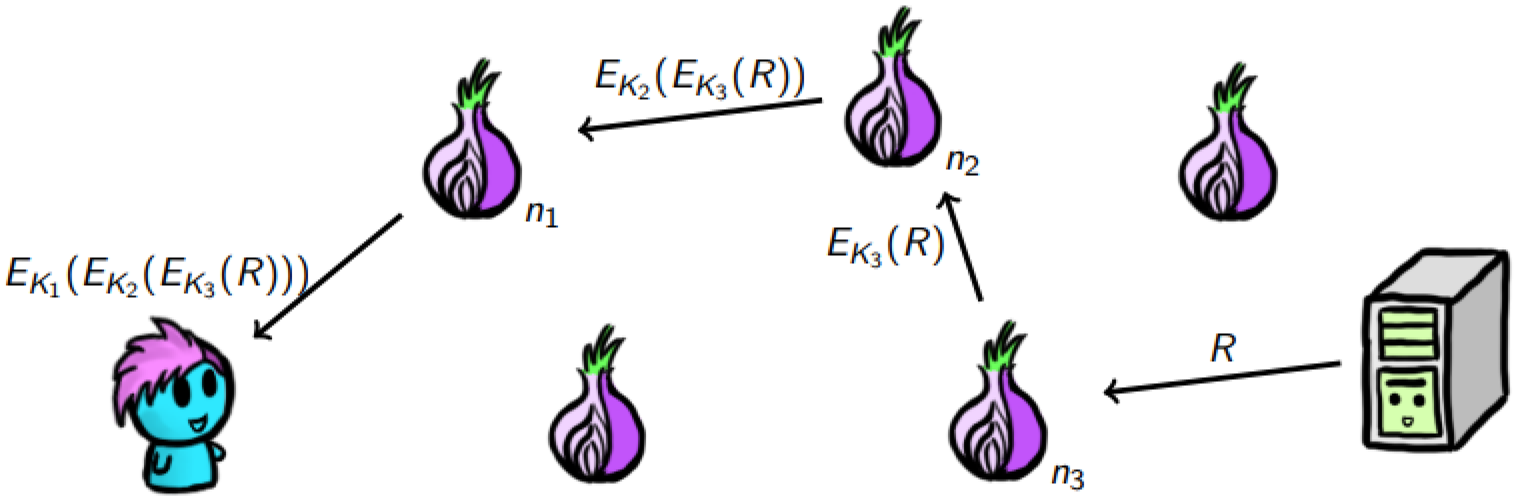



If connecting to a web server, M is encrypted (e.g., TLS)

# Replies in Tor

The server replies with R, sending it back to $n_3$. The nodes encrypt the message back and Alice decrypts all the layers.



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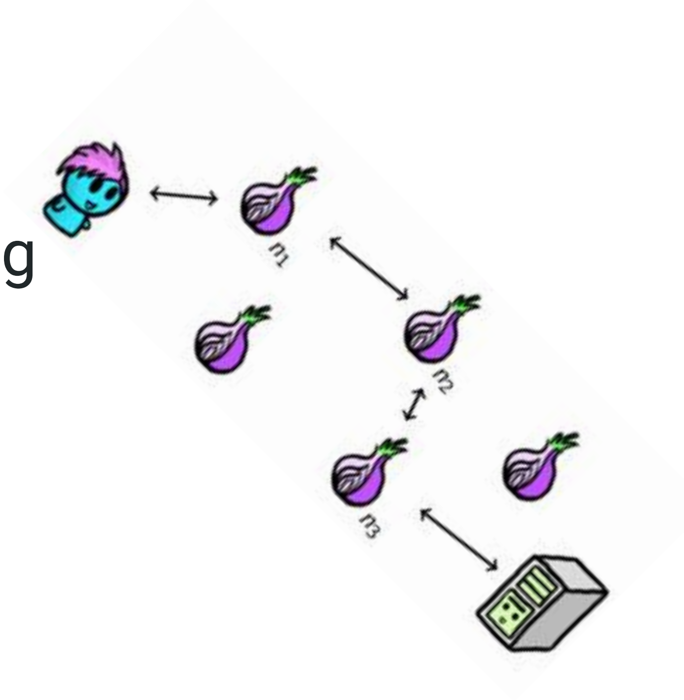

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- Node $n_1$ knows that Alice is using Tor, and that her next node is $n_2$, but does not know which website Alice is visiting
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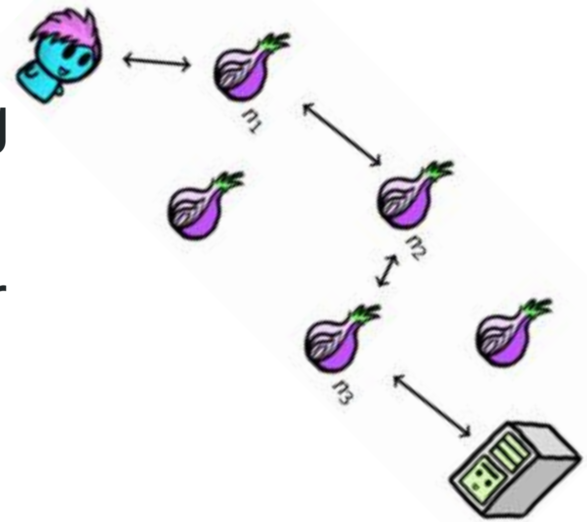

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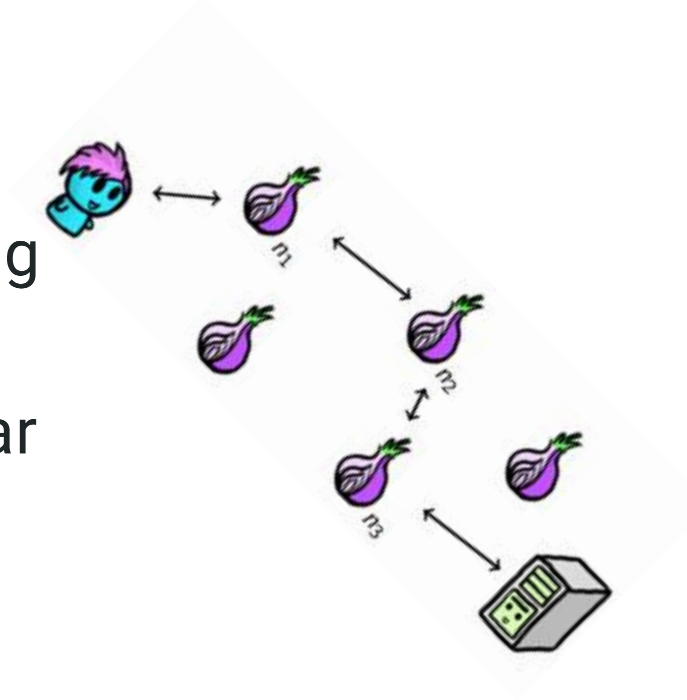
- The website itself only knows that it got a connection from Tor node $n_3$



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**A:** Tor does not protect against a global passive adversary. The adversary could de-anonymize Alice.

# Answer some more...

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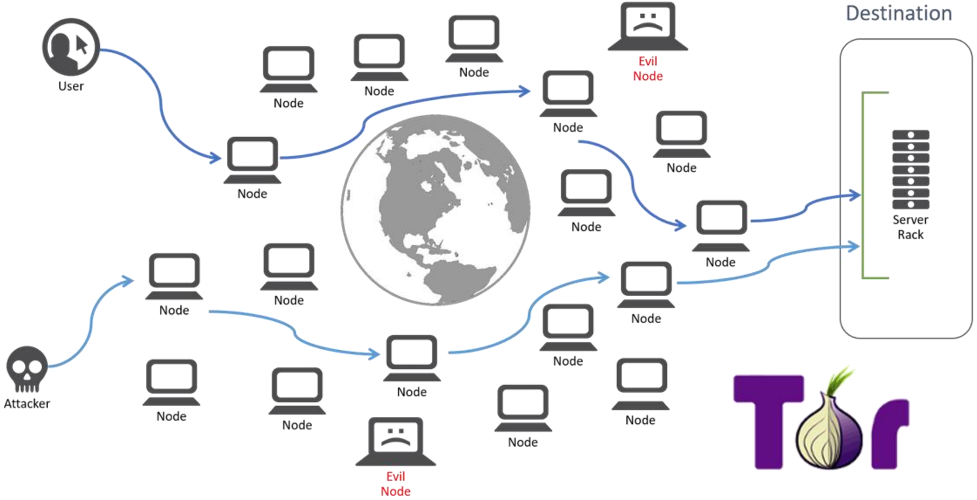
**A:** Traffic correlation attacks can easily de-anonymize Alice

# Last One…For Now

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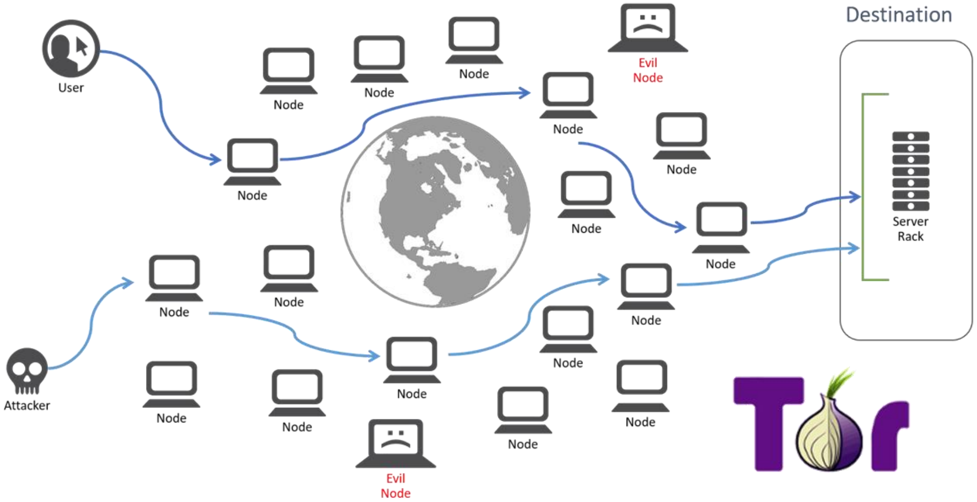



**Q:** : Why do we usually pick 3 nodes?

**A:** It’s a sweet spot between privacy and latency. More nodes usually do not provide more anonymity.

# Path Selection

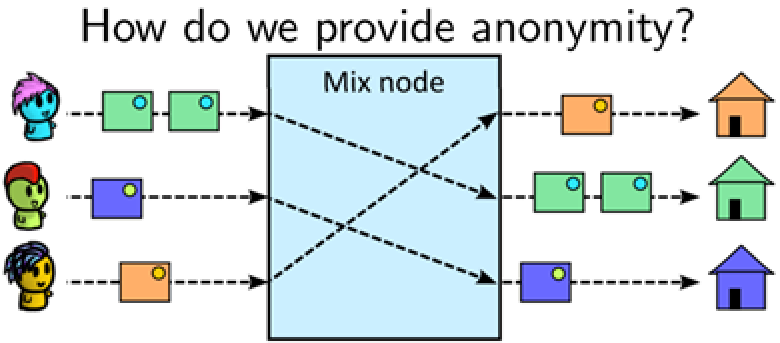
- We want to avoid a global passive adversary: choose nodes in different ISPs/countries
- How concentrated is the geographical distribution of Tor relays?

# Path Selection

- Path selection algorithms can help
  - With anonymity: by picking nodes that are in different countries/ISPs
  - With performance: latency is affected by this
- Don’t forget that countries can collaborate as well
- We cannot use defenses that work in mixes (due to delay); those are called high-latency anonymous communication systems for a reason!
  - Mix-nodes focus on mixing and anonymizing traffic, making it more difficult to trace the source of the data.

# Mixes

# Mixes: Basic Operations



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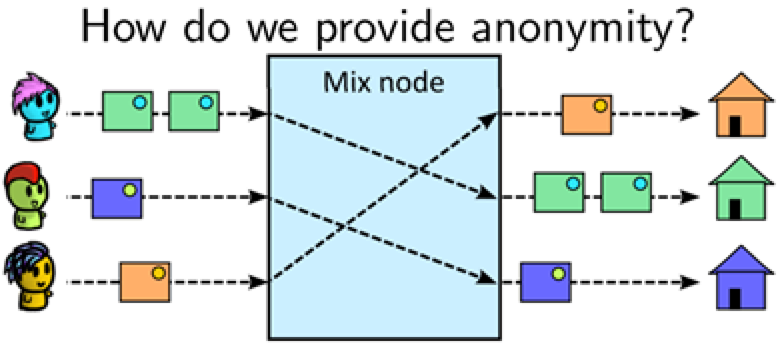


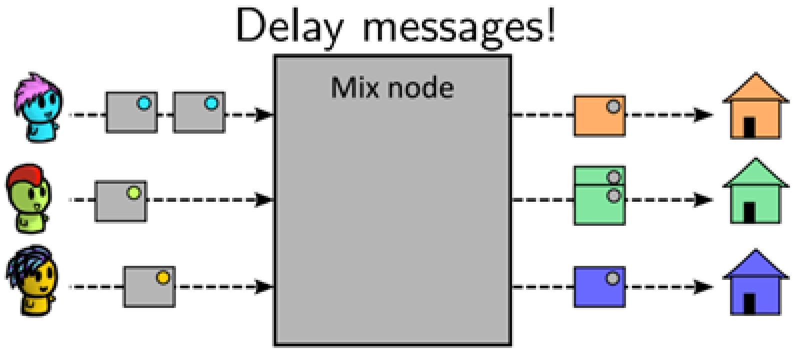

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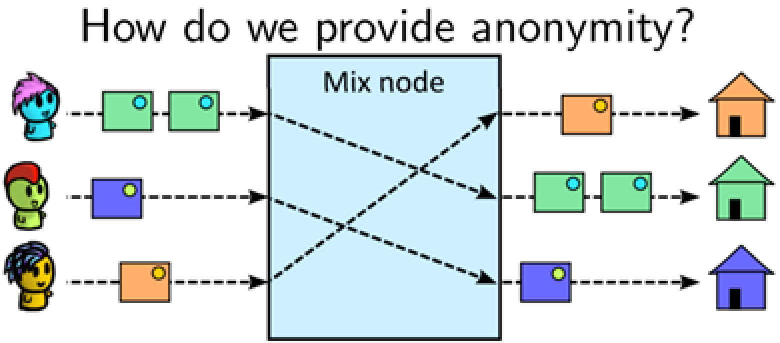


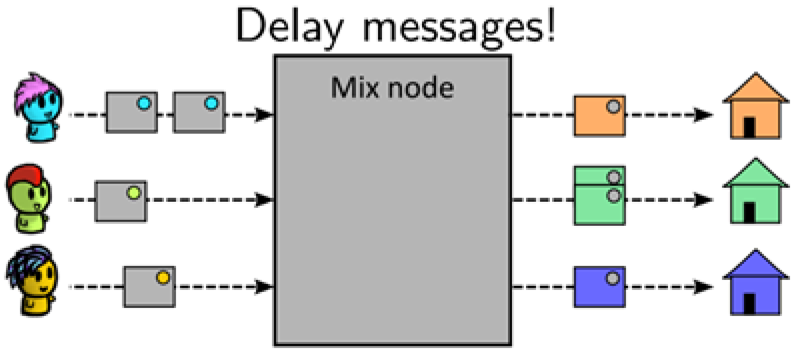


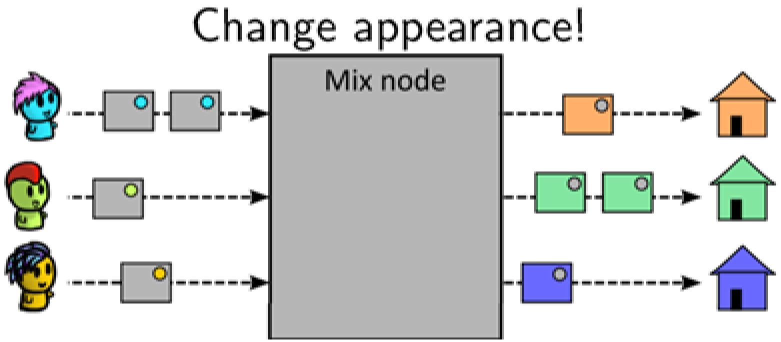


(e.g., changing headers or adding dummy data)

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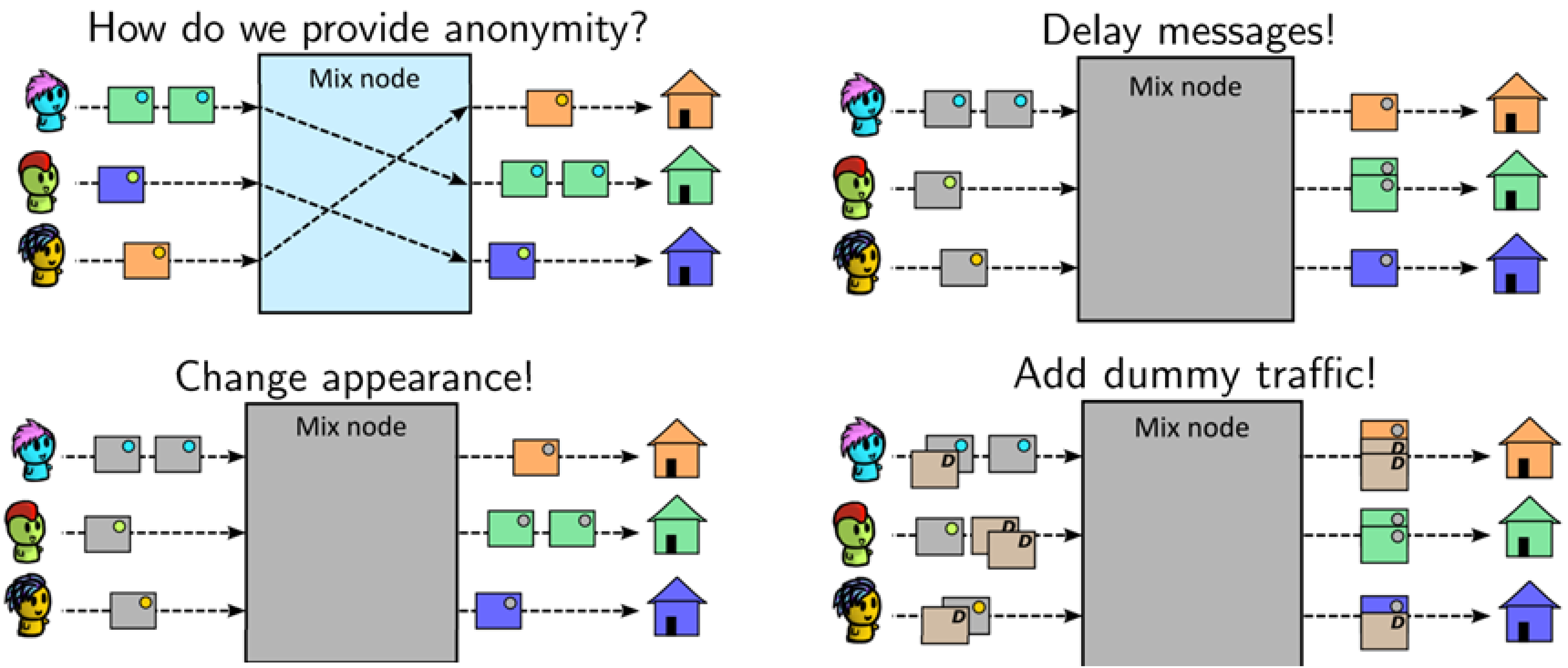
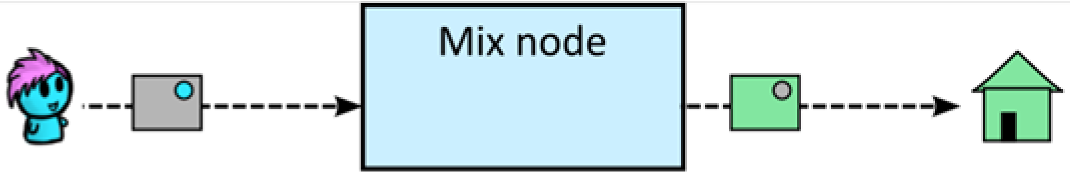


# Operation 1: Changing Appearance

**Q:** How can we achieve this? (clue: we have some crypto tools!)



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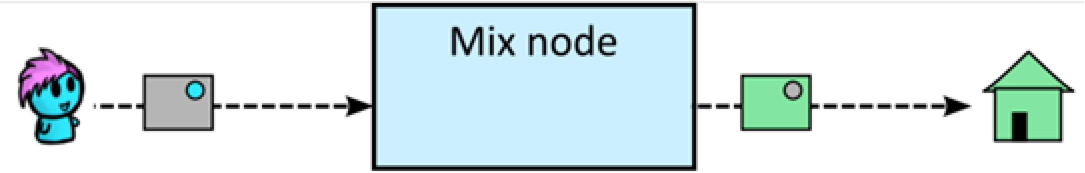
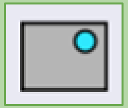
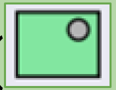
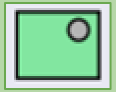



**A:** We can encrypt the output message with the Mix's key

 $= E_{K\_mix}($  $)$

 $= E_{K\_Bob}(m)$

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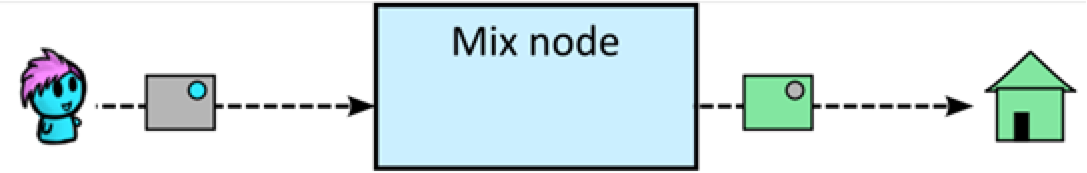


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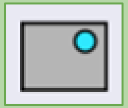
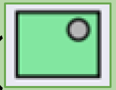
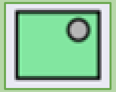
 $= E_{K\_mix}($  $)$

 $= E_{K\_Bob}(m)$

This "layered encryption" concept is called onion routing, and we saw it earlier in Tor.

# Operation 2: Delaying Messages

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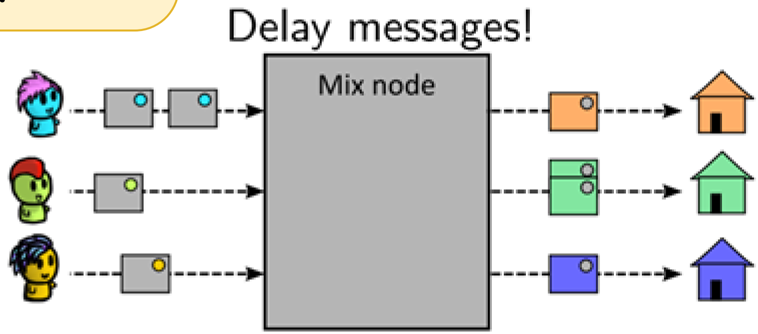
- Do we add a random delay to each message?
- Do we add a deterministic delay to each message?
- Do we add a constant delay to each message?



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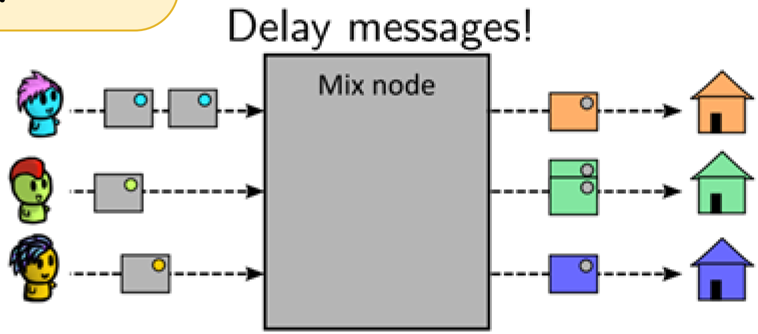
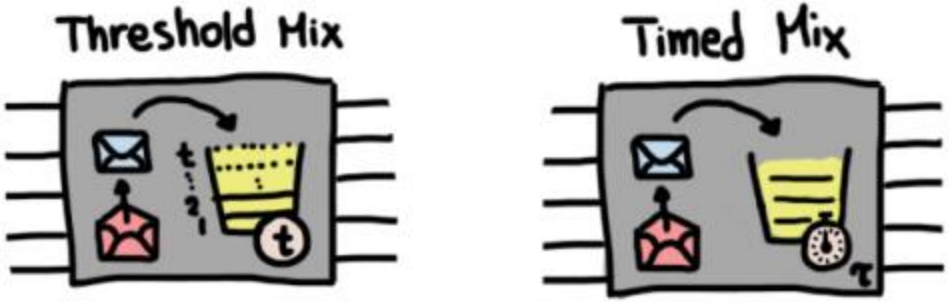



Deterministic delay: it's not constant, it depends on the arrival time and/or other messages. We will see some examples next!

# Threshold and Timed Mixes

- Some popular mixes types are threshold and timed mixes.
- These mixes gather messages until a **flushing condition** triggers.
- When this condition happens, this marks the end of a **round**
  - Threshold mix: it gathers $t$ messages, then it flushes them.
  - Timed mix: it gathers messages until a timer set to $\tau$ seconds expires, then it flushes them.

# Threshold and Timed Mixes

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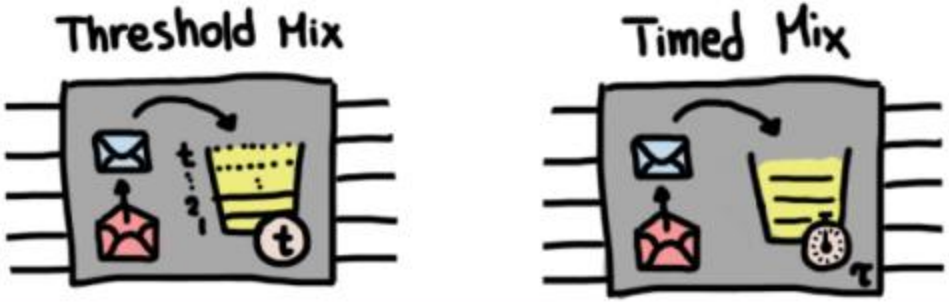
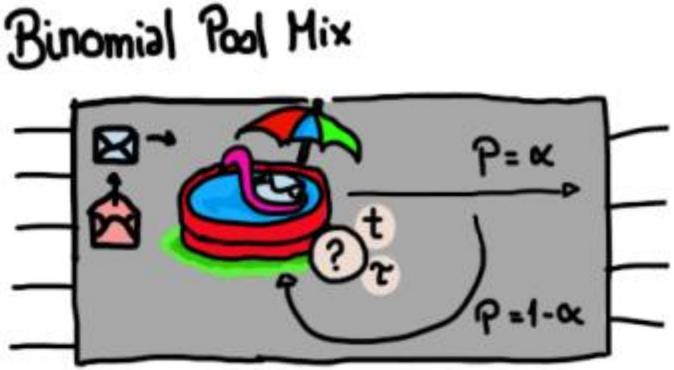


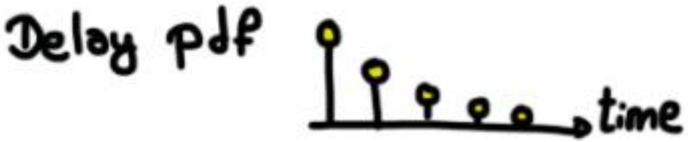

**Q:** Which of the two is better?

**A:** It depends... the threshold mix ensures a certain mixing size, the timed mix ensures a maximum message delay.

# Pool Mixes

- When a (threshold/timed) mix keeps some messages inside after a round ends, it is called a **pool mix.**
- The **binomial** pool mix keeps each message inside with probability α



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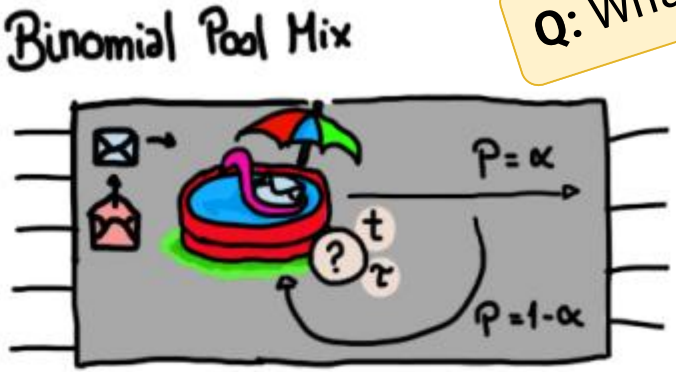
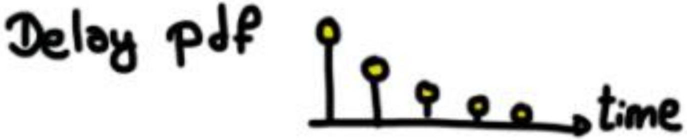
**Q:** What are the pros and cons of this?



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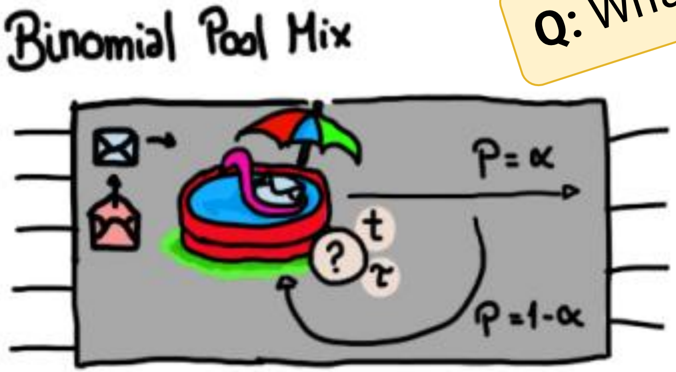




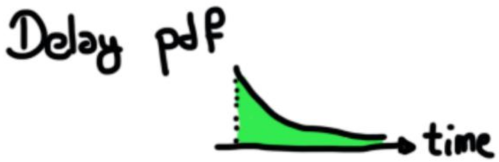
**Q:** What are the pros and cons of this?

**A: Pros**, more anonymity

**A: Cons**, more delay

# Continuous-time or Stop-and-Go (SG) Mixes

- Some mixes do not work on “batches” or “rounds”, and instead delay each message independently: these are called continuous-time mixes or Stop-and-Go (SG) mixes.
- Mixes that delay messages following an exponential distribution are very popular (Loopix, nym).
- The user can choose the delay and include it in the message

# Mixnets

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**Q:** Why?

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- We can chain mixes to create a mixnet.
- Mixnets have different topologies, depending on which nodes a message can travel between.

# Mixnet Topologies

Let's discuss pros and cons of each topology!


**One after another**

- Pros: Increased Anonymity, Robustness, Reduced Correlation Risks, Scalability, Layered Security
- Cons: Latency, Complexity, Resource Intensive, Single Point of Failure

# Mixnet Topologies

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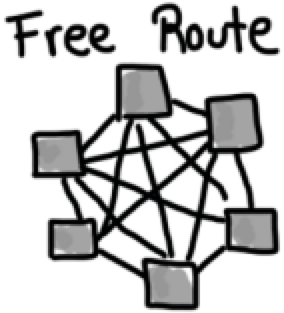
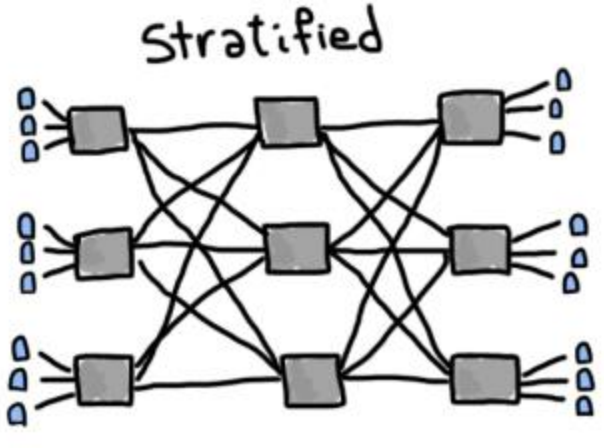



**All of them are connected**

- Pros: Increased Anonymity, Resilience to Node Compromise, Reduced Latency, Load Balancing
- Cons: Complexity, Resource Intensive, Vulnerability to Certain Attacks (e.g., If an adversary controls multiple nodes), Difficulty in Implementing Security

# Mixnet Topologies

Let's discuss pros and cons of each topology!




**Each layer is fully connected to the next layer**

- Pros: Enhanced Anonymity, Granular Control, Resilience, Traffic Management
- Cons: Complexity, Dependency on Layer Integrity(e.g., if one layer is compromised, it could jeopardize the entire system)

# Operation 3: Dummy Messages

**Q:** Where do we add dummy traffic?

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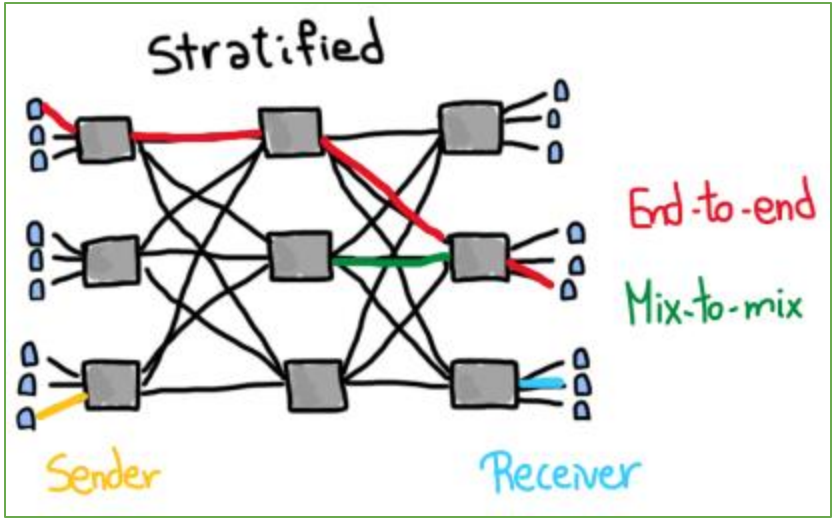
**Q:** Where do we add dummy traffic?

**A:** Anywhere, everywhere!



# Recap 1

**Q:** What are the three basic operations of a mix node to provide anonymity? Why is each operation important?

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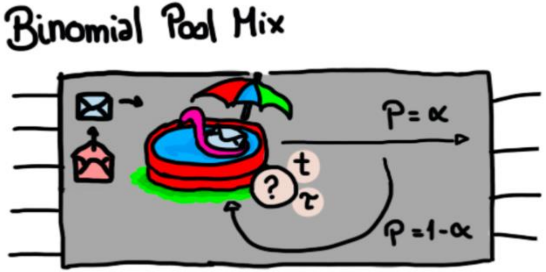


**Q:** Binomial pool mix: pros and cons of increasing the probability of forwarding a message α?

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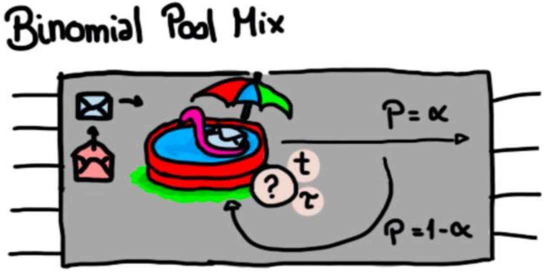
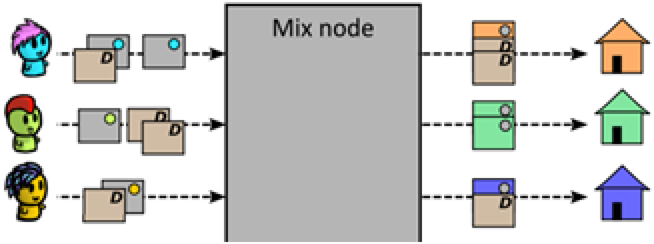



**A:** Increasing α decreases anonymity and delay

# Recap 2

**Q:** Dummy traffic: pros and cons of increasing the amount of dummy messages?



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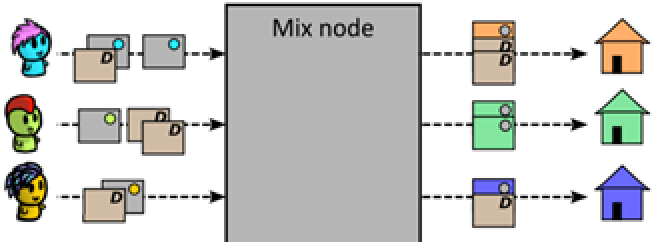


**A:** More dummies require more bandwidth, but increase anonymity

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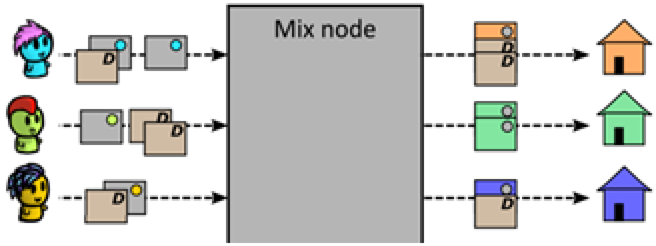
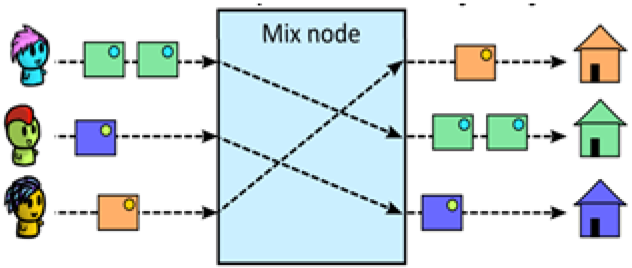



**A:** More dummies require more bandwidth, but increase anonymity

**Q:** What happens if the number of senders increases?



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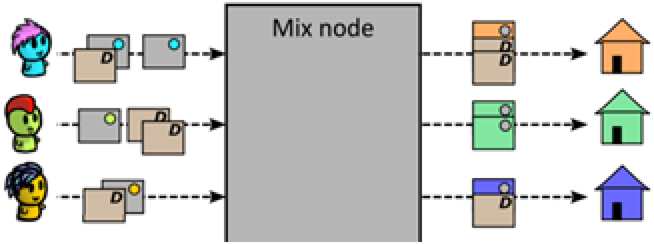


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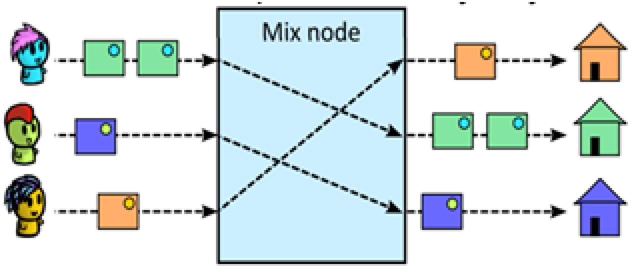



**A:** Depends on the actual mix/setting, but usually *anonymity loves company.* More people using the system usually improves its anonymity level.

# Anonymity Trade-Offs

Anonymity has a cost. We can increase anonymity by:

- Adding more message delay
  - It has to be added “cleverly” (e.g., a constant delay does not work)
- Adding more dummy traffic
  - It has to be added “cleverly” (e.g., simulating real sending behavior)
- When the number of users increases
  - Effectiveness depends on the type of mix, the mix topology, etc.

# Remailers, A Brief History

# Remailers: Very Simple Type 0, (1993–1996)

The best known being anon.penet.fi.

- Send email to anon.penet.fi
- It is forwarded to your intended recipient
- “From” address is changed to anon43567@anon.penet.fi
  - (but your original address is stored in a table)
- Replies to the anon address get mapped back to your real address and delivered to you
- ≈ 10 000 emails per day (≈ 700 000 users)

# Anon.penet.fi, works as long as…

- No one's ‘ … o or from anon.pen…
- The opera… ardware), and the s… uncompr…
- The mapp… esses is kept secret

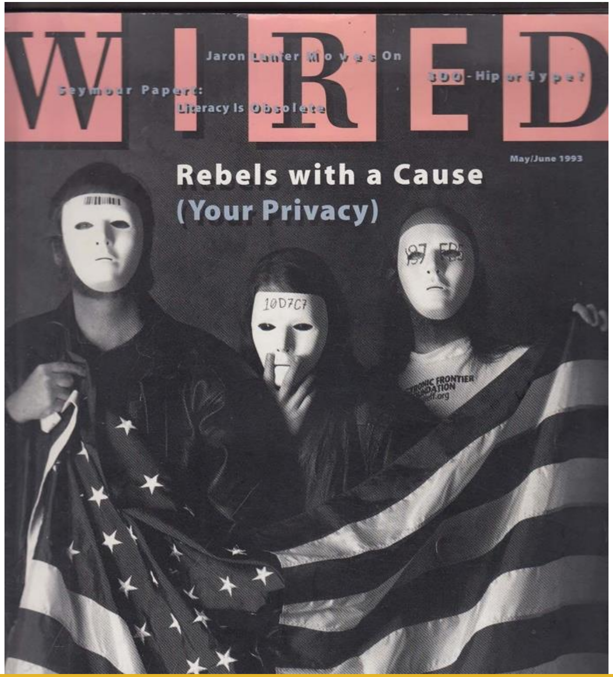

Unfortunately, a … rts of the list, and he shut down th… rotect it

# Type 1 Remailers

## Cypherpunk (type 1) removed the central point of trust

- Messages are now sent through a “chain” of several remailers, with dozens to choose from
- Each step in the chain is encrypted to avoid observers following the messages through the chain
- Remailers also delay and reorder messages

Support for pseudonymity* is dropped: no replies!



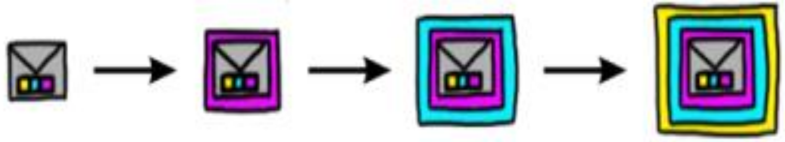

*An assumed name that conceals one's true identity

# Nym servers / Pseudonymous remailers

How to do replies? (i.e., recovering pseudonymity)

- “nym servers” mapped pseudonyms to “reply blocks” that contained a nested encrypted chain of type I remailers.
- Alice picks a list of nym servers

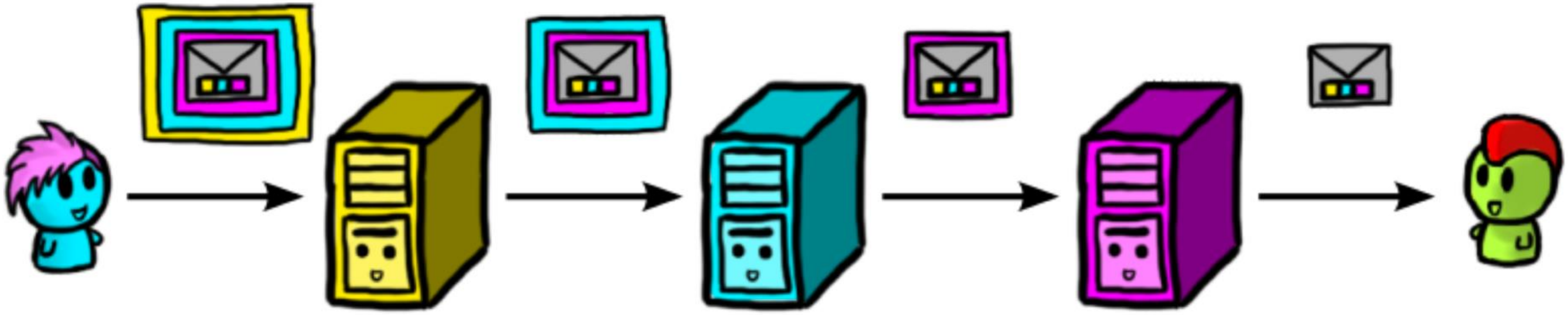
- Then, Alice builds her message using layered encryption
- The message contains a chain of reply blocks(+Alice pseudonymous address)



# Nym servers / Pseudonymous remailers

How to do replies? (i.e., recovering pseudonymity)

- The remailer forwards the message, but the sender's identity remains hidden. The reply block is included in the forwarded message.



- Bob replies by attaching his response to the end of the reply blocks
  - The reply is anonymized before being sent to the original sender

# Type II remailers

Mixmaster (type II) remailers appeared in the late 1990s

- Constant-length messages to avoid an observer watching “that big file” travel through the network
- Protections against replay attacks
- Improved message reordering

Requires a special email client to construct the message fragments

# Type III remailers

Mixminion (type III) remailer appears in the 2000s

- Native (and much improved) support for pseudonymity
  - No longer reliant on type I reply blocks
  - Instead, relies on mix networks
- Improved protection against replay and key compromise attacks

But it's not very well deployed or mature, i.e., "you shouldn't trust Mixminion with your anonymity yet"

# The Nym Network [Claudia Diaz, Harry Halpin, and Aggelos Kiayias (2021)]