

CS489/698

Privacy, Cryptography, Network and Data Security

Network Anonymity

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

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...
- Meta-data: any other information that is not data
 - When communication occurs
 - Who communicates
 - How often do they communicate
 - ...

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

Is this bad?

Very much so!

The U.S. government "kill[s] people based on metadata"

Former head of the National Security Agency, Gen. Michael Hayden

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

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

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?

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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.

Tor is?

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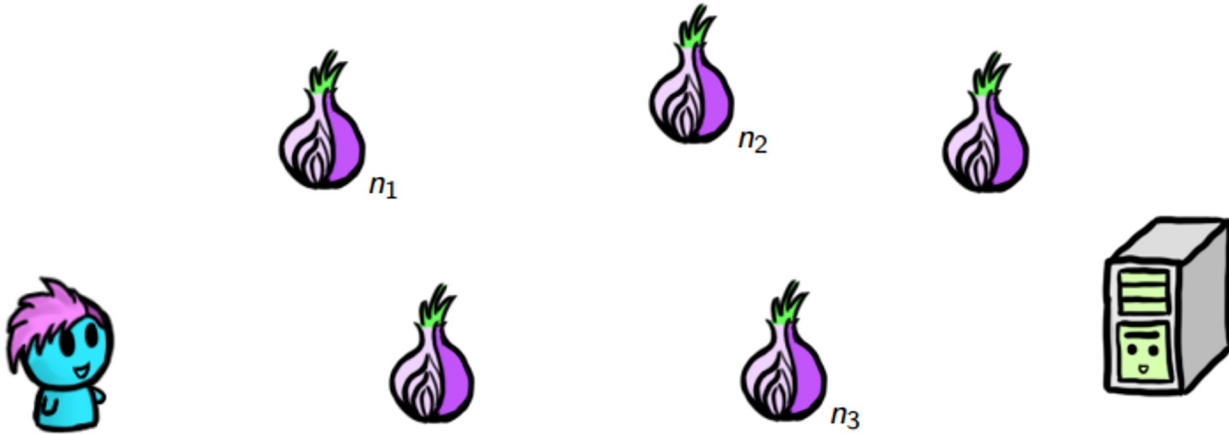


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Tor is not TOR!

Tor: Building a Circuit (I)

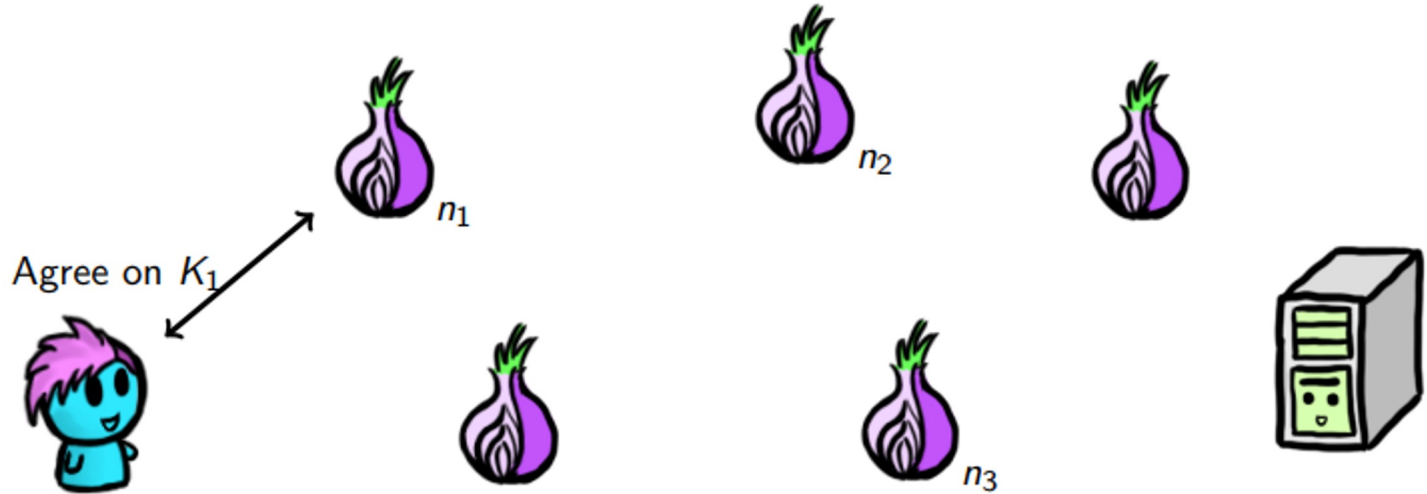
Goal: Alice wants to connect to a server without revealing her IP address



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

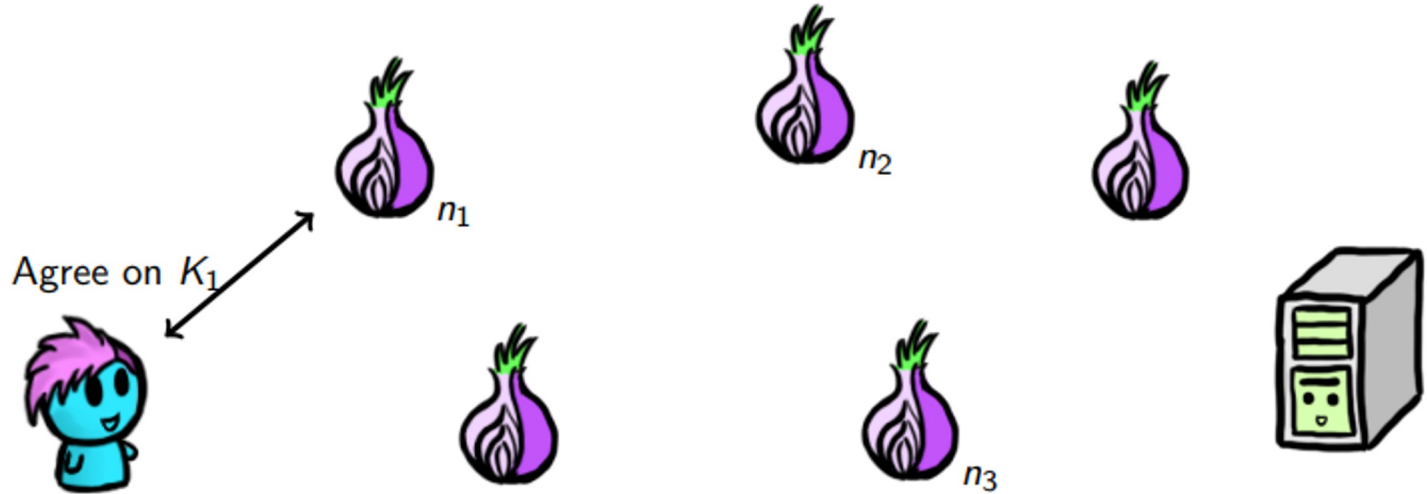
Tor: Building a Circuit (II)

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



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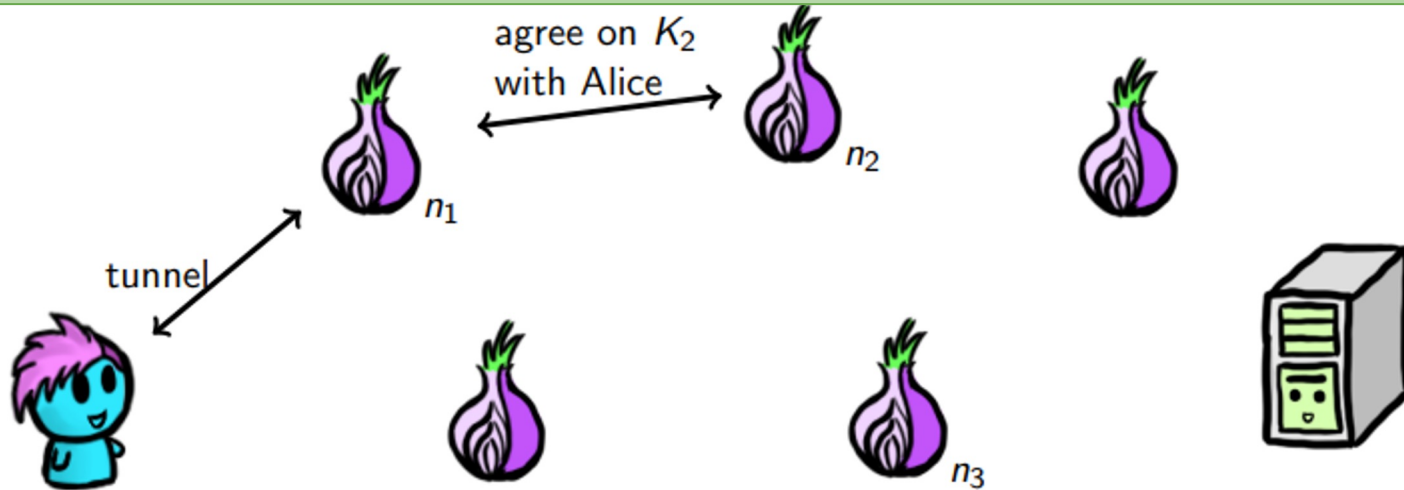
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The result is a secret key K_1 shared by Alice and n_1

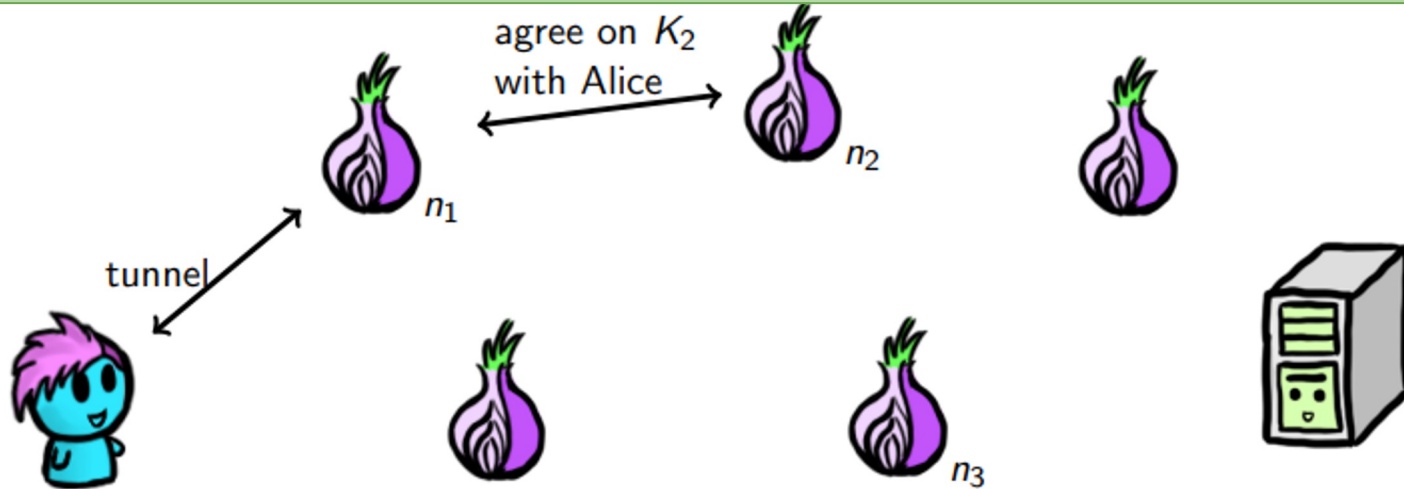
Tor: Building a Circuit (III)

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



Tor: Building a Circuit (III)

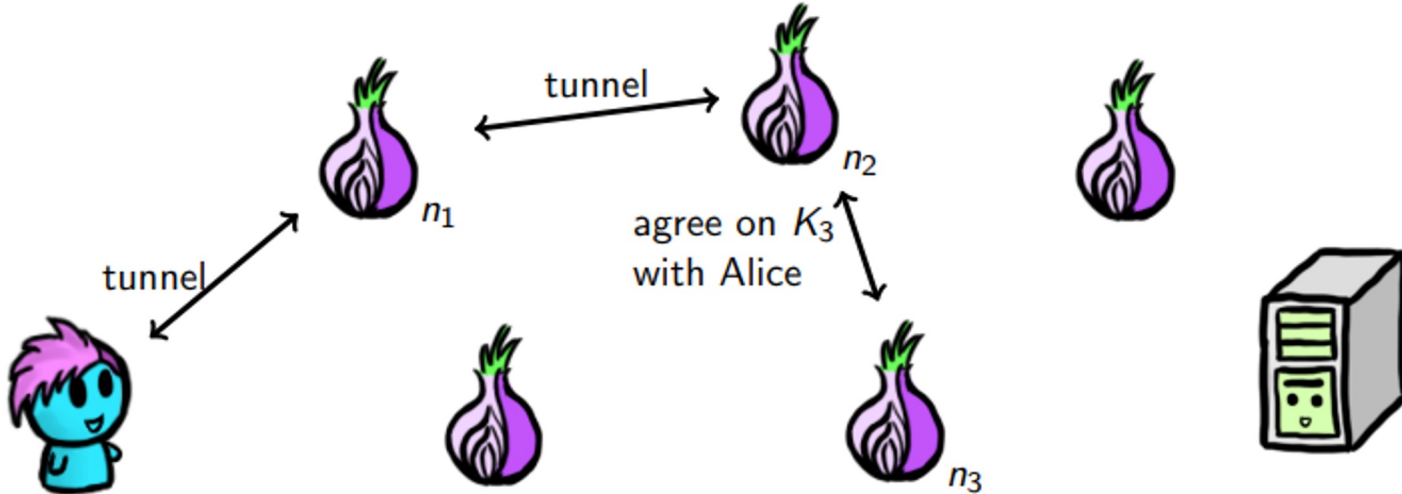
Alice tells n_1 to contact a second node (n_2), and establishes a new encrypted comm.channel to n_2 , tunneled within the previous one to n_1



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

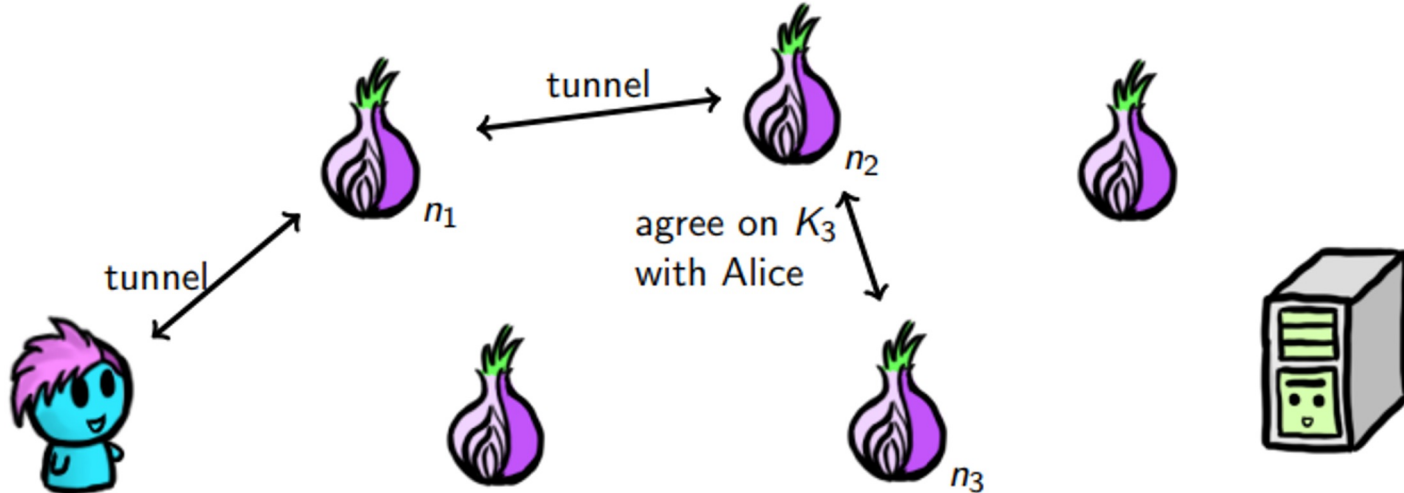
Tor: Building a Circuit (IV)

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



Tor: Building a Circuit (IV)

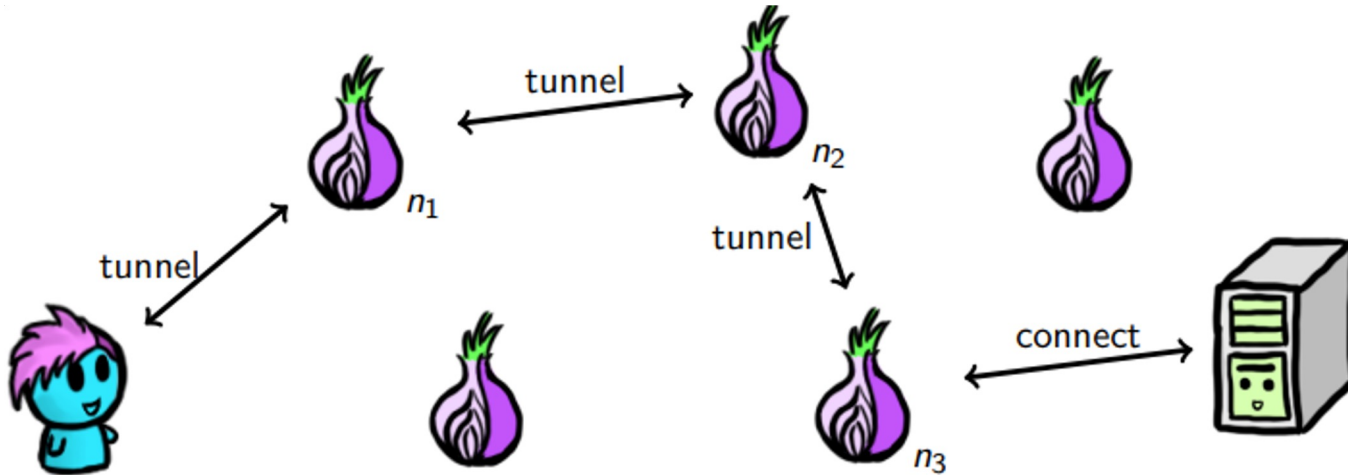
Alice tells n_2 to contact a third node (n_3), establishes a new encrypted communication channel to n_3 , tunneled within the previous one to n_2



The result is a secret key K_3 shared between Alice and n_3 , which is unknown to n_1 and n_2

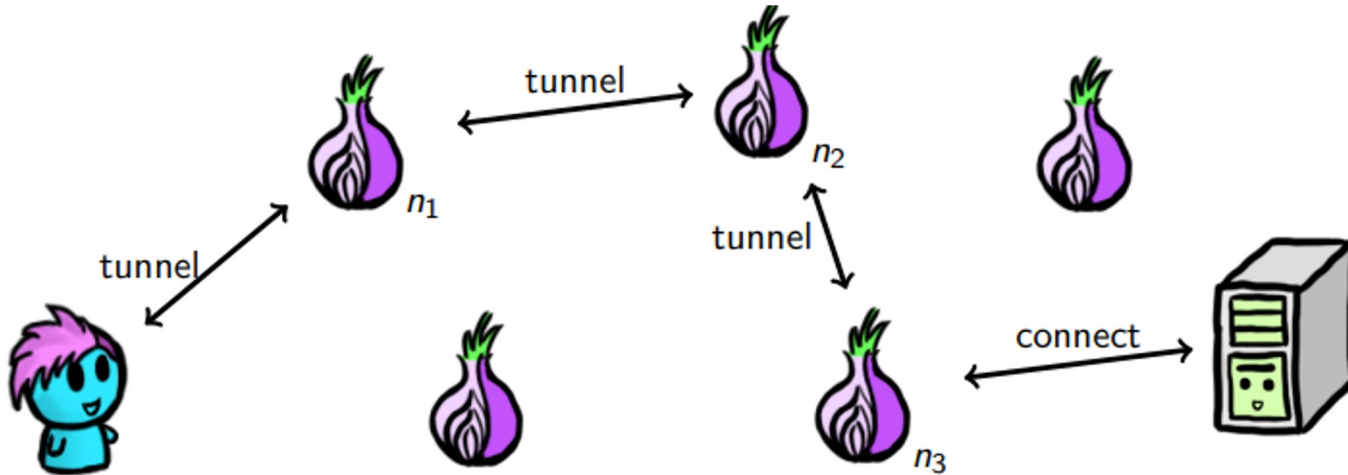
Tor: Building a Circuit (V)

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



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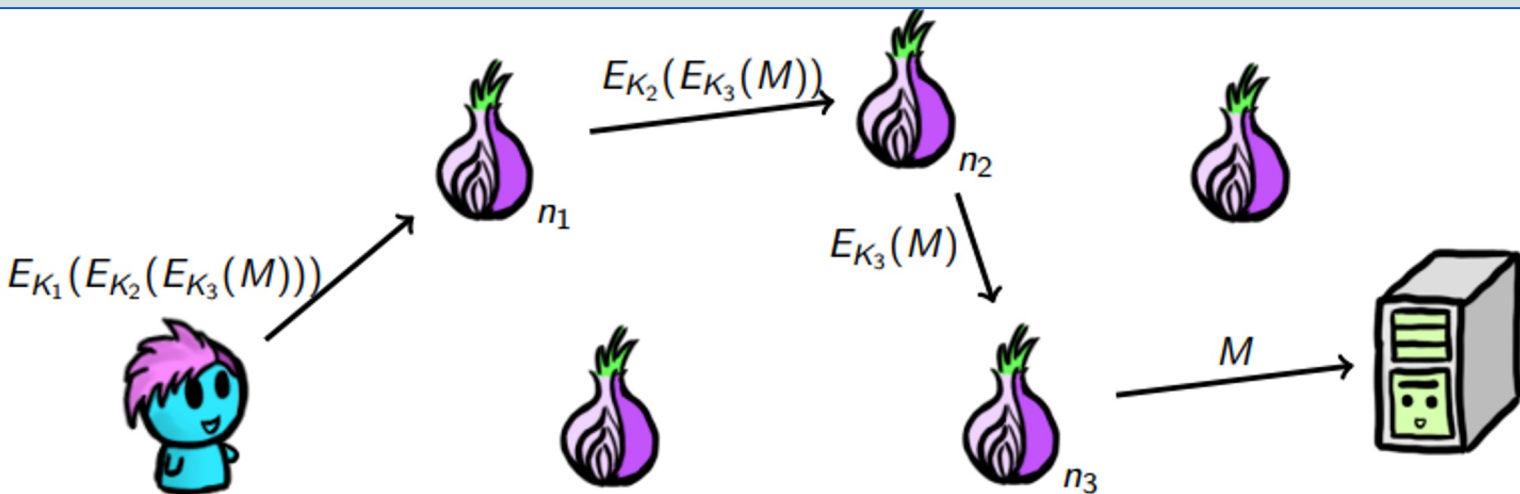
... And so on, for as many steps as she likes (usually 3) ...



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

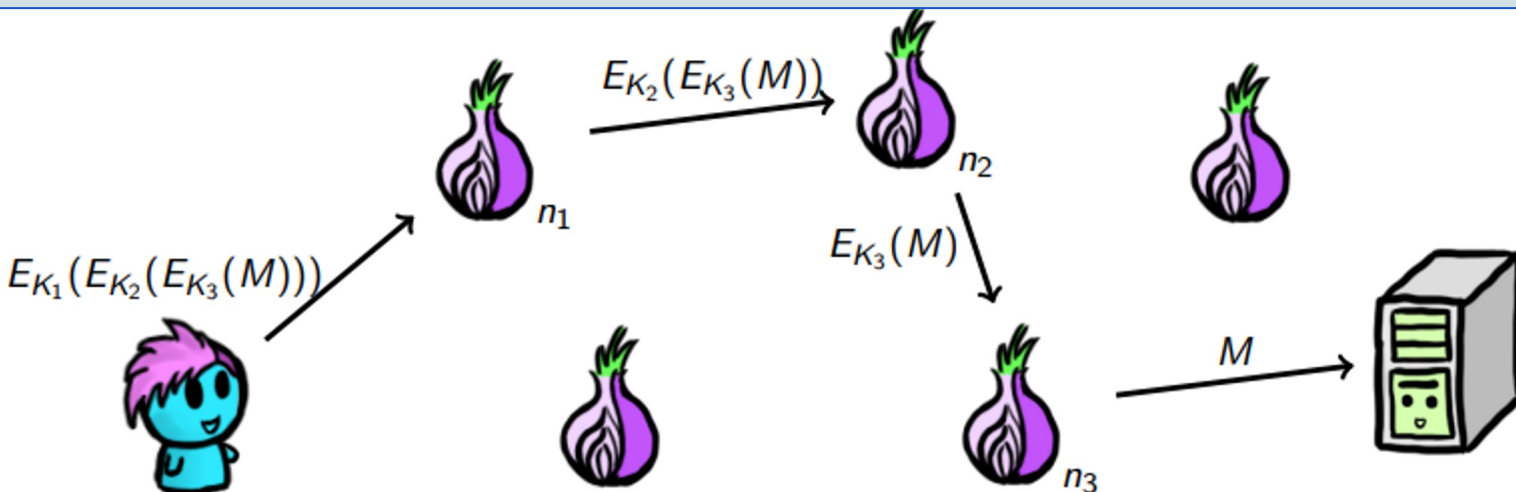
Sending Messages with Tor

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



Sending Messages with Tor

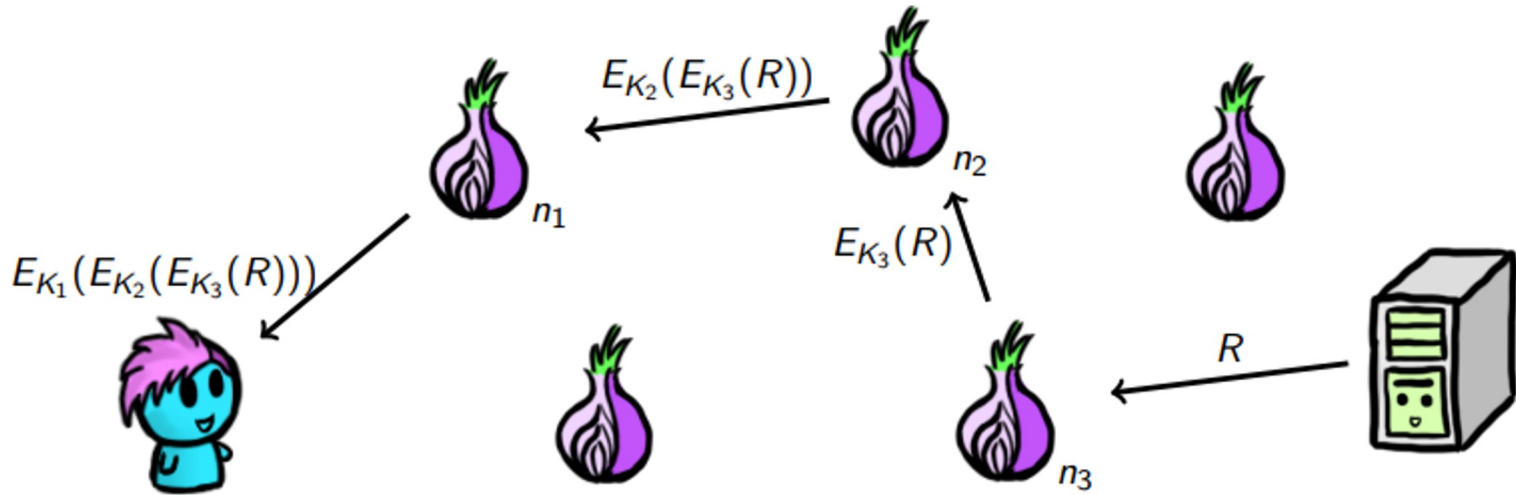
Alice encrypts her message “like an onion”; each node peels a layer off and forwards it to the next step



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

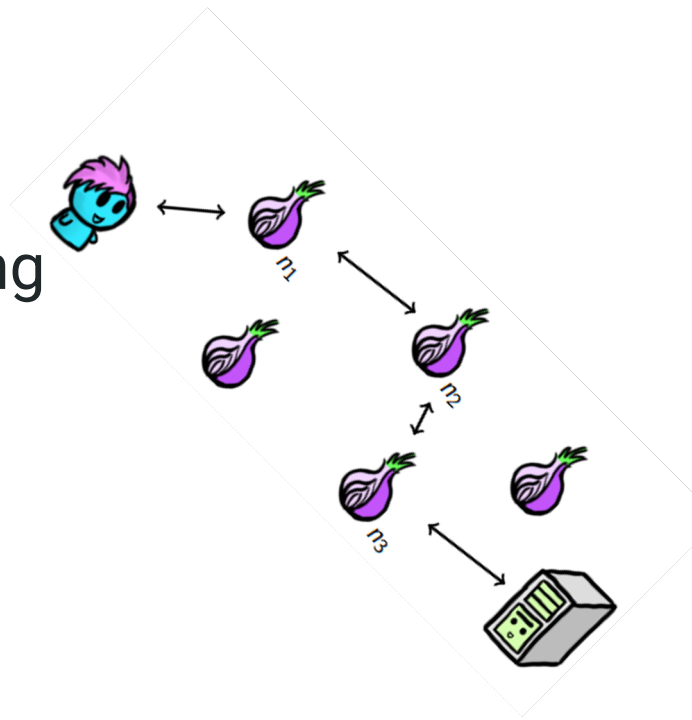
Replies in Tor

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



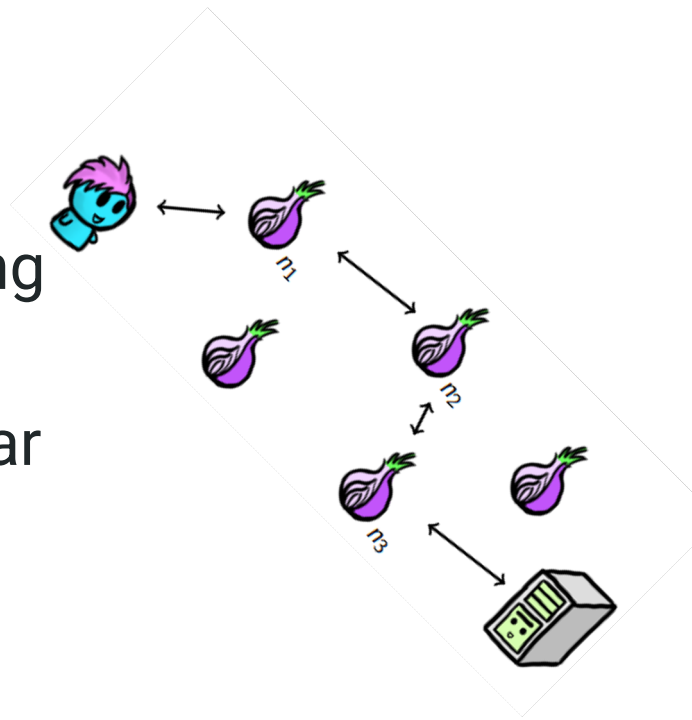
Who knows what?

- 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



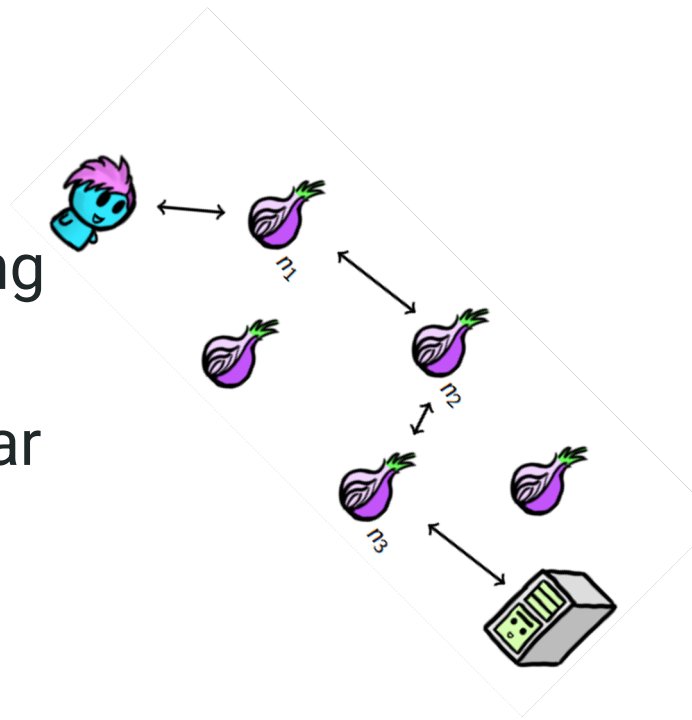
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- Node n_3 knows some Tor user (with previous node n_2) is visiting a particular website, but doesn't know who



Who knows what?

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- Node n_3 knows some Tor user (with previous node n_2) is visiting a particular website, but doesn't know who
- The website itself only knows that it got a connection from Tor node n_3



Answer this...

Q: Why must Alice choose all nodes, instead of letting each node pick the next one?

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Q: What happens if Eve can inspect all network links? (a global passive adversary)

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

Answer some more...

Q: What happens when Eve can inspect the incoming and outgoing traffic of a single node?

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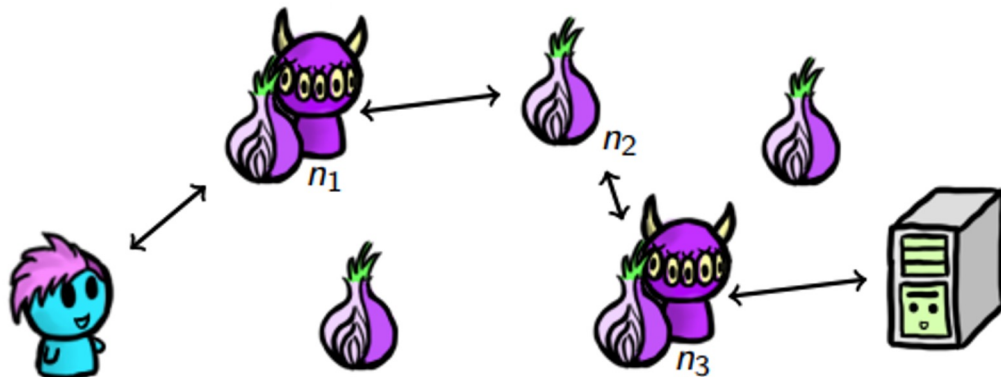
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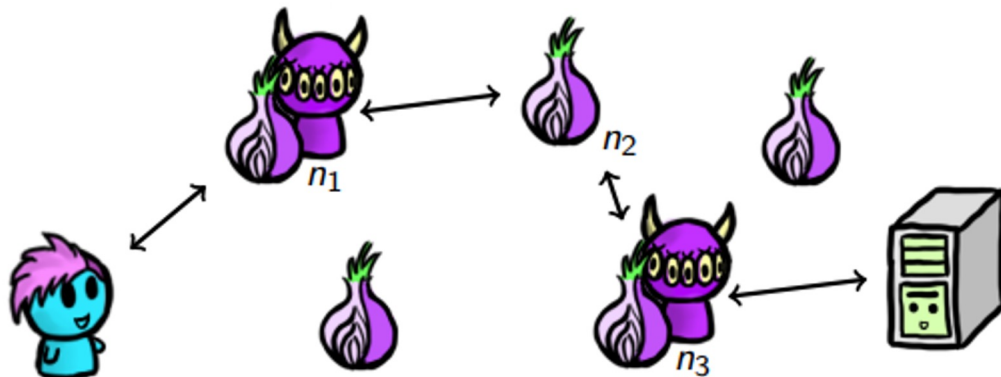
A: Traffic correlation attacks can easily de-anonymize Alice

Last One...For Now



Q: : Why do we usually pick 3 nodes?

Last One...For Now



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

What else can Tor do?

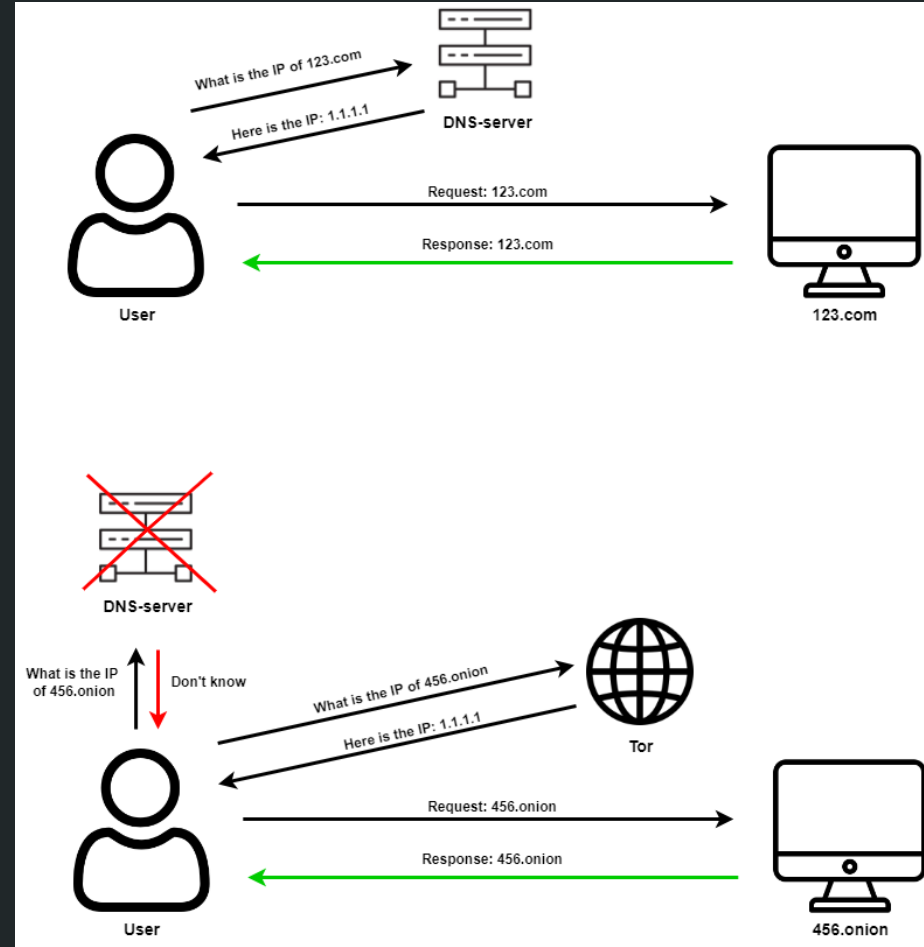
An image of an iceberg floating in the ocean. The tip of the iceberg is visible above the water surface, while a much larger, jagged mass of ice is submerged below the surface. A green rounded rectangular box is overlaid on the image, containing the text 'Ever heard of the dark web?'.

Ever heard of the dark web?

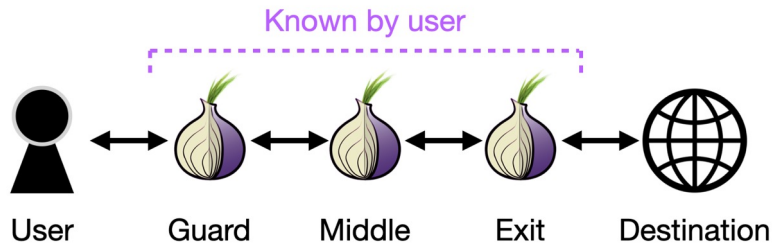
What is the dark web?

- Encrypted online content that is **not** indexed by conventional search engines and can only be accessed using specific browsers, such as the [Tor Browser](#).

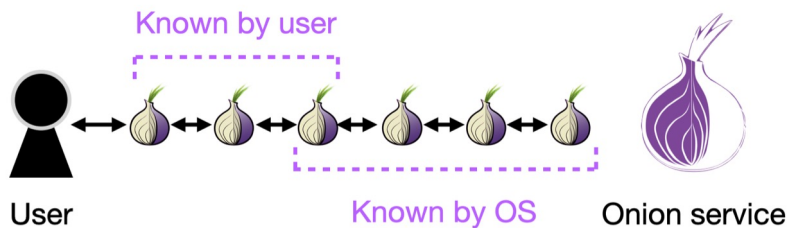
Onion Services



What is the difference?



(a) Traditional Tor circuits

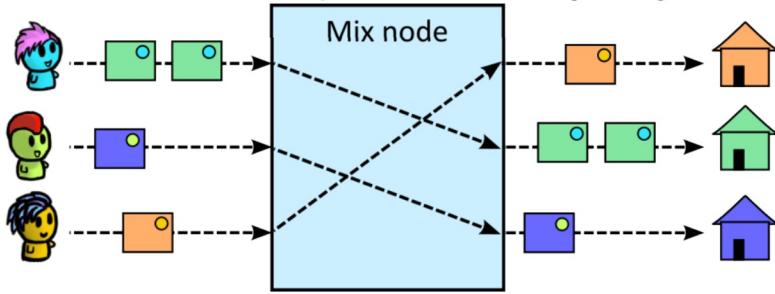


(b) Onion service Tor circuits

Mixes

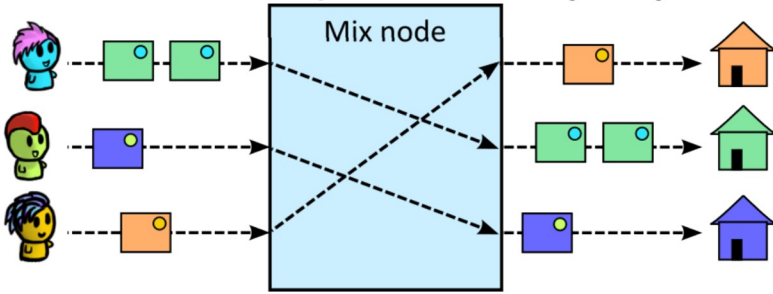
Mixes: Basic Operations

How do we provide anonymity?

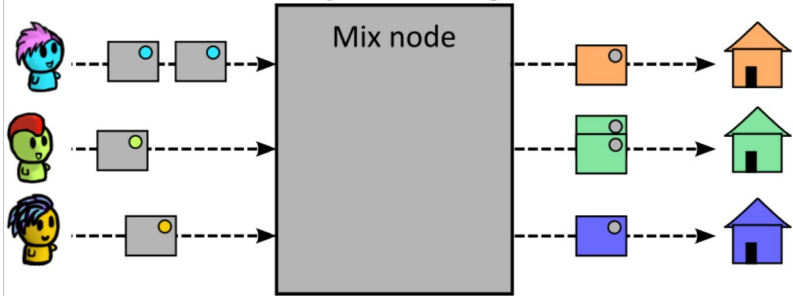


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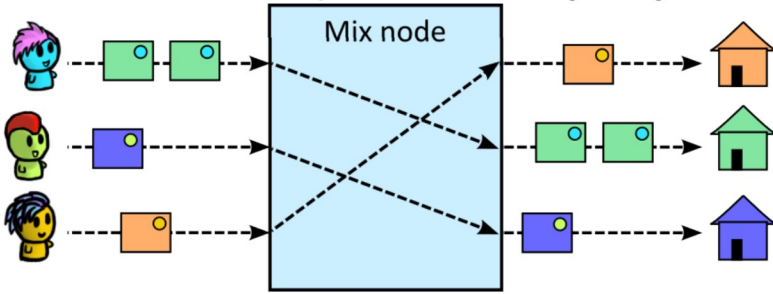


Delay messages!

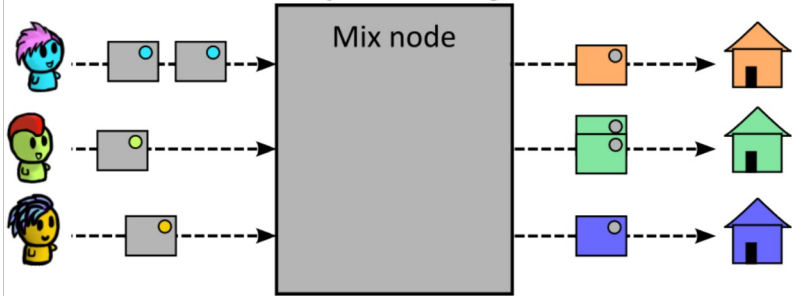


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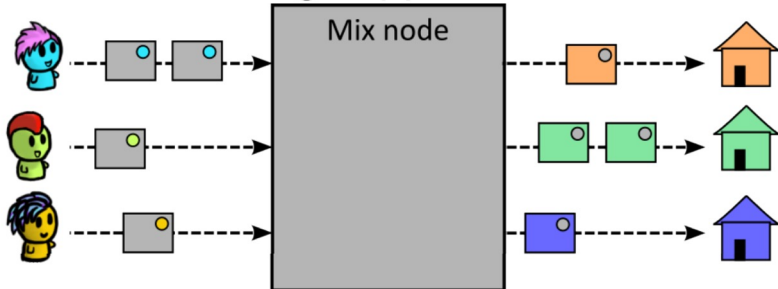
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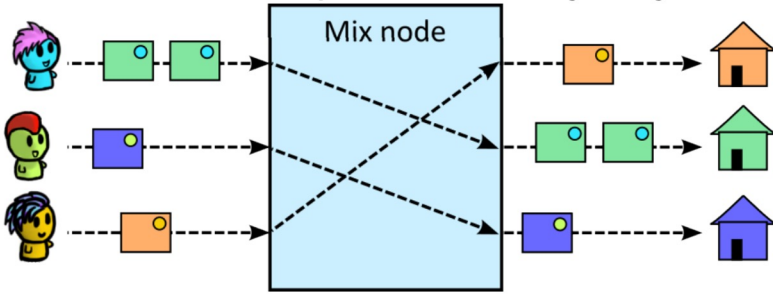


Change appearance!

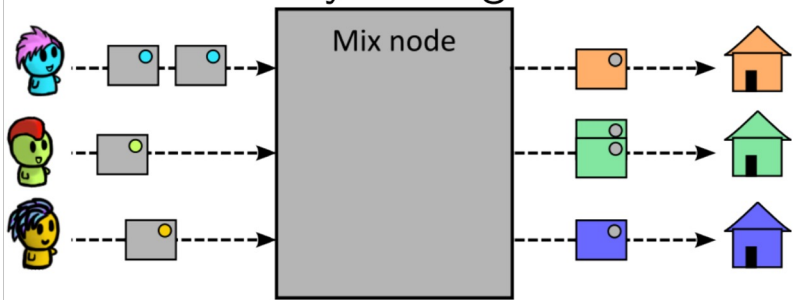


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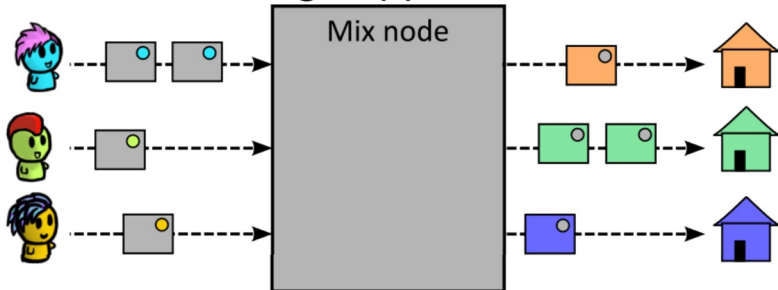
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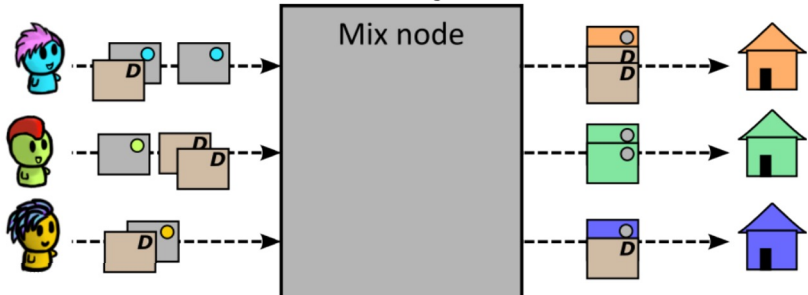
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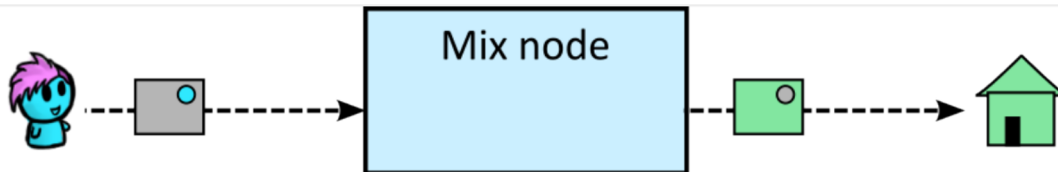


Add dummy traffic!



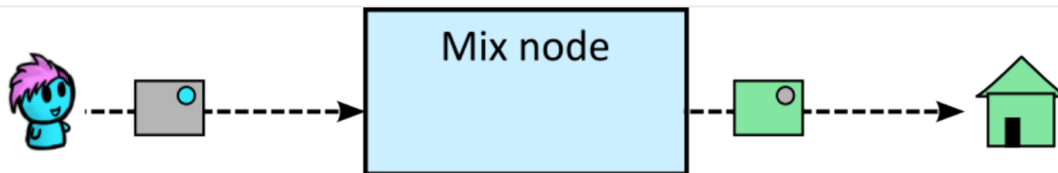
Operation 1: Changing Appearance

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



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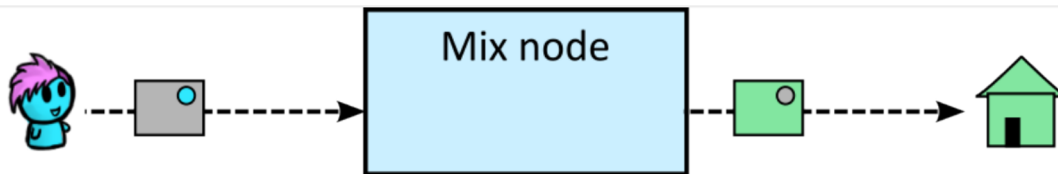
A: We can encrypt the output message with the Mix's key

$$\boxed{\text{Grey square with blue circle}} = E_{K_{\text{mix}}}(\boxed{\text{Green square with grey circle}})$$

$$\boxed{\text{Green square with grey circle}} = E_{K_{\text{Bob}}}(m)$$

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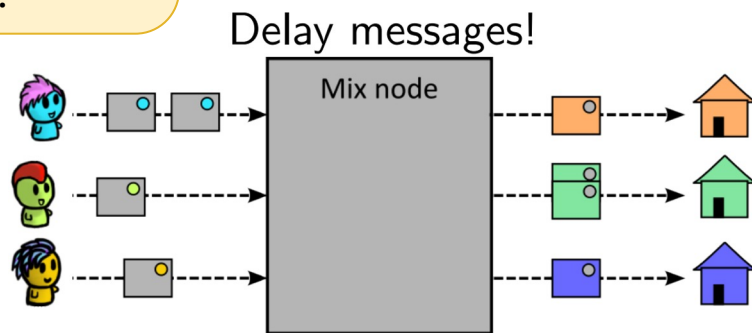
$$\text{Green Square} = E_{K_{\text{Bob}}}(m)$$

This "layered encryption" concept is the same as onion routing!

Operation 2: Delaying Messages

Q: How do we do this?

- 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?

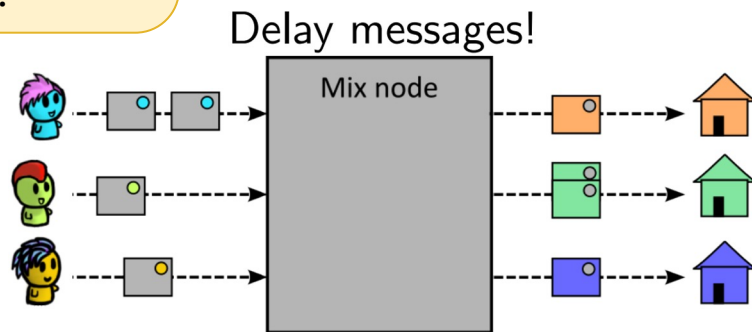


Operation 2: Delaying Messages

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- Do we add a constant delay to each message?

A: Yes. Yes. No.



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

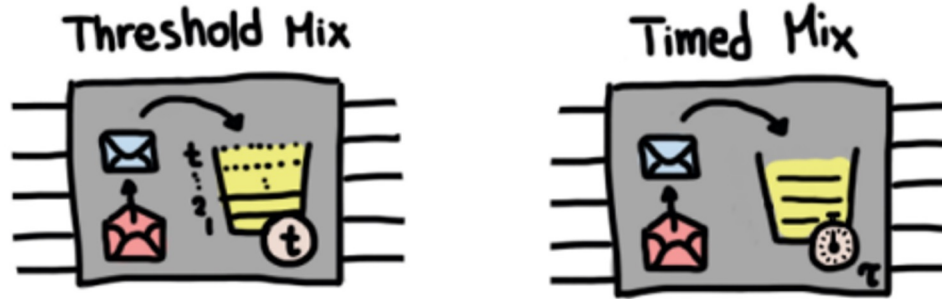
- Some popular mixes types are threshold and timed mixes.
- These mixes gather messages until a **flushing condition** triggers.
- When this condition happens, this marks the end of a **round**
 - Threshold mix: it gathers t messages, then it flushes them.
 - Timed mix: it gathers messages until a timer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

Threshold and Timed Mixes



Q: Which of the two is better?

Threshold and Timed Mixes



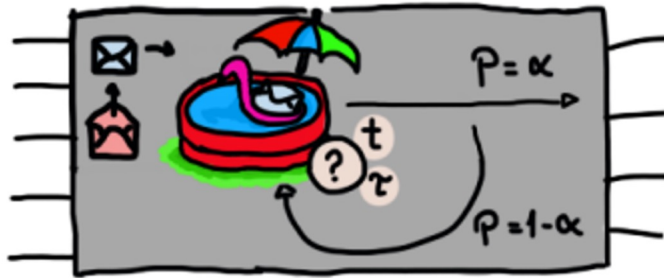
Q: Which of the two is better?

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

Binomial Pool Mix

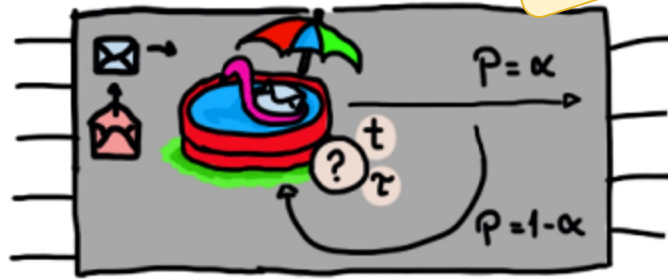


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Binomial Pool Mix



Q: What are the pros and cons of this?

A: Pros, more anonymity

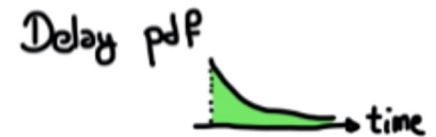
A: Cons, more delay

Delay pdf

time

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 delay and include it in the message



Mixnets

Mixnets

Sending messages through a **single mix is not great**

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

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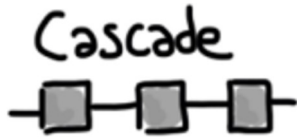
One after another



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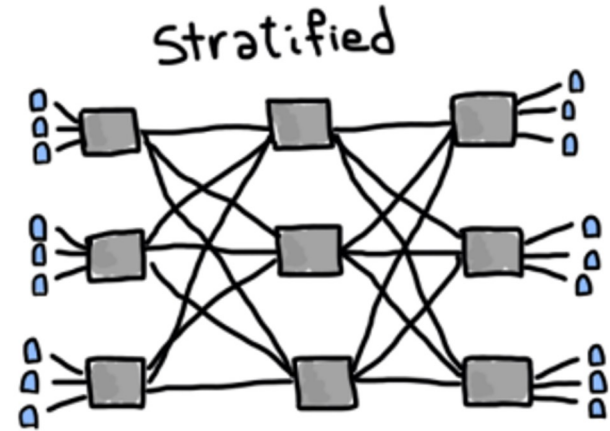
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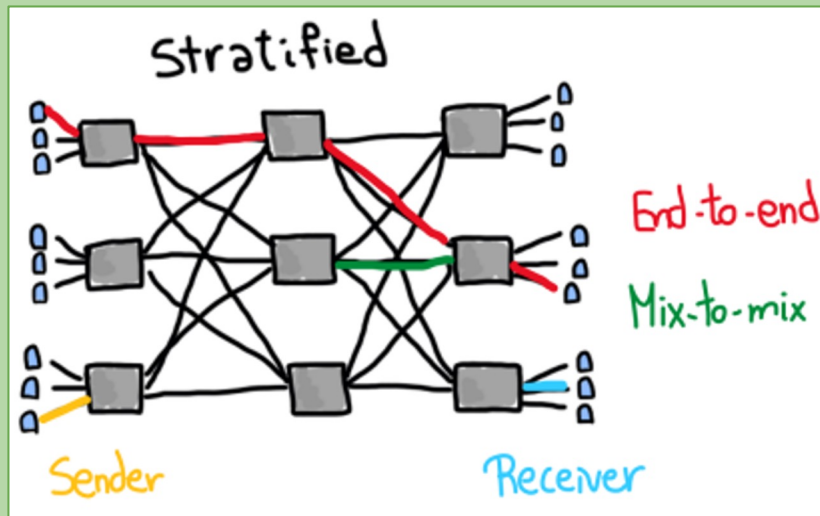


Each layer is fully connected to the next layer

Operation 3: Dummy Messages

Q: Where do we add dummy traffic?

A: Anywhere, everywhere!



Checkpoint 1

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

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A: Increasing t improves anonymity but increases delay

Checkpoint 2

Q: Timed mixes: pros and cons of increasing the time τ ?

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

Checkpoint 2

Q: Timed mixes: pros and cons of increasing the time τ ?

A: Increasing τ improves anonymity but increases delay

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

A: Increasing α decreases anonymity and delay

Checkpoint 3

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

Q: What happens if the number of senders increases?

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 Summary

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 og address is stored in a table)
- Replies to the anon address get mapped back to your real address and delivered to you
- $\approx 10\,000$ emails per day ($\approx 700\,000$ users)

Anon.penet.f, works as long as...

- No one's watching the Internet connections to or from anon.penet.fi
- The operator of anon.penet.fi, the machine (hardware), and the software all remain trustworthy and uncompromised
- The mapping of anon addresses to real addresses is kept secret

Unfortunately, a lawsuit forced Julf (the operator) to turn over parts of the list, and he shut down the whole thing, since he could no longer legally protect it

Cypherpunk (Type 1) Remailers

- 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!

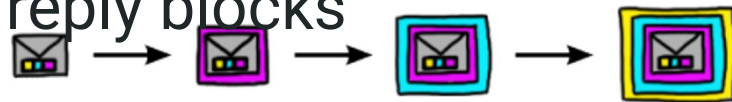
Nym servers / Pseudonymous remailers

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



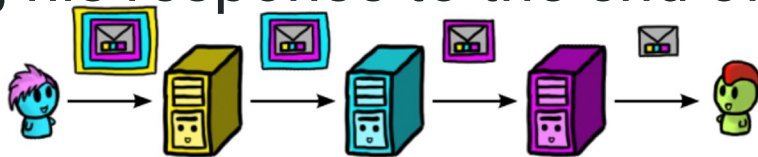
- Then, Alice builds her message using layered encryption
- The message contains a chain of reply blocks



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, and builds her message using layered encryption
- The message contains a chain of reply blocks
- Bob replies by attaching his response to the end of the reply blocks



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”