Privacy Enhancing Technologies

Chapter: Anonymous Communication

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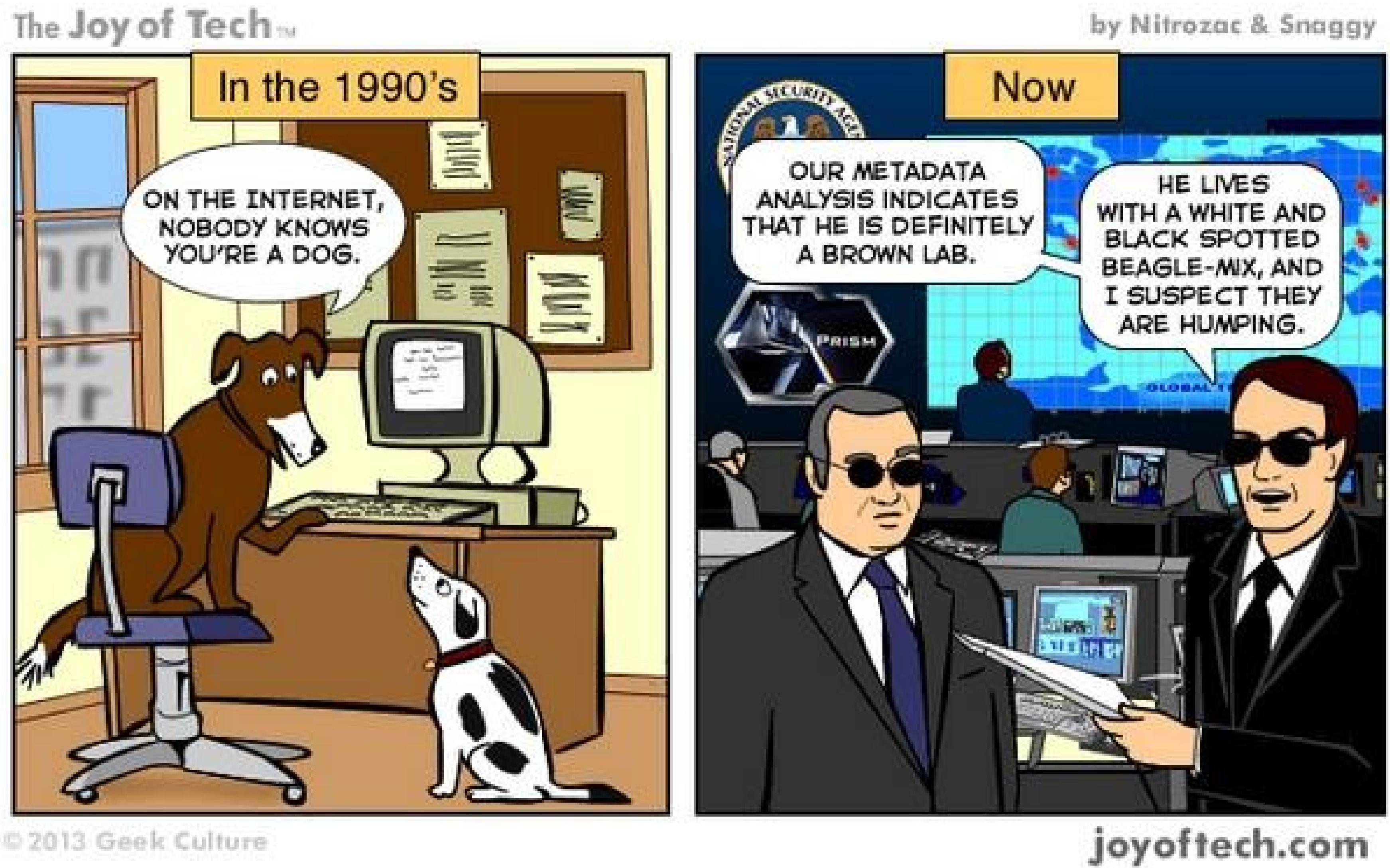
Can you click yes?

Learning Goals

- Understand the Problem
  - Motivation & Setting
  - Dimensions & Terminology

- Understand the Solution(-space)
  - Solution ideas and prominent protocols
  - Effects of design decisions

Motivation


The Joy of Tech™
by Nitrozac & Snaggy
In the 1990's
ON THE INTERNET, NOBODY KNOWS YOU'RE A DOG.
Now
OUR METADATA ANALYSIS INDICATES THAT HE IS DEFINITELY A BROWN LAB.
HE LIVES WITH A WHITE AND BLACK SPOTTED BEAGLE-MIX, AND I SUSPECT THEY ARE HUMPING.
PRISM
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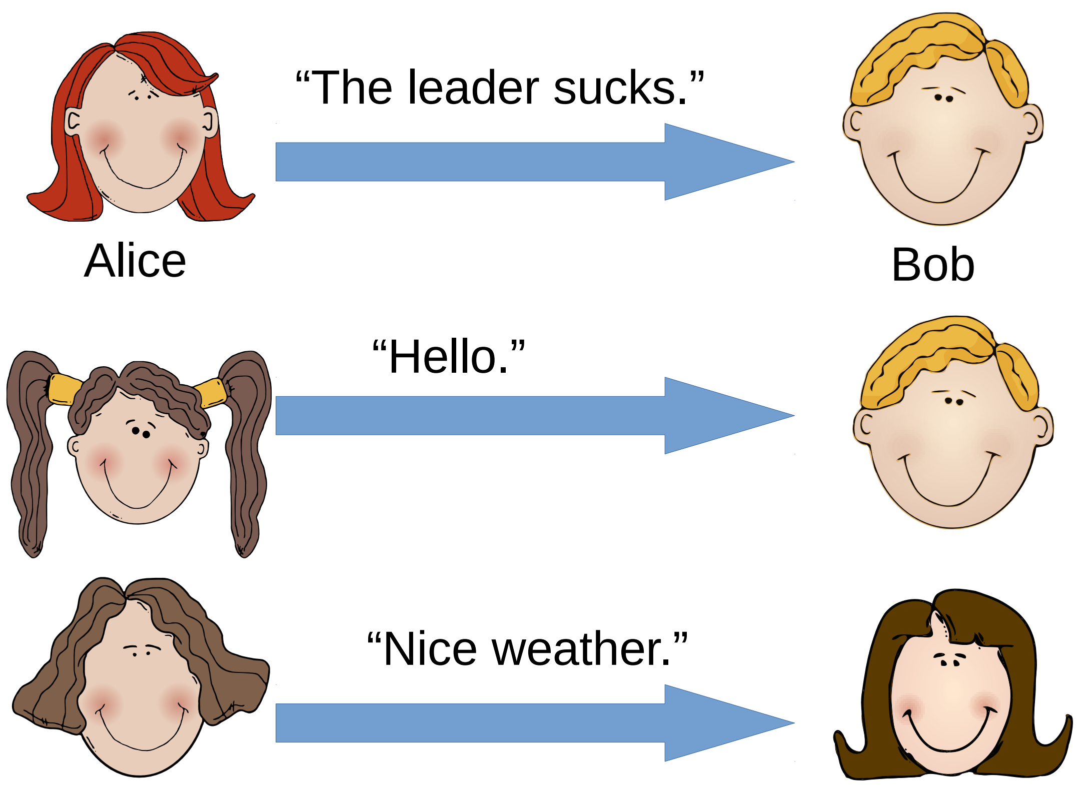
Motivation

- Protect Privacy in Communications to:
  - View sensitive content
  - Avoid impersonation
  - Avoid profiling and tracking by advertising companies (price discrimination)
  - Avoid profiling and tracking by governments (manipulation)
  - Guarantee freedom of speech
  - Enable applications: electronic voting, whistle blowing,…

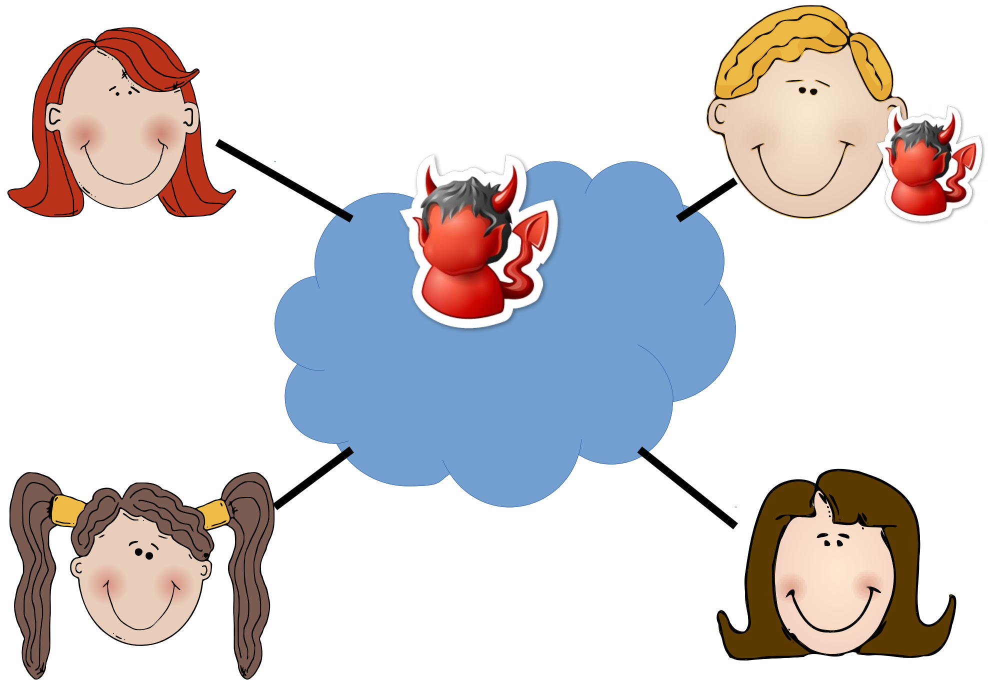
Setting

Communications that are happening

Sender message receiver



Network, on which they happen



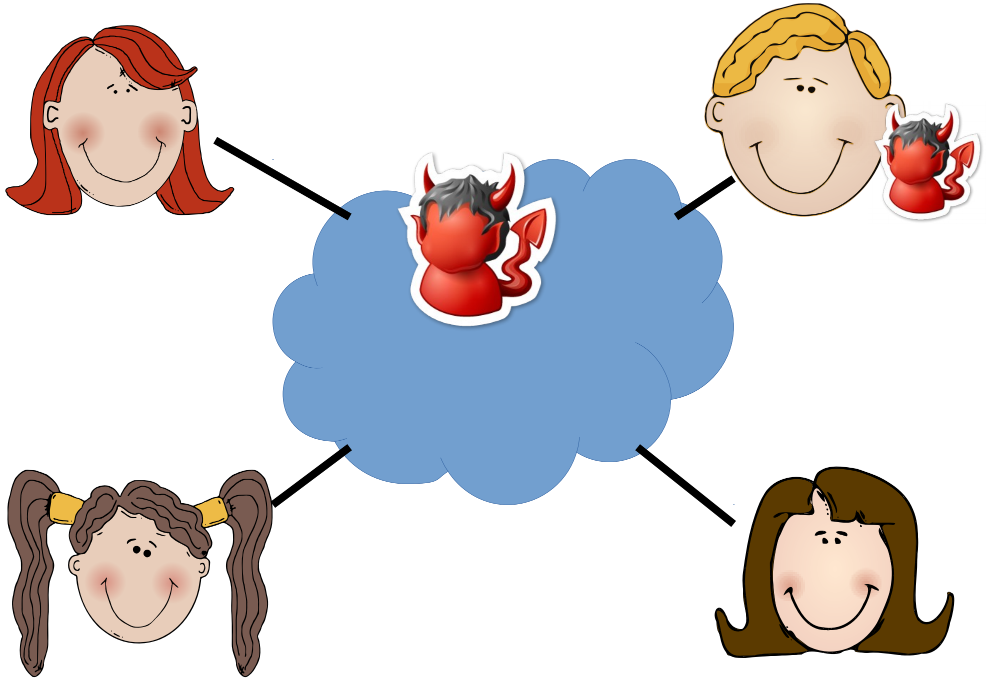
Does encryption protect Alice from the adversary?

Encryption is not enough

- Does not hide anything if the receiver is adversarial
- Does not hide meta data:
  - Sender-receiver relationships (IP addresses)
  - Activity
  - Cookies
  - Browser fingerprinting

    → all can be used to identify and profile users

Encryption is an amazing tool, but not enough!



Learning Goals

- Understand the Problem
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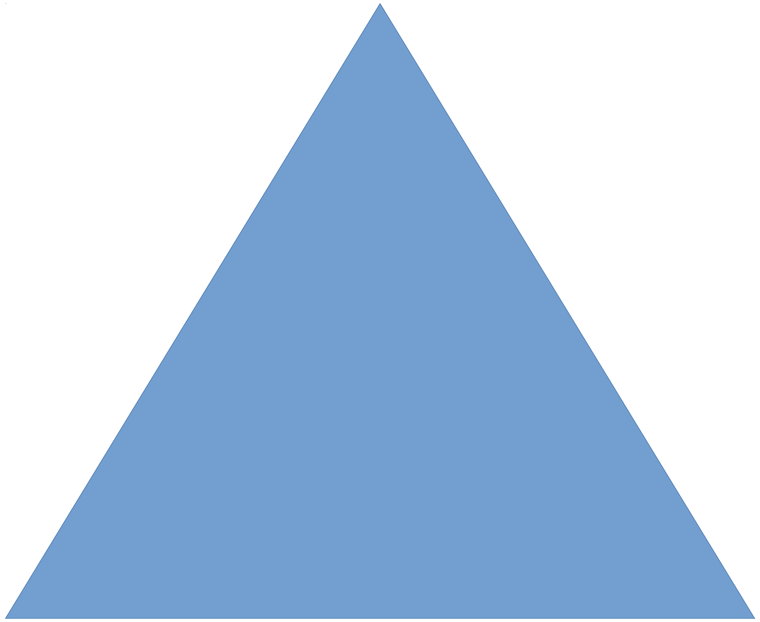
Criteria

What’s protected?



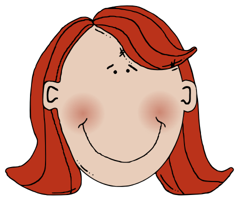
Against what adversary?

At what cost?

What’s protected? Terminology

Anonymity: “Anonymity of a subject means that the subject is not identifiable within a set of subjects, the **anonymity set**. ”

Reality



Alice does the action

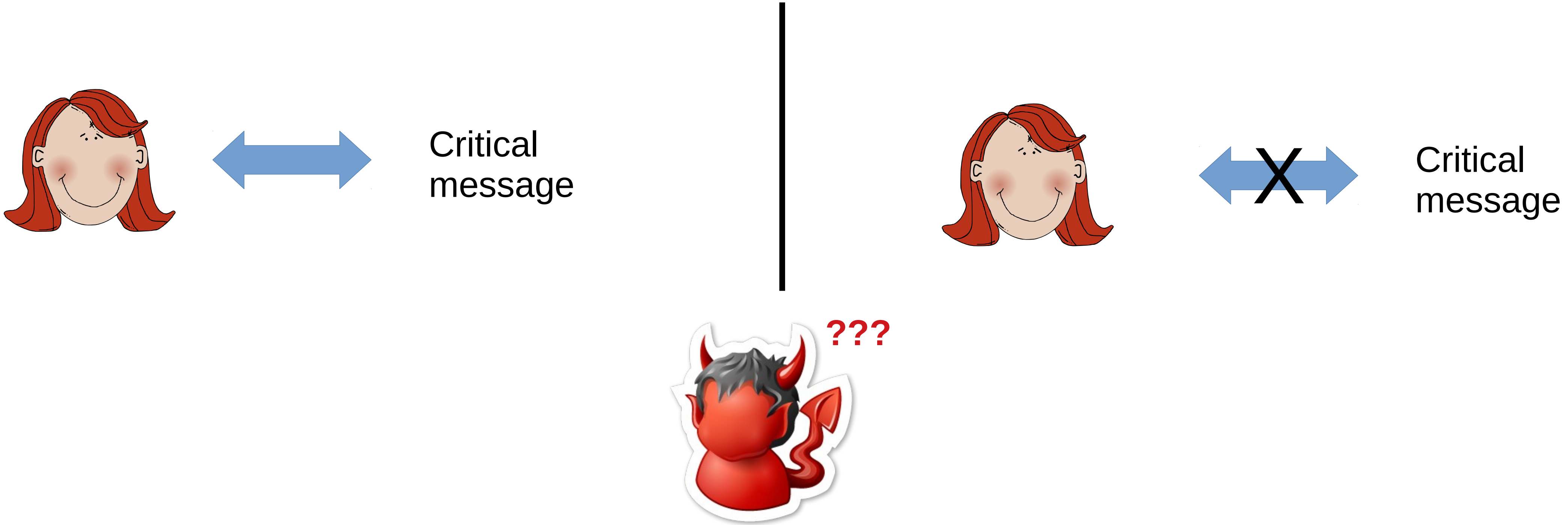
Adversary learns

Someone in the anonymity set does the action

https://tools.ietf.org/id/draft-hansen-privacy-terminology-00.html

What’s protected? Terminology

Unlinkability: “Unlinkability of two or more items [..] means that [..] the attacker cannot sufficiently distinguish whether these [items] are related or not.”



https://tools.ietf.org/id/draft-hansen-privacy-terminology-00.html

What’s protected? Terminology

- **Undectectability**: “Undetectability of an item [..] means that the attacker cannot sufficiently distinguish whether it exists or not. “

Critical message sent

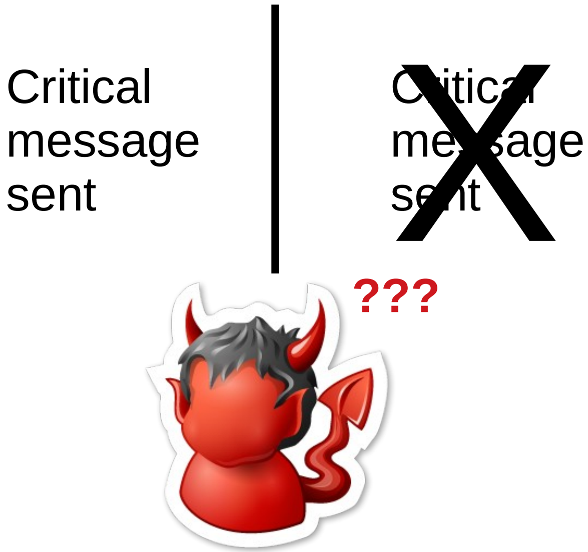
~~Critical message sent~~

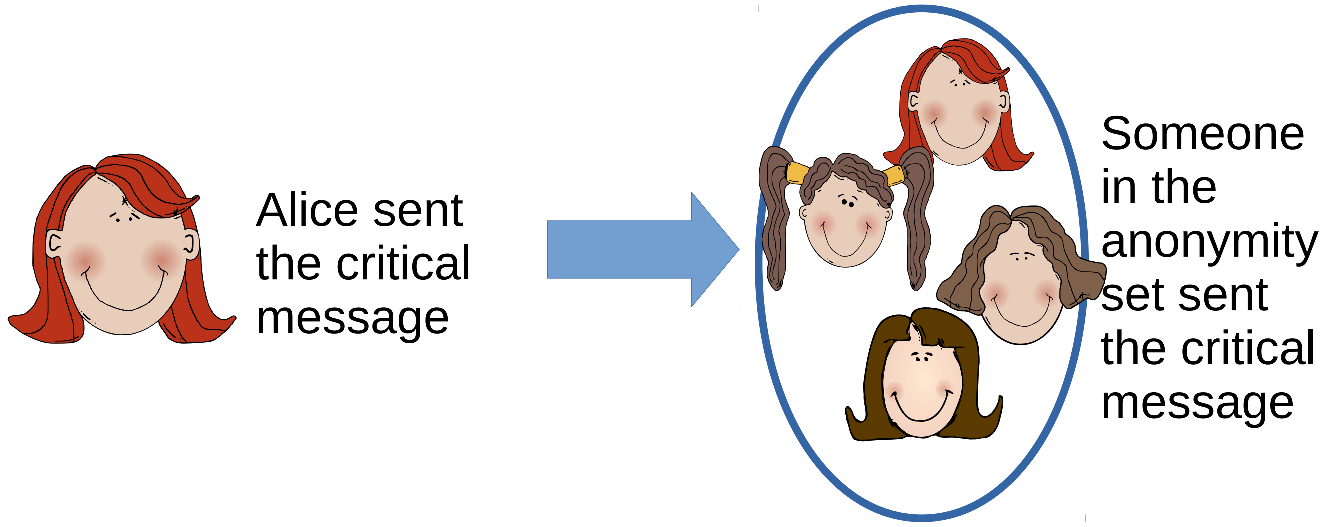
???

https://tools.ietf.org/id/draft-hansen-privacy-terminology-00.html

What's protected? Terminology

- Unobservability: "Unobservability of an item [..] means
  - undetectability of the [item] against all subjects uninvolved in it and
  - anonymity of the subject(s) involved in the [item] even against the other subject(s) involved in that [item]."





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What’s protected?

Typically of interest: Sender, Receiver and Message

→ we’ll focus on sender protection for this lecture

- **Relationships**
  - e.g. Sender-Message Unlinkability (often called Sender Anonymity) – we do not learn who sends which message
  - e.g. Sender-Receiver Unlinkability (often called Relationship Anonymity) – we do not learn who communicates with whom
- **Activity**
  - e.g. Sender Unobservability – we do not learn who sends something

More protection goals possible

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Is Sender-Message Unlinkability stronger than Sender Unobservability?

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More protection goals possible

Is Sender-Receiver Unlinkability stronger than Sender-Message Unlinkability?

What’s protected?

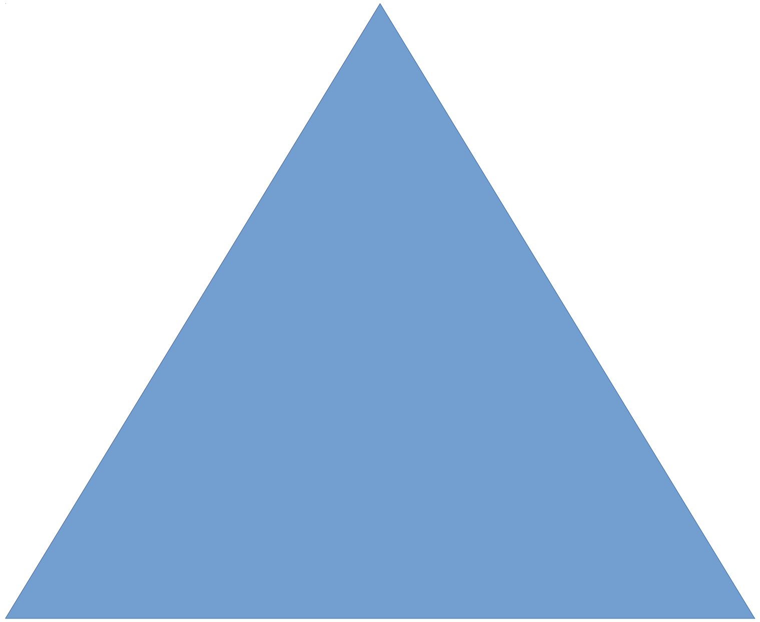
Sender Unobservability

Sender-Receiver Unlinkability

Sender-Message Unlinkability

Criteria

What’s protected?



Against what adversary?

At what cost?

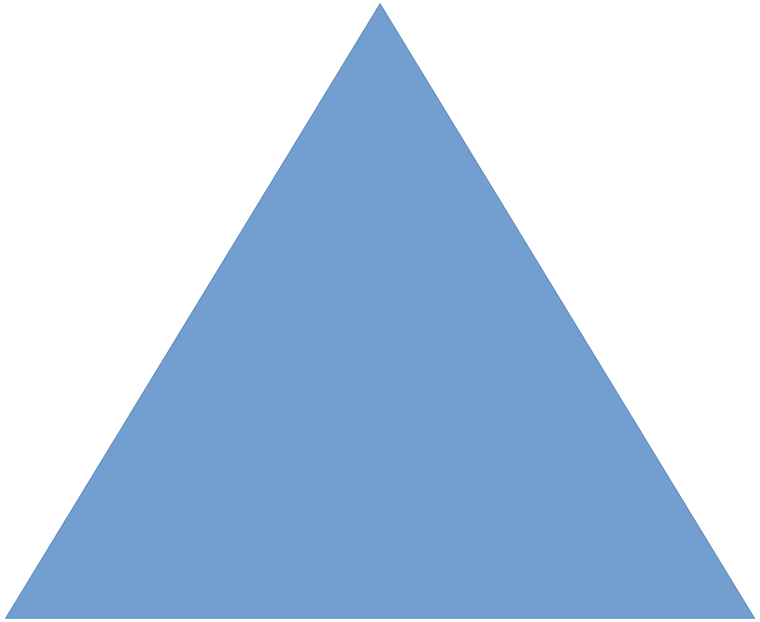
Against what adversary?

- Area? Local vs. Global, Links vs. Nodes etc.
- Actions? Eavesdropping (Passive)/ Modification, Dropping, Delay (Active)

  → we'll focus on passive adversaries for this lecture
- Participant? Internal vs. External
- Time? Temporary vs. Permanent
- Change resources/strategy? Static vs. Adaptive
- Restricted computation power?

Criteria

What’s protected?



Against what adversary?

At what cost?

At what cost?

- Latency
- Bandwidth

- Functionality
- Other security goals (availability)
- Additional assumptions (public key infrastructure etc.)

Learning Goals

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- Understand the Problem
  - Motivation and Setting
  - Dimensions and Terminology

- Understand the Solution(-space)
  - Solution ideas and prominent protocols:
    - Random Walk
    - Onion Routing
    - Mix Networks
    - Dummy Traffic
    - DC Networks
  - Effects of design decisions

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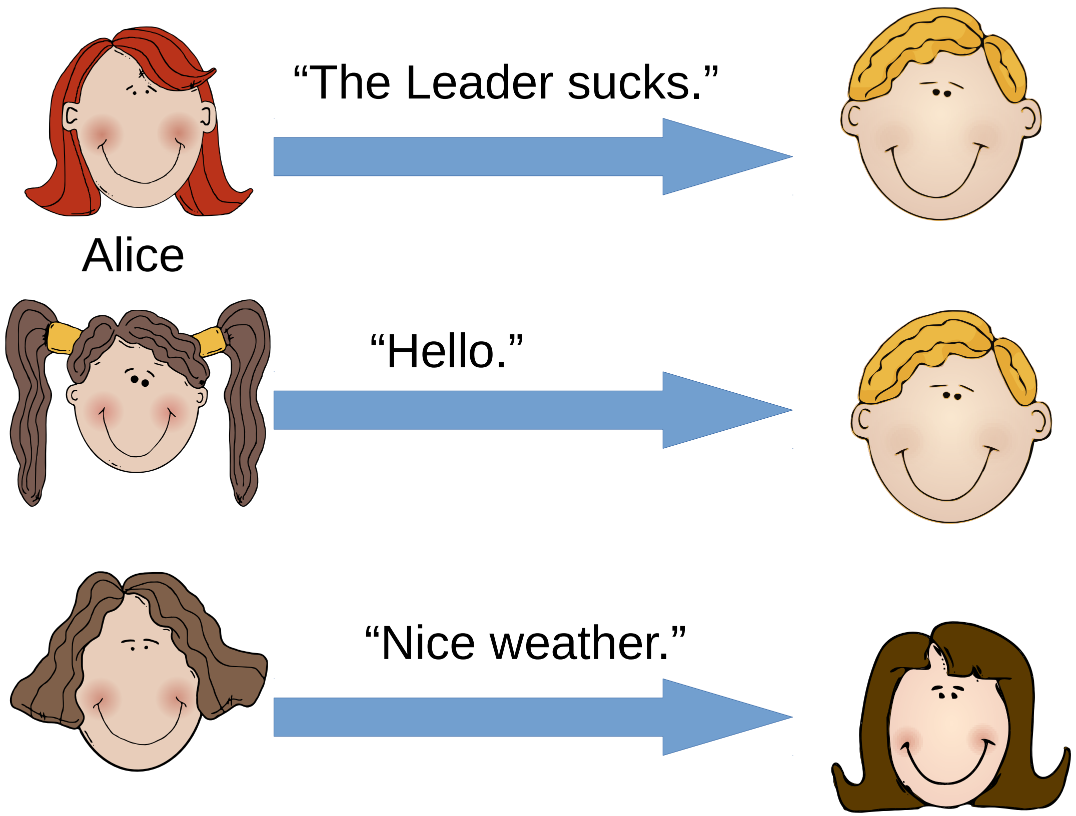
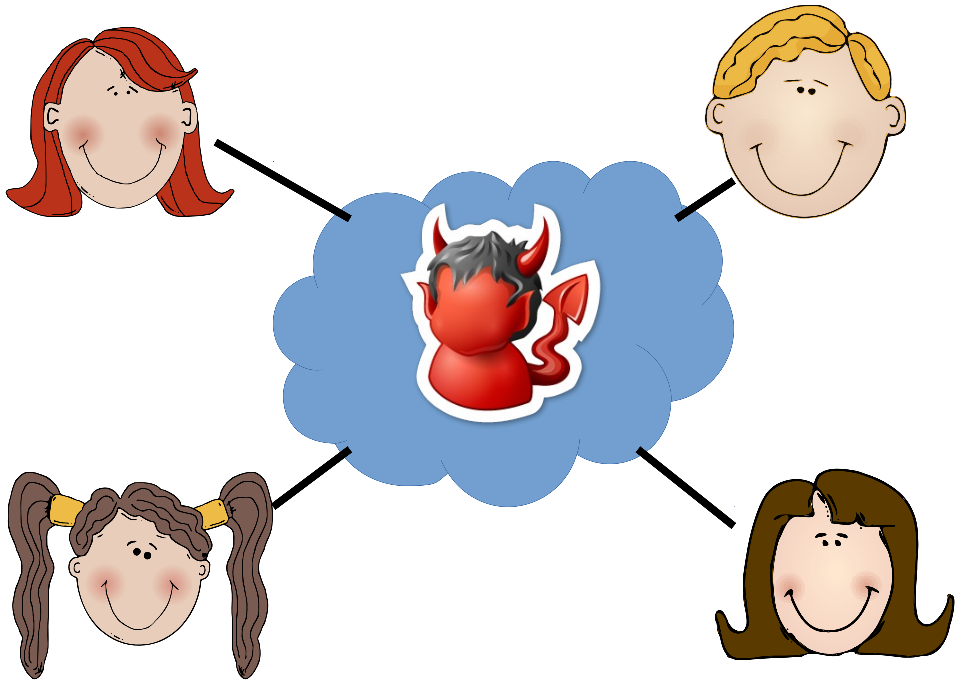
Setting

The Communications that happen

Sender message receiver

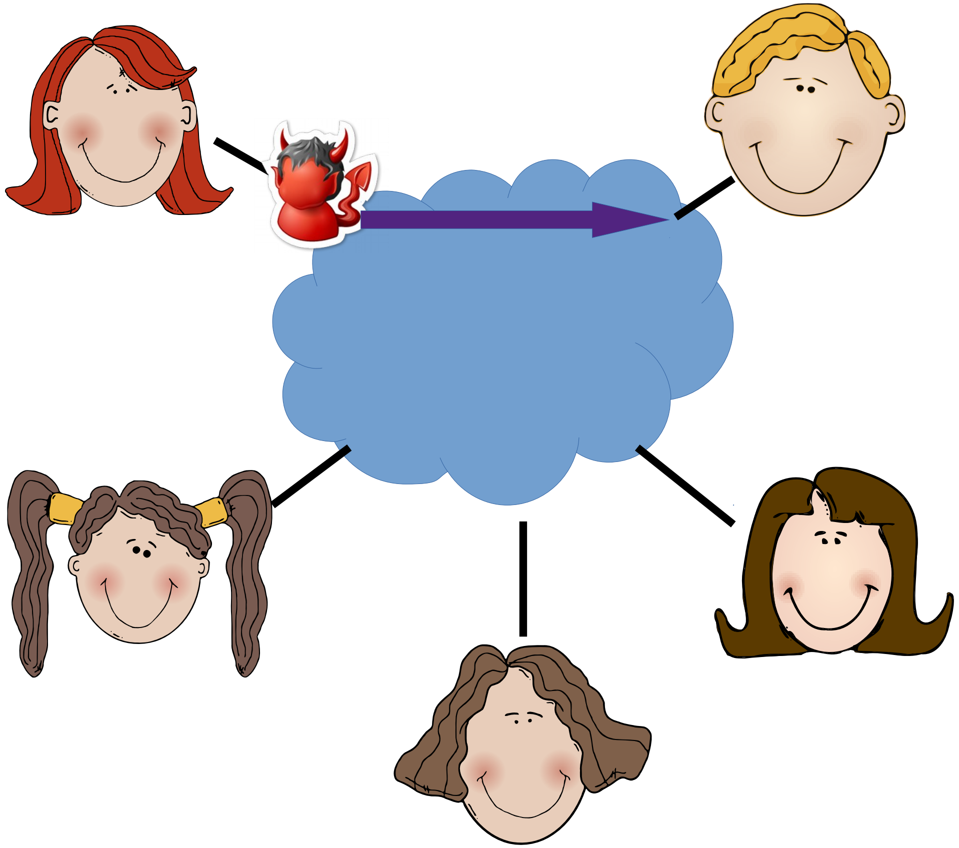


The network on which they happen



Without any protection

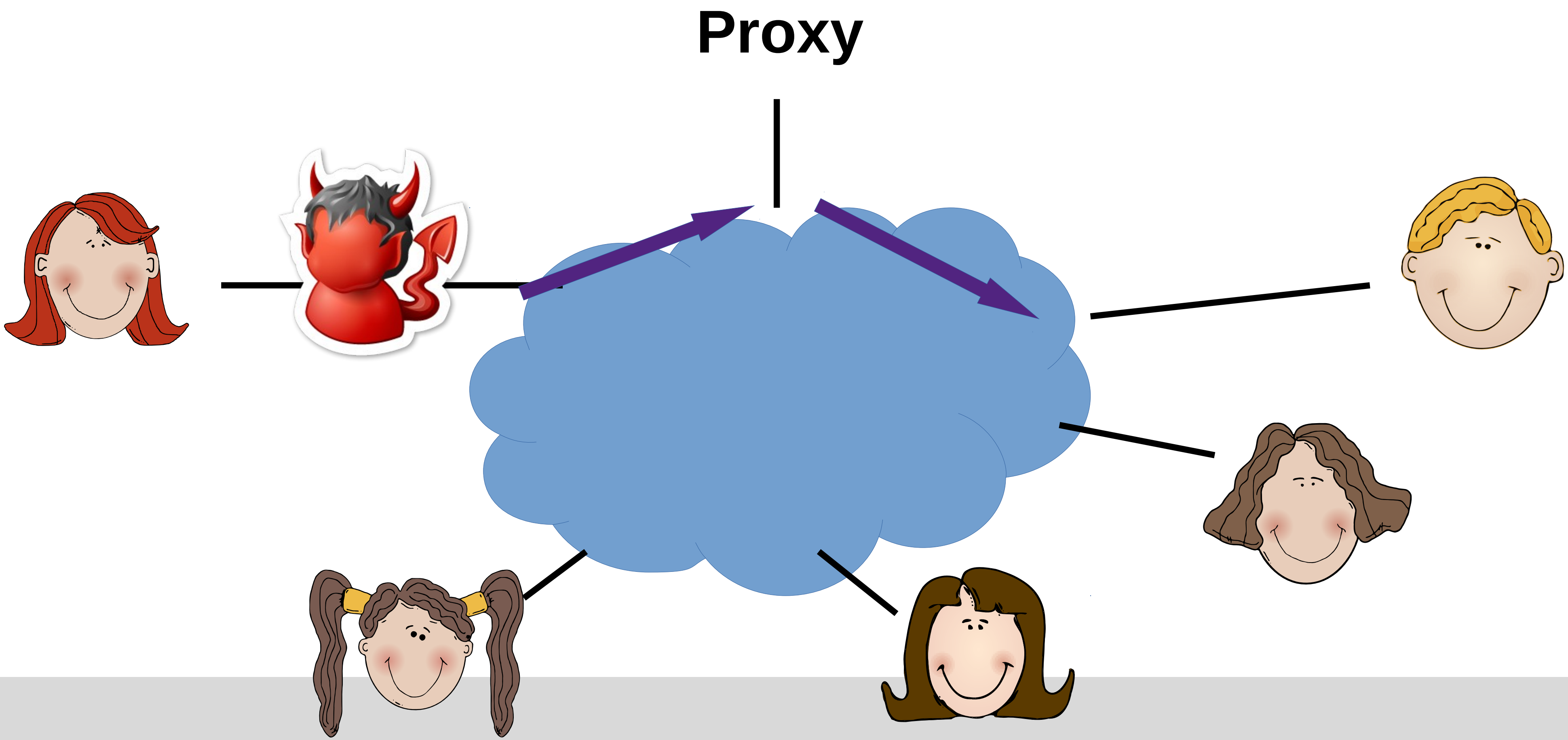
- Direct connection observable



Using a Proxy

Principle 1: Indirection

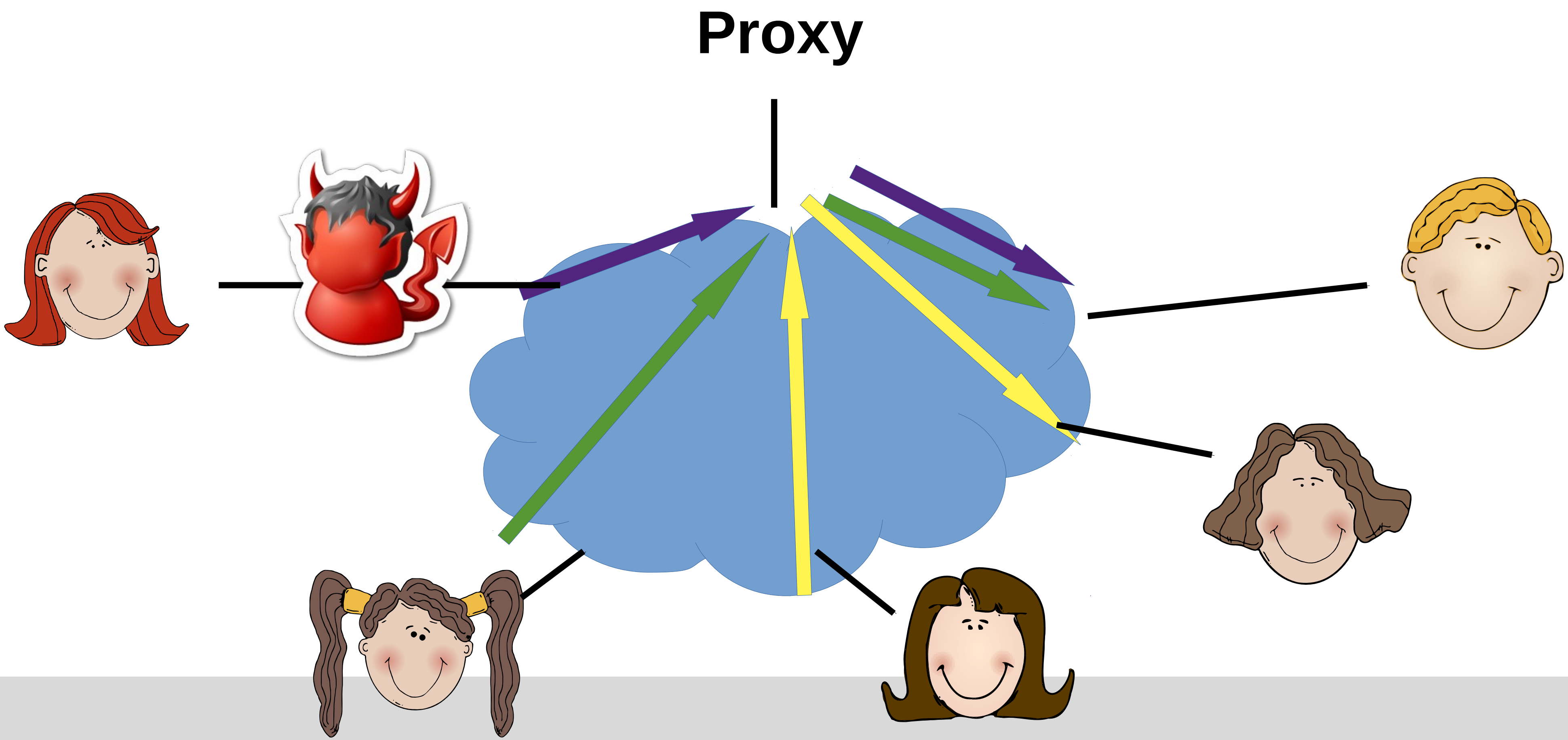
Alice sends message and receiver address to a proxy, who then forwards the message to the receiver



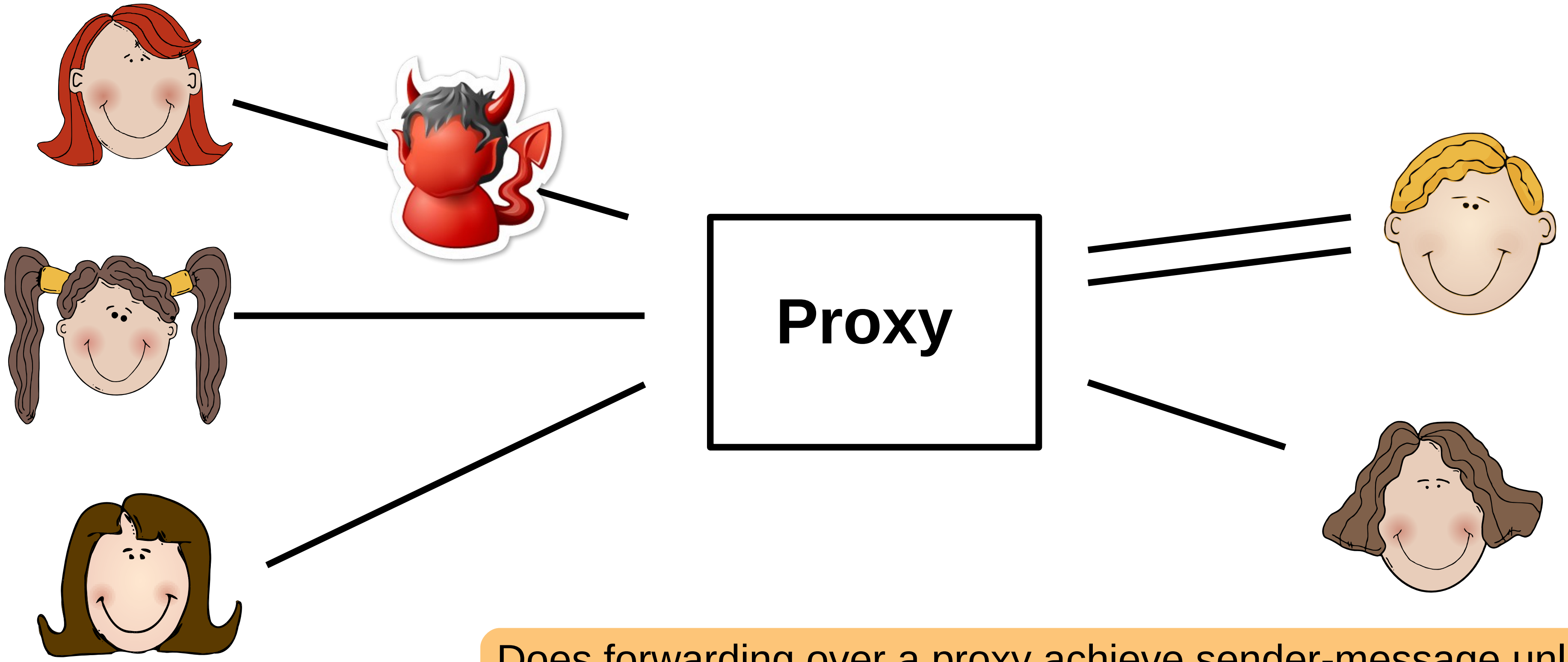
Using a Proxy

Principle 1: Indirection

Alice sends message and receiver address to a proxy, who then forwards the message to the receiver, all other senders do the same



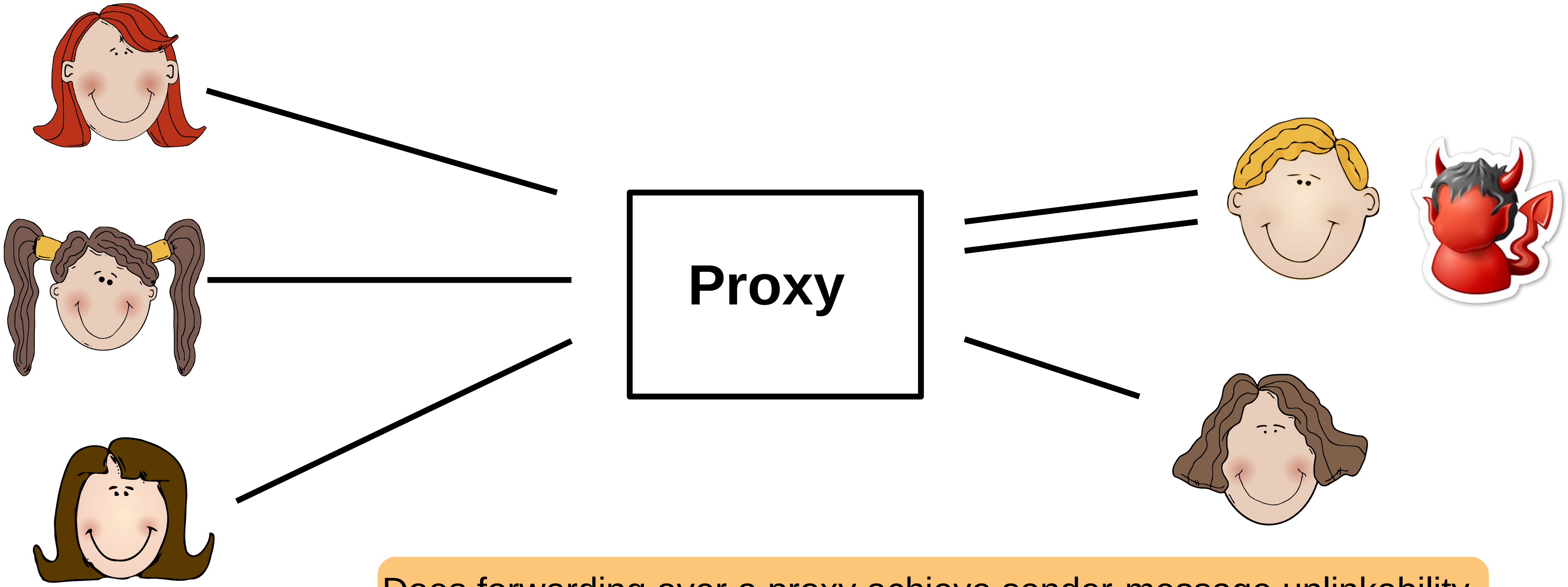
Using a Proxy
Principle 1: Indirection



Does forwarding over a proxy achieve sender-message unlinkability against a passive, local adversary at the senders?

Using a Proxy

Principle 1: Indirection

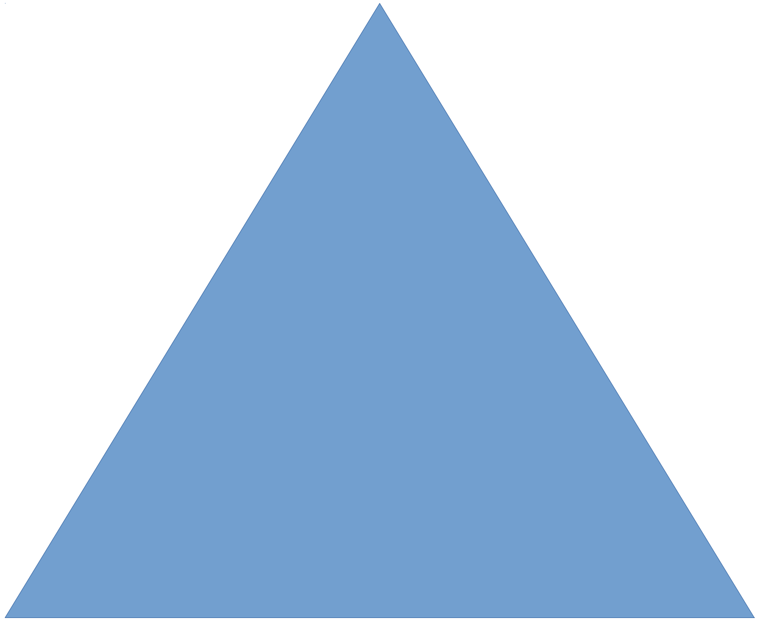


Does forwarding over a proxy achieve sender-message unlinkability against a corrupt, passive receiver?

Using a Proxy

Sender-Message Unlinkability

Sender-Receiver Unlinkability



Passive receiver as adversary

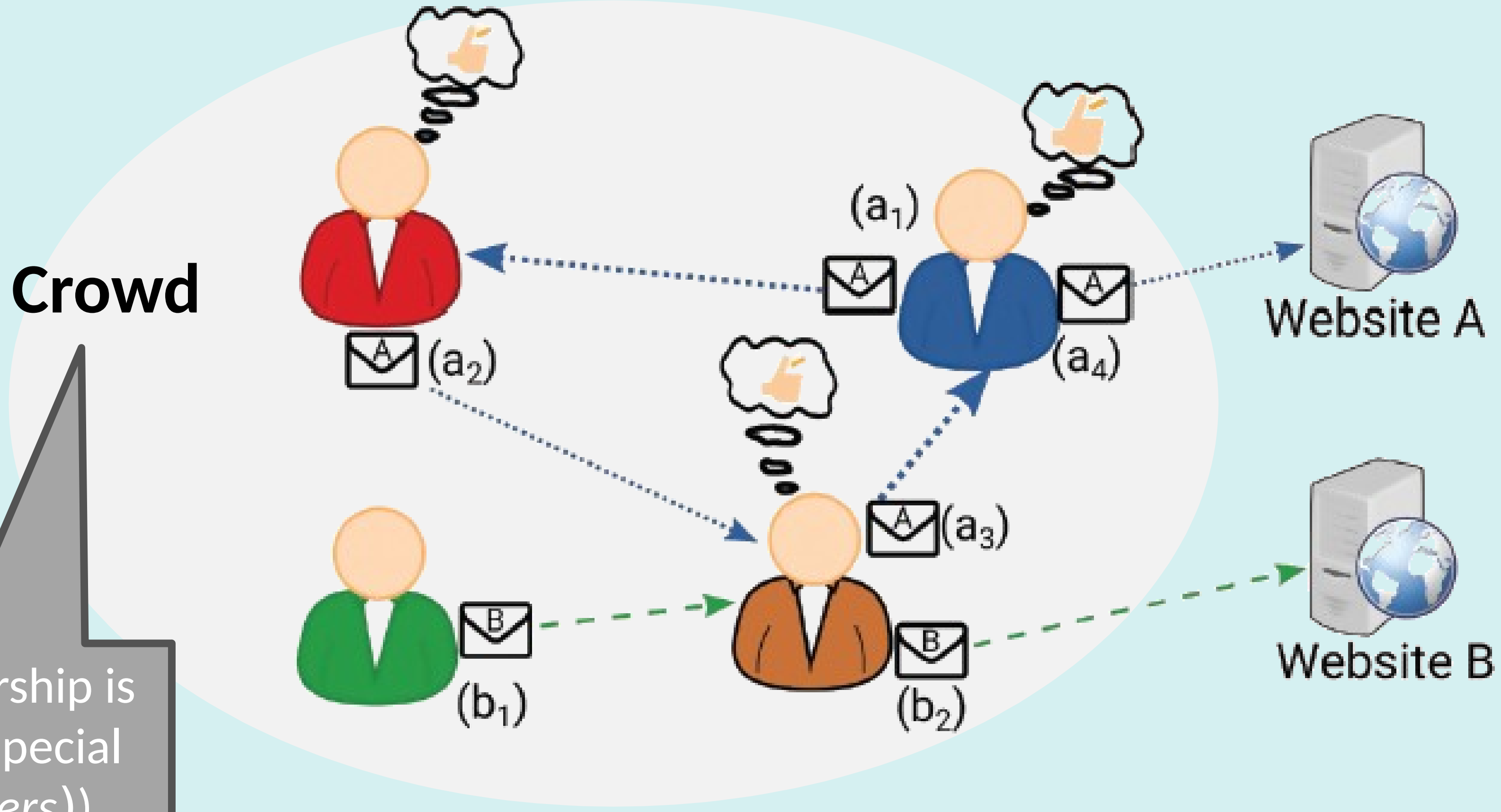
Slightly higher latency
need a proxy

Random Walk Protocols

- Typically use peer-to-peer network structure
- Forward message to randomly selected neighbor
- *Example: Crowds* (1998) for anonymous web browsing

Reiter, Michael K., and Aviel D. Rubin. "Crowds: Anonymity for web transactions." ACM transactions on information and system security (TISSEC) 1.1 (1998): 66-92.

Random Walk concept (Crowds)



Crowd Membership is controlled by special nodes (*blenders*))

Crowds

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- All nodes are grouped into „crowds“
- Nodes within a crowd might connect to each other for relaying a communication:
  - user randomly selects a node and sends her message (i.e., website request)
  - this node flips a biased coin to decide whether to send the request directly to the receiver or to forward it to another node selected uniform at random,
  - this continues until the message arrives at the destination.
  - The server replies are relayed through the same nodes in reverse order.

Can an internal adversary, corrupting n-2 participants, identify the sender of a message (with high probability)?

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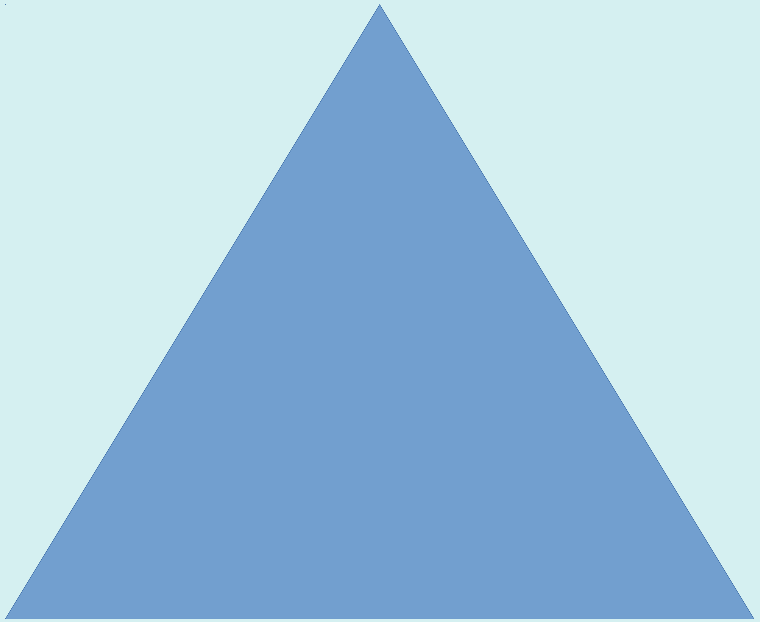
Crowds

Sender Unobservability



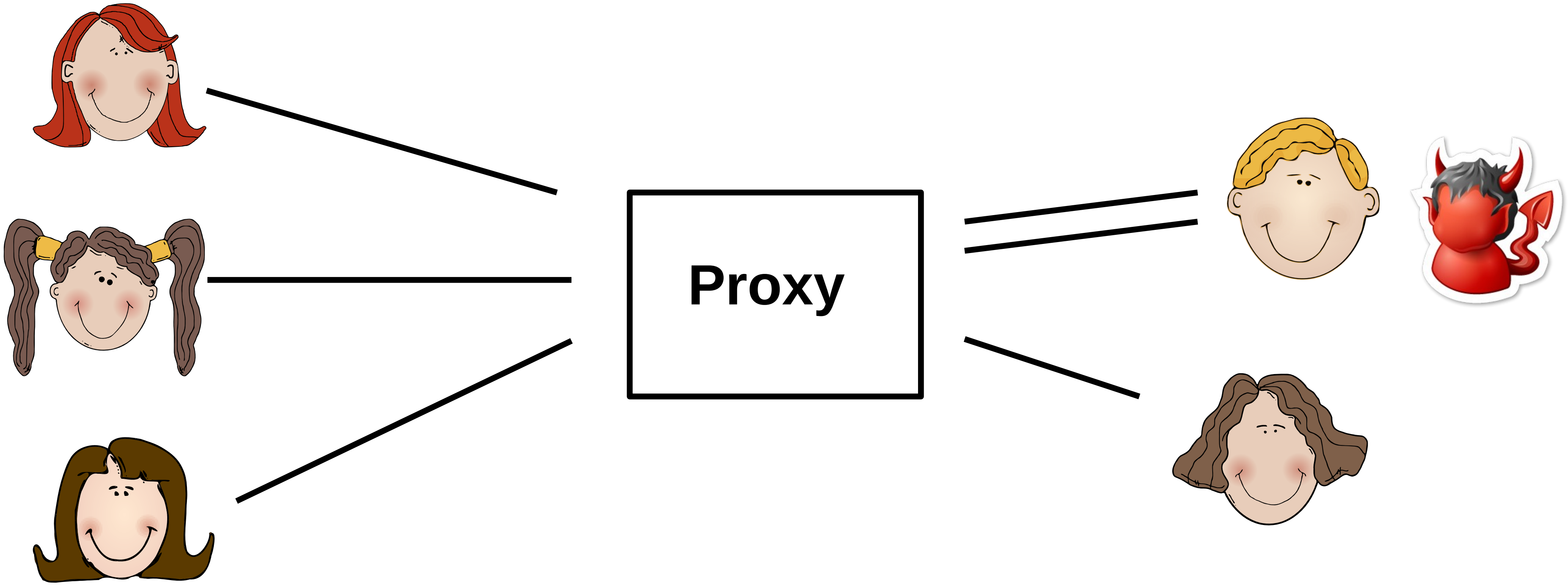
Passive **external** receiver

Higher latency
Management overhead
Availability risk (blenders)

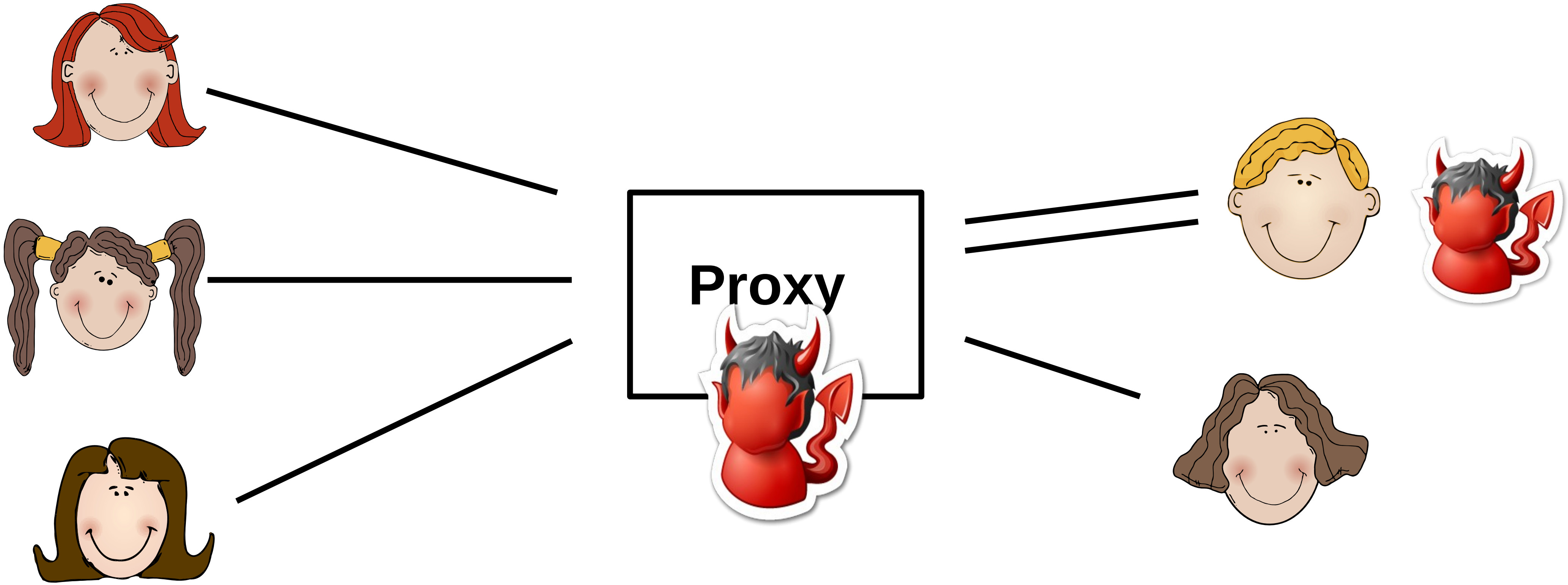
Summary Random walk

- Non-deterministic route selection
- Protection against external adversary
- Internal adversary improves estimation of sender based on timing information (predecessor attack)
  - Crowds is a representative example
    - Semi de-centralized
    - ✉ blenders are single points of failure

Using a Proxy



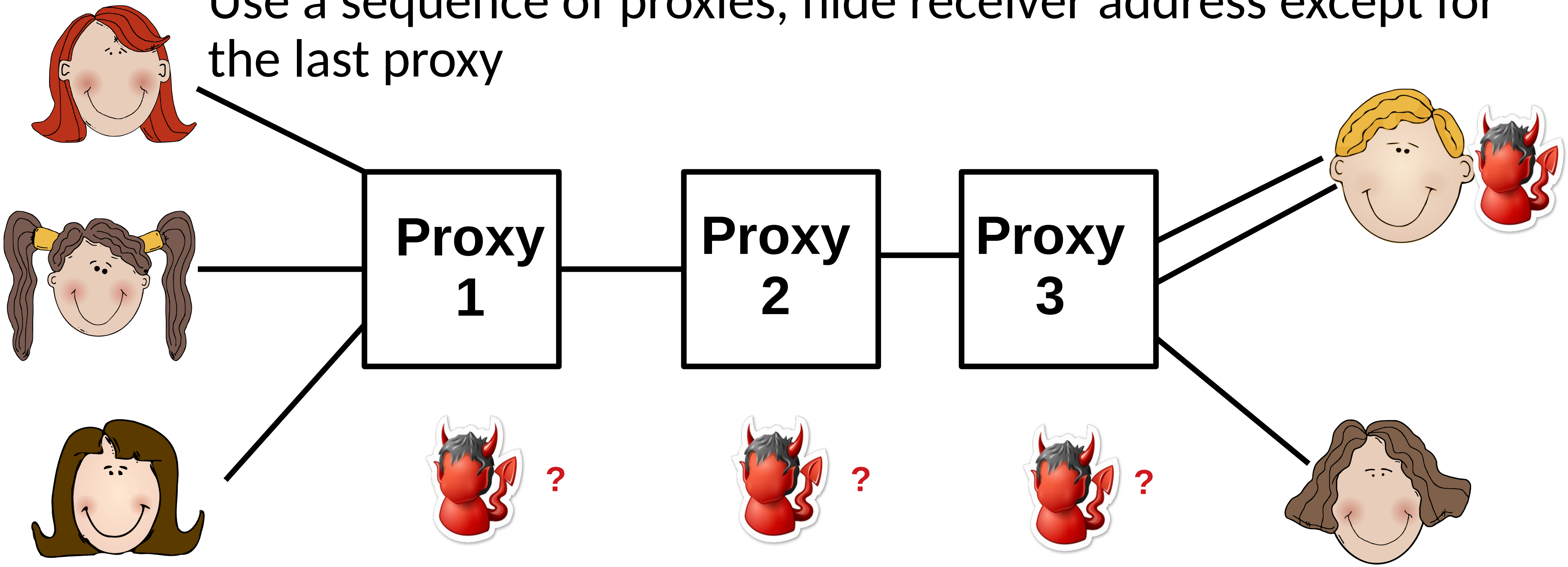
Using a Proxy



Using a Proxy Chain

Principle 2: Distribution of Trust

Use a sequence of proxies, hide receiver address except for the last proxy



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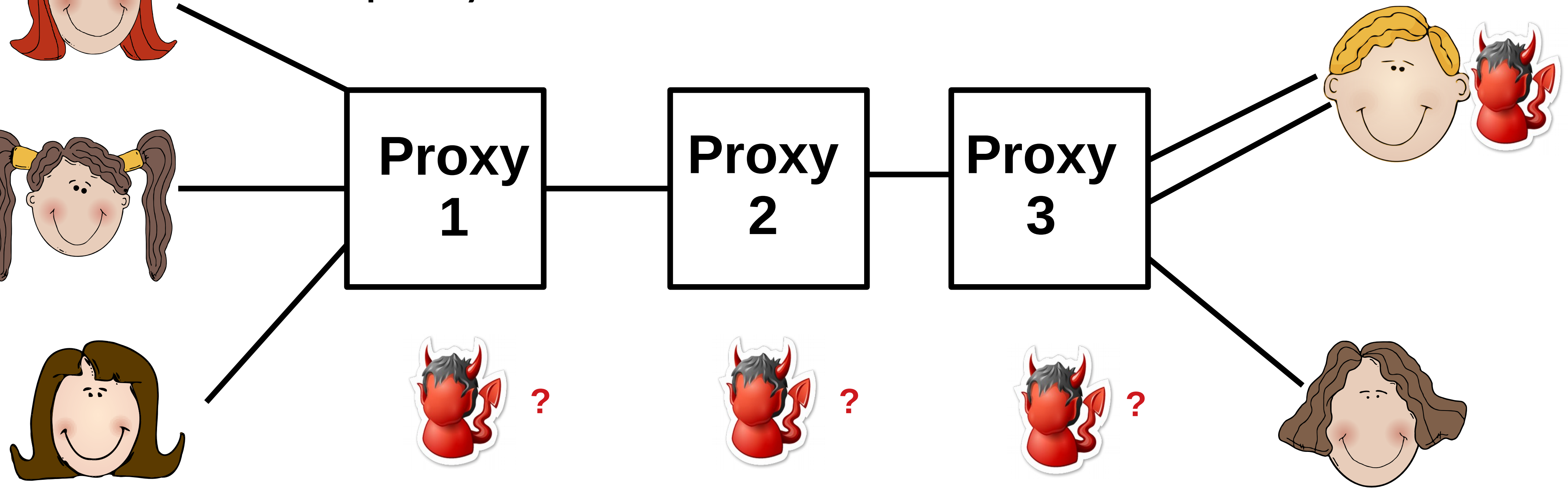
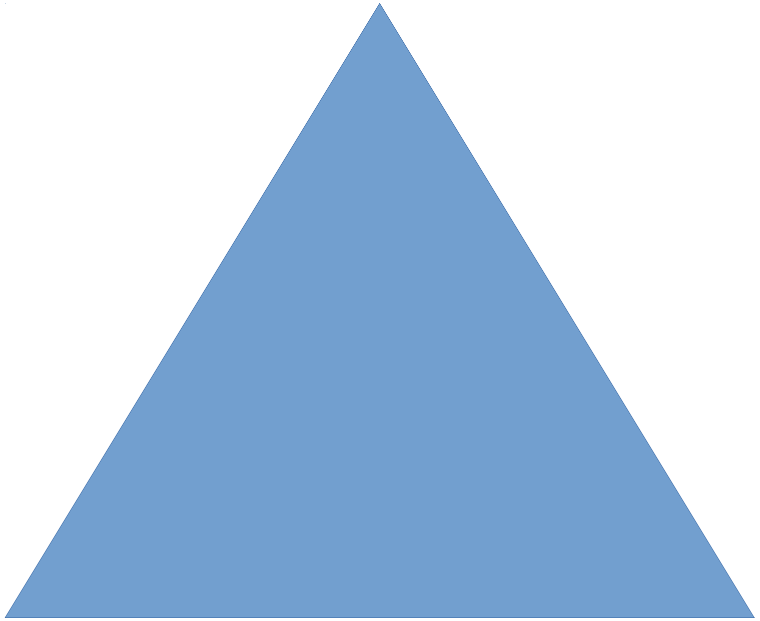


How many proxies need to be **corrupt** to break sender-**receiver** unlinkability against a corrupt receiver?

Using a Proxy Chain

Sender-Message Unlinkability

Sender-Receiver Unlinkability



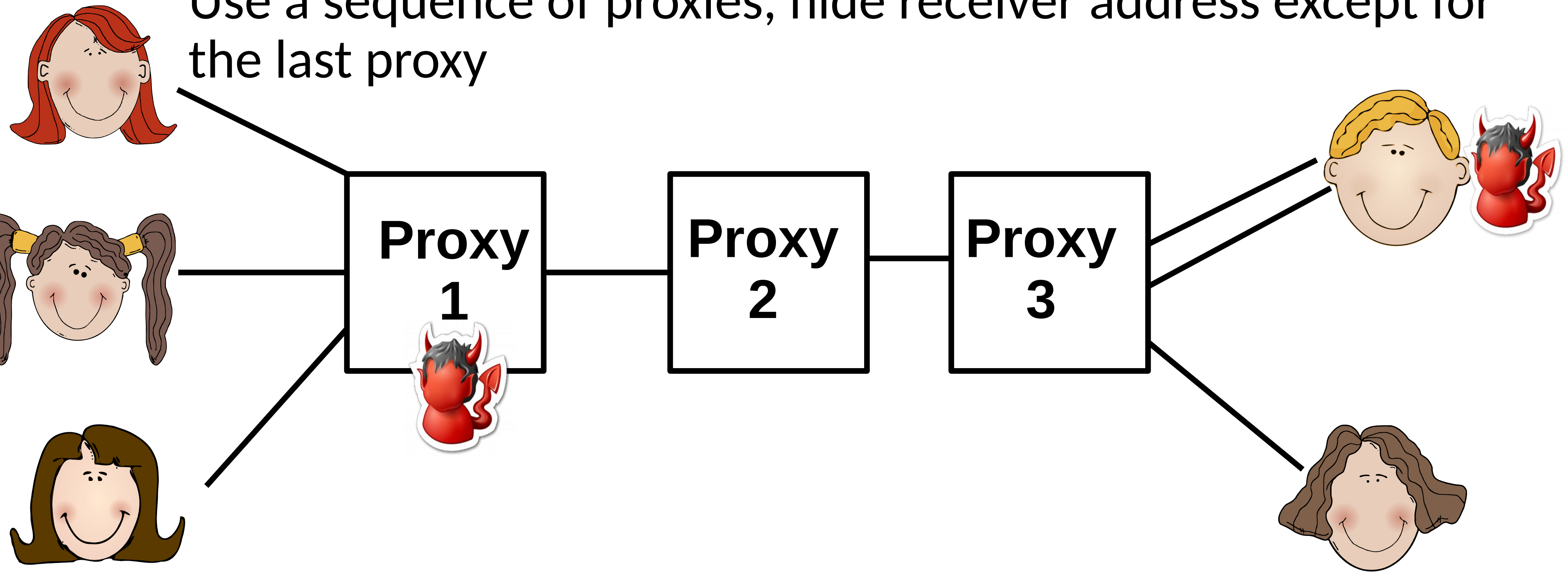
Passive corrupt receiver +
All except first proxy

higher latency
need multiple proxies
Computation overhead to hide receiver address

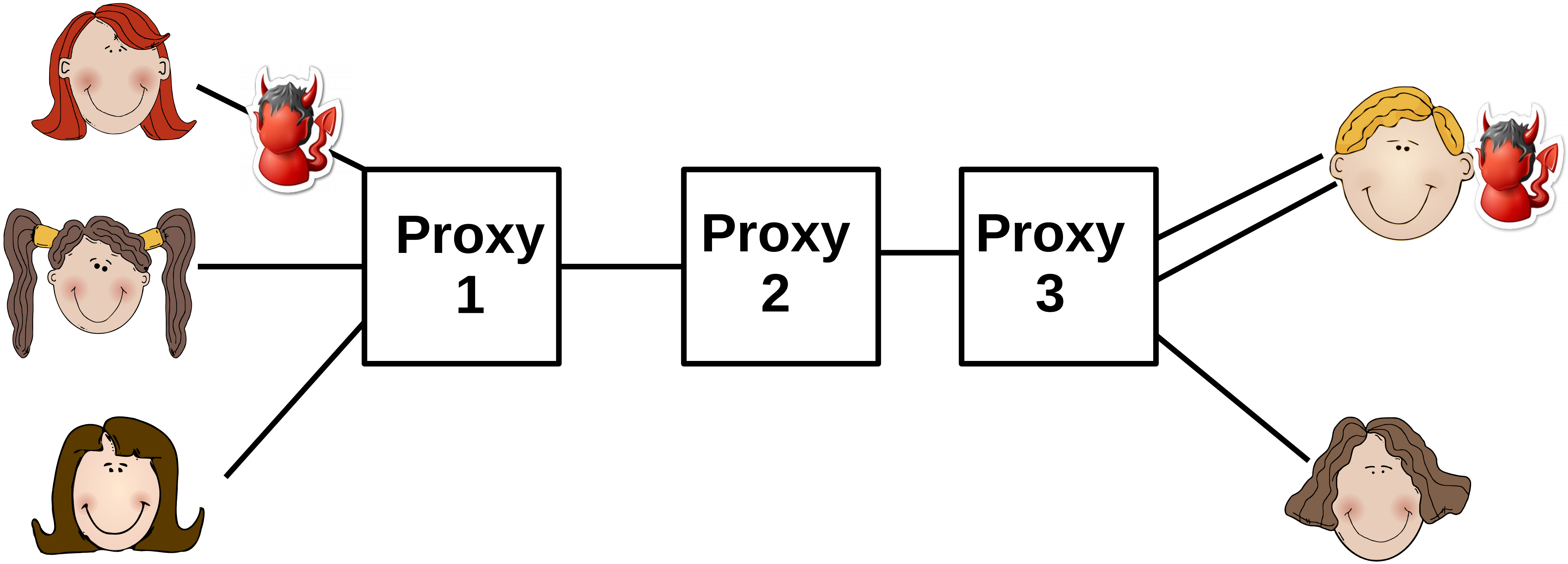
Using a Proxy Chain

Principle 2: Distribution of Trust

Use a sequence of proxies, hide receiver address except for the last proxy

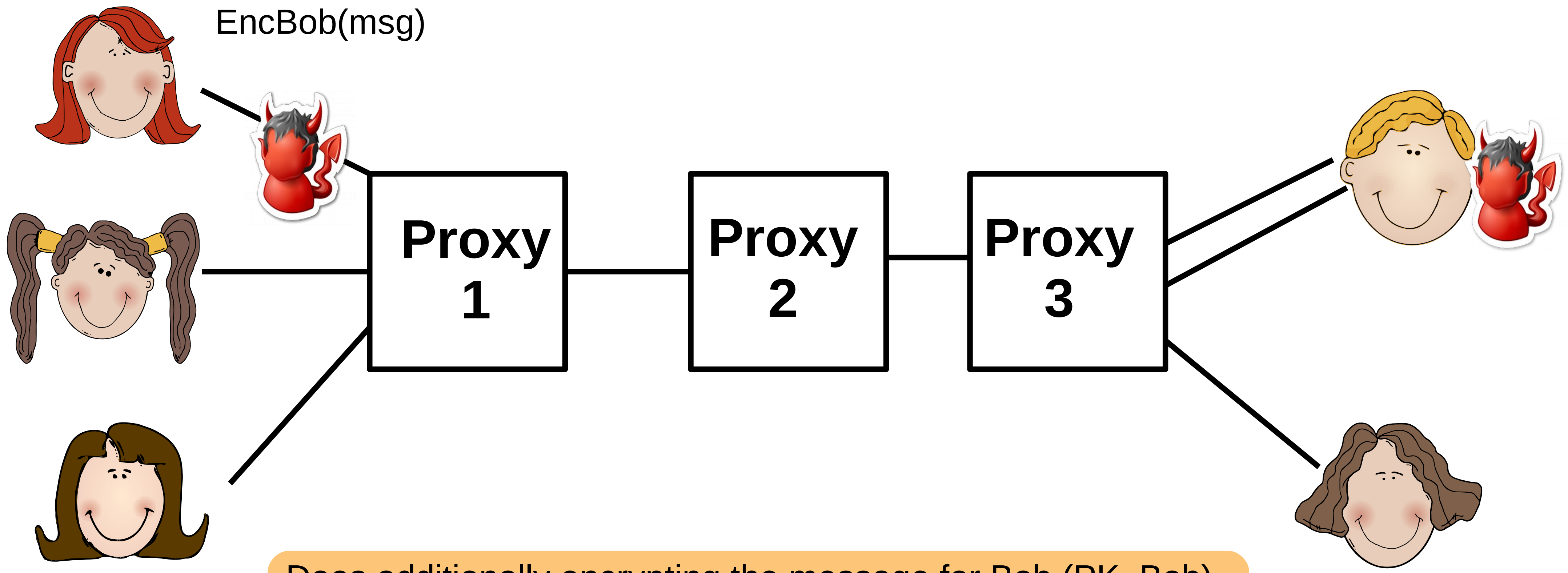


Using a Proxy Chain



Linking via the message works also if adversary is on first link

Adding end-to-end encryption

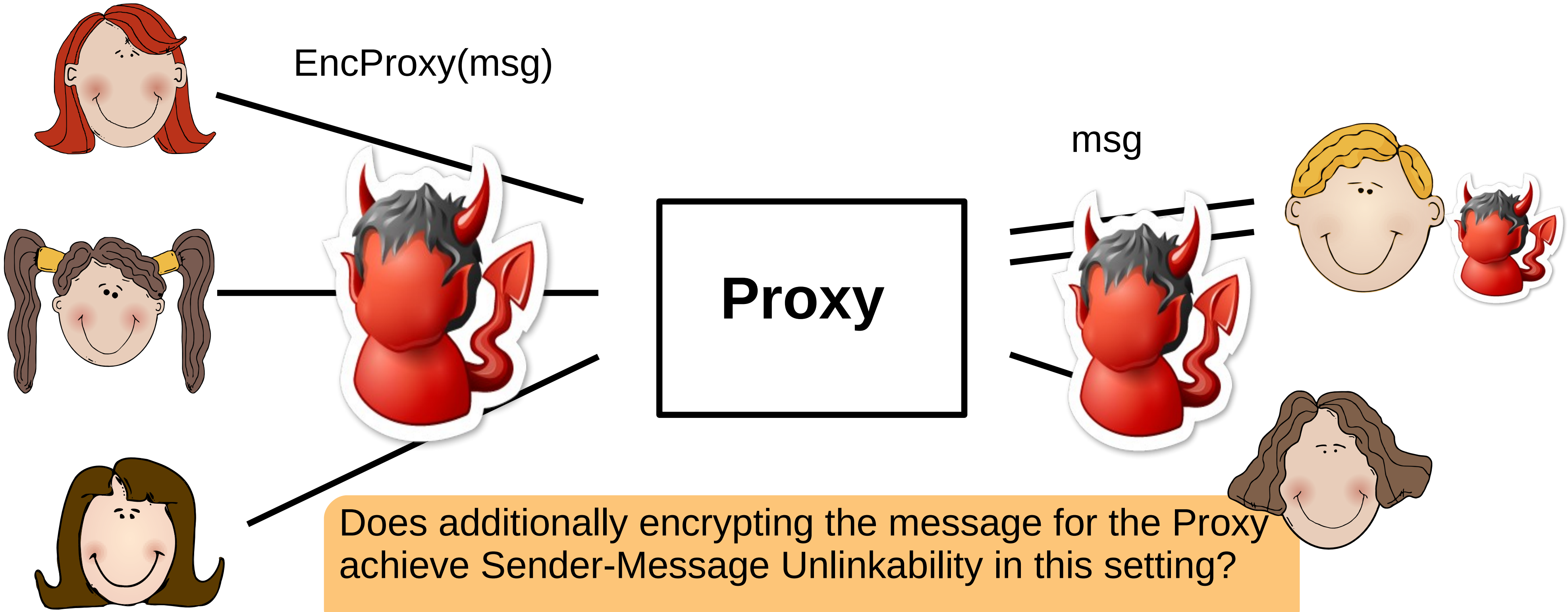


Does additionally encrypting the message for Bob (PK_Bob) achieve Sender-**Message** Unlinkability?

Adding Encryption

Principle 3: Unlink Observations

Principle 4: Randomize Observations

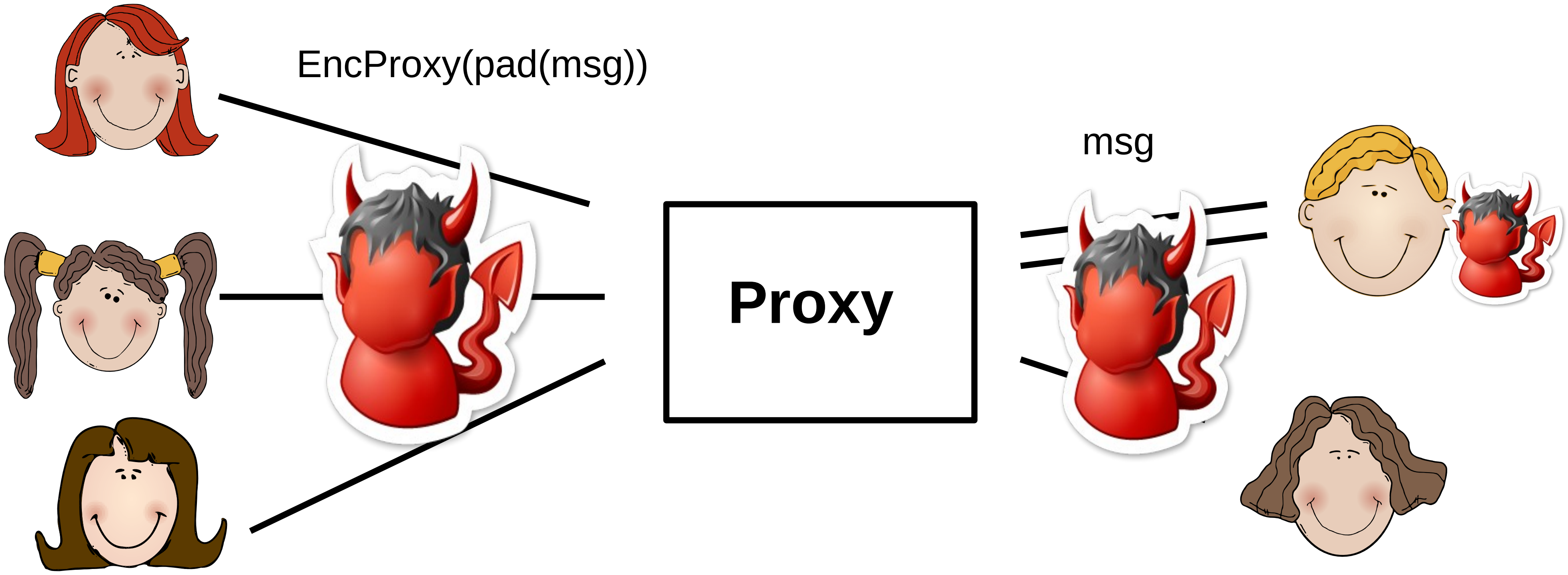


Does additionally encrypting the message for the Proxy achieve Sender-Message Unlinkability in this setting?

Padding against linking based on length

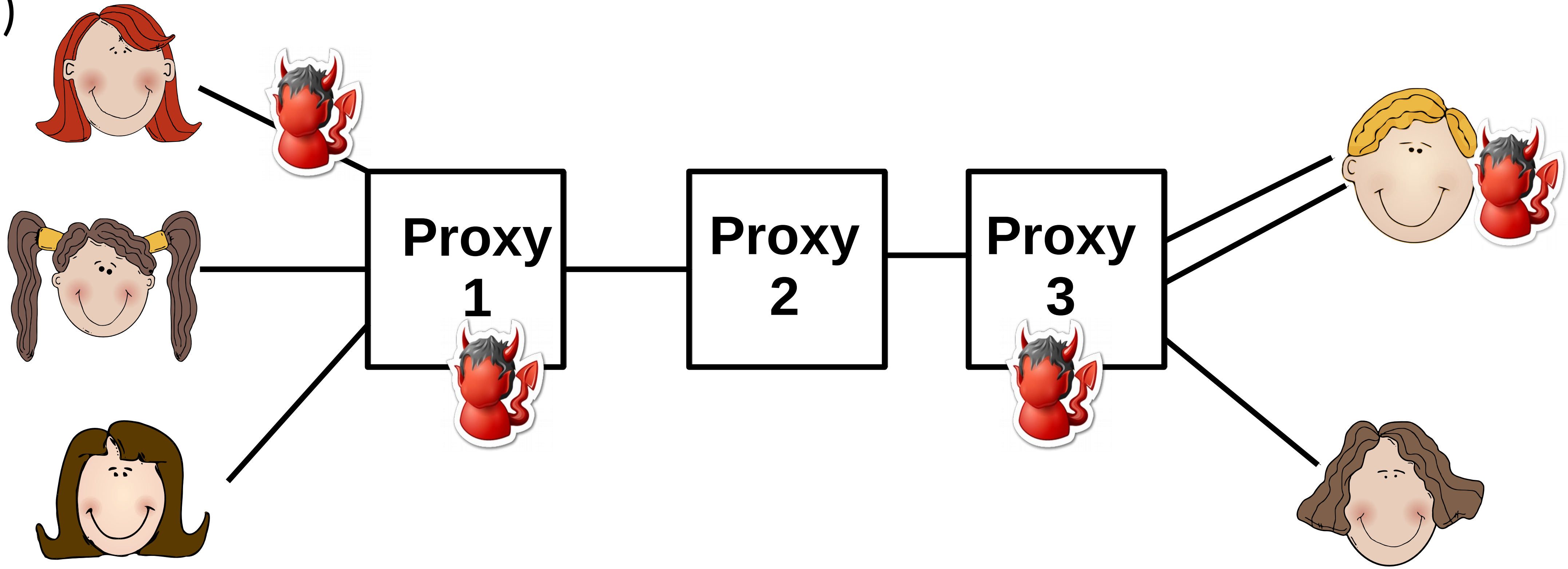
Principle 5: Fix Observations (& Principle 3)

Padding: add random bits to the message to ensure a fixed total length

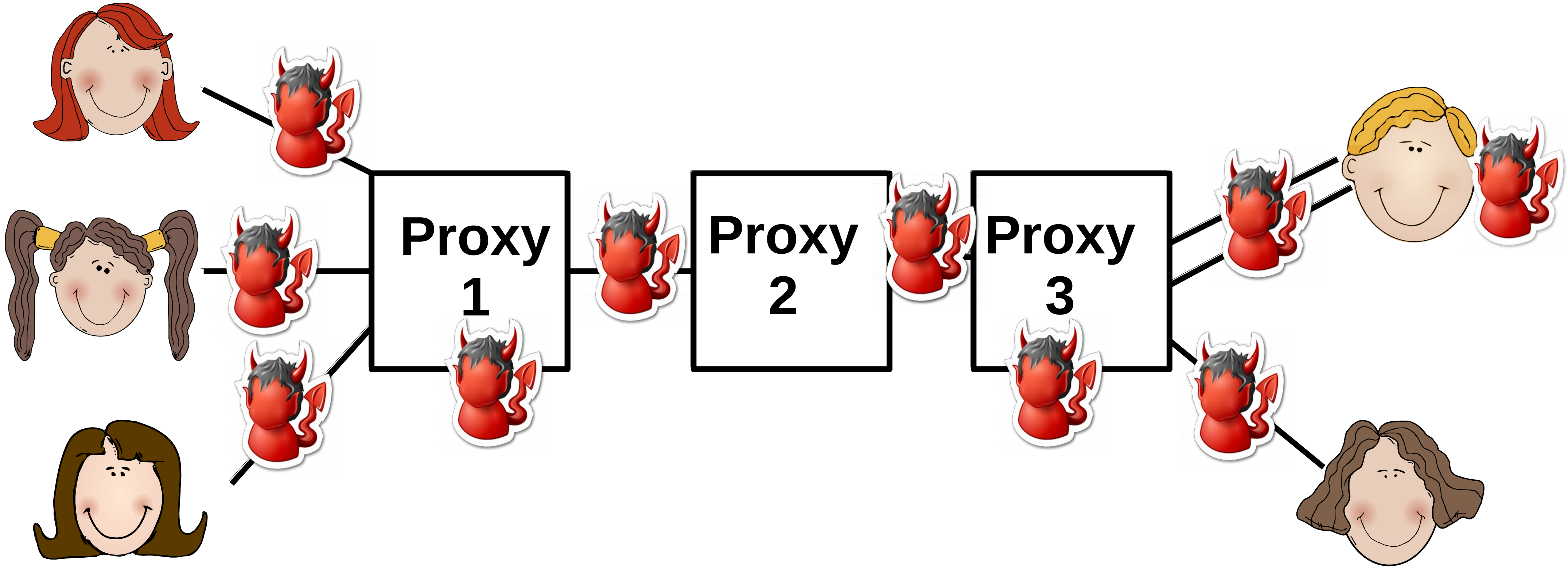


Layered Encryption

- Pad message to fixed length: pad(msg)
- EncProxy1(EncProxy2(EncProxy3(msg,Rec)))
- Usually for confidentiality: EncProxy1(EncProxy2(EncProxy3(EncRec(msg), Rec)))



Layered Encryption + Padding

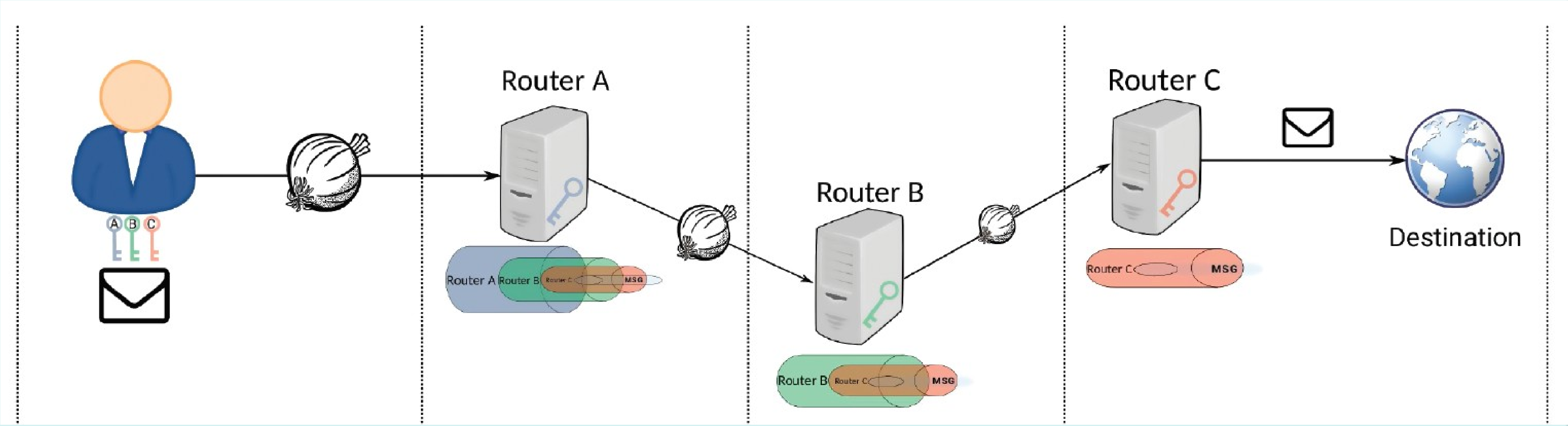


Unlinks sender & receiver, as well as sender & message cryptographically even against a global passive adversary and up to n-1 corrupt proxies!

Timing and Traffic Analysis attacks still possible

Protocol Class: Onion Routing

uses layered encryption and padding
here: proxies = routers (= relays)



Clever tunnel setup: constructing symmetric keys for performance

Onion Routing concept

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- Setup: Sender picks sequence of routers and exchanges symmetric keys
- Sending a message:
  - Pad and encrypt message in a layered fashion
  - **Include routing instruction into layered encryption**:
    EncRouter1(Router2, EncRouter2(Router3, EncRouter3(Rec, msg)))
  - Forwards result (=onion) to the first router

- Onion Routers (ORs):
  - Receive the onion, remove one layer of encryption, pad it and forward it to the next hop.
  - The first node (entry node) <u>is aware of the identity of the sender and the next hop</u>
  - The last node (exit node) is <u>aware of the final destination, message and its predecessor node</u>.

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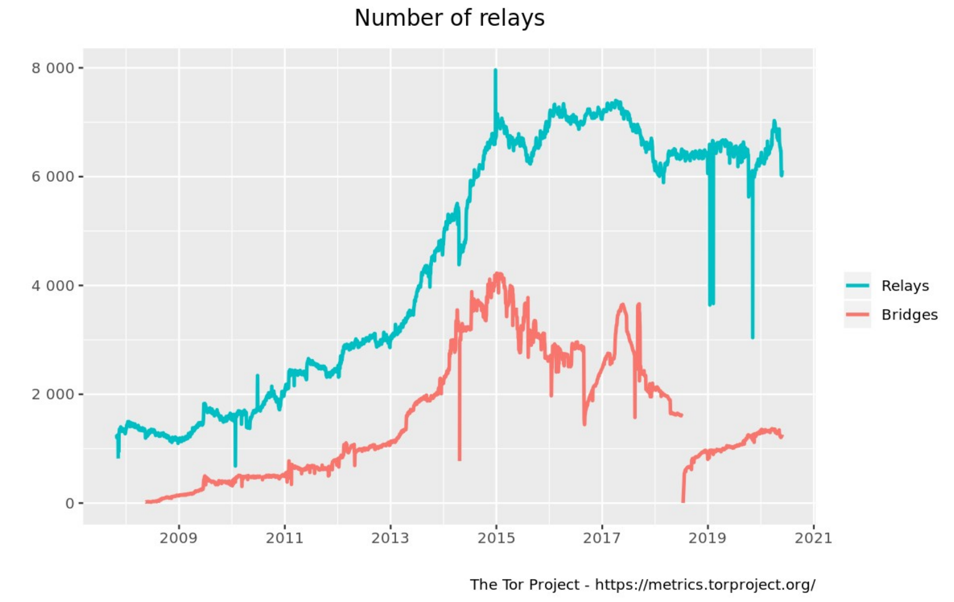
The Onion Router (Tor)

- Largest, most well deployed anonymity preserving service on the Internet
  - Publicly available since 2002
  - Continues to be developed and improved
  - Instrumental to the Arab Spring in 2010 and Snowden's revelations in 2013
- Currently, ~7,000* Tor relays around the world
  - All relays are run by volunteers
- ~ 2,000,000* users
- Extensions (better security, efficiency, deployability)

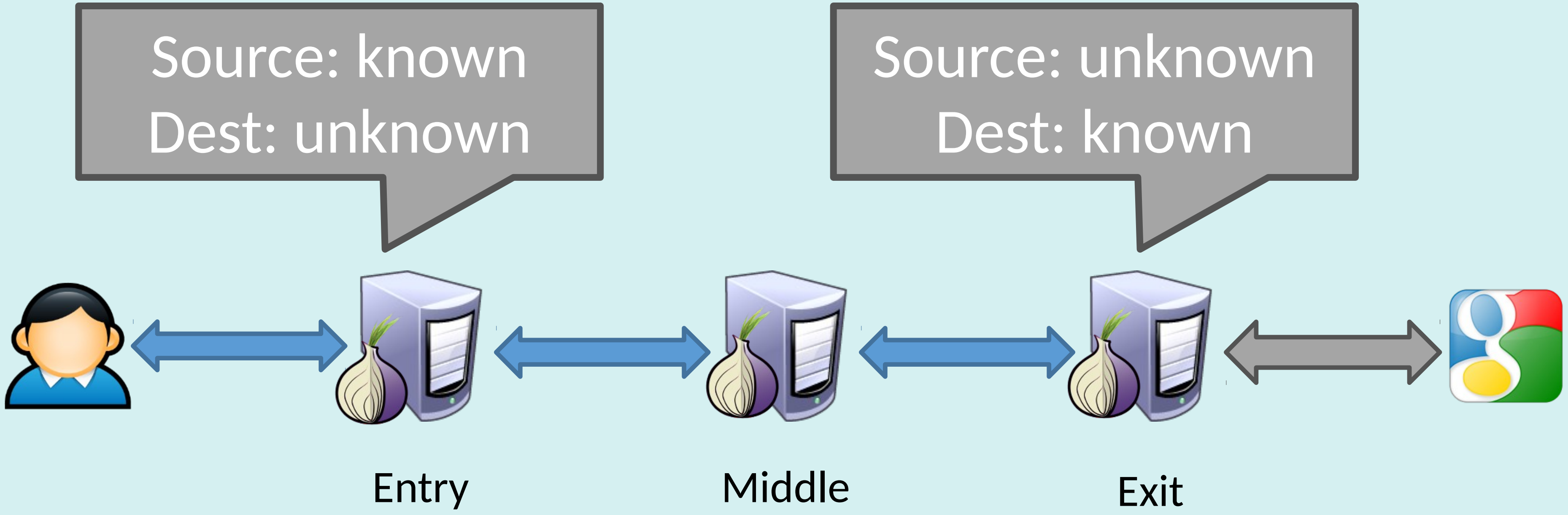


* https://metrics.torproject.org

Onion Routing protocols: TOR

- TOR has trusted Authoritative Servers that:
  - Publish a list (called <u>consensus</u>) of available relays and their information (IP, keys)
  - Updates it regularly (typically every hour)
- Users run a SW called Onion Proxy that handles all TOR related processes
  - E.g., it gets the *consensus* and selects nodes (usually 3) to build a circuit
  - Node selection policy: high-bandwidth nodes with higher probability
  - Build new circuits periodically

TOR's Privacy



- Tor users can choose any number of relays
  - Default configuration is 3

Does Tor achieve Sender-Receiver Unlinkability against a global passive adversary?

Traffic Analysis and timing attacks!

Predecessor Attack

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- Client periodically builds new circuits
  - Over time the chances to pick corrupt first and last relay increase!

- Mitigation: Guard nodes
  - Tor client selects a few relays at random to use as entry points
    - Pick stable and reliable guards (long uptimes, high bandwidth)
  - uses only those relays for her first hop during a few months

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TOR and Onion Routing Summary

- Use layered encryption, padding and a proxy-chain to distribute trust and unlink observations
- FIFO-like forwarding, no delay
- Susceptible to traffic analysis and timing attacks of the global passive adversary (or first and last router) → Guards as mitigation
- Sender-Message and Sender-Receiver Unlinkability for local adversaries
- Applicable to low latency services (e.g., browsing)

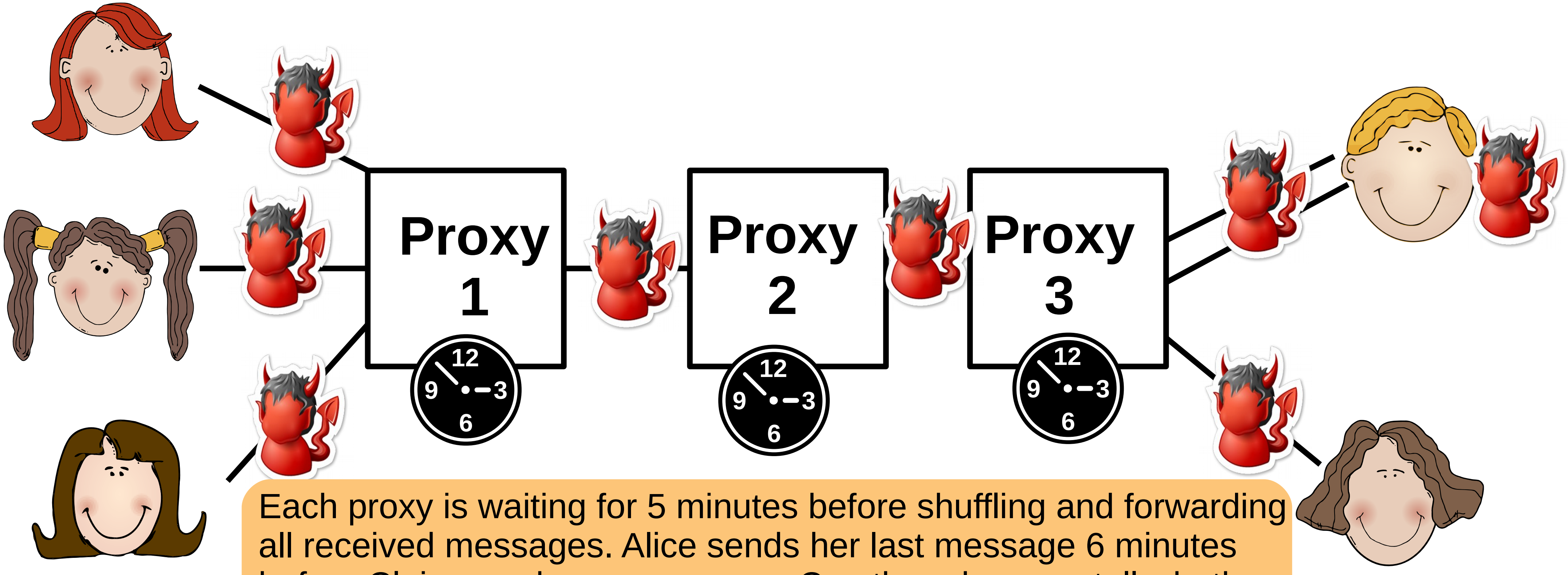
more users = larger anonymity set

Protect against Timings – Mixing

Principle 3 & 4 (unlink & randomize observations)

Timings & traffic patterns are used for linking…

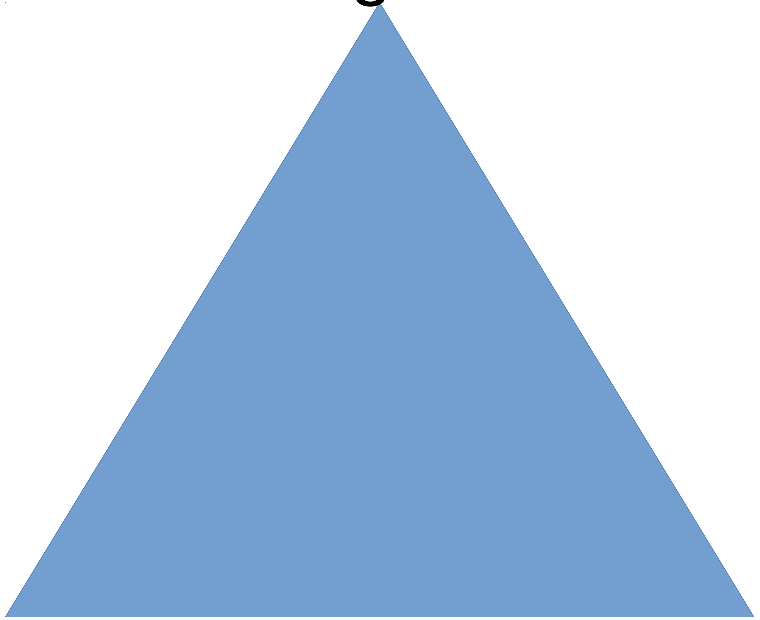
→ collect message at each proxy (delay) and forward in random order



Each proxy is waiting for 5 minutes before shuffling and forwarding all received messages. Alice sends her last message 6 minutes before Claire sends any message. Can the adversary tell whether a received message is from Alice or Claire?

Layered Encryption, padding and Mixing

Sender-Message Unlinkability
Sender-Receiver Unlinkability
(for users sending in the same round)



Global passive adversary, corrupt receiver and up to n-1 corrupt proxies

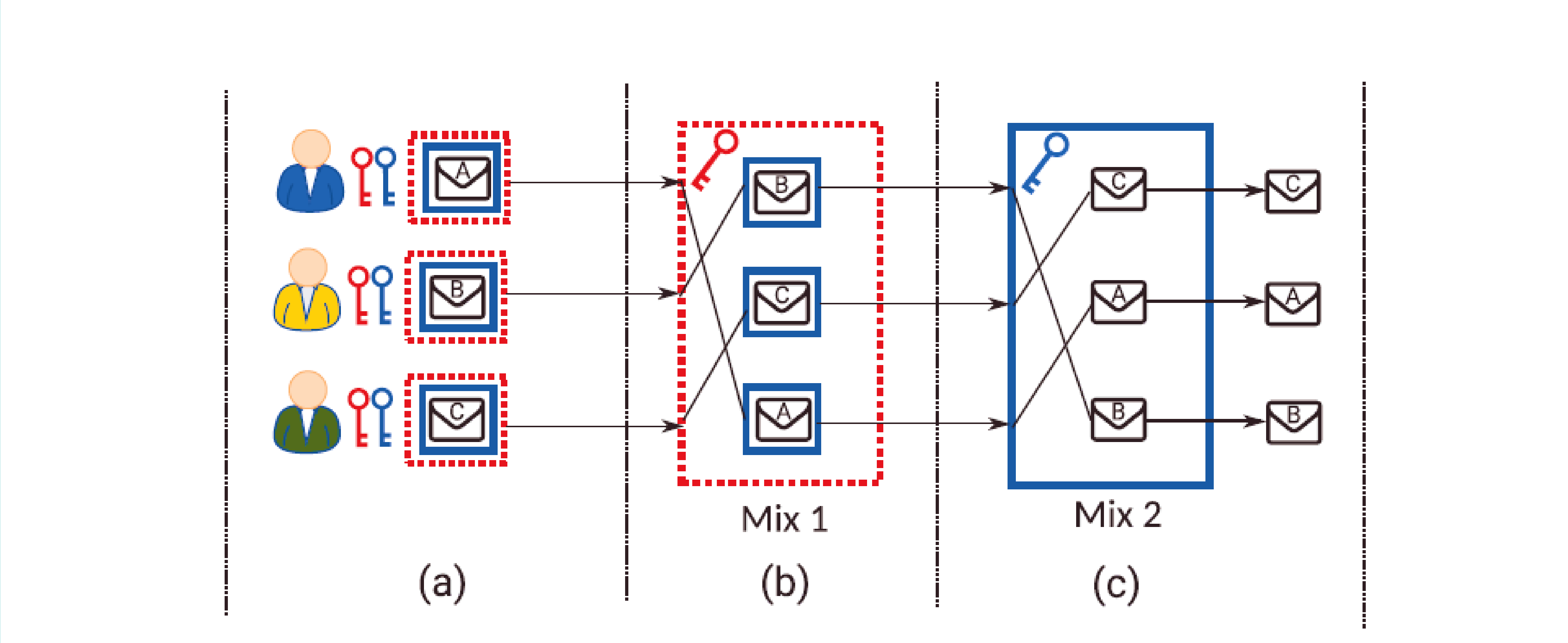
Much higher latency
slightly more computation at proxies
Need proxies

Mix Systems: concept

- originally proposed by Chaum (1981)
- Proxies = *mixes* (= *mixes nodes* = *relays*):
  - cryptographically transform messages to unlink input and output messages based on content or size (layered encryption and padding)
  - Shuffle ("mix") input messages and output them in a reshuffled form to unlink messages based on their order/timing
- Different (*mix) node selection strategies* and *mixing strategies*

Chaum’s Mix: Mix Cascade

relay messages through a **fixed** sequence of mix nodes



Chaum's Mixnet:

- ***Mix Cascade***: relay messages through a fixed sequence of mixes
  - mixes are **selected deterministically**
  - *Fixed size* messages encrypted (in a layered fashion) with the public key of each mix in the cascade
  - Message transfer: each mix:

    - waits for messages (**until k received**)

    - decrypts the corresponding layer with its private key

    - shuffles messages (*sorts lexicographically*)

    - forwards batch of messages to the next mix
  - repeated until the last mix delivers the data to its final destination

Mix node selection strategies

- Availability drawback: Cascades = **single point of failure**
- *Improve Availability: Free-route* mix networks
  - route is not fixed, any sequence of nodes from the network can be used for relaying messages

Mixing strategies

- Flushing algorithm: specifies the precise timing when messages are forwarded
  - Timed mixes: enforce a time restriction for flushing out messages

Does the privacy of timed mixes decrease
(i.e. smaller anonymity sets) if the traffic is low?

Mixing strategies

- Flushing algorithm: specifies the precise timing when messages are forwarded
  - Timed mixes: enforce a time restriction for flushing out messages
  - Threshold mixes: collect messages until a threshold is reached

Does the privacy of of threshold mixes decrease
(i.e. smaller anonymity sets) if the traffic is low?

Mix Systems: mixing strategies

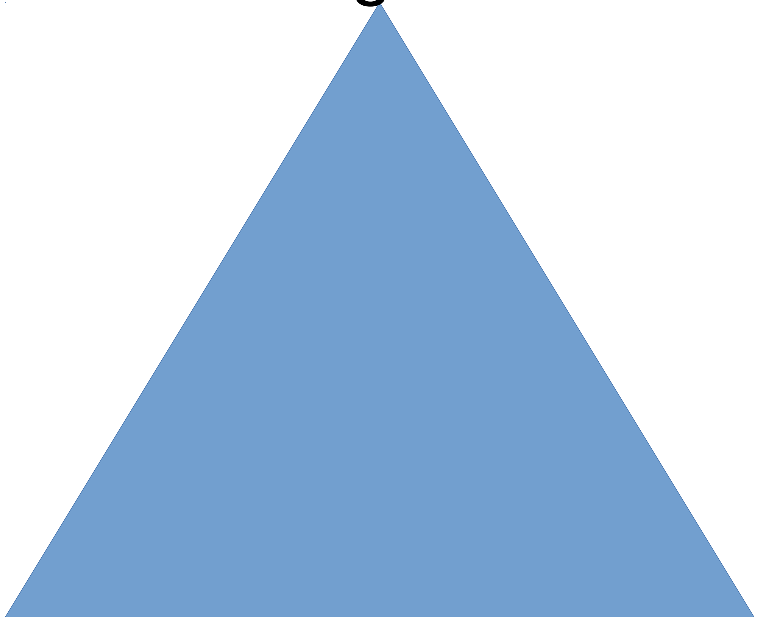
- Timed Mixes: enforce a time restriction for flushing out messages
  - vulnerable to low traffic
- Threshold mixes: collect messages until a threshold is reached
  - Very high latency if the traffic load is low
- *Stop-and-Go* mixes: independent random delays are assigned to each mix
  - Performance is not dependent of the other users
  - Vulnerable when incoming traffic is low
- Pool Mixes: keep messages in pool, send out randomly selected messages, if new messages arrive
  - Suitable for fluctuating traffic

Mix Systems: Summary

- Layered encryption, padding and delaying in a proxy chain
- Show very heterogeneous designs: *free-route* vs. *Cascades*, *pool vs. Threshold vs. Stop-and-go vs. Timed*
- *Unlink senders from messages and receivers* ***also in the timing dimension*** *against global adversaries*
- High-latency
  - non-interactive services where users are willing to tolerate delays that can range from seconds to hours
  - suitable for services like e-mail and electronic voting

Layered Encryption, padding and Mixing

Sender-Message Unlinkability
Sender-Receiver Unlinkability
(for users sending in the same round)

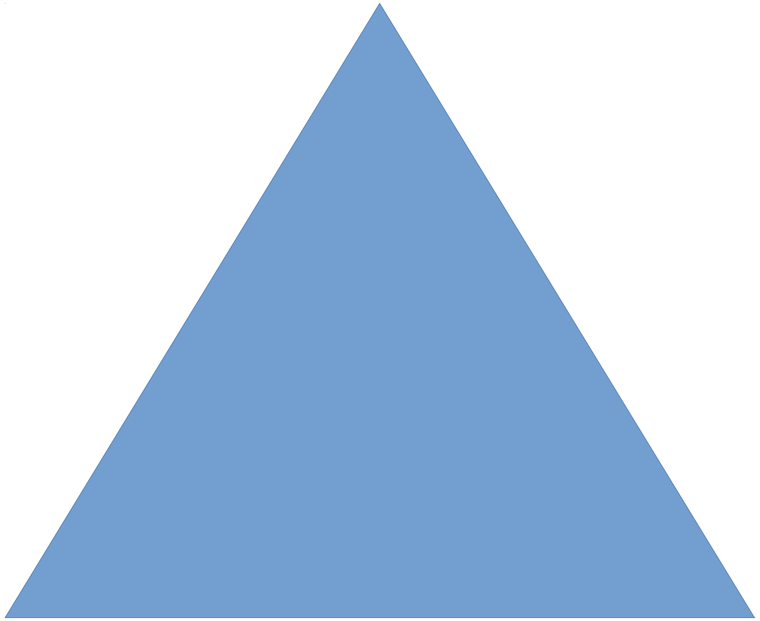


Global passive adversary, corrupt receiver and up to n-1 corrupt relays

Much higher latency
slightly more computation at proxies
Need proxies

Hiding Activity and Frequencies

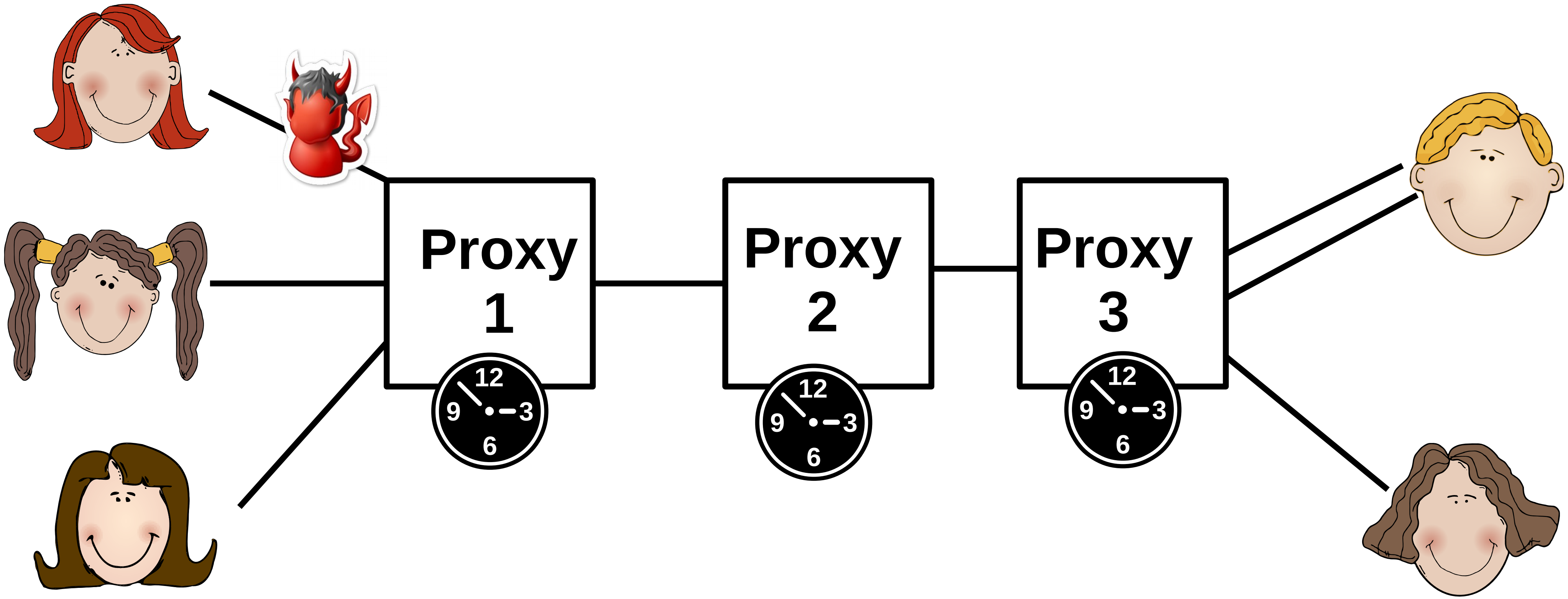
Sender Unobservability



Local adversary at
the sender

Hiding Activity and Frequencies

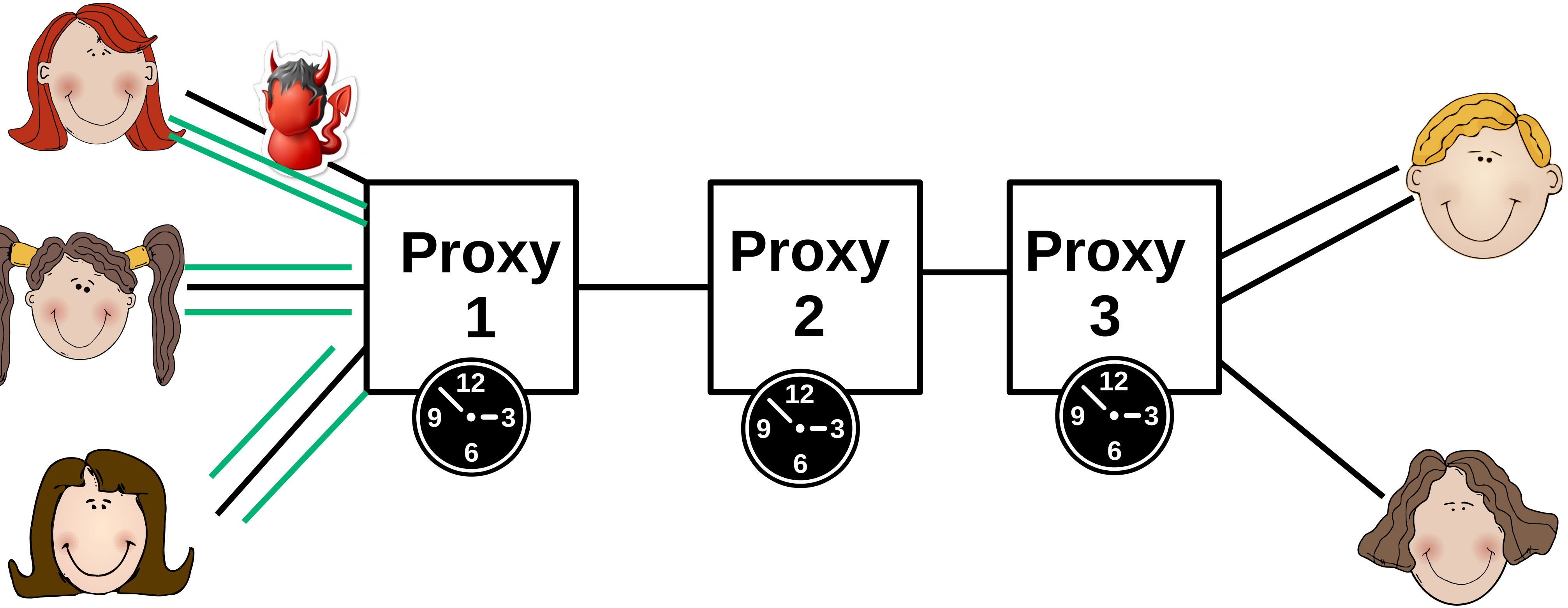
- Every packet is a “real” communication



Dummy Traffic

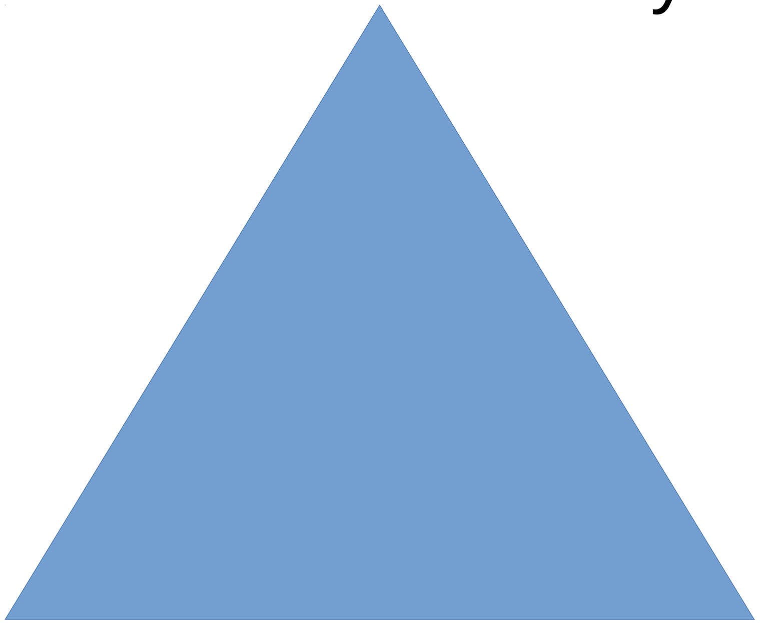
Principle 4 or 5 (randomize or fix observations)

- Add “fake” communications that are dropped at some party
- Need to be indistinguishable from real communications for the adversary



Adding Dummy Traffic on the first link to Mixing

(upgrade to)
Sender Unobservability
[also increases anomity set]



Local adversary at the first link

(additional)
Bandwidth overhead = network load

Types of Dummy Traffic

- Strategy: to a fixed number of communications or randomize number per round and user
- Area: end-to-end, link-based or anything in between
- Communication partner: real user or dedicated party
- Amount: e.g. >=1 (hide activity) or = max number of delivered messages (hide frequency)

- Combination of choices determines the cost in terms of bandwidth overhead

Dummy Traffic: Summary

- Usually combined with other techniques (e.g. Mixing, Onion Routing)
- Hide activity and sending/receiving frequencies
- Many variations with different cost and effects possible
- Improves anonymity set size

An alternative Approach to unlink Senders and Messages?

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For receivers: Broadcast! The message is received by everyone!

Can we make it look like the messages is sent from every user
(without trusting all other users)?

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An alternative Approach to unlink Senders and Messages?

For receivers: Broadcast! The message is received by everyone!

Can we make it look like the messages is sent from every user (without trusting all other users)?

YES, and Chaum knows how: we ensure that every user contributes a part needed to recover the final message…

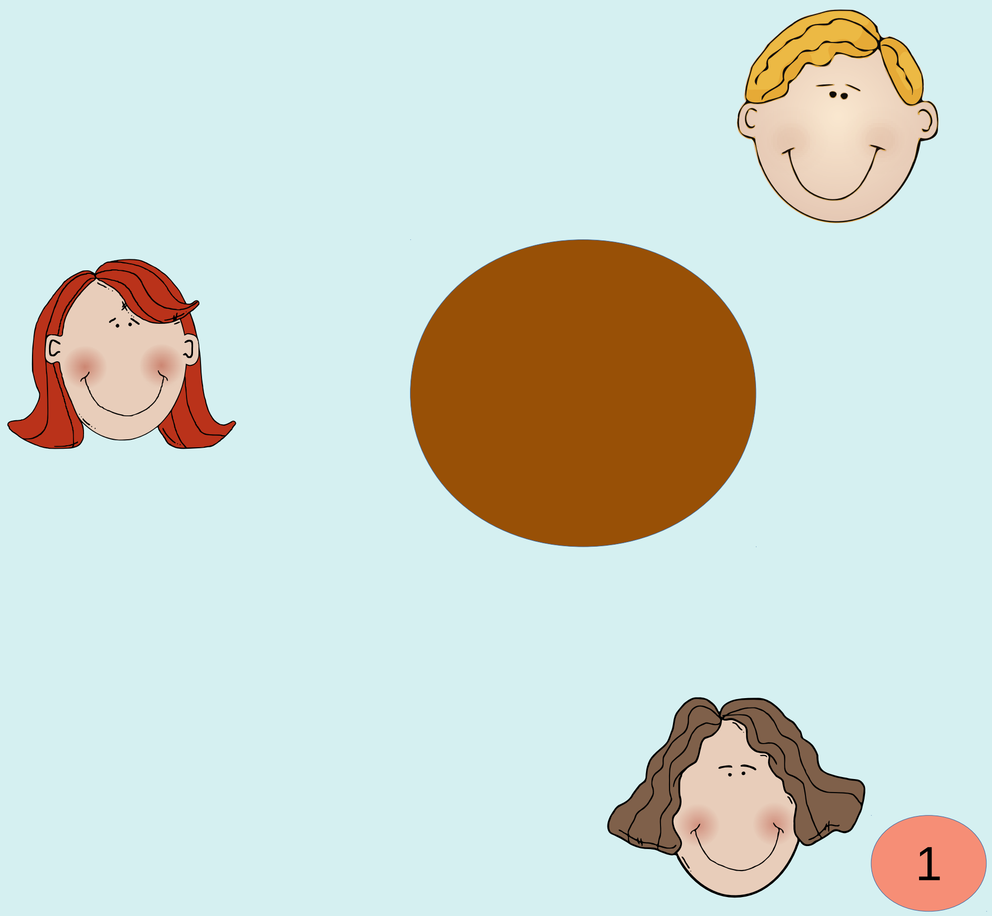
DC-Nets concept

- The idea of DC-Nets was first proposed by Chaum (1988)
- Inspired by a scenario:
  - 3 cryptographers went for dinner

  - they learn that the bill is payed

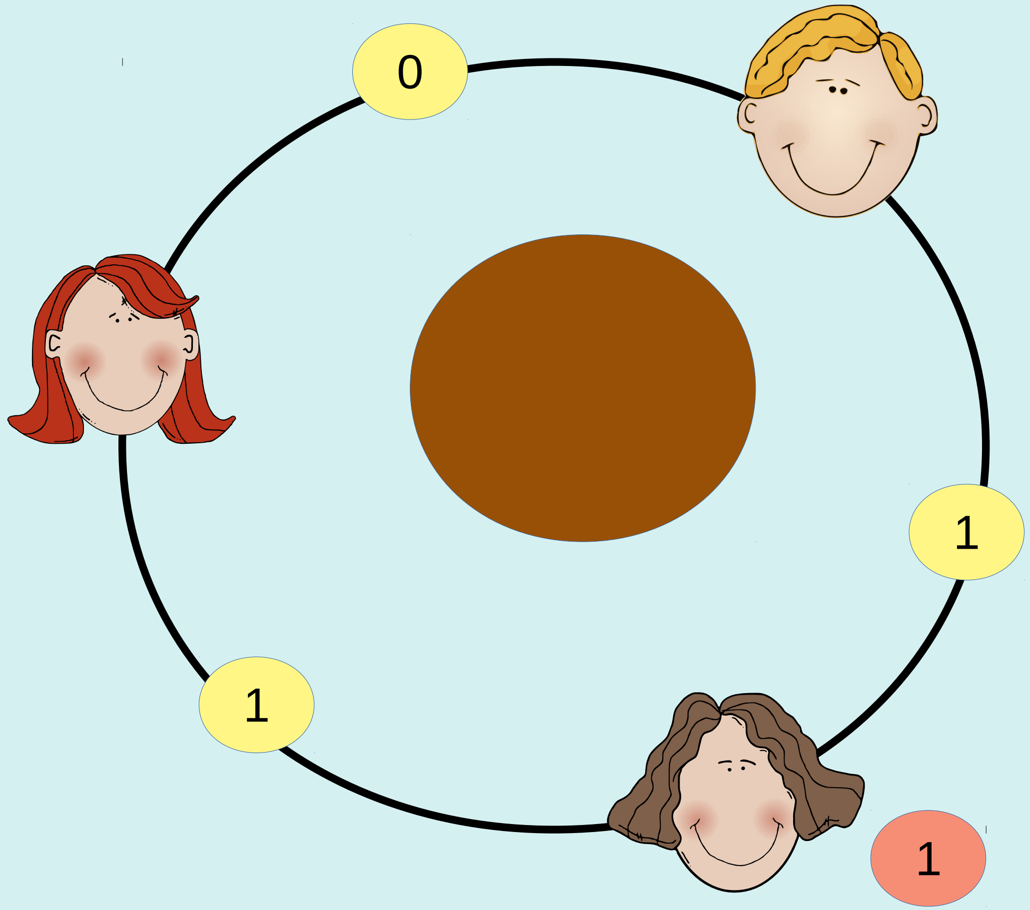
  Was the dinner payed anonymously by one of them or by the National Security Agency (NSA)?

  - can they figure this out while respecting anonymity?



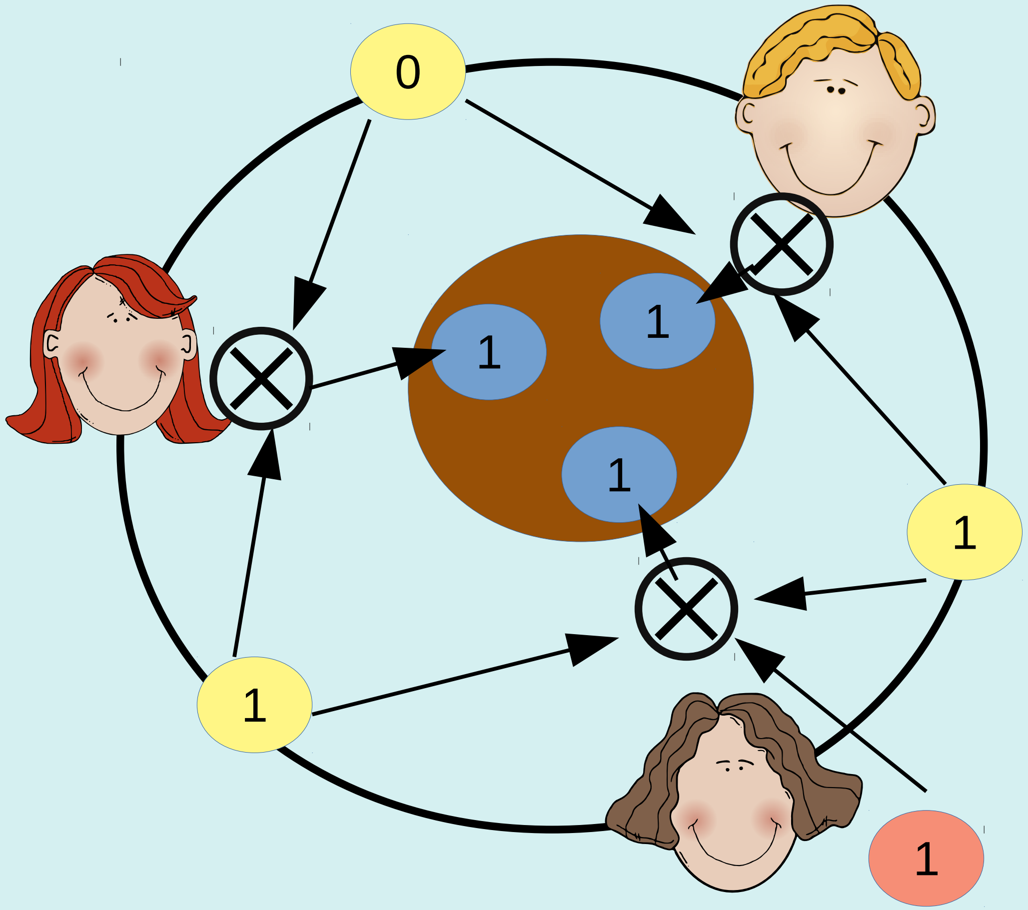
DC-Nets concept: superposed Sending

- Flip a coin with each neighbor



DC-Nets concept: superposed Sending

- Flip a coin with each neighbor
- XOR coin results
- If you payed: reverse result of XOR
- Reveal local result



DC-Nets concept: superposed Sending

- Flip a coin with each neighbor
- XOR coin results
- If you payed: reverse result of XOR
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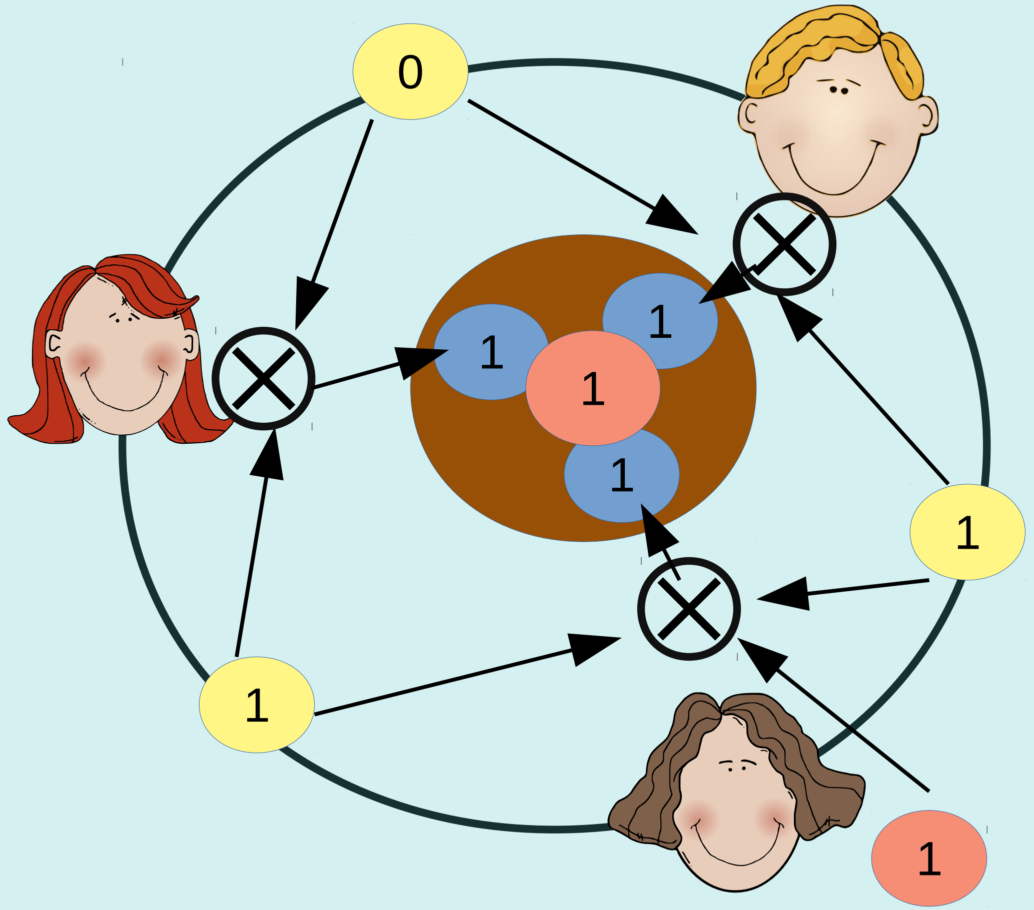
- XOR all local results:

  0: NSA payed for the dinner

  1: A cryptographer payed for the dinner



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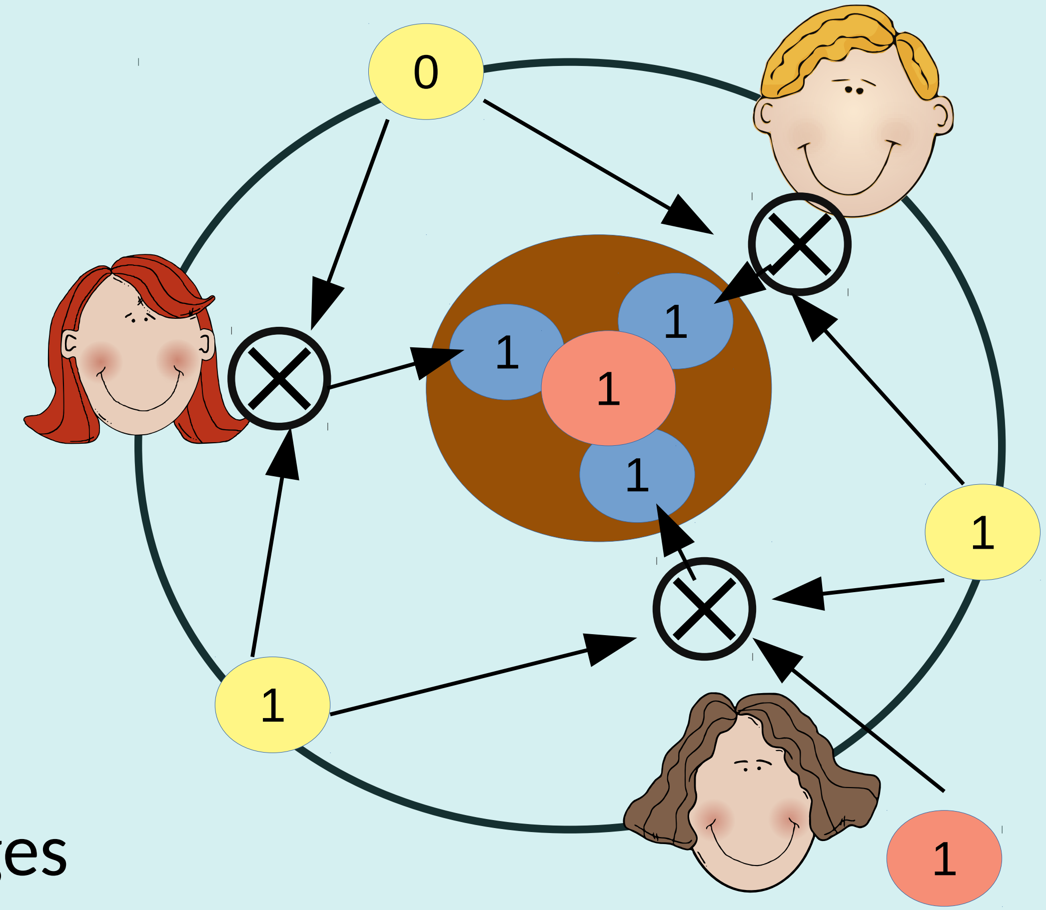


- Transmits 1 bit → Repeat for longer messages

DC-Nets: protocol features

Assume: At most one person sends per round

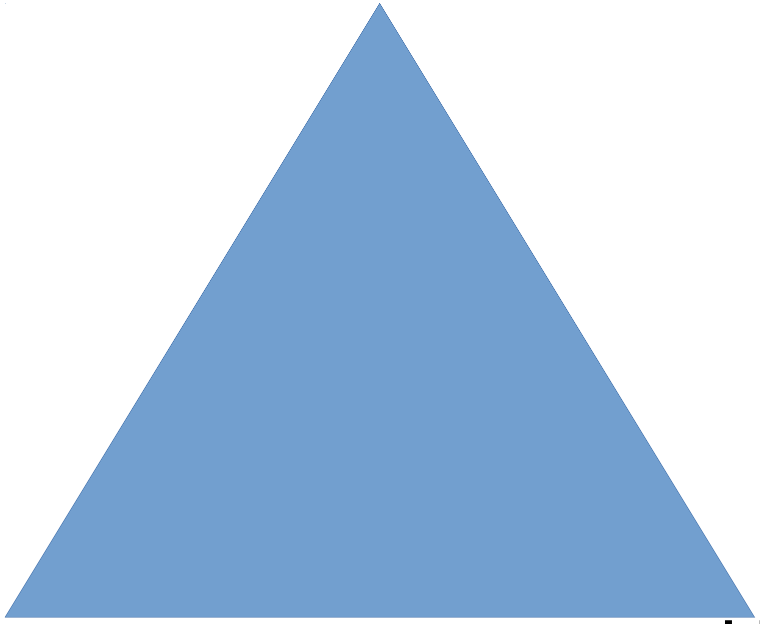
Collisions are possible!

- 1 sender: message is delivered
- 2 senders: both try to send and the output will be their messages XORed
- Can be used to disrupt the protocol (availability)

- New proposals introduce topology modifications and mechanisms to detect disruption

Superposed Sending

Sender-Unobservability



Global passive adversary and up to n-2 corrupt participants

High bandwidth overhead
Collisions and DoS
Scalability issues

Learning Goals

- Understand the Problem
  - Motivation and Setting
  - Dimensions and Terminology

- Understand the Solution(-space)
  - Solution ideas and prominent protocols:
    - Random Walk
    - Onion Routing
    - Mix Networks
    - Dummy Traffic
    - DC Networks
  - Effects of design decisions

Summary Principles:

- Principle 1: Indirection
- Principle 2: Distribution of Trust
- Principle 3: Unlink Observations
- Principle 4: Randomize Observations
- Principle 5: Fix Observations

Summary Strategies:

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- Proxy
- Proxy Chain
- Encryption
- Padding
- Delays (Mixing)
- Dummy Traffic
- Superposed Sending (DC-Nets)

Protocol classes

Name	Goal (Sender side)	Adversary	Cost
Random Walk	Sender-Receiver Unlinkabiliity, Sender-Message Unlinkability	External, passive	(Low) Latency
Onion routing	Sender-Receiver Unlinkabiliity, Sender-Message Unlinkability	Local adversary	Low Latency
Mixnets	Sender-Receiver Unlinkabiliity, Sender-Message Unlinkability	Global, passive, corrupt up to n-1 mixes on path	High Latency
+ Dummy Traffic	Sender Unobservability	variable	Bandwidth
DC-Nets	Sender Unobservability	Global, passive, corrupt up to n-2 participants	Bandwidth, DoS vulnerability

Summary

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- Criteria (the 3 “what”s)

- Overview over solution space
- Understanding of the interplay of adversary, goal and cost
- Understanding of combination of strategies in protocols

- We focused on passive attacks and sender protection (there is much more to learn if you’re interested!)

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Further reading

- Protocol Overview: Shirazi, Fatemeh, et al. "A survey on routing in anonymous communication protocols." ACM Computing Surveys (CSUR) 51.3 (2018): 1-39.
- Goals: Kuhn, Christiane, et al. "On Privacy Notions in Anonymous Communication." Proceedings on Privacy Enhancing Technologies 2 (2019): 105-125.
- Crowds: Reiter, Michael K., and Aviel D. Rubin. "Crowds: Anonymity for web transactions." ACM transactions on information and system security (TISSEC) 1.1 (1998): 66-92.
- Tor: Dingledine, Roger, Nick Mathewson, and Paul Syverson. Tor: The second-generation onion router. Naval Research Lab Washington DC, 2004.

Further reading

Karlsruhe Institute of Technology

- Tor: https://www.torproject.org/
- Chaum Mix: Chaum, David L. "Untraceable electronic mail, return addresses, and digital pseudonyms." Communications of the ACM 24.2 (1981): 84-90.
- DC-Net: Chaum, David. "The dining cryptographers problem: Unconditional sender and recipient untraceability." Journal of cryptology 1.1 (1988): 65-75.
- Predecessor attacks: Wright, Matthew K., et al. "The predecessor attack: An analysis of a threat to anonymous communications systems." ACM Transactions on Information and System Security (TISSEC) 7.4 (2004): 489-522.

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