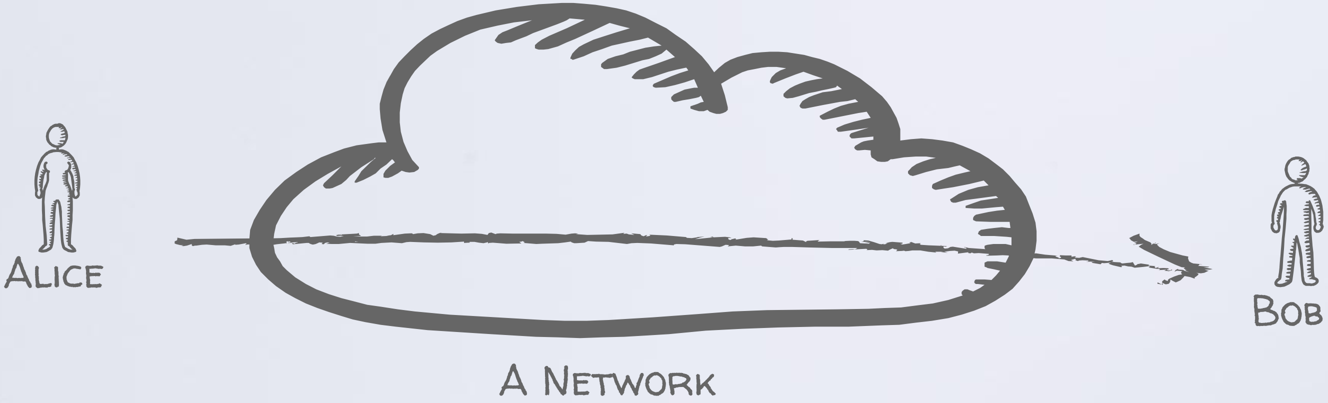
Traffic Analysis

high latency anonymous communications

Carmela Troncoso*
IMDEA Software Institute

*Thanks to George Danezis for sharing slides

Privacy in electronic communications



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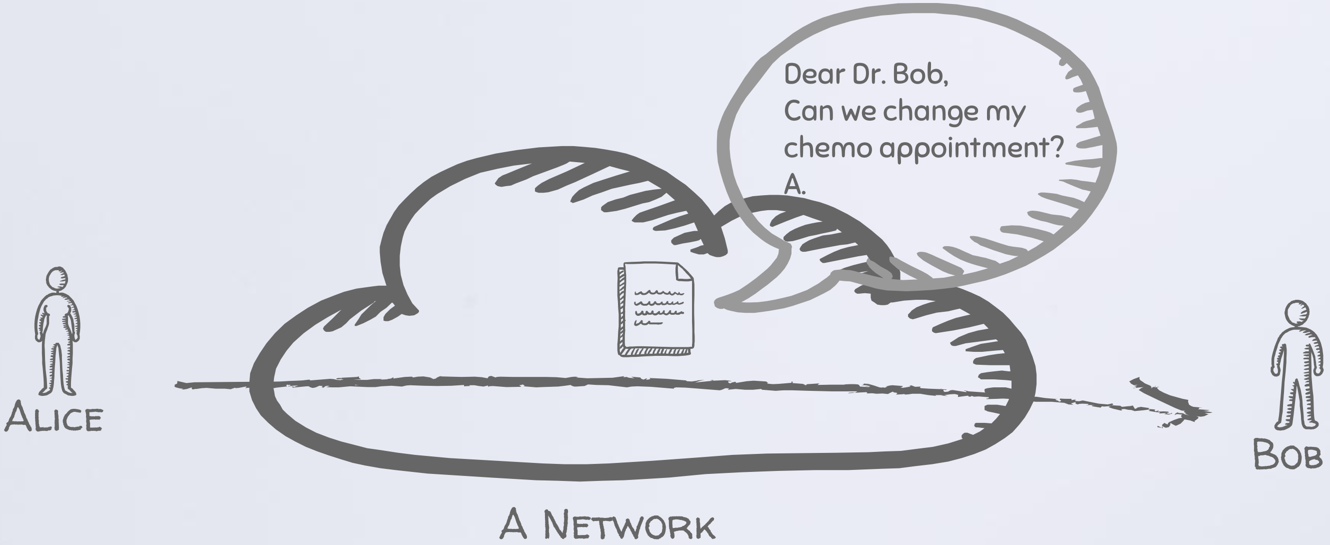


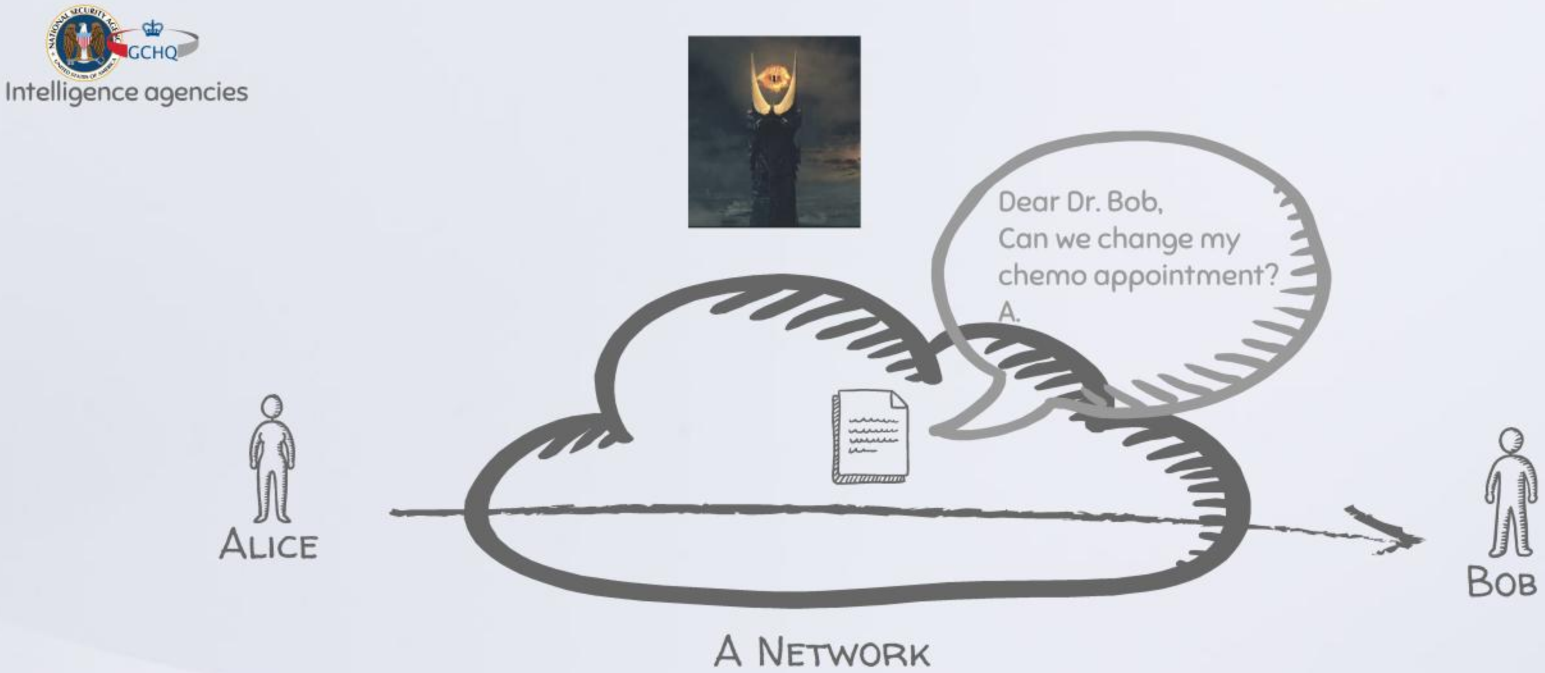
Dear Dr. Bob,
Can we change my chemo appointment?
A.

Alice

Bob

A Network

Privacy in electronic communications



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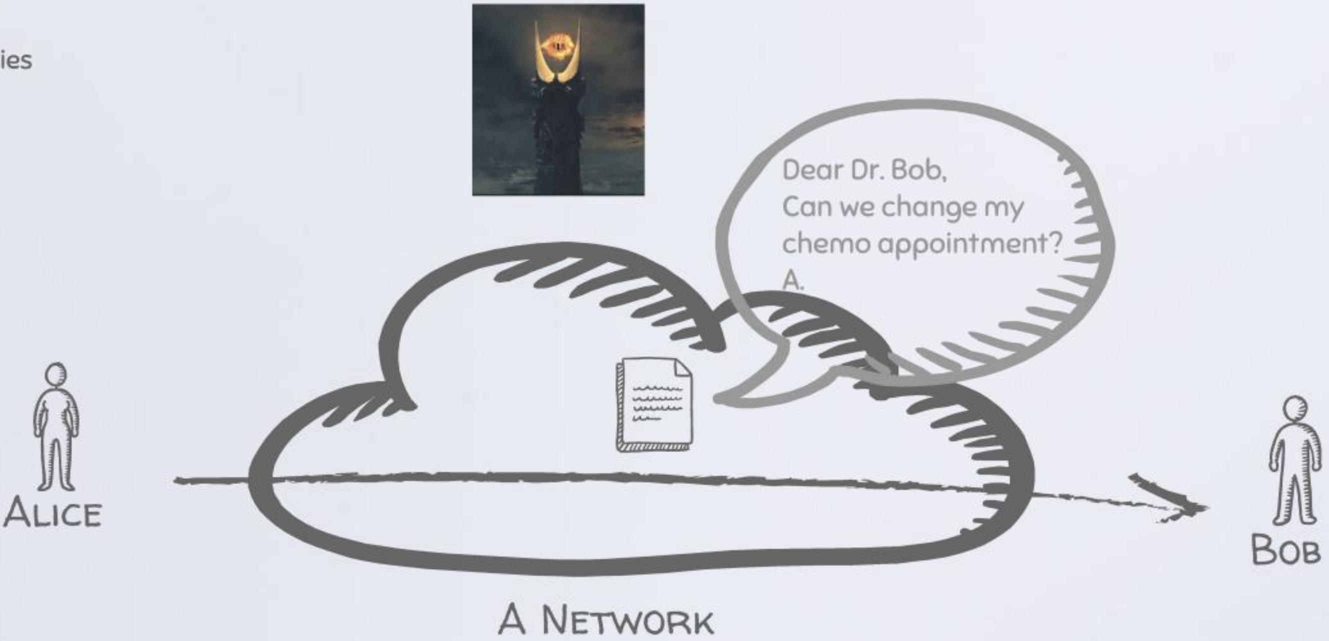
SysAdmins

ISPs



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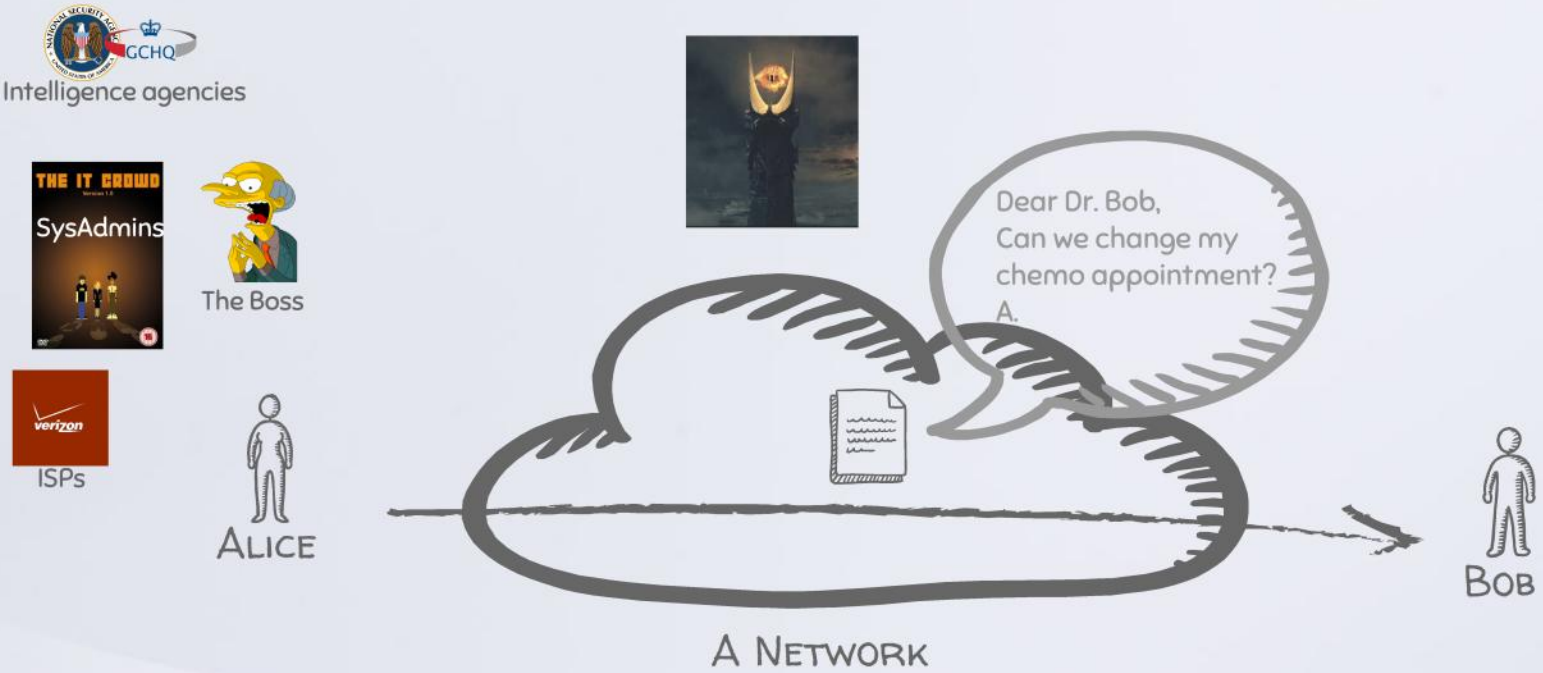

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Your Children

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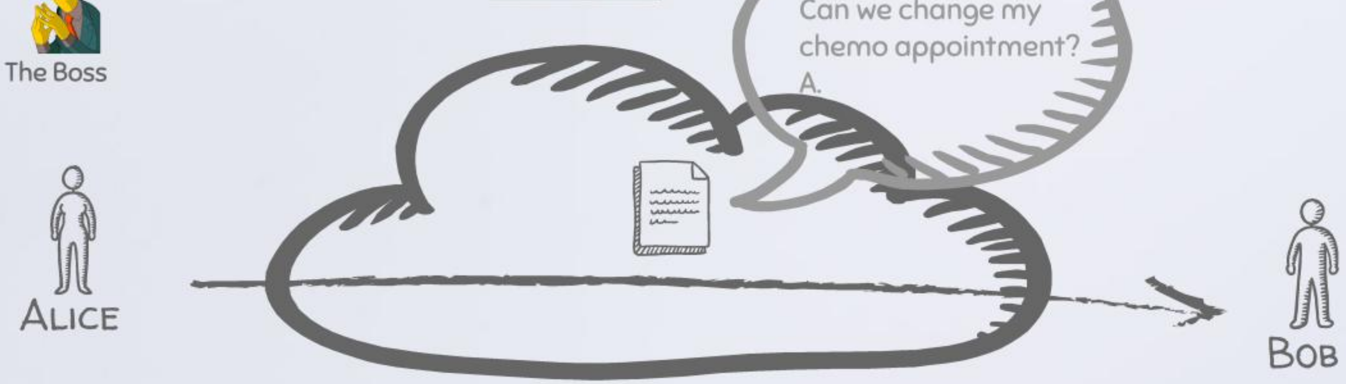
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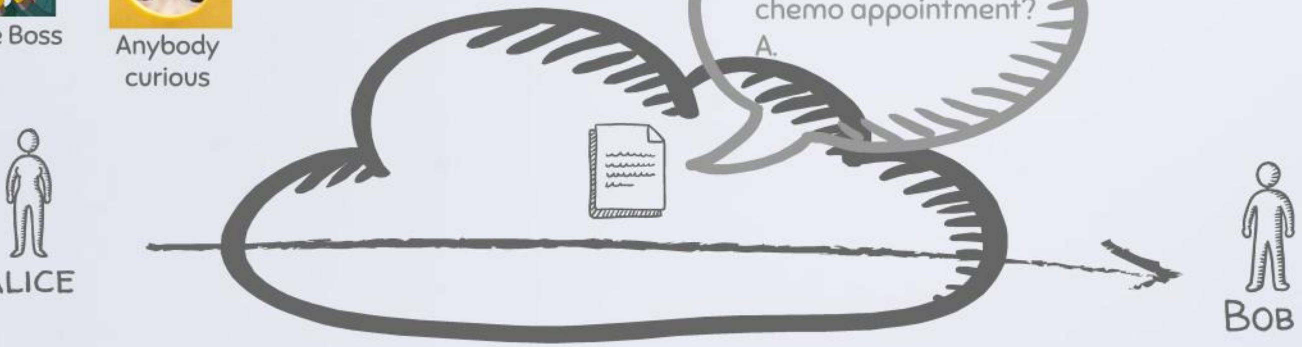

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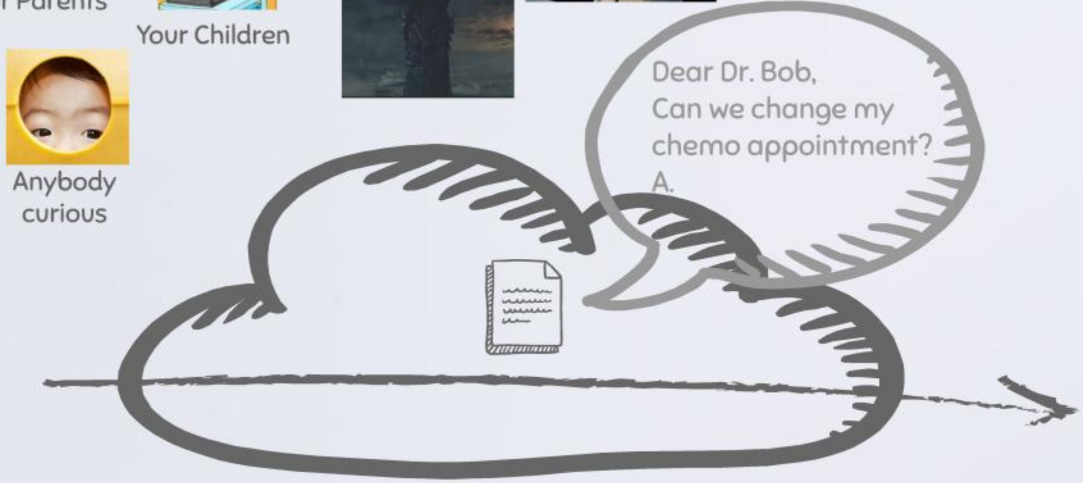

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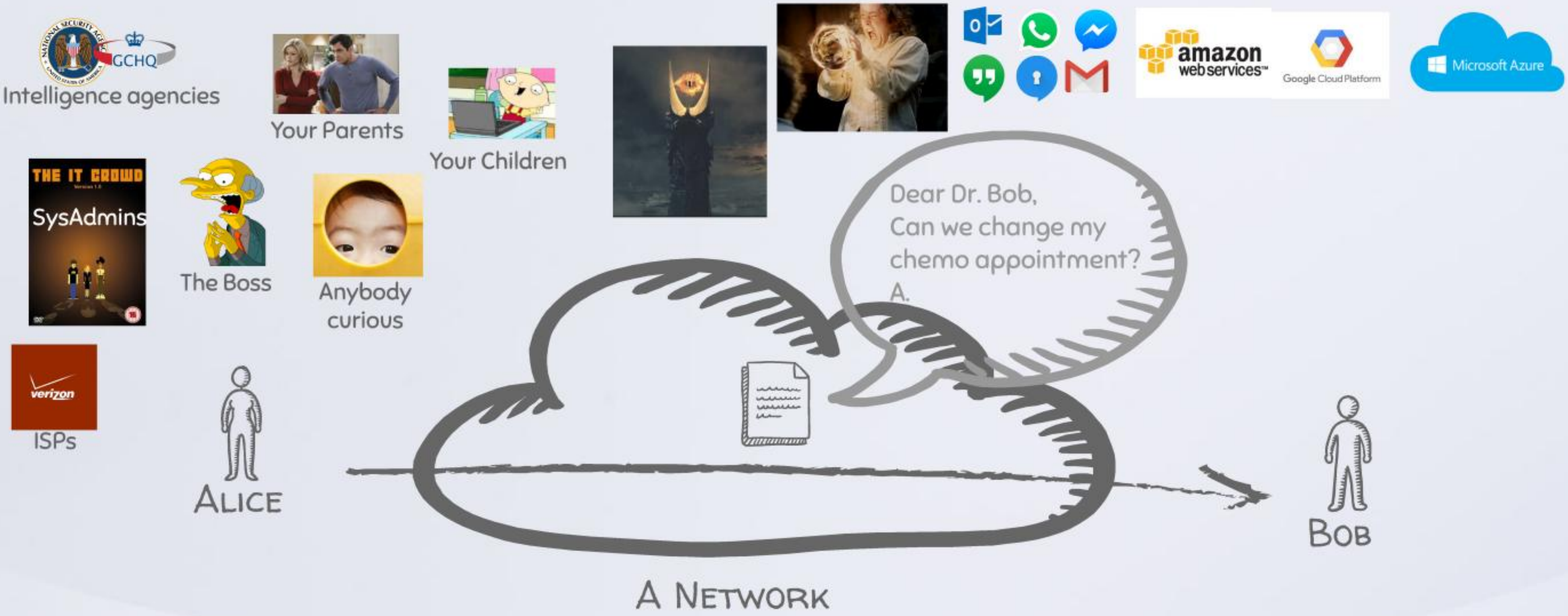

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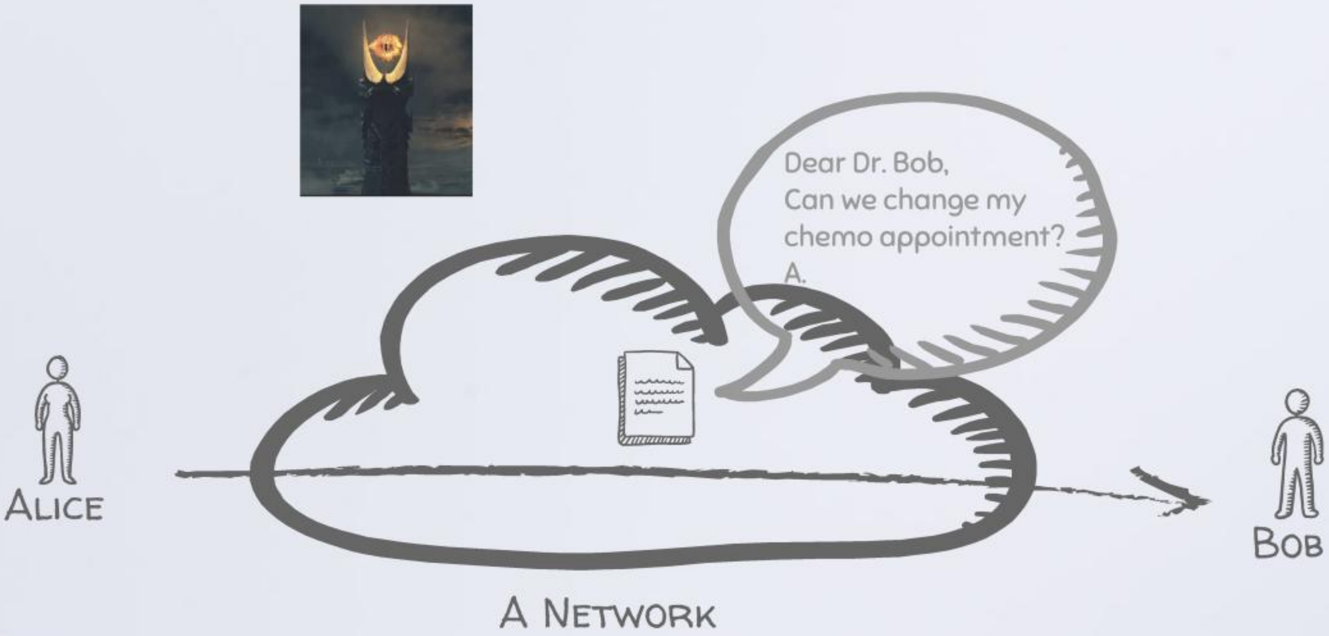

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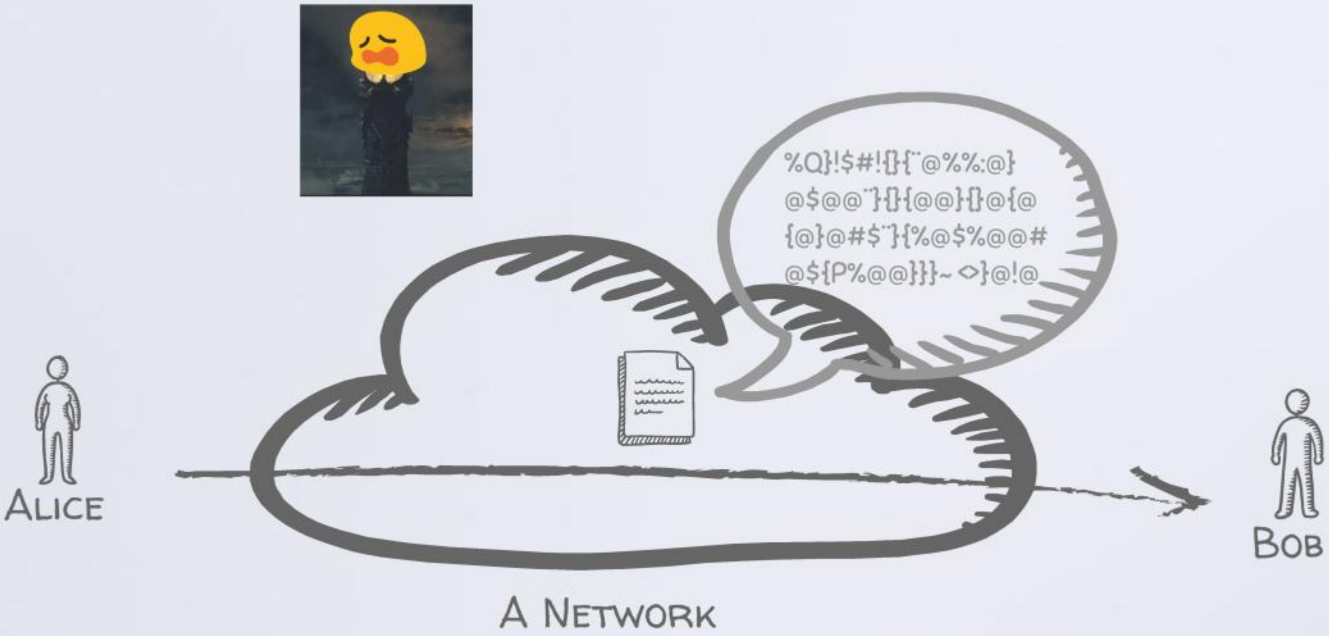

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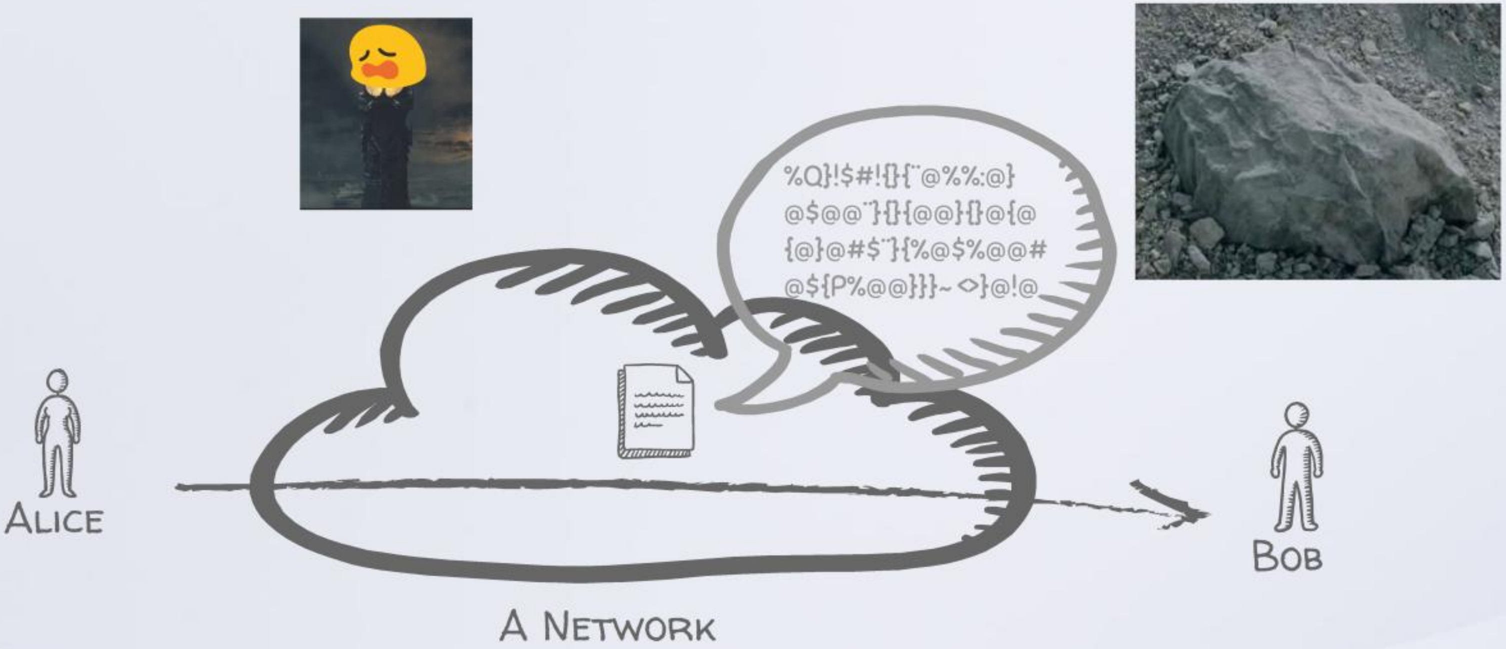

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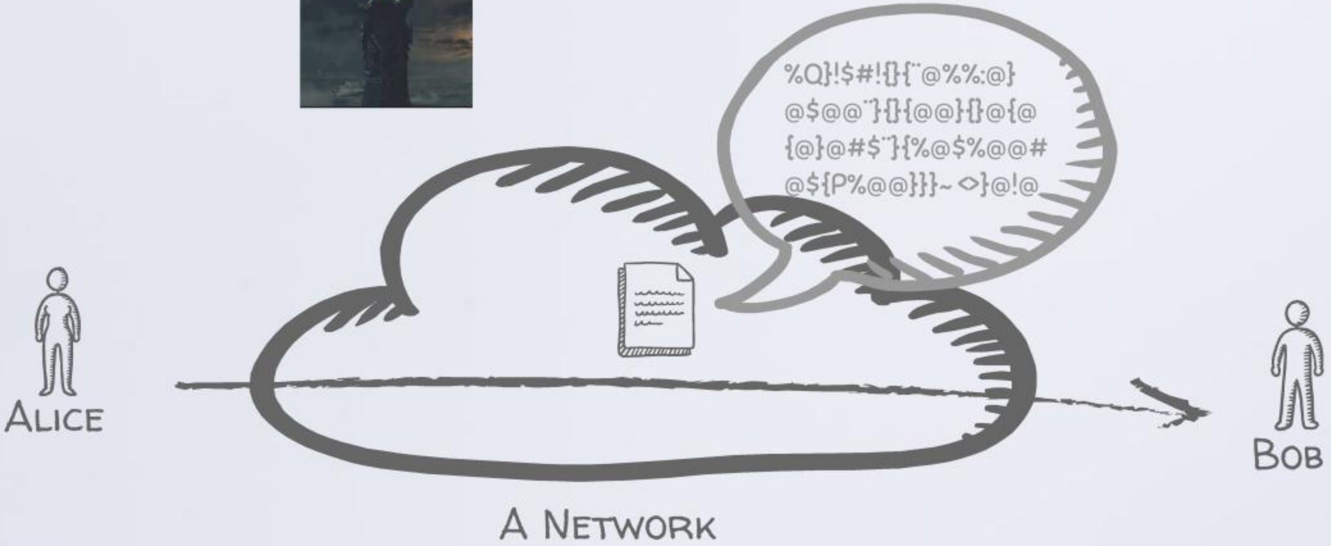

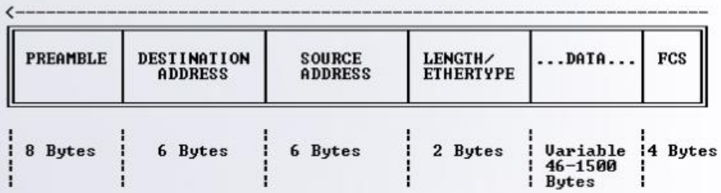

PREAMBLE	DESTINATION ADDRESS	SOURCE ADDRESS	LENGTH/ ETHERTYPE	...DATA...	FCS
8 Bytes	6 Bytes	6 Bytes	2 Bytes	Variable 46-1500 Bytes	4 Bytes

Ethernet
(IEEE 802.3, 1997)

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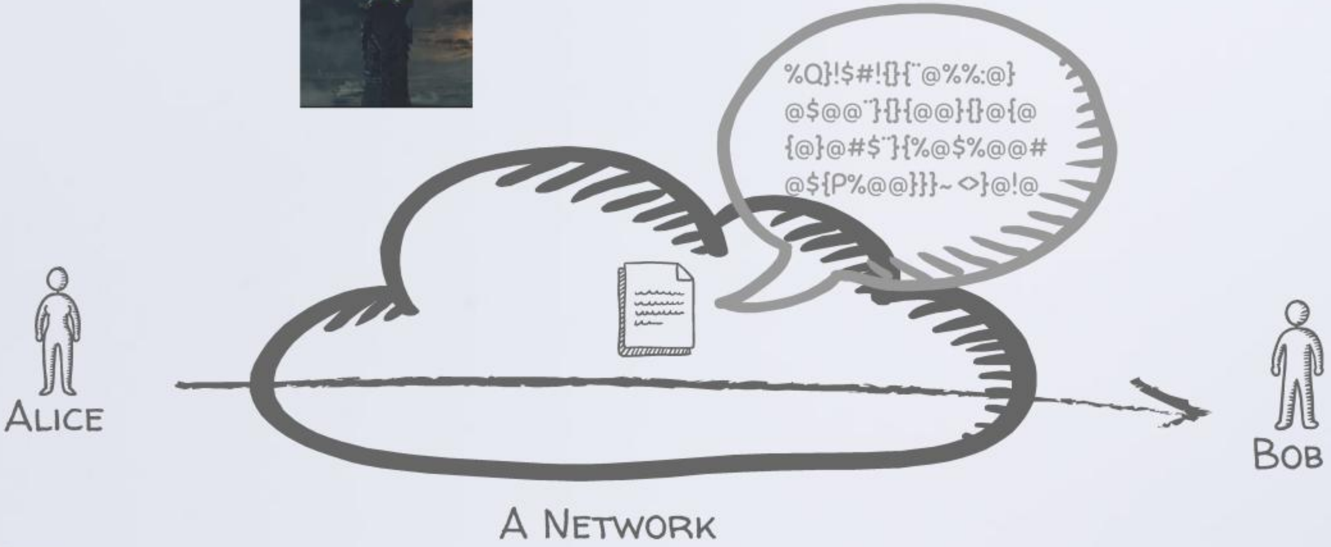

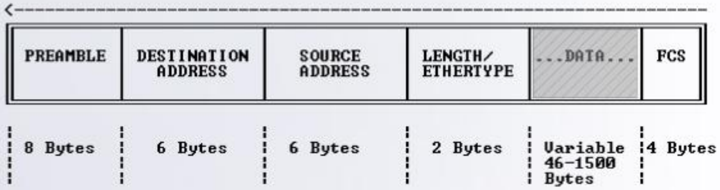

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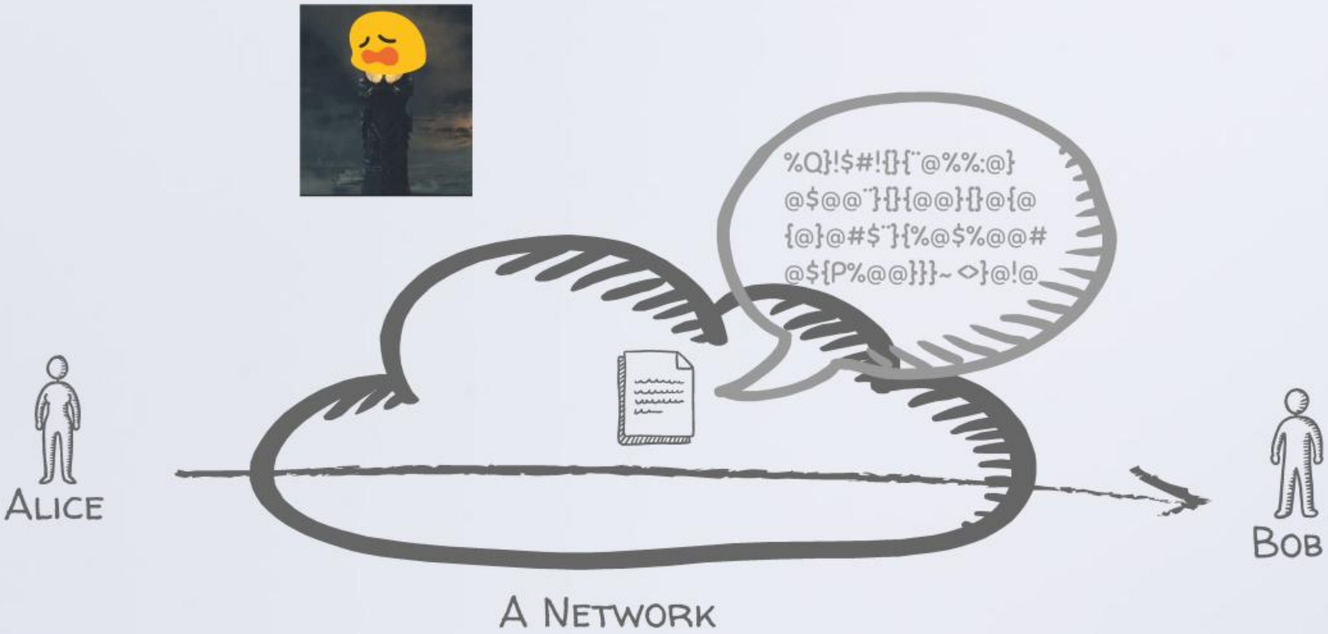

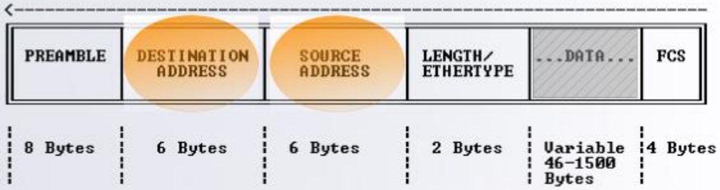

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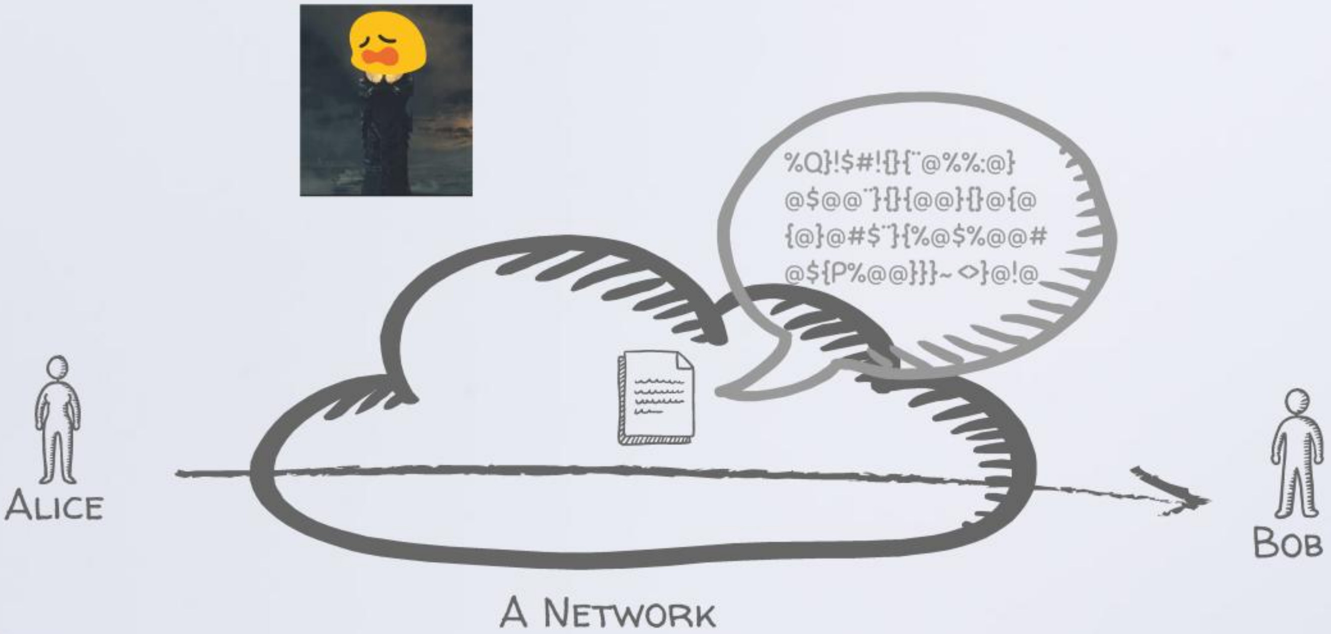

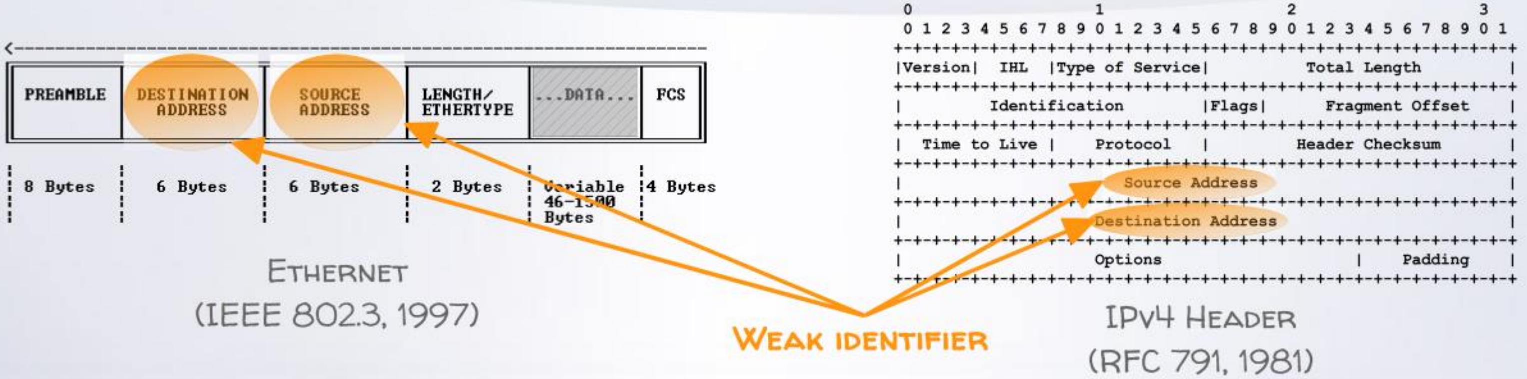

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 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
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|Version|  IHL  |Type of Service|          Total Length         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|         Identification        |Flags|      Fragment Offset    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Time to Live |    Protocol   |         Header Checksum       |
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|                       Source Address                          |
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|                    Destination Address                        |
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|                    Options                    |    Padding    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

IPv4 Header
(RFC 791, 1981)

Weak identifier

Same
for TCP,
SMTP,
IRC,
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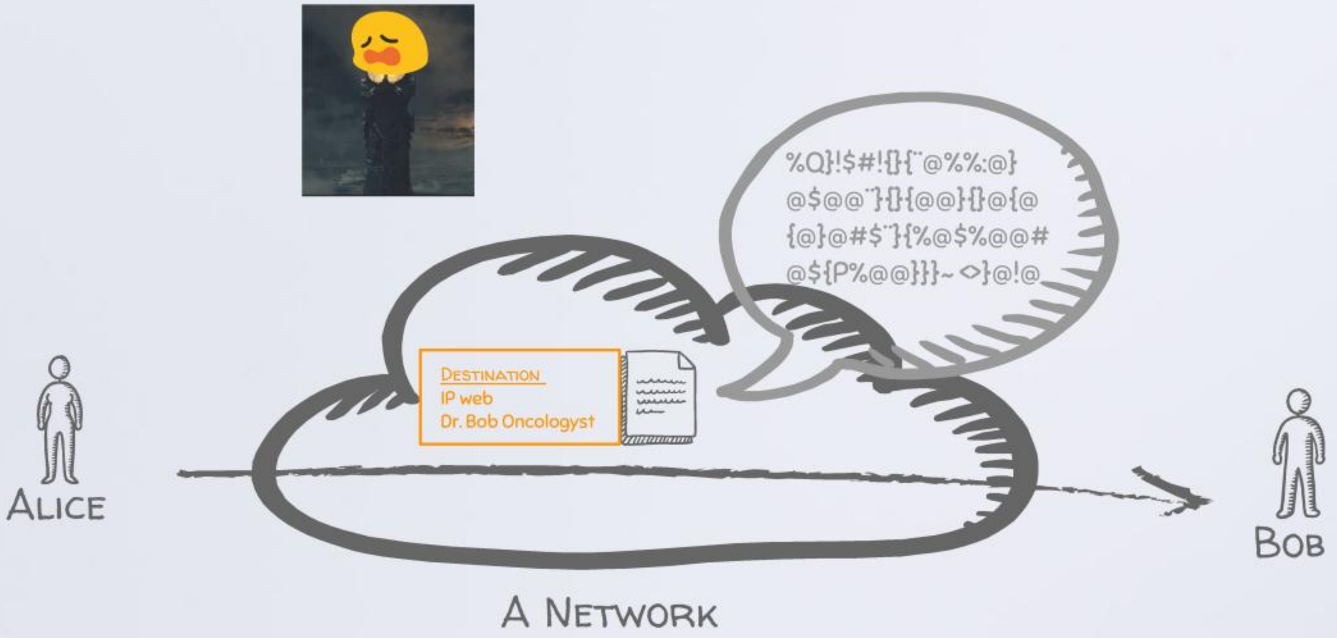

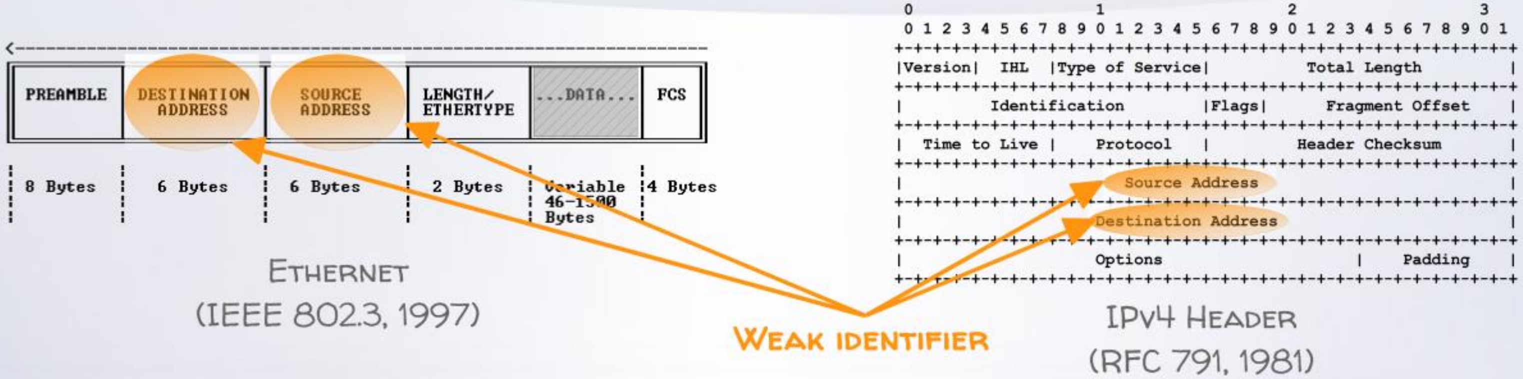

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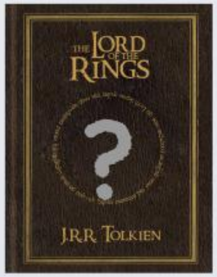
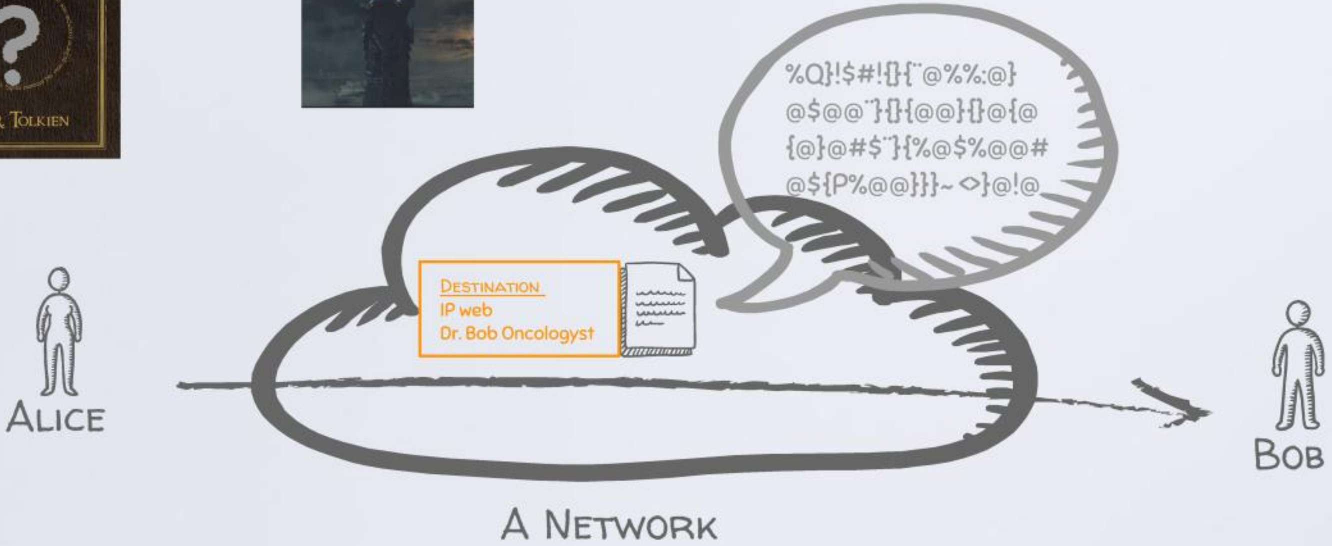
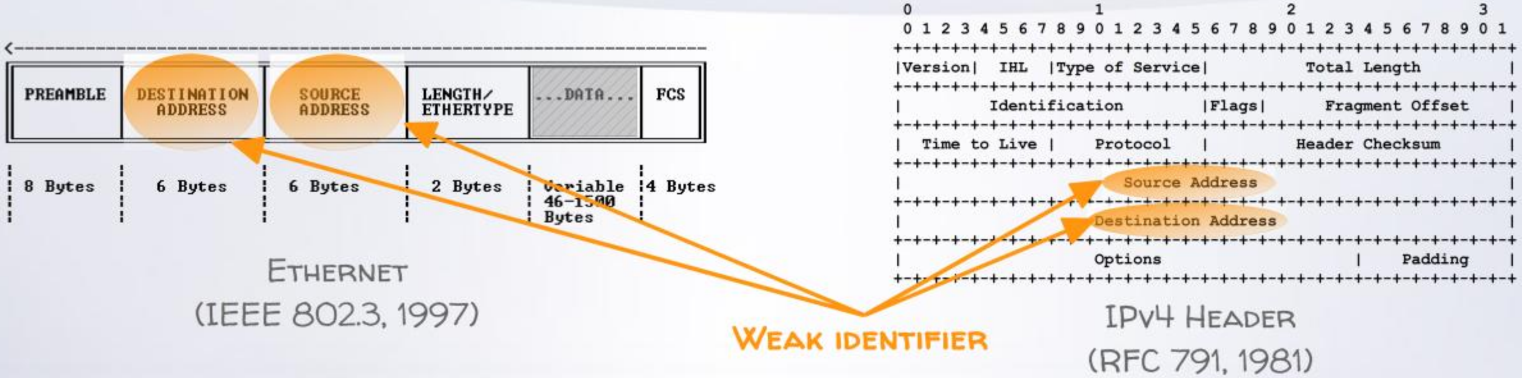
OMG!! The problem is Traffic Analysis!!







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Making use of "just" traffic data of a communication (aka metadata) to extract information

(as opposed to analyzing content or perform cryptanalysis)

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- Timing, frequency, duration
- Location
- Volume
- Device

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Military Roots

– M. Herman: "These non-textual techniques can establish **targets' locations**, order-of-battle and **movement**. Even when messages are not being deciphered, traffic analysis of the target's Command, Control, Communications and intelligence system and its patterns of behavior provides indications of his **intentions** and **states of mind**"

– **WWI**: British troops finding German boats.

– **WWII**: assessing size of German Air Force, fingerprinting of transmitters or operators (localization of troops).

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Diffie, Whitfield, and Susan Landau. Privacy on the line: The politics of wiretapping and encryption. MIT press, 2010.
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Nowadays

– Diffie&Landau: "Traffic analysis, not cryptanalysis, is the backbone of communications intelligence"

– Stewart Baker (NSA): "metadata **absolutely tells you everything about somebody's life**. If you have enough metadata, you don't really need content."

– Tempora, MUSCULAR → XkeyScore, PRISM

– Also "good" uses: recommendations, location-based services,

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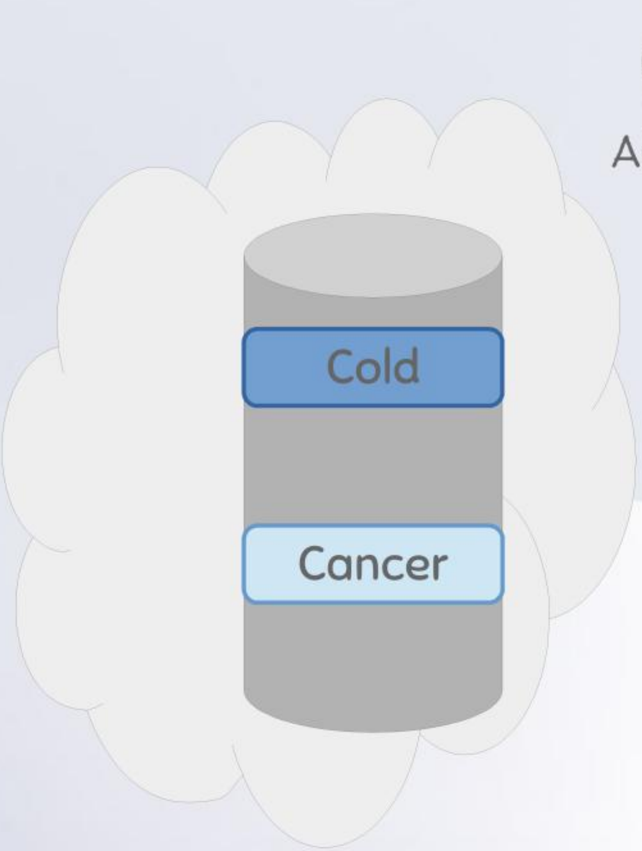
Actually, any **Meta Data** is sensitive!!



Alice

Cold

Cancer

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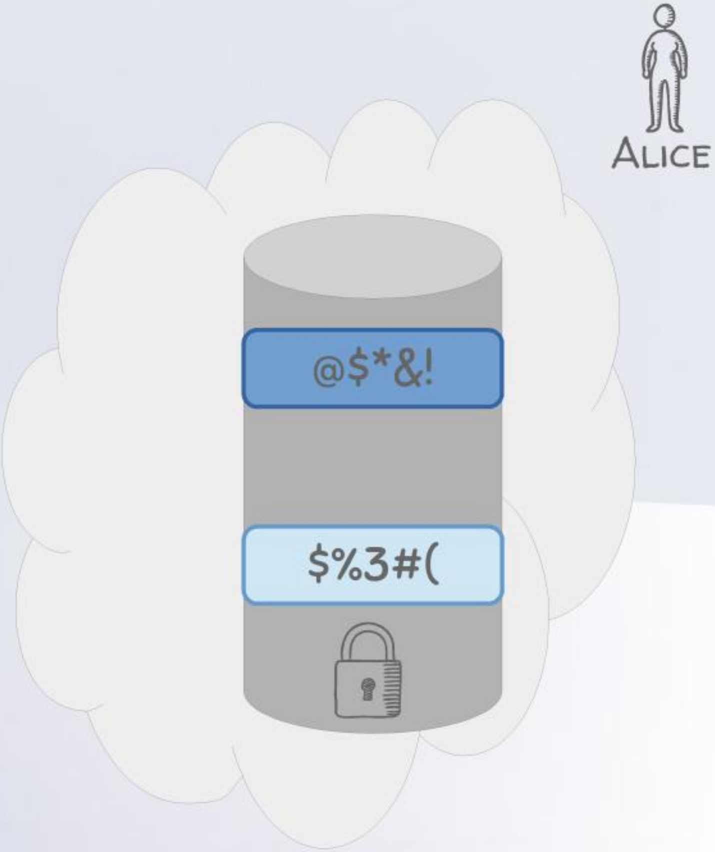

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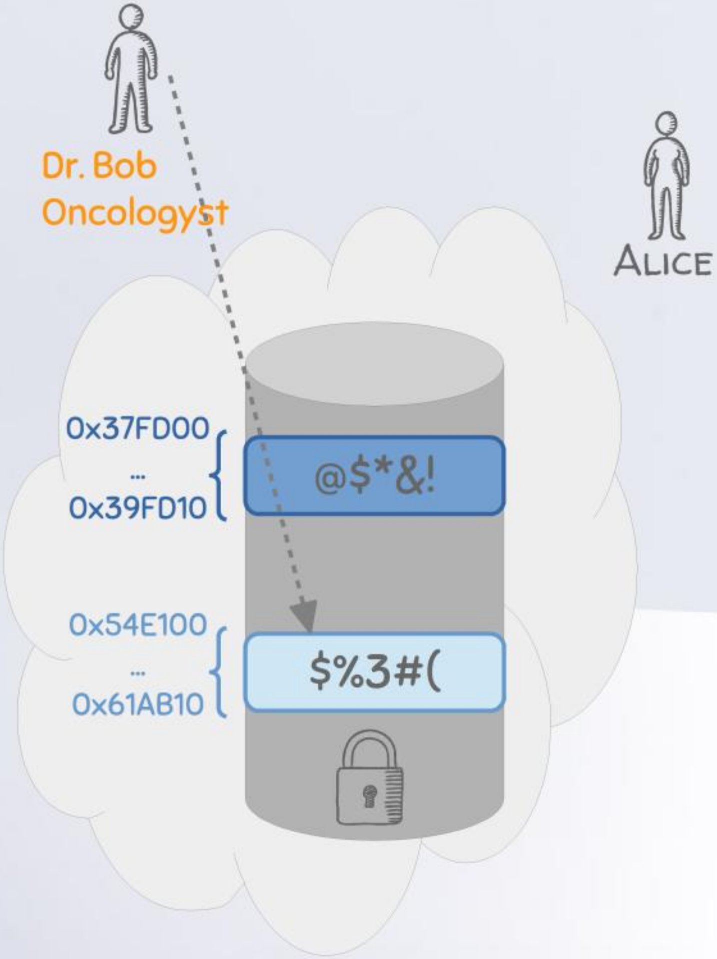

Dr. Bob
Oncologyst

Alice

0x37FD00
...
0x39FD10

@$*&!

0x54E100
...
0x61AB10

$%3#(

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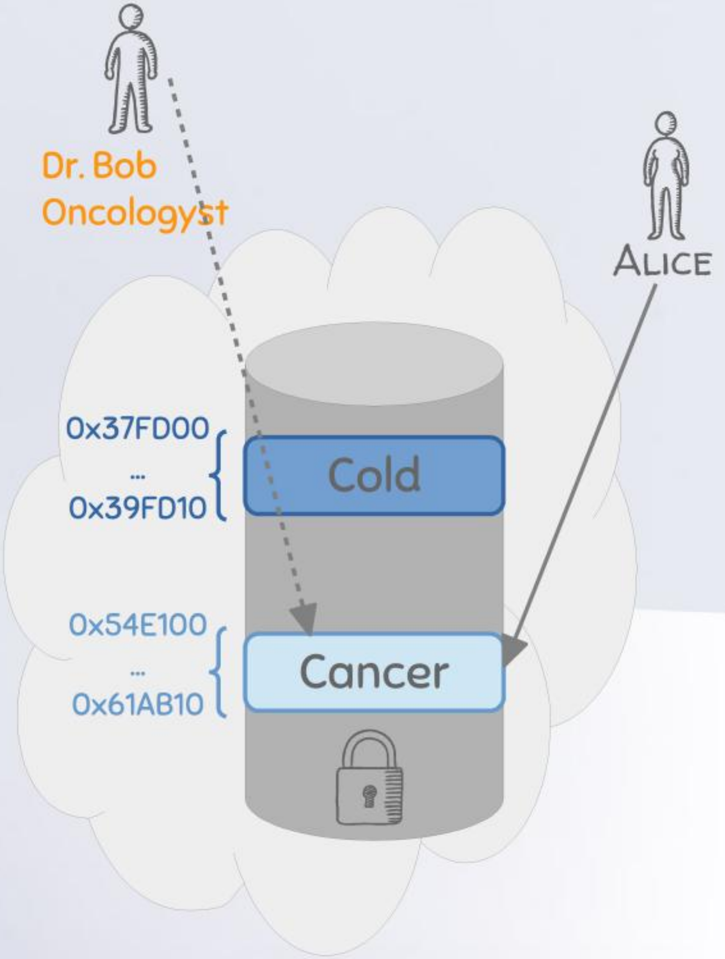

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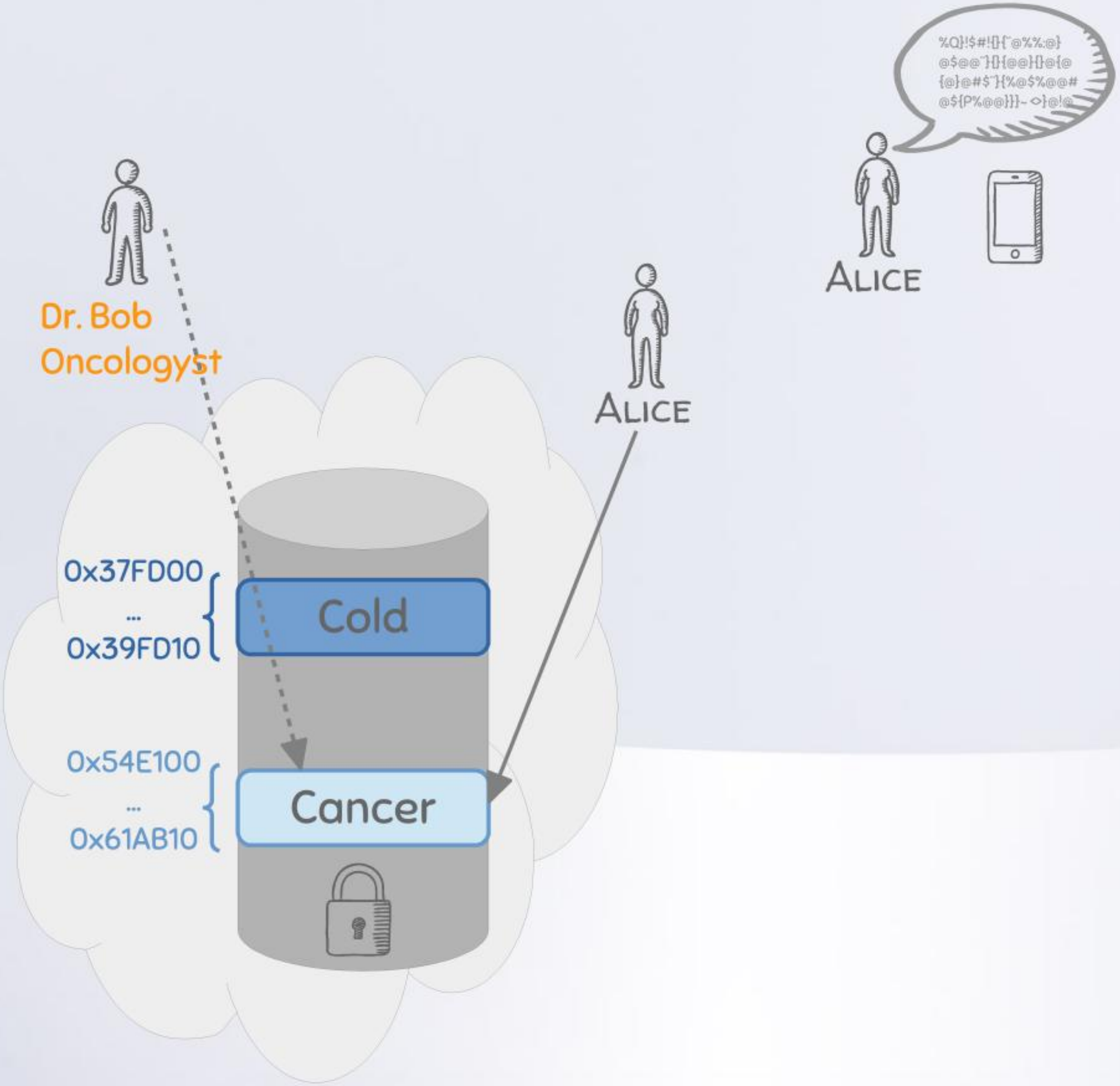

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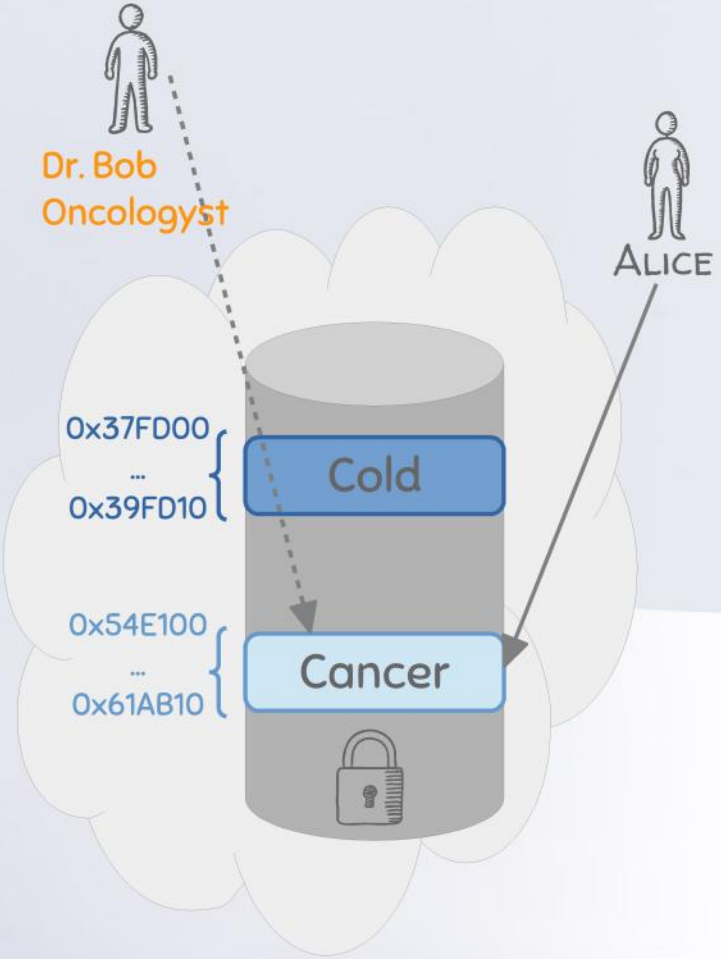

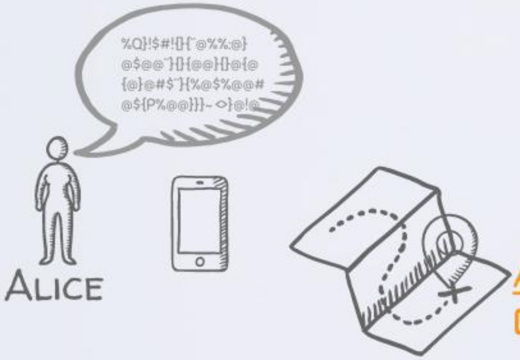

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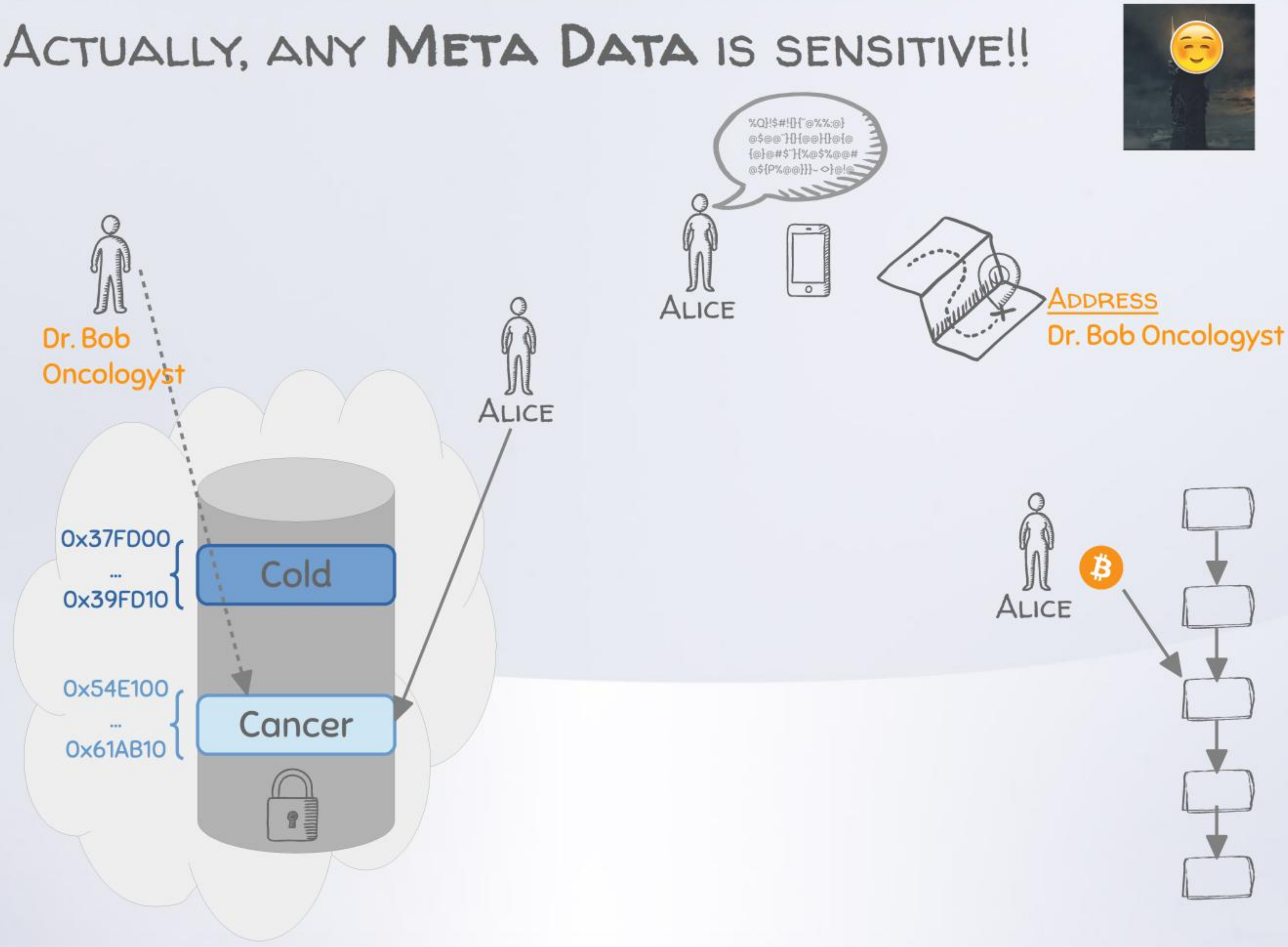

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Alice

0x37FD00 ... 0x39FD10 Cold

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Alice

Address

Dr. Bob Oncologyst

Alice

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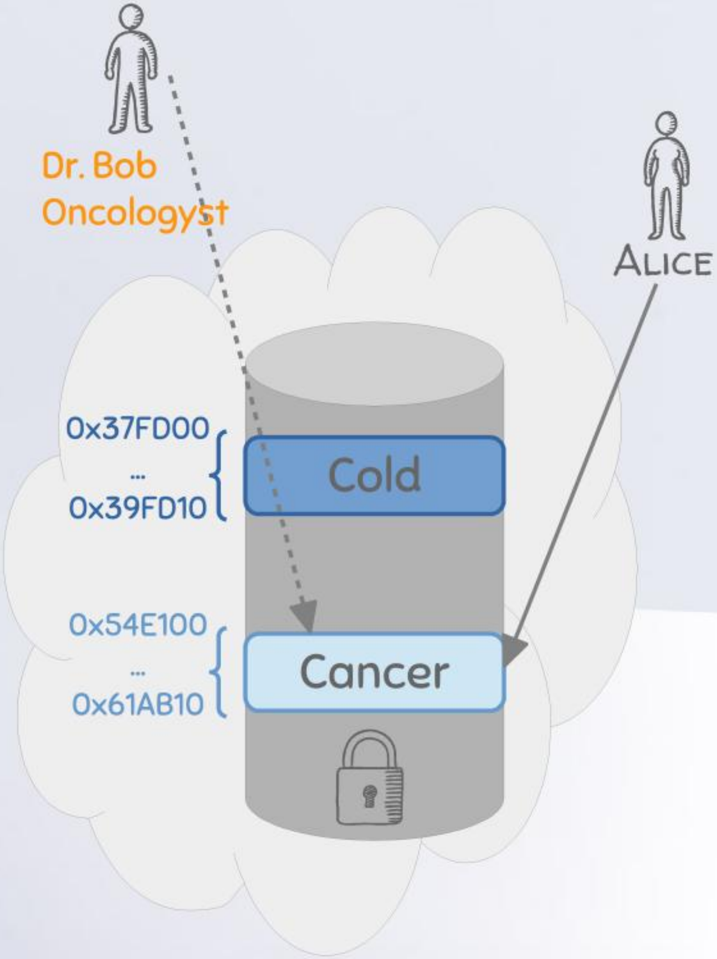
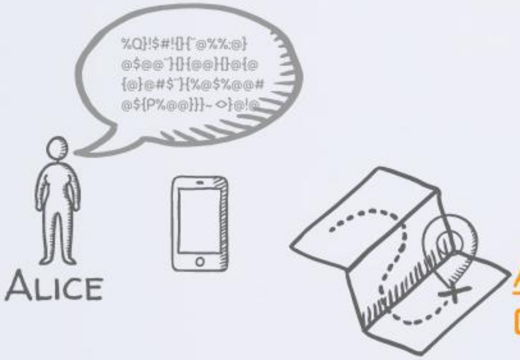
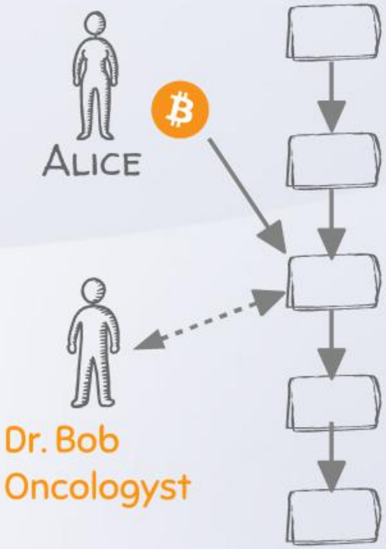


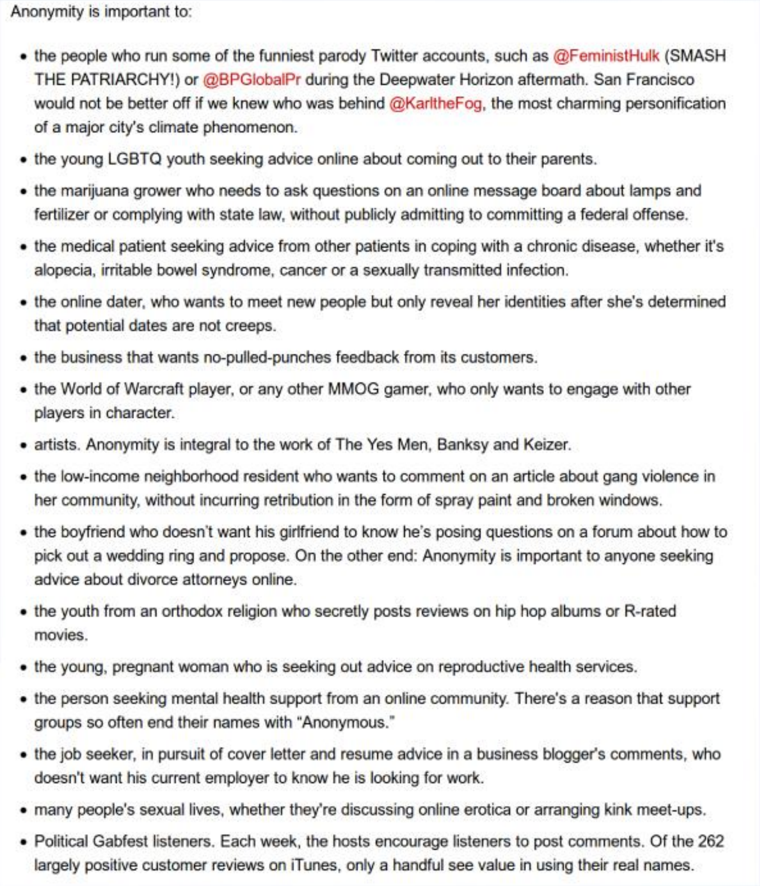




We need to protect the communication layer!

Anonymous communications

- **General applications**
  - Freedom of speech
  - Profiling / price discrimination
  - Spam avoidance
  - Investigation / market research
  - Censorship resistance
- **Specialized applications**
  - Electronic voting
  - Auctions / bidding / stock market
  - Incident reporting
  - Witness protection / whistle blowing
  - Showing anonymous credentials!

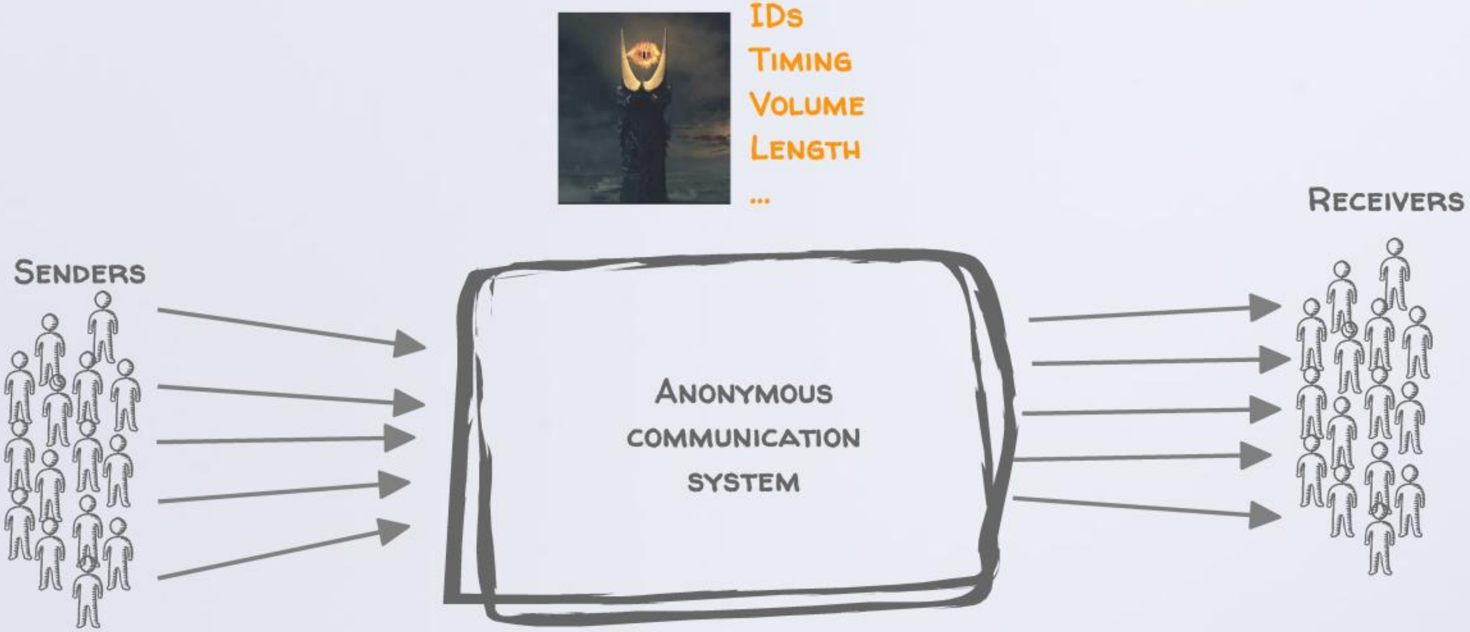


Anonymity is important to:

- the people who run some of the funniest parody Twitter accounts, such as @FeministHulk (SMASH THE PATRIARCHY!) or @BPGlobalPr during the Deepwater Horizon aftermath. San Francisco would not be better off if we knew who was behind @KarltheFog, the most charming personification of a major city's climate phenomenon.
- the young LGBTQ youth seeking advice online about coming out to their parents.
- the marijuana grower who needs to ask questions on an online message board about lamps and fertilizer or complying with state law, without publicly admitting to committing a federal offense.
- the medical patient seeking advice from other patients in coping with a chronic disease, whether it's alopecia, irritable bowel syndrome, cancer or a sexually transmitted infection.
- the online dater, who wants to meet new people but only reveal her identities after she's determined that potential dates are not creeps.
- the business that wants no-pulled-punches feedback from its customers.
- the World of Warcraft player, or any other MMOG gamer, who only wants to engage with other players in character.
- artists. Anonymity is integral to the work of The Yes Men, Banksy and Keizer.
- the low-income neighborhood resident who wants to comment on an article about gang violence in her community, without incurring retribution in the form of spray paint and broken windows.
- the boyfriend who doesn't want his girlfriend to know he's posing questions on a forum about how to pick out a wedding ring and propose. On the other end: Anonymity is important to anyone seeking advice about divorce attorneys online.
- the youth from an orthodox religion who secretly posts reviews on hip hop albums or R-rated movies.
- the young, pregnant woman who is seeking out advice on reproductive health services.
- the person seeking mental health support from an online community. There's a reason that support groups so often end their names with "Anonymous."
- the job seeker, in pursuit of cover letter and resume advice in a business blogger's comments, who doesn't want his current employer to know he is looking for work.
- many people's sexual lives, whether they're discussing online erotica or arranging kink meet-ups.
- Political Gabfest listeners. Each week, the hosts encourage listeners to post comments. Of the 262 largely positive customer reviews on iTunes, only a handful see value in using their real names.

https://www.eff.org/deeplinks/2013/10/online-anonymity-not-only-trolls-and-political-dissidents
http://geekfeminism.wikia.com/wiki/Who_is_harmed_by_a_%22Real_Names%22_policy%3F

Anonymous communications: abstract model



IDs
Timing
Volume
Length
...

Senders

Anonymous communication system

Receivers

- Bitwise unlinkability
  - Crypto to make inputs and outputs bit patterns different
- (re)packetizing + (re)schedule
  - Destroy patterns (traffic analysis resistance)

Anonymous communications: abstract model

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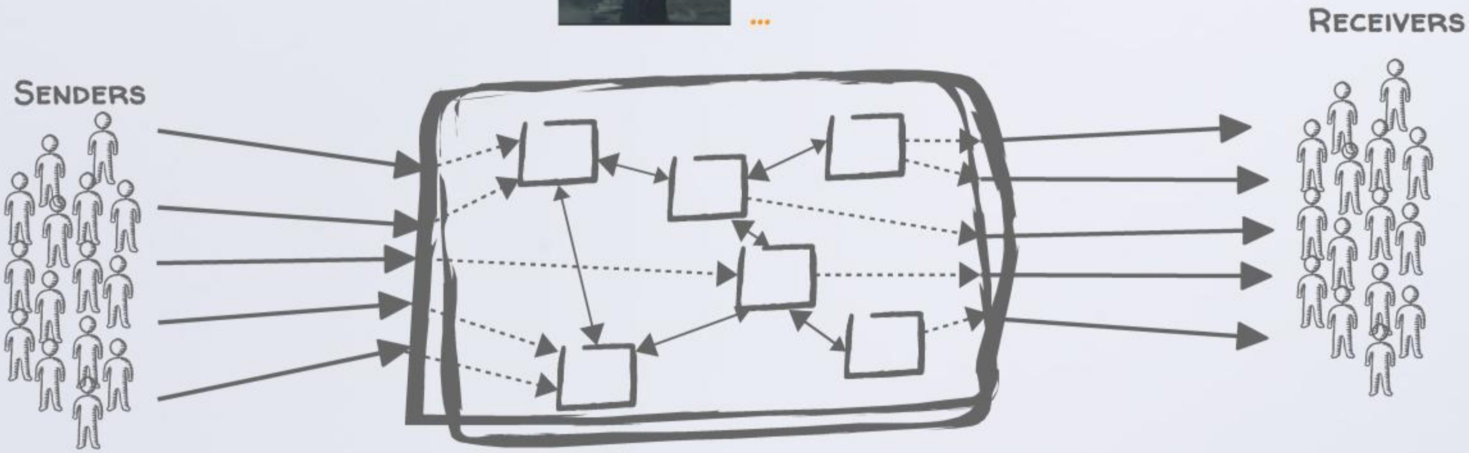

Senders

Receivers

- Bitwise unlinkability
  - Crypto to make inputs and outputs bit patterns different
- (re)packetizing + (re)schedule + (re)routing.
  - Destroy patterns (traffic analysis resistance)
  - Load balancing
  - Distribute trust

Anonymous communications: abstract model

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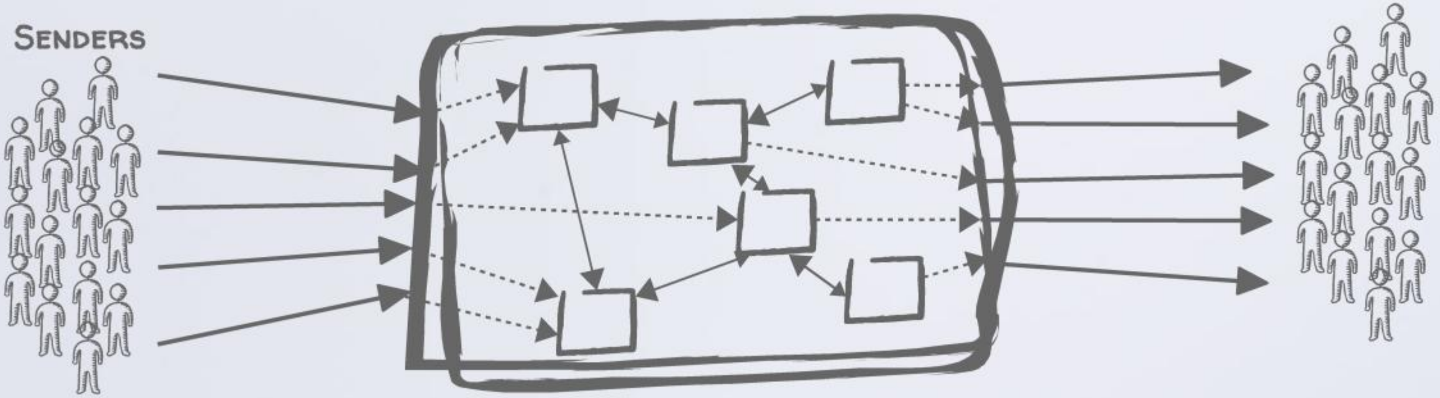

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  - Crypto to make inputs and outputs bit patterns different
- (re)packetizing + (re)schedule + (re)routing.
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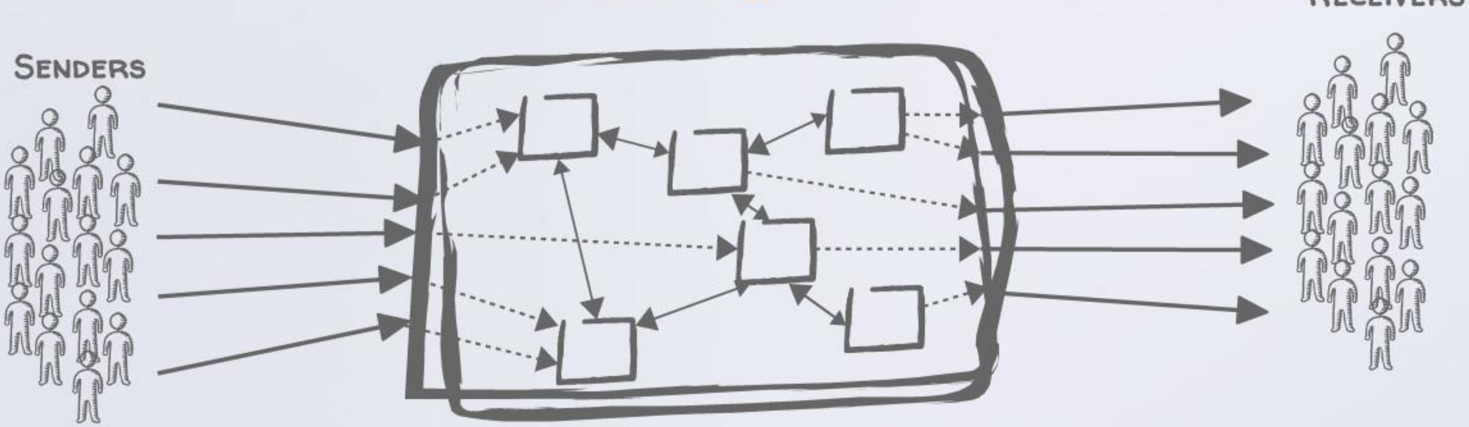
  - Load balancing
  - Distribute trust

In theory should work, but in practice…

IDs
Timing
Volume
Length
…



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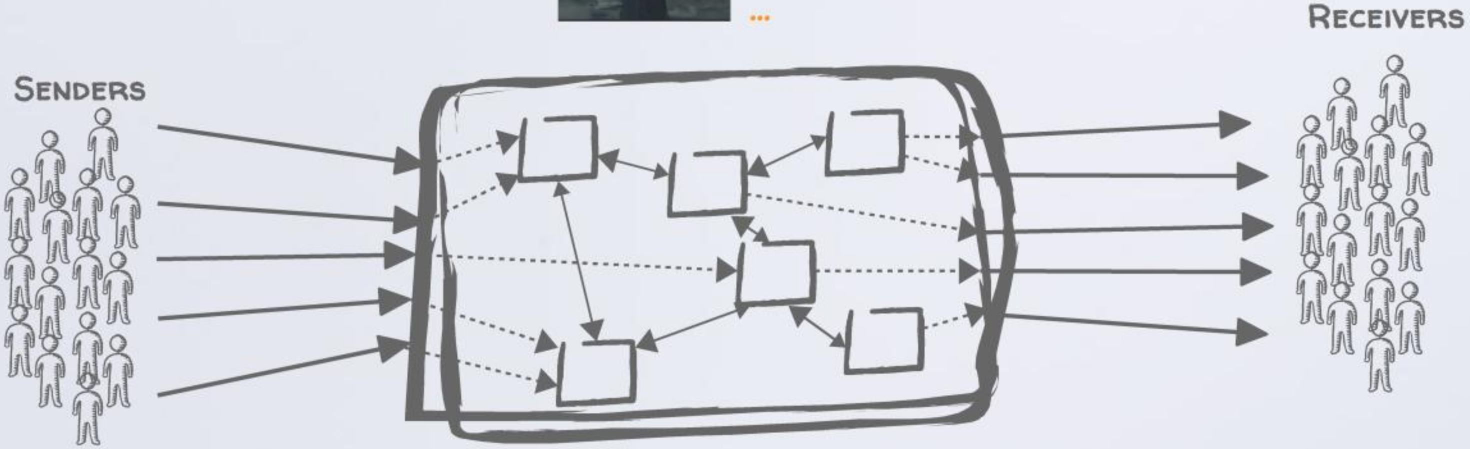

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Bandwidth

Delay 😕

Churn

Intrinsic network differences

Trust?

… STILL VULNERABLE TO TRAFFIC ANALYSIS

Find profiles and communication patterns
persistent relationships show up

Trace traffic based on patterns
number of packets, delays, … differ per flow

Identify traffic based on their patterns (e.g., website fingerprinting)
same traffic always looks similar

Users' past history
timing correlated to caches

Device identification / location
hosts' hardware particular characteristics

Identify users based on choices
not everybody can choose everything

Recover content
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Trace packets based on routing algorithms
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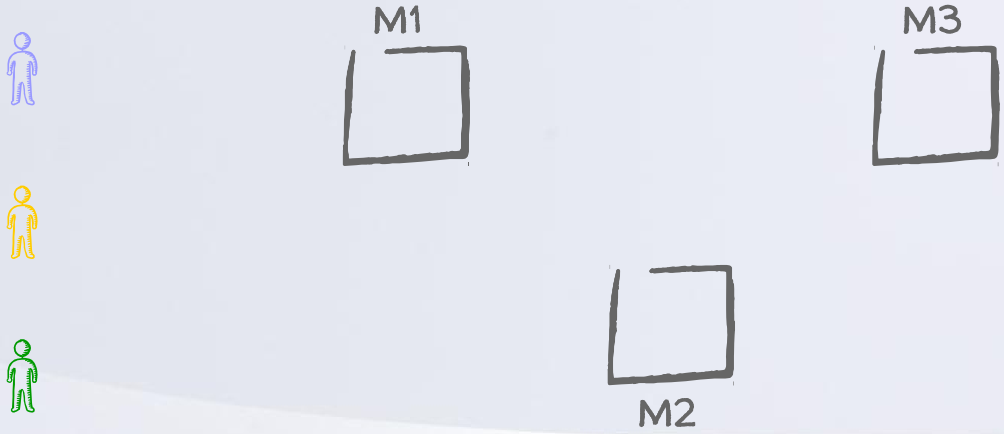

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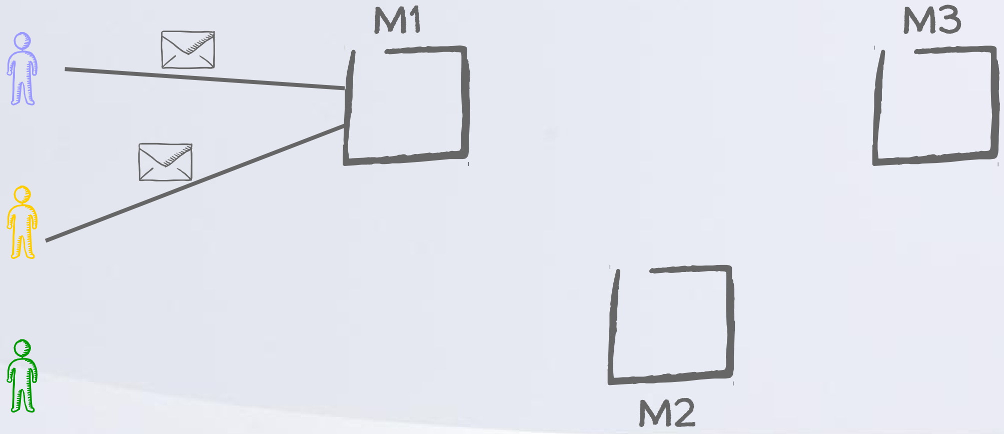

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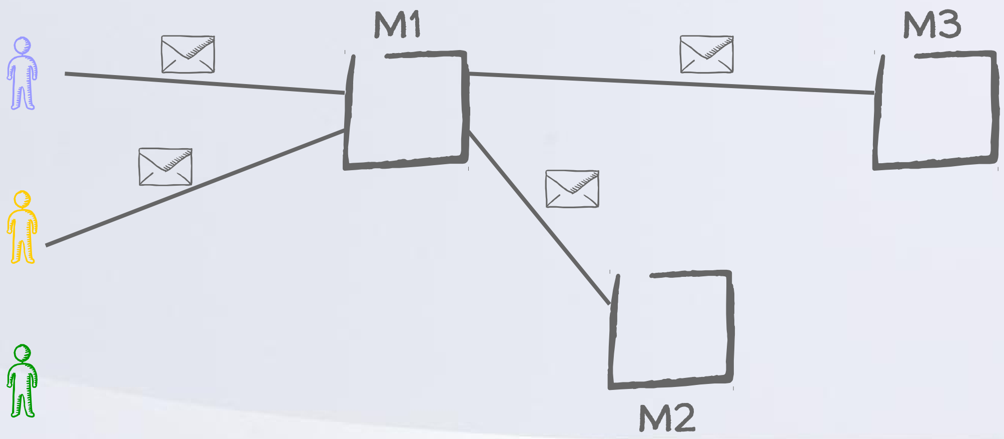

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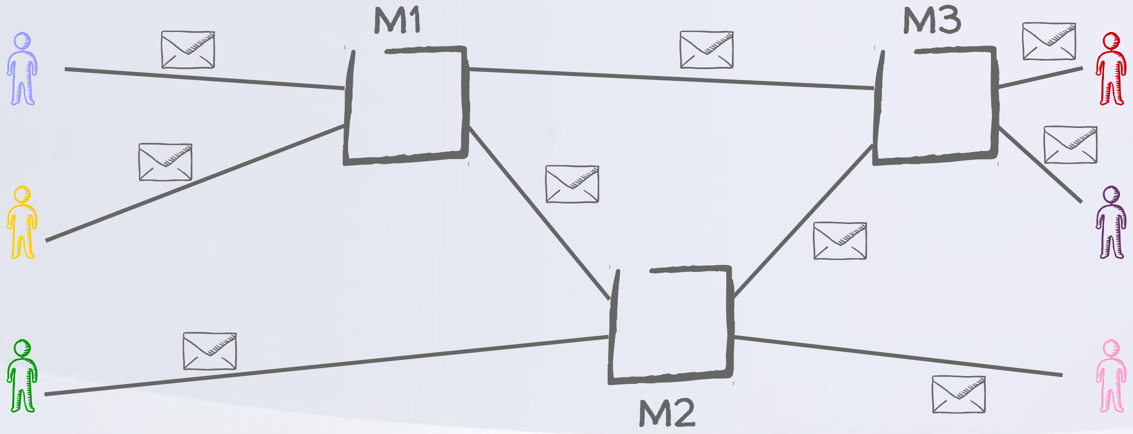

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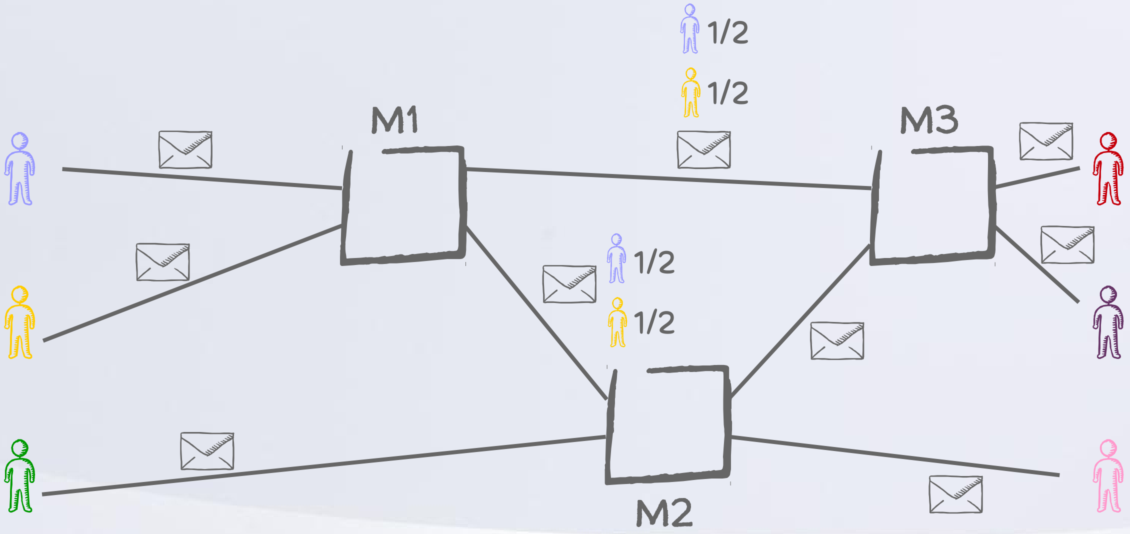

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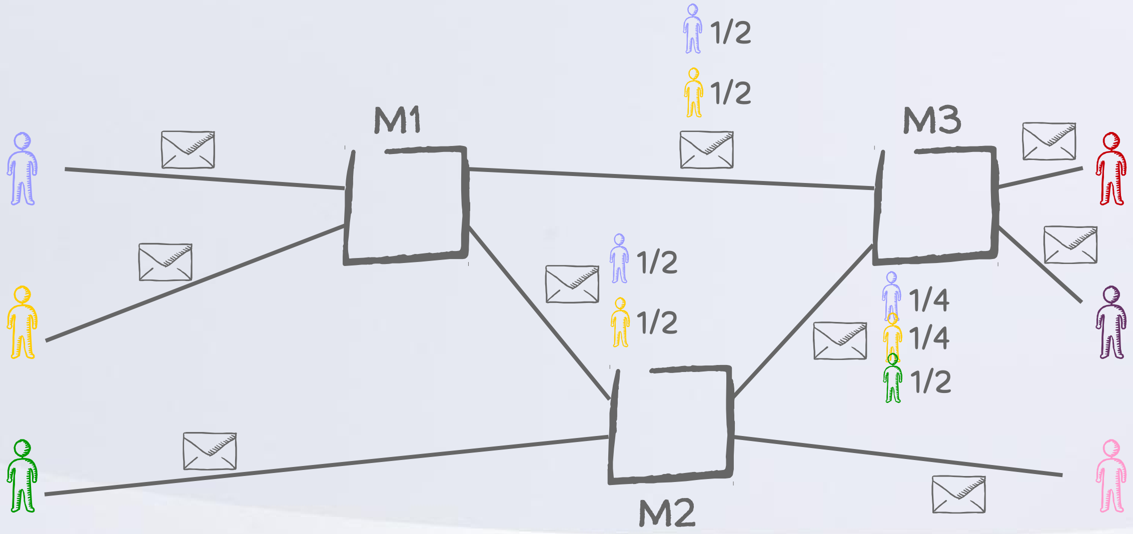

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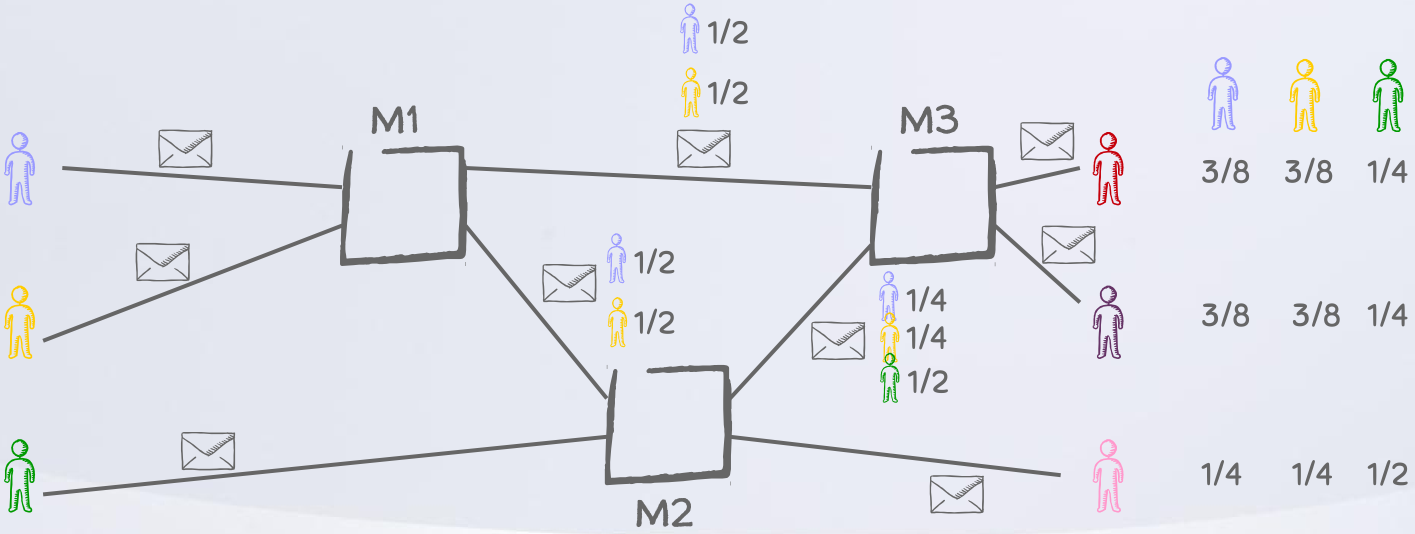

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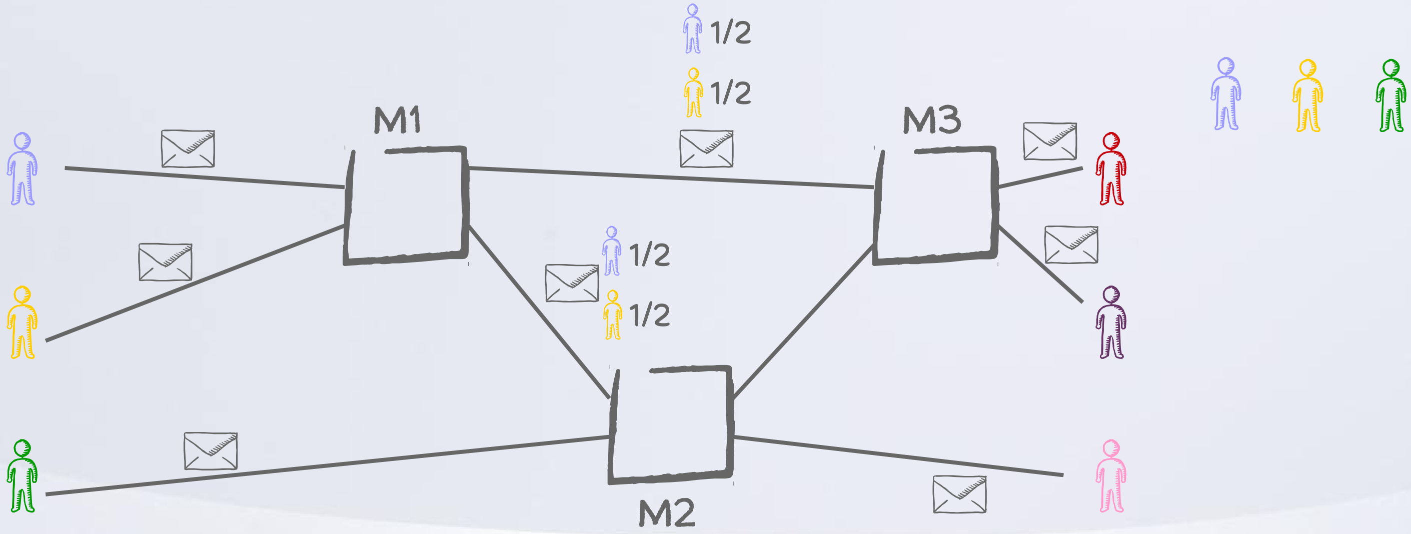

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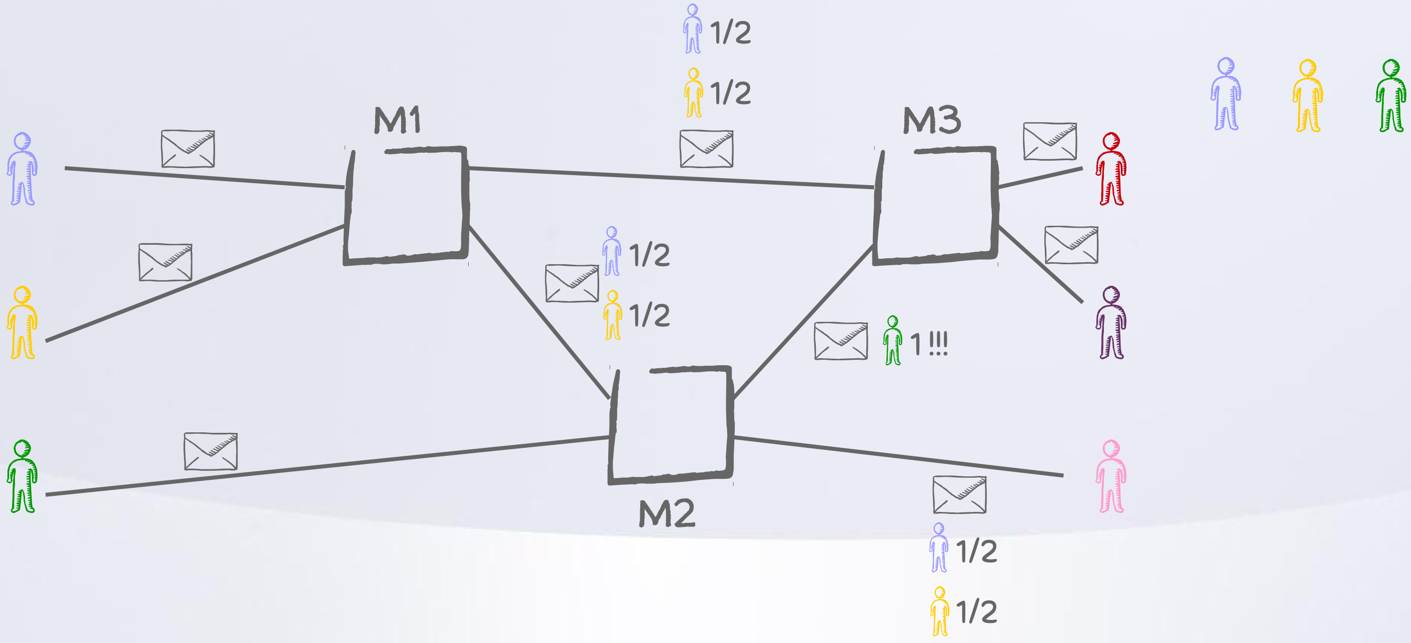

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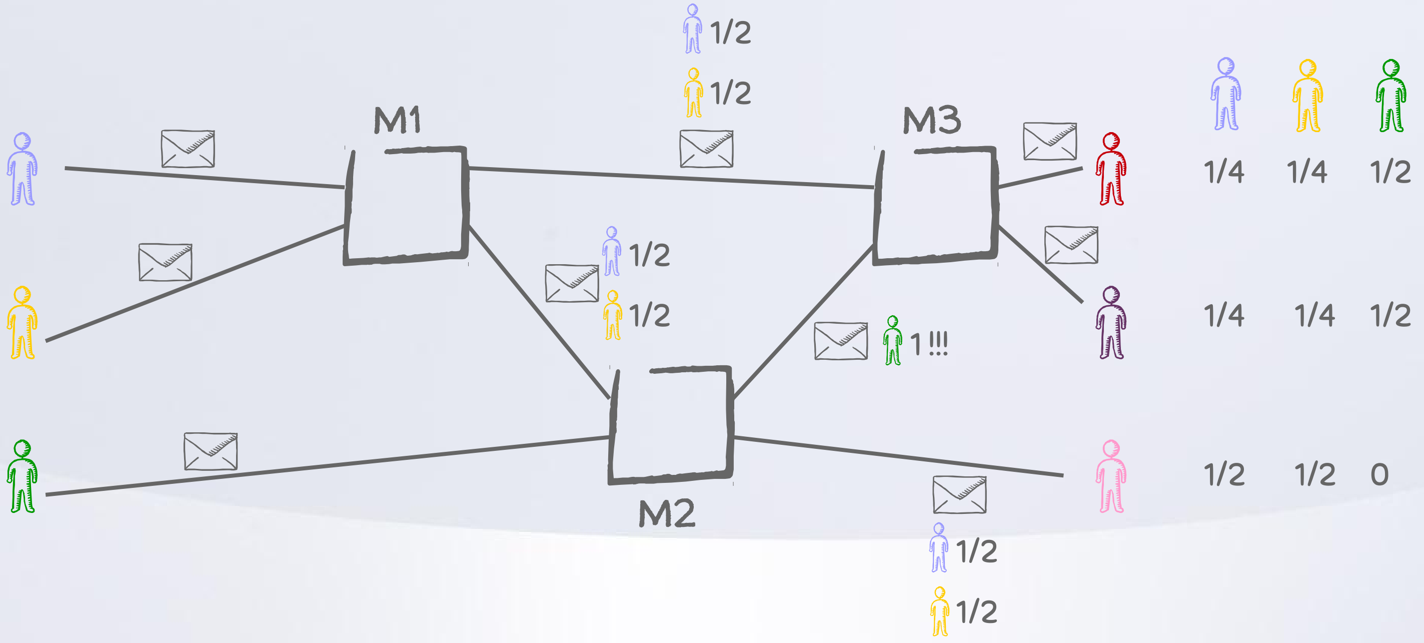

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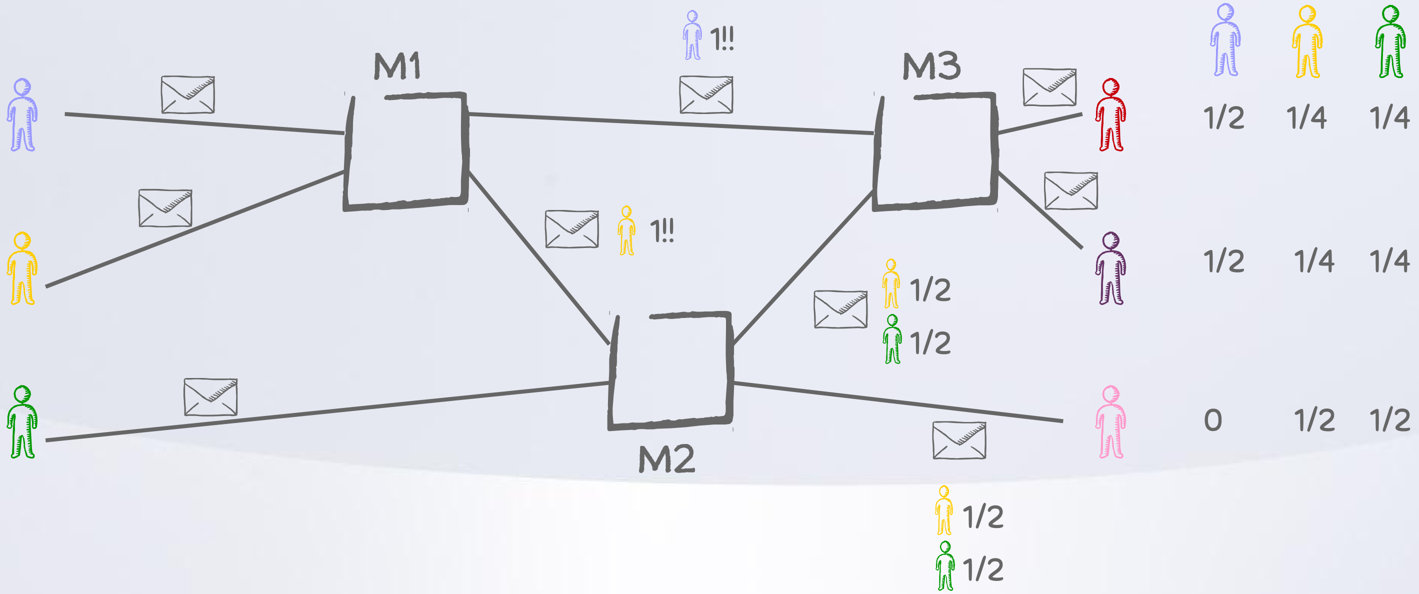

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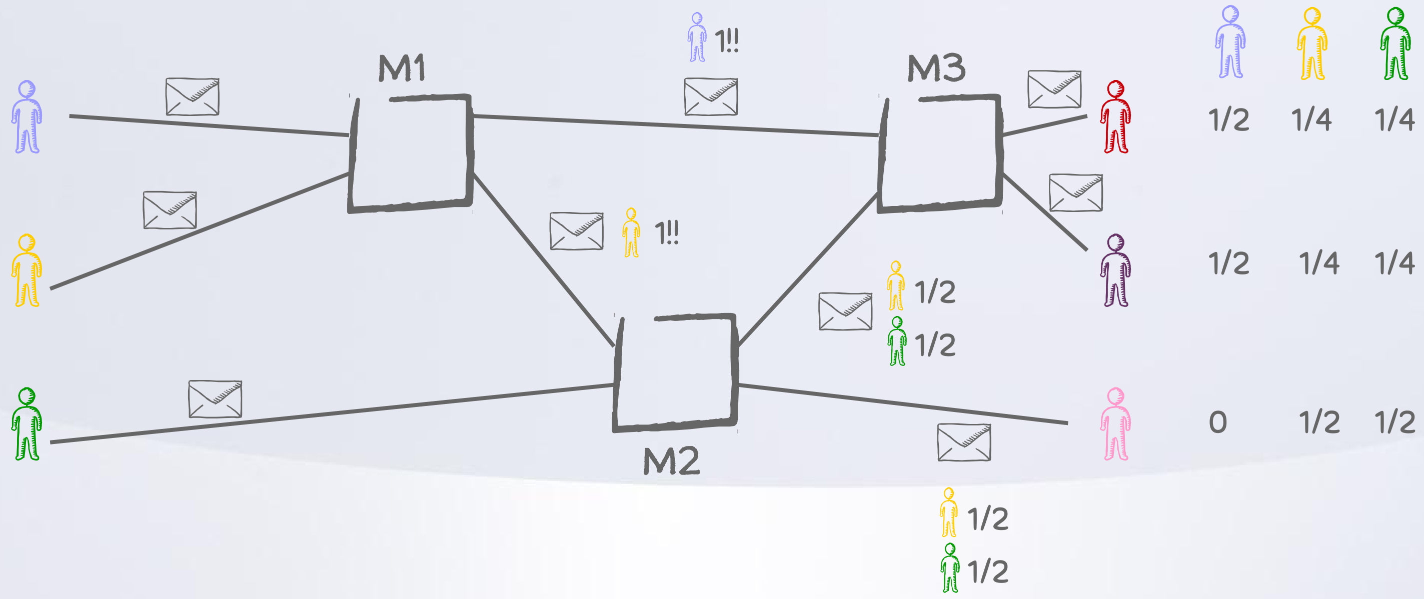

Non trivial given observation!!

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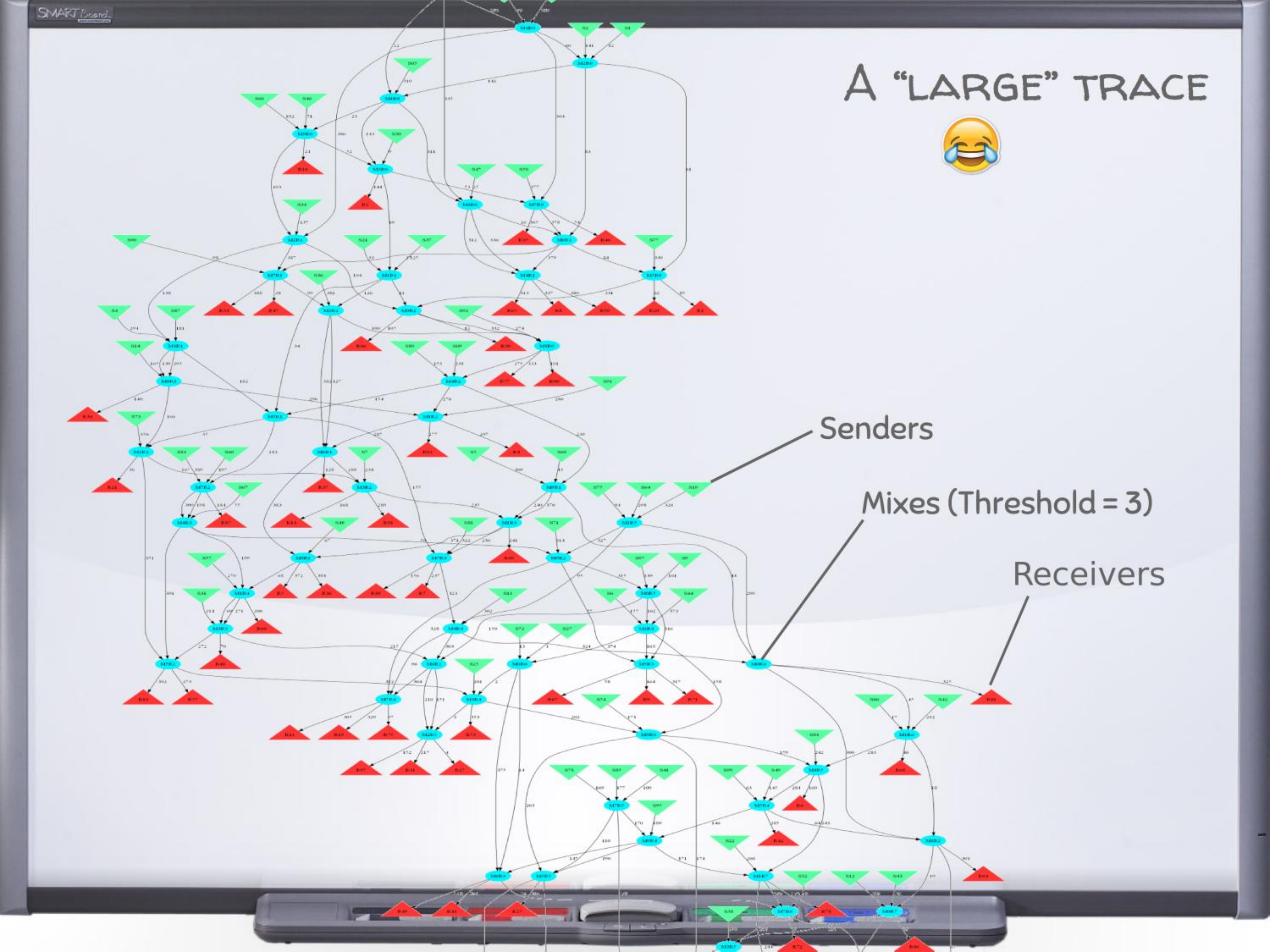
A "LARGE" TRACE 😂



Senders

Mixes (Threshold = 3)

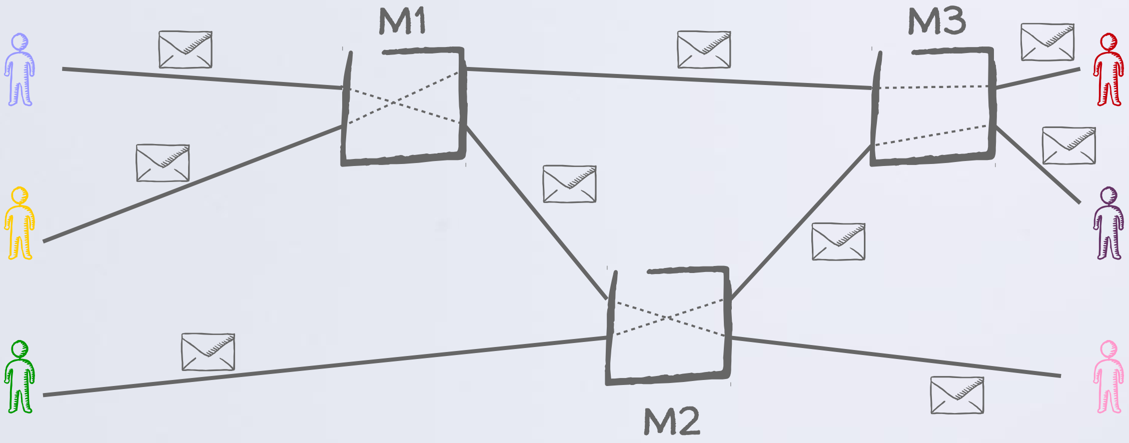
Receivers

Redefining the problem

Given what we see (Observation) and the system operation (Constraints)

Probability of mixes "Hidden State"?

(or Probability of each possible path?)



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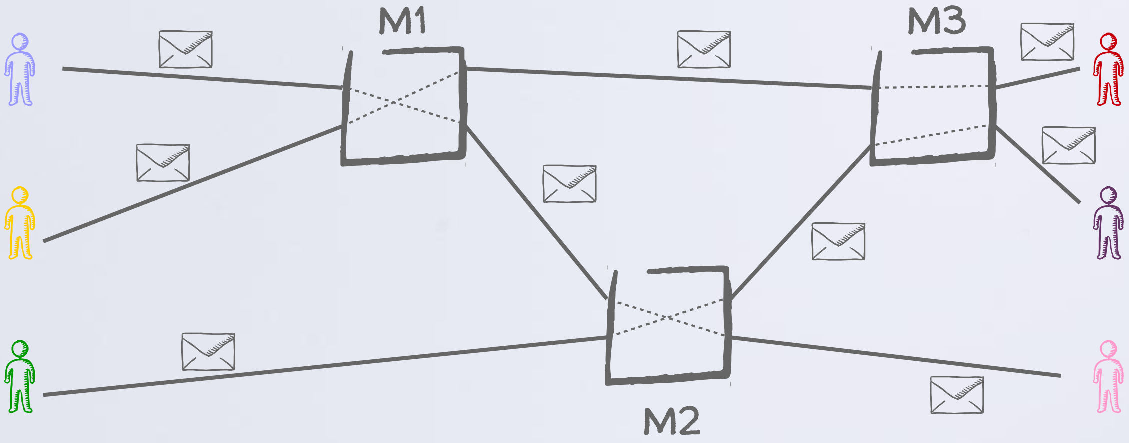

$$Pr[HS|O,C]=\frac{Pr[O|HS,C]\cdot Pr[HS|C]}{\sum_{HS} Pr[HS,O|C]}$$

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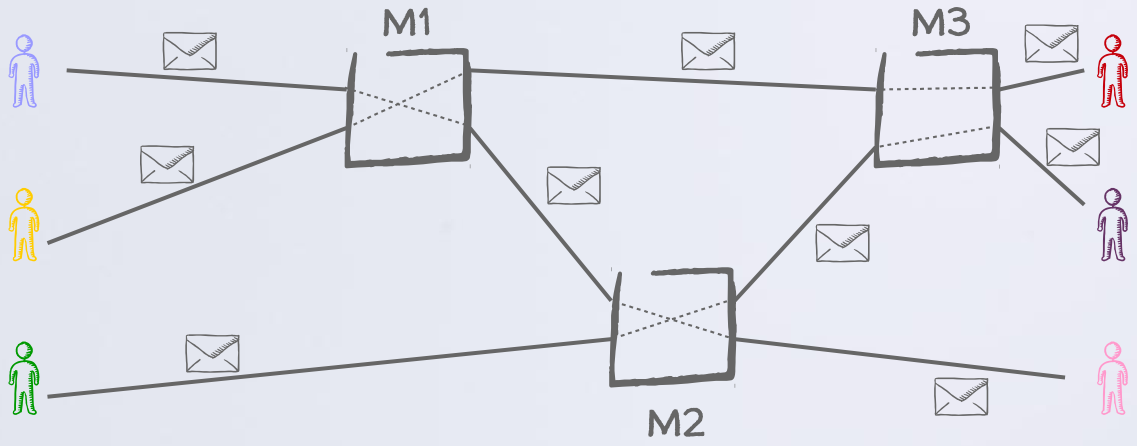

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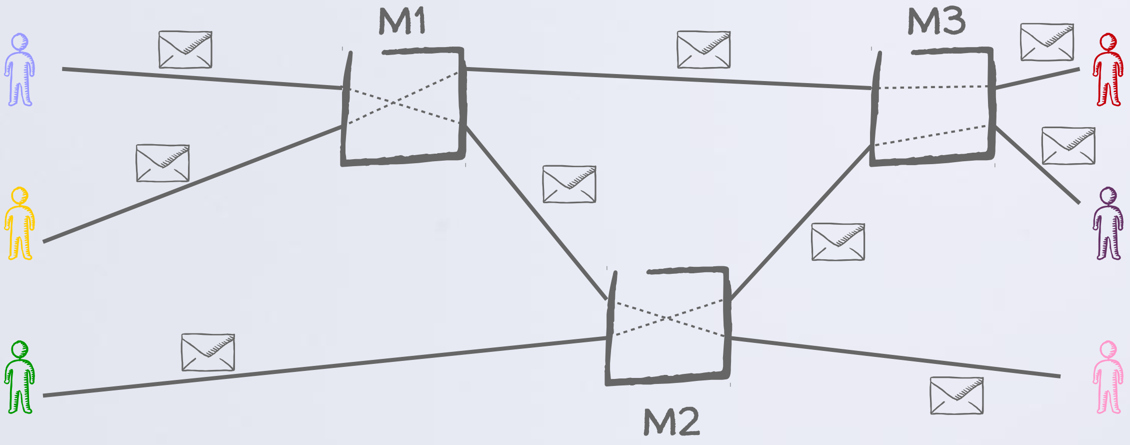

$$Pr[HS|O,C]=\frac{Pr[O|HS,C]\cdot Pr[HS|C]}{\sum_{HS} Pr[HS,O|C]}=\frac{Pr[O|HS,C]\cdot K}{Z}=\frac{Pr[Paths|C]\cdot K}{Z}$$

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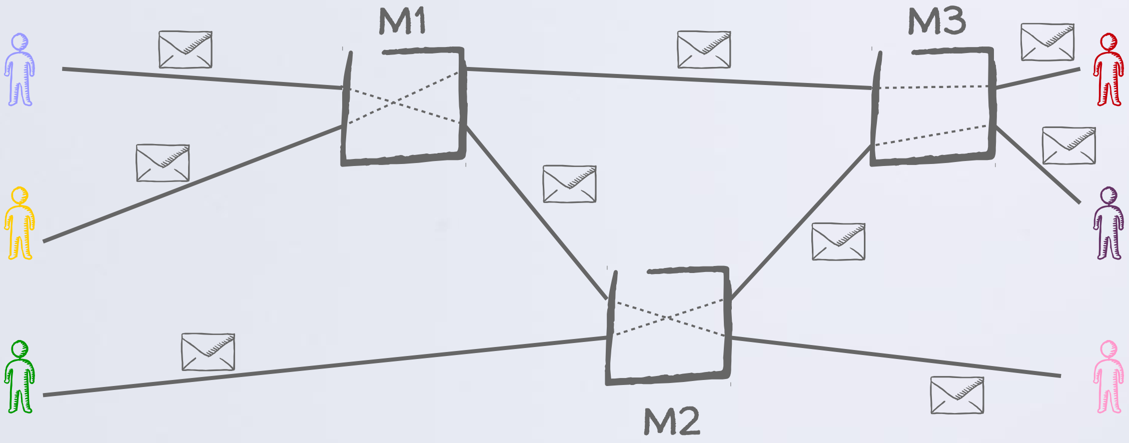

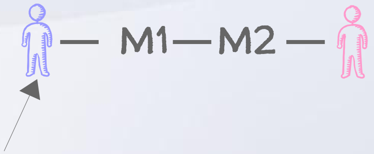

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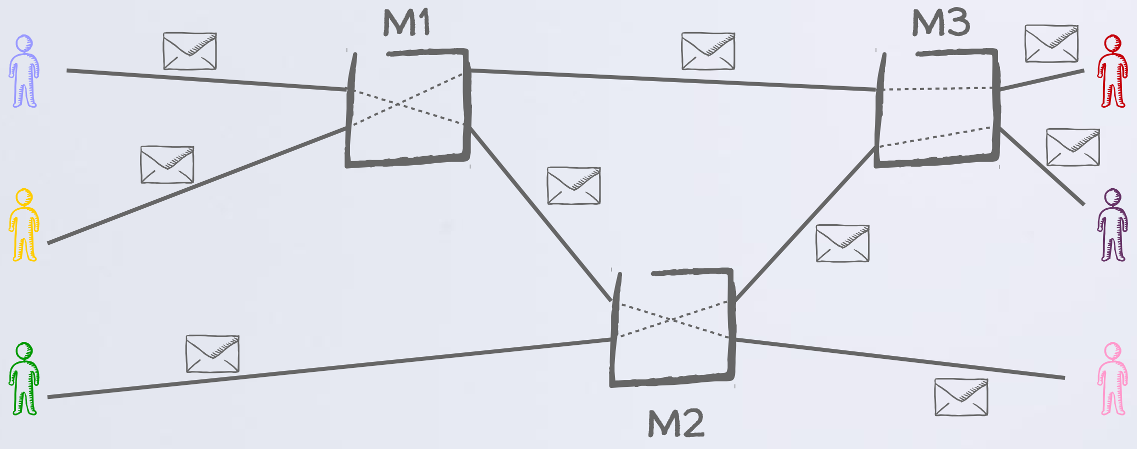

Software!! we can compute :)

— M1—M2 —

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We usually care about marginal probabilities, not all (Pr[→ |O,C]) ← SAMPLING!!

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Takeaways attacks on routes

- Traffic analysis is non trivial when there are constraints

- Traffic analysis as inference problem: systematic!
  - Probabilistic model: can incorporate most attacks
    - Can integrate knowledge on path probability computation
      - More constraints → less anonymity but more complexity
    - Combines well with other inferences: e.g., long-term attacks (in a minute)

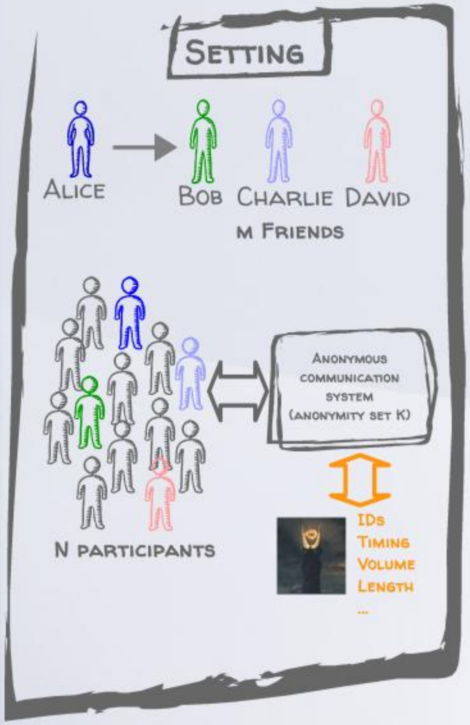
- Sampling methods to extract marginal probabilities

Finding persistent communications
Disclosure Attacks

In reality...

- Alice has few friends with whom she communicates often
- Alice is not always online (at least not active)

Can Sauron learn Alice's friends?



Setting

Alice

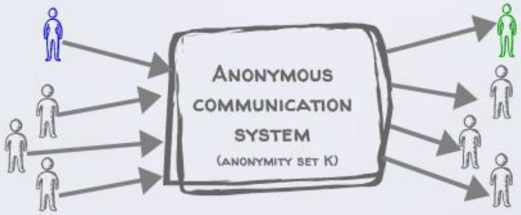
Bob Charlie David

m Friends

N participants

Anonymous communication system (anonymity set K)

IDs
Timing
Volume
Length
...



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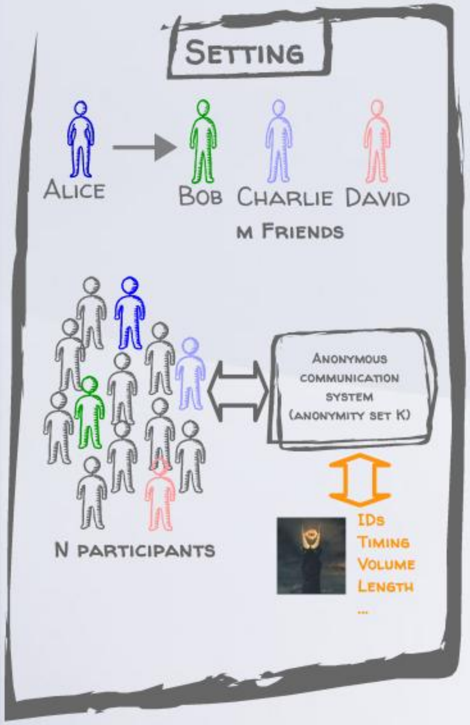

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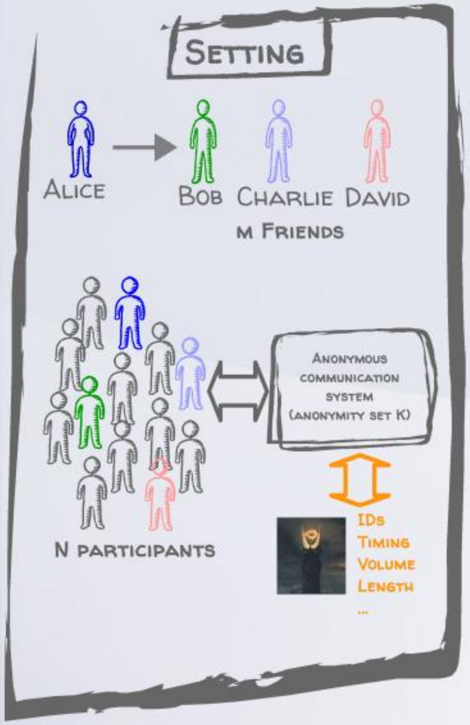
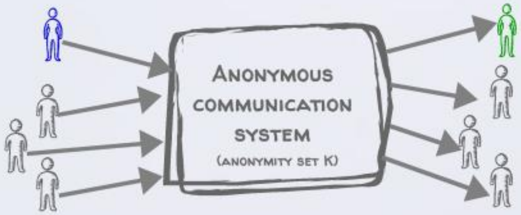


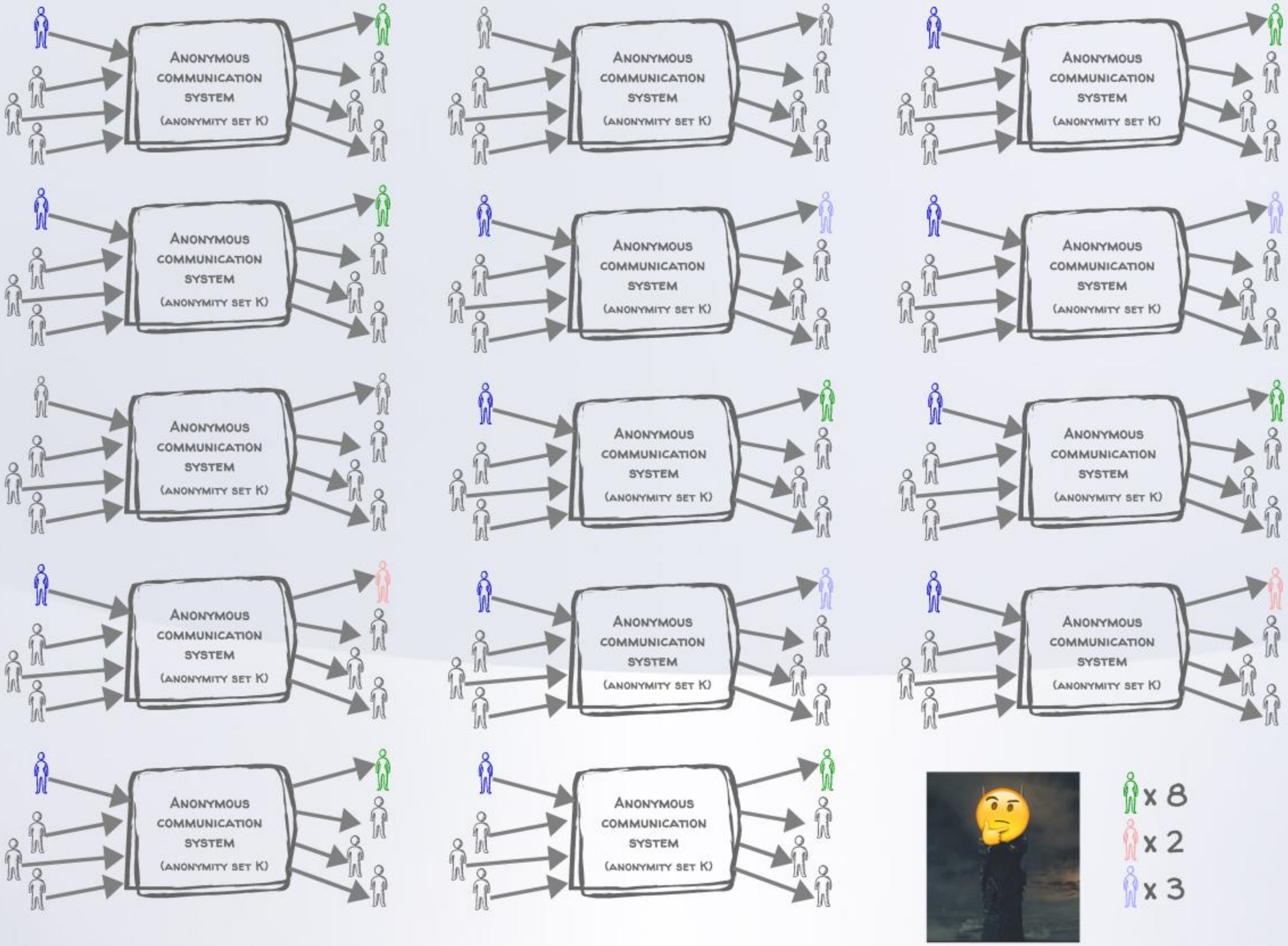


1– sees Alice sending a single message to the system

2– Anonymity set size = K

3– Perfect!

As time goes by and Alice sends more messages...



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x 8

x 2

x 3

Let's "do" the math

Approach 1: Statistical Disclosure Attack

- Alice's friends will be in the sets more often than random receivers. How often?
  Expected number of messages per receiver after t rounds:
  - $\mu_{other} = (1 / N) \cdot (K-1) \cdot t$
  - $\mu_{Alice} = (1 / M) \cdot t + \mu_{other}$
- Just count the number of messages per receiver when Alice is sending!
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N=20 m=3 K=5 t=45

Alice's Friends={[0, 13, 19]}

Round	Receivers	SDA
1	**[15, 13, 14, 5, 9]**	**[13, 14, 15]**
2	[19, 10, 17, 13, 8]	[13, 17, 19]
3	[0, 7, 0, 13, 5]	[0, 5, 13]
4	[16, 18, 6, 13, 10]	[5, 10, 13]
5	[1, 17, 1, 13, 6]	[10, 13, 17]
6	[18, 15, 17, 13, 17]	[13, 17, 18]
7	[0, 13, 11, 8, 4]	[0, 13, 17]
8	[15, 18, 0, 8, 12]	[0, 13, 17]
9	[15, 18, 15, 19, 14]	[13, 15, 18]
10	[0, 12, 4, 2, 8]	[0, 13, 15]
11	[9, 13, 14, 19, 15]	[0, 13, 15]
12	[13, 6, 2, 16, 0]	[0, 13, 15]
13	[1, 0, 3, 5, 1]	[0, 13, 15]
14	[17, 10, 14, 11, 19]	[0, 13, 15]
15	[12, 14, 17, 13, 0]	[0, 13, 17]
16	[18, 19, 19, 8, 11]	[0, 13, 19]
17	[4, 1, 19, 0, 19]	[0, 13, 19]
18	[0, 6, 1, 18, 3]	[0, 13, 19]
19	[5, 1, 14, 0, 5]	[0, 13, 19]
20	[17, 18, 2, 4, 13]	[0, 13, 19]
21	[8, 10, 1, 18, 13]	[0, 13, 19]
22	[14, 4, 13, 12, 4]	[0, 13, 19]
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20	[17, 18, 2, 4, 13]	[0, 13, 19]
21	[8, 10, 1, 18, 13]	[0, 13, 19]
22	[14, 4, 13, 12, 4]	[0, 13, 19]
23	[19, 13, 3, 17, 12]	[0, 13, 19]
24	[8, 18, 0, 10, 18]	[0, 13, 18]

Approach 1: Statistical Disclosure Attack

- Alice's friends will be in the sets more often than random receivers. How often? Expected number of messages per receiver after t rounds:
  - $\mu_{other} = (1 / N) \cdot (K-1) \cdot t$
  - $\mu_{Alice} = (1 / M) \cdot t + \mu_{other}$

- Just count the number of messages per receiver when Alice is sending!
  - $\mu_{Alice} > \mu_{other}$

Danezis, George. "Statistical disclosure attacks." Security and Privacy in the Age of Uncertainty, 2003.
Danezis, George, Claudia Diaz, and Carmela Troncoso. "Two-sided statistical disclosure attack." PETS, 2007.
Mathewson, Nick, and Roger Dingledine. "Practical traffic analysis: Extending and resisting statistical disclosure." PETS, 2004
Troncoso, Carmela, Benedikt Gierlichs, Bart Preneel, and Ingrid Verbauwhede. "Perfect matching disclosure attacks." PETS, 2008

Let's "do" the math

N=20 m=3 K=5 t=45
Alice's Friends={[0, 13, 19]}

Round	Receivers	SDA
1	**[15, 13, 14, 5, 9]**	**[13, 14, 15]**
2	[19, 10, 17, 13, 8]	[13, 17, 19]
3	[0, 7, 0, 13, 5]	[0, 5, 13]
4	[16, 18, 6, 13, 10]	[5, 10, 13]
5	[1, 17, 1, 13, 6]	[10, 13, 17]
6	[18, 15, 17, 13, 17]	[13, 17, 18]
7	[0, 13, 11, 8, 4]	[0, 13, 17]
8	[15, 18, 0, 8, 12]	[0, 13, 17]
9	[15, 18, 15, 19, 14]	[13, 15, 18]
10	[0, 12, 4, 2, 8]	[0, 13, 15]
11	[9, 13, 14, 19, 15]	[0, 13, 15]
12	[13, 6, 2, 16, 0]	[0, 13, 15]
13	[1, 0, 3, 5, 1]	[0, 13, 15]
14	[17, 10, 14, 11, 19]	[0, 13, 15]
15	[12, 14, 17, 13, 0]	[0, 13, 17]
16	**[18, 19, 19, 8, 11]**	**[0, 13, 19]**
17	[4, 1, 19, 0, 19]	[0, 13, 19]
18	[0, 6, 1, 18, 3]	[0, 13, 19]
19	[5, 1, 14, 0, 5]	[0, 13, 19]
20	[17, 18, 2, 4, 13]	[0, 13, 19]
21	[8, 10, 1, 18, 13]	[0, 13, 19]
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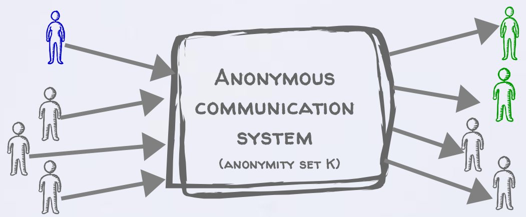
Let's "do" the math



P🧍🧍= probability that 🧍sends a message to 🧍

x^r = vector of n# of messages sent round r ($x^r_{🧍}$=1)

y^r = vector of n# of messages received round r ($y^r_{🧍}$ = 2)

H = [x^1,x^2,x^3, … ,]

Approach 2: Least Squares Disclosure Attack

- Maximum likelihood approach: solve a Least Squares minimizing mean squared error between real and estimated profiles

Pérez-González, Fernando, and Carmela Troncoso. "Understanding statistical disclosure: A least squares approach." PETS, 2012.
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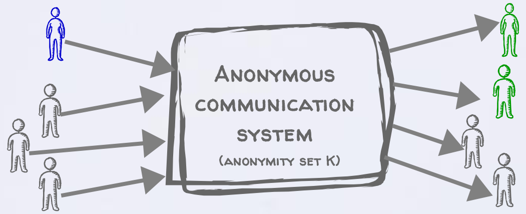
Let's "do" the math



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Approach 2: Least Squares Disclosure Attack

- Maximum likelihood approach: solve a Least Squares minimizing mean squared error between real and estimated profiles

$$\hat{p} = \underset{p}{\arg\min} \| y - Hp \| \qquad p_{i,j} \leqslant 1 \qquad \sum_i p_{i,j} = 1$$

$$\Rightarrow \quad \hat{p} = (H^T H)^{-1} H^T y$$

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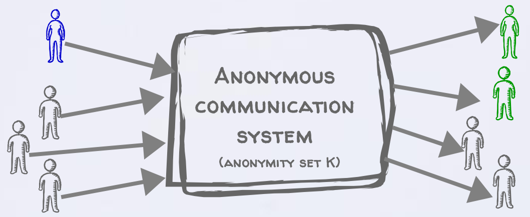

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$$\hat{p} = \underset{p}{\arg\min} \| y - Hp \| \qquad \Longrightarrow \qquad \hat{p} = (H^T H)^{-1} H^T y$$
$$p_{i,j} \leqslant 1$$
$$\sum_i p_{i,j} = 1$$

- Analytical expressions that describe the evolution of the profiling error

▲Users

$$MSE = \| p - \hat{p} \|^2 = \boxed{\frac{1}{t}} \left(\boxed{N} - 1 + \boxed{\frac{1}{k}} \right) \left(\boxed{N} - \sum_j \boxed{\frac{f_j^2}{f^2 N}} \right)$$

▼rounds

▼Batch size

▼Senders that send a lot

▲Receivers receive from many

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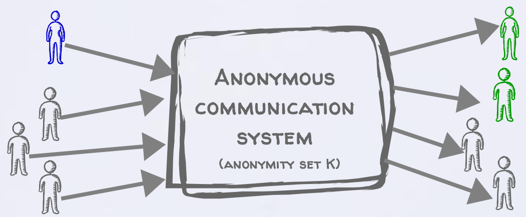
LET'S "DO" THE MATH



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APPROACH 2: LEAST SQUARES DISCLOSURE ATTACK

- Maximum likelihood approach: solve a Least Squares minimizing mean squared error between real and estimated profiles

$$\hat{p} = \arg\min_{p} \| y - Hp \| \qquad p_{i,j} \leqslant 1 \qquad \sum_i p_{i,j} = 1$$

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- Analytical expressions that describe the evolution of the profiling error

Enables systematic design!

Design as ptimization problem

▲Users

$$MSE = \| p - \hat{p} \|^2 = \boxed{\frac{1}{t}} \left(\boxed{N} - 1 + \boxed{\frac{1}{k}} \right) \left(\boxed{N} - \sum_j \boxed{\frac{f_j^2}{f^2 N}} \right)$$

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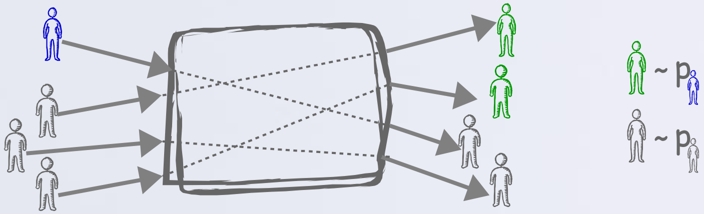
Let's "do" the math

Profile Alice $\rho_{🧍} \sim \Psi$

Profile Others $\rho_{🧍} \sim \Psi$



Mapping $M_i \sim \mathbf{M}$

Approach 3: Disclosure attack as an inference problem

- What we are looking for: $\Pr[\rho_{🧍}, \rho_{🧍}, M_i \mid O, M, \Psi]$

- More concretely, marginal probabilities & distributions
  - Pr[Alice->Bob] – Are Alice and Bob friends?
  - M_x – Who is talking to whom at round x?
  - Solve through sampling!

Profiles: $\Pr[\rho_{🧍}, \rho_{🧍} \mid M_i, O, M, \Psi, K]$

(Direct sampling by sampling Dirichlet dist.)

Mappings: $\Pr[M_i \mid \rho_{🧍}, \rho_{🧍}, O, M, \Psi, K]$

(Direct sampling of the matching link by link)

Danezis, George, and Carmela Troncoso. "Vida: How to use bayesian inference to de-anonymize persistent communications." PETS, 2009.

Persistent patterns Takeaways

- Near-perfect anonymity is not perfect enough!
  - High level patterns cannot be hidden for ever
  - Unobservability / maximal anonymity is needed
- Three approaches to the problem (actually I skipped the seminal work)

SDA

- Simple
- Fast!
- Best result not guaranteed
  - Only that one

LSDA

- Flexible
- Fast!
- Optimal result (MSE)
  - But only that one
- Error prediction
- Design tool!

Bayesian Inference

- Flexible
- "expensive"
- Distribution
  - Many quantities
  - Confidence intervals
- Not best solution

Agrawal, Dakshi, and Dogan Kesdogan. "Measuring anonymity: The disclosure attack." IEEE Security & Privacy, 2003
Kesdogan, Dogan, and Lexi Pimenidis. "The Hitting Set Attack on Anonymity Protocols." Information Hiding, 2004

Are we doomed? – Challenges

- Countermeasures – Systematic design?
  - Delay: plain batching does not seem the best
    - Pool mixes
    - Attacks can be adapted to account for more complex delay patterns
  - Dummy traffic: include “fake packets” to disorient the adversary
    - How do we make them indistinguishable?
    - Who decides about them?
  - Weaker protections suffice for other adversary models
    - e.g. Tor partial adversary
- Privacy metric, what is the goal?
- Modeling adversarial knowledge

Summary

- The Lord of The Rings is a great timeless book
- Crypto protects data, but does not always protect privacy
- Traffic analysis is the art of exploiting meta-data to extract information
- Traffic analysis can exploit a gzillion features: protecting efficiently is difficult!
    - Recovering persistent patterns, tracing messages in restricted routes
- Design privacy-preserving systems is **far** from trivial

institute imdea software

THANKS!

ANY QUESTIONS?

More about privacy:
https://www.petsymposium.org/
http://www.degruyter.com/view/j/popets

17TH PRIVACY ENHANCING TECHNOLOGIES SYMPOSIUM
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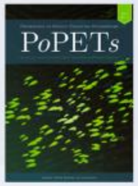
MINNEAPOLIS, MN, USA



2018 BARCELONA! DEADLINES: 31 AUG, 30 NOV, 28 FEB

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https://software.imdea.org/~carmela.troncoso/
(these slides will be there soon)

Template: http://www.brainybetty.com/
Figures: SlidesCarnival