Traffic Analysis:

or... encryption is not enough

Carmela Troncoso*
IMDEA Software Institute

Summer Research Institute

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*Thanks to George Danezis for sharing slides

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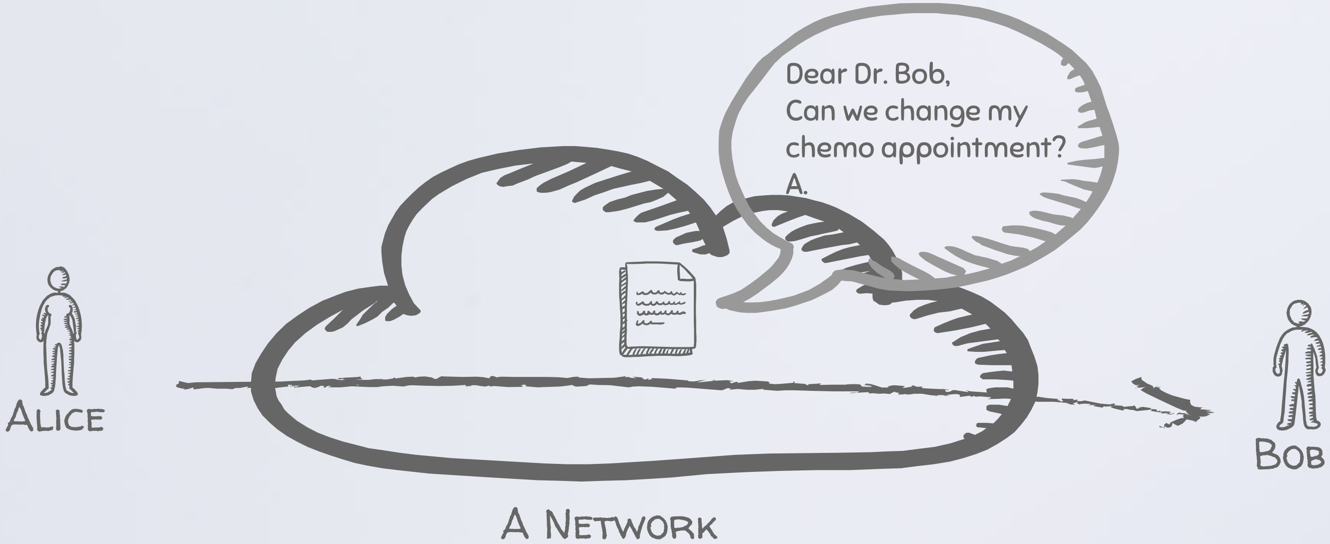
Privacy in electronic communications



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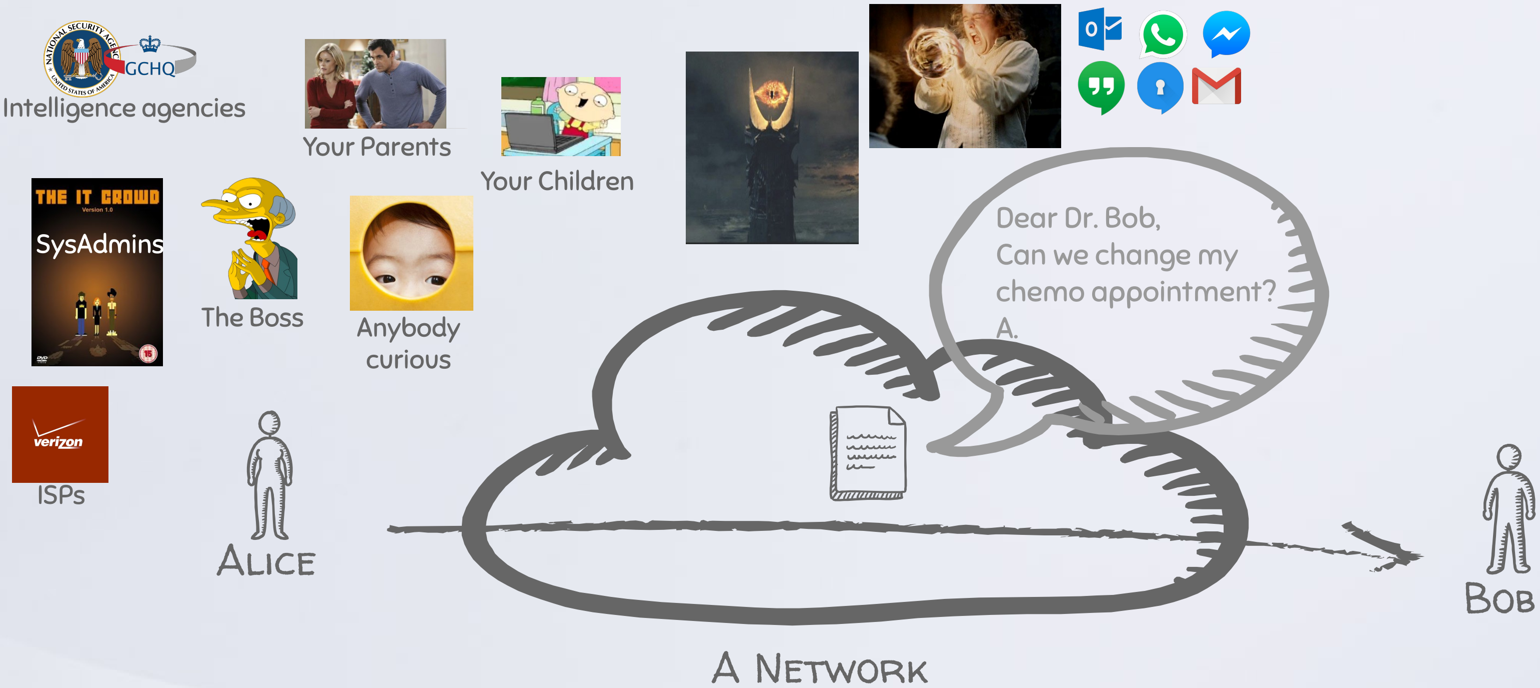

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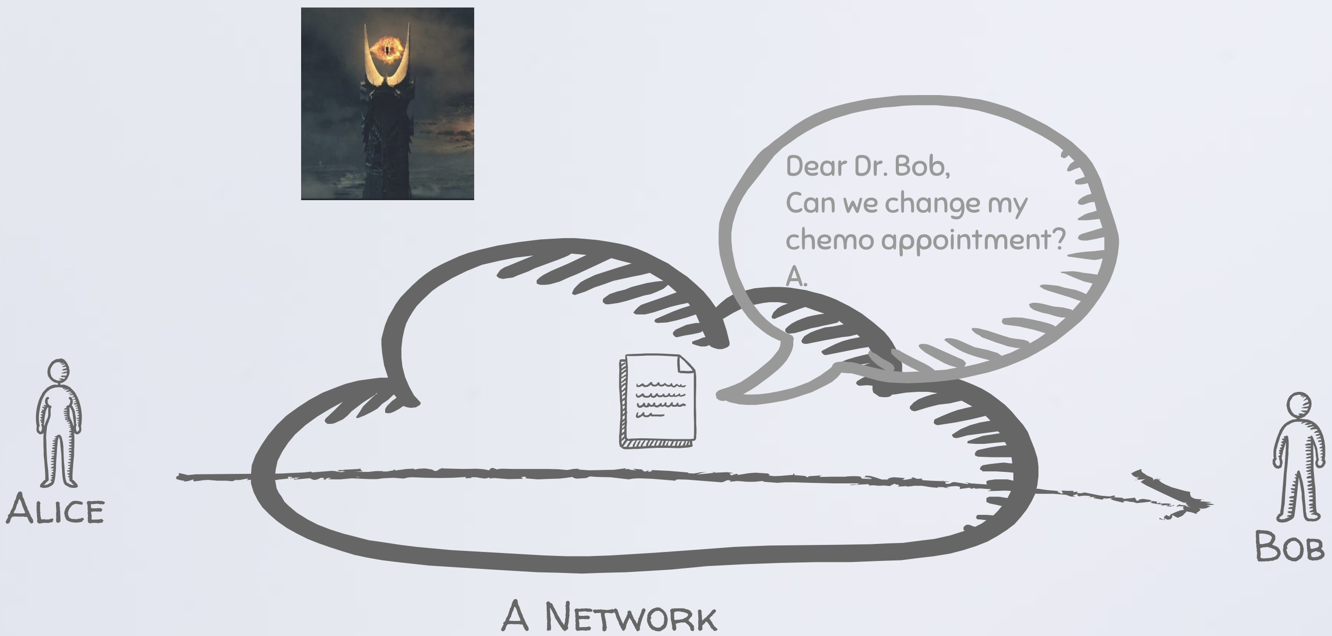

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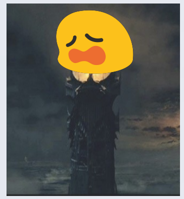

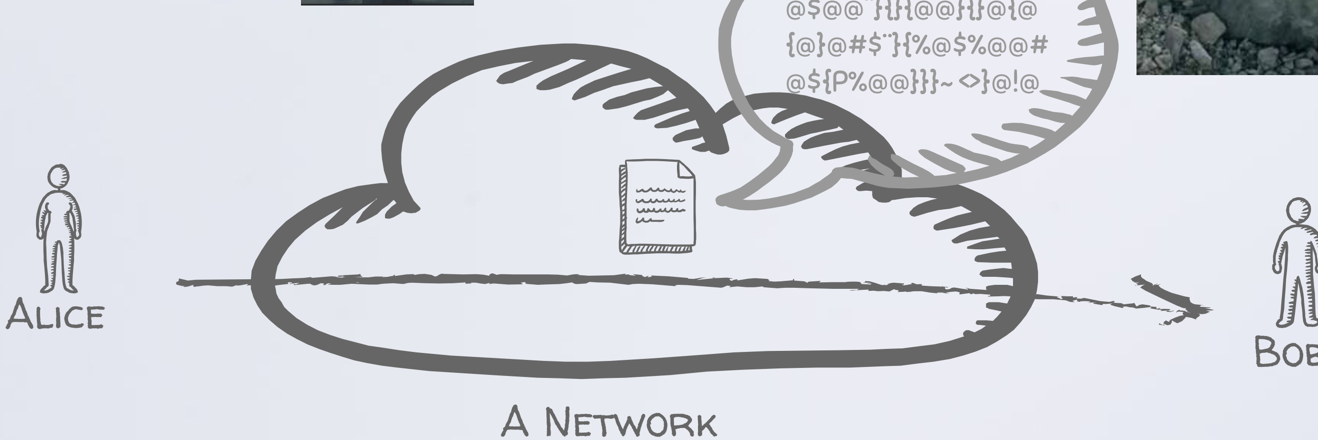

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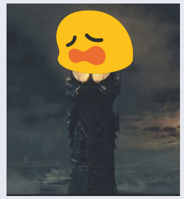

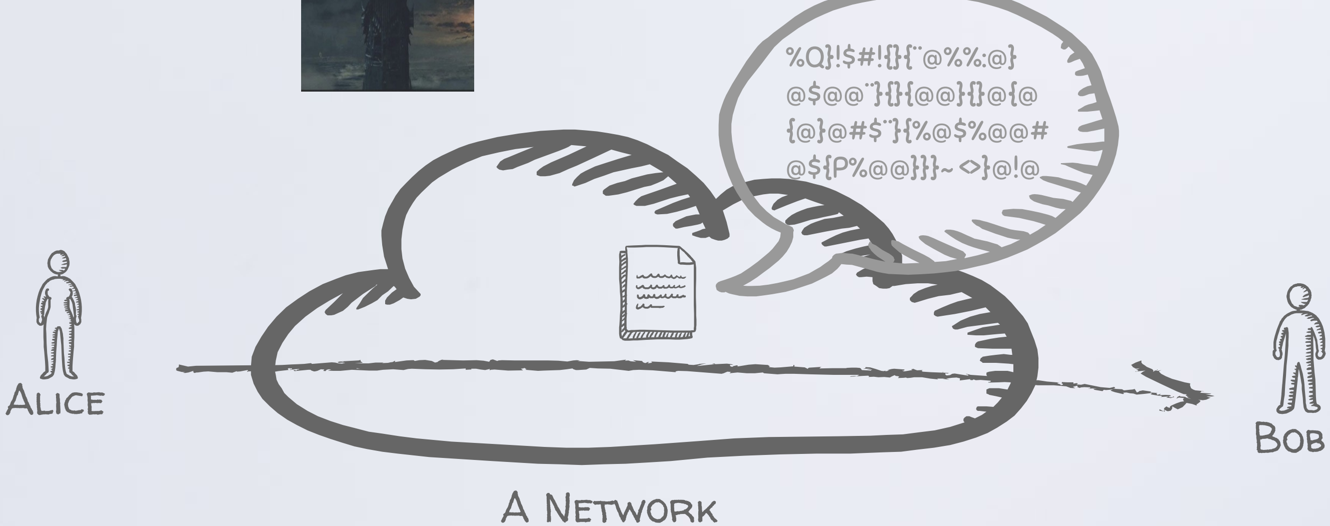

Preamble	Destination Address	Source Address	Length/ Ethertype	...Data...	FCS
8 Bytes	6 Bytes	6 Bytes	2 Bytes	Variable 46-1500 Bytes	4 Bytes

Ethernet
(IEEE 802.3, 1997)

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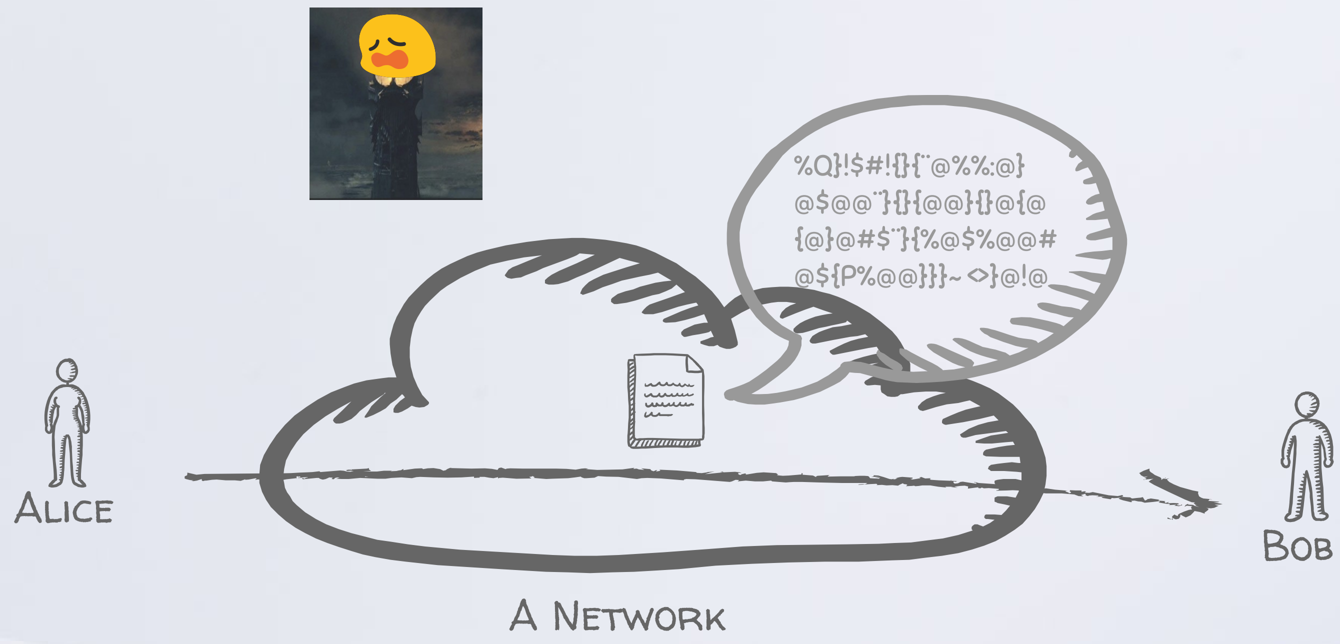

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Ethernet
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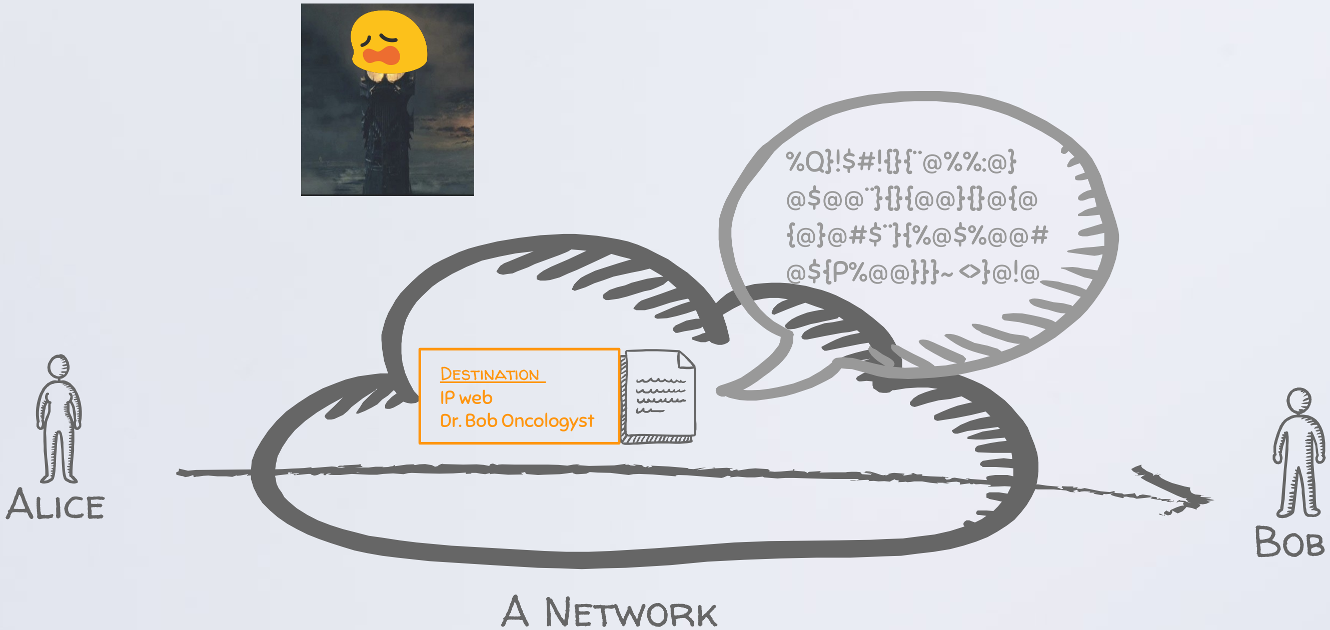
```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|Version|  IHL  |Type of Service|          Total Length         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+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

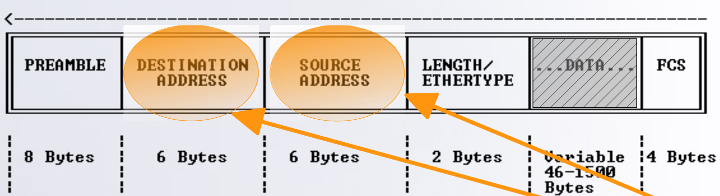
IPv4 Header
(RFC 791, 1981)

Weak identifier

Same for TCP, SMTP, IRC, HTTP, ...

But we can encrypt! What is the problem?





Ethernet
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Weak identifier

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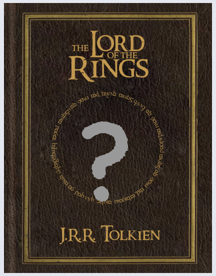
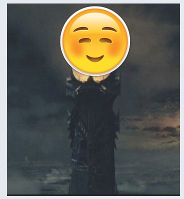
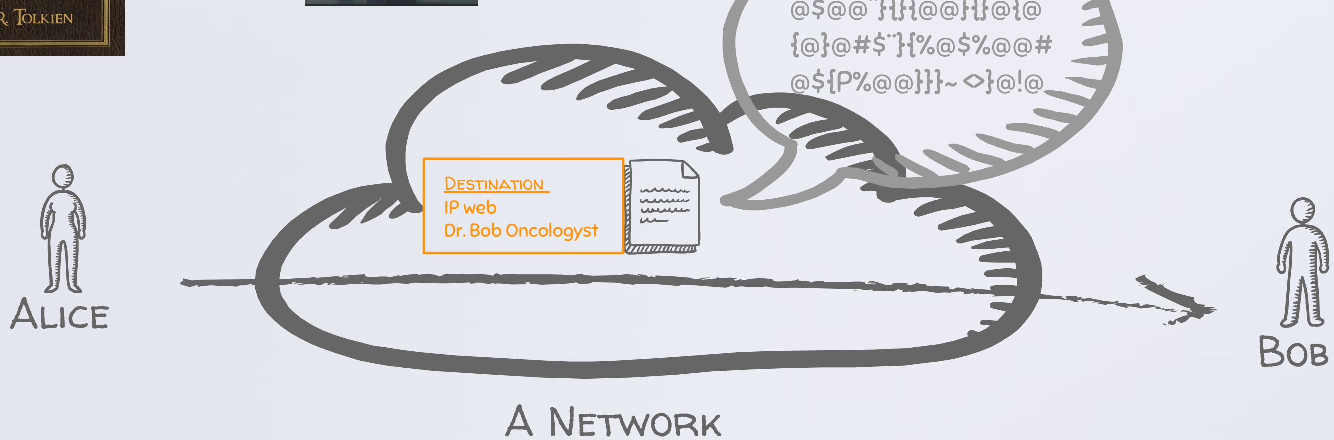
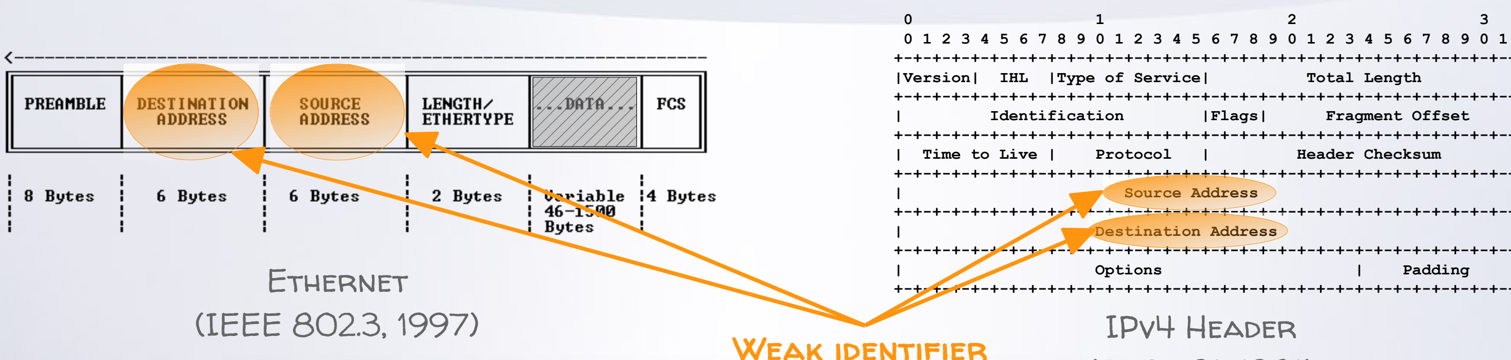
OMG!! The problem is Traffic Analysis!!









Ethernet
(IEEE 802.3, 1997)

IPv4 Header
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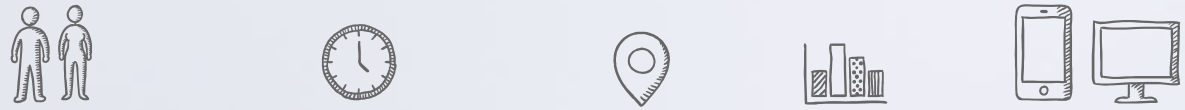
Same for TCP, SMTP, IRC, HTTP, ...

Traffic WHAT?

Wikipedia: traffic analysis is the process of intercepting and examining messages in order to deduce information from patterns in communication

Making use of "just" traffic data of a communication (aka metadata) to extract information (as opposed to analyzing content or perform cryptanalysis)



Identities of communicating parties | Timing, frequency, duration | Location | Volume | Device

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).

→

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,

Herman, Michael. Intelligence power in peace and war. Cambridge University Press, 1996.
Diffie, Whitfield, and Susan Landau. Privacy on the line: The politics of wiretapping and encryption. MIT press, 2010.
http://www.theguardian.com/world/interactive/2013/nov/01/snowden-nsa-files-surveillance-revelations-decoded

We need to protect the communication layer!

Anonymous communications

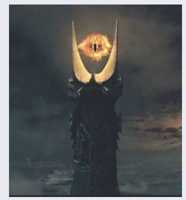
- **General applications**
  - Freedom of speech
  - Profiling / price discrimination
  - Spam avoidance
  - Investigation / market research
  - Censorship resistance
- **Specialized applications**
  - Electronic voting
  - Auctions / bidding / stock market
  - Incident reporting
  - Witness protection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

Anonymity is important to:

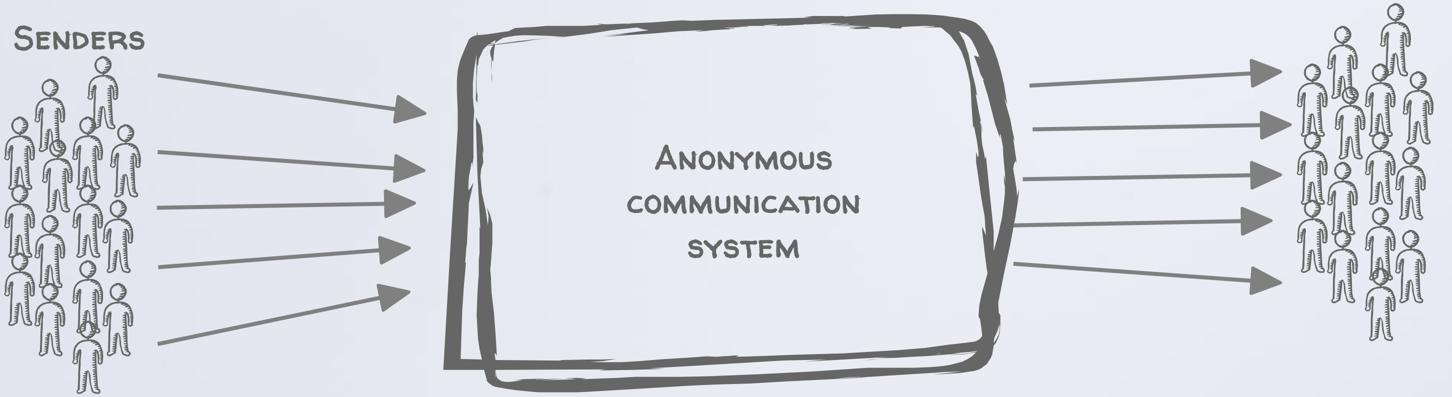
- the people who run some of the funniest parody Twitter accounts, such as @FeministHulk (SMASH THE PATRIARCHY!) or @BPGlobalPr during the Deepwater Horizon aftermath. San Francisco would not be better off if we knew who was behind @KarltheFog, the most charming personification of a major city's climate 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
...



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

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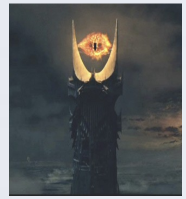

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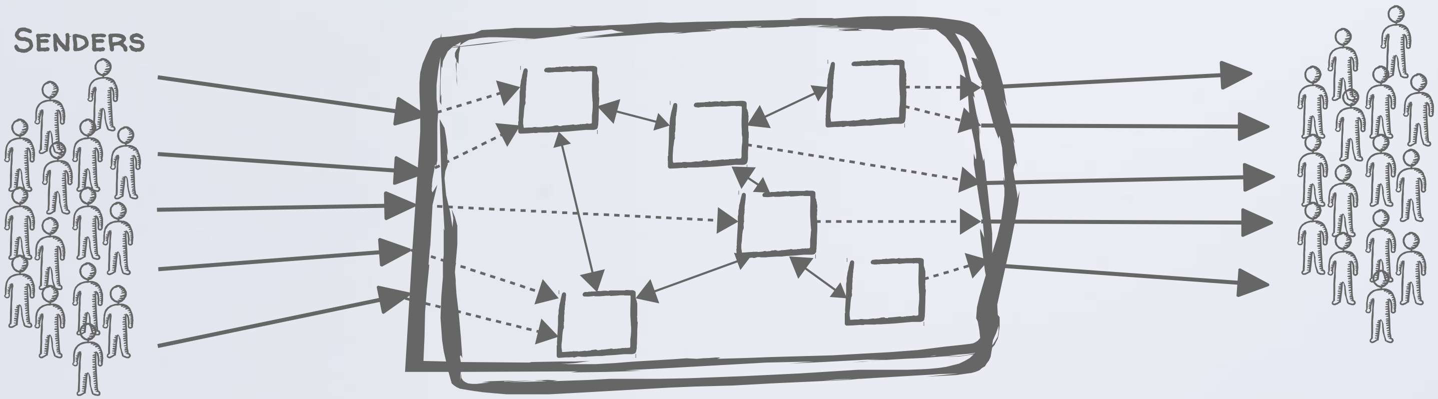

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- (Re)packetizing + (re)schedule + (re)routing,
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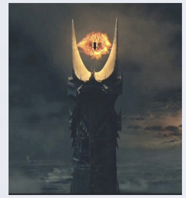
  - Load balancing
  - Distribute trust

In theory should work, but in practice…



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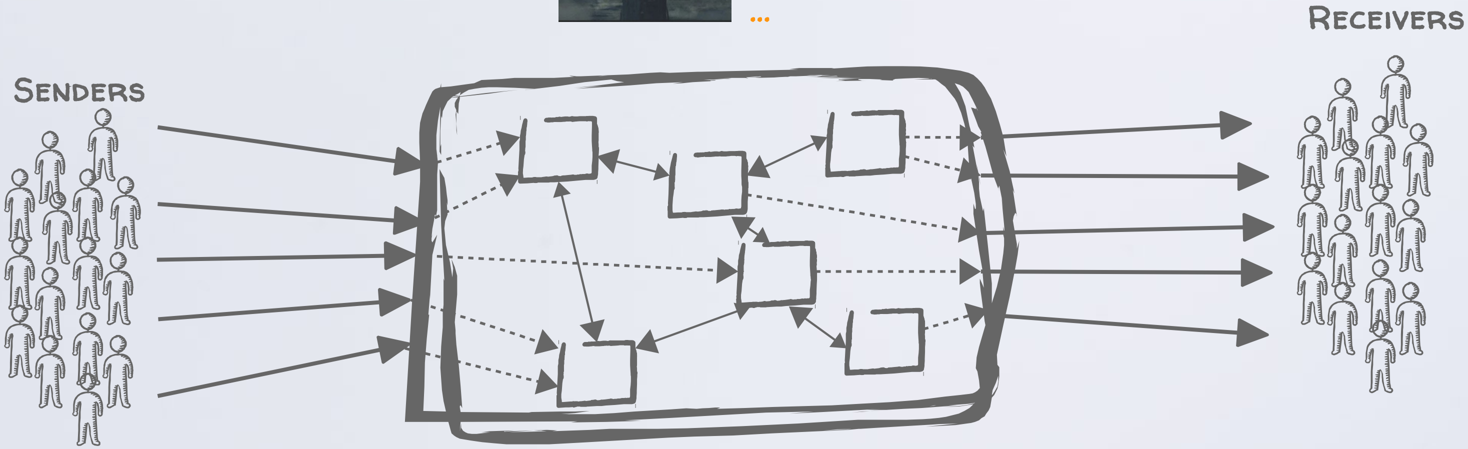

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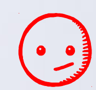
Bandwidth
Delay
Churn
Intrinsic network differences
Trust?



... STILL VULNERABLE TO TRAFFIC ANALYSIS

Find profiles and communication patterns
persistent relationships show up

Device identification / location
hosts' hardware particular characteristics

Identify users based on choices
not everybody can choose everything

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

Recover content
timing and length of packets

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

Trace packets based on routing algorithms
not all routes are possible

Users' past history
timing correlated to caches

Many, many, many, many, many more....

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Danezis, George, and Paul Syverson. "Bridging and fingerprinting: Epistemic attacks on route selection." PETS, 2008.
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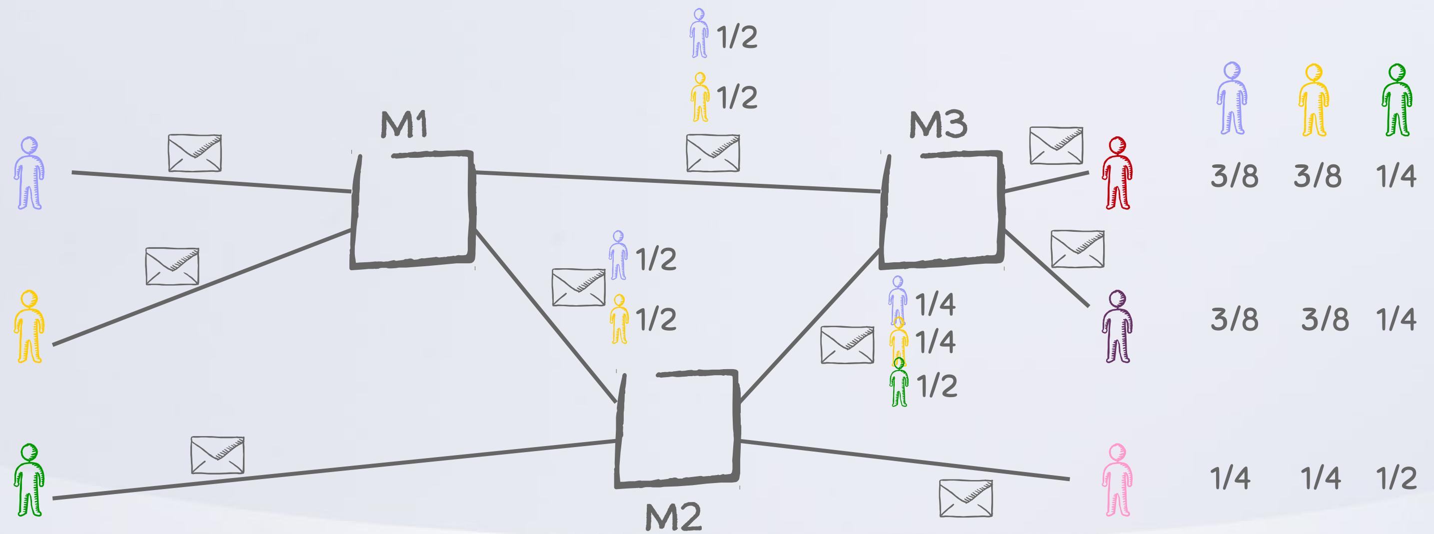
Where do messages go?

☐ **Threshold mix:** collects t messages, and outputs them changing their appearance and in a random order



Where do messages go?

not everything is possible (e.g., max 2 hops)

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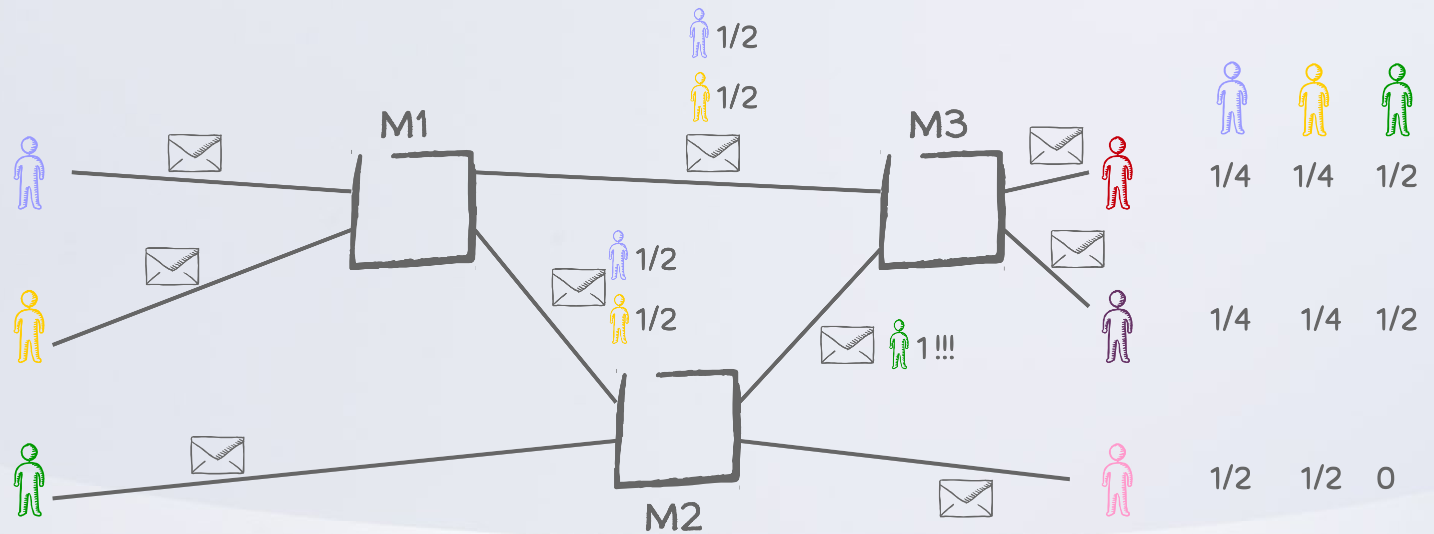
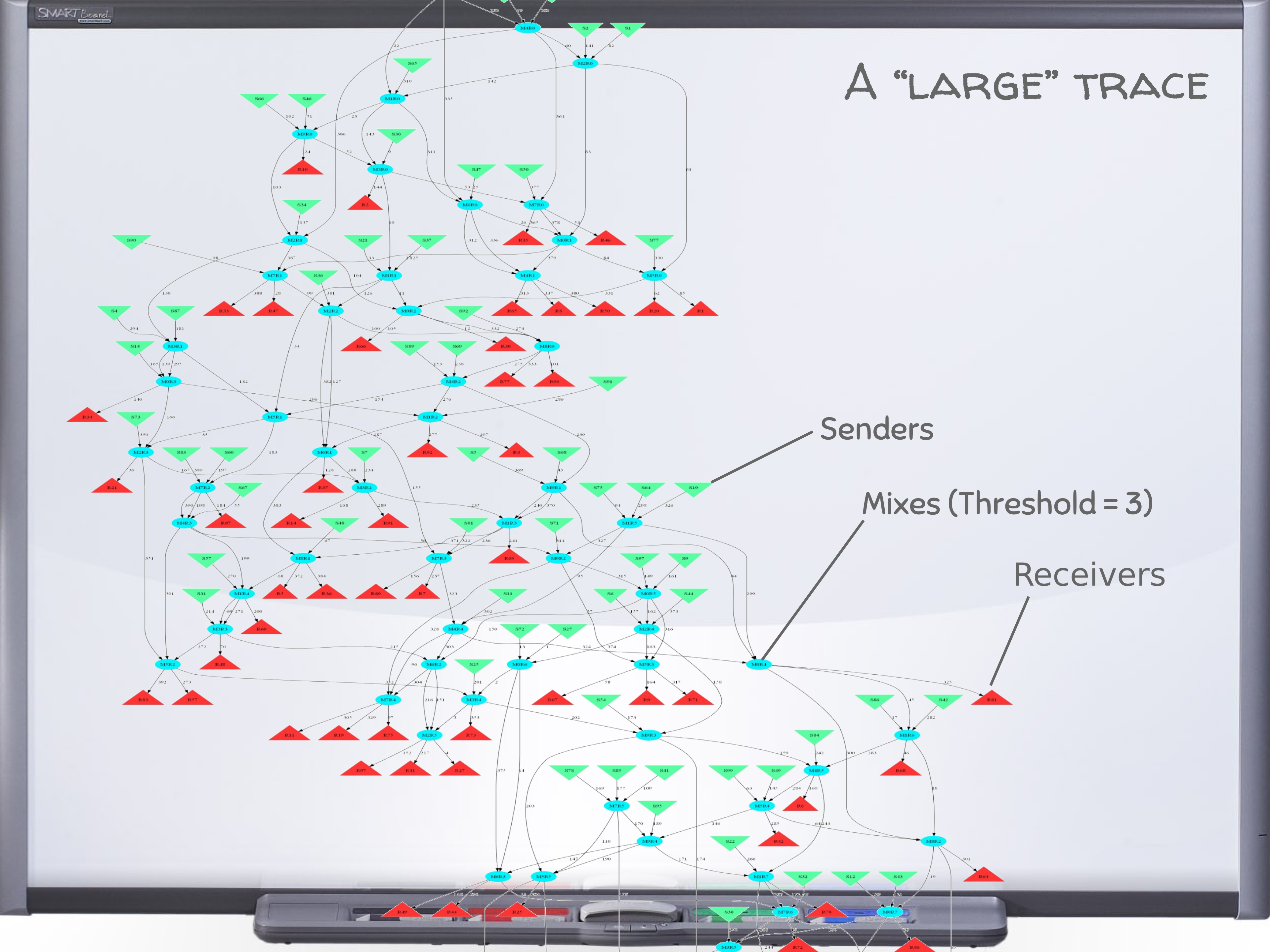


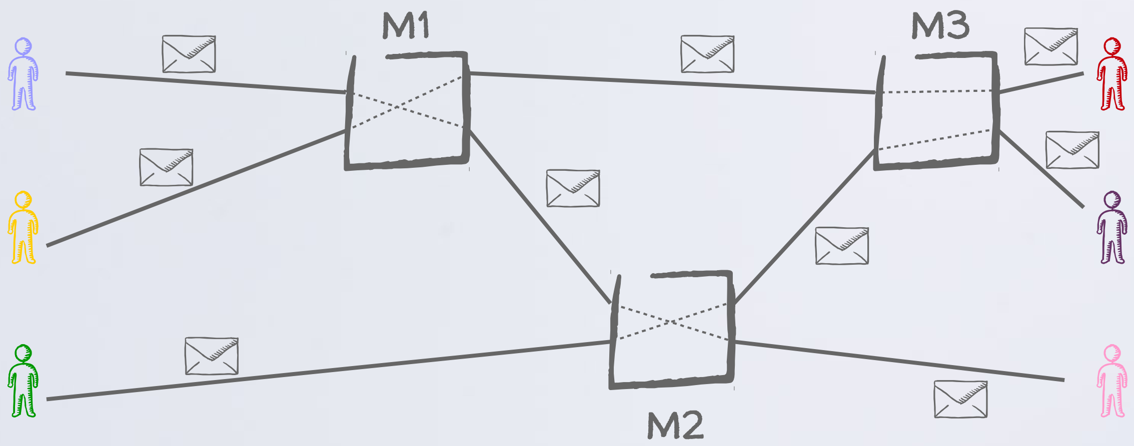
Non trivial given observation!!

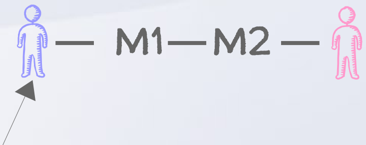
A "large" trace



Redefining the problem

Given what we see (Observation) and the system operation (Constraints)
Probability of mixes "Hidden State"?
(or Probability of each possible path?)





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

Actually…

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

	3/8	3/8	1/4
	3/8	3/8	1/4
	1/4	1/4	1/2

$$Pr[A\rightarrow B|O,C]=\sum_{HS} I(A\rightarrow B\in HS)\cdot Pr[HS|O,C]$$

But we could also compute them using samples. If we had:

$$HS_{1,} HS_{2,} HS_{3,} \ldots, HS_{N} \sim Pr[HS|O,C]$$

Simply count:

$$Pr[A\rightarrow B|O,C]=\frac{\sum_{HS} I(A\rightarrow B\in HS)}{N}$$

MCMC

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

$$\prod_{senders} Pr[Path|C]$$

Example: in Tor a path is one guard, one middle, one exit chosen with respect to a know algorithm “proportionally” to their bandwidth

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)
- MCMC methods to extract marginal probabilities
  - Systematic
  - Only generative model needed

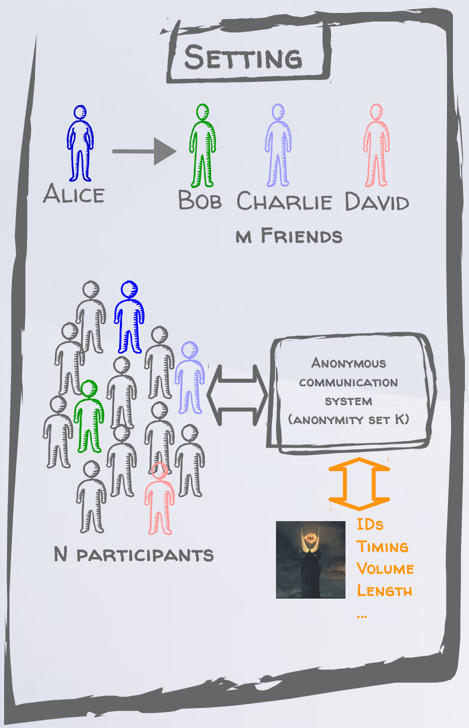
Finding persistent communications

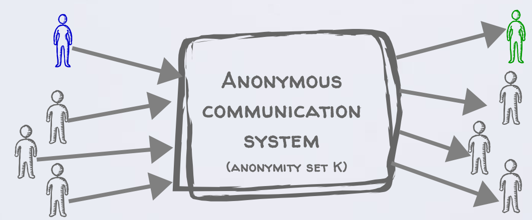
Disclosure Attacks

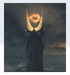
In reality...

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

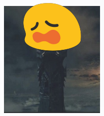
Can Sauron learn Alice's friends?



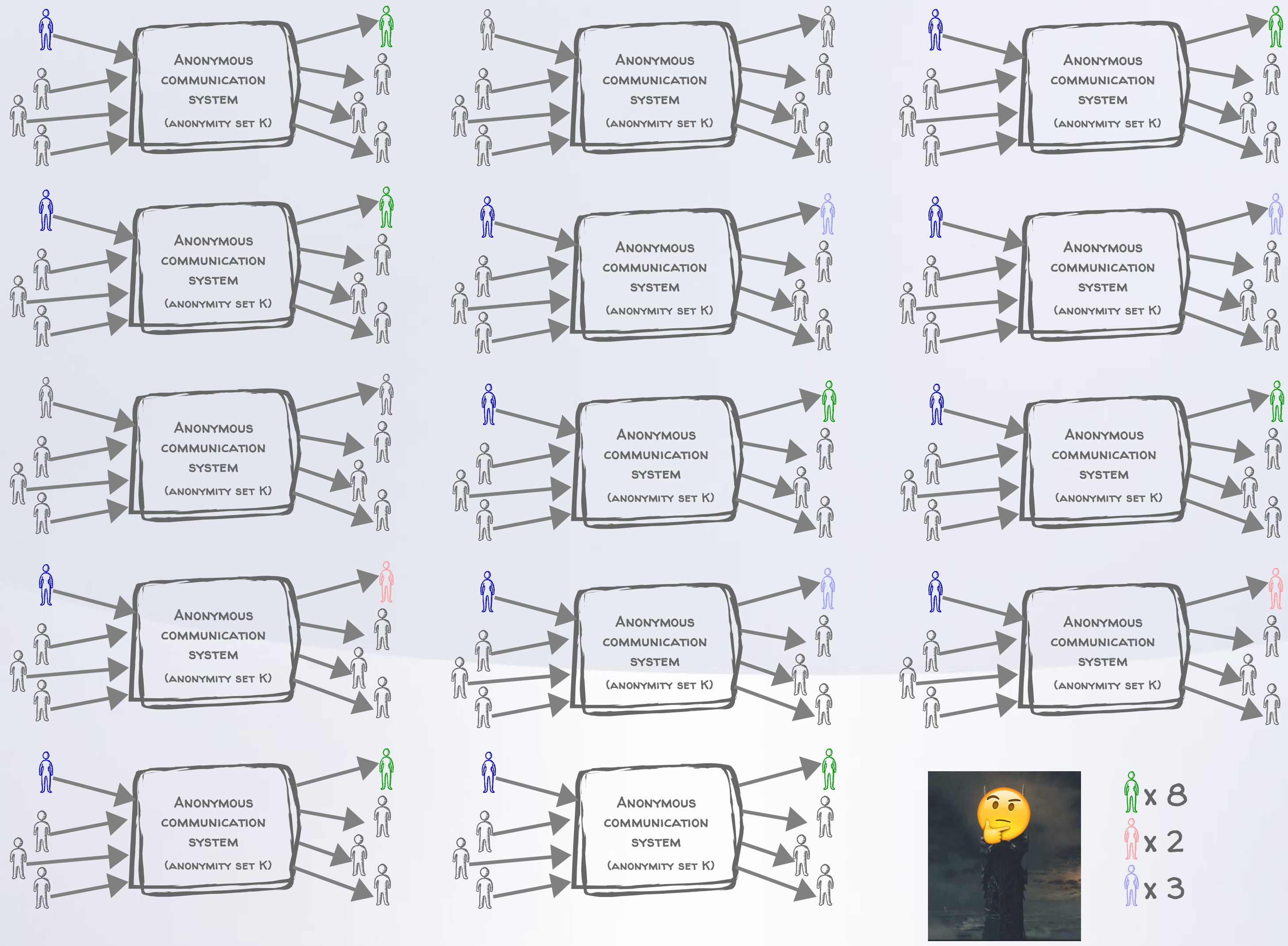


1–  sees Alice sending a single message to the system

2– Anonymity set size = K

3– Perfect! 

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



Let's "do" the math

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

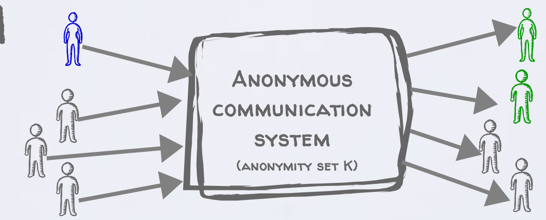
Round	Receivers	SDA
1	**[15, 13, 14, 5, 9]**	**[13, 14, 15]**
2	[19, 10, 17, 13, 8]	[13, 17, 19]
3	[0, 7, 0, 13, 5]	[0, 5, 13]
4	[16, 18, 6, 13, 10]	[5, 10, 13]
5	[1, 17, 1, 13, 6]	[10, 13, 17]
6	[18, 15, 17, 13, 17]	[13, 17, 18]
7	[0, 13, 11, 8, 4]	[0, 13, 17]
8	[15, 18, 0, 8, 12]	[0, 13, 17]
9	[15,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



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)

$H = [x^1, x^2, x^3, \ldots,]$

Approach 2: Least Squares Disclosure Attack

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

$$\hat{p} = \arg\min_p \| y - Hp \| \quad p_{i,j} \leq 1 \quad \sum_i p_{i,j} = 1$$

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

- Analytical expressions that describe the evolution of the profiling error

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

↑ Users

↓ rounds

↓ Batch size

↓ Senders that send a lot

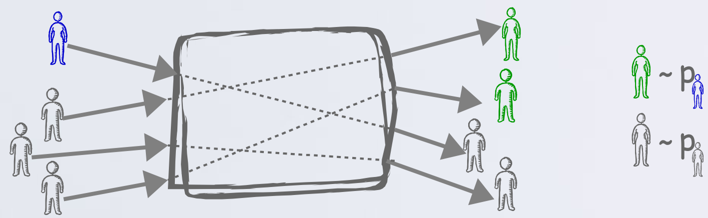
↑ Receivers receive from many

Pérez-González, Fernando, and Carmela Troncoso. "Understanding statistical disclosure: A least squares approach." PETS, 2012.
Oya, Simon, Carmela Troncoso, and Fernando Pérez-González. "Do dummies pay off? limits of dummy traffic protection in anonymous communications." PETS, 2014
Perez-Gonzalez, Fernando, Carmela Troncoso, and Simon Oya. "A least squares approach to the static traffic analysis of high-latency anonymous communication systems." TIFS 2014

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)

Gibbs Sampling

- Allows sampling from complex distributions when their marginal distributions are easy to sample from.
- Example: Sample Pr[A,B | O]
- For sample s in (0, SAMPLES):
  - For iteration j in (0, ITERATIONS):
    - $a_j \sim A$ with $\Pr[A \mid B=b_{j-1}, O]$
    - $b_j \sim B$ with $\Pr[B \mid A=a_j, O]$
  - $\text{Sample}_s = (a_{\text{SAMPLES}}, b_{\text{SAMPLES}})$

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!

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?

- Countermeasures
  - 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?
  - This is GPA, other adversary models?
    - Actually Tor has other goal!

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
- Different attack flavors provide different trade-offs

Challenges

- Countermeasures! Dummies? Delays? Efficient combination
  - Systematic design?
- Privacy metric, what is the goal?
- Modeling adversarial knowledge
- Other fields… location privacy, behavioral/contextual authentication

THANKS!

ANY QUESTIONS?

More about traffic analysis: https://www.petsymposium.org/

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

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

LET'S "DO" THE MATH

APPROACH 0: (HITTING SET) DISCLOSURE ATTACK

- Idea: "the only people that are in the intersection of all Alice's rounds are her friends"
- Guess the set of friends of Alice:
  - Constraint $|R_A'| = m$
  - Accept if an element is in the output of each round
- Downside: Cost
  - N receivers, m size – (N choose m) options
  - Exponential → Bad [good approximations exist]
- Comparison:
  - Computationally very expensive
  - Limited model
  - Difficult to apply to complex systems

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

Round	Receivers	SDA	HS
1	**[15, 13, 14, 5, 9]**	**[13, 14, 15]**	**685**
2	[19, 10, 17, 13, 8]	[13, 17, 19]	395
3	[0, 7, 0, 13, 5]	[0, 5, 13]	257
4	[16, 18, 6, 13, 10]	[5, 10, 13]	203
5	[1, 17, 1, 13, 6]	[10, 13, 17]	179
6	[18, 15, 17, 13, 17]	[13, 17, 18]	175
7	[0, 13, 11, 8, 4]	[0, 13, 17]	171
8	[15, 18, 0, 8, 12]	[0, 13, 17]	80
9	[15, 18, 15, 19, 14]	[13, 15, 18]	41
10	[0, 12, 4, 2, 8]	[0, 13, 15]	16
11	[9, 13, 14, 19, 15]	[0, 13, 15]	16
12	[13, 6, 2, 16, 0]	[0, 13, 15]	16
13	[1, 0, 3, 5, 1]	[0, 13, 15]	4
14	[17, 10, 14, 11, 19]	[0, 13, 15]	2
15	[12, 14, 17, 13, 0]	[0, 13, 17]	2
16	**[18, 19, 19, 8, 11]**	**[0, 13, 19]**	**1**
17	[4, 1, 19, 0, 19]	[0, 13, 19]	1
18	[0, 6, 1, 18, 3]	[0, 13, 19]	1
19	[5, 1, 14, 0, 5]	[0, 13, 19]	1
20	[17, 18, 2, 4, 13]	[0, 13, 19]	1
21	[8, 10, 1, 18, 13]	[0, 13, 19]	1
22	[14, 4, 13, 12, 4]	[0, 13, 19]	1
23	[19, 13, 3, 17, 12]	[0, 13, 19]	1
24	[8, 18, 0, 10, 18]	[0, 13, 18]	1

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