Applied Crypto: Passwords & Signal & Tor

Administrivia:
Exam Logistics

- https://cs161.org/exam
  - READ IT: This is just the tl;dr summary
  - And do Homework 3 now...
    At least the part about the exam logistics!
  - Scope is everything up to and including this lecture
- Basic concept
  - You have arbitrary ***hand-written*** paper notes
    - You can compose them on a tablet with a stylus interface but you need to print them out
  - You do the exam on your computer from a pre-distributed encrypted PDF
  - Proctoring is through your phone/second device over Zoom
  - Possible of a "Trust but verify" quick oral quiz afterwards
    - Explain how to solve a variant of a question you successfully solved on the exam

Why this structure?

- We need to do what we can to ensure academic honesty
  - We also have hidden techniques we are using as well
  - If I told all of you "The exam is unproctored and we have no mechanism to detect, respond, or validate that you don't cheat"...
  - I would be ***personally insulted and a total failure if 100% of you DIDN'T CHEAT!***
    - I want my students to be rational, and under those conditions it would be irrational not to cheat
- At the same time, there is a non-linear relationship between effectiveness and burden
  - I doubt the aggressive CS162-style starring on reddit 17 page protocol is significantly better at dissuading dishonesty

Concerns about student privacy

- You will be notified in advance of which TA will be proctoring you
  - For any reason you can switch proctors if you reach out in advance
- You can join using your SID rather than your name
  - Plus zoom on phone sucks for looking at other people's rooms
- If you are not comfortable with this setup, reach out for arranging off-line recording
- If you temporarily lose connectivity, don't worry
  - Focus on the exam, not your Internet connection
- If you need to get up and go to the bathroom, stretch, etc...
  Go ahead

Reminder: Cryptographic Hashes...

- We love ourselves some cryptographic hashes
  - SHA_256, SHA_384, SHA3_256, SHA3_384
- Reminder on the properties:
  - Irreversible:
    Given H(X), it is infeasible to find X short of simply trying all possibilities
  - First preimage resistant:
    Given H(X), it is infeasible to find any X' such that H(X) = H(X')
  - Second preimage resistant:
    It is infeasible to find X and Y such that X != Y and H(X) = H(Y)

A Couple Other Hash Properties...

- They accept arbitrarily large inputs
- They "look" random
  - Change a single bit on the input and each output bit has a 50% chance of flipping
  - And until you change the input, you can't predict which output bits are going to change
- The ones we talked about are ***fast***
  - Can operate at many many MB/s:
    Faster at processing data than block ciphers

A Hash Problem: Proof of work...

- Alice wants Bob to waste a bunch of CPU resources
  - But wants to quickly ***check*** that Bob wasted that much CPU
- Alice -> Bob: "Here is a message ***M*** and a factor ***x***"
  - Make sure ***M*** has a nonce in it
- Now Bob needs to provide ***M'*** such that it starts with ***M*** and H(***M'***) starts with ***x*** zero bits
- Alice computes H(***M'***) and verifies that it starts with ***x*** zero bits
  - Alice now knows that Bob is expected to have had to create 2^x separate M's and hash them until he found one that matched

What this provides

- You can use it in a protocol where the user has to waste something...
  - EG, proposals for sending mail as a way of reducing spam
    - It wouldn't: Bad guys can get lots of CPU resources
- Have other options too
- CAPTCHAs:
  - Those "prove your human" web puzzles:
    It is a proof you wasted a few seconds of a human's time
    (Or that you paid \$.01 to waste a few seconds of a human's time)
- Proof of ***wait***
  - Alice has a secret key ***k***
  - Alice to Bob sends "Don't contact me until time ***T***, here is HMAC(***k***,***T***)"
  - When Bob gets back, he says "***T***, HMAC(***k***,***T***)"
  - Alice then verifies ***T*** is in the past and HMAC(***k***,***T***)

Passwords

- The password problem:
  - User Alice authenticates herself with a password ***P***
- How does the site verify later that Alice knows ***P***?
- Classic:
  - Just store {**Alice, *P***} in a file...
- But what happens when the site is hacked?
  - The attacker now knows Alice's password!
- Enter "Password Hashing"

Password Hashing

- Instead of storing {**Alice, *P***}...
  - Store {**Alice, H(*P*)**}
- To verify Alice, when she presents ***P***
  - Compute **H(*P*)** and compare it with the stored value
- Problem: Brute Force tables...
  - Most people chose bad passwords...
    And these passwords are known
  - Bad guy has a huge file...
    - **H(P1), P1**
      H(P2), P2
      H(P3), P3...
  - Ways to make this more efficient ("Rainbow Tables")

A Sprinkle of Salt...

- Instead of storing {**Alice, H(P)**}, also have a user-specific string, the "Salt"
  - Now store {**Alice, Salt, H(P||Salt)**}
  - The salt ideally should be both long and random, but it isn't considered "secret": rather it is a ***nonce***
- As long as the salt is unique...
  - An attacker who captures the password file has to ***brute force*** Alice's password on its own
- Its still an "off-line attack" (Attacker can do all the computation he wants) but...
  - At least the attacker can't ***precompute*** possible solutions

Slower Hashes...

- Most cryptographic hashes are designed to be ***fast***
  - After all, that is the point: they should not only turn **H(🐮)** to hamburger... they need to do it quickly
- But for password hashes, we ***want*** it to be slow!
  - Its OK if it takes a good fraction of a second to ***check*** a password
    - Since you only need to do it once for each legitimate usage of that password
  - But the attacker needs to do it for each password he wants to try
- Slower hashes don't change the ***asymptotic difficulty*** of password cracking but can have huge practical impact
  - Slow rate by a factor of 10,000 or more!

PBKDF2

- "Password Based Key Derivation Function 2"
  - Designed to produce a long "random" bitstream derived from the password
- Used for both a password hash and to generate keys derived from a user's password
  - PBKDF(PRF, P, S, c, len):
    - **PRF** == Pseudo Random Function (e.g. HMAC-SHA256)
    - **P** == Password
    - **S** == Salt
    - **c** == Iteration count
    - **len** == Number of bits/bytes requested
    - **DK** == Derived Key

```
PBKDF(PRF,P,S,c,len){
  DK = ""
  for i = 1,range(len/blocksize)+1){
    DK = DK || F(PRF,P,S,c,i)
  }
  return DK[0:len]
}

F(PRF,P,S,c,i){
  UR = U = PRF(P, S||INT_32(i))
  for j = 2; j <= c; ++j {
    U = PRF(P, U)
    UR = UR ^ U
  }
  return UR
}
```

Comments on PBKDF2

- Allows you to get effectively an arbitrary long string from a password
  - ***Assuming*** the user's password is strong/high entropy
- Very good for getting a bunch of symmetric keys from a single password
  - You can also use this to seed a pRNG for generating a "random" public/private key pair
- Designed to be slow in computation...
  - But it does ***not*** require a lot of memory:
    Other functions are also expensive in memory as well, e.g. scrypt & argon2

Passwords...

- If an attacker can do an ***offline*** attack, your password must be ***really good***
  - Attacker simply tries a huge number of passwords in parallel using a GPU-based computer: buy a bunch of used Nvidia 2080 supers from all those upgrading to 3080s
  - So you need a ***high entropy*** password:
    - Even xkcd-style is only 10b/word with a 1000 word dictionary, so need a 7 or more ***random word*** passphrase to resist a determined attacker
- Life is far better is if the attacker can only do ***online*** attacks:
  - Query the device and see if it works
  - Now limited to a few tries per second and ***no parallelism!***

... and iPhones

- Apple's security philosophy:
  - In your hands, the phone should be everything
  - In anybody else's, it should (ideally) be an inert "brick"
- Apple uses a small co-processor in the phone to handle the cryptography
  - The "Secure Enclave"
- The rest of the phone is untrusted
  - Notably the memory: ***All*** data must be encrypted:
    The CPU requests that the Secure Enclave unencrypt data and some data (e.g., your credit card for ApplePay) is only readable by the Secure Enclave
- They also have an ability to effectively erase a small piece of memory
  - "Effaceable Storage": this takes a good amount of EE trickery

Crypto and the iPhone Filesystem

- A lot of keys encrypted by keys...
  - But there is a random master key, $\mathbf{k_{phone}}$, that is the root of all the other keys
- Need to store $\mathbf{k_{phone}}$ encrypted by the user's password in the flash memory
  - PBKDF2(P,...) = $\mathbf{k_{user}}$
- But how to prevent an off-line brute-force attack?
  - Also have a 256b ***random*** secret burned into the Secure Enclave that you can use for encryption
    - Need to take apart the chip to get this!
  - Even the secure enclave can't ***read*** this secret, only ***use*** this secret as a key for hardware cryptographic engines
- Now the user key is not just a function of ***P***, but $E(K_{secret}, P)$
  - Without the secret, ***can not*** do an offline attack
- All ***online*** attacks have to go through the secure enclave
  - After 5 tries, starts to slow down
  - After 10 tries, can (optionally) nuke $\mathbf{k_{phone}}$!
    - Erase just that part of memory -> effectively erases the entire phone!
  - Even compromising the secure enclave limits guessing to 10 per second!

Backups...

- Of course there is a ***necessary*** weakness:
  - Backing up the phone copies all the data off in a form not encrypted using the in-chip secret
    - After all, you need to be able to recover it onto a new phone!
- So someone who can get your phone...
  And can somehow managed to have it unlocked
  - Thief, abusive boyfriend, cop...
    - Hold it up to your face (iPhone X) or Fingerprint (5s or beyond)
    - And then sync it with a new computer
- Change of policy for iOS-11:
  - Now you also need to put in the passcode to trust a new computer:
    Can't create a backup without knowing the passcode

Signal and Tor

- Signal is a messenger protocol and implementation
  - Signal (the company) is a 501(c)3 nonprofit
  - The protocol is also used by WhatsApp, Facebook Messenger, etc...
- Tor is an anonymity tool
  - Designed to provide anonymous but real-time network connectivity in the face of an ***aggressive but local adversary***
- Common (bad) information security advice is "Use Signal, Use Tor"
  - In reality, Signal is a great protocol, but some security compromises are annoying in the implementation, so for most, WhatsApp is about as good
  - While Tor is often not just a placebo but ***poison***!

End-To-End Messengers

- We love ***end to end*** cryptographic protocols...
  - After all, we just saw why we might want them
- We love ***forward secrecy***...
  - After all, we want things to stay secret even if our keys are compromised
- Forward secrecy is "easy" for online protocols
  - Just make sure to do a DHE/ECDHE key exchange, and throw away the session key when done
- Forward secrecy is ***much more annoying*** for an offline protocol
  - Alice wants to share data with Bob, but Bob is ***not online***
    - Like in project 2...
    - Or any messenger system!

Signal Requirements For Key Agreement

- Three parties: Alice, Bob, and a messenger server
  - The messenger server is like the file store in project 2, an ***untrusted*** entity
  - A ***separate*** mechanism is used to provide ***key transparency***
- Bob is ***offline***:
  - He has prearranged data stored on the messenger server
- Alice and Bob want to create an ephemeral (DH) key...
  - To use for then encrypting messages
- They need ***mutual authentication***
  - Assuming Alice and Bob have the correct public keys, ***only*** Alice and Bob could have agreed on a key
- They also need ***deniability***
  - Alice or Bob can't create a record ***proving*** the other side participated in creating the key:
    So no "Alice just signs her DH..." design

Extended Triple Diffie-Hellman

- Key idea:
  - Lets use multiple Diffie-Hellman exchanges combined into one
    - Some to perform mutual authentication
    - Some to generate an ephemeral key
    - Shove them ALL into a hash-based key derivation function
- They use elliptic curves, but the design would be the same for conventional DH, so we will use the former
  - We will use ***DH(A,B)*** as ***DH(g^a,g^b)*** where we know ***a*** but not ***b***.
    (So ***A*** is our private value, ***B*** is someone else's public value)
  - Also have ***Sign(K,M)*** for signing and ***KDF(KM)*** which derives a bunch of session keys for a hash-based key derivation function (e.g. ***PBKDF2*** with only a couple iterations)

Lots of Keys!

- All keys have both a public & private component
  - Private components always stay with Alice and Bob
  - Anything broadcast is always the public component
- Alice:
  - $\boldsymbol{IK_A}$: Alice's identity key: for both DH and signatures
  - $\boldsymbol{EK_A}$: Alice's ephemeral key: Created randomly just to talk to Bob.
- Bob:
  - $\boldsymbol{IK_B}$: Bob's identity key, long lived
  - $\boldsymbol{SPK_B}$: Bob's signed rekey, rotates ~weekly/monthly
    - Has corresponding signature $\boldsymbol{Sign(IK_b, SPK_b)}$
  - $\boldsymbol{OPK_B}$: Bob's one time use keys (One Time Prekey)
    - Can run out, but designed to increase security when available

Before We Start: Bob to Server, Server to Alice

- Bob uploads:
  - IK_B, SPK_B, $Sign(IK_B, SPK_B)$, $\{OPK_B^1, OPK_B^2, OPK_B^3 \ldots\}$
- Now when Alice wants to talk to Bob...
- Gets from the server:
  - IK_B, SPK_B, $Sign(IK_B, SPK_B)$, $OPK_B^?$
  - Told which ***OPK*** it is or "There are no ***OPKs*** left"
    - ***OPKs*** are designed to prevent replay attacks:
      Bob will ***never*** allow any particular ***OPK*** to be used twice
- This is now the input into Alice's DH calculations

Alice now does a lot of DH...

- ***DH1 = DK(IK_A, SPK_B)***
  - Acts as authentication for Alice when Bob does the same
- ***DH2 = DK(EK_A, IK_B)***
  - Forces Bob to do mutual authentication
- ***DH3 = DK(EK_A, SPK_B)***
  - Adds in ephemeral ***EK_A*** to short lived ***SPK_B***
- ***DH4 = DK(EK_A, OPK_B)***
  - Adds in one-time used ***OPK_B***, if available
- ***SK = HKDF(DH1 || DH2 || DH3 || DH4)***
  - Skip DH4 if no one time pre-keys are available
- Now discard the private part of EKA and the intermediate DH calculations

Now Alice Sends To Bob

- ***IK_A, EK_A***, which ***OPK*** used (if any), and ***$E(SK, M, IK_A \| IK_B)$***
  - Using an AEAD encryption mode: ***Authenticated Encryption with Additional Data*** modes allow additional data to be protected by the MAC but sent in the clear: In this case ***IK_A*** and ***IK_B***
- Bob can do the same DH calculations to generate SK
  - Since Bob knows the private keys corresponding to the public values Alice used
  - If it fails to verify the AEAD data abort

Key Transparency

- For now, Alice and Bob are trusting the server to report $\boldsymbol{IK_A}$ and $\boldsymbol{IK_B}$ correctly
  - If the server lies, 🤷‍♂️
- Fortunately there is an answer:
  If Alice and Bob are ***ever*** together:
  - One person's phone displays $\boldsymbol{H(IK_A \mathbin{||} IK_B)}$ as a QR Code
  - Other person's phone verifies that it is the same
- Plus the voice channel...
  - Display "Two Words" on screen:
    $\boldsymbol{F(H(IK_A \mathbin{||} IK_B \mathbin{||} SK))}$
  - Assumption is a MitM attacker can't fake a voice conversation quickly enough, so if each person says one of the words...

Considerations

- Authentication requires the out-of-channel methods
  - Otherwise no guarantees
- Replay attacks
  - Only if no OPK is available: Can be potentially bad
- Deniability
  - No cryptographic proofs available as to the sender/receiver!

And Then Ratchets...

- A "ratchet" is a one-way function for message keys
  - ***Ratchet(K_i)*** -> ***K_{i+1}***, ***MK_i***
  - But can't take ***K_{i+1}*** and ***MK_i*** to find ***K_i***
- A symmetric key ratchet is easy
  - We've seen these already:
    Any secure PRNG with rollback resistance is a ratchet
  - Can do it slightly more efficiently with HMAC:
    HMAC(K_i, 0x01) -> ***MK_i***
    HMAC(K_i, 0x02) -> ***K_{i+1}***
- Its OK to keep around the intermediate session keys
  - Thanks to HMAC we can't go backwards with them anyway:
    Needed for out of order messages

Signal adds in DH ratchets too...

- So for a few messages in a chain you use a symmetric key ratchet...
  - You gain forward secrecy by discarding the old internal state
- But occasionally you rekey with an additional DH
  - Used to add into the ratchet internal state: update K_i to $H(K_{i-1} \| DH)$
- Acts to reset everything with even more randomness
  - So even if you compromise Bob's device at time ***T*** and steal all the keys...
  - You can't decrypt old messages that aren't on Bob's device:
    can't run the symmetric ratchet backwards
  - You can't decrypt subsequent messages once Bob & Alice use a DH ratchet

The Protocol is Great... BUT!

- The app itself does some ehh thing in the usability/security tradeoff...
  - ***No mechanism to back-up messages***!
    If your phone is toast, your messages are gone!
  - ***No mechanism to migrate to a new phone***!
    If you upgrade to a new phone, your messages are gone!
  - ***Auto-notifies all those where you are in their contacts that they join***
- This is where WhatsApp has a huge competitive advantage
  - They allow backup of messages, message migration etc...

Tor: The Onion Router Anonymous Websurfing

- Tor actually encompasses many different components
- The Tor network:
  - Provides a means for anonymous Internet connections with low(ish) latency by relaying connections through multiple Onion Router systems
- The Tor Browser bundle:
  - A copy of FireFox extended release with privacy optimizations, configured to only use the Tor network
- Tor Hidden Services:
  - Services only reachable though the Tor network
- Tor bridges with pluggable transports:
  - Systems to reach the Tor network using encapsulation to evade censorship
- Tor provides three separate capabilities in one package:
  - Client anonymity, censorship resistance, server anonymity

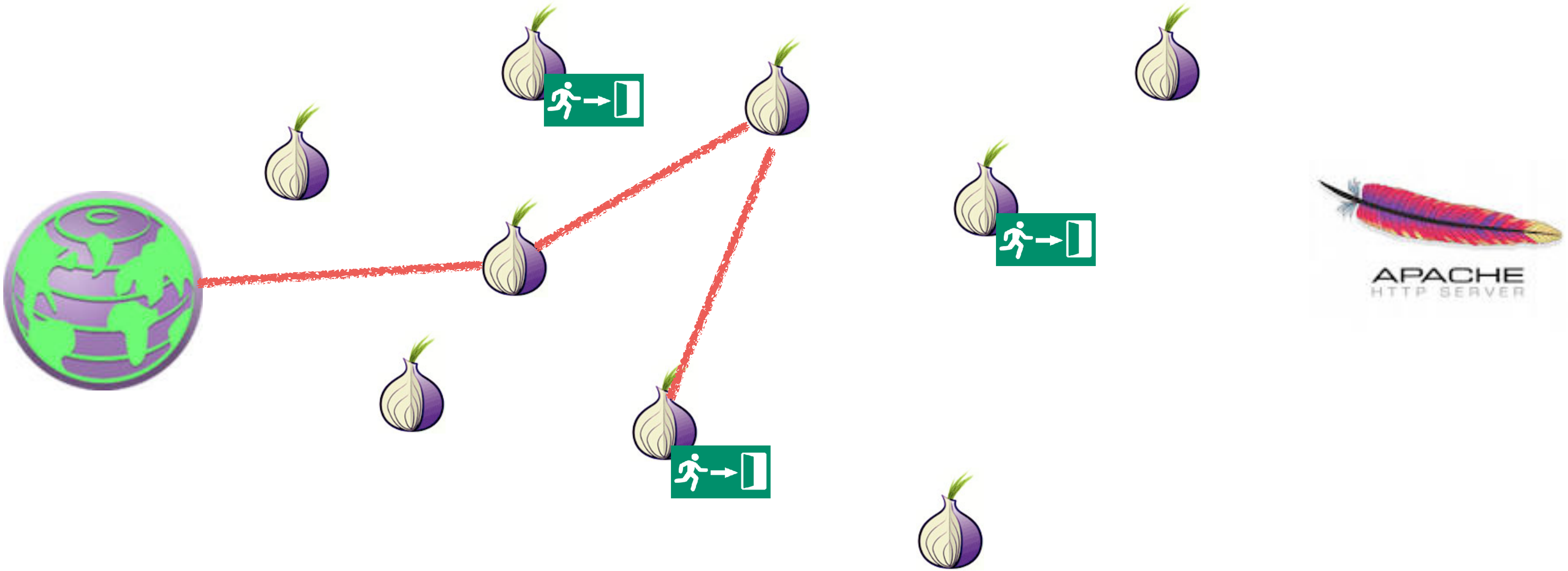
The Tor Threat Model: Anonymity of content against ***local*** adversaries

- The goal is to enable users to connect to other systems "anonymously" but with low latency
  - The remote system should have no way of knowing the IP address originating traffic
  - The local network should have no way of knowing the remote IP address the local user is contacting
- Important what is excluded: The ***global*** adversary
  - Tor does not even attempt to counter someone who can see ***all*** network traffic: It is probably ***impossible*** to do so and be low latency & efficient

The High Level Approach: Onion Routing

- The Tor network consists of thousands of independent Tor nodes, or "Onion Routers"
  - Each node has a distinct public key and communicates with other nodes over TLS connections
- A Tor circuit encrypts the data in a series of layers
  - Each hop away from the client removes a layer of encryption
  - Each hop towards the client adds a layer of encryption
- During circuit establishment, the client establishes a session key with the first hop…
  - And then with the second hop through the first hop
- The client has a ***global*** view of the Tor Network:
  The directory servers provide a list of all Tor relays and ***their public keys***

Tor Routing In Action



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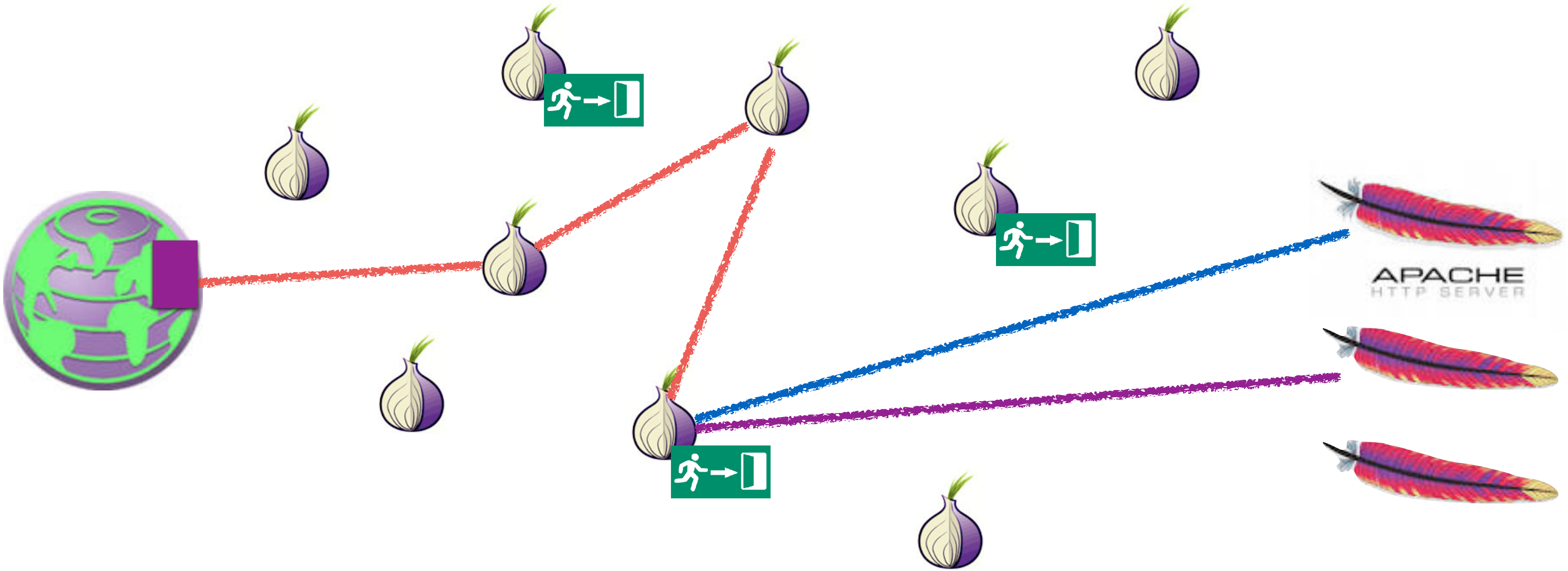


Creating the Circuit Layers…

- The client starts out by using an authenticated DHE key exchange with the first node…
  - OR1 creates g^a, signs it with its private key, sends g^a, **Sign**(K_{priv_or1}, g^a) to client
    Client creates g^b, sends it to OR1
    Client does **Verify**(K_{pub_or1}, g^a)
  - Creating a session key K_{OR1} as $H(g^{ab})$
    - This first hop is commonly referred to as the "guard node"
- It then tells OR1 to extend this circuit to OR2
  - Through that, creating a session key for the client to talk to OR2 that OR1 ***does not know***
  - And OR2 doesn't know what the client is, just that it is somebody talking to OR1 requesting to extend the connection...
- It then tells OR2 to extend to OR3…
  - And OR1 won't know where the client is extending the circuit to, only OR2 will

Unwrapping the Onion

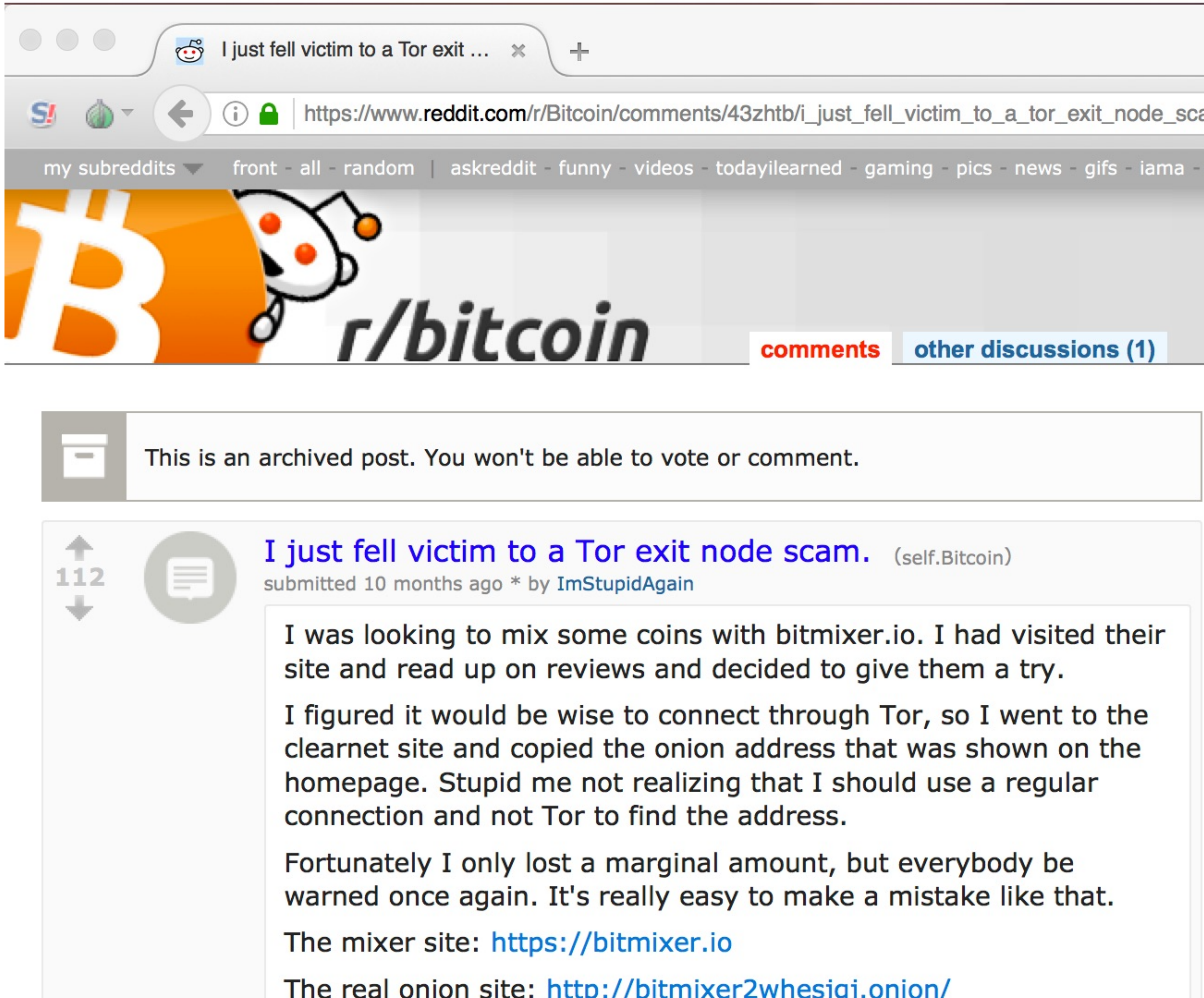
- Now the client sends some data…
  - $E(\boldsymbol{K_{or1}}, E(\boldsymbol{K_{or2}}, E(\boldsymbol{K_{or3}}, \text{Data})))$
- OR1 decrypts it and passes on to OR2
  - $E(\boldsymbol{K_{or2}}, E(\boldsymbol{K_{or3}}, \text{Data}))$
- OR2 then passes it on…
- Generally go through at least 3 hops…
  - Why 3? So that OR1 can't call up OR2 and link everything trivially
- Messages are a fixed-sized payload

The Tor Browser…

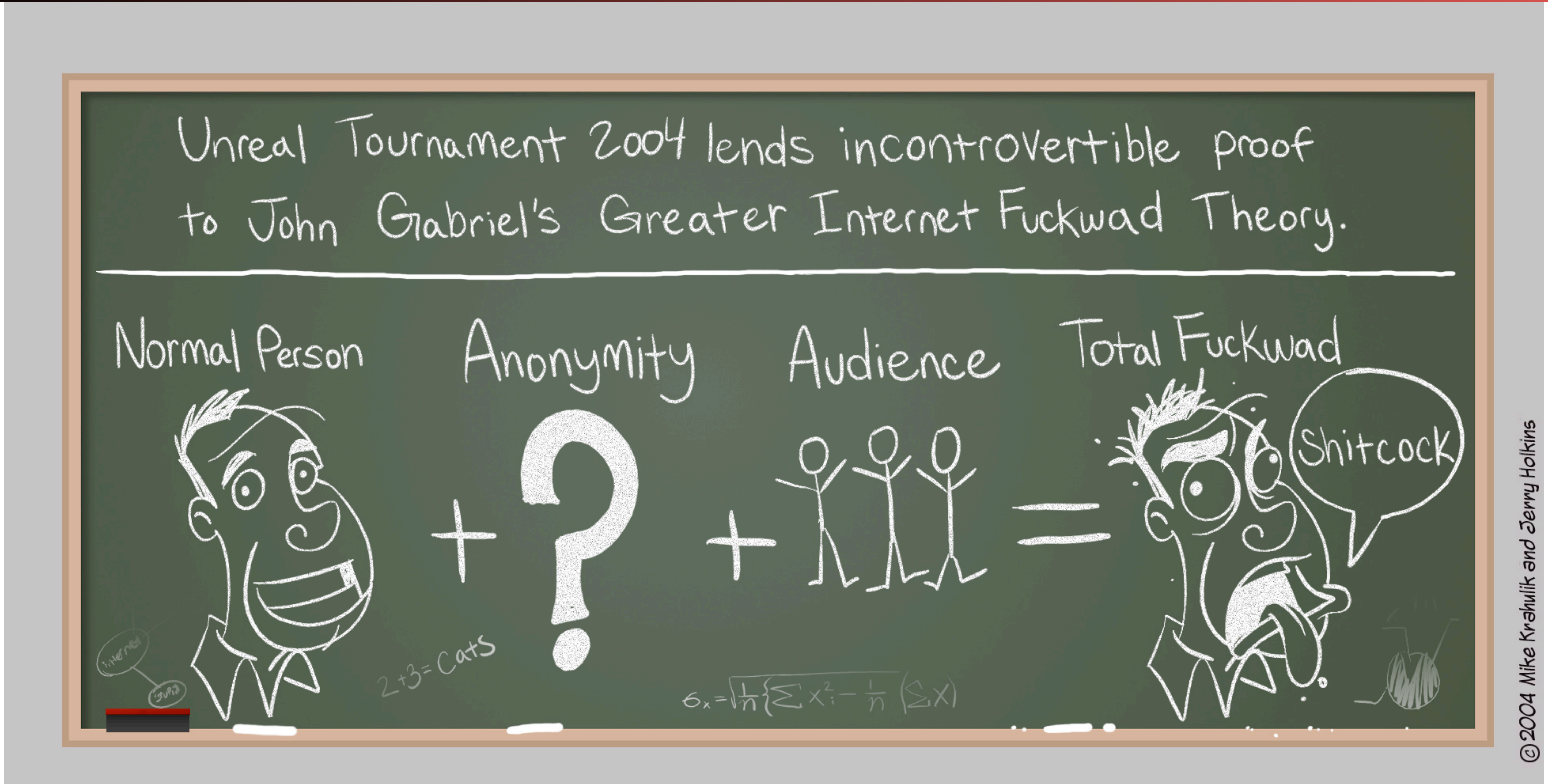
- Surfing "anonymously" doesn't simply depend on hiding your connection…
- But also configuring the browser to make sure it resists tracking
  - No persistent cookies or other data stores
  - ***No deviations from other people*** running the same browser
- Anonymity ***only works in a crowd***…
  - So it really tries to make it all the same
- But by default it makes it easy to say "this person is using Tor"

But You Are Relying On Honest Exit Nodes…

- The exit node, where your traffic goes to the general Internet, is a man-in-the-middle…
  - Who can see and modify all non-encrypted traffic
  - The exit node also does the DNS lookups
- Exit nodes have not always been honest…



Anonymity Invites Abuse…
(Stolen from Penny Arcade)



This Makes Using Tor Browser Painful…

And Also Makes Running Exit Nodes Painful…

- If you want to receive abuse complaints…
  - Run a Tor Exit Node
- Assuming your ISP even allows it…
  - Since they don’t like complaints either
- Serves as a large limit on Tor in practice:
  - Internal bandwidth is plentiful, but exit node bandwidth is restricted
- Know a colleague who ran an exit node for research...
  - And got a ***visit from the FBI***!

One Example of Abuse: The Harvard Bomb Threat…

- On December 16th, 2013, a Harvard student didn't want to take his final in "Politics of American Education"…
  - So he emailed a bomb threat using Guerrilla Mail
  - But he was "smart" and used Tor and Tor Browser to access Guerrilla Mail
- Proved easy to track
  - "Hmm, this bomb threat was sent through Tor…"
  - "So who was using Tor on the Harvard campus…" (look in Netflow logs..)
  - "So who is this person…" (look in authentication logs)
  - "Hey FBI agent, wanna go knock on this guy's door?!"
- There is no magic Operational Security (OPSEC) sauce…
  - And again, anonymity only works if there is a crowd

Censorship Resistance: Pluggable Transports

- Tor is really used by separate communities
  - Anonymity types who want anonymity in their communication
  - Censorship-resistant types who want to communicate despite government action
    - The price for "free" censorship evasion is that your traffic acts to hide other anonymous users
- Vanilla Tor fails the latter ***completely***
- So there is a framework to deploy bridges that encapsulate Tor over some other protocol
  - So if you are in a hostile network...
  - Lots of these, e.g. OBS3 (Obfuscating Protocol 3), OBS4, Meek...
  - But its an arm's race