RAPTOR:
Routing Attacks on Privacy in Tor



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Joint work with

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Acknowledgment for Slides

Laurent Vanbever
ETH Zurich



WE ARE
ANONYMOUS



WE ARE NOT
ANONYMOUS FOR LONG.



WE ARE NOT
ANONYMOUS FOR LONG.
COURTESY OF BGP.

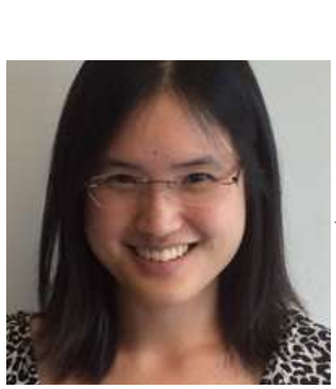
Internet communications are *not* anonymous

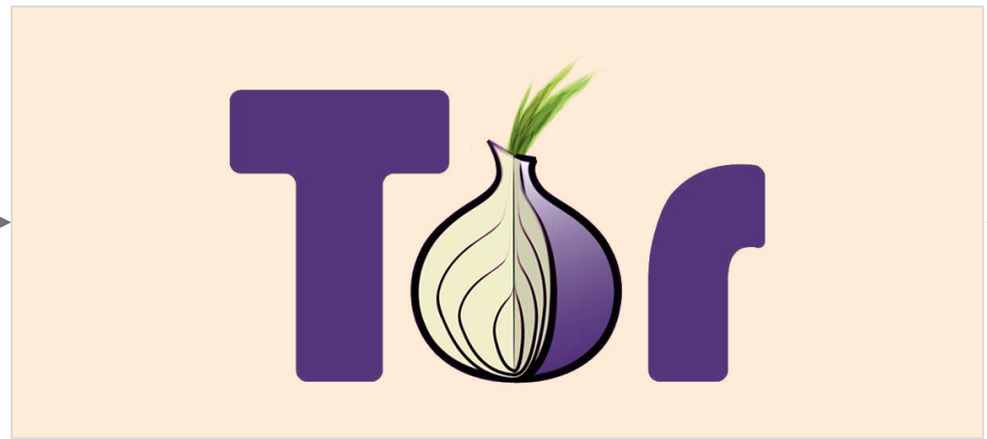
Looking at an Internet communication, one can

- infer who is talking to whom
- infer physical locations
- use that to track behavior and interests

even if the communication is encrypted

Tor aims at preventing adversaries to follow packets between a sender and a receiver





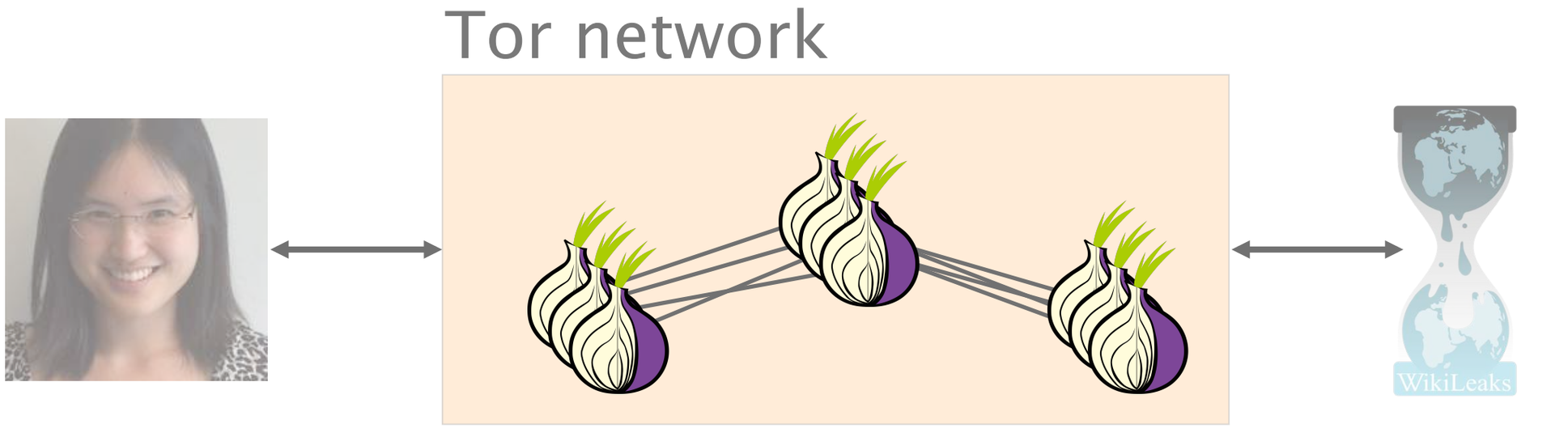


client

server

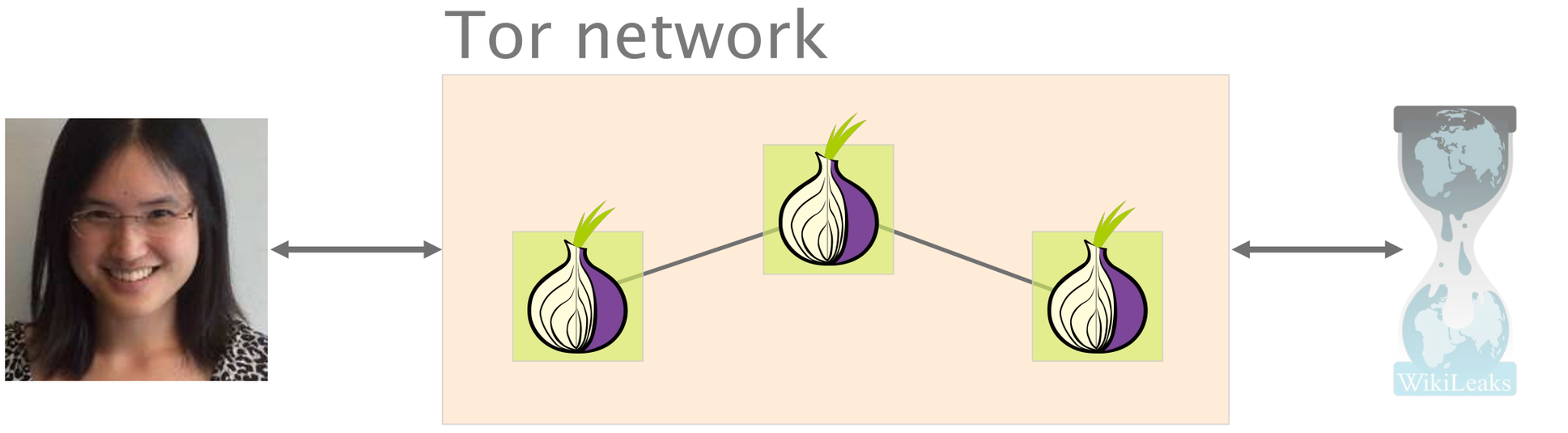
To do that,

Tor bounces traffic around a network of relays

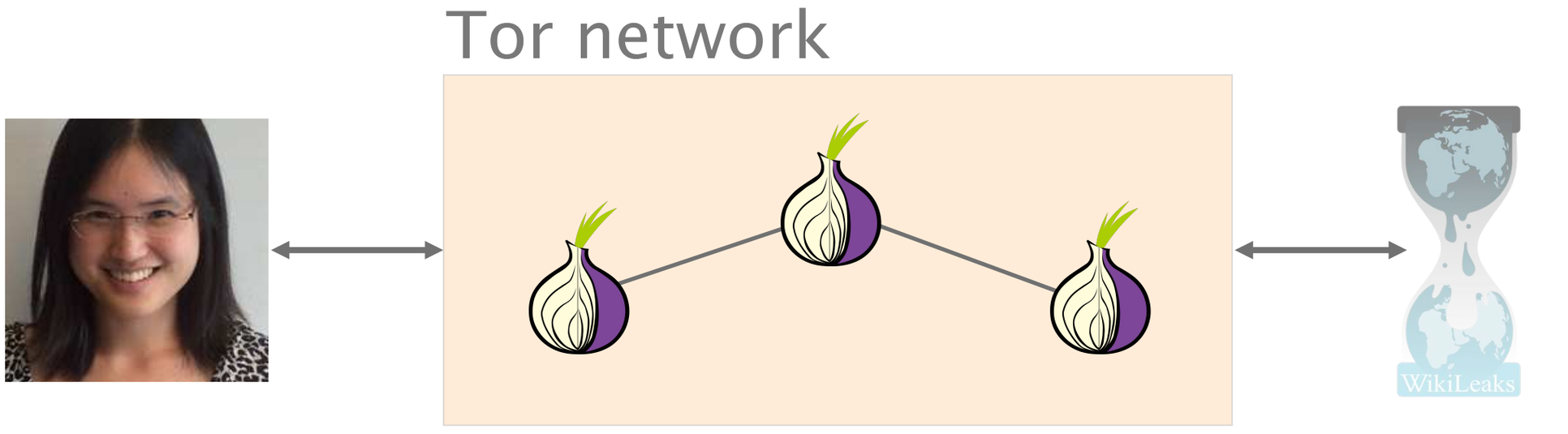


Tor clients start by selecting

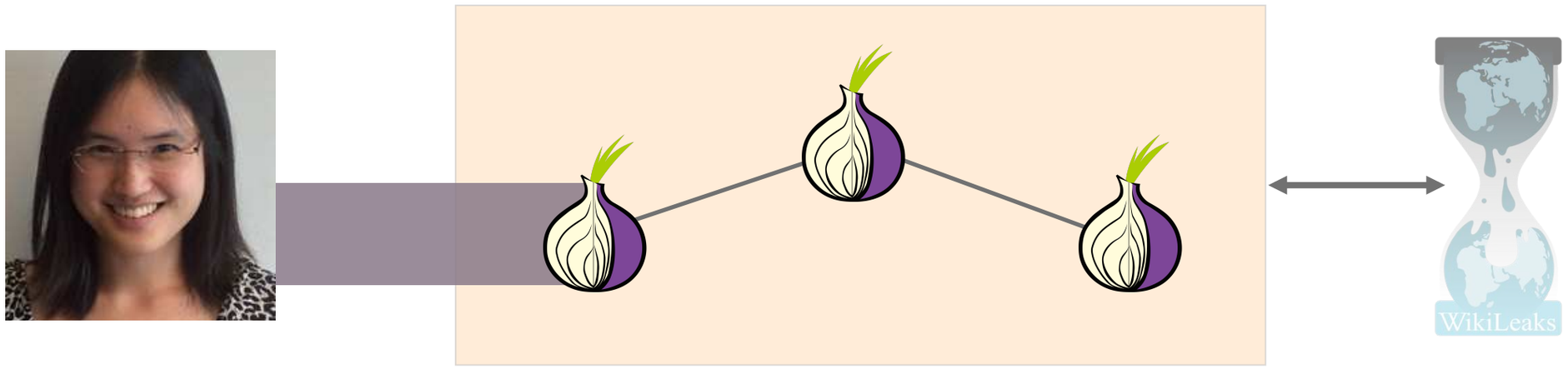
3 relays, one of each type



Tor clients then incrementally
build encrypted circuits through them

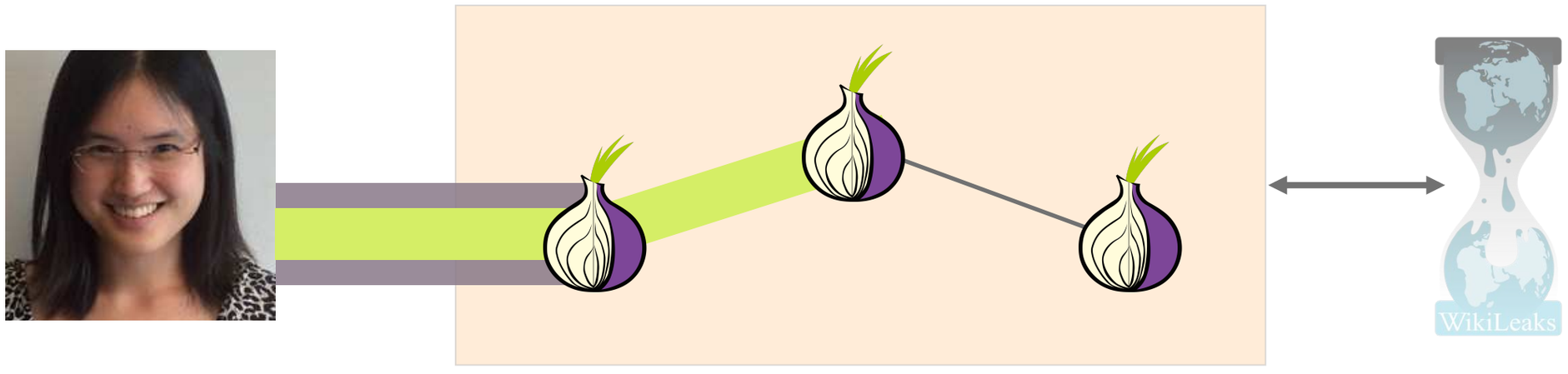


Tor network



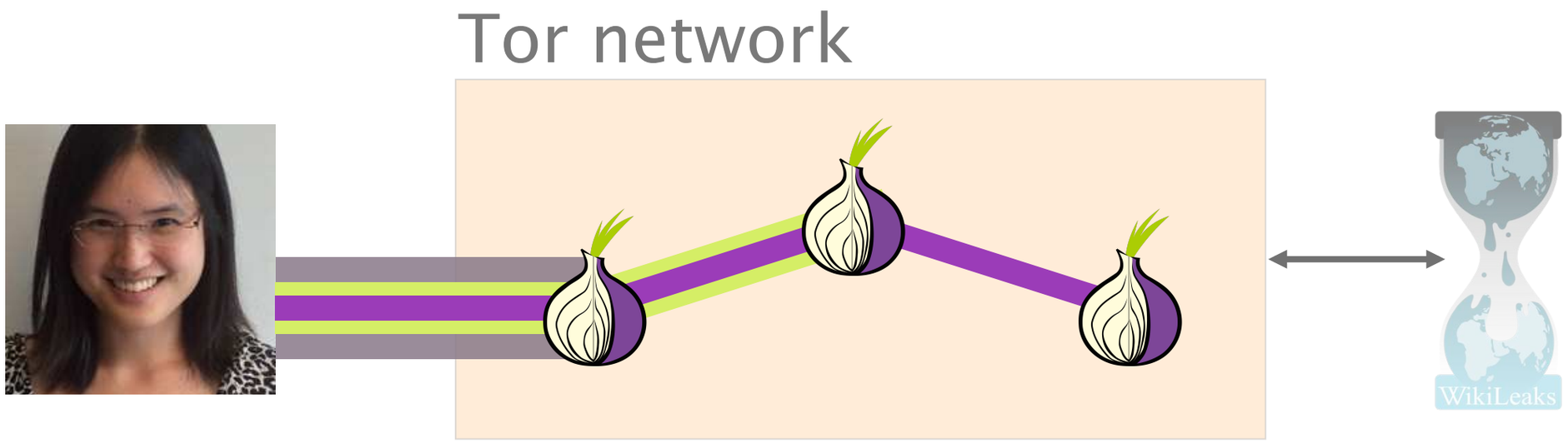
client entry middle exit server

Tor network



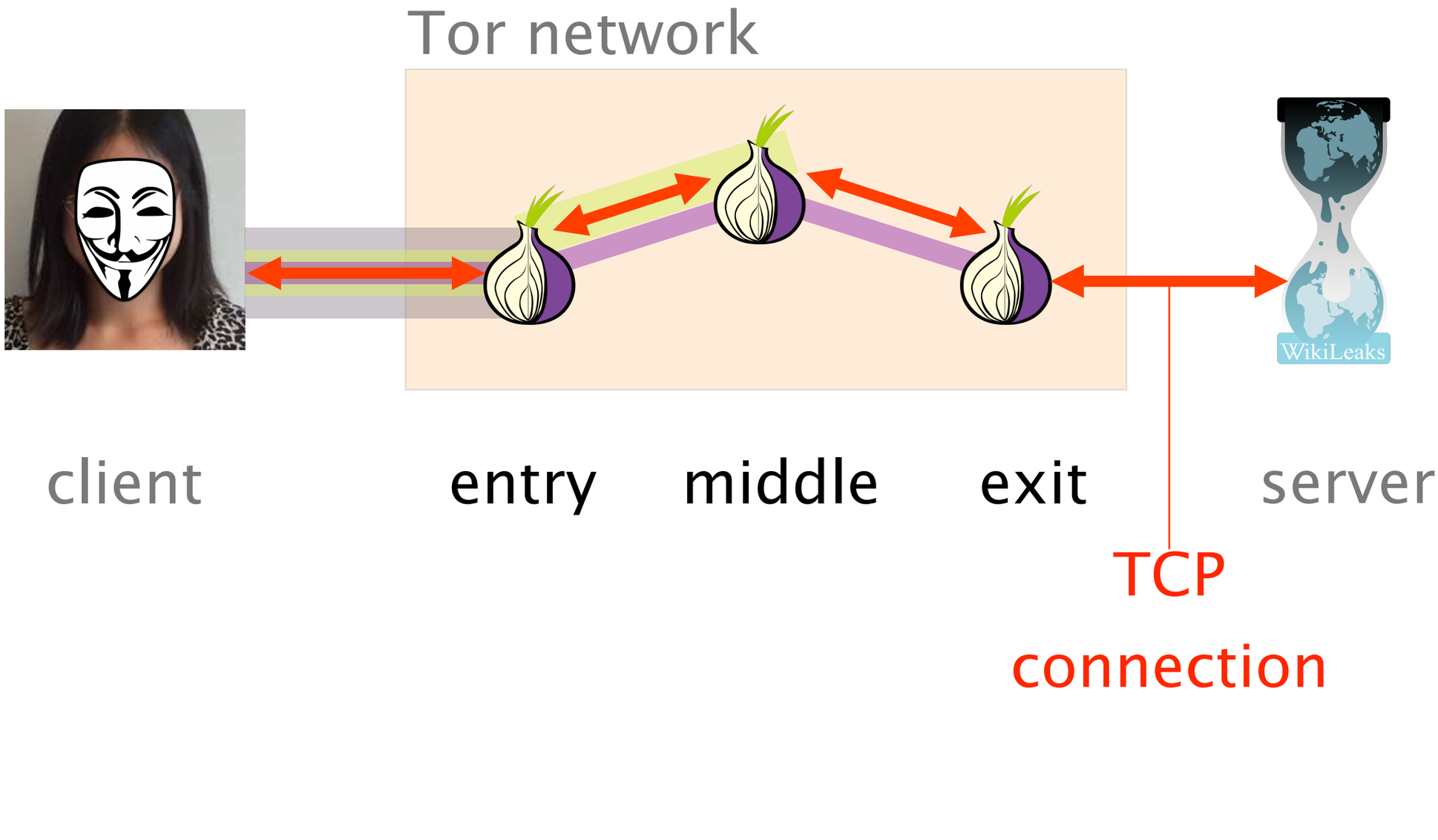
client entry middle exit server

Tor network

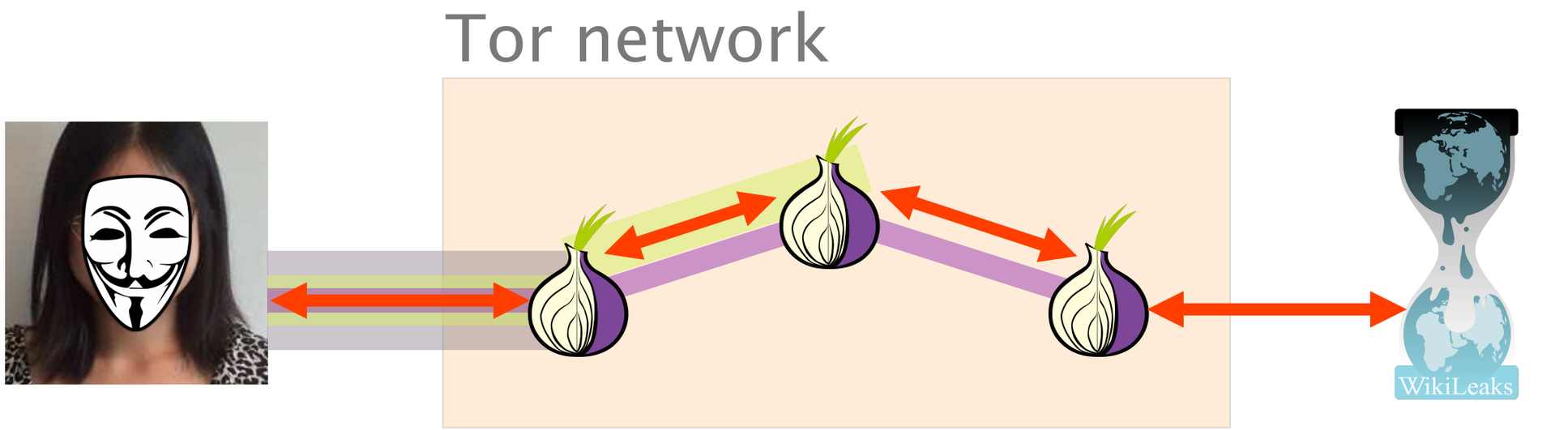


client entry middle exit server

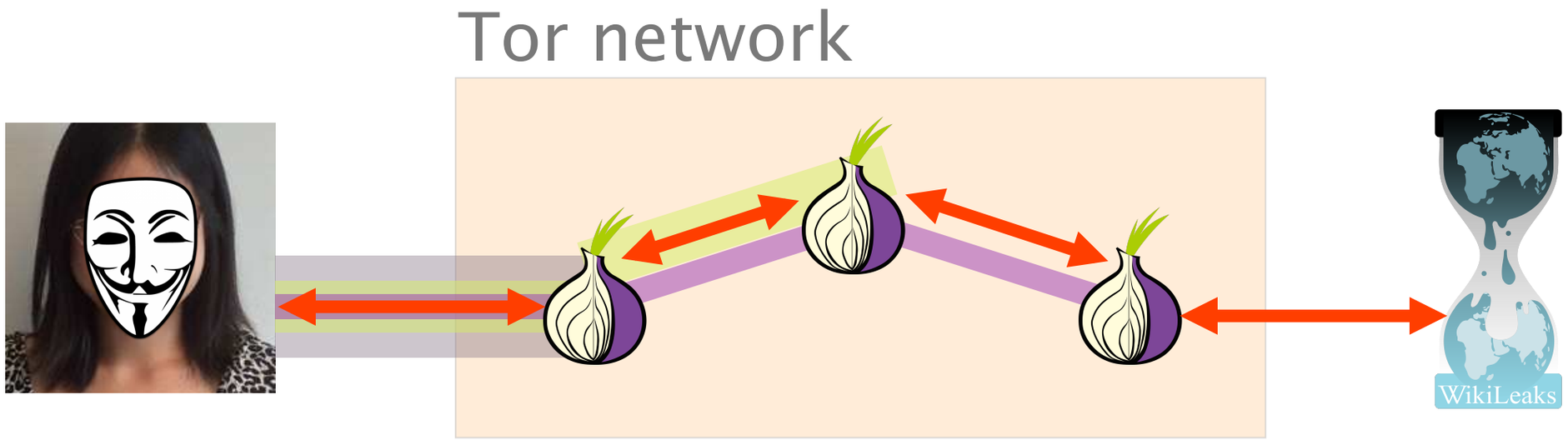
Anonymous communication takes place by forwarding across consecutive tunnels



Not a single Tor entity knows the association (client, server)



Tor network

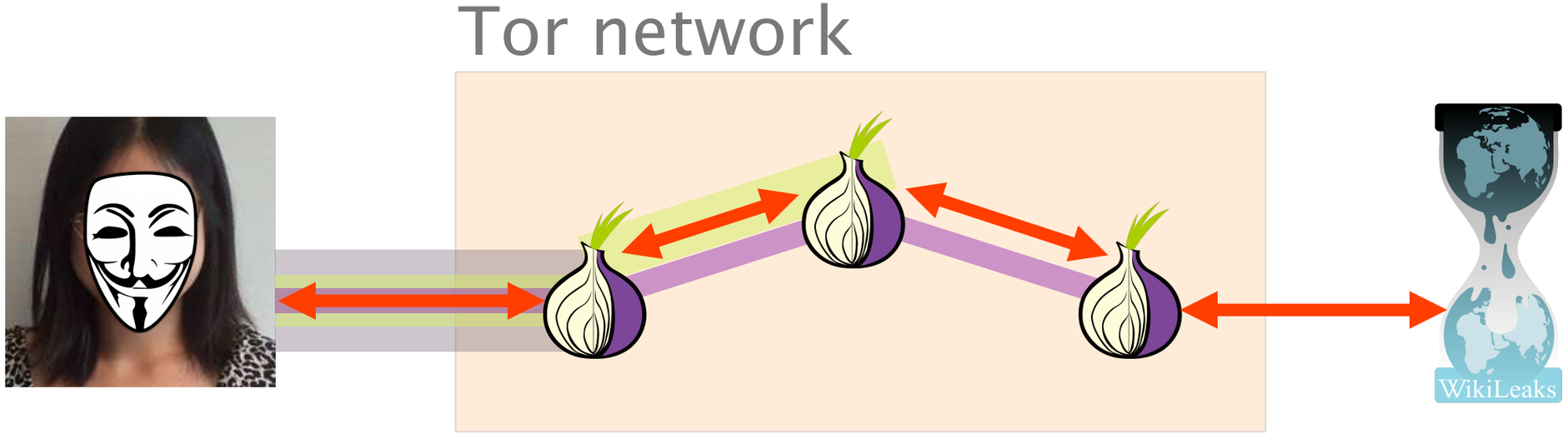


client entry middle exit server

knows the source,

not the destination

Tor network

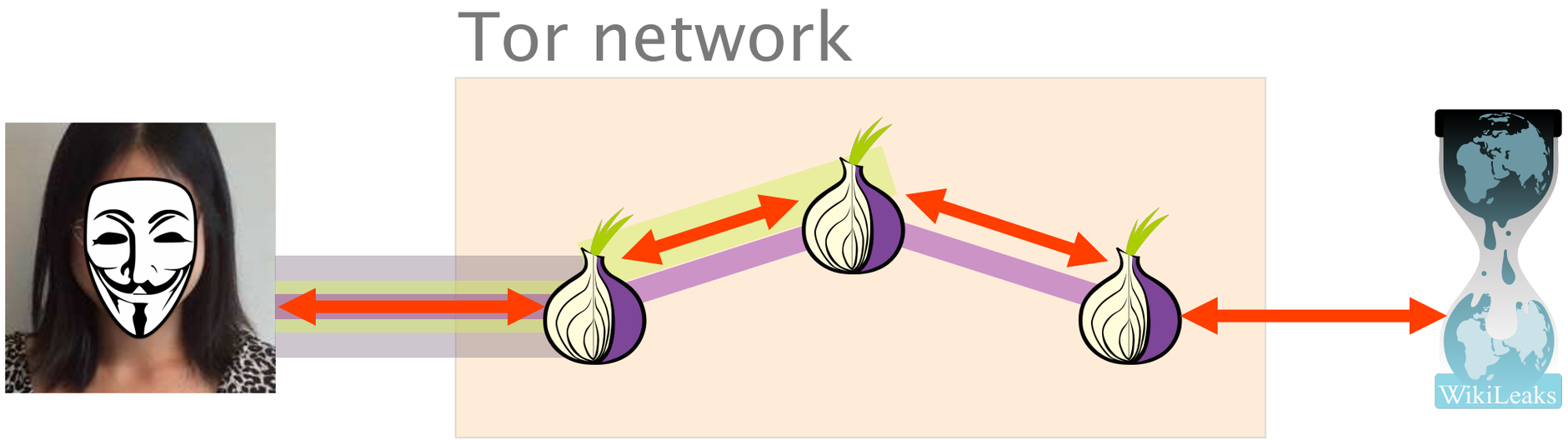


client entry middle exit server

knows neither the source,

nor the destination

Tor network

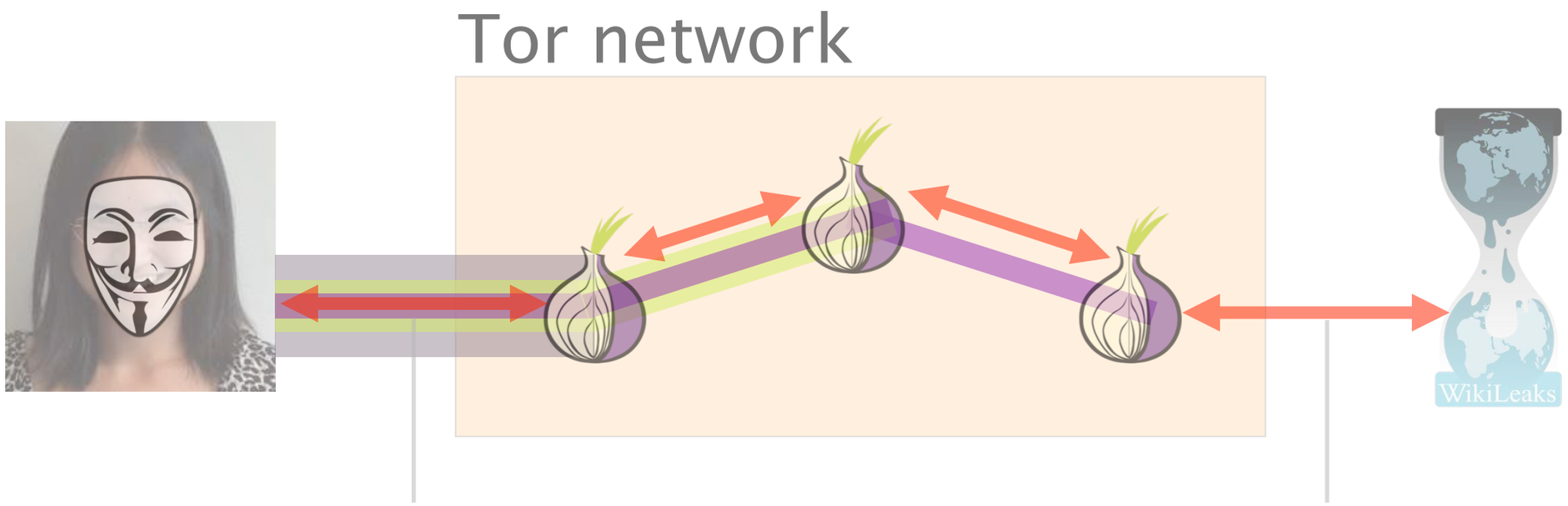


client entry middle exit server

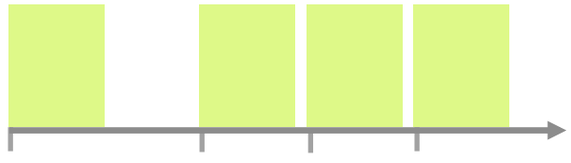
knows the destination,

not the source

Traffic entering and leaving Tor is highly correlated

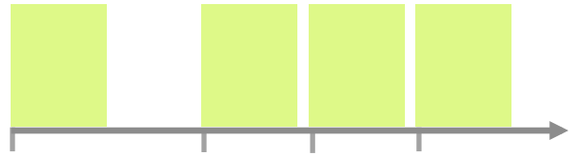


client-to-entry connection



transmission time

exit-to-server connection



transmission time

highly correlated

By correlating client-to-entry & exit-to-server flows, one can effectively deanonymize Tor users

Traffic correlation attacks require to see client-to-entry and exit-to-server traffic

Traffic correlation attacks require to see client-to-entry and exit-to-server traffic

How?

Two ways

Manipulate Tor
malicious relays

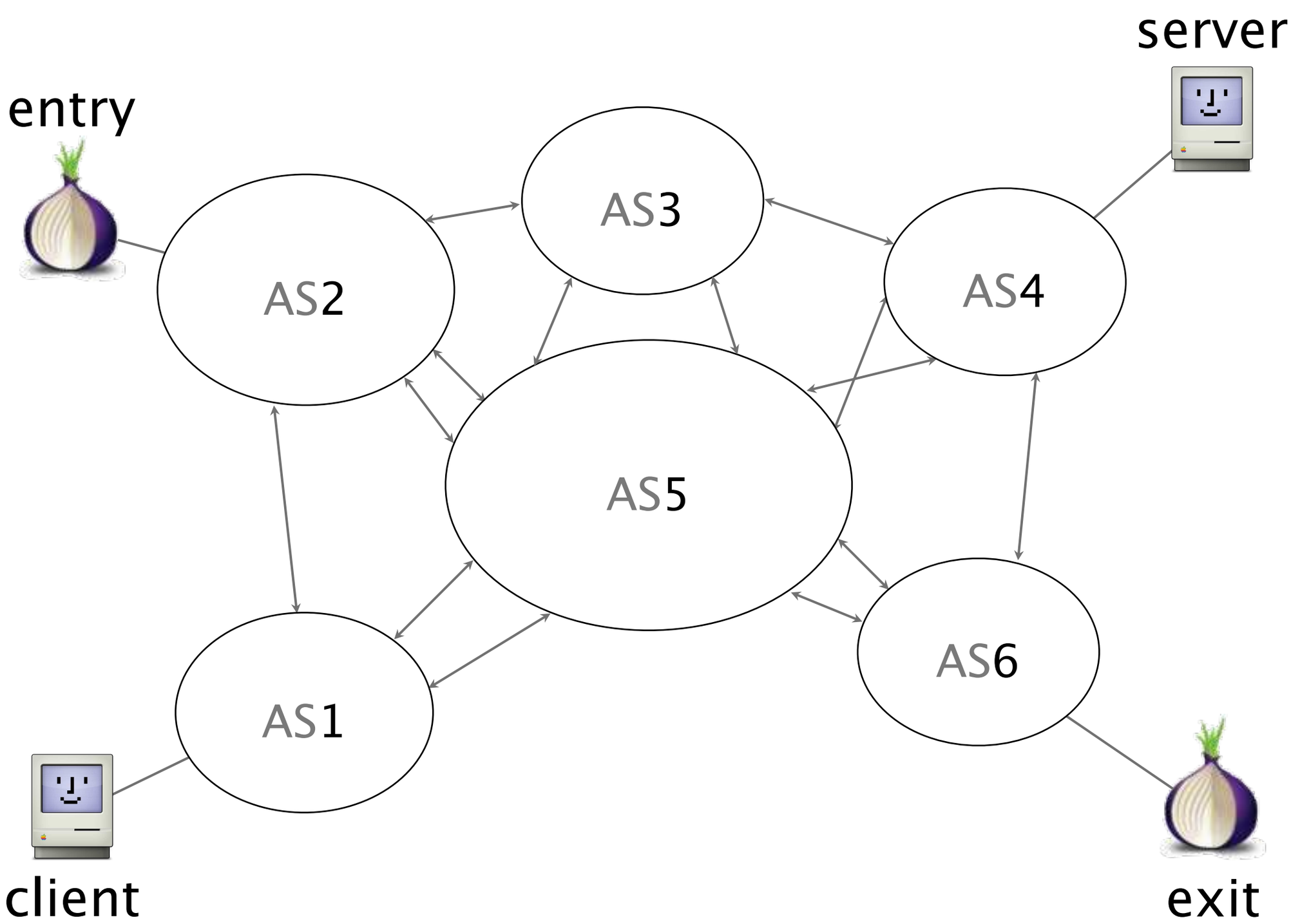
Manipulate routing
malicious networks

Two ways

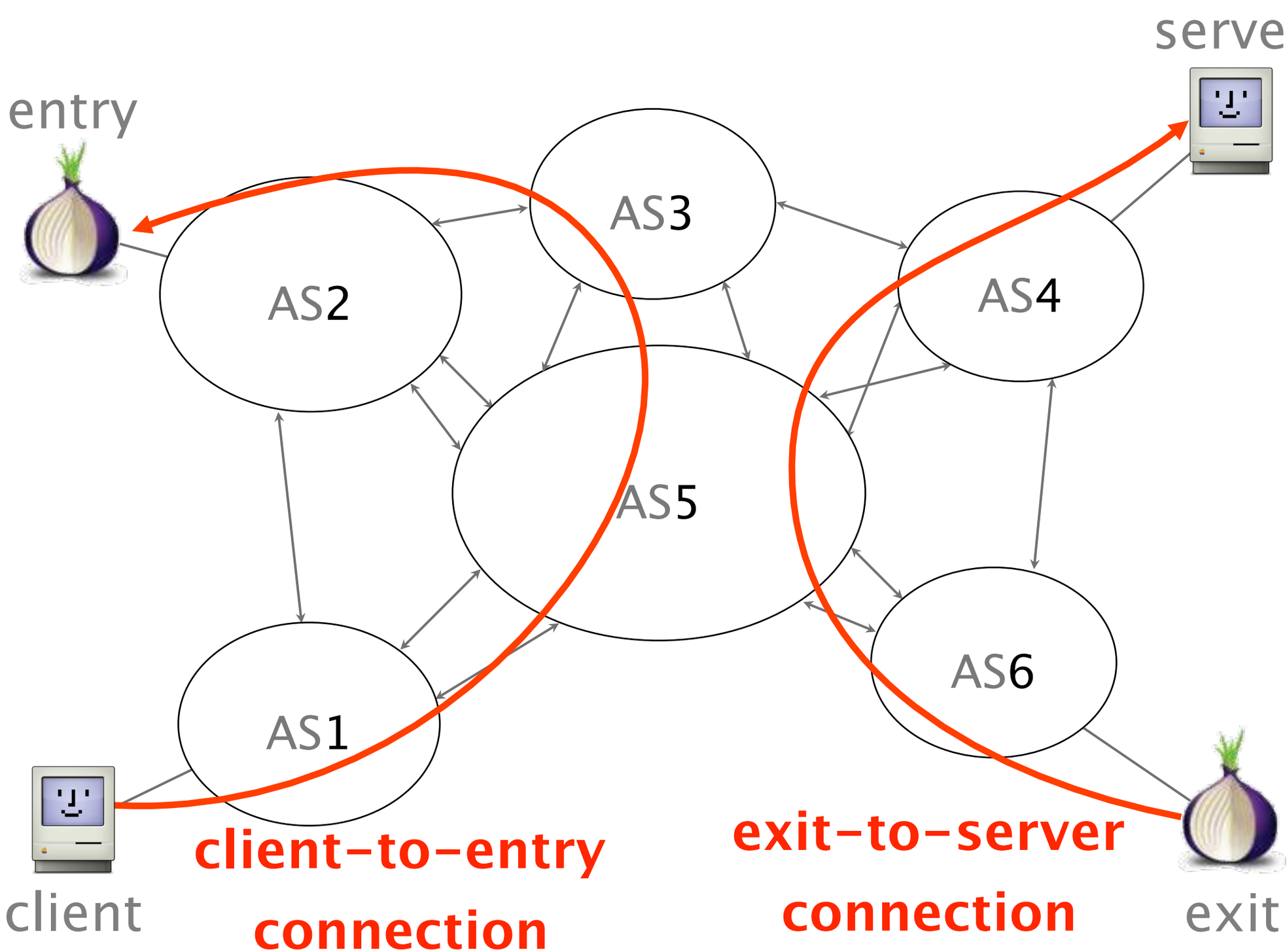
Manipulate Tor
malicious relays

Manipulate routing
malicious networks

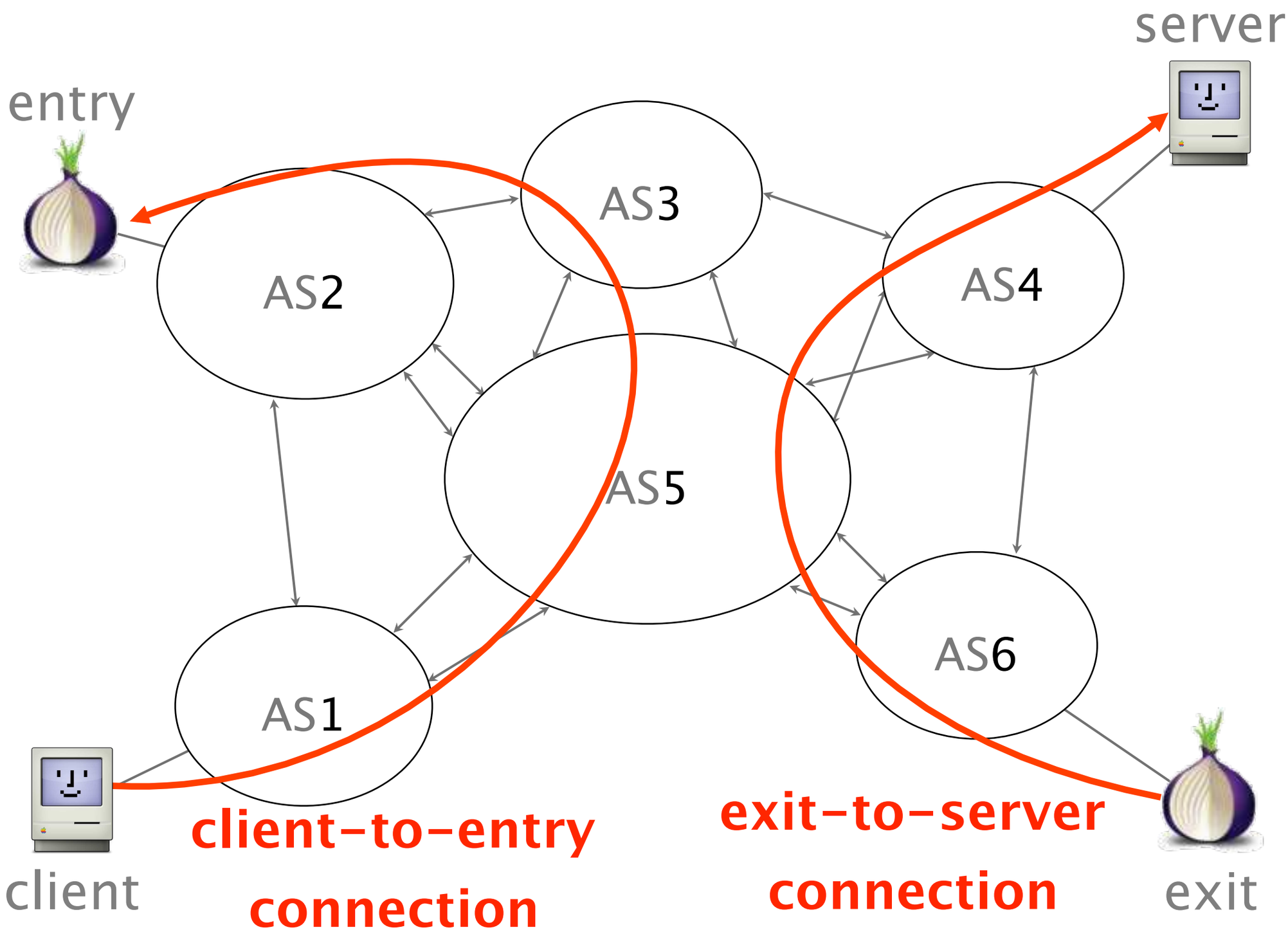
This talk

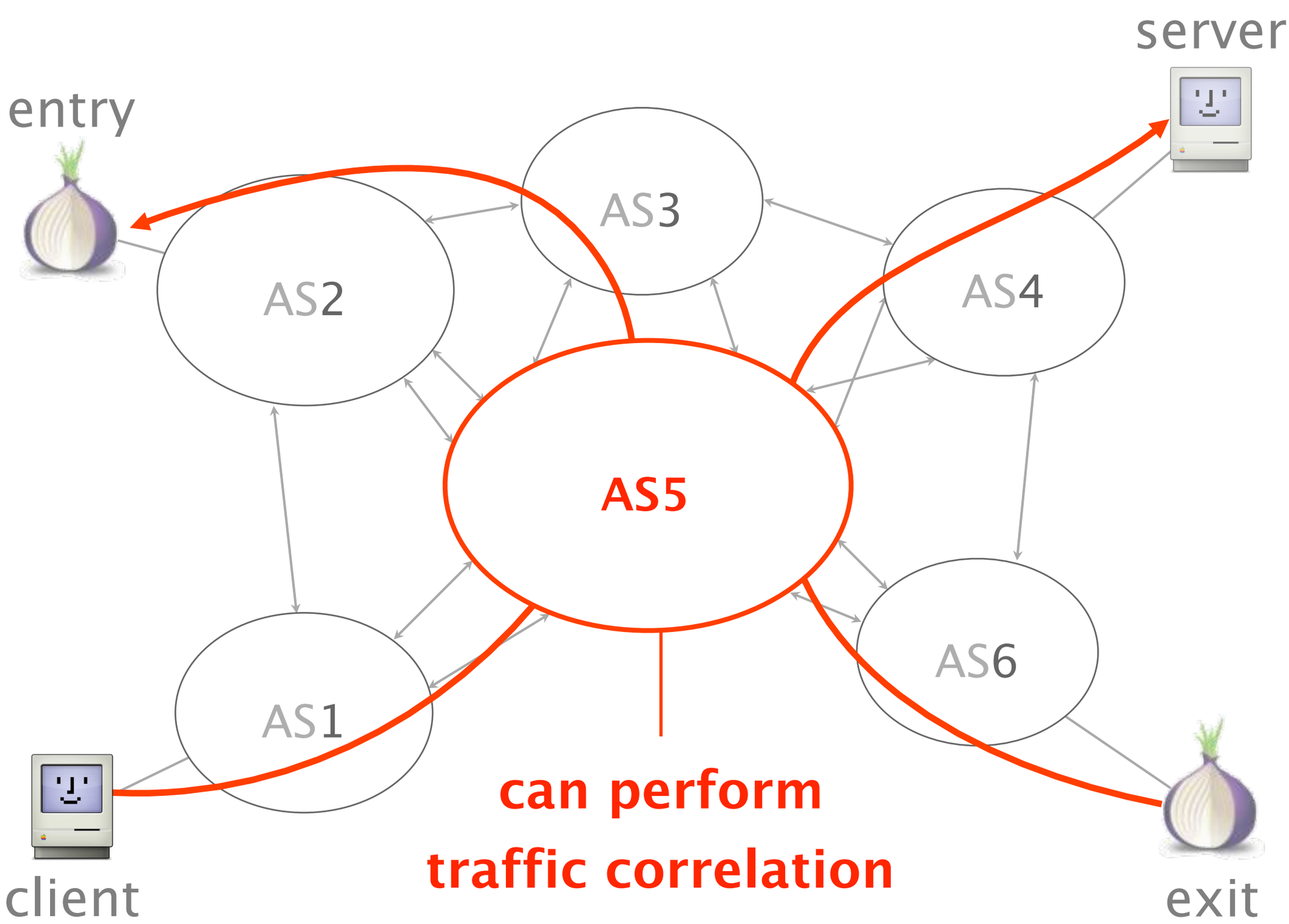

server
entry
AS3
AS2
AS4
AS5
AS6
AS1
client
exit

Tor connections get routed according to BGP



Traffic correlation attacks require to see client-to-entry *and* exit-to-server traffic




server
entry
AS3
AS2
AS4
AS5
AS6
AS1
client
exit
can perform
traffic correlation

Network-level adversaries are known

Related work

2004	Location diversity in anonymity networks	Feamster and Dingledine
2007	Sampled traffic analysis by Internet-exchange-level adversaries	Murdoch and Zieliński
2009	AS-awareness in Tor Path Selection	Edman and Syverson
2013	Traffic correlation on Tor by realistic adversaries	Johnson *et al.*

However, these works assume

that the Internet is static

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… which is not the case

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Contribution What's the impact on Tor?

RAPTOR Attacks:

User anonymity decreases over time due to BGP dynamics

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RAPTOR Attacks

Asymmetric routing
path from A to B != from B to A

Natural BGP convergence
policy changes, failures, etc.

Active BGP manipulation
IP prefix hijack, interception (MITM)…

RAPTOR:

Routing Attacks on Privacy in Tor



1 Attacks

All your traffic belongs to me

2 Results

Eyes wide open

3 Countermeasures

Close the curtains

RAPTOR:

Routing Attacks on Privacy in Tor



1 Attacks

All your traffic belongs to me

Results

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Countermeasures

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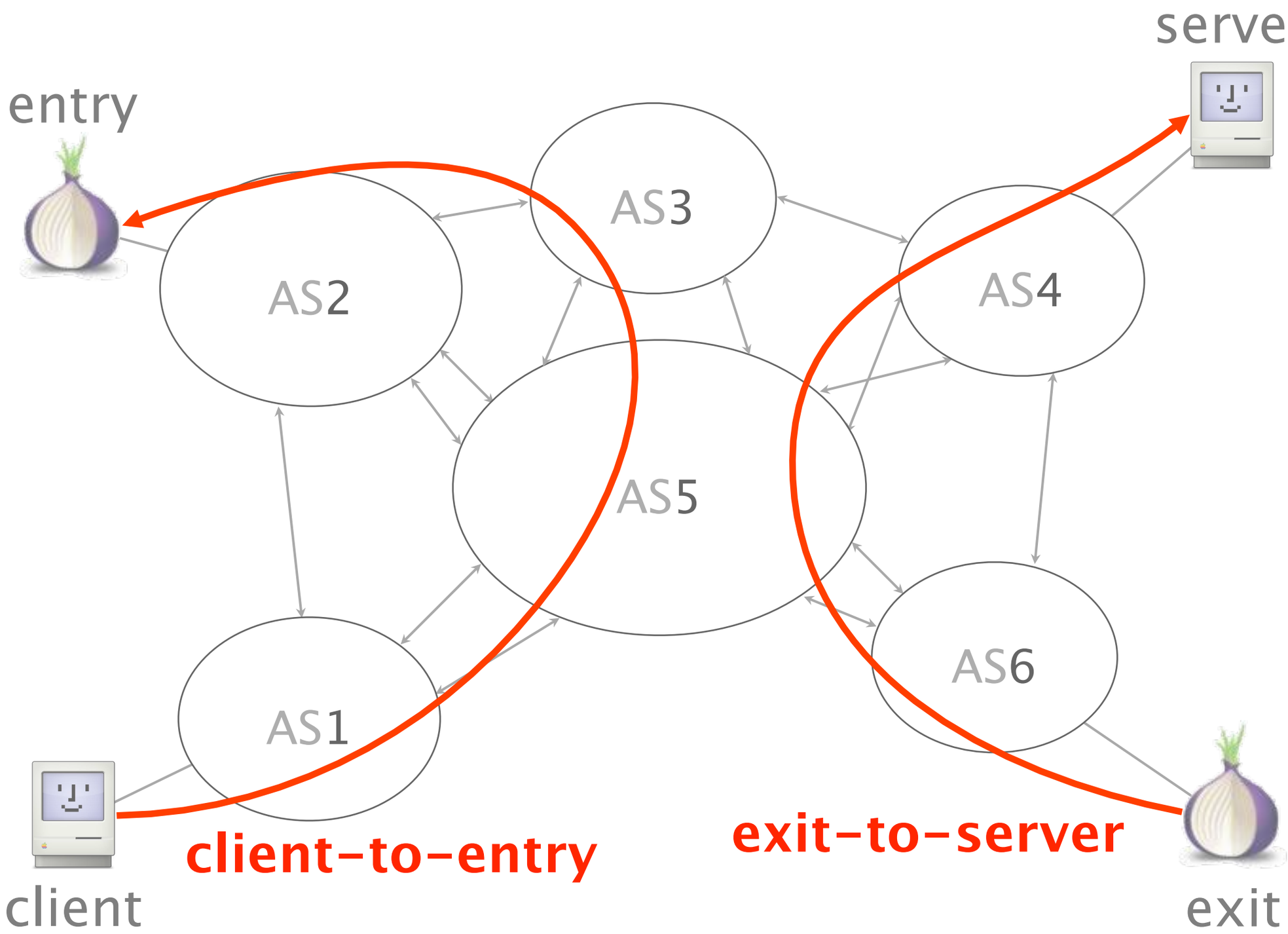
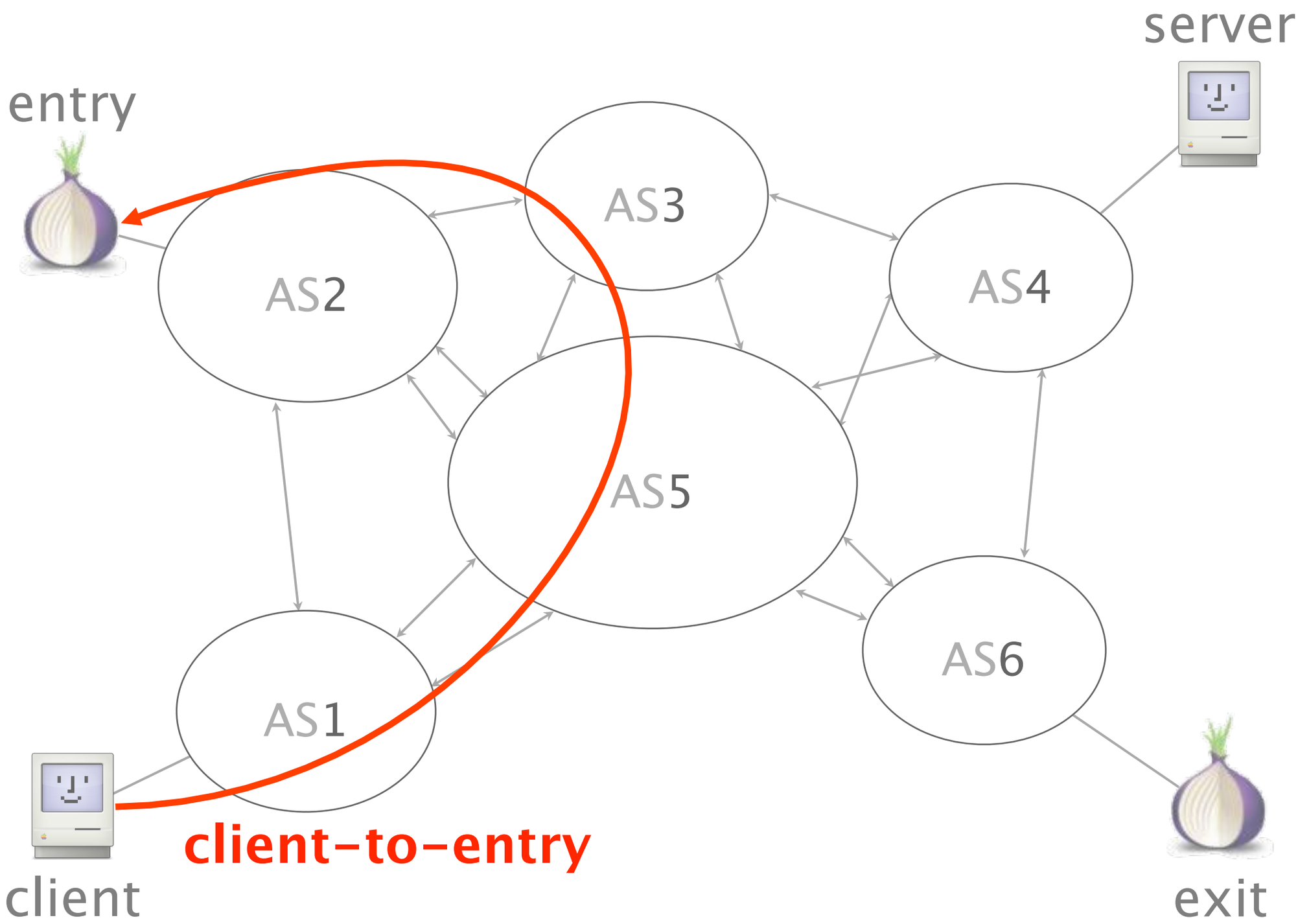
RAPTOR #1.

Asymmetric routing increases
the numbers of AS-level adversaries

So far, we have considered one side of Tor traffic: client-to-entry and exit-to-server



However, because of policies, routing is often *asymmetric*



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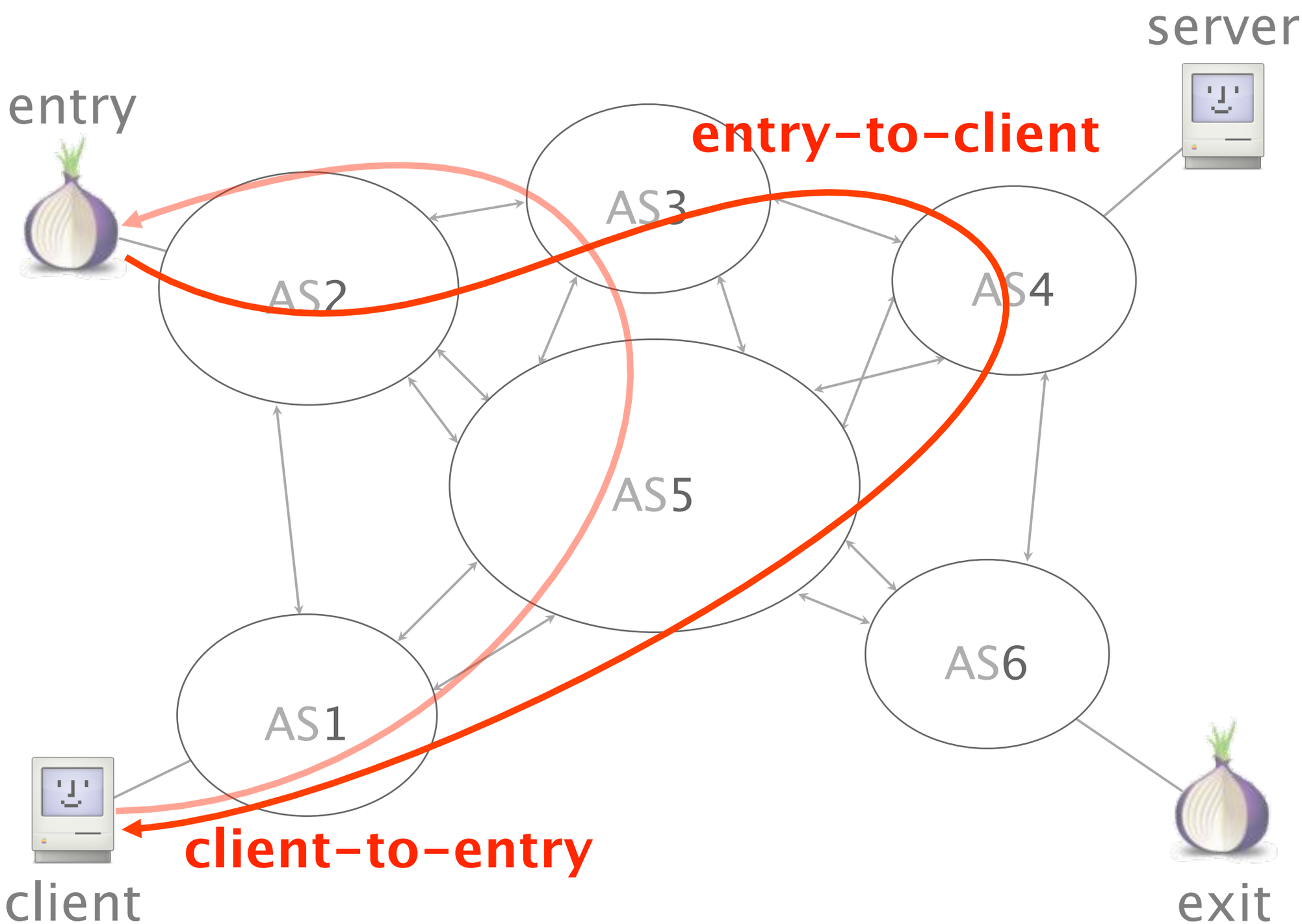
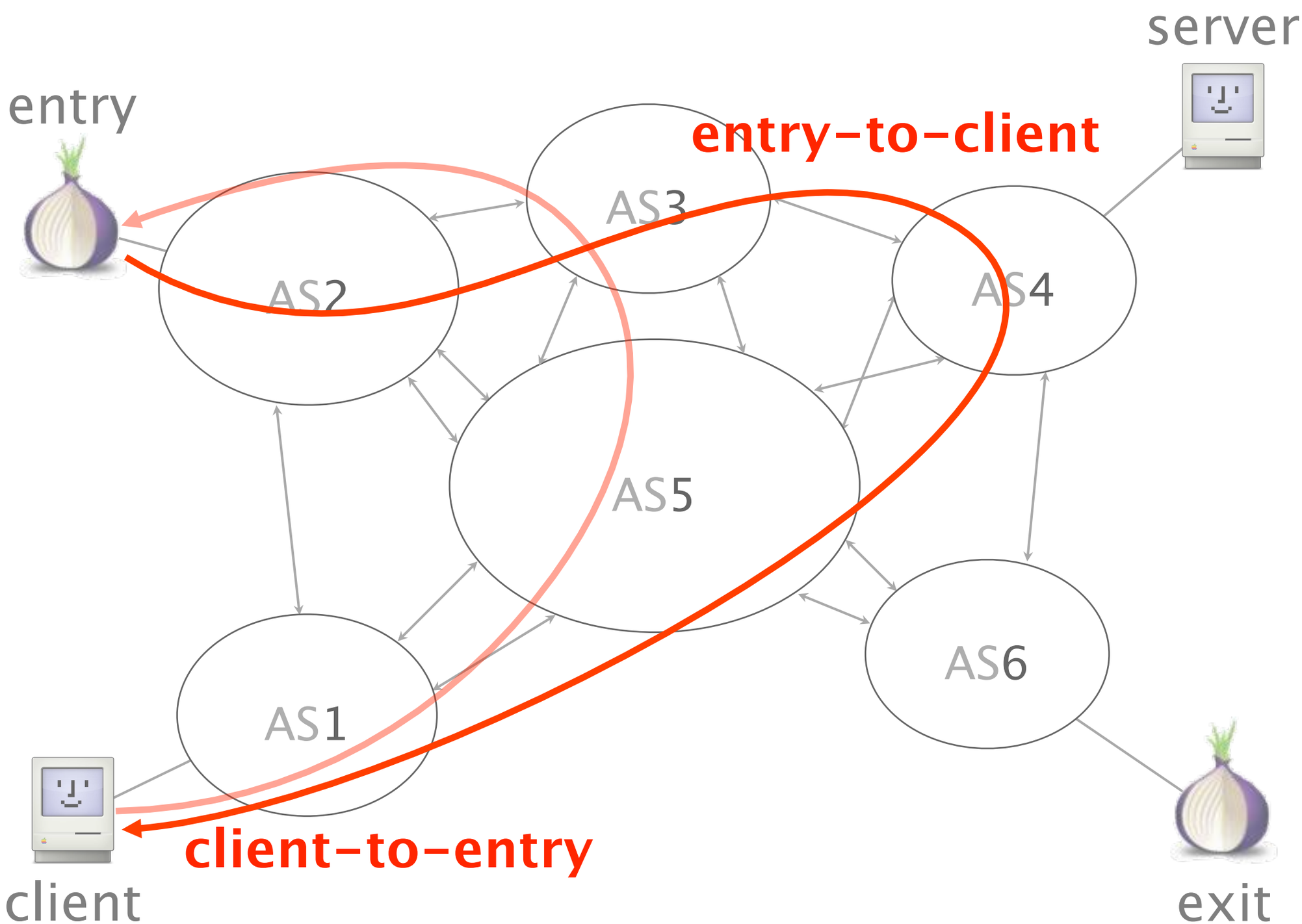
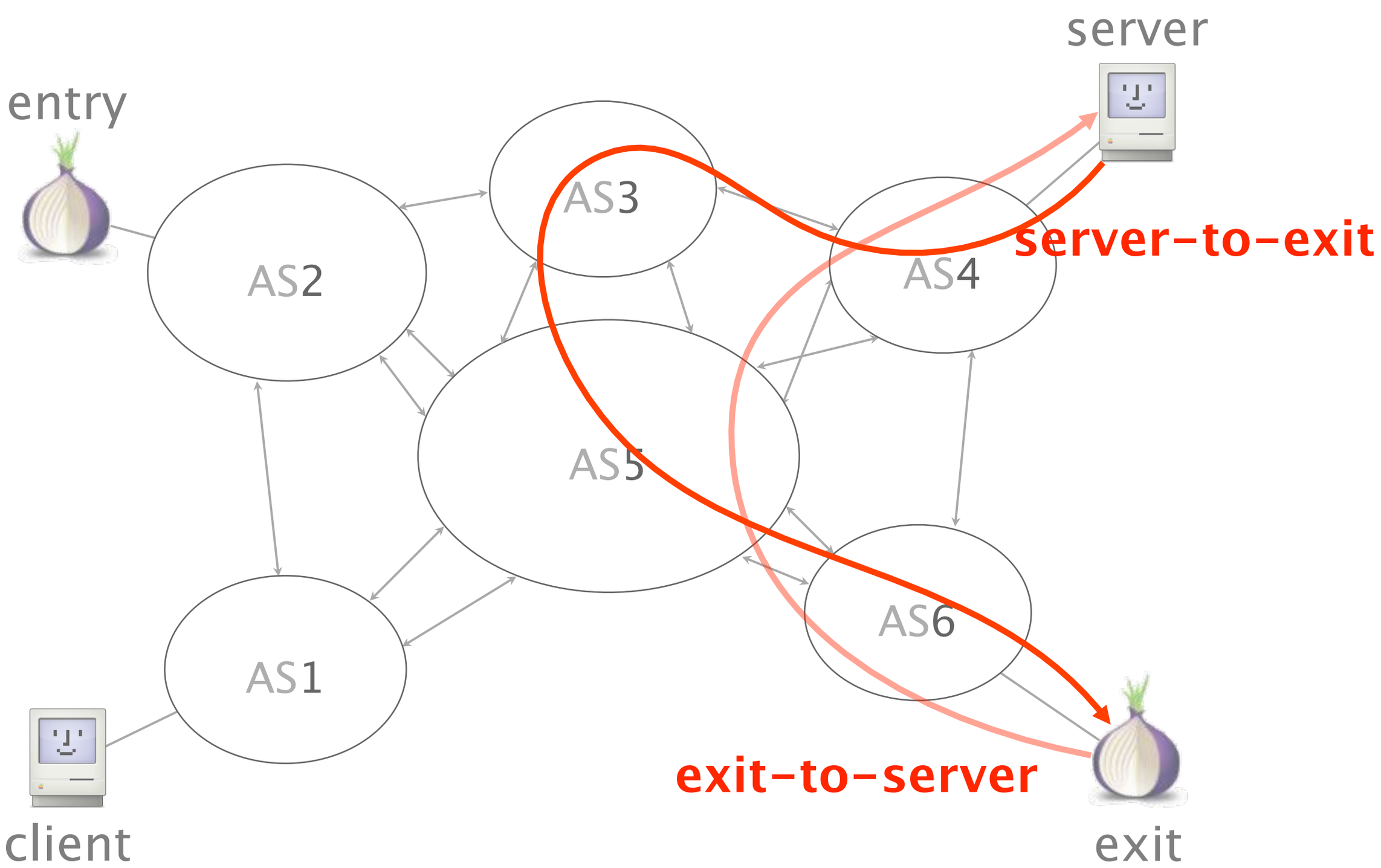


While AS4 does not see client-to-entry traffic, it sees entry-to-client traffic



The same applies to server-to-exit traffic



In terms of timing properties, both sides of a TCP connection are highly correlated

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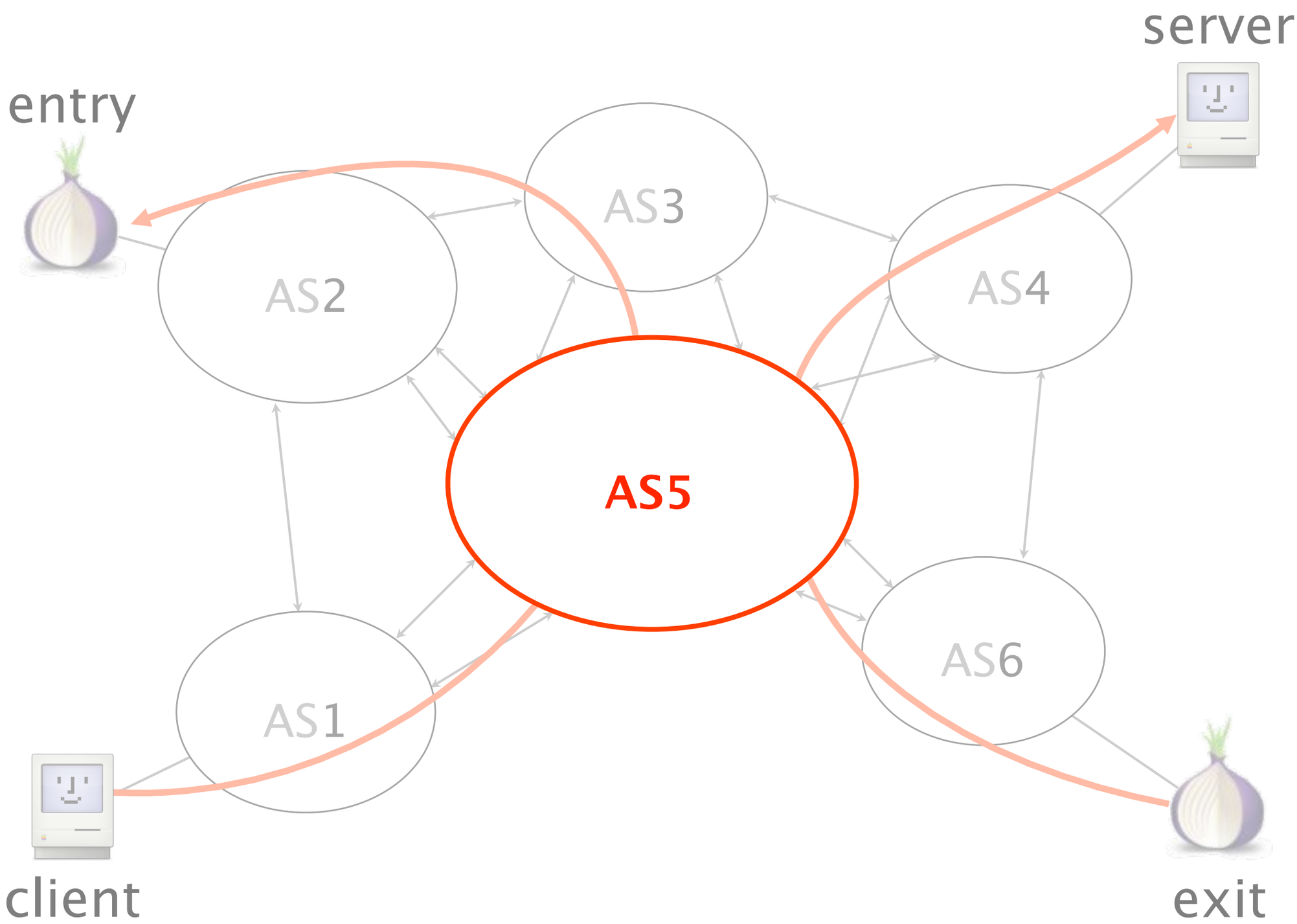
highly correlated

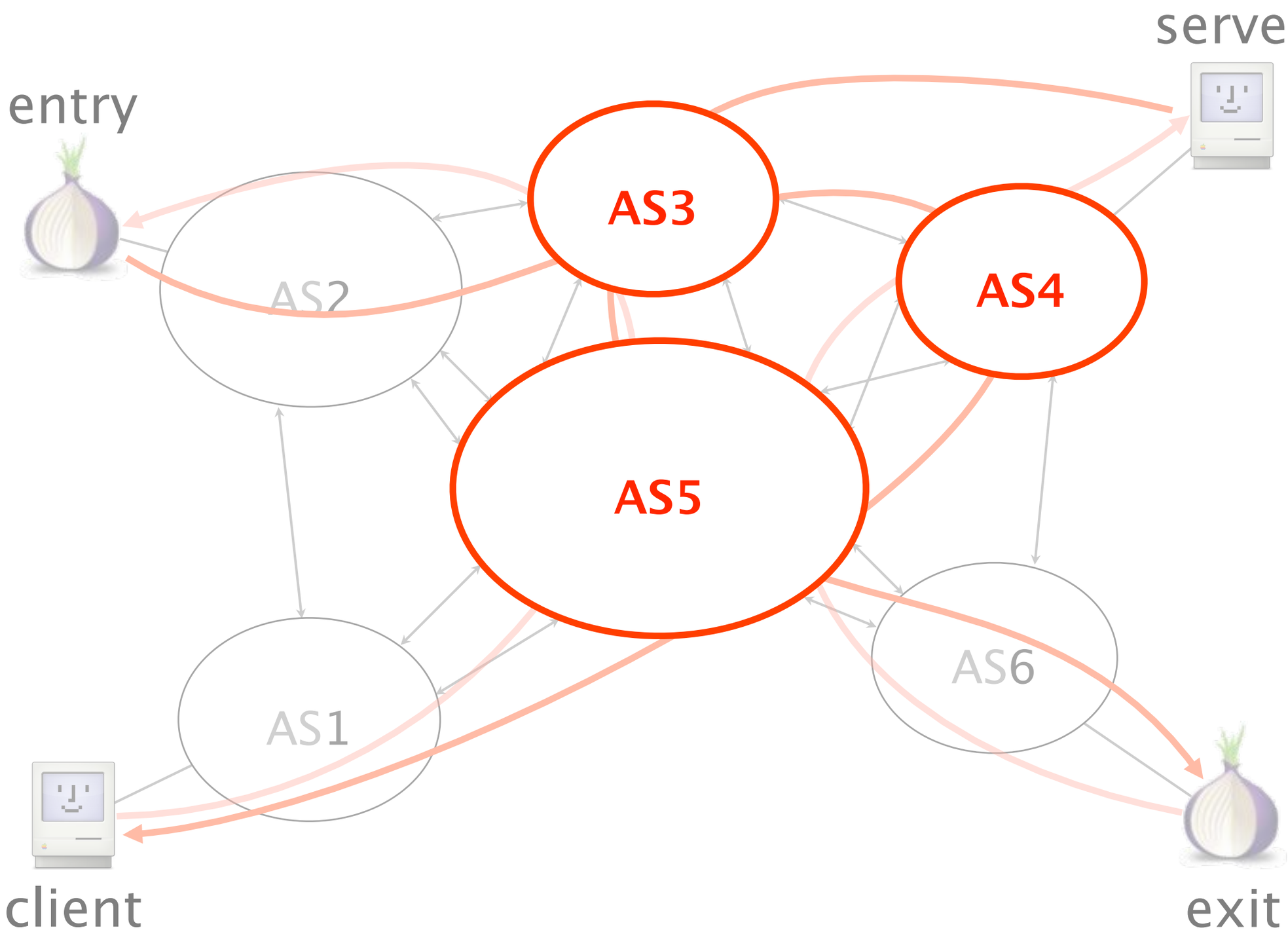
When collecting TCP
timing information,
seeing one direction (*e.g.*, data packets)
is almost equivalent to
seeing two directions (ACKs & data packets)

Considering only one direction, only AS5 is potentially compromising



Considering both directions,

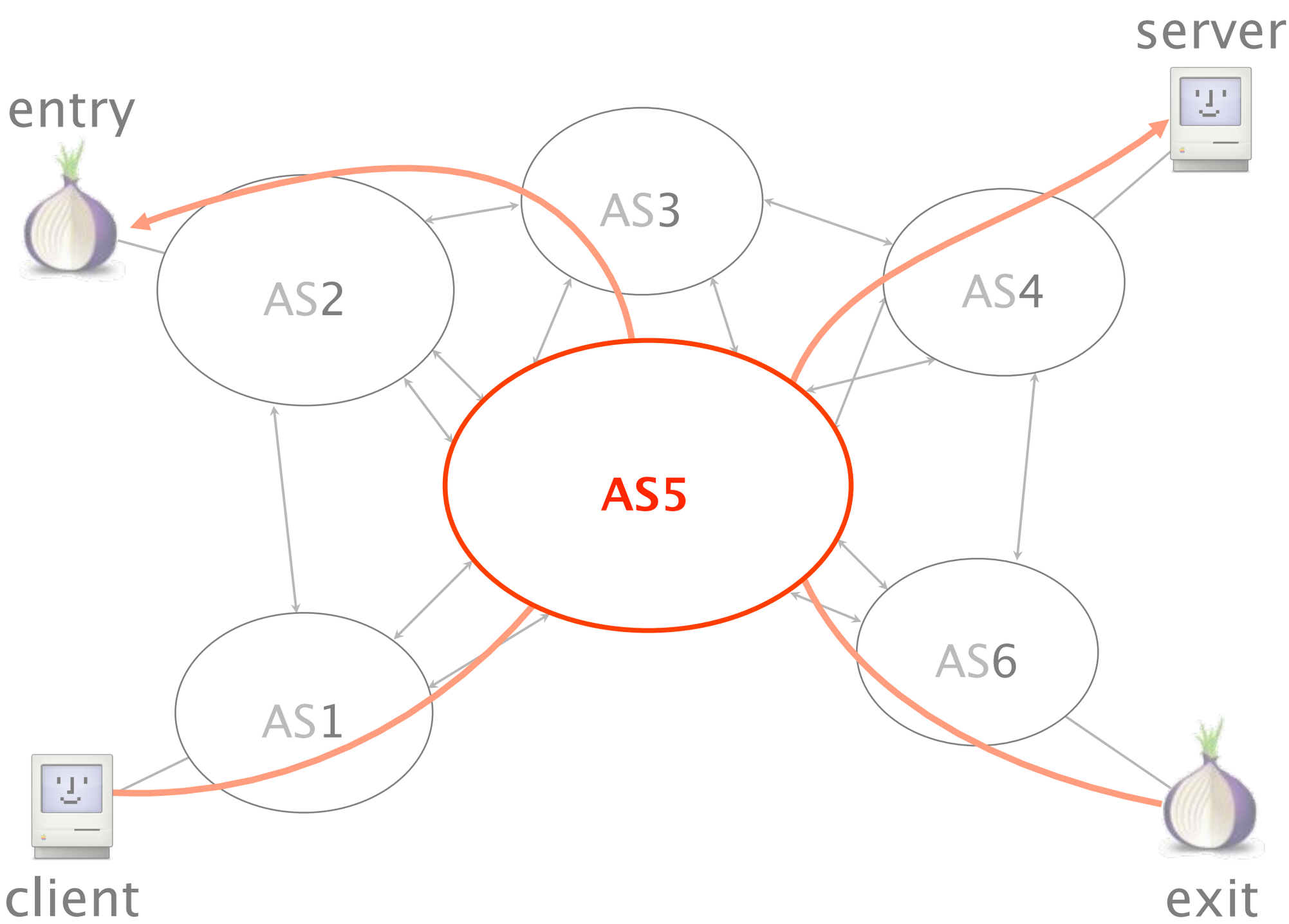
AS3, AS4 and AS5 are potentially compromising



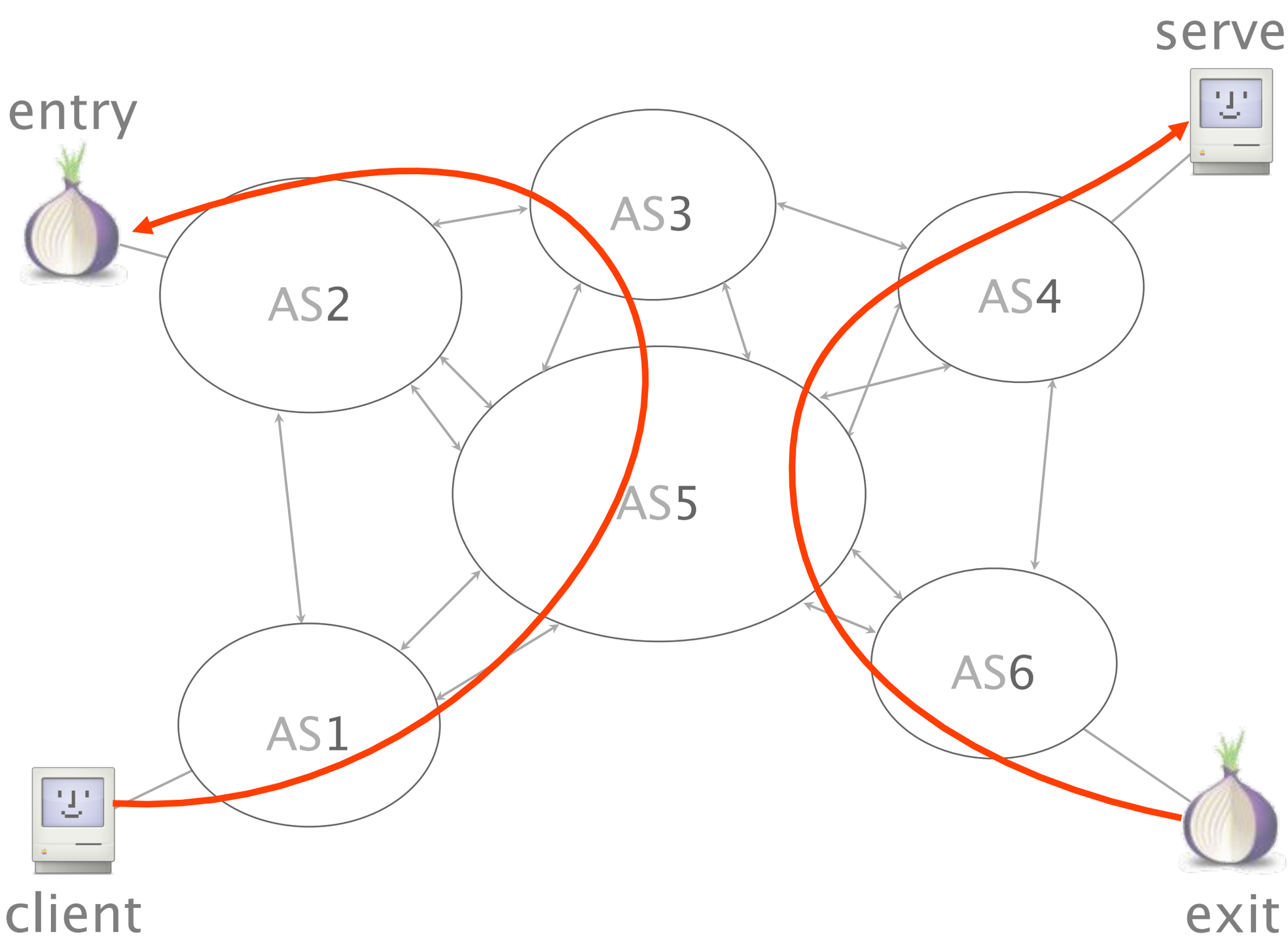
RAPTOR #2.

Natural BGP dynamics increases the number of AS-level adversaries

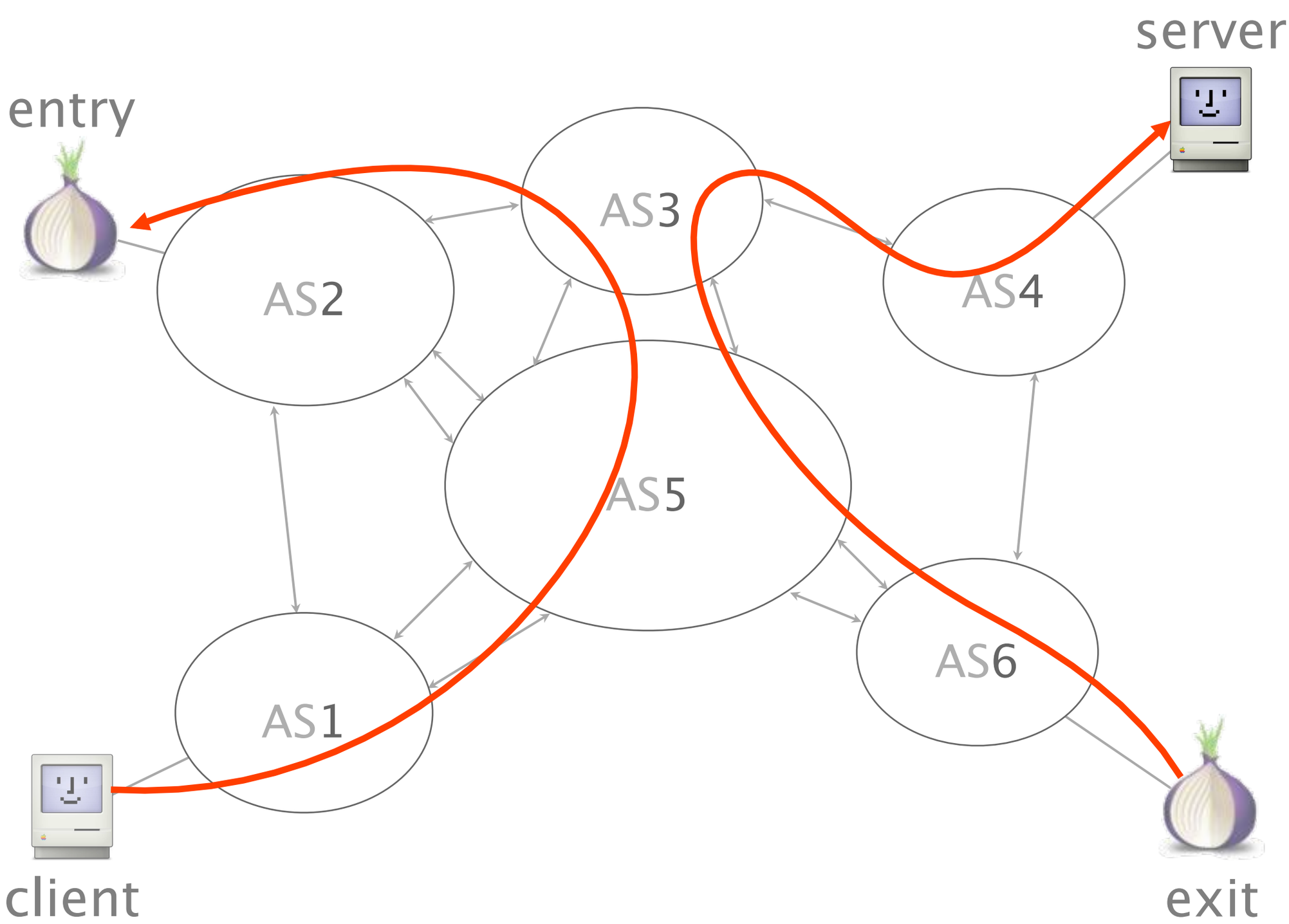
Initially, only AS5 is compromising



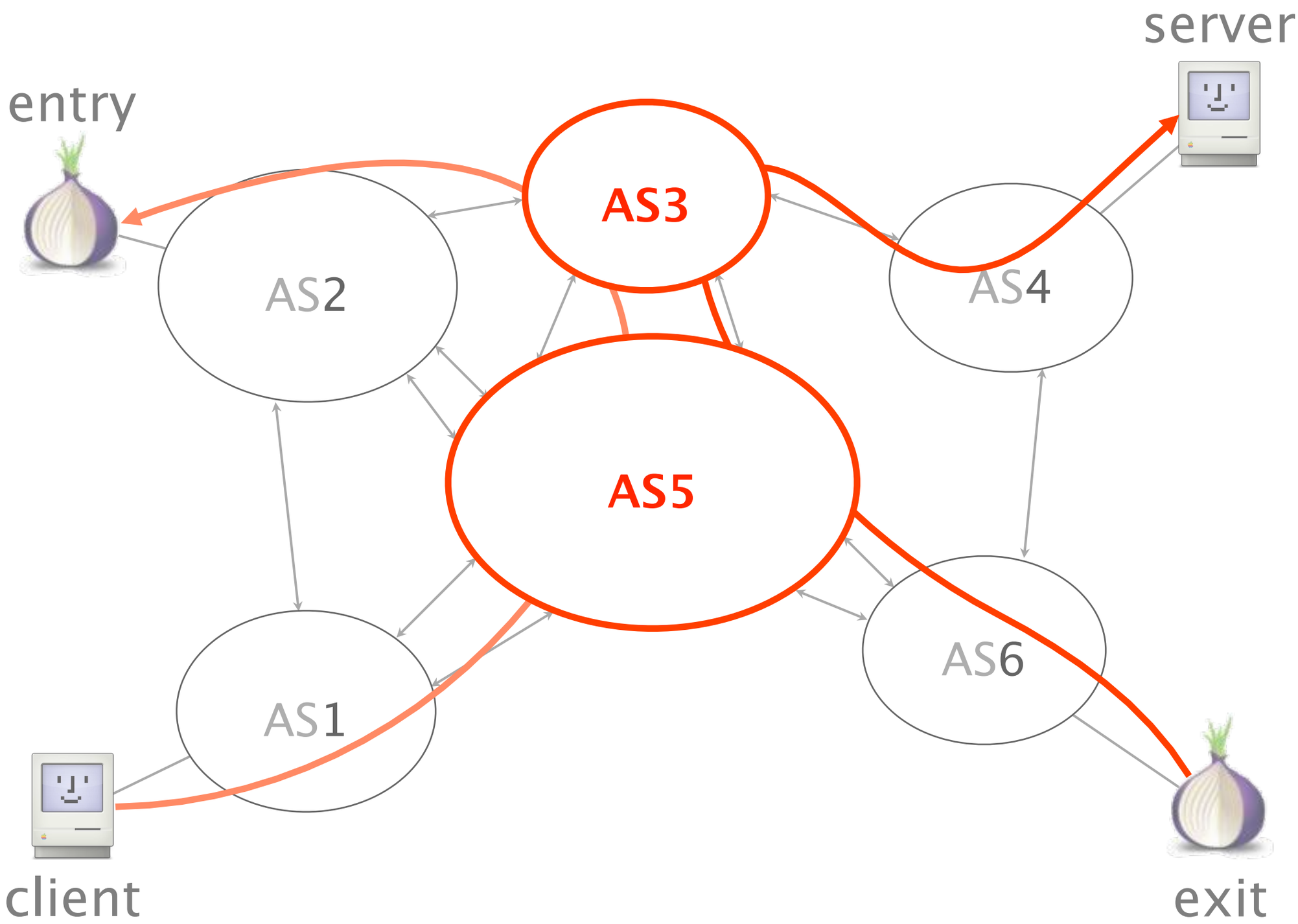
Assume that the link between AS4 and AS5 fails



Traffic gets rerouted via AS3



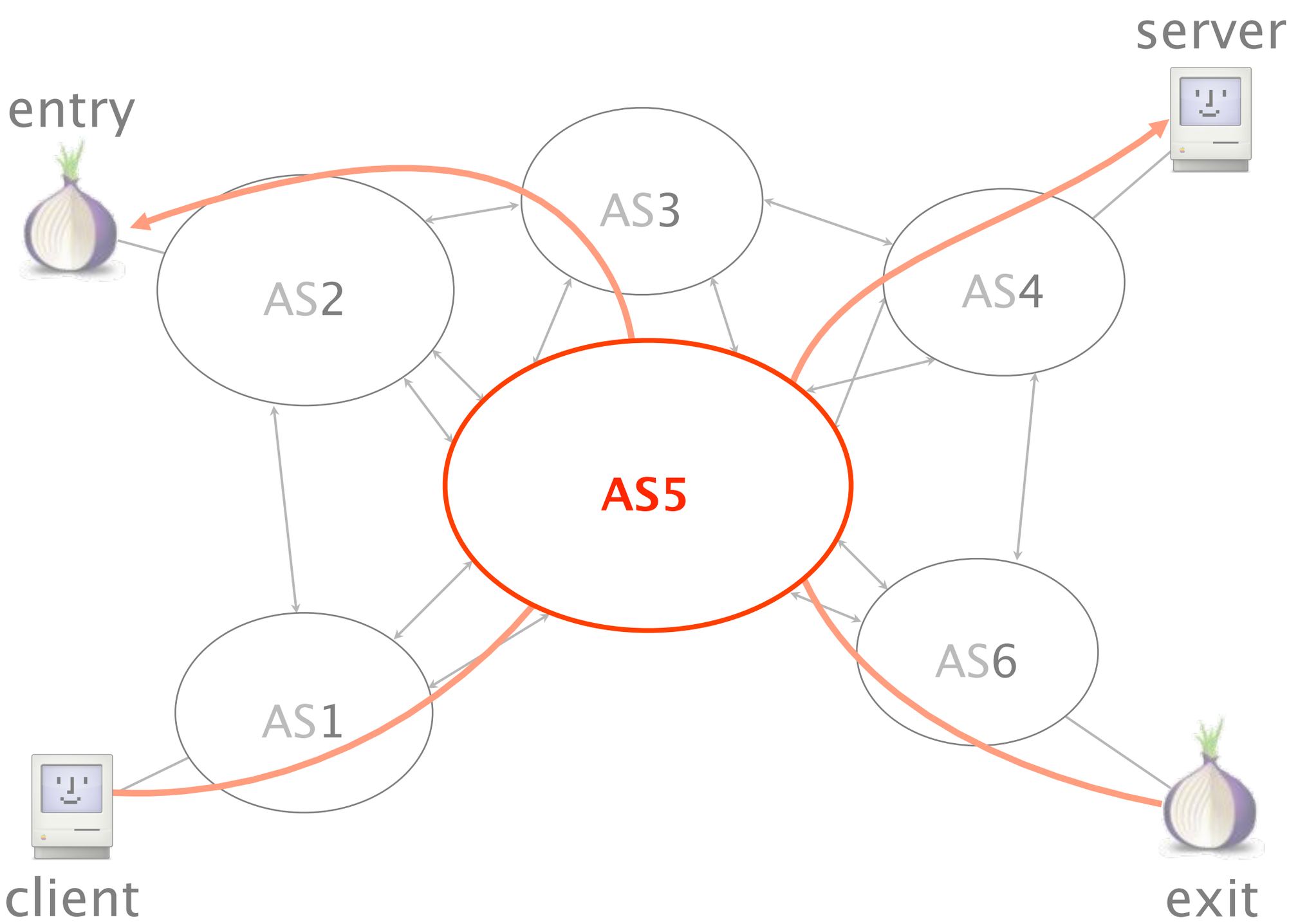
Now, both AS3 and AS5 are seeing client-to-entry and exit-to-server traffic



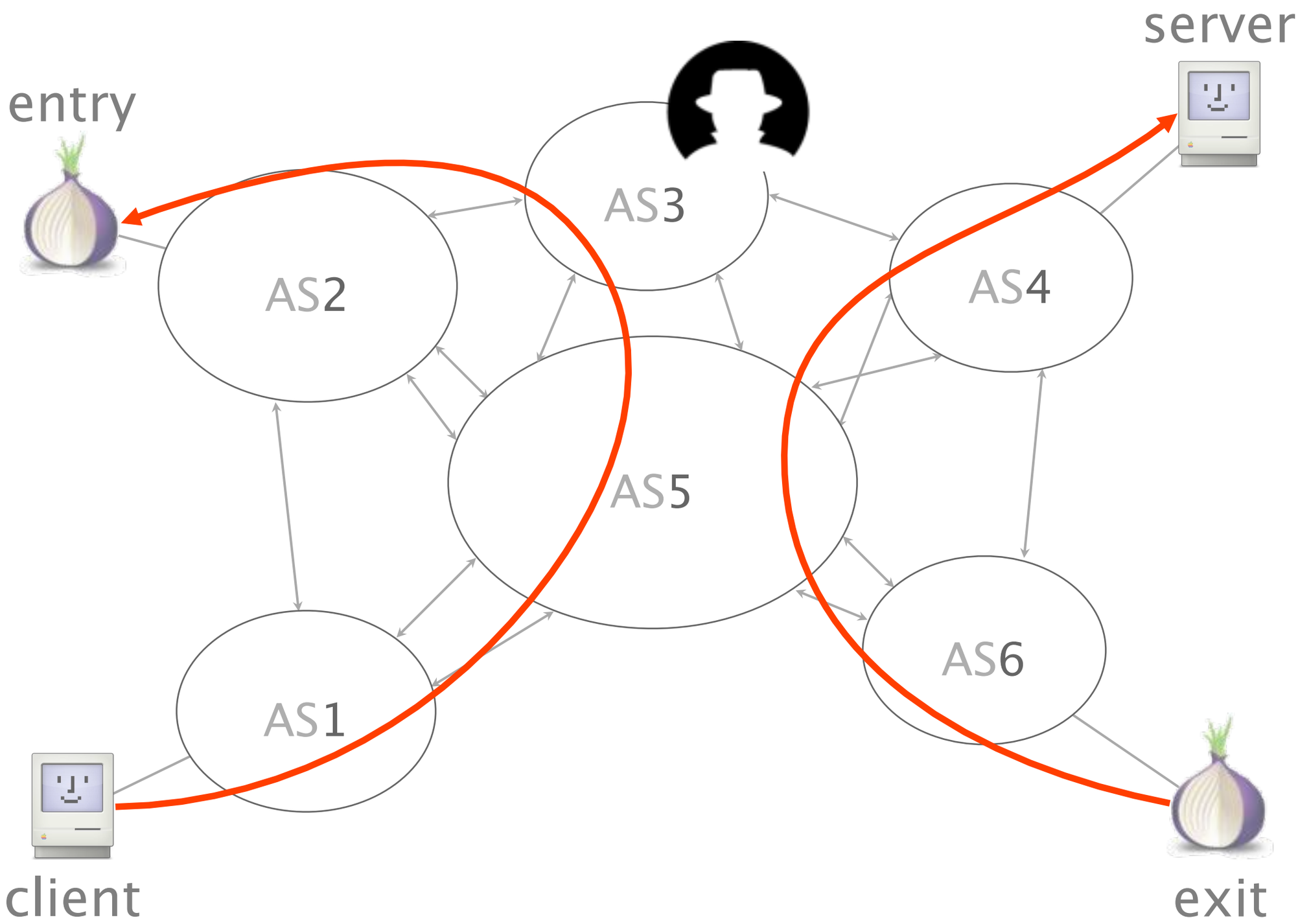
RAPTOR #3.

BGP hijacking attacks enable on-demand, fine-grained Tor attacks

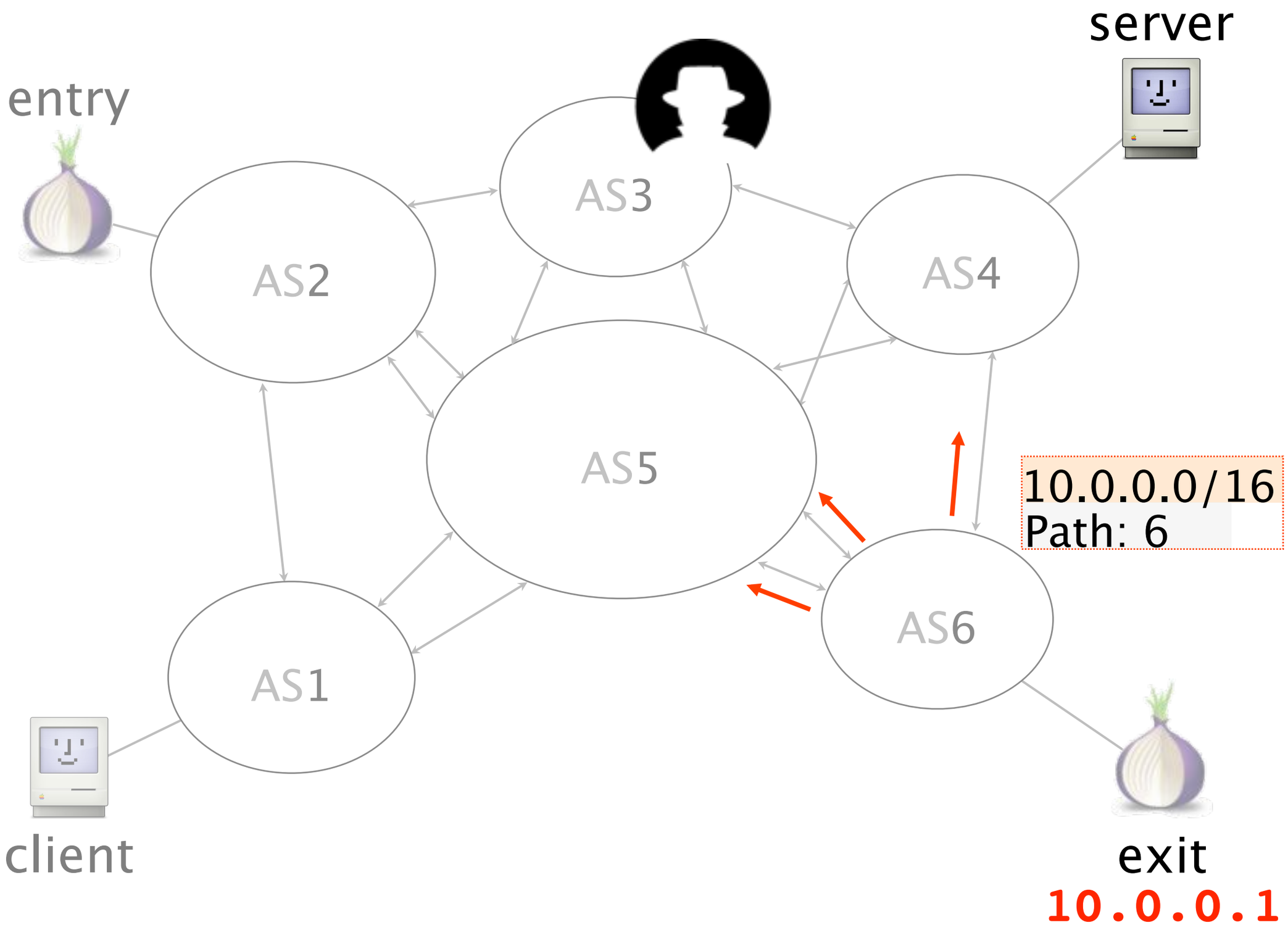
Initially, only AS5 is compromising



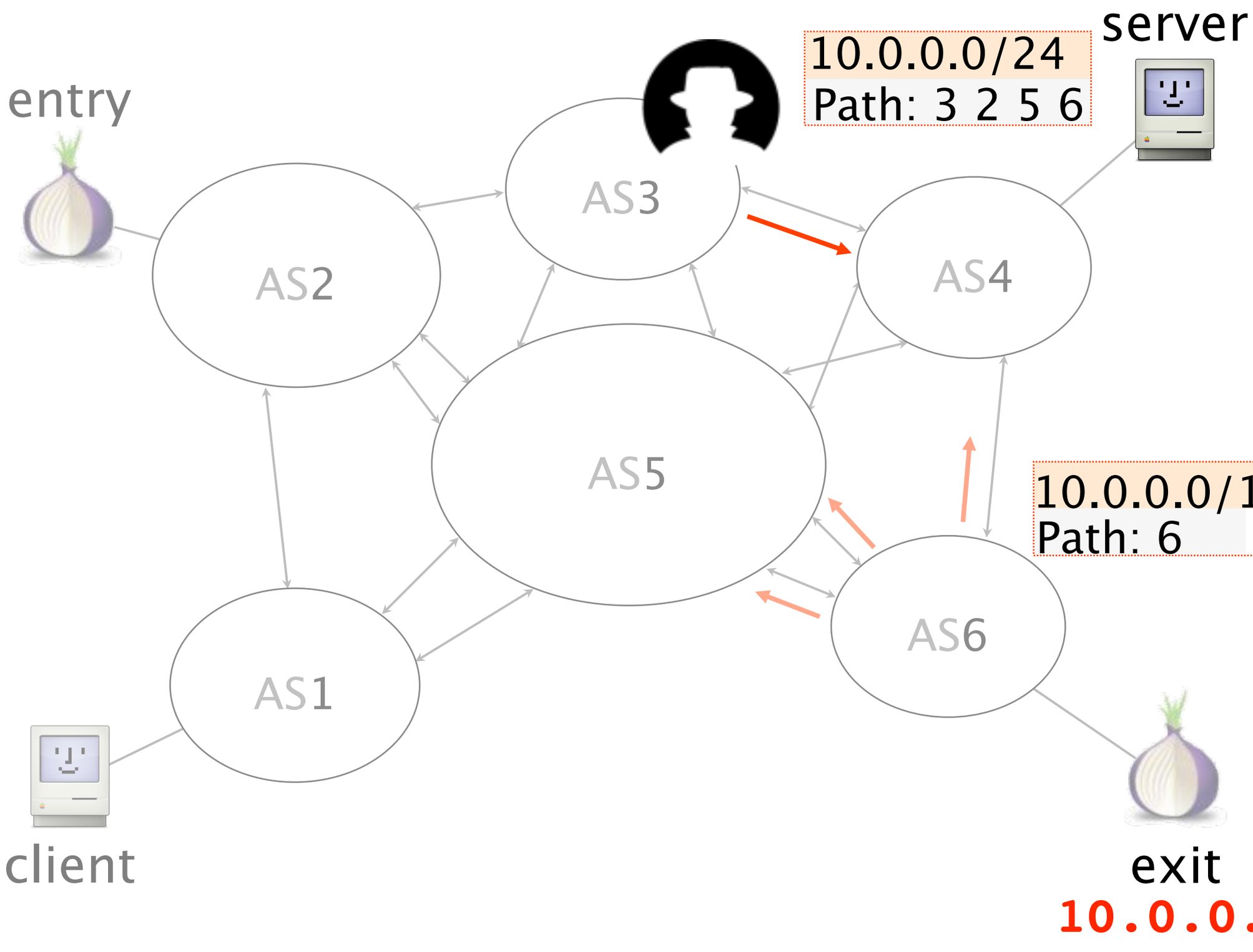
Assume that AS3 is a malicious AS, and wants to observe Tor traffic

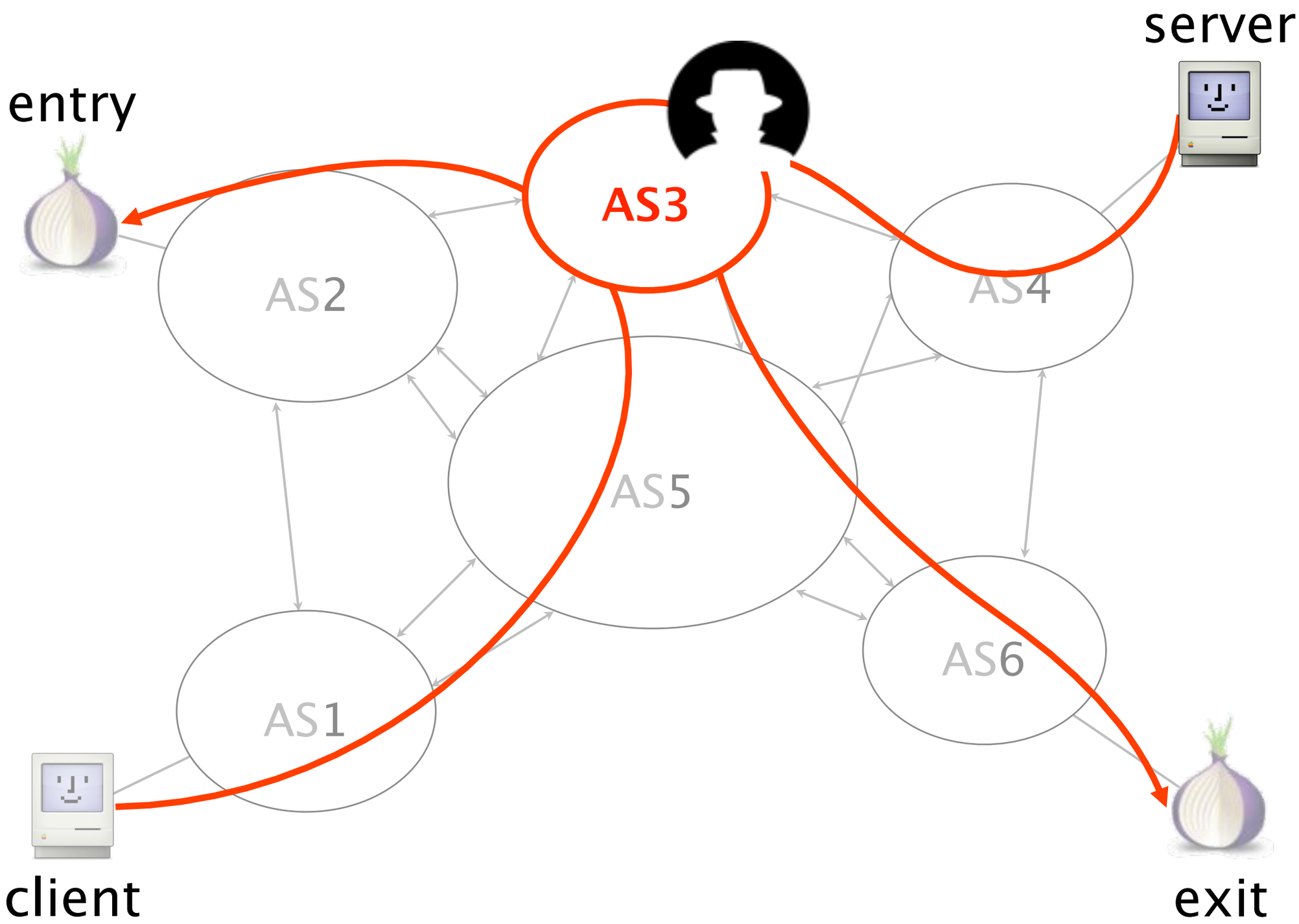


AS3 can put itself on server-to-exit paths by hijacking Tor prefixes



AS3 can put itself on server-to-exit paths by hijacking Tor prefixes




server
entry
AS3
AS2
AS4
AS5
AS6
AS1
client
exit

In April 2014,

Indosat leaked >320k BGP routes over 2 hours

Indonesia Hijacks the World



photo by null0 on Flickr | CC

Yesterday, Indosat, one of Indonesia's largest telecommunications providers, leaked large portions of the global routing table multiple times over a two-hour period. This means that, in effect, Indosat claimed that it "owned" many of the world's networks. Once someone makes such an assertion, typically via an honest mistake in their routing policy, the only question remaining is how much of the world ends up believing them and hence, what will be the scale of the damage they inflict? Events of this

Indosat

One of Indonesia's largest tele-communications providers

Affected 44 Tor Relays

Include 38 guard and 17 exit

11 were both guard and exit

RAPTOR:
Routing Attacks on Privacy in Tor



Attacks

All your traffic belongs to me

2 Results

Eyes wide open

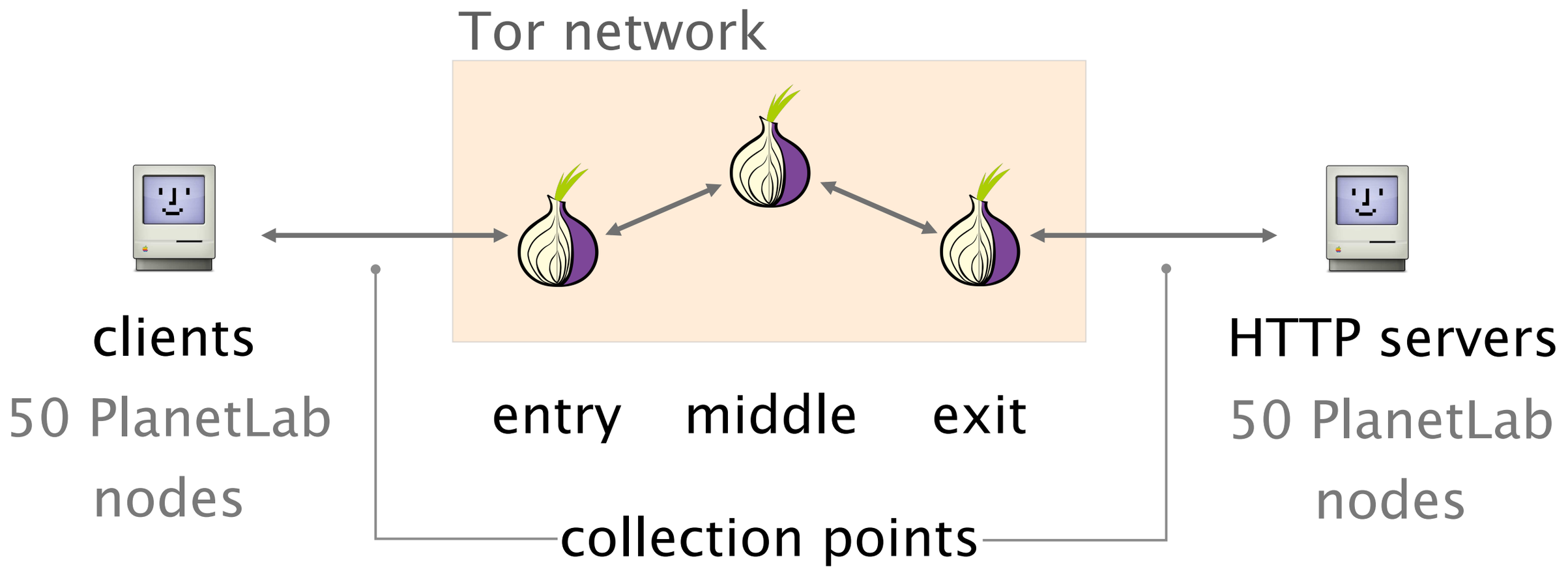
Countermeasures

Close the curtains

RAPTOR #1.

Asymmetric traffic analysis is highly efficient

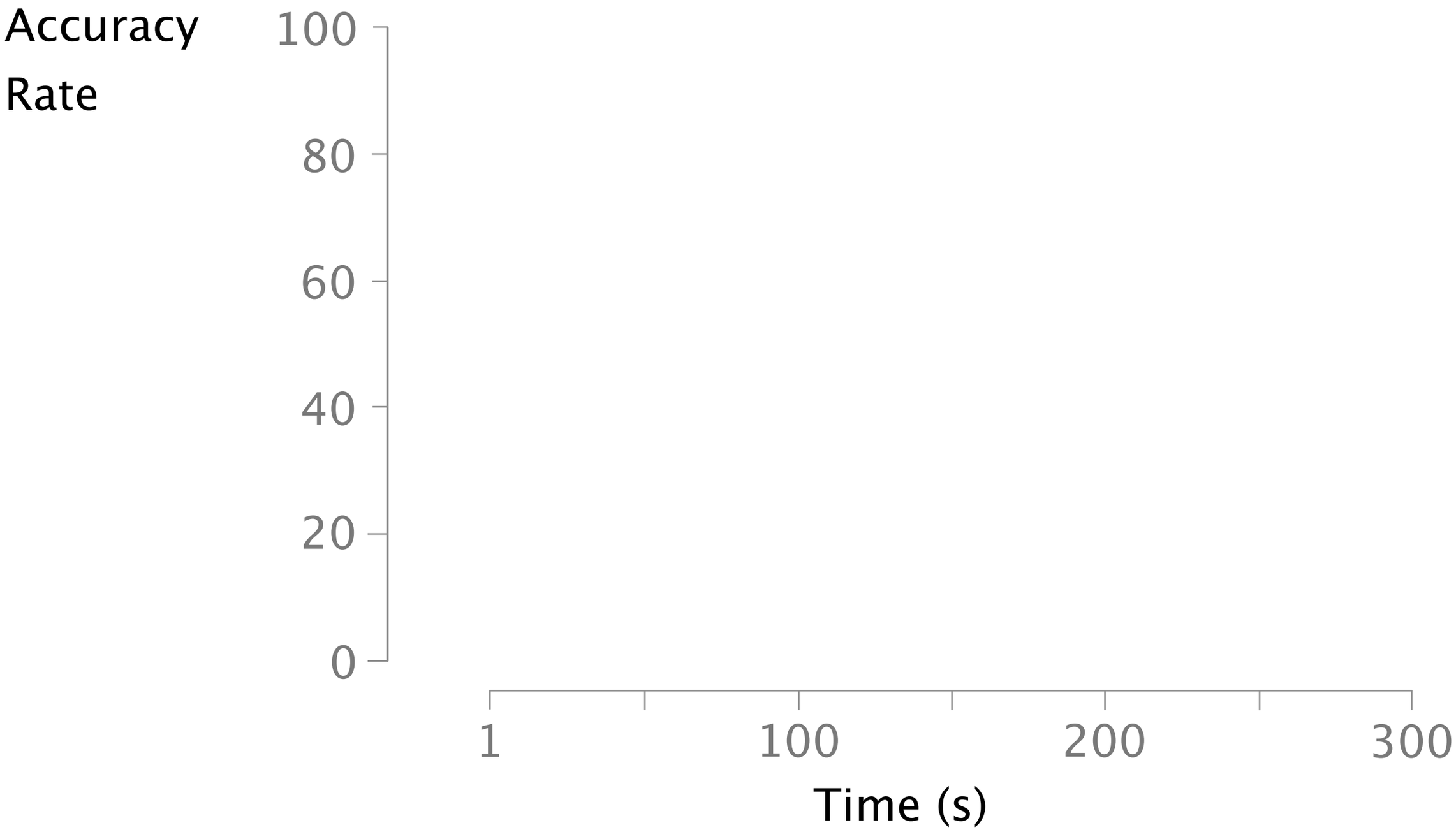
We collected traces by downloading 100 Mb files through Tor



After 5 min, we were able to deanonymize ~95% of the pairs—with *no* false positives

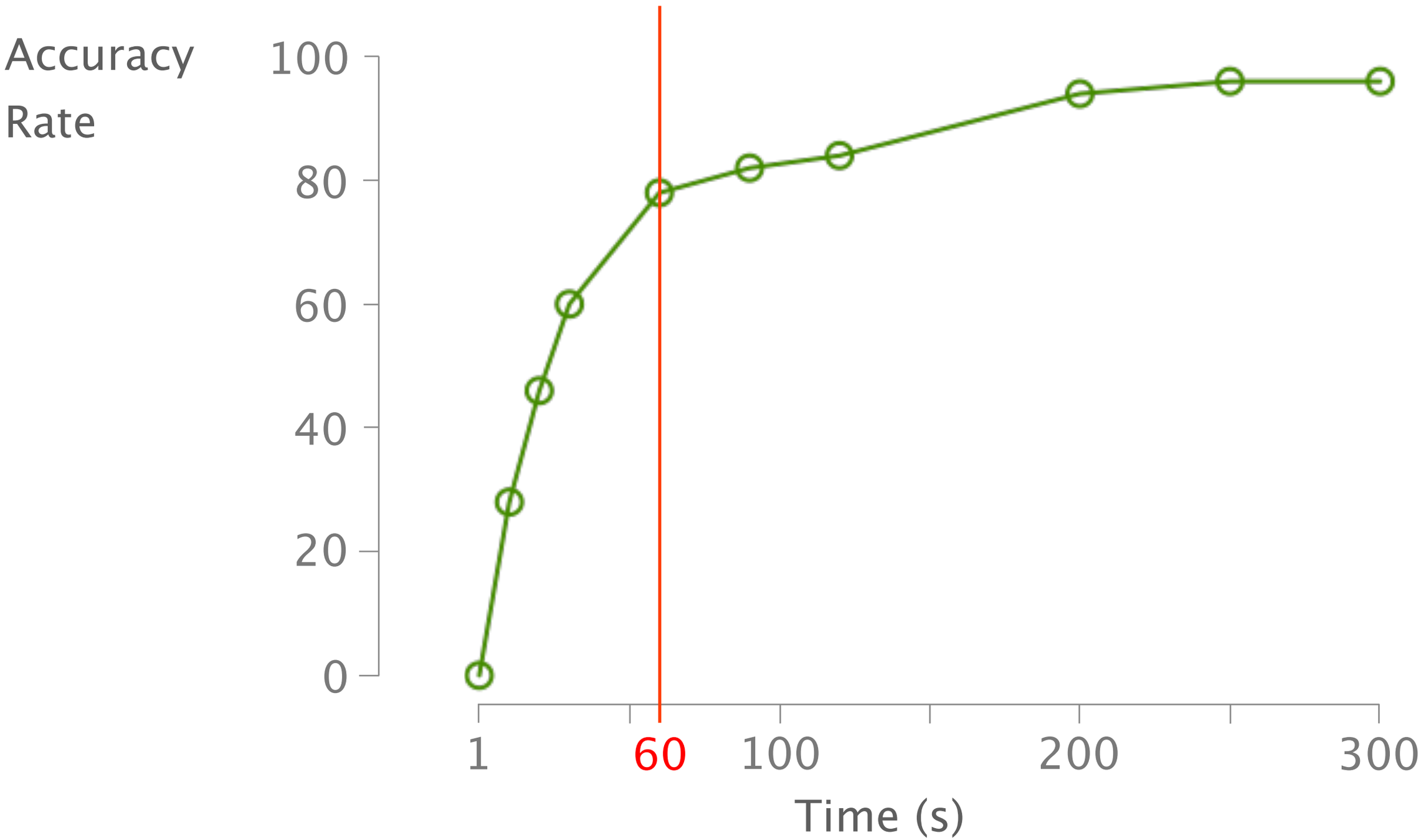
	client ACK & server ACK	client ACK & server data	client data & server ACK	client data & server data
detection rate	96 %	94 %	96 %	94 %
false negative	4 %	6 %	4 %	6 %
false positive	0 %	0 %	0 %	0 %

Detection accuracy quickly increases with time



Detection accuracy quickly increases with time,

reaching 80% within only a minute



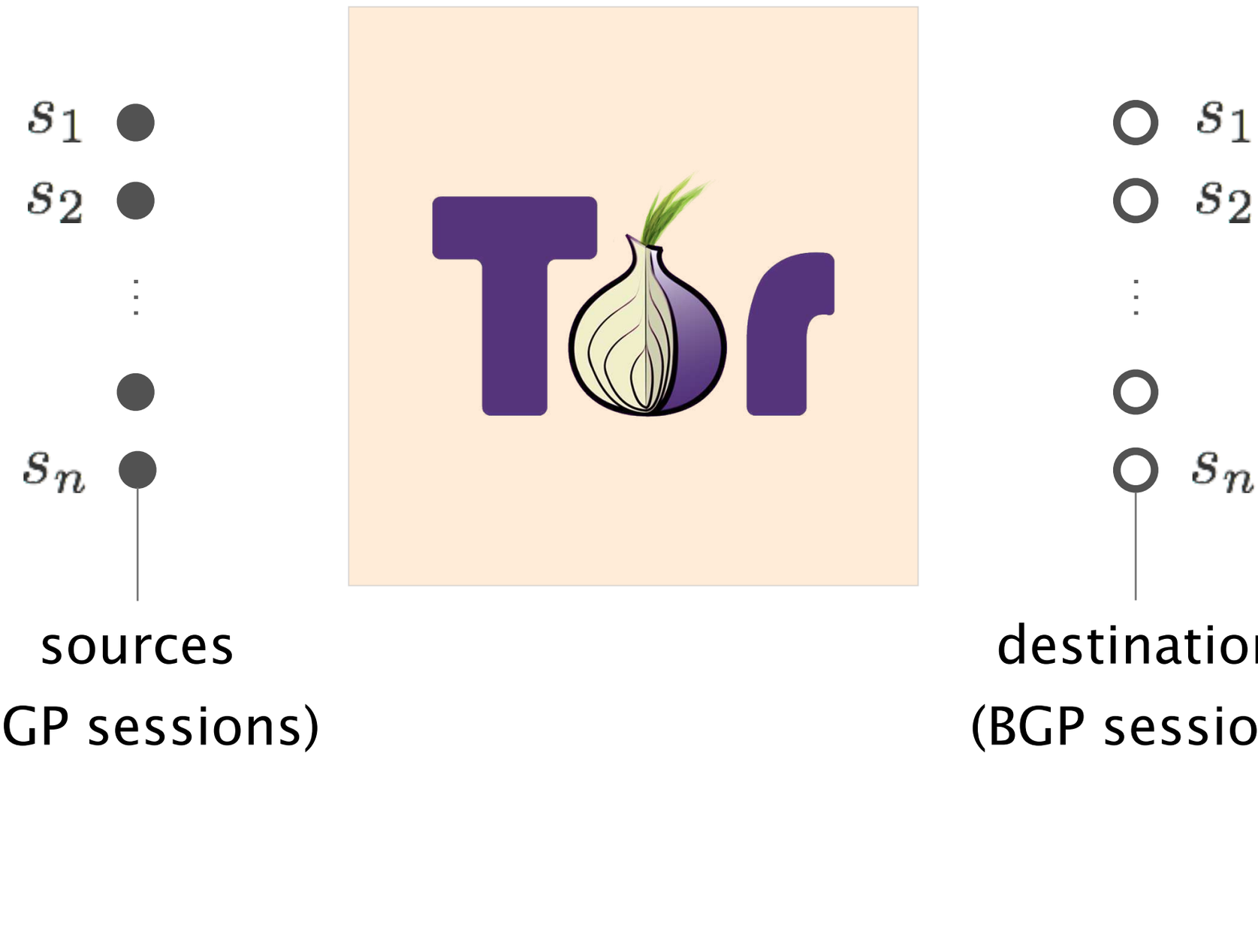
RAPTOR #2.

Churn significantly increases the number of compromising ASes

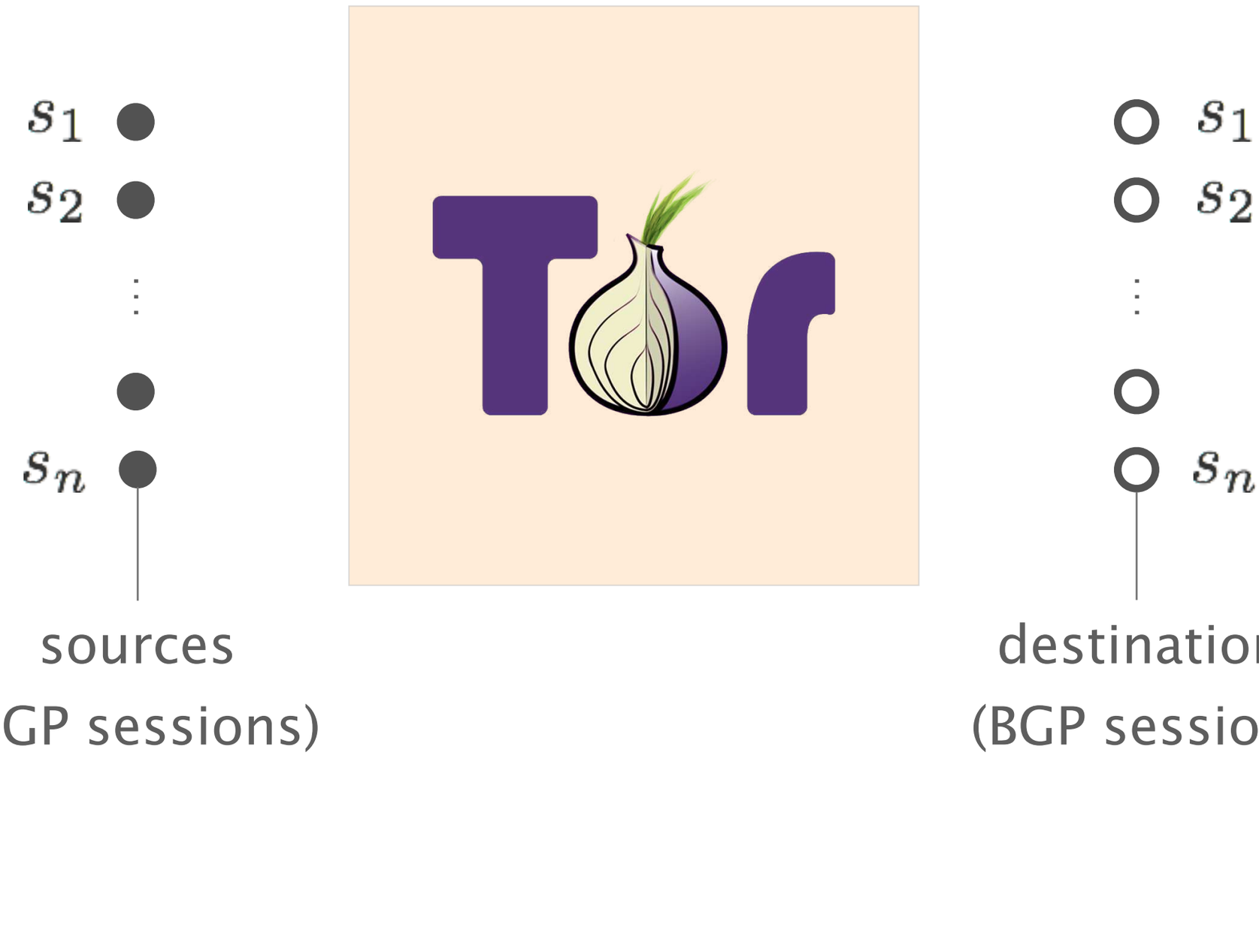
We measured the effect of churn
by collecting BGP updates for 1 month (Jan 15)

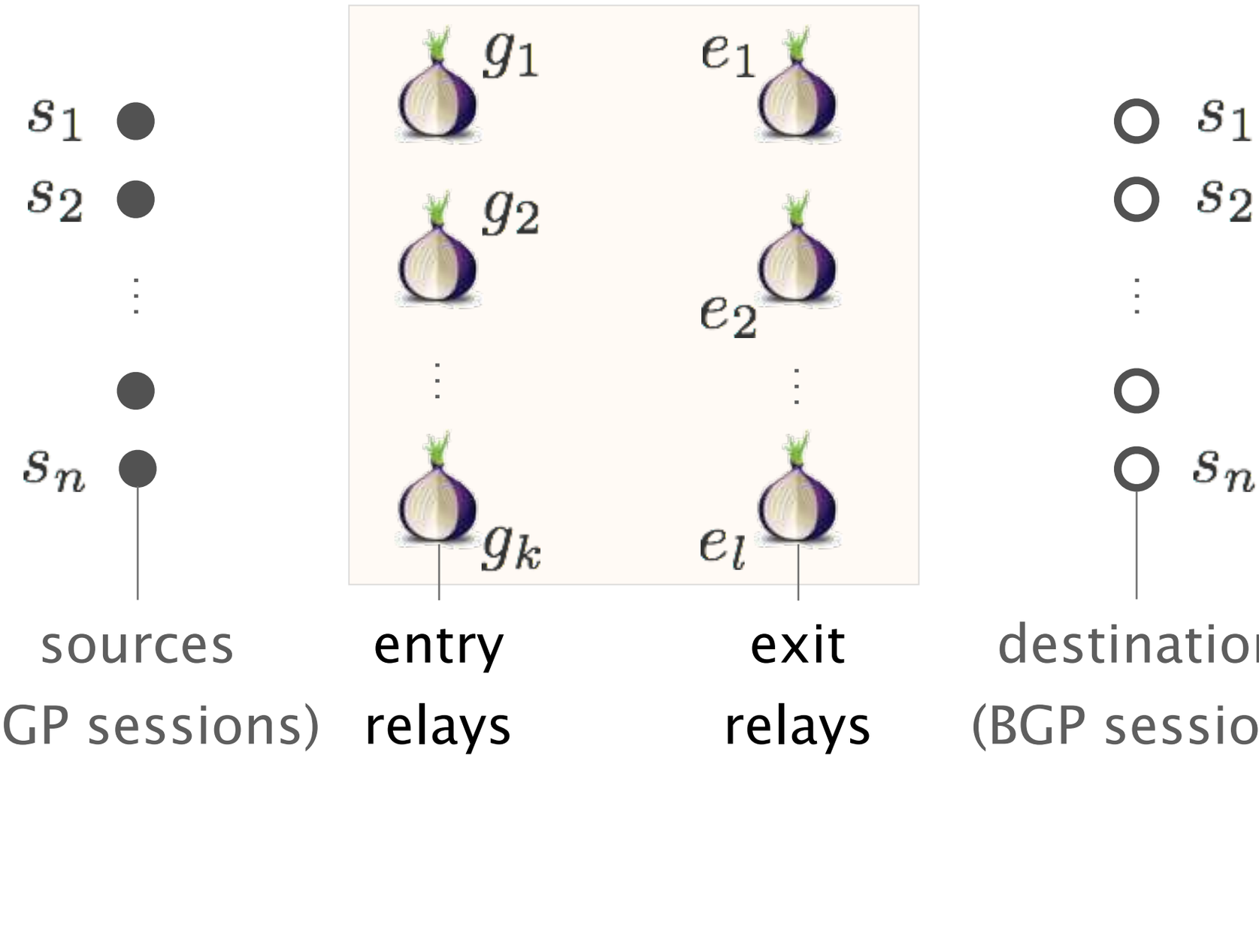
# BGP sessions (6 RIPE RIS collectors)	250+
# BGP prefixes	550k
# BGP updates announcements/withdraws	612+ millions

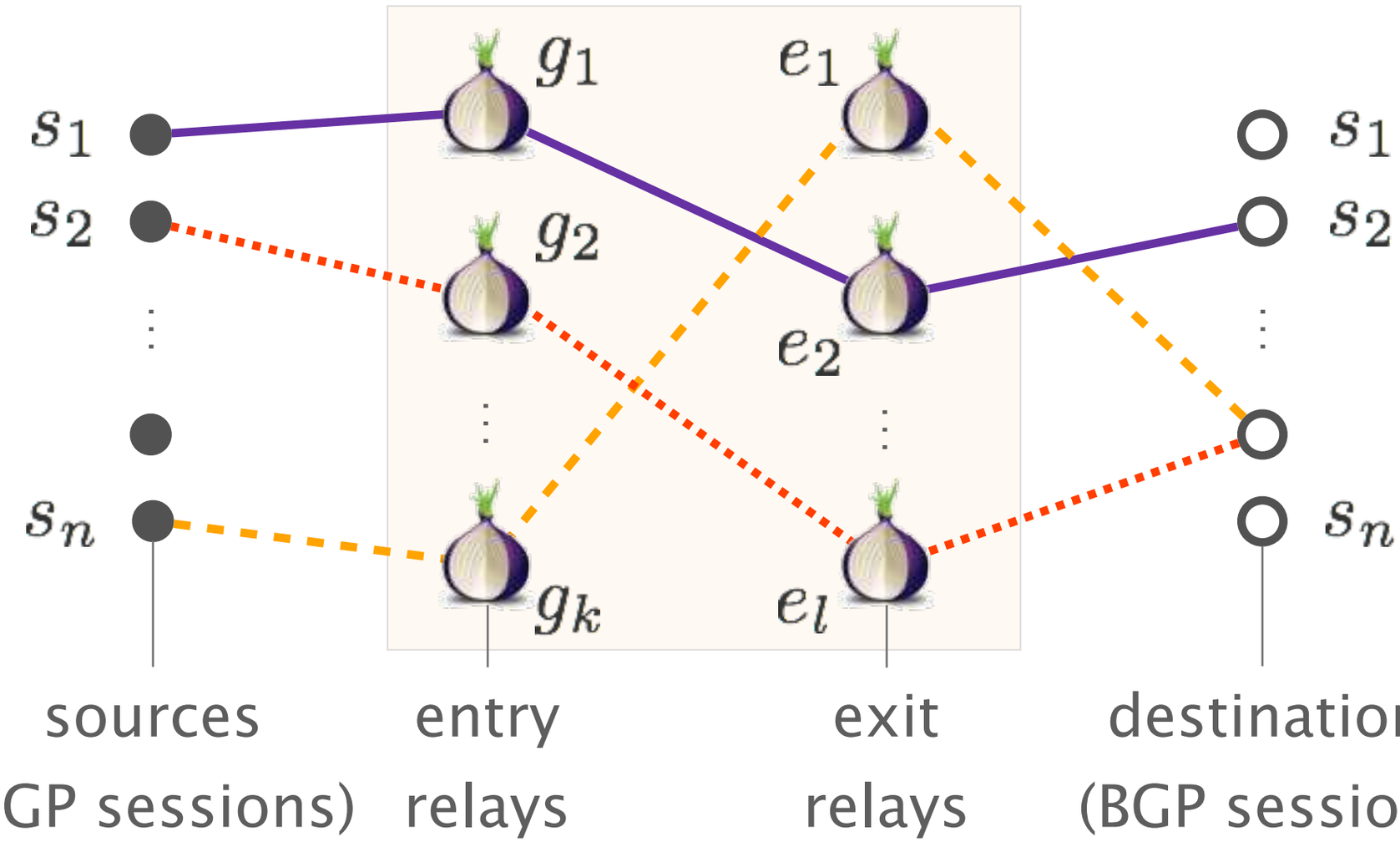
We considered each BGP session as a Tor user or destination

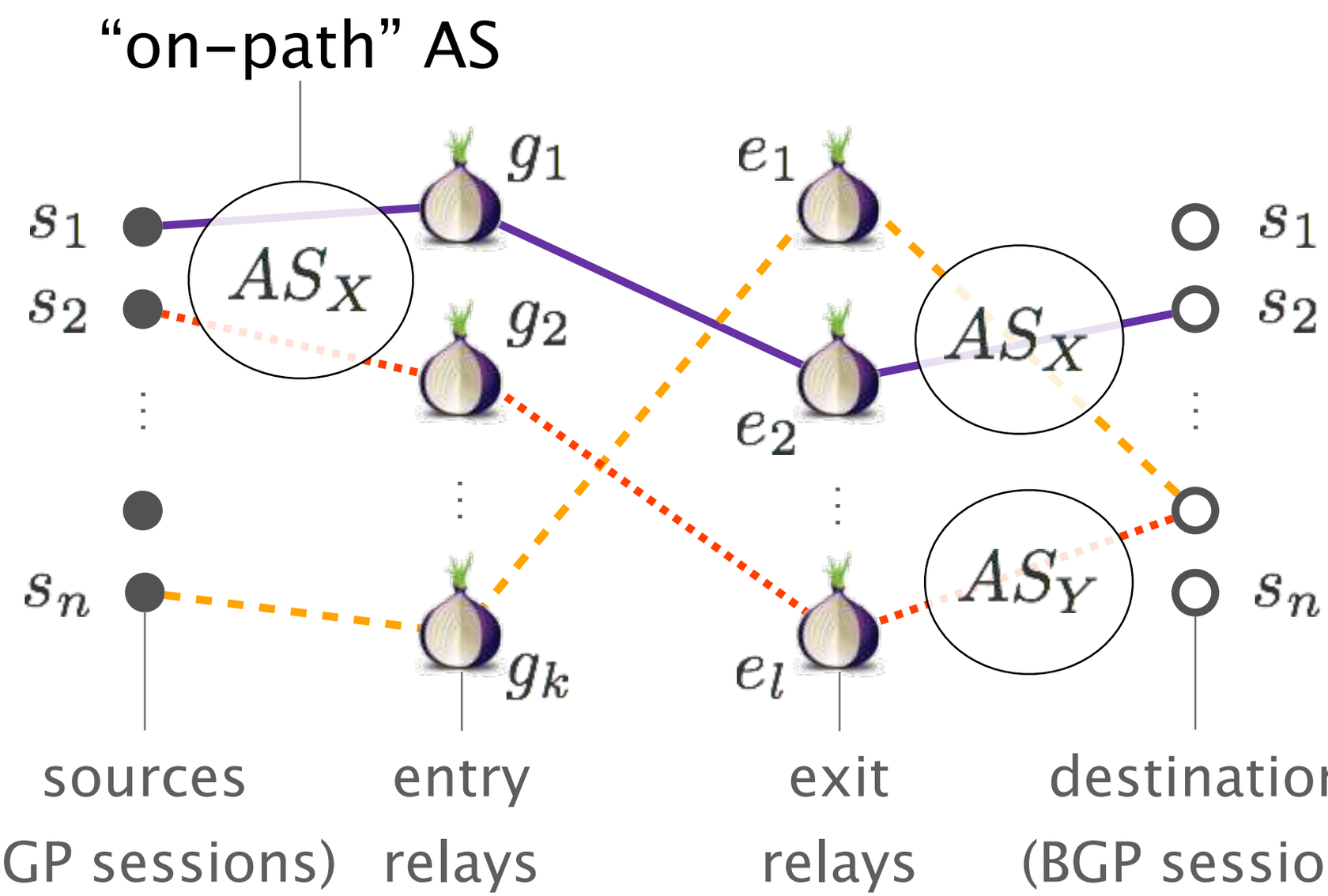


On each session, we computed the ASes used to reach each entry and exit relays

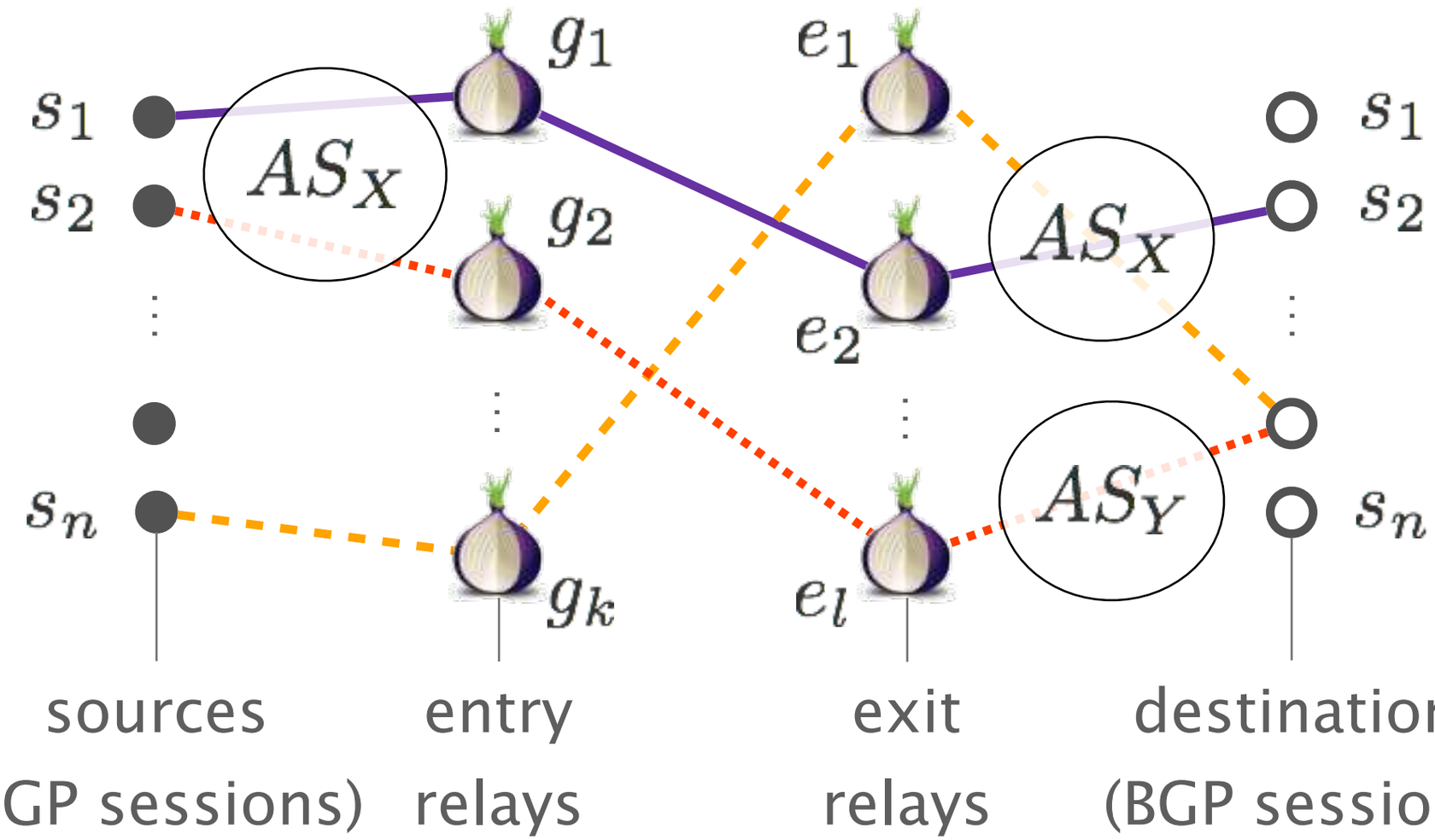



s_1
s_2
s_n
g_1
g_2
g_k
e_1
e_2
e_l
s_1
s_2
s_n
sources
(BGP sessions)
entry
relays
exit
relays
destinations
(BGP sessions)

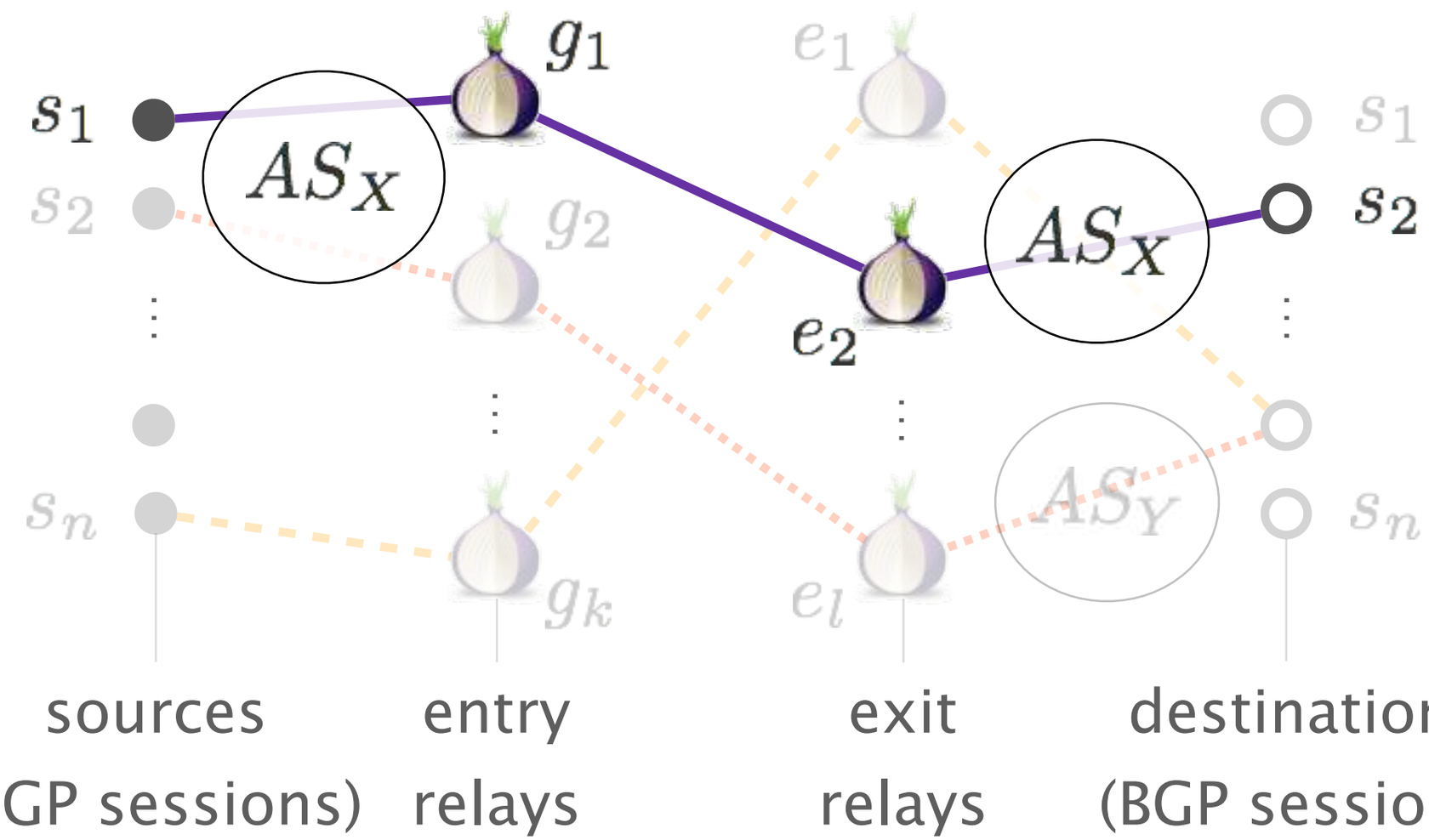

s_1
s_2
s_n
g_1
g_2
g_k
e_1
e_2
e_l
s_1
s_2
s_n
sources
(BGP sessions)
entry
relays
exit
relays
destinations
(BGP sessions)


"on-path" AS
s_1
s_2
s_n
AS_X
g_1
g_2
g_k
e_1
e_2
e_l
AS_X
AS_Y
s_1
s_2
s_n
sources
(BGP sessions)
entry
relays
exit
relays
destinations
(BGP sessions)

An AS is compromising when it ends up simultaneously on a (src, entry) and (exit, dest) path



ASX is compromising for the TOR circuit (g1, e2) and (s1,s2)

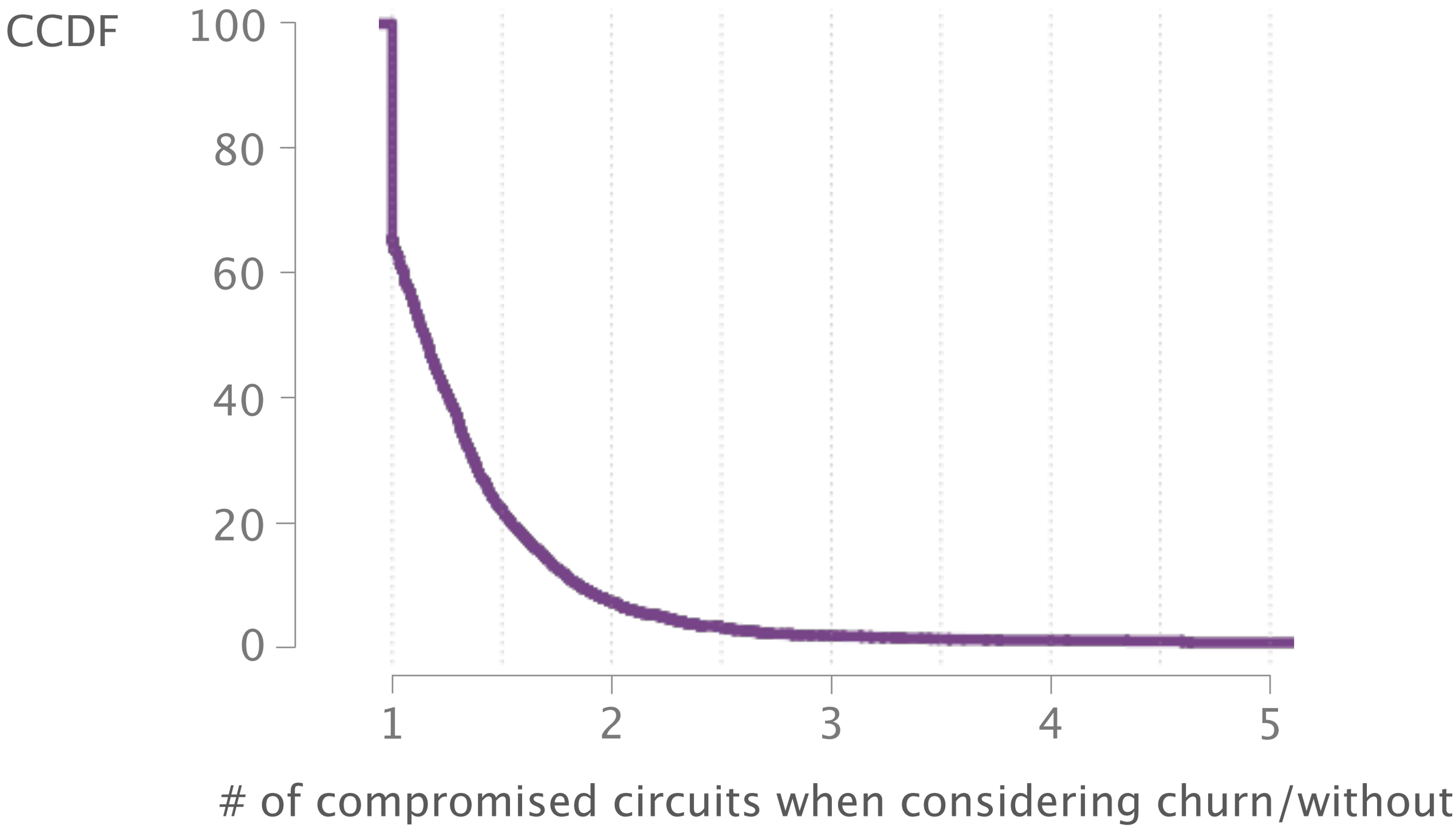


When considering churn…

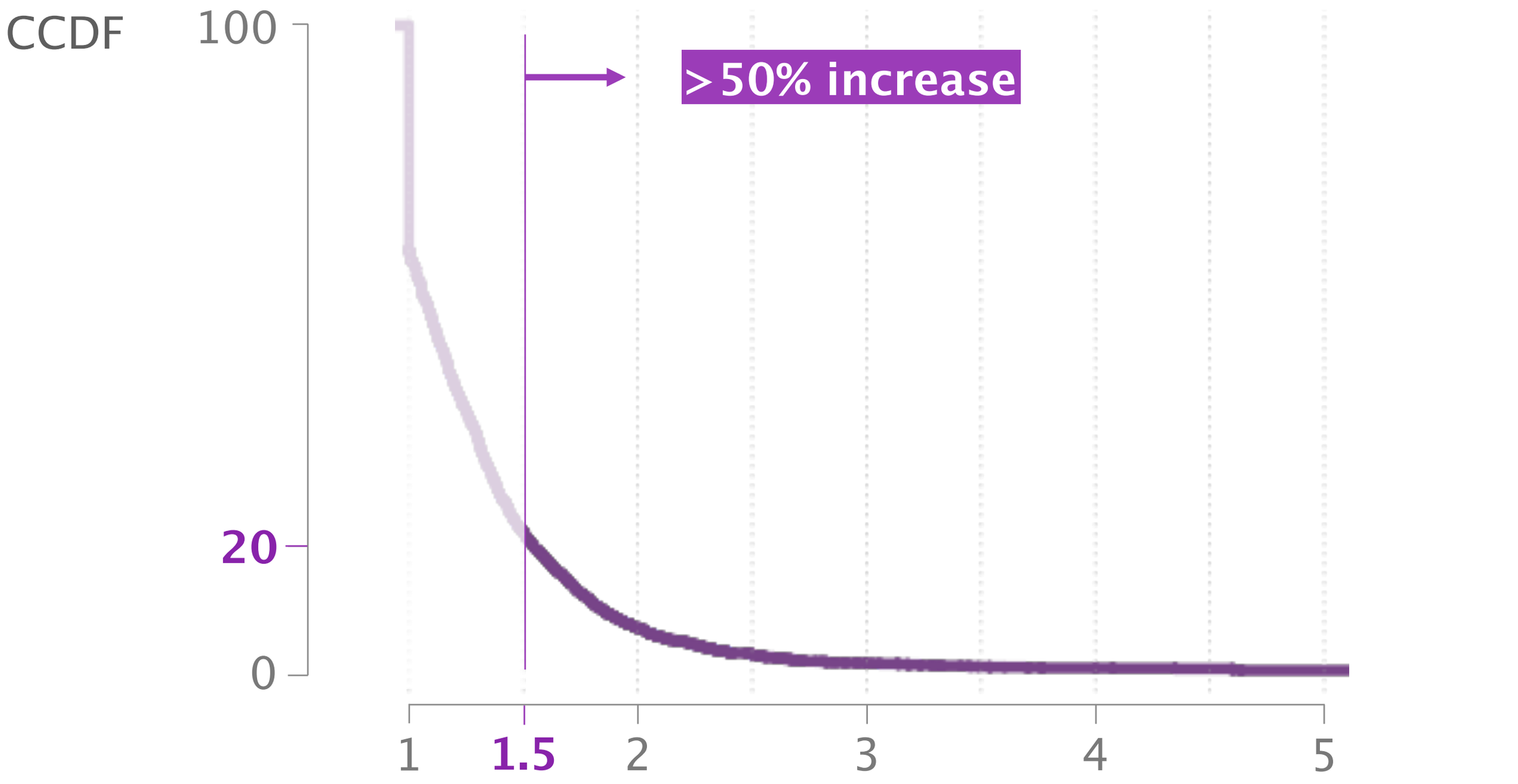
How many more ASes are compromising, and for how many TOR circuits?


CCDF
100
80
60
40
20
0
1
2
3
4
5
# of compromised circuits when considering churn/without

60% of the pairs (src, dst) sees an increase of compromised circuits



20% of the pairs sees an increase of more than 50%!



RAPTOR #3.

BGP hijack works in the wild

We successfully performed a BGP attack on an existing Tor entry relay

Our experiments did not compromise the privacy or safety of real Tor users

We attacked our own traffic

not actual user-generated Tor traffic

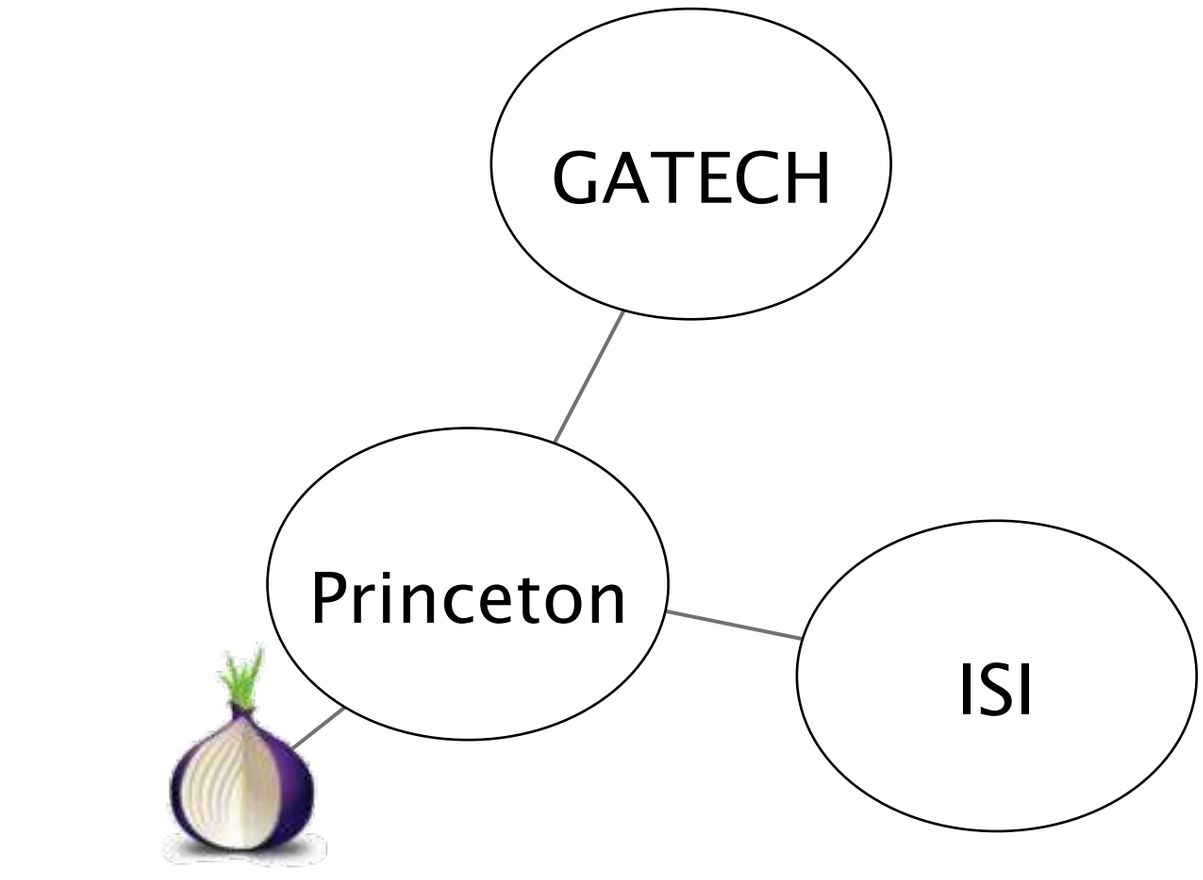
We attacked our own relay

hijacking our own IP prefix

We firewalled our relay

dropping any traffic not generated by us

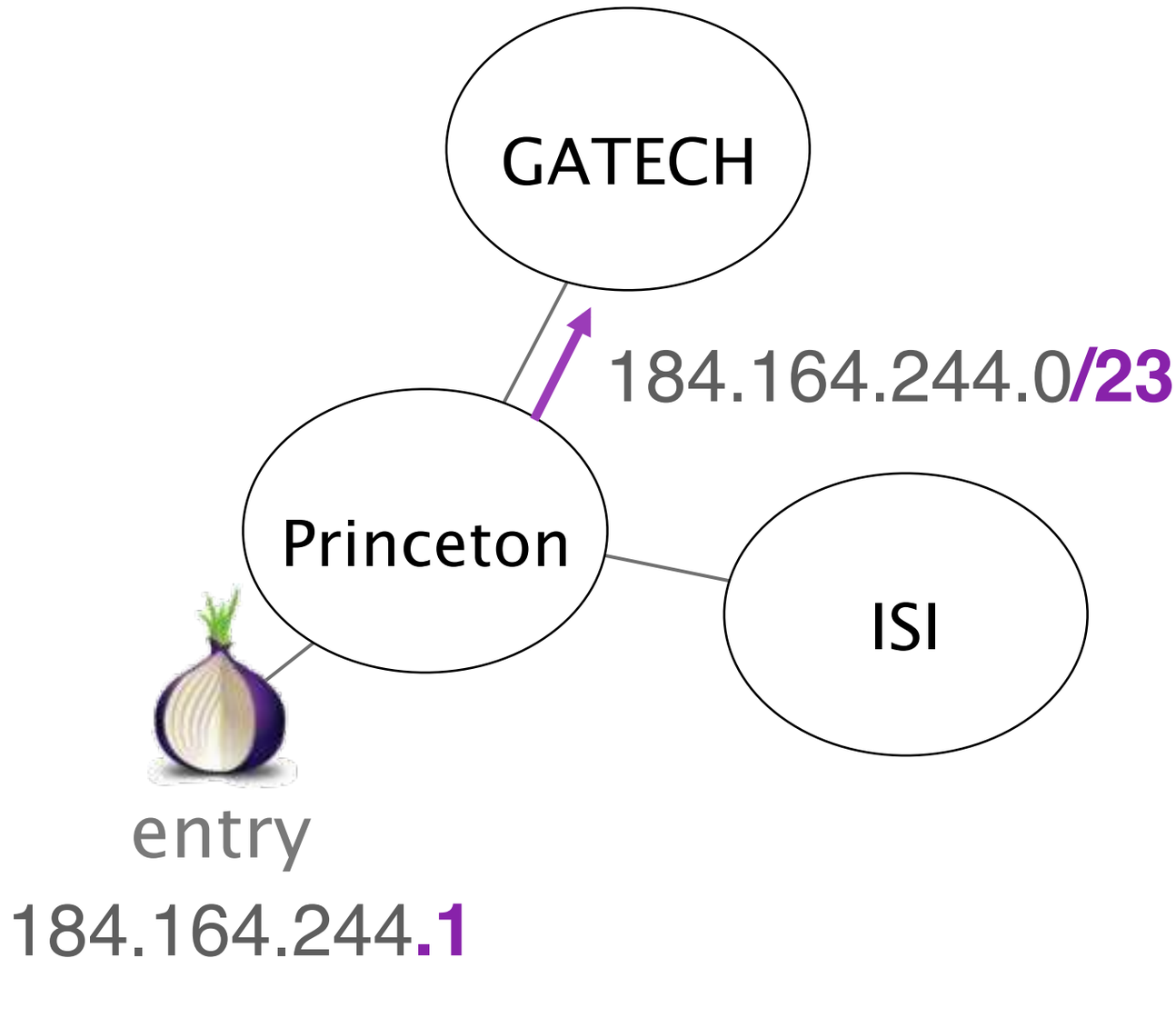
We hosted an entry relay in Princeton



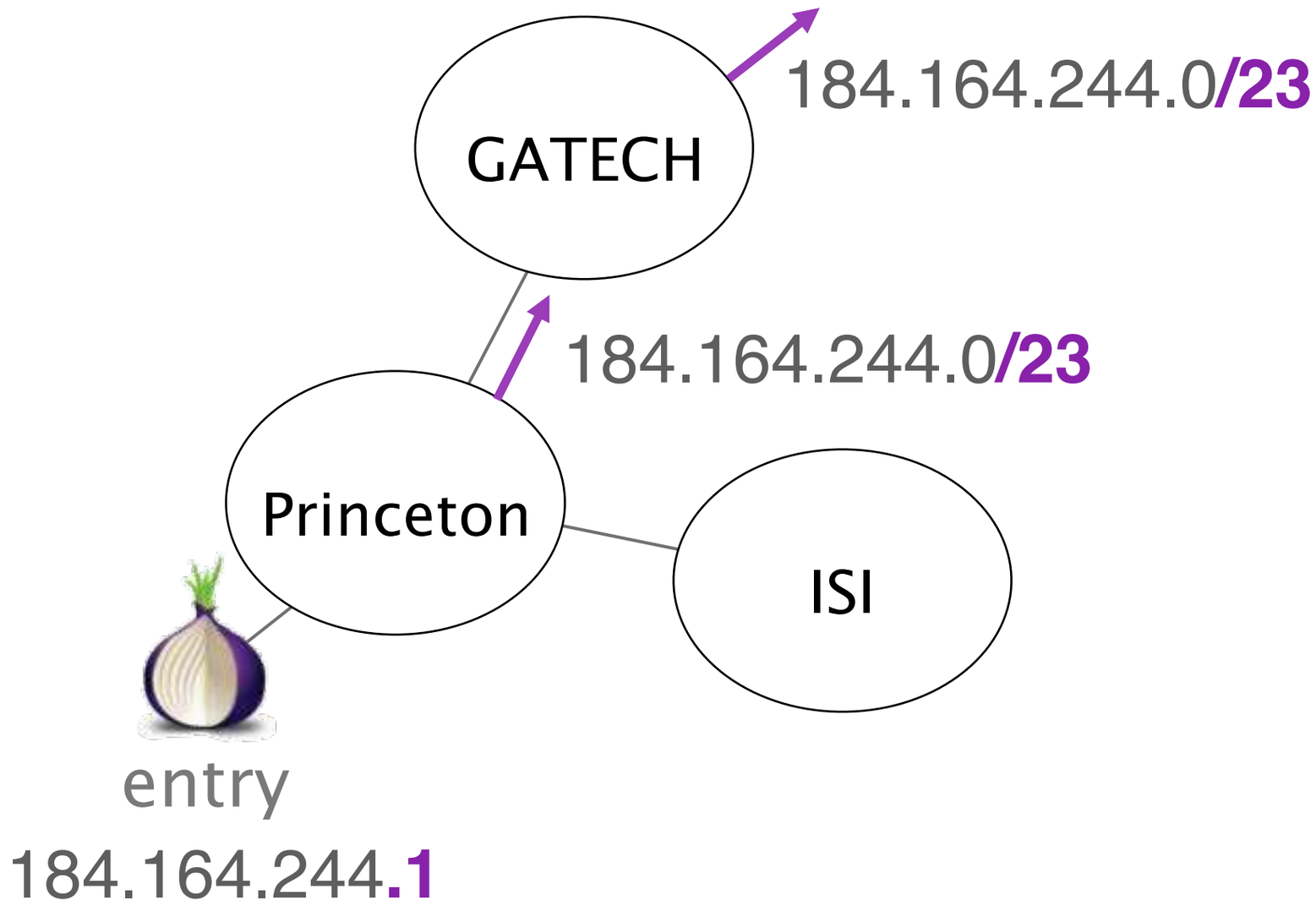
entry

184.164.244.**1**

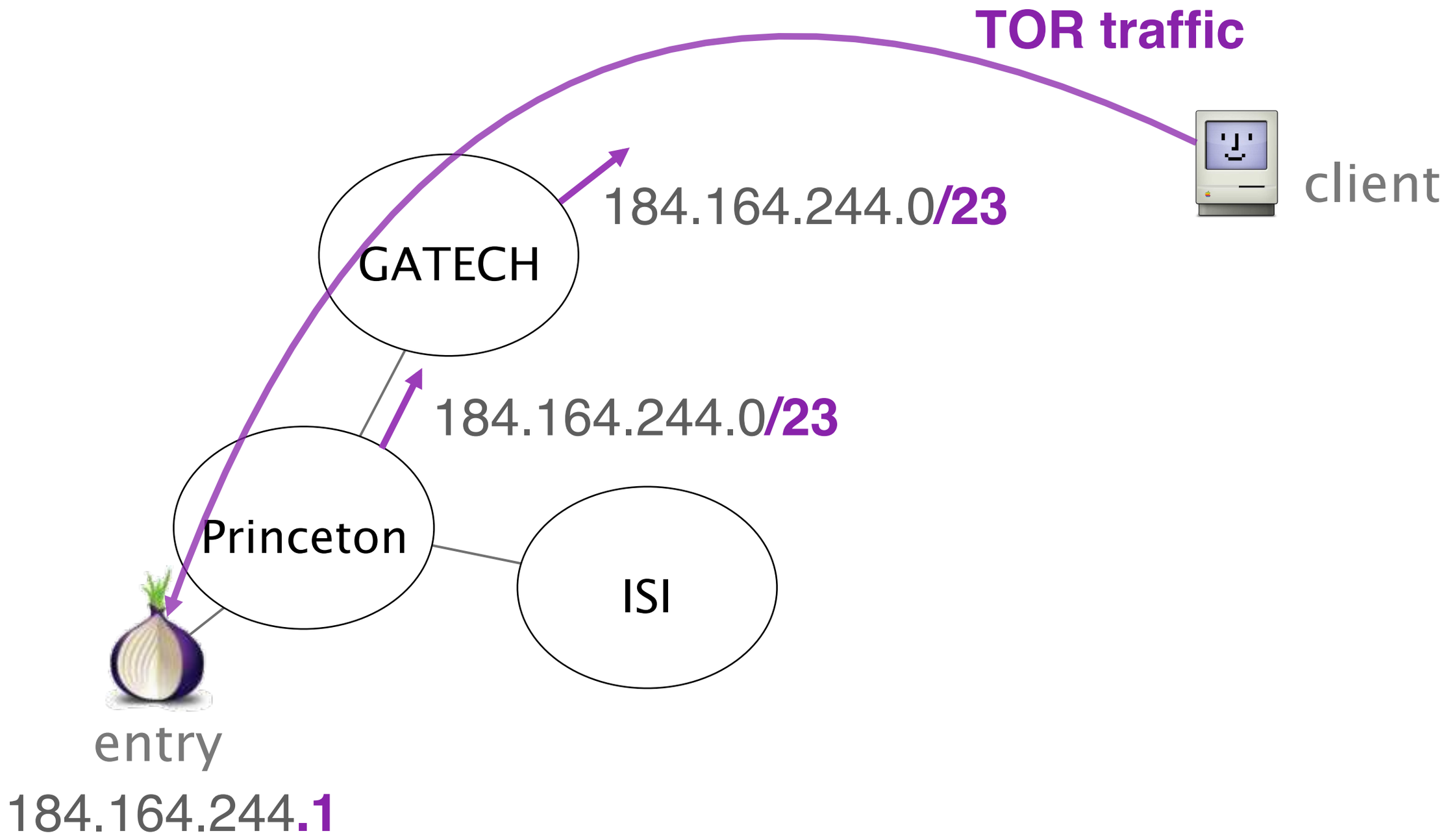
We advertised the covering IP prefix via GATECH



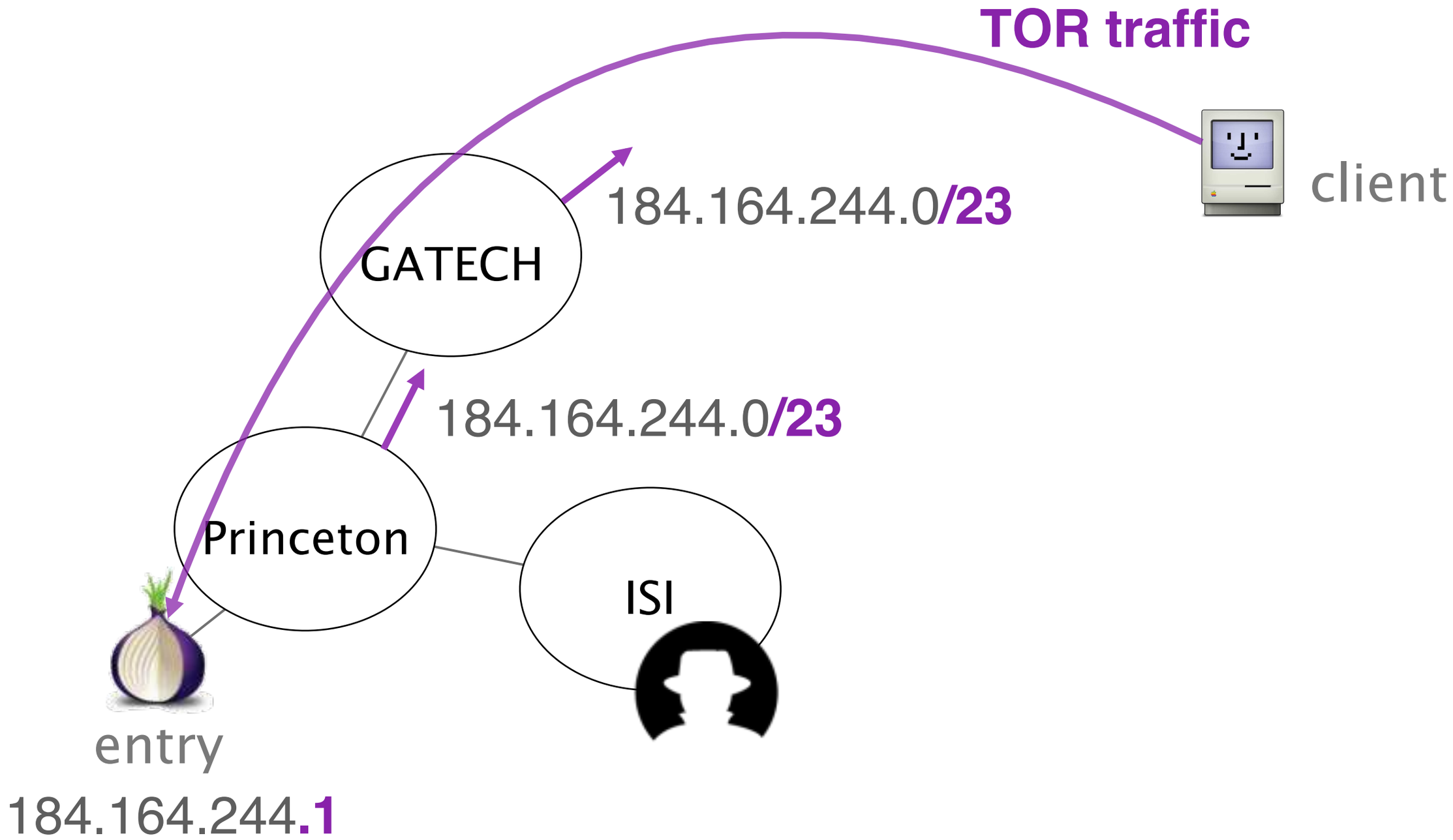
GATECH relayed on prefix to the entire Internet



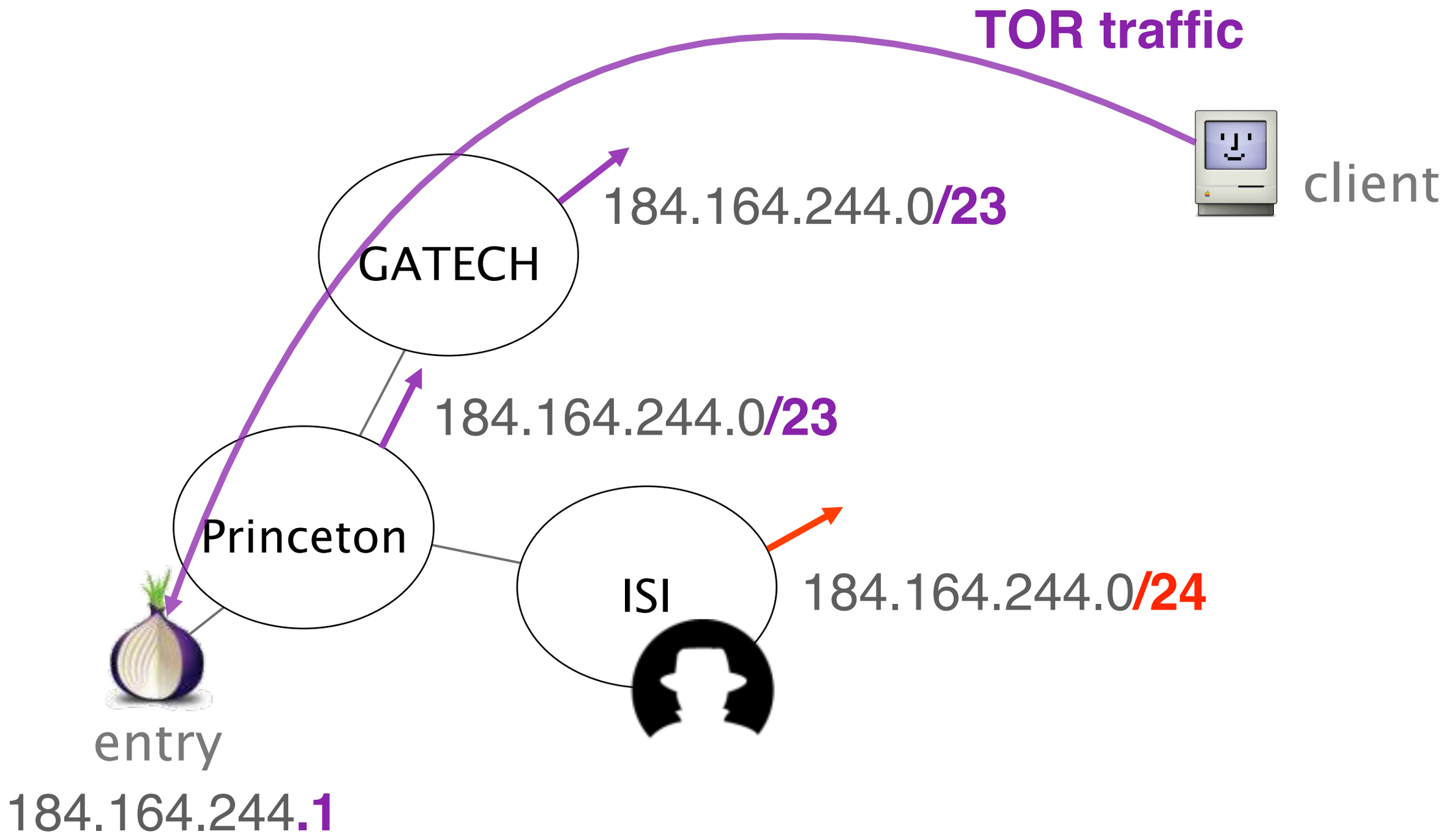
Tor traffic started to flow



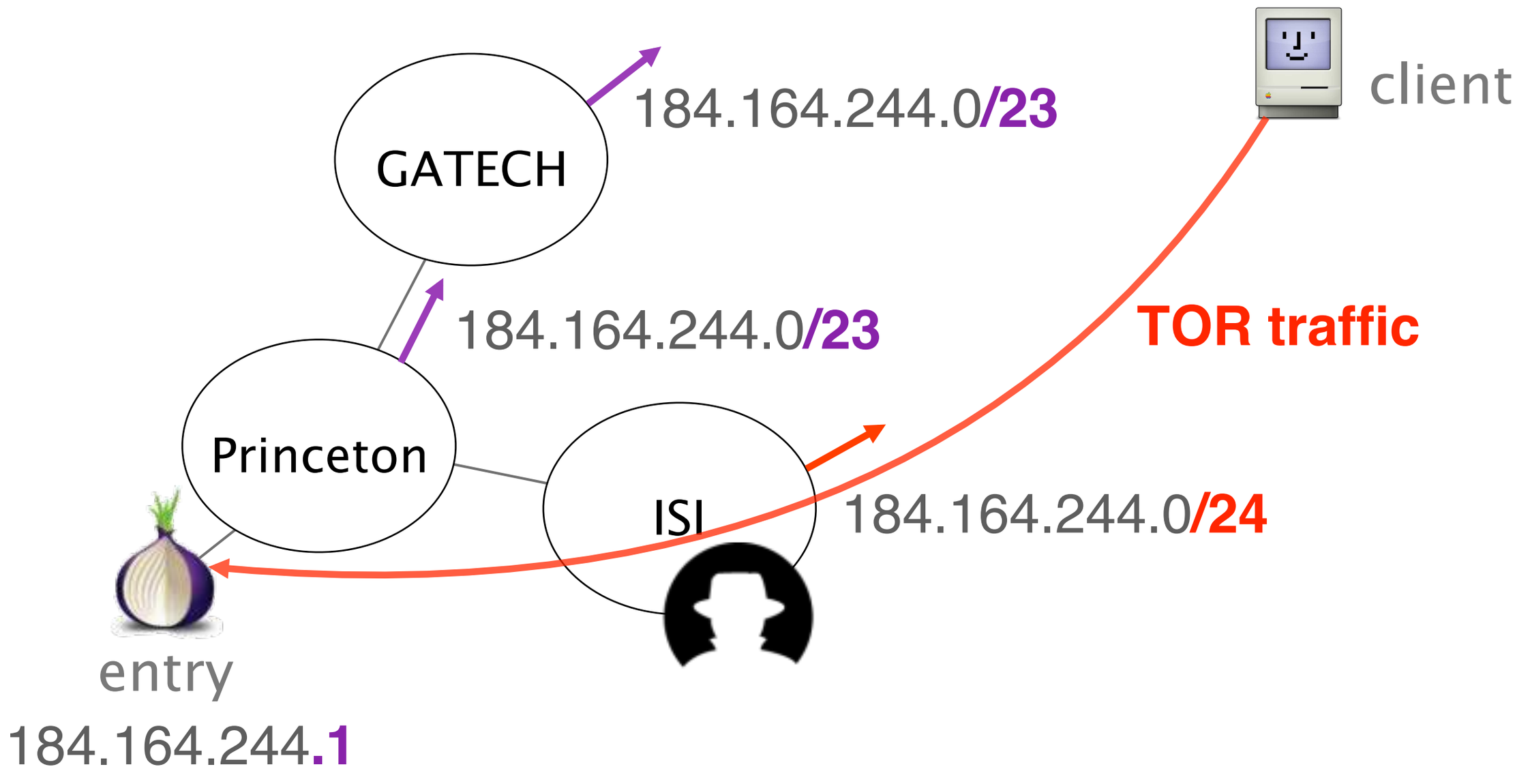
After 20 sec, we announced
a more-specific prefix via ISI



After 20 sec, we announced a more-specific prefix via ISI



As forwarding is based on the longest-match, all traffic soon started to enter via ISI



Traffic to
entry relay

Gatech
(legitimate)

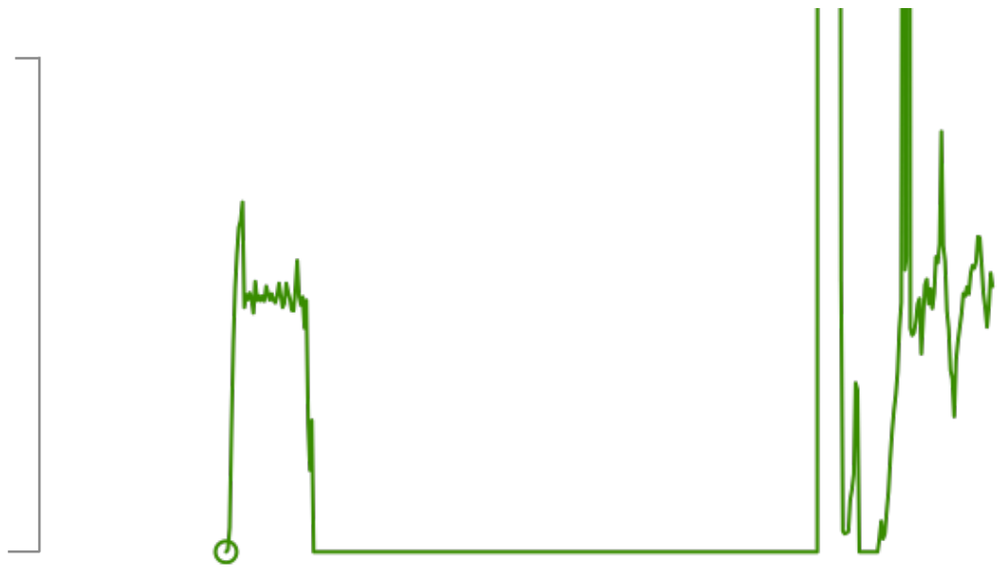
ISI
(attacker)

20

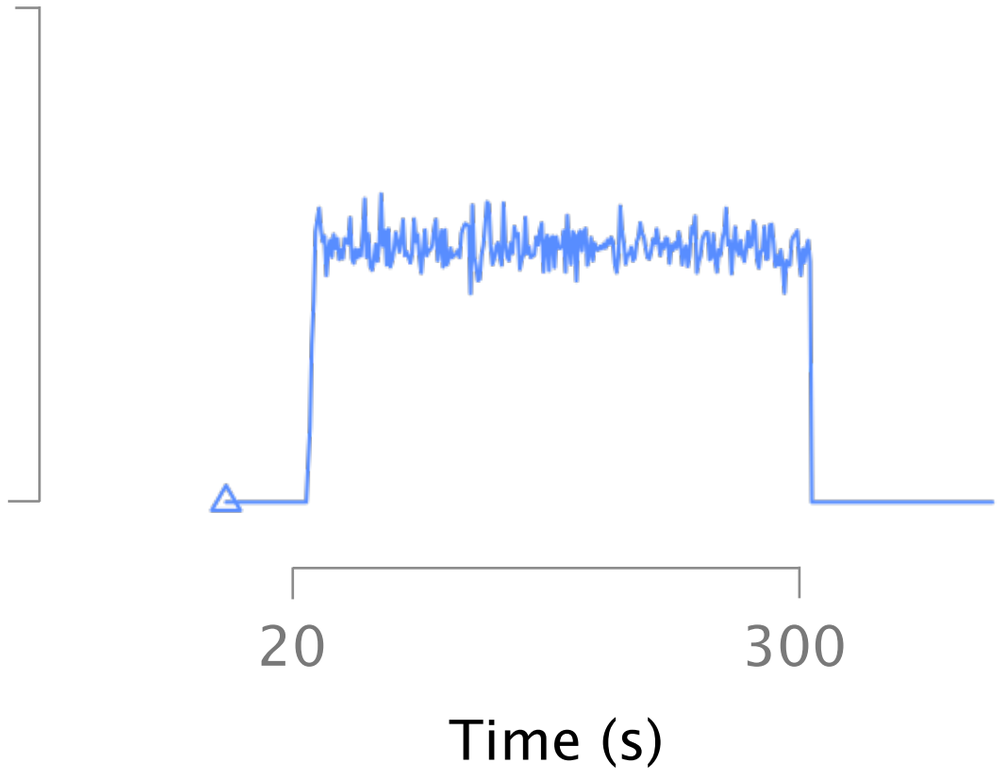
300

Time (s)

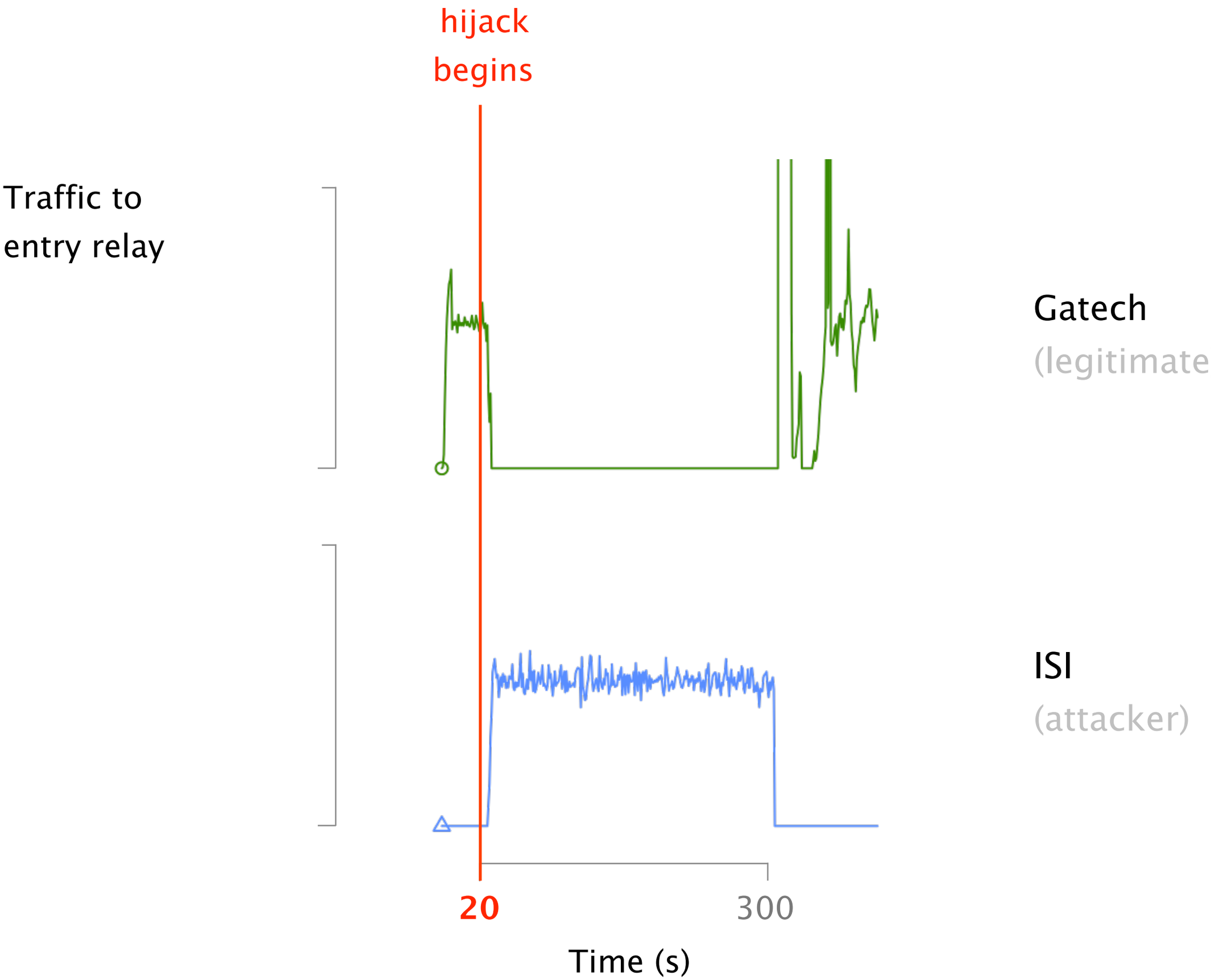
Traffic to
entry relay

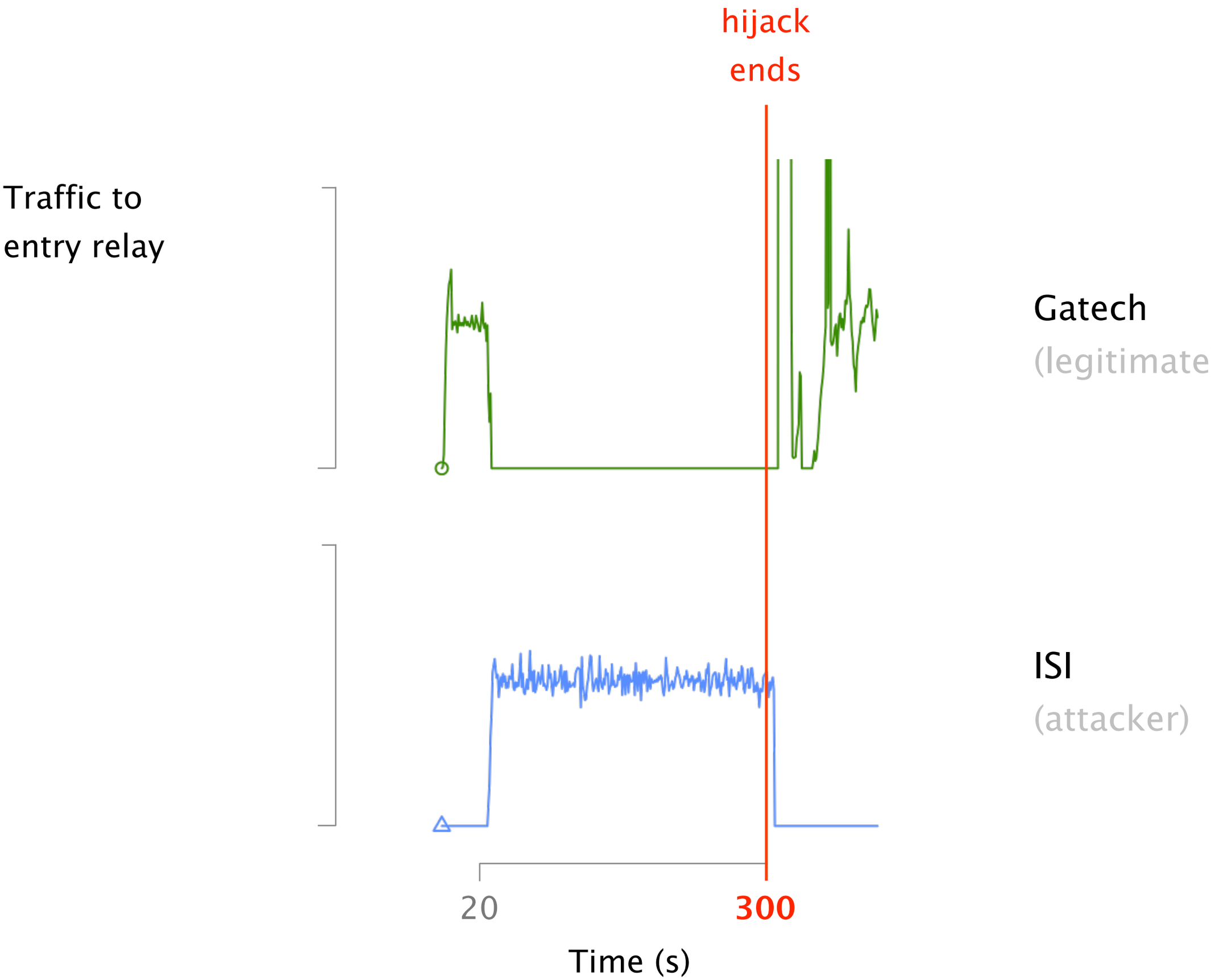


Gatech
(legitimate)

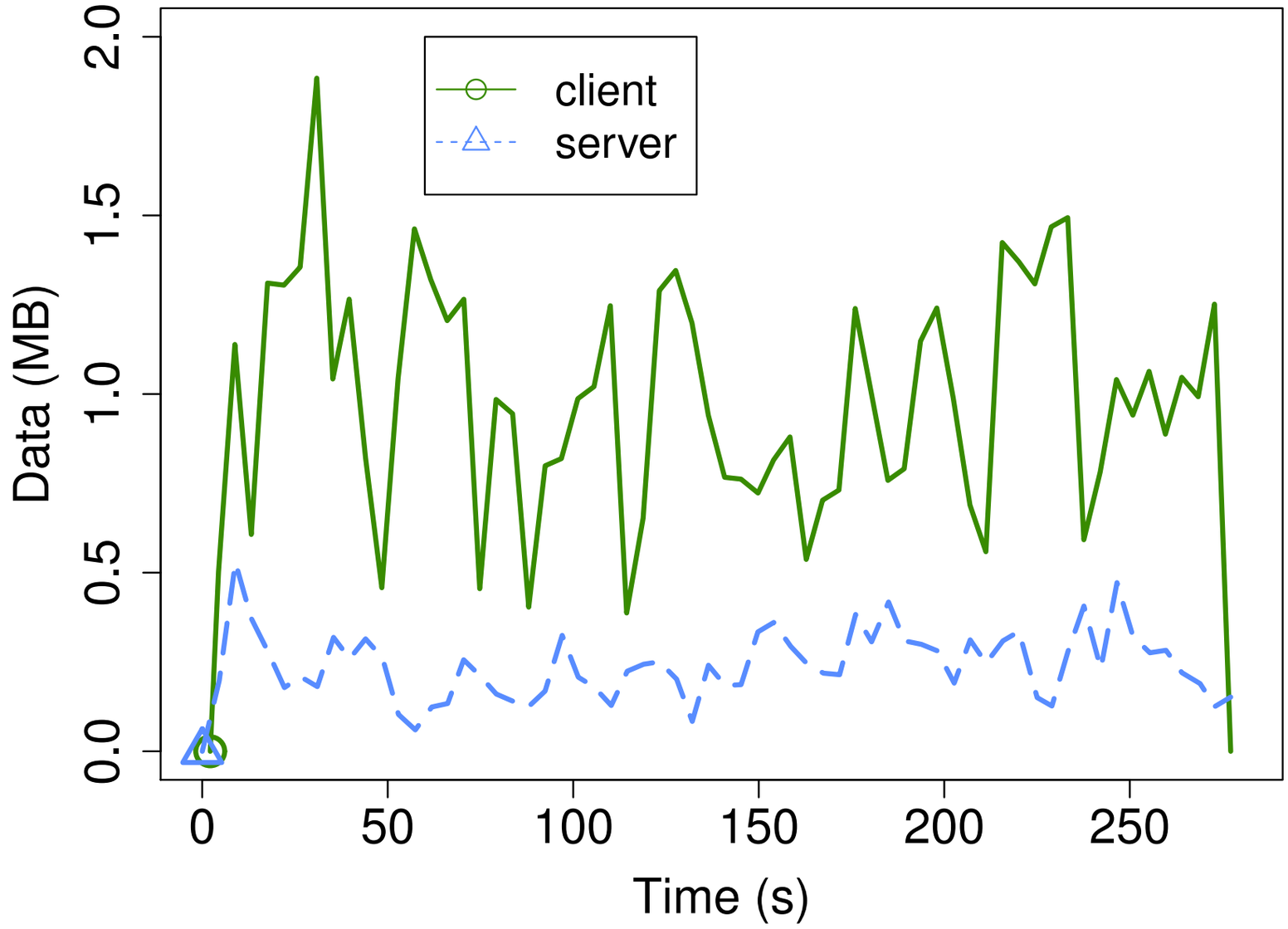


ISI
(attacker)

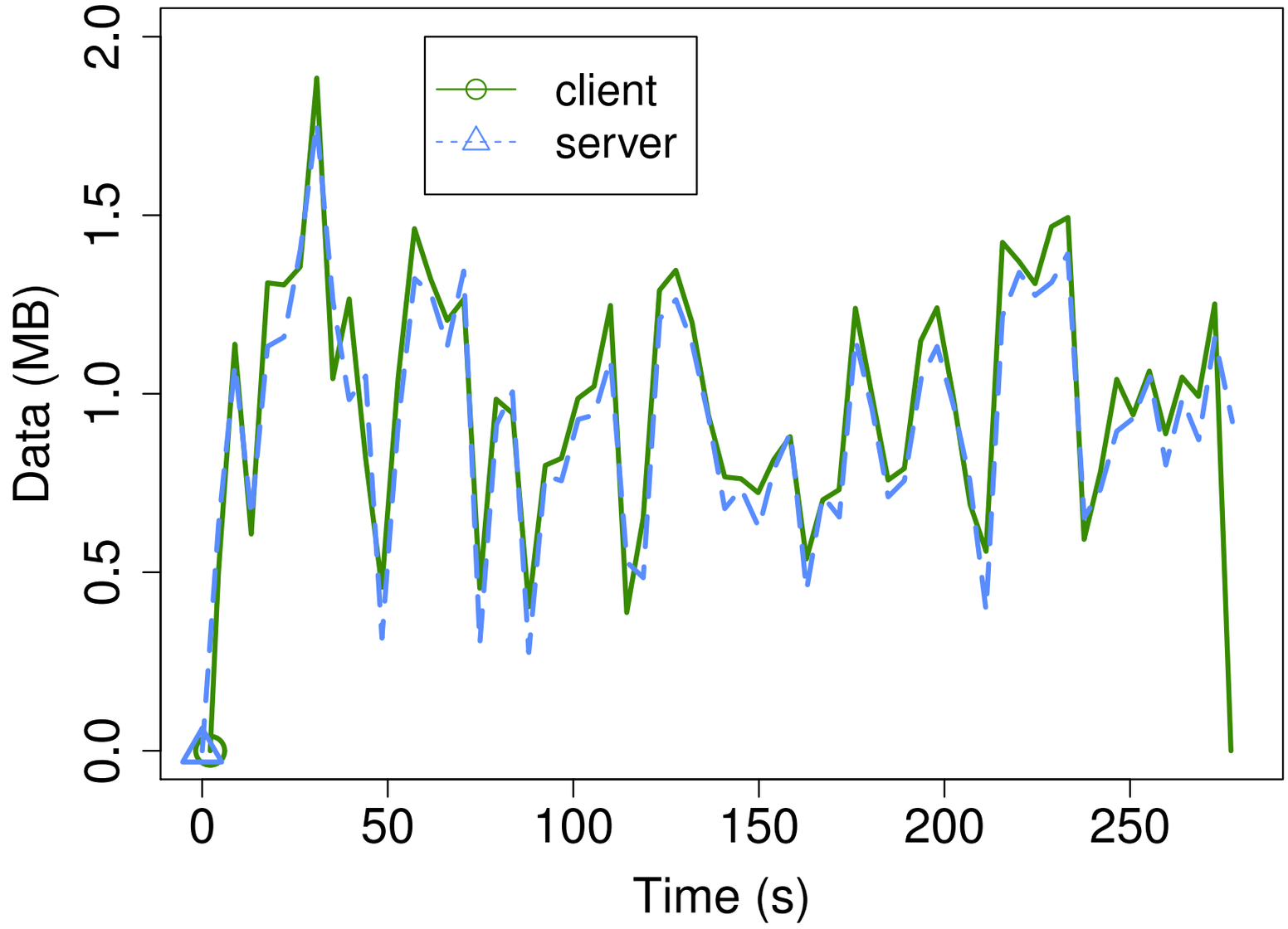

hijack
begins
Traffic to
entry relay
Gatech
(legitimate)
ISI
(attacker)
20
300
Time (s)


hijack
ends
Traffic to
entry relay
Gatech
(legitimate)
ISI
(attacker)
20
300
Time (s)

By correlating TCP ACK traffic collected at ISI with TCP ACK traffic collected at the HTTP servers, we were able to deanonymize 90% of the pairs



Client ACK v.s. Server ACK analysis: an uncorrelated pair



Client ACK v.s. Server ACK analysis: a correlated pair

BGP interception attacks are concerning

90% of the prefixes hosting relays are shorter than /24

making them vulnerable to more-specific attacks

Known attacks did *already* intercept Tor traffic

e.g., Indosat in 2011 (~5 relays) and 2014 (~44 relays)

70 prefixes host ~30% of all entries & exits

announced by only 6 ASes

RAPTOR:
Routing Attacks on Privacy in Tor



Attacks

All your traffic belongs to me

Results

Eyes wide open

3 Countermeasures

Close the curtains

To protect itself, Tor should become more aware of the network underlying it

Countermeasures

Tools

Natural dynamism

Route manipulation

Asymmetric analysis

	Countermeasures	Tools
Natural dynamism	prefer stable relays	BGP monitoring
Route manipulation		
Asymmetric analysis		

	Countermeasures	Tools
Natural dynamism		
Route manipulation	discard “suspicious” relays prefer close relays	BGP monitoring + BGPsec
Asymmetric analysis		

	Countermeasures	Tools
Natural dynamism		
Route manipulation		
Asymmetric analysis	encrypt transport header	IPsec

These countermeasures help, but come with tradeoffs

	Countermeasures
Natural dynamism	prefer stable relays
Route manipulation	discard “suspicious” relays prefer close relays
Asymmetric analysis	encrypt transport header

These countermeasures help, but come with tradeoffs

	Countermeasures	Tradeoffs
Natural dynamism	prefer stable relays	more power to fewer relays
Route manipulation	discard “suspicious” relays prefer close relays	
Asymmetric analysis	encrypt transport header	not widely used (easier to detect)

RAPTOR:

Routing Attacks on Privacy in Tor



Attacks

All your traffic belongs to me

Results

Eyes wide open

Countermeasures

Close the curtains

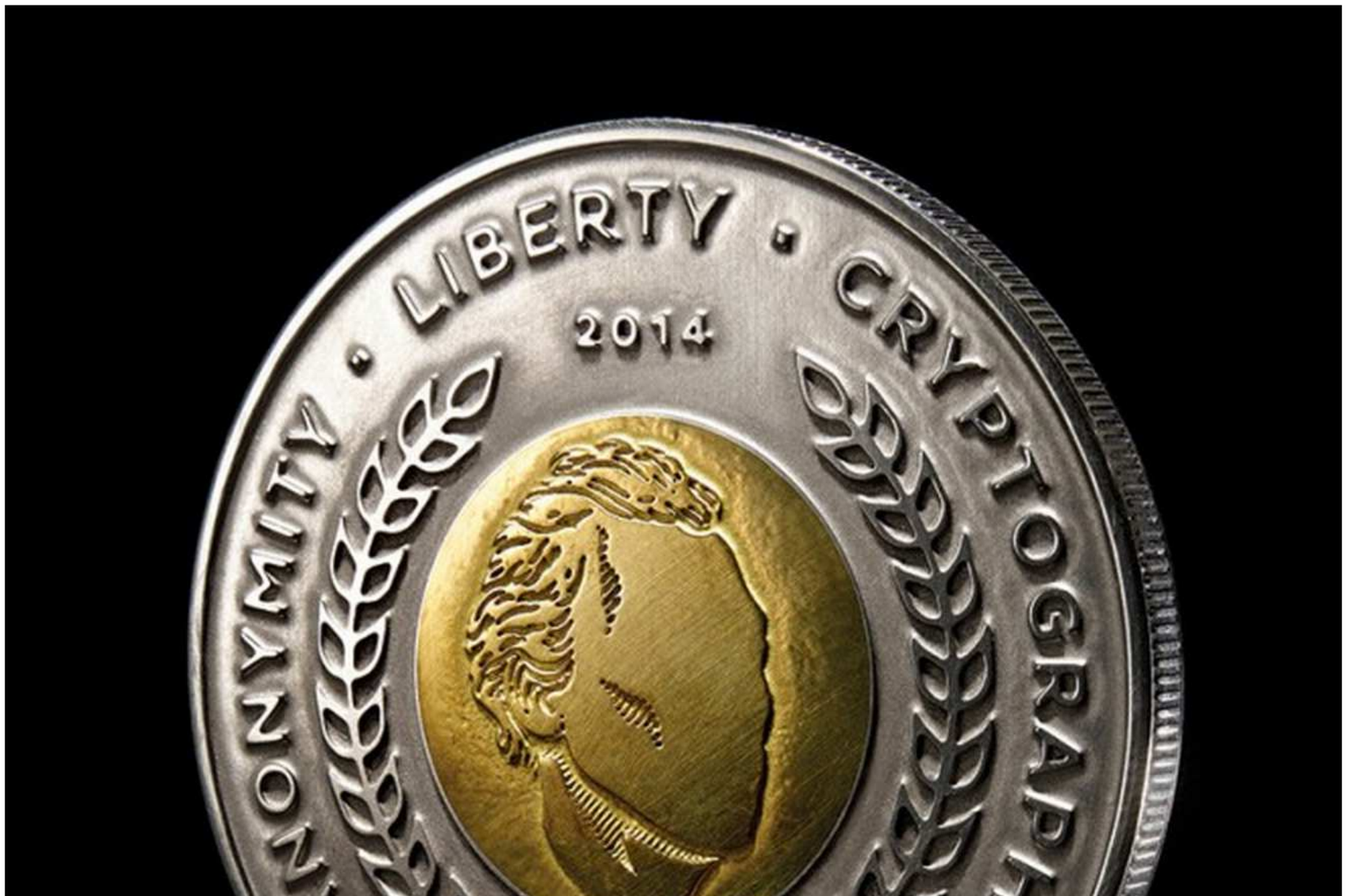
BGP is not only a problem for Tor…

THREAT LEVEL

Hacker Redirects Traffic From 19 Internet Providers to Steal Bitcoins

BY ANDY GREENBERG 08.07.14 | 1:00 PM | PERMALINK

Share 1.0k Tweet 1,464 +1 213 Share 512 Pin it



… A bitcoin thief redirected a portion of online traffic from no less than 19 Internet service providers, including data from the networks of Amazon and other hosting services like DigitalOcean and OVH, with the goal of stealing cryptocurrency from a group of bitcoin users…

… A bitcoin thief redirected a portion of online traffic from no less than 19 Internet service providers, including data from the networks of Amazon and other hosting services like DigitalOcean and OVH, with the goal of stealing cryptocurrency from a group of bitcoin users…

OVH is the top AS in terms of # Tor relays hosted

… A bitcoin thief redirected a portion of online traffic from no less than 19 Internet service providers, including data from the networks of Amazon and other hosting services like DigitalOcean and **OVH**, with the goal of stealing cryptocurrency from a group of bitcoin users…

Internet routing matters
when it comes to user anonymity

BGP dynamics decreases user anonymity over time

natural & induced, exacerbated by asymmetric routing

The threat is real. Attacks are efficient

validated in the field, on the live Tor network

Countermeasures help—to an extent

we need a better understanding of their impacts

RAPTOR:
Routing Attacks on Privacy in Tor



Yixin Sun

Princeton University

http://raptor.princeton.edu/

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Oscar Li, Jennifer Rexford,
Mung Chiang, Prateek Mittal

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