The BEAST Wins Again: Why TLS Keeps Failing to Protect HTTP

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Joint work with K. Bhargavan, C. Fournet, A. Pionti, P.-Y. Strub

INTRODUCTION

- **Introduction**
- Cookie Cutter
- Virtual Host Confusion
  - Crossing Origin Boundaries
  - Shared Reverse Proxies
  - Shared Session Cache
  - SPDY Connection Pooling
- Triple Handshake
- Conclusion

Why do we need TLS?

1. **Authentication**
   – Must be talking to the right guy
2. **Integrity**
   – Our messages cannot be tampered
3. **Confidentiality**
   – Messages are only legible to participants
4. Privacy?
   – Can’t tell who we are and what we talk about

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Active Attacks (MitM)

Passive Attacks (Wiretapping)

What websites expect of TLS

- **Web attacker**
  - Controls malicious websites
  - User visits honest and malicious sites in parallel
  - Web/MitB attacks: CSRF, XSS, Redirection…
- **Network attacker**
  - Captures (passive) and tampers (active) packets

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- **Network attacker** (Strictly stronger)
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What websites expect of TLS

If a website W served over HTTP is **secure against a Web attacker**, then serving W over HTTPS makes it **secure against a network attacker**.

What websites expect of TLS

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HTTPS weaknesses

- TLS optional by default in HTTP
- Cookies helplessly broken
- TLS adds own identity and session systems
  - May not agree with the HTTP ones
- HTTPS MITM is a beast
  - Arbitrary requests, run JS, side channels…

Not in this talk

- Heartbleed, GnuTLS SID corruption
  – No excuse for memory corruption bugs
- “Goto fail”, GnuTLS SA-2014-2, CCS bug
  – No excuse for bad implementation of protocol
- Broken PKI (ANSSI, Indian CCA)
  – Can’t be helped, but improving overall

In this talk

- **Active network attacks against HTTPS**
  - Public networks
  - DNS attacks
  - Corporate/ISP proxies
  - Governments
- **TLS exploits enabled by HTTP capabilities**

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Beastly Attacks

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In this talk

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  - Governments
- **TLS exploits enabled by HTTP capabilities**

Only useful against strongest websites
(Google, Facebook, Twitter, Amazon…)

Beastly Attacks

Beastly Attacks

- Renegotiation attack [Ray, Rex '09]
  - Protocol logic flaw; nice cookie exploit
- BEAST [Rizzo, Duong '11]
  - Adaptive chosen plaintext + block boundary
  - Exploits known IV vulnerability
  - Can recover encrypted data

Beastly Attacks

- CRIME/BREACH [Rizzo Duong ’12; Prado et al ‘13]
  - Adaptive chosen plaintext + Length side channel
  - Timing variant TIME [Be’ery, Shulman ‘13]
- Padding Oracle [Vaudenay ‘02]
  - Timing variant Lucky13 [Al Fardan, Paterson et al. ‘13]
- More timing attacks are likely

COOKIE CUTTER

CANCEL HSTS AND STEAL SECURE SESSION COOKIES

- ✓ *Introduction*
- ➢ Cookie Cutter
- ➢ Virtual Host Confusion
  - ➢ Crossing Origin Boundaries
  - ➢ Shared Reverse Proxies
  - ➢ Shared Session Cache
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Reminder: HTTPS is optional

- Attack: SSL stripping [Marlinspike, BH'09]
  - Attacker proxies HTTP requests to HTTPS server
- Defences:
  - Strict Transport Security (HSTS)
  - HTTPS Everywhere and similar extensions
  - User awareness

Reminder: HTTPS and cookies

- Shared HTTP/HTTPS cookie store
- Cookies don't follow SOP
  - No port; non-public DNS suffix of domain
- **'secure'** flag: don't send over HTTP
- Server can't tell if set over HTTP or HTTPS

Reminder: HTTPS and cookies

"HTTPS is **insufficient to prevent a network attacker from obtaining or altering a victim's cookies** [...]; by default, **cookies do not provide confidentiality or integrity from network attackers**, even when used in conjunction with HTTPS."

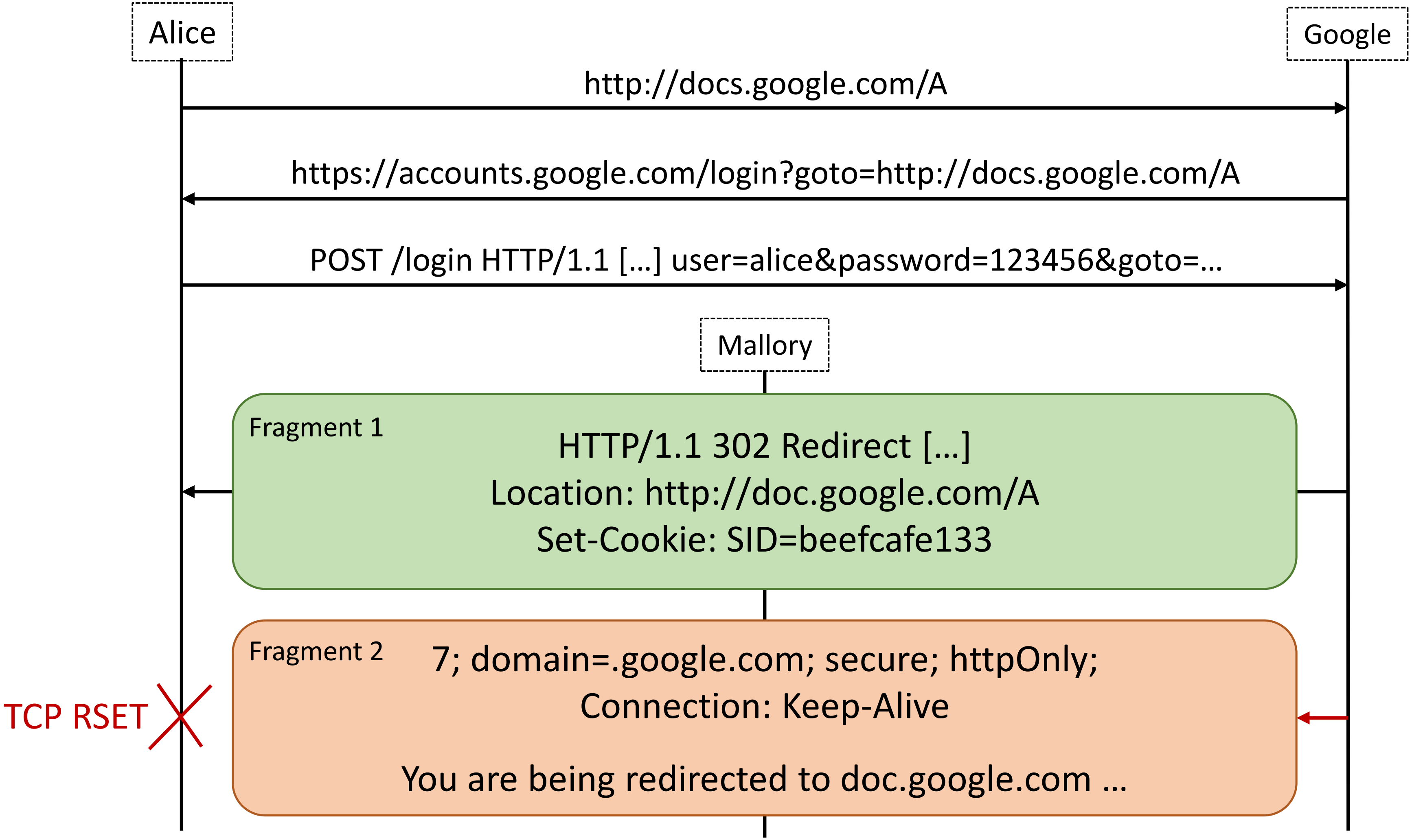
Adam Barth, RFC 6265

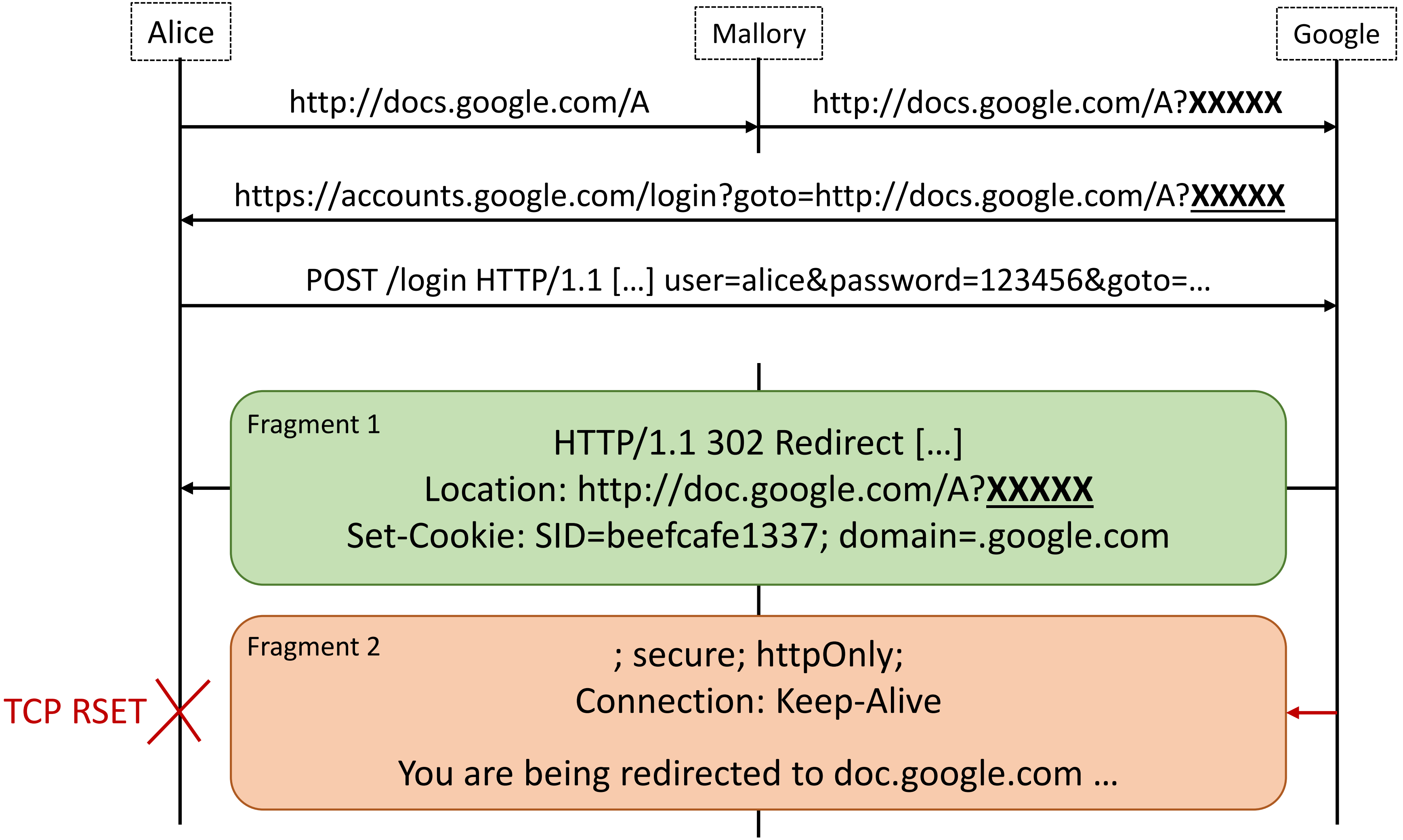
Reminder: cookie forcing

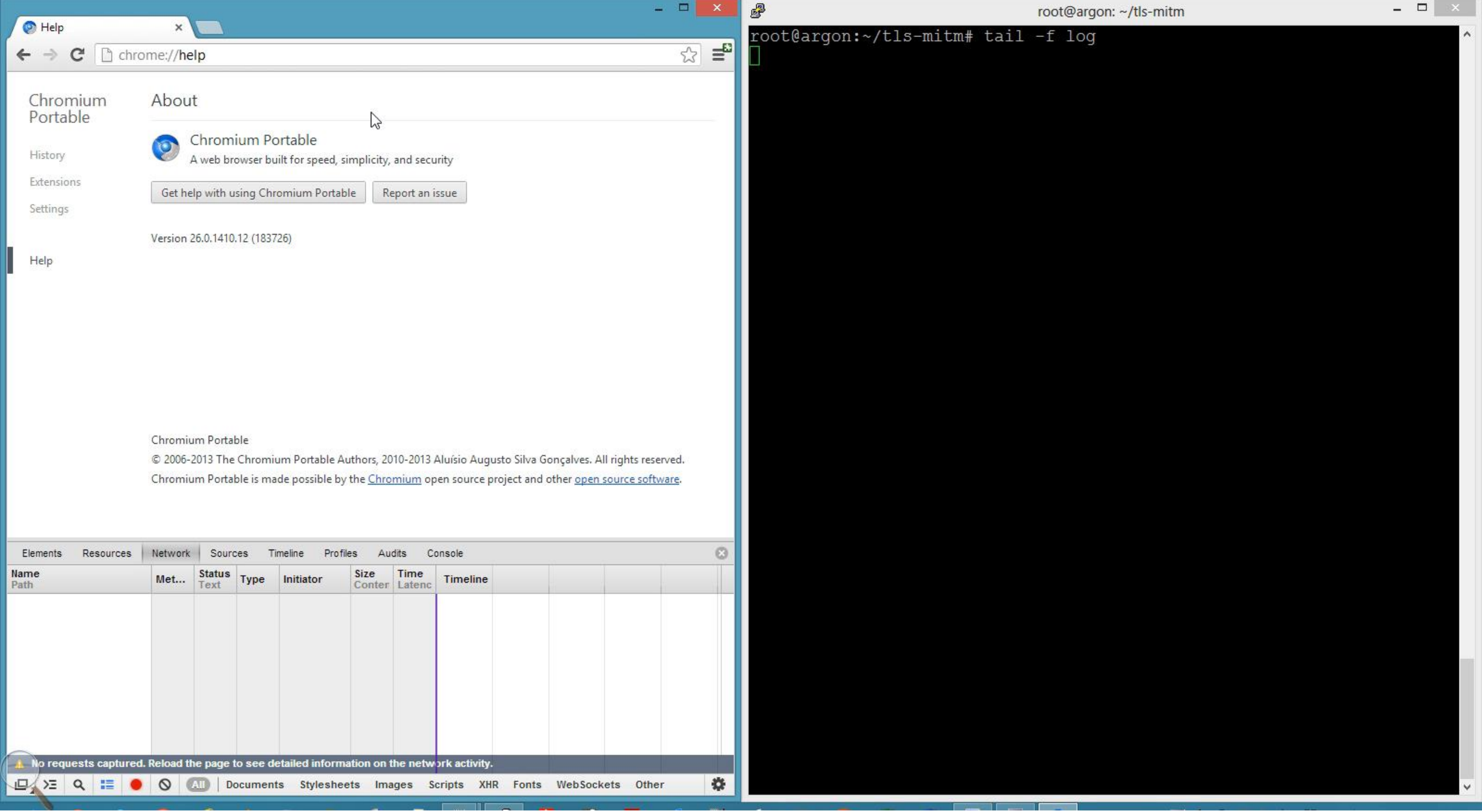
- Impact has increased in modern applications
  - Asynchronous actions (AJAX)
  - No user feedback to session replacement
  - User data sent to attacker account
- Defeats many CSRF protections too
  - The deputies are still confused, Lundeen, BHEU’13

Defending against cookie forcing

- Do not use cookies
- Use HSTS (not HTTPS Everywhere)
  - **With includeSubDomains option**
  - **On top-level domain of website**
  - **Do not use any subdomain** (unless sent to top once)
- Bind cookie to TLS channel (Chrome: Channel ID)


Alice
Google
http://docs.google.com/A
https://accounts.google.com/login?goto=http://docs.google.com/A
POST /login HTTP/1.1 […] user=alice&password=123456&goto=…
Mallory
Fragment 1
HTTP/1.1 302 Redirect […]
Location: http://doc.google.com/A
Set-Cookie: SID=beefcafe133
Fragment 2
7; domain=.google.com; secure; httpOnly;
Connection: Keep-Alive
You are being redirected to doc.google.com …
TCP RSET


Alice
Mallory
Google
http://docs.google.com/A
http://docs.google.com/A?XXXXX
https://accounts.google.com/login?goto=http://docs.google.com/A?XXXXX
POST /login HTTP/1.1 […] user=alice&password=123456&goto=…
Fragment 1
HTTP/1.1 302 Redirect […]
Location: http://doc.google.com/A?XXXXX
Set-Cookie: SID=beefcafe1337; domain=.google.com
Fragment 2
; secure; httpOnly;
Connection: Keep-Alive
You are being redirected to doc.google.com …
TCP RSET


Help
chrome://help
Chromium Portable
History
Extensions
Settings
Help
About
Chromium Portable
A web browser built for speed, simplicity, and security
Get help with using Chromium Portable
Report an issue
Version 26.0.1410.12 (183726)
Chromium Portable
© 2006-2013 The Chromium Portable Authors, 2010-2013 Aluísio Augusto Silva Gonçalves. All rights reserved.
Chromium Portable is made possible by the Chromium open source project and other open source software.
Elements Resources Network Sources Timeline Profiles Audits Console
Name Path
Met...
Status Text
Type
Initiator
Size Conter
Time Latenc
Timeline
No requests captured. Reload the page to see detailed information on the network activity.
All Documents Stylesheets Images Scripts XHR Fonts WebSockets Other
root@argon: ~/tls-mitm
root@argon:~/tls-mitm# tail -f log

Cookie cutter: ingredients

- TLS weakness: **truncation** [Wagner, WEC'96]
  - TLS (close_notify alert) vs TCP (RSET) termination
  - Well known (Pironti, BH'13)
- HTTP weaknesses
  - Plaintext injection (e.g. semi-open redirector)
  - Security depending on **presence** of header/flag
  - Liberal parsing of malformed HTTP messages

Cookie cutter: impact

- If browser accepts the truncated cookie, it is stored **without the secure flag**
- *Need an HTTP request to sniff cookie*
- What about HSTS?
  - Strict-Transport-Security: max-age=1**0000; incl…**
  - **Truncate max-age to get rid of HSTS** in <10s

Cookie cutter: mitigation

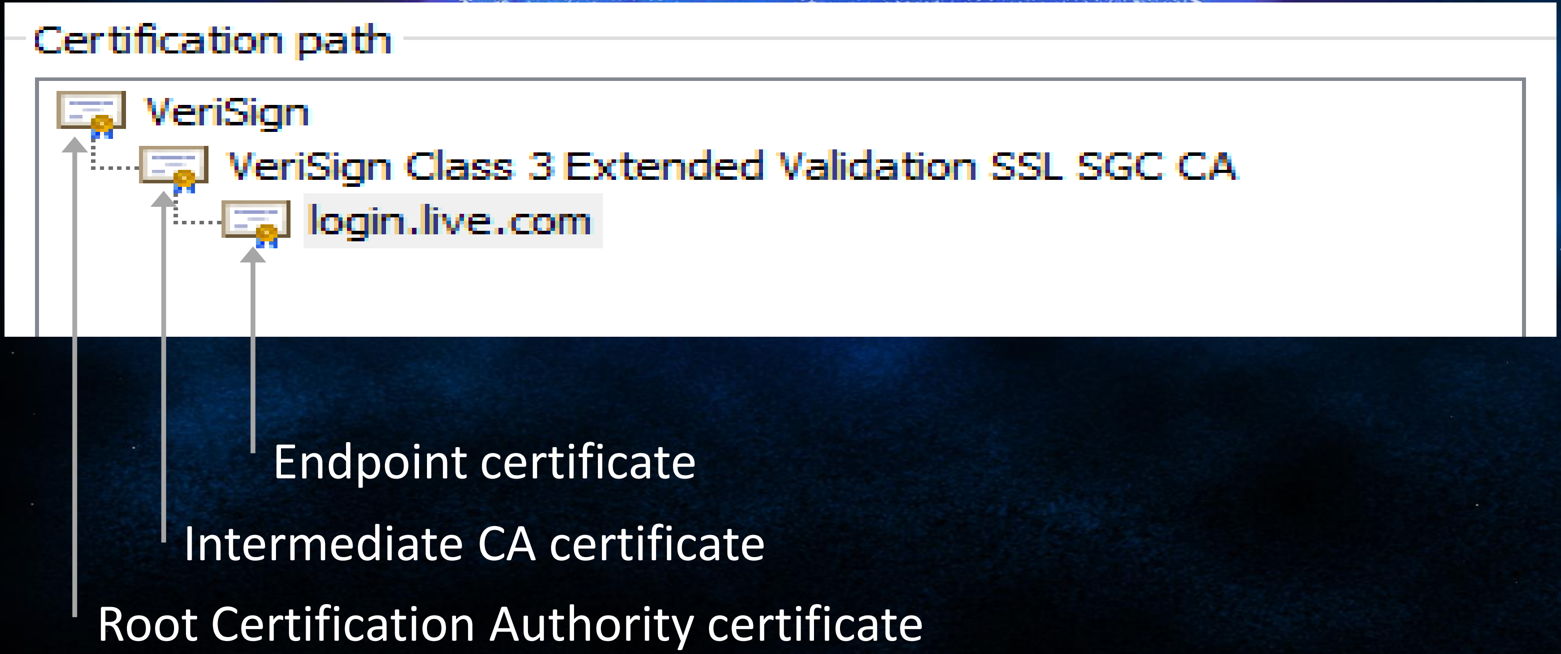
- Reject malformed HTTP messages / headers
- Enforce close_notify (chunked encoding?)
- Chromium: CVE-2013-2853
- Safari: APPLE-SA-2014-04-22-1
- IE and FF correctly reject truncated headers

VIRTUAL HOST CONFUSION

BREAK SAME ORIGIN POLICY AND CERTIFICATE VALIDATION

- ✓ *Introduction*
- ✓ *Cookie Cutter*
- ➢ **Virtual Host Confusion**
  - ➢ Crossing Origin Boundaries
  - ➢ Shared Reverse Proxies
  - ➢ Shared Session Cache
  - ➢ SPDY Connection Pooling
- ➢ Triple Handshake
- ➢ Conclusion

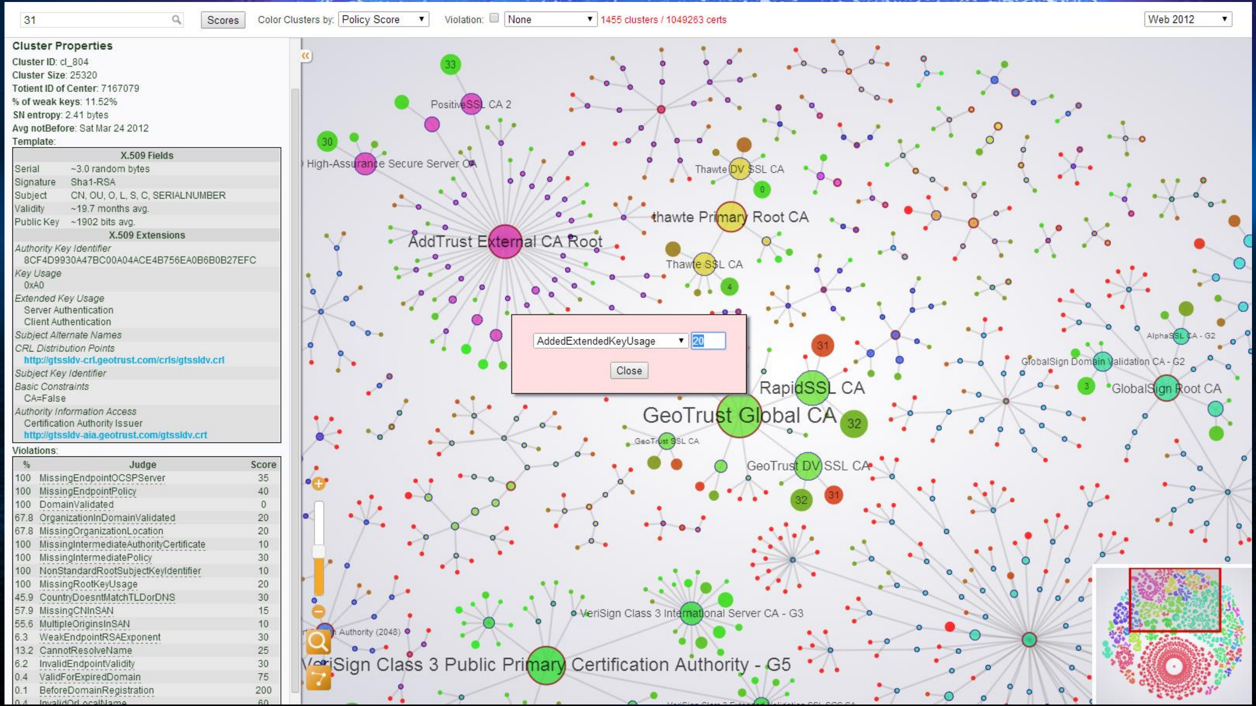
Public Key Infrastructure (PKI)



Are certificates checked properly?

- Apple Secure Transport: “goto fail” (2014)
- GnuTLS: check_if_ca (2014)
- NSS (and others): null byte in CN (BH 2009)
- …
- IE: CA constraint ignored (2002)
- Path length, key usage, signature, revocation…

Can CAs be trusted?

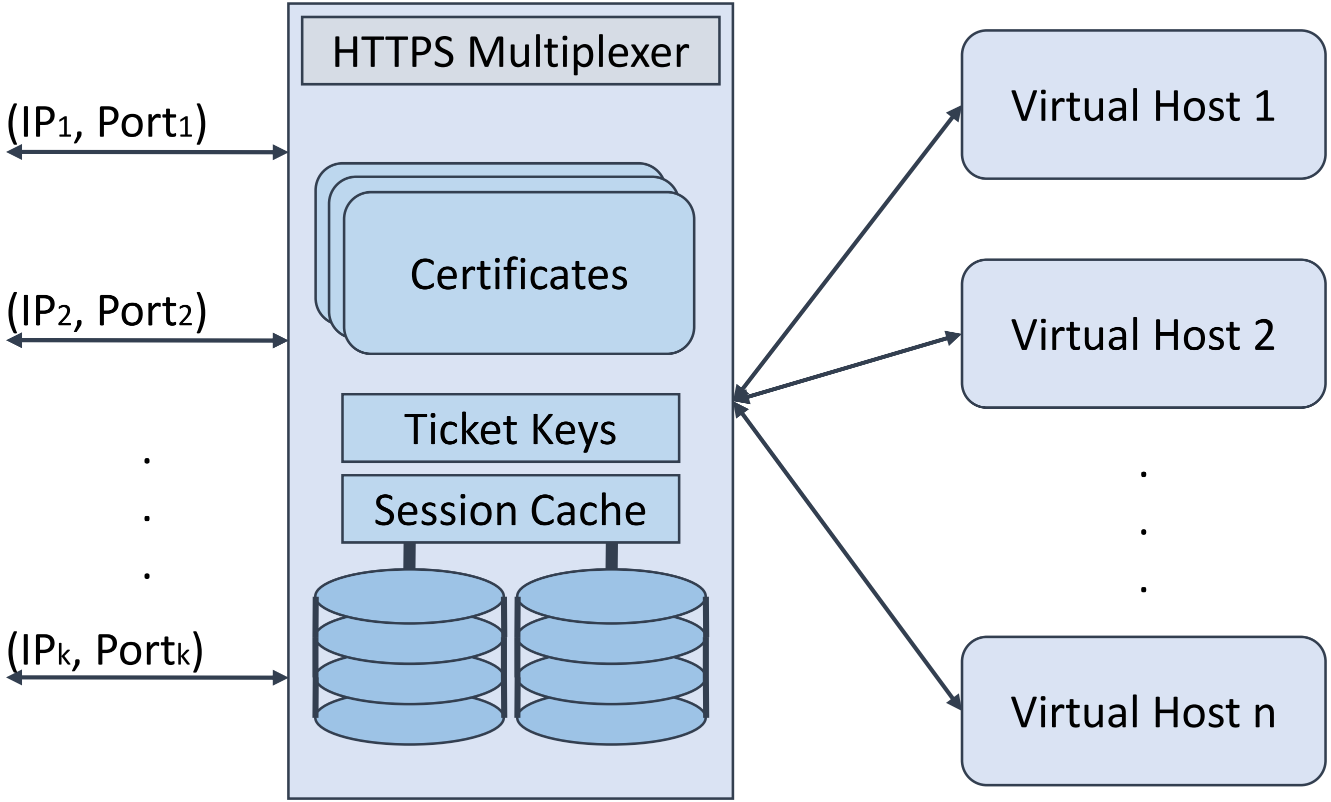


With M. Abadi, A. Birrell, I. Mironov, T. Wobber and Y. Xie (NDSS'14)

PKI madness

- BlackHat: 2009, 2010, 2011, 2012
  - Marlinspike, Sotirov, Jarmoc, Hansen…
- Academic papers (see e.g. Clark et al. survey)
- Certificate Transparency, DANE, TACK, Perspectives, Convergence, …

Background: HTTPS multiplexing



Background: HTTPS multiplexing

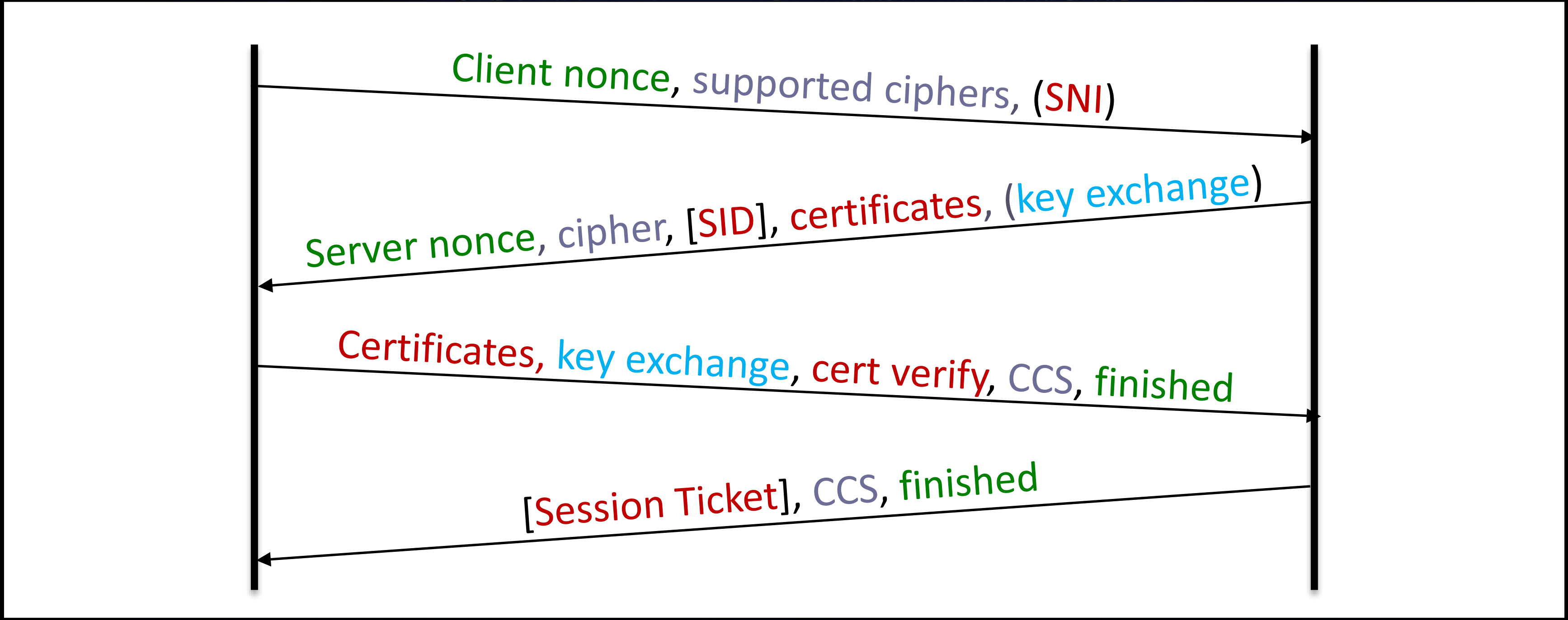
Request processing
Produce response

https://x.y.com:4443/u/v?a=K&b=L#hash

Routing
Select virtual host

Kept by
Browser

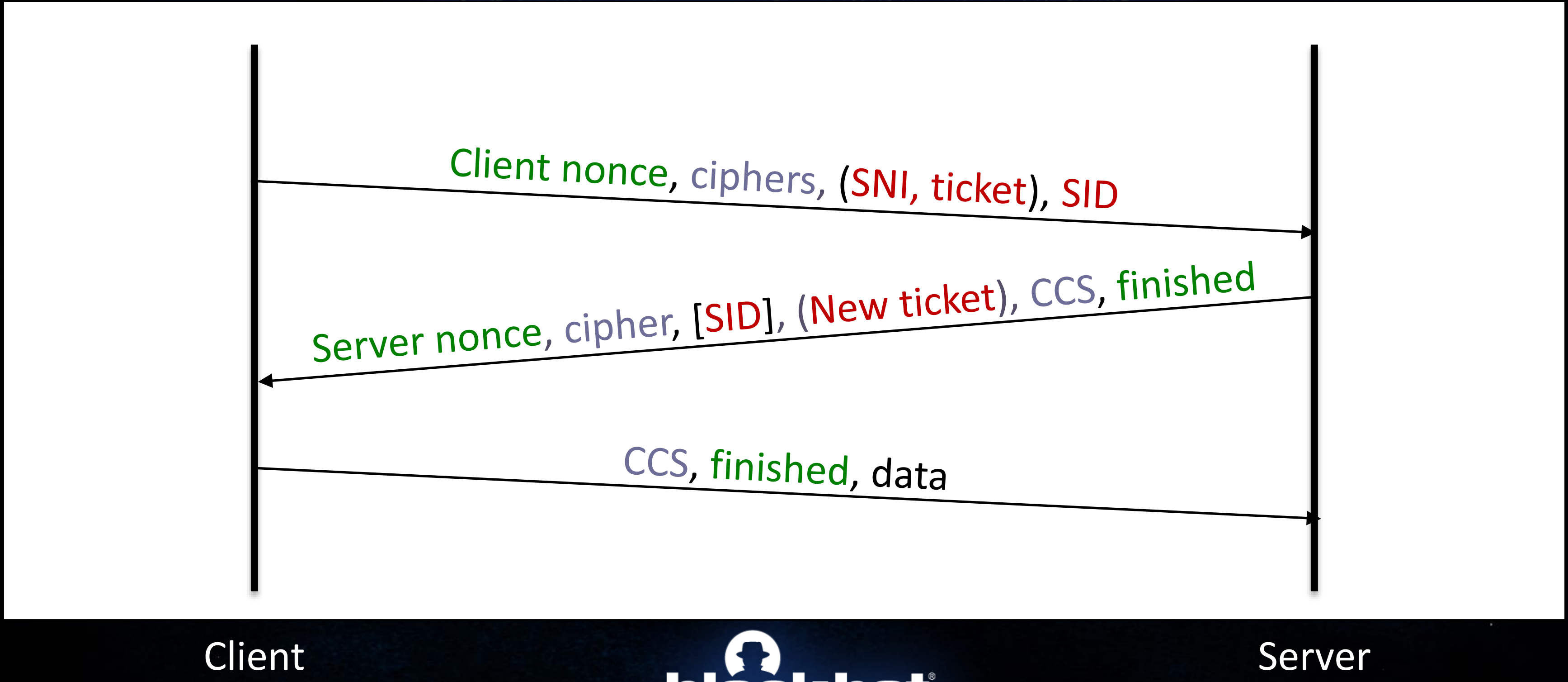
Background: TLS handshake



Client

Server

Background: TLS resumption



TLS vs HTTP identity

- **Transport layer**
  - Server Name Indication (SNI)
  - Certificate (union of CN and SAN)
  - Session identifier
  - Session Ticket
- **Application layer**
  - Host header

Virtual host configuration

- IP address and port
- Name (for SNI and Host header)
- Certificate
- Session cache, session ticket key
- Ciphers, client authentication, OCSP staple …

Request routing

- (IP, port) of request = (IP, port) of chosen host
- TLS settings picked from host whose name matches SNI, **or default (fallback)**
- Request is routed to host whose name matches Host header, **or default** (**fallback**)

Virtual host confusion

- Fallback: no guarantee selected host was **intended** to handle the request:
  - Could be meant for **different port**
  - Could be meant for **different IP address** that shares the **same certificate** (or overlapping one), **session database** or **ticket encryption key**
- Known vector [Jackson, CCS'07]

Simple Examples

- Two TLS servers on the same domain but on different ports
  - Port always ignored in Host header.
  - Attacker can redirect freely between ports
  - **Port is essentially useless for same-origin policy**

Simple Examples

- One certificate {x.a.com, y.a.com} (or *.a.com)
- Server at IP X only handles x.a.com
- Server at IP Y only handles y.a.com
  - Attacker can redirect packets from X to Y
  - Server at Y returns a page from y in x.a.com origin

Host confusion ingredients

- TLS weaknesses
  - Resumption authenticates nothing (not even SNI)
  - Downgrade to SSL3 to get rid of SNI and ticket
  - Multi-domain and wildcard certificates
- HTTP weakness
  - Virtual host fallback: a request for x.com should not return a page meant to be served on y.com

How to exploit

Virtual host confusion can **transfer weaknesses and vulnerabilities** (e.g. XSS, user contents, open redirectors, cross-protocol redirections, X-Frame-Options, CORS, …) across **origins**

- Transfer XSS in mxr.nozilla.org to addons (Hansen & Sokol, HTTPS Can Byte Me, BH'10)

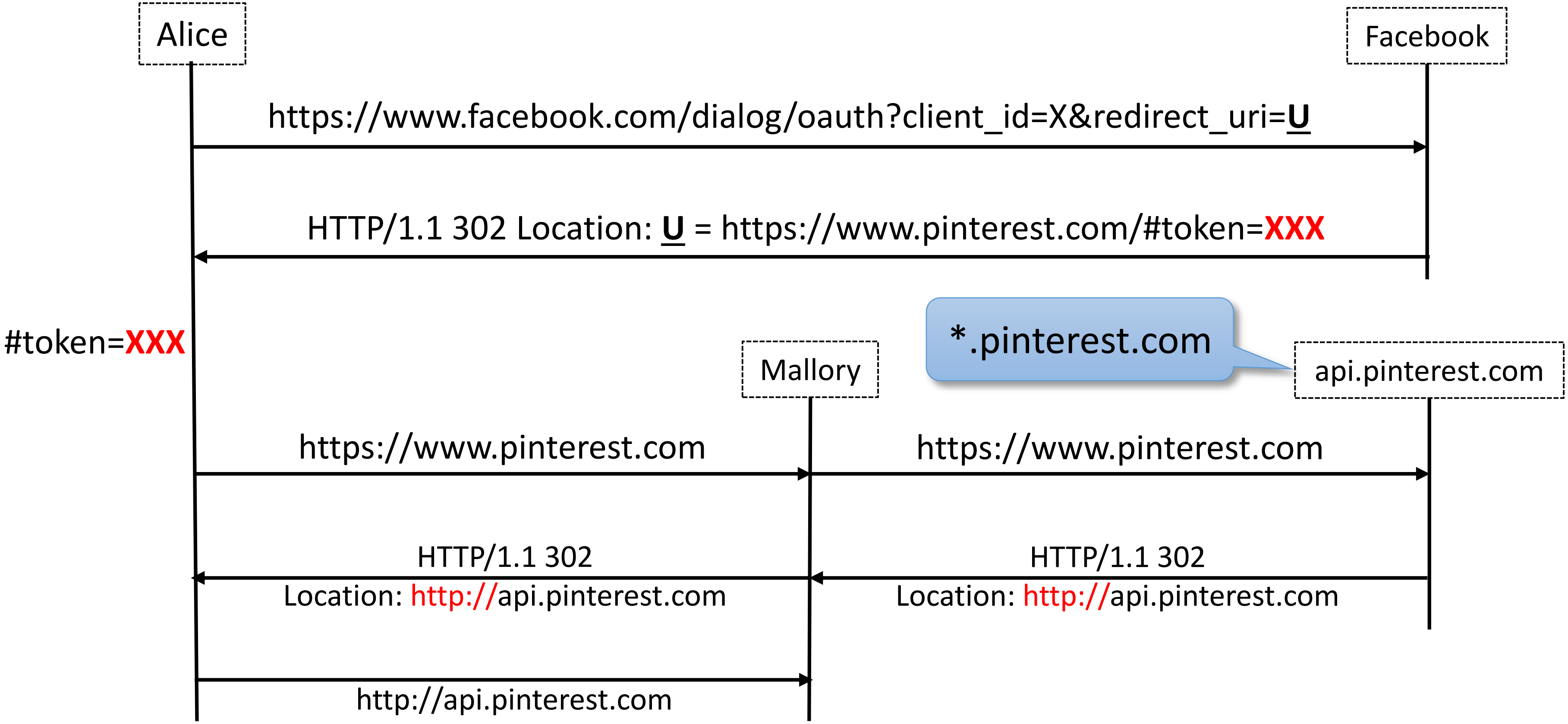
CROSSING ORIGIN BOUNDARIES

STEAL OAUTH/OPENID TOKENS, SECRET URL FRAGMENTS…

- ✓ *Introduction*
- ✓ *Cookie Cutter*
- ➢ Virtual Host Confusion
  - ➢ **Crossing Origin Boundaries**
  - ➢ Shared Reverse Proxies
  - ➢ Shared Session Cache
  - ➢ SPDY Connection Pooling
- ➢ Triple Handshake
- ➢ Conclusion

Cross-protocol redirection is harmful

- OAuth redirect_uri access control is origin based
- If the token origin can be confused with **any origin with a redirect-to-HTTP**, attacker wins
  - Token is in *URL fragment* (preserved by redirection): attacker can inject script in HTTP response to steal it
- Cross-protocol redirection **should be avoided**
  - **Attack built into Google**: nosslsearch.google.com


Alice
Facebook
https://www.facebook.com/dialog/oauth?client_id=X&redirect_uri=U
HTTP/1.1 302 Location: U = https://www.pinterest.com/#token=XXX
#token=XXX
Mallory
*.pinterest.com
api.pinterest.com
https://www.pinterest.com
https://www.pinterest.com
HTTP/1.1 302
Location: http://api.pinterest.com
HTTP/1.1 302
Location: http://api.pinterest.com
http://api.pinterest.com

root@argon: ~

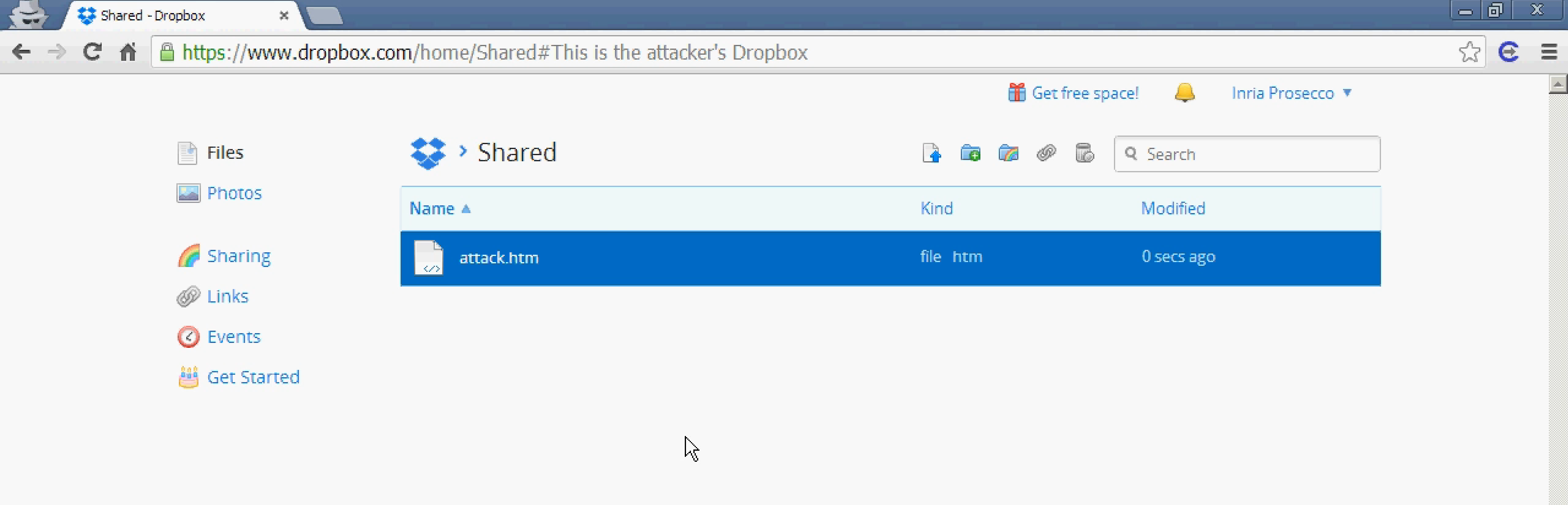
```
root@argon:~# ping www.pinterest.com
PING pinterest.com (174.129.239.78) 56(84) bytes of data.
^C
--- pinterest.com ping statistics ---
1 packets transmitted, 0 received, 100% packet loss, time 0ms

root@argon:~# ping api.pinterest.com
PING api-origin.pinterest.com (54.225.157.104) 56(84) bytes of data.
^C
--- api-origin.pinterest.com ping statistics ---
2 packets transmitted, 0 received, 100% packet loss, time 1006ms

root@argon:~#
```

Exploit: user contents

- Host confusion with user content origin
- Common to use different top-level domain to avoid related-domain cookie attacks
  - dropboxusercontent.com, googleusercontent.com
- **User content origins should use separate certificates**

Exploit: user contents

- Data **on the user's own account** is often on a higher trust domain to access session cookie
  - Dropbox: own files on dl-web.dropbox.com
- **Short lived cookie forcing** allows temporary forcing of attacker session
  - Break into high trust origin, recover victim session



1. Attacker stores malicious file on his account
2. Temporary forcing of attacker session on victim
3. Rebind www.dropbox.com to dl-web.dropbox.com
4. Compromise victim’s session

Help Privacy More

EXPLOIT: SHARED SESSION CACHE

CONFUSE ORIGINS ACROSS CERTIFICATES

- ✓ *Introduction*
- ✓ *Cookie Cutter*
- ➢ Virtual Host Confusion
  - ✓ *Crossing Origin Boundaries*
  - ➢ Shared Reverse Proxies
  - ➢ **Shared Session Cache**
  - ➢ SPDY Connection Pooling
- ➢ Triple Handshake
- ➢ Conclusion

Beware of TLS session cache

- 3 kinds of TLS authentication:
  - Certificate
  - Valid session identifier in server cache
  - Valid session ticket encrypted by server key
- If a session cache or ticket key is shared across servers with different hosts, **certificate check can be completely bypassed**

Beware of TLS session cache

- Session cache sharing more common than ticket key sharing across servers
  - Seen on Amazon, Mozilla and Yahoo servers
- To exploit, **downgrade connection to SSL3**
  - Tickets have precedence over session identifier

root@argon: ~

root@argon:~#

1. Create SSL3 session on bugzilla.mozilla.org
2. Point bugzilla.mozilla.org to git.mozilla.org
3. Resume session and request malicious file
4. Virtual host fallback

EXPLOIT: SHARED REVERSE PROXY

IMPERSONATE THOUSANDS OF TOP RANKED WEBSITES

- ✓ *Introduction*
- ✓ *Cookie Cutter*
- ➢ Virtual Host Confusion
  - ✓ *Crossing Origin Boundaries*
  - ➢ **Shared Reverse Proxies**
  - ✓ *Shared Session Cache*
  - ➢ SPDY Connection Pooling
- ➢ Triple Handshake
- ➢ Conclusion

Beware of shared reverse proxies

- Shared reverse proxies are common (e.g. CDN)
- Handling of TLS is always awkward
  – CloudFlare: domain packing in one certificate
  – Akamai: dedicated IP for customer certificate
  – Google Apps: SNI (or dedicated IP)
- What is the fallback virtual host?
  – Akamai: default host is an open proxy (!)

Demo: Akamai

Preventing host confusion

- **Do not mix low-trust and high-trust (sub)domains in certificates**
- **Configure a fallback host on every IP, that returns an error code** (not a redirection)
  - Nginx: default_server option of listen directive
  - Apache: first VirtualHost that matches IP/port

TLS session configuration

- **Server-side cache only required for SSL3 and can often be disabled**
  – If required, server should have proper cache partition or let admin configure explicit shards (shared:XYZ:1m)
- **With a server-wide ticket key, make sure all servers have the same configured hosts**
  – Isolation of name-based hosts is weak in TLS

SPDY CONNECTION POOLING

WHO'S CONFUSING WHAT NOW?

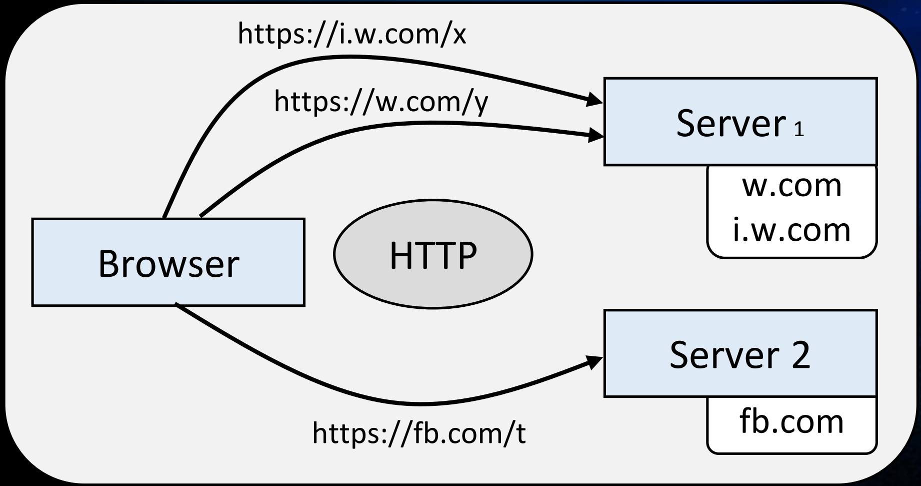
- ✓ *Introduction*
- ✓ *Cookie Cutter*
- ➢ Virtual Host Confusion
  - ✓ *Crossing Origin Boundaries*
  - ✓ *Shared Reverse Proxies*
  - ✓ *Shared Session Cache*
  - ➢ **SPDY Connection Pooling**
- ➢ Triple Handshake
- ➢ Conclusion

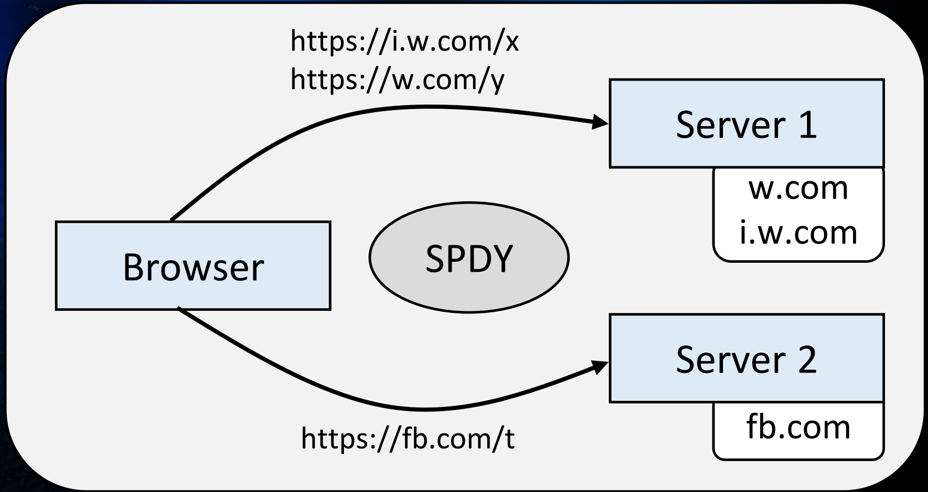
SPDY connection pooling

- Problem: websites use subdomains for origin isolation; requires a handshake for each
- Idea: let's reuse sessions even for requests to a different domain if:

  1. **New domain covered by initial certificate**
  2. **DNS points to same server**

SPDY connection pooling





SPDY connection pooling

- None of the security theorems proved on TLS apply to browsers that reuse connections
- Every session-specific guarantees extends to all domains in the session's certificate
- Standard in current HTTP2 IETF drafts

Exploits

Sorry, not patched yet

USA 2014

TRIPLE HANDSHAKE

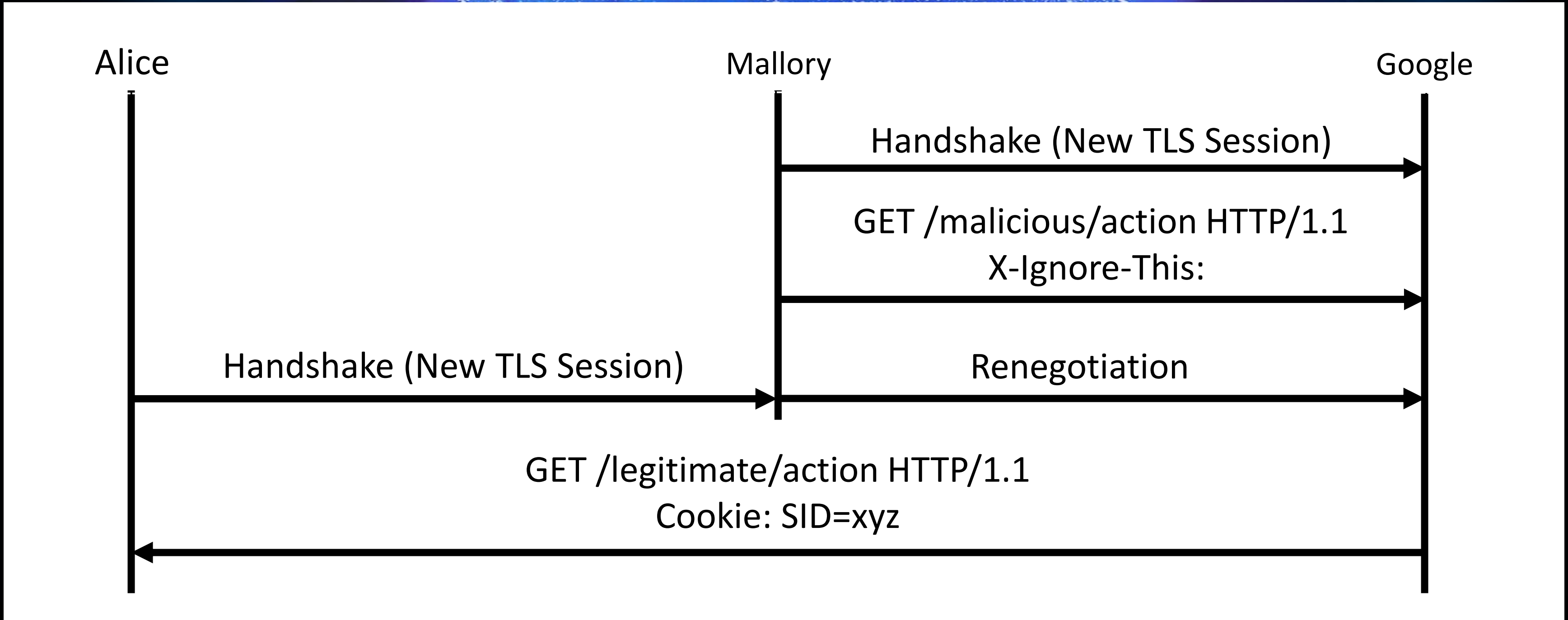
BREAKING CLIENT CERTIFICATE AUTHENTICATION

- ✓ *Introduction*
- ✓ *Cookie Cutter*
- ✓ *Virtual Host Confusion*
  - ✓ *Crossing Origin Boundaries*
  - ✓ *Shared Reverse Proxies*
  - ✓ *Shared Session Cache*
  - ✓ *SPDY Connection Pooling*
- ➢ **Triple Handshake**
- ➢ Conclusion

Reminder: TLS Handshake

- Handshake creates **new TLS session**
- Key exchange yields pre-master secret (PMS)
- Master secret: hash of PMS and nonces
- **Session parameters**: PMS, client & server certificates, cipher, session identifier

Background: Ray & Rex 2009 Attack



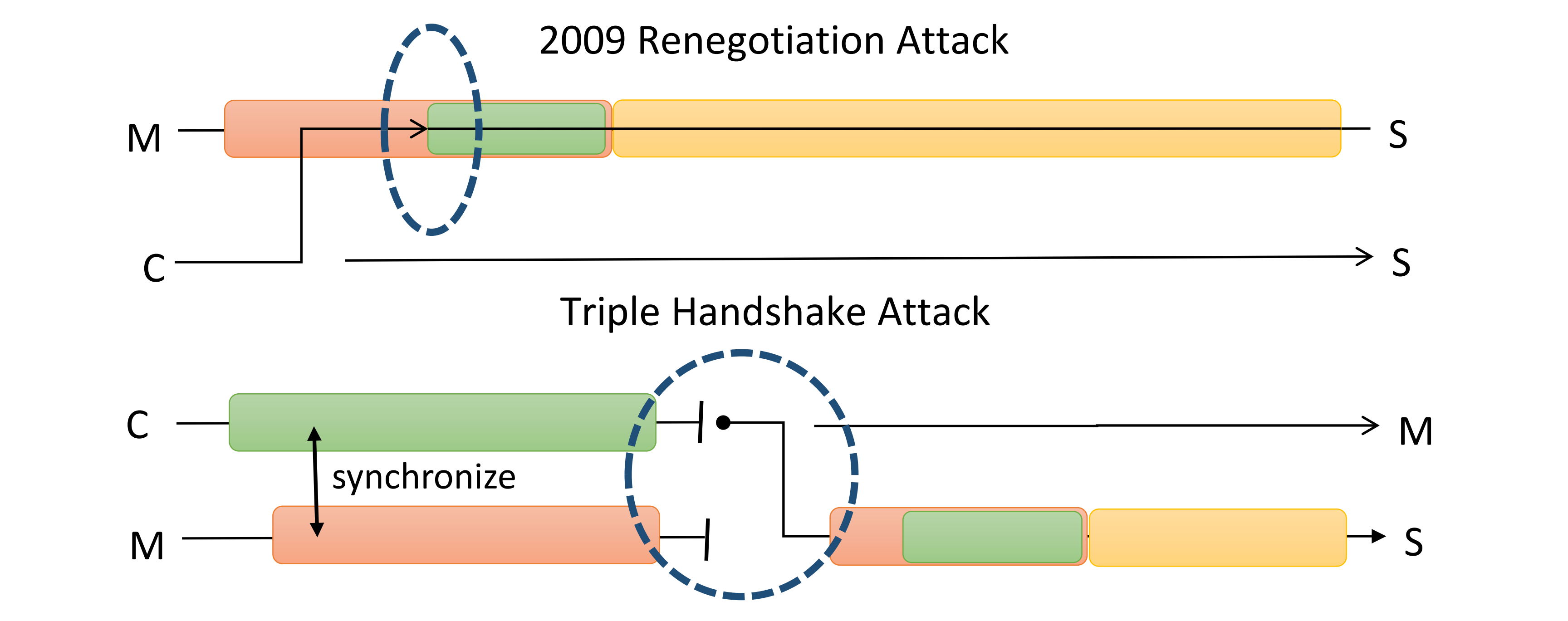
Background: Ray & Rex 2009 Attack

- TLS Weakness
  - Renegotiation doesn't bind old and new sessions
  - Implementations allow server certificate to change
  - Implementations concatenate data across sessions
- HTTP Weakness
  - Message format is unstructured: can inject prefix

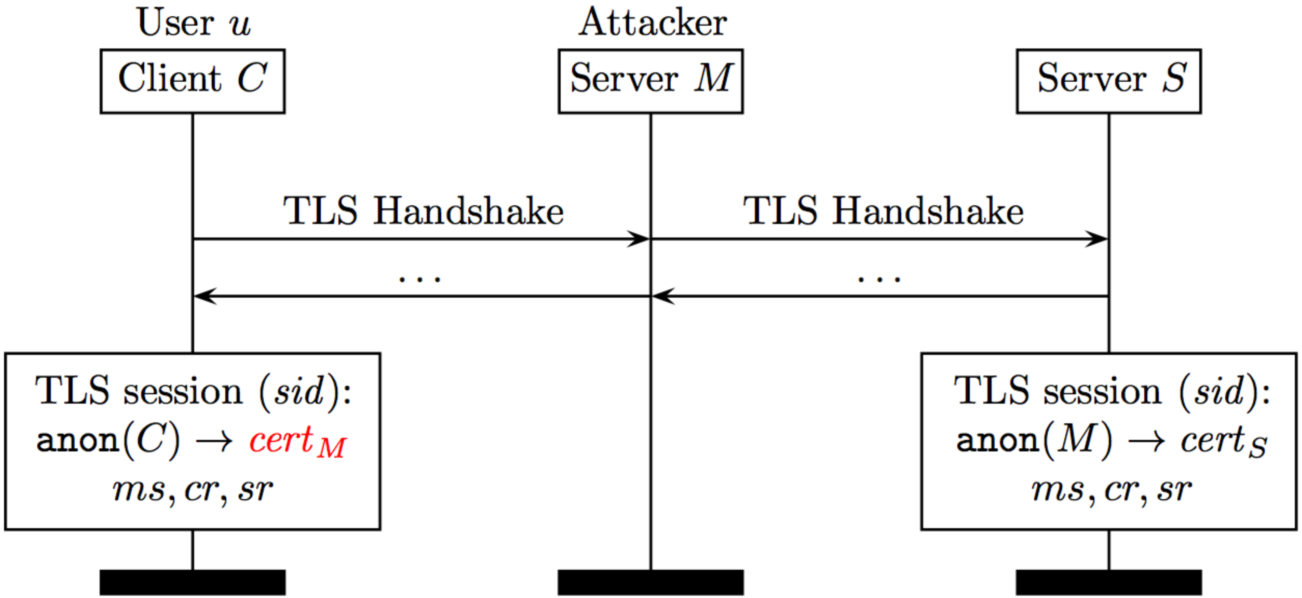
Mitigation: Ray & Rex 2009 Attack

- Mandatory renegotiation indication extension
- SRI = verify_data (hash of message log) of latest handshake on current connection
- SRI binds new TLS session to previous one
- Fresh connection: empty SRI

TLS session headache



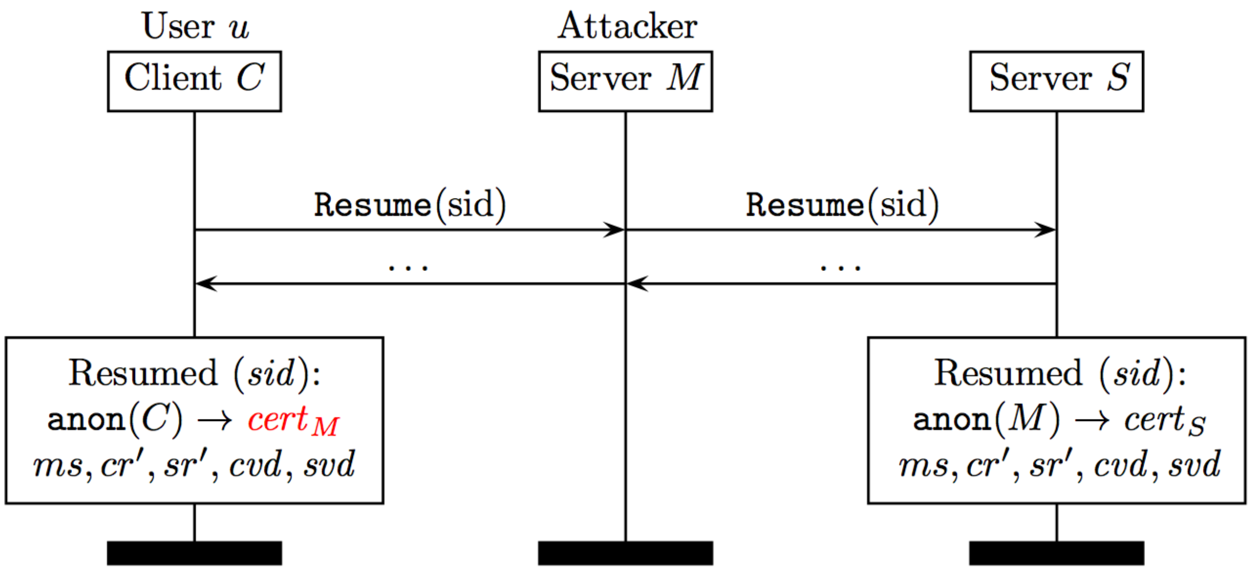
3Shake Step 1



3Shake Step 1

- C <-> M and M <-> S use same PMS
  – RSA: M re-encrypts C's PMS under S' public key
  – DHE: M sends degenerate group parameters
- **PMS, MS, sid aren't unique to a TLS session**

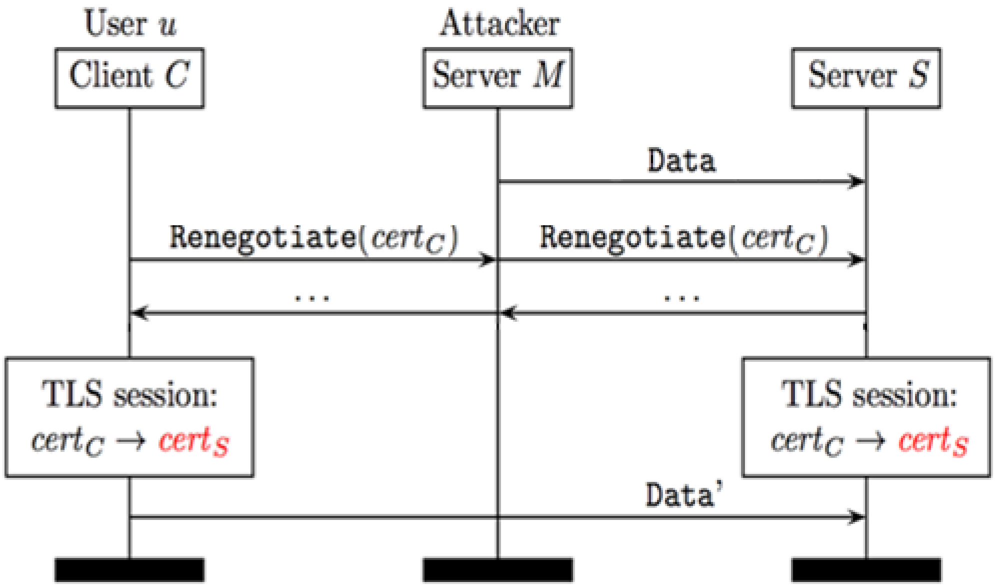
3Shake Step 2



3Shake Step 2

- Resume C <-> M on C <-> S
  - TLS resumption doesn’t preserve authentication
- M doesn’t need to tamper any message: C and S agree on the same verify_data
- ***tls-unique* binding broken after resumption**

3Shake Step 3

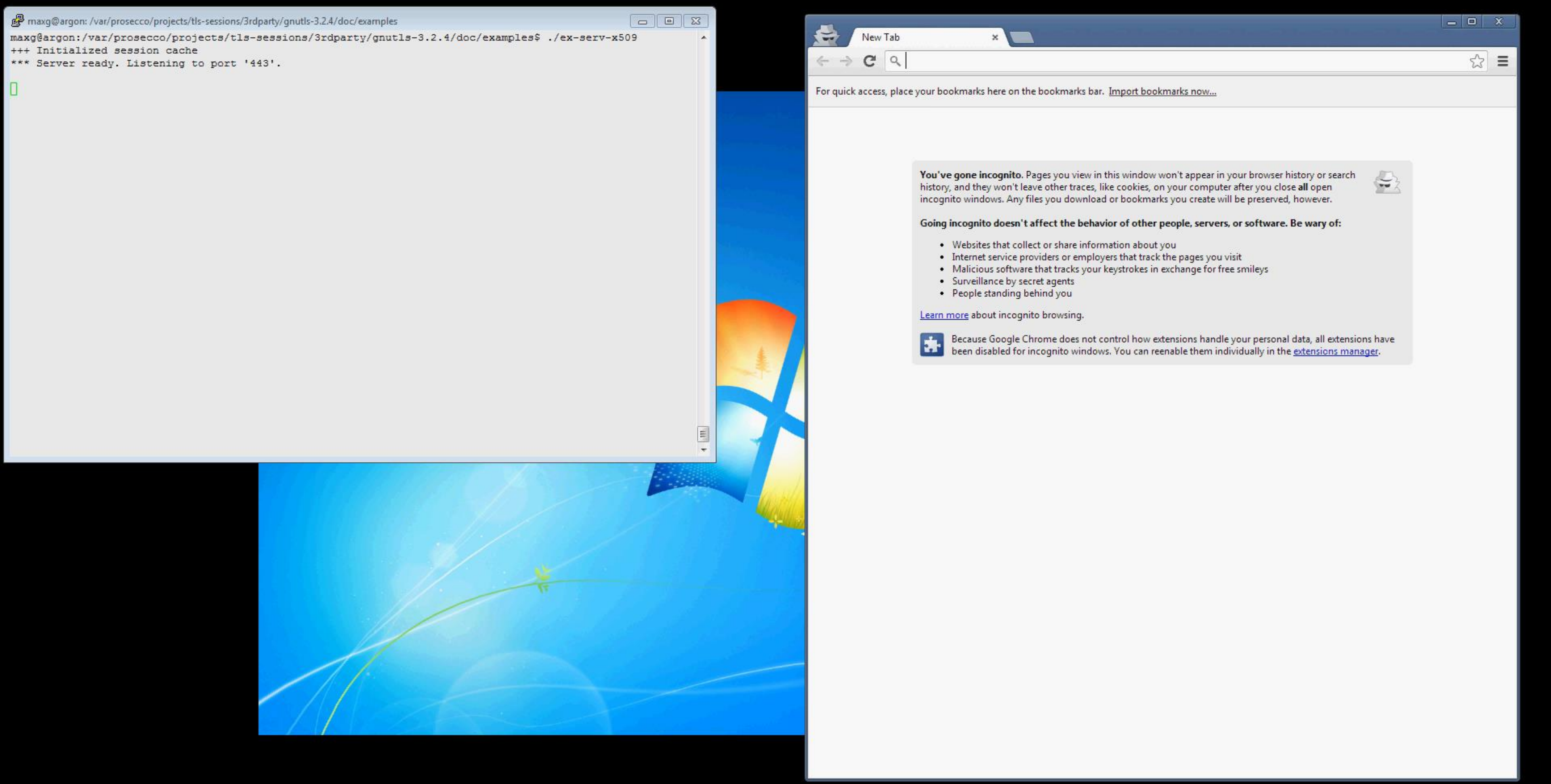


Data (injected by M) =
GET /secret/data HTTP/1.1
Host: S
X-Ignore-This:

Data' (sent by C) =
GET / HTTP/1.0
Host: M
…

3Shake Step 3

- M can trigger C <-> S renegotiation
  - *Certificate can still change*
- If S asks for client certificate, **C thinks she logs in on M, but actually authenticates to S**
- M can inject data to S before renegotiation
  - *Implementations still concats data across sessions*


maxg@argon: /var/prosecco/projects/tls-sessions/3rdparty/gnutls-3.2.4/doc/examples
maxg@argon:/var/prosecco/projects/tls-sessions/3rdparty/gnutls-3.2.4/doc/examples$ ./ex-serv-x509
+++ Initialized session cache
*** Server ready. Listening to port '443'.
New Tab
For quick access, place your bookmarks here on the bookmarks bar. Import bookmarks now...
You've gone incognito. Pages you view in this window won't appear in your browser history or search history, and they won't leave other traces, like cookies, on your computer after you close all open incognito windows. Any files you download or bookmarks you create will be preserved, however.
Going incognito doesn't affect the behavior of other people, servers, or software. Be wary of:
Websites that collect or share information about you
Internet service providers or employers that track the pages you visit
Malicious software that tracks your keystrokes in exchange for free smileys
Surveillance by secret agents
People standing behind you
Learn more about incognito browsing.
Because Google Chrome does not control how extensions handle your personal data, all extensions have been disabled for incognito windows. You can reenable them individually in the extensions manager.

3Shake Impact

- Conditions
  - C is willing to authenticate on M with her certificate
  - C ignores certificate change during renegotiation
  - S concatenates the data sent by M and C
- Impact
  - M can inject **malicious data authenticated as C on S**

3Shake Mitigation

- C can block server certificate changes
  - Chomium (CVE-2013-6628)
  - Safari (APPLE-SA-2014-04-22-2)
  - Internet Explorer (KB257591)
- We propose MS’ = PRF(PMS, tls-session-hash)
  - *tls-session-hash* = hash of the handshake messages that created the session up to client key exchange

draft-bhargavan-tls-session-hash

CONCLUSION

WHY TLS FAILS TO PROTECT HTTP

- ✓ *Introduction*
- ✓ *Cookie Cutter*
- ✓ *Virtual Host Confusion*
  - ✓ *Crossing Origin Boundaries*
  - ✓ *Shared Reverse Proxies*
  - ✓ *Shared Session Cache*
  - ✓ *SPDY Connection Pooling*
- ✓ *Triple Handshake*
- ➢ **Conclusion**

Lessons: Cookie Cutter

- ~~"Liberal in what you accept"~~
  - Parsing is security critical, malformed = reject
- Security should **not rely on anything being present** (*additions* can relax security)
- Beware of side-effects on data processed before its integrity is confirmed

Lessons: virtual host confusion

- We want:
  - *Routing to only depend on authenticated inputs*
  - *Consistent routing on servers sharing credentials*
- **<u>Your job</u> to achieve authenticated, consistent routing in current HTTPS software**
- **Beware of the "same-certificate policy"**
  - **Same-certificate attacker is possible!**

Lessons: triple handshake

- **We have a big TLS API problem**
  - TLS isn't just a drop-in socket replacement
  - All difficult problems *handed off to the application*
- Crypto values from handshake (PMS, MS, SID, verify_data) don't identify session or participants
  - Will be fixed; lesson learned for TLS 1.3

What we are doing about it

- miTLS: verified TLS implementation
  - No more "goto fail" bugs
  - Performance vs "heartbleed" trade-off
- Verified protocol libraries
  - TLS API is too difficult for applications to use
  - Verify TLS + thin protocol wrapper together
- WebSpi, F*: evaluating the security of websites

QUESTIONS

Thanks

Google
Mozilla
Microsoft
Facebook

HackerOne
Dropbox
Akamai
Apple

Adam Langley
Piotr Sikora
Anton Mityagin
Brian Sniffen

Alex Rice
Stephen Ludin
Eric Rescola
Ryan Sleevi