Protecting encrypted cookies from compression side-channel attacks

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Introduction

Encryption and compression

Symmetric key encryption

A *symmetric key encryption* scheme is a triple of algorithms:

- KeyGen() –> k
- $\text{Enc}_k(m)$ –> c
- $\text{Dec}_k(c)$ –> m

KeyGen and Enc can be probabilistic

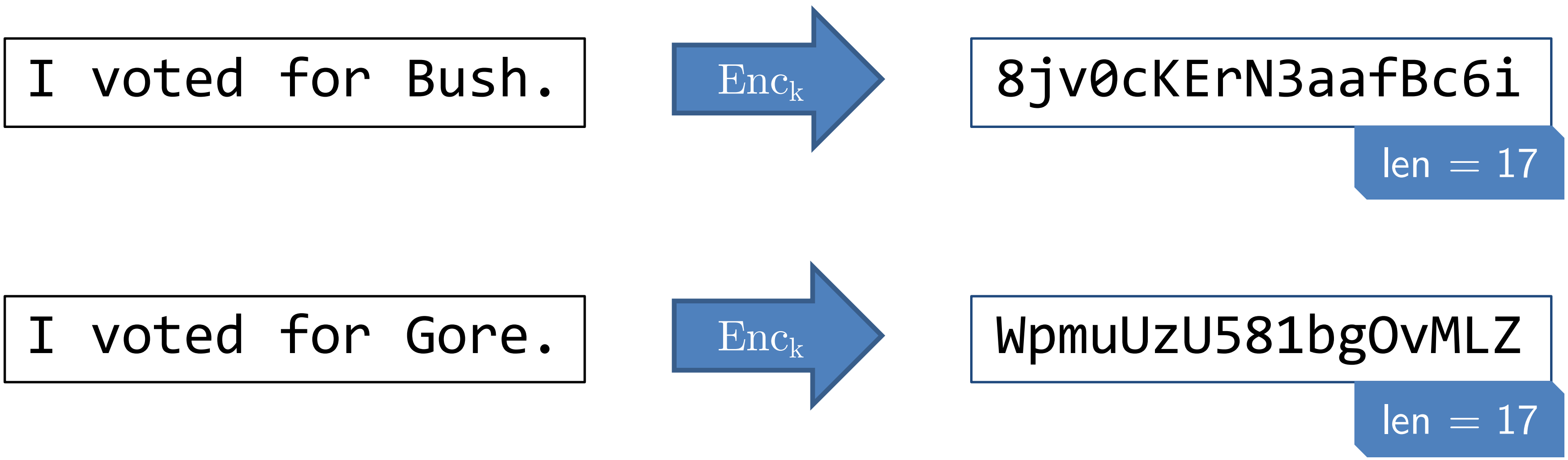
Main security goal:

- **indistinguishability**

Attacker cannot tell apart encryptions of two messages of the same length:

$\text{Enc}_k(m_0)$ looks like $\text{Enc}_k(m_1)$ when $|m_0|=|m_1|$

Symmetric key encryption



same length input => same length output

Compression

A *compression scheme* is a pair of algorithms:

- Comp(m) –> o
- Decomp(o) –> m

Comp may be probabilistic (but usually isn't)

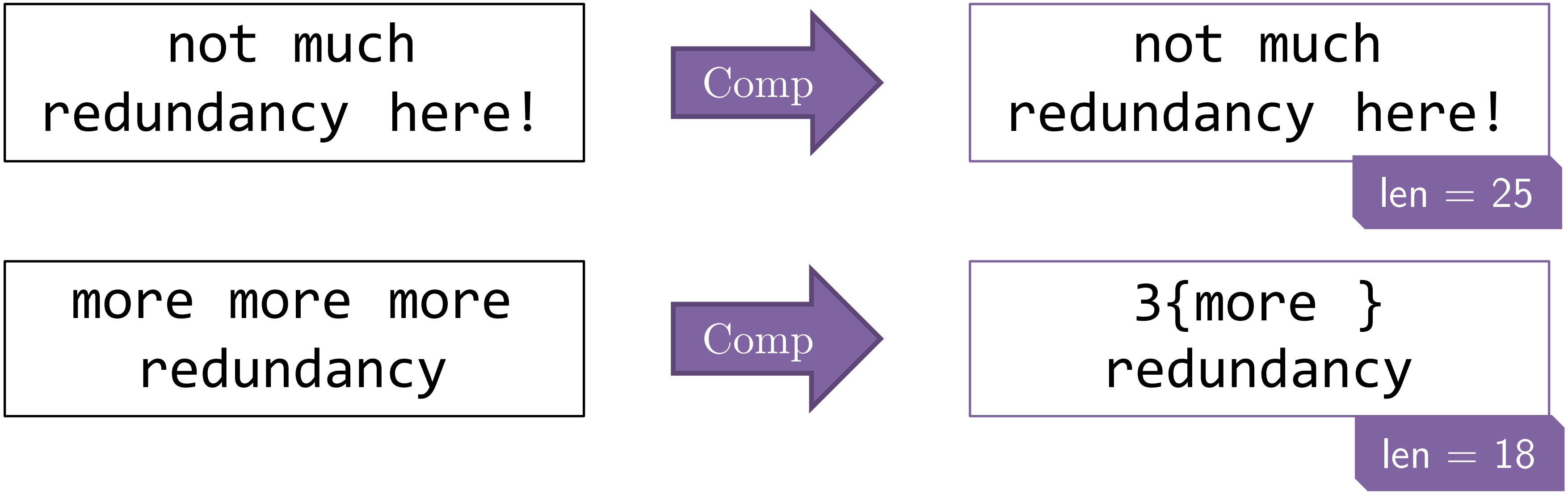
Main security goal:

- **none**

Main functionality goal:

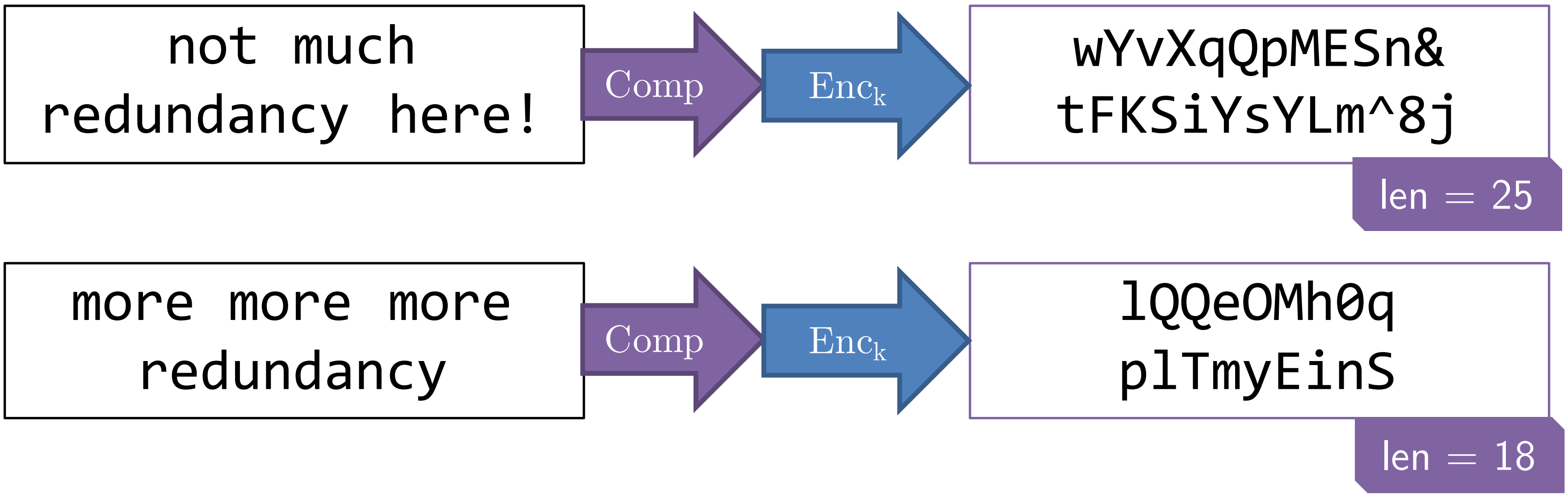
- $|\text{Comp}(m)| << |m|$ for common distribution of m
- Can't be true for all m due to Shannon's theorem

Compression



same length input => possibly different length output

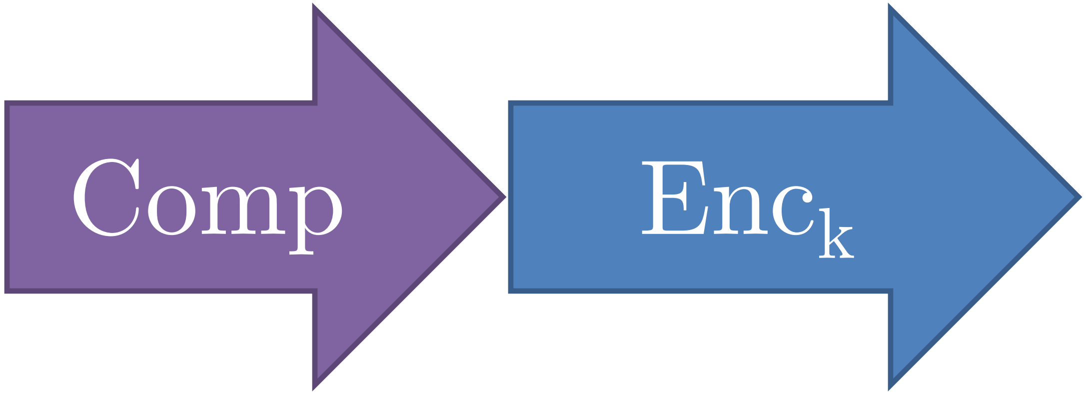
Compression then encryption



same length input => possibly different length output

A test

Man. U. 2005-2014	Arsenal 2005-2014
lost lost	lost lost
WON! WON!	lost lost
WON! lost	lost lost
WON! lost	lost lost
WON! lost	lost lost


Comp
Enc_k

Which ciphertext is for which message?

```
yI5pDrFhPk3
15Cmymr6xCb
LTVEAx
```

```
D1fAGUR1zqv
lhXdX3c8qd+
BYBwK6dAnoG
GQGCmvFIM9/
s6WJjgr2
```

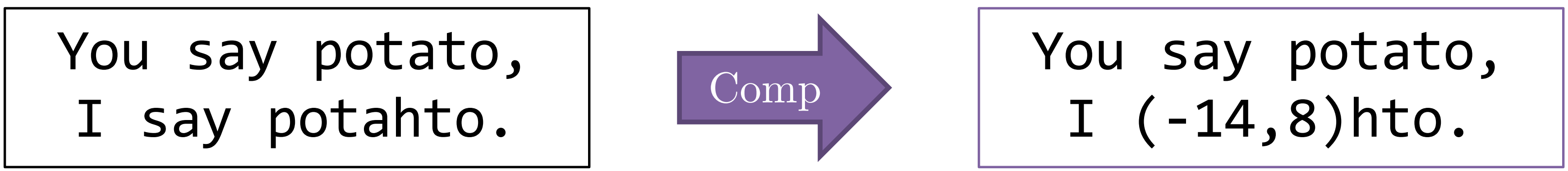
One message compresses more

```
  Arsenal
 2005-2014
10{lost }
```

```
   Man. U.
  2005-2014
  2{lost }
  2{WON! }
3{WON! lost }
```

Deflate (LZ77) compression algorithm

- Replaces repeated strings with back references (distance, length) to previous occurrence.



- Important parameter: **window size**
  - How far back does it go to search for occurrences?
  - a.k.a. dictionary size

Combining user secrets + adversary input

- Suppose you have a secret
- and combine it with adversarial data
- then compress and encrypt

- **Adaptive** attacker can use this to learn your secret

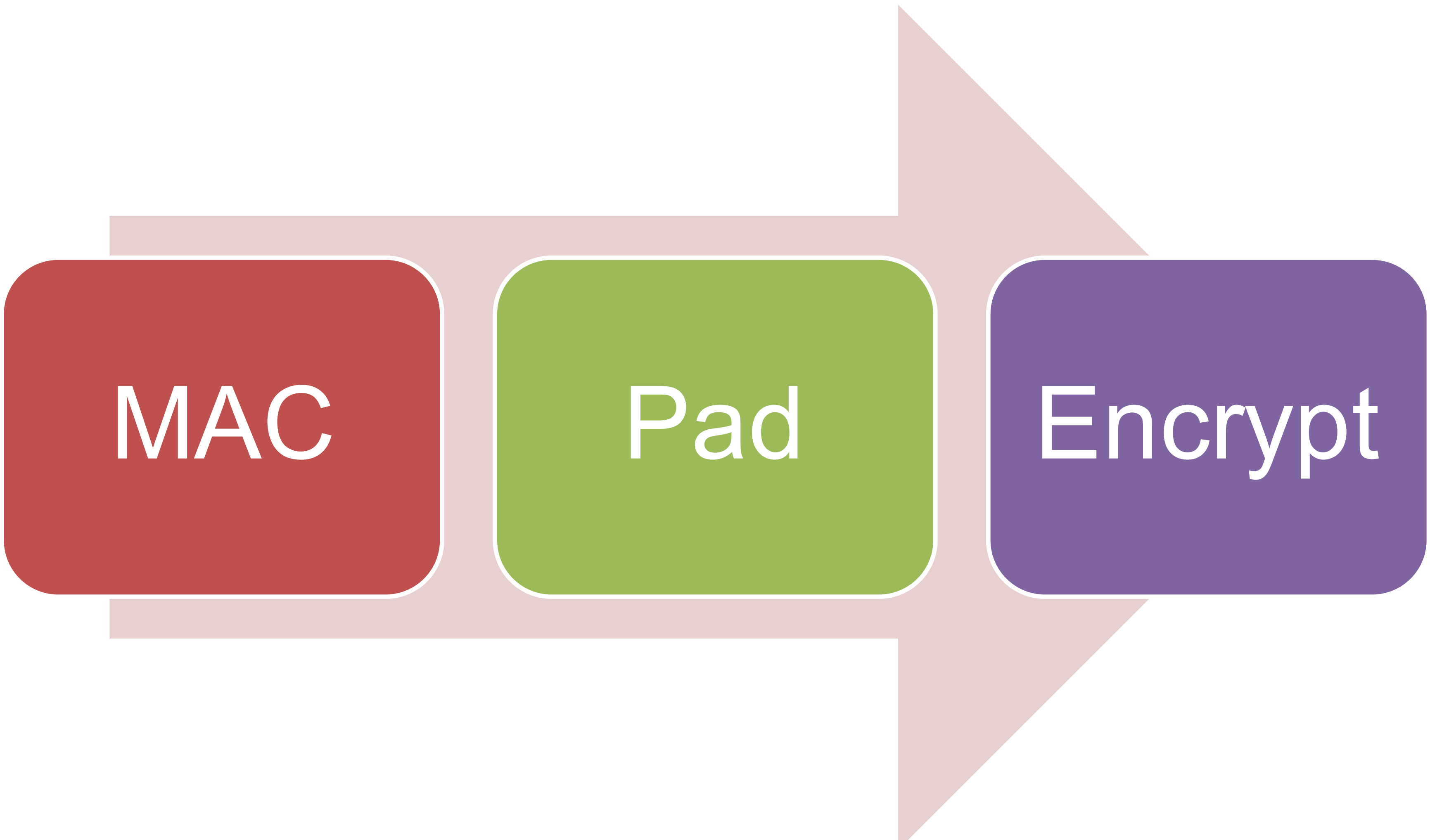
CRIME attack on compression in TLS

TLS = Transport Layer Security protocol

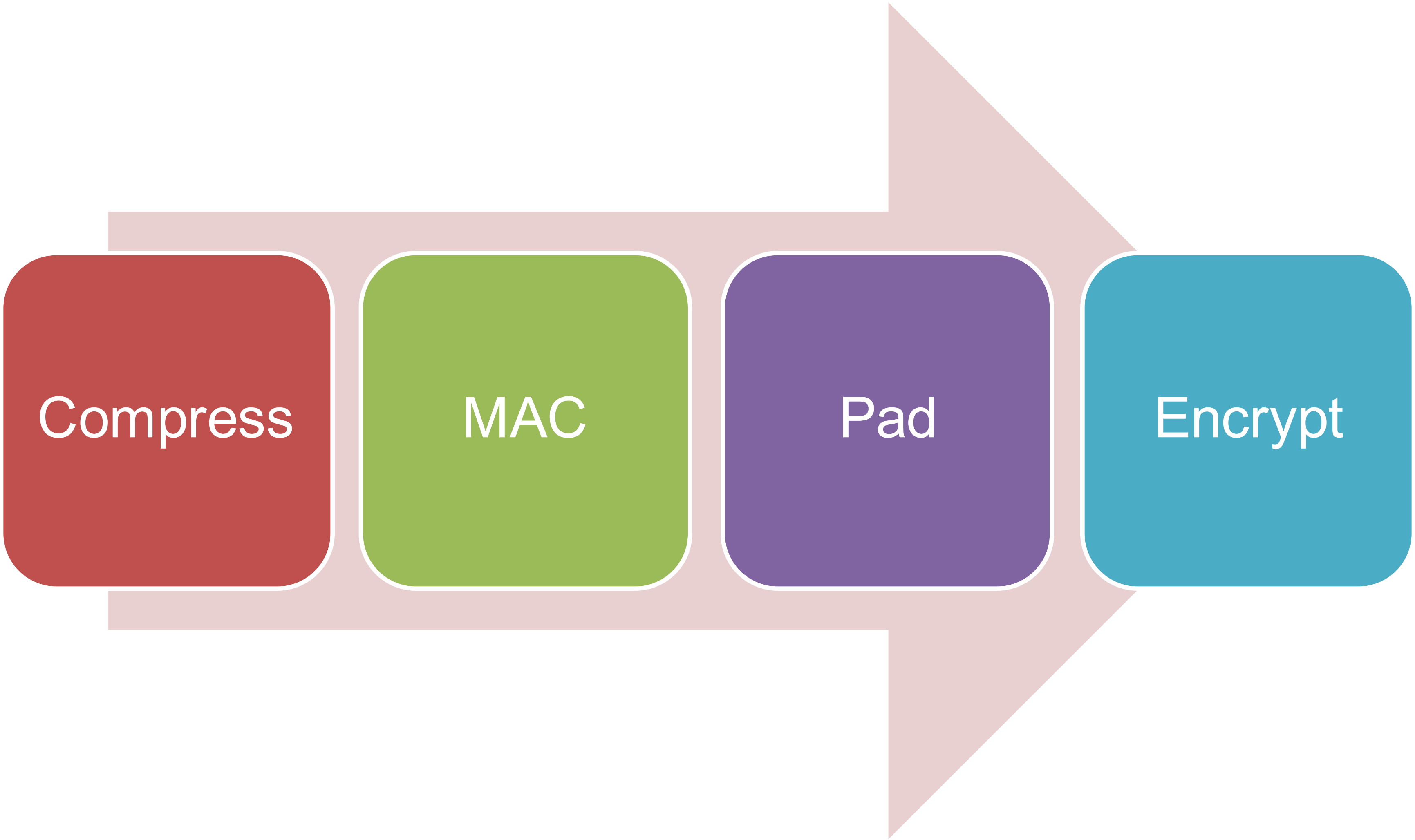
a.k.a. SSL (Secure Sockets Layer)

a.k.a. the “s” in “https”

TLS record layer



Compression in TLS record layer



Transmitting an HTTP request

User
- Requests www.facebook.com

Browser (HTTP)
- Creates GET request with saved cookie

Browser (TLS)
- Input: HTTP message
- Compress
- MAC
- Pad
- Encrypt

Send over Internet

Secret values in HTTP documents

GE /

The URL can be adversary-supplied data

Host: www.

User-Agent: Mozilla/5.0 (Macintosh; Intel Mac OS X 10.10; rv:34.0) Gecko/20100101 Firefox/34.0

Accept: text/html,a lication/xml;q=0.9,*/*;q=0.8

This secret cookie identifies my session to Facebook

Accept-Lang

Accept-Enco

DNT: 1

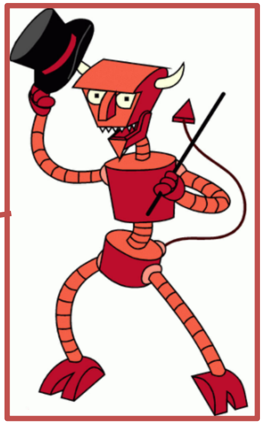
Cookie: datr=DzK9VBnObWDqfL7XLwGSSEsu; reg_fb_ .com%2F; reg_fb_gate=https%3A%2F%2Fwww.facebook.com%2F; dpr=2

Connection: keep-alive

Cache-Control: max-age=0

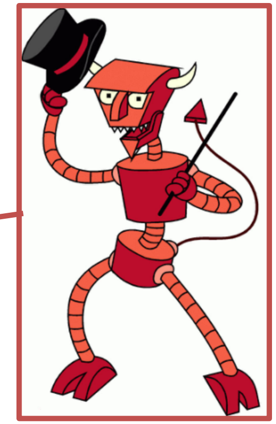
Attack

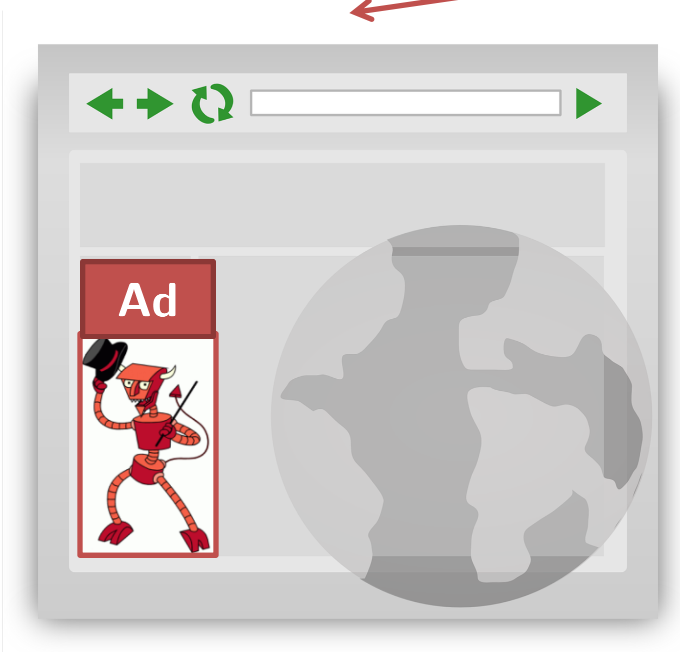
Please send a GET request for
`https://www.facebook.com/?datr=A`



Attack

Please send a GET request for
`https://www.facebook.com/?datr=A`

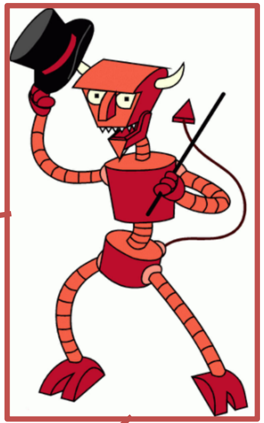


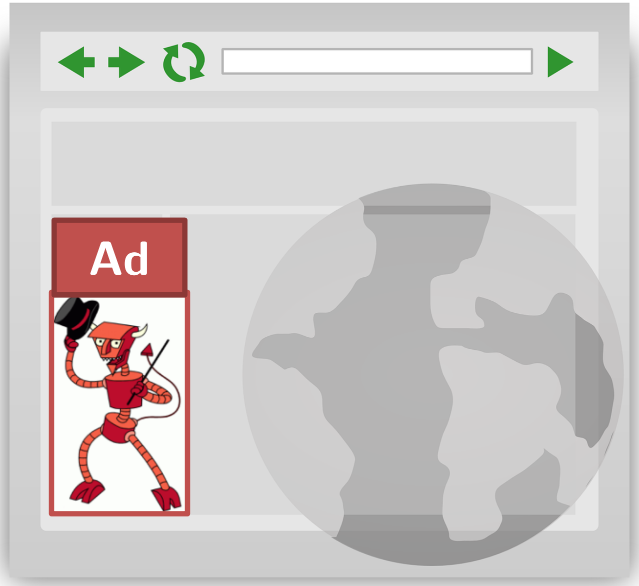



```
GET /?datr=A
Host: www.facebook.com
Cookie: datr=DzK9VBnObW
DqfL7XLwGSSEsu
...
```

Attack

Please send a GET request for
`https://www.facebook.com/?datr=A`





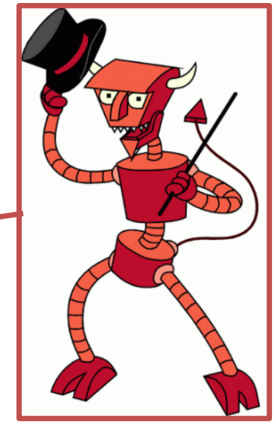
Observes compressed
& encrypted request

VGytgpDn/1Ym5oCdB3Vh2
D5EmdjLRdkx7tEvKG43WJ
yD++cx8CJlBbetQejiXLX
+oQO9bnUMYQwtglOSf9bf
oyWJkYxHsKfqYNqWAfCIg
8U5BK92Ayvk858MJOnTuK

len = 204

Attack

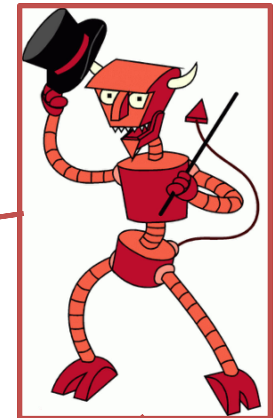
Please send a GET request for
`https://www.facebook.com/?datr=B`




```
GET /?datr=B
Host: www.facebook.com
Cookie: datr=DzK9VBnObW
DqfL7XLwGSSEsu
...
```

Attack

Please send a GET request for
`https://www.facebook.com/?dat[illegible]=B`



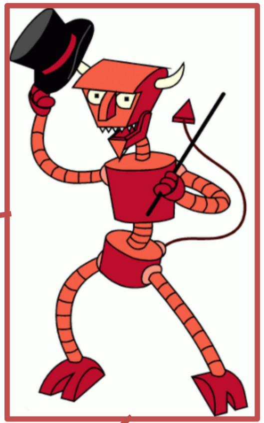
Observes compressed & encrypted request

UQ5ItQ1Y4BVCy37Fhu5K4
hyre7l5P4pWwAYfvnzg9m
R5Qq250PF1yQpf83AFJ34
QS+9BPjUnBzVGENe15r29
rY9tRfIFAdE8ecEmVTFtl
zHy+8EIwxDK67rxM29clJ

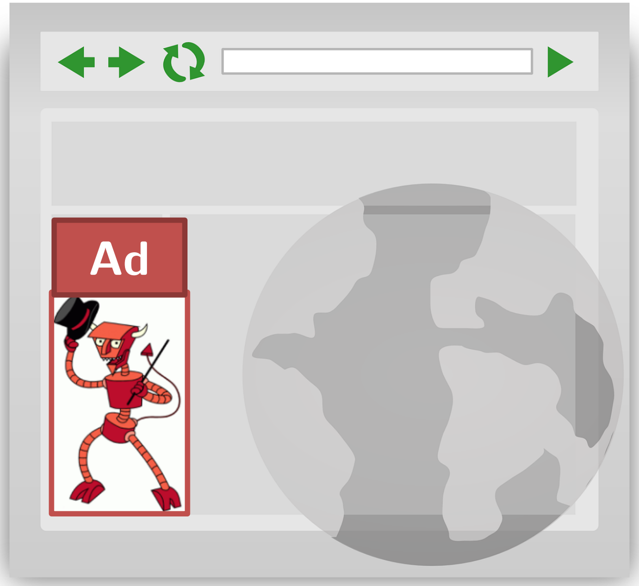
len = 204

Attack

Please send a GET request for
`https://www.facebook.com/?data=C`



Observes compressed
& encrypted request




```
Wdb42n0LeQbVweAoiCZxE
j9O0U+qaGPPbe9Sebz2Dx
GhYWj9U4X0cKYyBpTSpB4
4dOqd4DpCscHEsBdg0p6q
DXiSBJ+MLOKbpRvAAmPhy
9Sn9VPnsHgKyB4I1lgCKA
```

len = 204

Attack

Please send a GET request for
`https://www.facebook.com/?datr=D`

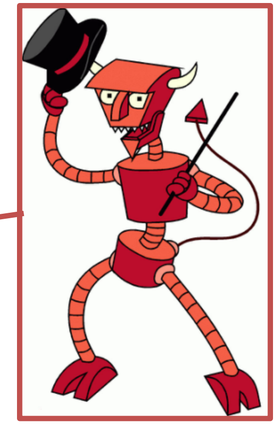
Observes compressed & encrypted request

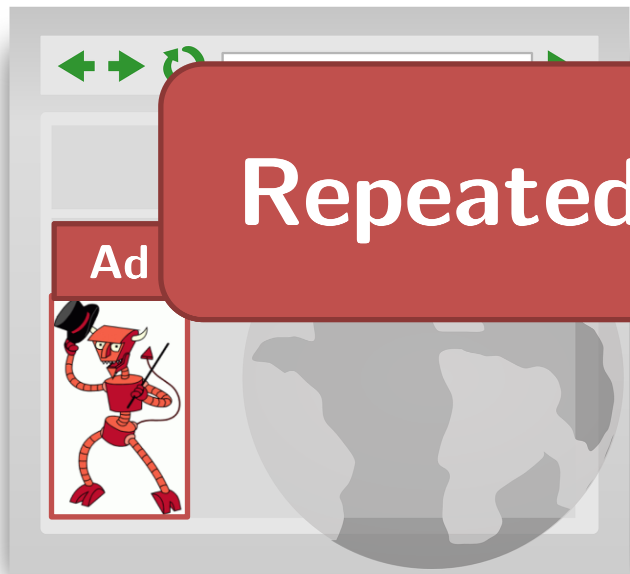

```
O8Gb8JwSuoNrcQ7190KSs
nM7n22lOtByzmvv555ZP+
+4lNW2wIuRrTF6KlKdjOB
425VVDUbKKdHNF9YaaxTy
lVWBVo1ApZ4PTSnB1J0pt
jAsecGXjRXOXTwye
```

len = 199

Attack

Please send a GET request for
https://www.facebook.com/?datr=D



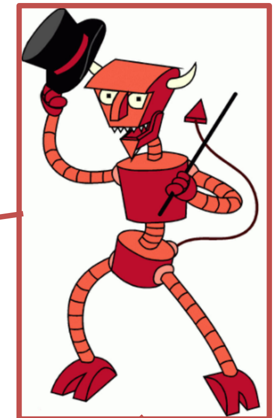


Repeated text => compression

```
GET /?datr=D
Host: www.facebook.com
Cookie: datr=D:K9VBnObW
DqfL7XLwGSSEsu
...
```

Attack

Please send a GET request for
https://www.facebook.com/?data=Da



Observes compressed
& encrypted request

Ok3MV18blnYFIjz2tcucQ
x2mJ8MLULVqMSYO9Lo1r0
wxwjEG8pLwaPaVtrnf46l
ypdqbYQ22oJw63ixkS1HR
QVfz8UKs9tOhPvTAwUiwS
yukxrKq9x9I+3fO8lv8aU

len = 205

CRIME attack on TLS "Compression Ratio Info-leak Made Easy"

- Rizzo and Duong [ekoparty 2012]

- Victim visits adversary-controlled page
- Adversarial Javascript causes browser to make many requests
- Figure out 1st letter of cookie
- Figure out 2nd letter of cookie
- Figure out 3rd letter of cookie
- ...

A few tricky bits to make it work in TLS:

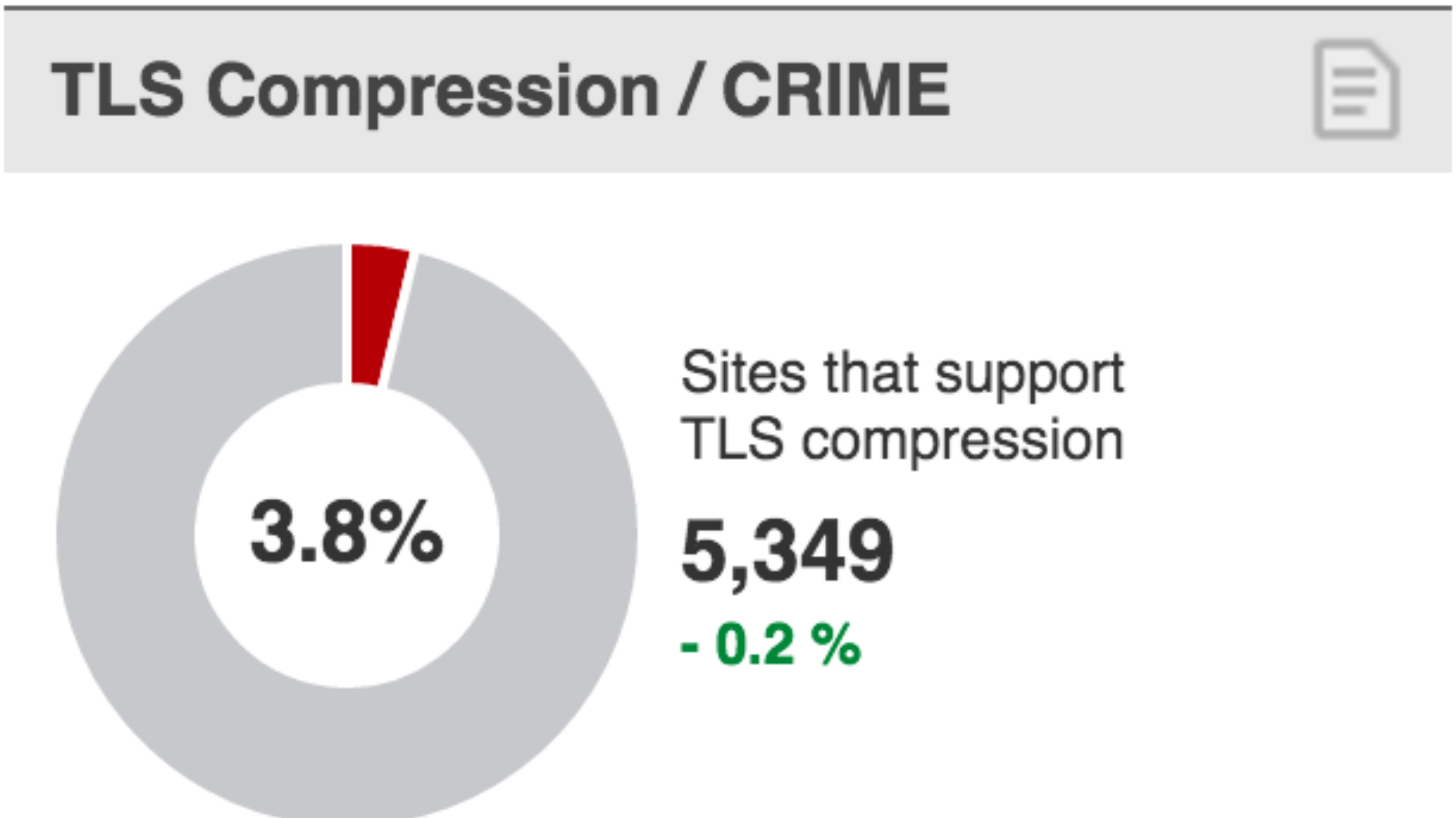
- TLS splits plaintext into 16K records then compresses and encrypts each record separately
- Need to ensure that you can observe length differences based on compression

- But it can be made to work!

CRIME wasn't new

- Kelsey [FSE 2002] theorized length-based attacks on compression-encryption with adversary-chosen prefix.

Impact of CRIME attack



November 5, 2015 ▪ https://www.trustworthyinternet.org/ssl-pulse/

But...

- Compression is present elsewhere on the Internet.

- HTTP allows gzip compression of the body

BREACH attack on compression in HTTP

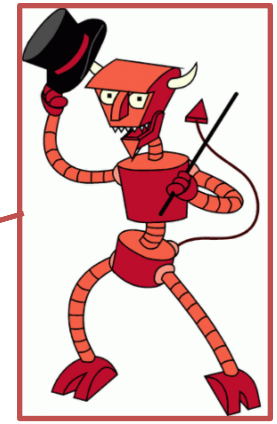
BREACH attack

- Attack against HTTP compression hypothesized in CRIME presentation

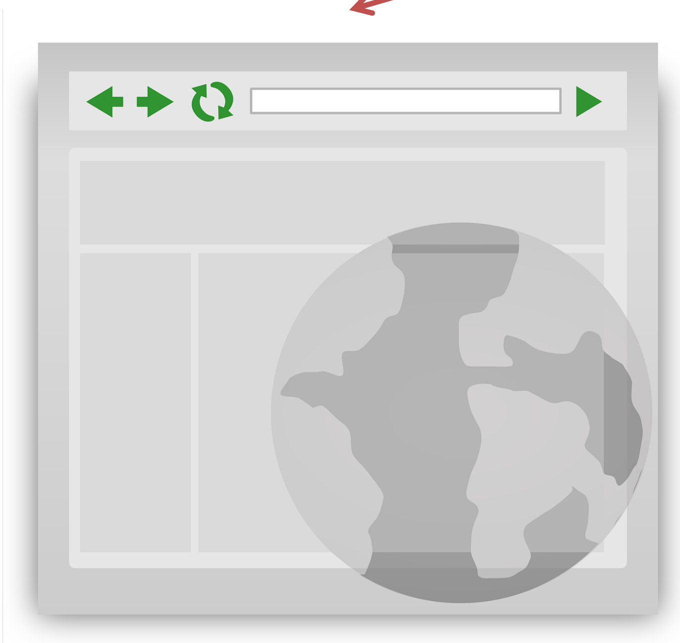
"Browser Reconnaissance and Exfiltration via Adaptive Compression of Hypertext"

- attack demonstrated against secrets in HTML
- Gluck, Harris, Prado [Black Hat 2013]

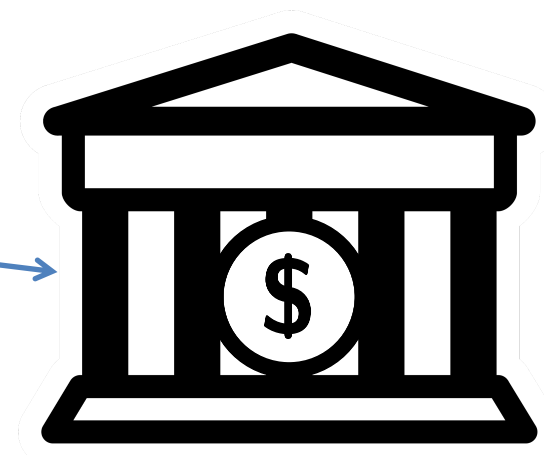
Cross-site request forgery



Please send a GET request for
`https://www.bank.com/transfer`
`?to=Eve&amount=1000000`



```
GET /transfer?to=Eve
&amount=1000000
Host: www.bank.com
Cookie: account=Alice
...
```



Anti-CSRF tokens

Protection strategy: server hides a random token in each HTML form it creates and will only execute action if received response contains that token.

```
<form action="/money_transfer" method="post">
<input type="hidden" name="csrftoken"
       value="OWT4NmQlODE4ODRjN2Q1NTlhMmZlYWE...">
...
</form>
```

BREACH Attack

Works against websites that echo user input in the same page as a valuable secret (e.g., anti-CSRF token).

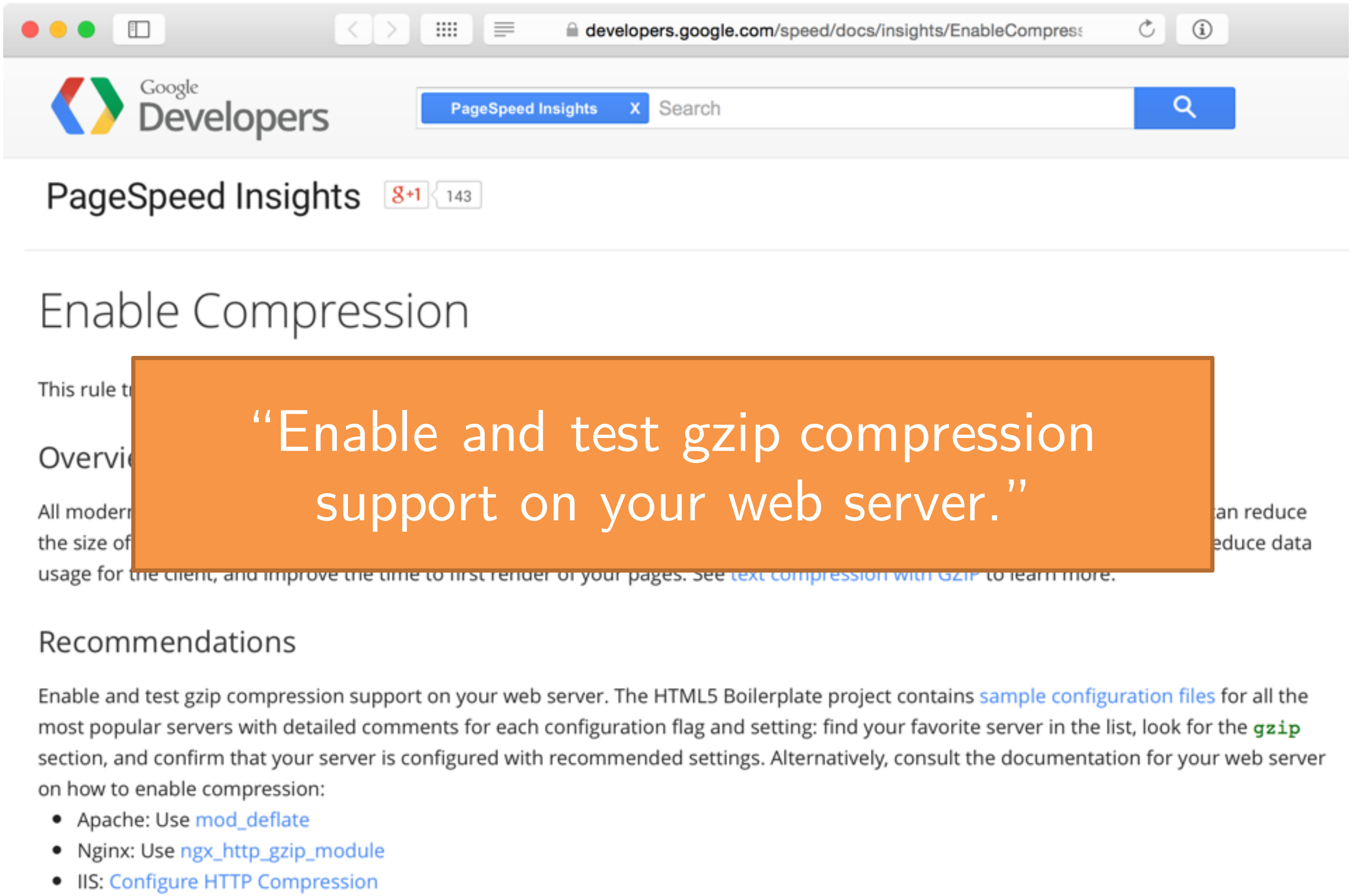
- combining user secrets + adversary input then compressing

```
<p>Welcome, <?=$_GET['username']?>.</p>
<form action="/money_transfer" method="post">
<input type="hidden" name="csrftoken"
       value="OWT4NmQlODE4ODRjN2Q1NTlhMmZlYWE...">
...
</form>
```

Recommendations from BREACH attack

1. Disabling HTTP compression
2. Separating secrets from user input
3. Randomizing secrets per request
4. Masking secrets (effectively randomizing by XORing with a random nonce)
5. Length hiding (by adding a random number of bytes to the responses)
6. Rate-limiting the requests

Impact of BREACH attack


developers.google.com/speed/docs/insights/EnableCompress

Google Developers

PageSpeed Insights X Search

PageSpeed Insights 8+1 143

Enable Compression

This rule t

Overvi

All moder ... an reduce
the size of ... educe data
usage for the client, and improve the time to first render of your pages. See text compression with GZIP to learn more.

Recommendations

Enable and test gzip compression support on your web server. The HTML5 Boilerplate project contains sample configuration files for all the most popular servers with detailed comments for each configuration flag and setting: find your favorite server in the list, look for the gzip section, and confirm that your server is configured with recommended settings. Alternatively, consult the documentation for your web server on how to enable compression:

- Apache: Use mod_deflate
- Nginx: Use ngx_http_gzip_module
- IIS: Configure HTTP Compression

"Enable and test gzip compression support on your web server."

Compression in network protocols

HTTP/1.1

- supports compression
- BREACH attack
- still widely used

SPDY

- supports compression
- CRIME/BREACH work against early versions

HTTP/2

- separate compression of every headers
- uses special algorithm HPACK for header compression

Others

- SSH
- PPTP
- OpenVPN
- XMPP
- IMAP
- SMTP
- (see CRIME slides)

Recommendations from BREACH attack

1. Disabling HTTP compression
2. Separating secrets from user input
3. Randomizing secrets per request
4. Masking secrets (effectively randomizing by XORing with a random nonce)
5. Length hiding (by adding a random number of bytes to the responses)
6. Rate-limiting the requests
7. Use non-adaptive compression algorithm

Security definitions

Encryption security: IND-CPA

$\underline{\mathrm{Exp}_{\Pi}^{\text{IND-CPA}}(\mathcal{A})}$

$k \xleftarrow{\$} \Pi.\mathrm{KeyGen}()$

$b \xleftarrow{\$} \{0,1\}$

$(m_0, m_1, st) \xleftarrow{\$} \mathcal{A}^{E}()$

if $|m_0| \neq |m_1|$, **then return** $\perp$

$c \leftarrow \Pi.\mathrm{Enc}_k(m_b)$

$b' \xleftarrow{\$} \mathcal{A}^{E}(c, st)$

return $(b' = b)$

$\underline{E(m)}$

return $\Pi.\mathrm{Enc}_k(m)$

Entropy-restricted encryption security: ER-IND-CPA [KelTam14]

$\underline{\mathrm{Exp}^{\text{ER-IND-CPA}}_{\Pi,\mathcal{L}}(\mathcal{A})}$

1: $k \xleftarrow{\$} \Pi.\mathrm{KeyGen}()$

2: $b \xleftarrow{\$} \{0,1\}$

3: $(m_0, m_1, st) \xleftarrow{\$} \mathcal{A}^E()$

4: **if** $m_0 \notin \mathcal{L}$ or $m_1 \notin \mathcal{L}$, **then return** $\perp$

5: $c \leftarrow \Pi.\mathrm{Enc}_k(m_b)$

6: $b' \xleftarrow{\$} \mathcal{A}^E(c, st)$

7: **return** $(b' = b)$

$$\mathcal{L} = \mathcal{L}_\ell = \{m \in \mathcal{M} : |\mathrm{Comp}(m)| = \ell\}$$

Kelsey/CRIME = Adaptive chosen prefix/suffix attack

- There is a secret value ck.
- Attacker can adaptively choose values m', m'' and receive

$$\mathrm{Enc}_k(\mathrm{Comp}(m' \mathbin{||} ck \mathbin{||} m''))$$

- Attacker's goal is to learn something about ck

New security definitions

Attacker's powers

Adaptively obtain encryptions of

$$m' \mid\mid ck \mid\mid m''$$

for m', m'' of the adversary's choice

Attacker's goals

- **Cookie recovery**: fully recover the secret cookie ck
- **Chosen cookie indistinguishability**: distinguish which of two chosen cookies ck_0, ck_1 is used
- **Random cookie indistinguishability**

Cookie-recovery (CR) security

$\underline{\mathrm{Exp}^{\mathsf{CR}}_{\Psi,\mathcal{CK}}(\mathcal{A})}$

1: $k \stackrel{\$}{\leftarrow} \Psi.\mathrm{KeyGen}()$
2: $ck \stackrel{\$}{\leftarrow} \mathcal{CK}$
3: $ck' \stackrel{\$}{\leftarrow} \mathcal{A}^{E_1,E_2}()$
4: **return** $(ck' = ck)$

$\underline{E_1(m', m'')}$

1: **return** $\Psi.\mathrm{Enc}_k(m' \| ck \| m'')$

$\underline{E_2(m)}$

1: **return** $\Psi.\mathrm{Enc}_k(m)$

Goal: fully recover the secret cookie *ck*.

- Models an attacker who is trying to steal a secret value to use
  - e.g. CRIME/BREACH
- Does not provide confidentiality of other parts of plaintext

Chosen cookie indistinguishability (CCI)

$\underline{\mathrm{Exp}^{\mathsf{CCI}}_{\Psi,\mathcal{CK}}(\mathcal{A})}$

1: $k \xleftarrow{\$} \Psi.\mathrm{KeyGen}()$

2: $(ck_0, ck_1, st) \xleftarrow{\$} \mathcal{A}^{E_2}()$
s.t. $|ck_0| = |ck_1|$

3: $b \xleftarrow{\$} \{0,1\}$

4: $b' \xleftarrow{\$} \mathcal{A}^{E_1,E_2}(ck_0, ck_1, st)$

5: **return** $(b' = b)$

$\underline{E_1(m', m'')}$

1: **return** $\Psi.\mathrm{Enc}_k(m' \| ck_b \| m'')$

$\underline{E_2(m)}$

1: **return** $\Psi.\mathrm{Enc}_k(m)$

Goal: determine which of two **chosen** cookies ck_0, ck_1 is used throughout

- Models an attacker who is trying to learn about cookies used
  - e.g., passive surveillance
- Does not provide confidentiality of other parts of plaintext

Random cookie indistinguishability (RCI)

$\text{Exp}^{\text{RCI}}_{\Psi,\mathcal{CK}}(\mathcal{A})$

1: $k \xleftarrow{\$} \Psi.\text{KeyGen}()$

2: $(ck_0, ck_1) \xleftarrow{\$} \mathcal{CK}$ s.t. $|ck_0| = |ck_1|$

3: $b \xleftarrow{\$} \{0,1\}$

4: $b' \xleftarrow{\$} \mathcal{A}^{E_1,E_2}(ck_0, ck_1)$

5: **return** $(b' = b)$

$E_1(m', m'')$

1: **return** $\Psi.\text{Enc}_k(m' \| ck_b \| m'')$

$E_2(m)$

1: **return** $\Psi.\text{Enc}_k(m)$

Goal: determine which of two **random** cookies ck_0, ck_1 is used throughout

- Intermediate notion, possibly still relevant
- Does not provide confidentiality of other parts of plaintext

Relations and separations

$$\mathsf{CCI} \implies \mathsf{RCI} \implies \mathsf{CR}$$

$$\mathsf{CR} \not\Longrightarrow \mathsf{RCI} \not\Longrightarrow \mathsf{CCI}$$

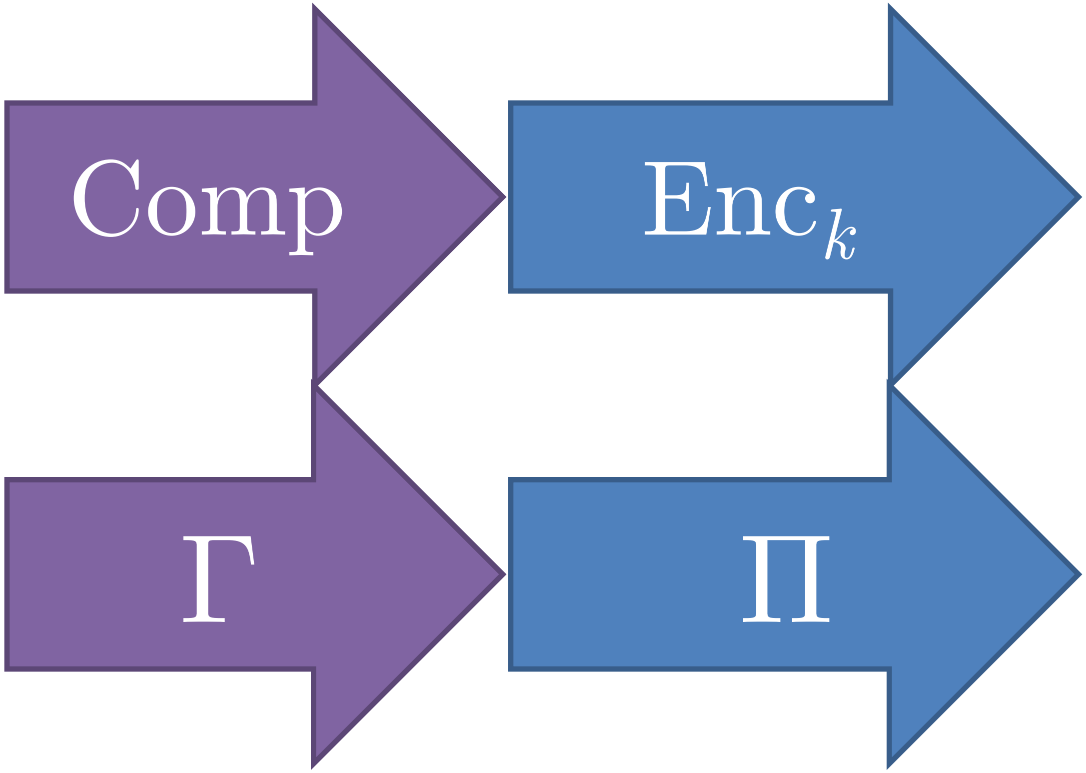
$$\mathsf{ER\text{-}IND\text{-}CPA} \implies \mathsf{IND\text{-}CPA} \implies \mathsf{CCI}$$

$$\mathsf{CCI} \not\Longrightarrow \mathsf{IND\text{-}CPA}$$

Compressing encryption

Definitions shown are all about encryption schemes.

- A compressing encryption scheme *is* an encryption scheme.



$$\Pi \circ \Gamma$$

Technique 1: Separating secrets

Idea: use a filter to separate secrets

Suppose all secrets in a particular application have a recognizable form:

```
<form action="/money_transfer" method="post">
<input type="hidden" name="csrftoken"
       value="OWT4NmQlODE4ODRjN2Q1NTlhMmZlYWE...">
...
</form>
```

Use a filter to separate out secrets and don't compress them:

```
/value="[A-Za-z0-9]*"/
```

Filter $f : \{0,1\}^* \rightarrow \{0,1\}^* \times \{0,1\}^*$

$\underline{\mathrm{SS}_{f,\Gamma}.\mathrm{Comp}(m)}$

$(pt_s, pt_{ns}) \leftarrow f(m)$

$\widetilde{pt_{ns}} \leftarrow \Gamma.\mathrm{Comp}(pt_{ns})$

return $pt_s \| \widetilde{pt_{ns}}$

$\underline{\mathrm{SS}_{f,\Gamma}.\mathrm{Decomp}(pt)}$

Parse $pt_s \| \widetilde{pt_{ns}} \leftarrow pt$

$pt_{ns} \leftarrow \Gamma.\mathrm{Decomp}(\widetilde{pt_{ns}})$

$m \leftarrow f^{-1}(pt_s, pt_{ns})$

return m

CCI-security of separating secrets

Let Π be an encryption scheme.

Let Γ be a compression scheme.

Let f be a safe filter.

Let $\mathrm{SS}_{f,\Gamma}$ be the separating-secrets scheme using filter f and compression scheme Γ.

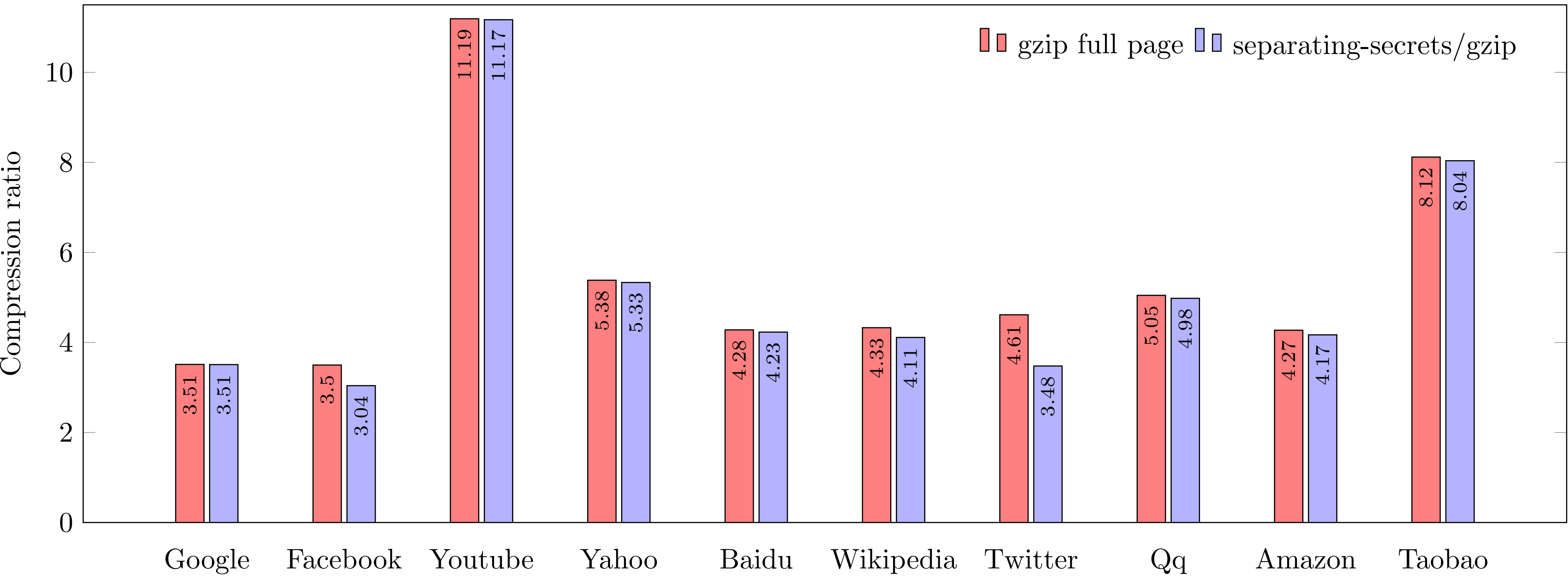
Then $\Pi \circ \mathrm{SS}_{f,\Gamma}$ is CCI-secure if Π is IND-CPA-secure.

$$\mathrm{Adv}^{\mathsf{CCI}}_{\Pi\circ\mathrm{SS}_{f,\Gamma},\mathcal{CK}}(\mathcal{A}) \leq q \cdot \mathrm{Adv}^{\mathsf{IND\text{-}CPA}}_{\Pi}(\mathcal{B}^{\mathcal{A}})$$

Experimental results

```
/value\s*=\s*"[A-Za-z0-9]+"|value\s*=\s*'[A-Za-z0-9]+'/
```

applied to HTML/Javascript/CSS on Alexa Top 10 websites



Discussion: separating secrets

Security:

- good (CCI) security,
  provided secrets really are separated

Compression:

- very good compression assuming few secrets and efficient filter

Caveats:

- Need a good filter
  - Data marked up to clearly delineate secrets
  - Some filters separate too much and too little
    - `/value="[A-Za-z0-9]*"/`
- Application support for separating/combining secrets

Technique 2: Fixed-dictionary compression

Idea: use a fixed (non-adaptive) dictionary

- Fix a dictionary that's suitable for your typical message distribution

- To compress a message, replace words in the dictionary with their index

Basic scheme: $\mathrm{FD}_{\mathcal{D},w}$

- $\mathcal{D}$: dictionary
  - e.g., $\mathcal{D} = \texttt{cookierecoveryattack}$
- w: length of substring to try replace

$$\mathrm{FD}_{\mathcal{D},4}.\mathrm{Comp}(\text{“}\texttt{recover the cookie}\text{”}) \to \texttt{7ver\_the\_1ie}$$

CRIME-like attack against fixed dictionary

- Attacker can try prefixes/suffices that try to match the beginning/end of cookie

- $D =$ `cookierecoveryattack`
- $ck =$ `iloveyou`

- Try $m' =$ `coo` so $m' \,||\, ck =$ `cooiloveyou`
- Try $m' =$ `ook` so $m' \,||\, ck =$ `ookiloveyou`
  - This one will be compressed => CRIME attack
- Success probability falls off ~exponentially

CR-security of fixed dictionary

Let Π be an encryption scheme.

Let $\mathcal{D}$ be a dictionary of d words each of length w.

Let $\mathcal{CK} = \Omega^n$.

$$\mathrm{Adv}^{\mathsf{CR}}_{\Pi \circ \mathrm{FD}_{\mathcal{D},w,\ell}}(\mathcal{A}) \leq \mathrm{Adv}^{\mathsf{IND\text{-}CPA}}_{\Pi}(\mathcal{B}) + 2^{-\Delta}$$

where

$$\Delta \geq \left(1 - d\left(1 - \left(1 - \frac{1}{|\Omega|^w}\right)^{n-3w+1}\right)\right) \cdot \log_2\left(|\Omega|^{n-2w} - |\Omega|^{n-2w} \cdot d\left(1 - \left(1 - \frac{1}{|\Omega|^w}\right)^{n-3w+1}\right)\right) .$$

Example parameters

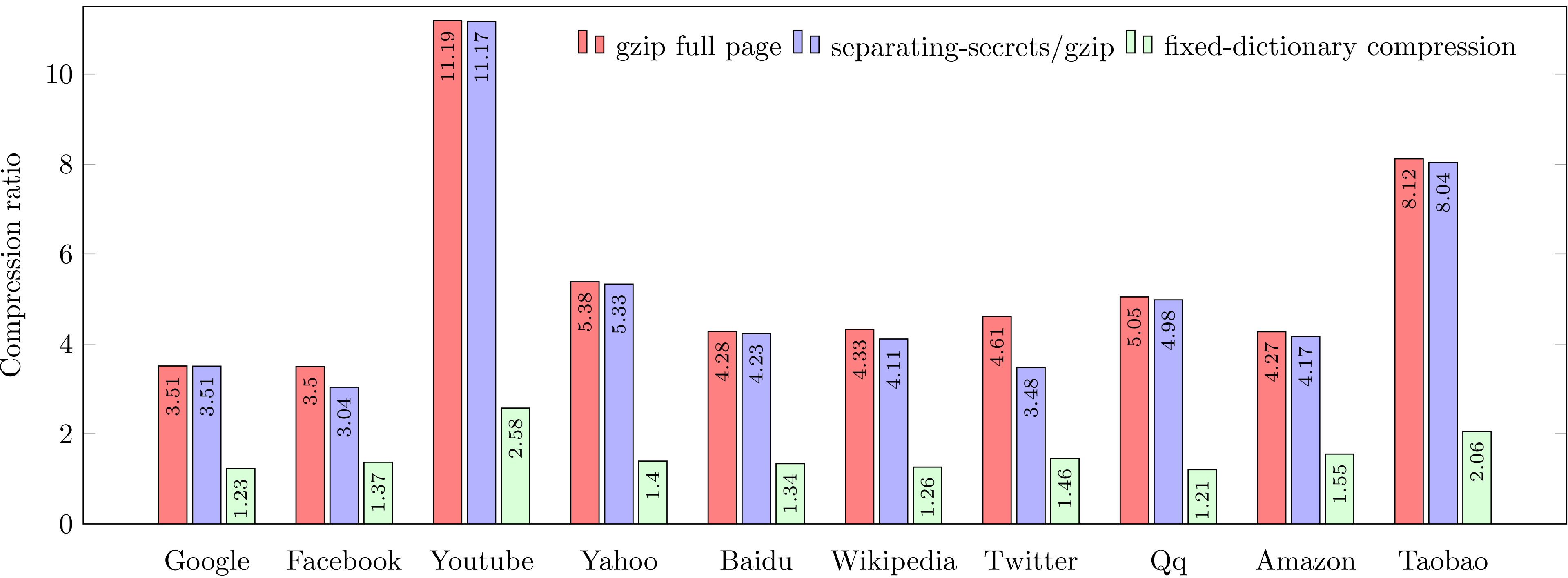
- cookies of $n = 16$ bytes
- dictionary of $d = 4000$ words
  each of length $w = 4$

=> $\Delta \geq 63.999695$

(compare with $8^{16} = 2^{128}$ bits of entropy)

Doubling d gives $\Delta \geq 63.999391$.

Experimental results



Discussion: fixed dictionary

Security:

- non-zero security (cookie recovery)
- not application dependent

Compression:

- poor compression

Conclusions

Kelsey/CRIME/BREACH attacks

- Combining user secrets with adversary input then compressing and encrypting leaks information

- Adaptive attacker can iteratively recover the secret

```
GET /?datr=A
Cookie: datr=DzK9VBnObWDqfL...
=> ciphertext len = 204
GET /?datr=B
Cookie: datr=DzK9VBnObWDqfL...
=> ciphertext len = 204
GET /?datr=C
Cookie: datr=DzK9VBnObWDqfL...
=> ciphertext len = 204
GET /?datr=D
Cookie: datr=DzK9VBnObWDqfL...
=> ciphertext len = 199
GET /?datr=Da
Cookie: datr=DzK9VBnObWDqfL...
=> ciphertext len = 205
```

Recommendations from BREACH attack

1. Disabling HTTP compression
2. Separating secrets from user input
3. Randomizing secrets per request
4. Masking secrets (effectively randomizing by XORing with a random nonce)
5. Length hiding (by adding a random number of bytes to the responses)
6. Rate-limiting the requests
7. Use non-adaptive compression algorithm

Summary of results

Security Definitions

- Cookie recovery (CR)
- Random cookie indistinguishability (RCI)
- Chosen cookie indistinguishability (CCI)

- Relations and separations
  - CCI => RCI => CR
  - ER-IND-CPA => IND-CPA => CCI

Techniques

Separating secrets:

- CCI-secure with a good filter

Fixed-dictionary:

- CR-secure with high-entropy secrets

Unsatisfying answers

- **Separating secrets** technique requires application changes or a good context-specific filter + application changes to be secure
- **Fixed dictionary** compression is more reliably secure but much poorer compression
- Both still don't protect the rest of the plaintext

- *Unavoidable*: Basic combination of compression and encryption will always leak some information about the plaintext

Surely we can do something better?

Something interesting: HPACK (RFC 7541)

- Header compression for HTTP/2
- Every header and every component of every header is compressed in its own context
  - Implementations can disable compression for "valuable" headers
- Uses a pre-established static dictionary + a dynamic dictionary
- Body still compressed all-at-once using gzip

- Merits more investigation

Protecting encrypted cookies from compression side-channel attacks

Janaka Alawatugoda, Douglas Stebila (QUT), Colin Boyd (NTNU) ▪ FC 2015 ▪ eprint 2014/724

Security Definitions

- Cookie recovery (CR)
- Random cookie indistinguishability (RCI)
- Chosen cookie indistinguishability (CCI)
- Separations and relations

Techniques

Separating secrets:

- CCI-secure with a good filter

Fixed-dictionary:

- CR-secure with high-entropy secrets

Future Directions

- Analysis of HPACK
- Where else is compression used?