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Affogato: Runtime Detection of Injection Attacks for Node.js

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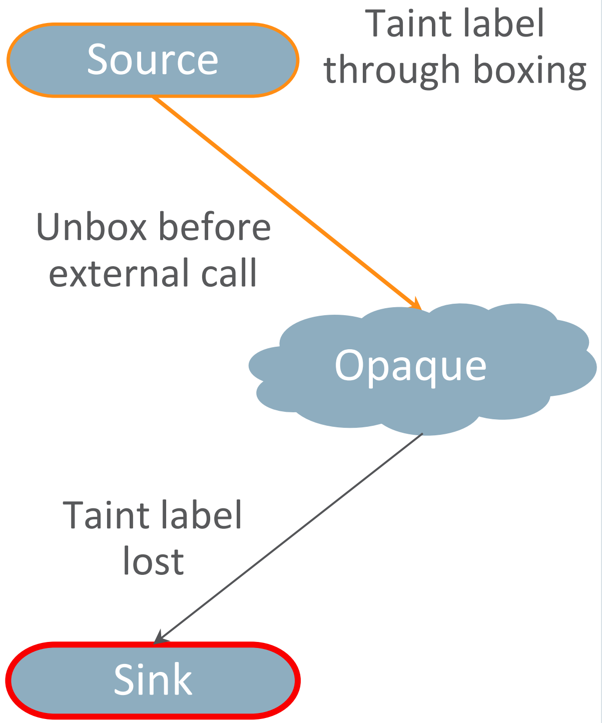
Why Investigate Node.js Security?

- Direct access to OS resources (file system, network) and databases
- No built-in security mechanisms
- Our Focus: taint analysis to detect injection attacks
  - **Still #1 vulnerability in OWASP Top 10 2017**
  - Web-servers are most popular class of Node.js applications in Github
    - Express: 39.1k ★ , Koa: 22k ★ , hapi: 9.7k ★, Restify: 8.4k ★, Fastify 7.5k ★

Challenges for Dynamic Taint Analysis

- Engine instrumentation approaches:
  - Engine creates and propagates taint labels
  - Very hard to maintain if you don’t own the engine, not flexible, too low-level
- Source instrumentation approaches:
  - Taint labels applied by wrapping primitives and extending objects with taint fields
  - Brittle, unsound w.r.t opaque code (see figure on right)



Prevalence of Opaque code

- Key observations
  - Calls to opaque functions are prevalent
  - JavaScript coerces most values to strings at runtime in Node.js
  - Taint-sensitive locations (i.e., operations that sanitise, validate or transform tainted inputs) are few

Built-in Object	Mean	Standard Deviation
Array	9.3	7.05
String	24.6	12.82
RegExp	1.73	4.84
All	62.47	21.41

Percentage of calls to opaque functions in our benchmarks

The Affogato Approach

- Instrumentation-based grey-box taint analysis
  - Combines **black-box** reasoning with **white-box** program analysis
  - White-box analysis at selective taint-sensitive locations (watchpoints)
    - At watchpoints, values are observed but never modified (non-intrusive)
  - Black-box reasoning infers data flows between watchpoints
- Non-intrusive analysis works well with source-level instrumentation
  - We use Jalangi2

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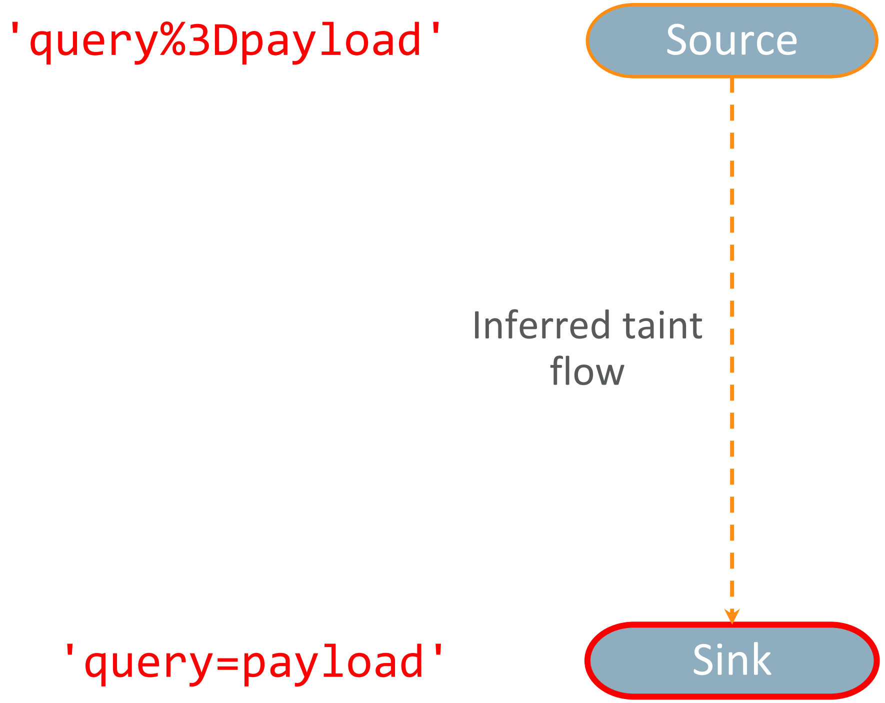
Black-box Taint Inference Between Watchpoints

- Uses string similarity to infer taint flows.
  - Based on edit-distance Pros:
    - Lightweight, i.e. limited amount of instrumentation
    - Robust (e.g. does not break the application)
  - Cons:
    - May introduce spurious taint flows (FPs)
    - May miss valid taint flows (FNs)



'query%3Dpayload'

Source

Inferred taint flow

'query=payload'

Sink

White-box Program Analysis

- At selective watchpoints
  - Handles string transformations
  - Unpacks strings
- Introduces the concept of dynamic request sensitivity
  - Deals with asynchronous nature of Node.js

White-box Program Analysis

String transformations

- At selective watchpoints, Affogato
  - Preserves taints
  - Unpacks strings
  - Removes taints (sanitizer)

```
//url is "localhost:8000?%24where=1%3D%3D1"
function (req, res) {
  var query = querystring.parse(req.url);
  //query is {"$where":"1==1"}
  mongo.collection.find(escape(query), {},
    function(e, docs)){});
}
```

White-box Program Analysis

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  - **Preserves taints**
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White-box Program Analysis

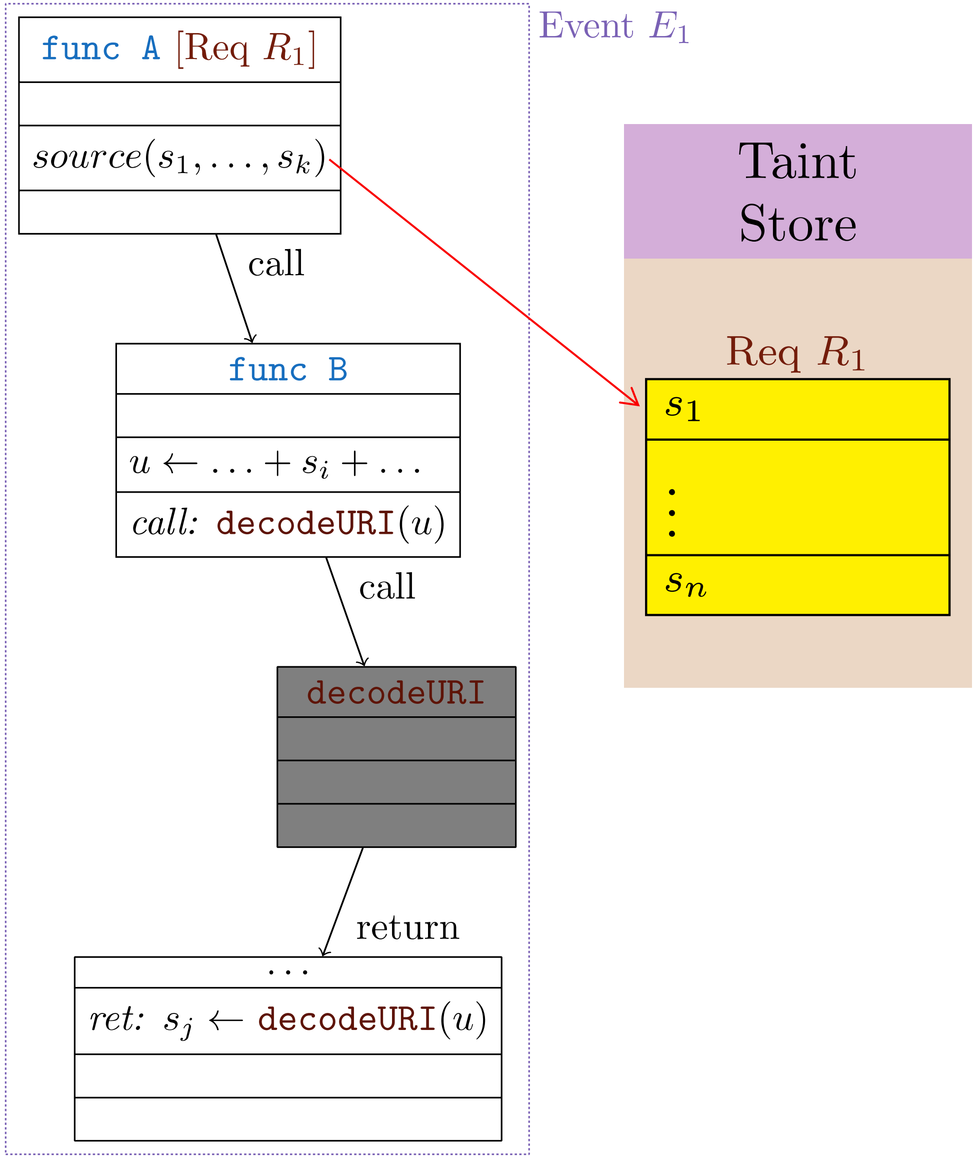
Dynamic request sensitivity

- Intertwined computations from different requests
  - Node.js allows serving multiple requests asynchronously
  - Might result in FP, e.g., tainted string values from request A inadvertently correlate with untainted string values from request B
- Request-sensitivity
  - Analogous to call site or object sensitivity in static analysis
  - Avoids cross-request correlations
  - We use request IDs to correlate request and response objects

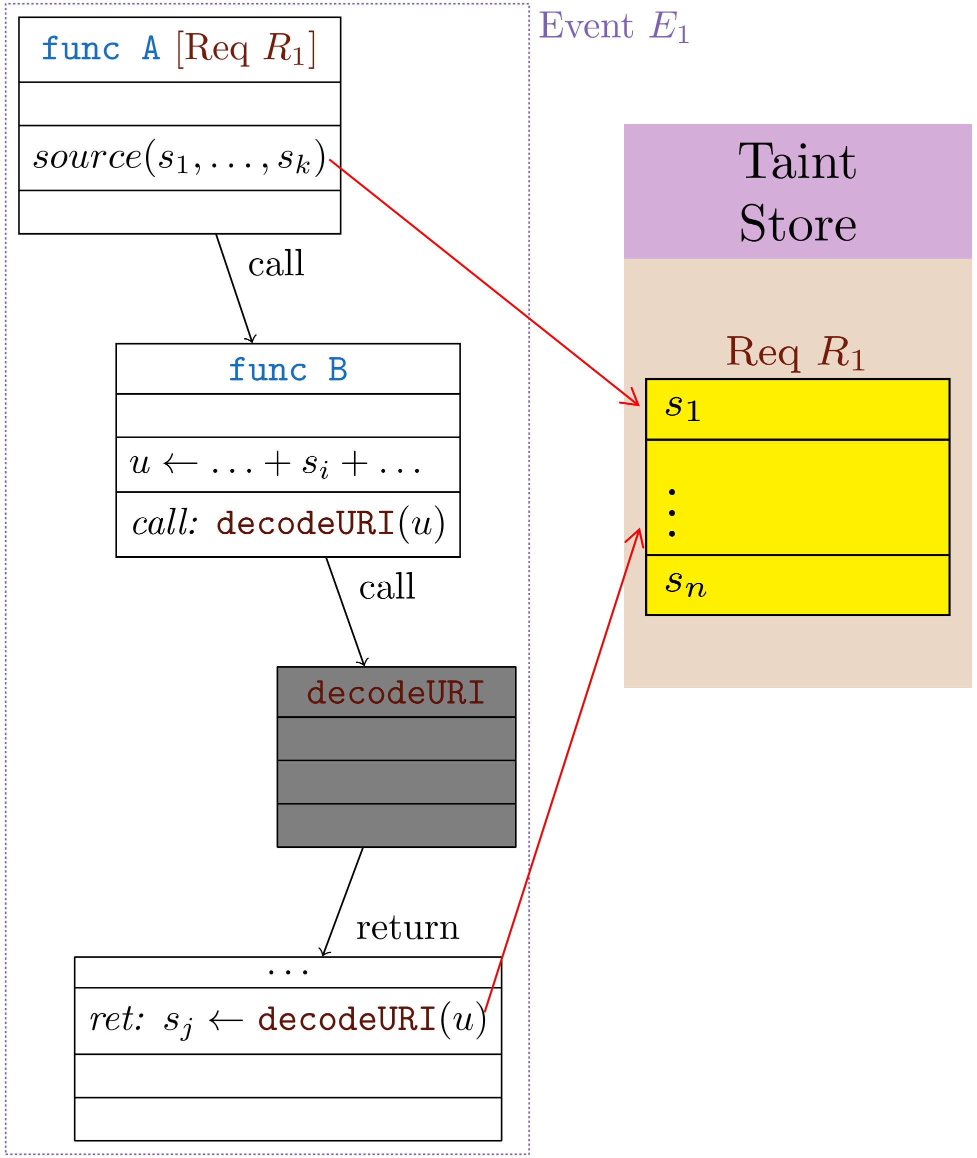
Example

Taint
Store

Example


Event E_1
func A [Req R_1]
$source(s_1, \ldots, s_k)$
call
func B
$u \leftarrow \ldots + s_i + \ldots$
call: decodeURI(u)
call
decodeURI
return
...
ret: $s_j \leftarrow$ decodeURI(u)
Taint Store
Req R_1
s_1
$\vdots$
s_n

Example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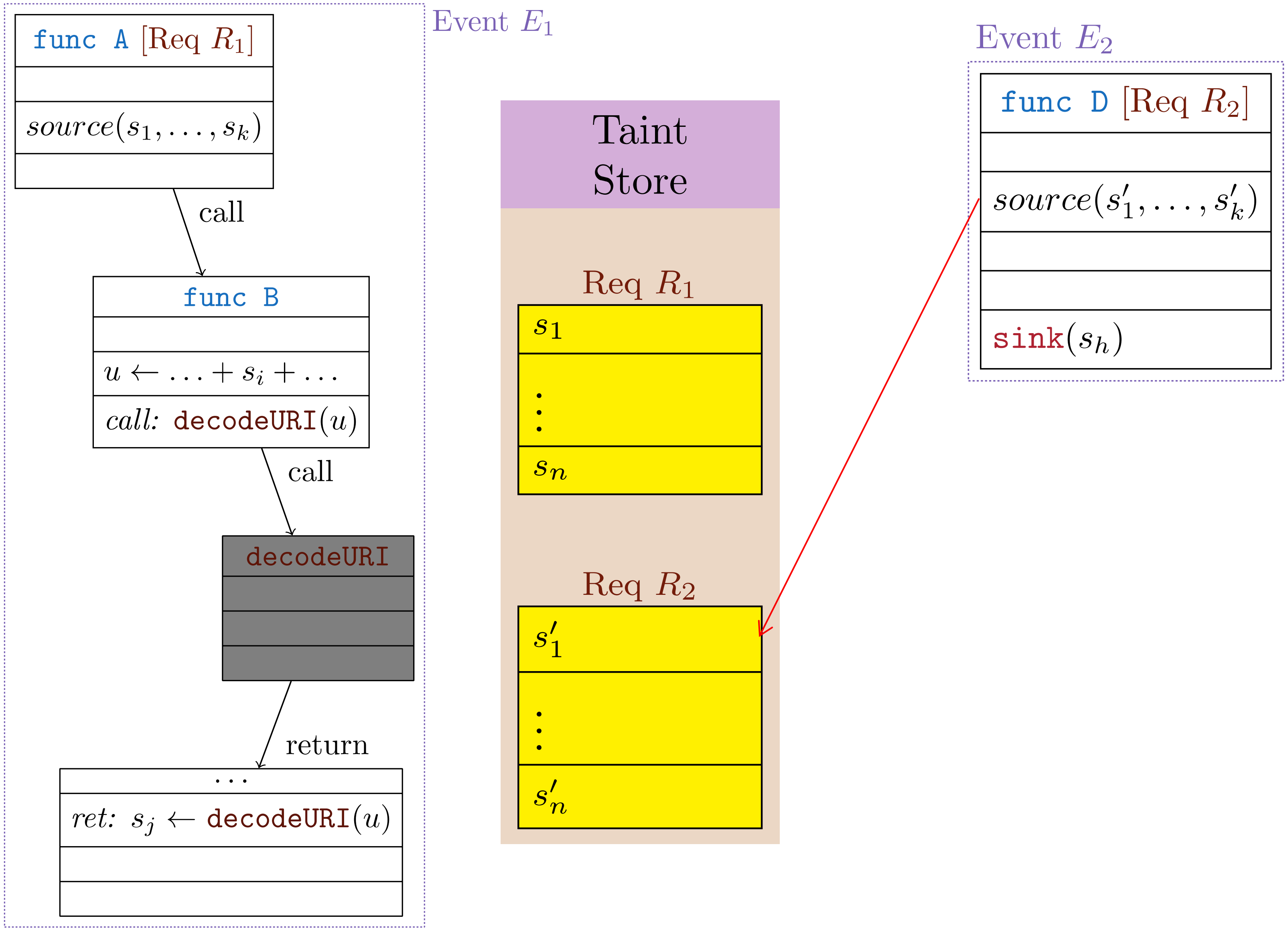

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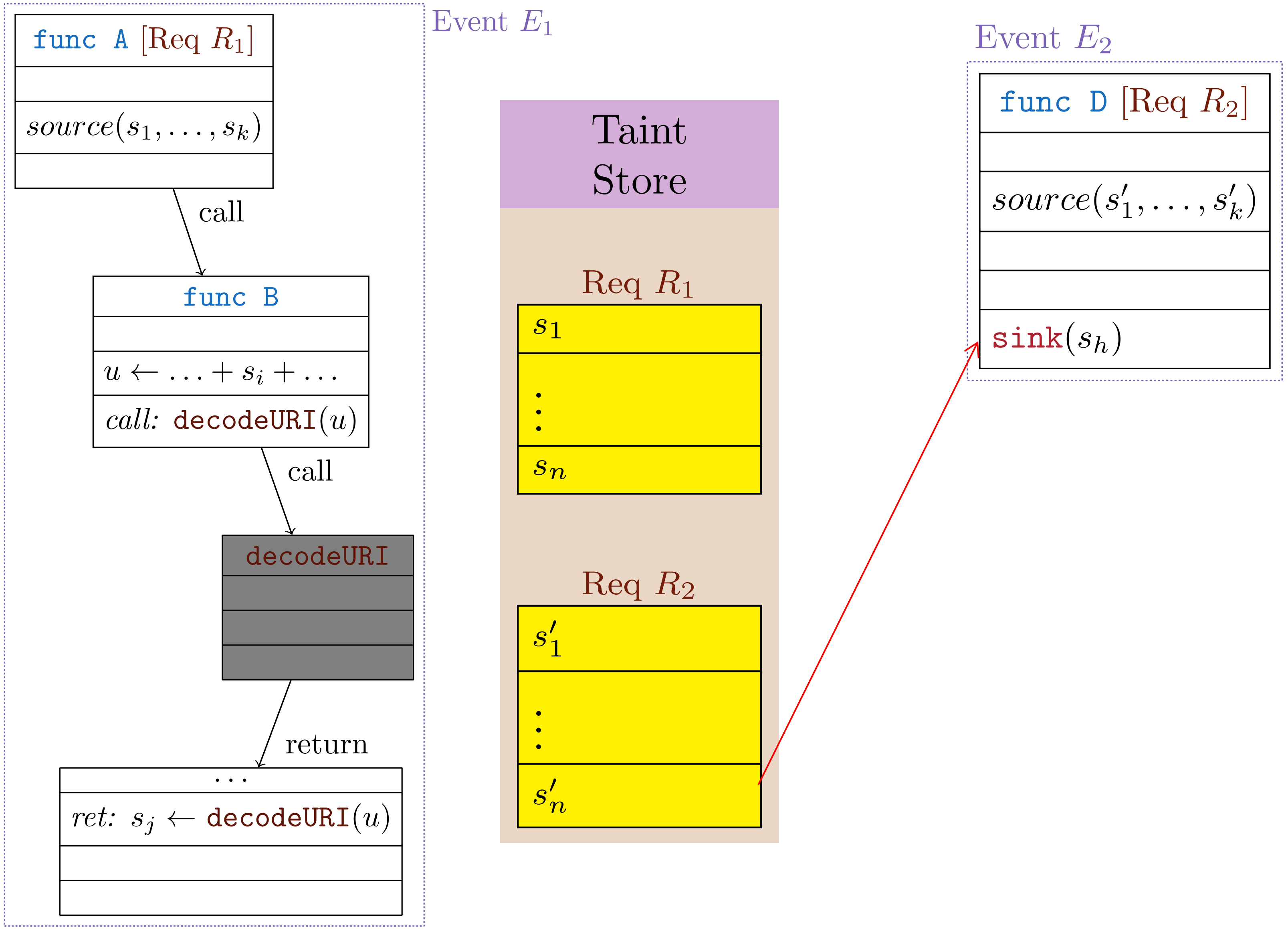
Example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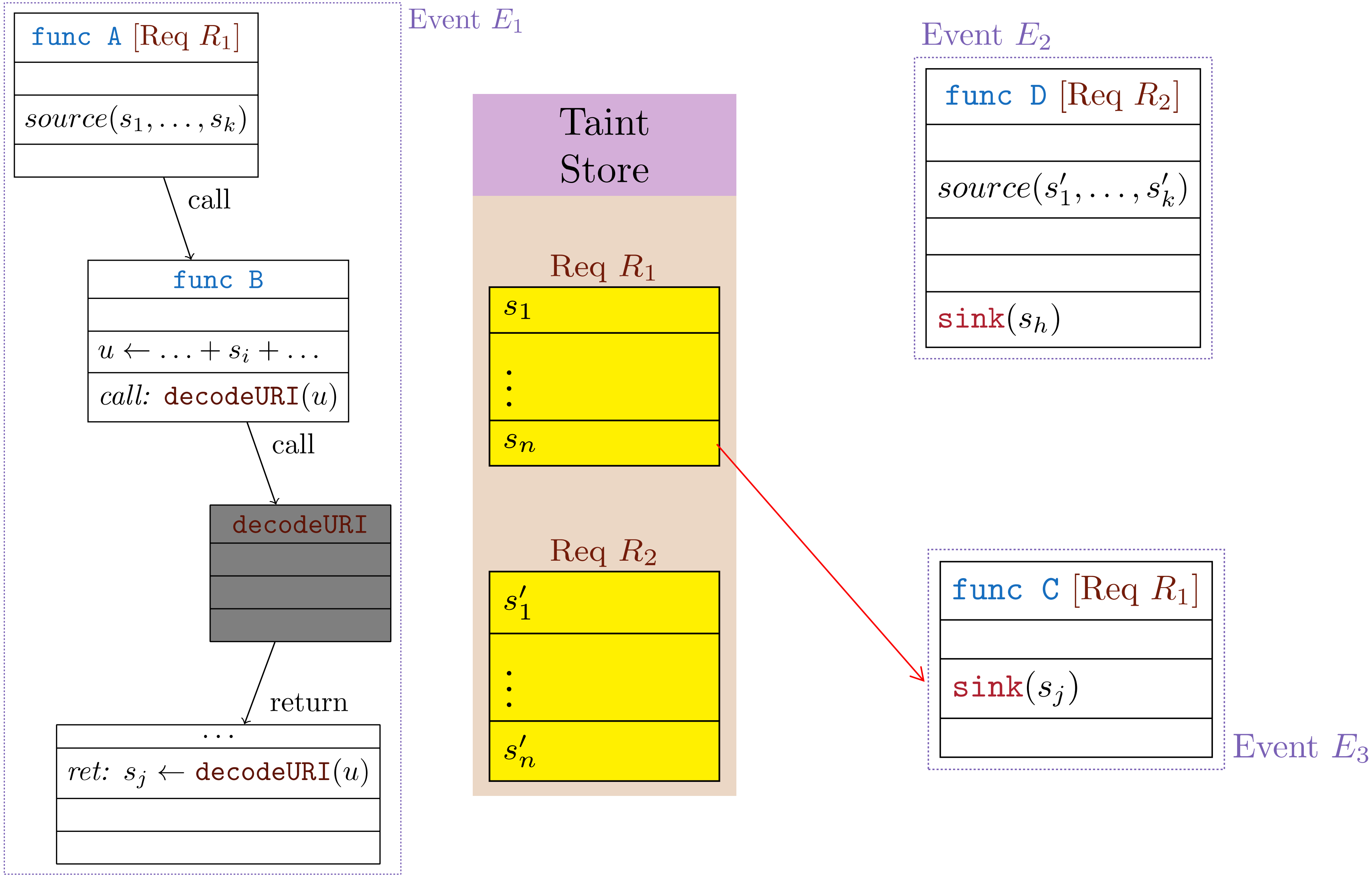
Taint Store
Req R_1
s_1
$\vdots$
s_n
Req R_2
s'_1
$\vdots$
s'_n
Event E_2
func D [Req R_2]
$source(s'_1, \ldots, s'_k)$
sink(s_h)

Example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s_n
Req R_2
s'_1
$\vdots$
s'_n
Event E_2
func D [Req R_2]
$source(s'_1, \ldots, s'_k)$
sink(s_h)
func C [Req R_1]
sink(s_j)
Event E_3

Implementation

- We use introspection to identify watchpoints based on configurations
  - To get reference to runtime objects
  - In contrast with signature-based approaches
  - E.g., functions are first-class citizens
    - so both `send` and `req.end` should be considered sinks when

```
var send = req.end
```

- Instrumentation
  - Currently we use Jalangi2
  - We plan to move to NodeProf, a new instrumentation framework for GraalVM
    - Supports ES6+
    - Features: selective instrumentation, built-in and library scope

Evaluation

- Average (1000 exec.) runtime overhead:
  - Instrumentation: 4.70 ×
  - Analysis: 1.19 ×

Benchmark	Finds vuln.	FP
Node Advisory	Yes	No
Node Advisory (fixed)	No	No
Synode [C-A. Staicu et al. NDSS'18]	Yes	No
NodeGoat	Yes	No

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- Effectiveness
  - No false positives
  - Sanitisers
  - Request sensitivity removes 3 FPs in mongui
  - Practicality
    - No FP even when fuzzed
    - Synode times out (1 hour) and prevents load of NodeGoat

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Conclusion

- We presented a **grey-box** taint analysis for Node.js
  - Supports opaque code
  - Successfully analyzes real-world applications
  - Can be more precise with more sophisticated program analysis
- This is just a starting point to find the sweetspot

Black-box reasoning

Sound and precise analysis

Questions?

New instrumentation framework for Node.js: NodeProf running on **GraalVM**
https://github.com/Haiyang-Sun/nodeprof.js

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Affogato is an Italian dessert where **hot** espresso is poured over **cold** ice cream.

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