Taint Analysis via CFL-Reachability

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03, January 2026

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- Examples

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- Taint analysis is a data-flow–based static analysis

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Core Question:

Does tainted data flow from a source to a sink along a valid execution?

Example: SQL Query Template

Intended Query

```
 SELECT balance
FROM AcctData
WHERE name = ’:n’ AND password = ’:p’
```

Malicious User Input

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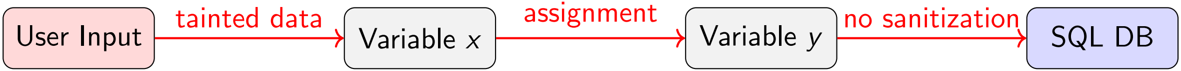
- Password check is commented out
- Sensitive data is leaked

Taint Propagation Graph



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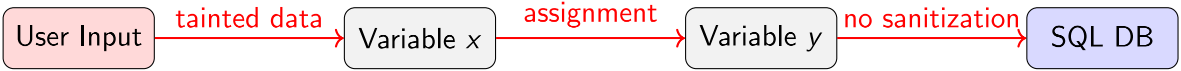

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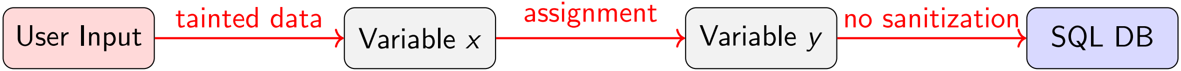

- Nodes represent program entities (variables or functions)
- Edges represent labeled data-flow relations

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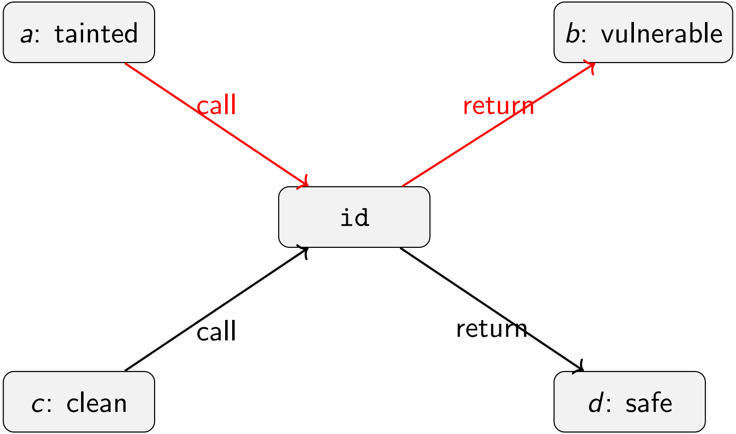
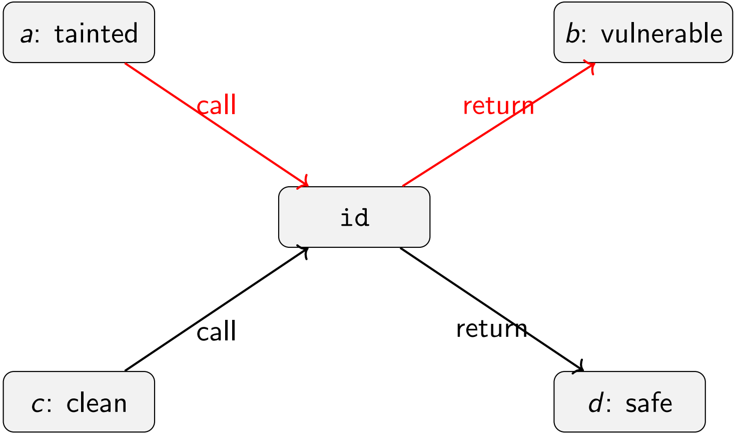
- Taint behavior depends on the calling context
- Context-insensitive analysis merges incompatible flows

Context-Insensitive Call Graph



Context-Insensitive Call Graph



Spurious taint flow appears due to context merging.

Invalid Reachability Path

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$$\text{call}_{\text{clean}} \;\; \text{return}_{\text{tainted}} \quad \text{(invalid)}$$

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- Σ: flow actions (call, return, assign)

Paths and Labels

A path

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Only some words correspond to valid executions.

Grammar for Valid Taint Flows

$$F \;\rightarrow\; FF \;\mid\; call_i \; F \; return_i \;\mid\; assign \;\mid\; \varepsilon$$

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- $\mathit{call}_i / \mathit{return}_i$: Procedure invocation and return matching call site i
- `assign`: Local data flow within a procedure
- **Result:** Only matching pairs $(\mathit{call}_i, \mathit{return}_i)$ are derivable. This filters out paths that do not correspond to feasible call stacks.

Taint Analysis as CFL-Reachability

Problem

Given $s, t \in V$, does there exist a path π from s to t such that

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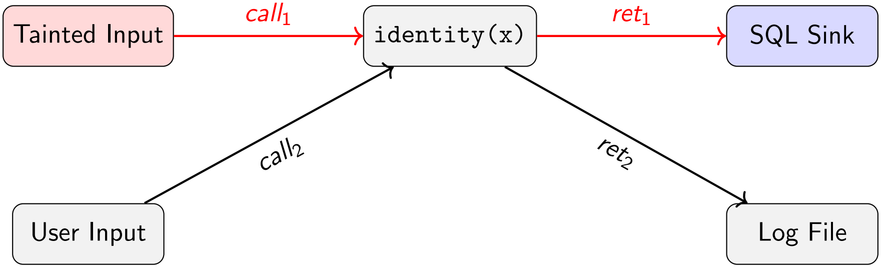
This exactly captures context-sensitive taint analysis.

Example 1: The Identity Crisis (Context Matching)



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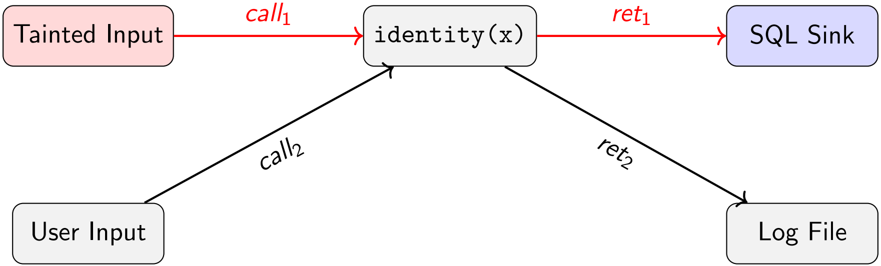

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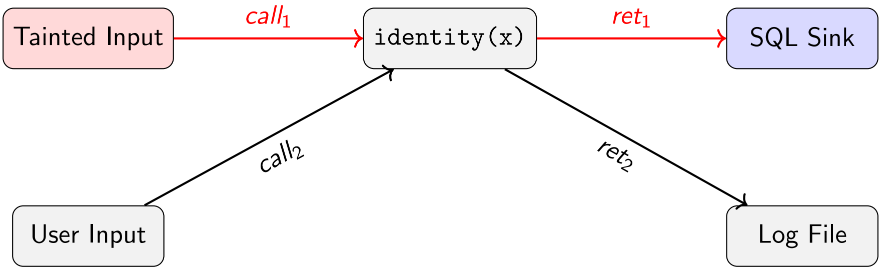

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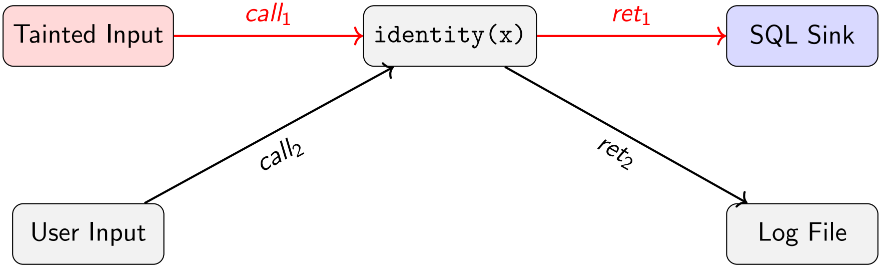

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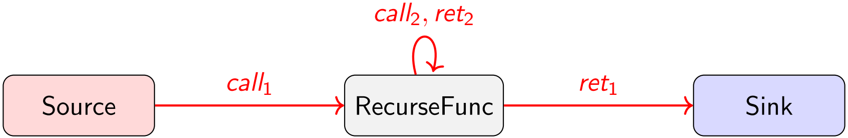
- **CFL Check:** $call_1 ret_2$ is **not** in $L(\mathcal{G})$ because indices 1 and 2 don't match.
- **Insight:** Grammar prevents tainted data from "leaking" into different call sites.

Example 2: Deep Recursion (Self-Referential Flow)



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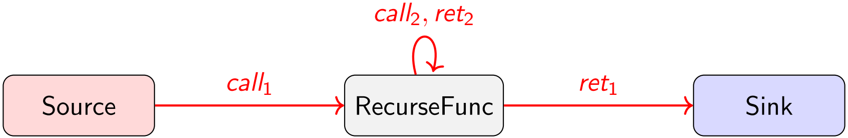

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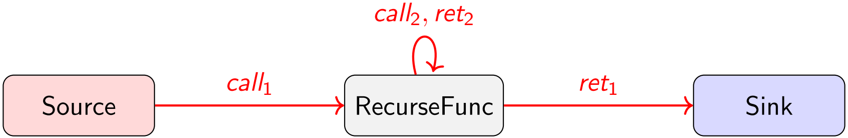

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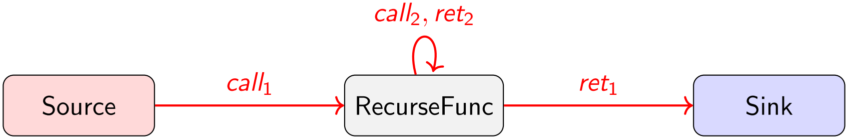

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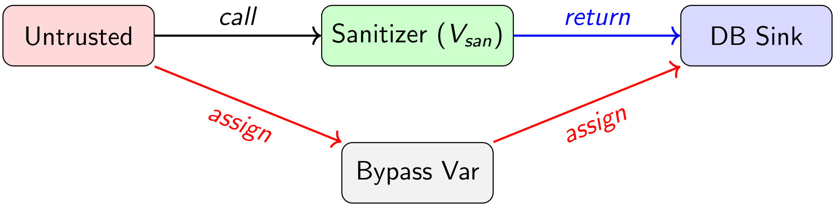
- **Word:** $\ell(\pi) = call_1(call_2)^n(ret_2)^n ret_1$.
- **CFL Validation:** This is a classic $a^n b^n$ structure. The grammar $F \rightarrow call_i F ret_i$ naturally accepts balanced recursive calls, ensuring the data eventually returns to the correct caller.

Example 3: Sanitization Logic (Path Selection)



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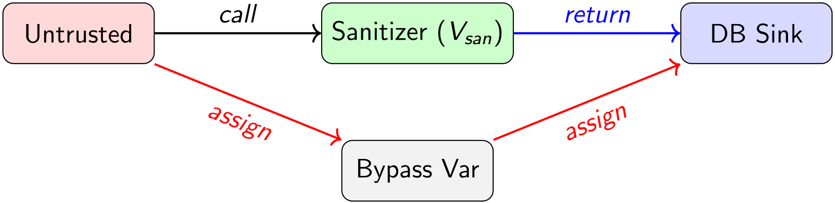

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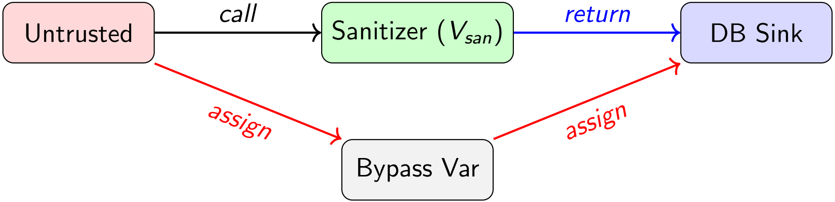

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- **Vulnerable Path:** $\pi_{bot} = (\text{Untrusted} \to \text{Bypass} \to \text{Sink})$. $\ell(\pi_{bot}) = assign \cdot assign \in L(\mathcal{G})$ and avoids V_{san}. **Violation detected.**

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- Context insensitivity yields false positives
- Valid executions form a context-free language
- CFL-reachability provides principled context sensitivity

References

- Aho, Alfred V., et al. Compilers: Principles, Techniques, and Tools. 2nd ed., Pearson Education, 2006.

Thank you

Questions?