Mind Your Metrics: How (Not) to Evaluate a Fuzzer

Kyle Dewey, Mehmet Emre, Ben Hardekopf

Teaser

- We argue that fuzzers are best evaluated by a quantitative comparison of unique bugs found
- We define an automated technique to accurately identify unique bugs found, dramatically simplifying this comparison
- We show that commonly used alternative metrics often disagree with the metric of unique bugs found, making them ultimately useless
- 24 new bugs found in SMT solvers (including Z3); **correctness** bugs found in each solver tested

Outline

- Background
- Metrics used in the literature
- An automated approach
- How metrics compare
- Conclusion

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MathSAT 5

Z3

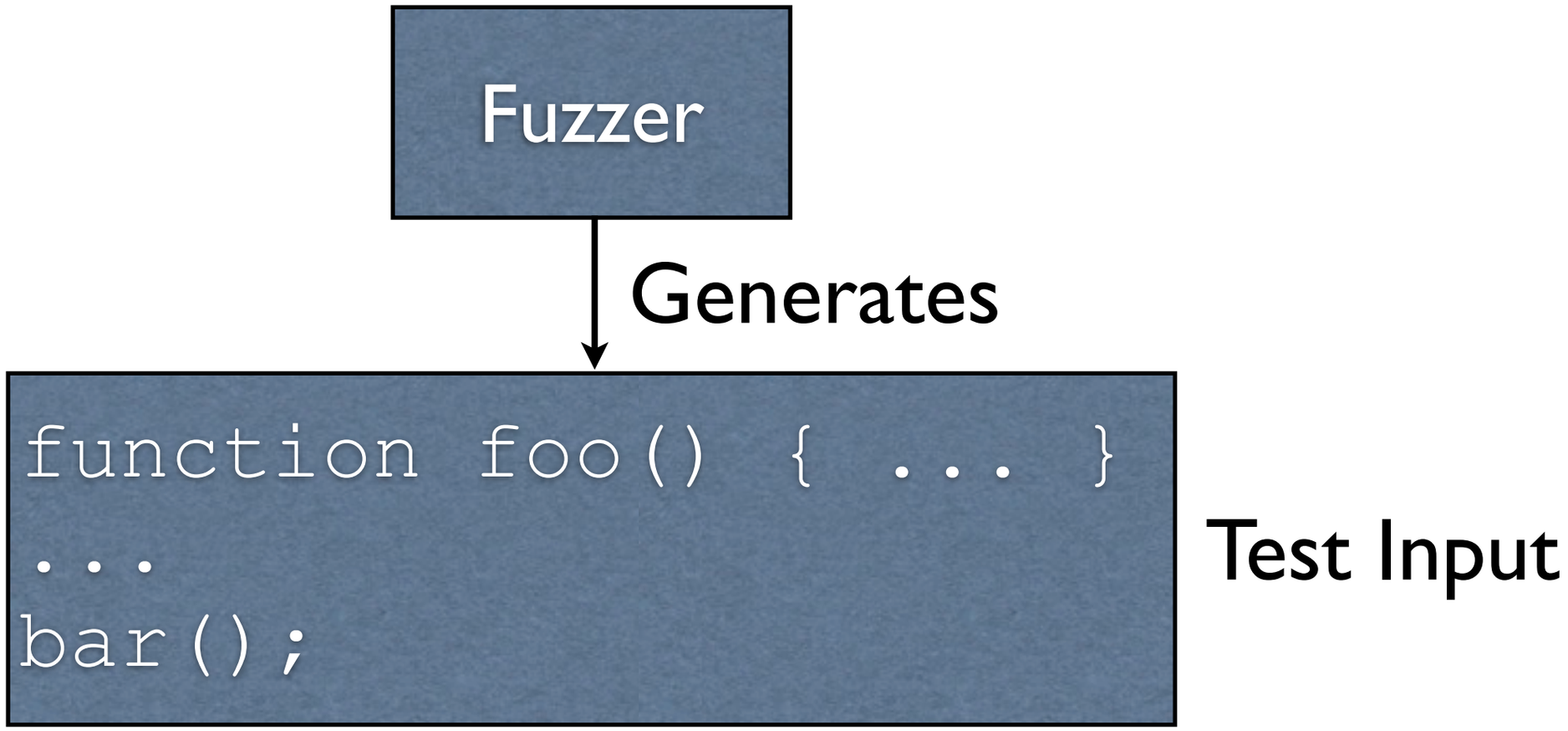
Automated Testing Motivation

- Writing correct software is hard
- Writing tests is time-consuming
- CPU cycles are cheap

Background: Fuzzing and Differential Testing

- Idea: generate an input via some process, known as a **fuzzer**
- Run input on different implementations
- If implementations disagree on result, bug has been found

Fuzzer


Fuzzer
Generates
function foo() { ... }
...
bar();
Test Input

Fuzzer

Generates

```
function foo() { ... }
...
bar();
```

Test Input

Executed on

Fuzzer

Generates

```
function foo() { ... }
...
bar();
```

Test Input

Executed on

Produce

42

42

53

Fuzzer

Generates

```
function foo() { ... }
...
bar();
```

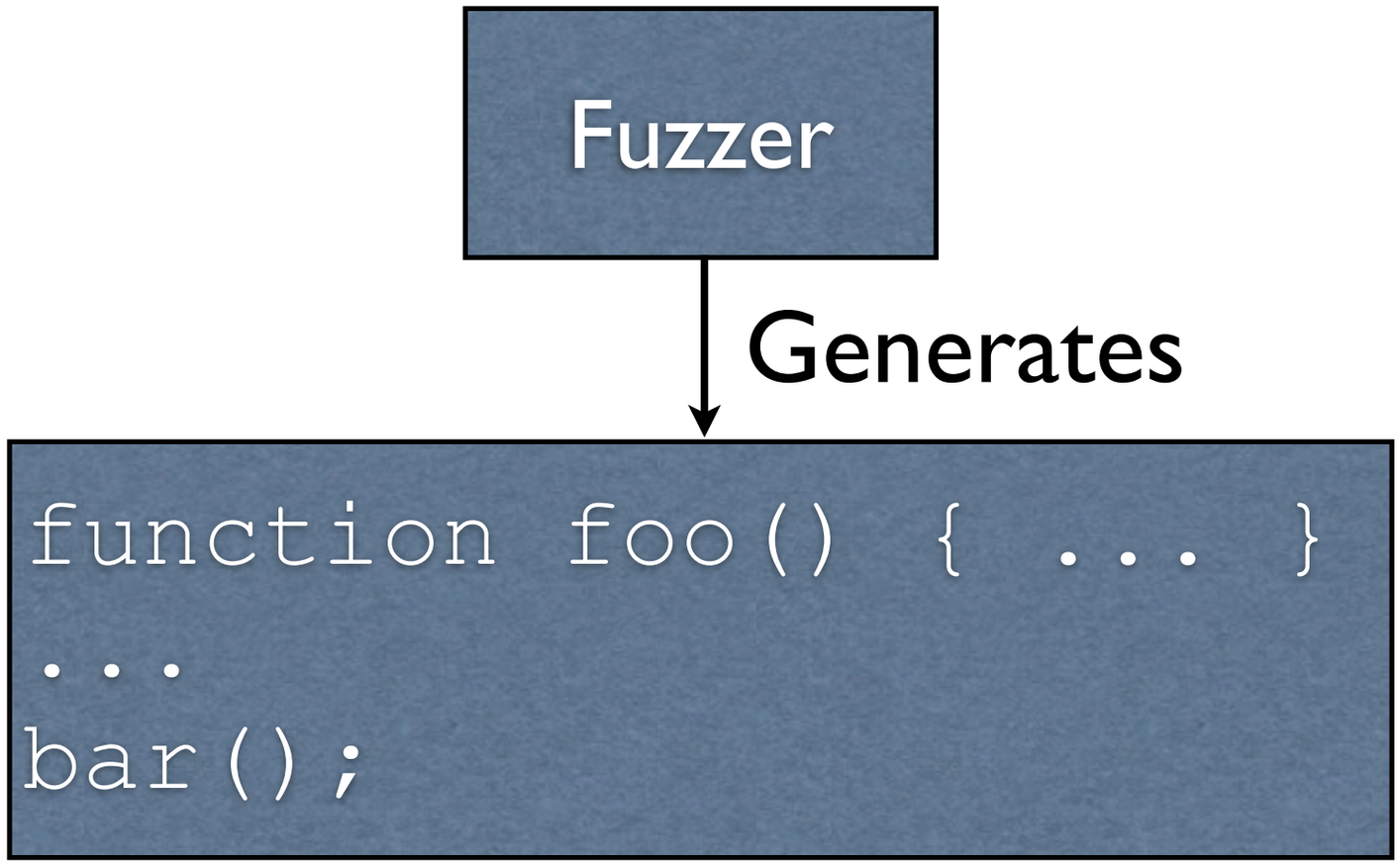
Test Input

Executed on

Produce

42

42 Mismatch: bug 53


Fuzzer
Generates
function foo() { ... }
...
bar();

Fuzzer 1

Generates

```
function foo() { ... }
...
bar();
```

Fuzzer 2

Generates

```
function baz() { ... }
...
blah();
```

Fuzzing is Broad

- Fuzzing is an active area of research
  - Many existing tools available
  - Many more fuzzing techniques available

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  - Many existing tools available
  - Many more fuzzing techniques available

- From a user perspective: which fuzzing technique should I apply for my domain?
- From a research perspective, why do we need a new fuzzing technique?

Answering these questions requires both a metric to compare fuzzers and a way of gathering this metric.

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“Obvious” metric: Unique Bugs Found per Unit Time

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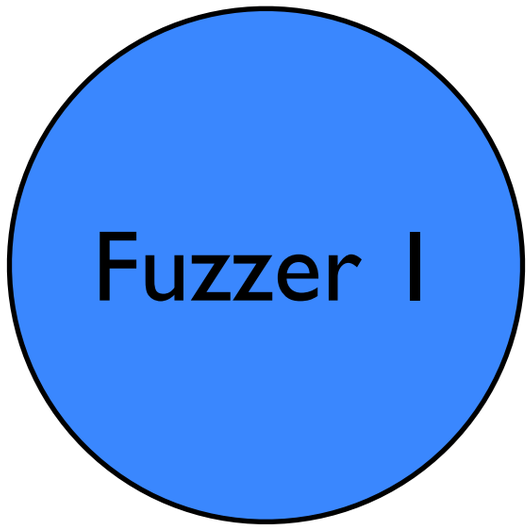
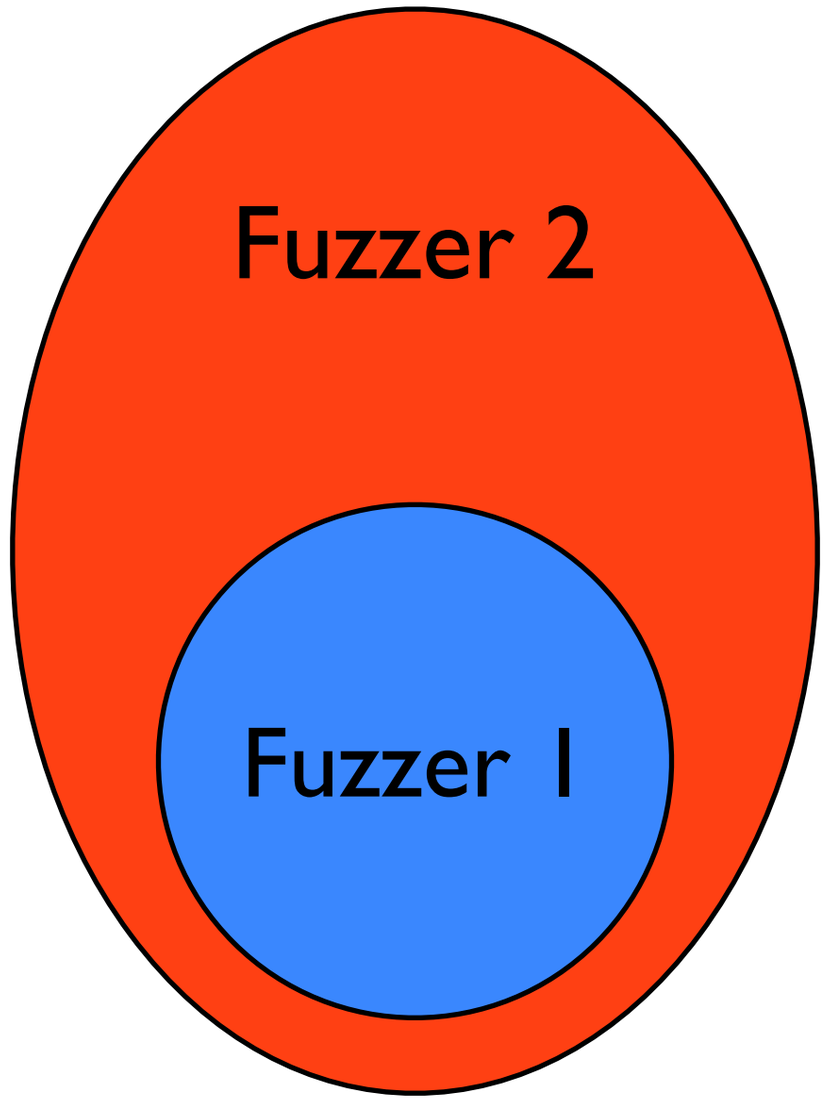
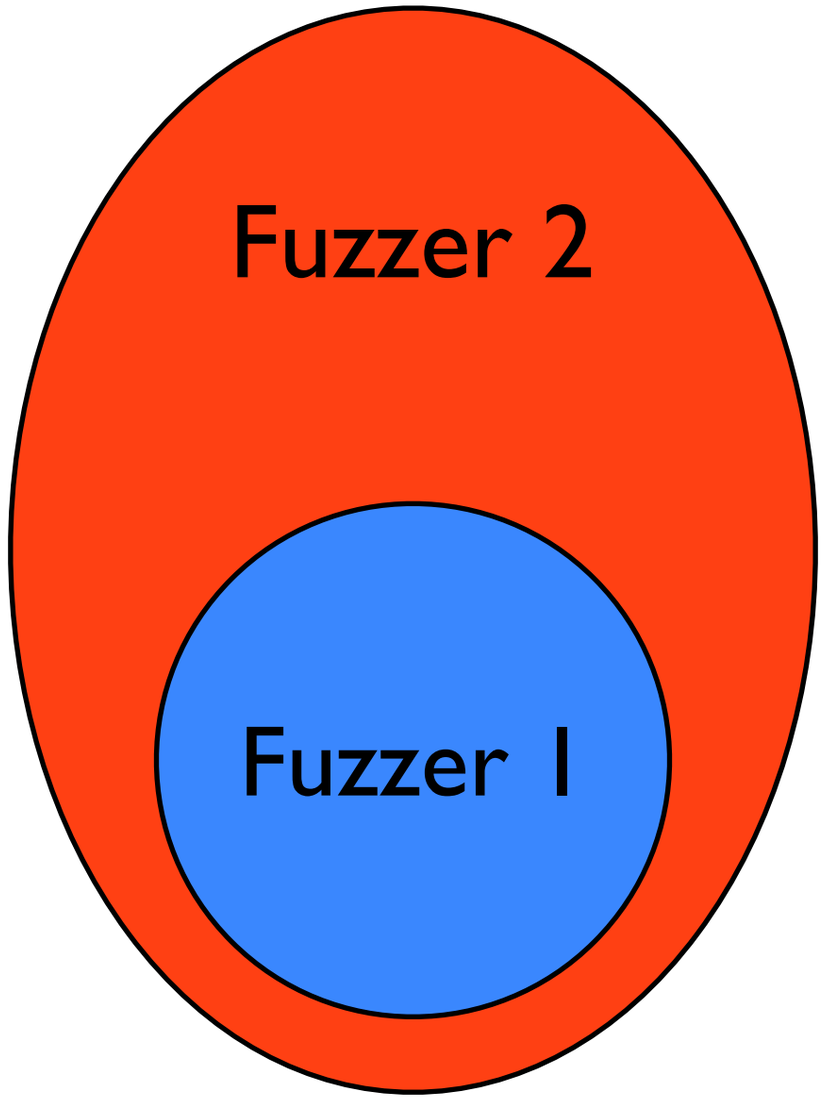


“Obvious” metric: Unique Bugs Found per Unit Time



“Obvious” metric: Unique Bugs Found per Unit Time

Clear winner:
Fuzzer 2



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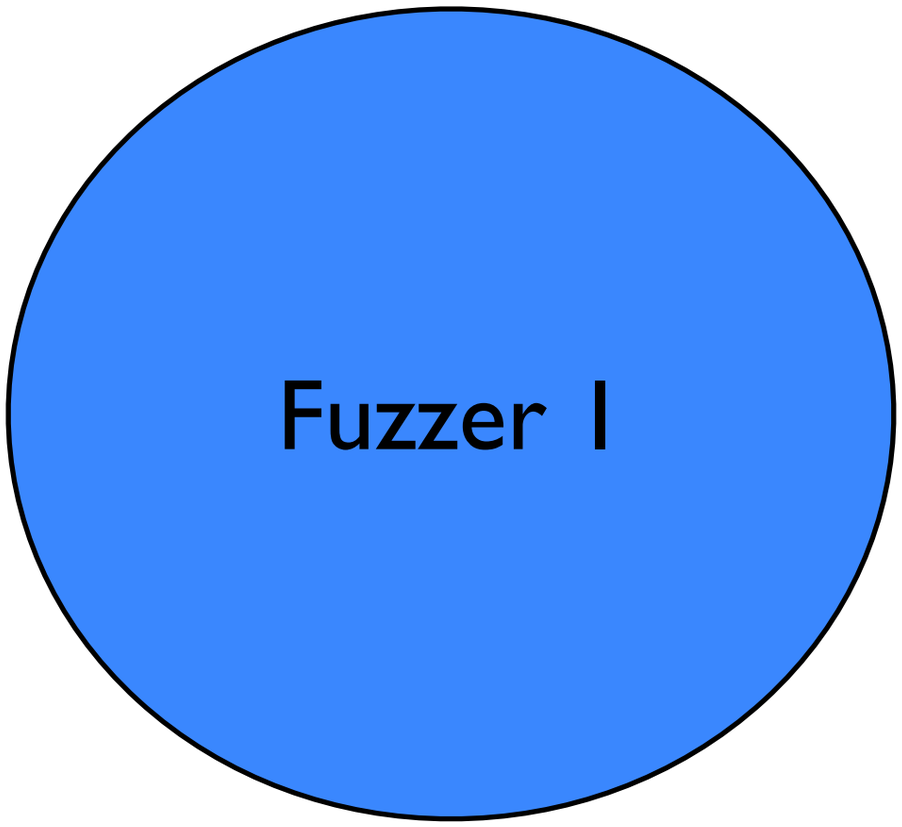
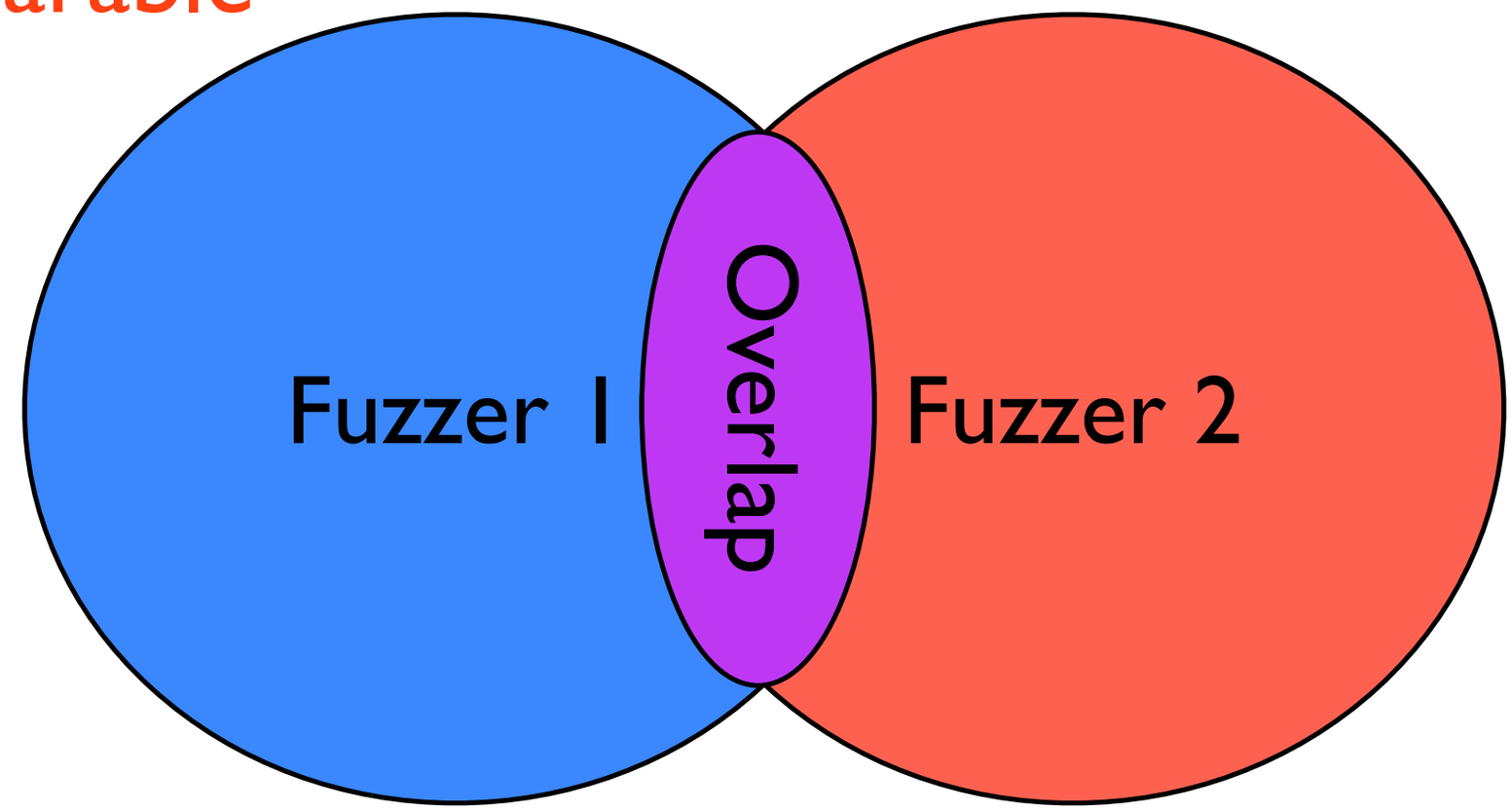


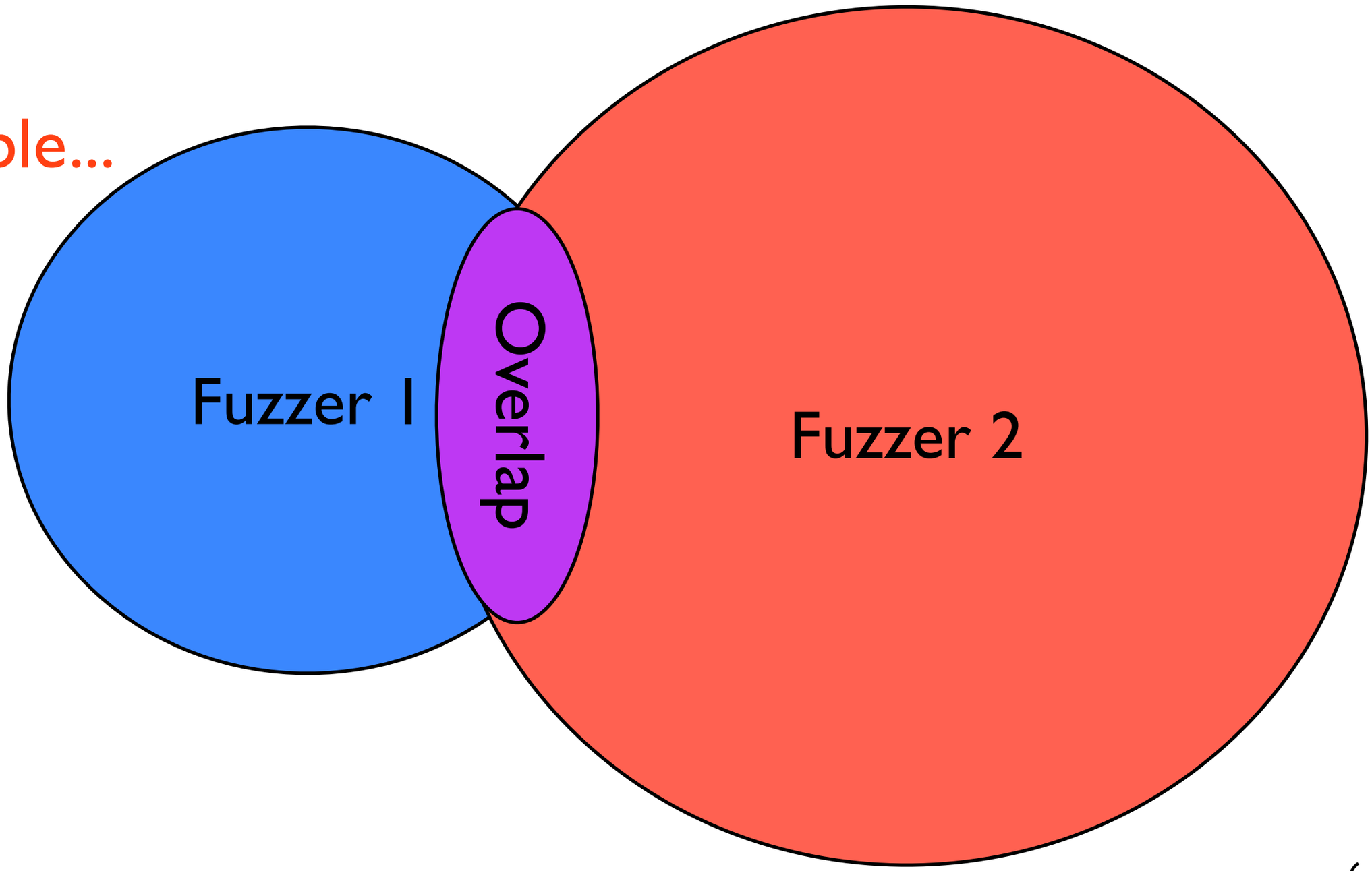
“Obvious” metric: Unique Bugs Found per Unit Time

Non-comparable



“Obvious” metric: Unique Bugs Found per Unit Time

Non-comparable...



“Obvious”

- This metric (unique bugs found) is **seldom** used
- Underlying reason why: it is **exceedingly** difficult to collect

Fuzzer

Generates

```
function foo() { ... }
...
bar();
```

Test Input

Executed on

Produce

42

42 Mismatch: bug 53

Fuzzer

Generates

```
function baz() { ... }
...
boo();
```

Test Input

Executed on

Produce

8

4 Mismatch: bug 8

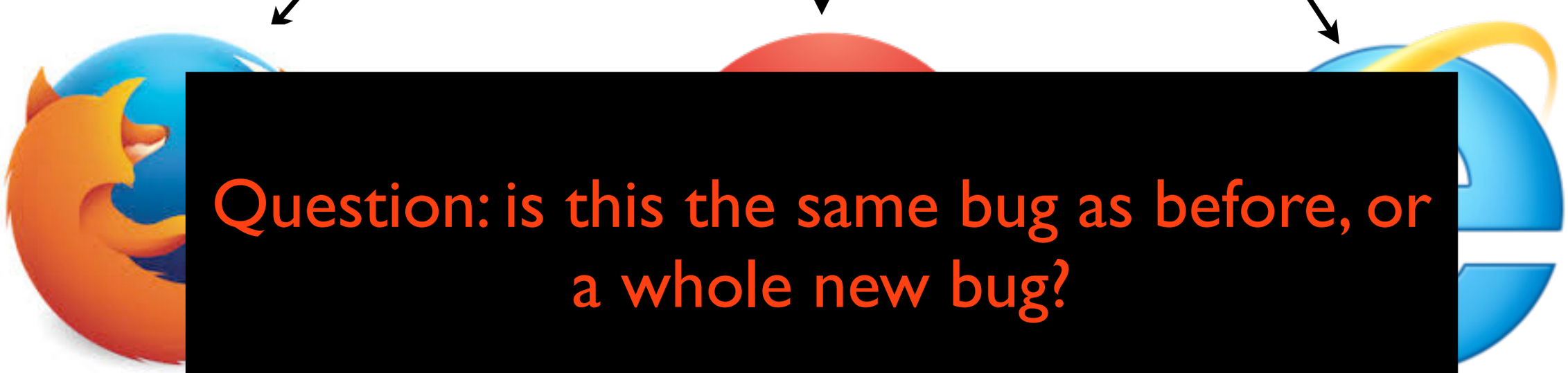
Fuzzer

Generates

```
function baz() { ... }
...
boo();
```

Test Input

Executed on



Question: is this the same bug as before, or a whole new bug?

Produce

8

4 Mismatch: bug 8

Unique Bugs?

- Ultimately, only the developers can answer this question
- Existing approaches require developer feedback and lots of manual effort
- End result: only **one** quantitative comparison of different fuzzing techniques in the literature uses this metric (that we know of), and it **was done incorrectly**

Workaround

- A number of "surrogate" metrics have been used, which are more easily collected
- The fundamental validity of these metrics has never before been evaluated

Surrogate #1: Crashes with Stack Traces

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Input: `217`

Output:

```
ASSERTION VIOLATION: line 32 in main.c
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Input: `217`

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Input: `438`

Output:

```
ASSERTION VIOLATION: line 32 in main.c
```

Surrogate #1: Crashes with Stack Traces

Input: `217`

Output:

```
ASSERTION VIOLATION: line 32 in main.c
```

Input: `438`

Output:

```
ASSERTION VIOLATION: line 32 in main.c
```

Input: `60`

Output:

```
ASSERTION VIOLATION: line 91 in foo.c
```

Surrogate #1: Crashes with Stack Traces

Input: `217`

Bug 1

Output:

```
ASSERTION VIOLATION: line 32 in main.c
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Input: `438`

Output:

```
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```

Input: `60`

Output:

```
ASSERTION VIOLATION: line 91 in foo.c
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Surrogate #1: Crashes with Stack Traces

Input: `217`

Bug 1

Output:

```
ASSERTION VIOLATION: line 32 in main.c
```

Input: `438`

Output:

```
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```

Input: `60`

Bug 2

Output:

```
ASSERTION VIOLATION: line 91 in foo.c
```

Surrogate #1: Crashes with Stack Traces

- Problem: ignores correctness bugs entirely
    - In so doing, assumes that crash bugs behave similarly as correctness bugs
    - Multiple fuzzing techniques exist which are specialized for finding correctness bugs
    - Ergo, we know this assumption is invalid in general

Surrogate #2: Count Bug-Inducing Inputs

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```
function foo() { ... }
...
bar();
```

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function foo() { ... }
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```

```
function baz() { ... }
...
boo();
```

Surrogate #2: Count Bug-Inducing Inputs

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function foo() { ... }
...
bar();
```

Two Bug-Inducing Inputs Found

```
function baz() { ... }
...
boo();
```

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Same Input

```
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...
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function foo() { ... }
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Two Bug-Inducing Inputs Found

Same Input

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function foo() { ... }
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```

Two Bug-Inducing Inputs Found

Same Input

```
function foo() { ... }
...
bar();
```

Techniques exist which very nearly do this.

Surrogate #2: Count Bug-Inducing Inputs

- Assumes that there is a one-to-one correspondence between bug-inducing inputs and bugs
  - No evidence exists to confirm or refute this assumption in general
  - Can very clearly break under certain circumstances
- This metric is easy to measure and **wildly popular**

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Goal for An Automated Approach

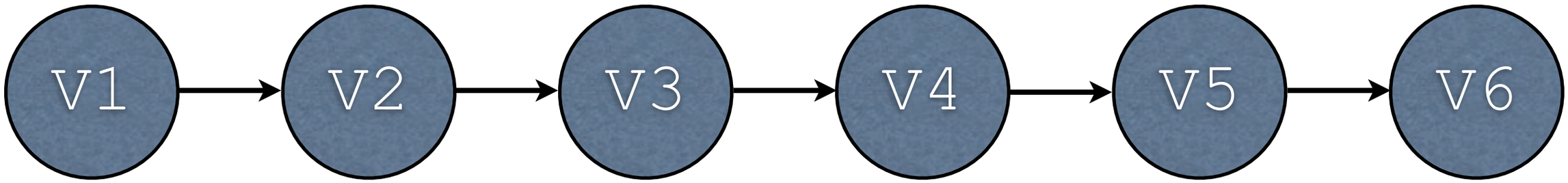
- Goal: be able to **automatically derive** the number of unique bugs found by a given fuzzer
  - For both crash and correctness bugs
  - Minimal manual effort

Assumptions

- The system under test is under version control, and each commit fixes at most one bug
- Past bugs behave similarly to new bugs
  - We will actually test an **older version** of the software

Approach

Approach



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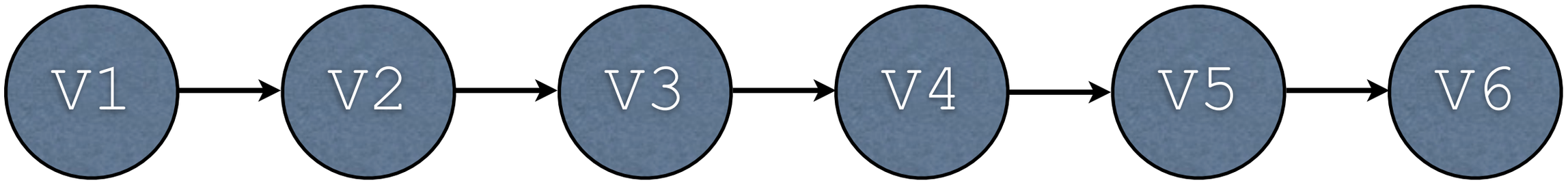
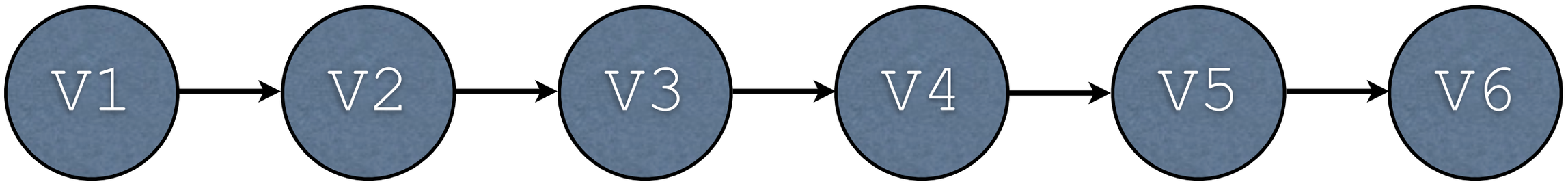


Three tests (`T1`, `T2`, `T3`) expose some number of bugs ≤ 3 on version `V1`

Approach



Idea: walk the versions until we hit one where a given test no longer triggers a bug.

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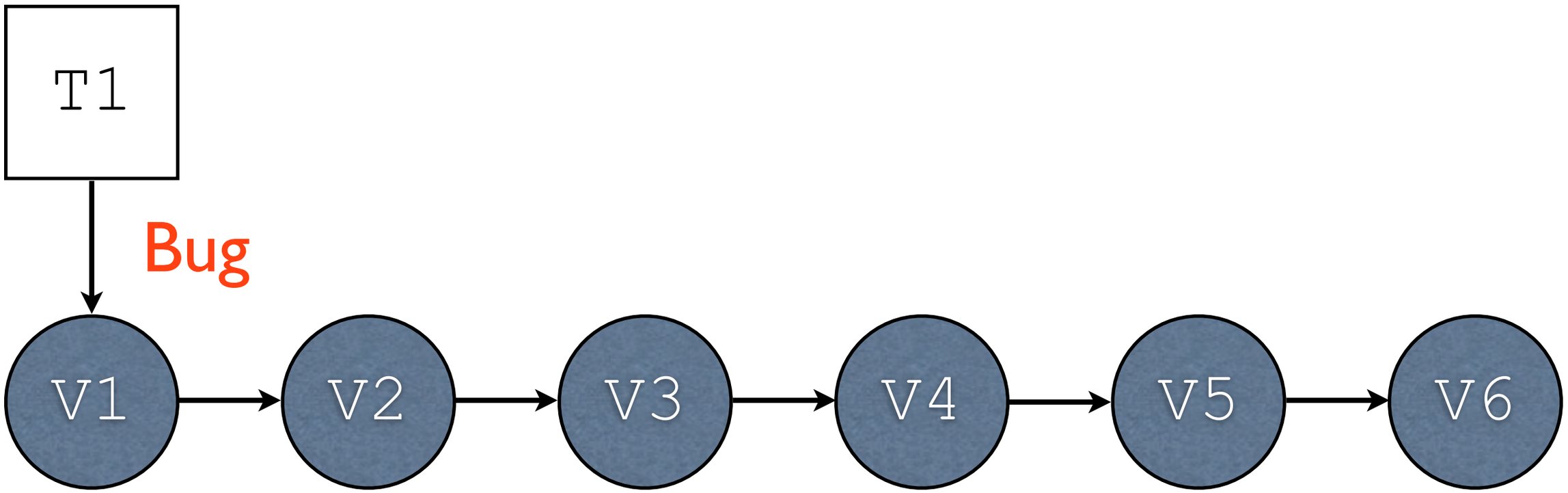

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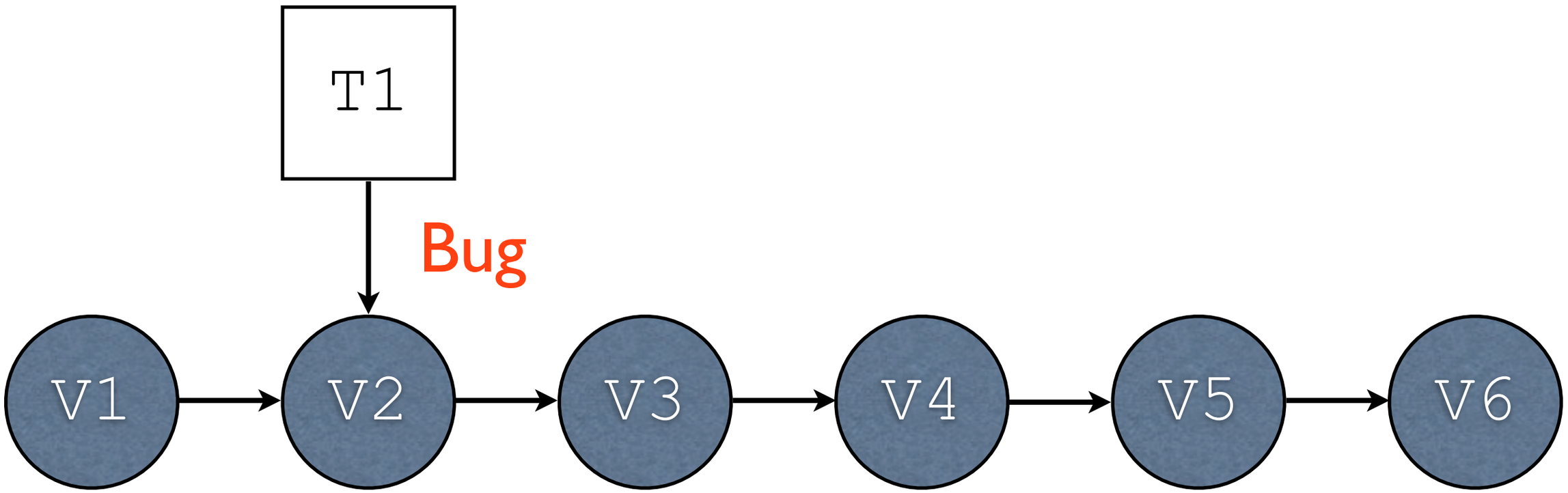

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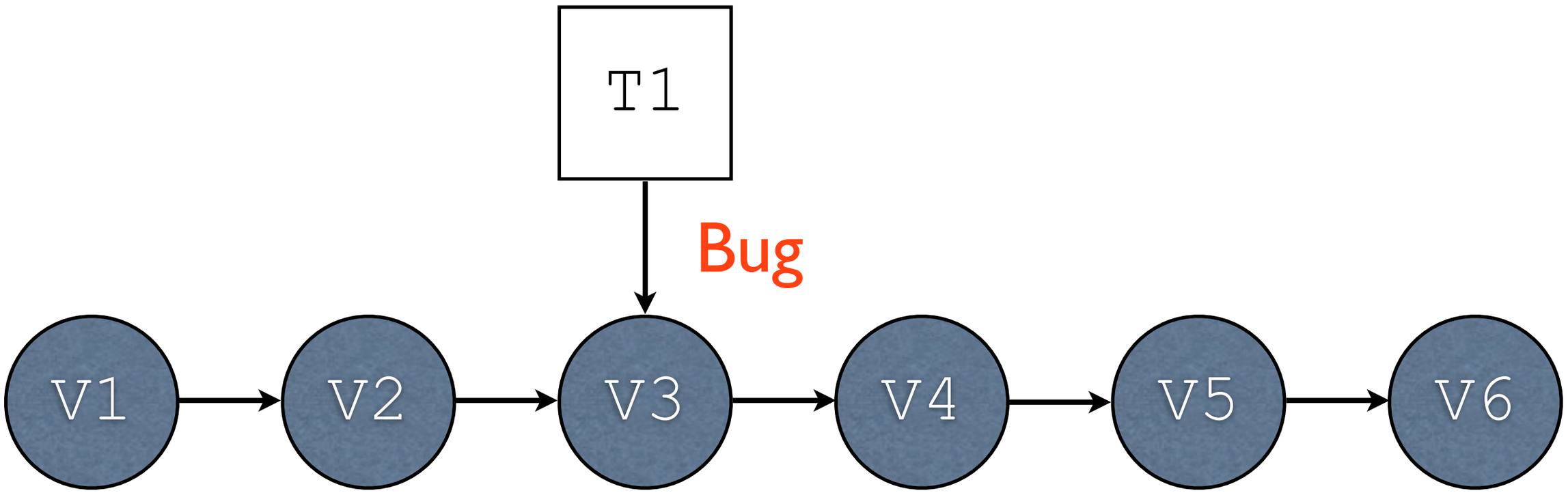

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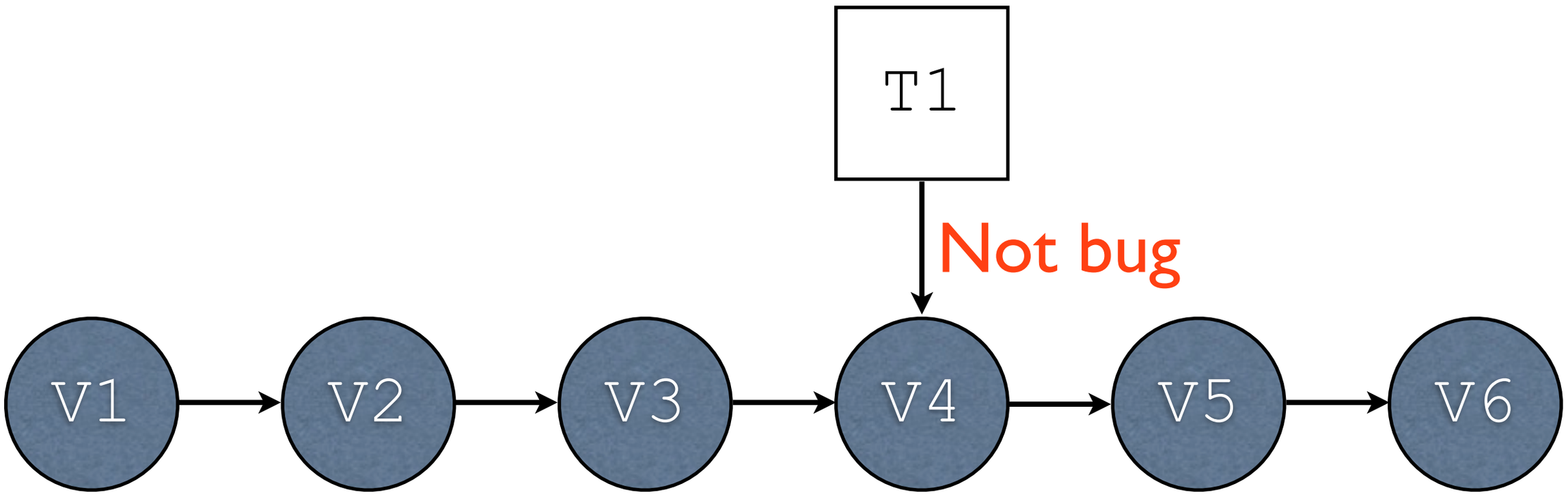

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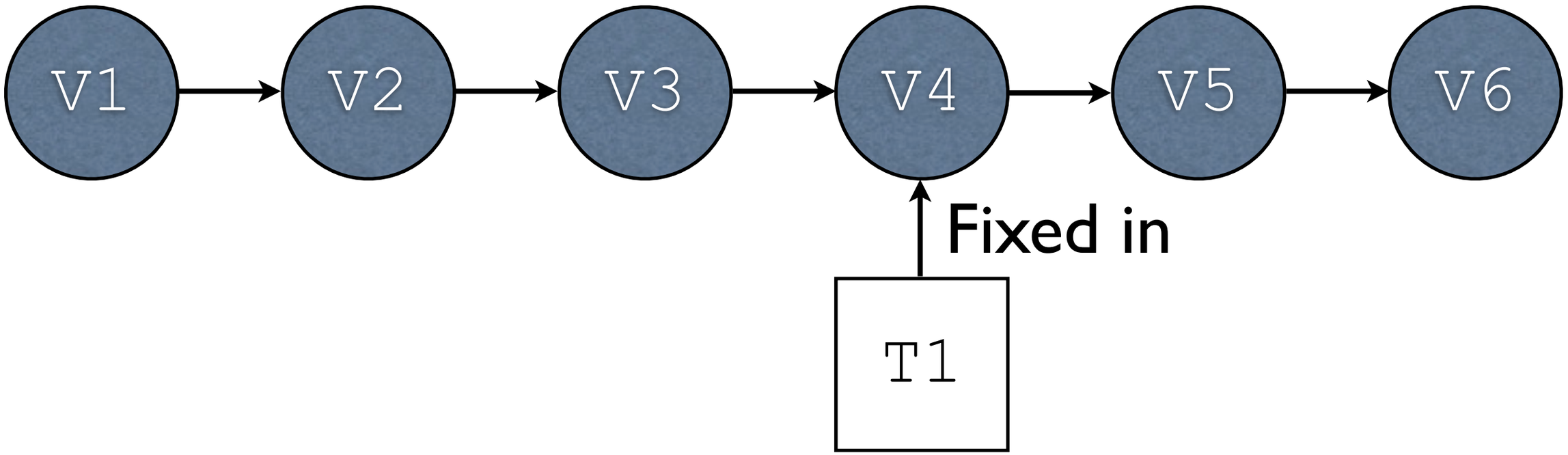

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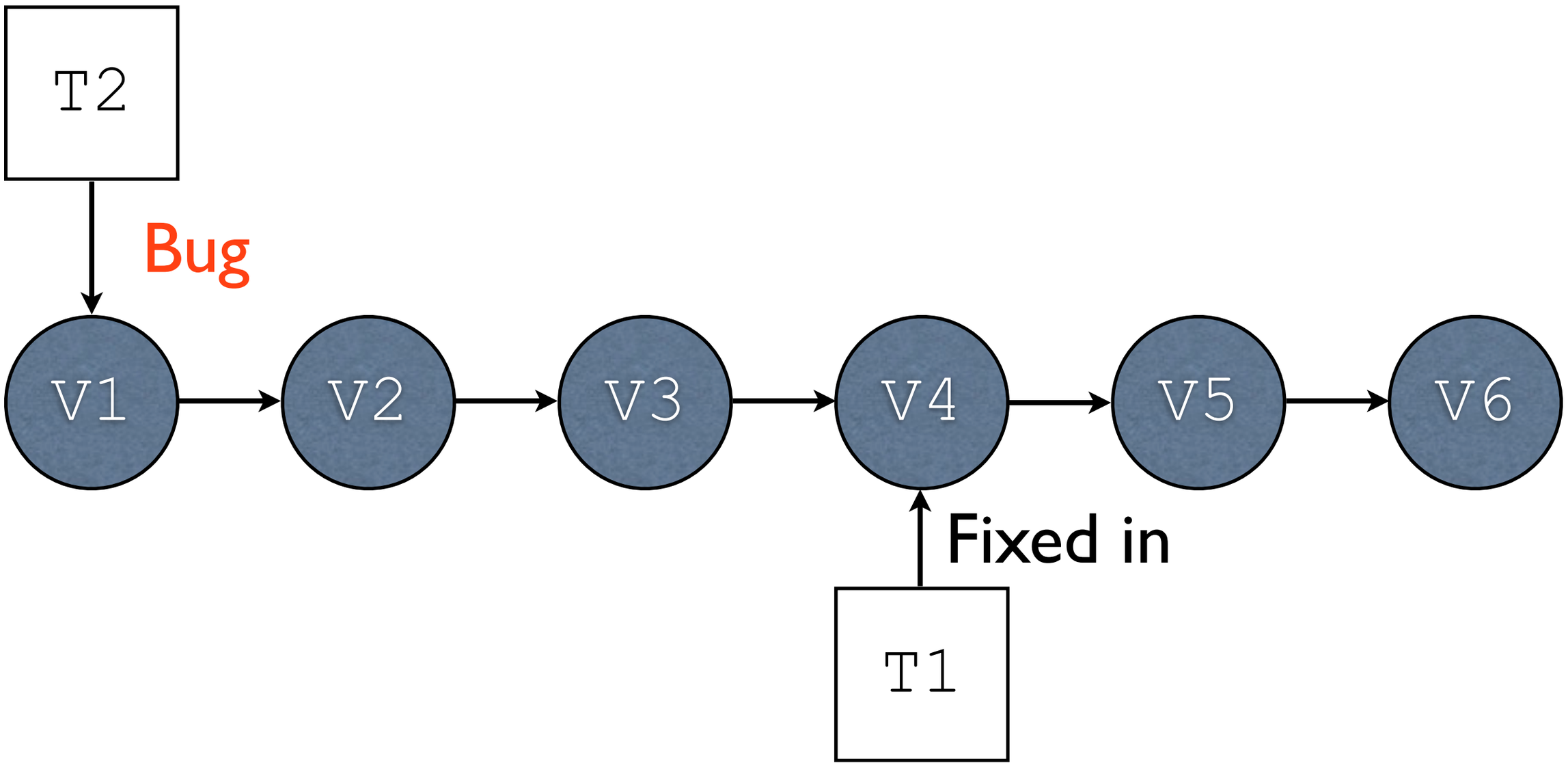

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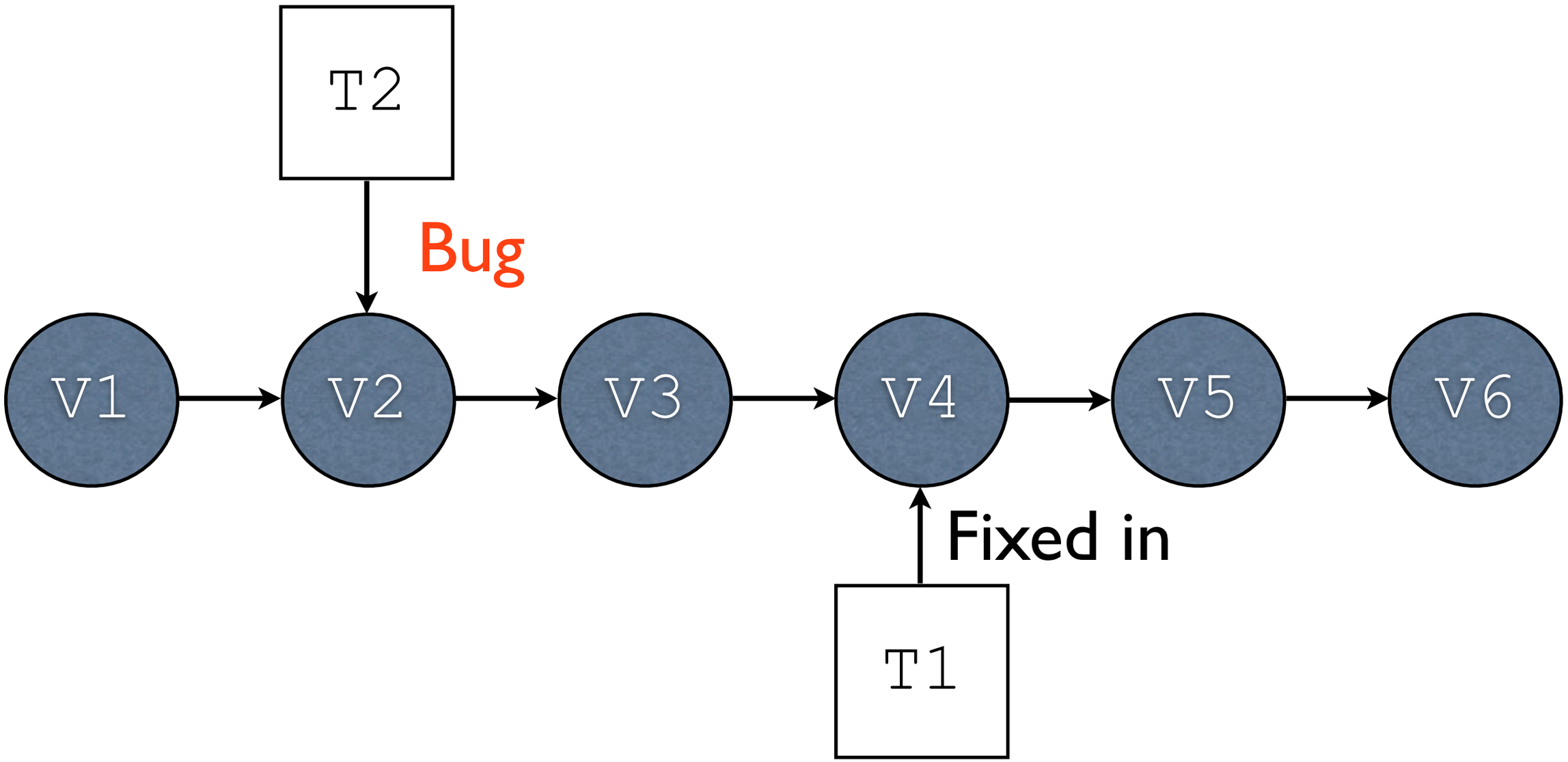

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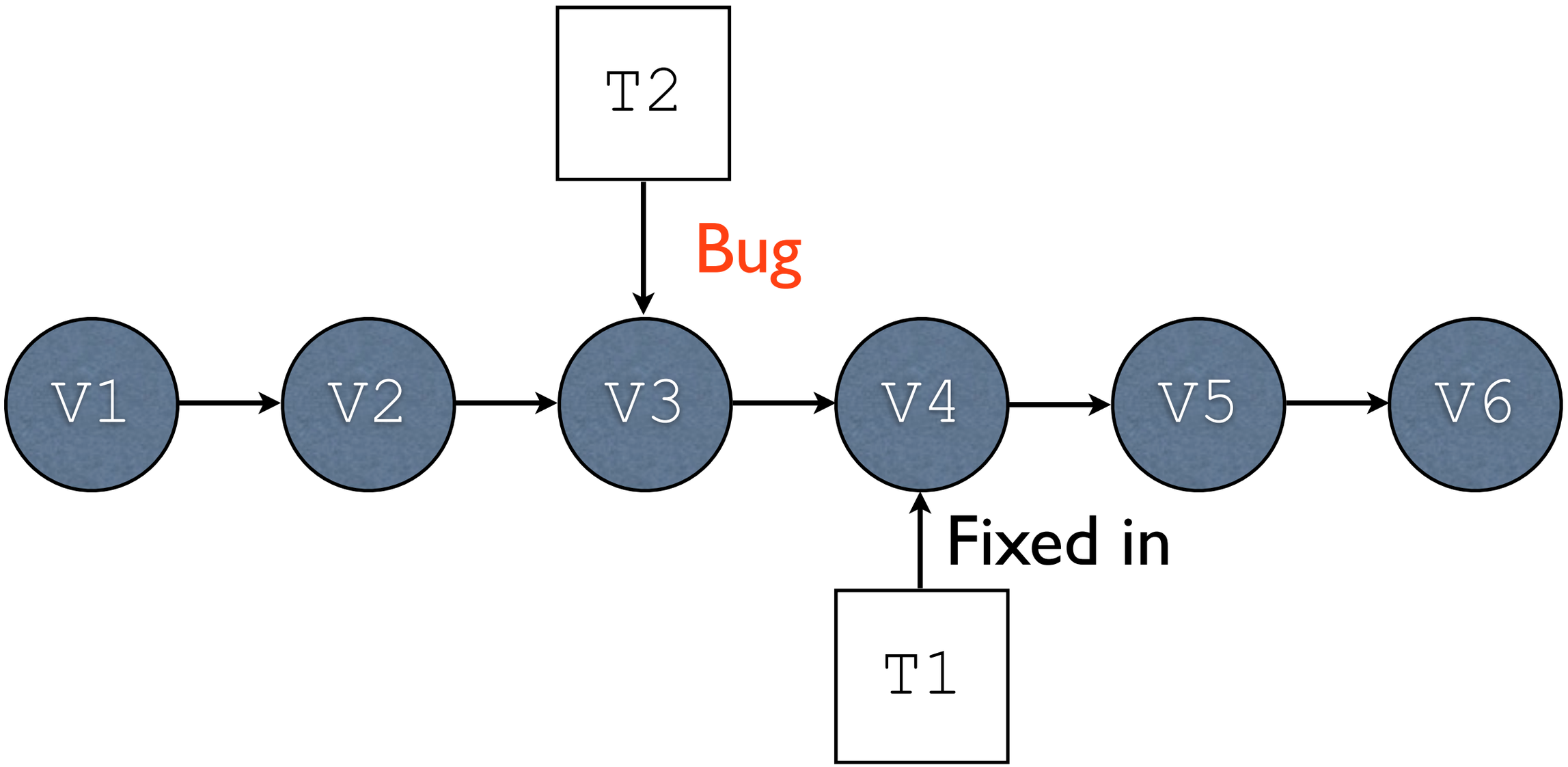

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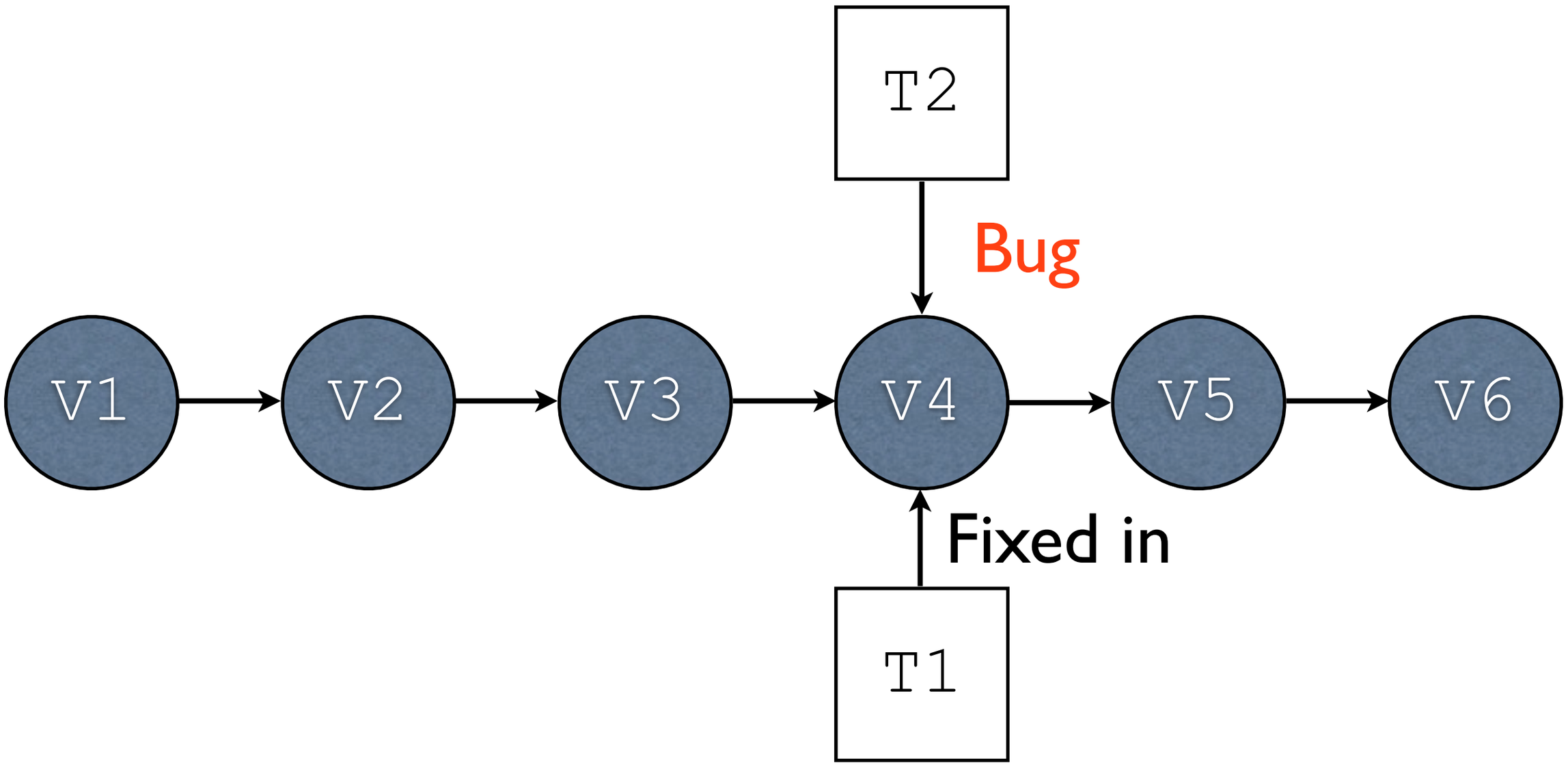

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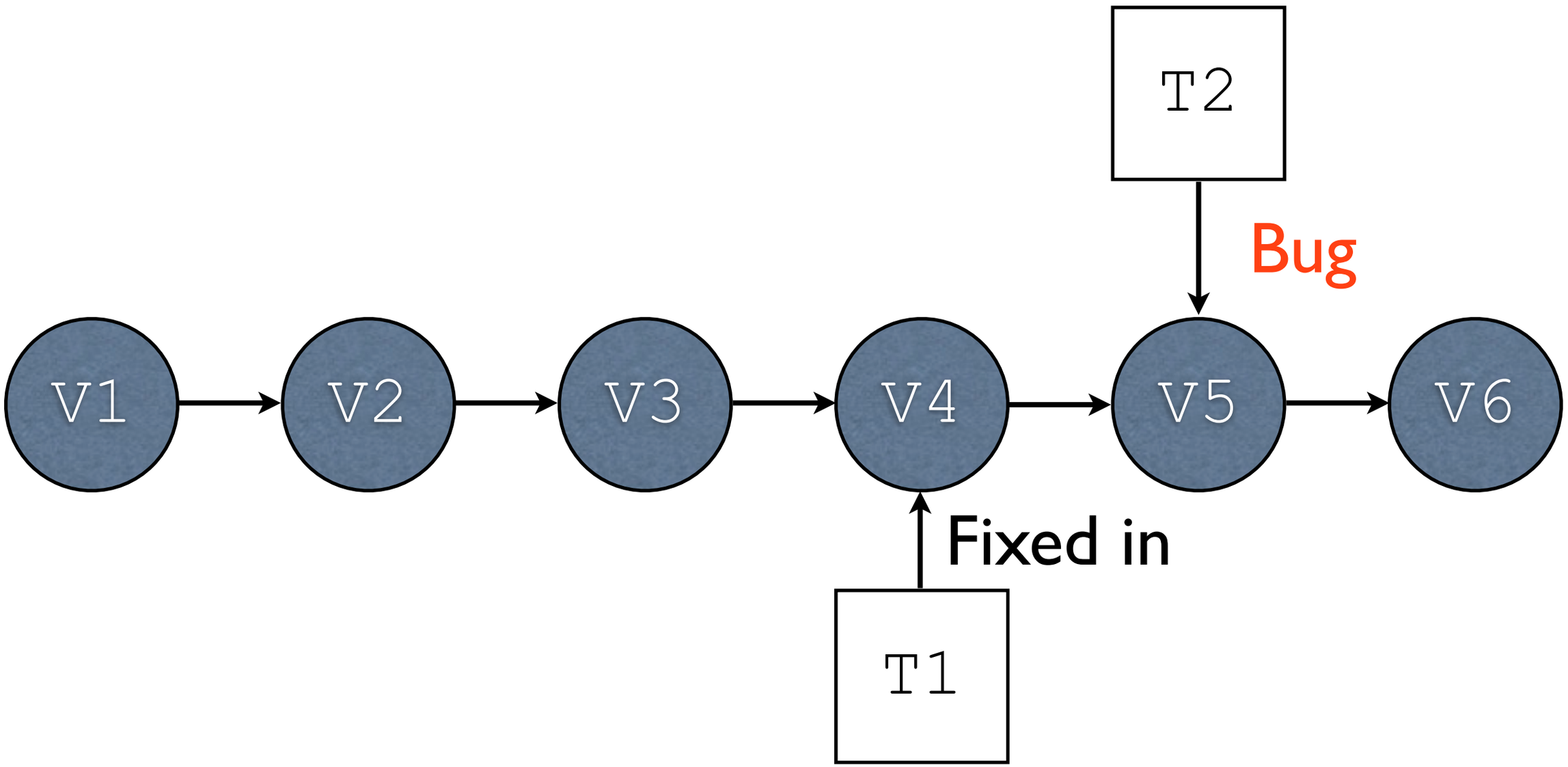

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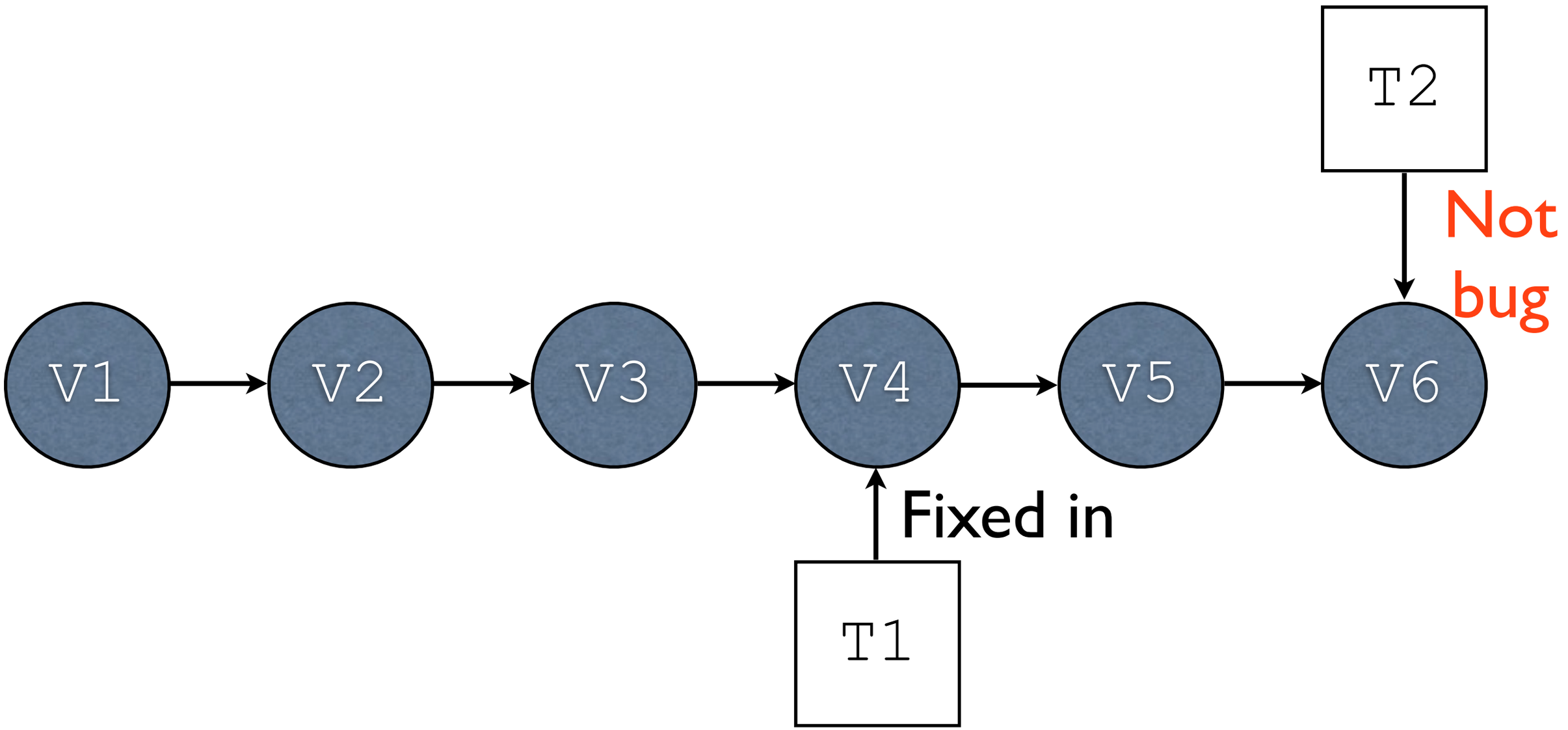

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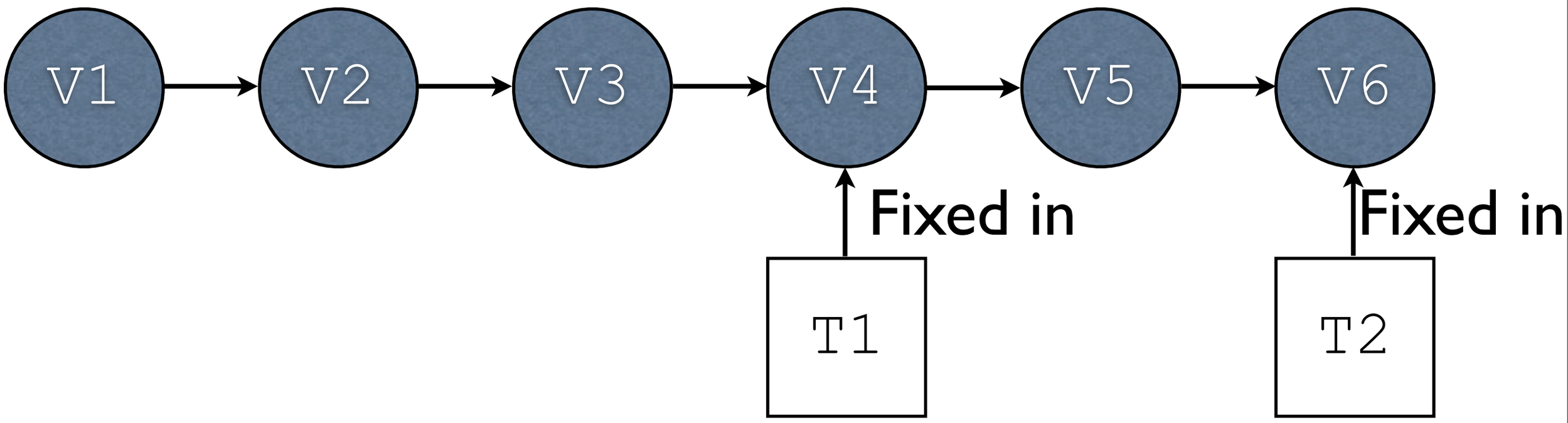

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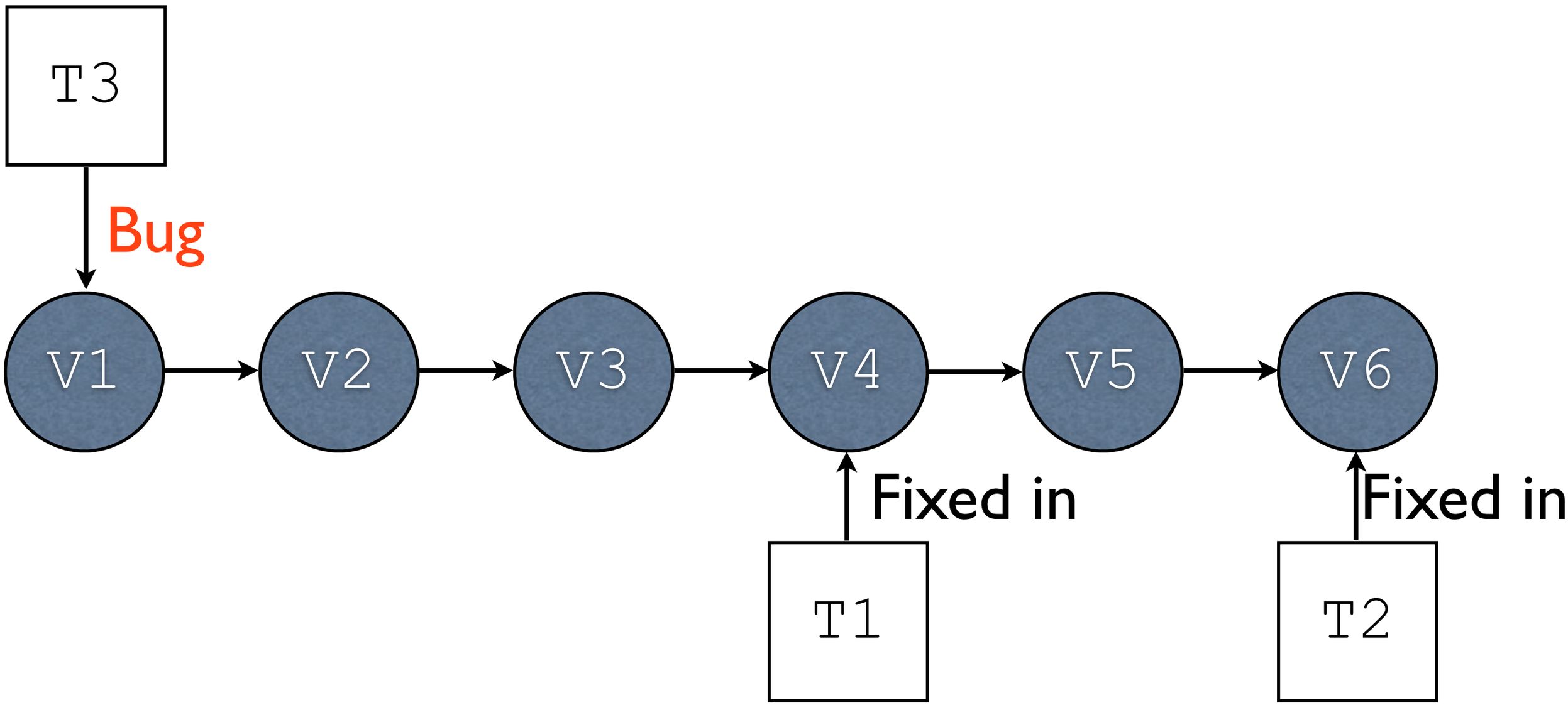

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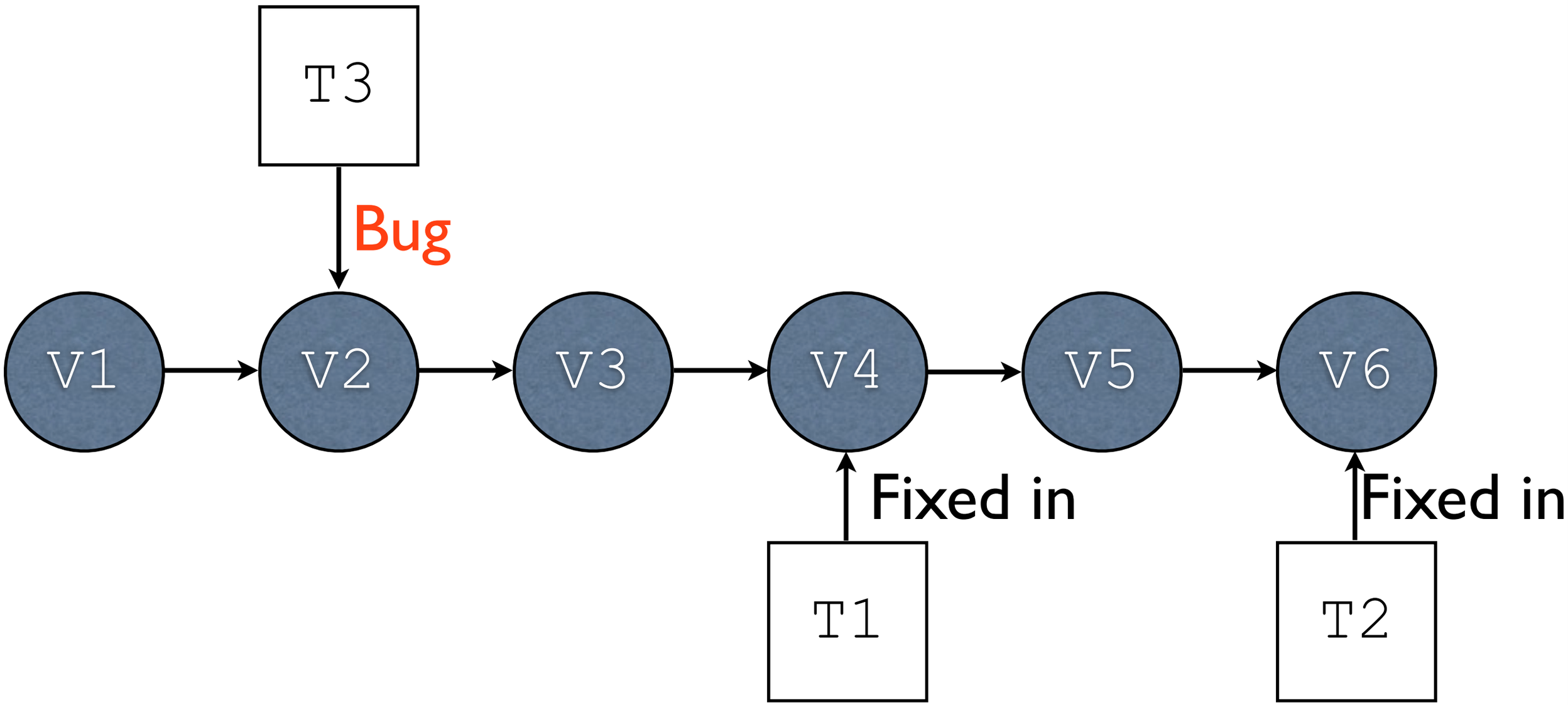

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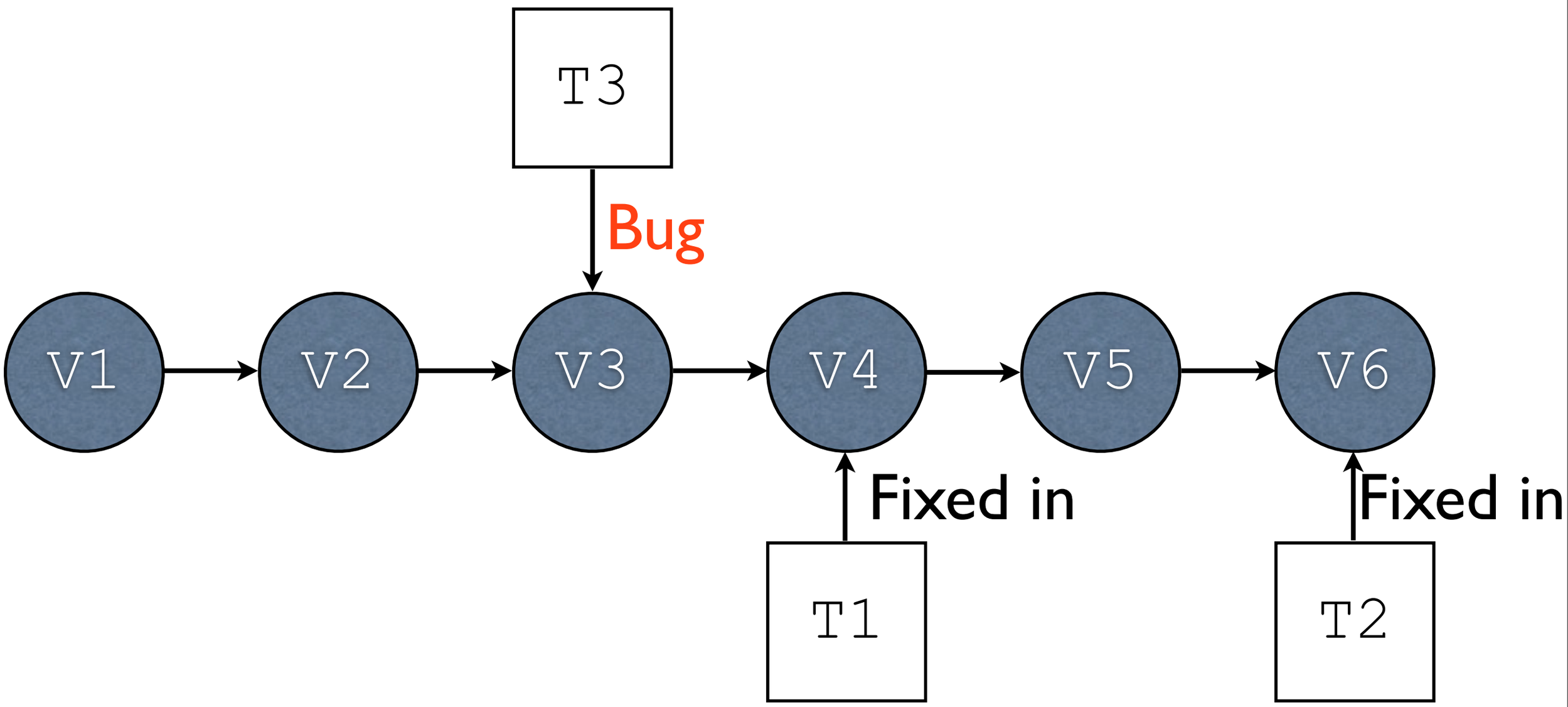

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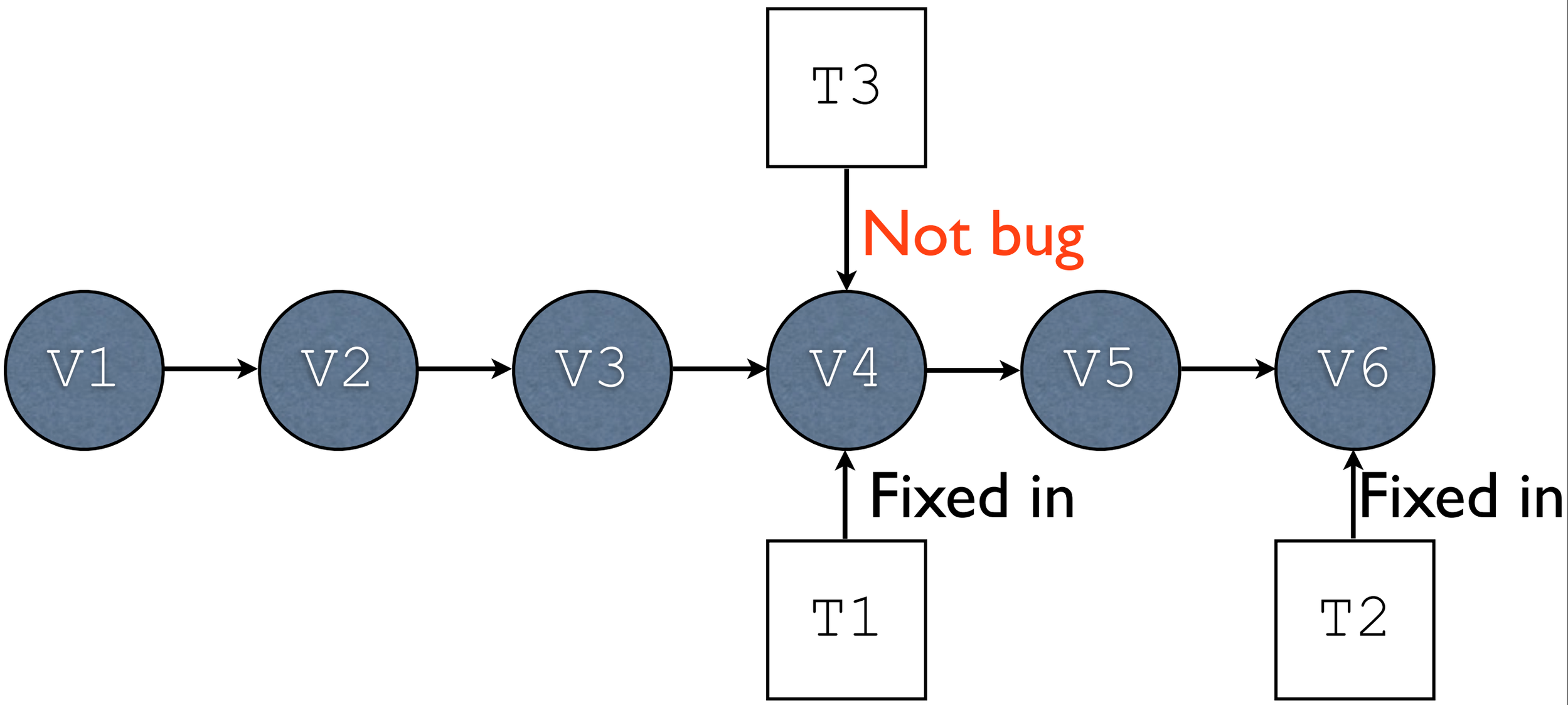

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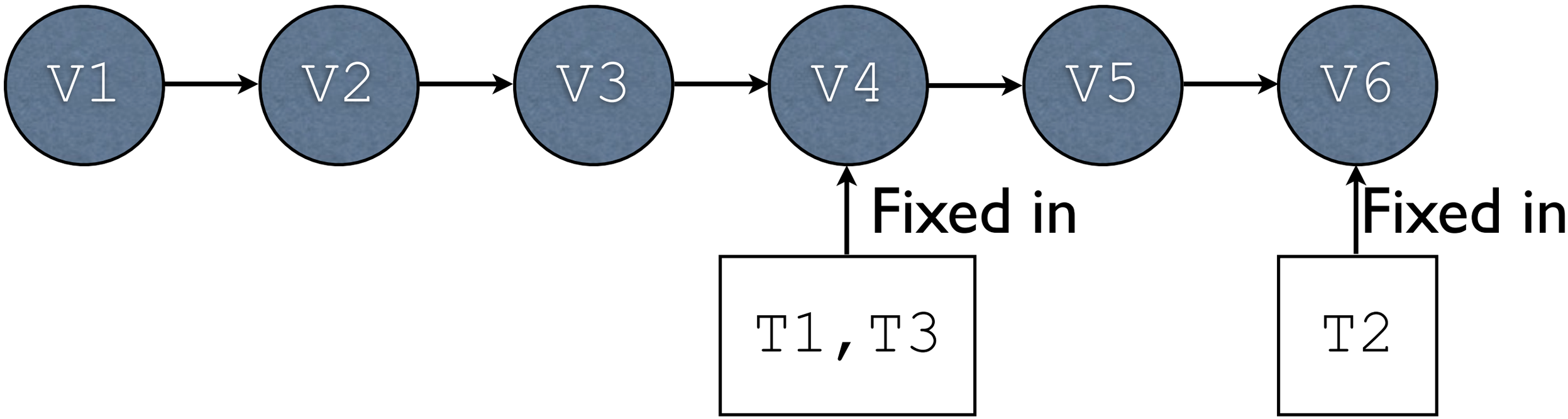
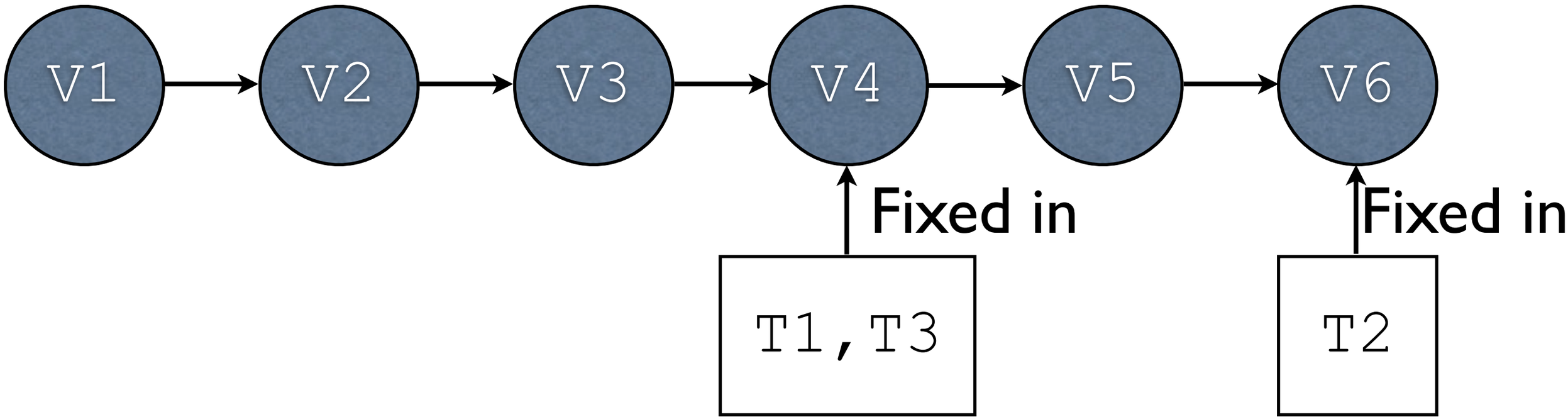


By the assumption that each version fixes at most one bug, `T1` and `T3` both trigger one bug (fixed in `V4`), and `T2` triggers another bug (fixed in `V6`).

Approach

End result: two unique bugs found



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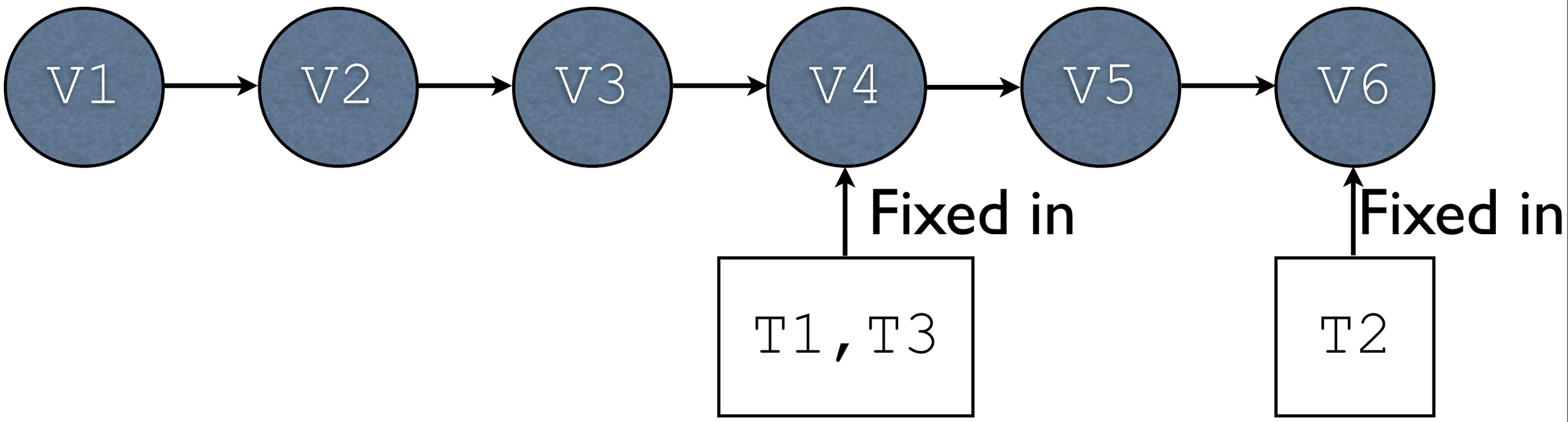
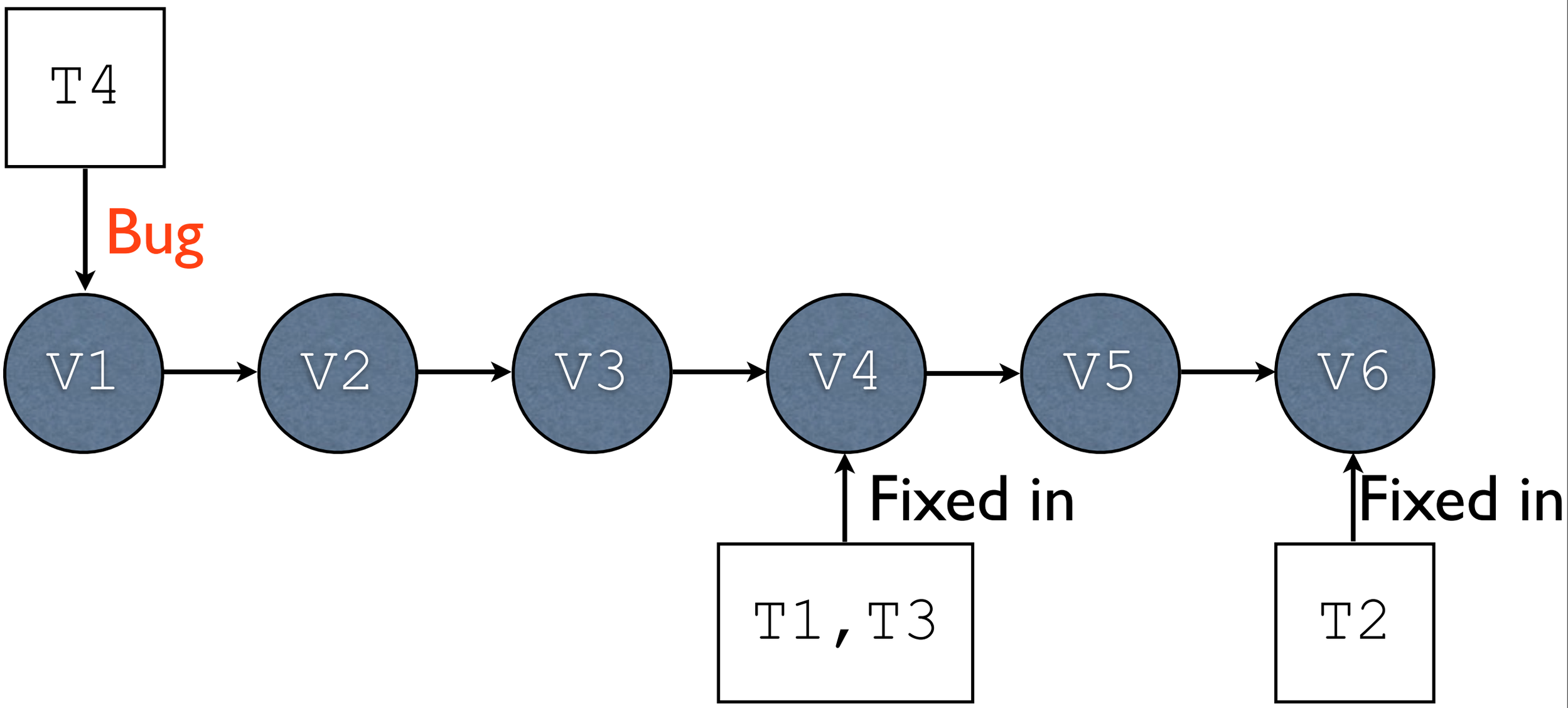


We could run out of versions on some inputs...

Approach



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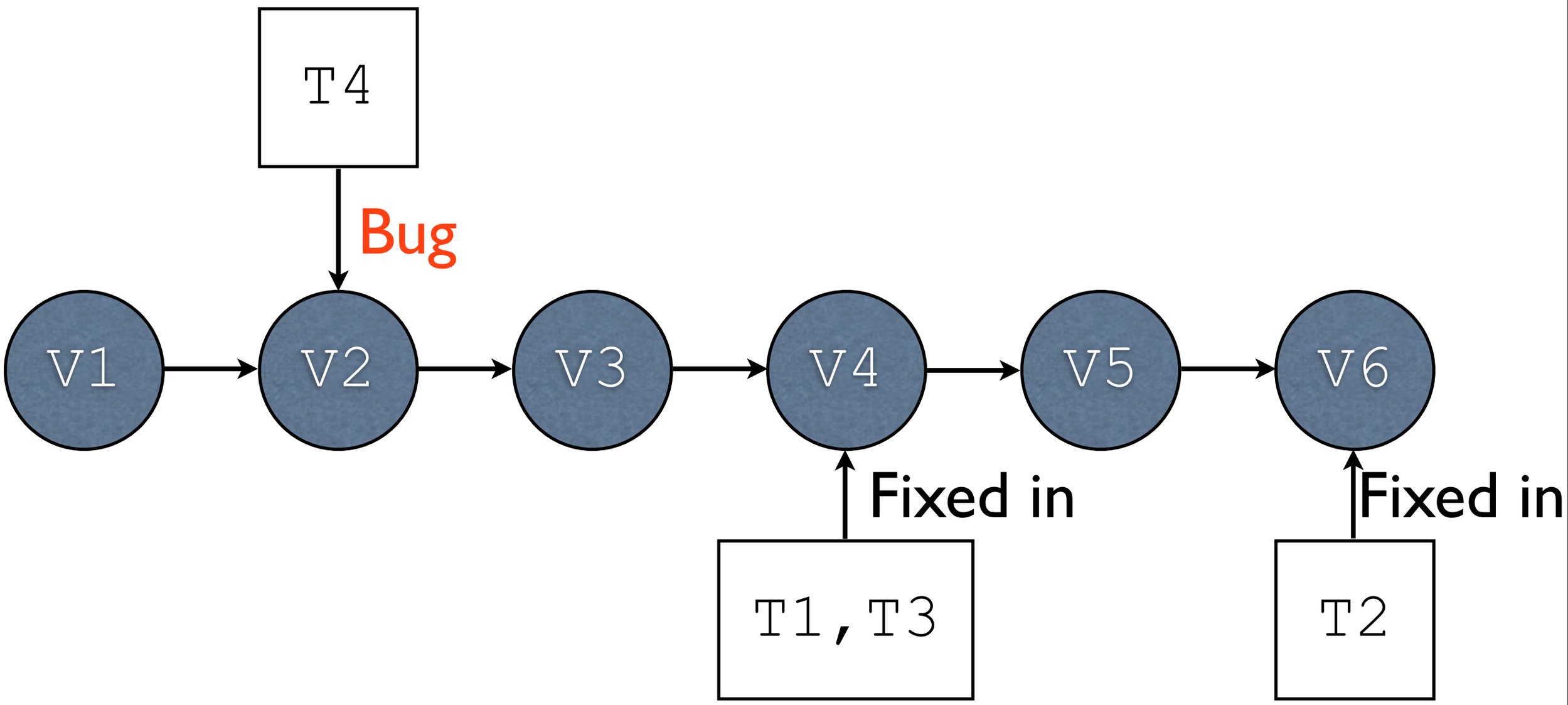

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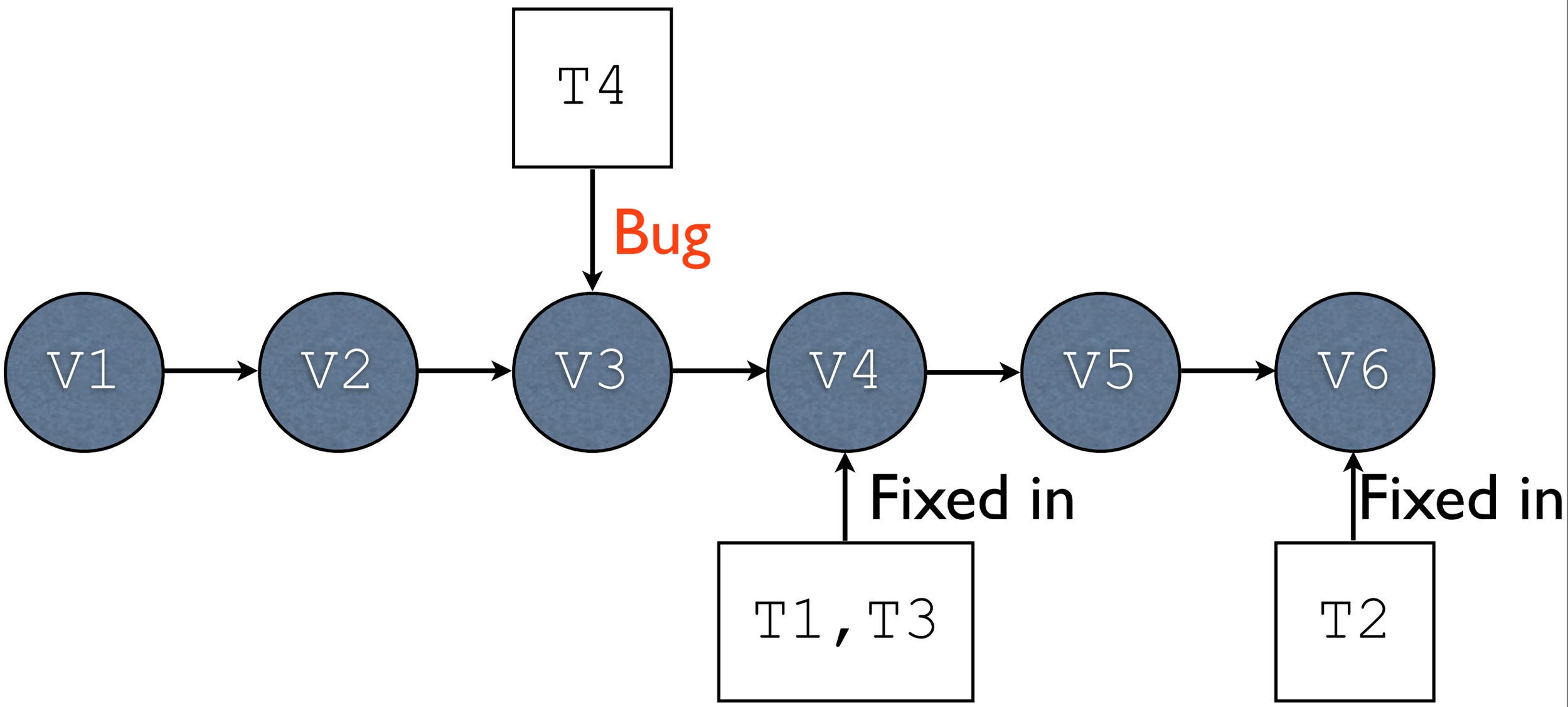

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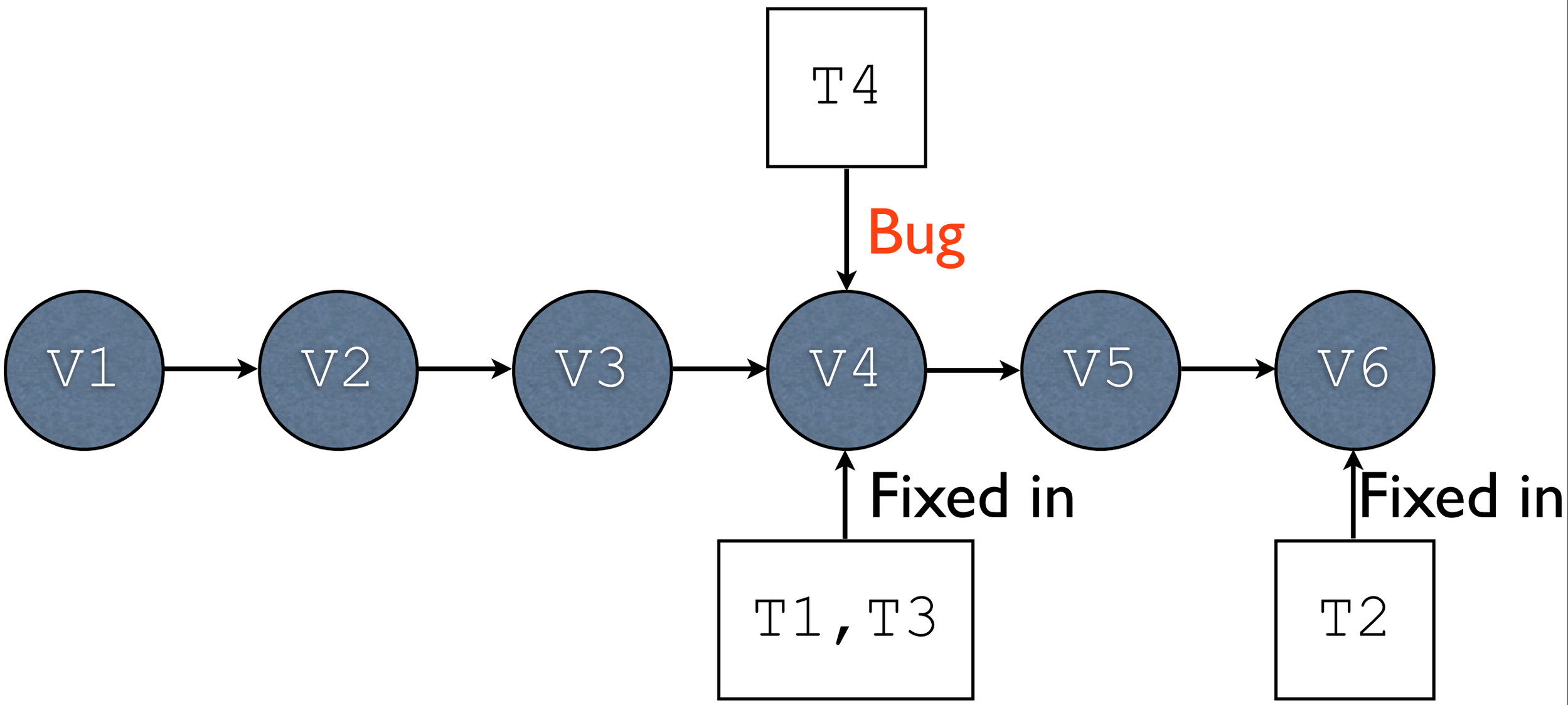

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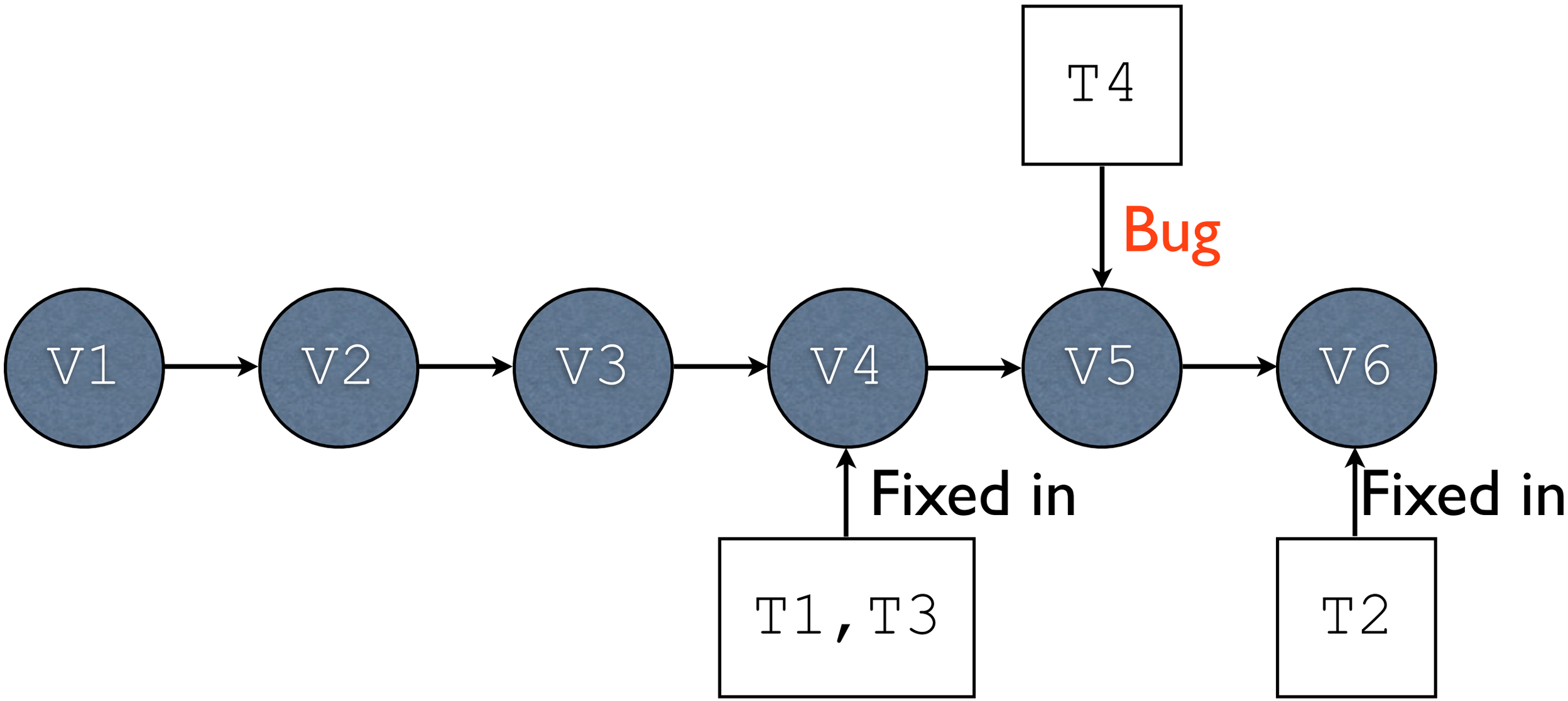

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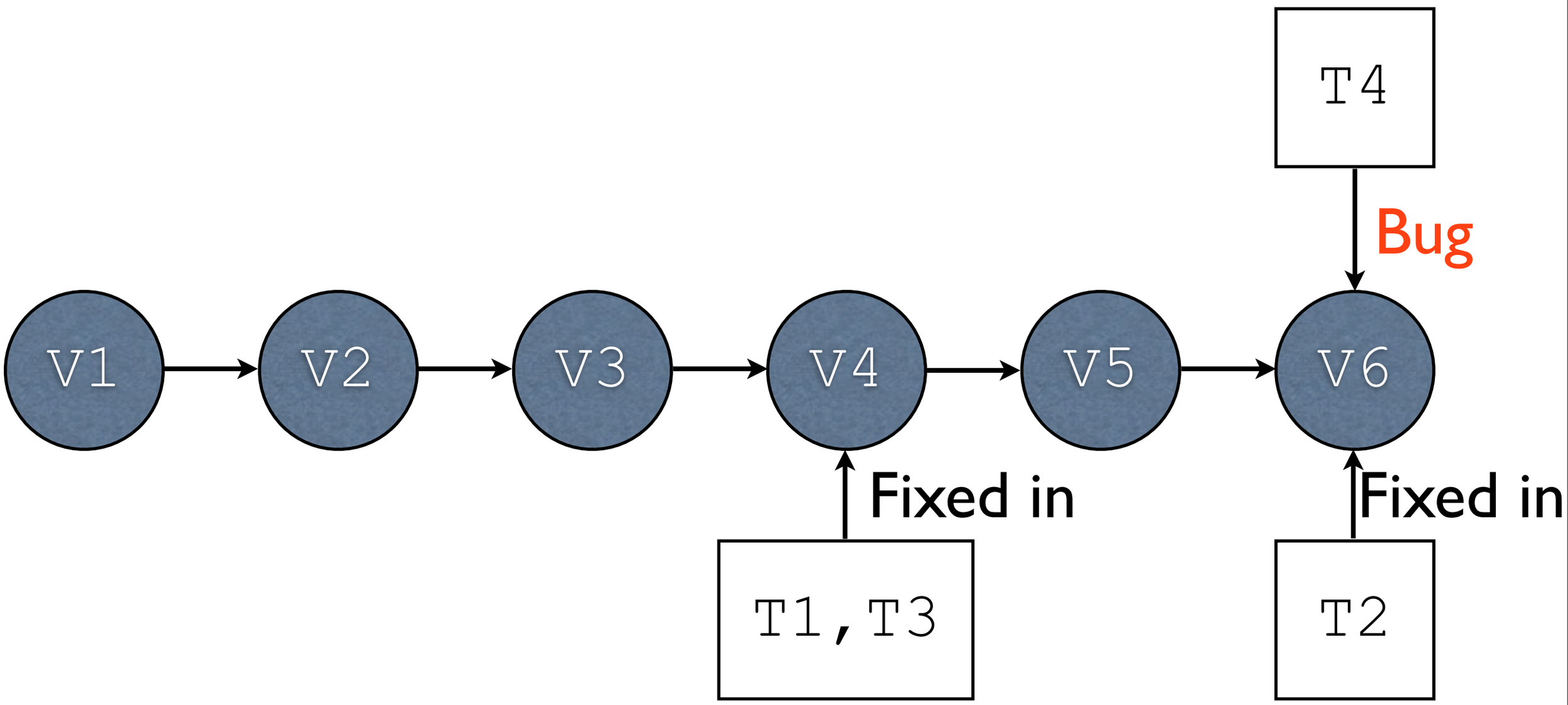

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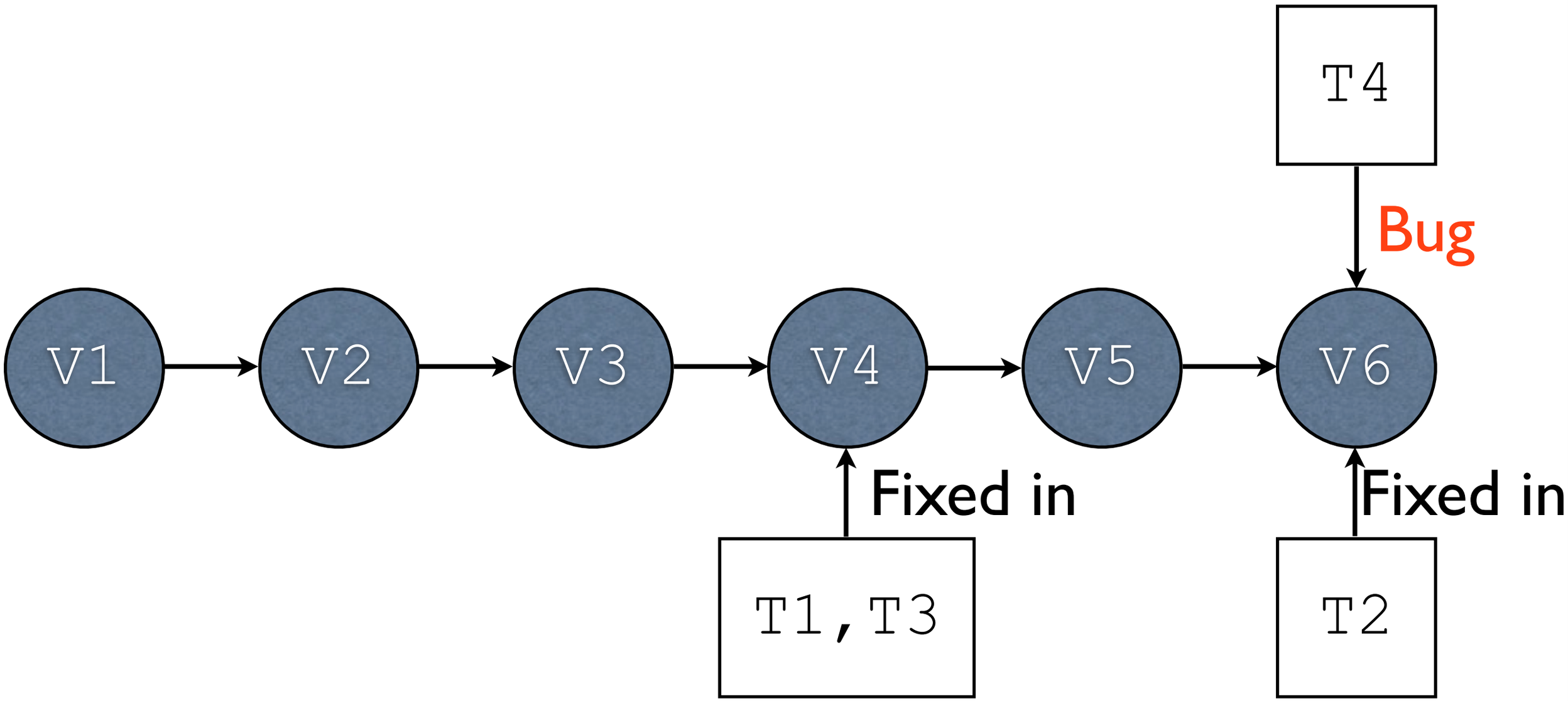

By the assumption that past bugs behave like new bugs, this is not significant.

New Bugs

- Can still report these bugs using existing approaches
    - Prompts developers to create new versions which fix the bugs
- Requires manual effort, but **only** if the evaluator wants to drop the assumption that new bugs behave like old ones, and then only for select bugs
- Existing approach is pure manual effort

Outline

- Background
- Metrics used in the literature
- An automated approach
- How metrics compare
- Conclusion

Experimental Goal

- We have a technique for easily measuring unique bugs
- Want to see how unique bugs compares to the aforementioned surrogate metrics
  - First time any such comparison has been performed
  - Can answer whether or not these surrogate metrics are worth collecting

Systems Under Test

- Interested in testing SMT solvers
  - Answer queries like $x \leq 7 \wedge y \geq 8$
    - Vitally important in software verification, among many others
- Solvers can be buggy, and buggy solvers mean invalid proofs
- Looked at Z3, CVC4, MathSAT5, and Boolector

Experimental Setup

- Developed four pairs of fuzzers for SMT-LIB
  - Each of the two fuzzers in a pair was radically different, but both attempted to test the same part of SMT-LIB
  - Whole pairs of fuzzers are not directly comparable to each other (each pair tests a distinct subset of SMT-LIB)

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Pair 1	Pair 2	Pair 3	Pair 4
F1 F2	F3 F4	F5 F6	F7 F8
(e.g., integers)	(e.g., BV)	(e.g., FP)	(e.g., SAT)

Measurement

- Fuzzers within a pair are directly comparable to each other
- For each metric, see which fuzzer in the pair is better
- Question: do surrogate metrics agree with the metric of unique bugs found?

Pair 1	Pair 2	Pair 3	Pair 4
F1 | F2	F3 | F4	F5 | F6	F7 | F8
(e.g., integers)	(e.g., BV)	(e.g., FP)	(e.g., SAT)

	Unique Bugs	Crash Bugs	Bug-Inducing Inputs
F1	2	0	231,254
F2	2	1	17,744
F3	6	2	260,085
F4	1	0	2,800
F5	9	3	20,796
F6	6	2	73,382
F7	12	2	11,917
F8	3	0	374

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Only in 2/4 cases did all three metrics agree

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Crash bugs usually agreed with unique bugs...

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...though not entirely (and we know they don't in general)

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Bug-inducing inputs does not correlate to bugs found.

Data Elided

- We looked at five other metrics, based on either bugs found or bug-triggering inputs
- Data for these metrics is very similar to that previously shown

Take-Home Points

- Take-home point #1: metrics based on actual bugs found tend to be consistent with each other (read: useful for comparison)
- Take-home point #2: metrics based on bug-triggering inputs look completely random (read: useless for comparison)

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Take-home point #3: SMT solvers are broken (24 bugs found; each solver had correctness bugs, including Z3).

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Conclusion

- Bug-based metrics are useful for comparison, and our automated evaluation technique makes these much easier to gather
- Our evaluation shows that metrics based on bug-inducing inputs are meaningless
    - Concerning, considering that **most existing work** uses these metrics
- SMT solvers tested are now a little less buggy (22 bugs fixed across all solvers tested)