# Detecting Anomalies

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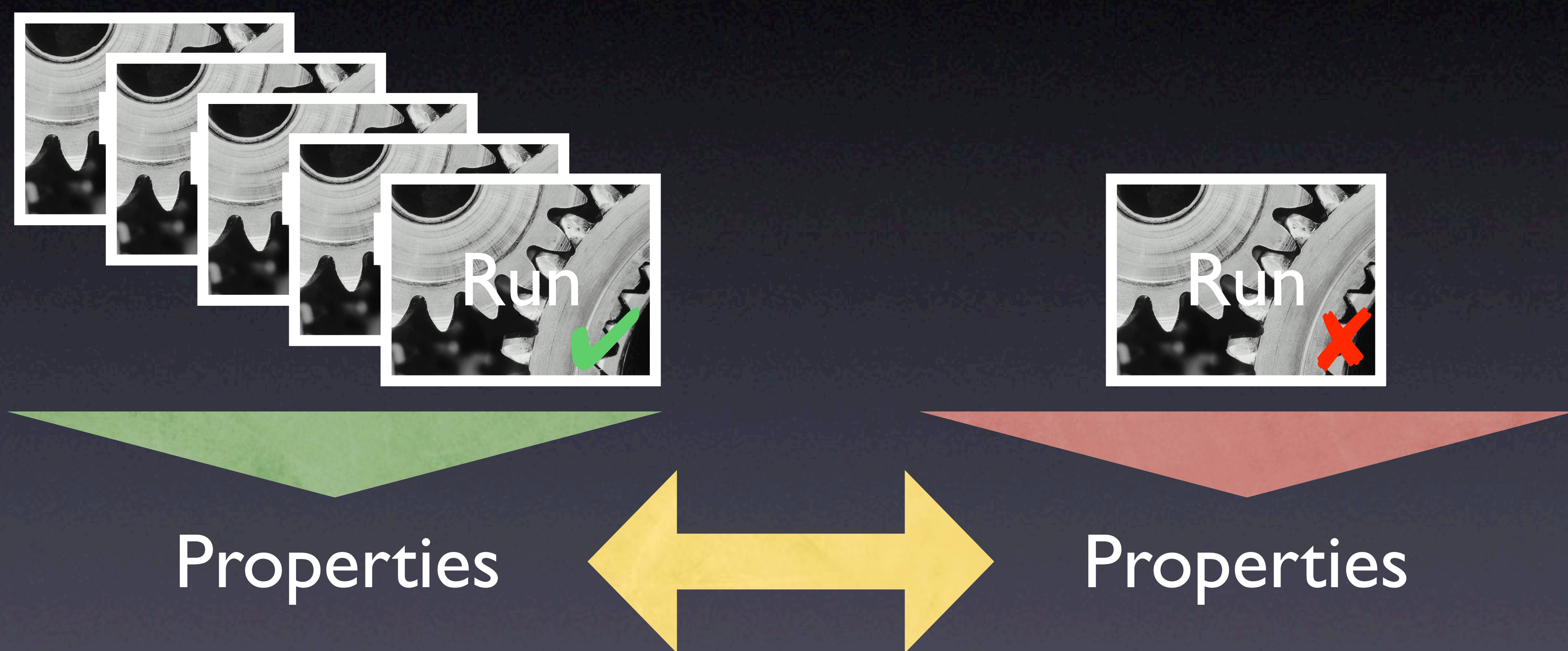
# What's abnormal?

- Suppose we determine common properties of all *passing* runs.
- Now we examine a run which *fails* the test.
- Any difference in properties *correlates with failure* – and is likely to hint at failure causes

# Detecting Anomalies




Differences correlate with failure

# Properties

Data properties that hold in all runs:

- "At f(), x is odd"
- "0 ≤ x ≤ 10 during the run"

Code properties that hold in all runs:

- "f() is always executed"
- "After open(), we eventually have close()"

# Techniques

| | | |
|---|---|---|
| Dynamic Invariants | Value Ranges | Sampled Values |

# Techniques

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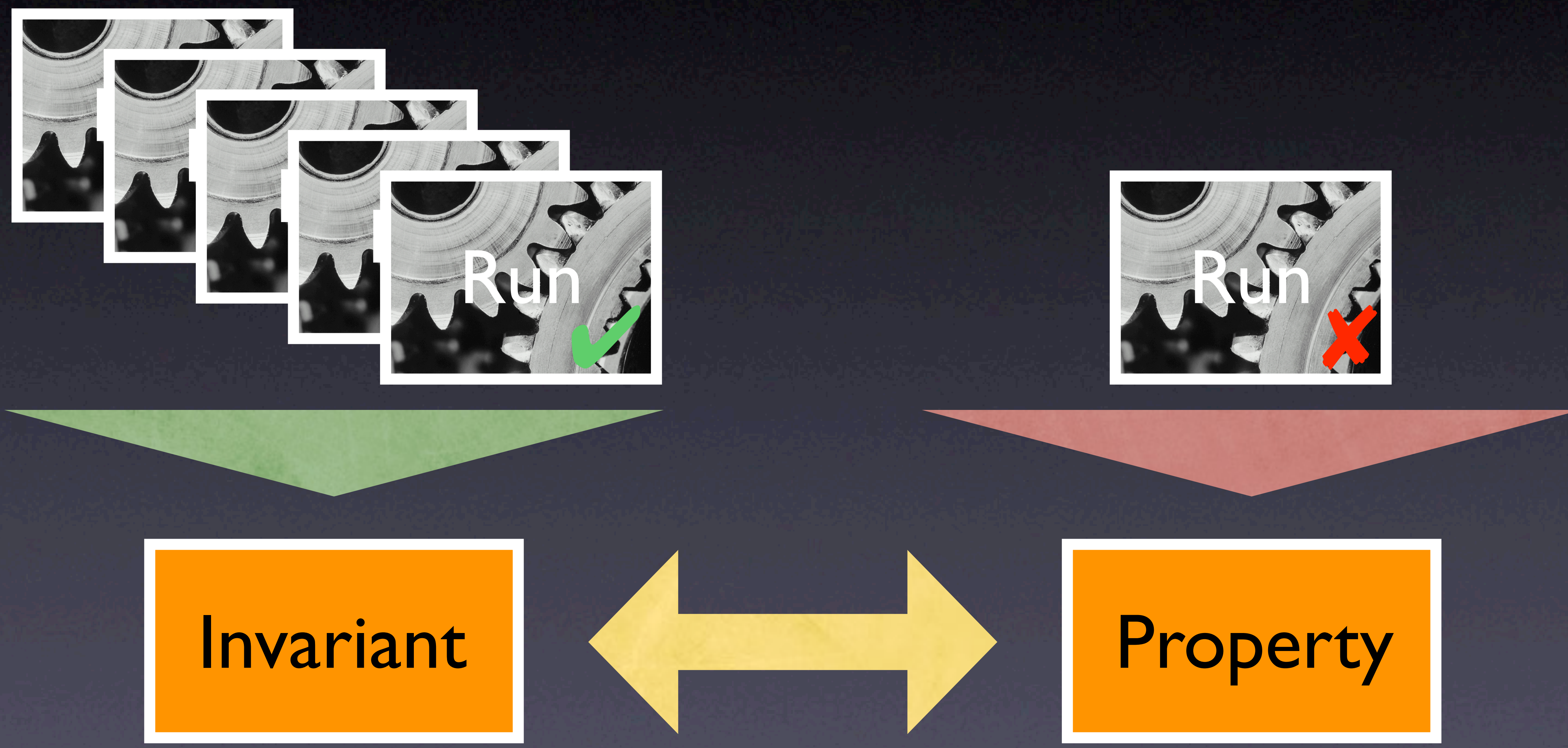
# Dynamic Invariants




At f(), x is odd

At f(), x = 2

# Daikon

- Determines *invariants* from program runs
- Written by Michael Ernst et al. (1998–)
- C++, Java, Lisp, and other languages
- analyzed up to 13,000 lines of code

# Daikon

```
public int ex1511(int[] b, int n)
{
    int s = 0;
    int i = 0;
    while (i != n) {
        s = s + b[i];
        i = i + 1;
    }
    return s;
}
```

**Precondition**

```
n == size(b[])
b != null
n <= 13
n >= 7
```

**Postcondition**

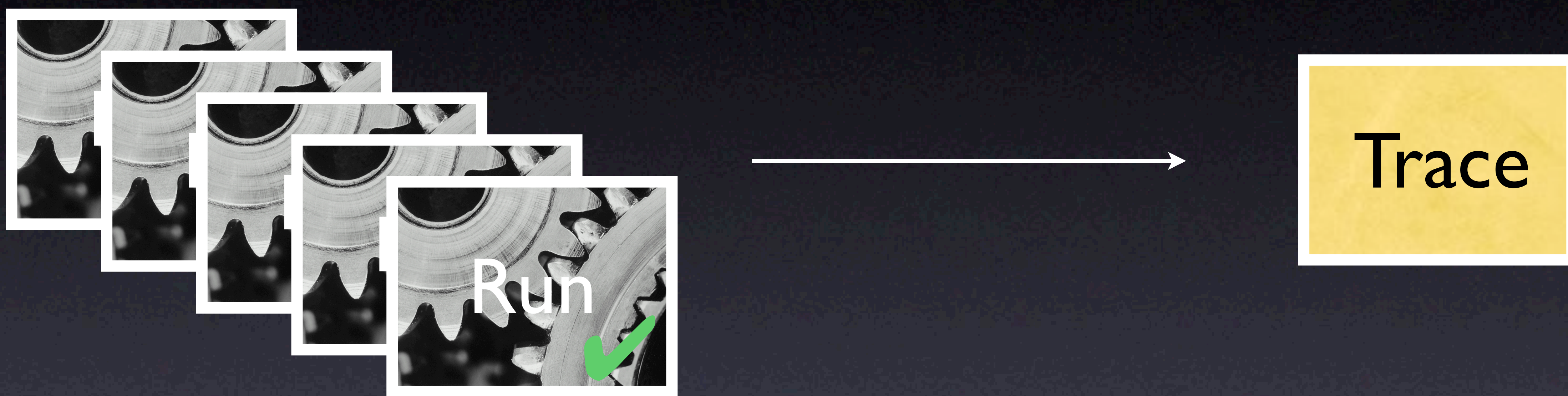
```
b[] = orig(b[])
return == sum(b)
```

- Run with 100 randomly generated arrays of length 7–13

# Daikon


Run
get trace
Trace
filter invariants
Invariant
report results
Postcondition
b[] = orig(b[])
return == sum(b)

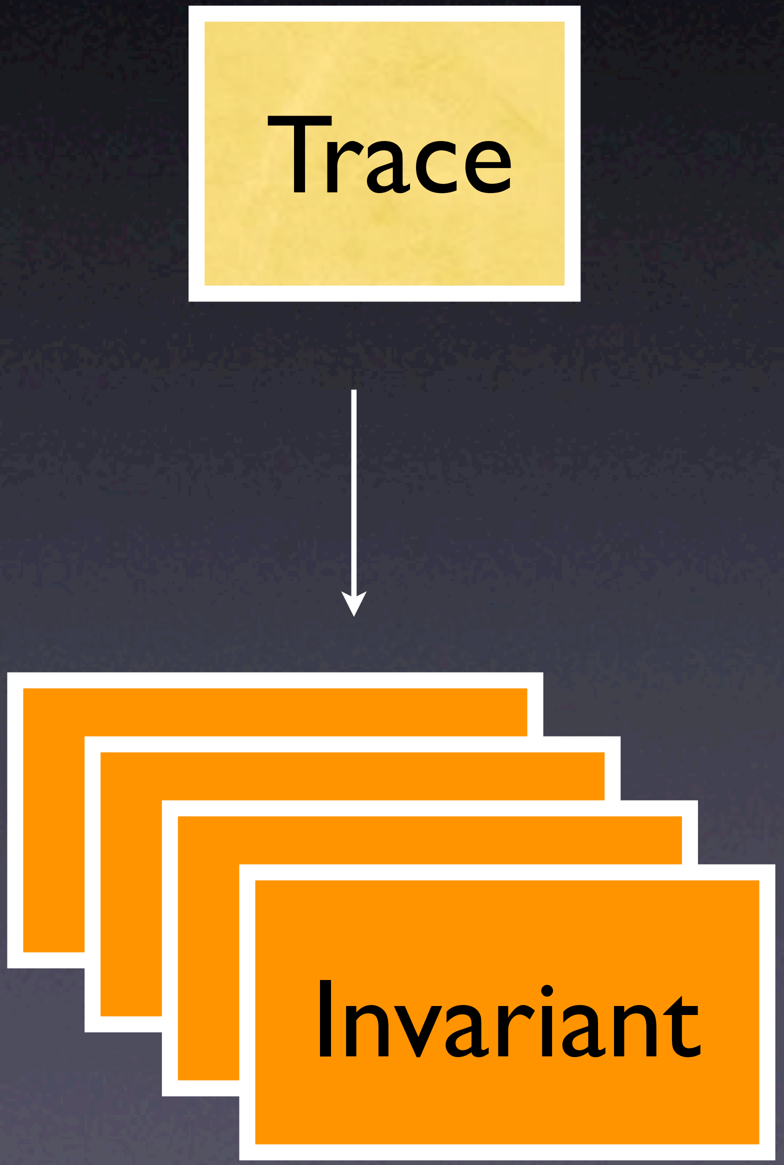
# Getting the Trace




- Records all variable values at all function entries and exits
- Uses VALGRIND to create the trace

# Filtering Invariants

- Daikon has a library of *invariant patterns* over variables and constants
- Only matching patterns are preserved



# Method Specifications

using *primitive data*

| | | |
|---|---|---|
| $x = 6$ | $x \in \{2, 5, -30\}$ | $x < y$ |
| $y = 5x + 10$ | $z = 4x + 12y + 3$ | $z = fn(x, y)$ |

using *composite data*

| | | |
|---|---|---|
| A subseq B | $x \in A$ | sorted(A) |

checked at method entry + exit

# Object Invariants

| |
|---|
| string.content[string.length] = '\0' |
| node.left.value ≤ node.right.value |
| this.next.last = this |

checked at entry + exit of public methods

# Matching Invariants

```
public int ex1511(int[] b, int n)
{
    int s = 0;
    int i = 0;
    while (i != n) {
        s = s + b[i];
        i = i + 1;
    }
    return s;
}
```

A == B

Pattern

s size(b[])
sum(b[])
n
orig(n)
return ...

Variables

# Matching Invariants

| == | s | n | size (b[]) | sum (b[]) | orig (n) | ret |
|---|---|---|---|---|---|---|
| s | | ✗ | | | ✗ | |
| n | ✗ | | | ✗ | | ✗ |
| size(b[]) | | | | | | |
| sum(b[]) | | ✗ | | | | |
| orig(n) | ✗ | | | | | ✗ |
| ret | | ✗ | | | ✗ | |

run 1

A == B

Pattern

s size(b[])
sum(b[])
n
orig(n)
return …

Variables

# Matching Invariants

| == | s | n | size (b[]) | sum (b[]) | orig (n) | ret |
|---|---|---|---|---|---|---|
| s | | ✗ | ✗ | | ✗ | |
| n | ✗ | | | ✗ | ✗ | ✗ |
| size(b[]) | ✗ | | | ✗ | | ✗ |
| sum(b[]) | | ✗ | ✗ | | ✗ | |
| orig(n) | ✗ | ✗ | | ✗ | | ✗ |
| ret | | ✗ | ✗ | | ✗ | |

run 2

A == B

Pattern

s size(b[])
sum(b[])
n
orig(n)
return …

Variables

# Matching Invariants

| == | s | n | size(b[]) | sum(b[]) | orig(n) | ret |
|---|---|---|---|---|---|---|
| s | | ✗ | ✗ | | ✗ | |
| n | ✗ | | | ✗ | ✗ | ✗ |
| size(b[]) | ✗ | | | ✗ | | ✗ |
| sum(b[]) | | ✗ | ✗ | | ✗ | |
| orig(n) | ✗ | ✗ | | ✗ | | ✗ |
| ret | | ✗ | ✗ | | ✗ | |

run 3

A == B

Pattern

s size(b[])
sum(b[])
n
orig(n)
return ...

Variables

# Matching Invariants

| == | s | n | size(b[]) | sum(b[]) | orig(n) | ret |
|---|---|---|---|---|---|---|
| s | | ✗ | ✗ | | ✗ | |
| n | ✗ | | | ✗ | ✗ | ✗ |
| size(b[]) | ✗ | | | ✗ | | ✗ |
| sum(b[]) | | ✗ | ✗ | | ✗ | |
| orig(n) | ✗ | ✗ | | ✗ | | ✗ |
| ret | | ✗ | ✗ | | ✗ | |

s == sum(b[])

s == ret

n == size(b[])

ret == sum(b[])

# Matching Invariants

```
public int ex1511(int[] b, int n)
{
    int s = 0;
    int i = 0;
    while (i != n) {
        s = s + b[i];
        i = i + 1;
    }
    return s;
}
```

s == sum(b[])

s == ret

n == size(b[])

ret == sum(b[])

# Enhancing Relevance

- Handle polymorphic variables
- Check for derived values
- Eliminate redundant invariants
- Set statistical threshold for relevance
- Verify correctness with static analysis

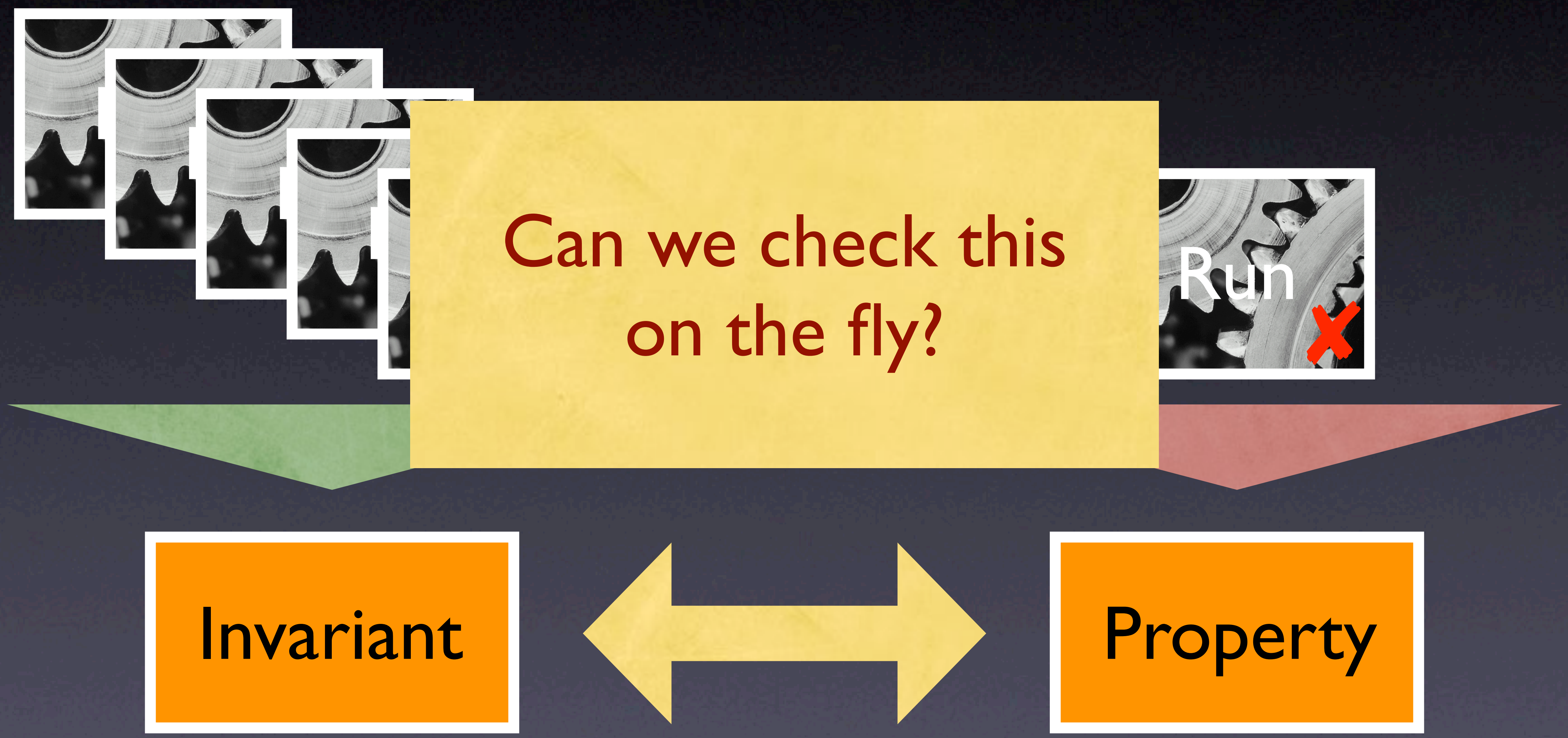
# Daikon Discussed

- As long as some property can be observed, it can be added as a pattern
- Pattern vocabulary determines the invariants that can be found (“sum()”, etc.)
- Checking all patterns (and combinations!) is expensive
- Trivial invariants must be eliminated

# Techniques

| | | |
|---|---|---|
| Dynamic Invariants | Value Ranges | Sampled Values |

# Dynamic Invariants



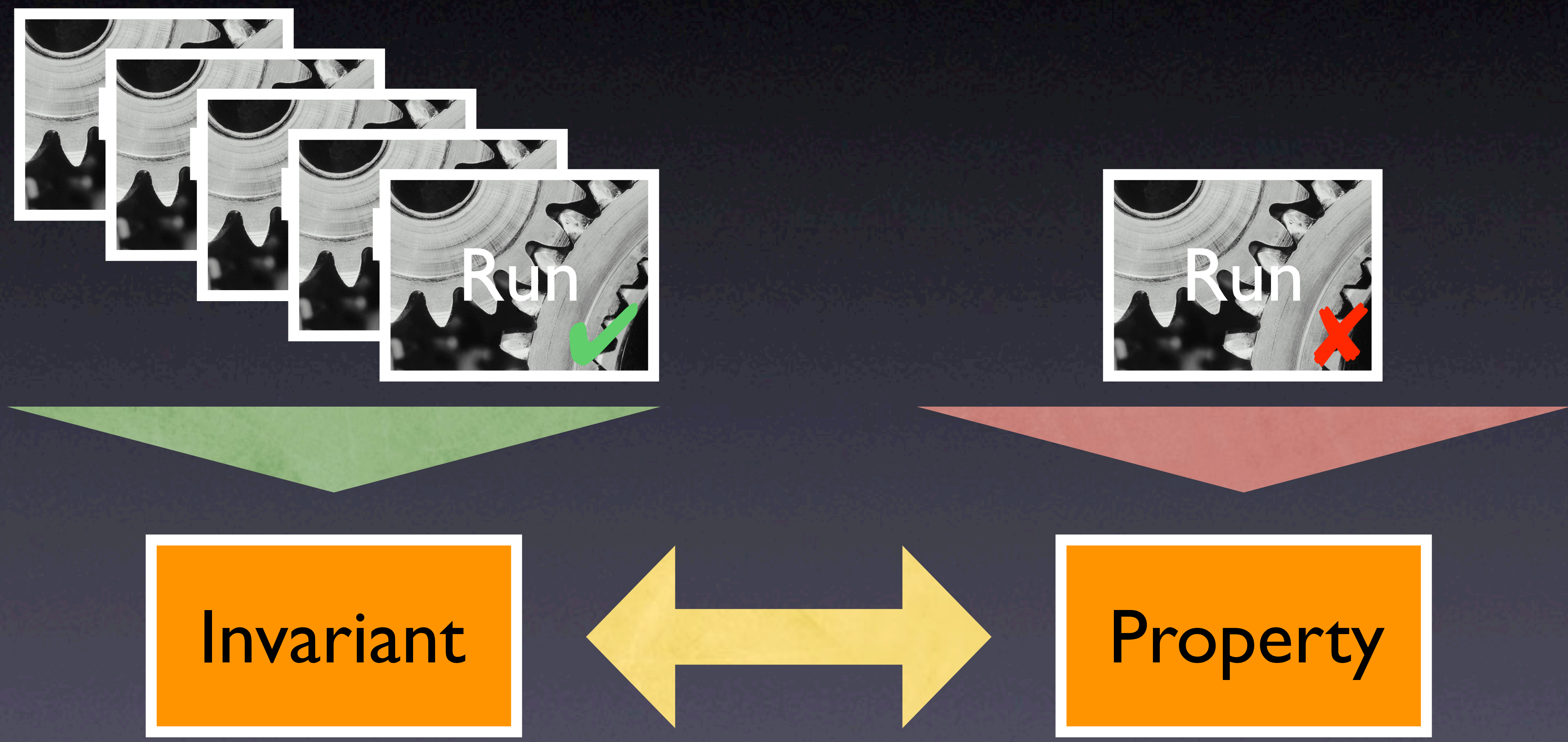

At f(), x is odd

At f(), x = 2

# Diduce

- Determines *invariants* and *violations*
- Written by Sudheendra Hangal and Monica Lam (2001)
- Java bytecode
- analyzed > 30,000 lines of code

# Diduce




Training mode

Checking mode

# Training Mode


- Start with empty set of invariants
- Adjust invariants according to values found during run

# Invariants in Diduce

For each variable, Diduce has a pair (V, M)

- V = *initial value* of variable
- M = *range of values:* i-th bit of M is cleared if value change in i-th bit was observed
- With each assignment of a new value W, M is updated to $M := M \wedge \neg (W \otimes V)$
- *Differences* are stored in same format

# Training Example

| Code | i | Values V | Values M | Differences V | Differences M | Invariant |
|---|---|---|---|---|---|---|
| `i = 10` | 1010 | 1010 | 1111 | – | – | $i = 10$ |
| `i += 1` | 1011 | 1010 | 1110 | 0001 | 1111 | $10 \leq i \leq 11 \wedge \lvert i' - i \rvert = 1$ |
| `i += 1` | 1100 | 1010 | 1000 | 0001 | 1111 | $8 \leq i \leq 15 \wedge \lvert i' - i \rvert = 1$ |
| `i += 1` | 1101 | 1010 | 1000 | 0001 | 1111 | $8 \leq i \leq 15 \wedge \lvert i' - i \rvert = 1$ |
| `i += 2` | 1111 | 1010 | 1000 | 0001 | 1101 | $8 \leq i \leq 15 \wedge \lvert i' - i \rvert \leq 2$ |

During *checking*, clearing an M-bit is an anomaly

# Diduce vs. Daikon

- Less space and time requirements
- Invariants are computed on the fly
- Smaller set of invariants
- Less precise invariants

# Techniques

| Dynamic Invariants | Value Ranges | Sampled Values |
| --- | --- | --- |

# Detecting Anomalies


Differences correlate with failure

# Liblit's Sampling

- We want properties of runs in the field
- Collecting all this data is too expensive
- Would a *sample* suffice?
- Sampling experiment by Liblit et al. (2003)

# Return Values

- Hypothesis: *function return values* correlate with failure or success
- Classified into positive / zero / negative

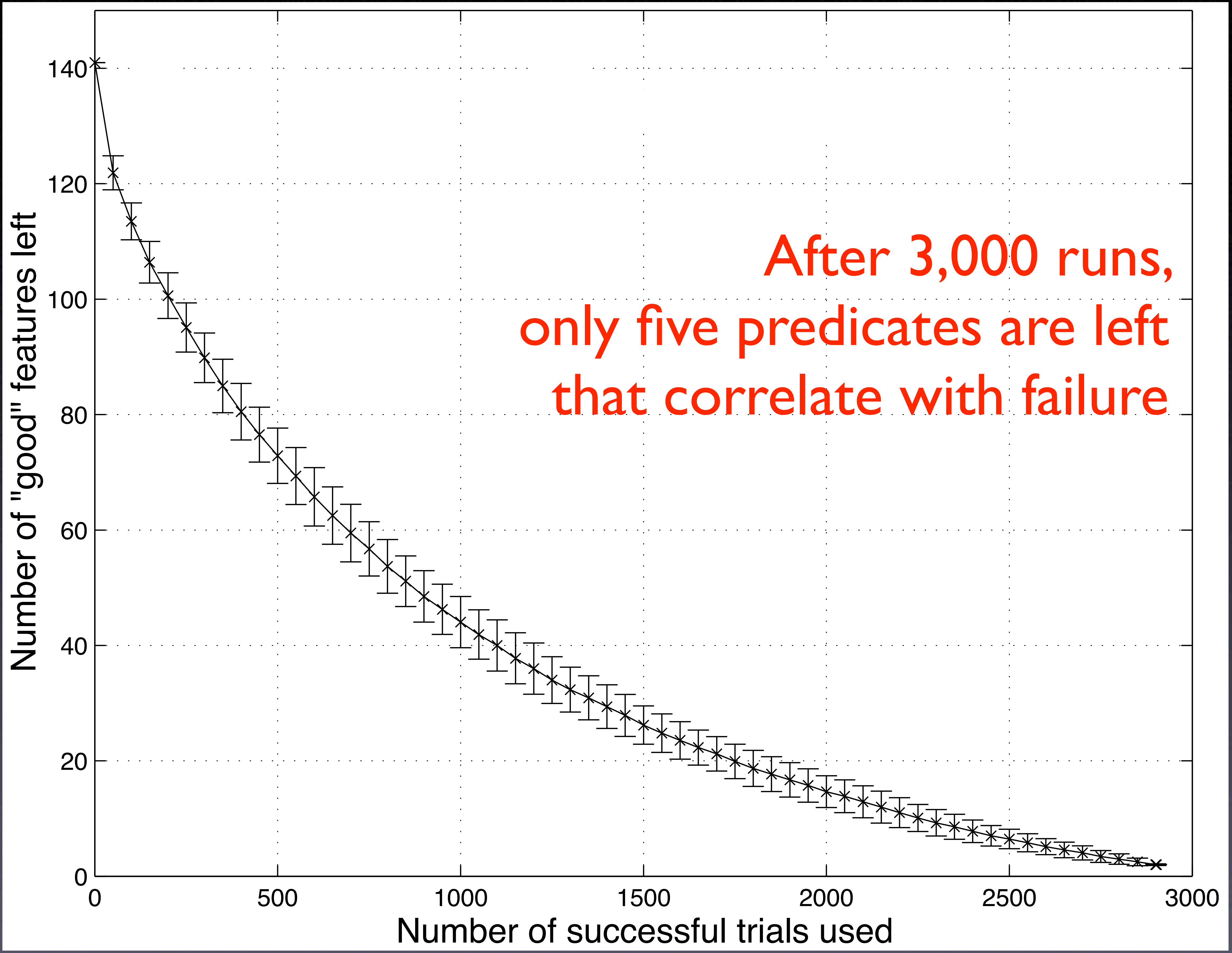
# CCRYPT fails

- CCRYPT is an interactive encryption tool
- When CCRYPT asks user for information before overwriting a file, and user responds with EOF, CCRYPT crashes
- 3,000 random runs
- Of 1,170 predicates, only file_exists() > 0 and xreadline() == 0 correlate with failure

# Liblit's Sampling


Properties

- Can we apply this technique to remote runs, too?
- 1 out of 1000 return values was sampled
- Performance loss <4%



After 3,000 runs,
only five predicates are left
that correlate with failure
Number of "good" features left
Number of successful trials used
0
20
40
60
80
100
120
140
0
500
1000
1500
2000
2500
3000

# Web Services

- Sampling is first choice for web services
- Have 1 out of 100 users run an instrumented version of the web service
- Correlate instrumentation data with failure
- After sufficient number of runs, we can automatically identify the anomaly

# Techniques

| | | |
|---|---|---|
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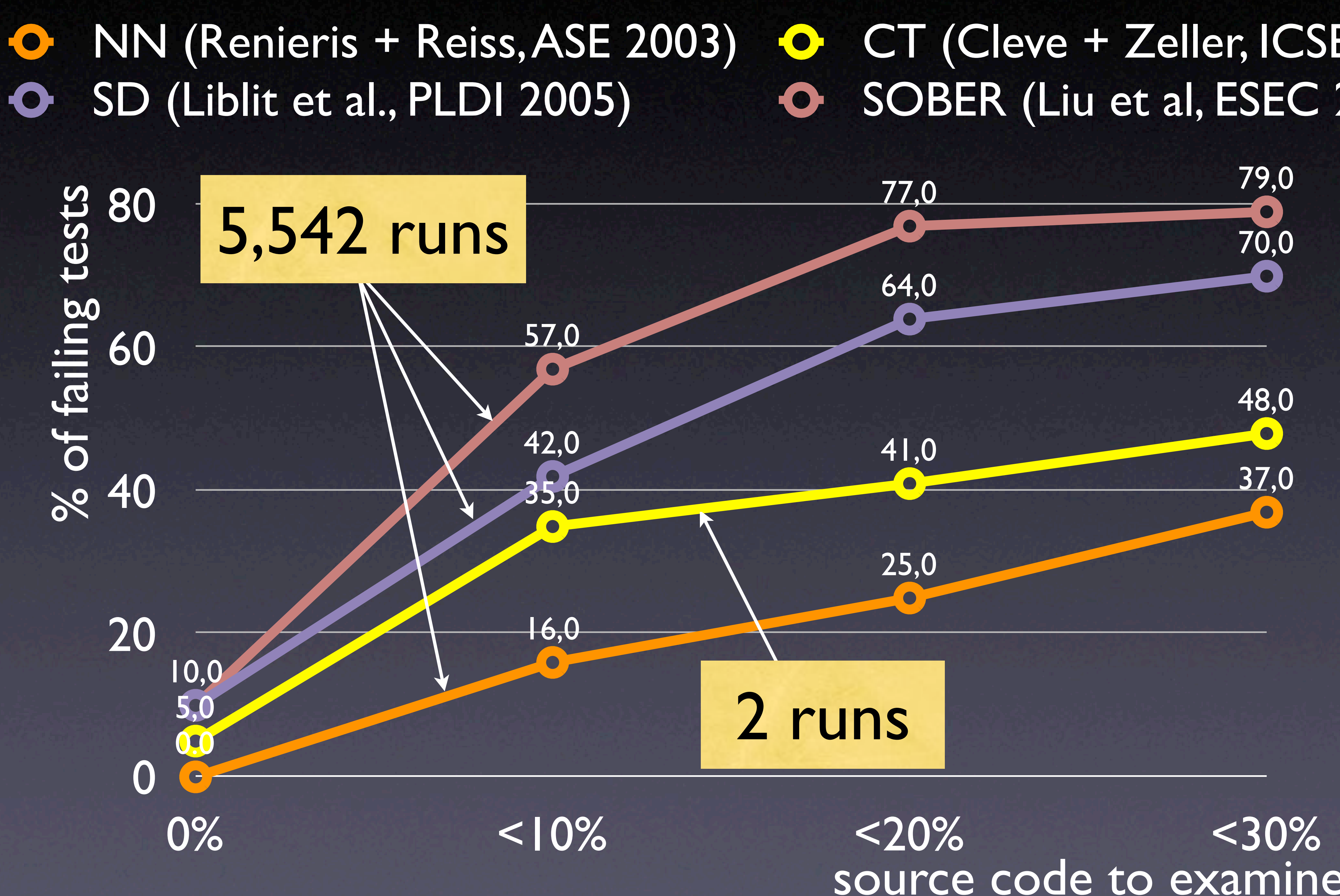
# Anomalies and Causes

- An anomaly is not a cause, but a correlation
- Although correlation ≠ causation, anomalies can be excellent hints
- Future belongs to those who exploit
  - Correlations in *multiple runs*
  - Causation in *experiments*

# Locating Defects




Results obtained from Siemens test suite; can not be generalized

# Concepts

- Comparing data abstractions shows anomalies correlated with failure
- Variety of abstractions and implementations
- Anomalies can be excellent hints
- Future: Integration of anomalies + causes