How to Crash Your Code Using Dynamic Symbolic Execution

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Joint work with Dawson Engler, Daniel Dunbar, Paul Marinescu, Peter Collingbourne, Paul Kelly, Junfeng Yang, Peter Pawlowski, Can Sar, Paul Twohey, Vijay Ganesh, David Dill, Peter Boonstoppel, JaeSeung Song, Peter Pietzuch

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Execution Generated Test Cases: How to Make Systems Code Crash Itself

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Abstract. This paper presents a technique that uses code to automatically generate its own test cases at run-time by using a combination of symbolic and concrete (i.e., regular) execution. The input values to a program (or software component) provide the standard interface of any testing framework with the program it is testing, and generating input values that will explore all the "interesting" behavior in the tested program remains an important open problem in software testing research. Our approach works by turning the problem on its head: we lazily generate, from within the program itself, the input values to the program (and

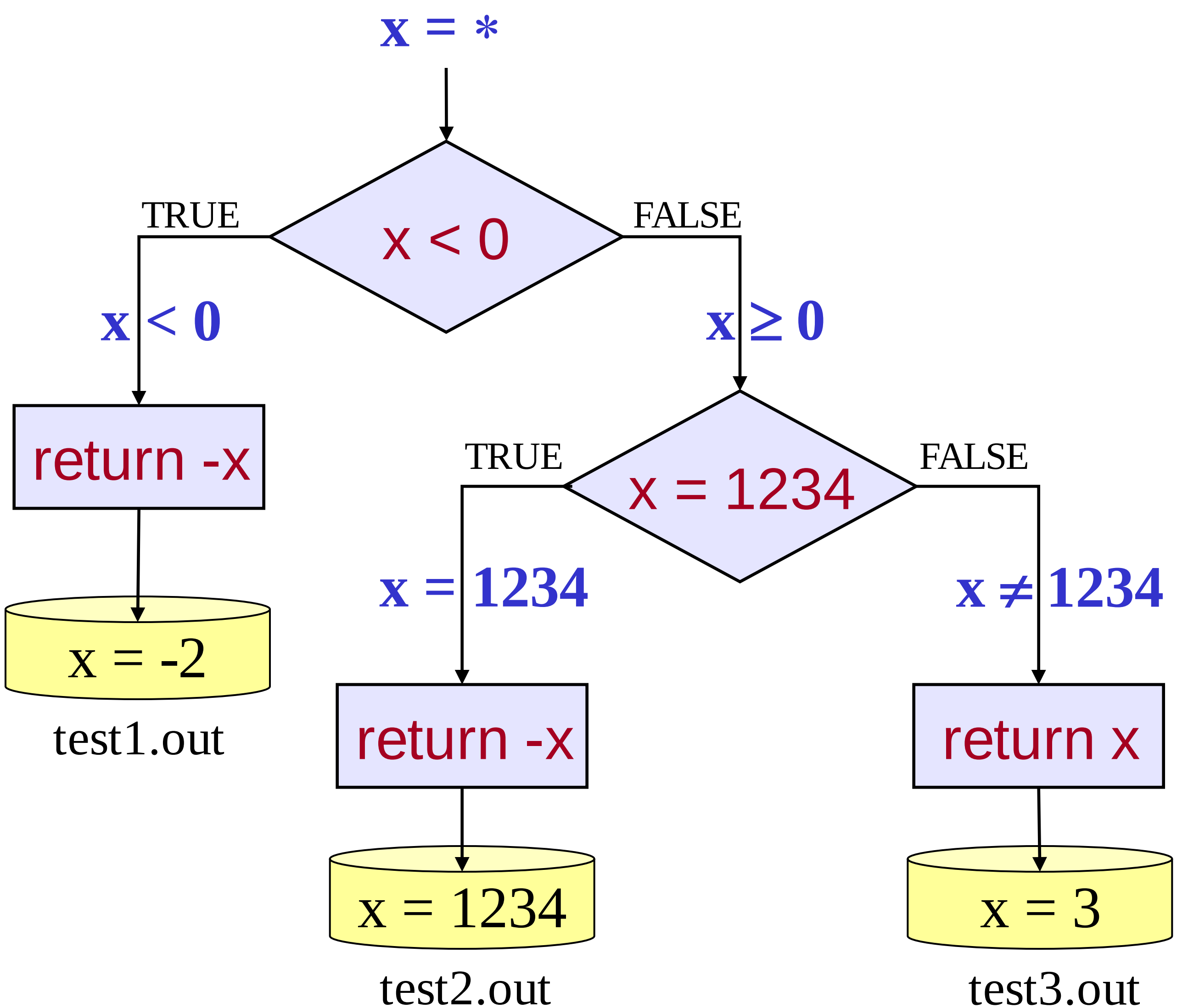
Dynamic Symbolic Execution

Automated technique for generating high-coverage test suites, and finding bugs in software systems

- Received significant interest in the last few years
- Many dynamic symbolic execution/concolic tools available as open-source:
  - **CREST, KLEE, SYMBOLIC JPF**, etc.
- Started to be adopted by the industry:
  - Microsoft (**SAGE, PEX**)
  - IBM (**APOLLO**)
  - Fujitsu (**KLEE/KLOVER, SYMBOLIC JPF**)
  - etc.

Toy Example

```
int bad_abs(int x)
{
    if (x < 0)
        return -x;
    if (x == 1234)
        return -x;
    return x;
}
```



All-Value Checks

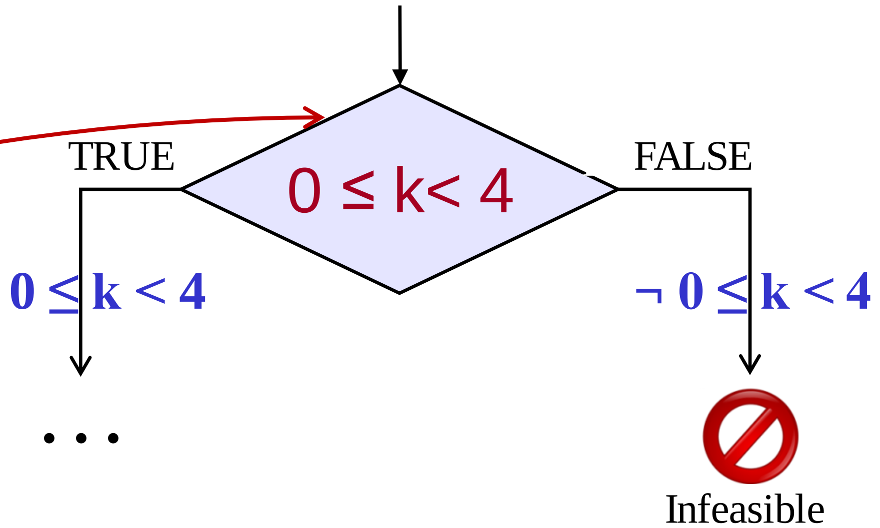
Implicit checks before each dangerous operation

- Pointer dereferences
- Array indexing
- Division/modulo operations
- Assert statements

All-value checks!

- Errors are found if **any** buggy values exist on that path!

```
int foo(unsigned k) {
  int a[4] = {3, 1, 0, 4};
  k = k % 4;
  return a[a[k]];
}
```



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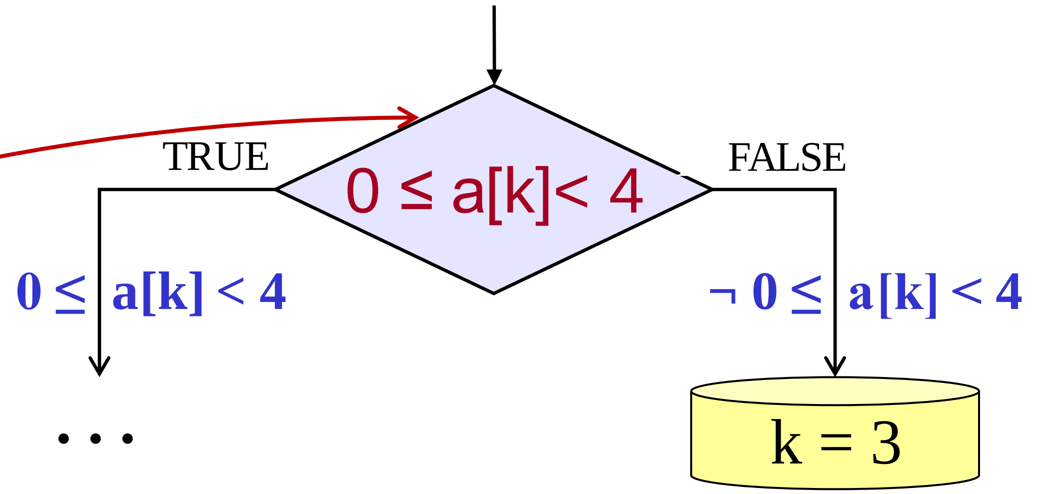


Buffer overflow!

Dynamic Symbolic Execution

- Each path is (essentially) explored separately
  - As in regular testing

- Mixed concrete/symbolic execution
  - All operations that do not depend on the symbolic inputs are (essentially) executed as in the original code!

Dynamic Symbolic Execution

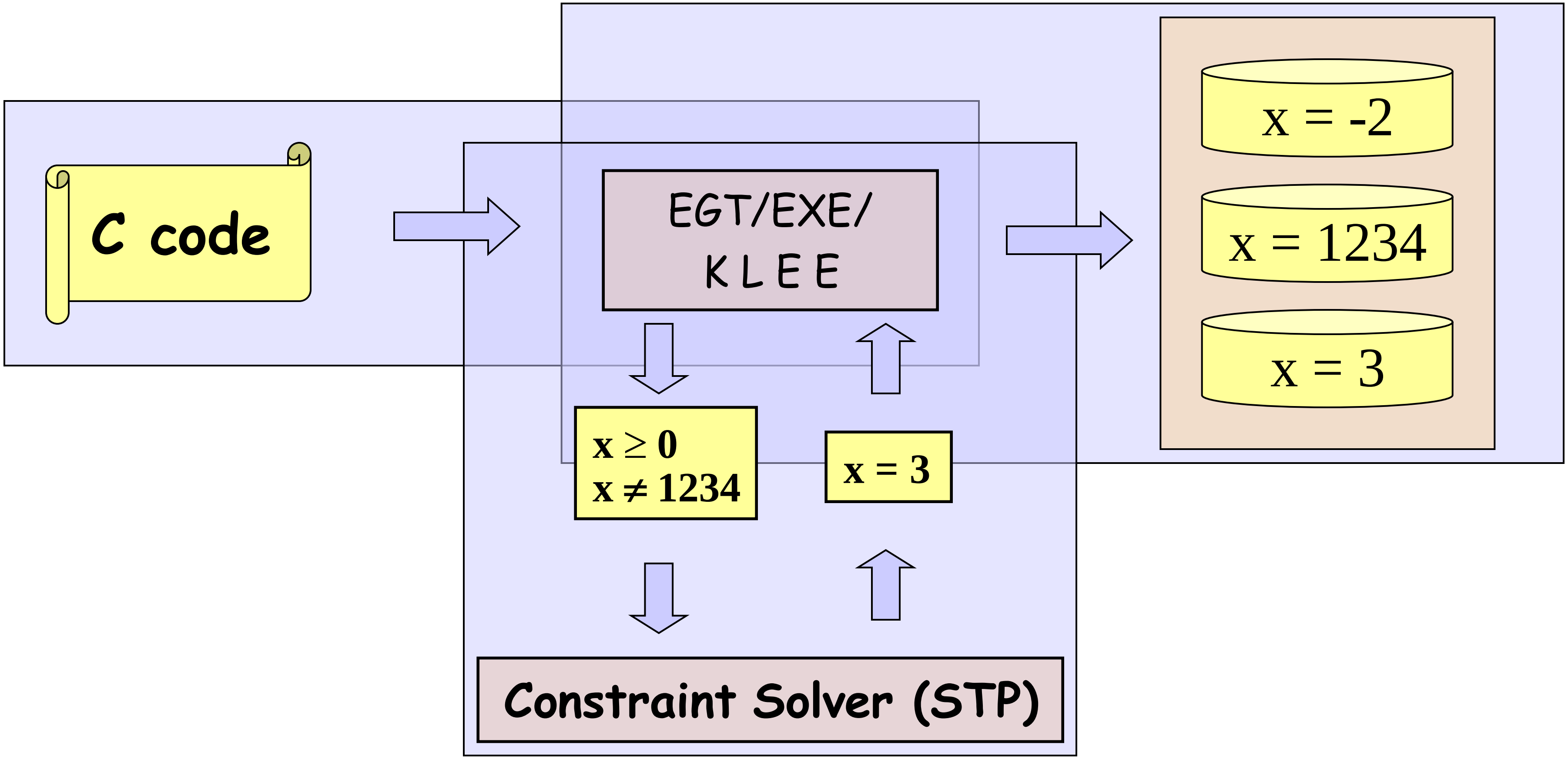
Advantages:

- Ability to interact with the outside environment
  - System calls, uninstrumented libraries
- Only relevant code executed symbolically
  - Without the need to extract it explicitly

...and disadvantages:

- Can only explore a finite number of paths!
  - Important to prioritize most "interesting" ones

Three tools: EGT, EXE, KLEE



Scalability Challenges

Path exploration challenges

Constraint solving challenges

Path Exploration Challenges

Naïve exploration can easily get "stuck"

- Employing search heuristics
- Dynamically eliminating redundant paths
- Statically merging paths
- Using existing regression test suites to prioritize execution
- etc.

Search Heuristics

- Coverage-optimized search
  - Select path closest to an uncovered instruction
  - Favor paths that recently hit new code
- Best-first search
- Random path search
- etc.

Random Path Selection

- Maintain a binary tree of active paths
- Subtrees have equal prob. of being selected, irresp. of size

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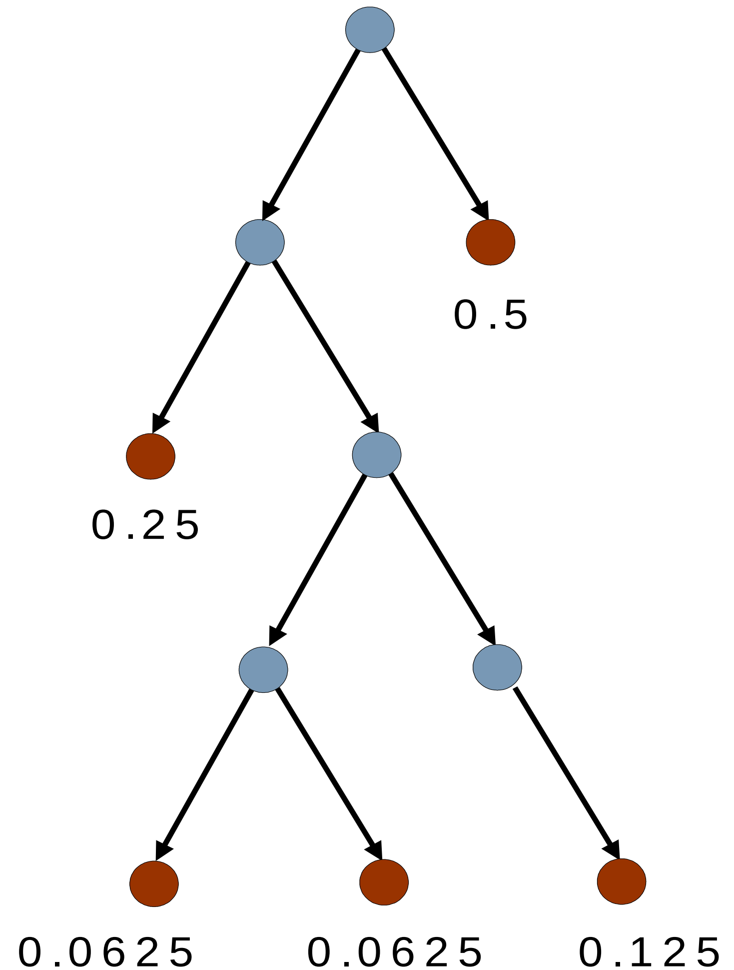
- NOT random state selection
- Favors paths high in the tree
  - less constraints
- Avoid starvation
  - e.g. symbolic loop



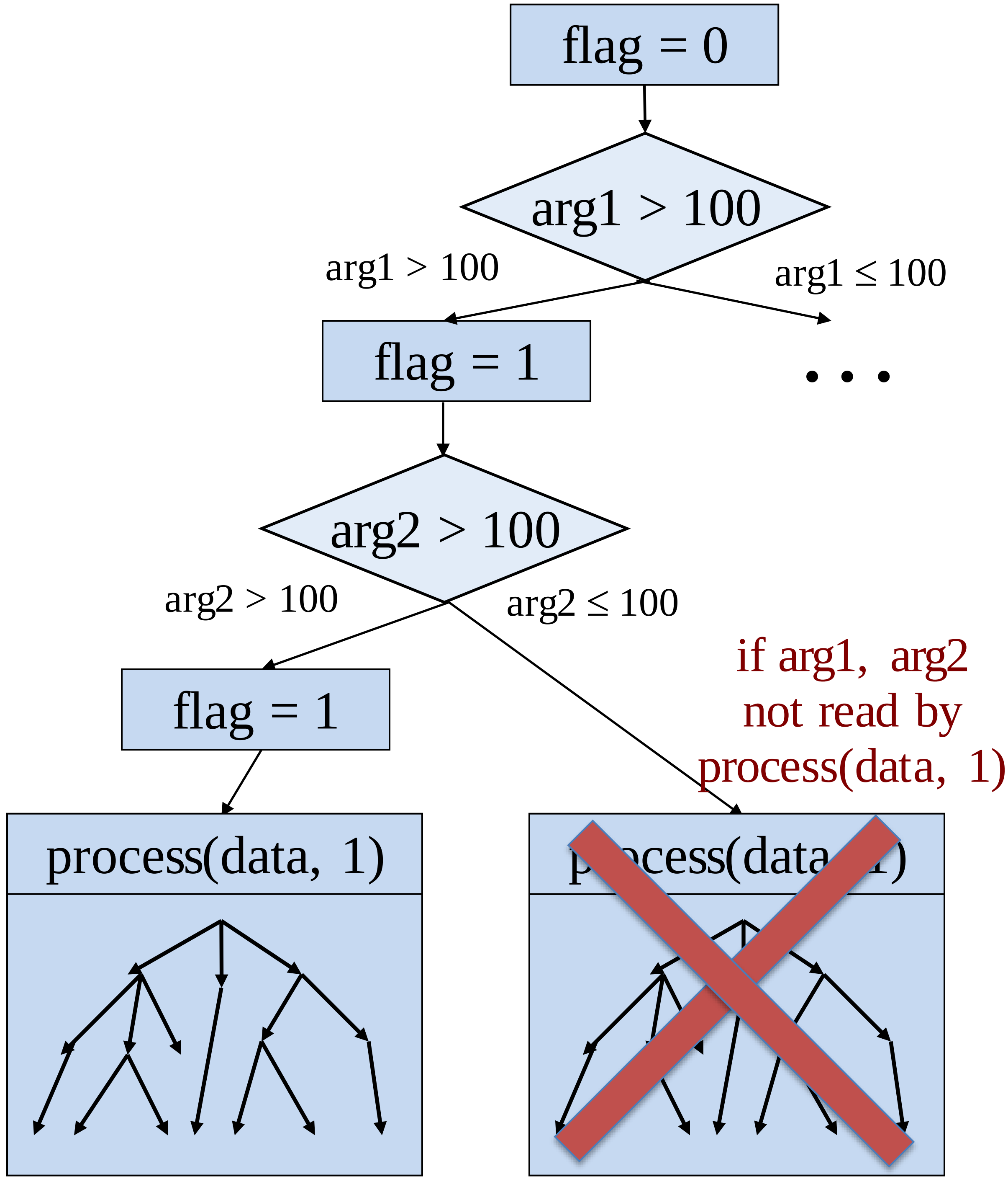
Which Search Heuristic?

Our latest system uses multiple heuristics in a round-robin fashion, to protect against individual heuristics getting stuck in a local maximum.

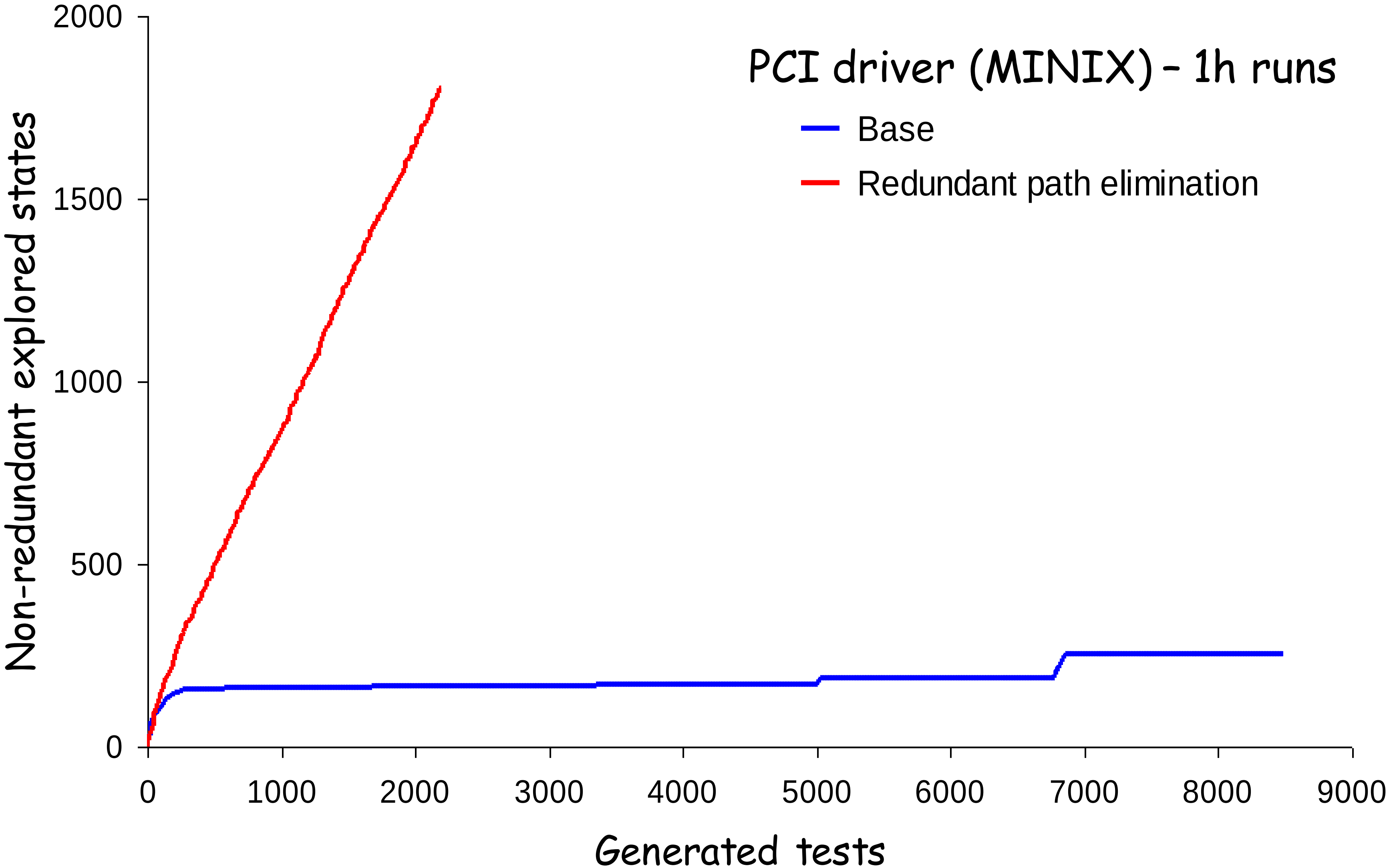
Eliminating Redundant Paths

- If two paths reach the same program point with the same constraint sets, we can prune one of them
- We can discard from the constraint sets of each path those constraints involving memory which is never read again

```
data, arg1, arg2 = *

flag =  0;

if (arg1 > 100)
    flag = 1;

if (arg2 > 100)
    flag = 1;

process(data, flag);
```

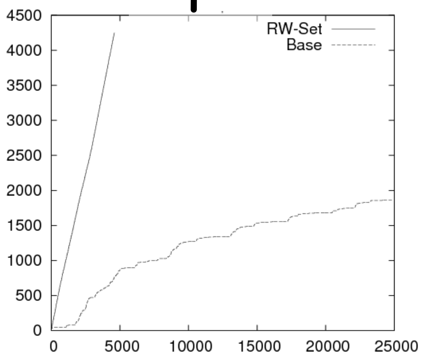


Many Redundant Paths

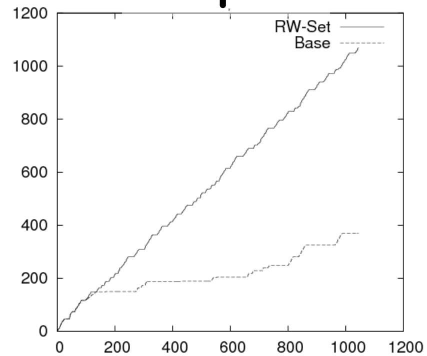


Lots of Redundant Paths

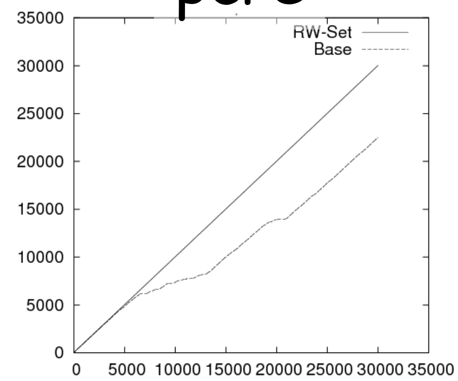
bpf



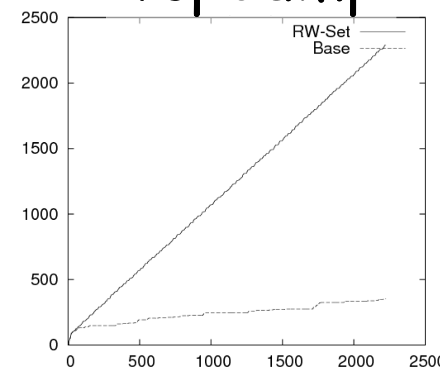
expat



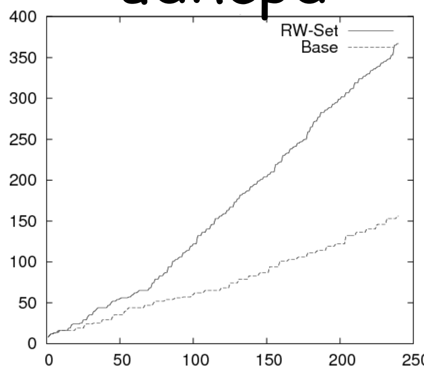
pcre



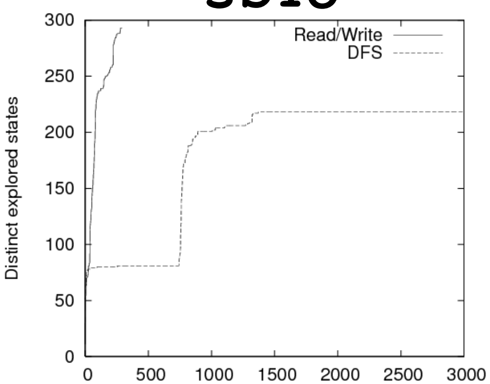
tcpdump



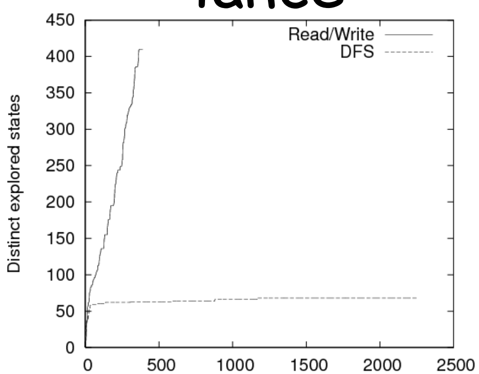
udhcpd



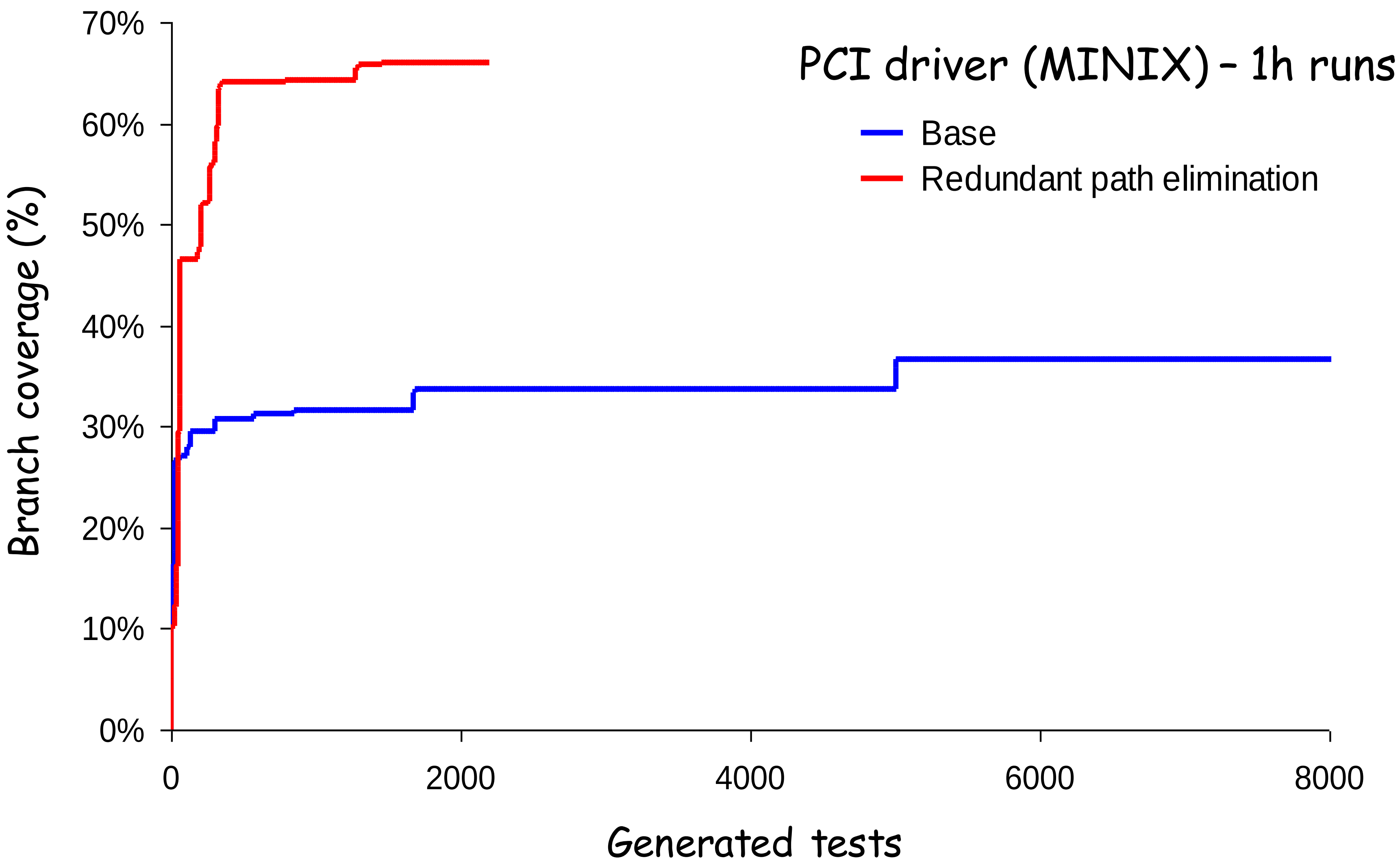
sb16



lance



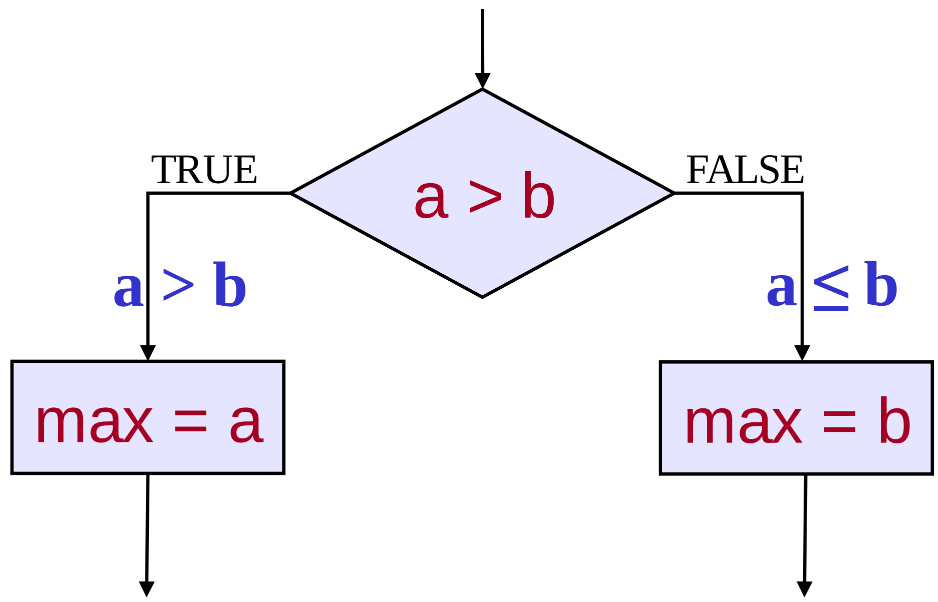
Redundant Path Elimination



Statically Merging Paths

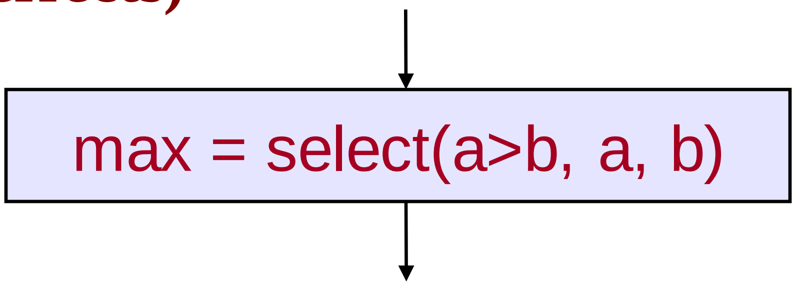
Default behaviour

```
if (a > b)
    max = a;
else max = b;
```



Phi-Node Folding (when no side effects)

```
if (a > b)
    max = a;
else max = b;
```



Statically Merging Paths

```
for (i=0; i < N; i++) {
    if (a[i] > b[i])
          max[i] = a[i];
    else max[i] = b[i];
}
```

- Default: 2^N paths
- Phi-node folding: 1 path

morph computer vision algorithm: $2^{256} \rightarrow 1$

Path merging ≡ Outsourcing problem to constraint solver

(which are often optimized for conjunctions of constraints)

Using Existing Regression Suites

- Most applications come with a manually-written regression test suite

```
$ cd lighttpd-1.4.29
$ make check
...
./cachable.t .......... ok
./core-404-handler.t .. ok
./core-condition.t .... ok
./core-keepalive.t .... ok
./core-request.t ...... ok
./core-response.t ..... ok
./core-var-include.t .. ok
./core.t .............. ok
./lowercase.t ......... ok
./mod-access.t ........ ok
...
```

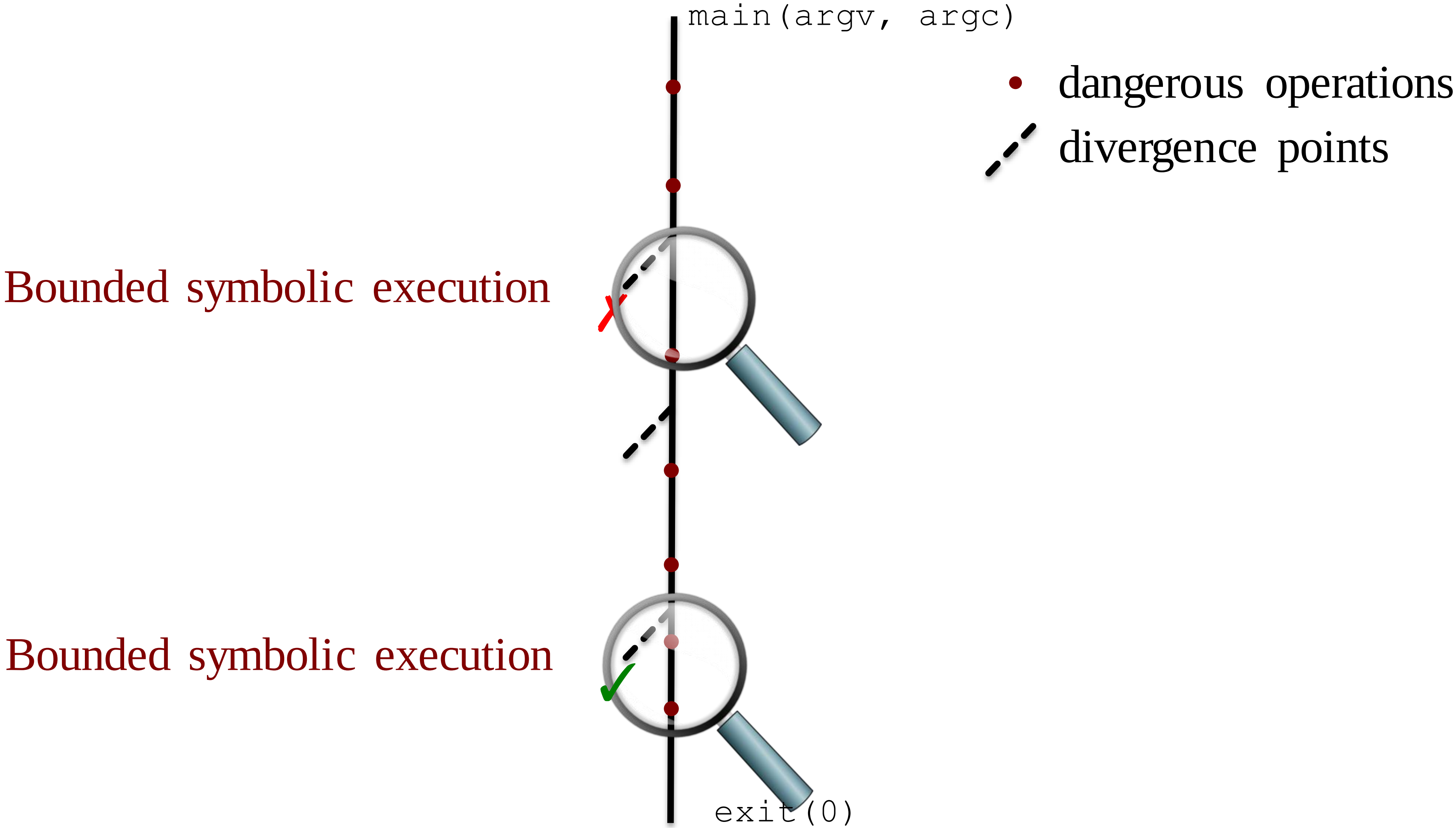
Regression Suites

PROS	CONS
• Designed to execute interesting program paths	• Execute each path with a single set of inputs
• Often achieve good coverage of different program features	• Often exercise the general case of a program feature, missing corner cases

ZESTI: Using Existing Regression Suites

1. Use the paths executed by the regression suite to bootstrap the exploration process (to benefit from the coverage of the manual test suite and find additional errors on those paths)
2. Incrementally explore paths around the dangerous operations on these paths, in increasing distance from the dangerous operations (to test all possible corner cases of the program features exercised by the test suite)

Multipath Analysis



Experimental Results
(or what it's good for)

High-coverage Test Generation

Generic Bug-Finding

Attack Generation

Semantic Error Detection via Crosschecking

Patch Testing

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Bug Finding with EGT, EXE, KLEE:
Focus on Systems and Security Critical Code

	Applications
UNIX utilities	Coreutils, Busybox, Minix (over 450 apps)
UNIX file systems	ext2, ext3, JFS
Network servers	Bonjour, Avahi, udhcpd, lighttpd
Library code	libdwarf, libelf, PCRE, uClibc, Pintos
Packet filters	FreeBSD BPF, Linux BPF
MINIX device drivers	pci, lance, sb16
Kernel code	HiStar kernel
Computer vision code	OpenCV (filter, remap, resize, etc.)
OpenCL code	Parboil, Bullet, OP2

- Most bugs fixed promptly

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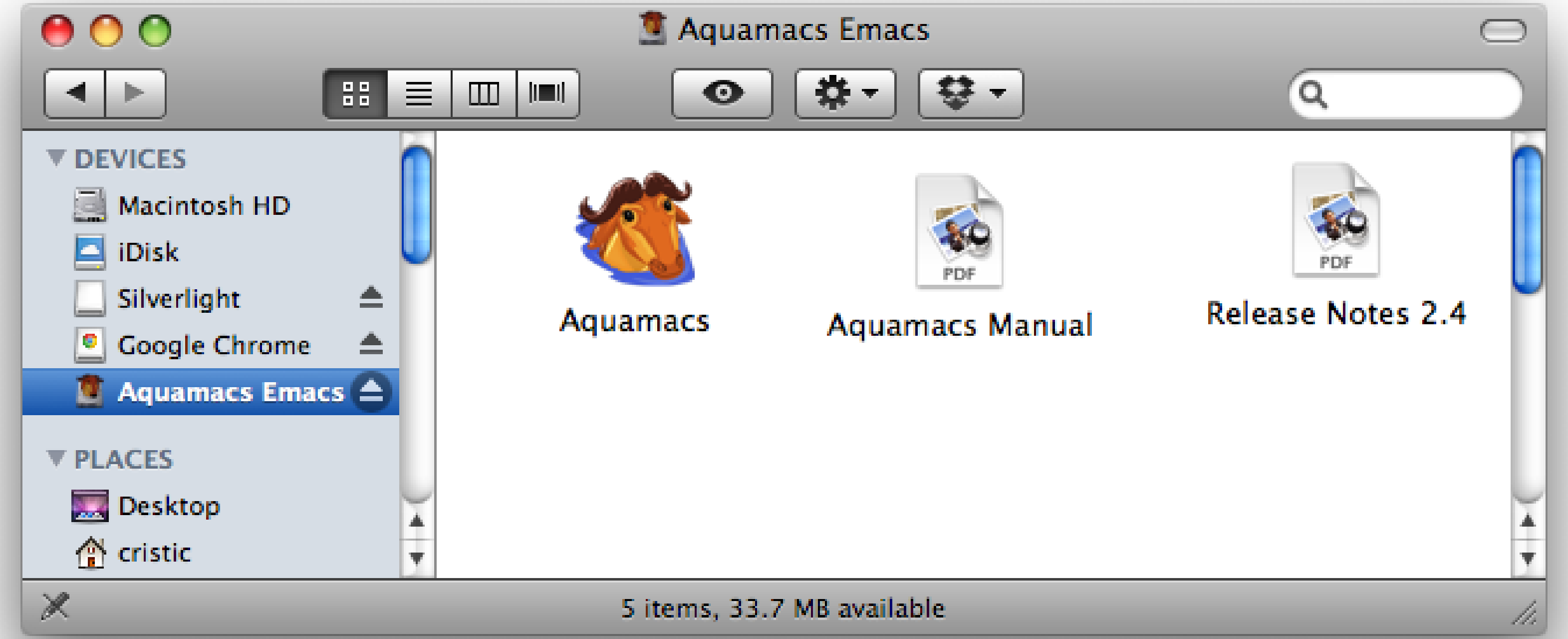
Attack Generation: File Systems

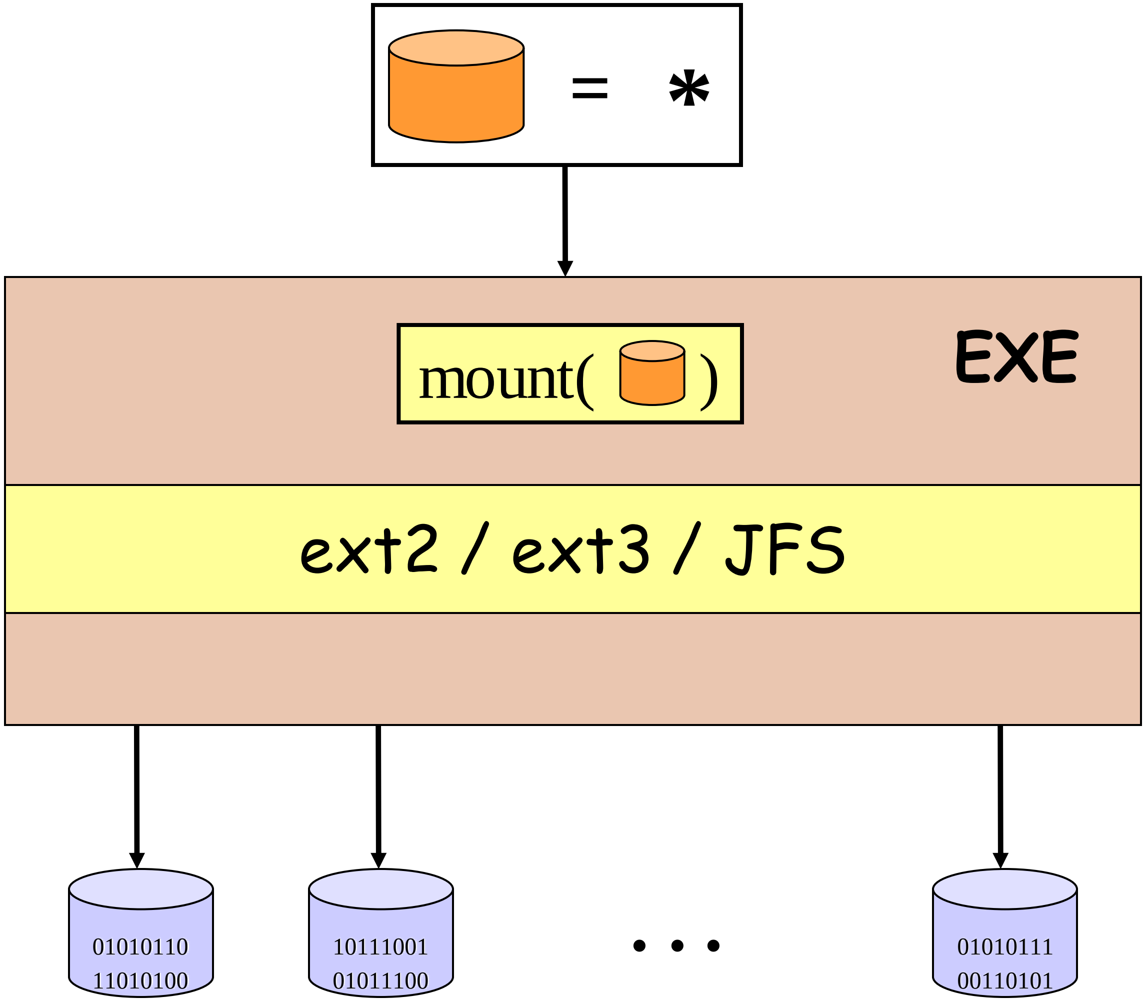
Some modern operating systems allow untrusted users to mount regular files as disk images!



Attack Generation – File Systems

- Mount code is executed by the kernel!
- Attackers may create malicious disk images to attack a system

Attack Generation – File Systems



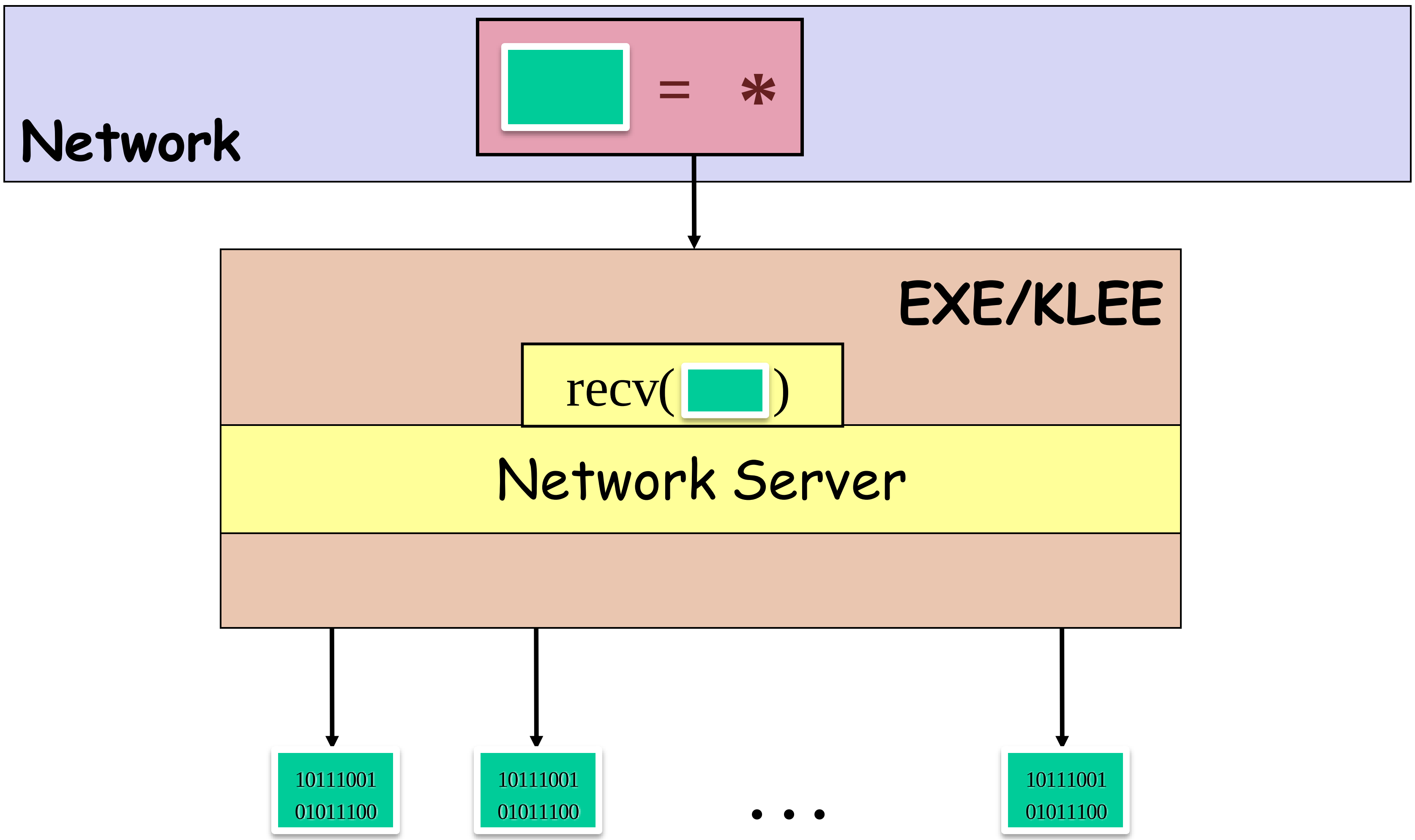
[Oakland 2006]

Disk of death (JFS, Linux 2.6.10)

Offset	Hex Values							
00000	0000	0000	0000	0000	0000	0000	0000	0000
. . .				. . .				
08000	464A	3135	0000	0000	0000	0000	0000	0000
08010	1000	0000	0000	0000	0000	0000	0000	0000
08020	0000	0000	0100	0000	0000	0000	0000	0000
08030	E004	000F	0000	0000	0002	0000	0000	0000
08040	0000	0000	0000	. . .				

- **64th sector of a 64K disk image**
- **Mount it and PANIC your kernel**

Attack Generation: Network Servers



[CCS 2006, ICCCN 2011]

Bonjour: Packet of Death

Offset	Hex Values							
0000	0000	0000	0000	0000	0000	0000	0000	0000
0010	003E	0000	4000	FF11	1BB2	7F00	0001	E000
0020	00FB	0000	14E9	002A	0000	0000	0000	0001
0030	0000	0000	0000	055F	6461	6170	045F	7463
0040	7005	6C6F	6361	6C00	000C	0001		

- **Causes Bonjour to abort, potential DoS attack**
- **Confirmed by Apple, security update released**

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Semantic Bugs

- Bugs shown so far are all generic errors
- What about semantic bugs?
- Can find **assert()** violations
  - Can verify assert statements on a per-path basis

Option 1: Use manually-written specifications!

Crosschecking (Equivalence Checking)

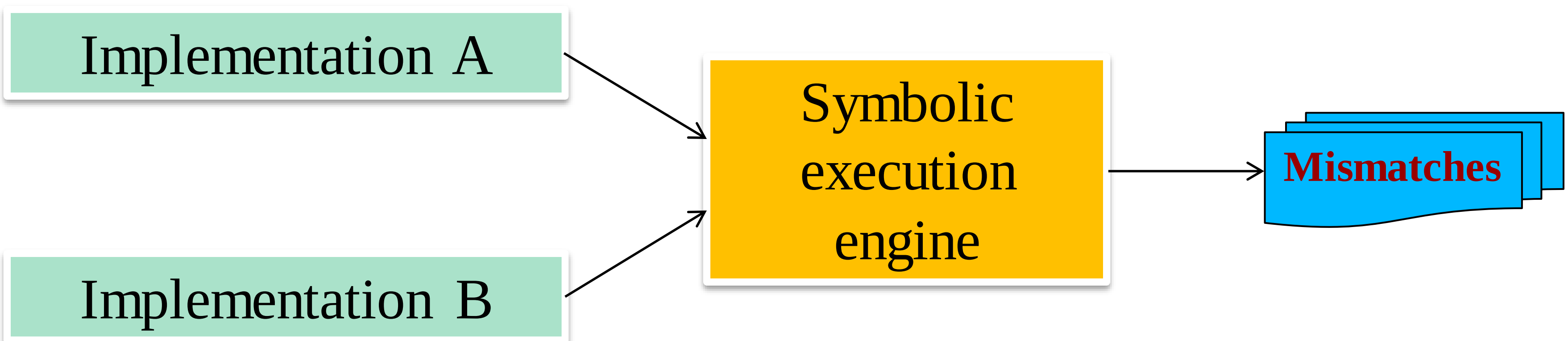
Option 2: Crosschecking!

- Successfully used in the past
- Great match for symbolic execution

Lots of available opportunities:

- Different implementations of the same functionality: e.g., libraries, servers, compilers
- Optimized versions of a reference implementation
- Refactored code
- Reverse computations: e.g., compress and uncompress

Crosschecking



We can find any mismatches in their behavior by:

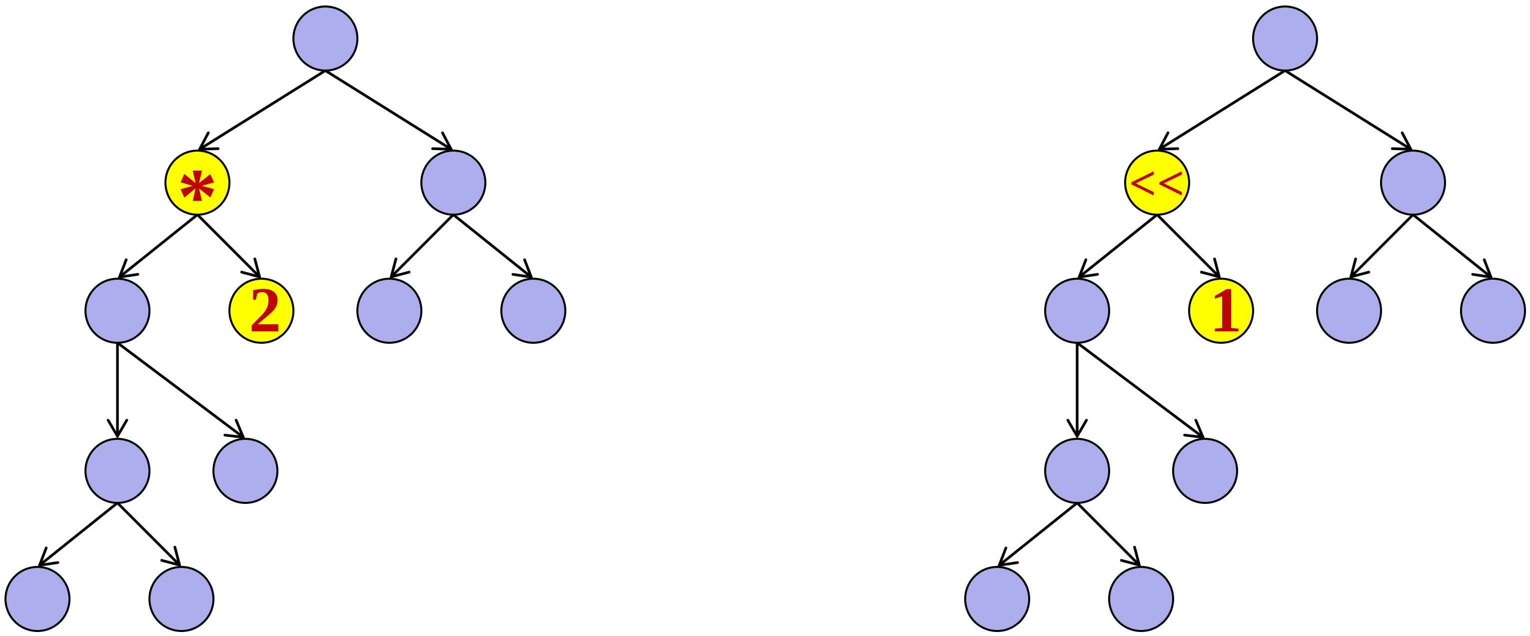
1. Using symbolic execution to explore multiple paths
2. Comparing the path constraints across implementations

Crosschecking: Advantages

- No need to write any specifications
- Constraint solving queries can be solved faster
- Can support constraint types not (efficiently) handled by the underlying solver, e.g., floating-point

Many crosschecking queries can be *syntactically* proved to be equivalent

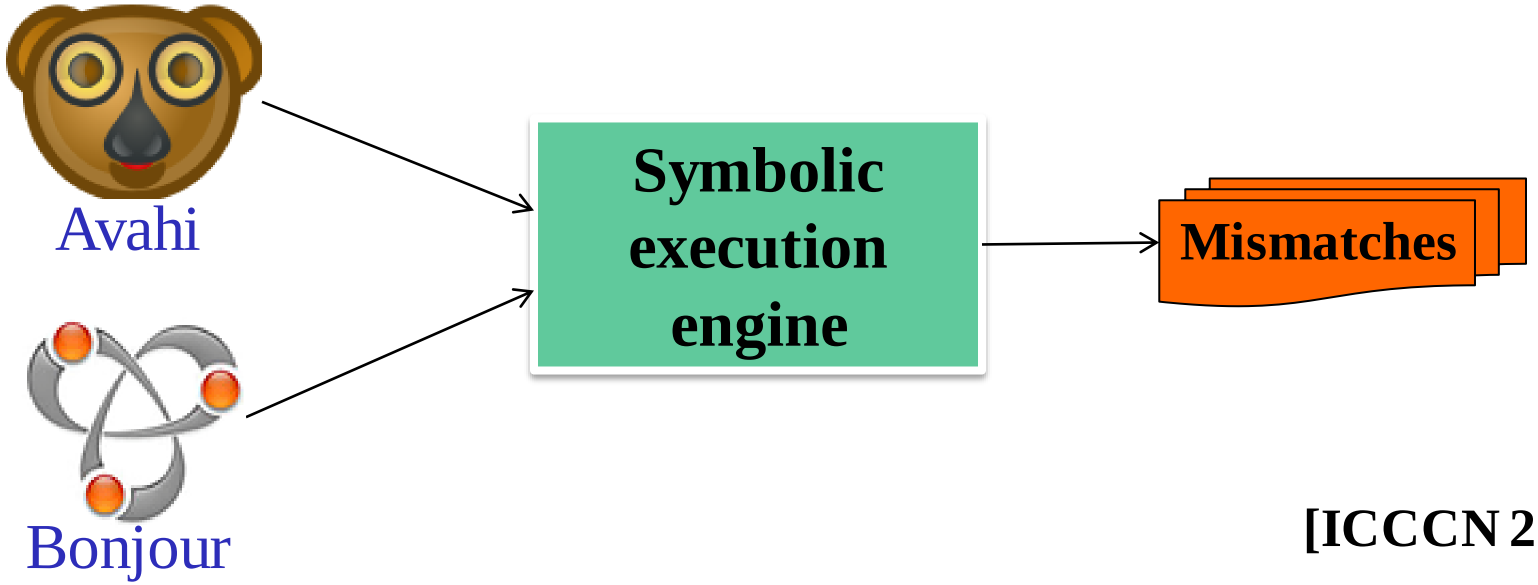
Crosschecking: Advantages



Many crosschecking queries can be *syntactically* proved to be equivalent

ZeroConf Protocol

- Enables devices to automatically configure themselves and their services and be discovered without manual intervention
- Two popular implementations: **Avahi** (open-source), and **Bonjour** (open-sourced by Apple)



[ICCCN 2011]

Server Interoperability
Bonjour vs. Avahi

Offset	Hex Values							
0000	0000	0000	0000	0000	0000	0000	0000	0000
0010	003E	0000	4000	FF11	1BB2	7F00	0001	E000
0020	00FB	0000	14E9	002A	0000	0000	0002	0001
0030	0000	0000	0000	055F	6461	6170	045F	7463
0040	7005	6C6F	6361	6C00	000C	0001		

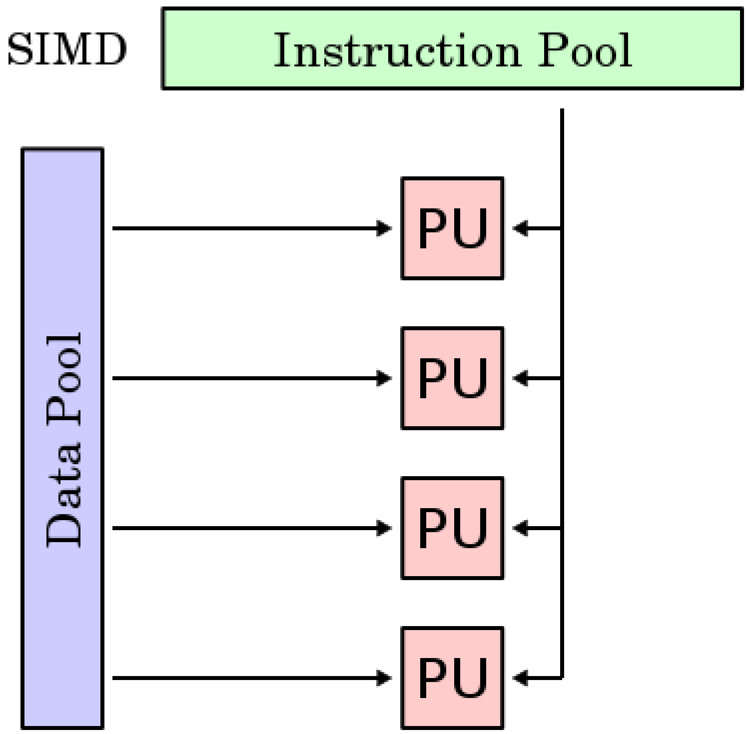
- **mDNS specification (§18.11):**

  "Multicast DNS messages received with non-zero Response Codes MUST be silently ignored."
- **Avahi ignores this packet, Bonjour does NOT**

SIMD Optimizations

Most processors offer support for SIMD instructions

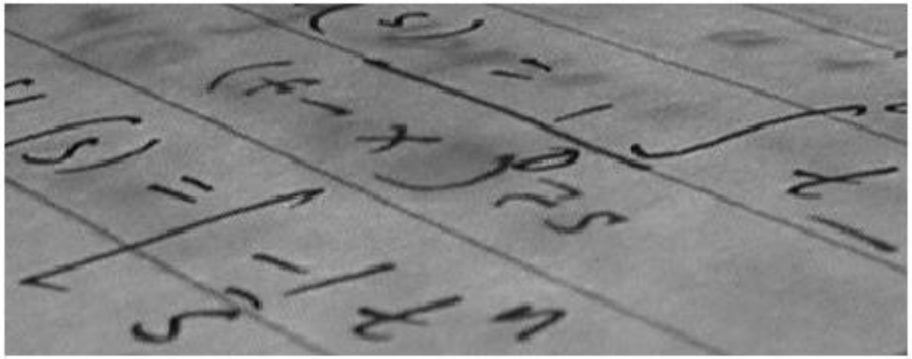
- Can operate on multiple data concurrently
- Many algorithms can make use of them (e.g., computer vision algorithms)



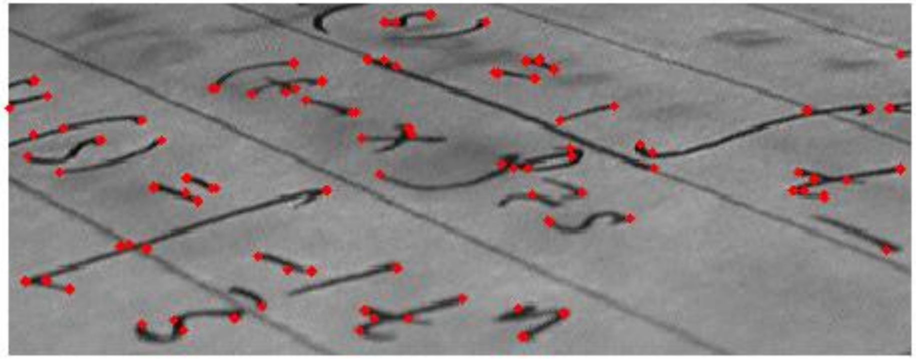
[EuroSys 2011]

SIMD Optimizations

OpenCV: popular computer vision library from Intel and Willow Garage



[Corner detection algorithm]



OpenCV Results

- Crosschecked 51 SIMD-optimized versions against their reference scalar implementations
  - Proved the bounded equivalence of 41
  - Found mismatches in 10
- Most mismatches due to tricky FP-related issues:
  - Precision
  - Rounding
  - Associativity
  - Distributivity
  - NaN values

Other Crosschecking Studies

UNIX utilities:
desktop vs. embedded

[OSDI 2008]

GPU Optimizations:
Scalar vs. GPGPU code

[HVC 2011]

DHCP servers:
desktop vs. embedded

[WiP]

uDHCPD

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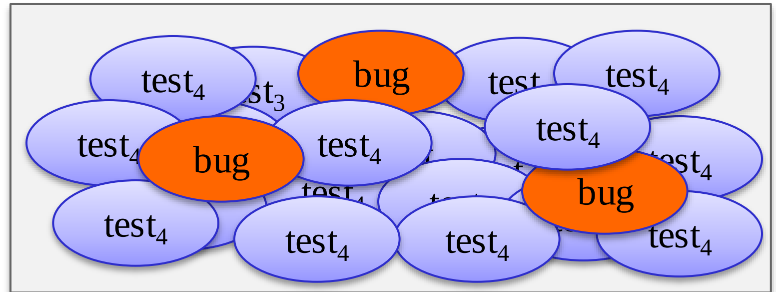
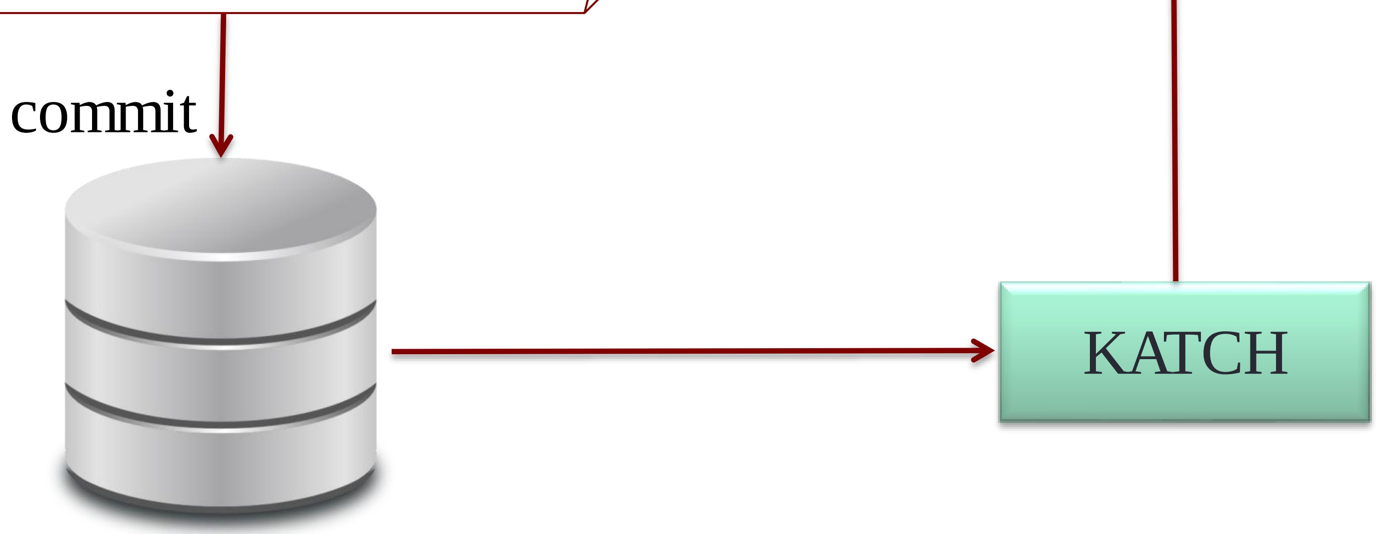
Semantic Error Detection
via Crosschecking

Patch Testing

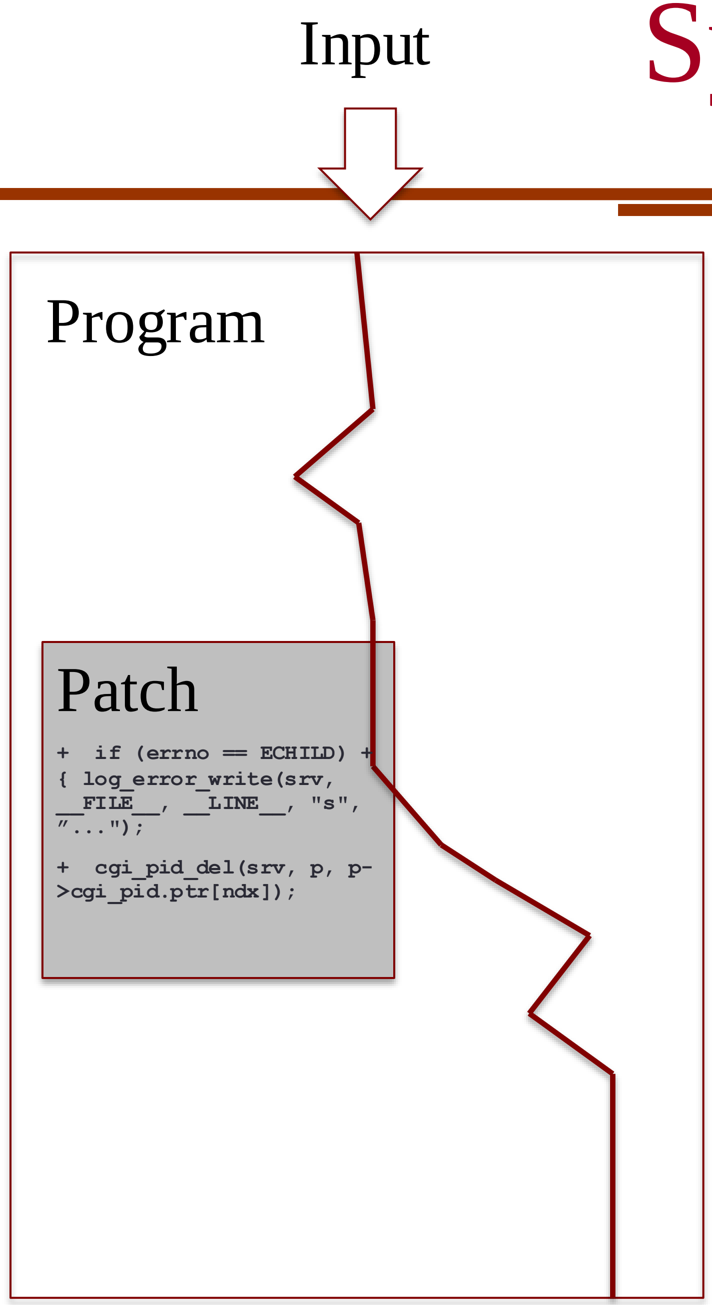
High-Coverage Symbolic Patch Testing
[Marinescu and Cadar, SPIN 2012]

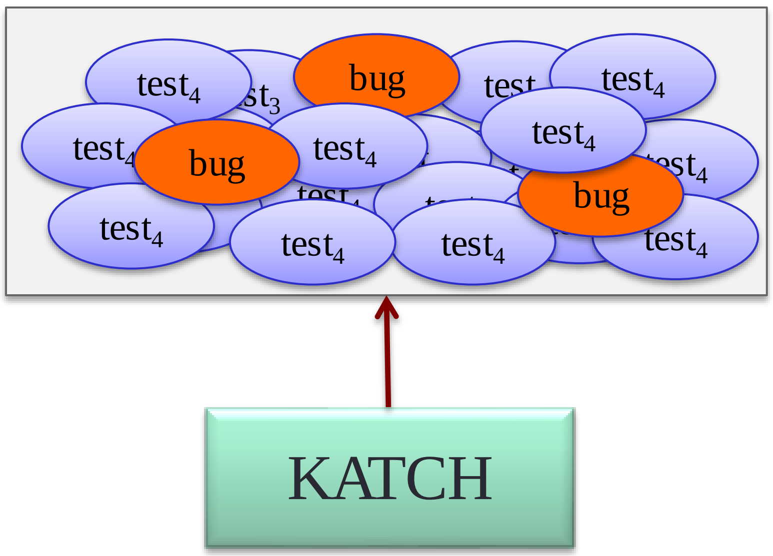
```
--- klee/trunk/lib/Core/Executor.cpp  2009/08/01 22:31:44 77819
+++ klee/trunk/lib/Core/Executor.cpp  2009/08/02 23:09:31 77922
@@ -2422,8 +2424,11 @@
       info << "none\n";
     } else {
       const MemoryObject *mo = lower->first;
+      std::string alloc_info;
+      mo->getAllocInfo(alloc_info);
       info << "object at " << mo->address
-           << " of size " << mo->size << "\n";
+           << " of size " << mo->size << "\n"
+           << "\t\t" << alloc_info << "\n";
```





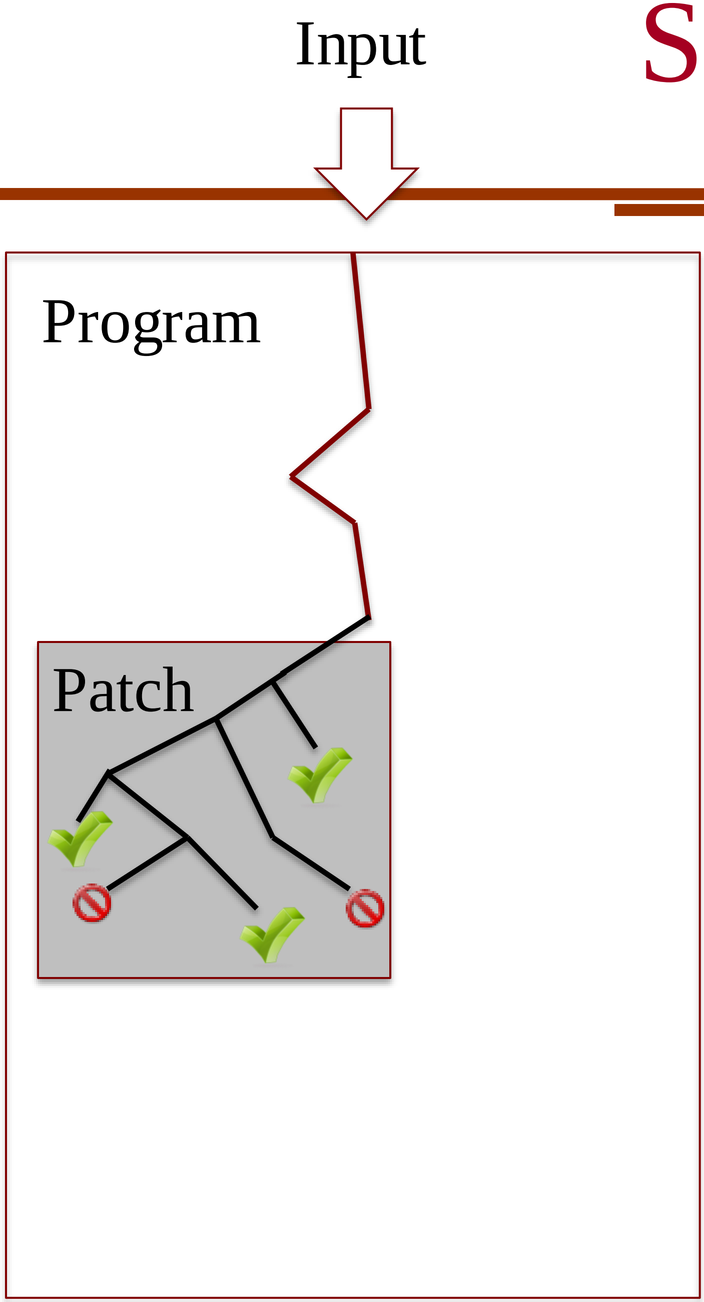
Symbolic Patch Testing

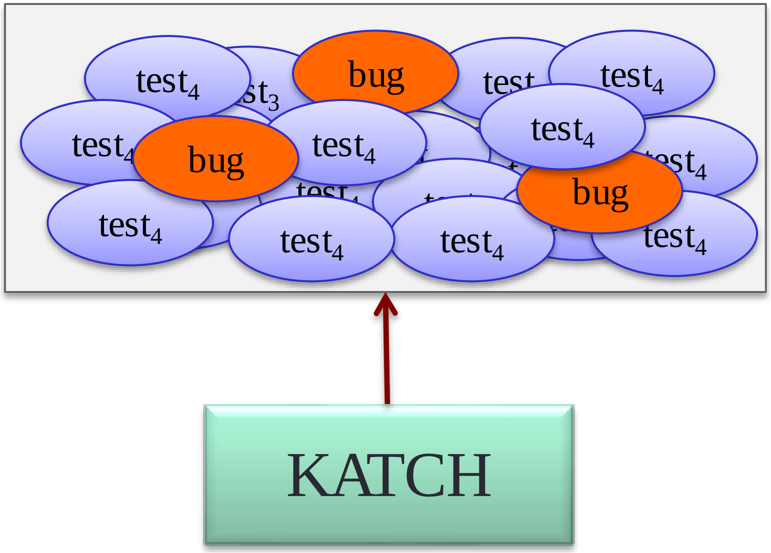




1. Select the regression input closest to the patch (or partially covering it)

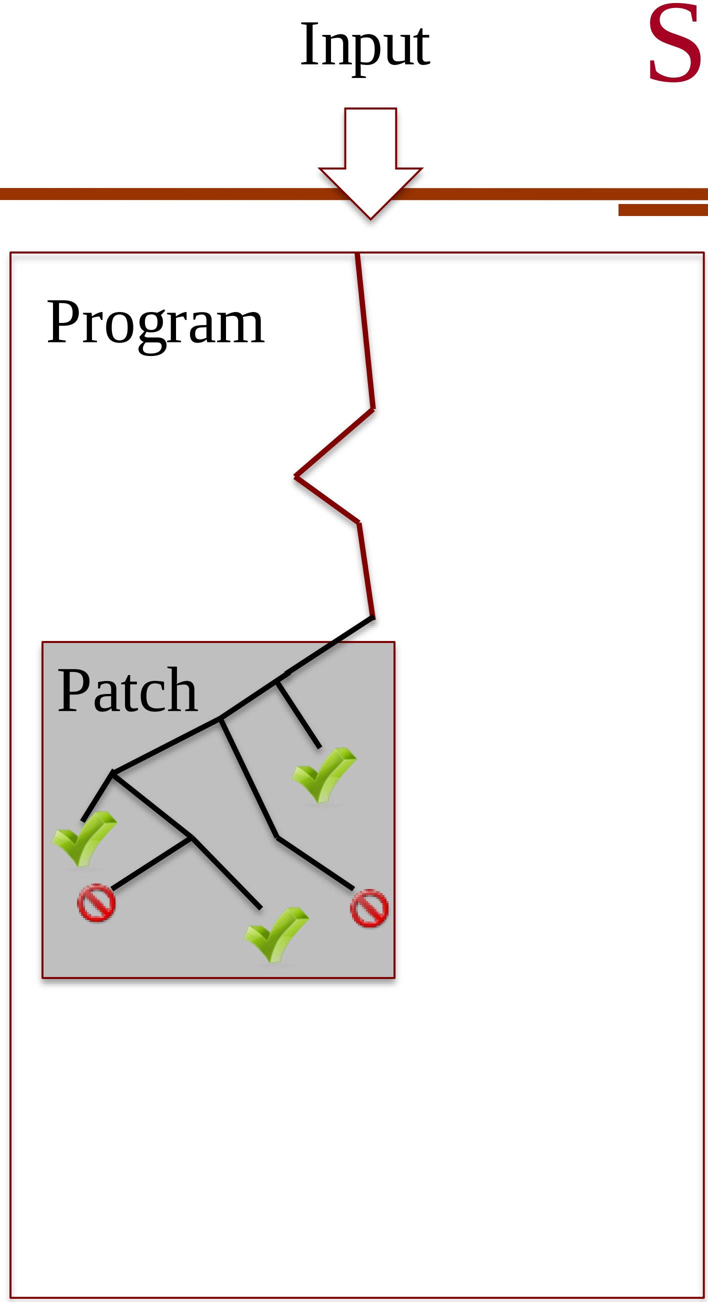
Symbolic Patch Testing

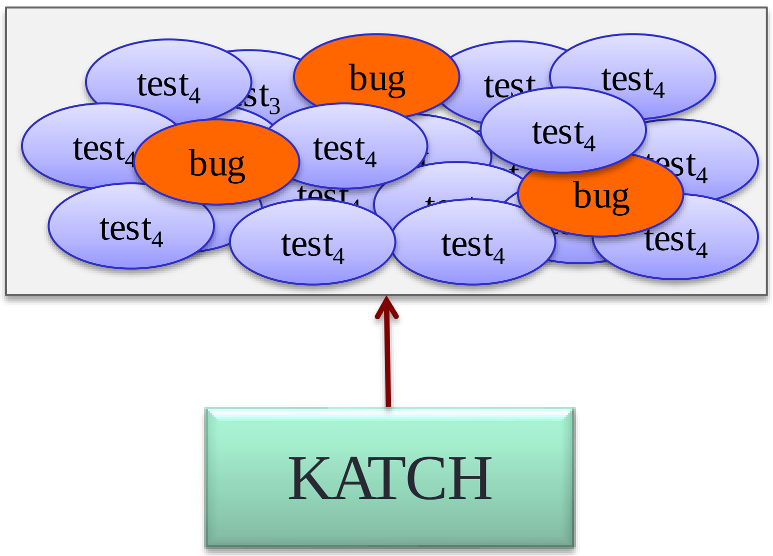




2. Greedily drive exploration toward uncovered statements in the patch

Symbolic Patch Testing





3. If stuck, identify the constraints that disallow execution to reach the patch, and backtrack

Preliminary Results

LIGHTTPD
fly light.

Powers several popular sites such as YouTube and Wikipedia

Revision	ELOC	Covered ELOC	
		Regression	KATCH
2631	20	15 (75%)	20 (100%)
2660	33	9 (27%)	24 (72%)
2747	10	4 (40%)	10 (100%)

Lighttpd r2631

Revision	ELOC	Covered ELOC	
		Regression	KATCH
2631	20	15 (75%)	20 (100%)

http://zzz.example.com/ → KATCH → https://zz.example.com/

Lighttpd r2660

Revision	ELOC	Covered ELOC	
		Regression	KATCH
2660	33	9 (27%)	24 (72%)

```
if (str ->ptr[i] >= '␣' && str->ptr[i] <= '~') {
    /* printable chars */
    buffer_append_string_len(dest,&str ->ptr[i],1);
} else switch (str->ptr[i]) {
case '"':
    BUFFER APPEND STRING CONST(dest, "\\\"");
    break;
```

Bug reported and fixed promptly by developers

Dynamic Symbolic Execution

- Automatically explores paths through a program
- Can generate inputs exposing both generic and semantic bugs in complex software
  - Including file systems, library code, utility applications, network servers, device drivers, computer vision code

KLEE: Freely Available as Open-Source

http://klee.llvm.org

- Over 200 subscribers to the klee-dev mailing list
- Extended in many interesting ways by several research groups, in the areas of:
  - wireless sensor networks
  - schedule memoization in multithreaded code
  - automated debugging
  - exploit generation
  - online gaming, etc.