EXE: Automatically Generating Inputs of Death

Cristian Cadar,
Vijay Ganesh, Peter Pawlowski,
David Dill, Dawson Engler

Stanford University

CCS 2006, Alexandria, VA

What is EXE?

- Goal: generate inputs that explore (ideally) all paths of real C systems code

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1. Bug-finding tool
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PCRE – expressions of death

```
[^[\0^\0]\*-?]{\0
[\*-\`[\0^\0]\`-?]{\0
[\*-\`[\0^\0]\`-?]\0
(?#)\?[[[\0\0]\-]{\0
(?#)\?[[[\0\0]\[]\0
(?#)\?[[[\0\0]\-]\0
(?#)\?[[[\0\0][\0^\0]]\0
(?#)\?[[[\0\0][\0^\0]\]\0
[\-\`[\0^\0]\`]{\0
[\*-\`[\0^\0]\`-?]\0
[\-\`[\0^\0]\`-]\0
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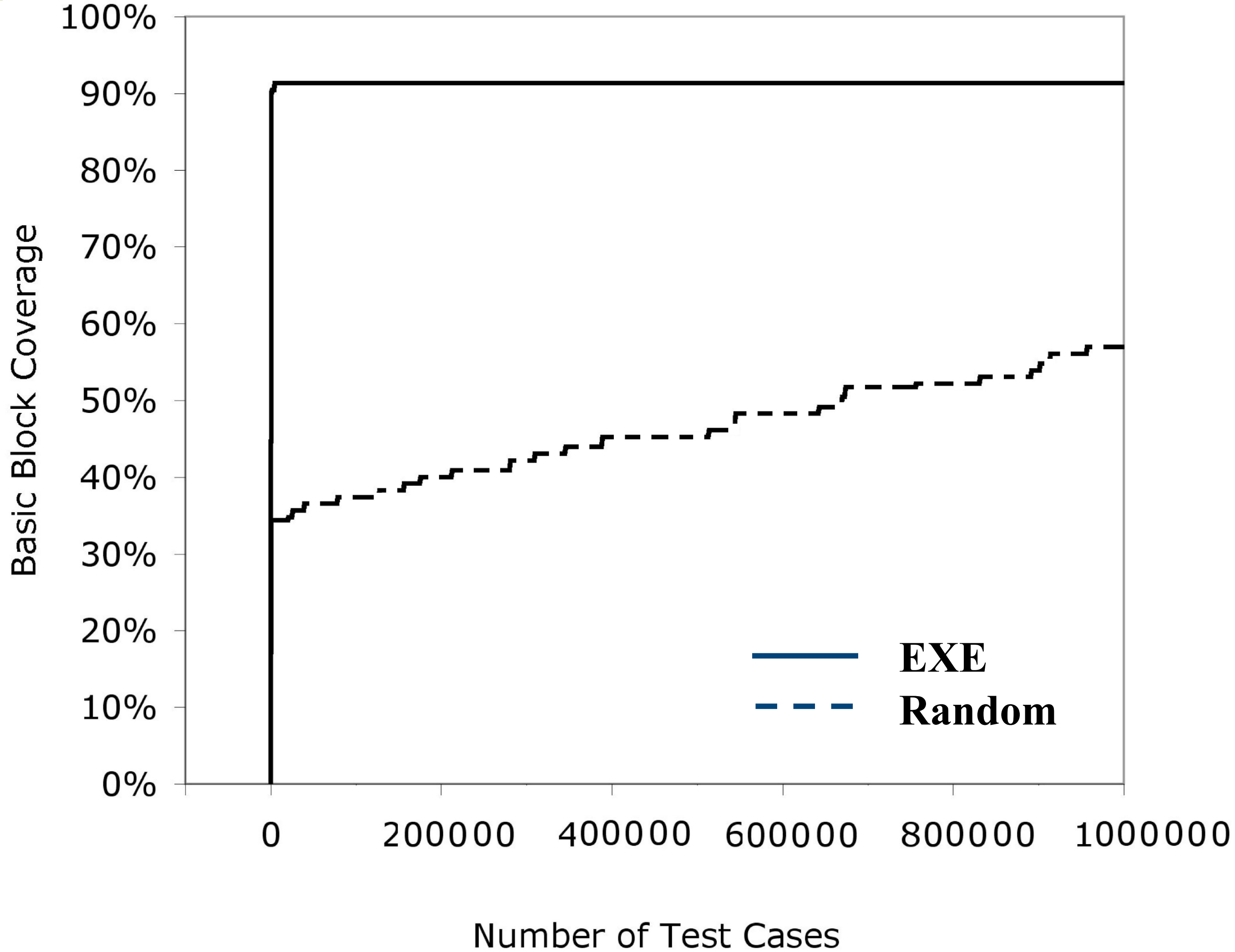
(?#)\?[:[[\0\0]\-]\0
(?#)\?[[[\0\0]\]\0
(?#)\?[[[\0\0][\0^\0]-]\0
(?#)\?[=[[\0\0][\0^\0]\?]\0
```

What is EXE?

- Goal: generate inputs that explore (ideally) all paths of real C systems code

1. Bug-finding tool
   - Produces concrete inputs that trigger attacks
2. Test case generator
   - Good statement/block, branch, path coverage

EXE vs. random (BPF)



Basic idea

- Use the code itself to construct its input
- Symbolic execution = collect constraints on inputs marked as *symbolic*

Example (simplified BPF code)

```
static inline void *skb_header_pointer(struct sk_buff  *skb,
                                        int offset,
                                        int len) {
    if (offset + len <= skb->len)
        return skb->data + offset;
    exit(1);
}
…
exe_make_symbolic(&offset);
…
u16* p = skb_header_pointer(skb, offset, 4);
u32 A = *p;
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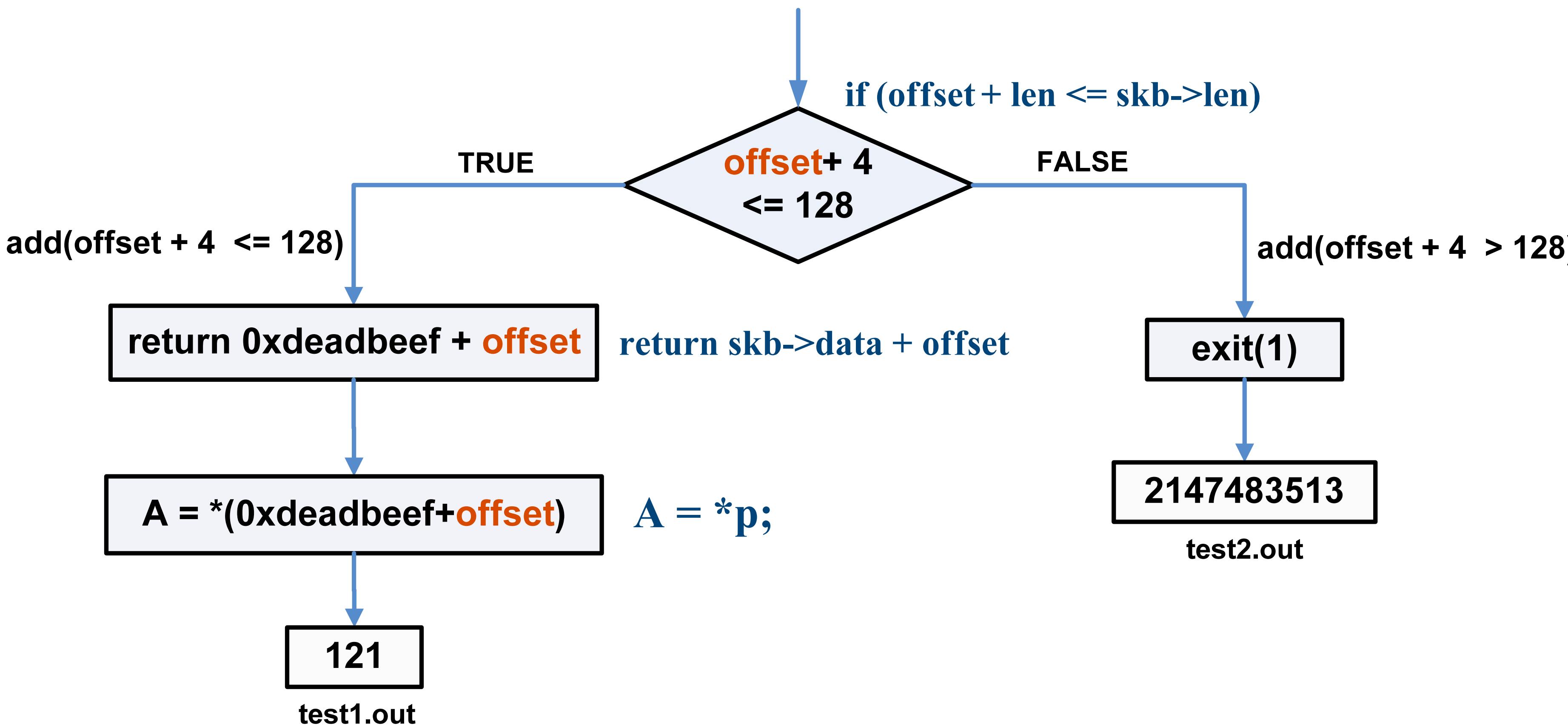
Running EXE

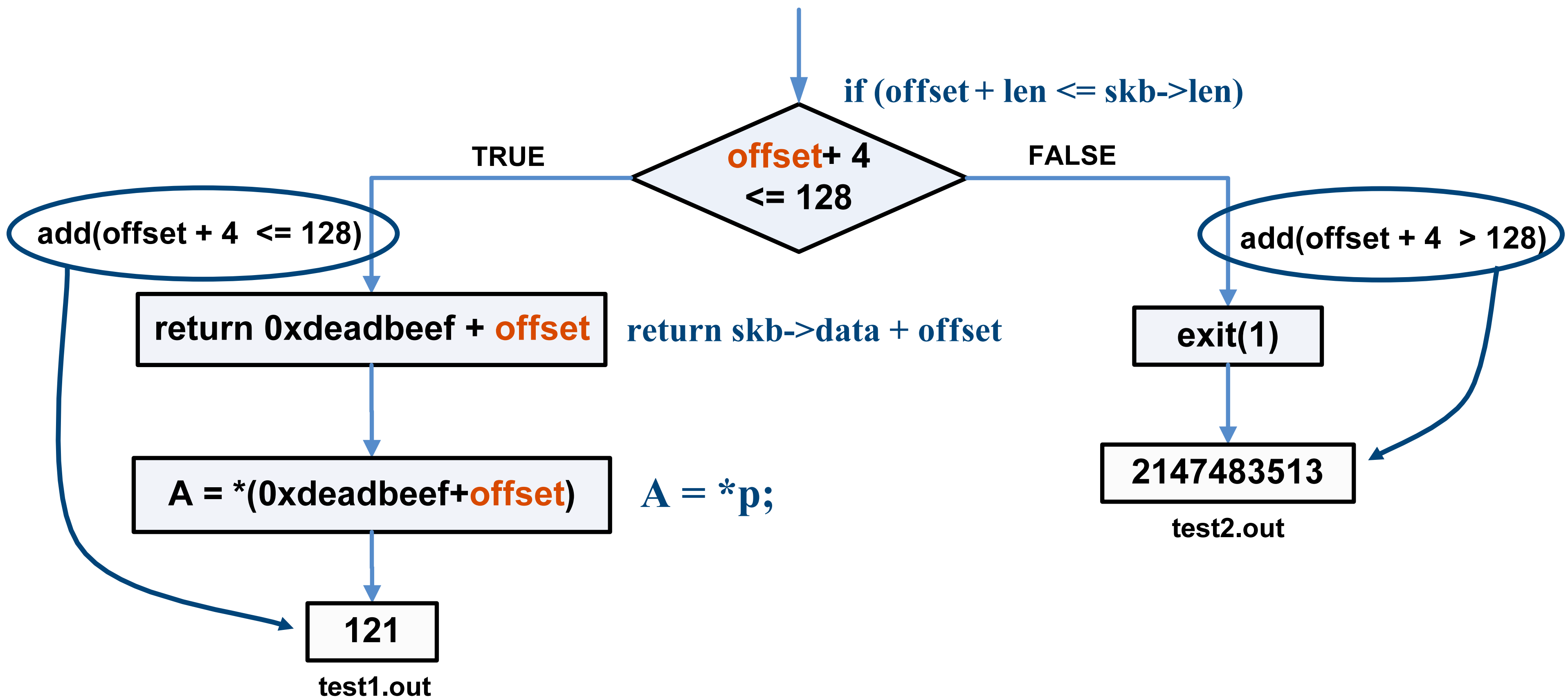
% exe-cc bpf.c

% ./a.out

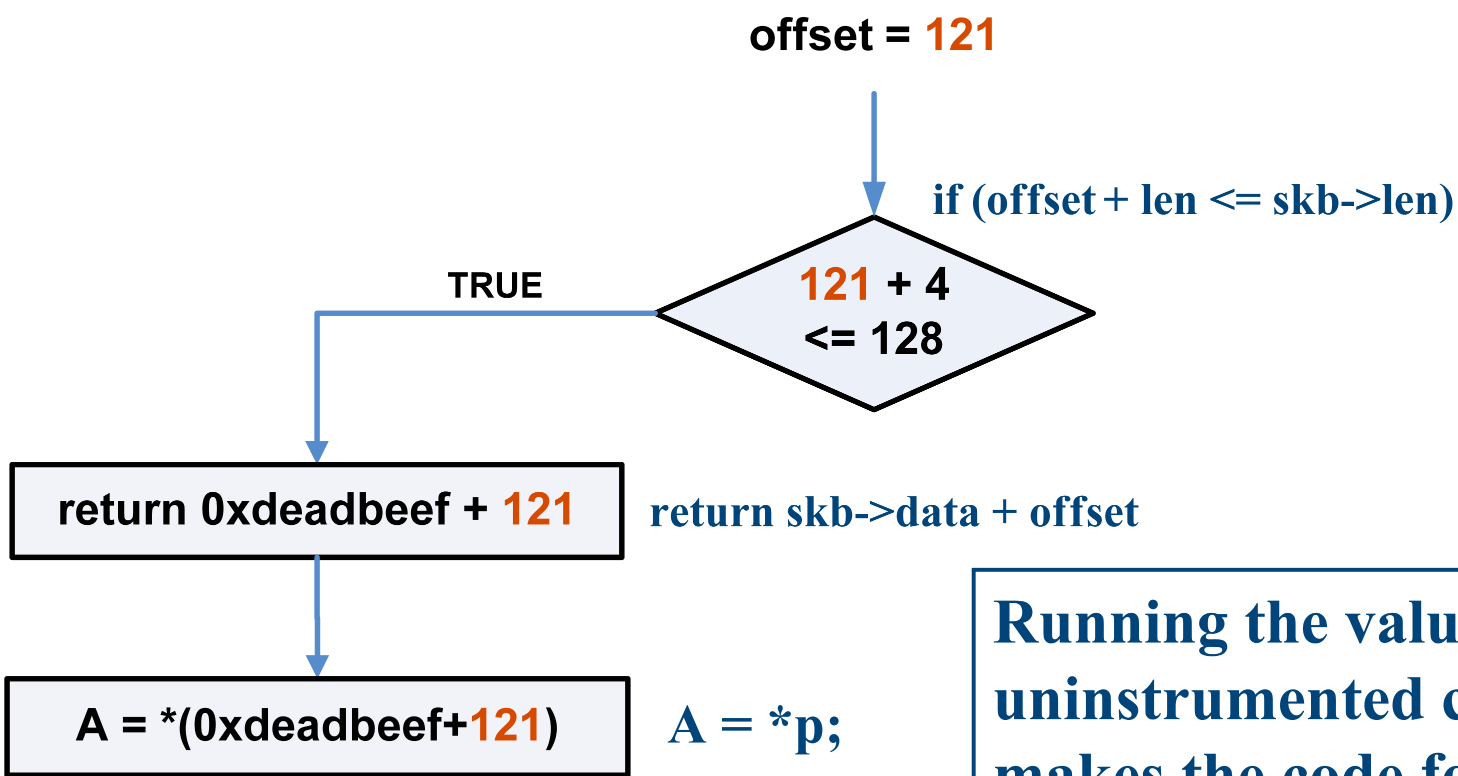
EXE execution



EXE execution

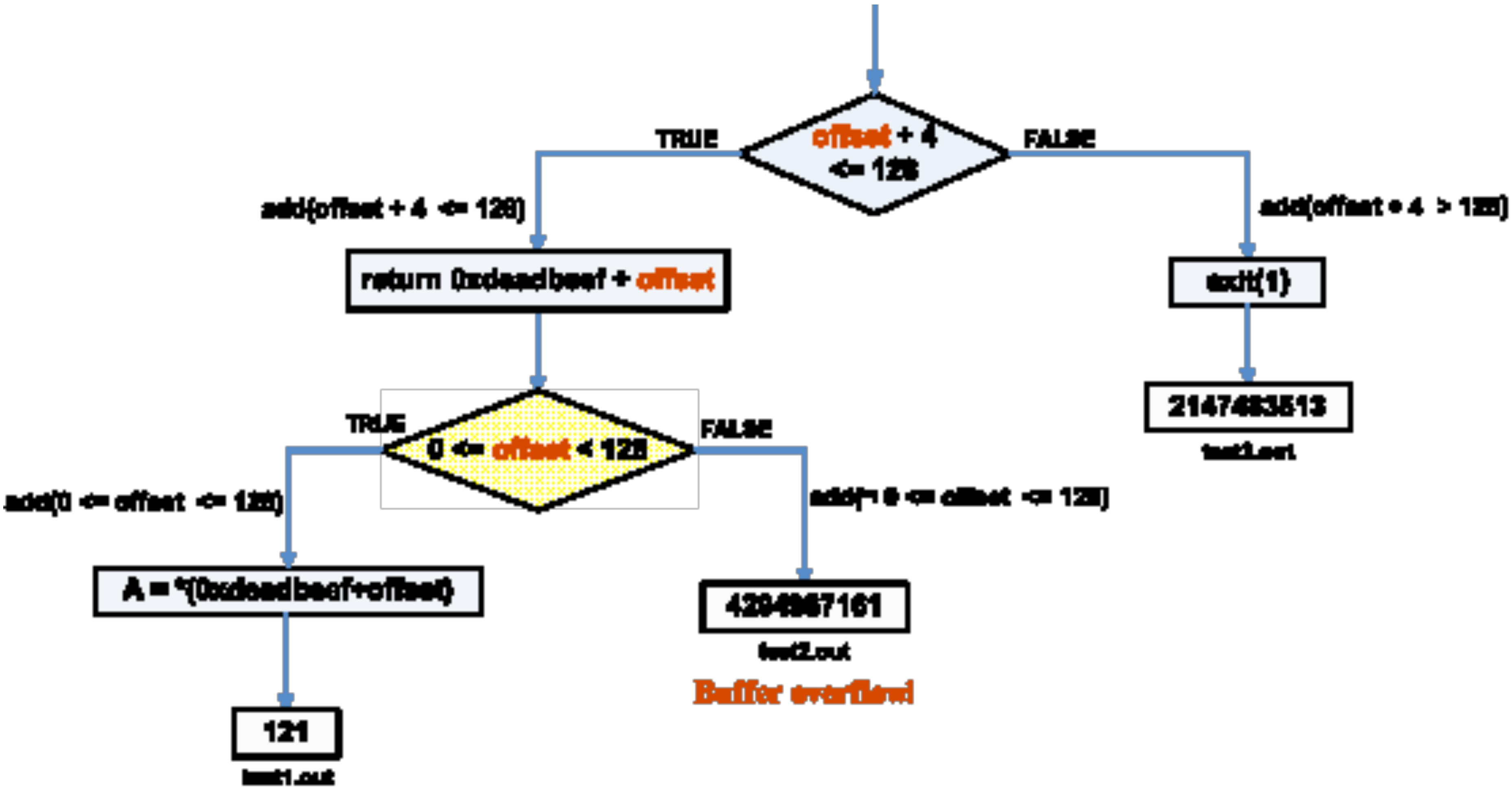


EXE execution



Running the values on the uninstrumented code makes the code follow the exact path on which the values were generated.

Implicit checks



Arbitrary checks

- By default, EXE looks for generic errors
- But, can check arbitrary properties:

```
assert(compress(uncompress(x)) == x);
```

Big challenge no. 1

- Systems code often observes the same bytes in different ways
  - Simple casts: signed to unsigned, int to char etc.
  - Pointer casting: treating array of bytes as: network packets, inodes, packet filters etc.

```
char buffer[N];
struct sk_buff *skb = (struct sk_buff*) buffer;
hlen = skb->len – skb->data_len;
```

Modeling of memory in EXE

- Mirror the (lack of) C type system
  - Untyped memory
    - Bind types to expressions, not bits
  - Bit-level accuracy
- Need constraint solver that has untyped memory and bit-level accuracy

STP

- Modern constraint solver, based on SAT
- Eagerly translates high-level constraints to SAT formula, using straightforward transformations
  - E.g., a 32-bit add is implemented as a ripple-carry adder
- Uses off-the-shelf SAT solver (MiniSAT)
- Declared the co-winner of the bitvector division of SMTLIB, held during CAV 2006

Bitvectors

- Untyped memory+bit-level accuracy
  - Bitvector data type:
    - Fixed length sequence of bits
      - Ex: 0110 is a constant, 4-bit bitvector
- Arrays of bitvectors

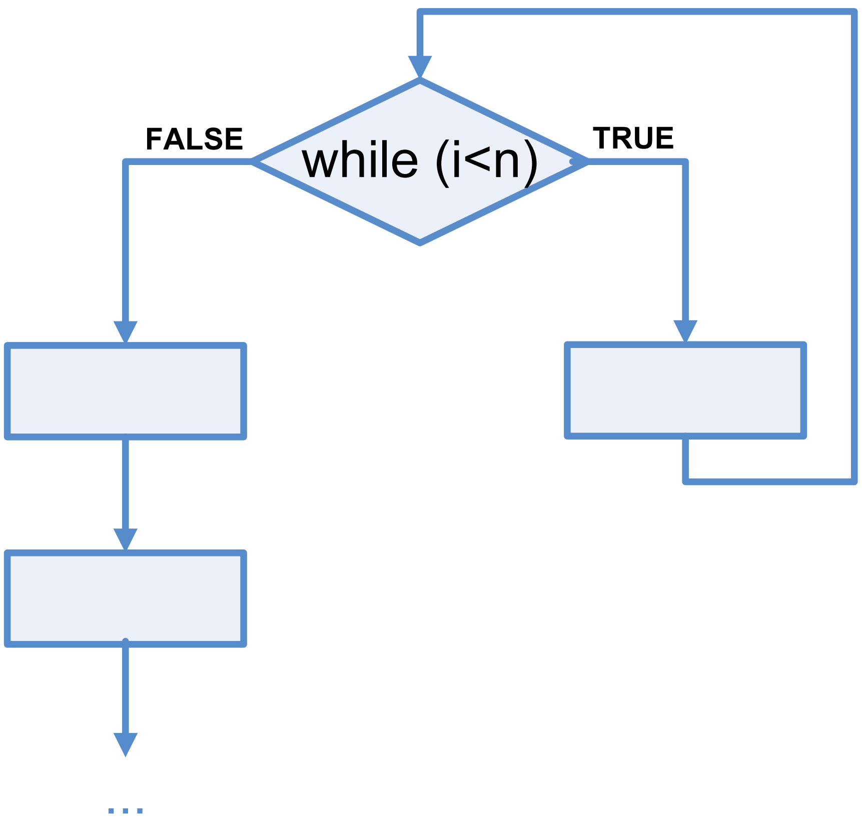
Bitvectors

- Bitvectors have all operations on integers
  - including multiplication, division, modulo
- EXE can translate all C expressions into STP constraints with bit-level precision
  - Except floating-point

Big challenge no. 2

- Exponential space
  - Goal: find bugs, achieve good coverage
  - Efficient exploration of the search space
    - Especially in the presence of loops
- Search heuristics

Search heuristics



- DFS used by default
- Best First search
  - Each forked EXE process calls into a server with its current state
  - Server chooses the next process to run based on some heuristic

Best first heuristic

- Current best first search heuristic
  - Pick the process at the line of code run the fewest number of times
  - Run it in DFS mode for a while, then iterate
  - Good statement/block coverage

Big challenge no. 3

- Reasoning about arrays in STP
- Example:
  - Symbolic index i, $0 \leq i < n$
  - $(a[i] = 7)$

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- Reasoning about arrays in STP
- Example:
  - Symbolic index i, $0 \leq i < n$
  - $(a[i] = 7) \Leftrightarrow$

$$
\begin{array}{l}
(a[0] = 7) \lor \\
(a[1] = 7) \lor \\
\ldots \\
\ldots \\
(a[n-1] = 7)
\end{array}
$$

Converting arrays to SAT

$(a[i_1] = e_1) \wedge (a[i_2] = e_2) \wedge (a[i_3] = e_3) \wedge (i_1+i_2+i_3=6)$

Converting arrays to SAT

$(a[i_1] = e_1) \land (a[i_2] = e_2) \land (a[i_3] = e_3) \land (i_1+i_2+i_3=6)$

$(v_1 = e_1) \land (v_2 = e_2) \land (v_3 = e_3) \land (i_1+i_2+i_3=6)$

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$(i_1 = i_2 \Rightarrow v_1 = v_2) \wedge (i_1 = i_3 \Rightarrow v_1 = v_3) \wedge$
$(i_2 = i_3 \Rightarrow v_2 = v_3)$

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$(i_1 = i_2 => v_1 = v_2) \wedge (i_1 = i_3 => v_1 = v_3) \wedge$

$(i_2 = i_3 => v_2 = v_3)$

Array elimination expands each formula by n(n-1)/2 terms, where n is the number of syntactically distinct indexes

Array-based refinement

$(a[i_1] = e_1) \wedge (a[i_2] = e_2) \wedge (a[i_3] = e_3) \wedge (i_1+i_2+i_3 = 6)$

$(v_1 = e_1) \wedge (v_2 = e_2) \wedge (v_3 = e_3) \wedge (i_1+i_2+i_3 = 6) \wedge$

$(i_1 = i_2 \Rightarrow v_1 = v_2) \wedge (i_1 = i_3 \Rightarrow v_1 = v_3) \wedge (i_2 = i_3 \Rightarrow v_2 = v_3)$

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Under-approximation UNSATISFIABLE → **Original formula UNSATISFIABLE**

Array-based refinement

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~~$(i_1 = i_2 \Rightarrow v_1 = v_2) \wedge (i_1 = i_3 \Rightarrow v_1 = v_3) \wedge (i_2 = i_3 \Rightarrow v_2 = v_3)$~~

$i_1 = 1$
$i_2 = 2$
$i_3 = 3$
$v_1 = e_1 = 1$
$v_2 = e_2 = 2$
$v_3 = e_3 = 3$

⇒

$(a[1] = 1) \wedge (a[2] = 2) \wedge (a[3] = 3) \wedge (1+2+3 = 6)$

Array-based refinement

$(a[i_1] = e_1) \land (a[i_2] = e_2) \land (a[i_3] = e_3) \land (i_1+i_2+i_3 = 6)$

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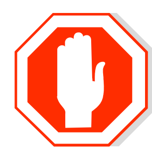
~~$(i_1 = i_2 \Rightarrow v_1 = v_2) \land (i_1 = i_3 \Rightarrow v_1 = v_3) \land (i_2 = i_3 \Rightarrow v_2 = v_3)$~~

$i_1 = 2$
$i_2 = 2$
$i_3 = 2$
$v_1 = e_1 = 1$
$v_2 = e_2 = 2$
$v_3 = e_3 = 3$

$(a[2] = 1) \land (a[2] = 2) \land (a[2] = 3) \land (2+2+2 = 6)$



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$(i_1 = i_2 \Rightarrow v_1 = v_2)$ ~~$\wedge (i_1 = i_3 \Rightarrow v_1 = v_3) \wedge (i_2 = i_3 \Rightarrow v_2 =$~~ $v_3)$

$i_1 = 2$
$i_2 = 2$
$i_3 = 2$
$v_1 = e_1 = 1$
$v_2 = e_2 = 2$
$v_3 = e_3 = 3$

$(a[2] = 1) \wedge (a[2] = 2) \wedge (a[2] = 3) \wedge (2+2+2 = 6)$

Evaluation

Solver	Total time (min)
CVCL	1006
STP (baseline)	56
STP (array-based refinement)	10

- 8495 test cases from our benchmarks
- Timeout set at 60 s.

- 100 x faster than CVCL
- 5 x faster than base STP

Evaluation

Solver	Total time (min)
CVCL	1006
STP (baseline)	56
STP (array-based refinement)	10
STP (all optimizations)	2

- 8495 test cases from our benchmarks
- Timeout set at 60 s.

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- 5 x faster than base STP

Results

- Berkeley Packet Filter
- Perl Compatible Regular Expressions Library
- udhcpd DHCPD server
- Linux file systems

Berkeley Packet Filter (BPF)

- Allows programmers to specify what network packets they want to receive
- Did not hope to find bugs
- Checked the FreeBSD and Linux implementations

BPF – Results

- Buffer overflows in both FreeBSD and Linux versions

FreeBSD filter of death:

```
s[0].code = BPF_STX;
s[0].k    =  0xfffffff0UL;
s[1].code = BPF_RET;
s[1].k    = 0xfffffff0UL;
```

Linux filter of death:

```
s[0].code = BPF_LD|BPF_B|BPF_ABS;
s[0].k    = 0x7fffffffUL;
s[1].code = BPF_RET;
s[1].k    = 0xfffffff0UL;
```

Perl Compatible Reg Exp (PCRE)

- Used by popular open-source projects
  - Apache, PHP, Postfix
- Found buffer overflows which crash PCRE
  - In pcre_compile, which compiles a pattern string into a regular expression
- Author notified, and promptly fixed the bug

PCRE – regex's of death

```
[^[\0^\0]\*-?]{\0
[\*-\`[\0^\0]\`-?]{\0
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(?#)\?[[[\0\0]\-]{\0
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```

udhcpd 0.9.8

- Clean, well-tested user-level DHCPD server
- Marked its input packet as symbolic, and changed its network read call to return symbolic data
- Found five memory errors

Linux file systems

- Generated disk images for ext2, ext3, JFS
- Found bugs in all systems – generated real disk images which when mounted, compromise or crash the Linux kernel
- *Automatically generating malicious disks using symbolic execution J. Yang, C. Sar, P. Twohey, C. Cadar, D. Engler*
  IEEE Security 2006

Disk of death (JFS, Linux 2.6.10)

Offset	*Hex Values*
00000	0000 0000 0000 0000 0000 0000 0000 0000
. . .	. . .
08000	464a 3153 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 0000 0000 0000 0000 0000
. . .	. . .
10000	

Related Work

- DART system [Godefroid, Klarlund, Sen]
- CUTE system [Sen, Marinov, Aga]
- CBMC [Clarke, Kroening]
  - Limitations in terms of handling systems code

Related Work

- Eager translation to SAT
  - UCLID, Cogent, Saturn
- Nelson-Oppen solvers
  - CVCL, Yices, SVC, Barcelogic Tools
- Hard to do side-by-side comparison
  - No common benchmarks
  - No common syntax

Summary

- EXE generates inputs that expose bugs and achieve good coverage
- STP constraint solver which enables EXE to solve constraints fast
- Systems code benchmarks
  - Found bugs in all of them
  - Generated inputs that trigger the bugs discovered

Questions?