EXecution generated Executions:
Automatically generating inputs of death.

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## Goal: find many bugs in systems code

- Generic features:
  - Baroque interfaces, tricky input, rats nest of conditionals.
  - Enormous undertaking to hit with manual testing.
- Random "fuzz" testing
  - Charm: no manual work
  - Blind generation makes hard to hit errors for narrow input range
  - Also hard to hit errors that require structure

```
int bad_abs(int x) {
   if(x < 0)
      return -x;
   if(x == 12345678)
      return -x;
   return x;
}
```

- This talk: a simple trick to finesse.

## EXE: EXecution generated Executions

- Basic idea: use the code itself to construct its input!
- Basic algorithm:
  - Symbolic execution + constraint solving.
  - Run code on symbolic input, initial value = "anything"
  - As code observes input, it tells us values input can be.
  - At conditionals that use symbolic input, fork
    - On true branch, add constraint that input satisfies check
    - On false that it does not.
  - exit() or error: solve constraints for input.
  - Rerun on uninstrumented code = No false positives.
  - IF complete, accurate, solvable constraints = all paths!

## The toy example

```
int bad_abs(int x) {
   if(x < 0)
      return -x;
   if(x == 12345678)
      return -x;
   return x;
}
```

- Initial state: x unconstrained
- Code will return 3 times.
- Solve constraints at each return = 3 test cases.

```
int bad_abs_exe(int x) {
   if(fork() == child)
      constrain(x < 0);
      return -x;
   else
      constrain(x >= 0);

   if(fork() == child)
      constrain(x == 12345678);
      return -x;
   else
      constrain(x != 12345678);
   return x;
}
```

## The mechanics

- User marks input to treat symbolically using either:

```
void make_symbolic(T *obj);
void make_symbolic_bytes(void *bytes, unsigned nbytes);
```

- Compile with EXE compiler, exe-cc. Uses CIL to
  - Insert checks around every expression: if operands all concrete, run as normal. Otherwise, add as constraint
  - Insert fork calls when symbolic could cause multiple acts
- ./a.out: forks at each decision point.
  - When path terminates use STP to solve constraints.
  - Terminates when: (1) exit, (2) crash, (3) EXE detects err
- Rerun concrete through uninstrumented code.

## Isn't exponential expensive?

- Only fork on symbolic branches.
  - Most concrete (linear).
- Loops? Heuristics.
  - Default: DFS. Linear processes with chain depth.
  - Can get stuck.
  - "Best first" search: chose branch, backtrack to point that will run code hit fewest times.
  - Can do better…
- However:
  - Happy to let run for weeks as long as generating interesting test cases. Competition is manual and random.

## Where we're going and why.

- One main goal:
  - At any point on program path have accurate, complete set of constraints on symbolic input.
- *IF* EXE has and can solve THEN
  - Can drive execution down all paths.
  - Can use path constraints to check if any input value exists that causes error such as div 0, deref NULL,etc.
  - Entire motivation: all path + all value for much code.
- Next:
  - Mechanics of supporting symbolic execution
  - Universal checks.
  - Results.

## Mixed execution

- Basic idea: given expression (e.g., deref, ALU op)
  - If all of its operands are concrete, just do it.
  - If any are symbolic, add as constraint.
  - If current constraints are impossible, stop.
  - If current path hits error or exit(), solve+emit.
  - If calls uninstrumented code: do call, or solve and do call
- Example: "x = y + z"
  - If y, z both concrete, execute. Record x = concrete.
  - Otherwise set "*x = y + z*", record x =symbolic.
- Result:
  - Most code runs concretely: small slice deals w/ symbolics.
  - Robust: do not need all source code (e.g., OS). Just run

DE2

## Untyped memory

- C code observes memory in mutiple ways
  - Signed to unsigned casts
  - Cast array of bytes to inode, superblock, pkt header
- Soln:
  - Cannot bind types to memory, must do to expressions
  - Represent symbolic memory using STP primitives: array of 8-bit bitvectors.
  - Bitvector=untyped, array=pointers (next)
  - Each read of memory generates constraints based on static type of read. Does not persist. Just encoded in constraint.

## Symbolic memory expressions.

- Given array of "a" of size "n" and in-bounds index "i".
  - "(a[i] == 0)" becomes

```
(i == 0 && a[0] == 0)
|| (i == 1 && a[1] == 0)
|| ..
|| (i == n-1 && a[n-1] == 0)
```

  - "a[i] = 4" could update any entry.
- Sol'n: map to STP array (translates to SAT).
  - Given "a[i]" where "i" is symbolic (other cases similar)
  - If "a" has no symbolic counterpart create one, "a_sym"
  - Record "a" corresponds to "a_sym"
  - Build constraints using a_sym[i_sym]

## Example: symbolic memory reads and writes

```
1 : #include <assert.h>
2 : int main() {
3 :     unsigned char i, j, k, a[4] = {11, 13, 17, 19};
4 :     make_symbolic(&i); // these macros make
5 :     make_symbolic(&j); // i, j, and k
6 :     make_symbolic(&k); // symbolic
7 :     if(i >= 4 || j >= 4 || k >= 4) // force in-bounds
8 :         exit(0);
9 :     a[i] = 1;
10:     if ( (a[j] + a[k] == 14) )
11:         assert((i != 1));
12: }
```

## Example: symbolic memory reads and writes

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12: }
```

taken branch: i != 1 && k == 1

A non-taken soln: i == 0 && k ==2

## Slide 9

**DE2** "accurately tracking constraints that only involve strongly typed scalars is realtively simple: just name the variables uniquely (as in the original source) and use these names consistenly in the original source."
Dawson Engler, 3/20/2006

## Automatic, systematic corner cases hitting

- Conditional: fork, both branches.
- Overflow: can "x + y", "x – y", "x * y" … overflow?
  - Build two symbolic expressions
  - E1: expression at precision of ANSI C's expression types.
  - E2: expression at essentially infinite precision.
  - If E1 could be different than E2, force it.

```
if(query(E1 != E2) == satisfiable) {
    if(fork() == child)
        add_constraint(E1 == E2);
    else
        add_constraint(E1 != E2);
}
```

- Others: truncation casts, signed->unsigned.

## Universal checks.

- Key: Symbolic reasons about many possible values simultaneously. Concrete about just current ones.
- Universal checks:
  - When reach dangerous op, EXE checks if any input exists that could cause it to blow up.
  - Builtin: div/mod by 0, NULL *p, memory overflow.

```
sym_expr div_transformation(sym_expr x, sym_expr y)
  if(query(y != 0) == satisfiable)
    if(fork())
      add_constraint(y != 0);
      return symbolic_expression(x / y);
    else
      add_constraint(y == 0);
      terminate_with_error("Found div by 0!\n");
```

## Generalized checking.

- "assert(sym_expr)"
  - EXE will systematically try to violate sym_expr.
  - Complete, accurate, solved path constraints = verification
- Scales with sophistication of correctness checks.
  - E.g., given f and inv can verify correct: inv(f(x)) = x.

```
#include <assert.h>
#include <netinet/in.h>
void main(void) {
    int x;
    make_symbolic(x);
    assert(htonl(ntohl(x)) == x);
}
```

## Putting it all together

```
int main(void) {
  unsigned i, t, a[4] = { 1, 0, 5, 2 };
  make_symbolic(&i);

  // ERROR: EXE catches potential overflow i >= 4.
  t = a[i];
  // At this point i < 4.

  // ERROR: EXE catches div by 0 when i = 1.
  t = t / a[i];
  // At this point i != 1 && i < 4.

  // Demonstrate simple gross casting (EXE handles arbitrary
  // casting but for exposition we only show simple casting)
  t = (unsigned)&a[0];
  t += i*4;
  // the value of t is equal to &a[i] at this point.

  // ERROR: EXE catches buffer overflow when i = 2.
  return a[*(unsigned *)t];      // Same as: return a[a[i]];
}
```

## Limits

- Missed constraints:
  - If call asm, or CIL cannot eat file.
  - STP cannot do div/mod: constraint to be power of 2, shift, mask respectively.
  - Cannot handle **p where "p" is symbolic: must concretize *p. (Note: **p still symbolic.)
  - Stops path if cannot solve; can get lost in exponentials.
- Missing:
  - No symbolic function pointers, symbolics passed to varargs not tracked.
  - No floating point.
  - long long support is erratic.

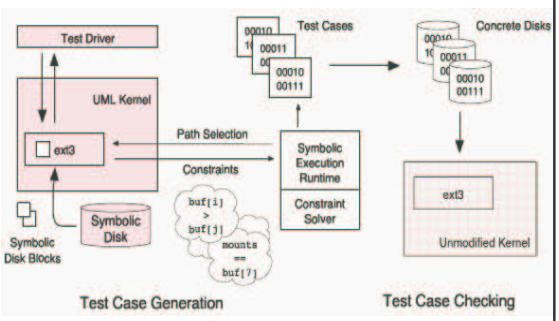
## Talk overview

- Goal: complete, accurate constraints on input.
- *IF* can do so, THEN:
  - Automatic all path coverage.
  - All value checking. (Sometimes verification)
  - Limits: missed constraints, NP-hard problem, loops.
- Does it work? Next.
  - Automatic generation of malicious disks.
  - Automatic generation of inputs of death.

## Automatically generating malicious disks.

- File systems:
  - Mount untrusted data as file systems (CD-rom, USB)
  - Let untrusted users mount files as file systems.
- Problem: bad people.
  - Must check disk as aggressively as networking code.
  - More complex.
  - FS guys are not paranoid.
  - Hard to random test: 40 if-statements of checking.
  - Result: easy exploits.
- Basic idea:
  - make disk symbolic, jam up through kernel
  - Cool: automatically make disk image to blow up kernel!

## A galactic view [Oakland'06]




## Checking Linux FSes with EXE

- Why UML?
  - Hard to cut Linux FS out of kernel. UML=check in situ.
  - Need to clone/wait for process.
  - Hard to debug OS on raw machine.
- Hacks to get Linux working
  - Disable threading
  - Replace asm functions (strlen, memcpy) with EXE versions
  - UML linked @ fixed (too small) location. Stripped down.
  - CIL could not handle 8 files. Compiled with gcc.
- Hacks to EXE:
  - v = e, with e symbolic: do not make v symbolic if e == val
  - No free of symbolic heap-allocated objects.

## Results

- Ext2:
  - Four bugs.
  - One buffer overflow = r/w arbitrary kernel memory
  - Three = kernel crash.
- Ext3:
  - Four bugs (copied from ext2)
- JFS:
  - One null pointer dereference.

## Generated disk for JFS, Linux 2.4.27.

| *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 | |

Create 64K file, set 64th sector to above. Mount.

## BPF, Linux packet filters

- "We'll never find bugs in that"
  - Some of most heavily audited, best written open source
  - Easy to pull out of kernel.
- Mark filter, packet as symbolic.
  - Symbolic = turn check into generator of concretes.
  - Safe filter check: generates all valid filters of length N.
  - Interpreter: will produce all valid filter programs that pass check of length N.
  - Filter on message: generates all packets that accept, reject.
- Results!

## Results: BPF, trivial exploit.

```
// Check that memory operations only uses valid addresses.
// => Check forgets LDX,STX!
if( (BPF_CLASS(p->code) == BPF_ST || (BPF_CLASS(p->code) == BPF_LD &&
     (p->code & 0xe0) == BPF_MEM)) && p->k >= BPF_MEMWORDS )
  return 0;
```

```
case BPF_LDX|BPF_MEM:
     X = mem[pc->k]; continue;
...
case BPF_STX:
     mem[pc->k] = X; continue;
```

## Linux Filter

- Generated filter:

```
// other filters that cause this error...
//    => BPF_LD|BPF_B|BPF_IND
//    => BPF_LD|BPF_H|BPF_IND
s[0].code = BPF_LD|BPF_B|BPF_ABS;
s[0].k    = 0x7fffffffUL;
s[1].code = BPF_RET;
s[1].k    = 0xffffffffUL;
```

- offset=s[0].k passed in; len=2,4

```
hline void * skb_header_pointer(struct sk_buff *skb, int offset, int len,
 int hlen = skb_headlen(skb);
 if (offset + len <= hlen)
          return skb->data + offset;
```

## Conclusion [Spin'05, Oakland'06]

- Automatic all-path execution, all-value checking
  - Make input symbolic. Run code. If operation concrete, do it. If symbolic, track constraints. Generate concrete solution at end (or on way), feed back to code.
  - Finds bugs in real code.
  - Zero false positives.
  - But, still very early in research cycle.
- Three ways to look at what's going on
  - Grammar extraction.
  - Turn code inside out from input consumer to generator
  - Sort-of Heisenberg effect: observations perturb symbolic inputs into increasingly concrete ones. More definitive observation = more definitive perturbation.

## Future work

- Automatic "hardening"
  - Assume: EXE finds error and has accurate, complete path constraints.
  - Then: can translate constraints to if-statements and reject concrete input that satisfies.
  - Example: wrap up disk reads. "Cannot mount." Or reject network packets that crash system.
- Automatic exploit generation.
  - Compile Linux with EXE. Mark data from copy_from_user as symbolic. (System call params if fancy)
  - Find paths to bugs.
  - Generate concrete input + C code to call kernel.
  - Mechanized way to produce exploits.