Fuzzing Forth

Apply Fuzz Tests to Forth

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Overview
Fuzzing Forth

- Introduction
- Correctness Notions
- Generators
- Mutators
- Sanitizers
- Tests
- Fuzzing
- Conclusion

Introduction

What fuzzing is all about?

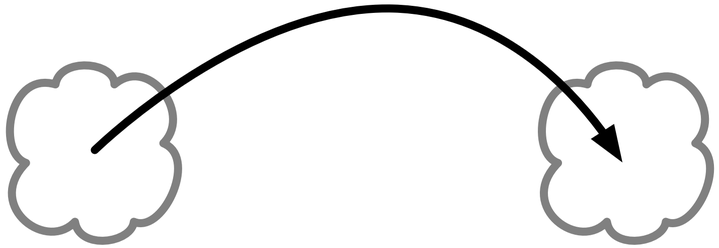
- We assure quality of applications by **testing**
  - Manually, especially for embedded systems → time consuming
  - Automatically, correct functions, regression, TestDrivenDevelopment
  - We mostly test the good cases, infrequently behaviour in bad situations
- ***Fuzz Tests*** or ***Fuzzing*** tests applications with arbitrary data to see if they break

"*Crash often crash early!*" - but automated

Correctness Notions

What's in a word?

- When is a word correct?
  - need to describe the behaviour of a word
  - an approach: a word does a state transition
    - from a current state
    - to a next state
    - can be deterministic or non deterministic



States

- States can be complicated
  - not just labels as with finite state machines
  - **Forth System State**: includes the stack and return stack content, all dictionary content, the existing definitions, etc.
  - **Computer State**: contents of files, memory content, etc.
  - **Environment State**: relevant state of external components
- Think of states as huge records or vectors
- A state or sets of states can be described by conditions

"the (set of all) states that satisfy the condition"

State Transitions

- many aspects of a state are not relevant for the transition and stay as they are
- a transition (i.e. the behaviour of a word) can be described by a pre-condition P and a post-condition Q

Stack Comments

- We describe conditions already in Forth with stack comments

0< (n -- flag)

n : The condition *TOS is a natural number* in the current state

-- : symbolizes the transition

flag: the condition *TOS is with all bits set (true) or all bits reset (false), i.e. a flag* in the next state

- stack diagrams are not sufficient to specify the operation exactly
  0> has the same stack effect but a different behaviour.

Stack Comments

0< (n -- flag)

...

flag: the condition *TOS is with all bits set (true) or all bits reset (false), i.e. a flag* in the next state

- the post-stack-condition is too weak
- stronger post condition for 0<:
  flag where TOS'=true if TOS<0, TOS'=false if TOS>=0

- appropriate pre- and post-condition can describe the behaviour of a word as precisely as desired, but they may be difficult to specify

Partial Correctness of a word (a transition)

A word ist partially correct with respect to conditions P and Q:

- if the current state satisfies the pre-condition P and **if the word terminates** (i.e. does not crash) then the next state satisfies the post-condition Q

if the current state does not satisfy the pre-condition then the next state is undefined (computer scientists model this often with non-terminating programs or arbitrary results).

Total Correctness of a word (a transition)

A word is totally correct with respect to conditions P and Q:

- if the current state satisfies the pre-condition P **then the word terminates** (i.e. does not crash) **and** the next state satisfies the post-condition Q

if the current state does not satisfy the pre-condition then the next state is undefined.

Robustness of a word (a transition)

A word is robust with respect to P and Q

- if it always does a transition to a next state.

- is totally correct with respect to P and Q
- if the current state does not satisfy the pre-condition then *an error is signalled.*
  - *throw an exception*
  - *return an distinct error value*
  - *...*

Fuzzing checks if an application i.e. its top-level words are robust

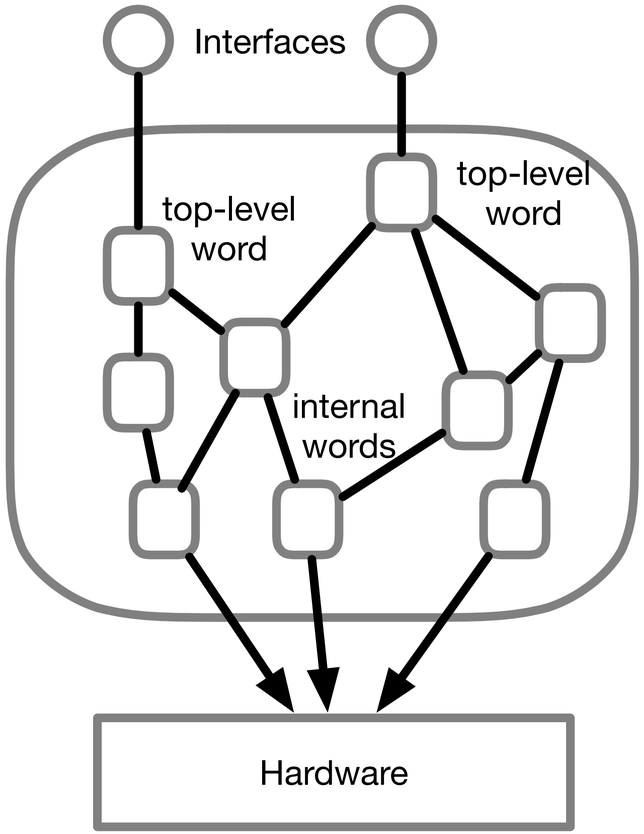
Fuzzing
What the fuzz?

Fuzzing checks if an application i.e. its top-level words are robust

- top level words are accessible for outside
- realize outside interfaces

- **Fuzzing**
  - **invoke a top-level words with arbitary data**
  - **check if the system crashes**

- Random data → generators and mutators
- best no crashes → sanitizers



Generators

How to create random data?

- We need to generate random (stack) items.
- even distribution but also normal and other distributions
- classical Starting Forth random number generator

```
( Random number generation -- High level )

VARIABLE rnd   HERE rnd !
: RANDOM  rnd @ 31421 *  6927 +  DUP rnd ! ;
: CHOOSE   ( u1 -- u2 )  RANDOM UM*  NIP ;
```

- linear congruence generator not good as factor for normal distribution

[1] http://www0.cs.ucl.ac.uk/staff/D.Jones/GoodPracticeRNG.pdf

Generators

How to create random data?

- KISS generators are simple and have better properties
- JKISS32 [1] is based on 32-bit integer arithmetic
  - passes all of the Dieharder tests and the BigCrunch tests

```
\ JKISS32 for 32Bit Systems (algorithm by David Jones)

Variable x  123456789 x !
Variable y  234567891 y !
Variable z  345678912 z !
Variable w  456789123 w !
Variable c  0 c !

: kiss ( -- x )
   y @  dup 5 lshift xor   dup 7 rshift xor   dup 22 lshift xor   y !
   z @ w @ + c @ +     w @ z !     dup 0< 1 and 0= 0= 1 and c !   2147483647 and w !
   x @ 1411392427 + x !
   x @ y @ + w @ + ;
```

Generators

How to create random data?

- create normal distribution from even distribution
- different algorithms such as Marsaglia polar method or Box Muller Transform require floating point
- Rule of 12 (sum and average) is simple and works on integers
  - but only valid if random delivers independent random values
  - linear congruence generators (such as random earlier) do not have this property, KISS does.

```
: CHOOSE   ( u1 -- u2 )   KISS UM*   NIP ;

: NORMAL ( u1 -- u2 )
    0   12 0 DO   OVER CHOOSE +   LOOP   12 / SWAP DROP ;
```

Generators

How to create random data?

- from CHOOSE and NORMAL we can build generators for typical Forth data
- cell data on the stack

```
: cgen ( -- b )  256 choose ;
: ngen ( -- n )  -1 choose ;
: +ngen ( -- n )  -1 1 rshift choose ;
: ugen ( -- u )  -1 choose ;
```

- strings of given exact or maximal length

or also with specific distribution

```
: 'x'gen ( -- c )  128 bl - choose bl + ;

: $=gen ( u1 -- c-addr u2 ) \ string is excactly u1 characters. allocates, must be freed after use
   dup allocate throw swap  2dup bounds ?DO  'x'generate I c! LOOP ;

: $gen ( u1 -- c-addr u2 ) \ string is shorter than u1 characters. allocates, must be freed after use
   choose $=gen ;
```

Generators

How to create random data?

- Generate random composed data structures such as
  - structs and
  - arrays or
  - linked lists, etc.

  by defining appropriate (recursive) generators.

```
: person-gen ( -- addr ) ... ;
```

Mutators

How to change existing data?

- Mutators are similar to generators but modify existing data
- cell data on the stack
  - **`cmut`** (char1 rate -- char2)
  - **`nmut`** (n1 rate -- n2)
  - **`+nmut`** (+n1 rate -- +n2)
  - **`umut`** (u rate -- u2)

- or strings
  - **`$=mut`** (c-addr1 u rate -- c-addr2 u) just changes the characters
  - **`$mut`** (c-addr1 u1 rate -- c-addr2 u2) changes length and character

Mutators

How to change existing data?

- Modify random composed data structures such as
  - structs and
  - arrays or
  - linked lists, etc.

  by defining appropriate (recursive) mutators.

```
: person-mut ( addr1 rate -- addr2 ) ... ;
```

Sanitizers

How to detect and signal crashes?

- If application crash, then it is hard to monitor them.

  → Turn crashes into reported errors

- **Sanitizers** check if inputs are valid
- Memory sanitizers - detect illegal memory access , throw for memory faults
- Stack Sanitizers - detect stack over and underflow
- Control flow sanitizers - check for valid return addresses on EXIT
- ...

Sanitizers

How to detect and signal crashes?

- Memory sanitizers - detect illegal memory access , throw for memory faults
  - @ ! c@ c! with valid memory test, throw memory-fault on invalid address
  - linked list of valid regions that are checked on access
  - bit-field of valid memory words or bytes

```
: ?valid ( addr -- addr ) dup valid? 0= #memory-fault and throw ;

: @ ( addr -- x ) ?valid @ ;
: ! ( x addr -- ) ?valid ! ;
```

Sanitizers

How to detect and signal crashes?

- Stack Sanitizers - detect stack underflow

```
: arguments ( i*x u -- i*x )
     >r depth r> u< #stack-underflow and throw ;

1 2 3    3 arguments   . . .   ( 3 2 1 )
```

- and overflows
  - much harder to detect, every push must check
  - might need hardware support

Sanitizers

How to detect and signal crashes?

- Control flow sanitizers - check for valid return addresses on EXIT

```
: exit ( i*x u -- i*x )  rdrop
   r@  invalid-return-addess?  #return-stack-imbalance and throw
;
```

- others:
  - check exception stack
  - ...

[1] ftp://ftp.taygeta.com/pub/Forth/Applications/ANS/tester.fr

Tests

How do we test?

- A popular framework for tests of forth words are testers derived from John Hayes ANS Forth tester [1]

```
{ 3 4 + -> 7 }
```

- Tests + on a single value.

- We can elaborated test suites from this, as Gerry Jackson does for Forth200x compliance.

Fuzzing
What the fuzz?

- In order to fuzz our applications
  - run the Hayes style unit tests - fix all bugs
  - define the top-level words (TLW) using sanitizers
  - run the Hayes style unit tests - no issue expected
  - run fuzz tests in this style

```
\ assuming TLW ( c-addr1 u1 c-addr2 u2 -- c-addr3 u3)

many times DO
  { 100 $gen  S" secret" 75 $mut TLW clearstack -> }
LOOP
```

Fuzzing Forth

Apply Fuzz Tests to Forth

Conclusion

What's below the bottom line?

- Correctness Notions - partial, total correctness, robustness
- Generators - KISS generator, rule of 12
- Mutators - change existing data
- Sanitizers - make crashes into reported errors
- Tests - Hayes style testing
- Fuzzing - stressing top level words (interfaces)

Questions?