定向覆盖模糊测试工具的设计与实现

毕业设计答辩

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What Fuzzing is?

Defination[1]

- **Fuzzing** Fuzzing is the execution of the PUT using input(s) sampled from an input space (the "fuzz input space") that protrudes the expected input space of the PUT.
  - PUT: Program Under Test
- **Fuzz testing** Fuzz testing is the use of fuzzing to test if a PUT violates a correctness policy.
- **Fuzzer** A fuzzer is a program that performs fuzz testing on a PUT.
- **Bug Oracle** A bug oracle is a program, perhaps as part of a fuzzer, that determines whether a given execution of the PUT violates a specific correctness policy.
- **Fuzz Configuration** A fuzz configuration of a fuzz algorithm comprises the parameter value(s) that control(s) the fuzz algorithm.
- **Seed** A seed is a (commonly well-structured) input to the PUT, used to generate test cases by modifying it.

What Fuzzing is?

Fuzz Testing

Input: $\mathbb{C}$, $\mathsf{t}_{\text{limit}}$

Output: $\mathbb{B}$ // a finite set of bugs

$\mathbb{B} \leftarrow \varnothing$

$\mathbb{C} \leftarrow$ **Preprocess**($\mathbb{C}$)

while $\mathsf{t}_{\text{elapsed}} < \mathsf{t}_{\text{limit}} \wedge$ **Continue**($\mathbb{C}$) **do**

  conf $\leftarrow$ **Schedule**($\mathbb{C}$, $\mathsf{t}_{elapsed}$, t_{limit})

  tcs $\leftarrow$ **InputGen**($conf$)

  // O_{bug} is embedded in a fuzzer

  $\mathbb{B}'$, execinfos $\leftarrow$ **InputEval**($conf$, tcs, O_{bug})

  $\mathbb{C} \leftarrow$ **ConfUpdate**($\mathbb{C}$, $conf$, $execinfos$)

  $\mathbb{B} \leftarrow \mathbb{B} \cup \mathbb{B}'$

return $\mathbb{B}$

Fuzzing Algorithm

```
Input: ℂ, t_limit
Output: 𝔹 // a finite set of bugs
𝔹 ← ∅
ℂ ← Preprocess(ℂ)
while t_elapsed < t_limit ∧ Continue(ℂ) do
    conf ← Schedule(ℂ, t_elapsed, t_limit)
    tcs ← InputGen(conf)
    // O_bug is embedded in a fuzzer
    𝔹′, execinfos ← InputEval(conf, tcs, O_bug)
    ℂ ← ConfUpdate(ℂ, conf, execinfos)
    𝔹 ← 𝔹 ∪ 𝔹′
return 𝔹
```

- $\mathbb{C}$:a set of fuzz configurations
- t_{limit}: timeout
- $\mathbb{B}$: a set of discovered bugs

Fuzzing Algorithm

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return 𝔹
```

PREPROCESS $(\mathbb{C}) \rightarrow \mathbb{C}$

- **Instrumentation**
  - grey-box and white-box fuzzers
  - static/dynamic(INPUTEVAL)
- **Seed Selection**
  - weed out potentially redundant configurations
- **Seed Trimming**
  - reduce the size of seeds
- **Preparing a Driver Application**
  - library Fuzzing, kernal Fuzzing

Fuzzing Algorithm

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    $\mathbb{C} \leftarrow$ ConfUpdate($\mathbb{C}$, *conf*, *execinfos*)
    $\mathbb{B} \leftarrow \mathbb{B} \cup \mathbb{B}'$
return $\mathbb{B}$

Stop Condition

- $t_{\text{elapsed}} < t_{\text{limit}}$
- CONTINUE ($\mathbb{C}$)$\rightarrow$ {True, False}
  - Determine whether a new fuzz iteration should occur

Fuzzing Algorithm

Input: $\mathbb{C}$, t_{limit}
Output: $\mathbb{B}$ // a finite set of bugs

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return $\mathbb{B}$

SCHEDULE ($\mathbb{C}$, $t_{elapsed}$, t_{limit}) $\rightarrow$ conf

- **Function**
  - Pick important information(conf)
- **FCS Problem**
  - *exploration*:Spent time on gathering more accurate information on each configuration to inform future decisions
  - *exploitation*:Spent time on fuzzing the configurations that are currently believed to lead to more favorable outcomes

Fuzzing Algorithm

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INPUTGEN (conf)$\longrightarrow$ tcs

- **function**
  - Generate testcases
- **classification**
  - Generation-based(*Model-based*)
  - Mutation-based(*Model-less*)
  - White-box Fuzzers: symbolic execution

Fuzzing Algorithm

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InputEval (conf, tcs, O_{bug})
$\rightarrow \mathbb{B}'$, execinfos

- **Fuzzing PUT**
  - tcs
  - $\mathbb{B}'$
- **Feedback Information**
  - conf, tcs
  - execinfos (tcs,crashes,stack backtrace hash,edge coverage,etc.)

Fuzzing Algorithm

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return $\mathbb{B}$

- CONFUPDATE ($\mathbb{C}$, conf, execinfos) $\rightarrow \mathbb{C}$
  - Update Fuzz Configuration(distinguishablity)
  - Seed Pool Update
- $\mathbb{B} \cup \mathbb{B}' \rightarrow \mathbb{B}$
  - Update Bugs Set

Fuzzing Algorithm

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Classification

The amount of collected information defines the color of a fuzzer[1].

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```

- **program instrumentation**
    - static
    - dynamic
- processor traces
- system call usage
- etc.

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Program Instrumentation

- Static
  - source code
  - intermediate code
  - binary-level
- Dynamic

Classification

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return 𝔹
```

Program Instrumentation

- Static
- Dynamic
  - dynamically-linked libraries
  - execution feedback: branch coverage, new path, etc.
  - race condition bugs: thread scheduling

Classification

Classification of Fuzzing

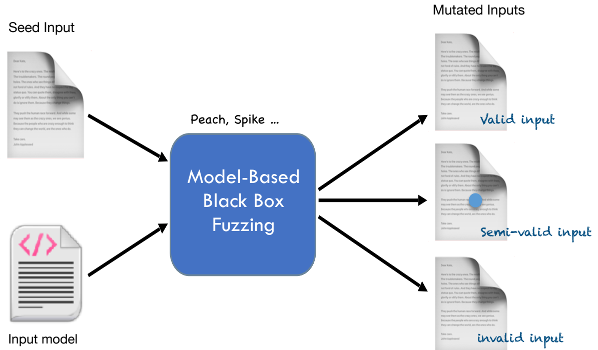
- **Black-box Fuzzing**
  - no program analysis, no feedback
- **White-box Fuzzing**
  - mostly program analysis
- **Grey-box Fuzzing**
  - no program analysis, but feedback

Why Grey-box Fuzzing ?

- Black-box Fuzzing

Defination: techniques that do not see the internals of the PUT,and can observe only the input/output behavior of the PUT, treating it as a black-box[1].

-No program analysis, no feedback



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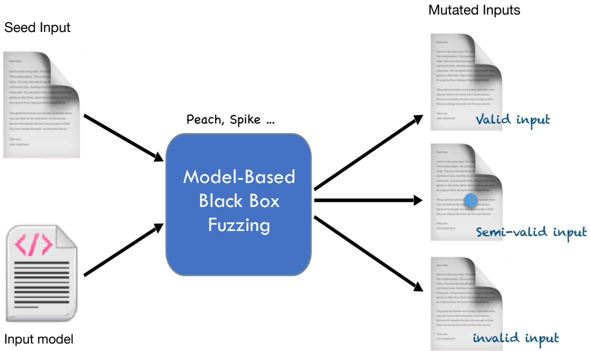


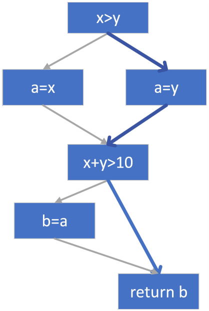
- You have no view of the PUT,but have some view of the input/output domain
- Fuzzing congfigurations are not changed according to some feedback
  - some fuzzer may add the testcases to seed pool
- Not effective

Why Grey-box Fuzzing ?

- White-box Fuzzing

  Defination: techniques that generates test cases by analyzing the internals of the PUT and the information gathered when executing the PUT[1].

  - Requires heavy-weight program analysis and constraint solving.



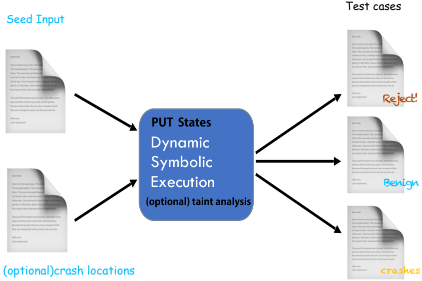
Cover more paths

$x \le y \wedge x+y \le 10$

$x \le y \wedge \neg x+y \le 10$

$\neg x \le y$

Program Analysis
- **Symbolic Excution**
- **Constrains Satisfation**



Why Grey-box Fuzzing ?

- White-box Fuzzing

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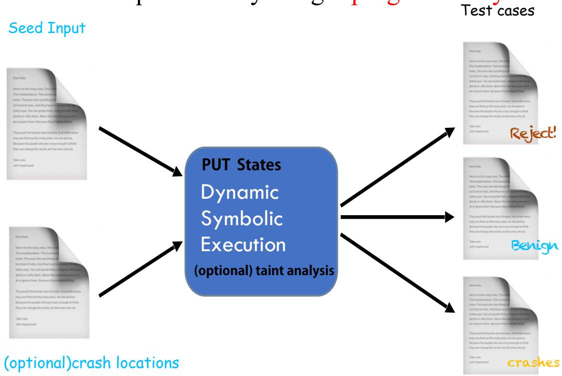
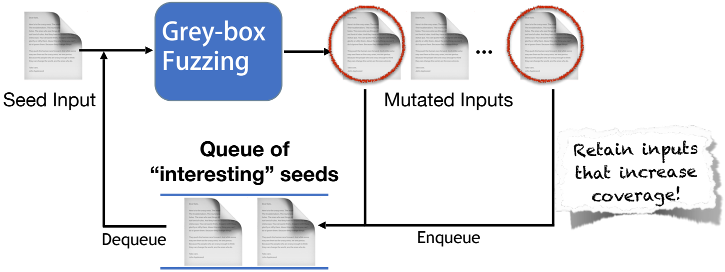


- You have the view of the PUT state(CFG,CG)
- Heavy-weight Program analysis (effective but not efficient!)

Why Grey-box Fuzzing ?

- Grey-box Fuzzing
  Defination: techniques that can obtain *some* information internal to the PUT and/or its executions to generates test cases[1].
  - Uses only lightweight instrumentation to glean some program structure
  - And coverage feedback



Why Grey-box Fuzzing ?

Grey-box Fuzzing is frequently used

- **State-of-the-art** in automated vulnerability detection
- **Extremely efficient** coverage-based input generation
  - All program analysis before/at instrumentation time.
  - Start with a seed corpus, choose a seed file, fuzz it.
  - Add to corpus only if new input increases coverage.

Why Directed Grey-box Fuzzing ?

Directed Fuzzing has many applications

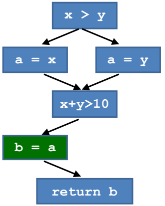
- **Patch Testing**: reach changed statements
- **Crash Reproduction**: exercise stack trace
- **SA Report Verification**: reach “dangerous” location
- **Information Flow Detection**: exercise source-sink pairs

Why Directed Grey-box Fuzzing ?

Directed Fuzzing

- **Goal:reach a specific target**
  - **Target Locations**: the line number in the source code or the virtual memory address at the binary level[2].
  - **Target Bugs**: use-after-free vulnerabilities, etc.

- **DSE:classical constraint satisfaction problem**
  - uses program analysis and constraint solving to generate inputs that systematically and effectively explore the state space of feasible paths[3].
  - **Program analysis** to identify **program paths** that reach given program locations.
  - **Symbolic Execution** to derive **path conditions** for any of the identified paths.
  - **Constraint Solving** to find an input



$$\varphi_1 = (x>y) \land (x+y>10)$$
$$\varphi_2 = \neg(x>y) \land (x+y>10)$$

Why Directed Grey-box Fuzzing ?

- **Effectiveness comes at the cost of efficiency**
- **Heavy-weight program analysis**

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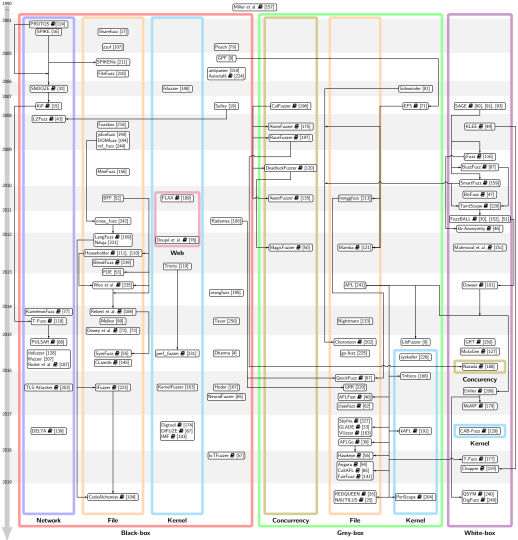
Genealogy tracing significant fuzzers' lineage[1]



[1] paper[1]-Figure1

Representative Work

- **AFLGo(2017)**[4]
- **Hawkeye(2018)**[5]

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    AFLGo
    Hawkeye

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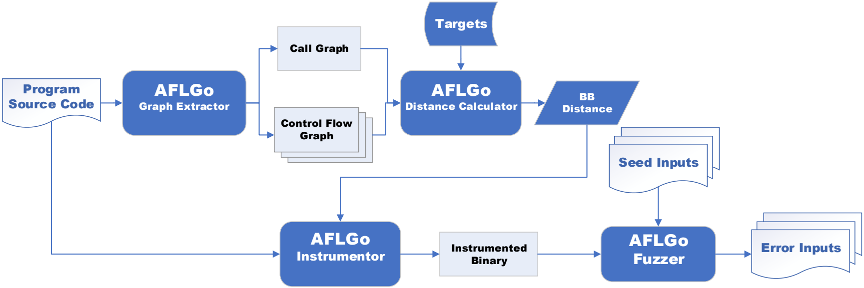
OverView

Directed Fuzzing as **optimisation problem!**

- **Instrumentation Time**
  1. Extract **call graph** (CG) and **control-flow graphs** (CFGs).
  2. For each **BB**, compute **distance** to target locations.
  3. Instrument program to **aggregate distance values**.
- **Runtime**
  1. collect coverage and distance **information**, and
  2. decide **how long to be fuzzed** based on distance.
     - If input is **closer** to the targets, it is fuzzed for **longer**.
     - If input is **further away** from the targets, it is fuzzed for **shorter**.

OverView

AFLGo Architecture



Algorithm

Directed Grey-box Fuzzing

```
Input: 𝕊 // a finite set of seeds
Input: 𝕋 // a finite set of targer sits
Output: 𝕊′ // a finite set of buggy seeds
𝕊′ ← ∅
SeedQueue ← 𝕊
Graphs ← GraphExt(Code)
BBdistance ← DisCalcu(𝕋, Graphs)
while !siganl ∧ t_elapsed < t_limit do
    s ← Dequeue(SeedQueue)
    trace ← Execution(s)
    distance ← SeedDis(trace, BBdistance)
    e ← AssinEnergy(s, t_elapsed, distance)
    for i ← 1 to e do
        s′ ← Mutation(s)
        if s′ crashes then 𝕊′ ← 𝕊′ ∪ s′
        if IsIntersting(s′) then Enqueue(s′, SeedQueue)
return 𝕊′
```

Instrumentation

```
Input: 𝕊 // a finite set of seeds
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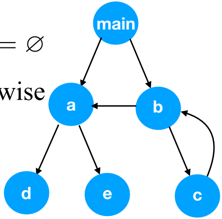
```

Instrumentation

- **Function-level target distance**[2]:using call graph (CG)

$$d_f(n, T_f) = \begin{cases} \text{undefined}, & \text{if } R(n, T_f) = \varnothing \\ [\sum_{t_f \in R(n,T_f)} d_f(n, t_f)^{-1}]^{-1}, & \text{otherwise} \end{cases}$$

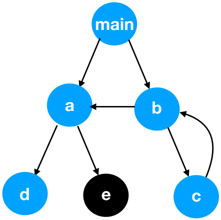


[2] R(n,Tf) is the set of all target functions that are reachable from n in CG

Instrumentation

- **Function-level target distance**:using call graph (CG)

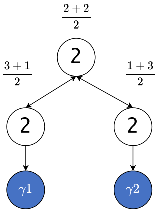
1. Identify **target functions** in CG



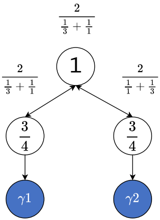
Instrumentation

- **Function-level target distance**:using call graph (CG)

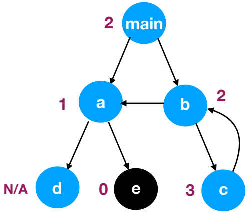
1. Identify **target functions** in CG
2. For each **function**, compute the **harmonic mean** of the **length of the shortest path** to targets



(a)arithmetic mean



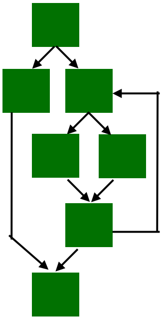
(b)harmonic mean



Instrumentation

- **Function-level target distance**:using call graph (CG)
- **BB-level target distance** [2]:using control-flow graphs (CFG)

$$d_b(m, T_b) = \begin{cases} 0, & \text{if } m \in T_b \\ c \cdot \min_{n \in N(m)} (d_f(n, T_f)), & \text{if } m \in T \\ \left[\sum_{t \in T} (d_b(m,t) + d_b(t, T_b))^{-1}\right]^{-1}, & \text{otherwise} \end{cases}$$



CFG for function b

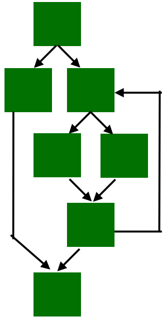
2

- N (m) is the set of functions called by basic block m
- T is the set of basic blocks in control-flow graph

Instrumentation

- **Function-level target distance**:using call graph (CG)
- **BB-level target distance** :using control-flow graphs (CFG)

1. Identify **target BBs** and assign distance 0 (none in function b)

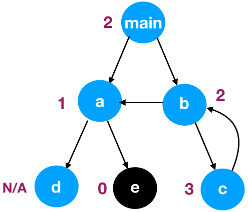


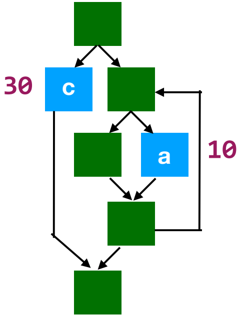
CFG for function b

Instrumentation

- **Function-level target distance**:using call graph (CG)
- **BB-level target distance** :using control-flow graphs (CFG)

1. Identify **target BBs** and assign distance 0
2. Identify BBs that **call function** and assign **10*FLTD**



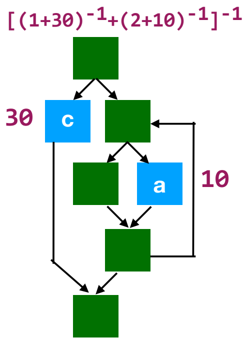


CFG for function b

Instrumentation

- **Function-level target distance**:using call graph (CG)
- **BB-level target distance** :using control-flow graphs (CFG)

1. Identify **target BBs** and assign distance 0
2. Identify BBs that **call function** and assign **10*FLTD**
3. For each BB, compute harmonic mean of (length of shortest path to any function-calling BB + 10*FLTD).



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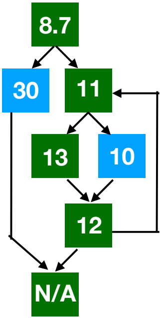


CFG for function b

Runtime

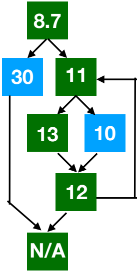
```
Input: 𝕊 // a finite set of seeds
Input: 𝕋 // a finite set of targer sits
Output: 𝕊′ // a finite set of buggy seeds
𝕊′ ← ∅
SeedQueue ← 𝕊
Graphs ← GraphExt(Code)
BBdistance ← DisCalcu(𝕋, Graphs)
while !siganl ∧ t_elapsed < t_limit do
    s ← Dequeue(SeedQueue)
    trace ← Execution(s)
    distance ← SeedDis(trace, BBdistance)
    e ← AssinEnergy(s, t_elapsed, distance)
    for i ← 1 to e do
        s′ ← Mutation(s)
        if s′ crashes then 𝕊′ ← 𝕊′ ∪ s′
        if IsIntersting(s′) then Enqueue(s′, SeedQueue)
return 𝕊′
```

Runtime

Seed distance[a] from instrumented binary

$$d(s, T_b) = \frac{\sum_{m \in \xi(s)} d_b(m, T_b)}{|\xi(s)|}$$

[a] $\xi(s)$ is the execution trace of a seed s

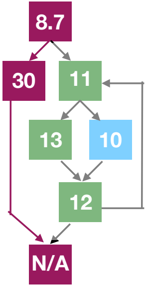


CFG for function b

Runtime

Seed distance from instrumented binary

- Two 64-bit shared memory entries
  - Aggregated BB-level distance values
  - Number of executed BBs



Seed Distance: 19.4
= (8.7+30)/2

Runtime

Seed distance from instrumented binary

- Two 64-bit shared memory entries
  - Aggregated BB-level distance values
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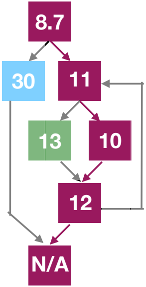


Seed Distance: 10.4
= (8.7+11+10+12)/4

Runtime

Directed Fuzzing as Optimisation Problem

- **Directed** Greybox Fuzzing
  - Assign **more energy** to seeds that are **closer** to the given targets
  - energy:The number of fuzz generated for a seed s is also called the energy of s.
- **Simulated Annealing**
  - To avoid **local minimum** rather than **global minimum** distance
  - **Sometimes** assign **more energy** to **further-away** seeds
- ***Exploration*** **vs** ***Exploitation***
  - **Exploration** phase:
    Energy of **closer** seeds similar to energy of **further-away** seeds
  - **Exploitation** phase:
    - Energy of **closer** seeds is assigned to be **higher** and higher
    - Energy of **further-away** seeds is assigned to be **lower** and lower

Runtime

Directed Fuzzing **as** **Optimisation Problem**

- **Temperature**
  $T \in [0, 1]$ specifies "importance" of distance.
  - normalized seed distance

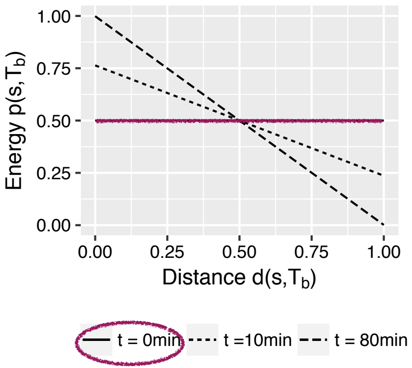
$$\tilde{d}(s, T_b) = \frac{d(s, T_b) - \text{minD}}{\text{maxD} - \text{minD}} \in [0, 1]$$

  - At T=1, **exploration** (normal AFL)
  - At T=0, **exploitation** (gradient descent)
- **Cooling schedule** :controls (global) temperature
  - Classically, exponential cooling.

Runtime

Integrating Simulated Annealing as power schedule

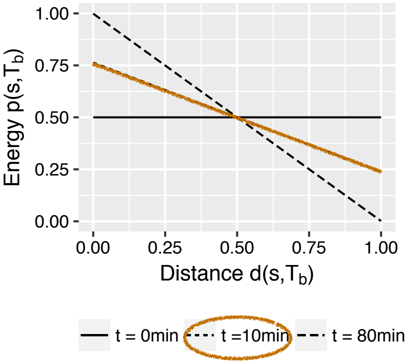
- In the beginning (t = 0min), assign the **same energy** to **all seeds**



Runtime

Integrating Simulated Annealing as power schedule

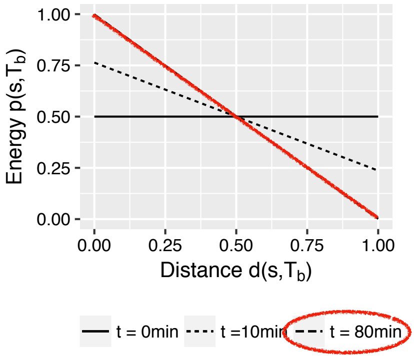
- In the beginning (t = 0min), assign the **same energy** to **all seeds**
- Later (t=10min), assigna **a bit more energy** to seeds that are **closer**



Runtime

Integrating Simulated Annealing as power schedule

- In the beginning (t = 0min), assign the **same energy** to **all seeds**
- Later (t=10min), assigna **a bit more energy** to seeds that are **closer**
- At exploitation (t=80min), assign **maximal energy** to seeds that are **closest**



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        if IsIntersting(s′) then Enqueue(s′, SeedQueue)
return 𝕊′
```

1 Background

2 Theory
    AFLGo
    Hawkeye

3 Work& Result

4 References

Desired Properties

- A Distance Metric **Avoiding bias**
  - **all traces** reachable to the target should be ***considered***
- Balance **Cost-Effectiveness**
  - precise static analysis ***can be*** **costly** but ***may not be*** **useful**

Some problems in AFLGo

The **distance** measure the **possibility** of reaching the target

```
void fa ( int i ){
  if ( i > 0) {
     fb ( i );
  }
  else {
     fb ( i *2);
     fc ();
  }
}
```

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void fa ( int i ){
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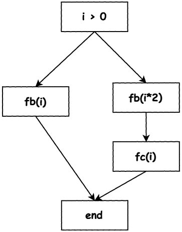

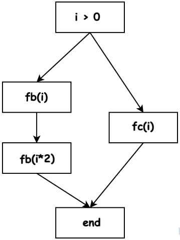

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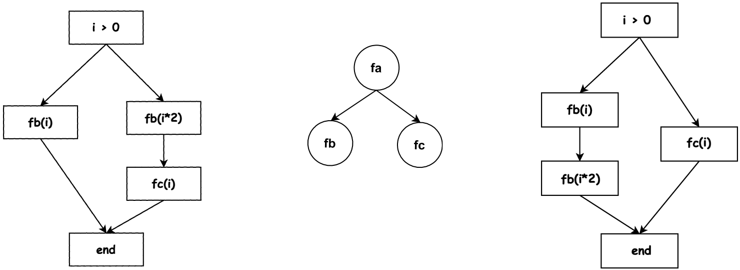

- **Adjacent-Function Distance Augmentation**
  - the distances from the calling function to the immediately called function ***may not be*** exactly the same
  - the distabces of fa $\rightarrow$ fb and fa $\rightarrow$ fc should depend on the ***context***

Some problems in AFLGo

Adjacent-Function Distance Augmentation

- f_1:Caller
- f_2:Callee
- C_N:Call sits occurrences of f_2 inside f_1
- C_B:No. of basic blocks in f_1 that contains more than one call site of f_2

$$d(f_1, f_2) = \Psi(f_1, f_2) \cdot \Phi(f_1, f_2) = \frac{\phi \cdot C_N + 1}{\phi \cdot C_N} \cdot \frac{\psi \cdot C_B + 1}{\psi \cdot C_B}$$

Some problems in AFLGo

Adjacent-Function Distance Augmentation

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void fa ( int i ){
   if ( i > 0) {
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      fb ( i *2);
      fc ();
   }
}
```

```
void fa ( int i ){
   if ( i > 0) {
      fb ( i );
      fb ( i *2);
   }
   else {
      fc ();
   }
}
```

let $\phi = 2$ and $\psi = 2$

$$\mathsf{d}(\mathsf{fa}, \mathsf{fb}) = \frac{2 \cdot 2 + 1}{2 \cdot 2} \cdot \frac{2 \cdot 2 + 1}{2 \cdot 2} = 1.56 \qquad \mathsf{d}(\mathsf{fa}, \mathsf{fb}) = \frac{2 \cdot 2 + 1}{2 \cdot 2} \cdot \frac{2 \cdot 1 + 1}{2 \cdot 1} = 1.87$$

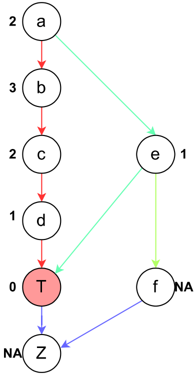
$$\mathsf{d}(\mathsf{fa}, \mathsf{fc}) = \frac{2 \cdot 1 + 1}{2 \cdot 1} \cdot \frac{2 \cdot 1 + 1}{2 \cdot 1} = 2.25 \qquad \mathsf{d}(\mathsf{fa}, \mathsf{fc}) = \frac{2 \cdot 1 + 1}{2 \cdot 1} \cdot \frac{2 \cdot 1 + 1}{2 \cdot 1} = 2.25$$

Some problems in AFLGo

A Distance Metric Avoiding bias

- Multiple targets are measured by distance
- At least one target has more than one viable path
- A seed exercises the longer path and is measured by this distance

The shortest path is always prioritized



Some problems in AFLGo

A Distance Metric Avoiding bias

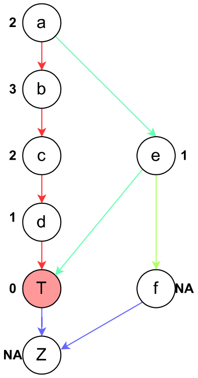
The shortest path is always prioritized

- $S_1 : a \to b \to c \to d \to T \to Z$
- $S_2 : a \to e \to T \to Z$
- $S_3 : a \to e \to f \to Z$

$$d(S_1, T) = \frac{2+3+2+1+0}{5} = 1.6$$

$$d(S_2, T) = \frac{2+1+0}{3} = 1$$

$$d(S_3, T) = \frac{2+1}{2} = 1.5$$



Some problems in AFLGo

- $\zeta(\mathsf{T_f})$:a finite function sets which can reach the targer function via the call chain
- $\xi(\mathsf{s})$:the execution trace of a seed s(functional level)

$$C_s(s) = \frac{|\xi(s) \cap \zeta(T_f)|}{|\zeta(T_f)|}$$

Some problems in AFLGo

- $\zeta(\mathsf{T_f})$:a finite function sets which can reach the targer function via the call chain
- $\xi(\mathsf{s})$:the execution trace of a seed s(functional level)

$$\mathsf{r(s)} = |\xi(\mathsf{s}) \cap \zeta(\mathsf{T_f})|$$

$$\mathsf{p(s)} = \widetilde{\mathsf{r}}(\mathsf{s}) \cdot (1 - \widetilde{\mathsf{d}}(\mathsf{s}, \mathsf{T_b})) \cdot (1 - \mathsf{T}) + 0.5\mathsf{T}$$

1 Background

2 Theory

3 Work& Result
   Work
   Result

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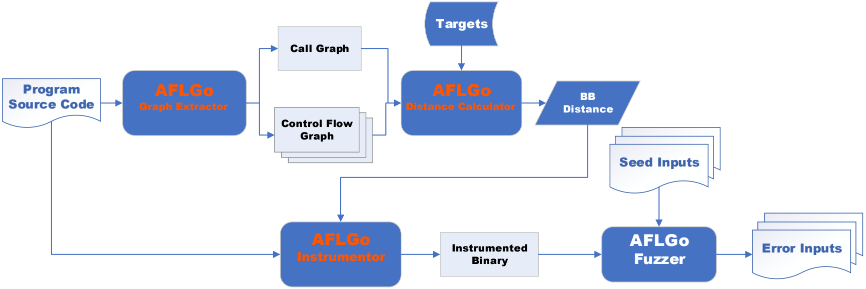
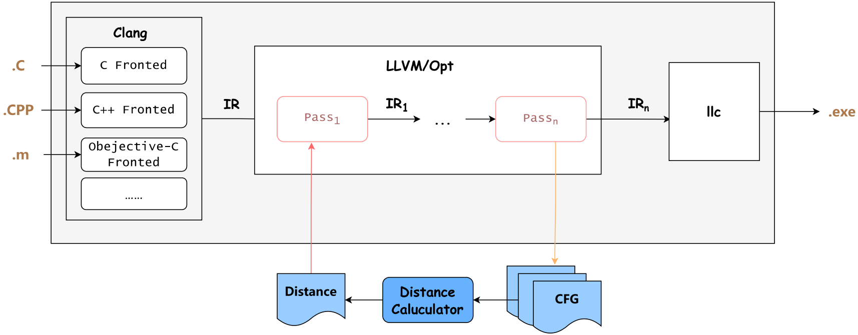
AFLGo Architecture & Technique



AFLGo Architecture & Technique



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1. Background
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4. References

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Thanks!