A Context-Sensitive Structural Heuristic for Guided Model Checking

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1. Introduction

- The use of embedded systems has become ubiquitous in recent times
- Growing complexity makes ad-hoc testing techniques insufficient
- Model checking exhaustively searches program states as shown in Fig. 1
- Computation resources often run out before finishing the search
- Guided search ranks states in order of interest with a heuristic
- Guided search explores interesting states first as in Fig. 2
- The goal is to find an error before running out of computation resources

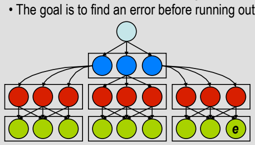


Fig 1: Breadth First Search

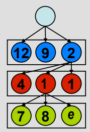


Fig 2: Guided Search

- Breadth-first search orders the search frontier in a FIFO as shown in Fig. 1
- Guided search orders the frontier in a priority queue as shown in Fig. 2
- The heuristic values on the states is the estimated distance to an error
- Explore states estimated closer to an error first

2. FSM Distance Heuristic

- FSM builds an Interprocedural Control Flow Graph (ICFG) statically
- A depth-first traversal of a program (Fig. 3) builds the ICFG shown in Fig. 4
- FSM maps the current state to a vertex in the ICFG as shown in Fig. 5
- It computes shortest path from a current state to an error state on the ICFG
- The length of the shortest path is returned as the heuristic estimate

```
main:
01:  ldx #1
02:  call foo
03:  add x,1
04:  call foo
05:   error
foo:
06:  pshx
07:  pulx
08:  rts
```

Fig 3: A program that calls foo twice and checks for an error

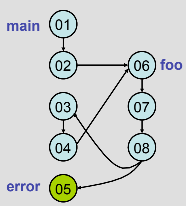


Fig 4: An ICFG for the program in Fig 3

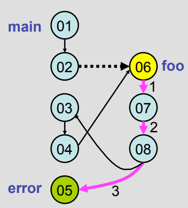


Fig 5: Path computed after the first call to foo : 3 steps

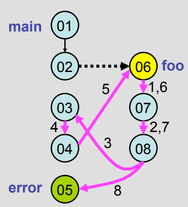


Fig 6: True Path to the error after the first call to foo : 8 steps

- The ICFG has no context information
- Cannot resolve the caller of foo on line 02 in Fig. 3
- FSM heuristic takes most conservative path as shown Fig. 5
- Underestimates the true distance to the error as shown in Fig. 6
- Need context information for callees to identify callers

3. Augmented Interprocedural Control Flow Graph (AICFG)

- An AICFG includes a bounded (k) calling context of function calls
- The bound k is specified by the user
- The program now has k slots for return addresses in the runtime stack
- A traversal of the program in Fig. 3 with k=1 creates the AICFG in Fig. 7
- The vertex (06,*03*) in Fig. 7 has information that it was called from line 02

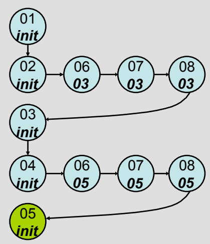


Fig 7: An AICFG for the program in Fig 3

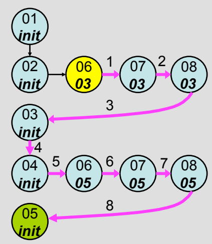


Fig 8: Path computed after the first call to foo on the AICFG : 8 steps

- The caller of foo can be resolved by the additional context information
- There is no underestimation in the path computed in Fig. 8
- Distance estimate computed on an AICFG is more accurate than the FSM
- For large k's the size of the AICFG can become prohibitive

4. Accuracy depends on *k*-bound

- The context information in the AICFG is limited by the bound
- The AICFG for the program in Fig. 9, with a k=1 is shown in Fig. 11
- The reduced call graphs in Fig. 10 shows the lost context in function g

main: 1 call x 2 call y error	f: 7 call g 8 rts	
x: 3 call f 4 rts	y: 5 call f 6 rts	g: 9 xyz a rts

Fig 9: A program with nested functions

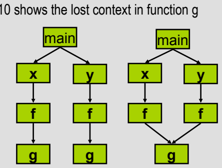


Fig 10: Reduced call graphs with and without full context information

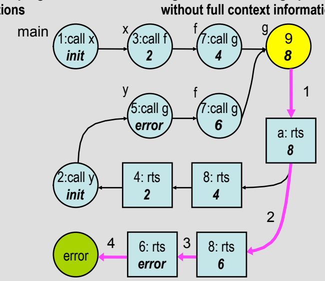


Fig 11: AICFG for Fig 9; path computed after first call to g is 4

- At function g, there is no knowledge of which caller invoked g in Fig. 11
- At depth greater than k, same underestimation problem as an ICFG

5. Extended FSM Distance Heuristic

- The extended FSM (EFSM) distance heuristic recovers calling context as shown in Fig. 12 by using the return addresses for function calls in the runtime stack
- The EFSM takes the runtime stack and extracts AICFG vertices as shown in Fig. 13 that represent the call trace to the current point of execution

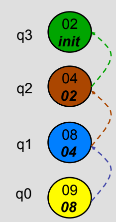


Fig 12: The call trace

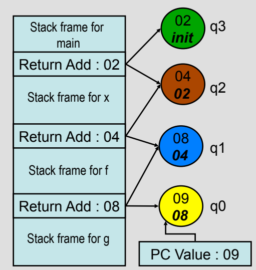


Fig 13: Extracting AICFG vertices based on the values of the runtime stack

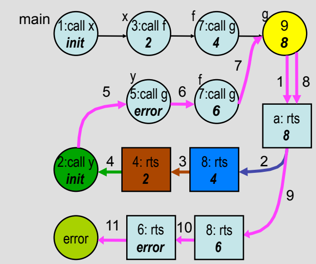
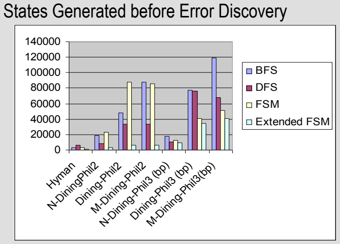


Fig 14: AICFG for Fig 9; path computed after first call to g by the EFSM is 11 steps

- The EFSM heuristic does a forward analysis from the current state (q0) on the AICFG in Fig. 14 to see if an error is reachable within the scope of the function g
- If an error is not reachable, or to find a shorter distance to the error, the EFSM heuristic unrolls the call trace by a single call to q1 in Fig. 12
- The EFSM heuristic again does a forward analysis on the AICFG in Fig. 14 at q2 on all unique paths in the function f that might lead to an error
- Repeat the pattern of unrolling the call trace and then doing a forward analysis on the AICFG until the call trace is exhausted
- The EFSM combines the dynamic information on the runtime stack in Fig. 13 with the static information on the AICFG in Fig. 14 to get a better heuristic estimate

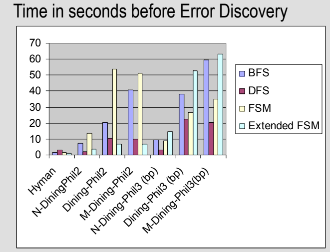
6. Results

States Generated before Error Discovery



- A visible decrease in number of states
- FSM guided search degenerates into a random search in some models

Time in seconds before Error Discovery



- Overhead in following call trace
- EFSM guided search is slower even though it expands fewer states
- Optimizes space over time
- Future work looks at the analysis overhead of the algorithm

7. Conclusions

- EFSM is admissible and consistent
- EFSM results in a better estimate of the distance to the error
- Explores fewer states before error discovery for a set of benchmark examples
- EFSM does better in models with densely connected transition graphs
- Extra memory used for building and storing the AICFG is negligible
- Structural heuristics make error discovery more tractable
- EFSM can be improved further by using data flow information

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