Call-Graph-Guided Verification

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Modular Verification

Goal: Infer procedure summaries that are…

- sufficient for verification
- efficiently computable
- sufficiently abstract and relevant to reason about the whole program

Challenges

- How should procedures be explored and in what environments (if any) should a procedure call be considered?
- How do we ensure procedure relevance *and* scalability?
- How would mutual recursion be handled?

Call Graph and Bounded Environments

Exploring Procedures and Environments

- Consider each procedure in an *environment* to learn over- and under-approximate summaries
- Environments represent possible counterexample paths
- Choose a finite path through the call graph:
  - Final call is the *target procedure* to consider
  - The rest of the procedures in the path make up the *environment*

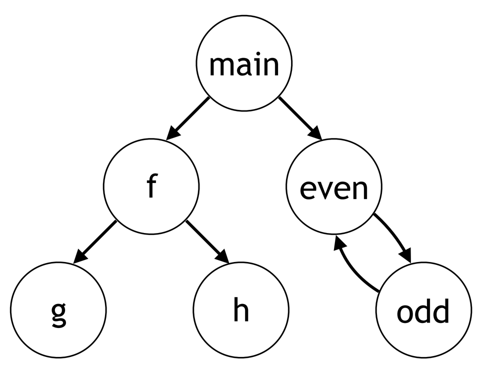
Scalability: Use Bounded Environments

- Longer call paths lead to larger queries and poor scalability
- Achieve scalability by *approximating* the environments
- A *b-bounded environment* captures at most the body of *b* procedures above the target procedure in the call graph path

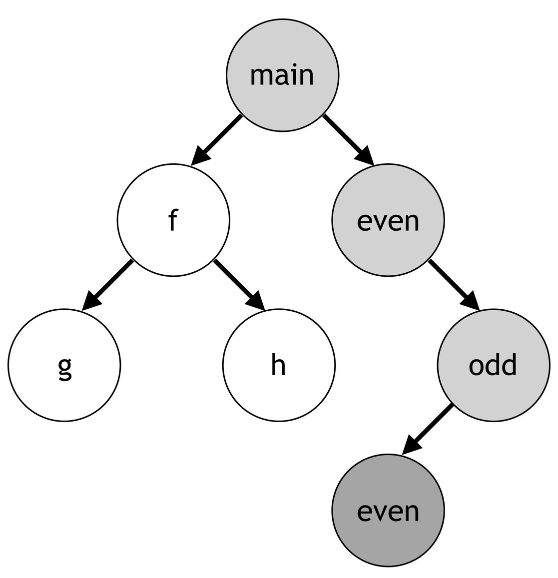
```
void main() {
  assert not(even(f() - 1));
}

int f() {
  return h(g());
}

int g() {
  return 2*havoc() + 1;
}

bool h(x) {
  return x + 1;
}
```

```
bool even(x) {
  assume (x >= 0);
  if (x==0) return true;
  else return odd(x - 1);
}

bool odd(x) {
  assume (x >= 1);
  if (x == 1) return true;
  return even(x - 1);
}
```

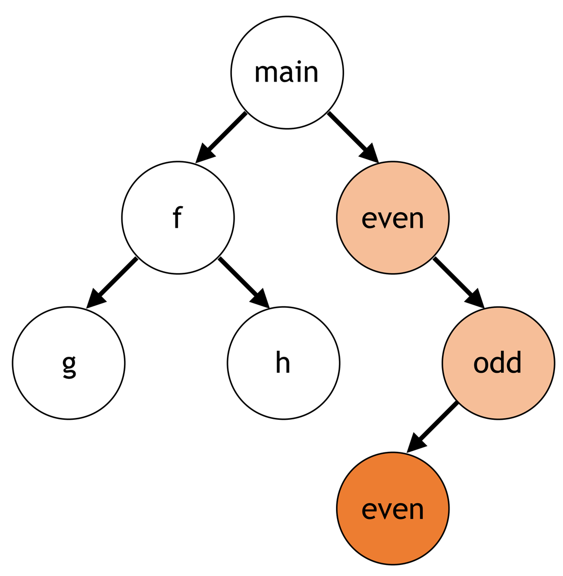
Example Program



Example Program Call



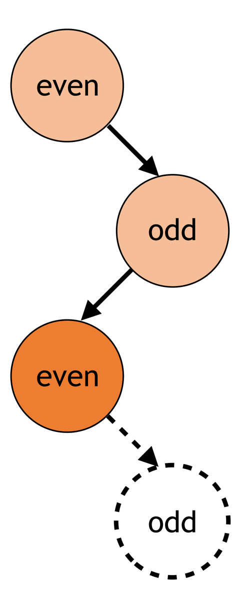
Full Environment (lighter) and Target Procedure



2-Bounded Environment (lighter) and Target Procedure

Mutual Recursion

- Handle recursion by performing *explicit induction*
- Handle mutual recursion by performing induction *under assumptions*
- Choice of assumptions: assume the negation of the (bounded) environment of procedures above the target
- Learn *implications among procedure summaries* — we call these Environment-Call (EC) lemmas



assume: odd.out ⇔ (1 + odd.in) mod 2 = 0

prove: even.out ⇔ even.in mod 2 = 0

Learning Procedure Summaries

Update Target's Under-Approximate Summary

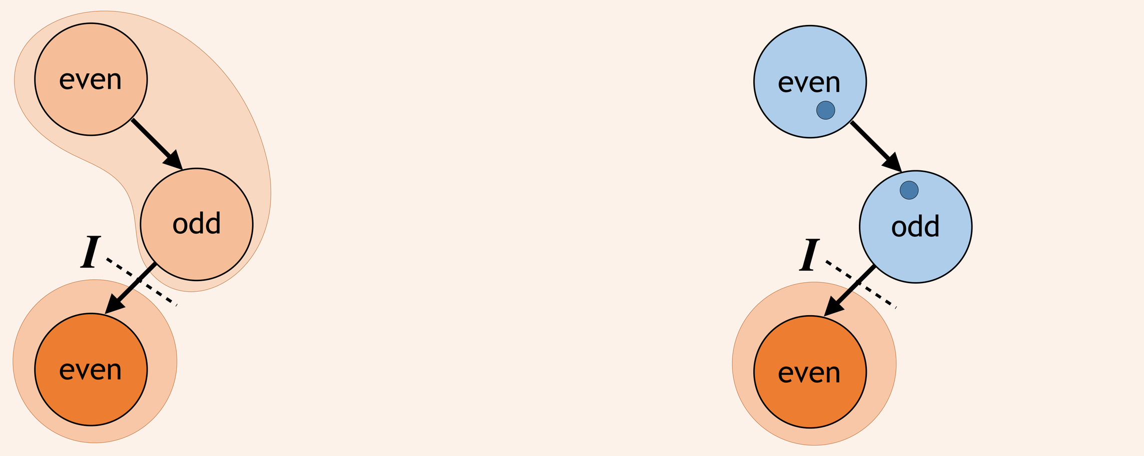
- Perform SMT check for under-approximation of procedure body and over-/under-approximation of environment
- If satisfiable, learn potential counterexample behaviors in target

Over-approximate Environment
Under-Approximate Procedure

Under-approximate Environment
Under-Approximate Procedure

Update Target's Over-Approximate Summary

- Perform SMT check for over-approximation of procedure body and over-/under-approximation of environment
- If unsatisfiable
  - find **interpolant** $\boldsymbol{I}$ that separates the target and environment
  - learn interpolant as over-approximation
- **With induction** to handle recursion
- **With assumptions** to handle mutual recursion



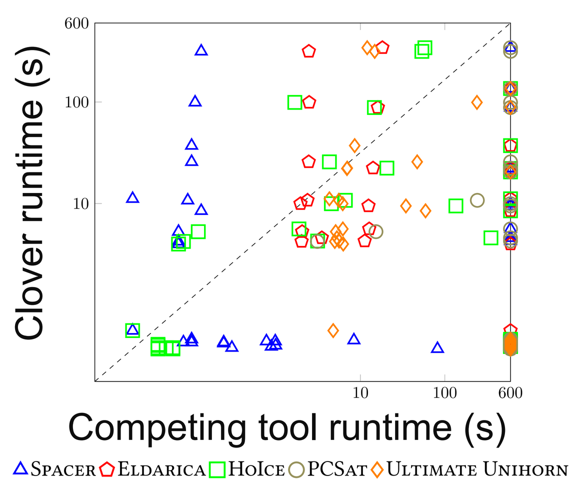
Over-approximate Environment
Over-Approximate Procedure

Under-approximate Environment
Over-Approximate Procedure

Experimental Results

	Clover	Spacer	Eldarica	HoIce	PCSat	Ultimate Unihorn
CHC-Comp	81	93	94	92	81	76
Mutual Recursion	24	12	0	0	0	0
Montgomery	16	6	14	14	3	13
s2n	6	5	0	2	N/A	6
Combination	2	0	0	0	0	0
Arrays	35	20	N/A	N/A	N/A	N/A

Number of examples in each set of benchmarks (shown on left) solved by each tool (shown on top)



Comparison of runtimes on the second set of benchmarks

- Clover: our prototype implementation
- Evaluated on three sets of benchmarks:
  1. 101 CHC-Comp 2019 benchmarks
  2. Benchmarks containing mutual recursion, programs based on Montgomery encoding and s2n, and combinations of these
  3. Benchmarks containing unbounded arrays
- Compared against other tools [1,2,3,4,5]
- Results demonstrate Clover is very effective for the latter two benchmark sets while remaining competitive with other tools on the first

References

[1] A. Champion, N. Kobayashi, and R. Sato, "Hoice: An ICE-based non-linear horn clause solver," in *APLAS*, ser. Lecture Notes in Computer Science, vol. 11275. Springer, 2018, pp. 146–156.

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[3] H. Hojjat and P. Ru¨mmer, "The ELDARICA horn solver," in *FMCAD*. IEEE, 2018, pp. 1–7.

[4] A.Komuravelli, A.Gurfinkel, and S.Chaki,"SMT-based model checking for recursive programs," *Formal Methods in System Design*, vol. 48, no. 3, pp. 175–205, 2016.

[5] Y. Satake, T. Kashifuku, and H. Unno, "PCSat: Predicate constraint satisfaction," 2019, https://chc-comp.github.io/2019/chc-comp19.pdf.

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