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Energy analysis of C program by analyzing its Horn clauses representation

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***Abstract*— In this paper, we present an approach to automatic resource (energy) analysis of C programs. Our approach combines ideas from abstract interpretation, ranking function synthesis and complexity analysis in a unified framework. Instead of acting on a source program, the analysis uses an intermediate language known as Constrained Horn clauses (CHCs) and computes bound in terms of the program's input parameters. Our approach is based on the method described by Sinn et al. where a program is abstracted to a lossy vector addition system with states (VASS). A VASS can be conveniently described by a set of CHCs where the constraints have a particular shape. Our analysis derives a VASS from the input Horn clauses using abstract interpretation and ranking function synthesis. Then it computes a lexicographic ranking function, which proves termination of the VASS. Finally a bound is computed directly from the VASS ranking functions. Resource consumption is obtained by multiplying the bound by a suitable resource measure.**

I. INTRODUCTION

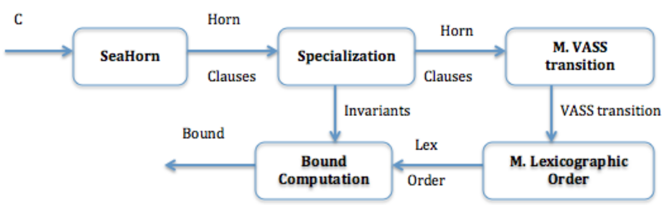
Static bound analysis or resource analysis of programs [1, 2, 3, 4, 5, 10, 12, 14, 15] is an active area of research. As a result of this, several tools and techniques with different flavors have emerged. The use of abstract interpretation [2, 10, 14], symbolic execution [12], computer algebra [1] and typing rules [3, 7, 8] for bound analysis are common in the literature. Some of these techniques are scalable but compute loose bounds while others compute tight bounds but are not scalable. Finding a balance between scalability of analysis and tightness of a bound is a matter of ongoing research. There are tools such as CiaoPP[1], SPEED [4], PUBS [1], Rank [2], LOOPUS [11, 12] which derive impressive bounds. Some of these tools are language dependent and others are not. So, we would like to purpose CHCs as an intermediate representation language for bound analysis since it provide a suitable intermediate form for expressing the semantics of a variety of programming languages (imperative, functional, concurrent, etc.) and computational models (state machines, transition systems, big- and small-step operational semantics, Petri nets, etc.). This makes us possible to reuse several years of works on constraint logic programming and exploit this representation for our purpose. In general, automatic complexity analysis has gained little attention compared to program verification and termination analysis though several interesting and useful properties about programs can be derived by bound analysis such as loops upper bounds, number of visits to a control location or instruction, the amounts of resources (time, energy, memory etc.) consumed by a program etc.

In this paper, we present an automatic approach to resource analysis of C programs, which uses CHCs as an intermediate language. It can be seen as an adaptation of the method described by Sinn et al. in [12]. We chose this method because it is more flexible than others for example CiaoPP, which involve solving cost equations and they might not have solutions, especially for mutually recursive loops. The program is first translated to a set of CHCs. The analysis then derives a VASS from it using abstract interpretation and ranking functions synthesis. Then it computes a lexicographic ranking function, which proves termination of the VASS. Finally a bound is computed directly from the VASS ranking function. To compute a bound for a program, each such step should be precise/succeed, therefore the choice of the techniques matter a lot. Our work, which is an adaptation of [12] has the following characteristics:

- Our analysis is based on Horn clause representation, which allows reuse of several state of the art tools developed for it, e.g. Horn specialisation, computing over-approximation of the set of Horn clauses etc.;
- Program abstraction: instead of symbolic execution and simple invariant generation as in [12] we use abstract interpretation, which is scalable and computes good invariants. Good invariants seem to be crucial for bound analysis;
- Ranking function generation: instead of guessing ranking functions from the generated invariants and checking if they are local ranking functions for a given transition [12], we use a complete approach based on [9, 13] for computation of ranking functions. They are complete in the sense that if a linear ranking function exists then they will find one. In [12] this is not guaranteed.
- Control flow abstraction and bound computation: furthermore we still benefit from the novelties of [12] for control flow abstraction and bound computation.

[1] Summary of our approach

The architecture of our tool-chain is depicted in Figure 1. The boxes represent different modules/ components and the label on the arrows shows the output or input to and from these components. Given a program written in *C*, we obtain a set of Horn clauses using SeaHorn [6]. The resulting set of clauses are specialised by a *specialzation module, which* also computes invariants for the clauses using abstract interpretation. These set of clauses are fed into the module of *VASS transition*, which computes a VASS. A lexicographic order for the given VASS is computed by the module *lexicographic order*. Then a bound is computed by the bound *computation module* from this lexicographic ordering.



Our running example is presented in Figure 2. It consists of two

nested loops, whose counters depend on the input parameters (*c* and *d*). The program terminates and has a linear bound since the outer loop can only be executed at most the initial value of *a* (that is *c*) times since *a* is decremented by 1 in each iteration of the outer loop. The counter variable *b* of the inner loop is conditionally increased by the outer loop, however this can only be done at most the initial value of *a* (that is *c*) times. So the inner loop can be executed at most *c+d* times. To derive a linear bound, a path sensitive reasoning is necessary. Given this program, our tool extracts three single path linear constraints (SLC) loops, two of them corresponding to the outer loop and one to the inner. Then it computes the local ranking functions for each such loops separately. Since the outer loop has two SLC loops it computes *a* as ranking function for both of the SLC loops and *b* for the SLC loop corresponding to the inner loop. Then the lexicographic ordering *(a,a,b)* is derived, which proves the termination of this program. But during bound computation the tool takes into account the effect of the outer loop on the ranking function of the inner one, that is, the local ranking function of the inner loop is increased by the outer at most by 1 in each iteration. So the inner loop can be executed at most *c+d* times. So the total bound is *c+d*. Let *E* be the worst case energy consumed by this program in one iteration, then *(c+d)*E* is the total energy consumed by this program in the worst case.

```
main( uint c, uint d){
  int a=c,b=d;
  while (a>0){
    if (*)
      b++;
    else
      while (b>0)
        b--;
    a--; }
  return 0;}
```

Figure 2: example program

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