Inlining in the Jive Compiler Backend

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Abstract

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

Contents

1 Introduction

Since the 1950s, compilers have played an important role in the way programming code is translated into machine languages. In broad terms, compilers perform two actions: the translation of human-readable code to machine language, and optimizing the translated programs. There exists many optimization techniques compilers use. One such optimization is inlining, exemplified below in Listing 1.

```
int foo(int x){
  return x + 3;
}

int bar(int y){
  return foo(y) + 2;
}

// bar() with foo() inlined:
int bar(int y){
  y + 3 + 2;
}
```

Listing 1: Function *foo()* inlined into function *bar()*.

Inlining is a straight-forward optimization, which replaces the call of a function with its body. However, the decision of which functions to inline has long been treated as "black magic", due to the non-existence of a perfect inlining heuristic. This report attempts to answer exactly that question for the new compiler backend Jive, introduced shortly.

The benefits of inlining are removal of function call overhead and unveiling of additional optimizations. The drawbacks are potential code- and work- duplication, shown in Listings 2 and 3, respectively. Additionally, inlining can also negatively affect the compile time, unless optimizations to counteract this are unveiled.

```
  typedef struct{
    int x;
    int y;
  } coords_t;


  coords_t* foo(){
    coords_t* a = (coords_t*) malloc(sizeof(coords_t));
    a->x = 1; a->y = 2;
    return a;
  }

  coords_t* bar(){
    coords_t* a = foo();
    coords_t* b = foo();

    b->x += a->x; .y += a->y;
    return b;
  }

  // bar() with foo() inlined, with code duplication
  coords_t* bar(){
    // Line which is duplicated unnecessarily
    coords_t* a = (coords_t*) malloc(sizeof(coords_t));
```

```
  a->x = 1; a->y = 2;
  // Line which is duplicating unnecessarily
  coords_t* b = (coords_t*) malloc(sizeof(coords_t));
  b->x = 1; b->y = 2;

  b->x += a->x; b.y += a->y;
  return b;
}
```

Listing 2: Code duplication in *bar()*, when inlining *foo()* into *bar()*.

```
int foo(int x){
  //Computationally expensive function,
  //such as Fibonacci for very high numbers
}

int bar(int y){
  return foo(y) + foo(y+4000);
}
```

Listing 3: Work duplication in *bar()*, when inlining *foo()* into *bar()*.

Todo: Describe layout/outline of paper. What does each section in turn discuss?

This report describes the inliner for the new compiler backend Jive. It will detail the decisions made for its architecture and heuristics. Jive takes program code in Intermediate Representation (IR) as input and works on a new IR representation, the Regionalized Value-State Dependence Graph (RVSDG[1]).

Not all functions are straight-forward to inline, such as recursive functions. Only an unknown subset of all recursive functions can be inlined, and if one is inlined incorrectly, it can lead to non-termination of the compiler. Recursive functions, the heuristics parameter space, and how the inliner enables rapid exploration of the parameter space, are other topics this report will discuss in turn. Recursive functions need to be handled carefully by an inliner for an additional reason.

With RVSDG being a new way to represent IR code, this report will also look into how the RVSDG affects the design of an inliner, and the process of inlining. Focus will be put on whether the RVSDG simplifies or complicates the implementation of the inliner, and the process of inlining compared to commonly used IRs.

Finally, we evaluate the implemented inliner before we conclude. Focus will be put on how different heuristics have different consequences, in terms of code- and work-duplication.

Further details of the assignment of this paper can be found in Appendix A.

[1]Detailed in Section 2.1.

2 Background

2.1 The Regionalized Value-State Dependence Graph

The RVSDG is a Directed Acyclic Graph (DAG).

An RVSDG has different kinds of nodes, and two types of edges. Nodes can be generalized into two categories detailed in this section; simple and complex nodes. Simple nodes are the nodes representing the most “basic operations” a program performs. Complex nodes are nodes which contain an RVSDG subgraph. The complex nodes presented below are the γ-, θ-, λ-, apply-, and ϕ-nodes. The edges will be discussed first.

Finish this introduction of the graph, don’t forget operations, “simple nodes”, like +, - and so on.
“Once a node contains a subgraph, it’s a complex node”.

2.1.1 Edges

One type of edge used in an RVSDG is the data dependence edge. This edge represents a data dependency one node has before it can be computed/executed.

The other type of edge is the state dependence edge. This edge is meant to keep the ordering of the nodes consistent with the original flow of execution, when there is no ordering by data dependencies between them. Stippled lines are commonly used to denote state dependence edges.

See figure X for an example of why state dependency edges are necessary for the RVSDG.

Make Fibonacci figure example with RVSDG nodes with a printf in main()

2.1.2 Simple nodes

Simple nodes are defined by their inability to contain an RVSDG subgraph.

Simple nodes are used in an RVSDG to represent simple operations, such as addition, subtraction, and similarly simple operations often referred to as *primitive operations* in programming languages.

2.1.3 Complex nodes

- **N-way statements**

  γ-nodes represent conditional statements. Each γ-node has two sets of inputs: the predicate, and all other edges its subgraph depend upon.

  An if-statement is represented as a γ-node containing the subgraph representing the body of the if-statement. If the predicate evaluates to true, the subgraph will be executed.

  If-else statements are also represented as γ-nodes, but they are divided[2] into two subsections. One subsection of the node contains the subgraph of what will happen if the predicate evaluates to true, and the other will contain the subgraph representing the body of the else- statement.

  Statements such as the ones listed in Listing X, are represented by nesting the γ-nodes representing each if-statement. Figure X illustrates this.

Make listing

Make figure

[2] Typically vertically.

- **Tail-controlled loops**

  θ-nodes represent tail loops in the program. They are equivalent to do-while loops containing the representation of the body of the loop. All dependencies any node in the subgraph of the θ-node may have, need to be routed into the θ-node so as to be available for the subgraph.

  Other loops, such as for-loops, can be represented by wrapping a θ-node inside of a γ-node with an empty false-subsection. For this to represent a for-loop, both the θ- and the γ-node need to each have the same predicate as the other.

  A for-loop would be presented with an if-else γ-node, with a θ-node in the body of the γ-node representing the "true" subgraph.

- **Functions**

  λ-nodes represent functions, and their *apply*-nodes are call sites of the function in the program. There should only exist one λ-node containing a subgraph in an RVSDG, per function in the program the RVSDG represents. As each *apply*-node represents a call site, all *apply*-node have an edge linking it to the λ-node corresponding to the function called.

- **Mutually recursive functions**

  ϕ-regions are nodes representing parts of the program's control flow where functions behave recursively, either by calling themselves, or two or more calling each other in turn (mutually recursive).

  To uphold the DAG properties of an RVSDG, there is only one edge going from the inner border of the ϕ-node to the outer border of its contained λ-node. Equivalently, an edge going out from the outer border of the λ-node, to the inner edge of the ϕ-node.

  There is hence no cycle, due to there being no edge going back to the start of the λ-node inside the ϕ-node.

  Need to justify the above two sentences.

Abovementioned Fibonacci example with examples of graphnodes, maybe code too?

3 Scheme

4 Methodology

5 Results

6 Discussion

7 Related Work

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As mentioned in Section 1, inlining has been done since the last half of the 20th century. Following comes the related research used as basis for the work done in this report.

W. Davidson and M. Holler [5] examine the hypothesis that the increased code size of inlined code affects the execution time on demand-paged virtual memory machines. Using equations developed to the describe an inlined programs' execution time, they test this hypothesis through the use of a source-to-source subprogram inliner.

Cavazos and F.P. O'Boyle [2] use a genetic algorithm in their auto-tuning heuristics to show how conjunctive normalform (CNF) can easily be used to decide if and when to inline a specific call site. They report between 17% and 37% execution time improvements without code size explosion, in java when testing on an Intel PC.

Serrano [9] implements an inliner in the Scheme programming language. The paper details an heuristic for which functions to inline in scheme, as well as an algorithm for how to inline recursive functions and non-recursive functions. Serrano reports an average run time preformance increase of 15% with the inlined Scheme programs.

Waterman's Ph.D. thesis [10] examines the use of adaptive compilation techniques in combination with an inlining heuristic. The thesis shows how CNF can be used for deciding which functions to inline, and examines how there is no single given correct set of parameters for the search space of his hillclimbing algorithm that his heuristic uses. Waterman reports consistently better or equal run time performance when compared to the GCC inliner and ATLAS.

D. Cooper, J. Harvey, and Waterman [4] continue on Waterman's PhD Thesis [10] research. Their paper details how proper use of the parameterization search space of an adaptive inlining scheme using the hillclimber algorithm can achieve great results compared to GCCs inlining scheme. Their results range from 4% to 31% run time performance increase when compared with GCCs inliner.

E. Hank et. al [7] introduce a new technique called *Region-Based Compilation*. They examine the benefits an aggressive compiler can gain from inlining in conjunction with very long instruction words (VLIW) architecture. They report that aggresive inlining can be expensive with an average code expansion of 400%. Yet, they also show that aggressive inlining is able to unveil further compiler optimizations, leading to averages of 50% of program execution time spent in functions with more than 1000 operations, instead of more than 80% of execution time spent in functions with less than 250 operations when run without inlining.

P. Jones and Marlow [8] explore an inlining approach for the Glasgow Haskell Compiler (GHC) detail the inner workings of the GHC. Their paper also introduces a novel approach for deciding which mutually recursive functions can be safely inlined without code explosion or non-terminating programs. Jones and Marlow report an average of 30% run time performance increase when using the default settings on the GHC inliner.

Barton et. al [1] tests whether the potential for loop fusion should be taken into consideration in the inlining decisions. They examine this through the use of the IBM®XL Compile Suite and measuring how many additional loops they were able to fuse in the SPECint2000 and SPECfp2000 benchmark suites. Their results indicate that the compiler already catches most of the potential loop fusion optimizations, and the results cannot justify an inter-procedural loop fusion implementation.

Deshpande and A. Edwards [6] detail how inlining should be done in the GHC, with a goal to improve parallelism of recursive functions by "widening" them into the equivalent of multiple recursive calls through unrolling recursion. They leave it as an exercise to the reader to find their performance results.

W. Hwu and P. Chang [3] explore how program profile information could be used to decide whether or not to inline C functions statically. Their motivation was to remove costly function calls in a C program, in addition to statically unveil potential optimizations. Through the use of the IMPACT-I C compiler, they profile dynamic program information, resulting in a call graph with weighted edges. They report an average elimination of dynamic function calls across their 14 test benchmarks at 16.17%.

Fix result report "0 to X%" or something instead of something they didn't actually report.

8 Conclusion

8.1 Further Work

9 References

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[4] Keith D. Cooper, Timothy J. Harvey, and Todd Waterman. An adaptive strategy for inline substitution. In *Proceedings of the Joint European Conferences on Theory and Practice of Software 17th International Conference on Compiler Construction*, CC'08/ETAPS'08, pages 69–84, Berlin, Heidelberg, 2008. Springer-Verlag.

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[8] Simon Peyton Jones and Simon Marlow. Secrets of the glasgow haskell compiler inliner. *J. Funct. Program.*, 12(5):393–434, July 2002.

[9] Manuel Serrano. Inline expansion: When and how? In *Proceedings of the9th International Symposium on Programming Languages: Implementations, Logics, and Programs: Including a Special Trach on Declarative Programming Languages in Education*, PLILP '97, pages 143–157, London, UK, UK, 1997. Springer-Verlag.

[10] Todd Waterman. *Adaptive Compilation and Inlining.* PhD thesis, Houston, TX, USA, 2006. AAI3216796.

A Project Description

(On next page)

Project Description: An Inliner for the Jive compiler

Nico Reissmann

December 12, 2014

Compilers have become an essential part of every modern computer system since their rise along with the emergence of machine-independent languages at the end of the 1950s. From the start, they not only had to translate between a high-level language and a specific architecture, but had to incorporate optimizations in order to improve code quality and be a par with human-produced assembly code. One such optimization performed by virtually every modern compiler is *inlining*. In principle, inlining is very simple: just replace a call to a function by an instance of its body. However, in practice careless inlining can easily result in extensive *work* and *code duplication*. An inliner must therefore decide carefully when and where to inline a function in order to achieve good performance without unnecessary code bloat.

The overall goal of this project is to implement and evaluate an inliner for the Jive compiler back-end. The project is split in a practical and an optional theoretical part. The practical part includes the following:

- Implementation of an inliner for the Jive compiler back-end. The inliner must be able to handle recursive functions and allow for the configuration of different heuristics to permit rapid exploration of the parameter space.
- An evaluation of the implemented inliner. A particular emphasis is given to different heuristics and their consequences for the resulting code in terms of work and code duplication.

The Jive compiler back-end uses a novel intermediate representation (IR) called the Regionalized Value State Dependence Graph (RVSDG). If time permits, the theoretical part of the project is going to clarify the consequences of using the RVSDG along with an inliner. It tries to answer the following research questions:

- What impact does the RVSDG have on the design of an inliner and the process of inlining?
- Does the RVSDG simplify/complicate the implementation of an inliner and the process of inlining compared to other commonly used IRs?

The outcome of this project is threefold:

1. A working implementation of an inliner in the Jive compiler back-end fulfilling the aforementioned criteria.
2. An evaluation of the implemented inliner.
3. A project report following the structure of a research paper.