Demand-driven Inlining in a Region-based Optimizer for ILP Architectures

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February 1, 2008

Abstract
Region-based compilation repartitions a program into more desirable compilation units using profiling information and procedure inlining to enable region formation analysis. Heuristics play a key role in determining when it is most beneficial to inline procedures during region formation. An ILP optimizing compiler using a region-based approach restructures a program to better reflect dynamic behavior and increase interprocedural optimization and scheduling opportunities. This paper presents an interprocedural compilation technique which performs procedure inlining on-demand, rather than as a separate phase, to improve the ability of a region-based optimizer to control code growth, compilation time and memory usage while improving performance. The interprocedural region formation algorithm utilizes a demand-driven, heuristics-guided approach to inlining, restructuring an input program into interprocedural regions. Experimental results are presented to demonstrate the impact of the algorithm and several inlining heuristics upon a number of traditional and novel compilation characteristics within a region-based ILP compiler and simulator.

1 Introduction

Advanced instruction-level parallel (ILP) computer architectures require aggressive and potentially costly whole program, or interprocedural, techniques for program analysis and optimization to fully exploit available parallelism. These interprocedural techniques are in contrast to intraprocedural code improvement techniques employed in a traditional procedure-oriented compiler, where analysis and optimization phases are independently applied to each procedure in isolation.

An approach for ILP that reduces the cost of aggressive interprocedural analysis and optimization is region-based compilation. Region-based compilation is a generalized trace selection approach that partitions a program into units of compilation, or regions, based on profile information. Using procedure inlining, where a procedure call site is replaced by the body of the called procedure, and restructuring a program into regions, the region-based compiler can perform code motion and other analyses and optimizations interprocedurally, while maintaining control over the compilation unit size and content. Unlike procedure-based compilation, region-based techniques bound the compilation unit size to better control optimization costs.

The key component of a region-based compiler is the region formation phase which partitions the program into regions using profile-guided heuristics with the intent that the ILP optimizer will be invoked with a scope that is limited to a single region at a time. Thus, the quality of the generated code depends greatly upon the ability of the region formation phase to create regions that a global optimizer can effectively transform in isolation for improved ILP. Because region-based compilation relies on an initial aggressive inlining phase,
region formation remains quite costly, particularly for large programs with many procedures and calls [20]. Selective use of inlining can prevent excessive code growth and control register pressure while improving analysis opportunities and performance [7].

In this paper, a strategy to overcome the issues caused by separate inlining and region formation phases is described and evaluated. Presented is a demand-driven approach to inlining and a set of inlining heuristics which are integrated within a region-based optimizer. To evaluate these techniques, the algorithm and various heuristics for guiding inlining decisions have been implemented within the Tramaran ILP research compiler [28]. In addition to standard metrics such as compilation time, code growth and execution time, novel metrics have been devised to compare the characteristics of regions, such as profile homogeneity and interprocedural scope, to measure the effectiveness of this new approach.

2 Region-based Compilation

A common characteristic of compiler analysis techniques, including those specifically for ILP architectures, is that they have been designed with the assumption that the original procedure boundaries created by the programmer are immutable. Procedures serve as the de facto unit of compilation. As a result, there is the potential for large procedures to either unacceptably increase compilation time or to be less aggressively optimized (or not optimized at all) in order to control compilation costs and maintain scalability. Procedure boundaries are a natural impediment to compilation effectiveness in many cases, requiring tradeoffs in terms of quality of optimization versus compilation time and memory requirements.

Hank et al. [20] proposed the region-based compilation framework as a solution to the problem of exposing interprocedural scheduling and optimization opportunities without the cost of very large procedure bodies created through inlining, or the expense and complexity of sophisticated interprocedural analysis and code motion. While it was shown to be especially beneficial in an ILP compiler, region-based compilation also can achieve both interprocedural scope and scalability in program analysis.

2.1 Fundamental region formation

Figure 1 depicts the organization of a region-based compiler framework. The source code enters the Profiler, where the source code is instrumented and executed to gather profile information which is then integrated into the source code. Intermediate code with profiling information is input to the Aggressive Inliner phase, where all inlining that can be done in the entire program, subject to some constraints, is performed. Next, in the Region Formation phase, regions are formed throughout the whole program, and each region is encapsulated as a procedure in the Encapsulation phase. The encapsulated regions are then passed to a high-level Optimizer phase before Reintegration into their original procedures. The result is passed to the Code Generator which includes a low-level optimization phase.

In this framework, a region is a collection of basic blocks and control flow edges selected for compilation as a unit [20]. More formally, a region is a subgraph of the control flow graph (CFG) of a procedure, created either based on the structure of the CFG or using profile information. Each region is encapsulated in a single-entry, single-exit CFG by adding dummy prologue and epilogue CFG nodes and boundary condition CFG nodes that convey pertinent data flow information. Regions are encapsulated in such a way that the optimizer can be invoked with a scope that is limited to a given region, which then appears to the rest of the compiler as a procedure. Side entries into regions can be removed by tail duplication, similar to superblock formation [22]. After optimization, each region is re-integrated into the original procedure in which the region existed by updating changes in data flow conditions, entry and exit points, and constraints on register allocation. Code is generated from the re-integrated procedure.

2.2 Example

The original profile-sensitive region formation algorithm is comprised of the following steps, performed between aggressive inlining and region encapsulation. These steps are performed until all blocks in the program have been included in some region. Figure 2 shows the results of performing the following steps of the algorithm. Figure 2(b) shows the code after aggressive inlining is performed on the code in Figure 2(a).
Step 1: Seed Selection - From among all basic blocks in the procedure not yet included in a region, select the block with the highest execution frequency; this is the seed block for a new region. In this simplified example, this is block 8, shown in Figure 2(b). Note that inlining was done previously.

Step 2: Region Expansion to Successors - A path of desirable successors is selected, starting at the seed block. Region expansion is guided by heuristics which halt the growth under a set of conditions such as: (1) a procedure call is reached, (2) a minimum acceptable execution frequency for a successor block is not met (e.g., at least 50% of the frequency of both its immediate predecessor in the region and that of the seed block, which in this simplified example is why block 6 is not selected in this step), or (3) a region size threshold (e.g., 200 basic blocks) is exceeded. The successors selected for seed block 8 are blocks 10, 11, 5 and 7.

Step 3: Region Expansion to Predecessors - A path of frequently executed predecessors to the seed block is chosen analogous to the selection of desirable successors. The resulting path after this step is the seed path of the region. In this case, blocks 2 and then 1 are added as predecessors of seed block 8.

Step 4: Region Expansion from All Blocks in the Seed Path - By selecting as above the desirable successors of all current blocks in the region, the region is grown along multiple control flow paths. Thus, block 3 is added to the region. The result of this step is a path-sensitive region. Blocks not yet in a region (blocks 6 and 9) are used to form additional regions.

To summarize, three regions are formed in the example. The largest region consists of blocks 1, 2, 3, 5, 7, 8, 10, and 11. The remaining blocks 6 and 9 form single block regions. Note that original block 4 was replaced by the inlined procedure G. Limitations include the potential for excessive code growth and unnecessary inlining due to the aggressive approach to inlining, leading to unscalability, and the training-data effect of profile-guided compilation. While Hank’s approach can achieve scalability during program analysis and optimization by allowing the compiler to control the size of regions, region formation is unscalable due to aggressive inlining.

3 Region Formation Analysis with Demand-driven Inlining

Interprocedural regions that include instructions from more than one procedure enable region-based compilation to uncover optimizations missed due to procedure boundaries. This section proposes an alternative approach to building interprocedural regions which performs inlining on a demand-driven basis integrated within region formation analysis is presented in this section. By delaying inlining decisions until region formation analysis, the characteristics of inlined code can be better controlled, reducing code growth and memory requirements. However, inlining performed in this demand-driven way introduces a number of issues that are not present in existing region formation techniques; these issues are enumerated, and a technique is
Figure 2: Example of the steps in Hank’s region formation algorithm.

proposed to addresses them. In the remainder of this paper, the approach of aggressive inlining followed by intraprocedural profile-sensitive region formation (i.e., Hank, et al.) is referred to as Phased-region, and the new demand-driven approach is called Demand-region.

3.1 Challenges in Forming Interprocedural Regions

Major issues to consider in the design of Demand-region are:

**Issue 1. Inlining is driven by the demand placed at procedure callsites as regions are formed.** Callsites may be encountered as a most frequent successor or predecessor of a block on a path within the current region being formed. The path selection process must determine at that point whether or not the callee should be inlined, a decision dependent on the heuristics used to guide inlining. If the decision is made to inline a procedure, it is inlined and region formation proceeds within the callee’s code. Thus, interprocedural regions are identified by having the region formation process cross procedure boundaries by inlining on demand.

**Issue 2. Region formation analysis must deal with multiple calls to the same procedure as it crosses procedure boundaries.** While region formation on the flattened, aggressively inlined code of Phased-region analyzes a distinct code segment for each callsite that has been inlined, region formation without prior inlining analyzes the same code for a procedure’s body for each callsite to that procedure. Depending on the context, a callee could be partitioned into different regions for different callsites. Demand-region should maintain separate information about a procedure for each inlinable callsite to that procedure, or partition the procedure the same each time.

**Issue 3. The ordering of procedures analyzed for region formation and inlining impacts compilation overhead.** Performing demand-driven inlining can lead to large compilation and runtime memory requirements similar to Phased-region if the order in which inlining and region formation is performed is not carefully considered. As a callsite is encountered in Demand-region, the region formation algorithm begins to form regions in the callee. Thus, the amount of code growth and the size of data structures needed during region formation are dependent on the handling of the worklist of blocks for partitioning as region formation crosses procedure boundaries.

**Issue 4. Procedures may not be inlined at every callsite.** While a procedure’s code is partitioned into regions on demand at callsites, at some of those callsites the decision may be made not to inline, resulting
in the procedure being partitioned into local regions in isolation of a calling context. Thus, a record of the inlining of each procedure should be maintained to identify procedures that need to be processed in isolation during region formation.

**Issue 5.** Total code growth is an imprecise limiting metric in Demand region since each region will be analyzed and optimized separately. A limit on the memory requirements for Phased region is achieved by restricting how large the program can grow in total size during the aggressive inlining pass; however, individual procedures may be able to grow very large. This is problematic, since memory requirements during analysis are proportional to the size of the largest procedure. Demand-driven inlining can also ensure that individual procedures do not grow excessively large by making use of heuristics that consider the impact of inlining before it is performed.

**Issue 6.** Region formation may be partially completed in multiple procedures simultaneously. With Demand region, region formation proceeds recursively. Region formation starts in a procedure, and when a callsite is reached it may continue recursively into the callee, temporarily suspending region formation in the caller. Thus, region formation is partially completed in the calling procedure and will only complete after region formation is completed in the callee. When additional levels of recursive region formation occur, region will be in various stages of completion along the entire call chain, completing as each callee invocation returns.

### 3.2 A Classification of Regions of a Procedure

The interprocedural region formation algorithm addresses each of the described issues, based on a classification of regions in a single procedure. Regions are classified with respect to individual procedures and callsites where they are invoked. Figure 3, which contains control flow graphs for three procedures and the formed regions in different shadings, illustrates each of the different classifications of regions. A region in \( f \) that includes either the entry or exit block of \( f \) is an interprocedural region. An interprocedural region can be either entry, exit, or pass-through. For each procedure \( f \), each callsite \( c \) with a call to \( f \) has a single entry region associated with \( f \), \( entry_{f,c} \) which is the region that contains the entry block of \( f \). At the one callsite in \( A \) to procedure \( B \) in the figure, the entry region associated with \( B \) contains not only the entry block in \( B \) but a path that passes through to the exit of \( B \), and contains the exit of \( B \) also. At the callsite in \( B \) to procedure \( C \), the entry region associated with \( C \) contains the entry block in \( C \) and only two other blocks in \( C \).

Similarly, each callsite \( c \) to procedure \( f \) has a single exit region, \( exit_{f,c} \). As is the case for the one callsite in \( A \) to \( B \), \( entry_{f,c} \) and \( exit_{f,c} \) could in fact be the same region because the region follows a path that passes through from entry to exit; in this case, it can be said that this region is an interprocedural pass-through region of \( f \) at callsite \( c \). All remaining regions containing blocks in \( f \) are local regions, or \( local_{f,c} \), as they

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*Figure 3: Illustration of region classification for individual procedures.*
do not involve blocks from the caller of $f$. Note that $f$ may not be partitioned into the same regions for every callsite to $f$, since region formation within $f$ is based on the context surrounding the callsite to $f$.

### 3.3 An Algorithm for Region Formation with Demand-driven Inlining

Figure 4 presents the organization of the Demand-region framework, and Figure 5 presents the region formation algorithm. Demand-region extends Phased-region in several important ways in order to form interprocedural regions without aggressive inlining. First, when a callsite is encountered as a region is being grown, FormRegions recursively calls itself to continue to grow the current region in the callee in the context of the caller, but without inlining at that time. Second, in order to minimize the size of the data structures maintained at any given time during region formation, all regions within a called procedure will be identified before FormRegions returns to region formation in the caller. Third, to enable formation of interprocedural regions through this recursive approach, FormRegions operates on regions rather than just basic blocks.

FormRegions begins with a worklist $B$ of all blocks in the current procedure $f$ for which it is forming regions. Successor and predecessor blocks are added to the current region only if they are desirable as defined in Section 2; Desirable(x,y) plays this role. Non-callsite blocks are appended to the region as in Phased-region. When a callsite $c$ is reached in the analyzed code, the recursive call to FormRegions forms regions local to the callee, say $g$, and then FormRegions returns with the entry and exit regions of $g$.

If there was not a pass-through region of $g$, entry$_{g,c}$ is concatenated with the region $R$ currently being formed in $f$ when the callsite was encountered (which completes that interprocedural region), and this merged region is added to the local $R$-list of completed regions in $f$. Next, a new region $R$ is begun, consisting solely of exit$_{g,c}$. If there is a pass-through region for $g$, this pass-through region is added to $R$, but $R$ is not necessarily complete at this point. Region formation continues in $f$ by adding blocks to $R$. Once all blocks on procedure $f$’s worklist $B$ are exhausted, the return parameters entry$R$ and exit$R$ are assigned the regions in $f$ that contain the entry and exit blocks, respectively. The local regions with respect to $f$ (all regions except the entry and exit regions of $f$) are optimized and code is generated for them, prior to returning the entry and exit regions.

The main steps of FormRegions are illustrated for a single callsite by the interprocedural CFGs in Figure 6. For clarity, the same fill patterns are used to differentiate the steps of the Demand-region algorithm in this figure as were used to describe the Phased-region algorithm in Figure 2. In this example, a pass-through region of $G$ exists, is returned to $F$ by FormRegions as both entry$R$ and exit$R$, and is appended to the currently forming region $R$. Procedures that are not inlined at every callsite, not inlined at all, or are potential procedure aliases, are identified after the region formation that began with the main program is complete. The parameter to FormRegions named isolated is set for these isolated procedures to indicate that only local regions are to be formed.
procedure FormRegions(f, isolated, entryR, exitR) {
    B = all blocks in proc f
    Rlist = ∅
    while (blocks remain in B) {
        R = Seed(B)
        seed = last block in R
        x = seed
        // Add desirable successors to seed path
        stack = R
        while (stack ≠ ∅) {
            y = Pop(stack)
            foreach successor of x, y ∈ B {
                if (Desirable(x, y))
                    if (y is proc call && y is inlinable) {
                        FormRegions(callee(y), 0, entryR, exitR)
                        if (entryR ≠ exitR) {
                            R = R ∪ entryR
                            Rlist = Rlist ∪ R
                            R = ∅
                        }
                        S = exitR
                    } else {
                        S = {y}
                        Push(stack, y)
                        B = B – {y}
                        R = R ∪ S
                    }
            }
        }
    }
    // Add desirable successors to seed path
    stack = R
    while (stack ≠ ∅) {
        y = Pop(stack)
        x = y
        // Add predecessors to region, analogous to adding
        // successors - code omitted for space limitations
    }
}

procedure Seed(B) {
    s = block with maximum weight in B
    B = B – s
    if (s is proc call) {
        FormRegions(callee(s), 0, entryR, exitR)
        if (entryR ≠ exitR) {
            R = R ∪ entryR
            Rlist = Rlist ∪ R
            R = ∅
        }
        S = exitR
    } else {
        S = {s}
        return S
    }
}

procedureCodeGen(Rlist) {
    foreach region R ∈ Rlist
        optimize R
        generate code for Rlist
}

Main() {
    FormRegions(main, 1, entryR, exitR)
    foreach proc f ≠ main
        if (not all callsites to f were inlined)
            FormRegions(f, 1, entryR, exitR)
}

Figure 5: Interprocedural algorithm for region formation with demand-driven inlining
3.4 Empirical Evaluation

An experimental comparison of the two region formation approaches, Demand_region and Phased_region, is described in terms of compilation memory requirements, code growth and runtime performance. Analysis of the characteristics of the resulting units of compilation, including the size, homogeneity of profile weights, and code size is performed to explain the results.

3.4.1 Methodology

These experiments were conducted using the Trimaran compiler system. With Phased_region as an existing component, Trimaran was a natural choice for this research. Significant implementation was performed to add the capability of demand-driven inlining, and to create a region formation module that incorporates demand-driven inlining and optimization. Also added was the ability to annotate each basic block with its procedure of origin to enable identification of code that was inlined. For this set of experiments, ten C benchmarks were used from SPEC 92 and 95 (www.spec.org) representing a variety of computations, code sizes and program characteristics. Table 1 includes numbers of source code lines and procedure definitions.

The benchmarks were compiled under three scenarios: (1) procedure-based compilation without any inlining or region formation, (2) region-based compilation using the Phased_region approach, and (3) region-based compilation using the Demand_region approach.

3.4.2 Results

Compilation memory requirements

Table 1 compares the compilation memory requirements for Phased_region versus Demand_region. Due to design considerations of the Trimaran framework, direct measurement of memory requirements was not possible. Instead, measurements of whole program size, procedure sizes, and static call chain lengths were taken, and estimates of memory requirements were computed according to each strategy for region-based compilation.

For Phased_region, the compilation memory requirements are computed as code size after aggressive inlining is performed, as measured in number of Lcode instructions, because the entire program may be held in memory during region formation and optimization (in the worst case). For Demand_region, first the
Table 1: Comparison of memory requirements during region formation, measured in Trimaran Lcode instructions.

| Benchmark   | Lines of C source code | Num. of proc. | Memory requirement Num. | Static call chain Avg. | Static call chain Max. | Procedure size Avg. | Procedure size Max. | Memory requirement Avg. | Memory requirement Worst |
|-------------|------------------------|---------------|-------------------------|------------------------|------------------------|---------------------|-----------------------|------------------------|------------------------|
| 008.espresso | 14850                  | 361           | 73997                   | 3                      | 5                      | 2059                | 3186                  | 1156                   | 2538                   |
| 023.eqntott | 3628                   | 62            | 11758                   | 3                      | 7                      | 1775                | 2300                  | 1156                   | 2538                   |
| 026.compress| 1503                   | 16            | 2601                    | 2                      | 5                      | 224                 | 244                   | 1270                   | 1800                   |
| 099.go      | 29246                  | 383           | 110842                  | 9                      | 23                     | 1764                | 1109                  | 1076                   | 3085                   |
| 124.m88ksim | 19092                  | 252           | 55783                   | 6                      | 11                     | 193                 | 333                   | 1195                   | 1923                   |
| 126.gcc     | 205627                 | 1170          | 1050754                 | 5                      | 13                     | 202                 | 1810                  | 2666                   | 4391                   |
| 130.li      | 7597                   | 357           | 31552                   | 22                     | 35                     | 112                 | 987                   | 1640                   | 3197                   |
| 132.jpeg    | 29259                  | 473           | 112188                  | 8                      | 14                     | 124                 | 2540                  | 1385                   | 2185                   |
| 134.perl    | 27044                  | 316           | 100063                  | 5                      | 15                     | 140                 | 1977                  | 1498                   | 2732                   |
| 147.vortex  | 67202                  | 1127          | 302409                  | 4                      | 12                     | 131                 | 2301                  | 1166                   | 2210                   |
| average     | 40505                  | 452           | 17363                   | 6                      | 11                     | 162                 | 1397                  | 1274                   | 2228                   |

Table 2: Percentage difference in average and maximum memory requirements of Phased_region and Demand_region.

| Benchmark   | Demand_region Phased_region % of average | Demand_region Phased_region % of maximum |
|-------------|------------------------------------------|------------------------------------------|
| 008.espresso | 4.3                                      | 7.0                                      |
| 023.eqntott | 9.8                                      | 21.6                                     |
| 026.compress| 48.8                                     | 69.2                                     |
| 099.go      | 1.0                                      | 2.8                                      |
| 124.m88ksim | 2.1                                      | 3.4                                      |
| 126.gcc     | 0.3                                      | 0.4                                      |
| 130.li      | 5.2                                      | 10.1                                     |
| 132.jpeg    | 1.2                                      | 1.9                                      |
| 134.perl    | 1.5                                      | 2.7                                      |
| 147.vortex  | 0.4                                      | 0.7                                      |
| average     | 7.5                                      | 12.0                                     |

average and maximum sizes of procedures in a benchmark were calculated. Next, the lengths of static acyclic call chains were measured at the source code level. The call chain length and procedure size information were then used to compute the average and maximum of the sum of procedure sizes along the average and maximum length call chains. The average value provides a good estimate of typical compilation memory usage for purposes of comparison, while the maximum value indicates the worst case.

The data in Table 2 shows that on average, Demand_region uses about 7.5% of the memory required by Phased_region for region formation for the benchmarks studied, over a range of roughly <1% to 49%. In the worst case, Demand_region uses an average of 12% of the memory required by Phased_region over a range of about <1% to 69%. Benchmarks with larger numbers of procedures and procedure calls, and more and longer call chains, benefited the most from Demand_region. While smaller benchmarks showed some benefit, the smallest, 026.compress, showed the least benefit, suggesting that Demand_region may be best suited to large applications.

**Code growth**

Code growth was measured as the percentage change in overall code size from the original program, shown in Table 3 as the percentage increase or decrease in size. To measure their code size used to calculate code growth, each benchmark was compiled in three ways: (1) without any inlining or region formation, (2) using
Table 3: Percentage change in code growth for Phased\textsubscript{region} and Demand\textsubscript{region}.

| Benchmark | Phased\textsubscript{region} | Demand\textsubscript{region} | Demand\textsubscript{region} - Phased\textsubscript{region} |
|-----------|-----------------------------|-----------------------------|---------------------------------------------------|
| 008.espresso | 21                          | 19                          | -2                                               |
| 023.eqntott | 24                          | 26                          | +2                                               |
| 026.compress | 26                          | 25                          | -1                                               |
| 099.go      | 22                          | 25                          | +3                                               |
| 124.m88ksim | 21                          | 20                          | -1                                               |
| 126.gcc     | 22                          | 23                          | +1                                               |
| 130.li      | 20                          | 23                          | +3                                               |
| 132.ipex    | 21                          | 24                          | +3                                               |
| 134.perl    | 22                          | 23                          | +1                                               |
| 147.vortex  | 21                          | 21                          | 0                                                |
| average     | 22.0                        | 22.9.1                      | +0.9                                             |

Table 4: Percentage change in execution time for Phased\textsubscript{region} and Demand\textsubscript{region} compared to procedure-based.

| Benchmark | Phased\textsubscript{region} | Demand\textsubscript{region} | Demand\textsubscript{region} - Phased\textsubscript{region} |
|-----------|-----------------------------|-----------------------------|---------------------------------------------------|
| 008.espresso | -6.13                       | -1.12                       | 5.01                                              |
| 023.eqntott | -3.17                       | -2.14                       | 1.03                                              |
| 026.compress | -3.11                       | 26.88                       | 29.99                                             |
| 099.go      | -6.28                       | 7.30                        | 13.58                                             |
| 124.m88ksim | -4.65                       | -2.40                       | 2.25                                              |
| 126.gcc     | -6.72                       | -5.00                       | 1.72                                              |
| 130.li      | -8.49                       | 12.50                       | 20.99                                             |
| 132.ipex    | -7.01                       | -5.99                       | 1.02                                              |
| 134.perl    | -4.22                       | -2.18                       | 2.04                                              |
| 147.vortex  | -6.90                       | -3.72                       | 3.18                                              |
| average     | -5.67                       | 2.41                        | 8.08                                              |

the Phased\textsubscript{region} strategy, and (3) using the Demand\textsubscript{region} strategy. Measurements were taken in terms of Lcode instructions of the resulting compiled programs. An increase in code size is represented by a positive value. For example, a value of 21 means that after compilation within a particular framework, the program is 21% larger than the same program compiled using the procedure-based approach.

On average, Demand\textsubscript{region} introduces < 1% more code than Phased\textsubscript{region}, over a range of 2% less to 3% more growth. In general, differences in code growth are not dramatic, due to the use of the global static code growth limit of 20% in both Phased\textsubscript{region} and Demand\textsubscript{region}. In practice, the 20% code growth limit prevents inlining once the code size has grown to 20% or more above the original size. However, a benchmark may grow to just below this limit, allowing one more instance of inlining to be performed. Demand\textsubscript{region} shows slightly more code growth than Phased\textsubscript{region} because Demand\textsubscript{region} is inlining in a different order, which can lead to the benchmark first growing to just below the limit, and then inlining a larger procedure which exceeds the limit considerably.

Runtime performance

Table 4 reports the percentage change in execution time. Negative values for percentage change in execution time indicate a performance speedup; the program ran faster compared to the procedure-based compilation. The last column shows the difference in the change in execution time between Demand\textsubscript{region} and Phased\textsubscript{region}, with a negative value indicating that a benchmark compiled using Demand\textsubscript{region} ran faster than when compiled with Phased\textsubscript{region}; a positive difference indicates that Phased\textsubscript{region} was faster.

For seven of the ten benchmarks, the results for execution time were quite similar for Phased\textsubscript{region} and Demand\textsubscript{region}, separated only by a few percentage points, which equates to fractions of a second in
Table 5: Comparison of number of compilation units for procedure-based, Phased$_{\text{region}}$ and Demand$_{\text{region}}$ (in Lcode instructions).

| Benchmark   | Proc.-based | Phased$_{\text{region}}$ | Demand$_{\text{region}}$ | Demand$_{\text{region}}$ − Phased$_{\text{region}}$ |
|-------------|-------------|--------------------------|--------------------------|-----------------------------------------------------|
| 008.espresso | 361         | 1787                     | 1774                     | -13                                                 |
| 023.eqntott  | 62          | 436                      | 476                      | 40                                                  |
| 026.compress | 16          | 117                      | 102                      | -15                                                 |
| 099.go       | 383         | 1838                     | 1888                     | 50                                                  |
| 124.m88ksim  | 252         | 1336                     | 1322                     | -13                                                 |
| 126.gcc      | 1170        | 6084                     | 6047                     | -37                                                 |
| 130.li       | 357         | 801                      | 793                      | -8                                                  |
| 132.ijpeg    | 373         | 3575                     | 3791                     | 216                                                 |
| 134.perl     | 316         | 822                      | 797                      | -25                                                 |
| 147.vortex   | 1127        | 5522                     | 5616                     | 94                                                  |
| average      | 452         | 2232                     | 2261                     | 29                                                  |

wall clock time. In particular, there are little or no differences in performance for 008.espresso, 023.eqntott, 124.m88ksim, 126.gcc, 132.ijpeg, 134.perl and 147.vortex. The drop in performance from Phased$_{\text{region}}$ to Demand$_{\text{region}}$ for 026.compress, 099.go and 130.li is due to naive heuristics for deciding whether to perform demand-driven inlining at a given callsite, and the way the prototype system handles demand-driven inlining of indirect recursive procedure calls. Specifically, with this implementation, it is possible for the code limit to be reached before inlining is performed in some of the high execution frequency regions, resulting in optimization loss. ILP processor utilization was also examined, with only insignificant variations noted.

Thus, while memory requirements are improved dramatically, runtime performance remains virtually unaffected in general. This improvement in memory requirements was the primary goal of performing demand-driven inlining during region formation in Demand$_{\text{region}}$. Since Demand$_{\text{region}}$ is implemented using the same region formation and inlining heuristics, leading to substantially similar regions, dramatic improvements to runtime performance could not be reasonably expected. The key innovation of Demand$_{\text{region}}$ is to integrate demand-driven inlining into region formation to reduce the requirements for memory during compilation.

### 3.5 Analysis of Compilation Unit Characteristics

Procedure restructuring affects the characteristics of the unit of compilation. Analyzing changes to program characteristics, such as the size, profile homogeneity and interprocedural scope of the unit of compilation, can further explain the impact on memory requirements, code growth and performance.

#### Unit size

Tables 5 and 6 report the total number of compilation units and average size in Lcode instructions for each of the studied benchmarks under the three different strategies for compilation. The two region-based compilation techniques result in very similar average region size and total number of regions, while the procedure-based strategy produces far fewer, though far larger, compilation units. Slight variations in sizes and numbers of regions are attributed to differences in the order in which callsites are inlined. The aggressive inlining of Phased$_{\text{region}}$ favors inlining frequently executed, smaller procedures over larger procedures due to the limit it places on total code growth and the inlining heuristic. Since the demand-driven inliner inlines as it is creating a region and reaches a callsite, it can reach the same specified limit for code growth at a different time due to different order of inlining. The demand-driven approach to inlining in Demand$_{\text{region}}$ and the recursive nature of the algorithm lead to a bottom-up inlining of regions. That is, the inlining is performed as the recursive calls to FormRegions return. The contribution of the Demand$_{\text{region}}$ approach is that it can significantly reduce compilation memory requirement, while creating number and size of regions comparable to those created by Phased$_{\text{region}}$. 

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Table 6: Comparison of average size of compilation units for procedure-based, Phased region and Demand region in Lcode instructions.

| Benchmark   | Proc.-based | Phased_region | Demand_region | Demand_region − Phased_region |
|-------------|-------------|----------------|---------------|-------------------------------|
| 008.espresso | 183         | 50             | 49            | -1                            |
| 023.eqntott | 169         | 33             | 31            | -2                            |
| 026.compress| 152         | 28             | 32            | +4                            |
| 099.go      | 234         | 55             | 51            | -4                            |
| 124.m88ksim | 155         | 31             | 30            | -1                            |
| 126.gcc     | 530         | 62             | 57            | -5                            |
| 130.li      | 81          | 47             | 49            | -2                            |
| 132.ijpeg   | 137         | 38             | 37            | -1                            |
| 134.perl    | 206         | 51             | 49            | -2                            |
| 147.vortex  | 161         | 35             | 34            | -1                            |
| average     | 201         | 43             | 42            | -1                            |

Table 7: Comparison of percentage of invariant compilation units and profile variance (homogeneity) for procedure-based, Phased region and Demand region.

| Benchmark   | Proc.-based                  | Phased_region | Demand_region | Demand_region |
|-------------|-----------------------------|---------------|---------------|---------------|
|             | Profile variance            | Pct. units invariant | Profile variance | Pct. units invariant | Profile variance | Pct. units invariant |
| 008.espresso | 0.362                       | 88.1          | 0.340         | 81.2          | 0.342         | 94.1              |
| 023.eqntott | 0.017                       | 96.1          | 0.001         | 97.6          | 0.020         | 97.6              |
| 026.compress| 0.313                       | 90.7          | 0.245         | 87.5          | 0.375         | 90.8              |
| 099.go      | 0.202                       | 87.1          | 0.203         | 88.2          | 0.203         | 91.0              |
| 124.m88ksim | 0.272                       | 92.1          | 0.249         | 92.9          | 0.292         | 93.3              |
| 126.gcc     | 0.132                       | 89.0          | 0.108         | 90.1          | 0.108         | 93.2              |
| 130.li      | 0.198                       | 90.3          | 0.208         | 88.5          | 0.203         | 94.2              |
| 132.ijpeg   | 0.273                       | 88.8          | 0.254         | 86.7          | 0.310         | 91.1              |
| 134.perl    | 0.212                       | 88.7          | 0.195         | 89.3          | 0.187         | 90.3              |
| 147.vortex  | 0.310                       | 90.7          | 0.259         | 91.1          | 0.261         | 93.1              |
| average     | 0.238                       | 90.2          | 0.215         | 89.3          | 0.239         | 92.9              |

Profile homogeneity

Profile homogeneity is defined as the measure of how similar the given unit of compilation is in terms of profile weight per instruction, operation or basic block. This variation on code density provides an indicator for the impact of region formation on optimization. More homogeneous compilation units enable the optimizer to easily identify and isolate heavily executed regions, and then selectively focus more attention on these more important regions and less attention elsewhere. This partitioning reduces the chance of leaving important portions of the code unoptimized or spending excessive time optimizing unimportant code.

Within the context of units of compilation, the profile homogeneity, or profile variance, is defined to be the measure of the degree of deviation, that is, the standard deviation, in profile weights for all basic blocks within a compilation unit. Table 7 shows the average profile variance and percentage of compilation units that are invariant for each benchmark. The average profile variance is an overall indication of how consistent the profile weights are within each of the benchmarks’ units of compilation. The closer the profile variance is to 0, the less variation there is in the profile weights overall for the benchmark, and the more homogeneous the benchmark.

The results in Table 7 indicate that in every case Demand region improves percentage of invariant units over both procedure-based compilation and Phased region. Phased region tended to gain in some cases and lose in others over procedure-based compilation. When there is an increase in the percentage of invariant code, there is generally also an increase in the profile variance of the code overall. This is due to the procedure restructuring done by region formation, which favors grouping more frequently executed code together, leaving less frequently executed code behind. Because less important code is not actively formed into more homogeneous regions, the profile weights of their containing regions are slightly more variant than
Table 8: Comparison of percentage of interprocedural operations in \textit{Phased\_region} and \textit{Demand\_region}.

| Benchmark   | \textit{Phased\_region} | \textit{Demand\_region} | \textit{Demand\_region} − \textit{Phased\_region} |
|-------------|--------------------------|--------------------------|-------------------------------------------------|
| 008.espresso | 20.7                     | 24.3                     | 3.6                                             |
| 023.eqntott  | 18.0                     | 23.8                     | 5.8                                             |
| 026.compress| 23.5                     | 25.9                     | 2.4                                             |
| 099.go       | 28.4                     | 26.7                     | -1.7                                            |
| 124.m88ksim | 22.9                     | 24.9                     | 2.0                                             |
| 126.gcc      | 19.3                     | 25.4                     | 6.1                                             |
| 130.li       | 30.2                     | 28.0                     | -2.2                                            |
| 132.ijpeg    | 23.0                     | 25.1                     | 2.1                                             |
| 134.perl     | 20.0                     | 24.9                     | 4.9                                             |
| 147.vortex   | 23.0                     | 25.7                     | 2.7                                             |
| **average**  | 22.9                     | 25.5                     | 2.6                                             |

regions of frequently executed code. It can be hypothesized that \textit{Demand\_region} produces less variant code over \textit{Phased\_region} because the integrated, demand-driven use of inlining within \textit{Demand\_region} uses the region formation desirability heuristic (50\% or greater execution frequency) to also guide inlining. Overall, the frequency of code inlined by \textit{Demand\_region} is likely to be greater than the more general, aggressive inlining approach in \textit{Phased\_region}.

**Interprocedural scope**

When specifically comparing regions to procedures, and regions formed using different techniques, a change in the number of interprocedural regions and the amount of interprocedural operations per region indicates the change in interprocedural scope. Recall that an interprocedural region is a region that includes instructions from more than one procedure. Interprocedural operations are the instructions in an interprocedural region that are from procedures other than the procedure in which formation of the region began. Before inlining is performed, all basic blocks are annotated with the block’s procedure of origin. With this origin information, the impact of region formation on interprocedural scope in a unit of compilation can be measured directly by calculating how much of the code within each unit originated outside itself. The percentage of interprocedural code in the program is measured as a simple ratio of the number of interprocedural operations to total operations.

Table 8 shows the average percent of code within regions that is from a procedure outside the region (i.e., interprocedural code). An improvement in the percentage is indicative of better interprocedural scope. An increase in interprocedural scope within the unit of compilation means that the potential for interprocedural optimization is increased without additional analysis.

In general, the percentage of interprocedural operations is similar for \textit{Phased\_region} and \textit{Demand\_region}. The differences in interprocedural scope under the two techniques are slight. The interaction of various factors leads to insight on how to improve the techniques. The slight increase in interprocedural scope for 008.espresso occurs with a slight decrease in code growth and little or no change to profile variance. For 023.eqntott, slight differences in code growth and variance would not indicate the larger increase in interprocedural scope seen for \textit{Demand\_region}. This change could be due to the slight reduction seen for average size of the unit of compilation for \textit{Demand\_region} for 023.eqntott, since the other factors were quite similar. The improvements to interprocedural scope seen with 126.gcc, 132.ijpeg, 134.perl and 147.vortex are likely due to slight decreases in the average size of the unit of compilation, which are magnified due to the large sizes of the benchmarks. Most puzzling is the increase in interprocedural scope seen with \textit{Demand\_region} applied to 026.compress, 099.go, 130.li, and to a lesser extent, 124.m88ksim, which exhibit significantly more variance and a definite reduction in runtime performance versus \textit{Phased\_region}. This seeming contradiction for these four benchmarks could be due to the effect of gaining interprocedural scope by restructuring, with the side-effect of leaving behind more invariant code in the process. An increase in code growth appears to be the cause of decreased interprocedural scope for 130.li.
4 Heuristics for Demand-driven Inlining

In the previous section, baseline heuristics were used to guide demand-driving inlining within region formation to establish the efficacy of the Demand_region approach as compared with Phased_region and traditional procedure-based compilation. This section explores a variety of heuristics designed to improve the performance of Demand_region, and discusses a number of classifications, factors and important issues that are integral to inlining heuristics design.

Because region formation drives inlining, the heuristics for a demand-driven inliner must consider the order that procedures are processed by the region formation phase and the characteristics of a callee at each callsite as it is encountered during region formation. Procedures that are analyzed later in the compilation may result in less inlined code within them and thus be less optimized since code growth restrictions could limit further inlining, and thus limit the interprocedural scope of that procedure. Therefore, procedures that have the highest potential for optimization, particularly instruction scheduling for ILP architectures, should be processed first by the region formation analysis phase. Thus, demand-driven inlining within a region-based compiler involves two general classes of heuristics, defined as: first-order heuristics that determine the order in which procedures are processed during region formation, and second-order heuristics that govern decisions about whether to inline at each callsite. Figure 7 illustrates the location within a region-based compilation framework of these two heuristics.

4.1 First-order Heuristics

First-order heuristics select the order to consider procedures for region formation, which will implicitly affect the order of demand-driven inlining decisions. Because demand-driven inlining within a given procedure is considered at callsites as region formation is performed for that procedure, the order of decisions for demand-driven inlining follows the flow-directed manner in which region formation is performed within a given procedure’s control flow graph.

The first-order heuristics studied in the research attempt to order procedures from most to least important in terms of optimization opportunity. In particular, three possible first-order heuristics for demand-driven inlining were examined. The most precise measurement of procedure importance is actual dynamic run-time profiling which comes at the cost of an initial instrumentation, compilation and execution. Procedures are ordered from highest to lowest percentage of overall run-time spent in the procedure, based on profiling information. It is worth noting that procedures which consume larger portions of execution time are likely to contain loops and callsites within the loops, which supports the importance of this heuristic to interprocedural region formation in a demand-driven framework.

Static estimates of importance provide less costly heuristics, but also tend to produce less precise information. One heuristic based on static estimates orders procedures from most to least number of static callsites.
within the procedure, and within that order from smallest to largest procedure size. More importance is assigned to procedures with the highest percentage of callsites compared with code size. This increases the chance that region formation will be performed interprocedurally, producing more scheduling and optimization opportunities, while controlling code growth by considering smaller procedures before larger ones.

Another ordering considered is based on the loop call weight of a procedure, assigning more importance to procedures which contain more callsites within loops, and increased importance for those callsites that are more deeply nested. The loop call weight is computed as: \( \sum_{i=1}^{n} \text{loopdepth}_i \times W \), where \( n \) is the number of callsites in a procedure, and \( W \) is the loop depth weight constant. A value of 10 is used for \( W \) to assign an order of magnitude increase in significance to successive loop depths, since, intuitively, interior loops consume more execution cycles than do their enclosing loops.

### 4.2 Second-order Heuristics

Second-order heuristics involve the decision about whether to inline each callee within a procedure as region formation reaches that callsite. While there are a number of heuristics already developed for this decision making, they have all been applied within a separate inlining phase without consideration of the interactions with region formation analysis, and in particular, demand-driven inlining. The second-order heuristics attempt to increase instruction scheduling and optimization opportunities while minimizing code growth. For correctness, procedures where there are mismatches in the number and types of parameters between the callsite and callee, when the compiler determines that memory regions associated with arguments to a procedure may overlap or are pointers, are not inlined.

To avoid high code growth, inlining is prevented once the overall code size has increased more than 20% percent above the original size. A code growth limit of 20% has been shown to minimize unnecessary code growth while still allowing beneficial inlining [20]. Similarly, inlining is prevented for procedures that are directly or indirectly recursive to avoid the potential for excessive code growth.

Procedures that are more frequently executed than a fixed frequency or with some desired ratio over the frequency of the caller are inlined. Region formation already uses this second-order heuristic, such that inlined procedures will always be executed at least 50% as frequently as the seed block of their enclosing region. Only procedures that are less than a static maximum size are inlined to limit code growth, and procedures with higher call overhead compared with their code size are inlined.

### 4.3 Empirical Evaluation

Experiments were conducted to study the effectiveness of a number of heuristic combinations (Table 9), and to determine which strategies can improve characteristics of the program and its runtime performance. The heuristic combinations were compared by measuring three effects in terms of the percentage change of each combination versus H0, the baseline method. In particular, the effects that were evaluated include: (1) code growth, (2) compilation time, including the time to compile the source code up through region formation and region-based optimization, and (3) execution time, which measures more directly the impact of inlining heuristics on region formation and region-based optimization, and ultimately on runtime performance. Note that the results in this section cannot be compared directly to those in Section 3 due to slight variations in implementation needed to incorporate the newer inlining heuristics.

When designing inlining heuristics, first-order heuristics should not ignore the goals of second-order heuristics. In particular, first-order heuristics should anticipate second-order heuristics by processing procedures early in the compilation that will benefit most from the interprocedural scope gained from demand-driven inlining. Second-order heuristics should rely on first-order heuristics to provide more important procedures earlier in the compilation, while constraining code growth so that procedures remaining to be handled by region formation can still benefit from demand-driven inlining. While the heuristics are the same for Phased_region in Section 3 and H1 in this section, for example, the implementation of the heuristics was modified to enable consistent comparison of results with the newer heuristics. Experimental results reported in Section 3 enable the initial valid comparison of Demand_region with the original, unmodified Phased_region framework.
Table 9: Summary of heuristic combinations.

| Name | First-order | Second-order | Intuition/Motivation |
|------|-------------|--------------|----------------------|
| H₀   | None        | None         | Baseline version of original region-based compilation. No inlining is performed. |
| H₁   | Run-time profile ordering. | Inlined procedures guaranteed to be executed at least 50% as frequently as seed block in their region [20]. | Original region-based compilation. Aggressive inlining with standard code growth limit, then region information; first- and second-order inlining heuristics as defined by [20]. |
| H₂   | Order by descending number of static callsites, then ascending procedure size. | Same as H₁, plus only in-line if callee size ≤ 25 [19]. | Demand-driven inlining with simple static heuristics; avoid more costly analysis in order to potentially improve compilation time. |
| H₃   | Same as H₂. | Same as H₁, plus prevent inlining direct or indirect recursion. | Demand-driven inlining with simple static heuristics. Increase number of procedures into which inlining is performed before code growth limit is reached, preventing successive inlining of recursive procedures. |
| H₄   | Order by decreasing loop call weight, then ascending procedure size. | Same as H₃. | Static estimation of profile information by equating loop characteristics with predicted execution frequency, for improved compilation time. |
| H₅   | Order by decreasing execution cycles, then ascending procedure size. | Same as H₃. | Actual runtime profile information should provide most precise information for guiding region formation and demand-driven inlining, for improved runtime performance. |
| H₆   | Same as H₅. | Same as H₃, plus minimum loop call weight of 10 to inline. (Note: a procedure containing a single loop is assigned a loop call weight of 10.) | Only inline if contains at least 1 call within at least one loop. Combines profile information to prioritize compilation of procedures, with potentially faster static loop characteristic estimation for making inlining decisions; should improve compilation time. |

4.3.1 Methodology

Implementation of the described techniques and experiments has been conducted in context of the Trimaran compiler [28]. The existing region formation module was enhanced to incorporate additional first-order inlining heuristics. The demand-driven inliner within Demand_region was extended with a number of new second-order inlining heuristics. In addition, the demand-driven inliner was more tightly integrated into the compiler, enabling a meaningful measurement of compilation time. The experiments were performed on the same set of benchmarks (Table 1, p. 9).

4.3.2 Results

Code growth

Table 10 reports the percentage increase in code growth for heuristics H₁ through H₆ versus the baseline compilation H₀. Code growth was measured directly by counting the number of Lcode instructions resulting from compilation using each of the heuristics.

Heuristic H₂ does a significantly better job than any of the other methods at limiting code growth. This is not surprising, since it uses a simple, static threshold that only allows inlining of small procedures. In general, heuristic H₁, or Phased_region in its basic form, does a little better in most cases than the remaining heuristics based on demand-driven inlining. The changes in code growth are generally slight, and in nearly all cases remained under the static limit of 20% used in earlier experiments, indicating these heuristics provide improved code growth control. Code growth for compress exceeded 20% for H₃, H₄, H₅ and H₆. This is due to an order of region formation, and therefore inlining, that causes a very large procedure to be inlined when the code growth limit had already nearly been reached.
Table 10: Percentage change in code growth over H0.

| Benchmark     | H1 | H2 | H3 | H4 | H5 | H6 |
|---------------|----|----|----|----|----|----|
| 008.espresso   | 8  | 1  | 20 | 20 | 17 | 17 |
| 023.eqntott   | 6  | 0  | 18 | 18 | 15 | 15 |
| 026.compress  | 17 | 0  | 23 | 23 | 21 | 21 |
| 099.go        | 9  | 3  | 12 | 11 | 8  | 8  |
| 124.m88ksim   | 8  | 1  | 16 | 15 | 12 | 12 |
| 126.gcc       | 10 | 2  | 15 | 15 | 8  | 8  |
| 130.li        | 8  | 0  | 8  | 6  | 4  | 4  |
| 132.jpeg      | 14 | 3  | 17 | 17 | 15 | 15 |
| 134.perl      | 11 | 1  | 18 | 17 | 12 | 12 |
| 147.vortex    | 15 | 3  | 16 | 16 | 13 | 13 |
| average       | 11 | 1  | 16 | 16 | 13 | 13 |

Table 11: Percentage change in compilation time over H0.

| Benchmark     | H1 | H2 | H3 | H4 | H5 | H6 |
|---------------|----|----|----|----|----|----|
| 008.espresso   | 2.1| 0.0| 2.0| 4.2| 4.9| 4.5|
| 023.eqntott   | 1.8| -0.1| 2.4| 4.8| 9.3| 7.9|
| 026.compress  | -8.3| -1.3| -2.8| 0.0| 5.6| 2.8|
| 099.go        | 3.0| -2.5| 6.5| 7.8| 10.0| 9.3|
| 124.m88ksim   | 4.0| -2.1| 27.6| 18.4| 27.6| 27.4|
| 126.gcc       | 2.9| -0.3| 21.1| 15.2| 15.4| 15.2|
| 130.li        | 4.5| 0.0| 26.8| 24.5| 25.6| 24.9|
| 132.jpeg      | 3.5| -1.0| 13.9| 13.5| 14.0| 13.8|
| 134.perl      | 2.8| -1.4| 14.8| 14.2| 15.3| 15.1|
| 147.vortex    | 3.7| 0.1| 4.8| 7.8| 3.0| 3.0|
| average       | 2.0| -0.9| 11.7| 11.0| 13.1| 12.4|

Compilation time

Results for compilation time for the heuristics are presented in Table 11. The change in compilation time as compared with H0 is shown as a percentage increase (positive) or decrease (negative). Compilation time for each heuristic was measured by timing the compilation through the optimized Lcode phase, just prior to the point when Trimaran outputs instrumented code for simulated execution on the target architecture. This timing includes any applicable phases for profiling, intermediate code generation, aggressive inlining, region formation (which may or may not include demand-driven inlining), and region-based optimization. The timings used were system times (i.e., wall clock times) accurate to the nearest 10th of a seconds, and were on the order of minutes or hours (not unusual for a research compiler).

In general, compilation time improves the most for H2 which uses the simplest inlining heuristic, and H1, the Phased_region compilation method. Due to the overhead introduced in the current implementation of demand-driven inlining, unusually high increases in compilation time were seen in most other cases where demand-driven inlining is used (H3 through H6).

It is interesting to note that for some of the benchmarks, 008.espresso, 023.eqntott, 026.compress, and 147.vortex, compilation time increased only slightly over H1 and H2 for the remaining heuristics. This indicates that other more complex factors may be helping to control compilation time in spite of the more advanced and time-consuming inlining heuristics being used.

Runtime performance

Relative changes in performance between the baseline heuristic H0 and the others are shown in Table 12. Performance was measured by running the programs using the Trimaran simulator, which involved an addi-
Table 12: Percentage change in execution time over H0.

| Benchmark     | H1  | H2  | H3  | H4  | H5  | H6  |
|---------------|-----|-----|-----|-----|-----|-----|
| 008.espresso  | -4.01 | 0.50 | -5.50 | 1.75 | 1.75 |
| 023.eqntott   | -3.17 | 1.31 | -4.02 | -6.11 | -1.90 | -1.90 |
| 026.compress  | -3.11 | 0.00 | -3.11 | -3.11 | -2.98 | -2.98 |
| 099.go        | -3.19 | 0.07 | 2.30  | -4.20 | -4.10 | -4.10 |
| 124.m88ksim   | -6.13 | -1.31 | -3.90 | -9.22 | -9.13 | -9.13 |
| 126.gcc       | -5.20 | -1.03 | -4.15 | -0.24 | -10.20 | -10.20 |
| 130.li        | -8.49 | -2.16 | -4.01 | -12.53 | -12.20 | -12.20 |
| 132.ijpeg     | -5.50 | 0.12 | -4.77 | -7.33  | -6.97 | -6.97 |
| 134.perl      | -5.50 | -1.90 | -4.79 | -10.43 | -9.54 | -9.54 |
| 147.vortex    | -3.05 | -1.71 | -5.10 | -9.25  | -9.21 | -9.21 |
| average       | -4.48 | -0.61 | -3.71 | -6.98 | -6.45 | -6.45 |

otional phase of compilation to instrument the Lcode output from region formation to execute in the simulated EPIC environment described earlier.

H3 was competitive with H1, but H4, H5 and H6 all showed general improvements in performance over H1. Overall, the best performance speedup was consistently demonstrated with heuristic H4, which uses the static loop call weight estimator and recursion prevention to guide inlining decisions. There was also little or no significant change in processor utilization (i.e., CPI) for most of the benchmarks under most of the heuristics.

### 4.3.3 Discussion

The code growth, compilation time and runtime performance for the benchmarks under different inlining heuristics interact in a number of ways. For the cases that cause more code growth, execution time also improves. The more naive heuristics of H2 lead to the smallest increases in code size and compilation time, but also do not improve performance as much as the other more sophisticated methods. Larger increases in code growth and compilation time do not always translate to improvements in execution time, indicating that bounding code growth is indeed important, as was believed. For example, when H3 was applied to 099.go, code size and compilation time increased more than with H2 while execution took longer, possibly due to recursive inlining of less important code.

The more scientific codes (124.m88ksim, 132.ijpeg, 147.vortex), tend to benefit the most from increases in code growth and compilation time (which is also optimization and scheduling time) in terms of their speedup, particularly for the most advanced profile-estimating (H4) and profile-based (H5 and H6) methods. Smaller benchmarks (026.compress, 023.eqntott), by both size and number of procedures, are less predictable, although significant performance gains are seen with H3 through H6, with most showing improvement over the original region-based technique (H1). Benchmarks with more recursion (026.compress, 099.go, 130.li) require more compilation time and gain comparatively less in performance improvements than the others.

The combination of heuristics in H4 proved consistently to be the most effective at controlling code growth and compilation time while improving runtime performance. The fact that H4 bases inlining decisions on the static loop call weight, which estimates runtime behavior, rather than the actual profiling information itself, as in H5 and H6, is significant, indicating that profiling may not be necessary for making good demand-driven inlining decisions during region formation. Profiling generally is more precise than static estimates because it directly measures program behavior at runtime, but requires more overhead and depends on the data used for the profiling.

### 4.4 Impact on Compilation Unit Characteristics

The experimental study in Section 3 examined how runtime performance can be improved by increasing interprocedural scope of compilation units, and reducing the profile variance of each unit. To test this hypothesis further, the characteristics of the compiled Lcode were measured after region formation for heuristics
Table 13: Comparison of number and average size of compilation units for three heuristics.

| Benchmark         | HØ Avg size Units (proc.) | H1 Avg size Units (reg.) | H4 Avg size Units (reg.) |
|-------------------|---------------------------|--------------------------|--------------------------|
| 008.espresso       | 183                        | 4267                     | 4710                     |
| 023.eqntott       | 169                        | 656                      | 755                      |
| 026.compress      | 152                        | 206                      | 218                      |
| 099.go            | 234                        | 5424                     | 5921                     |
| 124.m88ksim       | 155                        | 3494                     | 4027                     |
| 126.gcc           | 530                        | 41613                    | 43971                    |
| 130.li            | 81                         | 2427                     | 2546                     |
| 132.jpeg          | 137                        | 4720                     | 5109                     |
| 134.perl          | 206                        | 4395                     | 4891                     |
| 147.vortex        | 161                        | 11026                    | 11713                    |
| average           | 201                        | 7823                     | 8383                     |

HØ (the baseline, with no inlining or region formation), H1 (Phased-region, for comparison) and H4 (the overall best performing heuristic).

Unit size

Table 13 compares the compilation unit size characteristics resulting from the three heuristics, HØ, H1, and H4. Both H1 and H4 show significant improvement in control of the size of the unit of compilation, with average region sizes ranging from 3% to 19% of the original average procedure sizes. H4 consistently produces more compilation units than H1, which is reflective of comparative code growth measurements for the two heuristics. The average size of the unit of compilation decreases slightly from H1 to H4 by 0.1 to 0.9 Lcode instructions. Although such a slight decrease in the average sizes of compilation units cannot directly account for the longer compilation times seen with H4, the more significant increase factor is code growth which results from the increase in the number of compilation units that results from a decrease in average size; with more code to compile, compilation time naturally is increased.

Profile homogeneity

Table 14 shows the profile homogeneity and percentage of invariant code for these three heuristics. In most cases, H4 improved upon the amount of invariant code versus H1, while showing slight to moderate increases in the profile variance. The consistent increase in variance with the attending increase in percentage of invariant compilation units indicates that H4, as compared with H1, is simultaneously improving the profile homogeneity of more compilation units while increasing the variance of a smaller number of compilation units by relocating the more variant code. The benefit seen to the percentage of invariant compilation units reflects the improvement in runtime performance for H4 over H1.

Interprocedural scope

Table 14 also compares the change in interprocedural scope for H1 and H4 compared to the baseline heuristic HØ, which had 0% interprocedural code since no inlining was performed. Interprocedural scope improved in all cases when using the demand-driven heuristics of H4, which showed improvements of 1.2% to 8.7% over H1, as well. Improvements for H4 as compared with H1 were less significant for 008.espresso, 099.go, and 134.perl, which have more instances of direct recursion than 130.li, which exhibits significant indirect recursion. Indirect recursion within region formation leads to increased interprocedural regions as procedures are inlined into other procedures. Direct recursion, or self-recursion, leads only to the inlining of a procedure into itself, if at all. The smaller size and lower number of procedures in 023.eqntott and 026.compress led to the larger improvements to interprocedural scope due to a higher proportion of smaller procedures.
Table 14: Comparison of percentage of invariant compilation units and profile variance (homogeneity) for three heuristics, and resulting interprocedural scope.

| Benchmark | HØ Pct. units | Benchmark | H1 Pct. units | Benchmark | H4 Pct. units |
|-----------|---------------|-----------|---------------|-----------|---------------|
| 008.espresso | 0.368 | 93.1 | 0.388 | 93.7 | 0.361 | 94.0 |
| 023.eqntott | 0.020 | 97.7 | 0.001 | 97.8 | 0.022 | 98.6 |
| 026.compress | 0.313 | 92.1 | 0.210 | 93.7 | 0.275 | 93.8 |
| 099.go | 0.372 | 91.5 | 0.310 | 91.9 | 0.331 | 93.1 |
| 124.m88ksim | 0.308 | 93.9 | 0.260 | 94.4 | 0.311 | 94.9 |
| 126.gcc | 0.323 | 92.9 | 0.262 | 93.4 | 0.300 | 93.9 |
| 130.li | 0.208 | 93.7 | 0.208 | 93.7 | 0.203 | 94.2 |
| 132.jpeg | 0.281 | 93.2 | 0.201 | 93.8 | 0.239 | 94.2 |
| 134.perl | 0.270 | 94.3 | 0.189 | 94.5 | 0.249 | 95.2 |
| 147.vortex | 0.280 | 93.1 | 0.211 | 93.8 | 0.271 | 94.1 |
| average | 0.274 | 93.6 | 0.214 | 94.1 | 0.256 | 94.6 |

5 Related Work

Region-based compilation remains an active area of research, with promising applications to a Java virtual machine [9, 31] including a variety of adaptive techniques [5], and ILP optimization and scheduling frameworks [26, 33, 37]. Region formation is a form of interprocedural data flow analysis, a well-researched area with many benefits to ILP [17, 19, 29]. Disadvantages are that during analysis it can have unscalable memory requirements [16] or require exponential time with respect to program size [16]. Advances address the issue of unscalable memory and time requirements by using modular [25, 30] and demand-driven [16] approaches, while profile-driven analysis and optimization [3, 7, 10, 11, 12] are vital to code improvement and performance.

Procedure inlining is used to eliminate call overhead [6, 8] leading to fewer and faster calls [4], improve compiler analysis and optimization [4, 8], code locality and execution speed [8], provide more precise data flow information to generate more efficient code specialized to the callee [4, 6], and enable intra-procedural analysis and optimizations such as constant propagation and elimination of redundant operations to be applied at interprocedural scope [8, 19]. However, inlining can increase register pressure [6, 8, 15], code size [6, 8], instruction cache misses [4, 6, 8], and compilation time, which is more critical during dynamic compilation [6]. Extensive research into inlining heuristics and the factors that bolster or limit their effectiveness within procedure-oriented compilers has been performed [2, 4, 7, 8, 13, 15, 21, 23, 24, 36].

6 Conclusions and Future Work

Region-based compilation has already been shown to help increase ILP performance by enabling interprocedural code motion without the expense of large compilation units or interprocedural data flow analysis. This research has focused on improving the effectiveness of region-based compilation that integrates heuristics-guided inlining into region formation analysis. Experimental results comparing two region-based approaches demonstrated that a demand-driven approach to inlining, as compared to a phased aggressive inlining approach, can reduce memory requirements and code growth while improving runtime performance due to increased profile homogeneity and interprocedural scope. These improvements are further enhanced by making more informed inlining decisions, and reordering the processing of procedures by a region-based compiler, leading to further improvements to compilation unit characteristics, reflected as improved performance. Heuristics based on static analysis can be as effective as profile-based heuristics at guiding inlining decisions.

Partial inlining is an inlining technique that selectively inlines portions of a callee procedure into a callsite rather than the entire body of the callee [9, 14, 15, 27]. Region-based compilation naturally enables a form of partial inlining for the optimization phase of compilation [20]. The approach presented in this paper is being extended to the design of an algorithm for incorporating partial inlining into region-based compilation [34], including its applicability to object-oriented programming.
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