

Master Thesis

Rodrigo Caetano de Oliveira Rocha



Master of Science by Research
Institute of Computing Systems Architecture
School of Informatics
University of Edinburgh
2017

Abstract

Acknowledgements

This work was supported in part by the EPSRC Centre for Doctoral Training in Pervasive Parallelism, funded by the UK Engineering and Physical Sciences Research Council (grant EP/L01503X/1) and the University of Edinburgh.

Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

(Rodrigo Caetano de Oliveira Rocha)

Table of Contents

1	Introduction	1
2	Background	5
2.1	Basic Concepts of Graph Theory	5
2.2	LLVM Compiler Infrastructure	5
2.2.1	LLVM Virtual Instruction Set	6
2.2.2	Analysis and Transformation Passes	9
2.3	Early Work in Iterative Compilation	9
2.4	Program Profiling	10
2.5	Summary	10
3	Related Work	11
3.1	Iterative Compilation	11
3.2	Work and Input Size Metrics	12
3.3	Optimal Instrumentation	13
3.3.1	Static Estimates of Edge Frequencies	15
3.4	Summary	16
4	Online Iterative Compilation	17
4.1	Work-based Metric	17
4.2	Online Iterative Compilation Infrastructure	18
5	Work Instrumentation	19
5.1	Code Generation for the Instrumentation Probes	23
5.2	Relaxed Instrumentation	25
5.3	Other Possible Uses	28

6	Experimental Evaluation	29
6.1	Benchmarks	29
6.2	Evaluation of the Instrumentation	29
6.2.1	Case Studies	30
6.3	Evaluation of the Online Iterative Compilation	30
6.4	Summary	31
7	Conclusions and Future Work	35
	Bibliography	37

Chapter 1

Introduction

Modern optimising compilers have reached a high level of sophistication, providing a large number of optimisations. Because of the unpredictability of optimisation interactions, in addition to the growing complexity of processor architectures and applications, the correct choice of optimisations and their ordering can have a significant impact on the performance of the code being optimised (Pan and Eigenmann, 2006; Fursin et al., 2007; Kulkarni and Cavazos, 2012).

Each of these optimisations interacts with the code in complicated ways, depending on all other optimisations and the order they were applied to the code being optimised. Understanding the interactions of optimisations is very important in determining a good solution to the phase-ordering problem (Touati and Barthou, 2006; Kulkarni and Cavazos, 2012). Because of all those dependencies and interactions, although most compiler optimisations yield significant improvements in many programs, the potential for performance degradation in certain program patterns is known to compiler writers and many users (Pan and Eigenmann, 2006; Zhou and Lin, 2012; Kulkarni and Cavazos, 2012).

Efficiently selecting the best combination of compiler optimisations for a given program or program section remains an open problem. Compiler writers typically use a combination of experience and insight to construct the default sequences of prearranged optimisations found in compilers. However, these default pre-arranged set of optimisations do not include all possible optimisations and they are always applied in the same pre-defined fixed order, without regard the code being optimised (Pan and Eigenmann, 2006; Cavazos et al., 2007; Zhou and Lin, 2012; Kulkarni and Cavazos, 2012).

A well known compilation technique that addresses this challenge is iterative com-

pilation. Iterative compilation has the ability to adapt to new platforms, program and workload while still having a systematic and simple optimisation process. It works by repeatedly evaluating a large number of compiler optimisations until the best combination is found for a particular program (Fursin et al., 2007; Chen et al., 2010). The main challenge concerning iterative compilation is the need for efficiently exploring such a large optimisation space (Fursin et al., 2007; Cavazos et al., 2007; Zhou and Lin, 2012).

Until recently, most of existing work had been focusing on finding the best optimisation through repeated runs using a single input. Although they demonstrate the potential of iterative compilation, in real scenarios the user rarely executes the same input dataset multiple times (Bodin et al., 1998; Kisuki et al., 1999; Stephenson et al., 2003; Kulkarni et al., 2004; Agakov et al., 2006). Applying iterative compilation in light of a single input may not result in good performance when executing the optimised code with different inputs.

Most of real world applications are complex enough so that a single input case does not capture the whole range of possible scenarios and program behaviour (Haneda et al., 2006; Fursin et al., 2007; Chen et al., 2010, 2012b). Because programs can exhibit behaviours that differ greatly depending on the input, using a single input for iterative compilation can produce poor performance when executed with different inputs.

Recent work have been studying the impact of using multiple input datasets for performing iterative compilation. This previous work suggests that optimising based on a representative range of input datasets allows for selecting a robust compiler optimisation that produces good performance in real scenarios where the input is expected to change constantly (Haneda et al., 2006; Fursin et al., 2007; Chen et al., 2010, 2012b,a; Fang et al., 2015; Mpeis et al., 2016). Their results show that a limited number of input datasets may be sufficient to obtain a well optimised program for a wider range of different inputs (Haneda et al., 2006; Fursin et al., 2007; Chen et al., 2010, 2012b).

Finding such a robust combination of compiler optimisations by means of iterative compilation across a large range of inputs may be very time consuming. In order to speed up this process we intend to reduce the number of actual executions during the exploration of the optimisation space without much degradation of the final selected optimisation.

In this work, our main goal is to enable iterative compilation in *online* scenarios with the restriction of executing distinct inputs only once, while targeting optimal per-

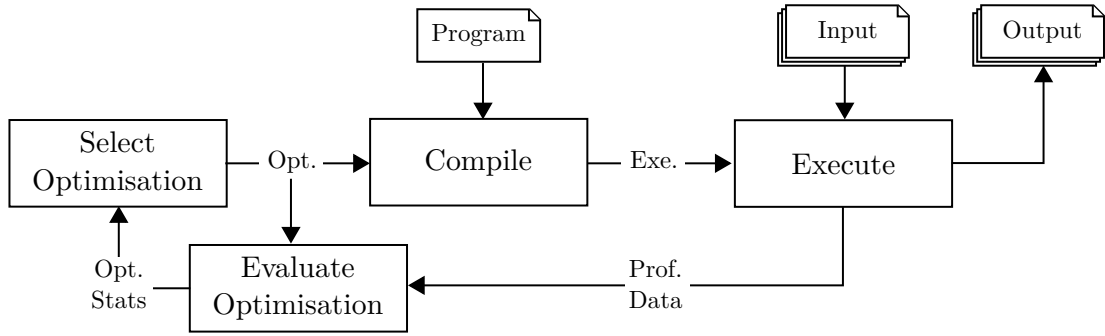


Figure 1.1: Overview of the execution engine for applying iterative compilation.

formance across different inputs. This online aspect is usually found in mobile and data centre platforms (Chen et al., 2012a; Fang et al., 2015; Mpeis et al., 2016), where the goal is to optimise programs based on the workload of a particular user (or group of users) between executions.

Measuring just execution time, for example, is useful only if the amount of work is constant between executions with different inputs. For this reason, we propose the use of a work-based metric in order to compare the performance of different optimisations across multiple executions of the program with distinct inputs.

Because of the restriction of not repeating inputs, we instrument the program for measuring the amount of work it performed during its execution. Having a low overhead instrumentation is essential in this online scenario for two main reasons: *(i)* the user is directly affected by large overheads; *(ii)* a highly intrusive instrumentation can have a significant impact on the effect of the optimisations.

Our main contributions are the following:

- The use of a work-based performance metric in order to enable *online* iterative compilation by comparing different combination of compiler optimisations even when executed with distinct inputs.
- We propose a relaxed instrumentation for low overhead profiling, with a controlled trade-off between accuracy and overhead.

Chapter 2

Background

2.1 Basic Concepts of Graph Theory

2.2 LLVM Compiler Infrastructure

LLVM was originally proposed as a *Low-Level Virtual Machine*¹, extending previous work on virtual instruction set architectures (Adve et al., 2003; Lattner and Adve, 2004). Since then, LLVM has evolved into an umbrella project that comprises a collection of modular and reusable compiler and toolchain technologies. The main components under the LLVM umbrella is the LLVM intermediate representation (IR) and the LLVM *Core* libraries.

The LLVM compiler infrastructure implements the classical *three-phase compiler* infrastructure, which consists of a frontend, an optimiser, and a backend. The frontend is responsible for parsing, validating and diagnosing errors in the source code. This parsed source code is then translated into an intermediate representation, which is the LLVM IR in this case. The optimiser is responsible for doing a broad variety of transformations, that are usually independent of language and target machine, to improve the code's performance. The backend, also known as the code generator, then translates the code from the intermediate representation onto the target instruction set. It is common for the backend to also perform some low-level optimisations that take advantage of unusual features of the supported architecture.

¹Although LLVM was initially an acronym for Low-Level Virtual Machine, it is now a brand that applies to the whole LLVM umbrella project.



Figure 2.1: Overview of the three-phase compiler infrastructure.

2.2.1 LLVM Virtual Instruction Set

LLVM IR is a low-level RISC-like virtual instruction set. It differs from other intermediate representations (e.g. GCC’s GENERICs or the most recent GCC’s GIMPLE) as it is defined as a first class language with well-defined semantics. Beyond being implemented as a language, LLVM IR is actually defined in three isomorphic forms: the textual format above, an in-memory data structure inspected and modified by optimizations themselves, and an efficient and dense on-disk binary *bitcode* format.

Unlike most RISC instruction sets, LLVM is strongly typed with a simple language-independent type system. LLVM’s type system can be used to implement data types and operations from high-level languages exposing their implementation behaviour to all stages of optimisation. This type system includes the type information used by sophisticated techniques, such as algorithms for pointer analysis, dependence analysis, and data transformations. LLVM also offers instructions for performing type conversions and low-level address arithmetic while preserving type information. Furthermore, LLVM IR also differs from RISC instruction sets as some details of the machine are abstracted away. For example, the calling convention is abstracted through call and ret instructions and explicit arguments. Another significant difference from machine code is that the LLVM IR has an infinite set of virtual registers (which are named with a % character), instead of having just a fixed set of named registers.

The LLVM type system is considered one of the most important features of its intermediate representation, as it enables several optimisations to be performed directly on the IR, without having to do extra analyses on the side before the transformation. The main first class types supported are: single value types, aggregate types, and labels. Single value types consist of integers of arbitrary bit width (e.g. `i32` denotes a 32-bit integer), floating-point of commonly used width (e.g. `half`, `float`, `double`, and `fp128`), pointers (e.g. `i32*`) and vector types. Vectors are used when multiple primitive data are operated in parallel using a single instruction (SIMD). A vector type is represented by the number of elements and an underlying primitive data type, e.g. `<4 x i32>` is a vector of four 32-bit integer values. Aggregated types consist of arrays and structures. Vectors are not considered to be aggregate types.

In addition to type information, LLVM IR also provides other high-level information that are useful for effectively performing several code analysis and transformations. This includes explicit control flow graphs (CFG) (Allen, 1970) and an explicit dataflow representation, by means of the infinite register set in *static single assignment* (SSA) form (Alpern et al., 1988; Cytron et al., 1989, 1991).

A control flow graph (CFG) is a directed graph in which the nodes represent basic blocks and the edges represent control flow paths, i.e. edges represent transfers of control (jumps) between basic blocks. A basic block is a straight-line sequence of instructions having only one entry point, i.e. the first instruction to be executed in the basic block, and only one exit point, i.e. the last instruction executed (Allen, 1970; Cytron et al., 1991). Figure 2.2 shows an example of a CFG constructed from the code in Listing 2.1.

An IR is in SSA form if and only if each virtual register is assigned exactly once and every use of registers occur after their definition. The primary advantage of using the SSA form is that it simultaneously simplifies and improves several compiler optimisations and analysis (Alpern et al., 1988; Cytron et al., 1991). Most of the industrial-strength compilers for imperative programming language rely heavily on the SSA form.

```

1 define i32 @odd_inc(i32 %arg) {
2 entry:
3   %rem = srem i32 %arg, 2
4   %cmp = icmp eq i32 %rem, 0
5   br i1 %cmp, label %if.then, label %if.else
6 if.then:
7   %add.1 = add i32 %arg, 1
8   br label %if.end
9 if.else:
10  %add.2 = add i32 %arg, 2
11  br label %if.end
12 if.end:
13  %ans = phi i32 [ %add.1, %if.then ], [ %add.2, %if.else ]
14  ret i32 %ans
15 }
```

Listing 2.1: An illustrative example of a function in textual LLVM IR. This function returns the argument incremented by one if it is even or by two if it is an odd integer.

Listing 2.1 shows an example of a function written using textual LLVM IR. Names starting with the @ character have a global scope, while names starting with % have a local scope. As stated previously, LLVM IR is strongly typed, which means that every virtual register is attributed a specific type (e.g. `i32 %arg` is of type `i32`, namely a 32-bit integer) as well as every operation (e.g. `add i32` expects all operands of type `i32`). Instructions use the three address format, which refers to the use of three operands by

most of the instructions. However, instructions with fewer or more operands may occur, e.g. the `ret` instruction have fewer operands, while the `phi` and the `call` instructions may have more than three operands.

Furthermore, the SSA form requires a special assignment statements called the ϕ -function (see line 13 of Listing 2.1). The ϕ -function receives as argument a list of virtual registers from different control flow predecessors of the point where the ϕ -function occurs. The control flow predecessors of each point in the CFG are listed in some arbitrary fixed order, and the i -th operand of ϕ -function is associated with the i -th predecessor. If control reaches the ϕ -function from its i -th predecessor, then the value of the i -th operand is attributed in the assignment. Each execution of a ϕ -function uses only one of the operands, but which one depends on the flow of control just before the ϕ -function.

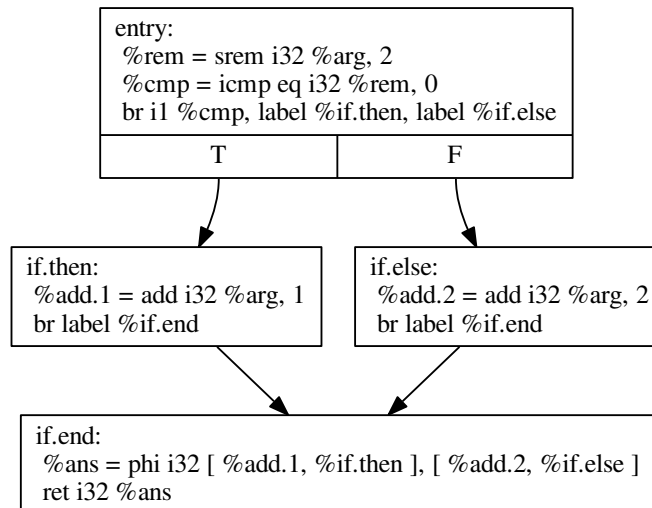


Figure 2.2: Control flow graph of the `odd_inc` function (see Listing 2.1).

In addition to virtual registers, LLVM also allows for stack allocated local variables. These are created by allocating data on the stack frame of the currently executing function. Data from the stack frame can be manipulated by using explicit memory access operations. Figure 2.2 shows an implementation of the `odd_inc` function using data allocated on the stack frame. This implementation avoids using the ϕ -function by keeping the answer on the stack.

LLVM provides an optimisation pass for promoting memory references to be reg-

ister references (called `-mem2reg`). It promotes `alloca` instructions which only have loads and stores as uses. An `alloca` is transformed by using dominator frontiers to place phi nodes, then traversing the function in depth-first order to rewrite loads and stores as appropriate.

```

1 define i32 @odd_inc_stack(i32 %arg) {
2 entry:
3   %addr = alloca i32
4   %rem = srem i32 %arg, 2
5   %cmp = icmp eq i32 %rem, 0
6   br i1 %cmp, label %if.then, label %if.else
7 if.then:
8   %add.1 = add i32 %arg, 1
9   store i32 %add.1, i32* %addr
10  br label %if.end
11 if.else:
12  %add.2 = add i32 %arg, 2
13  store i32 %add.2, i32* %addr
14  br label %if.end
15 if.end:
16  %ans = load i32, i32* %addr
17  ret i32 %ans
18 }

```

Listing 2.2: An example of the `odd_inc` function implemented using data allocated on the stack frame.

2.2.2 Analysis and Transformation Passes

The LLVM Pass Framework is an important part of the LLVM system, because LLVM passes are where most of the interesting parts of the compiler exist. Passes perform the transformations and optimizations that make up the compiler, they build the analysis results that are used by these transformations, and they are, above all, a structuring technique for compiler code.

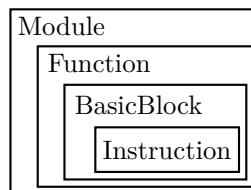


Figure 2.3: .

2.3 Early Work in Iterative Compilation

Original work in Iterative Compilation: single input and offline

2.4 Program Profiling

Basic background about profiling in general

2.5 Summary

Chapter 3

Related Work

3.1 Iterative Compilation

Specific work in Iterative Compilation about multiple inputs and online scenarios

Chen et al. (2010, 2012b) evaluate the effectiveness of iterative compilations across a large number of input test cases. Their main motivation is to answer the question: *How data input dependent is iterative compilation?* Their results show that it is possible to find a combination of compiler optimisations that achieves at least 86% of the maximum speedup across all input test cases. These optimal combinations are program-specific and yield average speedups up to $3.75\times$ over the highest optimisation level of compilers.

When optimising a program, the main method for iterative compilation used by Chen et al. (2010, 2012b) evaluates each combination of compiler optimisations across all the available inputs, i.e., if N is the number of input test cases and M is the total number of combinations of compiler optimisations, they perform a total of $O(NM)$ runs of the program being optimised. Furthermore, they use a pre-defined set of only 300 different combinations of compiler optimisations, which represents a very small sample of the optimisation search space for most modern compilers, e.g. LLVM has 56 distinct optimisation passes and GCC has about 47 high-level (SSA form) optimisation passes and about 25 low-level (RTL) optimisation passes, which in both cases result in much more than 2^{50} distinct combinations of compiler optimisations, without considering repetition.

Recent work (Chen et al., 2012a; Fang et al., 2015) have applied the same idea of performing input-dependent iterative compilation to distributed applications on data centres. In summary, each worker receives a subset of the input dataset, called the eval-

uation dataset, to perform an *online* iterative compilation of the code being executed. Each worker performs the same the method for iterative compilation used by Chen et al. (2010, 2012b), i.e., they evaluate each combination of compiler optimisations across all the evaluation dataset. However, because the optimisation is performed on-line, they usually consider a small evaluation dataset and a small number of compiler optimisations.

Fursin et al. (2007) addressed the problem of comparing the effect of two optimisations on two distinct inputs. For that purpose, they proposed to use instruction per cycle (IPC) as the metric for performing such comparison. Their result show that using IPC seems promising as a robust metric for iterative compilation across large input datasets. However, some specific optimisation techniques may affect the use of IPC as a robust metric, and specially IPC has been shown to provide poor performance estimation for multi-threaded programs (Alameldeen and Wood, 2006; Eyerman and Eeckhout, 2008). In particular, IPC can give a skewed performance measure if threads spend time in *spin-lock loops* or other synchronisation mechanisms. Some existing work on performance assessment suggest that total execution time should be used for measuring performance of multi-threaded programs (Alameldeen and Wood, 2006; Eyerman and Eeckhout, 2008). Alameldeen and Wood (2006) in particular suggest that a simple work-related metric should be used if the unit of work is representative enough. Work-related metrics have already been largely used for measuring performance of throughput-oriented applications, for other applications, however, choosing an appropriate unit of work can be more challenging (Alameldeen and Wood, 2006).

3.2 Work and Input Size Metrics

Talk about work-based metrics

Previous work have proposed profiling-based mechanism to estimate input sizes (Zaparanuks and Hauswirth, 2012; Coppa et al., 2014). Coppa et al. (2014) in particular propose the concept of *read memory size* for automatically estimating the size of the input passed to a routine, where *read memory size* represents the number of distinct memory cells first accessed by a read operation. In other words, the *read memory size* metric measures the size of the useful portion of the input's memory footprint. However, because we are interested in the amount of computational work performed in respect of a given input, the memory footprint of the input may not always have a direct correspondence to the amount of computational work.

Goldsmith et al. (2007) use *block frequency* as the measure for performance for empirically describing the asymptotic behaviour of programs, which is known as empirical computational complexity. Block frequency is a relative metric that represents the number of times a basic block executes (Ball and Larus, 1994, 1996). They argue in favour of block frequency due to its portability, repeatability and exactness, since it does not suffer from timer resolution problems or non-deterministic noises. Block frequency also has the advantage of being efficiently profiled by means of automatic code instrumentation (Knuth and Stevenson, 1973; Ball and Larus, 1994).

However, in the context of comparing different optimisations, although block frequency would be able to capture aspects of optimisations that simplify the control-flow graph (CFG), measuring work at the basic block resolution would not capture effects of optimisations at the instruction level. Because of that, we extend the idea of using basic block frequency to measure computational work by also considering the computational cost of each basic block. The computational cost of a basic block is given by weighting the instructions that it contains.

3.3 Optimal Instrumentation

In order to profile block frequency, the program can be instrumented with counters that determine how many times each basic block in a program executes. A naive instrumentation would consist basically of having a counter for each basic block which is incremented every time the basic block is reached. Although the naive instrumentation was commonly used in practice (Knuth, 1971), it is a very invasive instrumentation that imposes an unnecessarily high overhead in the instrumented program. An optimal instrumentation based on the principle of *conservation of flow* (Kirchhoff's first law¹) have been originally proposed by Nahapetian (1973) and Knuth and Stevenson (1973). While Knuth and Stevenson (1973) proposed an optimal solution for basic block profiling with *vertex counters*, Ball and Larus (1994) showed that an optimal basic block profiling with *edge counters* provides the best instrumentation for block frequency profiling. Further overhead reduction of the optimal instrumentation was later proposed by placing the counters in edges that are less likely to be executed Forman (1981); Ball and Larus (1994).

Definition 3.3.1 (Kirchhoff's first law). The amount of flow into a vertex equals the

¹Gustav Kirchhoff defined two equalities about electric circuits, known as Kirchhoff's circuit laws. The first one is about current and the second about potential difference.

```

1 // Inputs: CFG with the known edges flows from the cotree
2 // Output: Updated CFG with all edge flows
3 populateEdgeFlows(G) {
4     changed = true
5     while changed:
6         changed = false
7         for B in G.vertices():
8             unIN = count( G.unknownIncomingEdges(B) )
9             unOUT = count( G.unknownOutgoingEdges(B) )
10            if unIN==0 and unOUT==1:
11                //sum known incoming and outgoing edges in B
12                sIN = sum( G.incomingEdges(B) )
13                sOUT = sum( G.outgoingEdges(B) )
14                //update unknown outgoing edge in B with (sIN-sOUT)
15                G.setUnknownOutgoingEdge(B, (sIN-sOUT))
16                changed = true
17            if unIN==1 and unOUT==0:
18                //sum known incoming and outgoing edges in B
19                sIN = sum( G.incomingEdges(B) )
20                sOUT = sum( G.outgoingEdges(B) )
21                //update unknown incoming edge in B with (sOUT-sIN)
22                G.setUnknownIncomingEdge(B, (sOUT-sIN))
23                changed = true
24 }

```

Listing 3.1: A data-flow analysis for populating all edge flows based on the probed edges.

amount of output flow, i.e. the sum of the incoming edges of a vertex equals the sum of outgoing edges of the same vertex.

The optimal instrumentation places probes in edges as the basic block frequency can be derived by summing either the flow of the incoming or outgoing edges. However, it uses the Kirchhoff's first law in order to place probes in subset of the edges that allows to later infer the flow of all edges. Previous work have shown that a set of edges represents the minimum number of probes for profiling block frequency if and only if the complementary set of edges forms a spanning tree (Nahapetian, 1973; Ball and Larus, 1994). In other words, after determining a spanning tree of the CFG, probes need to be placed only in the edges from the complement of a spanning tree, usually called *cotree*. Because the edge frequencies satisfy Kirchhoff's first law, each edge flow can be uniquely determined as an algebraic sum of the known edge flows from the cotree (Nahapetian, 1973; Ball and Larus, 1994).

Algorithm 3.1 is guaranteed to terminate because the probed edge flows on the complement of a spanning tree are necessary and sufficient to compute all edge flows (Nahapetian, 1973; Forman, 1981). Intuitively, if all the edge flows are known for the complement of a spanning tree then at any leaf of the spanning tree there is only one unknown edge flow. This unknown edge flow can be calculated by Kirchhoff's first law. This process repeats until all the unknown edge flows have been calculated. Although this instrumentation algorithm is proved to produce the optimal placement of

probes for well-structured CFGs, it may produce sub-optimal placement for some unstructured CFGs (Ball and Larus, 1994).

This briefly described proof suggests that the edges can be more efficiently populated by a bottom-up propagation in the spanning tree. By performing a post-order traversal of the spanning tree, i.e. starting from the leaves, we can then apply the flow equation from the Kirchhoff's first law. At each node of the spanning tree, we first sum the known incoming and outgoing edges, and then the unknown edge flow will be computed by subtracting the minimum of the two sums from the maximum (as before). This bottom-up propagation allows to populate the edge flows in a single pass over the basic blocks.

Forman (1981) and Ball and Larus (1994) propose to optimise the placement of the probes with respect to edges that are less likely to be executed. It works by considering a weighting that assigns a non-negative value to each edge in the CFG. The overhead cost of profiling a set of edges is considered to be proportional to the sum of the weights of the edges. These weights can be obtained either by empirical measurements from previous executions or by static heuristic estimations at compile-time. In order to minimise the profiling overhead, the instrumentation computes the maximum spanning tree in order to avoid probing in frequently executed edges.

Notice that when instrumentation is performed guided by empirical measurements from previous executions, it means that edge profiling information is used in order to produce a better edge profiling instrumentation. The next section presents the main algorithms for producing static estimates for the weights of the edges in a CFG.

3.3.1 Static Estimates of Edge Frequencies

Ball and Larus (1993) presented a simple algorithm that predicts the outcome of conditional branches with a reasonably good accuracy. For this purpose, they used several branch heuristics that were derived by measuring, on a large number of programs, the probability of branches being taken in respect of some *ad-hoc* features from the programs. Their algorithm selects, for each branch, the first heuristic that applies to the branch, in a given priority order of the heuristics. The *ad-hoc* heuristics defined by Ball and Larus (1993) are:

Loop branch heuristic (probability 88%): Probability of an edge back to a loop's head being executed.

Loop exit heuristic (probability 80%): Probability that a comparison inside a loop

will *not* exit the loop. This heuristic does not apply to latch blocks, i.e. basic blocks that contain a branch back to the header of the loop.

Pointer heuristic (probability 60%): Probability that a comparison between two pointers, where one of them can be a null pointer, will fail.

Opcode heuristic (probability 84%): Probability that a comparison of an integer being less than zero, less than or equal to zero, or equal to a constant will fail.

Guard heuristic (probability 62%): For a comparison with a register as operand, where the register is defined in a successor basic block which is not a post-dominator. The probability that the successor basic block is reached.

Loop header heuristic (probability 75%): Probability of reaching a successor block that is a loop header (or pre-header) but not a post-dominator.

Call heuristic (probability 78%): Probability of reaching a successor block that is not a post-dominator but contains a function call.

Store heuristic (probability 55%): Probability of reaching a successor block that is not a post-dominator but contains a store instruction.

Return heuristic (probability 72%): Probability of reaching a successor block that contains a return instruction.

Wu and Larus (1994) proposed an algorithm for statically estimating edge frequencies, which improves on the work of Wagner et al. (1994) and Ball and Larus (1993). This algorithm is able to combine several heuristics of the outcome of a branch into an estimated probability of the branch being taken. Wu and Larus (1994) use the *ad-hoc* heuristics defined by Ball and Larus (1993) as their initial predictions. They also use the Dempster-Shafer theory (Shafer et al., 1976) that provides the necessary mathematical technique for combining evidences from the different heuristics in order to produce more accurate estimates. These branch probabilities can then be used to estimate execution frequencies for all the edges in a CFG.

3.4 Summary

Chapter 4

Online Iterative Compilation

4.1 Work-based Metric

In this section we define the work-based performance metric proposed for comparing different optimised versions of a program when executing with different inputs. We define the performance metric as the ratio between the amount of *work*, ΔW , performed during a period of time, Δt .

$$P = \frac{\Delta W}{\Delta t}$$

By measuring the amount of *work* done per unit of time we reduce the impact of input-dependent aspects and focus instead on the efficiency of the optimised program. For this metric, the main challenge is to precisely define what represents *work*.

We model the computational work ΔW as a linear equation based on block frequency information and a cost-model of the instruction set.

$$\Delta W = \varepsilon + \sum_B w(B)f(B)$$

where $f(B)$ represents the frequency of basic block B and $w(B)$ represents the computational work of executing B . We define the work of a basic block B as the sum of the cost of its instructions, i.e.,

$$w(B) = \sum_i w_i N_B(i)$$

where w_i is the cost of instruction i and $N_B(i)$ is the number of occurrences of instruction i in basic block B .

In this simplified model, we consider that w_i is constant across all programs and executions in the given target platform. However, $N_B(i)$ is program dependent but constant across executions, while $f(B)$ is both program and execution dependent, since

$f(B)$ can change when executing with different inputs. In other words, $N_B(i)$ is a static value known at compile-time and $f(B)$ is a dynamic value known only at run-time.

Similarly to previous work (Giusto et al., 2001; Powell and Franke, 2009; Brandolese et al., 2011), we derive the cost model for the instruction set by modelling the problem as a multi-variable linear regression, where the *regression coefficients* are the costs of the instructions and the *regressors* (or *explanatory variables*) are computed as $\sum_B N_B(i)f(B)$ for each instruction i .

$$\Delta W = \varepsilon + \sum_i \left(w_i \sum_B N_B(i)f(B) \right)$$

By having some empirical data after executing several benchmarks with different inputs, we can fit the linear model with this empirical data in order to obtain the costs of the instructions.

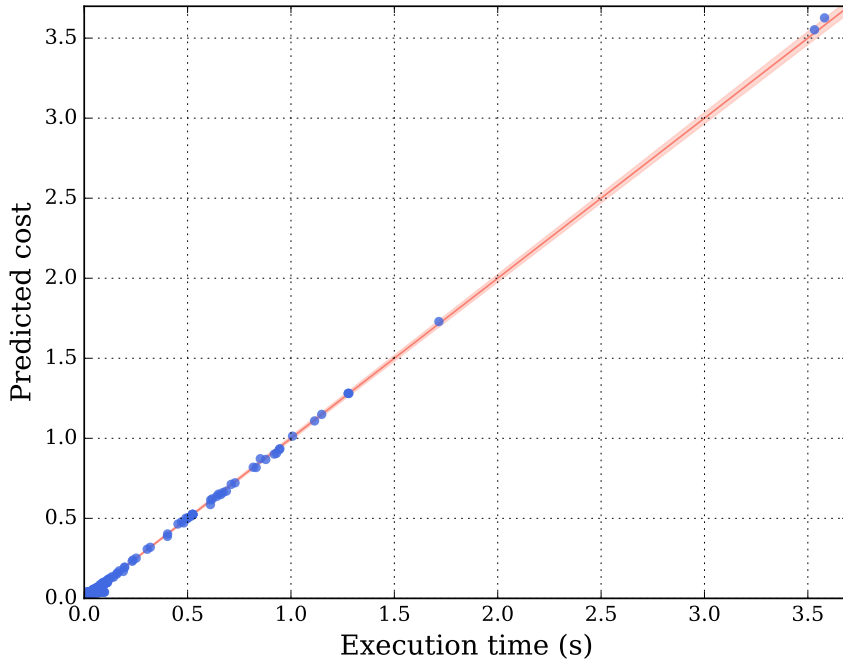


Figure 4.1: Linear model fitted from empirical data. The mean absolute error (MAE) for the fitted curve is of 7 milliseconds.

4.2 Online Iterative Compilation Infrastructure

Chapter 5

Work Instrumentation

In this section we describe how the computation of the work-metric can be performed during runtime by means of instrumenting the code. In particular, we adapt the optimal algorithm proposed originally for profiling block frequency (Nahapetian, 1973; Knuth and Stevenson, 1973; Ball and Larus, 1994). Afterwards, we propose a relaxed instrumentation that focus on further reducing the overhead by considering the trade-off between profiling accuracy and instrumentation overhead.

Because we define work as a linear equation on the block frequency counters, it is possible to embed its computation into the execution of the program. A naive instrumentation would consist basically of having a global counter that starts with the interception value, ϵ , and each basic block increments its own cost into the global counter. Although this instrumentation is easily implemented, it imposes a large overhead on the instrumented program. However, it is possible to insert fewer probes by carefully placing the probes in a way that is possible to reconstruct the complete profiling information Knuth and Stevenson (1973); Ball and Larus (1994).

We adapt the optimal block frequency instrumentation in order to perform the work profiling efficiently. Figure 5.1 shows a high-level overview of the complete work instrumentation algorithm. The highlighted sections are introduced or improved by our work profiling instrumentation. The instrumented code is assumed to be generated before optimising the code. This assumption is based on three key points: *i.* it guarantees that the work metric is independent of optimisation, i.e., the same input is always mapped to the same amount of work, regardless of the optimisation; *ii.* it simplifies the code generator; *iii.* it leverages from the optimisations to further improve the instrumentation code. Having a work metric is independent of optimisation is the most important reason for which we instrument the code before optimisations.

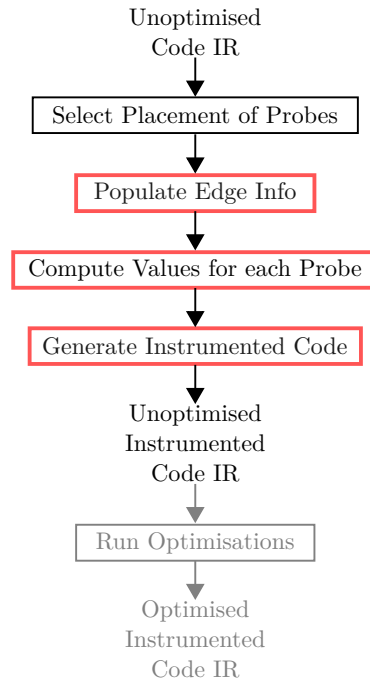


Figure 5.1: Overview of the work instrumentation algorithm.

The optimal placement of the probes works exactly as previously described in Section 3.3. It first computes the maximum spanning tree based on a weighing that assigns a non-negative value to each edge in the CFG. These weights can be obtained either by empirical measurements or heuristic estimations, and their goal is to avoid probing in frequently executed edges. Once we have the maximum spanning tree, probes are placed on every edge not in the spanning tree. Figure 5.2 shows an example of a CFG with a maximum spanning tree represented by the black edges, while the edges highlighted in red represent the placement of the probes.

In contrast to the naive instrumentation where each basic block records only its own amount of work, with the optimal profiling, the instrumented basic blocks need record an aggregated value of work that represents a path in the CFG. These values are constructed with some instrumented basic blocks speculatively assuming some paths while other probes correct when these assumptions are wrong (see for example $w(P_0)$ and $w(P_1)$ in Figure 5.2).

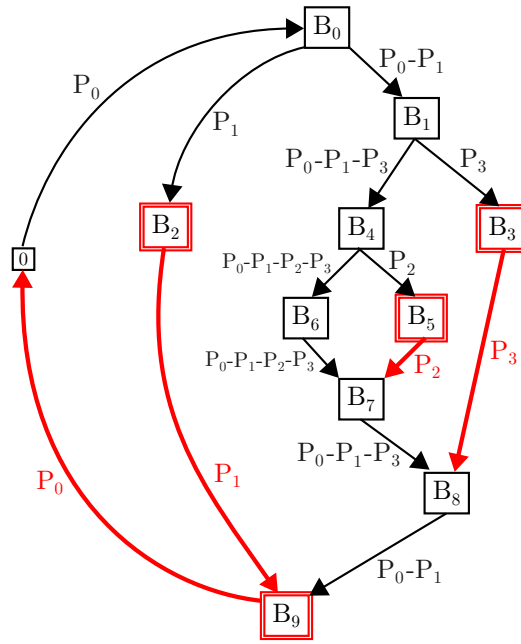
Because the algorithm for the optimal placement of the probes is proved to uniquely compute the block frequencies by propagating the probe counts, we adapt this algorithm in order to compose the aggregated values that will be instrumented in each probe, based on our model of computational work, ΔW , derived from the basic block frequencies (see Section ??). We perform a similar propagation of the probes in a sym-

```

1 // Inputs: CFG with the known edges flows of the chords
2 // Output: Updated CFG with all edge flows
3 populateEdgeInfo(G) {
4     //the instrumented edges are the only known edge flows
5     for e in instrumentedEdges(G):
6         B = instrumentedBlock(e)
7         inc[e] = set( {B} )
8         dec[e] = set()
9         knownInfo[e] = true
10
11     changed = true
12     while changed:
13         changed = false
14         for B in G.vertices():
15             unIN = count( G.unknownIncomingEdges(B,knownInfo) )
16             unOUT = count( G.unknownOutgoingEdges(B,knownInfo) )
17             if unIN==0 and unOUT==1:
18                 //sum known incoming and outgoing edges in B
19                 incSum = set()
20                 decSum = set()
21                 for predB in G.predecessors(B):
22                     incSum = incSum union dec[G.getEdge(predB, B)]
23                     decSum = decSum union inc[G.getEdge(predB, B)]
24                 for succB in G.successors(B):
25                     incSum = incSum union inc[G.getEdge(B, succB)]
26                     decSum = decSum union dec[G.getEdge(B, succB)]
27                 //update unknown outgoing edge in B with incSum and decSum
28                 e = G.getUnknownOutgoingEdge(B,knownInfo)
29                 inc[e] = incSum-decSum
30                 dec[e] = decSum-incSum
31                 knownInfo[e] = true
32                 changed = true
33             if unIN==1 and unOUT==0:
34                 //sum known incoming and outgoing edges in B
35                 incSum = set()
36                 decSum = set()
37                 for predB in G.predecessors(B):
38                     incSum = incSum union inc[G.getEdge(predB, B)]
39                     decSum = decSum union dec[G.getEdge(predB, B)]
40                 for succB in G.successors(B):
41                     incSum = incSum union dec[G.getEdge(B, succB)]
42                     decSum = decSum union inc[G.getEdge(B, succB)]
43                 //update unknown incoming edge in B with incSum and decSum
44                 e = G.getUnknownIncomingEdge(B,knownInfo)
45                 inc[e] = incSum-decSum
46                 dec[e] = decSum-incSum
47                 knownInfo[e] = true
48                 changed = true
49 }

```

Listing 5.1: Pseudocode of the data-flow analysis for assigning the values computed in each probe of the instrumentation for the profiling of the work metric.



Instrumented value for each probe P_i :

$$w(P_0) = w(B_0) + w(B_1) + w(B_4) + w(B_6) + w(B_7) + w(B_8) + w(B_9)$$

$$w(P_1) = w(B_2) - w(B_1) - w(B_4) - w(B_6) - w(B_7) - w(B_8)$$

$$w(P_2) = w(B_5) - w(B_6)$$

$$w(P_3) = w(B_3) - w(B_4) - w(B_6) - w(B_7)$$

Figure 5.2: Example of a CFG with its minimum spanning tree in black and the basic blocks highlighted in red represent the instrumented basic blocks with the placement of the probes.

bolic fashion, as illustrated in Figure 5.2. This symbolic propagation of the probes is implemented by the data-flow analysis described in Algorithm 5.1, and the final aggregated values are extracted from the edge information as described by Algorithm 5.2.

The data-flow analysis in Algorithm 5.1 keeps two sets for each edge, namely, the increment and the decrement sets. We consider that both sets represent the *edge expressions* shown in Figure 5.2, for which we define a *symbolic sum* by computing the union of the increment and decrement sets, respectively, with the appropriate cancellation of common elements. This data-flow analysis is based on the invariant that the symbolic sum of all the incoming edges must equals the symbolic sum of the outgoing edges. For example, the symbolic sum of the incoming edges of the basic block B_8 is $P_0 - P_1$, where P_3 is cancelled out.

Algorithm 5.2 reads the edge information for each basic block by computing the

```

1 // Inputs: 1) CFG with the known edges flows of the chords
2 //          2) Basic block targeted for probing
3 // Output: Work value to be incremented by the given probe B
4 instrValue(G, B, inc, dec) {
5     value = 0
6     for B in G.vertices():
7         incB = set()
8         decB = set()
9         for succB in G.successor(B):
10            incB = incB union inc[ G.getEdge(B, succB) ]
11            decB = decB union dec[ G.getEdge(B, succB) ]
12        if B in (incB - decB):
13            value = value + w(B)
14        if B in (decB - incB):
15            value = value - w(B)
16    return value
17 }
```

Listing 5.2: Pseudocode that describes how the edge information is used in order to extract the value that will be computed in a given instrumented basic block B_I . This algorithm could equally be implemented based on the predecessors.

symbolic sum of their respective incoming edges (or outgoing edges). From these *edge expressions*, we are able to compose the aggregated value of the probes. The positive terms in the edge expression of a basic block indicate that the amount of work of this basic block will be incremented in the probes represented by these positive terms, similarly, the negative terms indicate that the amount of work of this basic block will be decremented in the probes represented by these negative terms. For example, because the edge expression for the basic block B_8 is $P_0 - P_1$, the amount of work of B_8 , denoted by $w(B_8)$, is incremented in probe P_0 and decremented in P_1 .

5.1 Code Generation for the Instrumentation Probes

This section describes the code generator for the work instrumentation. Once we have the placement of the probes as well as the aggregated value computed for each probe, we insert the appropriate instructions for the probes of the work profiling. Because the instrumented code is assumed to be generated before optimising the code, the code generator has a straightforward code generation process. It produces the code for the probes using a local variable as it tends to improve optimisation opportunities. This variable acts as the local accumulator that will eventually be incremented into the global work counter.

For every function, the code generator allocates memory on the stack frame for the local work variable. In LLVM, allocated memory on the stack is automatically released when the function returns, therefore there is no need to generate code for that purpose.

Afterwards, the local work variable is set to zero.

```

1  %local.work = alloca i32
2  store i32 0, i32* %local.work

```

Listing 5.3: Code for the entry point of a function.

For every probe, the code generator produces memory access operations in addition to the actual increment of the local work counter. The value incremented to the local counter is the value computed by Algorithm 5.2.

```

1  %r1 = load i32, i32* %local.work
2  %r2 = add i32 %r1, 8
3  store i32 %r2, i32* %local.work

```

Listing 5.4: Code for a probe that increments the local work counter.

Because it produces instrumentation code using a local variable, eventually this local variable needs to be incremented into the global counter. This is performed at every exit point of the function, even if the basic block with the exit point was not selected for having a probe. For every exit point of the function, the code generator produces simple memory access operations that load the current values of both the local and the global counters, adds them together, and finally updates the global counter.

```

1  %r1 = load i32, i32* %local.work
2  %r2 = load i32, i32* @__work_counter
3  %r3 = add i32 %r1, %r2
4  store i32 %r3, i32* @__work_counter

```

Listing 5.5: Code at an exit point of a function.

For the special case where a probe belongs to a basic block which is also an exit point of the function, the code generator leverages from this scenario to produce a code for the probe that works in collaboration with the update of the global counter.

```

1  %r1 = load i32, i32* %local.work
2  %r2 = add i32 %r1, 273
3  %r3 = load i32, i32* @__work_counter
4  %r4 = add i32 %r2, %r3
5  store i32 %r4, i32* @__work_counter

```

Listing 5.6: Code for a probe that increments the local work counter and also updates the global counter at an exit point of a function.

After optimisations, the instrumented code can benefit from some of the transformations. For example, the optimisation pass for promoting memory to register (`-mem2reg`) is able to eliminate the local variable such that the local work counter is only kept in registers. The only explicit access to memory is performed when updating the global work counter.

```

1  ...
2  ;If probes from multiple paths reach a given point,
3  ;a phi operation is used for selecting the appropriate value.
4  ;Furthermore, the initial store of 0 is unnecessary.
5  %r1 = phi i32 [ 0, %entry ], [ %r2, %for.inc ]
6  ...
7  ;If there is only one value that reaches a given point,
8  ;this value can be directly used.
9  %r3 = add i32 %r1, 273
10 %r4 = load i32, i32* @__work_counter
11 %r5 = add i32 %r3, %r4
12 store i32 %r5, i32* @__work_counter

```

Listing 5.7: An illustrative example of how `-mem2reg` can optimise the instrumented code.

5.2 Relaxed Instrumentation

Although the optimal instrumentation significantly reduces the profiling overhead when compared to the naive instrumentation, from an average overhead of 79% to 13%, in some critical cases, even the optimal instrumentation can have an overhead of about 70% (see benchmark `adpcm_d` in Figure 6.3). In order to further reduce the overhead in these critical cases, we propose a relaxed instrumentation by trading off accuracy and overhead. Figure 5.3 shows an overview of the relaxed instrumentation algorithm. The highlighted section is introduced by the relaxed instrumentation on top of the previously defined optimal work instrumentation algorithm.

The relaxed instrumentation performs a post-processing on the resulting instrumentation of the optimal algorithm. The relaxation starts by extracting *extended* DAGs (directed acyclic graphs) from the CFG, as illustrated in Figure 5.4. Each loop (and the outer most region of the function) represents an extended DAG where any inner loop is considered to never execute, i.e. only the headers of the inner loops are included into the extended DAG.

For every extended DAG with a set of probes $\{P_0, P_1, \dots, P_k\}$, we relax the instrumentation accuracy by selecting a subset of the probes to be removed, subject to the maximum allowed percentage error, M .

We model the relaxation as a 0-1 Knapsack problem:

$$\begin{aligned}
 & \text{maximise } \sum_{i=0}^k f(P_i)x_i \\
 & \text{subject to } \sum_{i=0}^k \epsilon(P_i)x_i \leq M \text{ and } x_i \in \{0, 1\}
 \end{aligned}$$

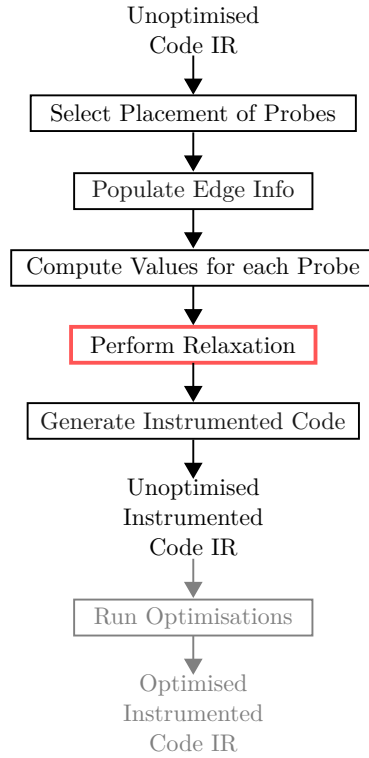


Figure 5.3: Diagram.

where $f(P_i)$ is the execution frequency of the instrumented basic block P_i , $\epsilon(P_i)$ is the percentage error of removing probe P_i relative to the minimum work value possible to compute in the extended DAG, and x_i denotes the probes selected for removal. Because the percentage error is computed based on the path with the minimum amount of work, $\epsilon(P_i)$ represents the maximum error possible that would be incurred when removing probe P_i . Furthermore, by constraining the percentage error of every extended DAG below a given threshold we guarantee that the final error of the relaxation will always be bounded by the threshold.

Let n_i be the number of times a given DAG i is executed, r_i be the relaxation (amount of work removed) in DAG i , and m_i be its minimum amount of work. Let $\frac{r_i}{m_i} \leq T$ for every i . Therefore, we can model the overall error of the relaxation as:

$$1 - \frac{n_1(m_1 - r_1) + n_2(m_2 - r_2) + \dots + n_k(m_k - r_k) + c}{n_1m_1 + n_2m_2 + \dots + n_km_k + c}$$

That is,

$$1 - \frac{n_1m_1 + n_2m_2 + \dots + n_km_k + c}{n_1m_1 + n_2m_2 + \dots + n_km_k + c} + \frac{n_1r_1 + n_2r_2 + \dots + n_kr_k}{n_1m_1 + n_2m_2 + \dots + n_km_k + c} =$$

$$\frac{n_1r_1 + n_2r_2 + \dots + n_kr_k}{n_1m_1 + n_2m_2 + \dots + n_km_k + c}$$

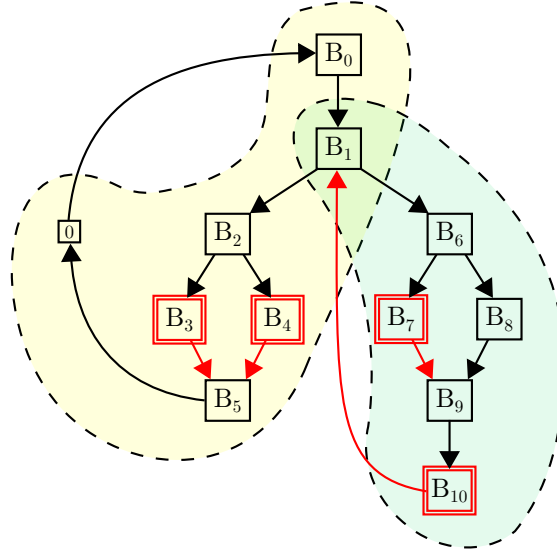


Figure 5.4: Example of a CFG containing a loop and its decomposition into extended DAGs when applying the relaxation.

If $\frac{r_j}{m_j}$ is the maximum ratio $\frac{r_i}{m_i}$ for every i , then

$$\begin{aligned} \frac{n_1 r_1 + n_2 r_2 + \dots + n_k r_k}{n_1 m_1 + n_2 m_2 + \dots + n_k m_k + c} &\leq \\ \frac{n_1 r_j + n_2 r_j + \dots + n_k r_j}{n_1 m_j + n_2 m_j + \dots + n_k m_j + c} &\leq \\ \frac{n_1 r_j + n_2 r_j + \dots + n_k r_j}{n_1 m_j + n_2 m_j + \dots + n_k m_j} \end{aligned}$$

If $N = \max\{n_i \text{ for every } i\}$, then

$$\begin{aligned} \frac{n_1 r_j + n_2 r_j + \dots + n_k r_j}{n_1 m_j + n_2 m_j + \dots + n_k m_j} &\leq \\ \frac{N r_j + N r_j + \dots + N r_j}{N m_j + N m_j + \dots + N m_j} &\leq \\ \frac{N k r_j}{N k m_j} = \frac{r_j}{m_j} &\leq T \end{aligned}$$

While the optimal placement of probes tries to place probes in edges that are less likely to be executed, the relaxation focus on removing probes that are more likely to be executed. The necessary block frequency information for optimising both the placement of probes can be acquired from profiles of previous executions of the program or by a static heuristic of the CFG during compilation.

For our experiments, we implemented two solvers for the 0-1 Knapsack problem: the optimal brute-force solver; the greedy heuristic based on sorting the items (Dantzig,

1957). We use the brute-force solver for DAGs with a small number of probes and the greedy heuristic when the number of probes is greater than a threshold. Some of the benchmarks have DAGs with several hundreds of probes, which could result in a long compilation time.

5.3 Other Possible Uses

Talk about how this instrumentation techniques (relaxation) could be applied to other profiling-based mechanism to estimate input sizes (Zaparanuks and Hauswirth, 2012; Coppa et al., 2014), namely *read memory size*

Chapter 6

Experimental Evaluation

In this section we discuss our experimental evaluation. First we describe the benchmarks with datasets used in the experiments. Afterwards, we discuss our results concerning the instrumentations for profiling our work metric. Finally we present the results of the online iterative compilation.

We implemented the instrumentations in LLVM 4.0. The target platform is a Linux-4.4.27 system with an Intel Core i7-4770 3.40GHz Skylake CPU with 16 GiB RAM.

6.1 Benchmarks

For the experimental evaluation we have used a subset of the *KDataSets* benchmark suit, which is the same benchmark and dataset suit used by Chen et al. Chen et al. (2010, 2012b). The *KDataSets* contains 1000 different inputs for each one of its benchmark programs. These benchmarks cover a broad spectrum of application scenarios, ranging from simple embedded signal-processing tasks to common mobile-phone and desktop tasks. The different inputs try to capture distinct characteristics in terms of workload sizes and how these workloads exercise different control flow paths. A summary of the benchmark and dataset suit is shown in Table 6.1.

6.2 Evaluation of the Instrumentation

In this section we evaluate the

Static results. Figure 6.4 shows percentage of instrumented basic blocks for the optimal and the relaxed instrumentation with different relaxation thresholds. The naive instrumentation always has 100% of the basic blocks instrumented, by definition.

Program	LOC	Input file size	Input description
qsort	154	32K-1.8M	3D coordinates
jpeg_d	13501	3.6K-1.5M	JPEG images
jpeg_c	14014	16K-137M	PPM images
tiff2bw	15477	9K-137M	TIFF images
tiff2rgba	15424		
tiffdither	15399		
tiffmedian	15870		
susan_c	1376	12K-46M	PGM images
susan_e	1376		
susan_s	1376		
adpcm_c	210	167K-36M	WAVE audios
adpcm_d	211	21K-8.8M	ADPCM audios
rsynth	4111		Text files
sha	197	0.6K-35M	Files of any format

Table 6.1: Description of the KDataSets with 1000 inputs for each benchmark (Chen et al. Chen et al. (2010, 2012b)).

Overhead results. Figure 6.3 shows overhead results. The `adpcm_d` benchmark is the most critical case amongst the evaluated benchmarks, with an overhead of about 62% with the optimal instrumentation. This benchmark consists mainly of a single hot loop with several branches inside it. The relaxation algorithm is able to reduce this overhead down to about 52% (with an error threshold of 1%) and 19% (with an error threshold of 2%) by removing only one and two probes from the hot loop, respectively. These two removed probes were placed in branches, inside the hot loop, with a high probability of being taken, but with a small contribution to the work measured in the loop.

Profile-guided Instrumentation.

Code size.

6.2.1 Case Studies

6.3 Evaluation of the Online Iterative Compilation

- Oracle-RM executes the program twice, for each input, and then measuring the real speedup for each compiler optimisation and uses the real speedup for selecting the best optimisation.

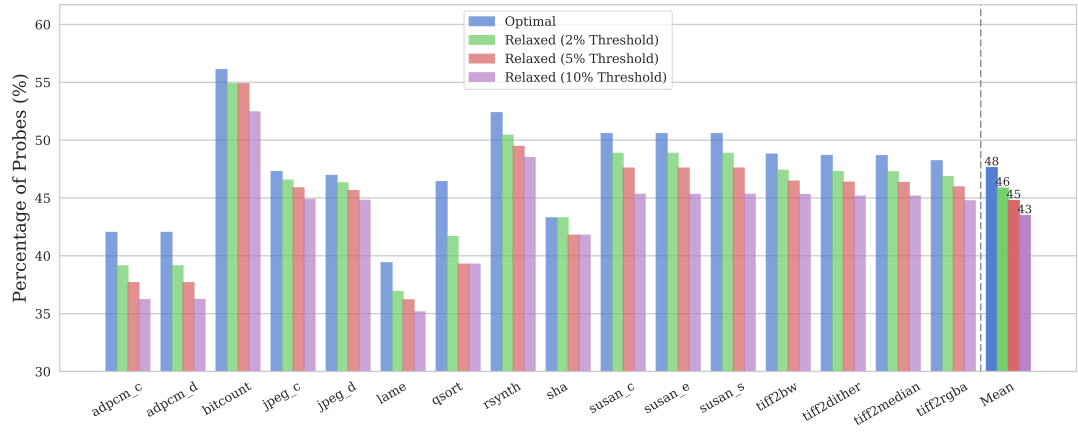


Figure 6.1: Percentage of instrumented basic blocks for the optimal and the relaxed instrumentation with different relaxation thresholds.

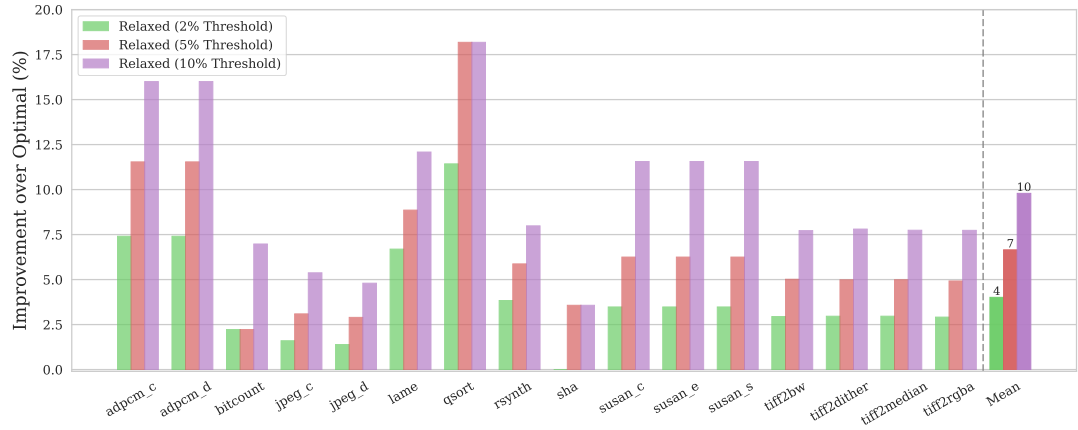


Figure 6.2: Percentage of instrumented basic blocks for the optimal and the relaxed instrumentation with different relaxation thresholds.

- Oracle-PP represents the *perfect* non-intrusive profiling by also executing the program twice, once for estimating the amount of work and the second for measuring its execution time. This version uses the work-based metric, $\frac{\Delta W}{\Delta t}$, during the iterative compilation search.

6.4 Summary

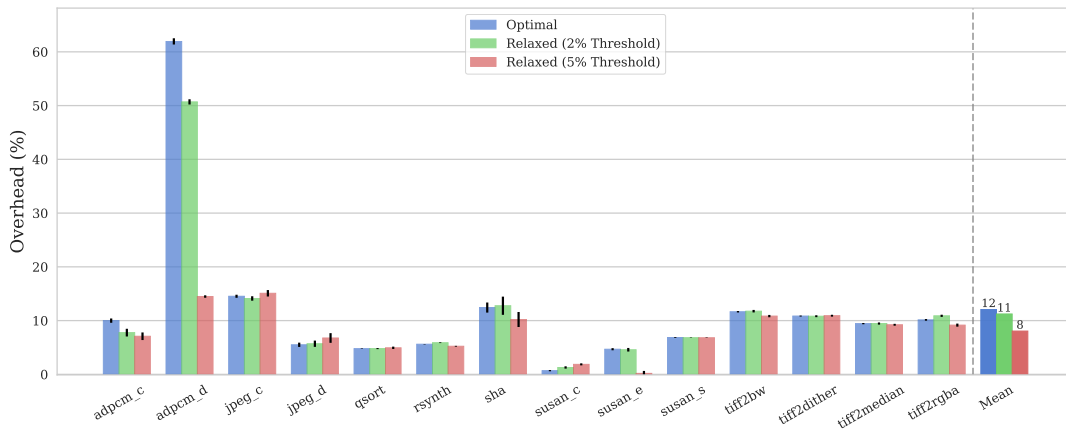
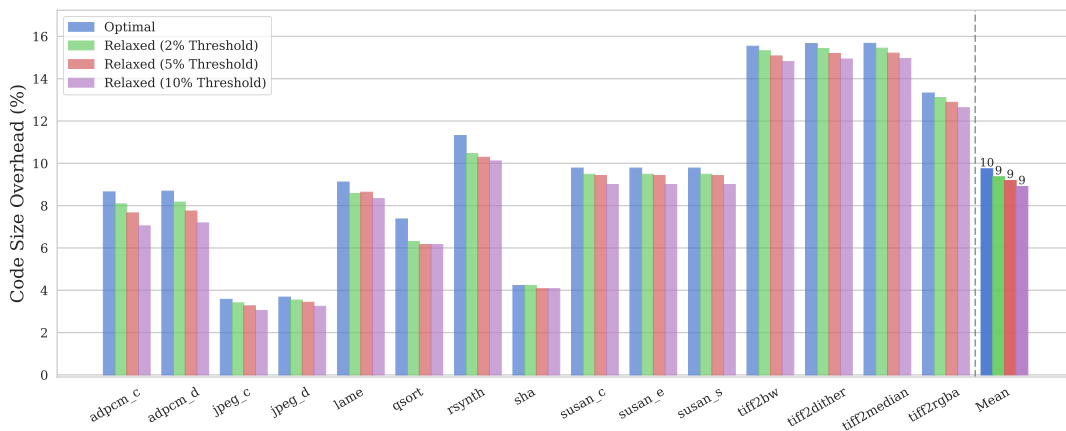
Figure 6.3: Overhead of the instrumentations compiled with `-O3`.

Figure 6.4: Percentage of instrumented basic blocks for the optimal and the relaxed instrumentation with different relaxation thresholds.

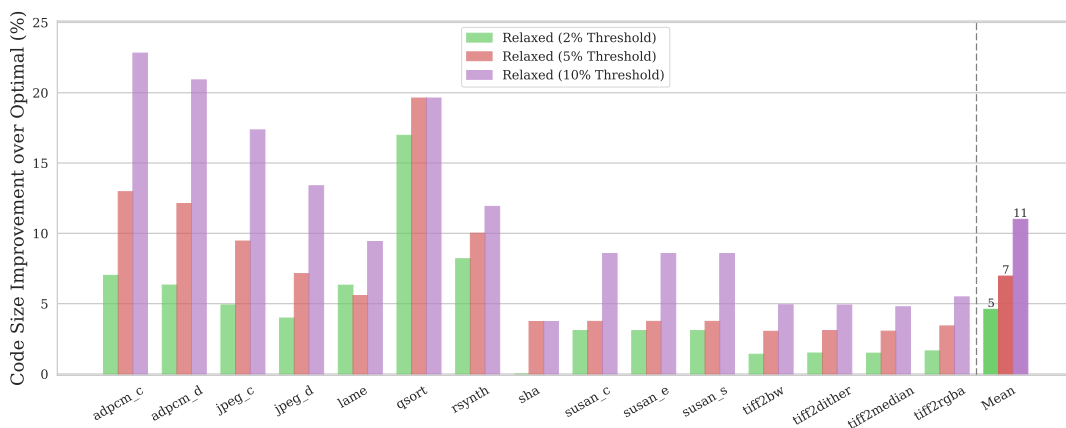


Figure 6.5: Percentage of instrumented basic blocks for the optimal and the relaxed instrumentation with different relaxation thresholds.

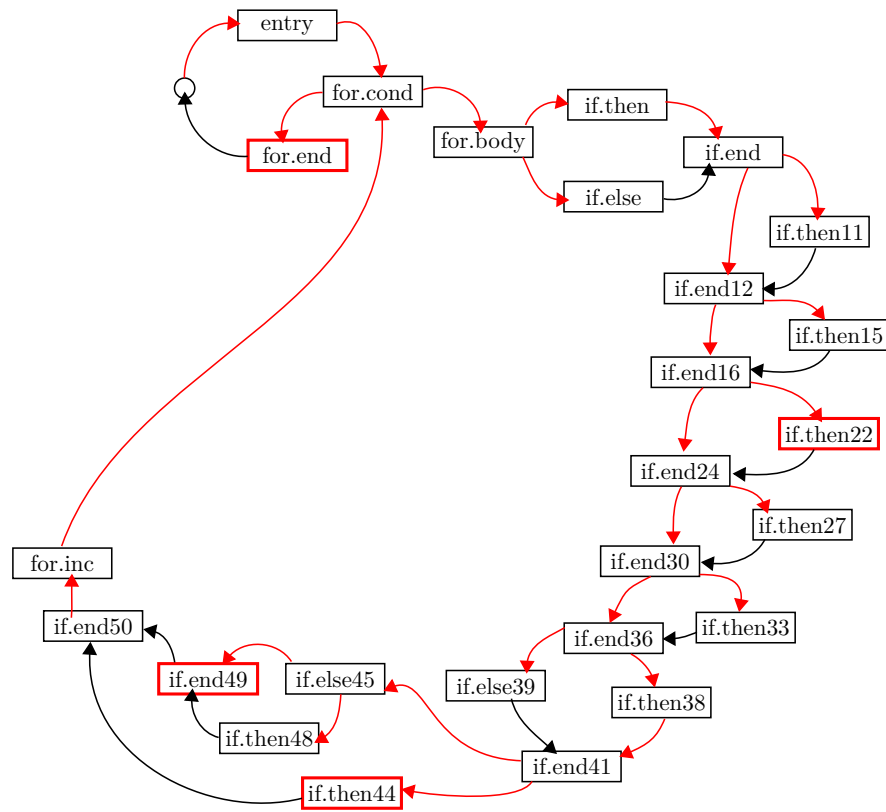
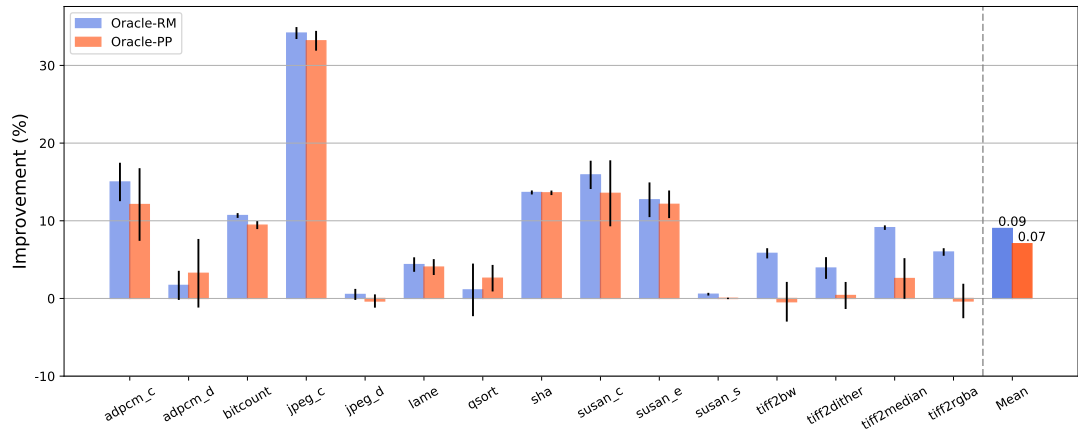
Figure 6.6: CFG of the main function in the `adpcm_d` benchmark.

Figure 6.7: Speedups observed with the online iterative compilation.

Chapter 7

Conclusions and Future Work

Bibliography

- Adve, V., Lattner, C., Brukman, M., Shukla, A., and Gaeke, B. (2003). Llva: A low-level virtual instruction set architecture. In *Proceedings of the 36th Annual IEEE/ACM International Symposium on Microarchitecture*, MICRO 36, pages 205–, Washington, DC, USA. IEEE Computer Society.
- Agakov, F., Bonilla, E., Cavazos, J., Franke, B., Fursin, G., O’Boyle, M. F. P., Thomson, J., Toussaint, M., and Williams, C. K. I. (2006). Using machine learning to focus iterative optimization. In *International Symposium on Code Generation and Optimization (CGO’06)*, pages 1–11.
- Alameldeen, A. R. and Wood, D. A. (2006). IPC considered harmful for multiprocessor workloads. *IEEE Micro*, 26(4):8–17.
- Allen, F. E. (1970). Control flow analysis. In *Proceedings of a Symposium on Compiler Optimization*, pages 1–19, New York, NY, USA. ACM.
- Alpern, B., Wegman, M. N., and Zadeck, F. K. (1988). Detecting equality of variables in programs. In *Proceedings of the 15th ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages*, POPL ’88, pages 1–11, New York, NY, USA. ACM.
- Ball, T. and Larus, J. R. (1993). Branch prediction for free. In *Proceedings of the ACM SIGPLAN 1993 Conference on Programming Language Design and Implementation*, PLDI ’93, pages 300–313, New York, NY, USA. ACM.
- Ball, T. and Larus, J. R. (1994). Optimally profiling and tracing programs. *ACM Trans. Program. Lang. Syst.*, 16(4):1319–1360.
- Ball, T. and Larus, J. R. (1996). Efficient path profiling. In *Proceedings of the 29th Annual ACM/IEEE International Symposium on Microarchitecture*, MICRO 29, pages 46–57, Washington, DC, USA. IEEE Computer Society.

- Bodin, F., Kisuki, T., Knijnenburg, P., O' Boyle, M., and Rohou, E. (1998). Iterative compilation in a non-linear optimisation space. In *Workshop on Profile and Feedback-Directed Compilation*, Paris, France.
- Brandolese, C., Corbetta, S., and Fornaciari, W. (2011). Software energy estimation based on statistical characterization of intermediate compilation code. In *Proceedings of the 17th IEEE/ACM International Symposium on Low-power Electronics and Design*, ISLPED '11, pages 333–338, Piscataway, NJ, USA. IEEE Press.
- Cavazos, J., Fursin, G., Agakov, F., Bonilla, E., O'Boyle, M. F. P., and Temam, O. (2007). Rapidly selecting good compiler optimizations using performance counters. In *International Symposium on Code Generation and Optimization (CGO'07)*, pages 185–197.
- Chen, Y., Fang, S., Eeckhout, L., Temam, O., and Wu, C. (2012a). Iterative optimization for the data center. In *Proceedings of the Seventeenth International Conference on Architectural Support for Programming Languages and Operating Systems, ASPLOS XVII*, pages 49–60, New York, NY, USA. ACM.
- Chen, Y., Fang, S., Huang, Y., Eeckhout, L., Fursin, G., Temam, O., and Wu, C. (2012b). Deconstructing iterative optimization. *ACM Trans. Archit. Code Optim.*, 9(3):21:1–21:30.
- Chen, Y., Huang, Y., Eeckhout, L., Fursin, G., Peng, L., Temam, O., and Wu, C. (2010). Evaluating iterative optimization across 1000 datasets. In *Proceedings of the 31st ACM SIGPLAN Conference on Programming Language Design and Implementation, PLDI '10*, pages 448–459, New York, NY, USA. ACM.
- Coppa, E., Demetrescu, C., and Finocchi, I. (2014). Input-sensitive profiling. *IEEE Transactions on Software Engineering*, 40(12):1185–1205.
- Cytron, R., Ferrante, J., Rosen, B. K., Wegman, M. N., and Zadeck, F. K. (1989). An efficient method of computing static single assignment form. In *Proceedings of the 16th ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages*, POPL '89, pages 25–35, New York, NY, USA. ACM.
- Cytron, R., Ferrante, J., Rosen, B. K., Wegman, M. N., and Zadeck, F. K. (1991). Efficiently computing static single assignment form and the control dependence graph. *ACM Trans. Program. Lang. Syst.*, 13(4):451–490.

- Dantzig, G. B. (1957). Discrete-variable extremum problems. *Operations Research*, 5(2):266–288.
- Eyerman, S. and Eeckhout, L. (2008). System-level performance metrics for multiprogram workloads. *IEEE Micro*, 28(3):42–53.
- Fang, S., Xu, W., Chen, Y., Eeckhout, L., Temam, O., Chen, Y., Wu, C., and Feng, X. (2015). Practical iterative optimization for the data center. *ACM Trans. Archit. Code Optim.*, 12(2):15:1–15:26.
- Forman, I. R. (1981). On the time overhead of counters and traversal markers. In *Proceedings of the 5th International Conference on Software Engineering*, ICSE '81, pages 164–169, Piscataway, NJ, USA. IEEE Press.
- Fursin, G., Cavazos, J., O'Boyle, M., and Temam, O. (2007). MiDataSets: Creating the conditions for a more realistic evaluation of iterative optimization. In *Proceedings of the 2Nd International Conference on High Performance Embedded Architectures and Compilers*, HiPEAC'07, pages 245–260, Berlin, Heidelberg. Springer-Verlag.
- Giusto, P., Martin, G., and Harcourt, E. (2001). Reliable estimation of execution time of embedded software. In *Proceedings of the Conference on Design, Automation and Test in Europe*, DATE '01, pages 580–589, Piscataway, NJ, USA. IEEE Press.
- Goldsmith, S. F., Aiken, A. S., and Wilkerson, D. S. (2007). Measuring empirical computational complexity. In *Proceedings of the the 6th Joint Meeting of the European Software Engineering Conference and the ACM SIGSOFT Symposium on The Foundations of Software Engineering*, ESEC-FSE '07, pages 395–404, New York, NY, USA. ACM.
- Haneda, M., Knijnenburg, P. M. W., and Wijshoff, H. A. G. (2006). On the impact of data input sets on statistical compiler tuning. In *Proceedings 20th IEEE International Parallel Distributed Processing Symposium*, pages 1–8.
- Kisuki, T., Knijnenburg, P. M. W., O'Boyle, M. F. P., Bodin, F., and Wijshoff, H. A. G. (1999). *A feasibility study in iterative compilation*, pages 121–132. Springer Berlin Heidelberg, Berlin, Heidelberg.
- Knuth, D. E. (1971). An empirical study of FORTRAN programs. *Software: Practice and Experience*, 1(2):105–133.

- Knuth, D. E. and Stevenson, F. R. (1973). Optimal measurement points for program frequency counts. *BIT Numerical Mathematics*, 13(3):313–322.
- Kulkarni, P., Hines, S., Hiser, J., Whalley, D., Davidson, J., and Jones, D. (2004). Fast searches for effective optimization phase sequences. In *Proceedings of the ACM SIGPLAN 2004 Conference on Programming Language Design and Implementation*, PLDI '04, pages 171–182, New York, NY, USA. ACM.
- Kulkarni, S. and Cavazos, J. (2012). Mitigating the compiler optimization phase-ordering problem using machine learning. In *Proceedings of the ACM International Conference on Object Oriented Programming Systems Languages and Applications*, OOPSLA '12, pages 147–162, New York, NY, USA. ACM.
- Lattner, C. and Adve, V. (2004). Llvm: A compilation framework for lifelong program analysis & transformation. In *Proceedings of the International Symposium on Code Generation and Optimization: Feedback-directed and Runtime Optimization*, CGO '04, pages 75–, Washington, DC, USA. IEEE Computer Society.
- Mpeis, P., Petoumenos, P., and Leather, H. (2016). Iterative compilation on mobile devices. In *Proceedings of the 6th International Workshop on Adaptive Self-tuning Computing Systems (ADAPT 2016)*.
- Nahapetian, A. (1973). Node flows in graphs with conservative flow. *Acta Informatica*, 3(1):37–41.
- Pan, Z. and Eigenmann, R. (2006). Fast and effective orchestration of compiler optimizations for automatic performance tuning. In *Proceedings of the International Symposium on Code Generation and Optimization*, CGO '06, pages 319–332, Washington, DC, USA. IEEE Computer Society.
- Powell, D. C. and Franke, B. (2009). Using continuous statistical machine learning to enable high-speed performance prediction in hybrid instruction-/cycle-accurate instruction set simulators. In *Proceedings of the 7th IEEE/ACM International Conference on Hardware/Software Codesign and System Synthesis*, CODES+ISSS '09, pages 315–324, New York, NY, USA. ACM.
- Shafer, G. et al. (1976). *A mathematical theory of evidence*, volume 1. Princeton university press Princeton.

- Stephenson, M., Amarasinghe, S., Martin, M., and O'Reilly, U.-M. (2003). Meta optimization: Improving compiler heuristics with machine learning. In *Proceedings of the ACM SIGPLAN 2003 Conference on Programming Language Design and Implementation*, PLDI '03, pages 77–90, New York, NY, USA. ACM.
- Touati, S.-A.-A. and Barthou, D. (2006). On the decidability of phase ordering problem in optimizing compilation. In *Proceedings of the 3rd Conference on Computing Frontiers*, CF '06, pages 147–156, New York, NY, USA. ACM.
- Wagner, T. A., Maverick, V., Graham, S. L., and Harrison, M. A. (1994). Accurate static estimators for program optimization. In *Proceedings of the ACM SIGPLAN 1994 Conference on Programming Language Design and Implementation*, PLDI '94, pages 85–96, New York, NY, USA. ACM.
- Wu, Y. and Larus, J. R. (1994). Static branch frequency and program profile analysis. In *Proceedings of the 27th Annual International Symposium on Microarchitecture*, MICRO 27, pages 1–11, New York, NY, USA. ACM.
- Zaparanuks, D. and Hauswirth, M. (2012). Algorithmic profiling. In *Proceedings of the 33rd ACM SIGPLAN Conference on Programming Language Design and Implementation*, PLDI '12, pages 67–76, New York, NY, USA. ACM.
- Zhou, Y. Q. and Lin, N. W. (2012). A study on optimizing execution time and code size in iterative compilation. In *2012 Third International Conference on Innovations in Bio-Inspired Computing and Applications*, pages 104–109.