A Comparison of Empirical and Model-driven Optimization
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Abstract—A key step in program optimization is the estimation of optimal values for parameters such as tile sizes and loop unrolling factors. Traditional compilers use simple analytical models to compute these values. In contrast, library generators like ATLAS use global search over the space of parameter values by generating programs with all combinations of parameter values, and running them on the actual hardware to determine which values give the best performance. It is widely believed that traditional model-driven optimization cannot compete with search-based empirical optimization because tractable analytical models cannot capture all the complexities of modern high-performance architectures, but few quantitative comparisons have been done to date.

To make such a comparison, we replaced the global search engine in ATLAS with a model-driven optimization engine, and measured the relative performance of the code produced by the two systems on a variety of modern high-performance architectures. Since both systems use the same code generator, any differences in the performance of the code produced by the two systems can come only from differences in optimization parameter values used by the two systems. Our experiments on ten different platforms show that model-driven optimization can be surprisingly effective, and can generate code with performance comparable to that of code generated by ATLAS using global search.

I. INTRODUCTION

The compiler community has developed a lot of technology for transforming high-level programs into programs that run efficiently on modern high-performance architectures [21], [10], [2]. Some of this work has introduced program transformations such as linear loop transformations [4], [24], [19], [7], loop tiling [25], [17], [18] and loop unrolling [2], for enhancing locality and parallelism. Other work has focused on analytical techniques for estimating optimal values for parameters associated with some of these transformations, such as tile sizes [22], [9], [5] and loop unroll factors [2]. Nevertheless, it is a fact universally recognized that current restructuring compilers do not generate code that can compete with hand-written code in efficiency even for a simple kernel like matrix multiplication. Therefore, performance-conscious programmers must still optimize their programs manually for each target platform, using a tedious trial and error procedure [13], [11].

A novel alternative to the tedium of manual optimization is to use self-tuning code generation. To produce an optimized matrix-matrix multiplication (MMM) routine, for example, a self-tuning system would generate a large number of programs for performing MMM, run all of them on the actual machine, and select the one that gives the best performance. The generated programs usually implement the same algorithm, but differ in the values they use for parameters such as tile sizes or loop unroll factors. In effect, the analytical techniques used in current compilers to derive optimal values for such parameters are replaced by a search over a suitably restricted space of parameter values. This self-tuning or empirical optimization approach is used by successful library generators such as ATLAS [23], which generates highly tuned Basic Linear Algebra Subroutines (BLAS), and FFTW [12] and SPIRAL [16], which generate FFT libraries. Experience shows that these library generators produce much better code than native compilers do on a wide range of modern high-performance architectures.

Our work was motivated by the desire to understand the performance gap between the codes produced by library generators and by restructuring compilers. One reason that compilers might be at a disadvantage is that they are general-purpose and must be able to optimize any program, whereas a library generator like ATLAS can focus on a particular problem domain. However, dense numerical linear algebra, the problem domain of ATLAS, is precisely the area that has been studied most intensely by the compiler community, and there is an extensive collection of well-understood transformations for optimizing dense linear algebra programs. Another reason might be that new transformations, unknown to the compiler community, are required to produce code of the same quality as the code produced by ATLAS. Even if there are no transformations missing from the compiler writer’s repertoire, it might be that compilers are performing transformations in the wrong order (the so-called “phase-ordering problem”). Finally, if phase-ordering is not an issue, perhaps the analytical models used by compilers to estimate optimal values for transformation parameters are overly simplistic, given the complex hardware of modern computers, so they are not able to produce good values for program optimization parameters.

To the best of our knowledge, no definitive studies exist to settle these matters.

Our research provides the first quantitative evaluation of the relative effectiveness of empirical search and analytical modelling in generating highly optimized code.

Figure 1 shows our experimental set-up, which makes use of the original ATLAS system (top of the figure) and a modified version (bottom of the figure) that uses analytical models instead of empirical search. Like any system that uses
empirical optimization, ATLAS has (i) a module that controls a

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global search that is used to determine optimal values for code

optimization parameters (mmsearch), and (ii) a module that

generates code, given these values (mmcase). The parameters

used by ATLAS are described in more detail in Section II;

for example, \( N_B \) is the tile size to be used when optimizing
code for the L1 data cache. In general, there is an unbounded
number of possible values for a parameter like \( N_B \) so it

is necessary to bound the size of the search space. When

ATLAS is installed, it first runs a set of micro-benchmarks
to determine hardware parameters such as the capacity of the
L1 data cache and the number of registers. These hardware
parameters are used to bound the search space. The mmsearch
module essentially enumerates each point within this bounded
search space, invokes the mmcase module to generate the
appropriate code (denoted by mini-MMM in the figure), runs
this code on the actual machine, and records its execution
time. At the end of the search, the parameter values that gave
the best performance are used to generate the library code. This
library code is a simple subset of C, which can be viewed
as portable assembly code, and it is compiled using a native
compiler such as GCC to produce the final executable.

We first studied the code generation module\(^1\), and deter-
mined that the code it produces can be viewed as the end result
of applying standard compiler transformations to high-level
BLAS codes, as described in Section II. This exercise was
necessary to rule out the possibility that ATLAS incorporated
some transformation, unknown to the compiler community,
that was critical for obtaining good performance. We also
verified that there was no phase-ordering problem with these
transformations. We then modified ATLAS by replacing the
search module, described in more detail in Section III, with
a module (mmmodel) that uses standard analytical models to
estimate optimal values for the optimization parameters, as
described in Section IV. Since both ATLAS and the modified
ATLAS use the same code generator, we are assured that
any difference in the performance of the generated code
results solely from different choices for optimization parameter
values. In Section V, we present experimental results on ten
different platforms, comparing

- the time spent to determine the parameter values,
- the values of the parameters, and

\(^1\)The description of ATLAS in this paper was arrived at by studying the

ATLAS source code. In case of any discrepancy between this description and

how the ATLAS system is actually implemented, the papers written by the

ATLAS project should be considered to be authoritative [23].
A. Memory Hierarchy Optimizations

The code shown in Figure 2 can be optimized by tiling for the L1 data cache and registers.

- **Optimization for the L1 data cache:**

  To improve locality, ATLAS implements an MMM as a sequence of mini-MMMS, where each mini-MMM multiplies sub-matrices of size \( N_B \times N_B \). \( N_B \) is an optimization parameter whose value must be chosen so that the working set of the mini-MMM fits in the L1 cache.

  In the terminology of restructuring compilers, the triply-nested loop of Figure 2 is tiled with tiles of size \( N_B \times N_B \), producing an outer and an inner loop nest. For the outer loop nest, code for both the JIK and IJK loop orders are implemented. When the MMM library routine is called, it uses the shapes of the input arrays to decide which version to invoke. For the inner loop nest, only the JIK loop order is used, with \((j', i', k')\) as control variables. This inner loop nest multiplies sub-matrices of size \( N_B \times N_B \), and we call this computation a mini-MMM.

- **Optimization for the register file:** ATLAS converts each mini-MMM into a sequence of micro-MMMS, where each micro-MMM multiplies an \( M_U \times 1 \) sub-matrix of \( A \) with a \( 1 \times N_U \) sub-matrix of \( B \) and accumulates the result into an \( M_U \times N_U \) sub-matrix of \( C \). \( M_U \) and \( N_U \) are optimization parameters that must be chosen so that a micro-MMM can be executed out of the floating-point registers. For this to happen, it is necessary that \( M_U + N_U + M_U \times N_U \leq N_B \), where \( N_B \) is the number of floating-point registers.

  In terms of restructuring compiler terminology, the \((j', i', k')\) loops of the mini-MMM from the previous step are tiled with tiles of size \( N_U \times M_U \times K_U \), producing an extra (inner) loop nest. The JIK loop order is chosen for the outer loop nest after tiling, and the KJI loop order for the inner loop nest.

  The resulting code after the two tiling steps is shown in Figure 3. To keep this code simple, we have assumed that all step sizes in these loops divide the appropriate loop bounds exactly (so \( N_B \) divides \( M, N, \) and \( K \), etc.). In reality, code should also be generated to handle the fractional tiles at the boundaries of the three arrays; we omit this clean-up code to avoid complicating the description. The strategy used by ATLAS to copy blocks of the arrays into contiguous storage is discussed later in this section. Figure 4 is a pictorial view of a mini-MMM computation within which a micro-MMMM is shown using shaded rectangles.

  To perform register allocation for the array variables referenced in the micro-MMMM code, the micro-MMMM loop nest \((j'', i'')\) in Figure 3 is fully unrolled, producing \( M_U \times N_U \) multiply-add statements in the body of the middle loop nest. In the unrolled loop body, each array element is accessed several times. To enable register allocation of these array elements, ATLAS introduces a scalar temporary for each element of \( A, B, \) and \( C \) that is referenced in the unrolled micro-MMMM code, and replaces array references in the unrolled micro-MMMM code with references to these scalars. Appropriate assignment statements are introduced to initialize the scalars corresponding to \( A \) and \( B \) elements. In addition, assignment statements are introduced before and after the \( k' \) loop to initialize the scalars corresponding to \( C \) elements, and to write the values back into the array respectively. It is expected that the back-end compiler will allocate floating-point registers for these scalars.

B. Pipeline scheduling

The resulting straight-line code in the body of the \( k'' \) loop is scheduled to make optimal use of the processor pipeline. Note that the operations in the \( k'' \) loop are the \( M_U + N_U \) loads of \( A \) and \( B \) elements required for the micro-MMMM, and the corresponding \( M_U \times N_U \) multiplications and additions. On hardware architectures that have a fused multiply-add instruction, the scheduling problem is much simpler because multiplies and adds are executed together. Therefore, we only discuss the more interesting case when a multiply-add instruction is not present. An optimization parameter \( FMA \) tells the code generator whether to assume that a fused multiply-add exists. The scheduling of operations can be described as follows.

- Construct two sequences of length \((M_U \times N_U)\), one containing the multiply operations and the other the add operations.
Interleave the two sequences, to create a single sequence of the form \(mul_1 \, mul_2 \, ... \, mul_L, \, add_1 \, mul_{L+1}, \, add_2 \, ...\) that is obtained by skewing the adds by a factor of \(L_s\), where \(L_s\) is an optimization parameter. Intuitively, this interleaving separates most dependent multiplies and adds by \(2 \times L_s - 1\) other independent instructions to avoid stalling the processor pipeline.

- Inject the \(M_U + N_U\) loads of the elements of \(A\) and \(B\) into the resulting sequence of arithmetic operations by scheduling a block of \(I_F\) (Initial Fetch) loads in the beginning and blocks of \(N_F\) loads thereafter as needed. \(I_F\) and \(N_F\) are optimization parameters.
- Unroll the \(k^{th}\) loop completely. The parameter \(K_U\) must be chosen to be large enough to reduce loop overhead, but not so large the body of the \(k^{th}\) loop overflows the L1 instruction cache.
- Software pipeline the \(k^{th}\) loop in such a way that some loads for one iteration are overlapped with arithmetic operations from the previous iteration.

Note that skewing of dependent adds and multiplies increases register pressure; in particular, the following inequality must hold to avoid register spills:

\[ M_U \times N_U + M_U + N_U + L_s \leq N_R \quad (1) \]

C. Additional details

There are several details we have not discussed so far.

- ATLAS chooses the outermost loop order (shown as JIK in Figure 3) during runtime. This technique is known as versioning, because it requires both versions of the code to be compiled in the library.
- The decision of which loop order to choose is based on the size of matrices \(A\) and \(B\). If \(A\) has fewer elements than \(B\) \((N < M)\), ATLAS chooses the JIK loop order. This guarantees that if \(A\) fits completely in L2 or higher cache level, it is reused successfully by the loop nest. By analogy, if \(B\) is the smaller matrix \((M < N)\), ATLAS chooses the IKJ loop order.
- For brevity, we consider only the JIK loop order in the rest of the paper.
- ATLAS usually copies tiles of matrices \(A\), \(B\) and \(C\) to sequential memory to reduce the number of conflict misses during the execution of a mini-MMM. If the matrices are large, copying can also reduce the number of TLB misses. Copying is performed in a manner that allows the copied tiles to be reused by different mini-MMMs. The comments in the pseudo-code in Figure 3 explain how this goal is achieved. For the JIK loop order ATLAS copies to contiguous memory as follows.
  - Copy all tiles of \(A\) before the beginning of the outermost \(j\) loop. This is necessary as these tiles are fully reused in each iteration of the \(j\) loop.
  - Copy all tiles from the \(j^{th}\) vertical panel of \(B\) before the beginning of the \(i\) loop. This is necessary as this panel is fully reused by each iteration of the \(i\) loop.
  - Copy the single \((i, j)\) tile of \(C\) before the beginning of the \(k\) loop. This is necessary as this tile is reused by each iteration of the \(k\) loop.

If the matrices are very small or if there is insufficient memory for copying tiles, the cost of copying might outweigh the benefits of reducing conflict misses during the computation. Therefore, ATLAS generates non-copying versions of mini-MMM as well, and decides at runtime which version to use. Without copying, the number of conflict misses and TLB misses may rise, so it makes sense to use a smaller tile size for the non-copying mini-MMM. In ATLAS, this tile size is another optimization parameter called \(N \times N_B\) (non-copying \(N_B\)). Roughly speaking, the non-copy version is used if (i) the amount of computation is less than some threshold \((M \times N \times K\) in Figure 2 is less than some threshold), and (ii) at least one dimension of one of the three matrices is smaller than \(3 \times NCN_B\). The non-copy version is used also when there is insufficient memory to perform the copying.

- ATLAS considers a primitive form of L2 cache tiling, driven by a parameter called CopyEdge. We will not discuss this parameter in this paper as our primary goal is to improve the mini-MMMM, which is independent of the actual CopyEdge value.

D. Discussion

Table I lists the optimization parameters for future reference.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N_B)</td>
<td>L1 data cache tile size</td>
</tr>
<tr>
<td>(NCN_B)</td>
<td>L1 data cache tile size for non-copying version</td>
</tr>
<tr>
<td>(M_U, N_U)</td>
<td>Register tile size</td>
</tr>
<tr>
<td>(K_U)</td>
<td>Unroll factor for (k^{th}) loop</td>
</tr>
<tr>
<td>(L_s)</td>
<td>Latency for computation scheduling</td>
</tr>
<tr>
<td>(FMA)</td>
<td>1 if fused multiply-add, 0 otherwise</td>
</tr>
<tr>
<td>(F_U, I_F, N_F)</td>
<td>Scheduling of loads</td>
</tr>
</tbody>
</table>

Table I: Summary of Optimization Parameters

It is intuitively obvious that the performance of the generated mini-MMMM code suffers if the values of the optimization parameters in Table I are too small or too large. For example, if \(M_U\) and \(N_U\) are too small, the \(M_U \times N_U\) block of computation instructions might not be large enough to hide the latency of the \(M_U + N_U\) loads, and performance suffers. On the other hand, if these parameters are too large, register spills will reduce performance. Similarly, if the value of \(K_U\) is too small, there is more loop overhead, but if this value is too big, the code in the body of the \(k^{th}\) loop will overflow the instruction cache and performance will suffer. The goal now is to determine optimal values of these parameters for obtaining the best mini-MMMM code.

III. Empirical Optimization in ATLAS

ATLAS performs a global search to determine optimal values for the optimization parameters listed in Table I. In principle, the search space is unbounded because most of the parameters, such as \(N_B\), are integers. Therefore, it is necessary...
to bound the search space, using parameters of the machine hardware; for example, $M_U$ and $N_U$, the dimensions of the register tile, must be less than number of registers.

Since ATLAS is self-tuning, it does not require the user to provide the values of such machine parameters; instead, it runs simple micro-benchmarks to determine approximate values for these parameters. It then performs a global search, using the machine parameter values to bound the search space.

A. Estimating machine parameters

The machine parameters measured by ATLAS are the following.

- $C_1$: the size of L1 data cache.
- $N_R$: the number of floating-point registers.
- $FMA$: the availability of a fused multiply-add instruction.
- $L_z$: although this is not a hardware parameter per se, ATLAS measures this optimization parameter directly using micro-benchmarks.

The micro-benchmarks used to measure these parameters are independent of matrix multiplication. For example, the micro-benchmark for estimating $C_1$ is similar to the one discussed in Hennessy and Patterson [14].

Two other machine parameters are critical for performance: (i) the L1 instruction cache size, and (ii) the number of outstanding loads that the hardware supports. ATLAS does not determine these explicitly using micro-benchmarks; instead, they are considered implicitly during the optimization of matrix multiplication code. For example, the size of the L1 instruction cache limits the $K_U$ parameter in Figure 3. Rather than estimate the size of the instruction cache directly by running a micro-benchmark and using that to determine the amount of unrolling, ATLAS generates a suite of mini-MMM kernels with different $K$ values, and selects the kernel that achieves best performance.

B. Global search for optimization parameter values

To find optimal values for the optimization parameters in Table I, ATLAS uses orthogonal search, which finds an approximation to the optimal value of a function $y = f(x_1, x_2, ..., x_n)$, an $n$-dimensional optimization problem, by solving a sequence of $n$ 1-dimensional optimization problems corresponding to each of the $n$ parameters. When optimizing the value of parameter $x_i$, it uses reference values for parameters $x_{i+1}, x_{i+2}, ..., x_n$, which have not yet been optimized. Orthogonal range search is an approximate method because it does not necessarily find the optimal value even for a convex function, but with luck, it might come close.

To specify an orthogonal range search, it is necessary to specify (i) the order in which the parameters are optimized, (ii) the set of possible values considered during the optimization of each parameter, and (iii) the reference value used for parameter $k$ during the optimization of parameters $1, 2, ..., k - 1$.

The optimization sequence used in ATLAS is the following.
1) Find best $N_B$.
2) Find best $M_U$ and $N_U$.
3) Find best $K_U$.
4) Find best $L_s$.
5) Find best $F_F$, $I_F$, and $N_F$.
6) Find best $N_CN_B$; a non-copy version of $N_B$.
7) Find best cleanup codes.

We now discuss each of these steps in greater detail.

1) Find best $N_B$: In this step, ATLAS generates a number of mini-MMMs for matrix sizes $N_B \times N_B$ where $N_B$ is a multiple of 4 that satisfies the following inequality:

$$16 \leq N_B \leq \min \left( 80, \sqrt[3]{C_1} \right) \tag{2}$$

The reference values of $M_U$ and $N_U$ are set to the values closest to each other that satisfy (1). For each matrix size, ATLAS tries two extreme cases for $K_U$: no unrolling ($K_U = 1$) and full unrolling ($K_U = N_B$).

The $N_B$ value that produces highest MFLOPS is chosen as “best $N_B$” value, and it is used from this point on in all experiments as well as in the final versions of the optimized mini-MMM code.

2) Find best $M_U$ and $N_U$: This step is a straightforward search that refines the reference values of $M_U$ and $N_U$ that were used to find the best $N_B$. ATLAS tries all possible combinations of $M_U$ and $N_U$ that satisfy inequality (1). Cases when $M_U$ or $N_U$ is 1 are treated specially. A test is performed to see if 1x9 unrolling or 9x1 unrolling is better than $3 \times 3$ unrolling. If not, unrolling factors of the form $1 \times U$ and $U \times 1$ for values of $U$ greater than 3 are not checked.

3) Find best $K_U$: This step is another simple search. Unlike $M_U$ and $N_U$, $K_U$ does not depend on the number of available registers, so it can be made as large as desired without causing register spills. The main constraint is instruction cache size. ATLAS tries values for $K_U$ between 4 and $N_B/2$ as well as the special values 1 and $N_B$. The value that gives best performance (based on $N_B$, $M_U$ and $N_U$ as determined from the previous steps) is declared the optimal value for $K_U$.

4) Find best $L_s$: In this step, ATLAS uses $L_s$ values in the interval $[1 : 1 : 6]$ to schedule the computations in the micro-MMM of Figure 3 to determine the best choice for $L_s$. It also ensures that the chosen value divides $M_U \times N_U \times K_U$ to facilitate instruction scheduling.

5) Find best $F_F$, $I_F$, and $N_F$: In this step, ATLAS searches for the values of $F_F$, $I_F$ and $N_F$. First, ATLAS determines the value of $F_F$ (0 or 1). Then, it searches for the best value of the pair $(I_F, N_F)$ where $I_F$ is in the interval $[2, M_U + N_U]$ and $N_F$ is in the interval $[1, M_U + N_U - I_F]$.

6) Find best $N_CN_B$: For the non-copying version of mini-MMM, ATLAS uses the same values of $M_U$, $N_U$, $F_F$, $I_F$, and $N_F$ that it uses for the copying version. Without copying, the likelihood of conflict misses is higher, so it makes sense to use a smaller L1 cache tile size than in the version of mini-MMM that performs copying. ATLAS searches for an optimal value of $N_CN_B$ in the range $[N_B : -4 : 4]$. We would expect performance to increase initially as the tile size is decreased, but decrease when the tile size becomes too small. ATLAS terminates the search when the performance falls by 20% or more from the best performance it finds during this search. Finally, some restricted searches for better values of $K_U$ and $L_s$ are done.
7) **Find best clean-up codes:** If the tile size is not a multiple of the original matrix size, there may be left-over rows and columns, at the boundaries of the matrices, that form fractional tiles. ATLAS generates clean-up code for handling these left-over rows and columns. These special tiles have one dimension of size \( N_B \) and another dimension of size \( L \), where \( L \) is between 1 and \( N_B - 1 \).

ATLAS generates cleanup codes as follows. For each value of \( L \) from \( N_B - 1 \) on down, it generates a specialized version of the mini-MMM code in which some of the loops are fully unrolled. Full unrolling is possible because the shapes of the operands are completely known. When the performance of the general version falls within 1% of the performance of the current specialized version, the generation process is terminated. The current \( L \) is declared to be the **Crossover Point**. At runtime, the specialized versions are invoked when the dimension of the left-over tile is greater than \( L \), while the general version is invoked for tile sizes smaller than \( L \).

**C. Discussion**

In optimization problems, there is usually a trade-off between search time and the quality of the solution. For example, we can refine the parameters found by ATLAS by repeating the orthogonal range search some number of times, using the values determined by one search as the reference values for the next search. It is also possible to use more powerful global search algorithms like simulated annealing. However, the potential for obtaining better solutions must be weighed carefully against the increase in installation time. We will address this point in the conclusions.

**IV. MODEL-BASED OPTIMIZATION**

In this section, we present analytical models for estimating optimal values for the parameters in Table I. To avoid overwhelming the reader, we first present models that ignore interactions between different levels of the memory hierarchy (in this case, L1 data cache and registers). Then, we refine the models to correct for such interactions.

**A. Estimating hardware Parameters**

Model-based optimization requires more machine parameters than the ATLAS approach because there is no search. The hardware parameters required by our model are as follows.

- \( C_1, B_1 \): the capacity and the line size of the L1 data cache.
- \( C_L \): The capacity of the L1 instruction cache.
- \( L_F \): hardware latency of the floating-point multiply instruction
- \( |ALU_{FP}| \): number of floating-point functional units
- \( N_R \): the number of floating-point registers.
- \( FMA \): the availability of a fused multiply-add instruction.

Empirical optimizers use the values of machine parameters only to bound the search space, so approximate values for these parameters are adequate. In contrast, analytical models require accurate values for these parameters. Therefore, we have developed a tool called X-Ray [3], which accurately measures these values.

**B. Estimating \( N_B \)**

We present our model for estimating \( N_B \) as a sequence of refinements for increasingly complex cache organizations, using the matrix multiplication code in Figure 5. The goal is to find the value of \( N_B \) that optimizes the use of the L1 data cache.

\[
\begin{align*}
\text{for } j & \in [0 : 1 : N_B - 1] \\
& \quad \text{for } i \in [0 : 1 : N_B - 1] \\
& \quad \quad \text{for } k \in [0 : 1 : N_B - 1] \\
C_{ij} &= C_{ij} + A_{ik} \times B_{kj}
\end{align*}
\]

Fig. 5. Schematic Pseudo-Code for mini-MMM

First, we consider a simple cache of capacity \( C_1 \), which is fully-associative with optimal replacement policy and unit line-size. There are no conflict misses, and spatial locality is not important.

The working set in memory of the mini-MMM loop nest in Figure 5 consists of three \( N_B \times N_B \) tiles, one from each of the matrices A, B, and C. For the rest of this section, we will refer to these tiles just as A, B, and C.

The working set fits entirely in the cache if Inequality (3) holds. If A, B, and C are copied to \( 3N_B^2 \) contiguous storage locations, Inequality (3) can also be viewed as determining the largest value of \( N_B \) for which there are no capacity or conflict misses during the execution of the mini-MMM in any cache organization (set-associative or direct-mapped). Although ATLAS usually copies tiles, the code in Figure 3 shows that the three copied tiles are not necessarily contiguous in memory. However, if the set-associativity of the L1 data cache is at least 3, there will be no conflict misses. This view of Inequality (3) will be useful in interpreting some of the experimental results of Section V.

\[3N_B^2 \leq C_1 \] (3)

A more careful analysis shows that it is not actually necessary for all three \( N_B \times N_B \) blocks to reside in the cache for the entire duration of the mini-MMM computation. Consider the mini-MMM code shown in Figure 5. Because \( k \) is the innermost loop, elements of C are computed in succession; once a given element of C has been computed, subsequent iterations of the loop nest do not touch that location again. Therefore, with this loop order, it is sufficient to hold a single element of C in the cache, rather than the entire array. The same reasoning shows that it is sufficient to hold a single column of B in the cache. Putting these facts together, we see that with this loop order, there will be no capacity misses if the cache can hold all of A, a single column of B, and a single element of C. This leads to Inequality (4).

\[N_B^2 + N_B + 1 \leq C_1 \] (4)

Inequality (4) determines the largest \( N_B \) for which there are no capacity misses during the execution of the mini-MMM, although there may be conflict misses if the cache is direct-mapped or set-associative. Notice that these conflict misses arise even if data from all three matrix tiles is copied into
contiguous memory, because the working set is larger than the capacity of the cache, and some elements will map to the same cache set.

1) Correcting for non-unit line size: In reality, caches have non-unit line size. Assume that the line size is $B_1$. If the three tiles are stored in column major order, both B and C are walked by columns and A is in cache for the entire duration of the mini-MMM. This leads to the refined constraint shown in Inequality (5).

$$\left[\frac{N^2_B}{B_1}\right] + \left[\frac{N_B}{B_1}\right] + 1 \leq \frac{C_1}{B_1}$$

2) Correcting for LRU replacement policy: We can further relax the restrictions of our cache organization to allow for Least Recently Used (LRU) replacement instead of optimal replacement. To determine the effects of LRU replacement on the optimal tile size $N_B$, we must examine the history of memory accesses performed by the loop nest. This analysis is similar to the analysis performed by the stack algorithm [20].

We start with the innermost loop of the mini-MMM loop nest. A single iteration $(j, i, k)$ of this loop touches elements

$$A_{ik}; B_{kj}; C_{ij};$$

where the most recently accessed element is written rightmost in this sequence.

Extending this analysis to the middle loop, we see that the sequence of memory access for a given value of the outer loop indices $(j, i)$ is the following (as before, the most recently accessed element is rightmost):

$$A_{0j}; B_{0j}; C_{ij}; A_{1j}; B_{1j}; C_{ij}; \ldots ; A_{N_B-1,j}; B_{N_B-1,j}; C_{ij};$$

Note that the location $C_{ij}$ is touched repeatedly, so the corresponding history of memory accesses is the following:

$$A_{0j}; B_{0j}; A_{1j}; B_{1j}; \ldots ; A_{N_B-1,j}; B_{N_B-1,j}; C_{ij};$$

Extending this to a single iteration $j$ of the outermost loop, we see that the sequence of memory accesses is the following (in left-to-right, top-to-bottom order):

$$A_{00}; B_{0j}; \ldots ; A_{0,N_B-1,j}; B_{N_B-1,j}; C_{0j};$$
$$A_{10}; B_{0j}; \ldots ; A_{1,N_B-1,j}; B_{N_B-1,j}; C_{1j};$$
$$\vdots$$
$$A_{N_B-1,0}; B_{0j}; \ldots ; A_{N_B-1,N_B-1,j}; B_{N_B-1,j}; C_{N_B-1,j};$$

Note that the column of $B$ is reused $N_B$ times, and thus the corresponding history of memory accesses is

$$A_{00}; \ldots ; A_{0,N_B-1}; C_{0j};$$
$$A_{10}; \ldots ; A_{1,N_B-1}; C_{1j};$$
$$\vdots$$
$$A_{N_B-1,0}; \ldots ; A_{N_B-1,N_B-1}; C_{N_B-1,j};$$

We do not want to evict the oldest element of this history $(A_{00})$ because, as we discussed before, A is completely reused in all iterations of the outermost loop. Therefore we need to choose $N_B$ is such a way that this whole history fits in the cache.

Furthermore, after the $j^{th}$ iteration of the outermost loop is complete, the $(j + 1^{st})$ iteration will bring in the $(j + 1^{st})$ column of B, which participates in an inner product with all the rows of A. Because of LRU, this new column will not be able to “optimally” replace the old $(j^{th})$ column of B, since the old column of B has been used quite recently. For the same reason the new element of C, namely $C_{0,j+1}$, will not be able to optimally replace the old $C_{0j}$. To account for this, we need extra storage for an extra column of B and an extra element of C.

Putting this all together, we see that if the cache is fully-associative with capacity $C_1$, line size $B_1$ and has an LRU replacement policy, we need to cache all of A, two columns of B and a column plus an element of C. This result is expressed formally in Inequality (6).

$$\left[\frac{N^2_B}{B_1}\right] + 3 \left[\frac{N_B}{B_1}\right] + 1 \leq \frac{C_1}{B_1}$$

3) Correcting to avoid micro-MMM clean-up code: Note that estimating $N_B$ using Inequality (6), it is possible to get a value for $N_B$ which is not an exact multiple of $M_U$ and $N_U$. This requires the generation of clean-up code for fractional register tiles at the boundaries of mini-MMM tiles. This complicates code generation, and generally lowers performance. We avoid these complications by trimming the value of $N_B$ determined from Inequality (6) so that it becomes a multiple of $M_U$ and $N_U$. The ATLAS code generator requires $N_B$ to be an even integer, so we enforce this constraint as well.

If $N_B'$ is the tile size obtained by using Inequality (6), we set $N_B$ to the value \(\left\lfloor \frac{N_B'}{\text{lcm}(M_U,N_U)} \right\rfloor \times \text{lcm}(M_U,N_U,2)\).

Note this requires that the value of $N_B$ be determined after the values of $M_U$ and $N_U$ have been determined as described below.

C. Estimating $M_U$ and $N_U$

One can look at the register file as a software controlled (optimal replacement), fully-associative cache with unit line size and capacity equal to the number of available registers $N_R$. Therefore we can use a variant of Inequality (4), to estimate the optimal register file tile size value.

The ATLAS Code Generator uses the KIJ loop order to tile the register file, and thus we need to cache the complete $M_U \times N_U$ tile of C, an $1 \times N_U$ row of B and a single element of A. Therefore the analog of Inequality (4) for registers is Inequality (7), shown below.

$$M_U \times N_U + N_U + 1 \leq N_R \quad (7)$$

Because the register file is software controlled, the ATLAS Code Generator is free to allocate registers differently than Inequality (7) prescribes. In fact, as discussed in Section II, it allocates a $M_U \times 1$ column of A, rather than a single element of A, to registers. Furthermore, it needs $L_s$ registers to store temporary values of multiplication operations to schedule for optimal use of the CPU pipeline. Taking into account these details, we refine Inequality (7) to obtain Inequality (8).

$$M_U \times N_U + N_U + M_U + L_s \leq N_R \quad (8)$$
$N_R$ is a hardware parameter, which is measured by the micro-benchmarks. The value of the optimization parameter $L_s$ is estimated as discussed in Section IV-E. Therefore the only unknowns in Inequality (8) are $M_U$ and $N_U$. We estimate their values using the following procedure.

- Let $M_U = N_U = u$. Solve Inequality (8) for $u$.
- Let $M_U = \max(u, 1)$. Solve Inequality (8) for $N_U$.
- Let $N_U = \max(N_U, 1)$
- Let $\langle M_U, N_U \rangle = (\max(M_U, N_U), \min(M_U, N_U))$.

D. Estimating $K_U$

Although $K_U$ is structurally similar to $M_U$ and $N_U$, it is obviously not limited by the size of the register file. Therefore the only practical limit for $K_U$ is imposed by the size of the instruction cache. To avoid micro-MMM clean-up code, we trim $K_U$ so that $N_U$ is a multiple of $K_U$. Note that if $K_U = N_B$, it is left unchanged by this update.

Therefore our model for estimating $K_U$ is to unroll the loop as far as possible within the size constraints of the L1 instruction cache, while ensuring that $K_U$ divides $N_B$. On most platforms, we found that the loop can be unrolled completely ($K_U = N_B$).

E. Estimating $L_s$

$L_s$ is the optimization parameter that represents the skew factor the ATLAS Code Generator uses when scheduling dependent multiplication and addition operations for the CPU pipeline.

Studying the description of the scheduling in Section II, we see that the schedule effectively executes $L_s$ independent multiplications and $L_s - 1$ independent additions between a multiplication $mul_i$ and the corresponding addition $add_i$. The hope is that these $2 \times L_s - 1$ independent instructions will hide the latency of the multiplication. If the floating-point units are fully pipelined and the latency of multiplication is $L_s$, we get the following inequality, which can be solved to obtain a value for $L_s$.

$$2 \times L_s - 1 \geq L_s$$

On some machines, there are multiple floating-point units. If $|ALU_{FP}|$ is the number of floating-point ALUs, Inequality (9) gets refined as follows.

$$\frac{2 \times L_s - 1}{|ALU_{FP}|} \geq L_s$$

Solving Inequality (10) for $L_s$, we obtain Inequality (11).

$$L_s = \left\lfloor \frac{L_s \times |ALU_{FP}| + 1}{2} \right\rfloor$$

Of the machines in our study, only the Intel Pentium machines have floating-point units that are not fully pipelined; in particular, multiplications can be issued only once every 2 cycles. Nevertheless, this does not introduce any error in our model because ATLAS does not schedule back-to-back multiply instructions, but intermixes them with additions. Therefore, Inequality (9) holds.

F. Estimating other parameters

Our experience shows that performance is insensitive to the values of $F_F$, $I_F$, and $N_F$ optimization parameters. Therefore we set $F_F = 1(true)$, $I_F = 2$ and $N_F = 2$.

FMA is a hardware parameter, independent of the specific problem, which in this case is MMM. We just use the value measured by the micro-benchmarks.

Finally, we set $NCNB = N_B$. That is, we use the same tile size for the non-copying version of mini-MMM as we do for the copying version. In our experiments, ATLAS always decided to use the copying version of mini-MMM, so the value of this parameter was moot. A careful model for $NCNB$ is difficult because it is hard to model conflict misses analytically. There is some work on this in the compiler literature but the models appear to be intractable [6], [8]. In some compilers, this problem is dealt with heuristically by using the effective cache capacity, defined to be a fraction (such as 1/3) of the actual cache capacity, when computing the optimal tile size. In our context, we could set $NCNB$ to the value determined from Inequality (6) with $C_1$ replaced with $C_1/3$. We recommend this approach should it become necessary to use a smaller tile size on some architectures.

G. Discussion

We have described a fairly elaborate sequence of models for estimating the optimal value of $N_B$. In practice, the value found by using Inequality (5), a relatively simple model, is close to the value found by using more elaborate models such as Inequality (6).

For the sake of completeness, we describe an even more elaborate model that captures multi-level memory hierarchy interactions (in this case, the interactions between the register file and the L1 data cache). In estimating $N_B$ in Section IV-B, we implicitly assumed that the computation works directly on the scalar elements of the tiles. As Figure 3 shows, the mini-MMM loop nest actually works on register tiles as opposed to scalars. We refine Inequality (6) by recognizing that considerations of rows, columns, and elements of $A$, $B$, and $C$ respectively must be replaced by considerations of horizontal panels, vertical panels, and register tiles instead. Taking this into account, we get Inequality (12).

$$\frac{\lfloor N_B^2 \rfloor}{B_1} + 3 \frac{N_B \times N_U}{B_1} + \frac{M_U}{B_1} \times N_U \leq \frac{C_1}{B_1}$$

V. Experimental Results

Models are to be used, not believed.

H. Theil ‘Principles of Econometrics’

In this section, we present the results of running ATLAS CGws and ATLAS Model on ten common platforms. Where appropriate, we also present numbers for handwritten BLAS and ATLAS Unleashed.

We did our experiments on the following platforms.

- RISC, Out-of-order
  - DEC Alpha 21264
  - IBM Power3
– IBM Power4
– SGI R12K
– Sun UltraSPARC IIIi

- EPIC, In-order
  – Intel Itanium2
- CISC, Out-of-order
  – AMD Opteron240
  – AMD AthlonMP
  – Intel Pentium III
  – Intel Pentium 4

For each platform, we present the following results.

- **Times:**
  – X-Ray: time taken by X-Ray to determine hardware parameters.
  – **ATLAS Micro-benchmarks:** time taken by the micro-benchmarks in ATLAS to determine hardware parameters.
  – **ATLAS Optimization Parameter Search:** time taken by global search in ATLAS for determining optimization parameter values.

We do not report the actual installation time of any of the versions of ATLAS because most of this time is spent in optimizing other BLAS kernels, generating library code, building object modules, etc.

- **Performance:**
  – **Optimization parameter values:** values determined by ATLAS CGw/S and ATLAS Model. Where appropriate, we also report these values for ATLAS Unleashed.
  – **MMM performance:** for matrices sized 100 × 100 to 5000 × 5000. We report performance of complete MMM computations using (i) native BLAS, and the code produced by (ii) ATLAS CGw/S, (iii) ATLAS Model, (iv) ATLAS Unleashed, and (v) the native Fortran compiler.

- **Sensitivity Analysis:** this describes the relative change of performance as we change one of the optimization parameters, keeping all other parameters fixed to the values found by ATLAS CGw/S. Sensitivity analysis explains how variations in the values of optimization parameters influence the performance of the generated mini-MMM kernel.
  – \( N_B \): change in mini-MMM performance when the value of \( N_B \) is changed
  – \( M_U, N_U \): change in mini-MMM performance when values of \( M_U \) and \( N_U \) are changed. Because optimal values of \( M_U \) and \( N_U \) depend on the same hardware resource (\( N_R \)), we vary them together.
  – \( K_U \): change in min-MMM performance when value of \( K_U \) is changed.
  – \( L_s \): change in mini-MMM performance when \( L_s \) is changed.
  – \( F_F, I_F \) and \( N_F \): we do not show sensitivity graphs for these parameters because performance is relatively insensitive to their values.

### A. DEC Alpha 21264

1) **mini-MMM:** On this machine the model-determined optimization parameters provided performance of about 100 MFLOPS (7%) slower than the ones determined by search. The reason of the difference is the suboptimal selection of the \( N_B \) parameter (84 for Atlas Model vs. 72 for ATLAS CGw/S), as can be seen in the \( N_B \) sensitivity graph of Figure 12(g).

2) **MMM Performance:** Figure 12(d) shows the MMM performance.

ATLAS Unleashed produces the fastest BLAS implementation, because it uses the highly-optimized, hand-tuned BLAS kernels written by Goto [15]. The native BLAS library (CXML) is only marginally slower.

Although the gap in performance of the mini-MMM codes produced by ATLAS CGw/S and ATLAS Model is 100 MFLOPS, the gap in performance of complete MMM computations is only about 50 MFLOPS (4%) for large matrices. Finally, we note that the GCC FORTRAN compiler is unable to deliver acceptable performance. We did not have access to the Compaq FORTRAN compiler, so we did not evaluate it.

3) **Sensitivity Analysis:** Figure 12(e) shows the sensitivity of performance to the values of \( M_U \) and \( N_U \). The optimal value is (4, 4), closely followed by (3, 6), and (6, 3). These match our expectations that optimal unroll factors are as close to square as possible, while dividing the tile size \( N_B = 72 \) without reminder.

Figure 12(f) shows the sensitivity of performance to the value of \( N_B \). Figure 12(g) shows a scaled-up version of this graph in the region of the optimal \( N_B \) value. The optimal value for \( N_B = 88 \). ATLAS does not find this point because it does not explore tile sizes greater than 80, as explained in Section III, but it chooses a tile size of 72, which is close to optimal. If we use Inequality (12) to determine \( N_B \) analytically, we obtain \( N_B = 84 \). Note that using the simpler model of Inequality (5), we obtain \( N_B = 90 \), which appears to be almost as good as the value determined by the more complex model.

The \( N_B \) sensitivity graph of Figure 12(g) has a saw-tooth of periodicity 4, with notable peaks occurring with a periodicity of 8. The saw-tooth of periodicity 4 arises from the interaction between cache tiling and register tiling - the register tile is (4, 4), so whenever \( N_B \) is divisible by 4, there is no clean-up code for fractional register tiles in the mini-MMM code, and performance is good. We do not yet understand why there are notable peaks in the saw-tooth with a periodicity of 8.

Figure 12(h) shows the sensitivity of performance to the value of \( K_U \). On this machine the entire mini-MMM loop body can fit into the L1 instruction cache for values of \( K_U \) up to \( N_B \). Performance is relatively insensitive to \( K_U \) as long as the value of this parameter is sufficiently large (\( K_U > 7 \)).

Figure 12(i) shows the sensitivity of performance to the value of \( L_s \). The graph is convex upwards, with a peak at 4. The multiplier on this machine has a latency of 4 cycles, so the model for \( L_s \) in Section IV, computes \( L_s = 5 \), which is
close to optimal. The inverted-U shape of this graph follows our expectations. For very small values of $L_s$, dependent multiplications and additions are not well separated and CPU pipeline utilization is low. As $L_s$ grows, the problem gradually disappears, until the performance peak is reached when the full latency of the multiplication is hidden. Increasing $L_s$ further does not improve performance as there is no more latency to hide. On the contrary, more temporary registers are needed to save multiplication results, which causes more register spills to memory, decreasing performance.

B. IBM Power 3

1) mini-MMM: On this machine, mini-MMM code produced by ATLAS Model is about 40 MFLOPS (3%) slower than mini-MMM code produced by ATLAS CGw/S. Figure 13(g) shows that one reason for this difference is the sub-optimal choice of $N_B$; fixing the values of all parameter other than $N_B$ to the ones chosen by ATLAS CGw/S and using the model-predicted value of 84 for $N_B$ results in mini-MMM code that performs about 100 MFLOPS worse than the mini-MMM code produced by ATLAS CGw/S.

2) MMM Performance: For multiplying large matrices, the handwritten BLAS as well as the codes produced by ATLAS CGw/S, ATLAS Model, and ATLAS Unleashed perform almost identically.

3) Sensitivity Analysis: Figure 13(f) shows the sensitivity of performance to the value of $N_B$. Figure 13(g) shows a scaled-up of this graph in the region of the optimal $N_B$ value. Figure 13(e) shows the sensitivity of performance to the values of $M_U$ and $N_U$.

Figure 13(h) shows the sensitivity of performance to the value of $K_U$. On this machine, the entire mini-MMM loop body can fit into the L1 instruction cache for values of $K_U$ up to $N_B$. Performance is relatively insensitive to $K_U$ as long as the value of this parameter is sufficiently large ($K_U > 5$). We do not understand the sudden drop in performance at $K_U = 3$.

Figure 13(i) shows the sensitivity of performance to the value of $L_s$. The Power 3 platform has a fused multiply-add instruction, which the ATLAS micro-benchmarks find and the Code Generator exploits, so performance does not depend on the value of $L_s$.

C. IBM Power 4

1) mini-MMM: On this machine, mini-MMM code produced by ATLAS Model is about 70 MFLOPS (2%) slower than mini-MMM code produced by ATLAS CGw/S. Figure 14(g) shows that one reason for this difference is a slightly sub-optimal choice of $N_B$; fixing the values of all parameter other than $N_B$ to the ones chosen by ATLAS CGw/S and using the model-predicted value of 56 for $N_B$ results in mini-MMM code that performs slightly worse than the mini-MMM code produced by ATLAS CGw/S.

2) MMM Performance: Figure 14(d) shows MMM performance. For large matrices, the hand-tuned BLAS perform the best, although by a small margin. The code produced by ATLAS Model, ATLAS CGw/S and ATLAS Unleashed perform almost identically.

3) Sensitivity Analysis: Figure 14(e) shows the sensitivity of performance to changes in the values of $M_U$ and $N_U$. The parameter values (4, 4) perform best, and these are the values used by both ATLAS CGw/S and ATLAS Model.

Figure 14(f) shows the sensitivity of performance to the value of $N_B$. Figure 14(g) shows a scaled-up graph in the neighborhood of the $N_B$ value determined by ATLAS CGw/S. Figure 14(f) shows that on this machine, $N_B$ values between 150 and 350 give the best performance of roughly 3.5 GFLOPS. Using Inequality (3) for the L2 cache (capacity of 1.5 MB) gives $N_B = 254$, while Inequality (12) gives $N_B = 436$, showing that on this machine, it is better to tile for the L2 cache rather than the L1 cache.

Figure 14(h) shows the sensitivity of performance to the value of $K_U$. The L1 instruction cache on this machine is large enough that we can set $K_U$ to $N_B$. As on the Power 3, unrolling by 3 gives poor performance for reasons we do not understand.

Figure 14(i) shows the sensitivity of performance to the value of $L_s$. The Power 4 platform has a fused multiply-add instruction, which the ATLAS micro-benchmarks find and the Code Generator exploits, so performance does not depend on the value of $L_s$.

D. SGI R12K

1) mini-MMM: On this machine, mini-MMM code produced by ATLAS Model is about 20 MFLOPS (4%) slower than mini-MMM code produced by ATLAS CGw/S. The performance of both codes is similar to that of mini-MMM code produced by ATLAS Unleashed.

2) MMM Performance: Figure 15(d) shows MMM performance. The hand-coded BLAS perform best but a small margin. This was the only machine in our study on which the native compiler (in this case, the SGI MIPSPro) generated relatively good code that was only 20% lower in performance than the hand-coded BLAS, at least for small matrices.

3) Sensitivity Analysis: Figure 15(e) shows the sensitivity of performance to the values of $M_U$ and $N_U$. This machine has a relatively large number of registers (32), so there is a fairly broad performance plateau in this graph.

Figure 15(f) shows the sensitivity of performance to the value of $N_B$. Figure 15(g) shows a scaled-up-of this graph in the region of the optimal $N_B$ value. Figure 15(f) shows that on this machine, $N_B$ values between 300 and 500 give the best performance of roughly 510 MFLOPS. Using Inequality (3) for the L2 cache (capacity of 4MB) gives $N_B = 418$, while Inequality (12) gives $N_B = 718$, showing that on this machine, it is better to tile for the L2 cache rather than the L1 cache.

Figure 15(h) shows the sensitivity of performance to the value of $K_U$. On this machine, the instruction cache is large enough that full unrolling ($K_U = N_B$) is possible.

Figure 15(i) shows the sensitivity of performance to the value of $L_s$. The R12K processor has a fused multiply-add instruction, so we would expect performance of the generated code to be insensitive to the value of $L_s$. While this is borne out by Figure 15(i), notice that Table 15(b) shows that the micro-benchmark used by ATLAS did not discover the fused
multiply-add instruction on this machine ($FMA = 0$)! The reason that the code produced by ATLAS CGw/S does well has to do with the back-end compiler (SGI MIPSPro). The ATLAS Code Generator schedules code using $L_s = 3$, but the SGI MIPSPro compiler is clever enough to discover the separated multiplies and adds, and fuse them. Figure 15(i) shows that the MIPSPro compiler is able to do this even when $L_s = 20$, which is impressive.

**E. Sun UltraSPARC IIIi**

1) mini-MMM: On this machine, mini-MMM code produced by ATLAS Model is about 160 MFLOPS (17%) faster than mini-MMM code produced by ATLAS CGw/S. The main reason for this is that the micro-benchmarks used by ATLAS incorrectly measured the capacity of the L1 data cache as 16 KB, rather than 64 KB. Therefore ATLAS only searched for $N_B$ values less than 44. Our micro-benchmarks on the other hand correctly measured the capacity of the L1 cache, so the model estimated $N_B = 84$, which gave better performance as can be seen in Figure 16(g).

2) MMM Performance: Figure 16(d) shows the MMM performance. On this machine, the hand-coded BLAS and ATLAS Unleashed performed roughly 50% better than the code produced by ATLAS CGw/S. The reason for this difference is that the mini-MMM code in ATLAS Unleashed (and perhaps the hand-coded BLAS) pre-fetches portions of the A and B matrices required for the next mini-MMM. This may be related to the Level-3 pre-fetching idea of Gustavson et al [1].

3) Sensitivity Analysis: Figure 16(e) shows the sensitivity of performance to the values of $M_U$ and $N_U$.

Figure 16(f) shows the sensitivity of performance to the value of the $N_B$. Figure 16(g) shows a scaled-up of this graph in the region of the optimal $N_B$ value. On this machine, as on many other machines, it is better to tile for the L2 cache, as can be seen in Figure 16(f). Using Inequality (3) for the L2 cache (capacity of 1 MB), we obtain $N_B = 208$, which gives roughly 1380 MFLOPS. Using Inequality (12), we obtain $N_B = 356$, which is close to the $N_B$ value in Figure 16(f) where the performance drops rapidly.

Figure 16(h) shows the sensitivity of performance to the value of the $K_U$. On this machine, the instruction cache is large enough that full unrolling ($K_U = N_B$) is possible.

Figure 16(i) shows the sensitivity of performance to the value of the $L_s$. This machine does not have a fused multiply-add instruction, so the value of the $L_s$ parameter affects performance. Both the model and ATLAS CGw/S find good values for this parameter.

**F. Intel Itanium 2**

1) mini-MMM: On this machine, the mini-MMM code produced by ATLAS Model is about 2.2 GFLOPS (55%) slower than mini-MMM code produced by ATLAS CGw/S. This is a rather substantial difference in performance, so it is necessary to examine the sensitivity graphs to understand the reasons why ATLAS Model is doing so poorly.

Figure 17(g) shows that one reason for this difference is that ATLAS Model used $N_B = 30$, whereas ATLAS CGw/S used $N_B = 80$. The value used by ATLAS Model is correct for the L1 data cache on this machine (16 KB). ATLAS CGw/S on the hand used a hard-coded value of 256KB for the capacity of the cache, so the expression $\min(80, \sqrt{C})$ in Inequality (2) evaluated to 80, the largest possible value of $N_B$ in the search space used by ATLAS. In essence, ATLAS CGw/S artificially sets the value of $N_B$ to 80! We discuss this issue further in the sensitivity results below.

2) MMM Performance: Figure 17(d) shows MMM performance. The hand-written BLAS and ATLAS Unleashed give the best performance. The code produced by ATLAS CGw/S runs about 1.5 GFlops slower than the hand-written BLAS, while the code produced by ATLAS Model runs about 3.5 GFlops slower.

3) Sensitivity Analysis: Figure 17(e) shows the sensitivity of performance to the values of $M_U$ and $N_U$. The Itanium has 128 general-purpose registers, so the optimal register tiles are relatively large. There is a broad plateau of $(M_U, N_U)$ values that give excellent performance.

Figure 17(f) shows the sensitivity of performance to the value of the $N_B$. Figure 17(g) shows a scaled-up of this graph in the region of the optimal $N_B$ value. Figure 17(f) shows that on this machine, the best performance is obtained by tiling for the L3 cache! Indeed, using Inequality (3) for the L3 cache (capacity of 3 MB), we obtain $N_B = 360$, which gives roughly 4.6 GFLOPS. Figure 17(f) shows that this value is close to optimal. Using Inequality (12), we obtain $N_B = 610$, which is close to the $N_B$ value in Figure 17(f) where the performance starts to drop.

Figure 17(h) shows the sensitivity of performance to the value of $K_U$. On the Itanium, unlike on other machines in our study, performance is highly sensitive to the value of $K_U$. The main reason is the large register tile ($M_U, N_U = (10, 10)$); after unrolling the micro-MMM loops, we get a very long straight-line code sequence. Furthermore, unrolling of the $k''$ loop creates numerous copies of this code sequence. Unfortunately, the L1 instruction cache on this machine has a capacity of 32 KB, so it can hold only about 9 copies of the micro-MMM code sequence. Therefore, performance drops off dramatically for values of $K_U$ greater than 9 or 10.

Since this is the only machine in our study in which the $K_U$ parameter mattered, we decided to investigate the sensitivity graph more carefully. Figure 6 shows a magnified version of Figure 17(h) in the interval $K_U \in [0, 15]$. We would expect the $K_U$ sensitivity graph to exhibit the typical inverted-U shape, and it more or less does. However, performance for $K_U = 7$ is significantly worse than the performance for $K_U = 6$, and $K_U = 8$, which appears anomalous.

The anomaly arises from clean-up code that is required when $K_U$ does not divide $N_B$ evenly (see the $k'$ loop in the tiled code in Figure 3). If we unroll the $k'$ loop by $K_U$, the number of times the completely unrolled micro-MMM code is replicated inside the mini-MMM is not $K_U$, but $K_U + N_B\%K_U$ (% is the remainder from integer division). The first term in the sum is the expected number of repetitions inside the unrolled $k'$ loop, while the second part is the clean-up code which takes care of the case when $K_U$ does not divide $N_B$ exactly. This second piece of code is still part of the mini-
MMMA loop nest, and it has to be stored in the L1 instruction cache during execution to achieve optimal performance.

For \( N_B = 80 \), performance increases initially as \( K_U \) increases because loop overhead is reduced. When \( K_U = 6 \), there are 8 copies of the unrolled micro-MMM code in the mini-MMM, and this is close to the I-cache limit. When \( K_U = 7 \), there are \( 7 + 80\% \times 7 = 10 \) copies of the micro-MMM code, which exceeds the I-cache limit, and performance drops substantially. However, when \( K_U = 8 \), there is no clean-up code, and there are only 8 copies of the unrolled micro-MMM code, so performance goes up again. Beyond this point, the code sizes overflow the I-cache and grow larger, and performance degrades gradually. Ultimately, performance is limited by the rate at which L1 I-cache misses can be serviced.

For \( N_B = 360 \), the trends are similar, but the effect of clean-up code is less because the clean-up code performs a smaller fraction of the computations of the \( k' \) loop (less than 1% compared to about 5% for \( N_B = 80 \)).

![Fig. 6. Intel Itanium 2: Sensitivity of performance to \( K_U \)](image)

Figure 17(i) shows the sensitivity of performance to the value of the \( L_s \). The Itanium has a fused multiply-add instruction, so performance is insensitive to the \( L_s \) parameter.

In summary, the code produced by ATLAS Model on this machine did not perform as well as the code produced by ATLAS CGw/S. However, this is because ATLAS Model tiled for the L1 cache, whereas on this machine, the best performance is obtained by tiling for L3 cache. ATLAS CGw/S gets better performance because the tile size is set manually, in effect, to a large value.

\[ (M_U, N_U) = (6, 1) \text{ code for x86 CISC} \]

One might expect that this code will not perform well because there are dependences between most of the instructions that arise from the use of temporary register \( rt \). In fact, experiments show that the code in Figure 7 performs well because of two architectural features of the Opteron.

1) **Out-of-order execution:** it is possible to schedule several multiplications in successive cycles without waiting for the first one to complete.

2) **Register renaming:** the single temporary register \( rt \) is renamed to a different physical register for each pair of

\[ rc_1 \leftarrow rc_1 \ldots rc_6 \leftarrow rc_6 \]

\[ \ldots \]

\[ \text{loop } k \]

\[ \begin{align*}
   & rb \leftarrow \bar{b}_1 \\
   & rt \leftarrow \bar{a}_1 \\
   & rt \leftarrow rt \times rb \\
   & rc_1 \leftarrow rc_1 + rt \\
   & rt \leftarrow \bar{a}_2 \\
   & rt \leftarrow rt \times rb \\
   & rc_2 \leftarrow rc_2 + rt \\
   & \vdots \\
   & rt \leftarrow \bar{a}_6 \\
   & rt \leftarrow rt \times rb \\
   & rc_6 \leftarrow rc_6 + rt \\
   & \ldots \\
   & \bar{c}_1 \leftarrow rc_1 \ldots \bar{c}_6 \leftarrow rc_6
\end{align*} \]
Performing instruction scheduling as described in Section II requires additional logical registers for temporaries, which in turn limits the sizes of the register tiles. When an architecture provides out-of-order execution and a small number of logical registers, it is better to use the logical registers for allocating larger register tiles and leave instruction scheduling to the out-of-order hardware core which can use the extra physical registers to hold the temporaries.

These insights permit us to refine the model described in Section IV as follows: for processors with out-of-order execution and a small number of logical registers, set \( N_U = 1 \), \( M_U = N_R - 2 \), \( FMA = 1 \).

To finish this story, it is interesting to analyze how the ATLAS search engine settled on these parameter values. Note that on a processor that does not have a fused multiply-add instruction, \( FMA = 1 \) is equivalent to \( FMA = 0 \) and \( L_s = 1 \). The code produced by the ATLAS code generator is shown schematically in Figure 8. Note that this code uses 6 registers for \( \bar{a} \) (\( r a_1 \ldots r a_6 \)), 1 register for \( \bar{b} \) (\( r b \)), 6 registers for \( \bar{c} \) (\( r c_1 \ldots r c_6 \)) and 1 temporary register (implicitly by the multiply-add statement). However, the back-end compiler (GCC) reorganizes this code into the code pattern shown in Figure 7.

\[
\begin{align*}
rc_1 & \leftarrow \bar{c}_1 \ldots rc_6 \leftarrow \bar{c}_6 \\
\ldots \\
\text{loop } k \\
\{ \\
ra_1 & \leftarrow \bar{a}_1 \\
rb & \leftarrow \bar{b}_1 \\
rc_1 & \leftarrow rc_1 + ra_1 \times rb \\
ra_2 & \leftarrow \bar{a}_2 \\
ra_3 & \leftarrow \bar{a}_3 \\
rc_2 & \leftarrow rc_2 + ra_2 \times rb \\
rc_3 & \leftarrow rc_3 + ra_3 \times rb \\
ra_4 & \leftarrow \bar{a}_4 \\
ra_5 & \leftarrow \bar{a}_5 \\
rc_4 & \leftarrow rc_4 + ra_4 \times rb \\
rc_5 & \leftarrow rc_5 + ra_5 \times rb \\
ra_6 & \leftarrow \bar{a}_6 \\
rc_6 & \leftarrow rc_6 + ra_6 \times rb \\
\}
\ldots \\
\bar{c}_1 & \leftarrow rc_1 \ldots \bar{c}_6 \leftarrow rc_6
\end{align*}
\]

Fig. 8. ATLAS unroll \((M_U, N_U) = (6, 1)\) code for x86 CISC.

Notice that the ATLAS code generator itself is not aware that the code of Figure 7 is optimal. However, setting \( FMA = 1 \) (even though there is no fused-multiply-add instruction) produces code that triggers the right instruction reorganization heuristics inside GCC, and performs well on the Opteron. This illustrates the well-known point that search does not need to be intelligent to do the right thing! Nevertheless, our refined model explains the observed performance data, makes intuitive sense, and can be easily incorporated into a compiler.

2) MMM Performance: Figure 18(d) shows the MMM performance. ATLAS Unleashed is once again the fastest implementation here, as it uses the highly-optimized, hand-tuned BLAS kernels, using the SSE2 SIMD instructions, for which the ATLAS Code Generator does not generate code. The native BLAS library is about 200 MFLOPS slower on average. ATLAS CGw/S and ATLAS Model perform at the same level as their corresponding mini-MMM kernels.

Refining the model as explained above brings ATLAS Model on par with ATLAS CGw/s. To bridge the gap between ATLAS CGw/S and user contributed code, we would need a different code generator – one that understands SIMD and prefetch instructions. GCC exposes these as intrinsic functions and we plan to explore this in our future work.

3) Performance Sensitivity Analysis: Figure 18(f) shows the sensitivity of performance to the value of the \( N_B \) optimization parameter. The first drop in performance is the result of L1 data cache misses starting to occur. This fact is accurately captured by our model for \( N_B \) in Inequality (12). Solving the inequality for \( C = 8192 \) (the L1 data cache capacity in double-sized floating-point values), we obtain \( N_B = 89 \). Similarly the second drop in performance in Figure 18(f) can be explained by applying the same model to the 1MB L2 cache.

Figure 18(e) shows the performance sensitivity to the values of the \( M_U \) and \( N_U \) optimization parameters. As discussed in Section V-G.1, the optimal value, is \((6, 1)\). From the graph we can see that the only plausible values are those with \( N_U = 1 \). Furthermore, performance increases while we grow \( M_U \) from 1 to 6, while it suddenly drops for \( M_U = 7 \). This is easily explained by our refined model, as \( M_U + 2 \leq N_R \) would require 9 registers, while only 8 are available.

Figure 18(h) shows the performance sensitivity to the value of the \( K_U \) optimization parameter. On this machine the entire mini-MMM loop body can fit into the L1 instruction cache for arbitrary \( K_U \) values (up to \( K_U = N_B \)). Performance is relatively insensitive to \( K_U \) as long as this unroll factor is sufficiently large (\( K_U > 10 \)).

Figure 18(i) shows the performance sensitivity to the value of the \( L_s \) optimization parameter. As we mentioned before, when \( FMA = 1 \), the \( L_s \) optimization parameter does not influence the generated code. Therefore, performance is constant with respect to \( L_s \).

H. AMD Athlon MP

The AMD Athlon implements the x86 instruction set, so we would expect the experimental results to be similar to those on the Opteron.

1) mini-MMM: Table 19(c) shows that on this machine, the mini-MMM code generated by ATLAS Model runs roughly 20% slower than the code generated by ATLAS CGw/S. Figure 19(f) shows that the choice of \( N_B \) made by the model is reasonable, while Figure 19(e) shows that the register-tile values were not chosen optimally by the model, as on the Opteron. The problem and its solution are similar to those on the Opteron.

2) MMM Performance: Figure 19(d) shows MMM performance. ATLAS Unleashed out-performs the other approaches.
by a significant margin. The hand-coded BLAS do almost as well, followed by ATLAS CGw/S.

3) Sensitivity Analysis: Figure 19(e) shows the sensitivity of performance to the values of \( M_U \) and \( N_U \).

Figure 19(f) shows the sensitivity of performance to the value of \( N_B \). Figure 19(g) shows a scaled-up of this graph in the region of the optimal \( N_B \) value. Both ATLAS Model and ATLAS CGw/S choose good values of \( N_B \). In Figure 19(g), the saw-tooth with period 2 arises from the overhead of executing clean-up code when the value of \( N_B \) is odd, and therefore not divisible by the value of \( M_U (= 2) \). As on other machines, we do not understand the saw-tooth with period 4 that has larger spikes in performance.

Figure 19(h) shows the sensitivity of performance to the value of \( K_U \). The L1 I-cache is large enough to permit full unrolling (\( K_U = N_B \)). However, the sensitivity graph of \( K_U \) is anomalous; performance is relatively low for all values of \( K_U \) other than \( K_U = N_B \). By examining the code produced by the native compiler (GCC), we found that this anomaly arose from interference between instruction scheduling in ATLAS and instruction scheduling in GCC. Notice that ATLAS CGw/S uses \( FMA = 0 \), so it attempts to schedule instructions and perform software pipelining in the mini-MMM code. Fully unrolling the \( k' \) loop (\( K_U = N_B \)) produces straight-line code which is easier for GCC to schedule.

To verify this conjecture, we redid the \( K_U \) sensitivity study with \( FMA \) set to 1. Figure 9 shows the results. Setting \( FMA = 1 \) dissuades the ATLAS code generator from attempting to schedule code, so GCC has an easier job, producing a \( K_U \) sensitivity graph that is in line with what we would expect.

Notice that our refined model, described in the context of the Opteron, does exactly on this. Using this model, mini-MMM performance is 1544 MFLOPS, which is faster than the performance of the mini-MMM produced by ATLAS CGw/S.

The code produced by ATLAS CGw/S and ATLAS Model arises mostly from the sub-optimal register tile chosen by the model, as explained in the context of the Opteron in Section V-G. Using (6, 1) as the register tile raises mini-MMM performance to 916 MFLOPS.

2) MMM Performance: Figure 20(d) shows MMM performance. The hand-coded BLAS perform at roughly 1100 MFLOPS, whereas the codes produced by ATLAS CGw/S and ATLAS Unleashed perform roughly at 900 MFLOPS. The code produced by ATLAS Model runs roughly at 850 MFLOPS; using the refined model improves performance to a point that is slightly above the performance of code produced by ATLAS CGw/S.

3) Sensitivity Analysis: Figure 20(e) shows the sensitivity of performance to the values of \( M_U \) and \( N_U \). Like all x86 machines, the Pentium III has a limited number of logical registers. Our base-line model picked (2, 1) for the register tile, whereas ATLAS CGw/S chose (4, 1). If we use the refined model described in Section V-G, the size of the register tile becomes (6, 1), and mini-MMM performance rises to 916 MFLOPS.

Figure 20(f) shows the sensitivity of performance to the value of \( N_B \). Figure 20(g) shows a scaled-up of this graph in the region of the optimal \( N_B \) value. The broad peak in Figure 20(f) arises from the influence of the L2 cache (capacity of 512 KB). Using Inequality (3) for the L2 cache, we obtain \( N_B = 104 \), which is the \( N_B \) values where the peak starts, while Inequality (12) gives \( N_B = 164 \), which corresponds to the \( N_B \) value where the peak ends. The L2 cache on the Pentium III is 8-way set-associative, so the drop in performance between \( N_B = 104 \) and \( N_B = 164 \) is small.

Figure 20(h) shows the sensitivity of performance to the value of the \( K_U \). On this machine, the L1 instruction cache is large enough to permit full unrolling (\( K_U = N_B \)).

Figure 20(i) shows the sensitivity of performance to the value of the \( L_s \). There is no fused multiply-add instruction, so performance is sensitive to the value of \( L_s \), but both ATLAS Model and ATLAS CGw/S find reasonable values for this parameter. If we use the refined model described in Section V-G, we set \( FMA = 1 \), and the value of the \( L_s \) parameter becomes irrelevant.

J. Pentium 4

1) mini-MMM: On this machine, mini-MMM code produced by ATLAS Model is about 600 MFLOPS (40%) slower than mini-MMM code produced by ATLAS CGw/S. This is mostly because of the sub-optimal register tile used by ATLAS Model; changing it to (6, 1) improves the performance of mini-MMM code produced by ATLAS Model to 1445 MFLOPS, which is only 50 MFLOPS (3%) less than the performance of the mini-MMM code produced by ATLAS CGw/S.

The mini-MMM produced by ATLAS Unleashed is roughly twice as fast as the mini-MMM produced by ATLAS Model because this code uses the SSE2 vector extensions to the x86 instruction set.

2) MMM Performance: Figure 21(d) shows the MMM performance. The hand-coded BLAS routines for this machine perform best, followed by the code produced by ATLAS Unleashed. Both the hand-coded BLAS and the code produced
by ATLAS Unleashed use the SSE2 vector extensions, and this accounts for most of the gap between these codes and the codes produced by ATLAS Model and ATLAS CGw/S. We do not know why the hand-coded BLAS perform substantially better than the code produced by ATLAS Unleashed.

The gap in performance between the codes produced by ATLAS CGw/S and ATLAS Model disappears if the refined model for register tiles is used.

3) Sensitivity Analysis: Figure 21(e) shows the sensitivity of performance to the values of $M_U$ and $N_U$. This figure shows that the best register tile is $(5, 1)$, which produces mini-MMM code that runs at 1605 MFLOPS. Using $(6, 1)$ as the register tile is not as good because it reduces performance to 1521 MFLOPS.

Figure 21(f) shows the sensitivity of performance to the value of the $N_B$. Figure 21(g) shows a scaled-up of this graph in the region of the optimal $N_B$ value. Both ATLAS Model and ATLAS CGw/S choose good tile sizes for the L1 cache. Tiling for the L2 cache gives slightly better performance. The L2 cache on this machine has a capacity of 256 KB; using Inequalities (3) and (12), we get $N_B = 105$ and $N_B = 180$, which agree well with the data.

Figure 21(h) shows the sensitivity of performance to the value of $K_U$. On this machine, the L1 instruction cache is large enough to permit full unrolling ($K_U = N_B$).

Figure 21(i) shows the sensitivity of performance to the value of $L_s$.

K. Discussion

The experimental results in this section can be summarized as follows. Figure 10 describes the analytical models used to compute values for the optimization parameters. This figure also shows the refined model used to compute register tile values for the x86 architecture.

Figure 11 shows the relative performance of the mini-MMM codes produced by ATLAS Model and by ATLAS Unleashed, using the performance of the codes produced by ATLAS CGw/S as the base line. We see that on all machines other than the Itanium, the codes produced by using the analytical models perform almost as well or slightly better than the codes produced using global search. On the Itanium, we saw that it is best to tile for the L3 cache, rather than the L1 cache. By using an artificially large, hard-coded value for the capacity of the L1 data cache, ATLAS CGw/S was able to obtain some of the benefits of tiling for higher-levels of the memory hierarchy. If we use this value for the capacity of the L1 cache, ATLAS Model produces mini-MMM code of comparable performance. Using the actual capacity of the L3 cache gives even better performance.

VI. CONCLUSIONS AND FUTURE WORK

The sciences do not try to explain, they hardly even try to interpret, they mainly make models. By a model is meant a mathematical construct which, with the addition of certain verbal interpretations, describes observed phenomena. The justification of

---

- **Estimating $FMA$:**
  - Use the machine parameter $FMA$
- **Estimating $L_s$:**
  - $L_s = \left\lfloor \frac{L_s \times |ALU_{FP}| + 1}{2} \right\rfloor$
- **Estimating $M_U$ and $N_U$:**
  - $M_U \times N_U + N_U + M_U + L_s \leq N_R$
  1) $M_U, N_U \leftarrow u$.
  2) Solve constraint for $u$.
  3) $M_U \leftarrow \max(u, 1)$.
  4) Solve constraint for $N_U$.
  5) $N_U \leftarrow \max(N_U, 1)$.
  6) If $M_U < N_U$ then swap $M_U$ and $N_U$.
- **Refined Model:** If $N_U = 1$ then
  - $M_U \leftarrow N_R - 2$
  - $N_U \leftarrow 1$
  - $FMA \leftarrow 1$
- **Estimating $N_B$:**
  - $\left\lceil \frac{N_B^2}{B_1} + 3 \left\lfloor \frac{N_B \times N_U}{B_1} \right\rfloor + \left\lfloor \frac{M_U}{B_1} \right\rfloor \times N_U \leq \frac{C_1}{B_1} \right\rceil$
  Trim $N_B$, to make it a multiple of $M_U$, $N_U$, and 2.
- **Estimating $K_U$:**
  - Choose $K_U$ as the maximum value for which mini-MMM fits in the L1 instruction cache. Trim $K_U$ to make it divide $N_B$ evenly.
- **Estimating $F_F$, $I_F$, and $N_F$:**
  - $F_F = 0, I_F = 2, N_F = 2$

---

Fig. 10. Summary of Model

Fig. 11. Summary of mini-MMM Performance
such a mathematical construct is solely and precisely that it is expected to work. John Von Neumann

Conventional wisdom in the compiler field holds that current compilers are unable to produce high-quality code because the analytical models they use to estimate optimization parameter values are overly simplistic compared to the complexity of modern high-performance architectures. There is even a growing belief that it is impossible to develop tractable and accurate analytical models, and that the only recourse for generating high quality code is to use empirical optimization. The results in this paper contradict this conventional wisdom, and suggest that there is no intrinsic reason why compilers cannot use analytical models to generate excellent code, at least for the BLAS.

This does not mean that search has no role to play in the generation of high-performance code. Systems like FFTW and SPIRAL use search not to choose optimal values for transformation parameters, but to choose an optimal algorithm from a whole suite of algorithms. We do not know if model-driven optimization is effective in this context. Even in the relatively simple context of the BLAS, there are aspects of program behavior that may not be worth modelling even if they can be modelled in principle. For example, the analytical models for $N_B$ described in Section IV ignore conflict misses. Although there is some work in the compiler literature on modelling conflict misses [6], [2], these models appear to be computationally intractable. Fortunately, the effect of conflict misses on performance can be reduced by appropriate copying. If necessary, the value of $N_B$ found by the model can be refined by local search in the neighborhood of the $N_B$ value predicted by the model. This combination of modelling and local search may be the most tractable approach for optimizing large programs for complex high-performance architectures.

However, it is important not to underestimate the challenge in improving general-purpose compilers to bridge the current performance gap with library generators. Although the techniques used by ATLAS, such as loop tiling, unrolling, and instruction scheduling, have been in the compiler literature for many years, it is not easy to incorporate them into general-purpose compilers. For example, transformations such as tiling are not always legal, so a general-purpose compiler must perform dependence analysis before transforming a program. In contrast, the implementor of a library generator focuses on one application and knows the precise structure of the code to be generated for that application, so he is not encumbered by the baggage required to support restructuring of general codes. At the very least, improving the state of the art of compilation technology will require an open compiler infrastructure which permits researchers to experiment easily with different transformations and to vary the parameters of those transformations. This has been a long-standing problem, and no adequate infrastructure exists in spite of many attempts.

An equally important conclusion of this study is that there is still a significant gap in performance between the code generated by ATLAS CGw/S and the BLAS routines. Although we understand some of the reasons for this gap, the problem of automating library generation remains open. The high cost of library and application tuning makes this one of the most important questions we face today.

REFERENCES

TABLE 12(a)
DEC ALPHA 21264 PLATFORM SPECIFICATION

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TABLE 12(b)
DEC ALPHA 21264 OPTIMIZATION PARAMETERS

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TABLE 12(c)
DEC ALPHA 21264 TIMINGS

Fig. 12(d). DEC Alpha 21264 MMM Performance

Fig. 12(e). DEC Alpha 21264: Sensitivity of performance to M_L and N_U

Fig. 12(f). DEC Alpha 21264: Sensitivity of performance to N_B

Fig. 12(g). DEC Alpha 21264: Sensitivity of performance to N_B (zoomed)

Fig. 12(h). DEC Alpha 21264: Sensitivity of performance to K_U

Fig. 12(i). DEC Alpha 21264: Sensitivity of performance to L_S
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**TABLE 13(a)**

IBM POWER 3 PLATFORM SPECIFICATION

Fig. 13(d). IBM Power 3 MMM Performance

Fig. 13(f). IBM Power 3: Sensitivity of performance to \( N_B \)

Fig. 13(h). IBM Power 3: Sensitivity of performance to \( K_L \)

Fig. 13(i). IBM Power 3: Sensitivity of performance to \( L_a \)

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**TABLE 13(b)**

IBM POWER 3 OPTIMIZATION PARAMETERS

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**TABLE 13(c)**

IBM POWER 3 TIMINGS

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Fig. 13(e). IBM Power 3: Sensitivity of performance to \( M_U \) and \( N_U \)

Fig. 13(g). IBM Power 3: Sensitivity of performance to \( N_B \) (zoomed)
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<td>Floating-Point Multiply Latency</td>
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<td>Has Fused Multiply Add</td>
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</tr>
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<td>Operating System</td>
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<tr>
<td>Fortran Compiler</td>
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**TABLE 14(a)**

IBM POWER 4 PLATFORM SPECIFICATION

---

**TABLE 14(b)**

IBM POWER 4 OPTIMIZATION PARAMETERS

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**TABLE 14(c)**

IBM POWER 4 TIMINGS

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![Fig. 14(d). IBM Power 4 MMM Performance](image)

![Fig. 14(e). IBM Power 4: Sensitivity of performance to $M_U$ and $N_U$](image)

![Fig. 14(f). IBM Power 4: Sensitivity of performance to $N_B$](image)

![Fig. 14(g). IBM Power 4: Sensitivity of performance to $N_B$ (zoomed)](image)

![Fig. 14(h). IBM Power 4: Sensitivity of performance to $K_U$](image)

![Fig. 14(i). IBM Power 4: Sensitivity of performance to $L_s$](image)
Feature | Value
--- | ---
Architecture | Out-Of-Order, RISC
CPU Core Frequency | 270 MHz
L1 Data Cache | 32 KB, 32 B/line, 2-way
L1 Instruction Cache | 32 KB, 32 B/line, 2-way
L2 Unified Cache | 4 MB, 32 B/line, 1-way
Floating-Point Registers | 32
Floating-Point Functional Units | 2
Floating-Point Multiply Latency | 2
Has Fused Multiply Add | Yes
Operating System | IRIX64
C Compiler | SGI MIPSPro C 7.3.1.1m
Fortran Compiler | SGI MIPSPro FORTRAN 7.3.1.1m

TABLE 15(a)

<table>
<thead>
<tr>
<th>SGI R12K PLATFORM SPECIFICATION</th>
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TABLE 15(b)

<table>
<thead>
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<th>SGI R12K OPTIMIZATION PARAMETERS</th>
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Fig. 15(d). SGI R12K MMM Performance

Fig. 15(e). SGI R12K: Sensitivity of performance to $M_U$ and $N_U$

Fig. 15(f). SGI R12K: Sensitivity of performance to $N_B$

Fig. 15(g). SGI R12K: Sensitivity of performance to $N_B$ (zoomed)

Fig. 15(h). SGI R12K: Sensitivity of performance to $K_U$

Fig. 15(i). SGI R12K: Sensitivity of performance to $L_s$
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<th>Feature</th>
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<tr>
<td>L1 Instruction Cache</td>
<td>32 KB, 32 B/line, 4-way</td>
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<tr>
<td>L2 Unified Cache</td>
<td>1 MB, 32 B/line, 4-way</td>
</tr>
<tr>
<td>Floating-Point Registers</td>
<td>32</td>
</tr>
<tr>
<td>Floating-Point Functional Units</td>
<td>2</td>
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<td>Floating-Point Multiply Latency</td>
<td>4</td>
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<td>Has Fused Multiply Add</td>
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<td>Operating System</td>
<td>SUN Solaris 9</td>
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<td>C Compiler</td>
<td>SUN C 5.5</td>
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<td>Fortran Compiler</td>
<td>SUN FORTRAN 95.7.1</td>
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TABLE 16(a)

SUN ULTRASPARC IIII PLATFORM SPECIFICATION

---

Fig. 16(d). Sun UltraSPARC IIIi MMM Performance

Fig. 16(f). Sun UltraSPARC III: Sensitivity of performance to $N_B$

Fig. 16(h). Sun UltraSPARC III: Sensitivity of performance to $K_U$

---

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<thead>
<tr>
<th>$N_B$</th>
<th>$M_{U}$, $N_{U}$, $K_U$</th>
<th>$L_s$</th>
<th>$PMA$</th>
<th>$P_{FU}$</th>
<th>$L_{FU}$</th>
<th>$N_{FU}$</th>
<th>MFLOPS</th>
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TABLE 16(b)

SUN ULTRASPARC IIII OPTIMIZATION PARAMETERS

---

Fig. 16(e). Sun UltraSPARC III: Sensitivity of performance to $M_U$ and $N_U$

Fig. 16(g). Sun UltraSPARC III: Sensitivity of performance to $N_B$ (zoomed)

Fig. 16(i). Sun UltraSPARC III: Sensitivity of performance to $L_s$

---

Fig. 16(c). Sun UltraSPARC III Timings

---

TABLE 16(c)

SUN ULTRASPARC IIII TIMINGS
TABLE 17(a)  
INTEL ITANIUM 2 PLATFORM SPECIFICATION

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Architecture</td>
<td>In-Order, EPIC, IA-64</td>
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<tr>
<td>CPU Core Frequency</td>
<td>1500 MHz</td>
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<tr>
<td>L1 Data Cache</td>
<td>16 KB, 64 B/line, 4-way</td>
</tr>
<tr>
<td>L1 Instruction Cache</td>
<td>16 KB, 64 B/line, 4-way</td>
</tr>
<tr>
<td>L2 Unified Cache</td>
<td>256 KB, 128 B/line, 8-way</td>
</tr>
<tr>
<td>L3 Cache</td>
<td>3 MB, 128B/line, 12-way</td>
</tr>
<tr>
<td>Floating-Point Registers</td>
<td>128</td>
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<td>Floating-Point Functional Units</td>
<td>2</td>
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<tr>
<td>Floating-Point Multiply Latency</td>
<td>4</td>
</tr>
<tr>
<td>Has Fused Multiply Add</td>
<td>Yes</td>
</tr>
<tr>
<td>Operating System</td>
<td>Linux 2.4.18-e.31smp</td>
</tr>
<tr>
<td>C Compiler</td>
<td>GNU C/C++ 3.3</td>
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<tr>
<td>Fortran Compiler</td>
<td>GNU Fortran 3.3</td>
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TABLE 17(b)  
INTEL ITANIUM 2 OPTIMIZATION PARAMETERS

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<th>Ls</th>
<th>MFLOPS</th>
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TABLE 17(c)  
INTEL ITANIUM 2 TIMINGS

Fig. 17(d). Intel Itanium 2 MMM Performance

Fig. 17(e). Intel Itanium 2: Sensitivity of performance to \( M_U \) and \( N_U \)

Fig. 17(f). Intel Itanium 2: Sensitivity of performance to \( N_B \)

Fig. 17(g). Intel Itanium 2: Sensitivity of performance to \( N_B \) (zoomed)

Fig. 17(h). Intel Itanium 2: Sensitivity of performance to \( K_U \)

Fig. 17(i). Intel Itanium 2: Sensitivity of performance to \( L_s \)
Table 18(a)
AMD Opteron 240 Platform Specification

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<thead>
<tr>
<th>Feature</th>
<th>Value</th>
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<tbody>
<tr>
<td>Architecture</td>
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<tr>
<td>CPU Core Frequency</td>
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<tr>
<td>L1 Data Cache</td>
<td>64 KB, 64 B/line, 2-way</td>
</tr>
<tr>
<td>L1 Instruction Cache</td>
<td>64 KB, 64 B/line, 2-way</td>
</tr>
<tr>
<td>L2 Unified Cache</td>
<td>1024 MB, 64 B/line, 16-way</td>
</tr>
<tr>
<td>Floating-Point Registers</td>
<td>8 x87</td>
</tr>
<tr>
<td>Floating-Point Functional Units</td>
<td>ADD + MUL + Memory</td>
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<tr>
<td>Floating-Point Multiply Latency</td>
<td>4</td>
</tr>
<tr>
<td>Has Fused Multiply Aid</td>
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</tr>
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<td>Operating System</td>
<td>Linux 2.4.19</td>
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<tr>
<td>C Compiler</td>
<td>GCC C/C++ 3.3.2</td>
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<td>Fortran Compiler</td>
<td>GNU Fortran 3.3.2</td>
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Table 18(b)
AMD Opteron 240 Optimization Parameters

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<td>1,</td>
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<td>L&lt;sub&gt;U&lt;/sub&gt;</td>
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Table 18(c)
AMD Opteron 240 Timings

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Fig. 18(d). AMD Opteron 240 MMM Performance

Fig. 18(e). AMD Opteron 240: Sensitivity of performance to M<sub>U</sub> and N<sub>U</sub>

Fig. 18(f). AMD Opteron 240: Sensitivity of performance to N<sub>B</sub>

Fig. 18(g). AMD Opteron 240: Sensitivity of performance to N<sub>B</sub> (zoomed)

Fig. 18(h). AMD Opteron 240: Sensitivity of performance to K<sub>U</sub>

Fig. 18(i). AMD Opteron 240: Sensitivity of performance to L<sub>S</sub>
### Table 19(a)

**AMD Athlon MP Platform Specification**

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<tr>
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<tr>
<td>L1 Data Cache</td>
<td>64 KB, 64 B/line, 2-way</td>
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<tr>
<td>L1 Instruction Cache</td>
<td>64 KB, 64 B/line, 2-way</td>
</tr>
<tr>
<td>L2 Unified Cache</td>
<td>256 KB, 64 B/line, 16-way</td>
</tr>
<tr>
<td>Floating-Point Registers</td>
<td>8</td>
</tr>
<tr>
<td>Floating-Point Functional Units</td>
<td>ADD + MUL + Memory</td>
</tr>
<tr>
<td>Floating-Point Multiply Latency</td>
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<tr>
<td>Has Fused Multiply Add</td>
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</tr>
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<td>Operating System</td>
<td>Linux 2.4.20</td>
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<td>C Compiler</td>
<td>GNU C/C++ 3.2.2</td>
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<tr>
<td>Fortran Compiler</td>
<td>GNU Fortran 3.2.2</td>
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### Table 19(b)

**AMD Athlon MP Optimization Parameters**

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### Table 19(c)

**AMD Athlon MP Timings**

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<td>1000</td>
<td>2000</td>
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<td>1500</td>
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<td>2500</td>
<td>500</td>
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Fig. 19(d). AMD Athlon MP MMM Performance

Fig. 19(e). AMD Athlon MP: Sensitivity of performance to $M_U$ and $N_U$

Fig. 19(f). AMD Athlon MP: Sensitivity of performance to $N_B$

Fig. 19(g). AMD Athlon MP: Sensitivity of performance to $N_B$ (zoomed)

Fig. 19(h). AMD Athlon MP: Sensitivity of performance to $K_U$

Fig. 19(i). AMD Athlon MP: Sensitivity of performance to $L_s$
TABLE 20(a)

PENTIUM III PLATFORM SPECIFICATION

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</thead>
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<tr>
<td>CPU Core Frequency</td>
<td>1266 MHz</td>
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<tr>
<td>L1 Data Cache</td>
<td>16 KB, 32 B/line, 4-way</td>
</tr>
<tr>
<td>L1 Instruction Cache</td>
<td>16 KB, 32 B/line, 4-way</td>
</tr>
<tr>
<td>L2 Unified Cache</td>
<td>512 MB, 32 B/line, 8-way</td>
</tr>
<tr>
<td>Floating-Point Registers</td>
<td>8</td>
</tr>
<tr>
<td>Floating-Point Functional Units</td>
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</tr>
<tr>
<td>Floating-Point Multiply Latency</td>
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</tr>
<tr>
<td>Has Fused Multiply Add</td>
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<tr>
<td>Operating System</td>
<td>Linux 2.4.20-28.8smp</td>
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<tr>
<td>C Compiler</td>
<td>GNU C/C++ 3.2</td>
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<tr>
<td>Fortran Compiler</td>
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TABLE 20(b)

PENTIUM III OPTIMIZATION PARAMETERS

<table>
<thead>
<tr>
<th>Model</th>
<th>M_L, N_L, K_L</th>
<th>L_F</th>
<th>PMA</th>
<th>P_D, P_F, N_F</th>
<th>MFLOPS</th>
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<td>CGw/S</td>
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<td>Unleashed</td>
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TABLE 20(c)

PENTIUM III TIMINGS

Fig. 20(d). Pentium III MMM Performance

Fig. 20(e). Pentium III: Sensitivity of performance to M_L and N_L

Fig. 20(f). Pentium III: Sensitivity of performance to N_B

Fig. 20(g). Pentium III: Sensitivity of performance to N_B (zoomed)

Fig. 20(h). Pentium III: Sensitivity of performance to K_L

Fig. 20(i). Pentium III: Sensitivity of performance to L_a
<table>
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<tr>
<th>Feature</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
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<tr>
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<td>L1 Data Cache</td>
<td>8 KB, 64 B/line, 4-way</td>
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<tr>
<td>L1 Instruction Cache</td>
<td>12 K uOps, 6 uOps/line, 8-way</td>
</tr>
<tr>
<td>L2 Unified Cache</td>
<td>512 KB, 128 B/line, 8-way</td>
</tr>
<tr>
<td>Floating-Point Registers</td>
<td>8</td>
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<td>Floating-Point Units</td>
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<tr>
<td>Operating System</td>
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<tr>
<td>C Compiler</td>
<td>GNU C v3.2.2</td>
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<tr>
<td>Fortran Compiler</td>
<td>GNU Fortran 3.2.2</td>
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**TABLE 21(a)**

**PENTIUM 4 PLATFORM SPECIFICATION**

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<td>L1 Data Cache</td>
<td>8 KB</td>
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<td>L2 Unified Cache</td>
<td>512 KB</td>
</tr>
<tr>
<td>Floating-Point Registers</td>
<td>8</td>
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<tr>
<td>Floating-Point Units</td>
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**TABLE 21(b)**

**PENTIUM 4 OPTIMIZATION PARAMETERS**

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<th>N_B</th>
<th>M_U, N_U, K_U</th>
<th>L_S</th>
<th>PMA</th>
<th>P_F, L_F, N_F</th>
<th>MFLOPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>CGw/S</td>
<td>28</td>
<td>3, 1, 28</td>
<td>1</td>
<td>0</td>
<td>0, 2, 1</td>
<td>1504</td>
</tr>
<tr>
<td>Unleashed</td>
<td>30</td>
<td>1, 1, 30</td>
<td>4</td>
<td>0</td>
<td>0, 2, 2</td>
<td>913</td>
</tr>
</tbody>
</table>

**TABLE 21(c)**

**PENTIUM 4 TIMINGS**

**Fig. 21(d).** Pentium 4 MMM Performance

**Fig. 21(e).** Pentium 4: Sensitivity of performance to M_U and N_U

**Fig. 21(f).** Pentium 4: Sensitivity of performance to N_B

**Fig. 21(g).** Pentium 4: Sensitivity of performance to N_B (zoomed)

**Fig. 21(h).** Pentium 4: Sensitivity of performance to K_U

**Fig. 21(i).** Pentium 4: Sensitivity of performance to L_S