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HELIX: Automatic Parallelization of Irregular Programs for Chip Multiprocessing

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ABSTRACT

We describe and evaluate HELIX, a new technique for automatic loop parallelization that assigns successive iterations of a loop to separate threads. We show that the inter-thread communication costs forced by loop-carried data dependences can be mitigated by code optimization, by using an effective heuristic for selecting loops to parallelize, and by using helper threads to prefetch synchronization signals. We have implemented HELIX as part of an optimizing compiler framework that automatically selects and parallelizes loops from general sequential programs. The framework uses an analytical model of loop speedups, combined with profile data, to choose loops to parallelize. On a six-core Intel® Core™ i7-980X, HELIX achieves speedups averaging 2.25×, with a maximum of 4.12×, for thirteen C benchmarks from SPEC CPU2000.

1. INTRODUCTION

Now that multicore processors are commonplace, there is a need for compilers that produce multi-threaded code from ordinary, irregular, single-threaded sources. There have been exciting demonstrations that ordinary irregular programs can be speeded up by compiling loops to multiple threads that run in parallel on a chip multiprocessor [19, 23, 30, 32, 34]. Much of this work is based on decoupled software pipelining (DSWP), which uses the structure of a loop’s dependence graph to divide it into threads without cyclic dependences [30]. With the aid of architectural extensions for inter-thread buffering, such thread pipelines have been shown to speed loops up substantially. However, DSWP is inherently constrained by the static structure of each loop’s body, which limits the number of hardware threads that can usefully be applied to the loop [34]. Recent work has used DSWP to expose other loop parallelization opportunities [19, 23, 32], and these hybrid approaches produce significant speedups on real systems when applied to selected benchmarks by hand, but they have yet to be automated.

For loops with no data dependences between iterations, a straightforward parallelization approach that scales well is to implement each iteration as a separate thread. (This has been called DOALL parallelism.) But for general loops, the costs of inter-thread communication have discouraged compiler writers from simply allocating a thread per iteration. The loop-carried dependences between iterations not only mean that computed results must be forwarded between threads, but also that some sections of a loop’s body must be executed in sequential order, which requires synchronization. However, as we will show, when the right loops are selected for parallelization, the cost of transferring computed results is a small fraction of total overhead. And the inter-thread signaling needed for synchronization can be minimized both by code optimization and by using simultaneous multi-threading (SMT). Based on these observations, we developed a new technique for loop parallelization called HELIX, which distributes the iterations of selected loops across a pool of threads bound to a ring of cores. The simplicity of the HELIX concept enables the use of a simple but accurate analytical model to estimate the speedup obtained by parallelizing a single loop. A heuristic, based on that model and on feedback from profiling runs, provides an efficient and effective algorithm for selecting loops to parallelize. We have developed new code analyses and transformations that minimize the number of signals required. We further reduce signal latency through SMT by giving each iteration thread a helper thread [26] to ensure that inter-core transmission of each signal begins as soon as it is sent. Where dependences force loop segments to execute in iteration order, we transform the parallelized code to reduce the size of such sequential segments and to run distinct sequential segments in parallel whenever possible.

HELIX is a fully automatic technique; it does not depend on source code annotations or modifications, or other forms of human intervention. It can achieve significant speedups of regular and irregular workloads on a real multicore processor. HELIX is the first technique using thread-level parallelism (TLP) among loop iterations that is able to achieve significant speedups without constraints such as a loop nesting limit, regular memory accesses, or regular control flow [4]. For thirteen C language benchmarks from the SPEC CPU2000 suite, the geometric mean of the resulting speedups on our six-core CPU is 2.25×, with a maximum of 4.12×.

The main contributions of the paper are: (1) a new general purpose parallelization technique, including a new set of code analyses and transformations, that is able to significantly reduce both the number of signals sent between threads and the TLP loss due to sequential segments; (2) a new approach that exploits SMT technology in a real system to further reduce signaling overhead; (3) an effective feedback-directed heuristic for selecting loops to parallelize (also useful for parallelization frameworks other than HELIX); (4)

1Helical Execution of Loop Iterations across cores.
for (...) {
    1: a = update(a);
    2: work1(a);
    3: b = update(b);
    4: work2();
}

Figure 1: Execution of code produced by HELIX for a dual-core processor. Note that code blocks 1 and 3 must each be executed sequentially, but since they are independent, HELIX overlaps them in time.

Figure 2: Insertion of Wait(d) and Signal(d) due to a RAW data dependence \( d = (a, b) \). Empty sequential segments handle dependences that span multiple iterations.

a demonstration that the amount of data to forward between loop iterations is small when loops are carefully chosen; and (5) an experimental evaluation on a broad range of applications.

The rest of the paper is arranged as follows. We describe the HELIX transformations and how to choose the right set of loops to parallelize in Section 2. Section 3 presents our experimental setup and HELIX’s speedups on the SPEC CPU2000 suite. Section 4 compares HELIX with related work. Finally, Section 5 presents our conclusions.

2. HELIX

Loops parallelized by HELIX run one at a time. The iterations of each parallelized loop run in round-robin order on cores of a single processor. HELIX applies code transformations to minimize the inefficiencies of sequential segments, data transfer, signaling, and thread management.

HELIX executes different sequential segments in parallel whenever possible, as shown in Figure 1, where sequential segments 1 and 3 overlap. To further reduce the effect of sequential segments on TLP, HELIX automatically chooses the most profitable loops to parallelize, which are usually those with the least code in sequential segments, and then it transforms the chosen loops to minimize their sequential code (see Step 5 of Section 2.1).

Transferring data between cores can be a significant source of overhead. However, as we show in Section 3, careful selection of the loops to parallelize keeps the amount of data needing to be forwarded between cores small, compared with the amount consumed within each iteration. To understand why, consider the code in Figure 2, which shows the structure of most sequential segments in our chosen loops. We show a read-after-write (RAW) dependence, the only kind that can lead to a data transfer. Here we have three blocks of code that are executed sequentially because of a data dependence between instructions \( a \) and \( b \). For successive loop iterations \( i \) and \( i + 1 \), running on cores \( c_i \) and \( c_{i+1} \) respectively, data needs to be transferred from \( c_i \) to \( c_{i+1} \) only if iteration \( i \) executes \( a \) and iteration \( i + 1 \) executes \( b \). Assuming that each branch in the loop body has equal probability of being taken or not, this would happen only 6.25% of the time.

The next source of inefficiency is signaling threads to notify them of events that have occurred (e.g., the end of a sequential segment). This is the main source of overhead for HELIX, and it is addressed by the code analyses and transformations described below. The number of signals sent in the system is minimized by exploiting redundancy among them and by transforming the code. Also, HELIX reduces the perceived signal latency by exploiting the SMT technology of the underlying platform. It couples each thread with a helper thread running on the same core. Helper threads mask a significant fraction of signal latency by “prefetching” signals. Moreover, HELIX schedules code to support this dynamic prefetching mechanism by separating signals in time.

Finally, HELIX efficiently organizes threads so that one main thread executes the code outside of parallelized loops. Within parallelized loops the main thread is joined by parallel and helper threads which are used as a pool to execute the separate loop iterations and prefetch signals respectively. The main and parallel threads are called iteration threads. To avoid overhead, the mapping of all threads to available cores is performed when the application starts and does not change. Figure 3(b) shows the resulting execution of a two-iteration loop on a processor with four cores. After configuring all parallel and helper threads, the main thread acts like a parallel thread. In this example, however, there are fewer iterations than threads, so the main thread does not need to execute any loop iterations. Once the loop is complete, parallel and helper threads wait for the next parallel loop to execute, and the main thread continues sequential execution of the program. When targeting \( N \) cores, HELIX produces \( 2N \) threads composed of one main thread, \( N - 1 \) parallel threads and \( N \) helper threads.
2.1 Algorithm for Parallelizing One Loop

HELIX works on an intermediate representation of a program. It takes as input a loop \( L \) to be optimized and modifies it as a side effect. After putting \( L \) into a normal form, it inserts code to satisfy control and data dependences, creating the sequential segments. Sequential segments are optimized first by shortening them through code scheduling, and then by elimination of redundant signals between cores. HELIX inserts instructions to forward data values between cores and to implement signals for synchronization. It then couples each iteration thread with a helper thread to prefetch signals dynamically. To support this prefetching of signals, the code of the iteration thread is rescheduled to space its outgoing signals more uniformly in time. Finally, HELIX links the parallelized loop back into the original program.

Step 1: Normalizing the loop. HELIX transforms loops by putting them into the form shown in Figure 3(a). A normalized loop has two regions, the prologue and the body. The prologue is the minimum set of instructions that must be executed to determine whether the next iteration’s prologue will be executed. Formally, the prologue includes loop instructions that are not post-dominated by the loop’s back edge in the control flow graph (CFG). Exits from the loop can only originate in the prologue. In general, this is a non-trivial subgraph of the CFG. The body is the rest of the loop. Notice that the body is composed of both sequential segments and code that can run in parallel. The transformed code resembles a while loop in which there are no instructions in the body that jump outside the loop.

Step 2: Identifying data dependences to satisfy. To detect data dependences, HELIX applies interprocedural pointer analysis to the whole program [17]. In order to avoid unnecessary synchronization, HELIX satisfies only the necessary loop-carried data dependences. These are a subset of loop-carried data dependences, where false (i.e., write-after-write and write-after-read) dependences, where false (i.e., write-after-write and write-after-read) dependences either through registers or the call stack are excluded, because each iteration is executed on a separate core with its own internal registers and call stack that are not exposed to other threads.

Data shared between threads includes live-in and live-out values (those produced outside the loop but consumed inside it and vice versa), and loop iteration live-in values (those produced by one loop iteration and consumed by another) [30]. Variables that hold these values are called loop boundary live variables. Memory locations of loop boundary live variables are kept within the allocation frame of the main thread. Accesses from parallel threads are performed through loads and stores and managed by synchronizing the loop-carried data dependences that involve them. Data dependences that result from reading and writing invariant or induction variables do not need to be synchronized. Invariant variables do not change between iterations and induction variables are locally computable from the iteration number and their values at the beginning of the loop [6]. \( D_{\text{Data}} \) is the set of dependences to synchronize.

Step 3: Starting next iterations. Iterations execute in a non-speculative manner, each starting in a parallel thread once the prologue of the preceding iteration has been executed. To satisfy the loop’s control dependences, iteration \( i + 1 \) starts only when it is certain that its prologue (at least) will be executed. That is known at the beginning of the body of iteration \( i \) (because the body cannot contain exits). Therefore, instructions to start the next iteration are added to the beginning of the body, which results in overlapping execution of bodies from different loop iterations. Note that HELIX does not require advance knowledge about the number of loop iterations to execute. However, when the number of iterations is known, HELIX produces a prologue that requires neither signals nor data to be transferred from previous iterations.

Step 4: Computing sequential segments. For every loop iteration and consumed by another) [30]. Variables that hold these values are called loop boundary live variables. Memory locations of loop boundary live variables are kept within the allocation frame of the main thread. Accesses from parallel threads are performed through loads and stores and managed by synchronizing the loop-carried data dependences that involve them. Data dependences that result from reading and writing invariant or induction variables do not need to be synchronized. Invariant variables do not change between iterations and induction variables are locally computable from the iteration number and their values at the beginning of the loop [6]. \( D_{\text{Data}} \) is the set of dependences to synchronize.

For every data dependence, \( d = (a, b) \in D_{\text{Data}} \), HELIX inserts Wait and Signal operations to ensure that occurrences of \( a \) and \( b \) in separate loop iterations will execute in the correct order. The instruction Wait\( (d) \) blocks execution of a thread until its previous thread sends a signal (i.e., a data signal), by executing Signal\( (d) \). The implementation of Wait and Signal in our testbed is described below. The effect of these operations is that the code between Wait\( (d) \) and Signal\( (d) \) executes in loop iteration order, satisfying the data dependence \( d \). For example, in Figure 4 the block Code\( B \) runs in loop iteration order while Code\( A \) and Code\( C \) execute in parallel.

For a data dependence \( d = (a, b) \), HELIX inserts Signal\( (d) \) at the earliest point along every path through the loop body at which it is provable that neither \( a \) nor \( b \) can be reached during the rest of the current iteration. These points are found using data flow analysis. Before either \( a \) or \( b \) is executed, HELIX ensures that all past iterations have already executed them, by inserting Wait\( (d) \) before each of them. It also makes sure that Wait\( (d) \) is executed before every Signal\( (d) \) in the iteration, even if neither \( a \) nor \( b \) happens to be executed. That means that the next iteration is unblocked only if no previous iterations (adjacent or distant) have yet to execute either \( a \) or \( b \). Therefore, data dependences between non-adjacent iterations are handled by sending signals via the threads for intervening iterations. Figure 2 shows typical sequential segments for a dependence between instruction \( a \), which writes \( x \), and instruction \( b \), which reads \( x \). Note that an actual data transfer occurs only when instruction \( b \) is reached, and then only if \( a \) was executed more recently than \( b \). Compared with synchronization, data transfer happens infrequently.

Step 5: Minimizing sequential segments. HELIX applies a method inlining and code scheduling pass in order to keep sequential segments small. If there is a data dependence between a function call within a loop and another instruction in that loop, this pass inlines the function call, provided it is not contained in a subloop (since that would inhibit shrinking the sequential segment). This heuristic strikes a good balance: it is conservative enough to avoid code blow-up that could thwart speedups in applications like the SPEC benchmarks, but it is liberal enough to optimize all the loops we parallelized with HELIX as tightly as they could be with unconstrained inlining.

After method inlining, the code is scheduled. For every sequential segment containing data dependence \( d = (a, b) \in D_{\text{Data}} \), instructions that are not directly or indirectly dependent on either \( a \) or \( b \) are moved after the segment. This reduces the problem shown in Figure 5. In this example, the parallel code is not well balanced across loop iterations, which causes unnecessary stalls if the sequential segment is kept at the end of the loop. For the same reason, the remaining instructions belonging to the sequential segment are
Thanks to the above theorem, HELIX can keep only the
steps required for loop-carried dependences is implemented
using a per-thread memory area called the
chronization required for loop-carried dependences is implemented
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Figure 5: Reducing execution stalls by percolating sequential
segments upwards.

Step 6: Minimizing signals. HELIX applies code optimizations that remove the redundancies introduced by naïve insertion of
Wait and Signal operations. It eliminates redundant Waits
tthrough data flow analysis. If every control path that leads to Waits,
contains another, Waits from the same dependence, then Waits
is redundant. Moreover, since sequential segments are percolated
upwards by Step 5, it may be possible to merge some of them to
reduce the overall number of signals. HELIX merges sequential
segments if they can be scheduled without parallel code between
them.

Finally, HELIX uses the synchronization of one dependence, say
d_j, to synchronize another, say d_i, provided d_j is redundant due to
d_i. A data dependence d_j is redundant due to d_i if Wait(d_i) is available (in the data flow sense) at every occurrence of Wait(d_j).
This redundancy relation can be viewed as a graph, called the data
dependence redundance graph, whose nodes are the data depend-
ences of a loop. This graph contains an edge d_j → d_i if and only if
d_i is redundant due to d_j. The following theorem specifies which subset of dependences need to be synchronized.

**Theorem 1.** Let \( G = (N, E) \) be a data dependence redundance graph and let \( N_{\text{no-synch}} \subseteq N \) be the set of dependences that includes every node without incoming edges and one node per
cycle of \( G \). Synchronizing the set \( N_{\text{no-synch}} \) synchronizes the entire set of dependences \( N \).

Thanks to the above theorem, HELIX can keep only the Waits that
are related to \( N_{\text{no-synch}} \).

**Step 7: Inserting inter-thread communication.** The syn-
chronization required for loop-carried dependences is implemented
using a per-thread memory area called the thread memory buffer,
which resides in the system’s shared memory. Threads are bound to
specific cores and they execute parallel loop iterations in round-
robin order. A thread uses its thread memory buffer to receive sig-
als from the thread that is executing the preceding iteration. For signalling purposes, a thread can only read from its own memory
buffer and can only write to the memory buffer of the successor
thread (the one that will execute the next loop iteration). The suc-
cessor/predecessor relation of parallel threads is statically fixed and
the last thread writes to the first thread’s buffer, thereby creating a
cycle of reads and writes through the buffers. The buffer of a
given thread is initialized by its predecessor before that thread is
unblocked by a control signal (i.e., a store to a per-thread memory
location called IterationFlag).

Loads and stores are inserted into the code to forward data pro-
duced and stored in loop boundary live variables. The Wait and
Signal operations are implemented using simple loads and stores.
Depending on the memory consistency model of the underlying
platform, memory barriers may need to be added before the loads
and after the stores. However, this is not required on our Intel-based
evaluation system (see Section 2.3).

**Step 8: Coupling with helper threads.** When a core, say
c_i, sends a signal to another, say c_j, it writes a value to a designated
memory location in the thread memory buffer, which places it into
c_i’s first private cache. The value is not forwarded to c_j’s private
cache until \( c_j \) issues the corresponding Wait instruction (i.e., a
load operation). It then takes several cycles for \( c_j \) to receive the
value (110 clock cycles in our testbed). The caches act as a pull
system. When cores have SMT capabilities, HELIX transforms the
caches into a push system for signaling, where \( c_j \) pushes the signal
to \( c_i \) as soon as it is produced. This leads to a significant reduction
in \( c_j \)’s waiting time. HELIX mimics a push memory system on
top of a pull one by coupling an additional helper thread to each
iteration thread running on the same core. Helper threads are in
charge of prefetching signals for their coupled iteration threads.

In Step 4, HELIX inserts Waits into the code such that every
path through the CFG contains all Waits instructions. An exam-
ple is shown in Figure 2. The code executed by the helper threads is a straight line of Waits, one per sequential segment, where a
Wait(d_i) is executed after Wait(d_j) if Wait(d_j) is available just before
Wait(d_i).

Since a given helper thread can prefetch one signal at a time, HE-
LIX schedules the code executed by iteration threads to space se-
quential segments evenly throughout the loop, until enough code
is inserted to achieve even signal prefetching. The algorithm for
this scheduling is described in Figure 6. To understand its impact,
consider Figure 7 which shows the run-time execution of a par-
allized loop that includes three sequential segments, SS1, SS2
and SS3. The first case, “No prefetching”, represents the execu-
tion of the code produced by Step 7. In this case, every signal
takes \( S \) clock cycles to be transferred between cores, because the
signal forwarding starts only when the receiver tries to enter the
corresponding sequential segment. The second case, “Prefetching
without balancing”, shows execution when helper threads are used
without the scheduling algorithm of Figure 6. In this case, only
the interval between SS3 and SS1 is long enough to prefetch the
signal, so only signals coming from SS1 are fully prefetched; the
others are just slightly prefetched. The last case, “Prefetching with
balancing”, shows how prefetching signals evenly leads to a bet-
ter use of idle core clock cycles. Note that when helper threads are
used (the second and third cases), prefetching a signal starts as
soon as the previous one has been prefetched or the previous iter-
ation leaves the corresponding sequential segment. Finally, note
that the overall time spent executing parallel code is constant over these
three cases \( \langle A + B + C \rangle \).

As input, the code scheduling algorithm of Figure 6 takes the loop
to schedule and the platform-dependent latencies for both an un-
prefetched and a fully prefetched signal. Initially, the code belong-
ing to loop \( L \) that can run in parallel is untagged (line 2). The
algorithm runs until there is no more untagged parallel code (check
Step 9: Merging parallel loops inside the program.

The function that contains a parallel loop might or might not be called within a loop that is running in parallel. Since only one loop can run in parallel at a time, HELIX keeps the sequential version of each parallel loop to use in case another one is already running in parallel. A conditional branch is inserted in a pre-header placed just before the two versions. Execution is directed to the parallel loop if no other parallel loop is executing (determined by a global variable). Otherwise execution proceeds with the sequential version of the loop.

When a loop has multiple successors, HELIX associates a unique value with each exit path of its prologue. The thread that executes the final iteration sets an exit variable to the value for the exit path taken. When all parallel threads have finished, the main thread checks this variable and jumps to the correct successor.

2.2 Choosing Loops to Parallelize

Transforming a loop into parallel threads can speed up loop execution, provided the benefits of concurrency outweigh the costs of inter-thread communication. The selection of loops to parallelize must be guided by the nature of the loops, the profile of the program given realistic inputs, and the properties of the transformation. Our approach devotes all cores of a processor to one parallelized loop at a time, so multiple independent loops cannot run concurrently, and loops nested within a parallel loop cannot be selected for parallelization. Therefore, selecting the most profitable loops to transform (i.e., loops that, if parallelized, best speed up the program) is critical for achieving significant speedups.

Different sets of loops correspond to separate solutions to the problem. To choose the best set of loops, we need to compare these solutions, by estimating and comparing their speedups. Since the number of possible solutions grows exponentially with the number of loops in the program, our approach constrains the number of sets considered in order to find a solution within reasonable time.

Our heuristic identifies the most promising loops to parallelize by using a graph we call the dynamic loop nesting graph. A simple model based on Amdahl’s law drives the search. Since loops are analyzed and executed one at a time, without merging or splitting, we use a model that computes the speedups of single loops.

**Speedup model.** Amdahl’s law [5, 18] describes the effect of applying N cores in parallel to a program that executes sequentially in unit time. However, parallelization of a loop can add significant overhead. Therefore, in choosing loops, we incorporate overhead in Amdahl’s law to produce the following speedup model for parallelization of a program: $Speedup(P, N, O) = \frac{1}{(1 - \frac{P}{N}) + \frac{O}{P}}$, where $O$ is the added overhead (e.g., due to thread synchronization). Since by hypothesis different parallelized loops cannot run simultaneously, we have $P = \sum_{i=1}^{Lop} P_i$ and $O = \sum_{i=1}^{Lop} O_i$, where $Lop$ is the number of parallelized loops, $P_i$ is the relative time spent running the code of loop $i$ outside its sequential segments (code regions executed sequentially to preserve program semantics) and $O_i$ is the added overhead for that loop. Terms $P_i$ and $O_i$ depend on the specific code transformation technique used to parallelize the loops. We later describe how we obtain those factors for the HELIX parallelizer.

**Loop selection algorithm.** Our algorithm for choosing the best loops to parallelize uses the speedup model described above, together with a dynamic loop nesting graph. The scope of our analysis is the whole program (hence multiple functions), and we consider a loop within a function called within a loop to be a subloop of the latter [6]. We extend the well-known loop nesting tree to have program-wide scope, and we call it the static loop nesting graph. It is not a tree because a function can have multiple callers. The dynamic loop nesting graph is a subgraph of the static graph that omits edges not traversed during profiling execution. For example, Figure 8 shows a fragment of the dynamic loop nesting graph from the SPEC CPU2000 benchmark 179.art. The graph is not a tree because function reset_nodes, which includes two loops, is called
The loop selection algorithm adds two attributes to each node (loop) in the dynamic loop nesting graph, which are set just before running the algorithm: the saved time \( T \) and the maximum saved time \( \text{max}T \). \( T \) is computed by exploiting the speedup model; it is set to the difference between the time spent in the sequential version of the loop and that in the parallel version. If no speedup is achieved, then \( T = 0 \). This attribute does not change during the execution of the algorithm. The \( \text{max}T \) attribute provides information about the time that could be saved by parallelizing either the current loop or the best combination of its subloops. Initially, \( \text{max}T \) is set equal to \( T \). The loop selection algorithm has two phases. The first propagates \( \text{max}T \) through the dynamic loop nesting graph. The second uses \( \text{max}T \) to identify loops to parallelize.

The first phase of the algorithm propagates \( \text{max}T \) through the graph from inner to outer loops. If the sum of the \( \text{max}T \) attributes of a loop’s subloops exceeds its current \( \text{max}T \) value, then that sum becomes its new \( \text{max}T \) attribute. This step repeats throughout the dynamic loop nesting graph until a fixed point is reached.

The second phase of the algorithm starts from the outermost loop nodes and searches downward until it reaches a node with \( \text{max}T \) equal to \( T \). The algorithm works top-down because by going deeper in the nested graph, we lose code to parallelize. Ideally we would choose outermost loops. However, time saved by parallelization can increase by going deeper because the fraction of time spent running in parallel might increase as sequential segments become smaller. Every time there is a split in the path (when a loop has multiple subloops), the search continues in all directions. Nodes that terminate the search with \( \text{max}T \) greater than zero represent the loop selected for parallelization. The rationale behind this phase is that there is no point in going below a node for which the time saved by parallelization equals or exceeds that for any combination of subloops.

Figure 8 shows the dynamic loop nesting graph after both phases of the algorithm have been applied. Note that parallelized loops belong to different nesting levels; in general, choosing loops at a fixed level (e.g., outermost loops) is not the best solution. Consider loops L8 and L9, which belong to the fourth loop nesting level. L8 is a better choice than its child L10 because the latter has a smaller body (i.e., less code to parallelize). On the other hand, even though L9 embraces more code than its child L11, the size of its sequential segments are larger than those of L11, so L11 has a larger \( T \) than L9. Since L11 has more code to run in parallel than L9, it is the more profitable loop to choose.

**HELIX speedup model.** By using generic parameters \( P_i \) and \( O_i \), the speedup model described above abstracts away details of the specific parallelization technique applied. After profiling the original program, we can compute those parameters specifically for HELIX. \( P_i \) is the time spent in the body of the \( i \)-th parallelized loop outside its sequential segments. \( O_i \), the overhead of that loop, is

\[
O_i = \text{Config}_i + \text{Sig}_i \times S + \left[ \frac{\text{Bytes}_i}{\text{CPU}\_\text{word}} \right] \times M \tag{1}
\]

where \( \text{Config}_i \) is the time spent to configure loop \( i \) (e.g., initialize thread memory buffers), \( \text{Sig}_i \) is the overall number of signals sent inside loop \( i \), which is equal to \( C\_\text{Sig}_i + D\_\text{Sig}_i + (N - 1) \times 2 \times I\_\text{vec}_i \) where \( C\_\text{Sig}_i \) and \( D\_\text{Sig}_i \) are the overall number of signals sent to satisfy control and data dependences within loop \( i \) respectively, and \( I\_\text{vec}_i \) is the number of times loop \( i \) is executed. For every invocation of loop \( i \), HELIX sends \( N - 1 \) signals to start or stop parallel threads. These occur just after the loop is configured and just after its last iteration is executed. Hence, \((N - 1) \times 2 \times I\_\text{vec}_i \) is the overall number of signals sent to start and stop parallel threads for loop \( i \). Factor \( S \) is the time spent per signal, which is assumed to be constant. Finally, \( \text{Bytes}_i \) is the number of bytes transferred between loop iterations, \( \text{CPU}\_\text{word} \) is the number of bytes of a CPU word and \( M \) is the time spent to transfer a CPU word between cores.

\( I\_\text{vec}_i \) is profiled from the original program and \( \text{Config}_i \) is profiled by adding the extra instructions needed to configure loop \( i \) to the original program just before loop \( i \). Finally, \( C\_\text{Sig}_i \) and \( D\_\text{Sig}_i \) are computed by profiling the overall number of iterations of loop \( i \): \( C\_\text{Sig}_i \) is equal to this number and \( D\_\text{Sig}_i \) is equal to the same number times the number of sequential segments per iteration in that loop, which is statically known.

**2.3 HELIX and Memory Consistency**

HELIX depends on memory consistency [2] and communication order. Some multicore processors guarantee that stores to memory performed by a single core are seen in the same executing order by others. If this memory consistency is not enforced by hardware, then HELIX adds memory barriers to enforce it. Since memory loads and stores are used for synchronization, the communication order discipline requires that stores to shared data locations come before the store of the synchronizing flag in the thread producing the shared values, and on the consuming side, the synchronizing flag is loaded and tested before any of the shared data. For control dependences, shared data is the contents of the thread memory buffer, and the synchronizing flag is \( \text{IterationFlag} \) (Step 7 from the HELIX algorithm). Note that this synchronization scheme works because the communication model of HELIX ensures that there can be only one reader and one writer per memory location at the same time. In this paper, we assume a single-chip Intel machine that provides total store ordering (see Section 8 of the Intel Developer’s Manual [1]), which is enough for our purposes. Therefore, in our testbed, HELIX satisfies both control and data dependences by using loads and stores. On the other hand, if this memory consistency did not exist, HELIX would need to insert memory barriers after synchronizing stores and before synchronizing loads.

**3. EVALUATION**

This section evaluates HELIX using the C language benchmarks from the SPEC CPU2000 suite, showing the speedups achieved on a commodity multicore single-die system. After describing the characteristics of the loops automatically chosen for parallelization by HELIX, we show that only a small fraction of the overall data consumed by loop iterations needs to be forwarded between cores, and we perform a limit study of signal prefetching to demonstrate the effectiveness of helper threads and to highlight the opportunity for further improvements. Moreover, we analyze the loop selection algorithm to explain why choosing the right loops to parallelize is
critical for achieving consistent speedups, and we assess the impact on this algorithm of over- or underestimating signal latency. We also demonstrate that blindly choosing loops at a single specific nesting level (e.g., outermost loops) can hide otherwise exploitable parallel code.

### 3.1 Experimental Setting

HELIX extends the ILDJIT compilation framework [8], version 0.7. ILDJIT generates native machine code from CIL bytecode, so we used GCC4CLI [14] to translate benchmarks written in C to CIL. ILDJIT has several advantages for this work. It has a rich intermediate representation (IR), including metadata descriptions of source data types. It supports code instrumentation at the IR level, and its built-in optimization suite is easy to extend with new code analysis and transformation passes.

**Benchmarks.** To evaluate our scheme we use 13 out of the 15 C language benchmarks from the SPEC CPU2000 suite, because GCC4CLI only supports C. We use the training inputs to select loops for parallelization, and the reference inputs for validation. The DDG analysis that we rely on [17] requires too much memory loops for parallelization, and the reference inputs for validation.

**Measuring Performance.** We compute speedups resulting from parallelization by running entire benchmarks to completion on a real system using the reference inputs. For each benchmark, in order to choose loops for parallelization, we first build a static loop nesting graph and a data dependence graph. Then we profile the graphs (using training inputs) to generate the dynamic loop nesting graph. Subsequent profiling runs for the HELIX-optimized form of each loop generate data on execution times by providing a breakdown of time spent configuring its parallel threads, executing its prologue, and executing its sequential segments. From this data, the algorithm described in Section 2.2 chooses a set of loops to parallelize.

The multi-threaded and, hence, non-deterministic, nature of the parallelized programs on a real system, we repeat each experiment a minimum of 10 times until the width of the 95% confidence interval is less than 5% of the sample mean.

**Hardware Platform.** Our experiments use an Intel® Core™ i7-980X with six cores, each operating at 3.33 GHz, with Turbo Boost disabled. The processor has three cache levels. The first two are private to each core and are 32KB and 256KB each. All cores share the last level 12MB cache, which is used to forward data values across cores of the same processor through the MESIF cache coherence protocol.

### 3.2 HELIX Evaluation

Table 1 shows the number of loops chosen by HELIX to parallelize and the total number of candidate loops. The fraction of loop-carried dependences inside the parallelized loops is low, highlighting the additional degree of freedom that HELIX is able to exploit, in contrast to techniques such as DSWP that must also handle intra-iteration data dependences. Moreover, Table 1 shows the drastic reduction in signals used for synchronization that Step 6 of the HELIX algorithm is able to achieve. Further, this table shows that only a small fraction of data has to be forwarded between cores. Finally, the maximum code size for each iteration thread that has to be loaded into the instruction cache is negligible, so the instruction cache miss rate is very low.

#### Importance of Reducing Signaling Overhead.

Signaling overhead is the main source of inefficiency in code produced by the HELIX algorithm. Both steps 6 and 8 (Section 2.1) constrain this overhead. Step 6 minimizes the number of overall signals sent per loop iteration. Step 8 minimizes the overhead per signal.

Figure 10 shows the speedups achieved for six cores when some steps of the HELIX transformation are disabled to illustrate their contribution. In each case, loops are chosen for parallelization using profile data obtained by instrumenting code produced for the specific case. As a result, HELIX avoids slowdown even when both steps 6 and 8 are disabled (first bar for each benchmark), so that signaling overhead is high. In this case, loops where most of the time is spent are not chosen by the HELIX transformation algorithm described in Section 2.2, because that would lead to a significant signaling overhead.

The second and third bars show what happens when step 8 or step 6 is disabled, respectively. Only a small speedup is achievable in either case. When step 8 is disabled, fewer signals are sent, but each one stalls execution for too many cycles (110 on our platform). When step 6 is disabled, even if step 8 reduces the overhead per signal, too many signals are sent overall.

The last bar of Figure 10 shows the effect of using both steps 6 and 8, but without benefit of the code scheduling algorithm described in Figure 6. The differences between this last bar and the second and third bars show that only when steps 6 and 8 are used together.
can significant speedups be obtained. Finally, the difference between the last bar and the speedups shown in Figure 9 shows that spacing sequential segments to help the signal prefetching mechanism improves speedups significantly, especially for benchmarks like equake, mesa, and vpr that require negligible amounts of data to be transferred between iterations.

3.3 Signal Prefetching

In order to evaluate the effectiveness of helper threads in improving TLP, we compare the speedups achieved by HELIX with two additional schemes. The first has each helper thread execute Wait instructions in the same order as its corresponding iteration thread. We call this matched prefetching. The second scheme represents an ideal scenario in which all signals are completely prefetched and available in the first level cache, even if this is unrealistic given the current code schedule. We call this ideal prefetching.

To compute speedups for matched and ideal prefetching we rely on the model introduced in Section 2.2. One parameter of this model is the signal latency $S$. Note that when there is no prefetching, this latency does not depend on the executed code. On the other hand, with the prefetching mechanism used by HELIX, this latency varies with the workload. We first compute the average number of clock cycles between the current sequential segment and the next one, then take the difference between that and the unprefetched signal latency (which represents the possible benefit of signal prefetching). We then compute the minimum of this benefit and the latency for a fully prefetched signal (which is four clock cycles in our system, the latency of a hit in the first level data cache). The signal latency to use in the model is computed on a per-loop basis by averaging this minimum value across sequential segments.

To measure the unprefetched signal latency on our system, we developed a microbenchmark that experimentally computes the number of clock cycles needed to send a signal between cores. We used it to test several implementations of Wait and Signal (including spin locking, snoop locking, collision avoidance locking, and tournament locking [35]), and found that our load-store implementation performs best on our platform. Its measured signal latency is 110 cycles, double the latency of single accesses to the last level cache (L3). This is because the receiving core must continuously check the memory location used to convey the signal and, therefore, needs to access the shared cache (L3), which takes 55 cycles. The sending core only writes to its L1 cache, but the value needs to be forwarded to the receiving core. This is similar to an access to the last level cache [1], which accounts for the other 55 cycles.

The difference between the geometric mean of speedups for HELIX and matched prefetching is 0.1, which shows the accuracy of Step 8 of the HELIX algorithm (see Section 2.1) in computing the sequence of Wait instructions executed by helper threads.

The geometric means of speedups for matched prefetching and ideal prefetching differ by 0.4, which shows the room that a code scheduling algorithm might have to reorganize code executed by it-
Recent work on DOALL parallelism has used code transformable, since the compiler cannot ensure correctness. However, relying on users to indicate whether loops can be parallelized across loop iterations. This technique is not fully automatic, and requires analysis of profile data to help the compiler estimate whether data dependences are independent. Tournavitis et al. [38] proposed an approach to loop parallelization that uses dependence information to target the DOACROSS technique. Xu and Chaudhary [40] developed a time stamp algorithm to execute loop iterations in parallel when they are detected at run time to be independent. Dynamic schemes to execute loop iterations in parallel when they are detected at run time to be independent have been proposed. These schemes can provide broader options available with HELIX, such as eliminating redundant synchronizations and thread-level speculation techniques to expose hidden parallelism in general purpose programs. In contrast, our work is non-speculative.

Decoupled software pipelining (DSWP) [30] addresses the limitations of the DOACROSS approach by extracting fine-grained pipeline parallelism. DSWP automatically breaks the CFG of each loop into strongly connected components (SCC) chosen to minimize the transfer of variables between threads and balance the computation load among threads. The technique can produce significant speedups when this kind of parallelism is available in the program. However, it is limited by the number of SCCs in each loop, which is usually much smaller than the loop iteration count. Bridges et al. [7] extended DSWP with thread-level speculation and manual insertion of source code extensions. This builds on the manual parallelization work of Prabhul and Okutukon [31]. Bridges’ approach parallelizes loop iterations speculatively and allows the compiler to choose among several valid program outcomes. Thies et al. [37] also use annotations that indicate pipeline boundaries for DSWP. However, these approaches rely on programmer assistance to explicitly add the language extensions.

Raman et al. [32] studied speculative parallelization using software transactional memory. They introduced a multi-threaded software transaction using memory versioning to separate speculative and non-speculative state. Speculative decoupled software pipelining [39] is used to parallelize loops with the speculative portion of the code wrapped in a transaction. In order to remove the constraint on the number of threads extracted, DSWP has been mixed with the DOALL technique [19, 33]. In [33], simulation is used to investigate a fast inter-thread communication hardware mechanism. In [19], the proposed approach is manually applied to the benchmarks considered. Finally, in all these works, the compiler is usually much smaller than the loop iteration count.

Elimination of redundant synchronizations has been studied for regular workloads [12, 13, 25]. Our work has the same goal, but for irregular workloads.

Code scheduling algorithms to improve TLP across loop iterations in already parallelized programs have been proposed. They target coarser-grained code sections than the ones HELIX operates on, and they do not consider the signaling problem, which we address by merging sequential segments with no loss of TLP. Finally, a code scheduling algorithm that targets the DOACROSS technique has been proposed. Since it is specific to DOACROSS, it cannot provide broader options available with HELIX, such as execution of independent sequential segments in parallel.

Dynamic schemes to execute loop iterations in parallel when they are detected at run time to be independent have been proposed. In [16] loop iterations are speculatively executed in parallel.
with the possibility of fixing the execution if they are mispredicted. In [42], loop iterations are executed in parallel after they are recognized to be independent at run time; in this work the focus is on minimizing the overhead due to the computation of the dynamic data dependences by performing an approximated and conservative analysis while the original code is in execution.

Exploiting SMT to help critical threads was introduced in [9] and adapted in different domains later on [22, 27]. We have shown how to adapt this idea to mitigate our specific problem of sending signals by automatically generating helper threads.

5. CONCLUSION
HELIX is a new, fully automatic parallelization technique that can speed up execution of irregular single-threaded programs on chip multiprocessors. Our experimental results show that by reducing communication costs and increasing thread level parallelism, HELIX achieves a mean speedup of $2.25 \times$ (with a maximum of $4.12 \times$) over a broad range of applications on a real six-core system. Choosing the right loops to parallelize is one key to the success of our implementation, which combines an analytical model of loop speedup with profiling data to choose the most profitable loop sets. Our results show that synchronization, not data transfer, is the main bottleneck, which can be significantly reduced by proper use of SMT technology. In future work, we expect our implementation to exploit fast hardware implementations of signaling to obtain better speedup.

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6. REFERENCES