Performance Analysis of Multithreaded Programs

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Papers for Today


Cilkview
Four Reasons for Scaling Losses in Cilk

• Insufficient parallelism
  — e.g. serial code sections

• Scheduling overhead
  — work is too fine grained to be distributed productively

• Insufficient data bandwidth
  — contention for cache or memory bandwidth

• Contention
  — for locks, false sharing
Cilk Execution DAG

vertex = strand
edge = ordering dependencies
Upper Bounds on Speedup

• **Background**
  — work law
    – $T_p \geq T_1 / P$
  — span law
    – $T_p \geq T_{\infty}$

• **Bounds on speedup**
  — work bound
    – $T_1 / T_p \leq P$
  — span bound
    – $T_1 / T_p \leq T_1 / T_{\infty}$
Burdened DAG Model

- Performance determined not just by intrinsic parallelism, but also by the overhead of the scheduler
  — thread migration by a steal is not free
- Model cost of potential thread migration by charging 15K cycles for each continuation and return edge

squares on return and continuation edges represent potential migration overhead
Cilkview Approach

- **Use Pin binary instrumentation tool**
- **Insert instrumentation into the program to measure**
  - number instructions along edges (work)
  - number of syncs
  - number of spawns
  - estimate addition to the critical path due to costs associated with steals along continuation and return edges
    - assume each steal may cost 15K instructions
- **Perform measurements in a serial execution of the DAG**
- **Use projections to estimate parallel performance under a range of conditions**
Performance Metrics

• Measured metrics
  — Work
  — Span
    – longest path through the DAG
  — Burdened span
    – longest path through the burdened DAG
  — Spawns
  — Syncs

• Derived metrics
  — Parallelism
    – Work / Span
  — Burdened parallelism
    – Work / (Burdened span)
  — Average maximal strand
    – Work / (1 + 2 * Spawns + Syncs)
Expected Speedup

Theorem: Let $T_1$ be the work of an application, and let $T_b$ be its burdened span. Then, a work-stealing scheduler running on $P$ processors can execute the application in expected time

$$T_p \leq T_1 / P + 2 \delta T_b,$$

where $\delta$ is the span coefficient.

See the paper for the proof.

The proof considers the additional cost of the burden for the number of steals in the expected case and adds that to the work.
Cilkview Output for Quicksort (10M numbers)
void stencil_loop (int t0, int t1,
        int x0, int x1, int y0, int y1,
        int z0, int z1){
    for(int t = t0; t < t1; ++t) {
        for(int z = z0; z < z1; ++z) {
            for(int y = y0; y < y1; ++y) {
                cilk_for(int x = x0; x < x1; ++x) {
                    // stencil computation kernel
                    stencil_kernel(t, x, y, z);
                } }
            } }
        } } } }
Case Study: A Stencil Computation - II

```c
void stencil_loop (int t0, int t1,
   int x0, int x1, int y0, int y1,
   int z0, int z1){
  for(int t = t0; t < t1; ++t) {
    for(int z = z0; z < z1; ++z) {
      for(int y = y0; y < y1; ++y) {
        cilk_for(int x = x0; x < x1; ++x) {
          // stencil computation kernel
          stencil_kernel(t, x, y, z);
        }
      }
    }
  }
}
```

- **Parallelism ~119**
- **Large difference between span and burdened span**
- **Burdened parallelism ~.87** — slowdown likely!
- **Low burdened parallelism** indicates that dynamic load balancing cost may swamp benefit of exploiting available parallelism

Parallelizing outer loop rather than inner loop would help
Limitations of Cilkview

• Analyzes the performance of the whole program

• Can analyze the performance of a region by inserting “start” and “stop” points in a program
  — cumbersome
  — error prone for large and complex code bases

• Tuning is equivalent to “guess and check”
Performance analysis of OpenMP
Challenge for OpenMP Tools

Typically, large gap between OpenMP source and implementation

Calling context for code in parallel regions and tasks executed by worker threads is not readily available
Difficulty: OpenMP Context is Distributed

Problem: full calling context may be distributed among threads
Additional Obstacles for Tools

- Differences in OpenMP implementations
  - static vs. dynamic linking
    - Oracle’s collector interface for tools supports only dynamic linking
    - static linking is often preferred for supercomputers
  - threads
    - Intel: extra *shepherd* thread
    - IBM: none
  - call stack
    - GOMP: master calls outlined function from user code
    - Intel and IBM: master calls outlined function from runtime
    - PGI: cactus stack

- No standard API for runtime inquiry
OMPT: An OpenMP Tools API

- **Goal:** a standardized tool interface for OpenMP
  - prerequisite for portable tools for debugging and performance analysis
  - missing piece of the OpenMP language standard

- **Design objectives**
  - enable tools to measure and attribute costs to application source and runtime system
    - support low-overhead tools based on asynchronous sampling
    - attribute to user-level calling contexts
    - associate a thread’s activity at any point with a descriptive state
  - minimize overhead if OMPT interface is not in use
    - features that may increase overhead are optional
  - define interface for trace-based performance tools
  - don’t impose an unreasonable development burden
    - runtime implementers
    - tool developers
Major OMPT Functionality

- **State tracking**
  - threads maintain state at all times (e.g., working, waiting, idle)
  - a tool can query this state at any time (async signal safe)

- **Call stack interpretation**
  - inquiry functions enable tools to reconstruct application-level call stacks from implementation-level information
    - identify which frames on the call stack belong to the runtime system

- **Event notification callbacks for predefined events**
  - mandatory callbacks for threads, parallel regions, and tasks
  - optional callbacks for identifying idleness and attributing blame
  - optional callbacks for tracing activity for all OpenMP constructs

- **Target device monitoring**
  - collect event trace on target
  - inspect, process, and record target events on host
## OMPT Callbacks

<table>
<thead>
<tr>
<th>Function</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>ompt_callback_thread_begin</td>
<td>ompt_callback_mutex_released</td>
</tr>
<tr>
<td>ompt_callback_thread_end</td>
<td>ompt_callback_dependencies</td>
</tr>
<tr>
<td>ompt_callback_parallel_begin</td>
<td>ompt_callback_task_dependence</td>
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<tr>
<td>ompt_callback_parallel_end</td>
<td>ompt_callback_work</td>
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<td>ompt_callback_task_create</td>
<td>ompt_callback_master</td>
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<td>ompt_callback_task_schedule</td>
<td>ompt_callback_target_map</td>
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<tr>
<td>ompt_callback_implicit_task</td>
<td>ompt_callback_sync_region</td>
</tr>
<tr>
<td>ompt_callback_target</td>
<td>ompt_callback_lock_init</td>
</tr>
<tr>
<td>ompt_callback_target_data_op</td>
<td>ompt_callback_lock_destroy</td>
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<tr>
<td>ompt_callback_target_submit</td>
<td>ompt_callback_mutex_acquire</td>
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<tr>
<td>ompt_callback_control_tool</td>
<td>ompt_callback_mutex_acquired</td>
</tr>
<tr>
<td>ompt_callback_device_initialize</td>
<td>ompt_callback_nest_lock</td>
</tr>
<tr>
<td>ompt_callback_device_finalize</td>
<td>ompt_callback_flush</td>
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<tr>
<td>ompt_callback_device_load</td>
<td>ompt_callback_cancel</td>
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<tr>
<td>ompt_callback_device_unload</td>
<td>ompt_callback_reduction</td>
</tr>
<tr>
<td>ompt_callback_sync_region_wait</td>
<td>ompt_callback_dispatch</td>
</tr>
</tbody>
</table>
# OMPT Callback API Requirements

<table>
<thead>
<tr>
<th>Return code abbreviation</th>
<th>N</th>
<th>S/P</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>ompt_callback_thread_begin</td>
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</tbody>
</table>

N = ompt_set_never  
S = ompt_set_sometimes  
P = ompt_set_sometimespaired  
A = ompt_set_always
OMPT Introspection API

"omptEnumerateStates"
"omptEnumerateMutexImps"
"omptSetCallback"
"omptGetCallback"
"omptGetThreadId"
"omptGetNumPlaces"
"omptGetPlaceProcIds"
"omptGetPlaceNum"
"omptGetPartitionPlaceNums"
"omptGetProcId"

"omptGetState"
"omptGetParallelInfo"
"omptGetTaskInfo"
"omptGetTaskMemory"
"omptGetNumDevices"
"omptGetNumProcs"
"omptGetTargetInfo"
"omptGetUniqueId"
"omptFinalizeTool"
Understanding Call Stacks of OpenMP

[Diagram showing call stacks for threads 1 and 2 with code segments A, B, and C.]
Case Study: LLNL’s LULESH with RAJA

Livermore Unstructured Lagrangian Explicit Shock Hydrodynamics

- Implementation using RAJA portability model
- Compiled with high optimization
  - icpc -g -O3 -msse4.1 -align -inline-max-total-size=20000 -inline-forceinline -ansi-alias -std=c++0x -openmp -debug inline-debug-info -parallel-source-info=2 -debug all
- Linked with OMPT-enabled LLVM OpenMP runtime
- Data collection
  - hpcrun -e REALTIME@1000 ./lulesh-RAJA-parallel.exe
    - implicitly uses the OMPT performance tools interface, which is enabled in our OMPT-enhanced version of the Intel LLVM OpenMP runtime
Case Study: LLNL’s LULESH with

Notable features:
- Seamless global view
- Inlined code
- “Call” sites
- Demangled “callee”
- Loops in context

2 18-core Haswell
72+1 threads
## Blame-shifting: Analyze Thread Performance

<table>
<thead>
<tr>
<th>Problem</th>
<th>Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Undirected Blame Shifting</strong>&lt;sup&gt;1,3&lt;/sup&gt;</td>
<td>A thread is idle waiting for work</td>
</tr>
<tr>
<td><strong>Directed Blame Shifting</strong>&lt;sup&gt;2,3&lt;/sup&gt;</td>
<td>A thread is idle waiting for a mutex</td>
</tr>
</tbody>
</table>

1. Tallent & Mellor-Crummey: PPoPP 2009  
2. Tallent, Mellor-Crummey, Porterfield: PPoPP 2010  
3. Liu, Mellor-Crummey, Fagan: ICS 2013
Blame-shifting Metrics for OpenMP

- **OMP_IDLE**
  - attribute idleness to insufficiently-parallel code being executed by other threads

- **OMP_MUTEX**
  - attribute waiting for locks to code holding the lock
    - attribute to the lock release as a proxy

- Measuring these metrics requires sampling using using a time-based sample source
  - REALTIME, CPUTIME, cycles
Simplified sketch

- **Initialization**: install callbacks
  - mandatory: thread begin/end, parallel region & task begin/end
  - blame shifting: wait begin/end, mutex release

- **When a profiling trigger fires**
  - if thread is waiting
    - apply blame shifting to attribute idleness to working threads
  - if thread is working
    - accept undirected blame for idleness of others
    - attribute work and blame to application-level calling context

- **When a mutex release occurs**
  - accept directed blame charged to that mutex
  - attribute blame to application-level calling context

**Attribute costs to application-level calling context**
- unwind call stack
- elide OpenMP runtime frames using OMPT frame information
- use info about nesting of tasks & regions to reconstruct full context
Directed Blame Shifting

- **Example:**
  - threads waiting at a lock are the symptom
  - the cause is the lock holder

- **Approach:** blame lock waiting on lock holder

- **Diagram:**
  - Fork
  - Lockwait
  - Join
  - Acquire lock
  - Release lock
  - Accumulate samples in a global hash table indexed by the lock address
  - Lock holder accepts these samples when it releases the lock
Example: Directed Blame Shifting for Locks

Blame a lock holder for delaying waiting threads

- Charge all samples that threads receive while awaiting a lock to the lock itself
- When releasing a lock, accept blame at all of the lock

almost all blame for the waiting is attributed here (cause)
Understanding Temporal Behavior

- Profiling compresses out the temporal dimension
  - temporal patterns, e.g. serialization, are invisible in profiles

- What can we do? Trace call path samples
  - sketch:
    - N times per second, take a call path sample of each thread
    - organize the samples for each thread along a time line
    - view how the execution evolves left to right
    - what do we view?
      
      assign each procedure a color; view a depth slice of an execution
Case Study: AMG2006

2 18-core Haswell
4 MPI ranks
6+3 threads per rank
Case Study: AMG2006

2 18-core Haswell
4 MPI ranks
6+3 threads per rank
2 18-core Haswell
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Case Study: AMG2006
Case Study: AMG2006

2 18-core Haswell
4 MPI ranks
6+3 threads per rank
12 nodes on Babbage@NERSC
24 Xeon Phi
48 MPI ranks
50+5 threads per rank

Case Study: AMG2006
Case Study: AMG2006

Slice
Thread 0 from each MPI rank

12 nodes on Babbage@NERSC
24 Xeon Phi
48 MPI ranks
50+5 threads per rank
Case Study: AMG2006

12 nodes on Babbage@NERSC
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48 MPI ranks
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Cilkprof
Cilkprof uses compiler instrumentation to gather detailed information about a Cilk program execution*

— measures how much work and span of the overall computation is attributable to the subcomputation that begins when the function invoked at that call site is called or spawned and that ends when that function returns

— analysis enables a programmer to evaluate the scalability of that call site — the scalability of the computation attributable to that call site — and how it affects the overall computation’s scalability

Currently, the tool lacks a user interface: it merely dumps a spreadsheet that relates costs to each call site

*Cilkview uses dynamic binary instrumentation with Pin to measure work.
Maintaining Work-Span Variables

For each function F, maintain work-span variables in shadow stack alongside the function call stack.

- Let u represent the spawn of F’s child with the longest span so far. u is initialized to the beginning of F on entry to F.

- **F.w**: work
  - work executed in the function so far

- **F.p**: prefix
  - span of the trace starting from the first instruction of F and ending with u
  - F.p is guaranteed to be on the critical path of F

- **F.l**: longest-child
  - span of the trace from the start of F through the return of the child that F spawns at u

- **F.c**: continuation
  - the span of the trace from the continuation of u through the most recently executed instruction in F
Cilkprof Algorithm

<table>
<thead>
<tr>
<th>F spawns or calls G:</th>
<th>Called G returns to F:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ( G.w = 0 )</td>
<td>5 ( G.p += G.c )</td>
</tr>
<tr>
<td>2 ( G.p = 0 )</td>
<td>6 ( F.w += G.w )</td>
</tr>
<tr>
<td>3 ( G.l = 0 )</td>
<td>7 ( F.c += G.p )</td>
</tr>
<tr>
<td>4 ( G.c = 0 )</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spawned G returns to F:</th>
<th>F syncs:</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 ( G.p += G.c )</td>
<td>14 if ( F.c &gt; F.l )</td>
</tr>
<tr>
<td>9 ( F.w += G.w )</td>
<td>15 ( F.p += F.c )</td>
</tr>
<tr>
<td>10 if ( F.c + G.p &gt; F.l )</td>
<td>16 else</td>
</tr>
<tr>
<td>11 ( F.l = G.p )</td>
<td>17 ( F.p += F.l )</td>
</tr>
<tr>
<td>12 ( F.p += F.c )</td>
<td>18 ( F.c = 0 )</td>
</tr>
<tr>
<td>13 ( F.c = 0 )</td>
<td>19 ( F.l = 0 )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>F executes an instruction:</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 ( F.w += 1 )</td>
</tr>
<tr>
<td>21 ( F.c += 1 )</td>
</tr>
</tbody>
</table>
Performance Metrics

• A Cilkprof measurement for a call site s consists of the following values for a set of invocations of s
  — execution count
    – the number of invocations of s accumulated in the profile
  — call-site work
    – the sum of the work of those invocations
  — the call-site span
    – the sum of the spans of those invocations

• Cilkprof additionally computes the parallelism of s as the ratio of s’s call-site work and call-site span
  — without recursive functions, Cilkprof could simply aggregate all executions of each call site
  — for recursive functions, must avoid overcounting the call-site work and call-site span
Space and Time Complexity

• For a Cilk program that
  — executes in $T_1$ time
  — has stack depth $D$

• Cilkprof’s work-span algorithm
  — runs in $O(T_1)$ time
  — using $O(D)$ extra storage
Case Study with Quicksort

```c
int partition(long array[], int low, int high) {
    long pivot = array[low + rand(high - low)];
    int l = low - 1;
    int r = high;
    while (true) {
        do { ++l; } while (array[l] < pivot);
        do { --r; } while (array[r] > pivot);
        if (l < r) {
            long tmp = array[l];
            array[l] = array[r];
            array[r] = tmp;
        } else {
            return (l == low ? l + 1 : l);
        }
    }
}

void pqsort(long array[], int low, int high) {
    if (high - low < COARSENING) {
        // base case: sort using insertion sort
    } else {
        int part = partition(array, low, high);
        cilk_spawn pqsort(array, low, part);
        pqsort(array, part, high);
        cilk_sync;
    }
}

int main(int argc, char *argv[]) {
    int n;
    long *A;
    // parse arguments
    // initialize array A of size n
    pqsort(A, 0, n);
    // do something with A
    return 0;
}
```

<table>
<thead>
<tr>
<th>Line</th>
<th>$T_1$</th>
<th>$T_\infty$</th>
<th>$T_1/T_\infty$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>408,150,528</td>
<td>408,150,528</td>
<td>1.0</td>
</tr>
<tr>
<td>21</td>
<td>741,312,781</td>
<td>116,591,841</td>
<td>6.4</td>
</tr>
<tr>
<td>22</td>
<td>761,041,165</td>
<td>125,360,000</td>
<td>6.1</td>
</tr>
<tr>
<td>31</td>
<td>790,518,060</td>
<td>141,902,681</td>
<td>5.6</td>
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</tbody>
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<td>597,298,216</td>
<td>98,119,730</td>
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<tr>
<td>691,808,220</td>
<td>118,447,199</td>
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## Cilkprof Overhead

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<th>Benchmark</th>
<th>Input size</th>
<th>Description</th>
<th>Overhead</th>
</tr>
</thead>
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<tr>
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