Low-overhead Loop Scheduling to Improve Performance of Scientific Applications

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Our strategies are in runtime system and compiler in SOLLVE slab
Motivating Example Code Structure

```c
#include <mpi.h>
int main(int argc, char** argv)
{
    MPI_Init(argc, argv);
    // input
    while (global_err < thresh)
    {
        MPI_Isend() / MPI_Irecv() / MPI_Waitall();
        for (i = 0; i < n; i++)
        {
            doCompute(n);
        }
        MPI_Collective_Op(&global_err);
        timestep++;
    }
    // output, viz
    MPI_Finalize();
}
```

1. [https://patterns.eecs.berkeley.edu/](https://patterns.eecs.berkeley.edu/)
Within-node Persistent Load Imbalance

Application-created imbalances.

These can be (mostly) handled if we had a perfect within-node load redistribution.

→ Within-node persistent imbalance causes significant slowdown in a multi-node run.
Transient Load Imbalance and its Potential Mitigation

Noise delays every iteration on some node

Here also: performance improves if we can perfectly redistribute work within each node

Noise amplification:
[PetriniCaseSC03], [hoeflerNoiseSC10]
How to Do Near-perfect Work Redistribution Within Node?

Focus on the OpenMP computation region in an MPI+OpenMP program

→ Let’s use OpenMP’s dynamic loop schedule provided.
#pragma omp parallel for schedule(static)
for(int i=0; i<n; i++)
    loop_body(i);

#pragma omp parallel for schedule(static)
for(int i=0; i<n; i++)
    loop_body(i);

#pragma omp parallel for nowait
for(int i=0; i<n; i++)
    loop_body(i);
#pragma omp parallel for schedule(dynamic)
for(int i=0; i<n; i++)
    loop_body(i);
Staggered Static/Dynamic Loop Scheduling

- Each thread finishes its static chunk.
- Then does dynamic chunks marked for it if available.
- Only if not, looks for other dynamic chunks from other threads to steal.

- Look at loop iteration space. Have spatial locality in static.
- Problem with spatial locality → don’t take advantage of prefetching engine for dynamic chunks.
CALU static/dynamic does better than Utenn’s PLASMA and Intel’s MKL

Less performance variation for static/dynamic $\rightarrow$ better scaling projection

[SHI12] Hybrid Static/dynamic Scheduling for Already Optimized Dense Matrix Factorization.
Software Architecture for Low-overhead Loop Scheduling

Software developed to easily create and experiment with new loop scheduling schemes

Results for Application Codes

1. uSched better than OpenMP guided

2. Optimizations always improve over uSched.

3. Combining different techniques seems to add on benefits, i.e., they don’t cancel benefit out.

4. Small code change, e.g., 41,421 loc to 41,982 loc (5.2%) for Rebound.

Figure: Performance improvement of MPI+OpenMP Rebound App. using lightweight loop scheduling on LLNL’s cab.
Loop Shift Proposal

- Add **loopshift** directive
- Must be nested within a work-sharing directive and parallel region
- Allow to map iterator of some inner loop of the work-sharing loop with some arithmetic expression
- Can use pre-defined variables such as thread identifier (tid) and number of threads (numthreads)

```c
#pragma omp parallel for
for (i = lbi; i < ubi; i++)
{
    int j;
   #pragma omp loopshift(j = (i + tid) % numthreads)
    for (j = lbj; j < ubj; j++)
    {
        /* do work */
    }
}
```

Listing 1: OpenMP LoopShift Directive
Data Locality in Tasking in OpenMP

Enhancing Support in OpenMP to Improve Data Locality in Application Programs Using Task Scheduling

Martin Kong, Vivek Kale

Lower execution time due to lower L3 due to lower DRAM cache traffic volume.

Lower energy consumption due to less data movement.
Using ECP’s SOLLVE for your Applications

- SOLLVE is a project to develop OpenMP for exascale
- Can link it to your app through following http://github.com/SOLLVE/sollve
- I’m working on making it available on Spack.
Proposal for User-defined Schedules in OpenMP

Example: glimpse of how a User-defined Schedule (UDS) might look like

```cpp
typedef struct {...} schedule_data;
void myDynsStart(...) {}  
void myDynsnext(...) {}  
void myDynsfini(...) {}

#pragma omp declare schedule(myDyn) start(myDynsStart) next(myDynsnext) fini(myDynsfini)
void example() {
    static schedule_data sd;
    int chunkSize = 4;

    #pragma omp parallel for schedule(myDyn, chunkSize:&sd)
    for(int i = 0; i < n; i++)
        c[i] = a[i]*b[i];
}
```

- The directive `declare schedule` connects a schedule with a set of functions to initialize the schedule and hand out the next chunk of iterations.
- The syntax of the clause `schedule` is extended to also accept an identifier denoting the UDS.
- Instead of calling into the RTL for loop scheduling, the compiler will invoke the functions of the UDS.
- Visibility and namespaces of these identifiers will be borrowed from User-Defined Reductions in OpenMP 5.0.
Lightweight Loop Scheduling in RAJA: lws-RAJA

Code through hand transformation or maybe ROSE/Orio/LLVM.

→ Significantly reduces lines of code for application programmer to use strategy: **easy-to-use strategies.**

→ Improves **portability of loop scheduling strategies.**
Load Balancing + Loop Scheduling Technique

1. Modify across-node load balancing in Charm++ to assign load to one PE in each node.
2. Use my loop scheduling strategies in CkLoop to optimize within node performance.

Key Idea:

This scheduler recently merged into Charm++; Development history here: https://bitbucket.org/viveklkalew/ckloop_schedule/src/master/
PIC using modified inter-node load balancing with adaptive loop scheduling is 19.13% faster than PIC using adaptive scheduling without load balancing.

The percentage improvement over the original Charm++ + CkParLoop is 17.20%.
Related Work

- SLATE [PLS19]
- Legion [AKL19]
- Hybrid MPI+OpenMP [LHS07]
- Habanero / Argobots [HMP18]
- Guided [AGS88] and Adaptive Scheduling [AGS19]
- RAJA [XRS18] and Kokkos [XKS18]
SOLLVE Thrust Areas Update

**Application Requirements**
- SOLLVE Spack package for application usage.
- Enable RAJA and Kokkos to target OpenMP
- Interactions with ECP applications and libraries including SLATE, Lattice QCD, miniVite QMCPack, ExaAM, Flash (ExaStar), E3SM.
- OpenMP feature wishlist ticketing system

**Standard and Specification Evolution**
- Fall 2019 OpenMP Face-to-Face in Auckland
- Release of OpenMP Technical Report 8 (Nov. 2019) containing OpenMP 5.0 Examples and features for OpenMP 5.1 with more descriptive features such as loop directive.

**OpenMP Scalable Runtime**
- Optimization of resource management and scheduling in the latest release of BOLT 1.0rc2; reduced overheads of OpenMP threads, useful for nested parallel regions.
- Work on improving support loop scheduling and tasking for OpenMP, in particular for load imbalanced applications.

**LLVM Compiler**
- Implementation of parallelizing and/or user-defined loop transformations in clang.
- Implementation of the OpenMP 5.0 declare mapper feature in Clang/LLVM.
- Optimization of GPU unified memory performance in Clang/LLVM.
- Implementation of performance portability features of OpenMP 5.0 such as declare variant.

**SAAS**
- OpenMP Scalable Runtime
- Accelerator
- Affinity
- Parallelism
- Tasking
- Memory Management

**Verification and Validation Suite**
- Work with a number of compiler teams who have used the V&V Suite to evaluate their products.
- Improved V&V suite to assess features in OpenMP for a large number of different ECP systems.
- Further developed V&V suite to consider computational patterns and algorithmic strategies used in many ECP application, such as testing OpenMP tasks used in SLATE.

**Training and Outreach**
- Webinars, Workshops, Events at ECP Annual Meeting, Tutorials, Hackathons

**ECP Value**
- Update
- Thrust

**OpenMP Services**
Ideas for Low-overhead Loop Scheduling for CPU+GPU

Problem:
- CPU stays idle during GPU computation
- CPU and GPU have different noise, GPU doesn’t have synchronization.
- Some part of the application timestep may need load balancing while other part may not.

An idea for a solution:
- Identify the parts
- Give GPU part that doesn’t need dynamic load balancing
- CPU part needs dynamic load balancing.
- For CPU part, use hybrid static/dynamic scheduling strategies.
  - Could implement with autotuning or runtime.
  - Use advanced patterns such as staggering.
New Loop Scheduling Strategy for Sparse Solvers

1. Use dynamic with chunk size 1 and see if hpctraceviewer reports lower amount of time spent in omp_barrier.
2. If confirmed, try to come up with a non-zero-count threshold of the submatrices to switch between dynamic and guided.
   
   ```
   if (#NZ > ...) { loop with guided schedule } else { loop with dynamic schedule }
   ```

   Look at hpctraceviewer data to keep omp_barrier time small.
3. Try tuning the chunk sizes for both dynamic and guided to minimize exec time. They can be different values. May need to tune #NZ
   threshold at the same time.

→ Conclusion: New loop scheduling strategies were developed based on needs of Sparse solvers, hypothesis from baseline results is that they will benefit and improve performance.
Summary

- Load imbalance within node is an **important** problem
- Novel schedulers **solve** the problem
  - Basic static/dynamic scheduling
  - Variants of scheduling strategies
  - Demonstration on applications using Software Architecture
    - Some with ROSE compiler from LLNL
- Proposed extensibility features facilitate novel loop schedulers
  - OpenMP UDS
- Making the scheduling strategies accessible
  - UDS in RAJA → integration
  - Charm++ + CkLoop: → combination
- More work with GPUs, special scheduling for sparse solvers,
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Works Cited (1)


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