Loop Scheduling in OpenMP

Vivek Kale

University of Southern California/Information Sciences Institute

Overview

- Loop Scheduling in OpenMP.
  - A primer of a loop construct
  - Definitions for schedules for OpenMP loops.
- A proposal for user-defined loop schedule for OpenMP
  - Need to allow for rapid development of novel loop scheduling strategies.
  - We suggest giving users of OpenMP applications control of the loop scheduling strategy to do so.
  - We call the scheme user-defined loop scheduling and propose the scheme as an addition to OpenMP.

OpenMP loops: A primer

- OpenMP provides a loop construct that specifies that the iterations of one or more associated loops will be executed in parallel by threads in the team in the context of their implicit tasks.[1]

```
#pragma omp for [clause[ [,] clause] ... ]
    for (int i=0; i<100; i++){}
```

- Loop needs to be in canonical form.
- The *clause* can be one or more of the following: `private(…)`, `firstprivate(…)`, `lastprivate(…)`, `linear(…)`, `reduction(…)`, **`schedule(…)`**, `collapse(...)`, `ordered[…]`, `nowait`, `allocate(…)`
- We focus on the clause ***`schedule(…)`*** in this talk.

1: OpenMP Technical Report 6. November 2017. http://www.openmp.org/press-release/openmp-tr6/

A Schedule for an OpenMP loop

```
#pragma omp parallel for schedule([modifier [modifier]:]kind[,chunk_size])
```

- A ***schedule*** in OpenMP is:
  - a specification of how iterations of associated loops are divided into contiguous non-empty subsets
    - We call each of the contiguous non-empty subsets a *chunk*
  - *and* how these chunks are distributed to threads of the team.[1]
- The *size of a chunk*, denoted as `chunk_size` must be a positive integer.

1: OpenMP Technical Report 6. November 2017. http://www.openmp.org/press-release/openmp-tr6/

The Kind of a Schedule

- A schedule *kind* is passed to an OpenMP loop schedule clause:
  - provides a hint for how iterations of the corresponding OpenMP loop should be assigned to threads in the team of the OpenMP region surrounding the loop.
- Five *kinds of schedules* for OpenMP loop[1]:
  - *`static`*
  - *`dynamic`*
  - *`guided`*
  - *`auto`*
  - *`runtime`*
- The OpenMP implementation and/or runtime defines how to assign chunks to threads of a team given the kind of schedule specified by as a hint.

1: OpenMP Technical Report 6. November 2017. http://www.openmp.org/press-release/openmp-tr6/

Modifiers of the Clause Schedule

- ***simd***: the chunk_size must be a multiple of the simd width. [1]
- ***monotonic***: If a thread executed iteration i, then the thread must execute iterations larger than i subsequently. [1]
- ***non-monotonic***: Execution order not subject to the monotonic restriction. [1]

1: OpenMP Technical Report 6. November 2017. http://www.openmp.org/press-release/openmp-tr6/

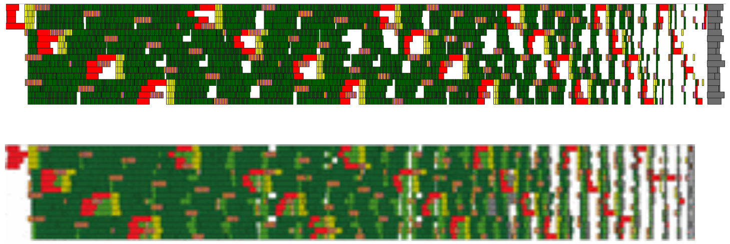
Need Novel Loop Scheduling Schemes in OpenMP

- Supercomputer architectures and applications are changing.
  - Large number of cores per node.
  - Speed variability across cores.
  - Complex dynamic behavior in applications themselves.
- So, we need new methods of distributing an application's computational work to a node's cores[1], specifically to schedule an application's parallelized loop's iterations to cores.
- Such methods need to
  - Ensure data locality and reduce synchronization overhead while maintaining load balance[2].
  - Be aware of inter-node parallelism handled by libraries such as MPICH[3].
  - Adapt during an application's execution.

1: R. D. Blumofe and C. E. Leiserson. Scheduling Multithreaded Computations by Work Stealing. Journal of ACM 46(5):720–748, 1999.
2: S. Donfack, L. Grigori, W. D. Gropp, and V. Kale. Hybrid Static/Dynamic Scheduling for Already Optimized Dense Matrix Factorizations. In IEEE International Parallel and Distributed Processing Symposium, IPDPS 2012, Shanghai, China, 2012.
3: E. Lusk, N. Doss, and A. Skjellum. A High-performance, Portable Implementation of the Message Passing Interface Standard. Parallel Computing, 22:789–828, 1996.

Utility of Novel Strategies Shown

- The utility of novel strategies is demonstrated in published work by V. Kale et al [1,2] and others.
- For example, static-dynamic scheduling mixed strategy with an adjustable static fraction.
  - Motivation: to limit the overhead of dynamic scheduling, while handling imbalances, such as those due to noise.



White: idle time

CALU using static scheduling (top) and f_d = 0.1 (bottom) with 2-level block layout run on AMD Opteron 16 core node.

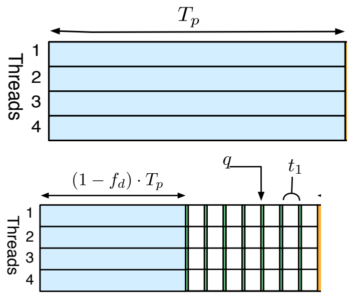


Diagram of static (top) and mixed static/dynamic scheduling (bottom) where f_d is the dynamic fraction.

1: S. Donfack, L. Grigori, W. D. Gropp, and V. Kale. Hybrid Static/Dynamic Scheduling to Improve Performance of Already Optimized Dense Matrix Factorizations, IPDPS 2012.
2: V. Kale, S. Donfack, L. Grigori, and W. D. Gropp. Lightweight Scheduling for Balancing the Tradeoff Between Load Balance and Locality 2014.

Need to Support A User-defined Schedule in OpenMP

- Practice of burying all of the scheduling strategy inside an OpenMP implementation, with little visibility in application code beyond the use of keywords such as ’dynamic’ or ’guided’, isn’t adequate for this purpose.
- OpenMP’s implementations, e.g., GCC’s libgomp [1] and LLVM’s OpenMP library [2] are difficult to change, which can hinder development of loop scheduling strategies at a rapid pace.

1. Documentation for GCC’s OpenMP library. https://gcc.gnu.org/onlinedocs/libgomp/ .
2. Documentation for LLVM’s OpenMP library. http://openmp.llvm.org/Reference.pdf/ .

Reasons for User-defined Schedules

- Flexibility.
  - Given the variety of OpenMP implementations, having a standardized way of defining a user-level strategy provides flexibility to implement scheduling strategies for OpenMP programs easily and effectively.
- Emergence of Threaded Runtime Systems.
  - Emergence of threaded libraries such as Argobots[1] and QuickThreads[2] argues in favor of a flexible specification of scheduling strategies also.
- Note that keywords *auto* and *runtime* aren't adequate.
  - Specifying auto or runtime schedules isn't sufficient because they don't allow for user-level scheduling.

1. S. Seo, A. Amer, P. Balaji, C. Bordage, G. Bosilca, A. Brooks, A. Castello, D. Genet, T. Herault, P. Jindal, L. Kale, S. Krishnamoorthy, J. Lifflander, H. Lu, E. Meneses, M. Snir, Y. Sun, and P. H. Beckman. Argobots: A lightweight threading tasking framework. 2016.
2. D. Keppel. Tools and techniques for building fast portable threads packages. Technical Report UWCSE 93-05-06, University of Washington Department of Computer Science and Engineering, May 1993.

Scheduling Code of libgomp

- The scheduling code in libgomp, for example, supports the static, dynamic, and guided schedules naturally.
- However, its code structure can't accommodate the number and sophistication of the strategies that we would like to explore.

→Adding a user-defined schedule into OpenMP libraries:

- is possible with effort for a given library.
- must be done differently for each library.

Specification of User-defined Scheduling Scheme

- We aim to specify a user-defined scheduling scheme within the OpenMP standard[1] .
- The scheme should accommodate an arbitrary user-defined scheduler.
- These are the elements required to define a scheduler.
  - Scheduler-specific data structures.
  - History record.
  - Specification of scheduling behavior of threads.

1. OpenMP Application Programming Interface. November 2015.

Potential Scheduling Data Structures

- The strategies should be allowed to use a subset or combination of:
  - Shared data structures.
  - Low-overhead steal-queues.
  - Exclusive queues meant for each thread.
  - Shared queues from which multiple threads can dequeue work, each representing a chunk of loop iterations.

History Tracking from Prior Invocations

1. To facilitate the ability to learn from recent history, e.g., values of slack in MPI communication[1,2] from previous outer iterations, the scheduling scheme should allow for passing a call-site specific history-tracking object[3] to the scheduler.
2. Examples of history information, i.e., attributes to track via history objects:
   - Previous values of dynamic fraction.
   - Iteration-to-core affinities.
   - Runtime performance profiles.

1. A. Faraj, P. Patarasuk, and X. Yuan. *A Study of Process Arrival Patterns for MPI Collective Operations*. In Proceedings of the 2006 ACM / IEEE Conference on Supercomputing, SC '06, Tampa, FL, USA, 2006. ACM.
2. B. Rountree, D. K. Lowenthal, B. R. de Supinski, M. Schulz, V. W. Freeh, and T. Bletsch. *Adagio: Making DVS Practical for Complex HPC Applications*. In Proceedings of the 23rd International Conference on Supercomputing, ICS '09, pages 460–469, Yorktown Heights, NY, USA. 2009. ACM.
3. V. Kale, T. Gamblin, T. Hoefler, B. R. deSupinski and W. D. Gropp. *Slack-conscious Lightweight Loop Scheduling for Scaling Past the Noise Amplification Problem*. Poster. SC 2012

Example: Library to Support Staggered Scheduling

- In earlier work[1], a loop scheduling library that supports a "staggered" scheduling strategy was implemented.
- It was implemented within an OpenMP parallel region by enclosing the loop body with macros `FORALL_BEGIN()` and `FORALL_END()` with appropriate parameters.

```
int start, end = 0;
static LoopTimeRecord* ltr;
double fd = 0.3;
#pragma omp parallel
      { int tid = omp_get_thread_num();
        int numThrds = omp_get_num_threads();
        FORALL_BEGIN(sds,tid,numThrds,0,n,start,end,fd)
        for(int i=start;i<end;i++)
         c[i] += a[i]*b[i];
        FORALL_END(sds,tid,start,end)
      }
```

1. The scheduling strategy's name and associated parameters are specified in the parameters of the macro.
2. Both macros invoke library functions corresponding to the strategy's name as specified in the macro call. The macro's parameters are passed to the user-defined scheduler functions.

1: V. Kale, A. P. Randles, V. Kale, and W. D. Gropp. Locality-Optimized Scheduling for Improved Load Balancing on SMPs. In Proceedings of the 21st European MPI Users' Group Meeting Conference on Recent Advances in the Message Passing Interface, volume 0, pages 1063–1074. Association for Computing Machinery, 2014.

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        FORALL_BEGIN(sds,tid,numThrds,0,n,start,end,fd)
        for(int i=start;i<end;i++)
         c[i] += a[i]*b[i];
        FORALL_END(sds,tid,start,end)
      }
```

FORALL_BEGIN(strat, ...) macro expansion

```
  strat_## LoopStart(..&start, &end, ..);
  do (loop not done)
     {
```

FORALL_END(strat, ...) macro expansion:

```
     }
while (strat_## LoopNext(... &start, &end, ..));
barrier;
```

1. The scheduling strategy's name and associated parameters are sp
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Proposal for User-defined Schedule in OpenMP

- We propose a user-defined scheduling scheme that is an adaptation of the above macro-based scheme.
  - Overcomes limitations of simple macro-based scheme.
- The proposed API used for a simple code is illustrated below.

```
double dynamicFraction = 0.3;
static LoopTimeRecord* ltr; // for history.
int chunkSize = 4;
#pragma omp parallel for schedule(user, staggered:chunkSize:dynamicFraction:ltr)
for(int i = 0; i < n; i++)
    c[i] = a[i]*b[i];
```

- The first parameter of the clause 'schedule' specifies a new schedule kind *user*.
- The second parameter specifies the scheduling strategy's name ***staggered***, optionally with the strategy-specific parameters.

Implementation of User-defined Schedule

- When a user specifies a schedule kind `user` and a strategy named `X`
  - They need to link a library that defines functions:
    - `X_loopStart()`, `X_loopNext()` and `X_init()`.
- `X_init()` allows a user-level scheduler to allocate and initialize its data structures that are to be used commonly across parallel loops that use `X`.
- The functions `X_loopStart()` and `X_loopNext()` determine a loop's indices that a thread should work on based on the parameter values for the scheduling strategy and of the loop.
- As long as one is allowed to define these functions, one can implement a user-defined scheduler.
- Every thread should call `X_loopNext()` repeatedly.

Every thread executes when starting a new loop:

```
 …
X_loopStart();
do  X_loopNext(); until done;
 // done flag is set by the user-defined
 // scheduler functions
```

Software Architecture for User-defined Schedule

myApplication.C

```
#include <mpi.h>

#include <omp-mod.h>

int main()
{
double dynamicFraction = 0.3;
static LoopTimeRecord* ltr; // for history.
int chunkSize = 4;
while(timestep <1000)
{
#pragma omp parallel for schedule(user,staggered:chunkSize:dynamicFraction:ltr)
for(int i = 0; i < n; i++)
    c[i] = a[i]*b[i];
 }

}
```

omp-mod.h

```
#include <userDefSched.h>


#define FORALL_BEGIN(strat, …) strat_## LoopStart(..&start, &end, ..);
  do (loop not done)
     {
#define FORALL_END(strat, …)
      }

while (strat_## LoopNext(… &start, &end, ..));
barrier();

switch(clause)
{
  'static':
  'dynamic':
  'guided':
  'auto':
  'runtime':
  'user':
}

strat_## LoopStart(..&start, &end, ..);{}
```

sd_Init():
- allocate shared data structures for loops that use strategy sd;

sd_LoopStart():
if I am the master thread,
- set up a data structure *loopParams*, along with a lock;
- signal other threads to start;

else
- wait for the signal from master thread;

use the shared loopParams data structure to calculate my static iterations and execute loop_body for that range;

sd_LoopNext():
lock loopParams; extract a chunk to work on; unlock loopParams;
if (no chunk available)
  wait for barrier; done=1;
else
  execute loop_body for the extracted chunk;

Static/dynamic Scheduling Using a Shared Data Structure

sd_LoopStart():

if I am the master thread,

- set up a data structure *loopParams*, along with a lock;
- signal other threads to start;

else

- wait for the signal from master thread;

- use the shared loopParams data structure to calculate my static iterations and execute loop_body for that range;

sd_LoopNext():

lock loopParams; extract a chunk to work on;
unlock loopParams;
if (no chunk available)
  wait for barrier; done=1;
else
  execute loop_body for the extracted chunk;

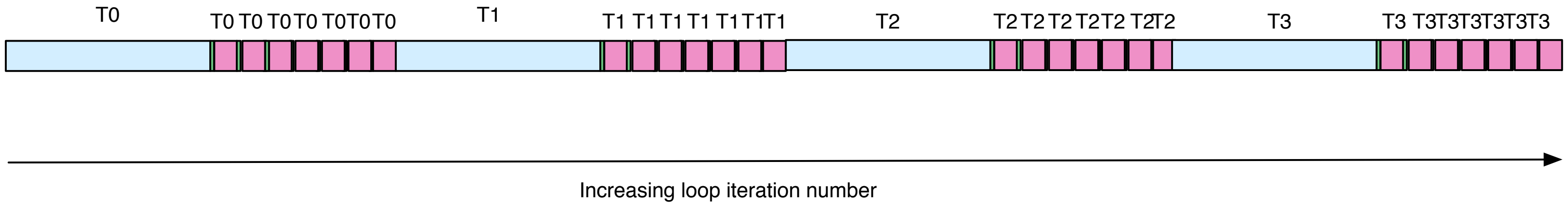
An Alternative Impl. of Static/Dynamic Strategy Using Steal Queues for Dynamic Iterations

sd2_LoopStart():
if I am the master thread
  — set up a data structure loopParams with loop parameters;
  — enqueue a single entry corresponding to dynamic range of iterations into thread 0's steal queue;
  — signal other threads to start;
else
  — wait for the signal from master thread;
- Use the shared data structure to calculate my static iterations and execute loopBody for that range;

sd2_LoopNext():

```
 - nextRange = myQueue.dequeue();
 if (nextRange  == NULL) nextRange = steal(random_neighbor);
 if (nextRange != NULL)
    L = nextRange->low; U = nextRange->high;
    if ( (U-L) > Threshold )
       - split the range in 2, enqueue them in my steal queue;
    else
       - execute loop body for iterations L:U;
       - update count of iterations completed to set the "done" flag when  done;
```

An Implementation of Staggered Static/Dynamic Strategy



staggered_LoopStart():

if I am the master thread

- set up a data structure *loopParams*;
- signal other threads to start;

else

- wait for the signal from master thread;

- enqueue entries corresponding to chunks of my dynamic range of iterations into my thread's steal queue;
- calculate my static iterations and execute loopBody for that range;

staggered_LoopNext():

nextRange = myQueue.dequeue();

if (nextRange == NULL) nextRange = steal(random_neighbor);

if (nextRange != NULL)

- L = nextRange->low; U = nextRange->high;
- execute loop body for my iterations L:U;
- update count of iterations completed to set the "done" flag when done;

Discussion of API's details

- We have sketched above a syntax for the API for user-level schedulers.
  - However, we expect that the API's details will be worked out with the community's consensus.
- Note that there is a precedent for adding user-defined functions in OpenMP standard.
  - The *combiner* function in user-defined reductions.

Summary

- Need for experimentation with sophisticated loop scheduling strategies.
- OpenMP community should discuss how to allow flexible specification of such strategies in a user's code and how to design a user-level scheduler library so that it can be portably used with any conforming OpenMP implementation.
- Supporting user-defined schedulers in this way will facilitate rapid development of scheduling strategies.
- I hope the experts will discuss these ideas at this conference.

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