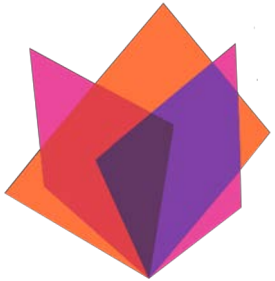
OpenMP

SC'20 Booth Talk Series

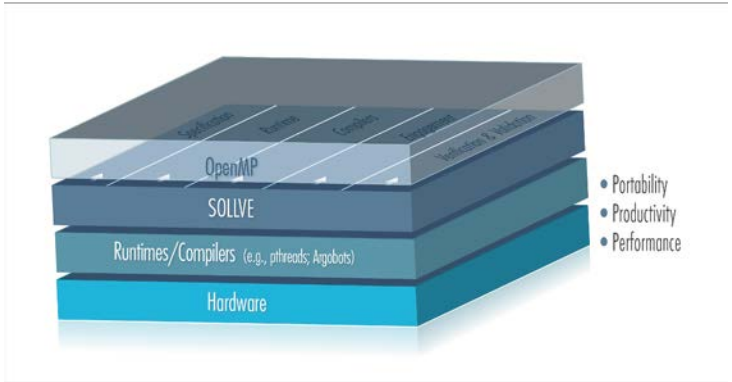
Locality-sensitive Loop Scheduling in SOLLVE's OpenMP



Vivek Kale, Brookhaven National Laboratory

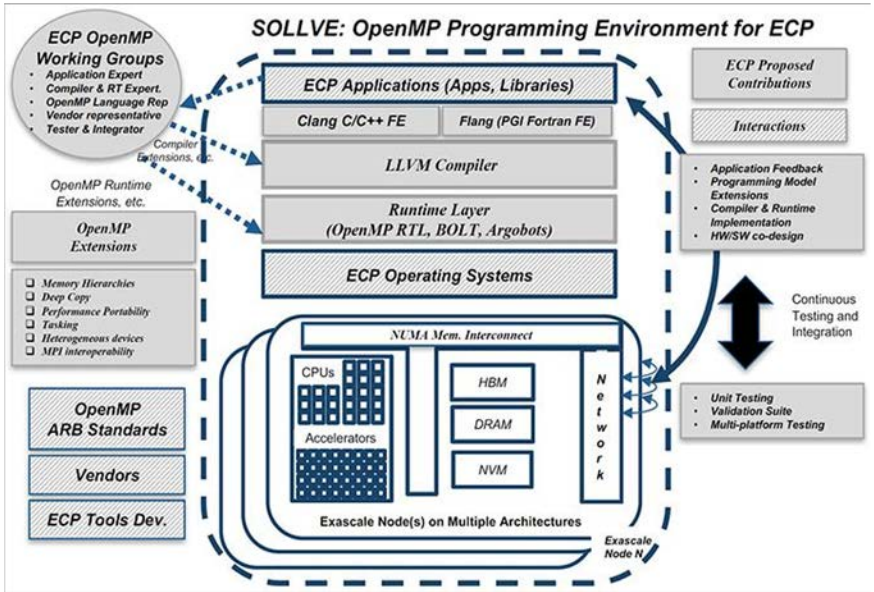
SOLLVE: DoE's fork of the LLVM OpenMP Implementation

- SOLLVE is a project to develop OpenMP for DoE exascale supercomputers.
- Can link it to your app through following http://github.com/SOLLVE/sollve
- Available on ECP Systems via Spack.



Our strategies are in runtime system and compiler in SOLLVE slab

SOLLVE Software Ecosystem



Motivating Example Code Structure

```
#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();
}
```

Outer Iteration

Computation region

A Loosely Synch MPI Comm.

A motif[1], e.g., n-body, Stencil, Dense Matrix Factorization, Sparse Matrix-Vector Multiplication

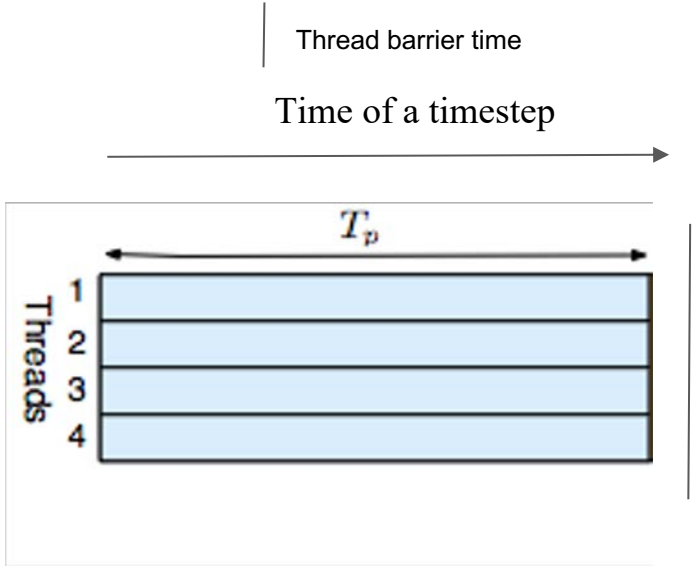
A Bulk Synch MPI Coll. Comm.

1. https://patterns.eecs.berkeley.edu/

How to Do Near-perfect Work Redistribution Within Node?

```
#include <mpi.h>
#include <omp.h>

int main(int argc, char** argv)
{
  while (timestep <1000 ) {
#pragma omp parallel for schedule(static)
     for(i=0; i<n; i++)
      loop_body(i);
      MPI_Op();
      timestep++;
     }
}
```

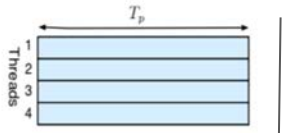


- Focus on the OpenMP computation region in an MPI+OpenMP program

→ Let's use OpenMP's dynamic loop schedule provided.

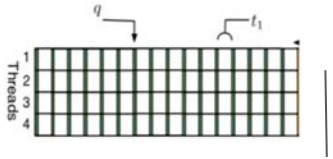
Hybrid Static/Dynamic Scheduling

Statically Scheduled Work | Dynamically Scheduled Work | Dequeue Overhead | Thread barrier



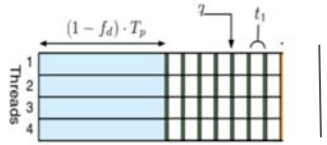
Susceptible to imbalance.

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



Scheduler overhead stretches time.

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

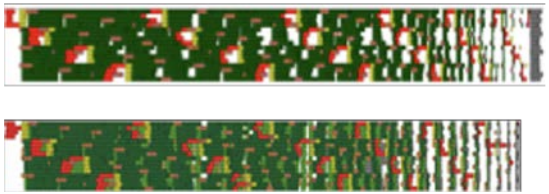


Can reduce imbalance and sched ovhd. simultaneously.

```
#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);
```

Utility of Novel Strategies Shown

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



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

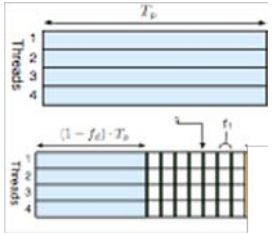
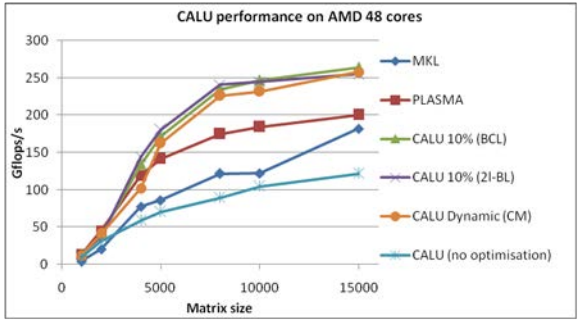
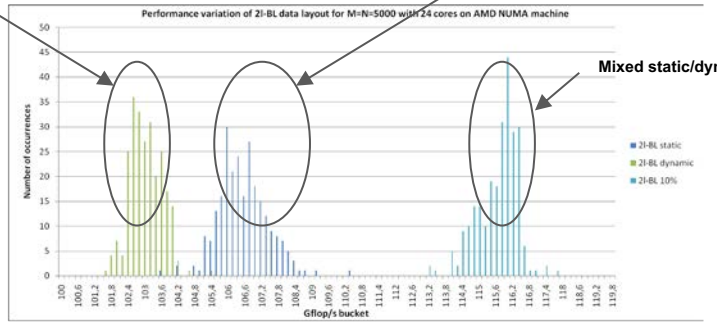


Diagram of static (top) and mixed static/dynamic scheduling (bottom) where f_d is the dynamic fraction.

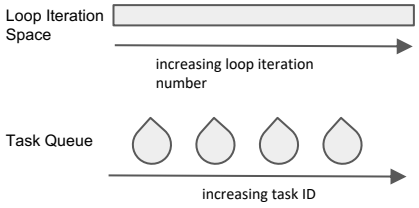


dynamic

static



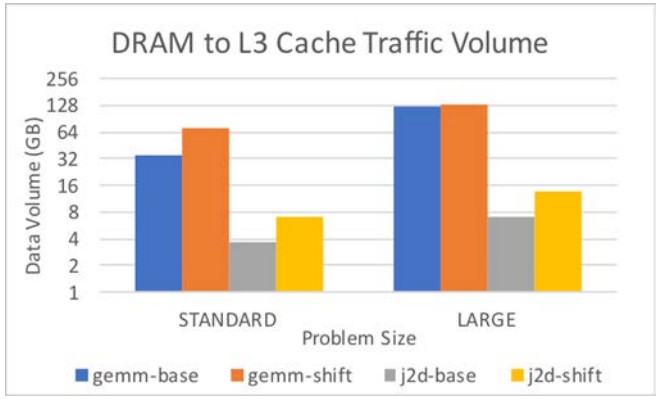
1: S. Donfack, L. Grigori, W. D. Gropp, and V. Kale. Hybrid Static/Dynamic Scheduling to Improve Performance of Already Optimized Dense Matrix Factorizations, IPDPS 2012.
2: V. Kale, S. Donfack, L. Grigori, and W. D. Gropp. Lightweight Scheduling for Balancing the Tradeoff Between Load Balance and Locality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



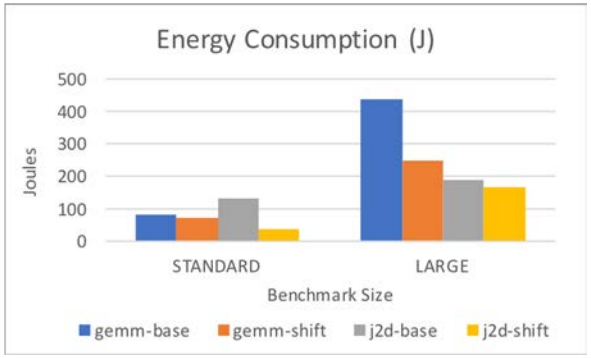
Data Locality in Tasking in OpenMP

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.

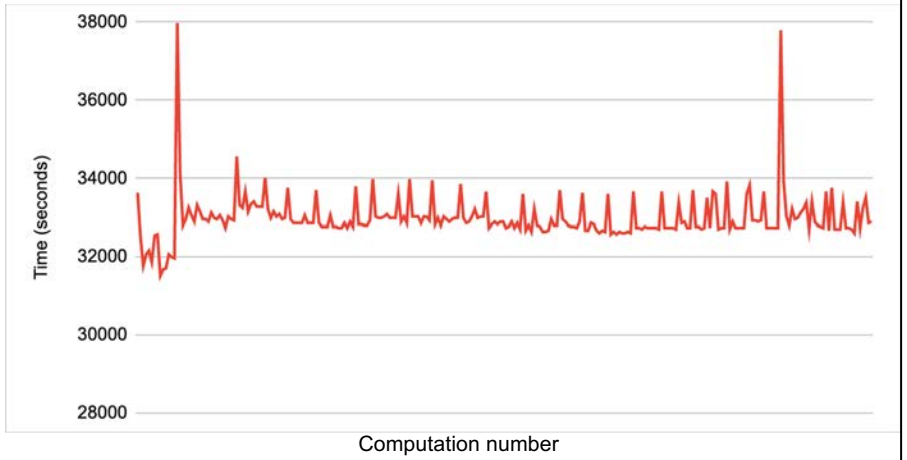


Lower energy consumption due to less data movement.

AutoDock Mini-app

Created mini-app that allows us to study approaches to writing OpenMP-based GPU code, and later multi-GPU code

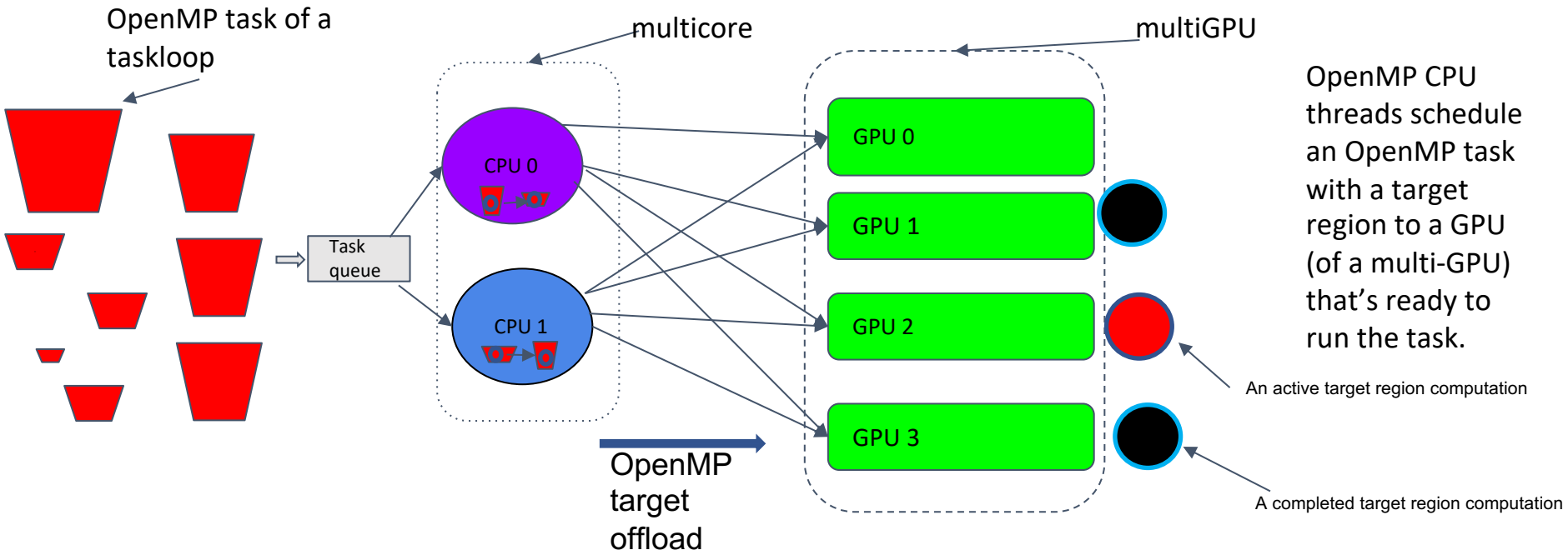
- Do T computations of floating-point vector multiplications, each of randomly chosen size between 0 and n, where n is an input to the program.
- **OpenMP CPU version**: OpenMP `parallel for` directive to parallelize T computations across CPU's cores.
- **OpenMP GPU version**: Augment the CPU version by putting a `target` directive having `map` and `nowait` clauses inside the OpenMP `parallel for` to parallelize T computations across GPU's SMs.



AutoDock mini-app with LLVM 11 on Summit shows that its task performance variation represents the behavior of full application.

Mini-app for AutoDock at https://github.com/SOLLVE/benchmarks/tree/master/ecp-omp/type2/autodock

OpenMP Task-to-multiGPU Scheduling



- Shared queue is used to represent GPUs and to manage access to them
- When a CPU acquires a GPU it launches its next task
- Several strategies used to map tasks to GPU

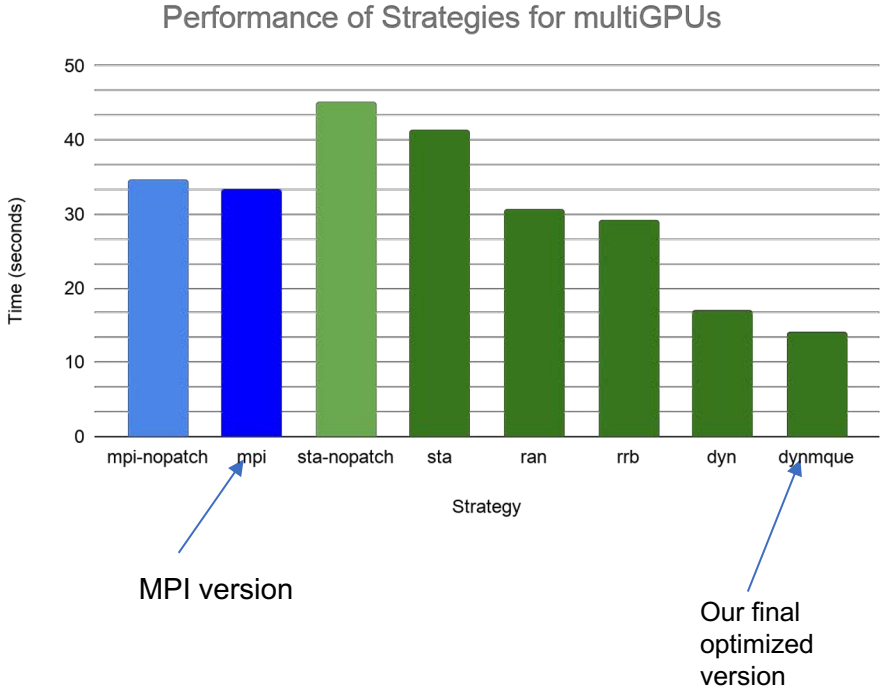
Task-to-GPU Scheduling Prototype

```
#pragma omp parallel
{
#pragma omp single
  {
#pragma omp taskloop shared(success)
    for (int i = 0; i < numTasks; i++) {
      const int dev = gpu_scheduler_dyn(occupancies, ndevs);
      output[i] = 0;
#pragma omp task depend(out : success[i])
      {
        success[i] = 0;
      }
#pragma omp task depend(inout : success[i])
      {
#pragma omp target device(dev)                                  \
        map(to: a[0:arrSize], b[0:arrSize], c[0:arrSize])   \
        map(tofrom: success[i:1], output[i:1], taskWork[i:1],
    occupancies[dev:1])
        {
          devices[dev]++;
          if (taskWork[i] > probSize) taskWork[i] = probSize;
          const int NN = taskWork[i];
          output[i] = doWork(c, a, b, taskWork[i]);
          success[i] = 1;
        }
      }
#pragma omp task depend(in : success[i])
      {
#pragma omp atomic
        occupancies[dev]--;
      }
    }
  }
}
```

```
inline unsigned gpu_scheduler_dyn(unsigned
*occupancies, int ngpus)
{
 short looking = 1;
 unsigned chosen;
 while (looking) {
 for (unsigned i = 0; i <ngpus; i++)
  {
   unsigned occ_i;
   #pragma omp atomic read
             occ_i = occupancies[i];
        if (occ_i == 0) {
              chosen = i;
              occupancies[chosen]++;
              looking = 0;
              break;
       }
    }
   }
  return chosen;
}
```

Results for Task-to-multi-GPU Strategies

- Ran AutoDock mini-app with uniformly random distribution, max task size 3400x3400.
- Compiled with LLVM 11 (with and without our patch) and executed on one node of Summit (42 CPU cores, 6 NVIDIA Tesla V100 GPUs, one thread per core).



- The MPI version of the AutoDock mini-app was used here for comparison.
- MPI (mpi-nopatch) gives 24.5x speedup over the CPU version with LLVM 11; static (sta-nopatch) gives 21.2x speedup over CPU version. MPI is 16.2% faster than this OpenMP node version.
- Round-robin (rrb) and random (ran) schedules partially alleviate load imbalance; dynmque provides lower-overhead scheduling.

→ Task-to-GPU scheduling techniques handle load imbalance, may reduce contention, and could be used to reduce data movement. Dynamic schedules improve performance 2X and more over MPI.

Proposal for User-defined Schedules in OpenMP

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

```
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];

}
```

UDS identifier

UDS parameters

- 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.

An Implementation of the Static/Dynamic Schedule with UDS

Data Structures for the User-defined Scheduler

```
// This is a user-supplied type that the UDS needs to store some information and state.
// This can be as easy as a single variable (e.g., for a dynamic) or something complex
// such as historic performance data gathered during past loop execution.
typedef struct {
int lb;
int ub;
int incr;
int counter;
double fs;
} loop_record_t;
```

User-defined scheduler.

mysd_start

Scheduler's Loop Start

```
// lb, ub, incr, and chunksz are formal parameters required by the specification. lr is a
// user-supplied formal parameter and there could be more if needed.
void mysd_start(int lb, int ub, int incr, int chunksz, loop_record_t * lr) {
// We assume that this function will be called by one thread. Thus, no
// synchronization will be required. This is a fast thing about the loop schedule.
    lr->lb = lb;
    lr->ub = ub;
    lr->incr = incr;
    lr->chunksz = chunksz;
}
```

```
#pragma omp declare schedule(mysd) init(mysd_start)
next(mysd_next)
void example() {
    static loop_record_t lr;
#pragma omp parallel for schedule(mysd, &lr)
    for (int i = 0; i < n; i++) {
        a[i] = s * a[i] * b[i];
    }
}
```

Mysd_next

Scheduler's Loop Next

```
// lower, upper are formal parameters required by the specification.
// lr is a user-supplied formal parameter and there could be more if needed.
// Signature: void X_next(int *, int *, ...)
void mysd_next(int * lower, int * upper, loop_record_t * lr) {
    int start;
 if(lr->counter < (lr->ub - lr->lb)/numThreads*lr->fs) {
     *lower = lr->fs*(lr->ub - lr->lb)/numThreads*lr->
     *upper = *lower + lr->fs*(lr->ub - lr->lb)/numthre
 ads;
      lr->counter += (*upper - *lower)/numThreads;
 }
 else
 {
 #pragma omp atomic capture
     {
         start = lr->counter;
         lr->counter += lr->chunksz * lr->incr;
     }
     *lower = start;
     *upper = start + lr->chunksz * lr->incr;
 }
```

Application loop specifying a User-Defined Schedule

Scheduler's Loop Finish

```
// Signature: void X_fini(...)
void mysd_fini(loop_record_t * lr) {
    // Do nothing
}
```

Extensions to OpenMP for Task-to-GPU Scheduling

- Previous results, showing need for load balancing along with data locality, motivate extensions to OpenMP.
- Such extensions should allow programmers to easily obtain application code performance through a locality-sensitive task-to-GPU load balancing.

Proposed Extension for OpenMP

Syntax:

```
#pragma omp target scheduler clause[ [
[,] clause] ... ] new-line
      structured-block
```

where clause is one of the following:

```
      num_devices(integer-expression)
      type( round_robin | dynamic |
  random | user_defined) affinity(
  temporal|spatial,)
  priority
```

Example of Extension: miniAutoDock

```
#pragma omp target scheduler num_devices(ndevs)
type(dynamic)
{
#pragma omp taskloop
  for(int i=0; i < numTasks; i++) {
    output[i] = 0;
#pragma omp target map(to: a[0:n*n], b[0:n*n],
c[0:n*n]) map(tofrom: output[i:1], work) nowait
    {
      const int NN = n * n;
      double work_start = 0;
      for (int j = 0; j < NN; j++)
         c[j] = sqrt(a[j] * b[j]);
      output[i] = c[NN];
    } // end target
  }// end taskloop
}
```

Lightweight Loop Scheduling in RAJA: lws-RAJA

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

```
#include "vSched.h"
#define FORALL_BEGIN(strat, s,e, start, end, tid, numThds )
loop_start_ ## strat
(s,e ,&start, &end, tid, numThds); do {
#define FORALL_END(strat, start, end, tid) } while(
loop_next_ ## strat (&start, &end, tid));
void* dotProdFunc(void* arg)
{
  int startInd = (probSize*threadNum)/numThreads; int endInd
=  (probSize*(threadNum+1))/numThreads;
  while(iter < numIters) {
   mySum = 0.0; //reset sum to zero at the beginning of the
product
   if(threadNum == 0) setCNY(static_fraction , constraint.
hunk_si
#pragma
FORALL_BEGIN(statdynstaggered , 0, probSize , startInd,endInd
,threadNum, numThreads)
for (i = startInd ; i < endInd; i++) mySum += a[i]*b[i]
 FORALL_END(statdynstaggered , startInd , endInd,threadNum)
pthread_mutex_lock(&myLock);
  sum += mySum;
  pthread_mutex_unlock(&myLock);
  pthread_barrier_wait(&myBarrier);
  if(threadNum == 0) iter++;
  pthread_barrier_wait(&myBarrier); } // end timestep loop
}
```

MPI+OpenMP code explicitly using lightweight scheduling.

RAJA User Code

```
RAJA::ReduceSum<RAJA::seq_reduce, double> seqdot(0.0);
RAJA::forall<RAJA::omp_lws>(RAJA::RangeSegment(0, N), [=]
(int i) {


seqdot += a[i] * b[i]; });


dot = seqdot.get();
std::cout << "\t (a, b) = " << dot << std::endl;
```

RAJA library implementation with policy `omp_lws`

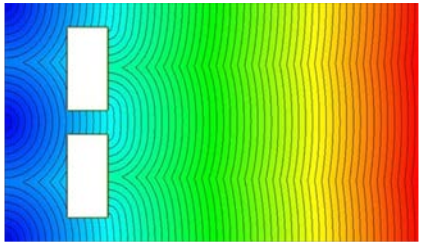
```
#include "vSched.h"
#define FORALL_BEGIN(strat, s,e, start, &end, tid, numThds) do {
#define FORALL_END(strat, start,tid)); start, end, tid, numThds )
loop_start_ ## strat (s,e ,&end, tid) } while( loop_next_ ## strat
(&start, &end)
template <typename Iterable , typename Func >
RAJA_INLINE void forall_impl(const omp_lws<&, Iterable&& iter, Func&&
loop_body) {
RAJA_EXTRACT_BED_IT(iter);
int startInd , endInd;
int threadNum = omp_get_thread_num();
int numThreads = omp_get_num_threads();
FORALL_BEGIN(statdynstaggered , 0, distance_it , startInd , endInd ,
threadNum , numThreads) for (decltype(distance_it) i = startInd; i <
endInd; ++i) {
loop_body(begin_it[i]); }
FORALL_END(statdynstaggered , startInd , endInd , threadNum)
}
```

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

→ Improves ***portability of loop scheduling strategies***.

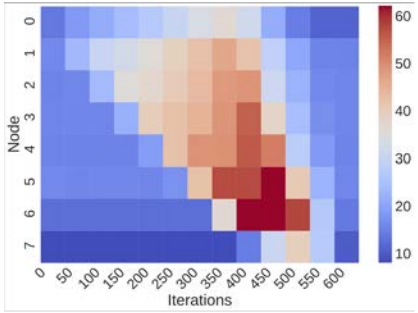
Load Imbalances Across and within-Node

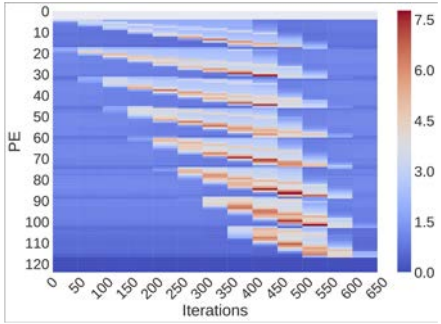
Snapshot of one timestep



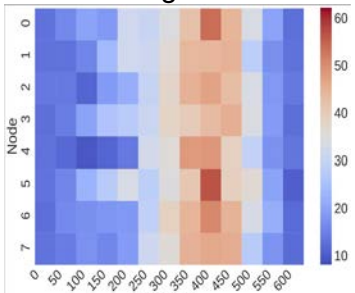
- Lassen is a front tracking code
- Most of the computation is near the surface of the front.
- Creates time-varying imbalances.

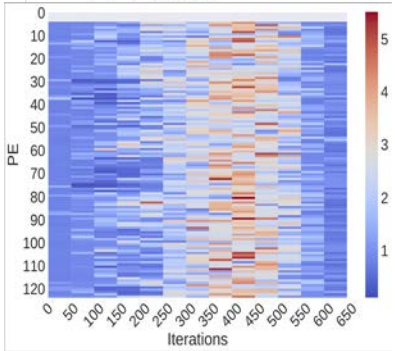
No Load bal.



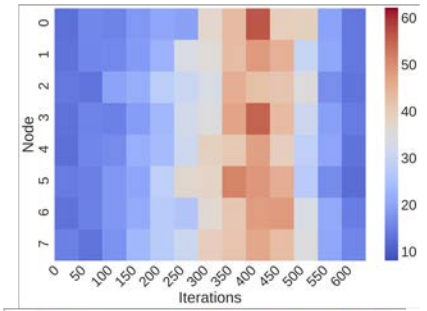


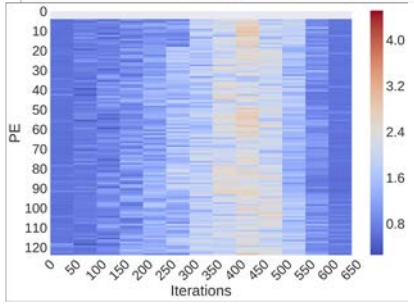
Across-node load balancing.





Across and within-node load balancing.

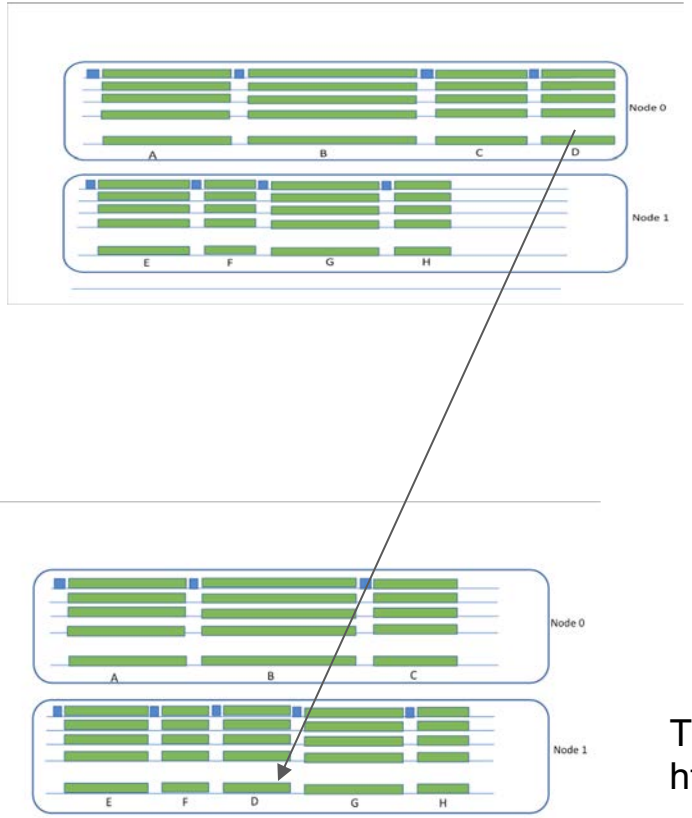


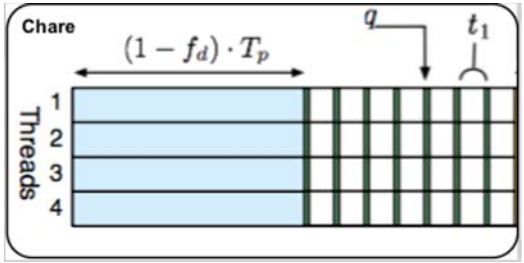


Courtesy from work with Harshitha and other members PPL with LLNL members, including Brian McCandles.

- Imbalance across nodes, and cores, have different dynamics as iterations progress.
- → Balancing both, in coordination, is necessary.

Load Balancing + Loop Scheduling Technique





Key Idea:

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.

This scheduler is merged into Charm++; Development history here: https://bitbucket.org/viveklkalew/ckloop_schedule/src/master/

Related Work

- DPLASMA, ParSec
- Legion
- Hybrid MPI+OpenMP
- Habanero
- OpenMP Guided Scheduling
- RAJA and Kokkos

Future Work

- Continue creating examples of user-defined schedules using LLVM OpenMP Implementation and experiment with them
- Improvements to tasking for GPUs
  - Improved task scheduling strategies
  - Improve task affinity
- Add into OpenMP specification and LLVM OpenMP Implementation support for task-to-multiGPU scheduling.
- An eventual and longer term goal is to upstream the scheduling strategies into LLVM
- We'll also be looking at developing libraries for heterogenous nodes that have intelligent runtime system support for handling load imbalance within-node, coordinating across-node load balancing with within-node load balancing.
- Finally, we'll look into performance portability of loop scheduling in particular though use of RAJA.

Summary

- Load imbalance within node is an **important** problem
- Novel schedulers **solve** the problem
  - Basic static/dynamic scheduling
  - Variants of scheduling strategies
  - More work on task-to-multiGPU scheduling with GPUs
- Proposed **extensibility features** facilitate novel loop schedulers
  - OpenMP UDS
  - OpenMP task-to-GPU target scheduler
- **Build on the** scheduling strategies and make them **accessible**
  - UDS in RAJA → integration
  - Charm++ + CkLoop: → combination

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