CS420 – Lecture 26

Marc Snir

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Parallel Programming Models and Systems

Parallel programming model: What are the parallel constructs and operations

Parallel programming systems: How are those expressed

A model (e.g., one-sided communication) can be expressed by libraries or languages
A system may support different models: E.g., OpenMP supports loop parallelism and task parallelism

Implicit Parallelism

Write sequential program, lean on compiler and hardware to execute in parallel.

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- Hardware helps by using register renaming to avoid "false dependencies" and by checking loads against the store queue

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Vectorization: Use instructions that perform vector operations

- Compiler helps by compiling simple loops into vector operations
- Hardware helps by providing vector registers and vector ALUs

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- Write code that is easy to vectorize
- Write code that access data with good (temporal/spatial) locality
- Use appropriate compiler options
- Don't write your own code if a library is available

Shared Memory Explicit Parallelism

- Language vs. pragmas vs. overloading
- Extensions to existing language (C++, Java) vs. something totally different (Chapel)
- More declarative (what to compute) vs. more imperative (how to compute)
- Data-driven partitioning vs. control-driven partitioning

Vector Parallelism

Fortran code:

```
real A(10,20), B(10,20)
logical L(10,20)
 A = A + 1.0
A = SQRT(A)
L = A .EQ. B
A(1:7,3) = B(2:8,1)*B(4:10,1)

real A(20,20,2)
A(:,:,1) = 0.25*(CSHIFT(A(:,:,0),1,1)+CSHIFT(A(:,:,0),-1,1)
                        +CSHIFT(A(:,:,0),1,2)+CSHIFT(A(:,:,0),-1,2))

real A(20)
integer IDX(20)
A = A(IDX)
```

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- Irregular code does not vectorize well

Explicit parallelism – Parallel Iterators

- Execute code for each element of a collection (STL container)
- Simplest: execute code for each element of a range
- Works best if it easy to split collection and iterates are independent, or are combined using a simple parallel algorithms, such as reduction

Java

```
double average = roster
 .parallelStream()
 .filter(p -> p.getGender() == Person.Sex.MALE)
 .mapToInt(Person::getAge)
 .average()
 .getAsDouble();
```

C++: `for_each`, `reduce`, `transform_reduce`, `copy_if` ...

Explicit Control parallelism – Multithreading

- Shared memory – all threads can access all variables (subject to scoping rules)
- *static multithreading:* A fixed number of threads coordinating through the use of shared variables – e.g. an OpenMP parallel section
- *dynamic multithreading:* A (possibly) fixed number of workers (called *threads* in OpenMP) are executing dynamically created tasks (or chunks of parallel iterates in OpenMP) – scheduler decides which worker executes which task,

Dynamic multithreading takes care of load balance

- Full language support (Java) vs. pragmas (OpenMP) vs. library (C++)
- More declarative (C++) or more imperative (OpenMP)

Main constructs

- Parallel iterator – Possibly nested
- Fork-join – Possibly nested
- Futures
- Divide&Conquer

Parallel iterator can be implemented as fork-join, but direct implementation can be much more efficient

Nested parallel loops and fork-join can generate irregular parallelism that stretches schedulers because of the need for global load balancing.

Full language support: e.g., Java

```
parallelFor  (lb, ub) .exec (new Loop()
   {
   // Thread-local variable declarations (optional)
    public void start()
   {
   // One-time thread-local initialization (optional method)
   }
   public void run (int i)
   {
   // Loop body code for iteration i (required method)
   }
   public void finish()
   {
   // One-time thread-local finalization (optional method)
   }
 });
```

Pragmas/Directives – E.g. OpenMP

- Less elegant than full language support
- Pragmatically, may encourage "sequential thinking"
- No fundamental differences

Library

E.g. Threads Building Blocks (TBB)
Sequential code:

```
void SerialApplyFoo( float a[], size_t n ) {
    for( size_t i=0; i!=n; ++i )
        Foo(a[i]);
}
```

Parallel loop 1

Programmer creates code that can execute a chunk of iterates

```
class ApplyFoo {
    float *const my_a;
public:
    void operator()( const blocked_range<size_t>& r ) const {
        float *a = my_a;
        for( size_t i=r.begin(); i!=r.end(); ++i )
           Foo(a[i]);
    }
    ApplyFoo( float a[] ) :
        my_a(a)
    {}
};
```

The function `parallel_for` is passed the entire iteration range and the newly defined class. `parallel_for` will chunk the iteration range and allocate the chunks to threads

```
void ParallelApplyFoo( float a[], size_t n ) {
    parallel_for(blocked_range<size_t>(0,n), ApplyFoo(a));
}
```

- No special compiler needed – only need to link to the TBB runtime library
- Code might be less efficient since compiler does not "understand" parallelism
- Syntax is more burdensome

Futures & Remote Procedure Call (RPC)

RPC: a function call that can be executed on a separate thread

- Is RPC executed synchronously or asynchronously?
- Does it return a result?
- What is the execution context?

C++ future is an asynchronous RPC that (usually) returns a value and has its own context (passed arguments and captured references)

Divide&Conquer

- If problem is small then solve problem sequentially
- Else
  - Divide problem into (two) independent subproblems
  - Solve two subproblems in parallel
  - Combine two subproblem solutions

Quicksort: Divide&conquer sorting algorithm where all work is done in the divide part

Mergesort: Divide&conquer sorting algorithm where all work is done in the combine part

Divide&Conquer logic can be implemented using recursive fork-join

Divide&Conquer in TBB

```
void ParallelQuicksort( T* begin, T* end ) {
 if( end-begin>=SMALL ) {
  using namespace std;
// Divide Code
   T* mid = partition( begin+1, end, bind2nd(less<T>(),*begin) );
   swap( *begin, mid[-1] );
// Recursion
  tbb::parallel_invoke( [=]{ParallelQuicksort( begin, mid-1 );},
      [=]{ParallelQuicksort( mid, end );} );
  } else {
// leaf code
   SerialQuicksort( begin, end );
   }
// empty combine code
}
```

TBB implements loop parallelism using the divide&conquer pattern.

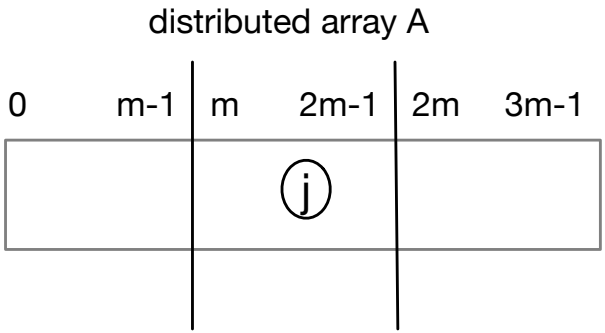
Distributed memory parallelism – E.g., MPI, Shmem

- *Static multiprocessing + distributed memory:* A fixed number of processes, each with its own address space.
- Each process can only access its address space
- Explicit calls are used to communicate across processes

  1-sided: Put/get
  2-sided: Send/receive
  Collective: broadcast/reduce
- MPI supports well send-receive and collectives; 1-sided is a later addition
- Shmem (Openshmem) supports well 1-sided

PGAS

People like the convenience of a global address space: Being able to access any entry in a large (distributed) array using global "names"



`x=A[j]` vs. `x = Get(proc=sizeof(A)/numproc, disp= sizeof(A)%numproc)`

PGAS model:

- Shared and private segments
- Global and local references

Solution

Example: Co-array Fortran (CAF) (now part of Fortran 2008)

```
real A(100) ! regular, local array
real B(100)[*] ! coarray: each process has an array with 100 entries
real C
C = B(15) ! access to the local copy of B -- regular load
C = B(15)[7] ! access to a possibly remote copy-- may need a get()
A(:) = B(:)[3] ! copy the entire array from a possibly remote process
```

Code is executed by each process

Example: Universal Parallel C (UPC)

```
shared float a[10][5]; // a is a global array distributed round-robin
float b; // local variable
b = a[3][2]; // access to a possibly remote entry
```

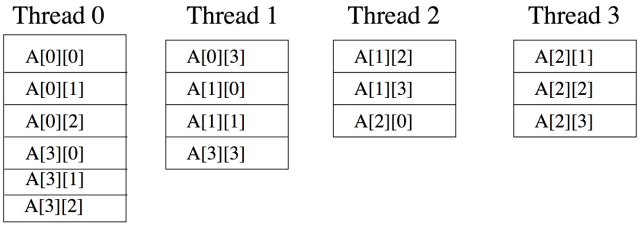
Code is executed at each process (called “thread” in UPC)

User can control the chunk size in the distribution of a global array

Assume THREADS = 4

```
shared [3] int A[4][THREADS];
```

will result in the following data layout:

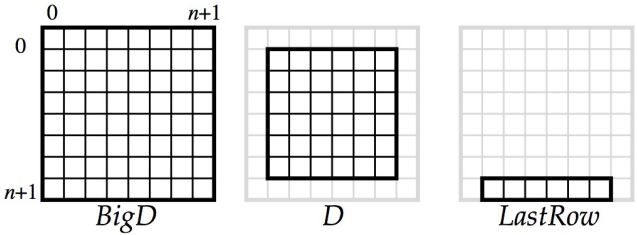


Partitioned Global Adress Space (PGAS)

- UPC pointers can be local (address) or global (rank, address)
- Dereferencing a global pointer is expensive (get/put)
- Global pointer arithmetic in UPC is expensive (less so in CAF or in UPC++)
- Hard to remember what is local and what is global in UPC (less so in CAF or UPC++)

Example Chapel – sequential

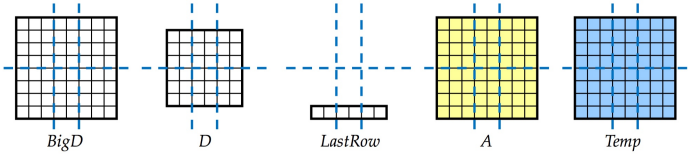
```
const BigD = {0..n+1, 0..n+1},
      D = BigD[1..n, 1..n],
      LastRow = D.exterior(1,0);

var A, Temp : [BigD] real;

A[LastRow] = 1.0;
do {
  forall (i,j) in D do
     Temp[i,j] = (A[i-1,j] + A[i+1,j] + A[i,j-1] + A[i,j+1]) / 4;
     const delta = max reduce abs(A[D] - Temp[D]);
     A[D] = Temp[D];
} while (delta > epsilon);
```



Chapel also supports sparse, irregular domains

Chapel parallel

```
const BigD = {0..n+1, 0..n+1} dmapped Block({1..n, 1..n}),
          D = BigD[1..n, 1..n],
          LastRow = D.exterior(1,0);
....
```



- The execution of the code is partitioned using the owner compute rule (data parallelism)
- Chapel's compiler compiles the codes to be executed on each process and the required communication (ghost cell updates)

A classification of distributed memory programming models

Data
- local – each process has its own address space
- global – shared arrays can be accessed by all processes

Control
- local – code is executed by each process
- global – there is logically one thread of execution; compiler distributes code execution to the processes

		Control	
		local	global
Data	local	MPI	?
	global	UPC	Chapel

Yet More Choice: Remorte Procedure Call

Some distributed memory libraries/languages (UPC++, X10, Charm++) support injecting calls into remote processes; the calls execute in the context of the remote process.

- Makes sense for a model with static, persistent threads, each with their own private data environment.

Charm++

- Basic Object is *Chare*: Contains data and external methods that can be called by other chares; the methods do not return values.
- Chares are distributed across compute nodes; there are typically multiple chares per node, and they can be migrated.

Charm++ Hello World

Header file (hello.h)

```
class Hello : public CBase_Hello {
  public:
  Hello(); // C++ constructor

  void sayHi(int from); // Remotely invocable "entry method"
};
```

Charm++ Interface file (hello.ci)

```
module hello {
  array [1D] Hello {
    entry Hello();
    entry void sayHi(int);
  };
};
```

Source file (hello.cpp)

```
#include "hello.decl.h"
#include "hello.h"

extern CProxy_Main mainProxy;
extern int numElements;

Hello::Hello() {
  // No member variables to initialize in this simple example
}
```

```
void Hello::sayHi(int from) {

  // Have this chare object say hello to the user.
  CkPrintf("Hello␣from␣chare␣#␣%d␣on␣processor␣%d␣(told␣by␣%d)\n",
  thisIndex, CkMyPe(), from);

  // Tell the next chare object in this array of chare objects
  // to also say hello. If this is the last chare object in
  // the array of chare objects, then tell the main chare
  // object to exit the program.
  if (thisIndex < (numElements - 1)) {
    thisProxy[thisIndex + 1].sayHi(thisIndex);
  } else {
    mainProxy.done();
  }
}

#include "hello.def.h"
```

Frameworks

- Have a fixed (simple) template of how parallelism is effected
- User plugs into the framework its own methods

Example: map-reduce
Example: Pregel (and many others) for graph analytics

Pregel

- Input is directed graph with values at vertices and edges
- Computation consists of a sequence of "supersteps"
- At each superstep each vertex can read values at incoming edges, update its own values, update values at outgoing vertices and send messages to other vertices (typically, its neighbors)
- Messages sent by a vertex at superstep s is accessed by other vertices at superstep $s + 1$ (bulk synchronous parallel programming model). Same for edge updates.

Pregel API

```
template <typename VertexValue,
typename EdgeValue,
typename MessageValue>
class Vertex {
  public:
  virtual void Compute(MessageIterator* msgs) = 0;
  const string& vertex_id() const;
  int64 superstep() const;
  const VertexValue& GetValue();
  VertexValue* MutableValue();
  OutEdgeIterator GetOutEdgeIterator();
  void SendMessageTo(const string& dest_vertex,
  const MessageValue& message);
  void VoteToHalt();
};
```

User only needs to overwrite the `Compute()` method, and magic happens.

How many programming systems?

The Holy Grail: One system used for mutithreading. distributed memory and accelerators (GPUs)

- Possible to achive only with high-level frameworks that are descriptive

MPI+X: One system for distributed memory and one for multithreading and GPUs

- E.g., MPI + OpenMP

MPI+X+Y: One system for distributed memory, one for mutithreading and one for GPU

- E.g., MPI + C++ + Cuda

- Using programming models adjusted to each hardware system can lead to better performance
- It also leads to code that is hardware to develop and maintain

- There is much more
  - Evolving features of MPI, OpenMP
  - New evolving general languages
  - Domain specific languages (DSL)
  - Frameworks & libraries
- Problem
  - Dominant systems (MPI, OpenMP) are inelegant but well-supported
  - Emerging systems are more elegant, but less well supported and may disappear