Parallel Algorithms

Lecture 8: Data Management

Ronald Veldema

Data Management

- What partition of the data goes where
- What granularity do we chooze
  - Can't answer this question in general
- When do we do what
  - Can't answer this question in general

What goes Where ?

- Object X on Machine Y ?
  - Compute where the data is ?
    - Dynamically ? Statically ?
- How do I get from here to there ?
- Use data structures matching the network ?
    - Hierarchical data layout if network is a tree
  - Note: we do not require a physical network of some topology
    - Virtual networks

Data mapping (1)

- Map data to CPUs
- In SPMD programs, map partition X to cpu Y
- Block distributing arrays/matrixes such that accesses will be
  - Sequential in memory
  - Require as few network accesses as possible
    - NP hard when trying to also optimize load balancing

Data mapping (2)

- example: given 1D array and 10 cpus:

```
 int j = cpu_number;
parfor (int i=0;i<1000;i++) {
      A[j] = i;
      j += number_of_cpus;
}

//   Put a[i] on cpu i.
```

Dynamically mapping work to network

- Divide and conquer
  - Work stealing: steal work from overloaded nodes
    - But with data management:
      - Steal selectively: steal tasks only where you already have some data of
- Master-slave
  - Master pushes work to idle nodes
    - Where master knows the client already has some data
  - Idle nodes pull work from master
    - Master selects a good task for client

Statically mapping work to network (1)

- HPF
  - Programmer specifies data layout for each array
  - For best performance programmer needs to know network layout
    - Fortran programs often ‘tuned’ for a specific network
- MPI
  - Send message to cpu #5, because #5 has the data

Statically mapping work to network (2)

```
// map ‘a’ to put every 3rd element on a cpu
for I=0;I<N;I+=3)
        a[I] *= 10;

// insert code here to remap ‘a’
// to put every 4th element on a cpu
for I=0;I<N;I+= 4)
        a[I] *=4;
```

Statically mapping work to network (3)

- Good HPF compilers try and
  - Minimize the number of remappings
    - Rewrite loops
  - Remap a[I] to a’[I] while still changing the rest of the array
    - Overlap communication with communication

Statically mapping work to network (4)

- Block cyclic distribution
  - Divide input in blocks, # blocks>> tasks
  - Round robin distribute blocks over machines
- Semi-random block distribution
  - Divide input in blocks, #blocks >> tasks
  - Machine X has block HashFunction(I)
- Random block distribution
  - Distribute blocks using a *real* random function
  - Maintain directory somewhere of where block I was mapped

Replication (1)

- Normally, in parallel programming
  - All code is replicated
  - Data exists only once
- Data replication is difficult
  - Where to place replicas
  - Where to find closest replica
  - How to keep replicas consistent

Replication (2)

- Replica consistency protocols
  - Invalidation protocols
    - Upon modification, other replicas are deleted
  - Update protocols
    - After modification, broadcast your copy
  - Merge protocols
    - Allow multiple modifying machines, replicas merged in future
      - Highest priority
      - First come, first serve
  - Lazy update
    - Only after a while update other replicas

Replication (2a)

- Case study: globedoc
  - It makes sense that for different objects/webpages, different replication strategies are best
    - Some pages/objects should be consistent at all times
      - A ‘current price & product’ page of a company
    - Some pages/objects can be relaxed consistent and replicated aggressively
      - The generic company home-page

Replication (2b)

- Globus
  - Millions of users, hundreds of replicas, files can be VERY large
  - Each file has a logical name
  - Each replica has a logical+physical name
  - File open
    - takes a logical name
    - Asks replica location service for a physical name given logical name
    - We can then use local name to open file
    - Users manually create replicas (using globus_copy_file)

Replication (3)

- Example: lazy partial data replication for dynamically scheduled independent loop iterations

```
parfor (int I=0;I<N; I++)
        a[I] = b[ f() ] * c[ g() ]
```

Compiler/programmer notices that:

- iterations are independent;
- single iteration depends on { I, f(), g() };
- b, c are readonly. If large: replicating b and c everywhere would cost a lot of memory/bandwidth.

Replication (4)

- Maintain a ‘work-queue’ of ‘I’ still to be done
  - At program startup queue contains [0..N]
  - Each processor asks ‘master’ and ‘steals’ an entry
    - Master should give entry where there is a large chance that that machine already has some of the data.
      - Master records where it has sent b[x] and c[x]
      - Master guesses/executes f(), g()

Replication (5)

Master Request history

I	f()	g()	target
0	0	0	1
1	1	2	3
2	2	3	4
3	3	2	2
4	…..		
5	…..		
6	…..		

Machine 1
b[0],c[0]

Machine 2
b[3],c[2]

Machine 3
b[1],c[2]

Machine 4
b[2],c[3]

Machine 3 finishes and asks master for work,
master should give an iteration where machine 3 is able to reuse one of the replicated b,c arrays

Prefetching (1)

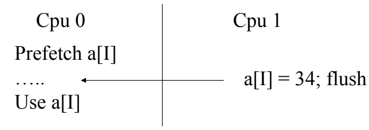
- Fetch data before its needed
  - Works both with message passing and with shared memory models
- How much to prefetch
- Prefetch data even if you might not need it ?

Prefetching (2)

- Most modern processors have some form of prefetch instruction/mechanism
  - Pentium4: prefetch <cache-level> <address>
- Message passing:
  - When requesting datum X, also fetch X's referred-to data
  - Stride detection for data accesses

Prefetching (3)

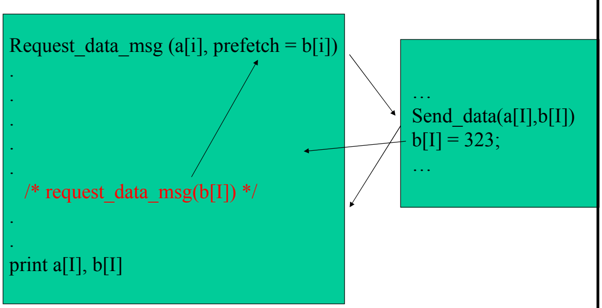
- Data consistency issues



Should cpu 0 see the change to a[I] ?
- depends on consistency model, programming model, prefetch semantics…

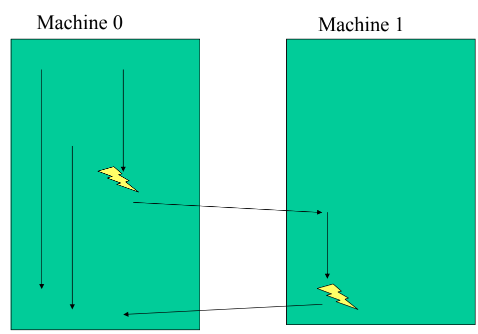
Prefetching (4)

- Data consistency issues



(sending prefetch request for 'b' with concurrent modifications to 'b')

Thread Migration (0)



Thread Migration (1)

- Policy
  - When to migrate
- Mechanism
  - How to migrate
- Different from remote procedure call
  - Thread is interupted & moved, not a single function as with RPC
  - Execution on another CPU can last arbitrarily long

Thread Migration (2)

- Policy
  - Move a thread to where the most data is to eliminate network latencies (reduce network trafic)
  - Move to less loaded machine (load balancing)
  - Move a thread back after N seconds ?
  - Move only if local state smaller than data in messages ?
  - When to move ?
    - After N times sending a message to a specific remote machine ?

Thread Migration (3)

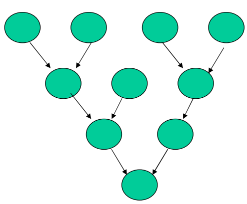
- Mechanism
  - How to handle open files
  - How to handle pointers
    - Pointers to local objects
    - Pointers on the stack
    - Pointers to objects on the stack

Thread Migration (4)

- Case study: “Harmony”
  - DSM system (shared memory simulation on top of a message passing: distributed memory machine)
  - Minimize both #messages & load imbalance
    - NP hard problem…
  - See paper (handed out)

Pointer jumping (1)

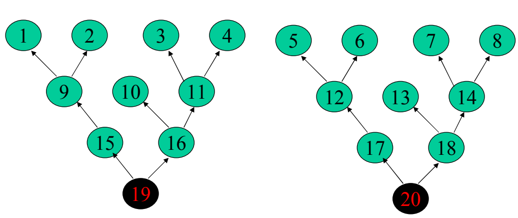
- Quickly find data in set of rooted directed trees
- Initially, the pointers are all pointing on wrong direction



Pointer jumping (2)

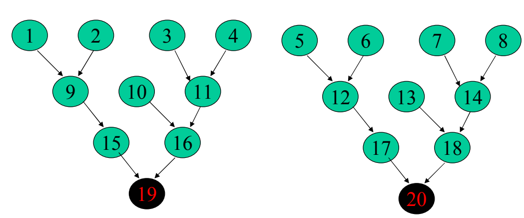
- Determine root S(j) of the tree containing node j for each j in the forest of directed trees
- Sequential:
  - Identify roots of forest
  - Reverse links
  - Depth first traversal

Pointer jumping (3)



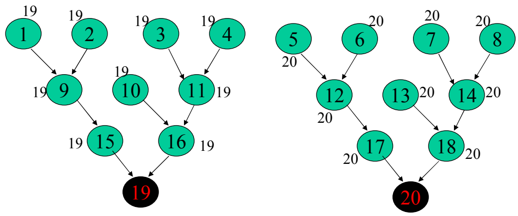
Step 1: identify roots of forest

Pointer jumping (4)



Step 2:reverse links

Pointer jumping (5)



Step 2:reverse links

Pointer jumping (6)

- Input: forest of rooted directed trees
  - Root has circular reference to itself so S(I) = I
- Output: S(I) is root of node I

```
// for every node try and find root in parallel
parfor 1 <= I <= n
        S(I) := P(I) // am I root ?
        while S(I) != S(S(I)) // already at root ?
                S(I) := S(S(I)) // one level deeper
```

Jump Pointer Prefetching (1)

- When using a linked data structure, add extra links to double, tripple etc indirections

```
Class LinkedListNode {
  Data d;
  LinkedListNode Next;
}
```

Before…

```
Class LinkedListNode {
    Data d;
    LinkedListNode Next;
    LinkedListNode NextNext;
    LinkedListNode NextNextNext;
}
```

After…

Jump Pointer Prefetching (2)

```
While (node != null) {
        process(node);
        node = node.Next;
}
```

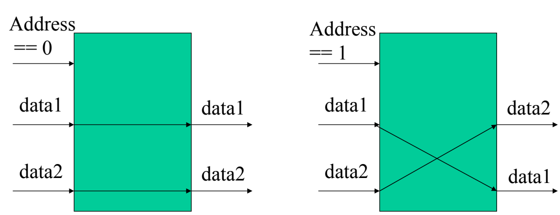
```
While (node != null) {
        process(node);
        prefetch node.NextNextNext;
        node = node.Next;
}
```

Network Properties

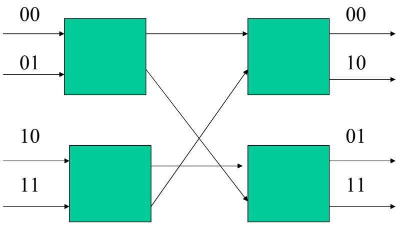
- static routing / switched
- bisection width
  - how many links can I remove before I divide network in two disconnected networks
- blocking network
  - switch can't be concurrently used by two packets to different destinations
- fully connected
  - Everybody has a connection to everybody else
  - Use virtual networks to create…
- neighbour connected

Omega network (1)

- how to route, crossbar switch

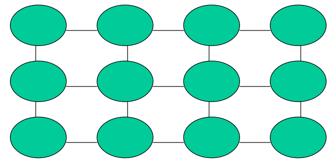


Omega Network (2)



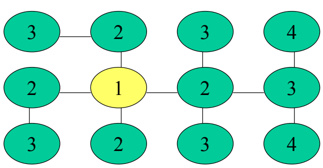
(shift left source address to get to destination address)

Latice (mesh) networks (1)



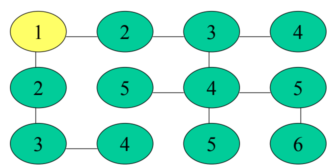
-Everyone is connected to a number of neighbours
-Many spanning trees possible…

Latice (mesh) networks (2)



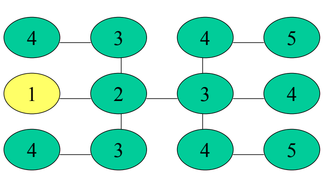
- Everyone is connected to a number of neighbours
- Many spanning trees possible…

Latice (mesh) networks (3)



- Everyone is connected to a number of neighbours
- Many spanning trees possible…

Latice (mesh) networks (4)



Map tree to mesh:
break all cycles by not using some links

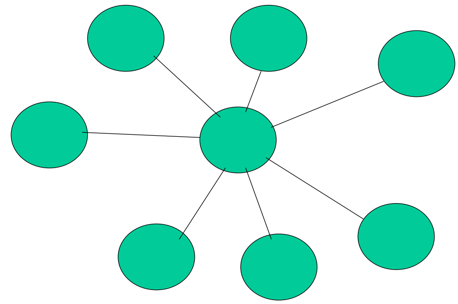
Latice (mesh) networks (5)

- Systolic matrix multiplication
  - NxN matrix
  - NxN mesh
- Systolic = matrixes are slowly ‘absorbed/consumed’ by the network

Latice (mesh) networks (6)

- Each time step
  - Cpu x,y computes
    - c[x,y] += a[x,m]*b[m,y]
  - Sends a[x,m] to east neighbour
  - Sends b[m,y] to north neighbour
- In n steps, everybody will have seen all ‘m’
  - Log(n) complexity

Star networks

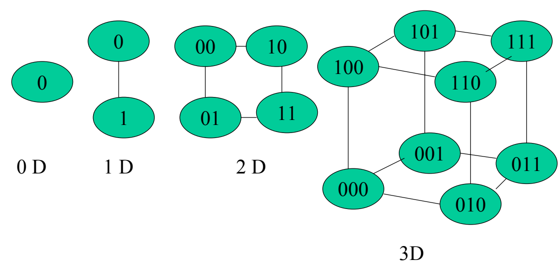


Star networks

```
Master:
   JobDistributor = new JobDistributor();

Each slave machine:
         Master m  = get_master();
         while not done:
                  job  = master.jobDistributor.get_job();
                  job.compute();
```

Hypercube networks (1)



*node I and J are connected if address is 1 bit less or more

Hypercube networks (2)

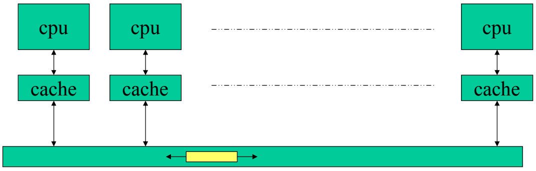
- Sum array elements on a hypercube
  - Element a[I] is on cpu I
  - Array size = N then log(n) cpus (n=$2^{d,}$ d=dimension)
  - Store result on cpu 0

```
// d = dimension, x iterates over subdimensions
// I am cpu ‘I’
for x=d-1 to 0
         if 0 <=I<=2^x-1 then // should I participate this iteration ?
                  a[I] = a[I] + a[ I^[x] ]
```

Hypercube networks

- Given a 8 node cluster: n=8, then 8=2^3, we thus have a 3D hypercube
- First iter:
  - a[0] += a[4], a[1]+=a[5], a[2] +=a[6], a[3] += a[7]
- Second iter:
  - a[0] = a[0]+a[4]+a[2]+a[6],
  - a[1] = a[1]+a[5]+a[3]+a[7]
- Third iter:
  - a[0] = a[0…7]
- Question: did we use static or dynamic routing ?

Bus based networks (1)



Bus based networks (2)

- Fast broadcast
  - Everybody receives a packet at the same time
- Bus snooping
  - Everybody listens to all packets, even the packets not destinated for you

Shared Memory Broadcast...

```
Class A {
  volatile int value;

  synchronized void bcast(int x) {
     value = x;
  }
}
```

On a SMP machine, with a snooping bus:
- the 'value' assign is seen by all processors
- all processors evict the old value from the cache

Matrix Transposition

- Diagonally mirror a 2D matrix

Matrix = NxM

(1,1) → (1,N)
↓ ....
(M,1) (M,N)

then transpose =

(1,1) → (M,1)
↓ ....
(1,N) (M,N)

now map (i,j) to processor P(i)

1) Matrix transposition = data remapping problem
2) Won't it be better to allocate matrix in transposed form ?

Matrix Multiplication (1)

- Let A and B be a n*n matrices
  - compute C = A*B

$$C = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} \\ b_{21} & b_{22} & b_{23} & b_{24} \\ b_{31} & b_{32} & b_{33} & b_{34} \\ b_{41} & b_{42} & b_{43} & b_{44} \end{bmatrix}$$

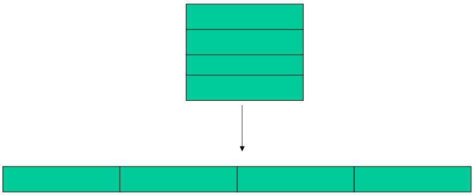
$$c_{ik} = \sum_{j=1}^{n} a_{ij} \times b_{jk}$$

This requires n multiplications and n-1 additions per element of C
So it takes n^3 multiplications and $n^3 - n^2$ additions to compute C

Martrix Multiplication (2)

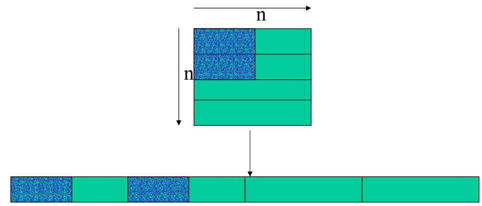
- Replicate A, B (read-only afterall !)
- Each cpu computes row J of C[I, J]
- Afterwards, merge rows to create complete C matrix

Inproving Matrix Memory Layout (1)

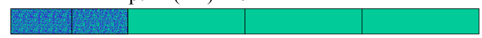


Access element A[I][j] of NxN matrix using:
ptr + (N*I) + J

Inproving Matrix Memory Layout (2)



Access element A[I][j] of NxN matrix using:
ptr + (n*I) + J



Access element A[I][j] of NxN matrix using ?

Mapping Matrix to Network (1)

- Map:

```
For (int I=0;I<N;I++)
    For (int I=0;I<N;I++)
        matrix[I][I]= matrix[I*3][I*3];
```

  - To a 2D mesh with N cpus
    - Put every 3rd element on a cpu

Mapping Matrix to Network (2)

0,0	0,3	0,6	0,9	0,12	0,15	0,18
3,0	3,3					
6,0						
9,0						9,18

Mapping Matrix to Network (3)

- Tradeoffs:
    - How to map array with different concurrent access patterns ?
    - Example:

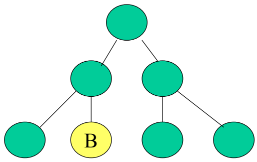
      A[I] = A[j*2] * N
      A[I] = A[j*3] * M
      Chooze between every 2nd or every 3rd on a cpu….

Mapping Matrix to Network (4)

- Compile time unknowns can make a-priori data-mapping hard
  - A[B[I]]
  - A[string2int(commandline[1])]

Barrier on a hierarchical network (1)

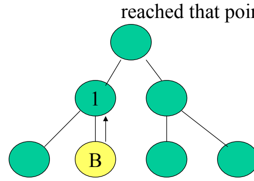
(barrier = point in code where cpus wait until all cpus have reached that point on the program)



Wants to enter barrier.

Barrier on a hierarchical network (2)

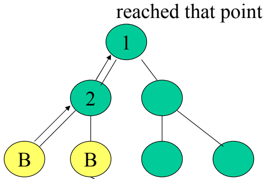
(barrier = point in code where cpus wait until all cpus have reached that point on the program)



1)Wants to enter barrier.
2) Sends “enter_barrier” to parent, parent sets “child_block_counter” to ‘1’

Barrier on a hierarchical network (3)

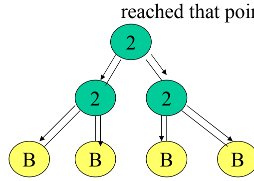
(barrier = point in code where cpus wait until all cpus have reached that point on the program)



1)Wants to enter barrier.
2) Sends “enter_barrier” to parent, parent sets “child_block_counter” to ‘1’
3) Same as 2, parent sends block message to parent

Barrier on a hierarchical network (4)

(barrier = point in code where cpus wait until all cpus have reached that point on the program)



1) Root receives a block counter for each of its Child nodes and sends a ‘barrier_release’ message

Barrier on different networks

- Hypecube
  - Same as tree
- Star
  - Central barrier on center node
- Mesh
  - Create virtual topology
    - spanning tree