CSE524 Parallel Computation

Lawrence Snyder
www.cs.washington.edu/CSEp524

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Course Logistics

- Teaching Assistant: Nathan Kuchta
- Text at Prof. Copy & Print, 4200, "The Ave"
- Class web page is our headquarters
- Take lecture notes -- the slides will be online sometime after lecture
- Occasional homework problems, mostly programming assignments
- Modest Project during last 2-3 weeks

Please ask questions when they arise

Text: *Principles of Parallel Pgmming*

- Why use it? For this class it's better than any book published
- It is a work in progress -- please be patient
- It has benefited from one pass by another class
- You can have a huge impact by commenting on:
  - Mention all organizational issues, confusions, poor explanations, technical errors, e.g. programming errors, etc.
  - Editors will scrub the text: Ignore spelling errors, grammar errors, punctuation errors, etc.
  - Use anonymous email for "private comments"

You may learn a lot about book writing!

Why Study Parallelism?

- After all, for most of our daily computer uses, sequential processors are plenty fast
  - It is a fundamental departure from the "normal" computer model, therefore inherently cool
  - The extra power from parallel computers is enabling in science, engineering, business, …
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Topic Overview

- Goal: To give a good idea of parallel computation
  - Concepts -- looking at problems with “parallel eyes”
  - Algorithms -- different resources; different goals
  - Languages -- reduce control flow; increase independence; new abstractions
  - Hardware -- the challenge is communication, not instruction execution
  - Programming -- describe the computation without saying it sequentially
  - Practical wisdom about using parallelism

Familiar Parallel Techniques

- SETI and BOINC techniques -- zillions of independent problem instances
- Pipelining -- perform multiple instances of a multi-step operation
- Overlapping computation and communication -- OS task switching
- Carry Look-ahead Adders -- logarithmic circuit to compute carries

Non-Parallel Techniques

- Distributed computing, e.g. client/server structure, is not usually parallel
- Divide-and-conquer is usually limited by “sending and receiving” the data instances
- Techniques that assume n^c processors for n size problem
- Almost all techniques that focus on reducing operation counts and building complex data structures

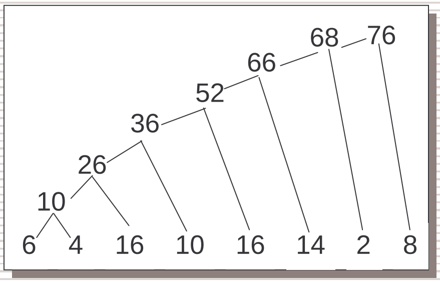
Parallel vs Distributed Computing

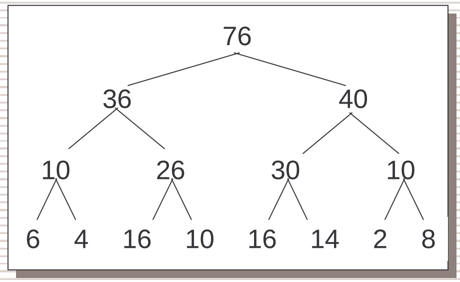
- Comparisons are often matters of degree

Characteristic	*Parallel*	*Distributed*
Overall Goal	Speed	Convenience
Interactions	Frequent	Infrequent
Granularity	Fine	Coarse
Reliable	Assumed	Not Assumed

Changing Paradigms

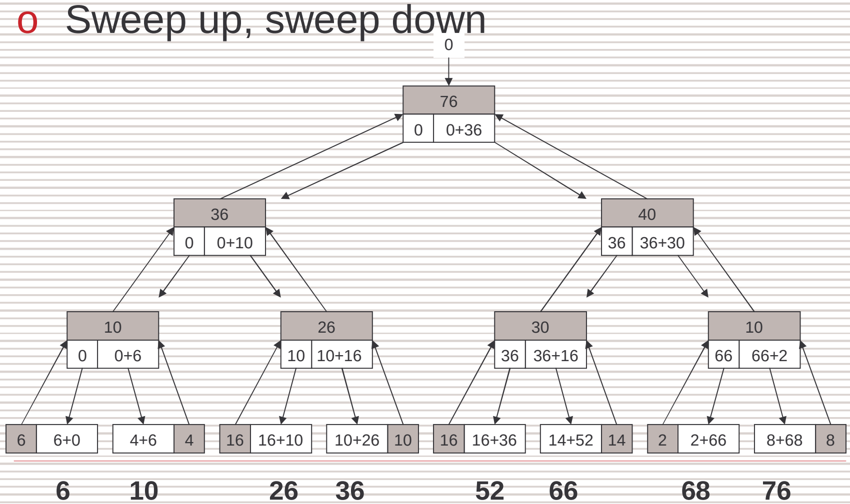
- Sequential summation to tree-based summation
  - Same number of operations; different order





Parallel Prefix

- Sweep up, sweep down



Fundamental Tool of || Pgmming

- Original research on parallel prefix algorithm published by

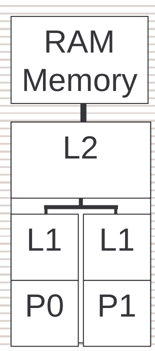
R. E. Ladner and M. J. Fischer
Parallel Prefix Computation
Journal of the ACM 27(4):831-838, 1980

The Ladner-Fischer algorithm requires twice as much time as simple tournament global sum

Applies to a wide class of operations

Write A Small Parallel Program

- Need to know something about machine … use multicore architecture



Count 3s Problem

- Ideal solution …
  - Sequential program

```
count = 0;
for (i=0; i<size; i++)
 {
   if (array[i] == 3)
      count += 1;
 }
```

  - + compiler magic

Compilers "Can't" Convert to ||ism

- Effort to compile to ||ism began in 1970s
- Research has occupied some of the best compiler writers
- Progress has been achieved
- Success so far limited to simple, clean cases

Intuition for low expectations: Fundamentally, compilers apply correctness *preserving* transformations … but generally, a parallel solution requires a *paradigm shift* from the sequential approach

Try 1: Divide Into Separate Parts

- Threading solution

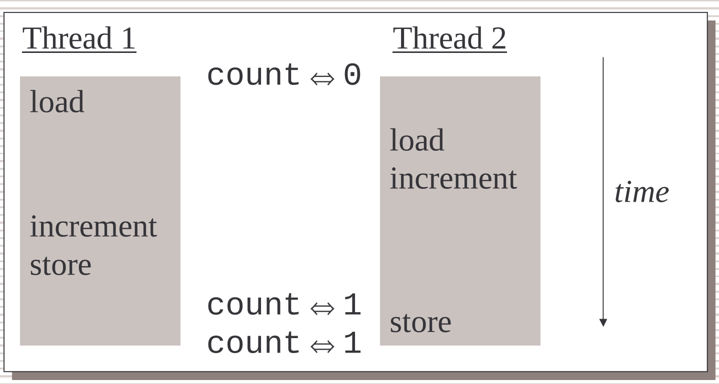
`length=16 t=4`

`array`	2	3	0	2	3	3	1	0	0	1	3	2	2	3	1	0
	Thread 0				*Thread 1*				*Thread 2*				*Thread 3*			

```
int length_per_thread = length/t;
int start = id * length_per_thread;
for (i=start; i<start+length_per_thread; i++)
   {
     if (array[i] == 3)
              count += 1;
   }
```

Try 1: Races

- Two processes interfere on memory writes



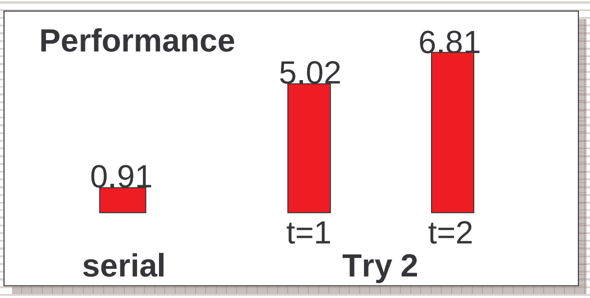
Try 2: Protect Memory References

- Protect Memory References

```
mutex m;
for (i=start; i<start+length_per_thread; i++)
    {
    if (array[i] == 3)
      {
        mutex_lock(m);
          count += 1;
        mutex_unlock(m);
      }
    }
```

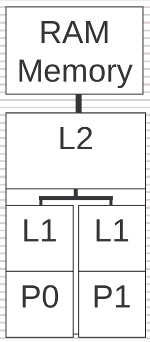
Try 2: Correct Program Runs Slow

- Serializing at the mutex
  - The processors wait on each other



Closer Look

- Lock Reference and Contention




```
mutex m;
for (i=start; i<start+length_per_thread; i++)
     {
     if (array[i] == 3)
        {
           mutex_lock(m);
             count += 1;
           mutex_unlock(m);
        }
     }
```

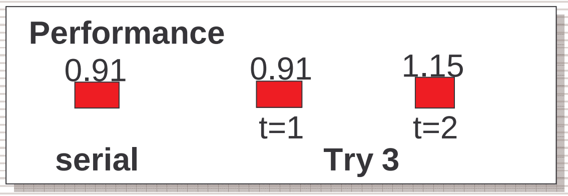
Try 3: Accumulate Into Private Count

- Each processor adds into its own memory; combine at the end

```
for (i=start; i<start+length_per_thread; i++)
     {
        if (array[i] == 3)
           {
              private_count[t] += 1;
            }
      }
mutex_lock(m);
  count += private_count[t];
mutex_unlock(m);
```

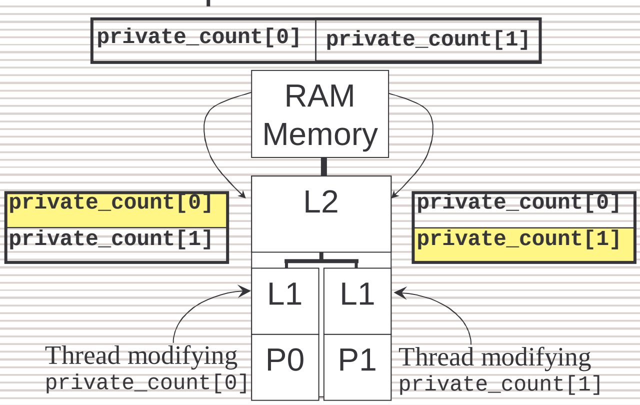
Try 3: Keeping Up, But Not Gaining

- Sequential and 1 processor match, but it’s a loss with 2 processors



Try 3: False Sharing

- Private var ≠ private cache-line



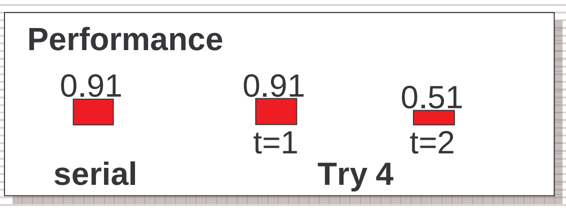
Try 4: Force Into Different Lines

- Padding the private variables forces them into separate cache lines and removes false sharing

```
struct padded_int
 {
    int value;
    char padding[128];
 }  private_count[MaxThreads];
```

Success!!

- Two processors are almost twice as fast



Is this the best solution???

Break

Our Goals In Parallel Programming

- Goal: Scalable programs with performance and portability
  - Scalable: More processors can be "usefully" added to solve the problem faster
  - Performance: Programs run as fast as those produced by experienced parallel programmers for the specific machine
  - Portability: The programs run well on all parallel platforms

Challenges of Parallel Programming

- Has different costs, different advantages
- Requires different, unfamiliar algorithms
- Must use different abstractions
- More complex to understand a program's behavior
- More difficult to control the interactions of the program's components
- Knowledge/tools/understanding more primitive

Program A Parallel Sum

- Return to problem of writing a parallel sum
- Sketch solution in class

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- and communication time = 30 ticks

Program A Parallel Sum

- Return to problem of writing a parallel sum
- Sketch solution in class
- when n > P
- and communication time = 30 ticks
- n = 1024, P = 8
- compute performance

Program A Parallel Sum

- Return to problem of writing a parallel sum
- Sketch solution in class
- when n > P
- and communication time = 30 ticks
- n = 1024
- compute performance
- Now scale to 64 processors

This analysis will become standard, intuitive

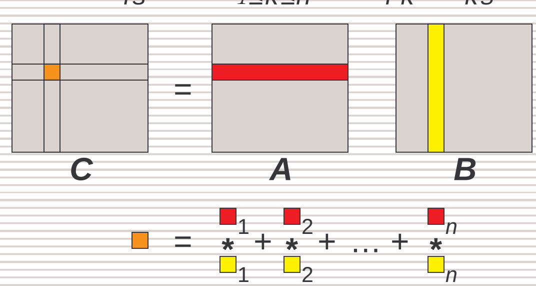
Matrix Product: || Poster Algorithm

- Matrix multiplication is most studied parallel algorithm (analogous to sequential sorting)
- Many solutions known
  - Illustrate a variety of complications
  - Demonstrate great solutions
- Our goal: explore variety of issues
  - Amount of concurrency
  - Data placement
  - Granularity

Exceptional by requiring O(n^3) ops on O(n^2) data

Recall the computation…

- Matrix multiplication of (square n x n) matrices ***A*** and ***B*** producing n x n result ***C*** where $\boldsymbol{C}_{rs} = \sum_{1 \le k \le n} \boldsymbol{A}_{rk} * \boldsymbol{B}_{ks}$

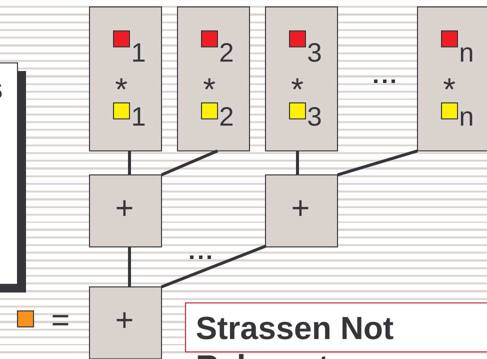


Extreme Matrix Multiplication

- The multiplications are independent (do in any order) and the adds can be done in a tree

O(*n*) processors for each result element implies O(n^3) total

Time: O(*log n*)



Strassen Not Relevant

O(*log n*) MM in the real world …

Good properties

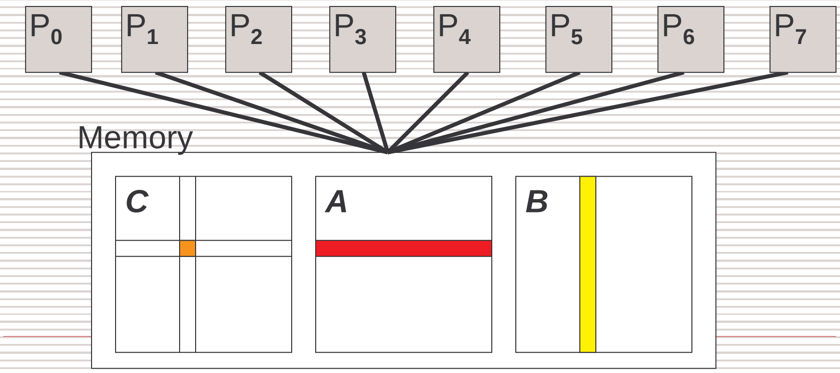
- Extremely parallel … shows limit of concurrency
- Very fast -- $log_2\, n$ is a good bound … faster?

Bad properties

- Ignores memory structure and reference collisions
- Ignores data motion and communication costs
- Under-uses processors -- half of the processors do only 1 operation

Where is the data?

- Data references collisions and communication costs are important to final result … need a model … can generalize the standard RAM to get PRAM



Parallel Random Access Machine

- Any number of processors, including n^c
- Any processor can reference any memory in "unit time"
- Resolve Memory Collisions
  - Read Collisions -- simultaneous reads to location are OK
  - Write Collisions -- simultaneous writes to loc need a rule:
    - Allowed, but must all write the same value
    - Allowed, but value from highest indexed processor wins
    - Allowed, but a random value wins
    - Prohibited

Caution: The PRAM is *not* model we advocate

PRAM says O(*log n*) MM is good

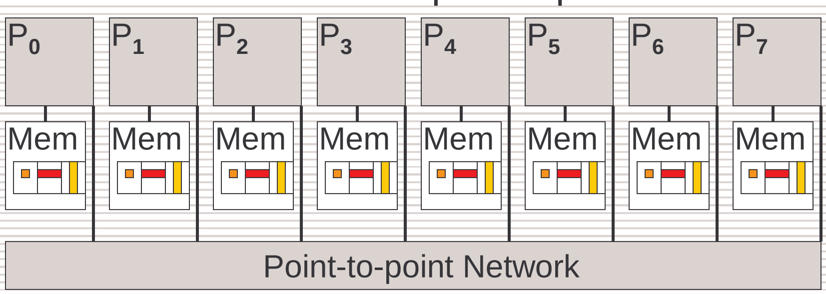
- PRAM allows any # processors => $O(n^2)$ OK
- ***A*** and ***B*** matrices are read simultaneously, but that's OK
- ***C*** is written simultaneously, but no location is written by more than 1 processor => OK

PRAM model implies O(*log n*) algorithm is best … but in real world, we suspect not

We return to this point next week

Where else could data be?

- Local memories of separate processors …

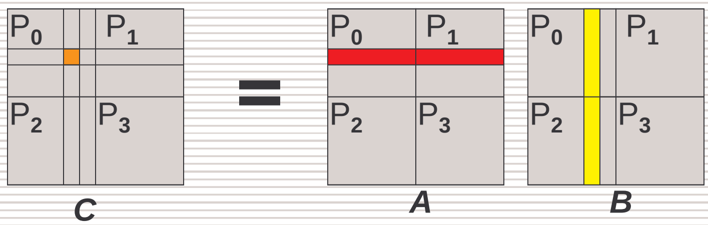


- Each processor could compute block of ***C***
  - Avoid keeping multiple copies of ***A*** and ***B***

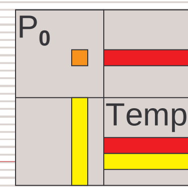
Architecture common for servers

Data Motion

- Getting rows and columns to processors

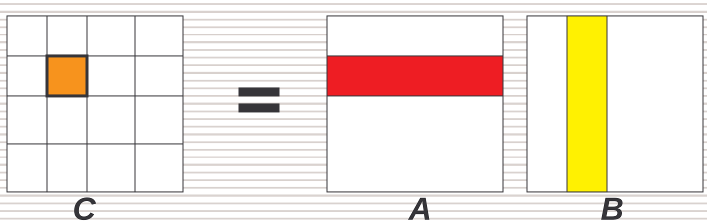


  - Allocate matrices in blocks
  - Ship only portion being used



Blocking Improves Locality

- Compute a *b* x *b* block of the result



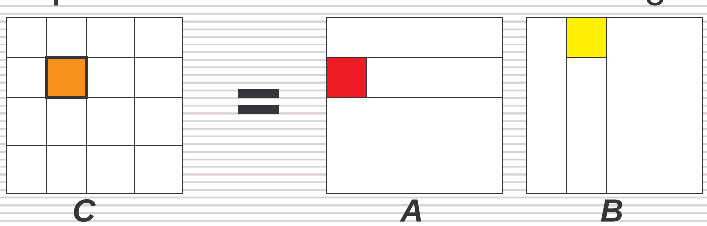
- Advantages
  - Reuse of rows, columns = caching effect
  - Larger blocks of local computation = hi locality

Caching in Parallel Computers

- Blocking = caching … why not automatic?
  - Blocking improves locality, but it is generally a manual optimization in sequential computation
  - Caching exploits two forms of locality
    - Temporal locality -- refs clustered in time
    - Spatial locality -- refs clustered by address
- *When multiple threads touch the data, global reference sequence may not exhibit clustering limited to one thread -- thrashing*

Sweeter Blocking

- It's possible to do even better blocking …



- Completely use the cached values before reloading

Best MM Algorithm?

- We haven't decided on a good MM solution
- A variety of factors have emerged
  - A processor's connection to memory, unknown
  - Number of processors available, unknown
  - Locality--always important in computing--
    - Using caching is complicated by multiple threads
    - Contrary to high levels of parallelism
- Conclusion: Need a better understanding of the constraints of parallelism

Next week, architectural details + model of ||ism

Next Week …

- Read Chapter 2 and study the CTA
  - You may need to answer questions on it …