Discuss …

- Do we think that the multicore processor will become the idealized parallel machine in the same way the 701 defined the RAM model?

Finishing the Discussion on CTA

- The CTA is supposed to guide us in finding good computations to run on parallel machines
- Using it should
  - Aid in producing programs exploiting locality
  - Insure the program distributes work 'well'
  - Other features, to be discussed later
- Consider HW2 …

Considering HW2

- Task: Recognize the well-formedness of ((xxx))
- An easy sequential solution …

```
open = 0;                       // keep count of opens
for (i=0; i<n; i++) {           // proceeding L to R
  if (A[i] == '(' ) open++;     // found one
  if (A[i] == ')' ) {           // here's a match
      open--;
      if (open < 0) break;      // oops, mismatch
```

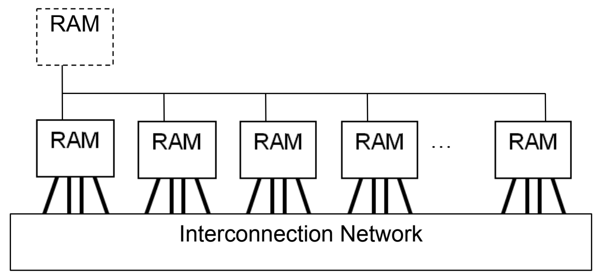
Does this look totally sequential??

Where Was The Focus?

- First step: Allocated work to processors, generally by dividing it evenly
- Next step: Found local, independent work to perform
- Next step: Focused on combining subproblems into a tree network
- Made correctness and termination conditions explicit

Completing the CTA Discussion

- Controller →
  - Not strictly needed
  - Often available
- How well does the CTA match other parallel architectures?
  - CMPs & SMPs
  - Clusters
  - Blue Gene



Precision of the CTA

- The CTA is a 'machine model' – an abstraction
- How can it be wrong?
  - Architecture has more features – shared memory
  - CTA predicts a certain behavior and features in the architecture make the program much faster
  - If it mispredicts … it's in trouble
- Isn't it a mistake for the CTA to ignore all the great stuff architects put in a processor

The CTA focuses on the parts that matter

Using the CTA

- Why should we believe it's right?
  - In his thesis (1993) Calvin Lin did a careful study of using the CTA as a programming model against the models used by others (whatever they were)
    - CTA consistently pointed programmers to better solutions
    - The CTA's effectiveness was independent of architecture
    - The apparent value of the model is emphasizing locality – always a benefit in computing
- The greatest value of the CTA would be if it is the basis for parallel programming languages

Threads

- A thread consists of program code, a program counter, call stack, and a small amount of thread-specific data
  - Threads share access to memory (and the file system) with other threads
  - Threads communicate through the shared memory
  - Though it may seem odd, apply the CTA model to thread programming -- emphasize locality, expect sharing to cost plenty

Processes

- A process is a thread in its own private address space
  - Processes do not communicate through shared memory, but need another mechanism like message passing
  - Key issue: How is the problem divided among the processes, which includes data and work
  - Processes (logically subsume) threads

Compare Threads & Processes

- Both have code, PC, call stack, local data
  - Threads -- One address space
  - Processes -- Separate address spaces
- Weight and Agility
  - Threads: lighter weight, faster to setup, tear down, more dynamic
  - Processes: heavier weight, setup and tear down more time consuming, communication is slower

Mostly we use 'thread' & 'process' interchangeably

Terminology

- Terms used to refer to a unit of parallel computation include: thread, process, processor, …
  - Technically, thread and process are SW, processor (including SMT) is HW
  - Usually, it doesn't matter
  - I will (try to) use "thread/process" for logical parallelism, and "processor" when I mean physical parallelism

Parallelism vs Performance

- Naïvely, many people think that applying *P* processors to a *T* time computation will result in *T*/*P* time performance
- Generally wrong
  - For a few problems (Monte Carlo) it is possible to apply more processors directly to the solution
  - For most problems, using *P* processors requires a paradigm shift
- Assume "P processors => T/P time" to be the best case possible

Better Intuition

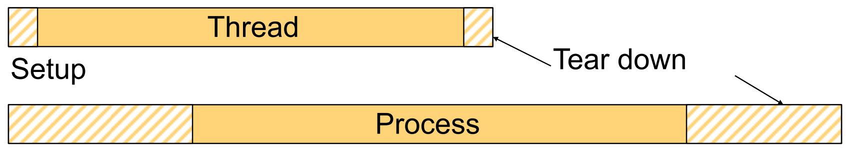
- (Because of the presumed paradigm shift) the sequential and parallel solutions differ so we do not expect a simple performance relationship between the two
  - More or fewer instructions must be executed
- Examples of other differences
  - The hardware is different
  - Parallel solution has difficult-to-quantify costs such as communication time, wait time, etc. that the serial solution does not have

More Instructions Needed

- To implement parallel computations requires overhead that sequential computations do not need
  - All costs associated with communication are overhead: locks, cache flushes, coherency, message passing protocols, etc.
  - All costs associated with thread/process setup
  - Lost optimizations -- many compiler optimizations not available in parallel setting
    - Instruction reordering

Performance Loss: Overhead

- Threads and processes incur overhead



- Obviously, the cost of creating a thread or process must be recovered through parallel performance:

$(t_1 + o_{su} + o_{td} + \text{cost}(t_2))/2 < t_2$

t_p = p proc execution time
o_{su} = setup, o_{td} = tear down
$\text{cost}(t_2)$ = all other || costs

More Instructions (Continued)

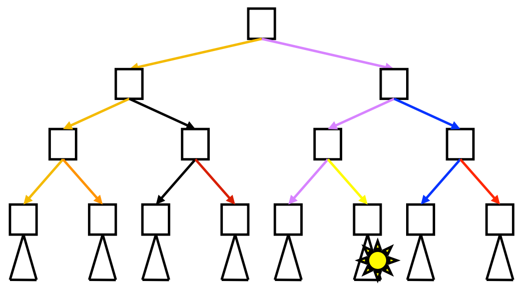
- Redundant execution can avoid communication -- a parallel optimization

New random number needed for loop iteration:
(a) Generate one copy, have all threads ref it … requires communication
(b) Communicate seed once, then each thread generates its own random number … removes communication and gets parallelism, but by increasing instruction load

A common (and recommended) programming trick

Fewer Instructions

- Searches illustrate the possibility of parallelism requiring fewer instructions



- Independently searching subtrees means an item is likely to be found faster than sequential

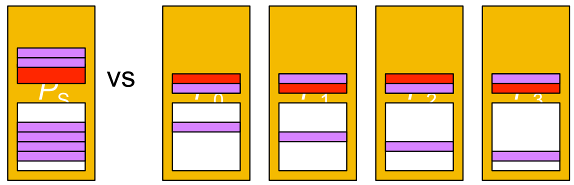
One vs Many

- Sequential hardware ≠ parallel hardware
  - There is more parallel hardware, e.g. memory
  - There is more cache on parallel machines
  - Sequential computer $\stackrel{?}{\neq}$ 1 processor of || computer, because of coherence hw, power, etc.
    - Important in multicore context
  - Parallel channels to disk, possibly

These differences *tend* to favor || machine

Superlinear Speed up

- Additional cache is an advantage of ||ism



- The effect is to make execution time < *T*/*P* because data (& program) memory references are faster
- Cache-effects help mitigate other || costs

Bottom Line …

- Applying *P* processors to a problem with a time *T* (serial) solution can be either … better or worse …
- It's up to programmers to exploit the advantages and avoid the disadvantages

Amdahl's Law

- If $1/S$ of a computation is inherently sequential, then the maximum performance improvement is limited to a factor of S

$$T_P = 1/S \times T_S + (1-1/S) \times T_S / P$$

T_S=sequential time
T_P=parallel time
P =no. processors

- Amdahl's Law, like the Law of Supply and Demand, is a fact

Gene Amdahl -- IBM Mainframe Architect

Interpreting Amdahl's Law

- Consider the equation

$$T_P = 1/S \times T_S + (1-1/S) \times T_S / P$$

- With no charge for || costs, let $P \rightarrow \infty$ then $T_P \rightarrow 1/S \times T_S$

The best parallelism can do to is to eliminate the parallelizable work; the sequential work remains

- Amdahl's Law applies to problem *instances*

Parallelism seemingly has little potential

More On Amdahl's Law

- Amdahl's Law assumes a fixed problem instance: Fixed *n*, fixed input, perfect speedup
  - The algorithm can change to become more ||
  - Problem instances grow implying proportion of work that is sequential may be smaller %
  - … Many, many realities including parallelism in 'sequential' execution imply analysis is simplistic

Two kinds of performance

- Latency -- time required before a requested value is available
  - Latency, measured in seconds; called *transmit time* or *execution time* or just *time*
- Throughput -- amount of work completed in a given amount of time
  - Throughput, measured in "work"/sec, where "work" can be bits, instructions, jobs, etc.; also called *bandwidth* in communication

Both terms apply to computing and communications

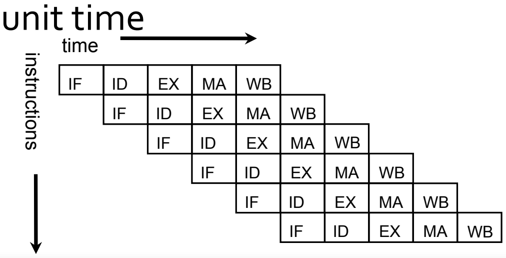
Latency

- Reducing latency (execution time) is a principal goal of parallelism
- There is upper limit on reducing latency
  - Speed of light, esp. for bit transmissions
  - In networks, switching time (node latency)
  - (Clock rate) x (issue width), for instructions
  - Diminishing returns (overhead) for problem instances

Hitting the upper limit is rarely a worry

Throughput

- Throughput improvements are often easier to achieve by adding hardware
  - More wires improve bits/second
  - Use processors to run separate jobs
  - Pipelining is a powerful technique to execute more (serial) operations in unit time



Better throughput often hyped as if better latency

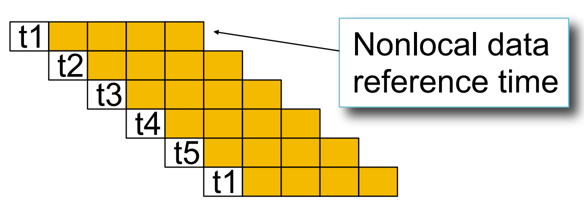
Latency Hiding

- Reduce wait times by switching to work on different operation (multithreading)
  - Old idea, dating back to Multics
  - In parallel computing it's called *latency hiding*
- Idea most often used to lower impact of λ cost
  - Have many threads ready to go …
  - Execute a thread until it makes nonlocal ref
  - Switch to next thread
  - When nonlocal ref is filled, add to ready list

Latency Hiding (Continued)

- Latency hiding requires …
  - Consistently large supply of threads ~ λ/e

  where e = average # cycles between nonlocal refs
  - Enough network throughput to have many requests in the air at once



- Latency hiding has been claimed to make shared memory feasible in the presence of large λ

There are difficulties

Latency Hiding (Continued)

- Challenges to supporting shared memory
  - Threads must be numerous, and the shorter the interval between nonlocal refs, the more
    - Running out of threads stalls the processor
  - Context switching to next thread has overhead
    - Many hardware contexts -- or --
    - Waste time storing and reloading context
  - Tension between latency hiding & caching
    - Shared data must still be protected somehow
  - Other technical issues

Performance Loss: Contention

- Contention -- the action of one processor interferes with another processor's actions -- is an elusive quantity
  - Lock contention: One processor's lock stops other processors from referencing; they must wait
  - Bus contention: Bus wires are in use by one processor's memory reference
  - Network contention: Wires are in use by one packet, blocking other packets
  - Bank contention: Multiple processors try to access different

Contention is very time dependent, that is, variable

Performance Loss: Load Imbalance

- Load imbalance, work not evenly assigned to the processors, underutilizes parallelism
  - The assignment of *work*, not data, is key
  - Static assignments, being rigid, are more prone to imbalance
  - Because dynamic assignment carries overhead, the quantum of work must be large enough to amortize the overhead
  - With flexible allocations, load balance can be solved late in the design programming cycle

The Best Parallel Programs …

- Performance is maximized if processors execute continuously on local data without interacting with other processors
  - To unify the ways in which processors could interact, we adopt the concept of dependence
  - A *dependence* is an ordering relationship between two computations
    - Dependences are usually induced by read/write
    - Dependences that cross process boundaries induce a

Dependences are well-studied in compilers

Example of Dependences

- Both true and false dependences

```
1.    sum = a + 1;
2.    first_term = sum * scale1;
3.    sum = b + 1;
4.    second_term = sum * scale2;
```

- Flow-dependence read after write; must be preserved for correctness
- Anti-dependence write after read; can be eliminated with additional memory

Removing Anti-dependence

- Change variable names

```
1.    sum = a + 1;
2.    first_term = sum * scale1;
3.    sum = b + 1;
4.    second_term = sum * scale2;
```

```
1.    first_sum = a + 1;
2.    first_term = first_sum * scale1;
3.    second_sum = b + 1;
4.    second_term = second_sum * scale2;
```

Granularity

- Granularity is used in many contexts…here *granularity* is the amount of work between cross-processor dependences
  - Important because interactions usually cost
  - Generally, larger grain is better
    + fewer interactions, more local work
    - can lead to load imbalance
  - Batching is an effective way to increase grain

Locality

- The CTA motivates us to maximize locality
  - Caching is the traditional way to exploit locality … but it doesn't translate directly to ||ism
  - Redesigning algorithms for parallel execution often means repartitioning to increase locality
  - Locality often requires redundant storage and redundant computation, but in limited quantities they help

Measuring Performance

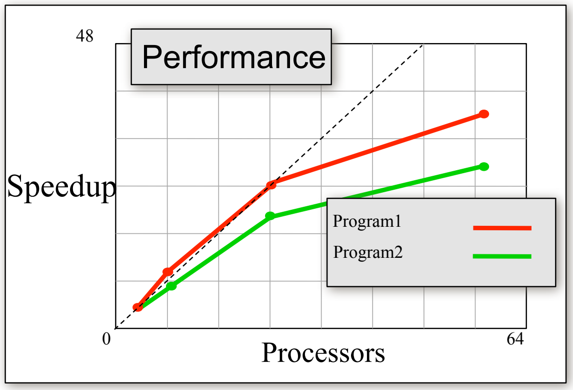
- Execution time … what's time?
  - 'Wall clock' time
  - Processor execution time
  - System time
- Paging and caching can affect time
  - Cold start vs warm start
- Conflicts w/ other users/system components
- Measure kernel or whole program

FLOPS

- Floating Point Operations Per Second is a common measurement for scientific pgms
  - Even scientific computations use many ints
  - Results can often be influenced by small, low-level tweaks having little generality: mult/add
  - Translates poorly across machines because it is hardware dependent
  - Limited application … but it won't go away!

Speedup and Efficiency

- Speedup is the factor of improvement for *P* processors: T_S/T_P



Efficiency = Speedup/*P*

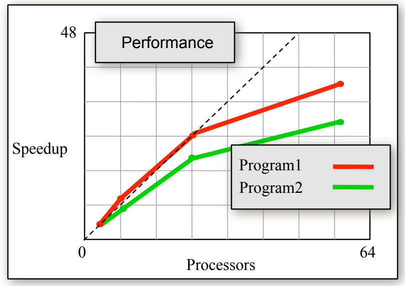
Issues with Speedup, Efficiency

- Speedup is best applied when hardware is constant, or for family within a generation
  - Need to have computation, communication in same ratio
  - Great sensitivity to the T_S value
    - T_S should be time of <u>best sequential program</u> on 1 processor of the ||-machine
    - $T_{P=1} \neq T_S$ Measures *relative speedup*

Relative speedup is often important but it must be labeled as such

Scaled v. Fixed Speedup

- As P increases, the amount of work per processor diminishes, often below the amt needed to amortize costs
- Speedup curves bend down
- Scaled speedup keeps the work per processor constant, allowing other effects to be seen
- Both are important



If not stated, speedup is fixed speedup

What If Problem Doesn't Fit?

- Cases arise when sequential doesn't fit in 1 processor of parallel machine
- Best solution is relative speed-up
  - Measure $T_{\pi=smallest\ possible}$
  - Measure T_P, compute T_π/T_P as having P/π potential improvement

We Will Return …

- Many issues regarding parallelism have been introduced, but they require further discussion … we will return to them when they are relevant

Summary of Key Points

- Amdahl's Law is a fact but it doesn't impede us much
- Inherently sequential problems (probably) exist, but they don't impede us either
- Latency hiding could hide the impact of λ with sufficiently many threads and much (interconnection) bandwidth
- Impediments to parallel speedup are numerous: overhead, contention, inherently sequential code, waiting time, etc.

Review Key Points (continued)

- Concerns while parallel programming are also numerous: locality, granularity, dependences (both true and false), load balance, etc.
- Happily: Parallel and sequential computers are different: More hardware means more fast memory (cache, RAM), implying the possibility of superlinear speedup
- Measuring improvement is complicated