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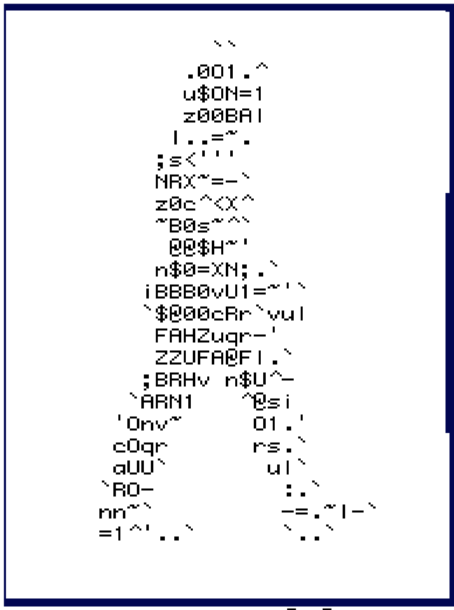
CS61C : Machine Structures

Lecture #42 – Parallel Computing

2005-05-09



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The California legislature is currently working on a bill to ban "remote hunting via the internet" after the incorporation of a Texas company specializing in a unique combination of robotics, web cameras, and weapons. Years of Counter Strike practice and I can't even get a meal out of it…

Scientific Computing

- **Traditional Science**
  - 1) Produce theories and designs on “paper”
  - 2) Perform experiments or build systems
  - Has become difficult, expensive, slow, and dangerous for fields on the leading edge
- **Computational Science**
  - Use ultra-high performance computers to simulate the system we’re interested in
- **Acknowledgement**
  - Many of the concepts and some of the content of this lecture were drawn from Prof. Jim Demmel’s CS 267 lecture slides which can be found at http://www.cs.berkeley.edu/~demmel/cs267_Spr05/

Example Applications

- Science
  - Global climate modeling
  - Biology: genomics; protein folding; drug design
  - Astrophysical modeling
  - Computational Chemistry
  - Computational Material Sciences and Nanosciences
- Engineering
  - Semiconductor design
  - Earthquake and structural modeling
  - Computation fluid dynamics (airplane design)
  - Combustion (engine design)
  - Crash simulation
- Business
  - Financial and economic modeling
  - Transaction processing, web services and search engines
- Defense
  - Nuclear weapons -- test by simulations
  - Cryptography

Performance Requirements

- Terminology
  - Flop – Floating point operation
  - Flops/second – standard metric for expressing the computing power of a system
- Global Climate Modeling
  - Divide the world into a grid (e.g. 10 km spacing)
  - Solve fluid dynamics equations to determine what the air has done at that point every minute
    - Requires about 100 Flops per grid point per minute
  - This is an extremely simplified view of how the atmosphere works, to be maximally effective you need to simulate many additional systems on a much finer grid

Performance Requirements (2)

- Computational Requirements
  - To keep up with real time (i.e. simulate one minute per wall clock minute): 8 Gflops/sec
  - Weather Prediction (7 days in 24 hours): 56 Gflops/sec
  - Climate Prediction (50 years in 30 days): 4.8 Tflops/sec
  - Climate Prediction Experimentation (50 years in 12 hours): 288 Tflops/sec
- Perspective
  - Pentium 4 1.4GHz, 1GB RAM, 4x100MHz FSB
    - ~320 Mflops/sec, effective
    - Climate Prediction would take ~1233 years

Reference:http://www.tc.cornell.edu/~lifka/Papers/SC2001.pdf

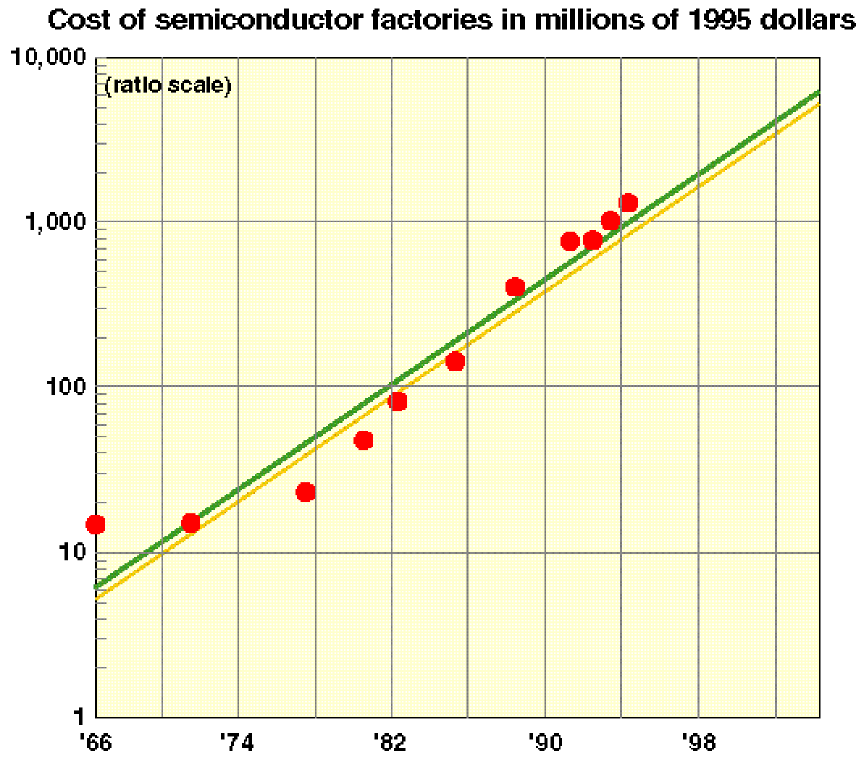
What Can We Do?

- Wait
  - Moore's law tells us things are getting better; why not stall for the moment?
- Parallel Computing!

Prohibitive Costs

° **Rock's Law**

- **The cost of building a semiconductor chip fabrication plant that is capable of producing chips in line with Moore's law doubles every four years**



Source: Forbes Magazine

How fast can a serial computer be?

° Consider a 1 Tflop/sec sequential machine:

- Data must travel some distance, r, to get from memory to CPU
- To get 1 data element per cycle, this means 10^{12} times per second at the speed of light, c = $3x10^8$ m/s. Thus r < $c/10^{12}$ = 0.3 mm
    - So all of the data we want to process must be stored within 0.3 mm of the CPU

° Now put 1 Tbyte of storage in a 0.3 mm x 0.3 mm area:

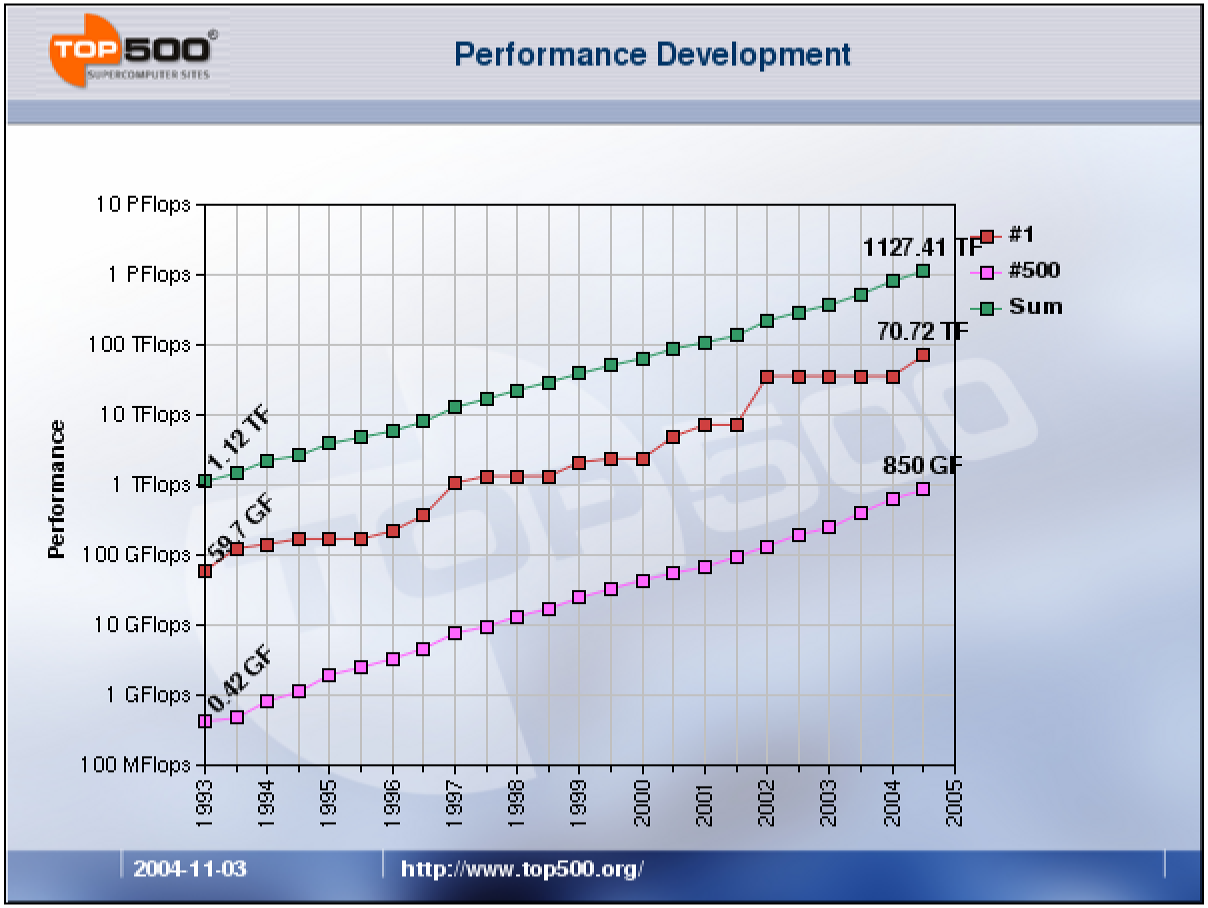
- Each word occupies about 3 square Angstroms, the size of a very small atom
- Maybe someday, but it most certainly isn't going to involve transistors as we know them

What is Parallel Computing?

- Dividing a task among multiple processors to arrive at a unified (meaningful) solution
  - For today, we will focus on systems with many processors executing identical code
- How is this different from Multiprogramming (which we've touched on some in this course)?
- How is this different from Distributed Computing?

Recent History

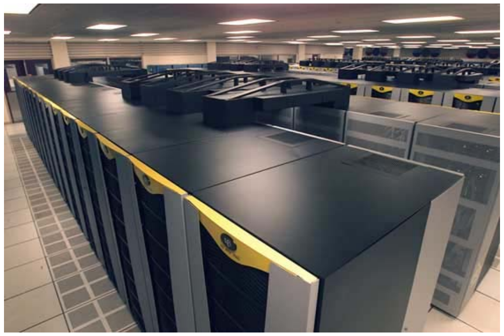
- Parallel Computing as a field exploded in popularity in the mid-1990s
- This resulted in an "arms race" between universities, research labs, and governments to have the fastest supercomputer in the world



Source: top500.org

Current Champions

BlueGene/L – IBM/DOE
Rochester, United States
32768 Processors, 70.72 Tflops/sec
0.7 GHz PowerPC 440



Columbia – NASA/Ames
Mountain View, United States
10160 Processors, 51.87 Tflops/sec
1.5 GHz SGI Altix

Earth Simulator – Earth Simulator Ctr.
Yokohama, Japan
5120 Processors, 35.86 Tflops/sec
SX6 Vector

Data Source: top500.org

Administrivia

- HKN evaluations on Monday
- Last semester's final + solutions online
- Final exam review
  - Sunday, 2005-05-08 @ 2pm in 10 Evans
- Final exam
  - Tuesday, 2005-05-14 @ 12:30-3:30pm in 220 Hearst Gym
  - Same rules as Midterm, except you get 2 double-sided handwritten review sheets (1 from your midterm, 1 new one)
    + green sheet [Don't bring backpacks]
    + swim trunks (TAs only)

Parallel Programming

- Processes and Synchronization
- Processor Layout
- Other Challenges
  - Locality
  - Finding parallelism
  - Parallel Overhead
  - Load Balance

Processes

- We need a mechanism to intelligently split the execution of a program
- Fork:

```
int main(...){
  int pid = fork();
  if (pid == 0) printf("I am the child.");
  if (pid != 0) printf("I am the parent.");
  return 0;
}
```

- What will this print?

Processes (2)

- We don't know! Two potential orderings:
  - I am the child.I am the parent.
  - I am the parent.I am the child.
  - This situation is a simple race condition. This type of problem can get far more complicated…
- Modern parallel compilers and runtime environments hide the details of actually calling fork() and moving the processes to individual processors, but the complexity of synchronization remains

Synchronization

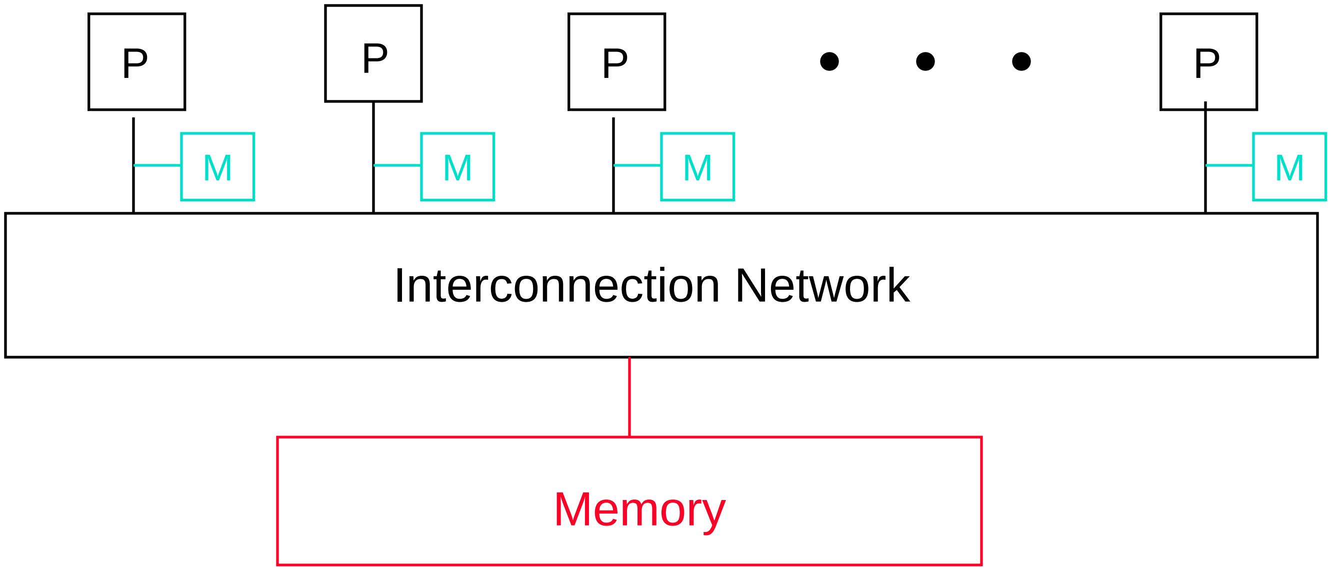
- How do processors communicate with each other?
- How do processors know when to communicate with each other?
- How do processors know which other processor has the information they need?
- When you are done computing, which processor, or processors, have the answer?

Synchronization (2)

- Some of the logistical complexity of these operations is reduced by standard communication frameworks
  - Message Passing Interface (MPI)
- Sorting out the issue of who holds what data can be made easier with the use of explicitly parallel languages
  - Unified Parallel C (UPC)
  - Titanium (Parallel Java Variant)
- Even with these tools, much of the skill and challenge of parallel programming is in resolving these problems

Processor Layout

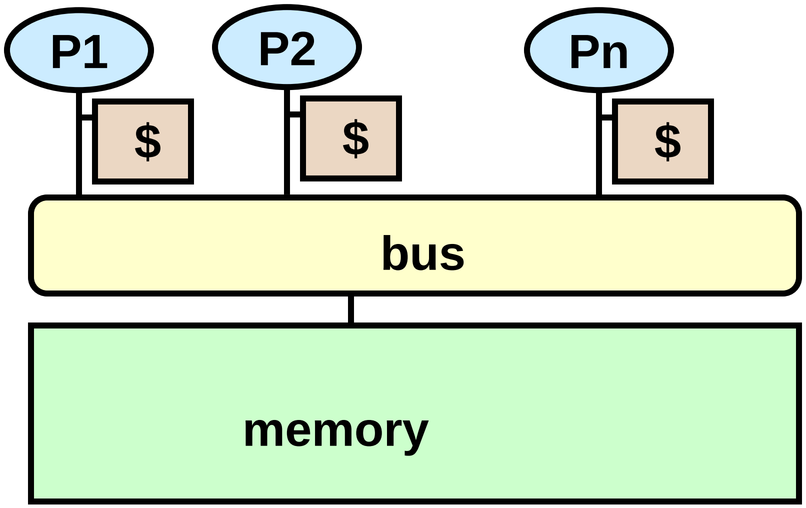
Generalized View



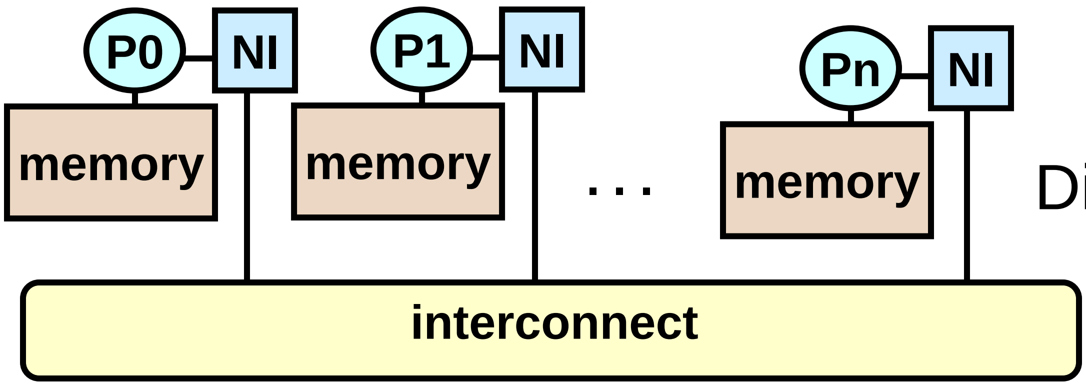
M = Memory local to one processor

Memory = Memory local to all *other* processors

Processor Layout (2)



Shared Memory



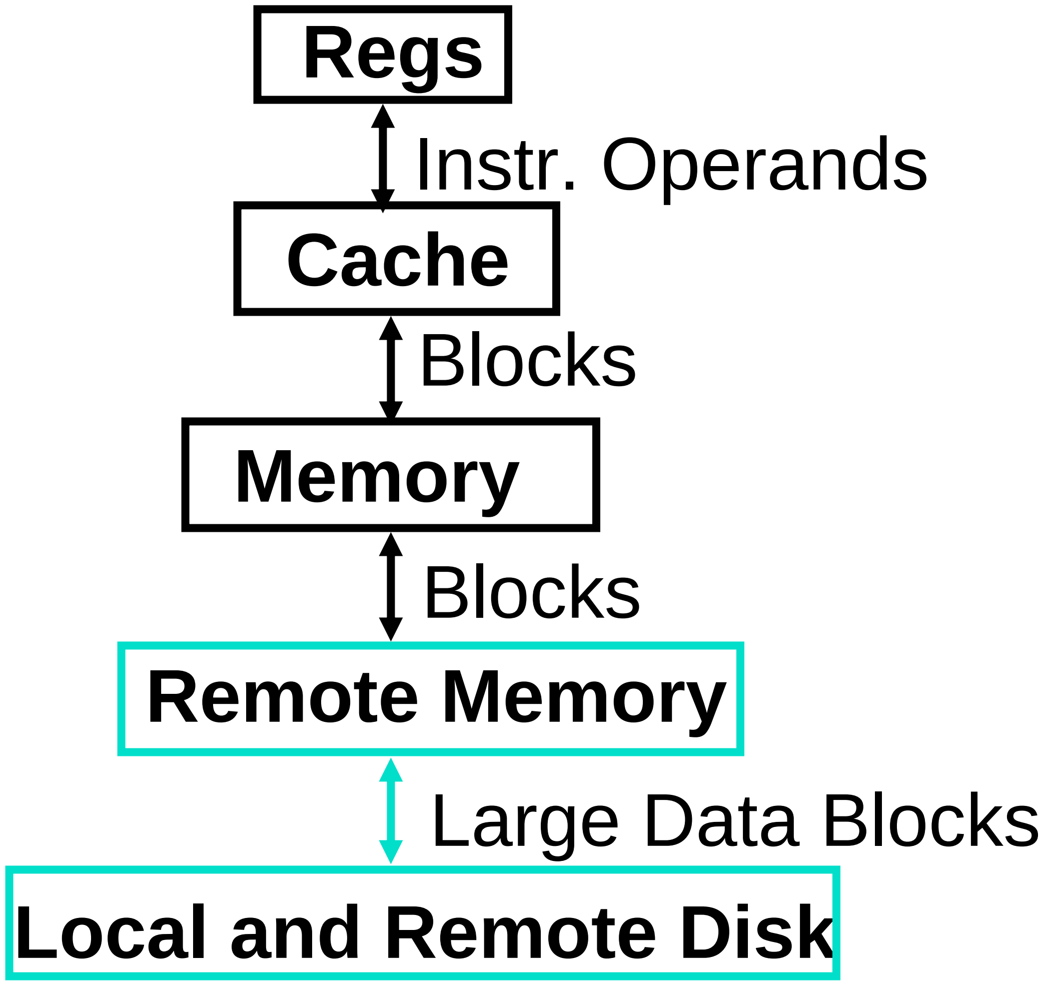
Distributed Memory

Processor Layout (3)

- Clusters of SMPs
  - n of the N total processors share one memory
  - Simple shared memory communication within one cluster of n processors
  - Explicit network-type calls to communicate from one group of n to another
- Understanding the processor layout that your application will be running on is crucial!

Parallel Locality

- We now have to expand our view of the memory hierarchy to include remote machines
- Remote memory behaves like a very fast network
  - Bandwidth vs. Latency becomes important



Amdahl's Law

- **Applications can almost never be completely parallelized**
- **Let s be the fraction of work done sequentially, so (1-s) is fraction parallelizable, and P = number of processors**

$$\text{Speedup}(P) = \text{Time}(1)/\text{Time}(P)$$

$$\le 1/(s + (1-s)/P)$$

$$\le 1/s$$

- **Even if the parallel portion of your application speeds up perfectly, your performance may be limited by the sequential portion**

Parallel Overhead

- Given enough parallel work, these are the biggest barriers to getting desired speedup
- Parallelism overheads include:
  - cost of starting a thread or process
  - cost of communicating shared data
  - cost of synchronizing
  - extra (redundant) computation
- Each of these can be in the range of milliseconds (many millions of flops) on some systems
- Tradeoff: Algorithm needs sufficiently large units of work to run fast in parallel (I.e. large granularity), but not so large that there is not enough parallel work

Load Balance

- Load imbalance is the time that some processors in the system are idle due to
  - insufficient parallelism (during that phase)
  - unequal size tasks
- Examples of the latter
  - adapting to “interesting parts of a domain”
  - tree-structured computations
  - fundamentally unstructured problems
- Algorithms need to carefully balance load

Summary

- Parallel Computing is a multi-billion dollar industry driven by interesting and useful scientific computing applications
- It is extremely unlikely that sequential computing will ever again catch up with the processing power of parallel systems
- Programming parallel systems can be extremely challenging, but is built upon many of the concepts you've learned this semester in 61c