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CSC 447: Parallel Programming for Multi-Core and Cluster Systems

Parallel Programming Drivers

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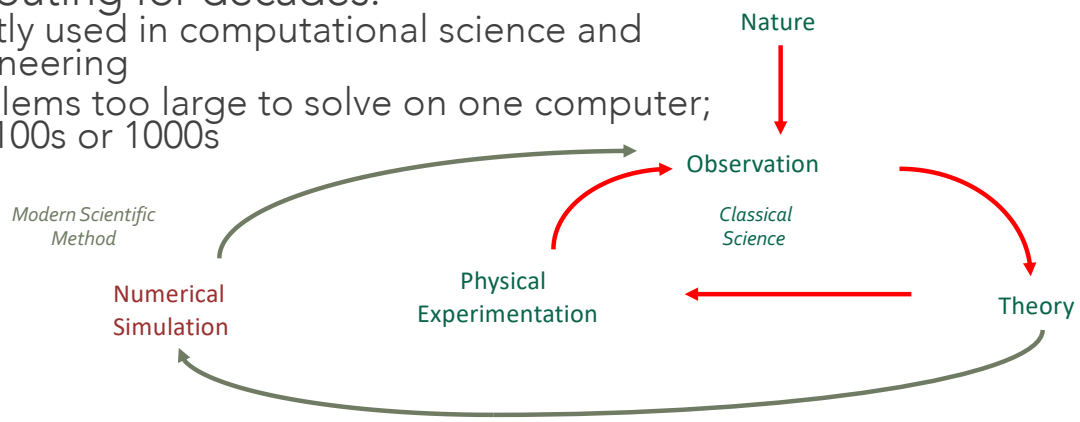
Why Parallel Computing Now?

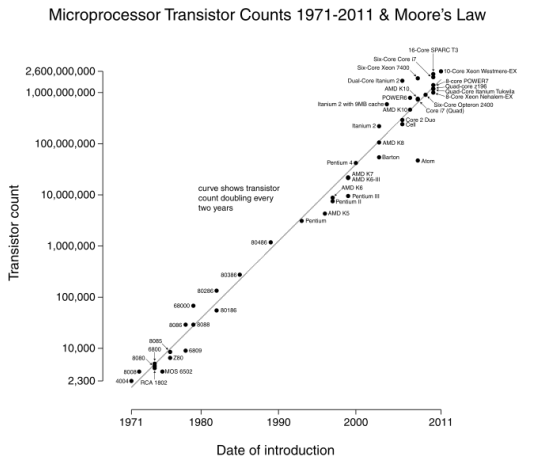
- Researchers have been using parallel computing for decades:
  - Mostly used in computational science and engineering
  - Problems too large to solve on one computer; use 100s or 1000s



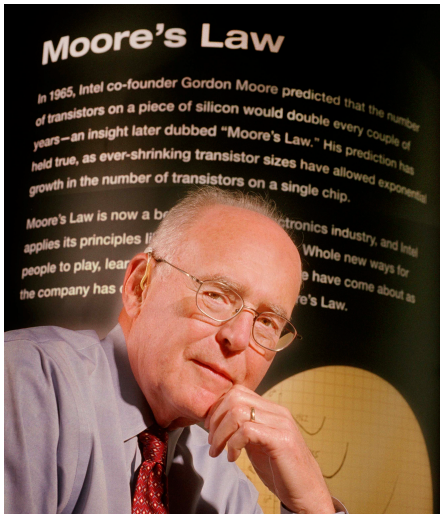
Why Parallel Computing Now?

- Many companies in the 80s/90s "bet" on parallel computing and failed
  - Computers got faster too quickly for there to be a large market
- Why an undergraduate course on parallel programming?
  - Because the entire computing industry has bet on parallelism
  - There is a desperate need for parallel programmers
- There are 3 ways to improve performance:
  - Work Harder
  - Work Smarter
  - Get Help
- Computer Analogy
  - Using faster hardware
  - Optimized algorithms and techniques used to solve computational tasks
  - Multiple computers to solve a particular task

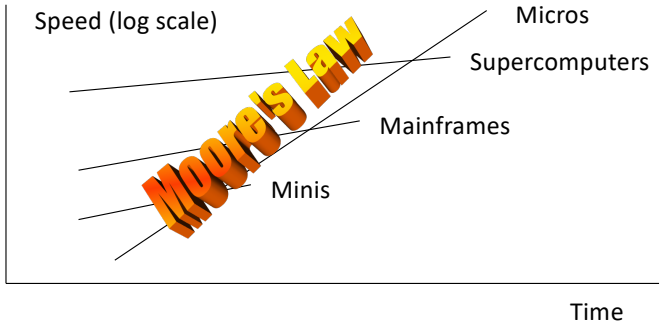
Technology Trends: Microprocessor Capacity



Gordon Moore (co-founder of Intel) predicted in 1965 that the transistor density of semiconductor chips would double roughly every 18 months.

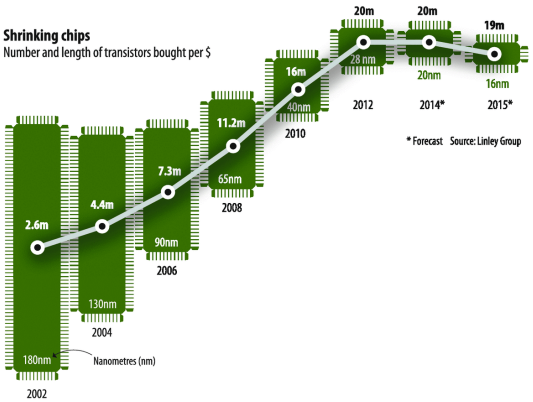


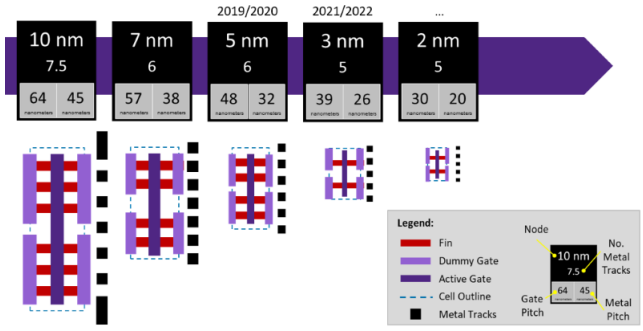
Technology Trends: Microprocessor Capacity



Microprocessors have become smaller, denser, and more powerful.

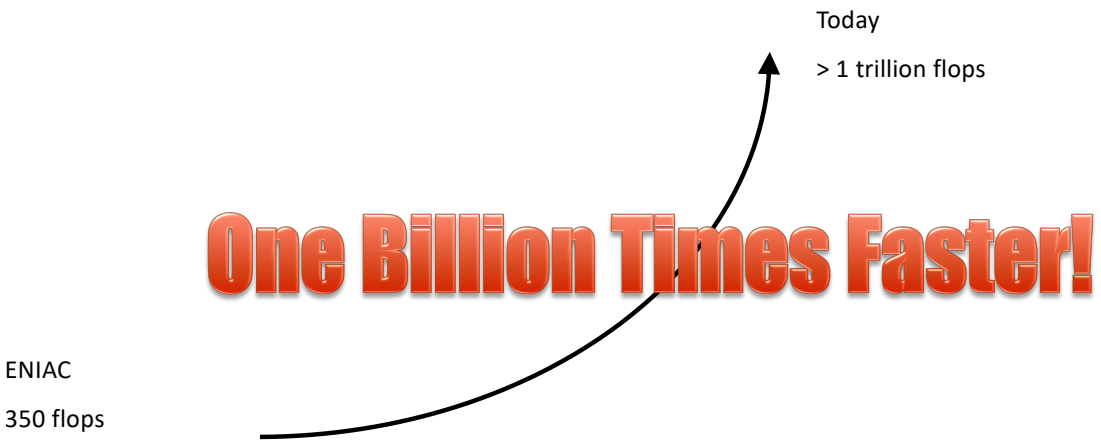
Technology Trends: Microprocessor Capacity





Microprocessors have become smaller, denser, and more powerful.

50 Years of Speed Increases



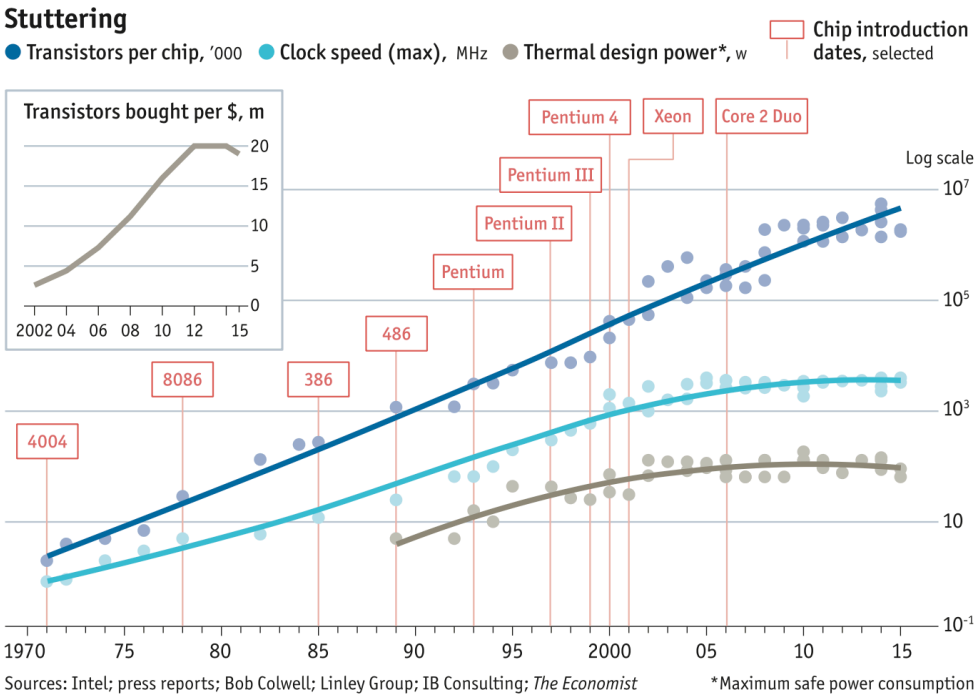
CPUs 1 Million Times Faster

- Faster clock speeds
- Greater system concurrency
  - Multiple functional units
  - Concurrent instruction execution
  - Speculative instruction execution

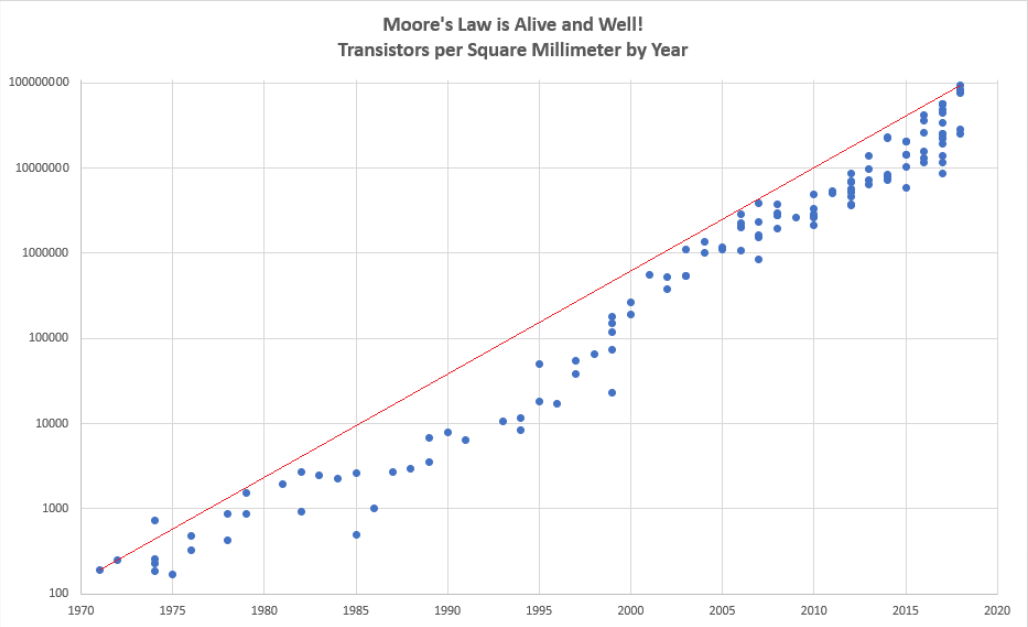
Systems 1 Billion Times Faster

- Processors are 1 million times faster
- Combine thousands of processors
- Parallel computer
  - Multiple processors
  - Supports parallel programming
- Parallel computing = Using a parallel computer to execute a program faster

Microprocessor Transistors and Clock Rate

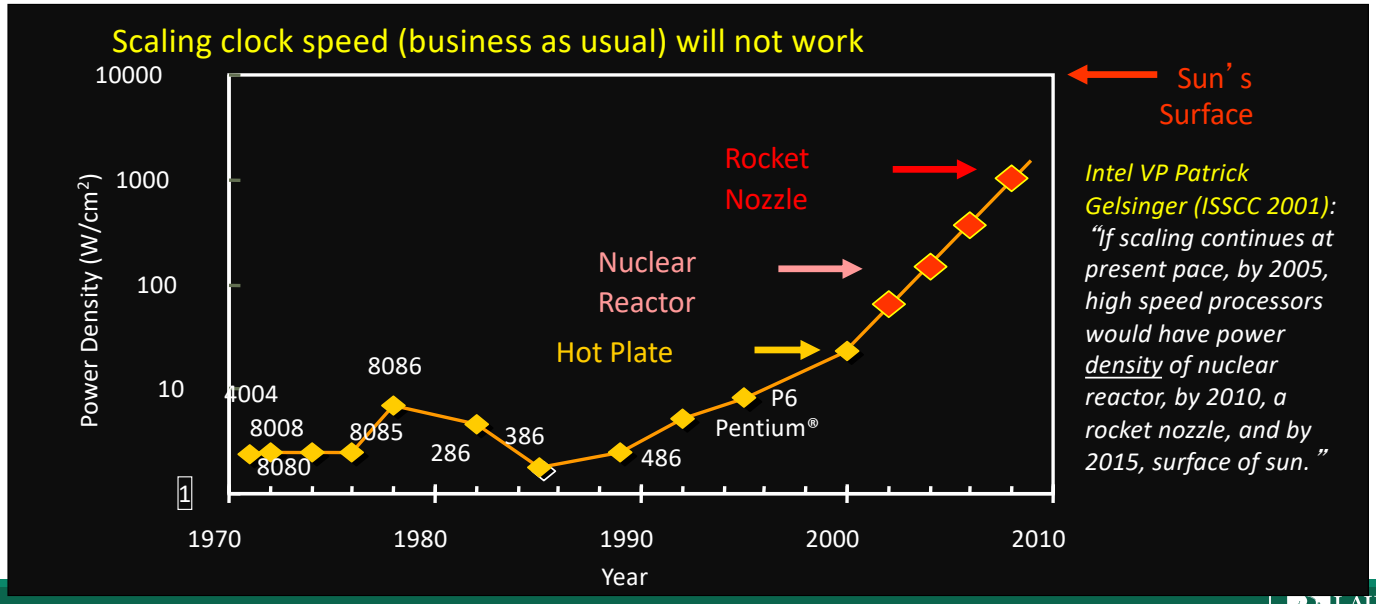


Microprocessor Transistors and Clock Rate



Why bother with parallel programming?
Just wait a year or two...

Limit #1: Power density



Parallelism Saves Power

- Exploit explicit parallelism for reducing power

  Power = (C * V² * F)/4 Performance = (Cores * F)*1

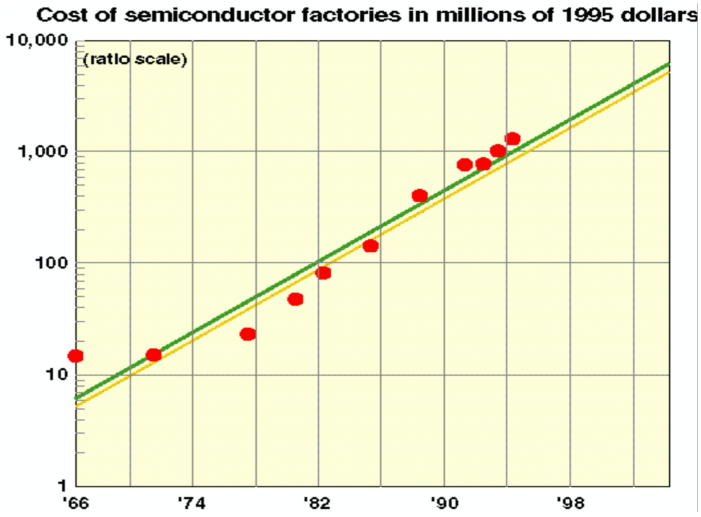
  Capacitance Voltage Frequency

- Using additional cores
  - Increase density (= more transistors = more capacitance)
  - Can increase cores (2x) and performance (2x)
  - Or increase cores (2x), but decrease frequency (1/2): same performance at ¼ the power
- Additional benefits
  - Small/simple cores → more predictable performance

Limit #2: Hidden Parallelism Tapped Out

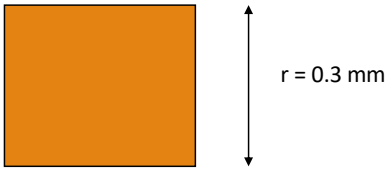
- Superscalar (SS) designs were the state of the art; many forms of parallelism not visible to programmer
  - Multiple instruction issue
  - Dynamic scheduling: hardware discovers parallelism between instructions
  - Speculative execution: look past predicted branches
  - Non-blocking caches: multiple outstanding memory ops
- Unfortunately, these sources have been used up

Limit #3: Manufacturing costs and yield problems limit use of density



- Moore's (Rock's) 2nd law: fabrication costs go up
- Yield (% usable chips) drops
- Parallelism can help
  - More smaller, simpler processors are easier to design and validate
  - Can use partially working chips:
  - E.g., Cell processor (PS3) is sold with 7 out of 8 "on" to improve yield

Limit #4: Speed of Light (Fundamental)



- Consider the 1 Tflop/s sequential machine:
  - Data must travel some distance, r, to get from memory to CPU.
  - To get 1 data element per cycle, this means 1012 times per second at the speed of light, c = 3x108 m/s.
    - Thus r < c/1012 = 0.3 mm.
- Now put 1 Tbyte of storage in a 0.3 mm x 0.3 mm area:
  - Each bit occupies about 1 square Angstrom, or the size of a small atom.
- No choice but parallelism

Parallel Programming Workflow

- Identify compute intensive parts of an application
- Adopt scalable algorithms
- Optimize data arrangements to maximize locality
- Performance Tuning
- Pay attention to code portability and maintainability

So what is the problem?

Writing (fast) parallel programs is hard!

Principles of Parallel Computing

- Finding enough parallelism (Amdahl's Law)
- Granularity
- Locality
- Load balance
- Coordination and synchronization

All of these things makes parallel programming even harder than sequential programming.

Finding Enough Parallelism (Amdahl's Law)

- Suppose only part of an application seems parallel
- Amdahl's law
  - let s be the fraction of work done sequentially, so (1-s) is fraction parallelizable
  - P = number of processors

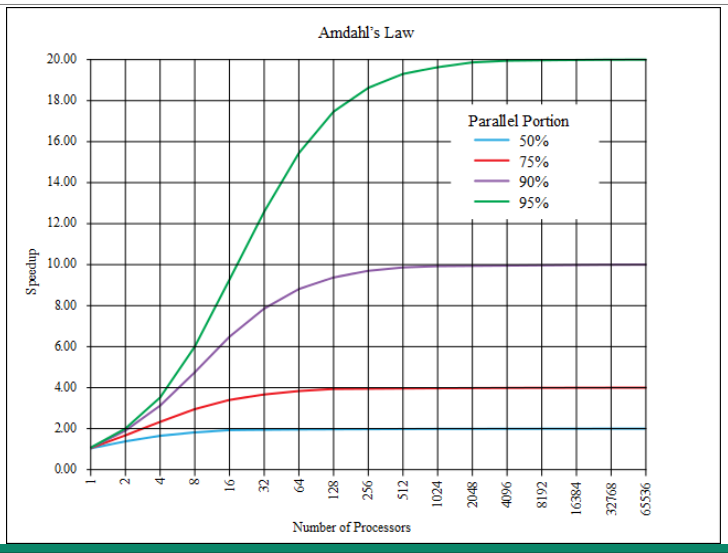
$$\text{Speedup}(P) = \text{Time}(1)/\text{Time}(P)$$

$$<= 1/(s + (1-s)/P)$$

$$<= 1/s$$

- Even if the parallel part speeds up perfectly performance is limited by the sequential part

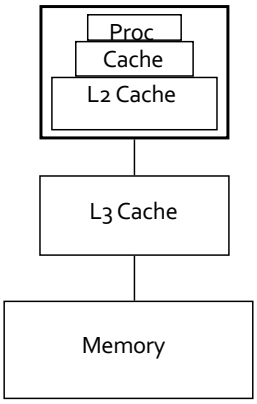
Finding Enough Parallelism (Amdahl's Law)

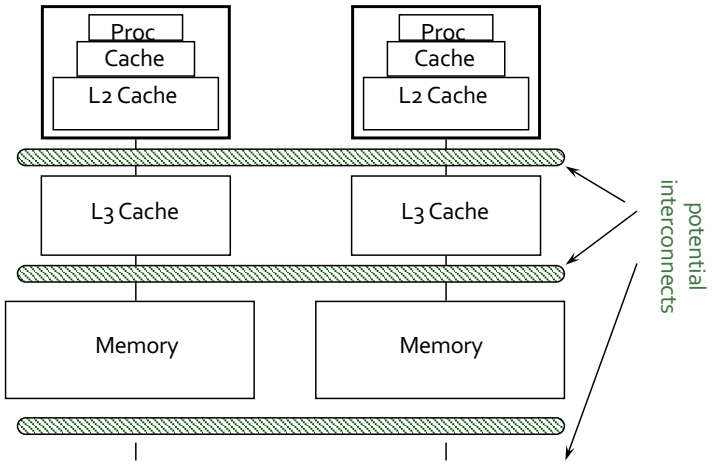


Granularity

- Given enough parallel work, this is the biggest barrier 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 (=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

Conventional Storage Hierarchy





Large memories are slow, fast memories are small

Storage hierarchies are large and fast on average

Parallel processors, collectively, have large, fast cache
- the slow accesses to "remote" data we call "communication"

Algorithm should do most work on local data

Locality

Load Balance/Imbalance

- 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
- Algorithm needs to balance load

Load Balance

Synchronization

- Need to manage the sequence of work and the tasks performing
- Often requires "serialization" of segments of the program
- Various types of synchronization maybe involved
  - Locks/Semaphores
  - Barrier
  - Synchronous Communication Operations

Performance Modeling

- Analyzing and tuning parallel program performance is more challenging than for serial programs.
- There is a need for parallel program performance analysis and tuning.

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So how do we do parallel computing?

Strategy 1: Extend Compilers

- Focus on making sequential programs parallel
- Parallelizing compiler
  - Detect parallelism in sequential program
  - Produce parallel executable program
- Advantages
  - Can leverage millions of lines of existing serial programs
  - Saves time and labor
  - Requires no retraining of programmers
  - Sequential programming easier than parallel programming
- Disadvantages
  - Parallelism may be irretrievably lost when programs written in sequential languages
  - Performance of parallelizing compilers on broad range of applications still up in air

Strategy 2: Extend Language

- Add functions to a sequential language
  - Create and terminate processes
  - Synchronize processes
  - Allow processes to communicate
- Advantages
  - Easiest, quickest, and least expensive
  - Allows existing compiler technology to be leveraged
  - New libraries can be ready soon after new parallel computers are available
- Disadvantages
  - Lack of compiler support to catch errors
  - Easy to write programs that are difficult to debug

Strategy 3: Add a Parallel Programming Layer

- Lower layer
  - Core of computation
  - Process manipulates its portion of data to produce its portion of result
- Upper layer
  - Creation and synchronization of processes
  - Partitioning of data among processes
- A few research prototypes have been built based on these principles

Strategy 4: Create a Parallel Language

- Develop a parallel language "from scratch"
  - occam is an example
- Add parallel constructs to an existing language
  - Fortran 90
  - High Performance Fortran
  - C*
- Advantages
  - Allows programmer to communicate parallelism to compiler
  - Improves probability that executable will achieve high performance
- Disadvantages
  - Requires development of new compilers
  - New languages may not become standards
  - Programmer resistance