Sources of Parallelism

- **Statements**
  - called “control parallel”
  - can perform a series of steps in parallel
  - basis of dataflow computers

- **Loops**
  - called “data parallel”
  - most common source of parallelism
  - each processor gets one (or more) iterations to perform
Applications

- **Easy (embarrassingly parallel)**
  - multiple independent jobs (i.e..., different simulations)

- **Scientific**
  - linear algebra
  - particle simulations

- **Databases**
  - biggest success of parallel computing
  - exploits semantics of relational calculus

- **AI**
  - search problems
  - pattern recognition and image processing (main SIMD use)
Issues in Application Performance

- **Speedup**
  - ratio of time on n nodes to time on a single node
  - hold problem size fixed
  - should really compare to best serial time
  - goal is linear speedup
  - super-linear speedup is possible due to:
    - adding more memory
    - search problems

- **Iso-Speedup**
  - scale data size up with number of nodes
  - goal is a flat horizontal curve

- **Amdahl's Law**
  - max speedup is $1/(\text{serial fraction of time})$

- **Computation to Communication Ratio**
  - goal is to maximize this ratio
How to Write Parallel Programs

- **Use old serial code**
  - compiler converts it to parallel
  - called the dusty deck problem

- **Serial Language plus Communication Library**
  - no compiler changes required!
  - PVM and MPI use this approach

- **New language for parallel computing**
  - requires all code to be re-written
  - hard to create a language that provides performance on different platforms

- **Hybrid Approach**
  - HPF - add data distribution commands to code
  - add parallel loops and synchronization operations
Application Example - Weather

- **Typical of many scientific codes**
  - computes results for three dimensional space
  - compute results at multiple time steps
  - uses equations to describe physics/chemistry of the problem
  - grids are used to discretize continuous space
    - granularity of grids is important to speed/accuracy

- **Simplifications (for example, not in real code)**
  - earth is flat (no mountains)
  - earth is round (poles are really flat, earth buldges at equator)
  - second order properties
Grid Points

- **Divide Continuous space into discrete parts**
  - for this code, grid size is fixed and uniform
    - possible to change grid size or use multiple grids
  - use three grids
    - two for latitude and longitude
    - one for elevation
    - Total of $M \times N \times L$ points

- **Design Choice: where is the grid point?**
  - left, right, or center of the grid
    - in multiple dimensions this multiples:
      - for 3 dimensions have 27 possible points
Variables

- **One dimensional**
  - m - geo-potential (gravitational effects)

- **Two dimensional**
  - pi - “shifted” surface pressure
  - sigmadot - vertical component of the wind velocity

- **Three dimensional (primary variables)**
  - <u,v> - wind velocity/direction vector
  - T - temperature
  - q - specific humidity
  - p - pressure

- **Not included**
  - clouds
  - precipitation
  - can be derived from others
Serial Computation

- Convert equations to discrete form
- Update from time \( t \) to \( t + \Delta t \)

```plaintext
foreach longitude, latitude, altitude
    \( u_{\text{star}}[i,j,k] = n * p[i,j] * u[i,j,k] \)
    \( v_{\text{star}}[i,j,k] = m[j] * p[i,j] * v[i,j,k] \)
    \( s_{\text{dot}}[i,j,k] = p[i,j] * \sigma_{\text{dot}}[i,j] \)
end

foreach longitude, latitude, altitude
    \[ D = 4 * \left( (u_{\text{star}}[i,j,k] + u_{\text{star}}[i-1,j,k]) * (q[i,j,k] + q[i-1,j,k]) + \right. \]
    \[ \text{terms in } \{i,j,k\}\{+,-\}\{1,2\} \]
    \( p_{\text{iq}}[i,j,k] = p_{\text{iq}}[i,j,k] + D * \Delta t \)
    \( \text{similar terms for } p_{\text{iu}}, p_{\text{iv}}, p_{\text{iT}}, \text{and } p \)
end

foreach longitude, latitude, altitude
    \( q[i,j,k] = p_{\text{iq}}[i,j,k]/\pi_{\text{iq}}[i,j,k] \)
    \( u[i,j,k] = p_{\text{iu}}[i,j,k]/\pi_{\text{iu}}[i,j,k] \)
    \( v[i,j,k] = p_{\text{iv}}[i,j,k]/\pi_{\text{iv}}[i,j,k] \)
    \( T[i,j,k] = p_{\text{iT}}[i,j,k]/\pi_{\text{iT}}[i,j,k] \)
end
```


Shared Memory Version

- in each loop nest, iterations are independent
- use a parallel for-loop for each loop nest
- synchronize (barrier) after each loop nest
  - this is overly conservative, but works
  - could use a single sync variable per item, but would incur excessive overhead
- potential parallelism is M * N * L
- private variables: D, i, j, k
- Advantages of shared memory
  - easier to get something working (ignoring performance)
- Hard to debug
  - other processors can modify shared data
Distributed Memory Weather

- decompose data to specific processors
  - assign a cube to each processor
    - maximize volume to surface ratio
    - minimizes communication/computation ratio
  - called a <block,block,block> distribution

- need to communicate \( \{i,j,k\}^{+,-}\{1,2\} \) terms at boundaries
  - use send/receive to move the data
  - no need for barriers, send/receive operations provide sync
    - sends earlier in computation too hide comm time

- Advantages
  - easier to debug
  - consider data locality explicitly with data decomposition

- Problems
  - harder to get the code running
Seismic Code

- **Given echo data, compute under sea map**
- **Computation model**
  - designed for a collection of workstations
  - uses variation of RPC model
  - workers are given an independent trace to compute
    - requires little communication
    - supports load balancing (1,000 traces is typical)
- **Performance**
  - max mfops = $O((F \times nz \times B^*)^{1/2})$
  - $F$ - single processor MFLOPS
  - $nz$ - linear dimension of input array
  - $B^*$ - effective communication bandwidth
    - $B^* = B/(1 + BL/w) \approx B/7$ for Ethernet (10msec lat., $w=1400$)
  - real limit to performance was latency **not** bandwidth
Database Applications

- Too much data to fit in memory (or sometimes disk)
  - data mining applications (K-Mart has a 4-5TB database)
  - imaging applications (NASA has a site with 0.25 petabytes)
    • use a fork lift to load tapes by the pallet

- Sources of parallelism
  - within a large transaction
  - among multiple transactions

- Join operation
  - form a single table from two tables based on a common field
  - try to split join attribute in disjoint buckets
    • if know data distribution is uniform its easy
    • if not, try hashing
Speedup in Join parallelism

- Books claims a speed up of $1/p^2$ is possible
  - split each relation into $p$ buckets
    - each bucket is a disjoint subset of the joint attribute
  - each processor only has to consider $N/p$ tuples per relation
    - join is $O(n^2)$ so each processor does $O((N/p)^2)$ work
    - so speedup is $O(N^2/p^2)/O(N^2) = O(1/p^2)$

- this is a lie!
  - could split into $1/p$ buckets on one processor
  - time would then be $O(p \times (N/p)^2) = O(N^2/p)$
  - so speedup is $O(N^2/p^2)/O(N^2/p) = O(1/p)$
    - Amdahl's law is not violated
Parallel Search (TSP)

- may appear to be faster than 1/n
  - but this is not really the case either

- Algorithm
  - compute a path on a processor
    - if our path is shorter than the shortest one, send it to the others.
    - stop searching a path when it is longer than the shortest.
  - before computing next path, check for word of a new min path
  - stop when all paths have been explored.

- Why it appears to be faster than 1/n speedup
  - we found the a path that was shorter sooner
  - however, the reason for this is a different search order!
Ensuring a fair speedup

- $T_{\text{serial}} = \text{faster of}$
  - best known serial algorithm
  - simulation of parallel computation
    - use parallel algorithm
    - run all processes on one processor
  - parallel algorithm run on one processor

- If it appears to be super-linear
  - check for memory hierarchy
    - increased cache or real memory may be reason
  - verify order operations is the same in parallel and serial cases
Quantitative Speedup

- **Consider master-worker**
  - one master and \( n \) worker processes
  - communication time increases as a linear function of \( n \)
  \[
  T_p = T_{COMP_p} + T_{COMM_p} 
  \]
  \[
  T_{COMP_p} = \frac{T_s}{P} 
  \]
  \[
  \frac{1}{S_p} = \frac{T_p}{T_s} = \frac{1}{P} + \frac{T_{COMM_p}}{T_s} 
  \]
  \[
  T_{COMM_p} \text{ is } P \times T_{COMM_1} 
  \]
  \[
  \frac{1}{S_p} = \frac{1}{P} + p \times \frac{T_{COMM_1}}{T_s} = \frac{1}{P} + \frac{P}{r_1} 
  \]
  where \( r_1 = \frac{T_s}{T_{COMM_1}} \)
  \[
  \frac{d(1/S_p)}{dP} = 0 \rightarrow P_{opt} = r_1^{1/2} \text{ and } S_{opt} = 0.5 \ r_1^{1/2} 
  \]

- **For hierarchy of masters**
  - \( T_{COMM_p} = (1+\log P)T_{COMM_1} \)
  - \( P_{opt} = r_1 \) and \( S_{opt} = r_1/(1 + \log r_1) \)