Parallel Computing Concepts

What is Parallel Computing?

Does it include:

- super-scalar processing (more than one instruction at once)?
- client/server computing?
- what if RPC calls are non-blocking?
- vector processing (same instruction to several values)?
- collection of PC's not connected to a network?

What is Parallel Computing?

For us, parallel computing requires:

- more than one processing element
- nodes connected to a communication network
- nodes working together to solve a single problem

Why Parallelism?

Speed

- need to get results faster than possible with sequential
  - a weather forecast that is late is useless
- could come from
  - more processing elements (P.E.)
  - more memory (or cache)
  - more disks

Why Parallellism?

Cost

- Cheaper to buy many smaller machines
- This is only recently true due to
  - VLSI
  - Commodity hardware

What Does a Parallel Computer Look Like?

Hardware

- processors
- communication
- memory
- coordination

Software

- programming model
- communication libraries
- operating system

Processing Elements (PE)

A Processing Element (PE) is a unit of usually commodity hardware that is capable of performing computation, usually supported by some amount of memory.

PE’s include processors, core, GPU cores, etc.

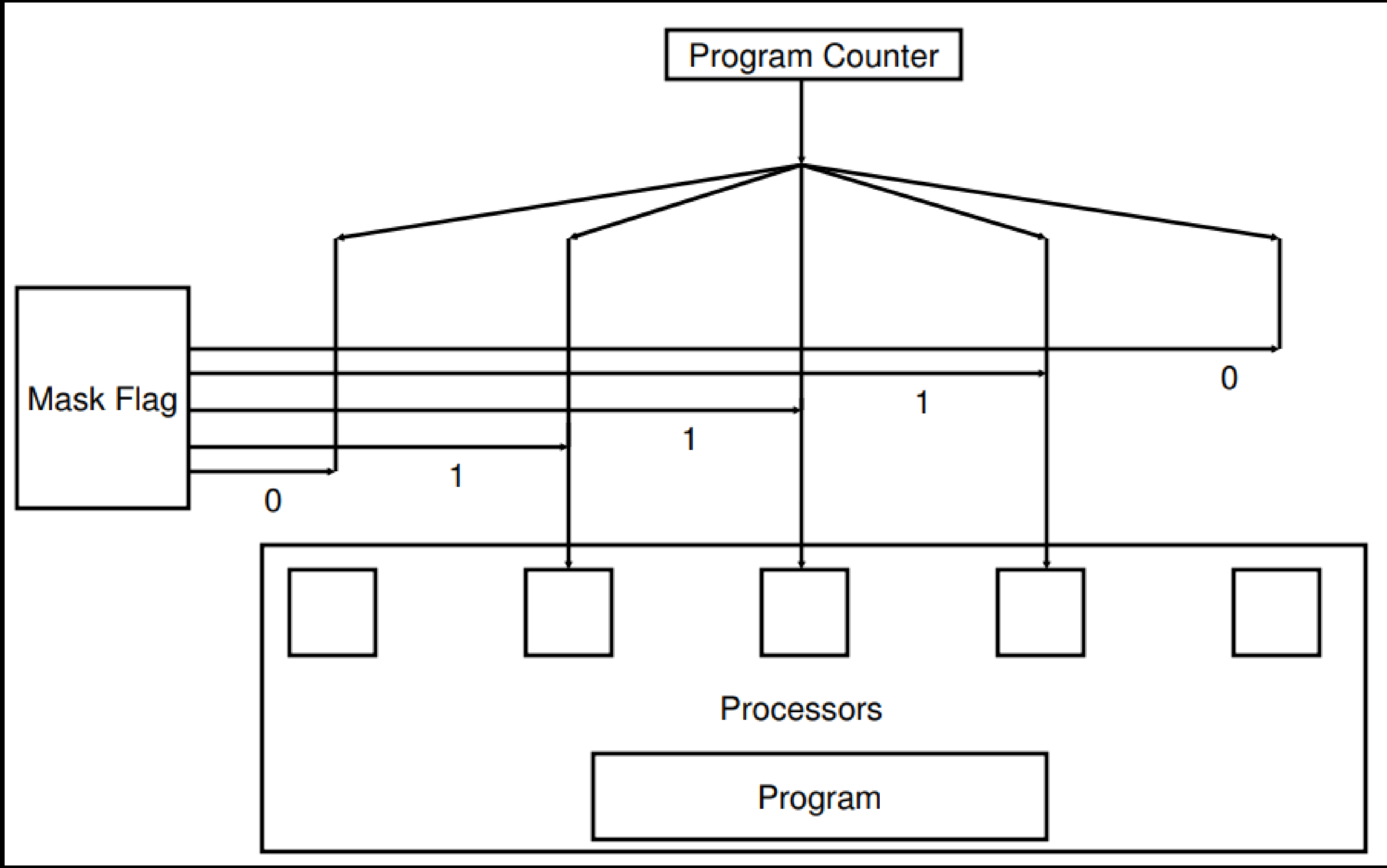
Key Processor Choices

- How many?
- How powerful?
- Custom or off-the-shelf?

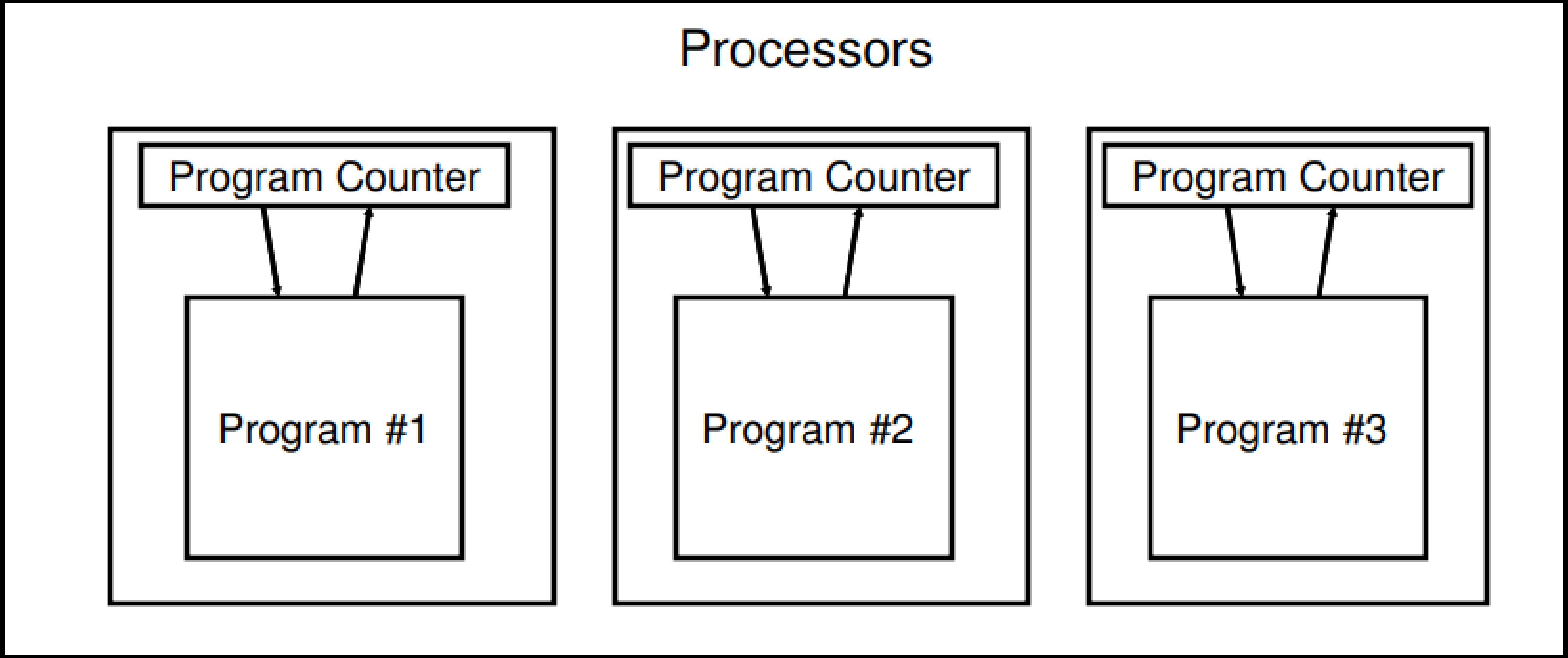
Major Styles of Parallel Computing

- SIMD - Single Instruction Multiple Data
  - one master program counter (PC)
- MIMD - Multiple Instruction Multiple Data
  - separate code for each processor
- SPMD - Single Program Multiple Data
  - same code on each processor, separate PC's on each
- Dataflow - instruction waits for operands
  - "automatically" finds parallelism

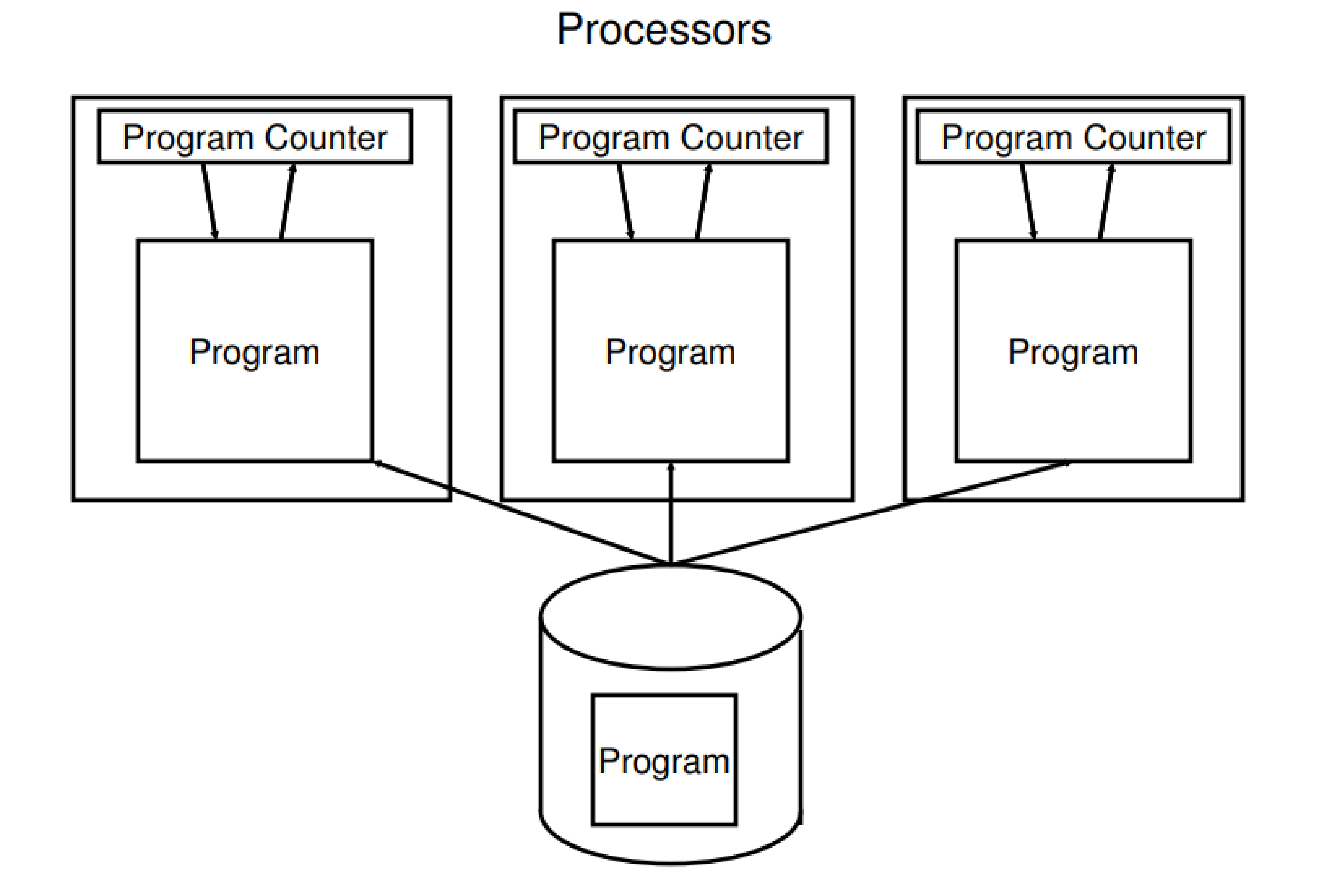
SIMD



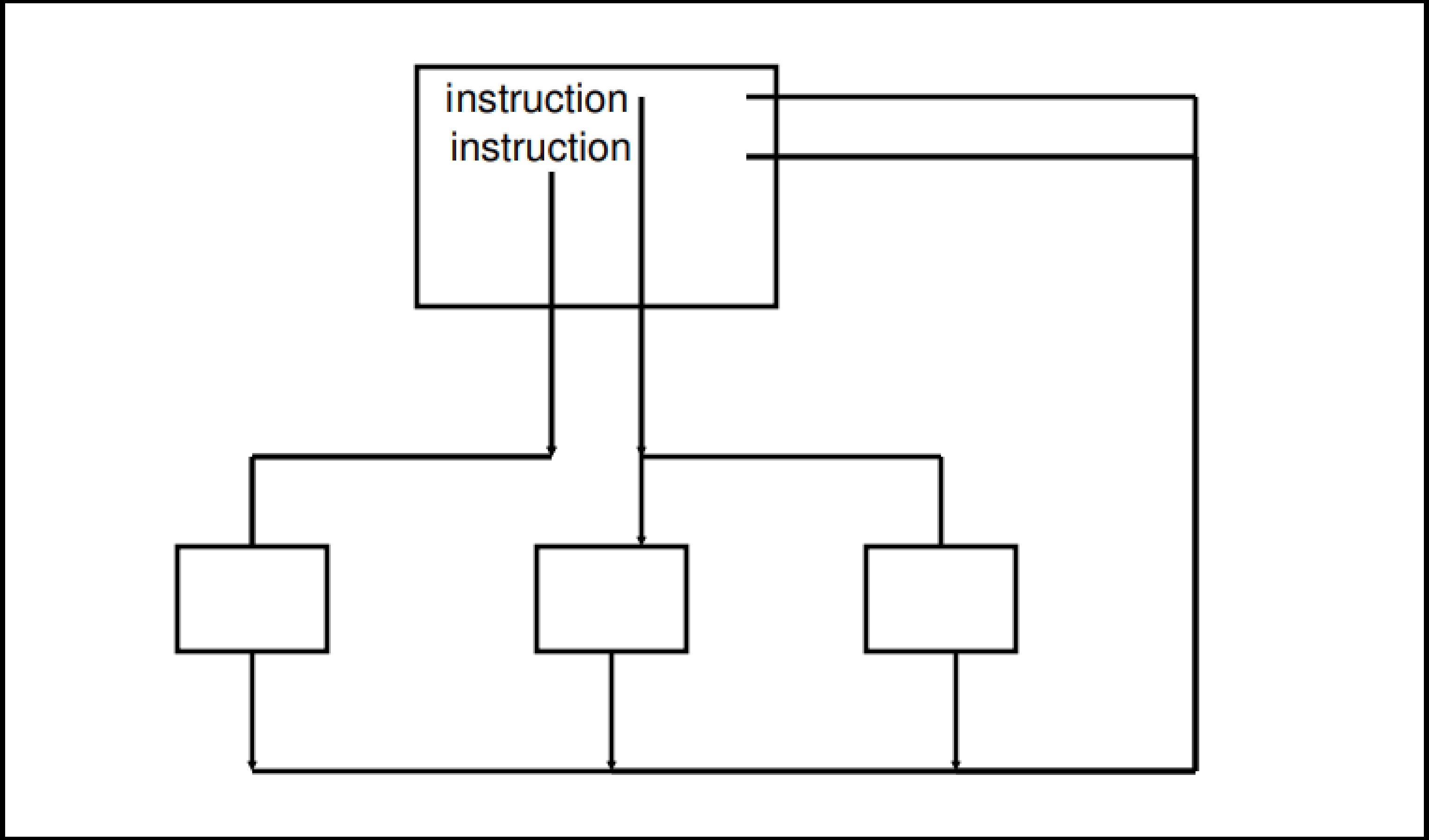
MIMD


Processors
Program Counter
Program #1
Program Counter
Program #2
Program Counter
Program #3

SPMD


Processors
Program Counter
Program
Program Counter
Program
Program Counter
Program
Program

Dataflow

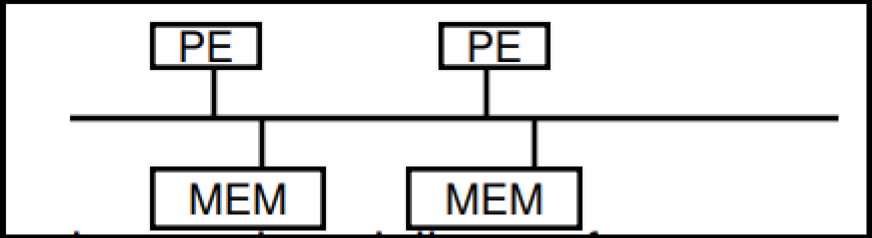


Interconnects

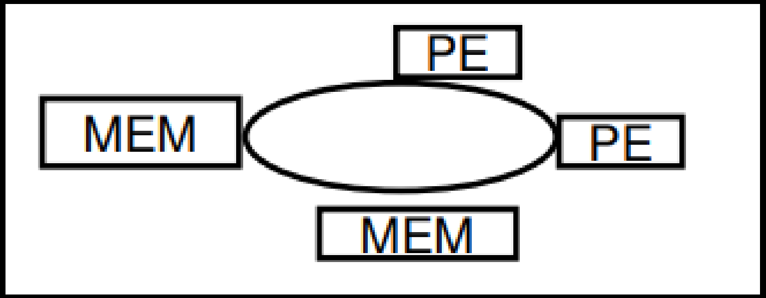
- An interconnect is a communication network used to commect Processing Elements.
- Also allows the Processing Elements to interact with memory, handle I/O, etc.
- The arrangement of PE’s using a communication network is called a “Topology” (not to be confused with topologies in mathematics).
- Key Performance Issues
  - latency: time for first byte
  - throughput: average bytes/second

Topologies

- bus - simple, but doesn't scale

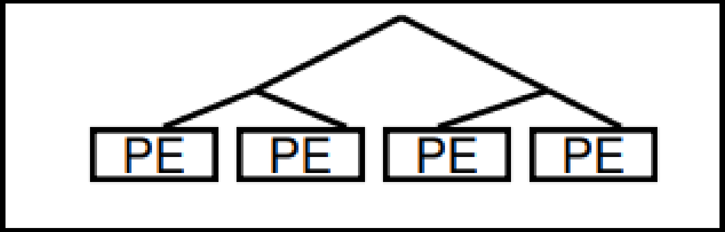


- ring - orders delivery of messages

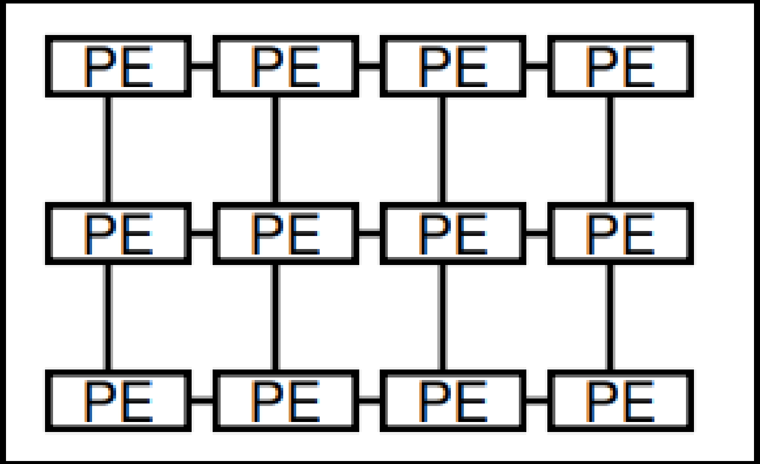


Topologies

- tree - needs to increase bandwidth near the top

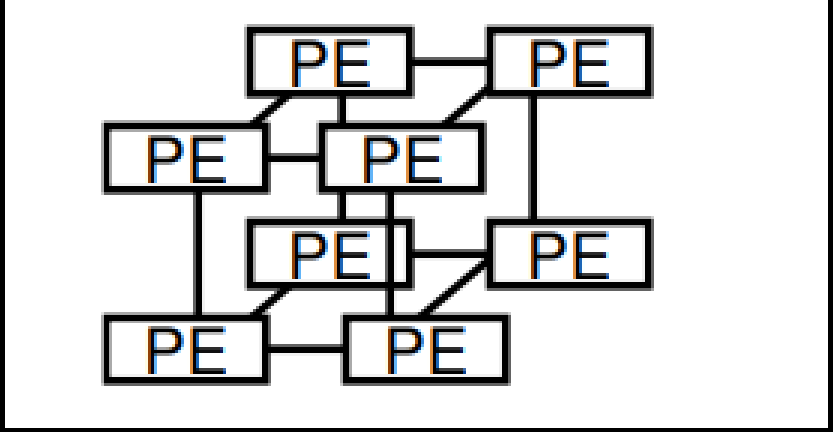


- mesh - two or three dimensions



Topologies

- hypercube - needs a power of number of nodes



Memory Systems

Key Performance Issues

- latency: time for first byte
- throughput: average bytes/second

Design Issues

- Where is the memory
  - divided among each node
  - centrally located (on communication network)
- Access by processors
  - can all processors get to all memory?
  - is the access time uniform?

Coordination

- Synchronization
    - protection of a single object (locks)
    - coordination of processors (barriers)
- Size of a unit of work by a processor
    - need to manage two issues
        - load balance - processors have equal work
        - coordination overhead - communication and sync.
    - often called “grain” size - large grain vs. fine grain

Sources of Parallelism

- Statements
  - called “control parallel”
  - can perform a series of steps in parallel
- Loops
  - called “data parallel”
  - most common source of parallelism
  - each processor gets one (or more) iterations to perform

Examples of Parallelism

- Easy (embarrassingly parallel)
  - multiple independent jobs (i.e..., different simulations)
- Scientific
  - Largest users of parallel computing
  - dense linear algebra (divide up matrix)
  - physical system simulations (divide physical space)
- Databases
  - biggest commerical success of parallel computing (divide tuples)
    - exploits semantics of relational calculus
- Artificial Intelligence
  - search problems (divide search space)
  - pattern recognition and image processing (divide image)

Metrics in Application Performance

Speedup (often call strong scaling)

- 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

Metrics in Application Performance

- Weak Scaling (also called Iso-Speedup)
  - scale data size up with number of nodes
  - goal is a flat horizontal curve
- Amdahl's Law
  - max speedup is 1/(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 (Parallel Virtual Machines)
- 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 * N * 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

Serial Computation

- Convert equations to discrete form
- Update from time t to t + delta t

- You do not need to understand the process here – just get the general idea of vector computations in loops

```
foreach longitude, latitude, altitude
        ustar[i,j,k] = n * pi[i,j] * u[i,j,k]
        vstar[i,j,k] = m[j] * pi[i,j] * v[i,j,k]
        sdot[i,j,k] = pi[i,j] * sigmadot[i,j]
end
foreach longitude, latitude, altitude
        D = 4 * ((ustar[i,j,k] + ustar[i-1,j,k]) * (q[i,j,k]
                + q[i-1,j,k]) + terms in {i,j,k}{+,-}{1,2}
        piq[i,j,k] = piq[i,j,k] + D * delat
        similar terms for piu, piv, piT, and pi
end
foreach longitude, latitude, altitude
        q[i,j,k] = piq[i,j,k]/pi[i,j,k]
        u[i,j,k] = piu[i,j,k]/pi[i,j,k]
        v[i,j,k] = piv[i,j,k]/pi[i,j,k]
        T[i,j,k] = piT[i,j,k]/pi[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 Version

- 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 communication time
- Advantages
  - easier to debug?
  - consider data locality explicitly with data decomposition
- Problems
  - harder to get the code running

Ensuring a fair speedup

- T_{serial} = 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