Performance Issues

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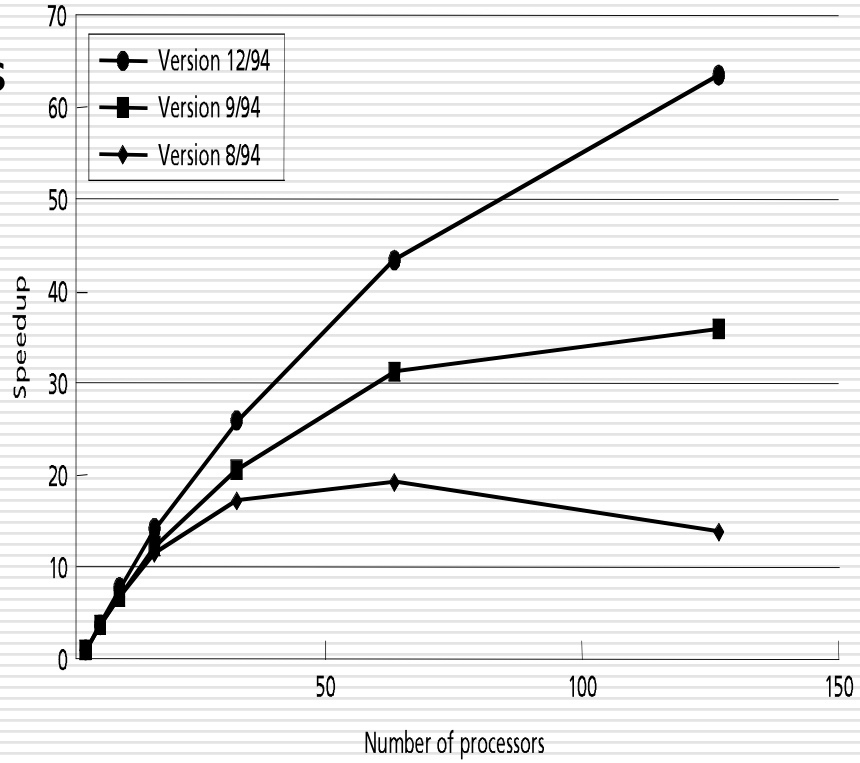
Overview

- Process of creating a parallel program
- Performance issues
- Architectural interactions
  - Three major programming models
  - What primitives must a system support?

Performance Goal: Speedup

- Architect Goal
  - Observe how program uses machine and improve the **design** to enhance performance
- Programmer Goal
  - observe how the program uses the machine and improve the **implementation** to enhance performance
- What do you observe?
- Who fixes what?



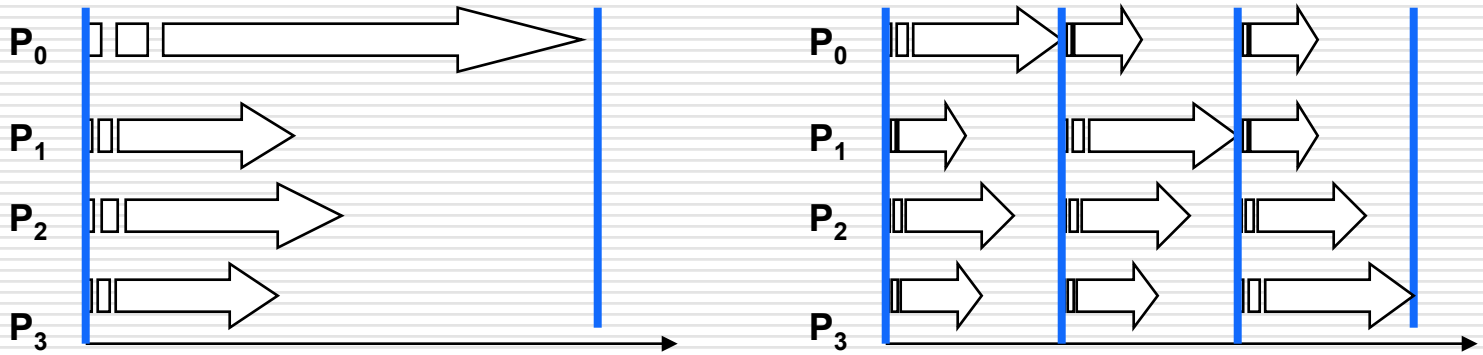
Analysis Framework

$$\text{Speedup} < \frac{\text{Sequential Work}}{\textit{Max}\ (\text{Work} + \text{Synch Wait Time} + \text{Comm Cost} + \text{Extra Work})}$$

- Communication and load balance NP-hard in general
  - Heuristic solutions work well in practice
- Fundamental Tension among:
  - Balanced load
  - Minimal synchronization
  - Minimal communication
  - Minimal extra work
- Good machine design mitigates the trade-offs

Load Balance and Synchronization

$$\text{Speedup}_{\text{problem}}(p) \leq \frac{\text{Sequential Work}}{\textit{Max}\ \text{Work on any Processor}}$$

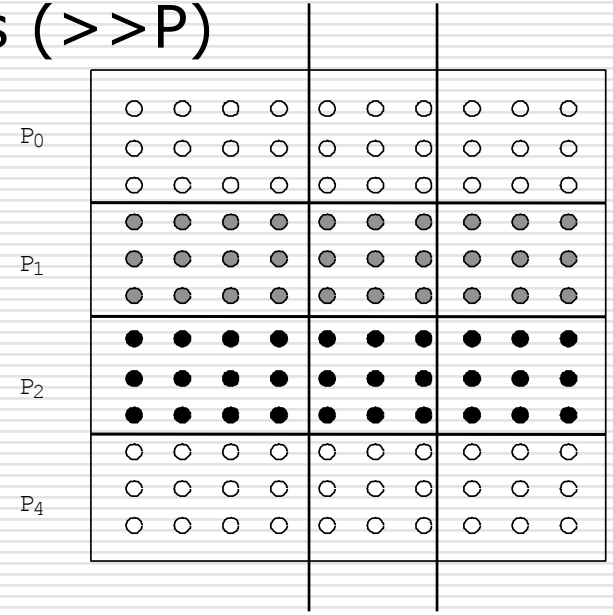


- Instantaneous load imbalance revealed as wait time
  - at completion
  - at barriers
  - at receive
  - at flags, even at mutex

$$\frac{\text{Sequential Work}}{\textit{Max}\ (\text{Work} + \text{Synch Wait Time})}$$

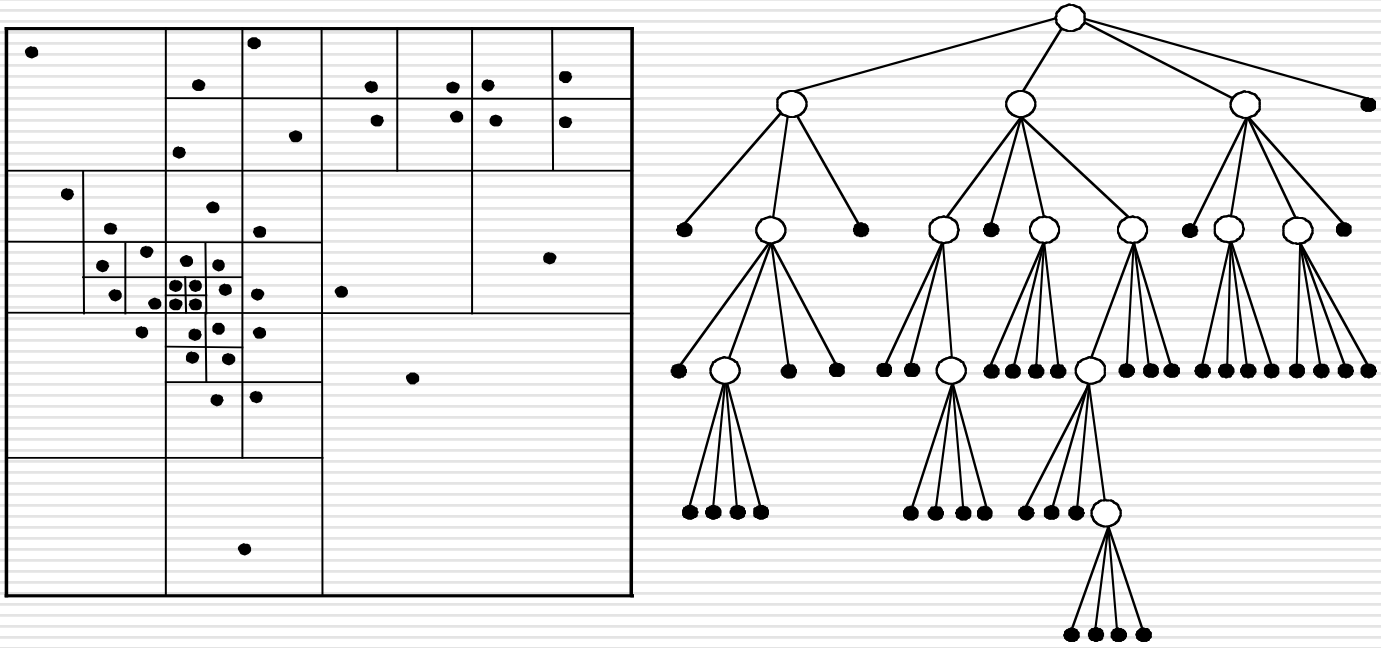
Improving Load Balance

- Decompose into more smaller tasks (>>P)
- Distribute uniformly
  - Variable-sized task
  - Randomize
  - Bin packing
  - Dynamic assignment
- Schedule more carefully
  - Avoid serialization
  - Estimate work
  - Use history info.




```
for_all i = 1 to n do
    for_all j = i to n do
        A[ i, j ] = A[i-1, j] + A[i, j-1] + ...
```

Example: Barnes-Hut



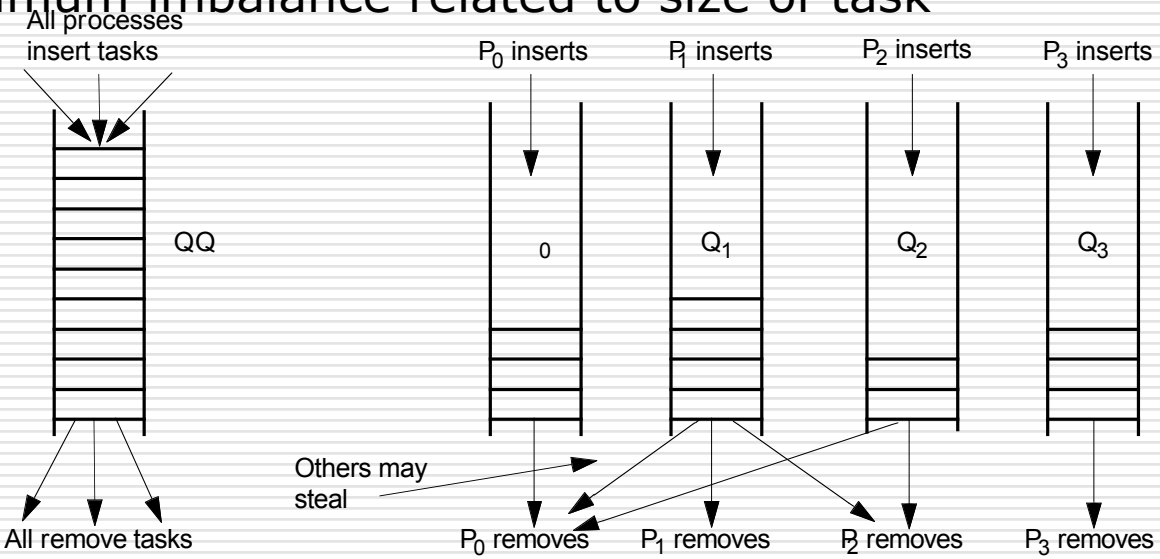
(a) The spatial domain

(b) Quadtree representation

- Divide space into roughly equal # particles
- Particles close together in space -> same processor
- Nonuniform, dynamically changing

Dynamic Scheduling: Task Queues

- Centralized versus distributed queues
- Task stealing with distributed queues
  - Compromise comm & locality, increase synchronization
  - Whom to steal from, how many tasks to steal, when done...
  - Maximum imbalance related to size of task

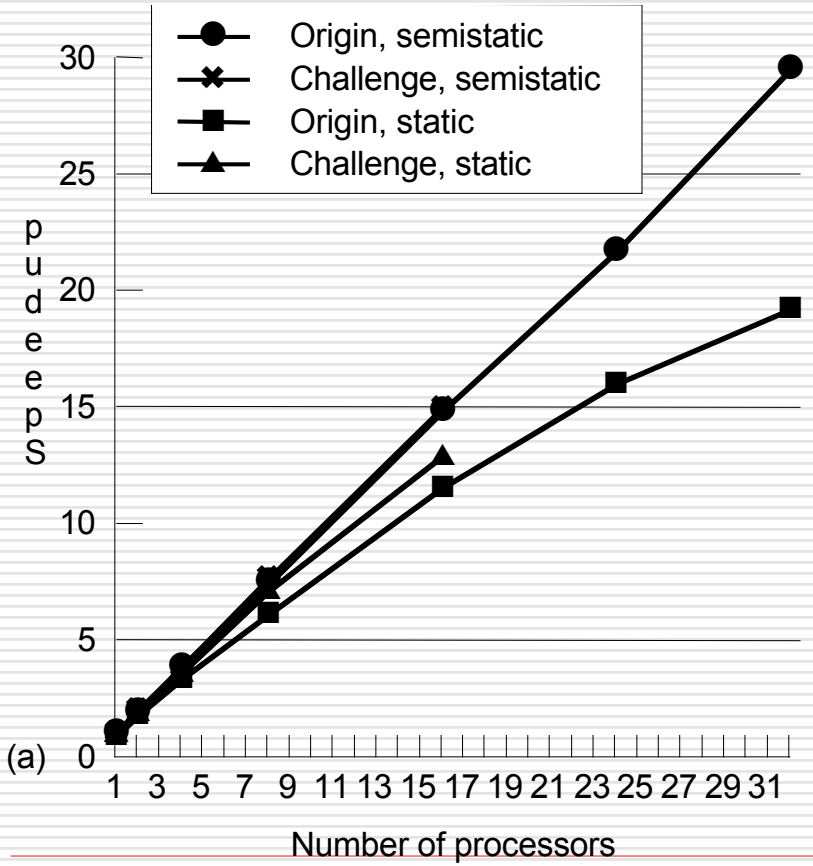


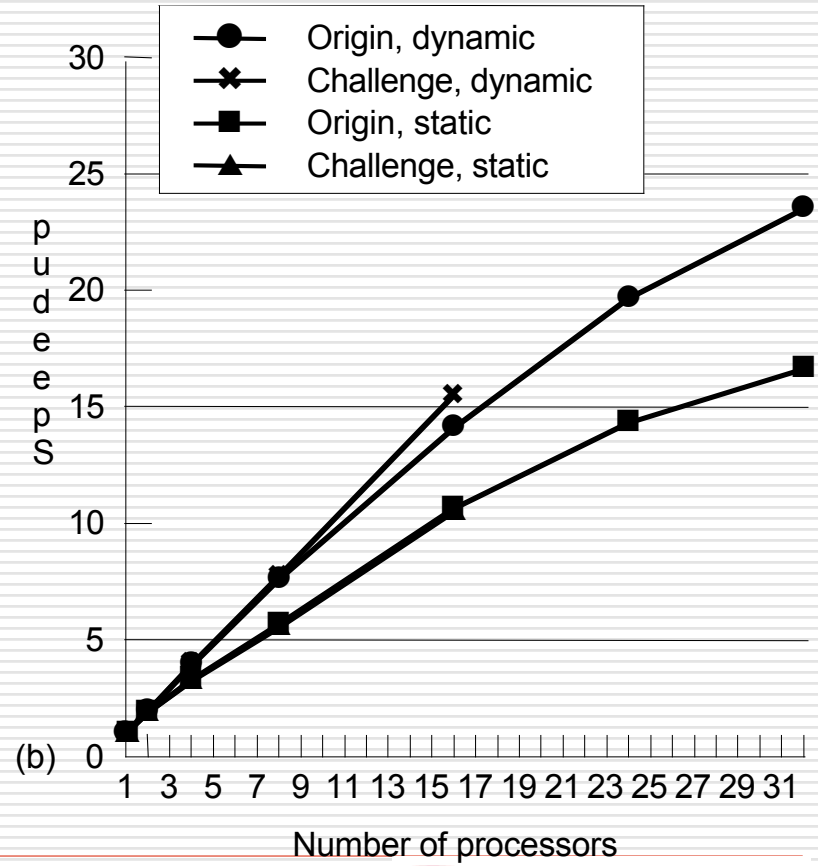
(a) Centralized task queue

(b) Distributed task queues (one per pr ocess)

Impact of Dynamic Assignment

- Barnes-Hut on SGI Origin 2000 (cache-coherent shared memory):





Self-Scheduling

```
volatile int row_index = 0;          /* shared index variable */


while (not done) {
    initialize row_index; barrier;
    while ((i = fetch_and_inc(&row_index) < n) {
        for (j = i; j < n; j++) {
            A[ i, j ] = A[i-1, j] + A[i, j-1] + ...
        }
    }
}
```

Reducing Serialization

- Careful about assignment and orchestration
  - Including scheduling
- Event synchronization
  - Reduce use of conservative synchronization
    - e.g. point-to-point instead of barriers, or granularity of pt-to-pt
  - But fine-grained synch more difficult to program, more synch ops.
- Mutual exclusion
  - Separate locks for separate data
    - e.g. locking records in a database: lock per process, record, or field
    - Lock per task in task queue, not per queue
    - Finer grain => less contention/serialization, more space, less reuse
  - Smaller, less frequent critical sections
    - Don't do reading/testing in critical section, only modification
  - Stagger critical sections in time

Impact of Load Balance Effort

- Parallelism Management overhead?
- Communication?
  - Amount, size, frequency?
- Synchronization?
  - Type? frequency?
- Opportunities for replication?

- What can architecture do?

Arch. Implications of Load Balance

- Naming
  - Global position-independent naming separates decomposition from layout
  - Allows diverse, even dynamic assignments
- Efficient Fine-grained communication & synch
  - More, smaller
    - Msgs
    - Locks
  - Point-to-point
- Automatic replication

Reducing Extra Work

- Common sources of extra work:
  - Computing a good partition
    - e.g. partitioning in Barnes-Hut or sparse matrix
  - Using redundant computation to avoid communication
  - Task, data and process management overhead
    - Applications, languages, runtime systems, OS
  - Imposing structure on communication
    - Coalescing messages, allowing effective naming
- Architectural Implications:
  - Reduce need by making comm. and orchestration efficient

$$\text{Speedup} \leq \frac{\text{Sequential Work}}{\textit{Max}\ (\text{Work} + \text{Synch Wait Time} + \text{Comm Cost} + \text{Extra Work})}$$

Reducing Inherent Communication

$$\text{Speedup} \leq \frac{\text{Sequential Work}}{\textit{Max}\ (\text{Work} + \text{Synch Wait Time} + \text{Comm Cost})}$$

- Communication is expensive!
- Measure: *communication to computation ratio*
- Inherent communication
  - Determined by assignment of tasks to processes
  - One produces data consumed by others

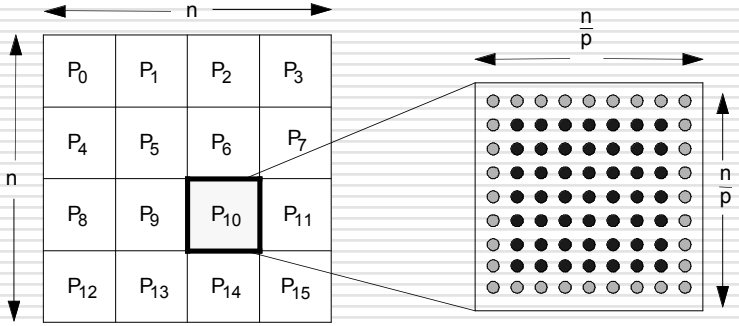
=> Use algorithms that communicate less

=> Assign tasks that access same data to same process

  - same row or block to same process in each iteration

Domain Decomposition

- Works well for scientific, engineering, graphics, ... applications
- Exploits local-biased nature of physical problems
  - Information requirements often short-range
  - Or long-range but fall off with distance
- Simple example: nearest-neighbor grid computation

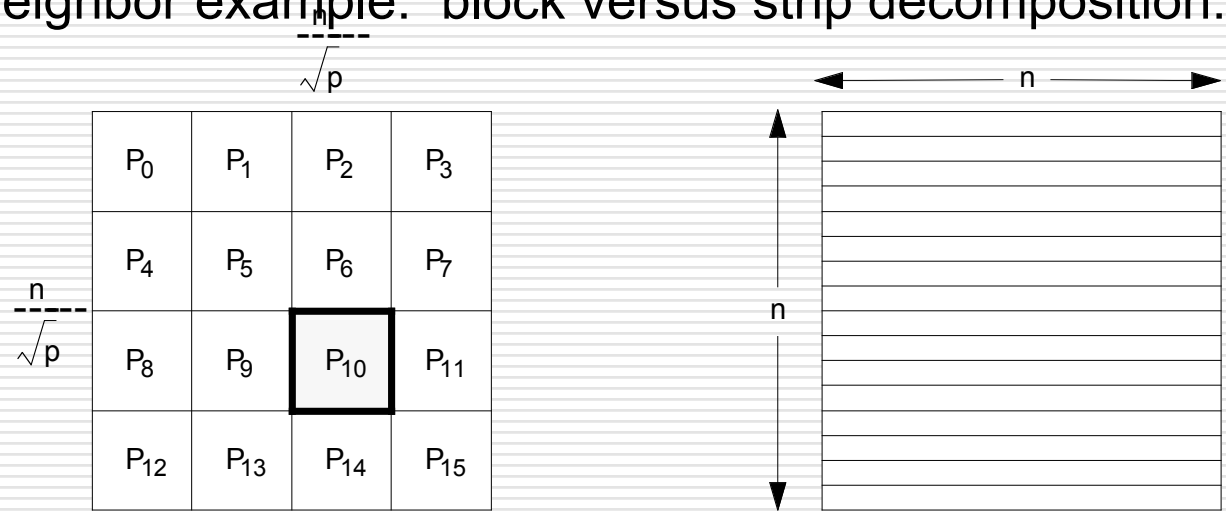


Perimeter to Area comm-to-comp ratio (area to volume in 3-d)

- Depends on *n*,*p*: decreases with *n*, increases with *p*

Domain Decomposition (contd)

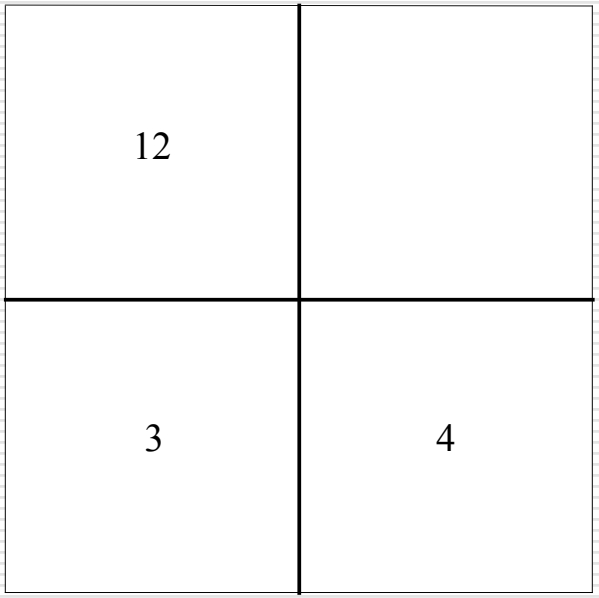
Best domain decomposition depends on information requirements
Nearest neighbor example: block versus strip decomposition:



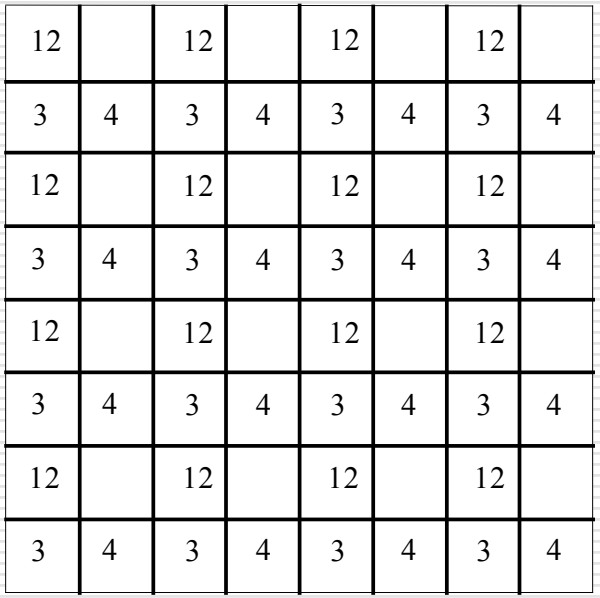
- Comm to comp: $\frac{4*\sqrt{p}}{n}$ for block, $\frac{2*p}{n}$ for strip
- Application dependent: strip may be better in other cases
  - E.g. particle flow in tunnel

Relation to load balance

- Scatter Decomposition, e.g. initial partition in Raytrace



Domain decomposition



Scatter decomposition

Preserve locality in task stealing

- Steal large tasks for locality, steal from same queues, ...

Implications of Comm-to-Comp Ratio

- Architects examine application needs to see where to spend effort
  - bandwidth requirements (operations / sec)
  - latency requirements (sec/operation)
    - time spent waiting
- Actual impact of comm. depends on structure and cost as well
- Need to keep communication balanced across processors as well

$$\text{Speedup\_} < \frac{\text{Sequential Work}}{\textit{Max}\ (\text{Work} + \text{Synch Wait Time} + \text{Comm Cost})}$$

Structuring Communication

- Given amount of comm., goal is to reduce cost
- Cost of communication as seen by process:

$$C = f * (o + l + \frac{n_c/m}{B} + t_c - overlap)$$

  - f = frequency of messages
  - o = overhead per message (at both ends)
  - l = network delay per message
  - n_c = total data sent
  - m = number of messages
  - B = bandwidth along path (determined by network, NI, assist)
  - t_c = cost induced by contention per message
  - *overlap* = amount of latency hidden by overlap with comp. or comm.

- Portion in parentheses is cost of a message (as seen by processor)
  - ignoring overlap, is *latency* of a message
- Goal: reduce terms in latency and increase overlap

Reducing Overhead

- Can reduce no. of messages *m* or overhead per message *o*
- *o* is usually determined by hardware or system software
  - Program should try to reduce m by coalescing messages
  - More control when communication is explicit
- Coalescing data into larger messages:
  - Easy for regular, coarse-grained communication
  - Can be difficult for irregular, naturally fine-grained communication
    - may require changes to algorithm and extra work
      - coalescing data and determining what and to whom to send
    - will discuss more in implications for programming models later

Reducing Network Delay

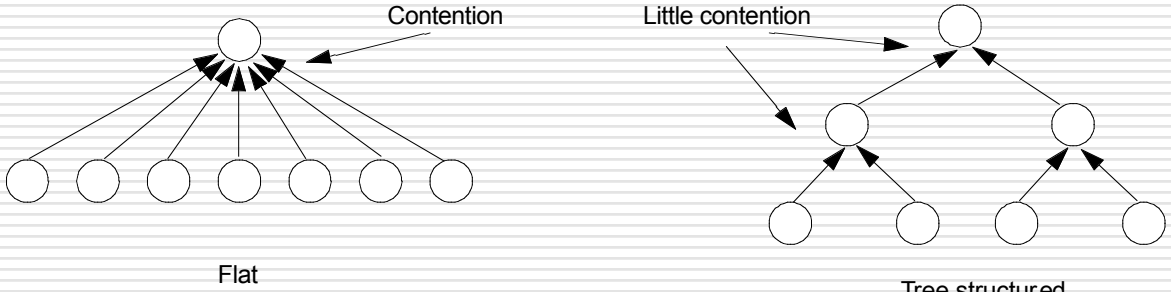
- Network delay component = $f*h*t_h$
  - h = number of hops traversed in network
  - t_h = link+switch latency per hop
- Reducing f: communicate less, or make messages larger
- Reducing h:
  - Map communication patterns to network topology
    - e.g. nearest-neighbor on mesh and ring; all-to-all
  - How important is this?
    - used to be major focus of parallel algorithms
    - depends on no. of processors, how t_h, compares with other components
    - less important on modern machines
      - overheads, processor count, multiprogramming

Reducing Contention

- All resources have nonzero occupancy
  - Memory, communication controller, network link, etc.
  - Can only handle so many transactions per unit time
- Effects of contention:
  - Increased end-to-end cost for messages
  - Reduced available bandwidth for individual messages
  - Causes imbalances across processors
- Particularly insidious performance problem
  - Easy to ignore when programming
  - Slow down messages that don't even need that resource
    - by causing other dependent resources to also congest
  - Effect can be devastating: *Don't flood a resource!*

Types of Contention

- Network contention and end-point contention (hot-spots)
- Location and Module Hot-spots
  - Location: e.g. accumulating into global variable, barrier
    - solution: tree-structured communication

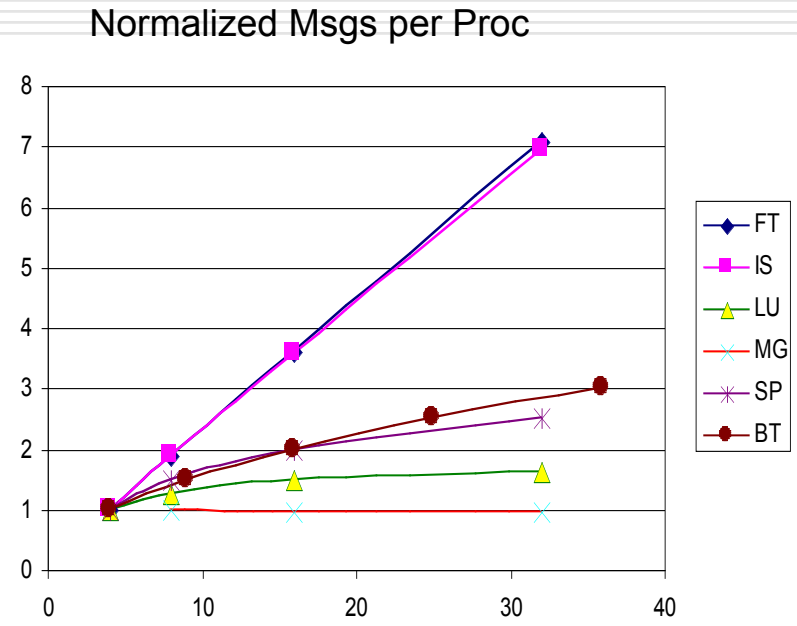


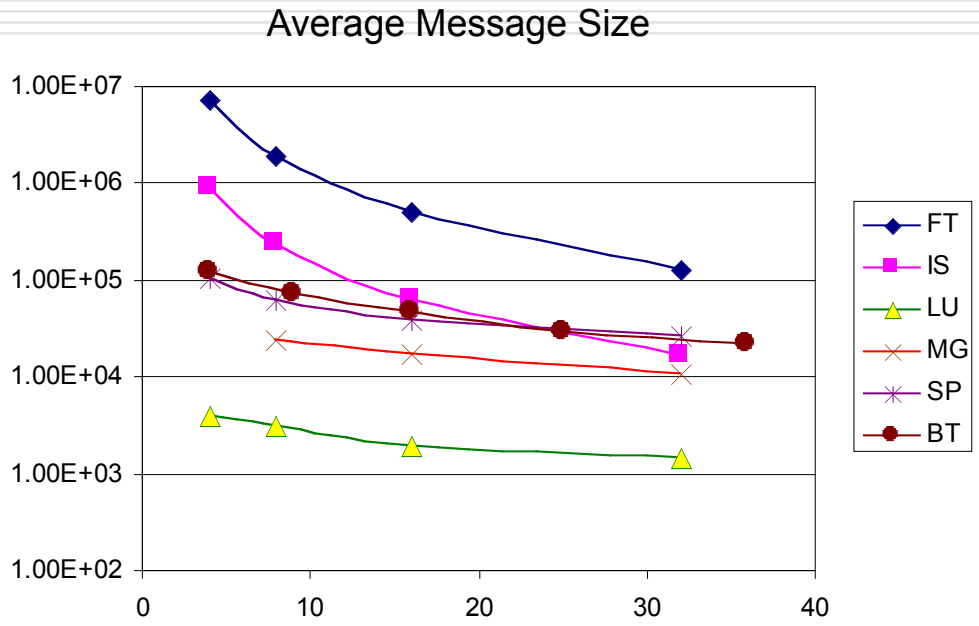
- Module: all-to-all personalized comm. in matrix transpose
  - solution: stagger access by different processors to same node temporally
- In general, reduce burstiness; may conflict with making messages larger

Overlapping Communication

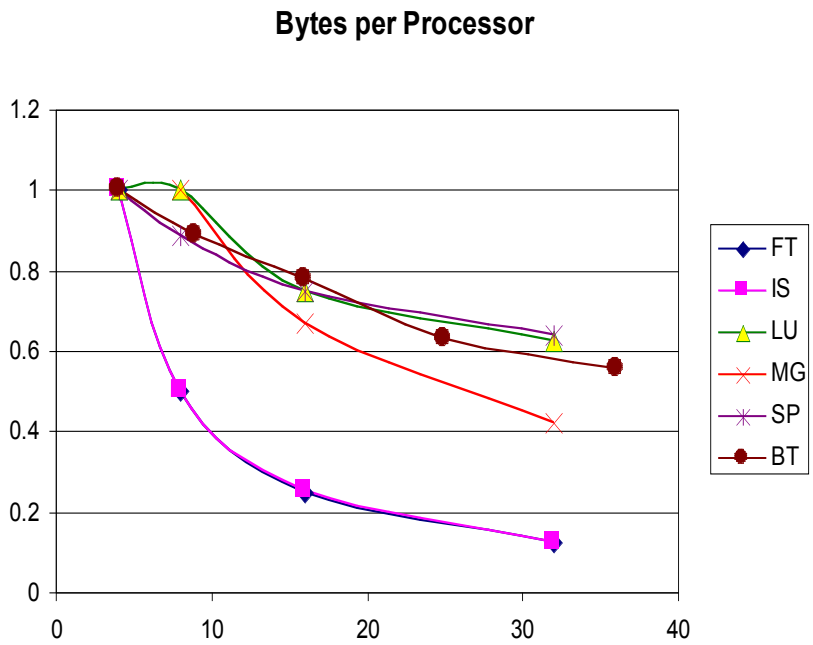
- Cannot afford to stall for high latencies
  - Even on uniprocessors!
- Overlap with computation or communication to hide latency
- Requires extra concurrency (*slackness*), higher bandwidth
- Techniques:
  - Prefetching
  - Block data transfer
  - Proceeding past communication
  - Multithreading

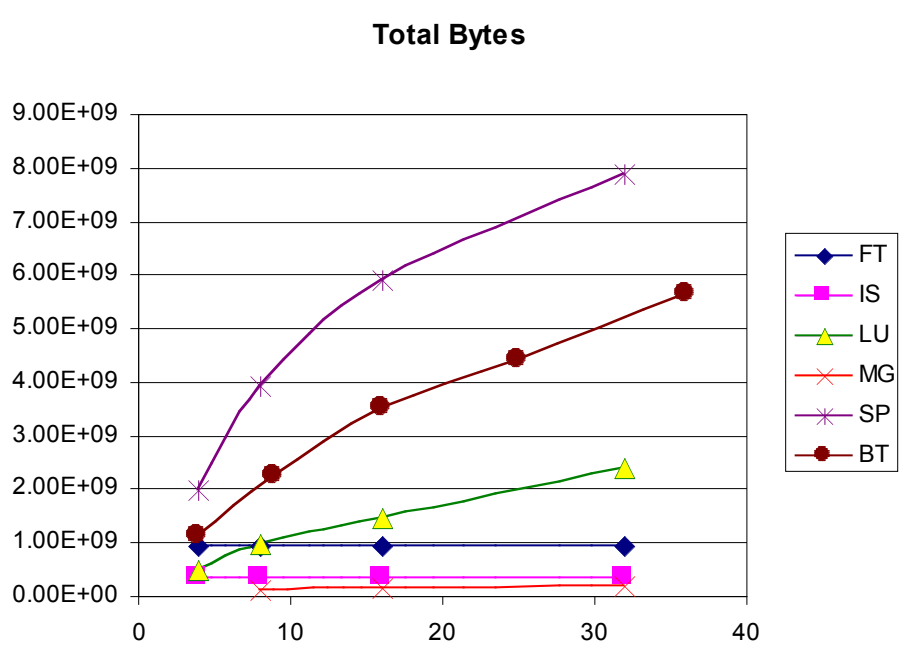
Communication Scaling (NPB2)





Communication Scaling: Volume





What is a Multiprocessor?

- A collection of communicating processors
  - View taken so far
  - Goals: balance load, reduce inherent communication and extra work
- A multi-cache, multi-memory system
  - Role of these components essential regardless of programming model
  - Prog. model and comm. abstr. affect specific performance tradeoffs

Memory-oriented View

- Multiprocessor as Extended Memory Hierarchy
  - as seen by a given processor
- Levels in extended hierarchy:
  - Registers, caches, local memory, remote memory (topology)
  - Glued together by communication architecture
  - Levels communicate at a certain granularity of data transfer
- Need to exploit spatial and temporal locality in hierarchy
  - Otherwise extra communication may also be caused
  - Especially important since communication is expensive

Uniprocessor

- Performance depends heavily on memory hierarchy
- Time spent by a program

  $Time_{prog}(1) = Busy(1) + Data\ Access(1)$

  - Divide by cycles to get CPI equation

- Data access time can be reduced by:
  - Optimizing machine: bigger caches, lower latency...
  - Optimizing program: temporal and spatial locality

Extended Hierarchy

- Idealized view: local cache hierarchy + single main memory
- But reality is more complex
  - Centralized Memory: caches of other processors
  - Distributed Memory: some local, some remote; + network topology
  - Management of levels
    - caches managed by hardware
    - main memory depends on programming model
      - SAS: data movement between local and remote transparent
      - message passing: explicit
  - Levels closer to processor are lower latency and higher bandwidth
  - Improve performance through architecture or program locality
  - Tradeoff with parallelism; need good node performance and parallelism

Artifactual Communication

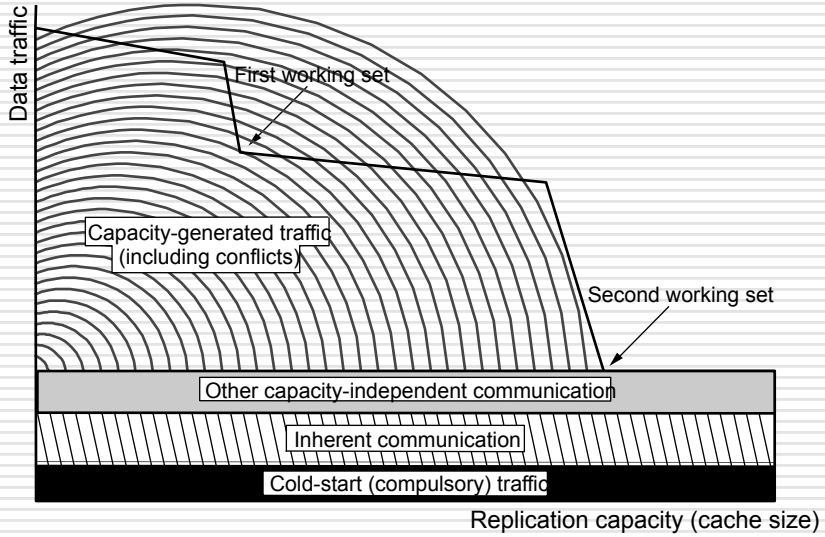
- Accesses not satisfied in local portion of memory hierachy cause communication
  - Inherent communication, implicit or explicit, causes transfers
    - determined by program
  - Artifactual communication
    - determined by program implementation and arch. interactions
    - poor allocation of data across distributed memories
    - unnecessary data in a transfer
    - unnecessary transfers due to system granularities
    - redundant communication of data
    - finite replication capacity (in cache or main memory)
  - Inherent communication assumes unlimited capacity, small transfers, perfect knowledge of what is needed.

Communication and Replication

- Comm induced by finite capacity is most fundamental artifact
  - Like cache size and miss rate or memory traffic in uniprocessors
  - Extended memory hierarchy view useful for this relationship
- View as three level hierarchy for simplicity
  - Local cache, local memory, remote memory (ignore network topology)
- Classify "misses" in "cache" at any level as for uniprocessors
    - compulsory or cold misses (no size effect)
    - capacity misses (yes)
    - conflict or collision misses (yes)
    - communication or coherence misses (no)
  - Each may be helped/hurt by large transfer granularity (spatial locality)

Working Set Perspective

- At a given level of the hierarchy (to the next further one)



- Hierarchy of working sets
- At first level cache (fully assoc, one-word block), inherent to algorithm
  - *working set curve* for program
- Traffic from any type of miss can be local or nonlocal (communication)

Orchestration for Performance

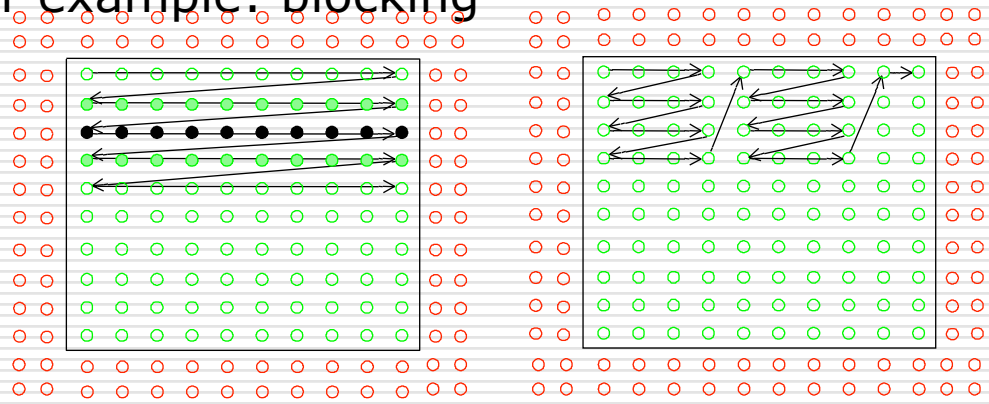
- Reducing amount of communication:
  - Inherent: change logical data sharing patterns in algorithm
  - Artifactual: exploit spatial, temporal locality in extended hierarchy
    - Techniques often similar to those on uniprocessors
- Structuring communication to reduce cost

Reducing Artifactual Communication

- Message passing model
  - Communication and replication are both explicit
  - Even artifactual communication is in explicit messages
    - send data that is not used
- Shared address space model
  - More interesting from an architectural perspective
  - Occurs transparently due to interactions of program and system
    - sizes and granularities in extended memory hierarchy
- Use shared address space to illustrate issues

Exploiting Temporal Locality

- Structure algorithm so working sets map well to hierarchy
  - often techniques to reduce inherent communication do well here
  - schedule tasks for data reuse once assigned
- Multiple data structures in same phase
  - e.g. database records: local versus remote
- Solver example: blocking



(a) Unblocked access pattern in a sweep (b) Blocked access pattern with B = 4

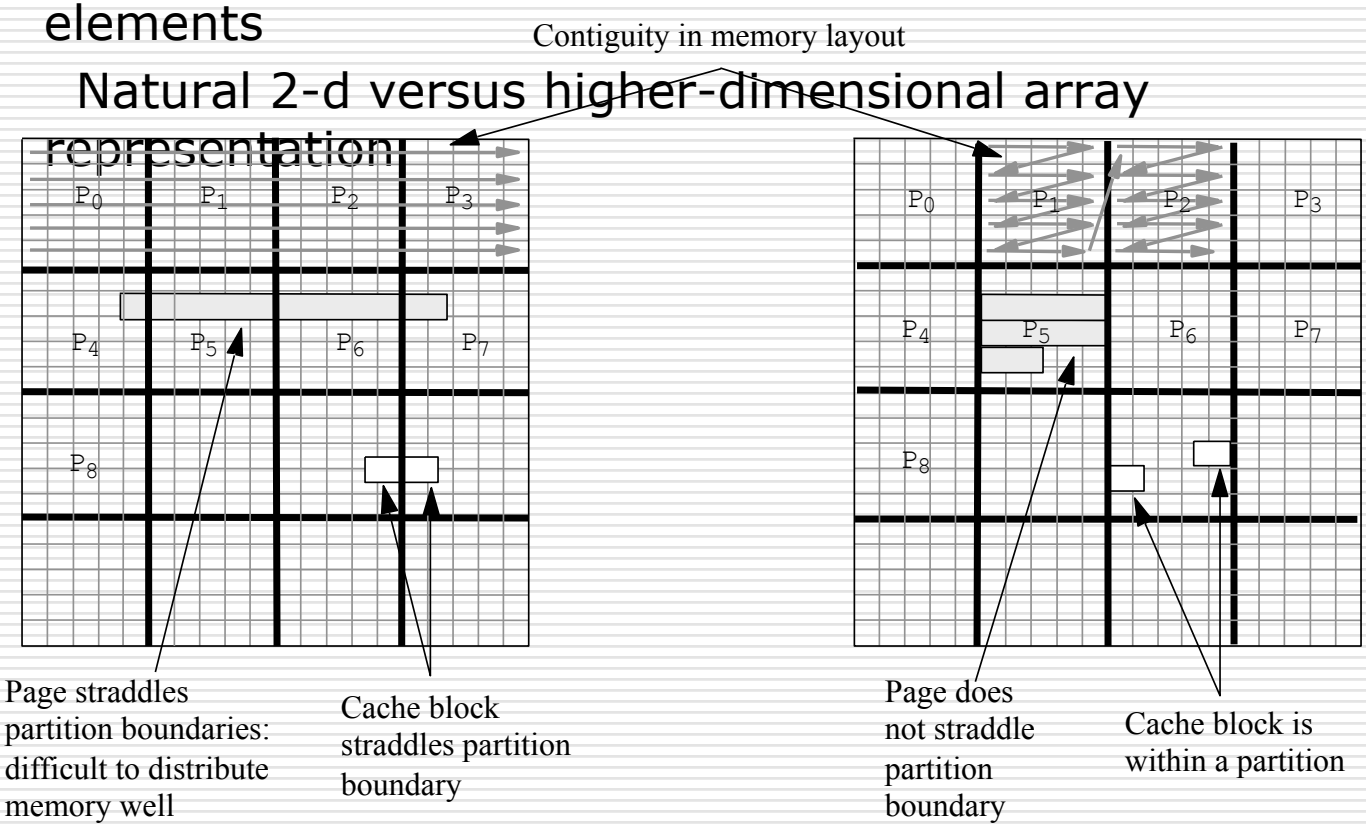
- More useful when $O(n^{k+1})$ computation on $O(n^k)$ data
  - many linear algebra computations (factorization, matrix multiply)

Exploiting Spatial Locality

- Besides capacity, granularities are important:
  - Granularity of allocation
  - Granularity of communication or data transfer
  - Granularity of coherence
- Major spatial-related causes of artifactual communication:
  - Conflict misses
  - Data distribution/layout (allocation granularity)
  - Fragmentation (communication granularity)
  - False sharing of data (coherence granularity)
- All depend on how spatial access patterns interact with data structures
  - Fix problems by modifying data structures, or layout/alignment
- Examine later in context of architectures
  - one simple example here: data distribution in SAS solver

Spatial Locality Example

- Repeated sweeps over 2-d grid, each time adding 1 to elements
- Natural 2-d versus higher-dimensional array representation



(a) Two-dimensional array

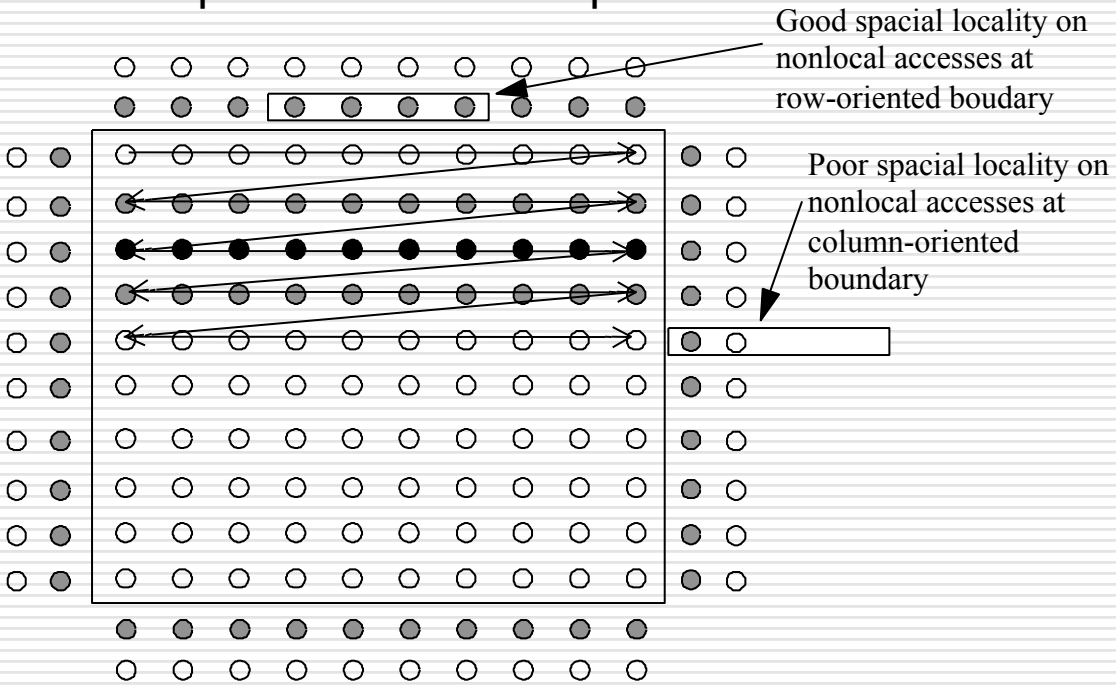
(b) Four-dimensional array

Architectural Implications of Locality

- Communication abstraction that makes exploiting it easy
- For cache-coherent SAS, e.g.:
  - Size and organization of levels of memory hierarchy
    - cost-effectiveness: caches are expensive
    - caveats: flexibility for different and time-shared workloads
  - Replication in main memory useful? If so, how to manage?
    - hardware, OS/runtime, program?
  - Granularities of allocation, communication, coherence (?)
    - small granularities => high overheads, but easier to program
- Machine granularity (resource division among processors, memory...)

Tradeoffs with Inherent Communication

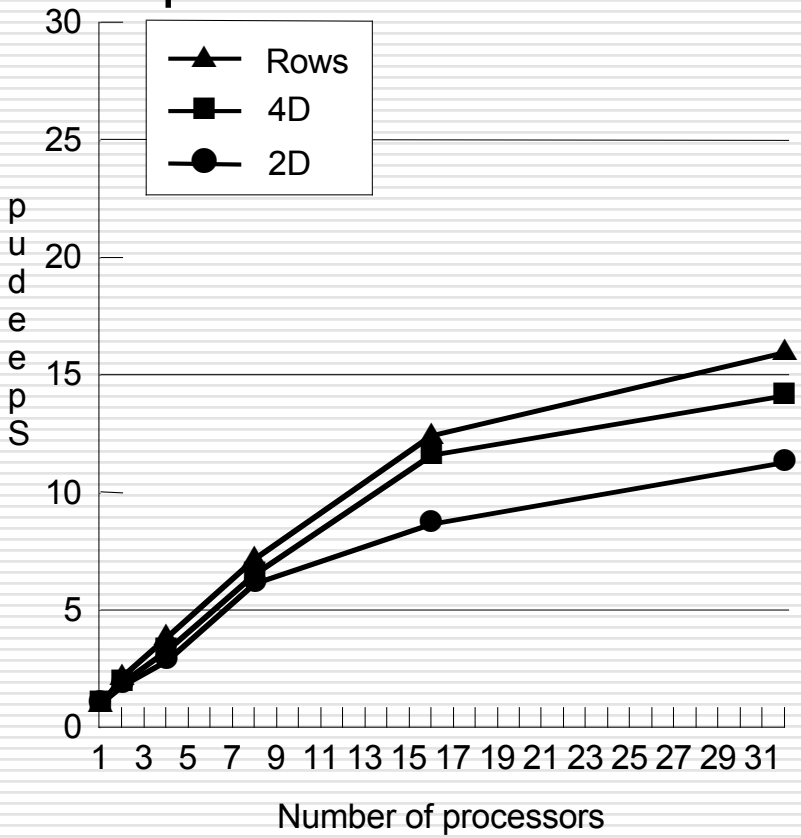
- Partitioning grid solver: blocks versus rows
  - Blocks still have a spatial locality problem on remote data
  - Rowwise can perform better despite worse inherent c-to-c ratio

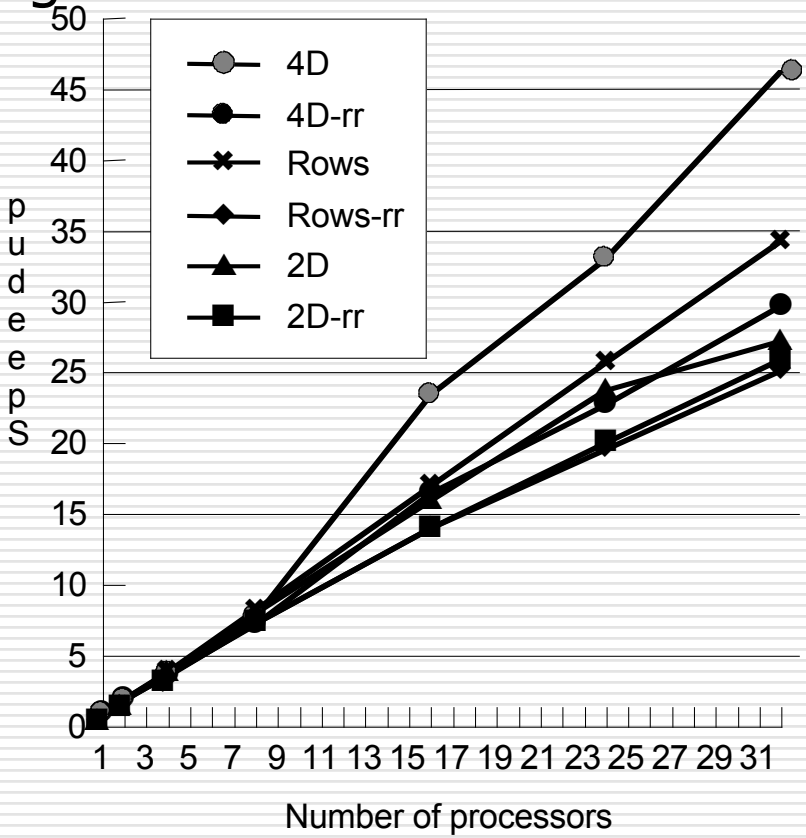


- Result depends on *n* and *p*

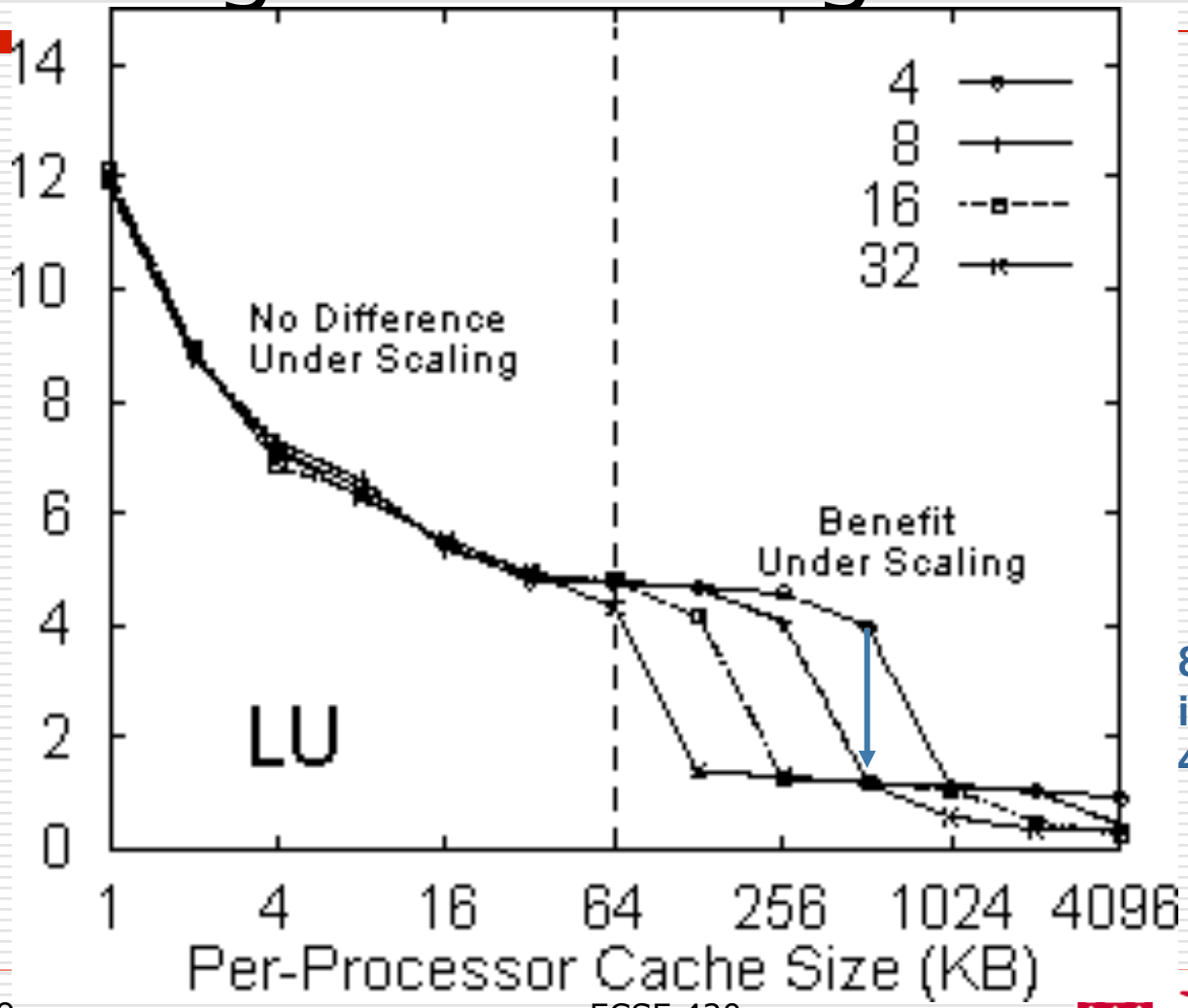
Example Performance Impact

- Equation solver on SGI Origin2000



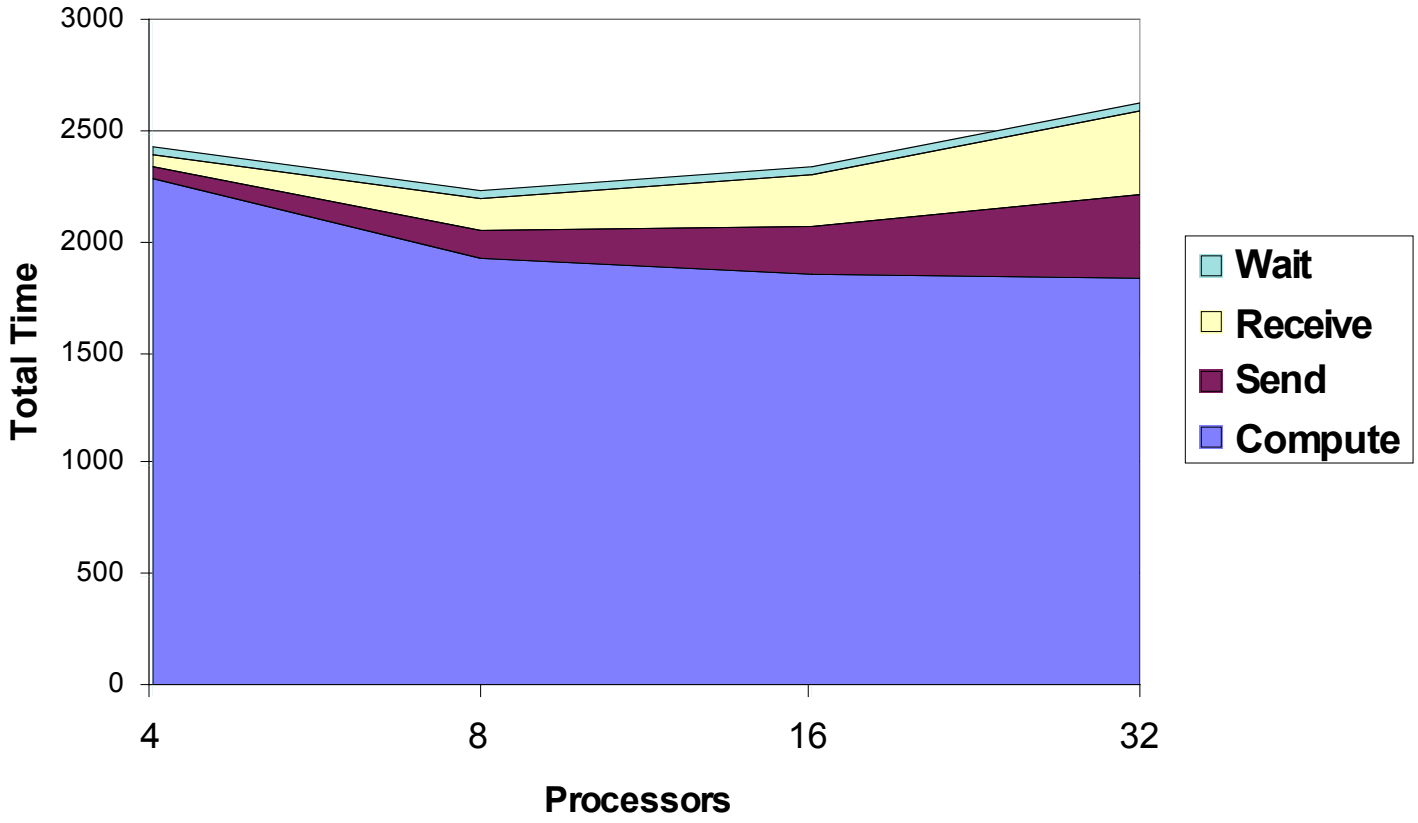


Working Sets Change with P



8-fold reduction in miss rate from 4 to 8 proc

Where the Time Goes: LU-a



Summary of Tradeoffs

- Different goals often have conflicting demands
  - Load Balance
    - fine-grain tasks
    - random or dynamic assignment
  - Communication
    - usually coarse grain tasks
    - decompose to obtain locality: not random/dynamic
  - Extra Work
    - coarse grain tasks
    - simple assignment
  - Communication Cost:
    - big transfers: amortize overhead and latency
    - small transfers: reduce contention