ECE 669

Parallel Computer Architecture

Lecture 9

Workload Evaluation

Outline

- Evaluation of applications is important
- Simulation of sample data sets provides important information
- Working sets indicate grain size
- Preliminary results offer opportunity for tuning
- Understanding communication costs
  - Remember: software and communication!

Workload-Driven Evaluation

- Evaluating real machines
- Evaluating an architectural idea or trade-offs

=> need good metrics of performance

=> need to pick good workloads

=> need to pay attention to scaling

  - many factors involved

- Today: narrow architectural comparison
- Set in wider context

Evaluation in Uniprocessors

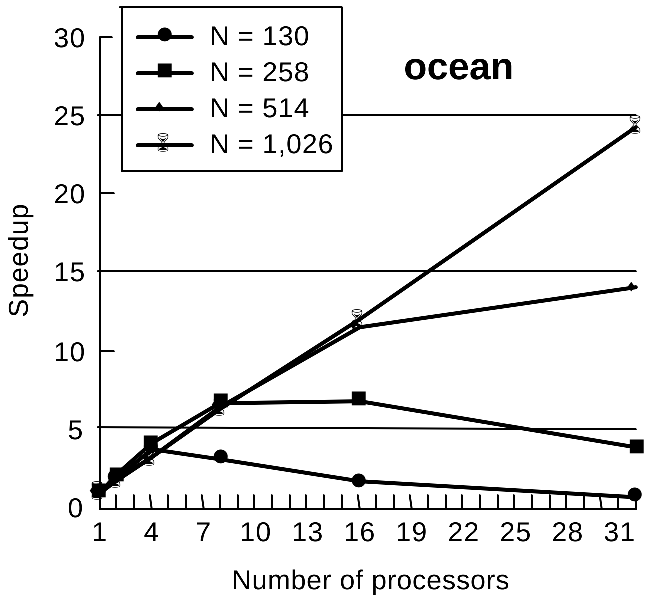
- **Decisions made only after quantitative evaluation**
- **For existing systems: comparison and procurement evaluation**
- **For future systems: careful extrapolation from known quantities**
- **Wide base of programs leads to standard benchmarks**
    - **Measured on wide range of machines and successive generations**
- **Measurements and technology assessment lead to proposed features**
- **Then simulation**
    - **Simulator developed that can run with and without a feature**
    - **Benchmarks run through the simulator to obtain results**
    - **Together with cost and complexity, decisions made**

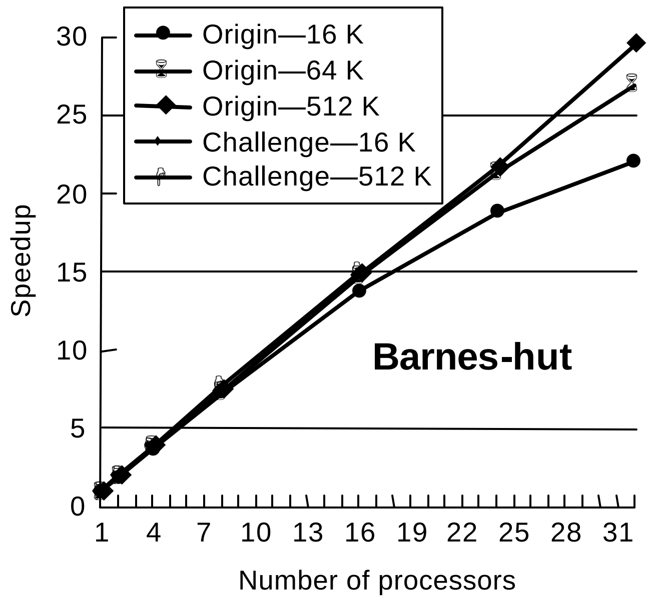
More Difficult for Multiprocessors

- What is a representative workload?
- Software model has not stabilized
- Many architectural and application degrees of freedom
  - Huge design space: no. of processors, other architectural, application
  - Impact of these parameters and their interactions can be huge
  - High cost of communication
- What are the appropriate metrics?
- Simulation is expensive
  - Realistic configurations and sensitivity analysis difficult
  - Larger design space, but more difficult to cover
- Understanding of parallel programs as workloads is critical
  - Particularly interaction of application and architectural parameters

A Lot Depends on Sizes

- Application parameters and no. of procs affect inherent properties
  - Load balance, communication, extra work, temporal and spatial locality
- Interactions with organization parameters of extended memory hierarchy affect communication and performance
- Effects often dramatic, sometimes small: application-dependent





Understanding size interactions and scaling relationships is key

Scaling: Why Worry?

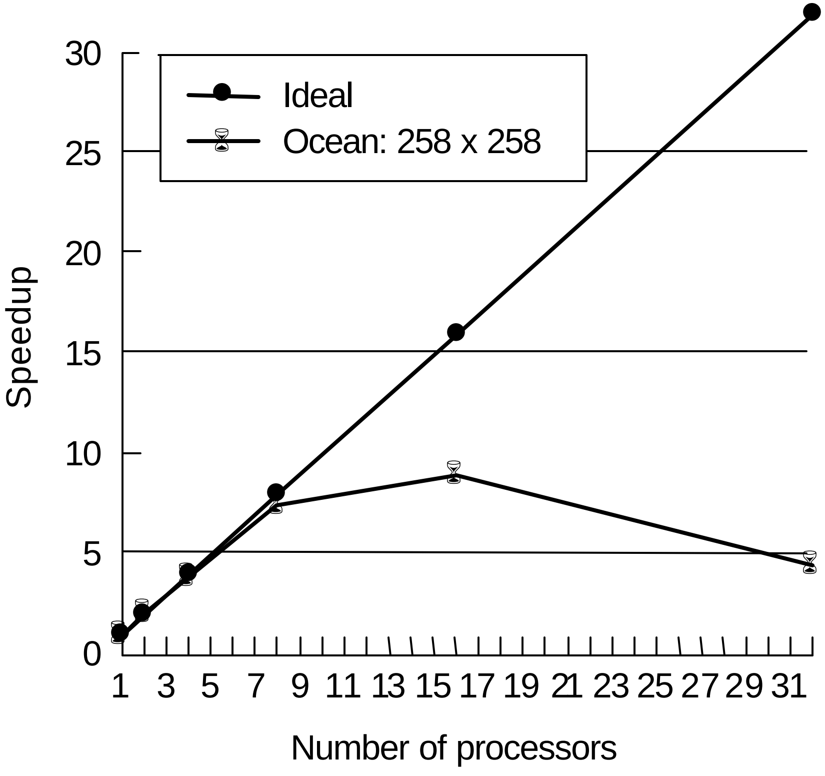
- Fixed problem size is limited
- Too small a problem:
  - May be appropriate for small machine
  - Parallelism overheads begin to dominate benefits for larger machines
    - Load imbalance
    - Communication to computation ratio
  - May even achieve slowdowns
  - Doesn’t reflect real usage, and inappropriate for large machines
    - Can exaggerate benefits of architectural improvements, especially when measured as percentage improvement in performance
- Too large a problem
  - Difficult to measure improvement (next)

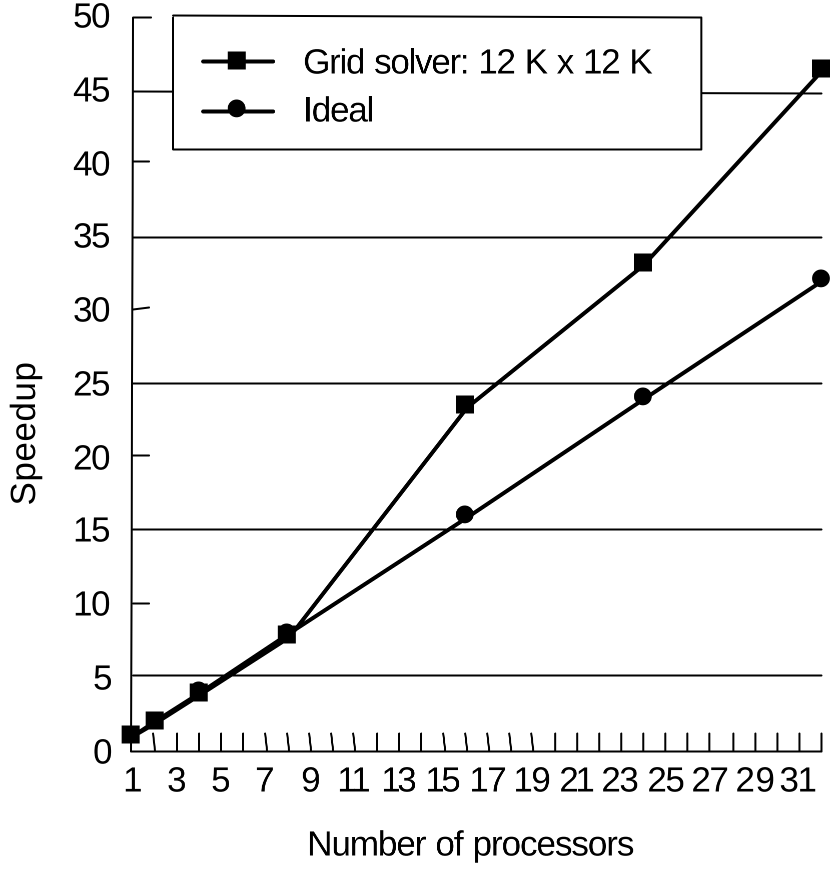
Too Large a Problem

- **Suppose problem realistically large for big machine**
- **May not “fit” in small machine**
  - **Can’t run**
  - **Thrashing to disk**
  - **Working set doesn’t fit in cache**
- **Fits at some *p*, leading to *superlinear speedup***
- **Real effect, but doesn’t help evaluate effectiveness**
- **Finally, users want to scale problems as machines grow**
  - **Can help avoid these problems**

Demonstrating Scaling Problems

- Small Ocean and big equation solver problems on SGI Origin2000



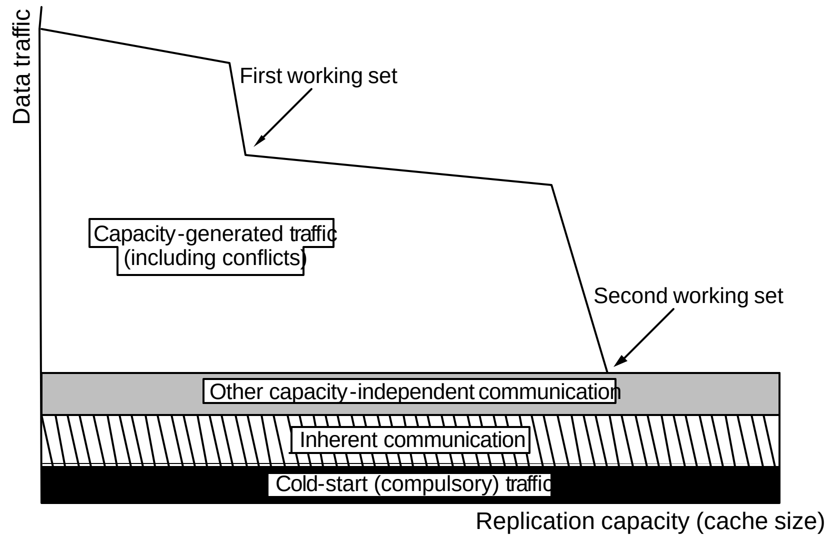


Communication and Replication

- View parallel machine as extended memory hierarchy
  - Local cache, local memory, remote memory
  - 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)
- Communication induced by finite capacity is most fundamental artifact
  - Like cache size and miss rate or memory traffic in uniprocessors

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)**

Workload-Driven Evaluation

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Questions in Scaling

- ***Scaling a machine*: Can scale power in many ways**
  - **Assume adding identical nodes, each bringing memory**
- ***Problem size*: Vector of input parameters, e.g. *N* = (*n*, *q*, D*t*)**
  - **Determines work done**
  - **Distinct from *data set size* and *memory usage***
- **Under what constraints to scale the application?**
  - **What are the appropriate metrics for performance improvement?**
    - **work is not fixed any more, so time not enough**
- **How should the application be scaled?**

Under What Constraints to Scale?

- **Two types of constraints:**
  - **User-oriented, e.g. particles, rows, transactions, I/Os per processor**
  - **Resource-oriented, e.g. memory, time**
- **Which is more appropriate depends on application domain**
  - **User-oriented easier for user to think about and change**
  - **Resource-oriented more general, and often more real**
- **Resource-oriented scaling models:**
  - ***Problem constrained* (PC)**
  - ***Memory constrained* (MC)**
  - ***Time constrained* (TC)**

Problem Constrained Scaling

- User wants to solve same problem, only faster
  - Video compression
  - Computer graphics
  - VLSI routing
- But limited when evaluating larger machines

$$Speedup_{PC}(p) = \frac{Time(1)}{Time(p)}$$

Time Constrained Scaling

- **Execution time is kept fixed as system scales**
  - **User has fixed time to use machine or wait for result**
- **Performance = Work/Time as usual, and time is fixed, so**

$$\textit{SpeedupTC(p)} = \frac{Work(p)}{Work(1)}$$

- **How to measure work?**
  - **Execution time on a single processor? (thrashing problems)**
  - **Should be easy to measure, ideally analytical and intuitive**
  - **Should scale linearly with sequential complexity**
    - **Or ideal speedup will not be linear in *p* (e.g. no. of rows in matrix program)**
  - **If cannot find intuitive application measure, as often true, measure *execution time with ideal memory system on a uniprocessor***

Memory Constrained Scaling

- **Scale so memory usage per processor stays fixed**
- **Scaled Speedup: Time(1) / Time(p) for scaled up problem**
  - **Hard to measure Time(1), and inappropriate**

$$\textbf{Speedup}_{MC}(p) = \frac{Work(p)}{Time(p)} \times \frac{Time(1)}{Work(1)} = \frac{\text{Increase in Work}}{\text{Increase in Time}}$$

- **Can lead to large increases in execution time**
  - **If work grows faster than linearly in memory usage**
  - **e.g. matrix factorization**
    - **10,000-by 10,000 matrix takes 800MB and 1 hour on uniprocessor. With 1,000 processors, can run 320K-by-320K matrix, but ideal parallel time grows to 32 hours!**
    - **With 10,000 processors, 100 hours ...**

Scaling Summary

- Under any scaling rule, relative structure of the problem changes with P
  - PC scaling: per-processor portion gets smaller
  - MC & TC scaling: total problem get larger
- Need to understand hardware/software interactions with scale
- For given problem, there is often a natural scaling rule
  - example: equal error scaling

Types of Workloads

- ***Kernels:*** **matrix factorization, FFT, depth-first tree search**
- ***Complete Applications:*** **ocean simulation, crew scheduling, database**
- ***Multiprogrammed Workloads***

° Multiprog. ______ Appls ______ Kernels ______ Microbench.

Realistic
Complex
Higher level interactions
Are what really matters

Easier to understand
Controlled
Repeatable
Basic machine characteristics

Each has its place:

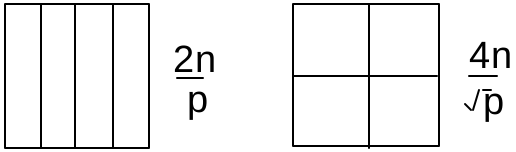
Use kernels and microbenchmarks to gain understanding, but applications to evaluate effectiveness and performance

Coverage: Stressing Features

- **Easy to mislead with workloads**
  - **Choose those with features for which machine is good, avoid others**
- **Some features of interest:**
  - **Compute v. memory v. communication v. I/O bound**
  - **Working set size and spatial locality**
  - **Local memory and communication bandwidth needs**
  - **Importance of communication latency**
  - **Fine-grained or coarse-grained**
    - **Data access, communication, task size**
  - **Synchronization patterns and granularity**
  - **Contention**
  - **Communication patterns**
- **Choose workloads that cover a range of properties**

Coverage: Levels of Optimization

- **Many ways in which an application can be suboptimal**
  - ***Algorithmic*, e.g. assignment, blocking**



  - ***Data structuring*, e.g. 2-d or 4-d arrays for SAS grid problem**
  - ***Data layout, distribution and alignment*, even if properly structured**
  - ***Orchestration***
    - **contention**
    - **long versus short messages**
    - **synchronization frequency and cost, ...**
  - **Also, random problems with “unimportant” data structures**
- **Optimizing applications takes work**
  - **Many practical applications may not be very well optimized**

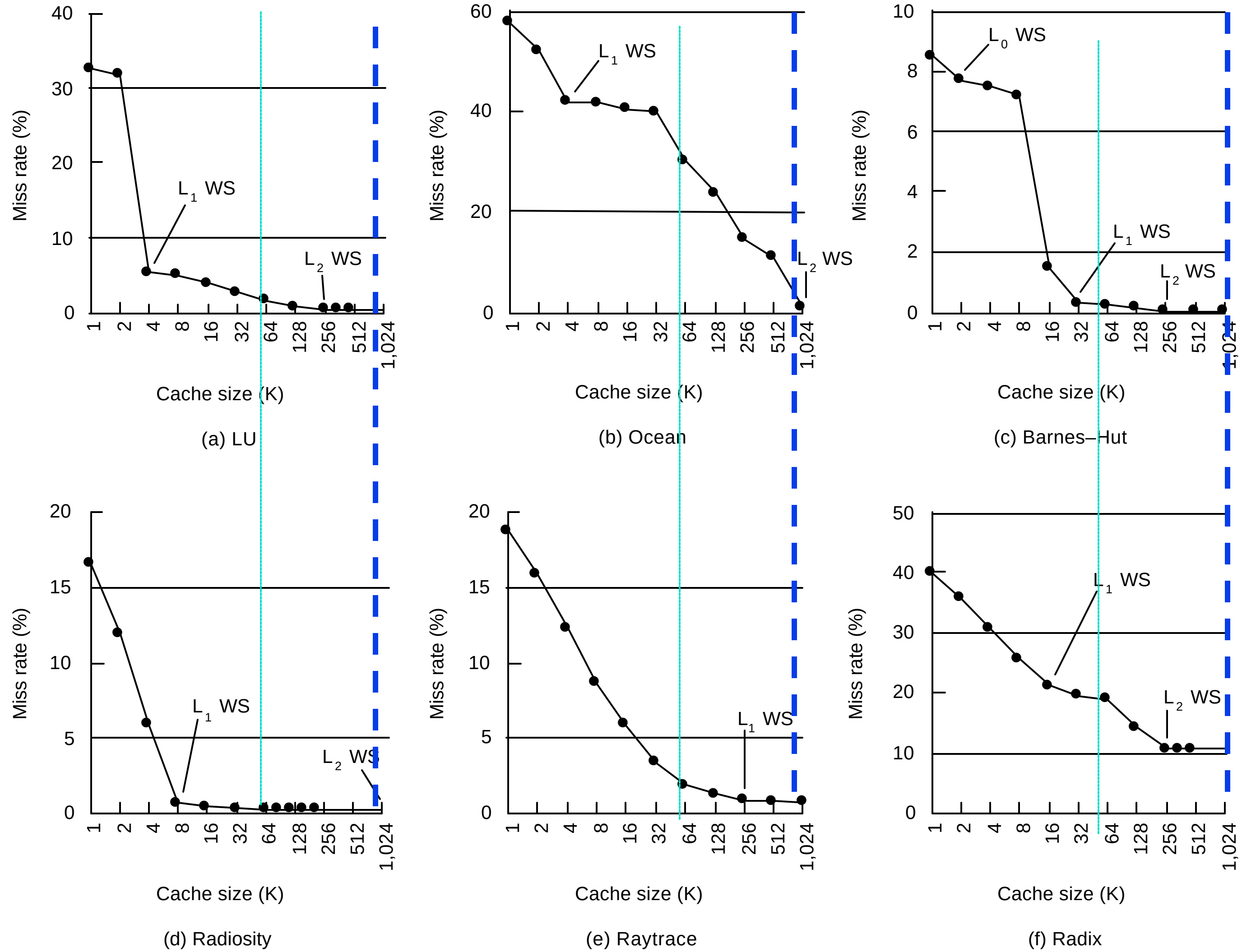
Concurrency

- **Should have enough to utilize the processors**
  - **If load imbalance dominates, may not be much machine can do**
  - **(Still, useful to know what kinds of workloads/configurations don't have enough concurrency)**
- ***Algorithmic speedup*: useful measure of concurrency/imbalance**
  - **Speedup (under scaling model) assuming all memory/communication operations take zero time**
  - **Ignores memory system, measures imbalance and extra work**
  - **Uses PRAM machine model (Parallel Random Access Machine)**
    - **Unrealistic, but widely used for theoretical algorithm development**
- **At least, should isolate performance limitations due to program characteristics that a machine cannot do much about (concurrency) from those that it can.**

Steps in Choosing Problem Sizes

- **Variation of characteristics with problem size usually smooth**
  - So, for inherent comm. and load balance, pick some sizes along range
- **Interactions of locality with architecture often have thresholds (knees)**
  - Greatly affect characteristics like local traffic, artifactual comm.
  - May require problem sizes to be added
    - to ensure both sides of a knee are captured
  - But also help prune the design space

Our Cache Sizes (16x1MB, 16x64KB)

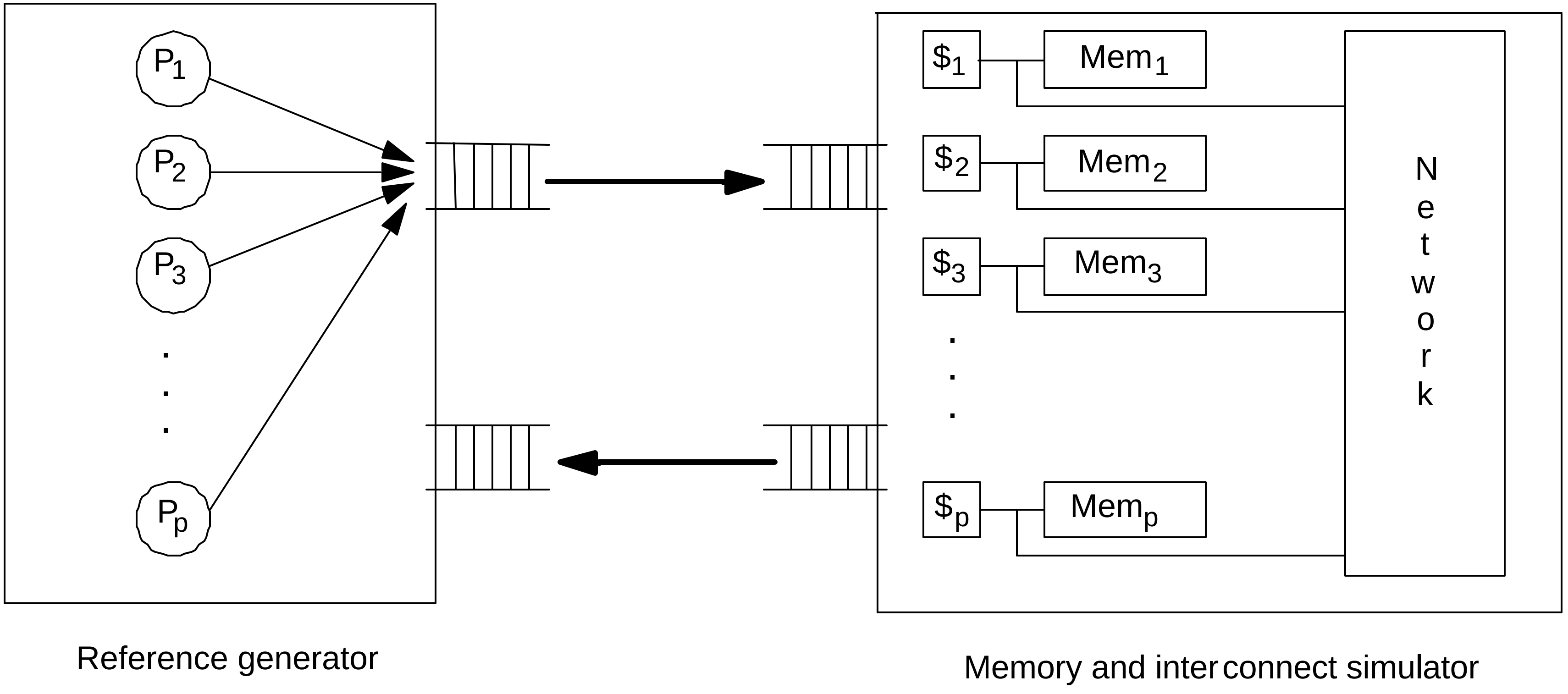


Multiprocessor Simulation

- Simulation runs on a uniprocessor (can be parallelized too)
  - Simulated processes are interleaved on the processor
- Two parts to a simulator:
  - Reference generator: plays role of simulated processors
    - And schedules simulated processes based on *simulated time*
  - Simulator of extended memory hierarchy
    - Simulates operations (references, commands) issued by reference generator
- Coupling or information flow between the two parts varies
  - Trace-driven simulation: from generator to simulator
  - Execution-driven simulation: in both directions (more accurate)
- Simulator keeps track of simulated time and detailed statistics

Execution-driven Simulation

- **Memory hierarchy simulator returns simulated time information to reference generator, which is used to schedule simulated processes**



Summary

- **Evaluate design tradeoffs**
  - many underlying design choices
  - prove coherence, consistency
- **Evaluation must be based on sound understandng of workloads**
  - drive the factors you want to study
  - representative
  - scaling factors
- **Use of workload driven evaluation to resolve architectural questions**