COMP 633 - Parallel Computing

Lecture 7
September 9, 2021

SMM (2)
OpenMP Programming Model

- Reading for next time
  - OpenMP tutorial: look through secns 3-5 plus secn 6 up to exercise 1

Topics

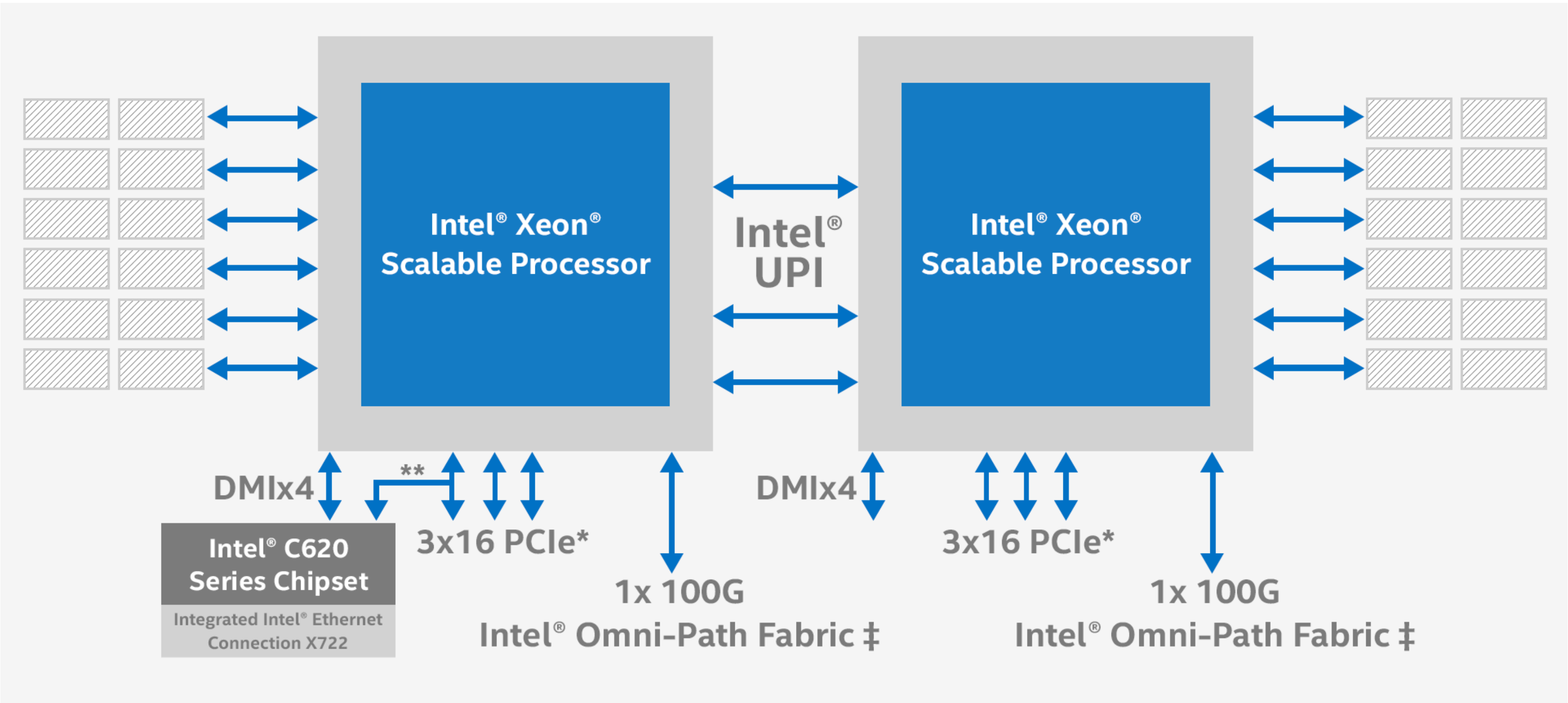
- OpenMP shared-memory parallel programming model
  - loop-level parallel programming
- Characterizing performance
  - performance measurement of a simple program
  - how to monitor and present program performance
  - general barriers to performance in parallel computation

Shared-memory programming models

- Work-Time programming model
  sequential programming language + `forall`
  - PRAM execution
    - synchronous
    - scheduling implicit (via Brent's theorem)
  - W-T cost model (work and steps)

- Loop-level parallel programming model
  sequential programming language + directives to mark `for` loop as "forall"
  - shared-memory multiprocessor execution
    - asynchronous execution of loop iterations by multiple threads *in a single address space*
      - must avoid dependence on synchronous execution model
    - scheduling of work across threads is controlled via directives
      - implemented by the compiler and run-time systems
  - cost model depends on underlying shared memory architecture
    - can be difficult to quantify
    - but some general principles apply

Example shared-memory machine



Phaedra

- 10 compute cores per socket, total 20 cores
- Single shared physical address space
  64 GB memory per socket, 128 GB total shared memory
- Cache-coherence protocol for performance

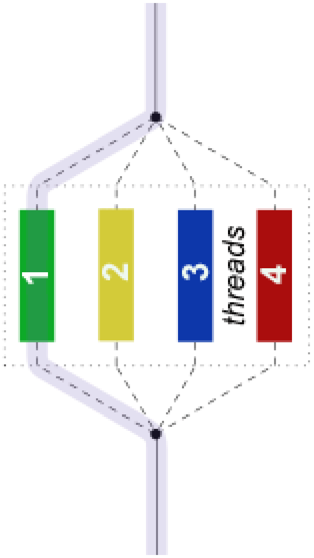
OpenMP

- OpenMP
  - parallelization directives for mainstream performance-oriented sequential programming languages
    - C/C++ , Fortran (88, 90/95)
  - directives are written as comments in the program text
    - ignored by non-OpenMP compilers
    - honored by OpenMP-compliant compilers in "OpenMP" mode
  - directives specify
    - parallel execution
      - create multiple threads, generally each thread runs on a separate core in a CC-NUMA machine
    - partitioning of variables
      - a variable is either shared between threads OR each thread maintains a private copy
    - work scheduling in loops
      - partitioning of loop iterations across threads

- C/C++ binding of OpenMP
  - form of directives
    - #pragma omp . . . .

OpenMP parallel execution of loops

```
   …
printf("Start.\n");
for (i = 1; i < N-1; i++) {
    b[i] = (a[i-1] + a[i] + a[i+1]) / 3;
}
printf("Done.\n");
   …
```



- Can different iterations of this loop be executed simultaneously?
  - for different values of *i*, the body of the loop can be executed simultaneously
- Suppose we have *n* iterations and *p* threads ?
  - we have to *partition* the iteration space across the threads

OpenMP directives to control partitioning

```
  …
printf("Start.\n");
#pragma omp parallel for shared(a,b) private(i)
for (i = 1; i < N-1; i++) {
    b[i] = (a[i-1] + a[i] + a[i+1]) / 3;
}
printf("Done.\n");
  …
```

- The parallel directive indicates the next *statement* should be executed by all threads
- The for directive indicates the work in the loop body should be partitioned across threads
- The shared directive indicates that arrays a and b are shared by all threads.
- The private directive indicates i has a separate instance in each thread.
- The last two directives would be inferred by the OpenMP compiler

OpenMP components

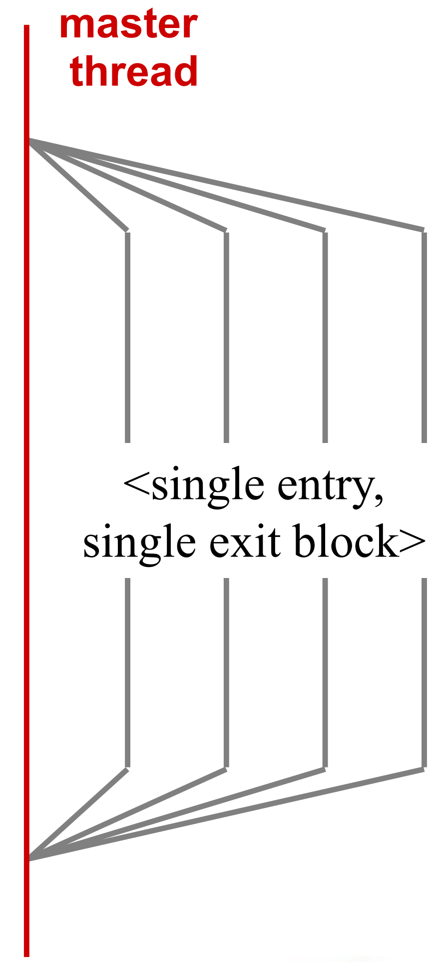
- Directives
  - specify parallel vs sequential regions
  - specify shared vs private variables in parallel regions
  - specify work sharing: distribution of loop iterations over threads
  - specify synchronization and serialization of threads
- Run-time library
  - obtain parallel processing resources
  - control dynamic aspects of work sharing
- Environment variables
  - external to program
  - specification of resources available for a particular execution
    - enables a single compiled program to run using differing numbers of processors

C/OpenMP concepts: parallel region

```
#pragma omp parallel shared(…) private(…)
<single entry, single exit block>
```

Fork-join model

- master thread forks a team of threads on entry to block
  - variables in scope within the block are
    - shared among all threads
      - » if declared outside of the parallel region
      - » if explicitly declared shared in the directive
    - private to (replicated in) each thread
      - » if declared within the parallel region
      - » if explicitly declared private in the directive
      - » if variable is a loop index variable in a loop within the region
- the team of threads has dynamic lifetime to end of block
  - statements are executed by all threads
- the end of block is a barrier synchronization that joins all threads
  - only master thread proceeds thereafter



C/OpenMP concepts: work sharing

```
#pragma omp for schedule(…)
for (<var> = <lb>; <var> <op> <ub>; <incr-expr>)
    <loop body>
```

- Work sharing
  - only has meaning inside a parallel region
  - the *iteration space* is distributed among the threads
    - several different scheduling strategies available
  - the loop construct must follow some restrictions
    - <var> has a signed integer type
    - <lb>, <ub>, <incr-expr> must be loop invariant
    - <op>, <incr-expr> restricted to simple relational and arithmetic operations
  - implicit barrier at completion of loop

Complete C program (V1)

```
#include <stdio.h>
#include <omp.h>
#define N 50000000
#define NITER 100

double a[N],b[N];
main ()
{
  double t1,t2,td;
  int i, t, max_threads, niter;

  max_threads = omp_get_max_threads();
  printf("Initializing:  N = %d, max # threads = %d\n", N, max_threads);

   /*
   * initialize arrays
   */
  for (i = 0; i < N; i++){
    a[i] = 0.0;
    b[i] = 0.0;
  }
  a[0] = b[0] = 1.0;
```

Program, contd. (V1)

```
  /*
   * time iterations
   */
  t1 = omp_get_wtime();
  for (t = 0; t < NITER; t = t + 2){

      #pragma omp parallel for private(i)
      for (i = 1; i < N-1; i++)
        b[i] = (a[i-1] + a[i] + a[i+1]) / 3.0;

      #pragma omp parallel for private(i)
      for (i = 1; i < N-1; i++)
        a[i] = (b[i-1] + b[i] + b[i+1]) / 3.0;
  }

  t2 = omp_get_wtime();
  td = t2 - t1;
  printf("Time per element = %6.1f ns\n", td * 1E9 / (NITER * N));
}
```

Program, contd. (V2 – enlarging scope of parallel region)

```
    /*
     * time iterations
     */
    t1 = omp_get_wtime();

    #pragma omp parallel private(i,t)
    for (t = 0; t < NITER; t = t + 2){

        #pragma omp for
        for (i = 1; i < N-1; i++)
           b[i] = (a[i-1] + a[i] + a[i+1]) / 3.0;

        #pragma omp for
        for (i = 1; i < N-1; i++)
          a[i] = (b[i-1] + b[i] + b[i+1]) / 3.0;
    }

    t2 = omp_get_wtime();
    td = t2 – t1;
    printf("Time per element = %6.1f ns\n", td * 1E9 / (NITER * N));
  }
```

Complete program (V3 – page and cache affinity)

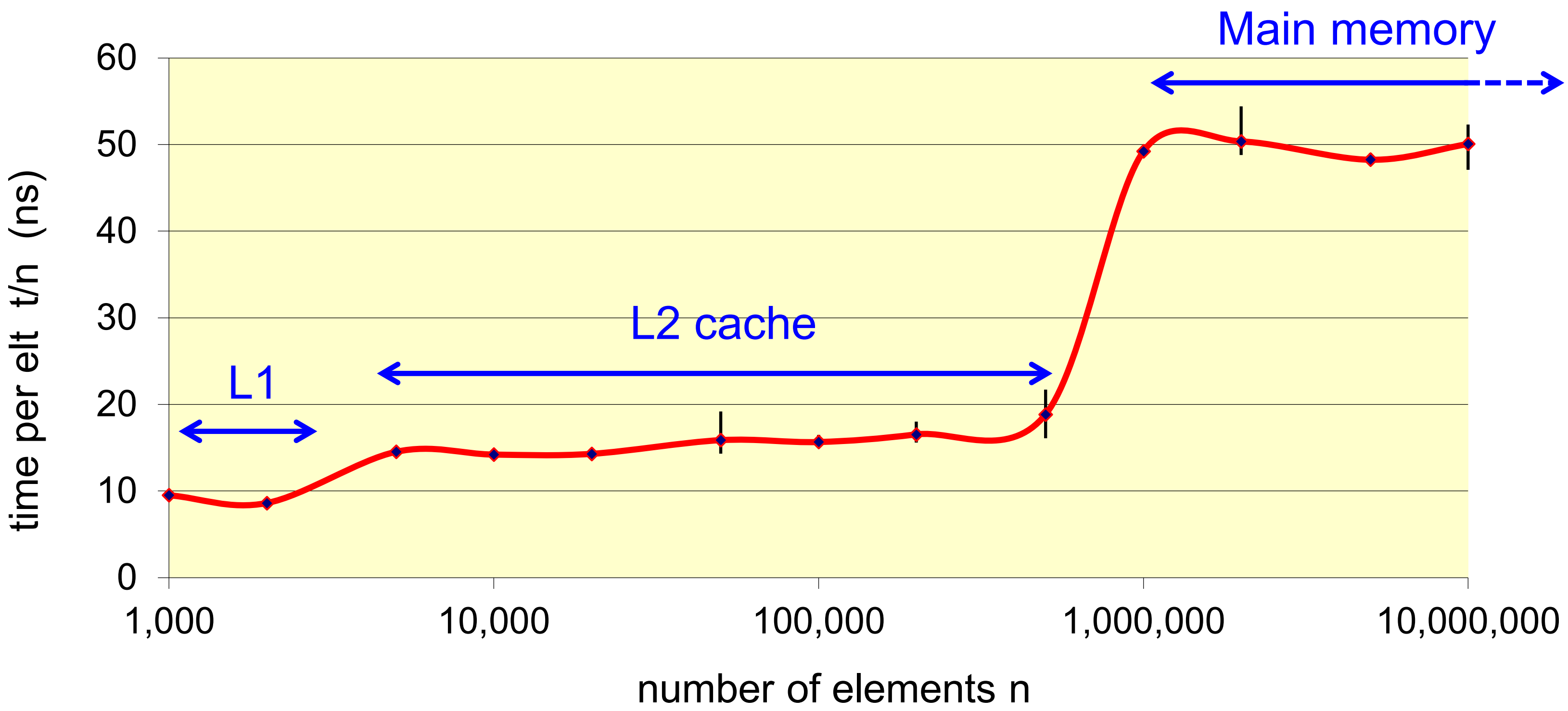
```
#include <stdio.h>
#include <omp.h>
#define N 50000000
#define NITER 100

double a[N],b[N];

main ()
{
  double t1,t2,td;
  int i, t, max_threads, niter;

  max_threads = omp_get_max_threads();
  printf("Initializing:  N = %d, max # threads = %d\n", N, max_threads);

  #pragma omp parallel private(i,t)
  { // start parallel region

      /*
       * initialize arrays
       */
      #pragma omp for
      for (i = 1; i < N; i++){
         a[i] = 0.0;
         b[i] = 0.0;
      }

      #pragma omp master
      a[0] = b[0] = 1.0;
```

Program, contd. (V3 – page and cache affinity)

```
  /*
   * time iterations
   */
  #pragma omp master
  t1 = omp_getwtime();

     for (t = 0; t < NITER; t = t + 2){

         #pragma omp for
         for (i = 1; i < N-1; i++)
             b[i] = (a[i-1] + a[i] + a[i+1]) / 3.0;

         #pragma omp for
         for (i = 1; i < N-1; i++)
            a[i] = (b[i-1] + b[i] + b[i+1]) / 3.0;
     }
  }  // end parallel region

  t2 = omp_get_wtime();
  td = t2 – t1;
  printf("Time per element = %6.1f ns\n", td * 1E9 / (NITER * N));
}
```

Effect of caches

- Time to update one element in *sequential execution*
  - `b[i] = (a[i-1] + a[i] + a[i+1]) / 3.0;`
  - depends on where the elements are found
    - registers, L1 cache, L2 cache, main memory

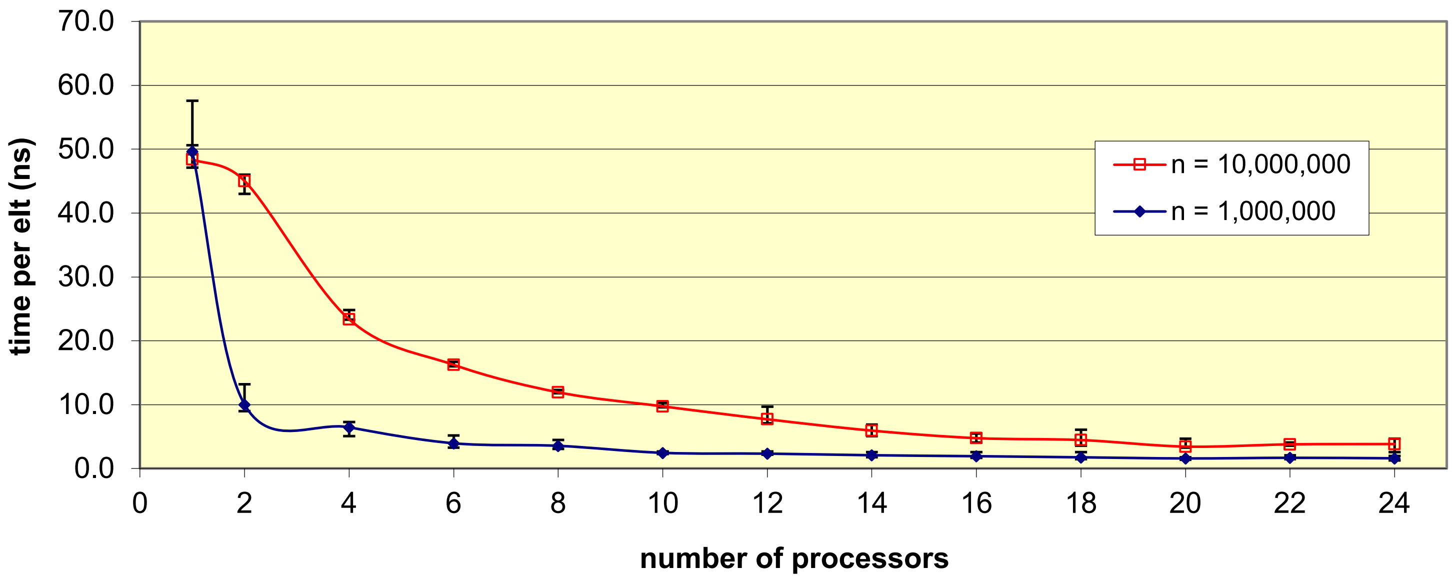


How to present scaling of parallel programs?

- Independent variables
  - either
    - number of processors p
    - problem size n
- Dependent variable (choose)
  - Time (secs)
  - Rate (opns/sec)
  - Speedup $S = T_1 / T_p$
  - Efficiency $E = T_1 / pT_p$
- Horizontal axis
  - independent variable (n or p)
- Vertical axis
  - Dependent variable (e.g. time per element)
  - May show multiple curves (e.g different values of n)

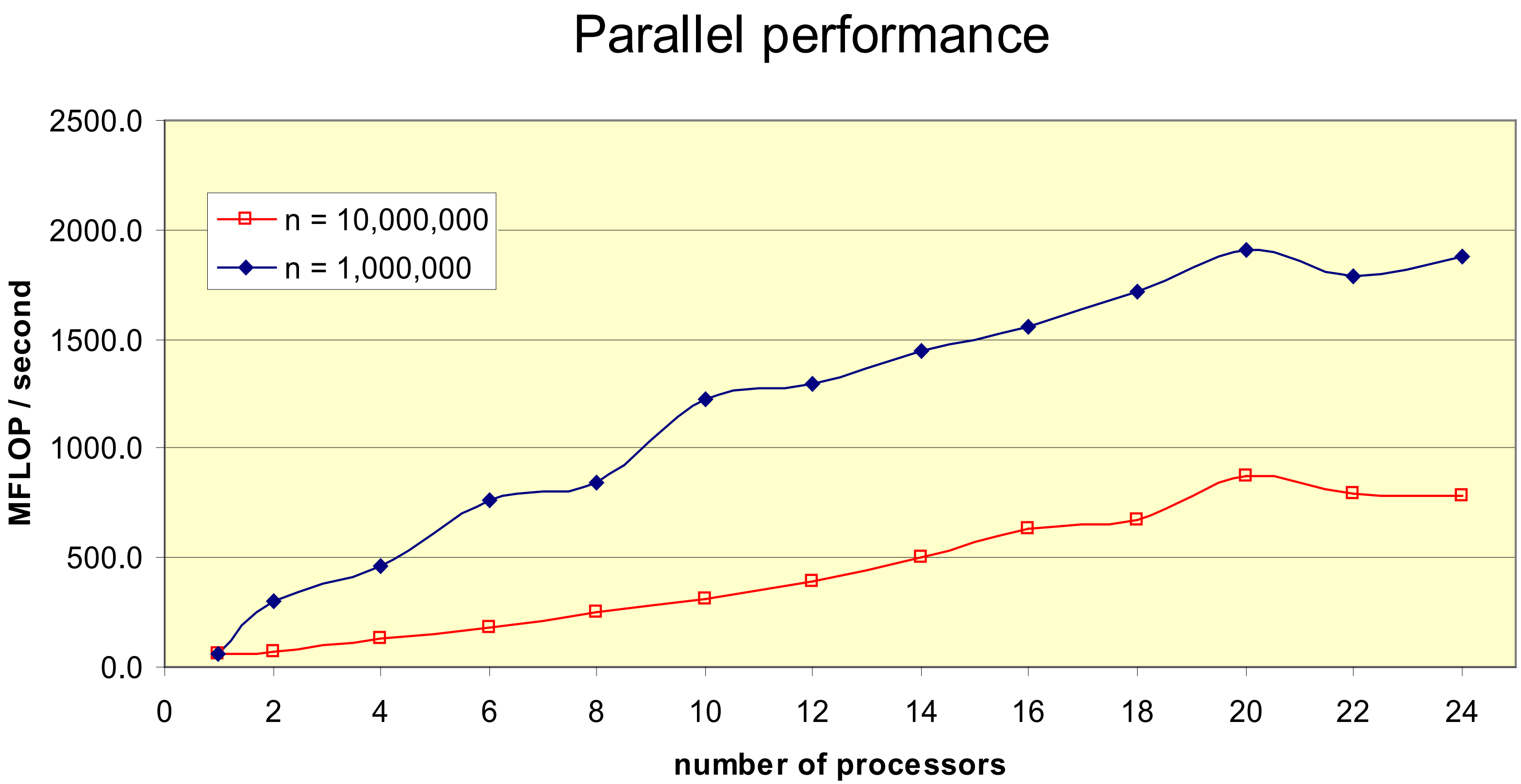
Time

- Shortest time is our true goal
  - But hard to judge improvements because values get very small at large p



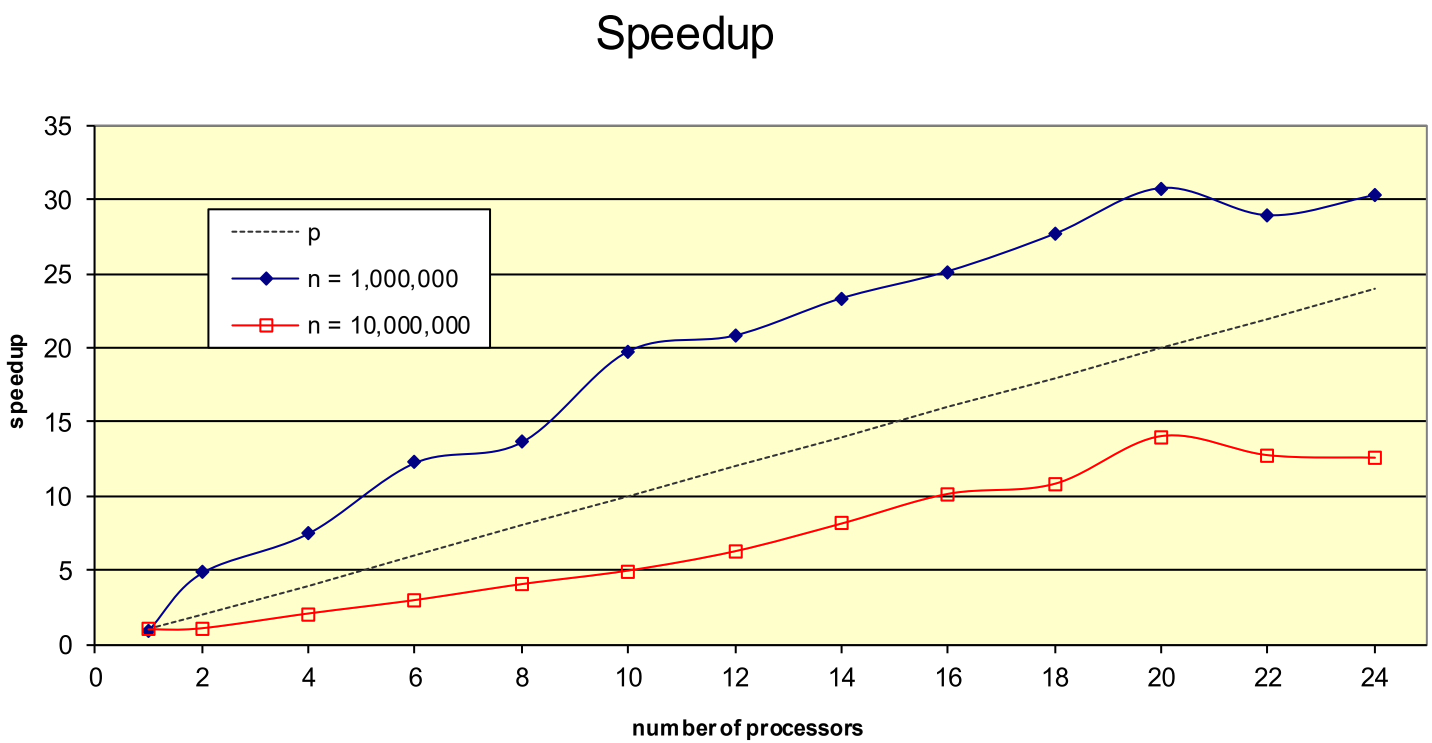
Execution rate (MFLOP / second)

- Shows work per time
  - easier to judge scaling
  - highest detail at large n, p
  - how to measure MFLOPS?



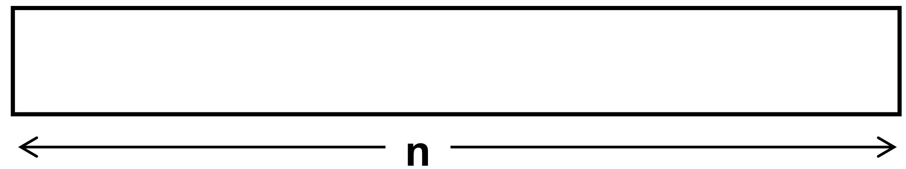
Speedup

- Speedup of run time relative to single processor (t_1 / t_p)
  – How to define t_1?
    - run time of parallel algorithm at p = 1?
    - run time of best serial algorithm?
  – Superlinear speedup ?

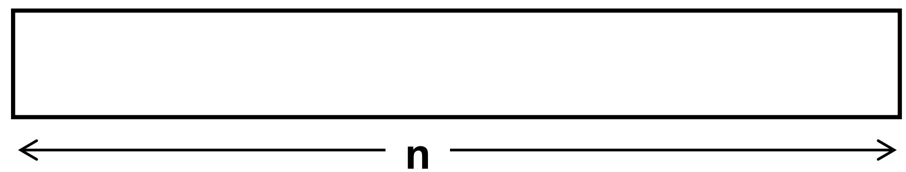


OpenMP: scheduling loop iterations

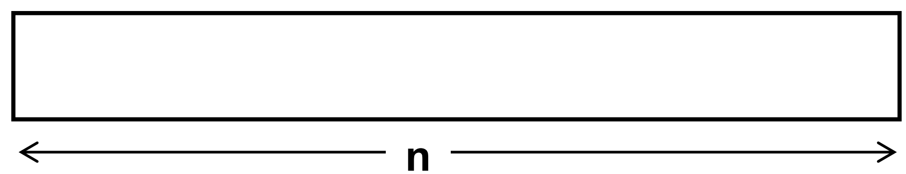
- Scheduling a loop with n iterations using p threads
  - The unit of scheduling is a chunk of k iterations
  - T_i means iteration(s) executed by thread i
- `schedule(static,k)`
  - Chunks mapped to threads in at entry to loop
  - default k = n/p



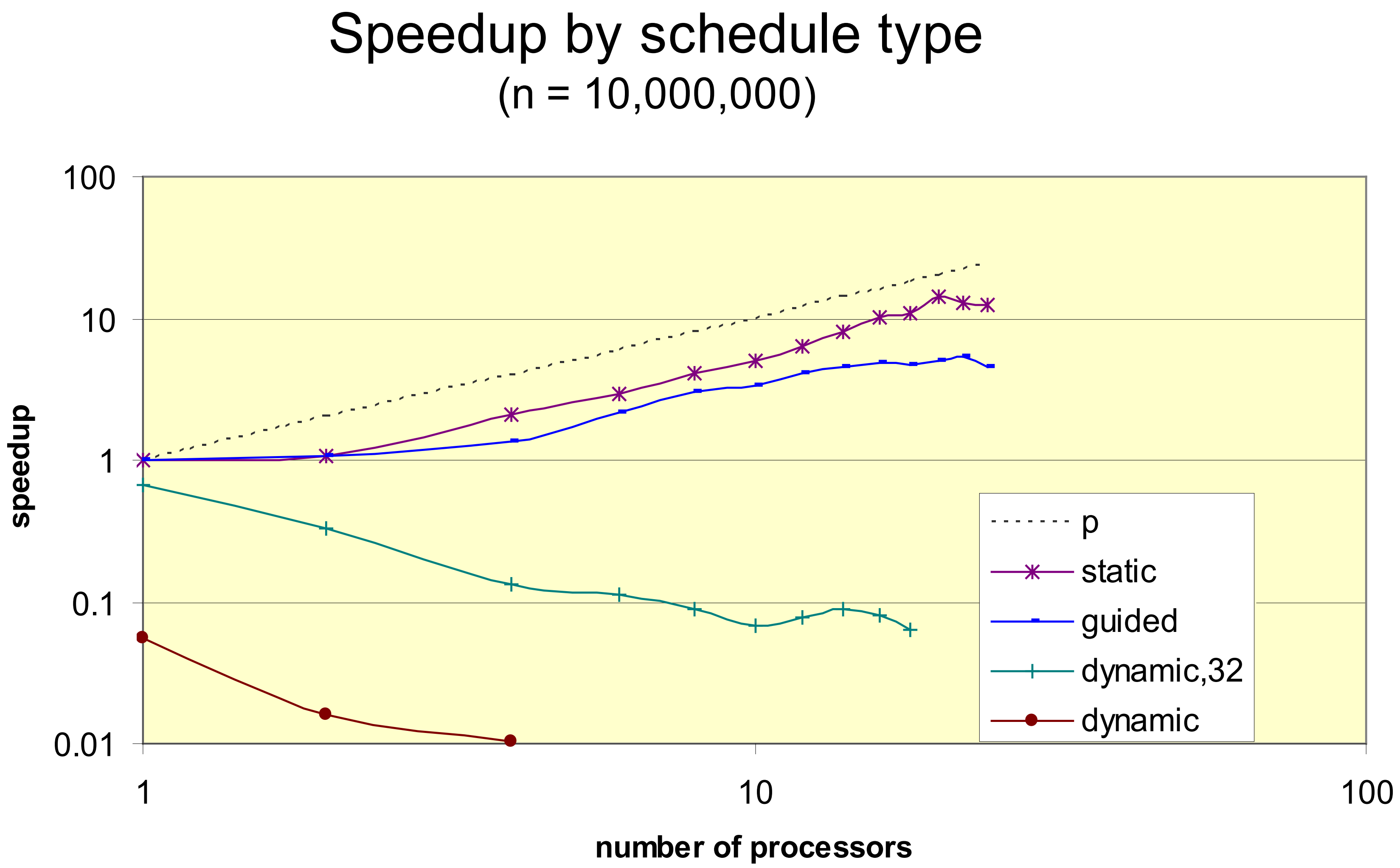
- `schedule(dynamic,k)`
  - chunks handed out consecutively to ready threads
  - default k = 1



- `schedule(guided,k)`
  - size d chunk handed to first available thread
  - d decreases exponentially from n/p down to k: $d_{i+1} = (1-1/p)d_i$ where $d_0=n/p$
  - default k = 1



Varying scheduling strategy: diffusion problem

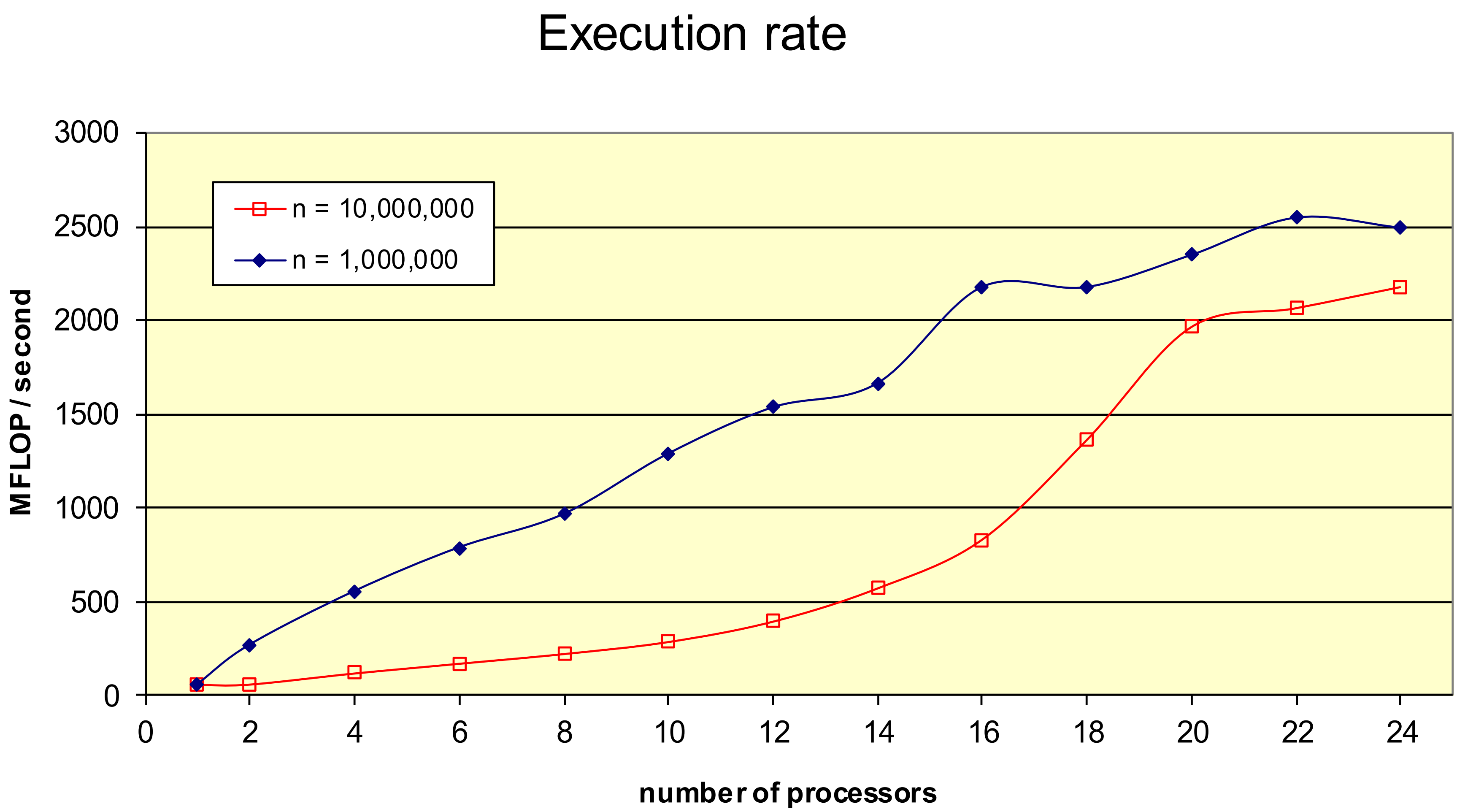


Causes of poor parallel performance

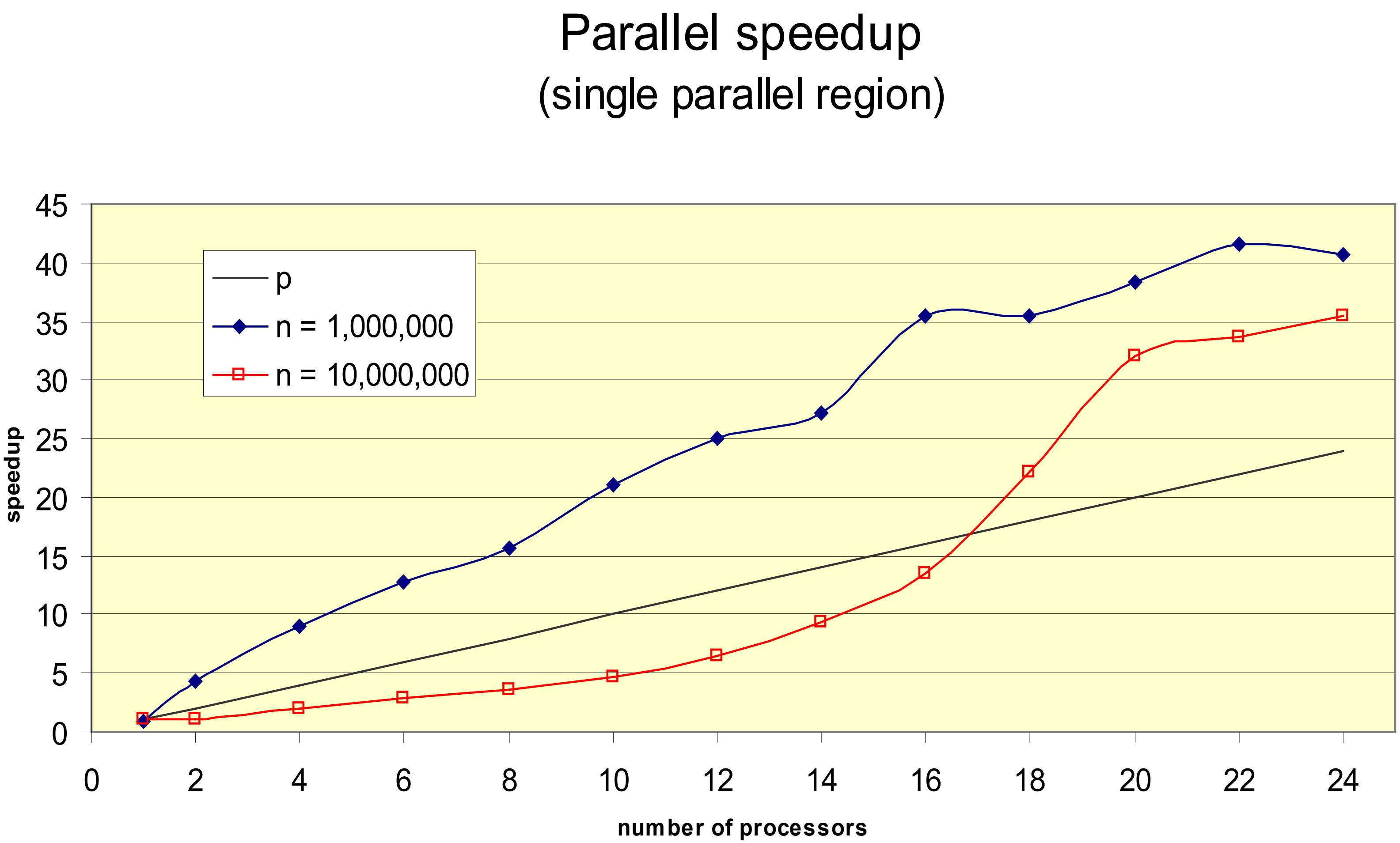
Possible suspects:

- Low computational intensity
  - Performance limited by memory performance
- Poor cache behavior
  - access pattern has poor locality
  - access pattern is poorly matched to CC-NUMA
- Sequential overhead
  - Amdahl's law
    - fraction f serial work limits speedup to 1/f
- Load imbalance
  - Unequal distribution of work, <u>or</u>
  - Unequal thread progress on equal work
    - busy machine, uncooperative OS
    - CC-NUMA issues
- Bad luck
  - Insufficient sampling - show timing variation on plots!

Cache-related mysteries



Cache-related mysteries: speedup



OpenMP on CC-NUMA

- Performance guidelines
  - shared data structures
    - use cache-line spatial locality
      - linear access patterns (read and write)
      - structs with components grouped by access
    - don't mix reads and writes to same data on different processors
      - use phased updates
    - avoid *false sharing*
      - unrelated values sharing a cache line *updated* by multiple threads
    - make sure data structures are physically distributed across memory
      - by parallel initialization
        - » artifact of page placement policy under e.g. Linux
      - by explicit placement directives and page allocation policies

OpenMP on CC-(N)UMA

- Other guidelines
  - Enlarge parallel region
    - to retain processor – data affinity
    - to avoid overhead of repeated entry to parallel region in an inner loop
  - Use appropriate work distribution schedule
    - static, else
    - guided, else
    - dynamic with large chunksize
    - runtime-specified schedule involves relatively small overhead
  - Don’t use too many processors
    - OS scheduling of threads behaves erratically when machine is oversubscribed
    - be aware of dynamic thread adjustment (OMP_DYNAMIC)

Reductions and critical statements

- a reduction loop does not have independent iterations

```
for (i=0; i<n; i++) {
    sum = sum + a[i];
}
```

- the loop may be parallelized by inserting a critical section
  - the critical directive <u>serializes</u> a single statement or block

```
#pragma omp parallel for
  for (i=0; i<n; i++) {
      #pragma omp critical
      sum = sum + a[i];
  }
```

  - but this is a poor strategy!

- a reduction loop can be identified using a `reduction` directive

```
#pragma omp parallel for reduction(+: sum)
  for (i=0; i<n; i++) {
      sum = sum + a[i];
  }
```

Implementation of reduction directive

- A better implementation of the reduction loop

```
sum = 0;
#pragma omp parallel
{
    int i, local_sum = 0;
    #pragma omp for
    for (i=0; i<n; i++) {
        local_sum = local_sum + a[i];
    }
    #pragma omp critical
    sum = sum + local_sum;
}
```

  – reduces number of critical operations from *n* to *p*

- other reduction strategies
  – serialization: master thread sequentially combines local_sum values
  – tree-based reduction
  – hybrid strategy

  OpenMP compiler should generate code that selects optimal strategy at run time