Introduction to shared memory parallel programming with OpenMP

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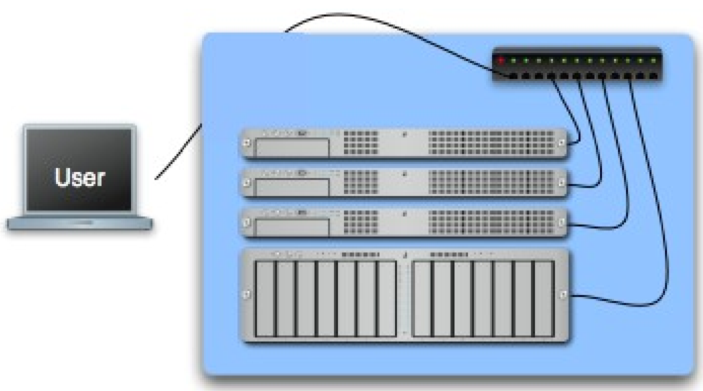
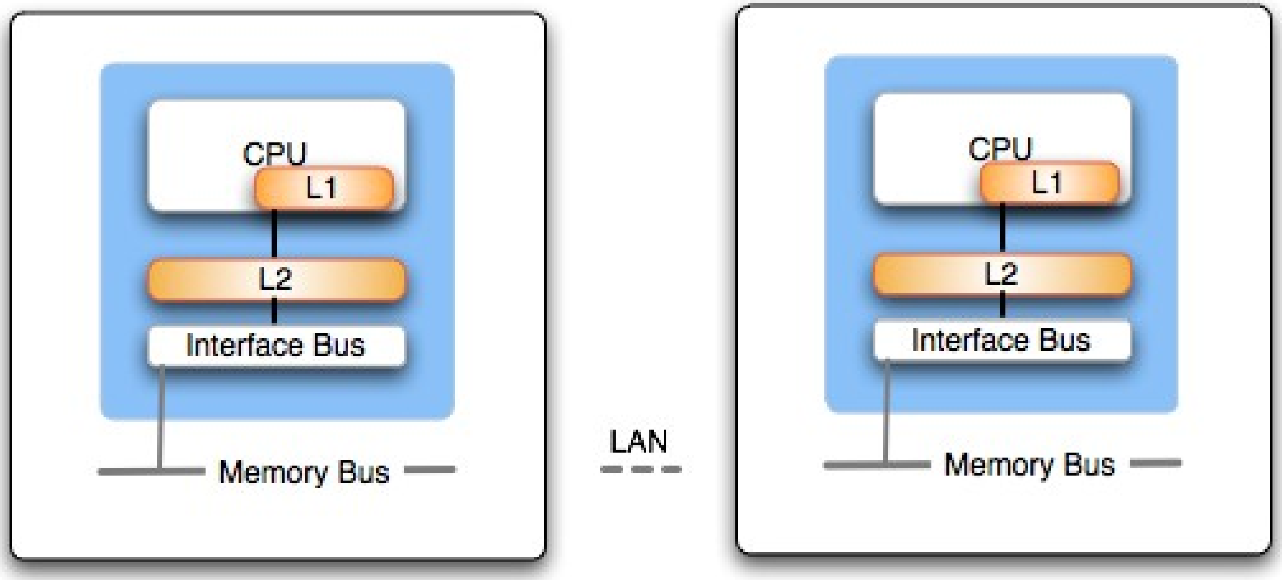
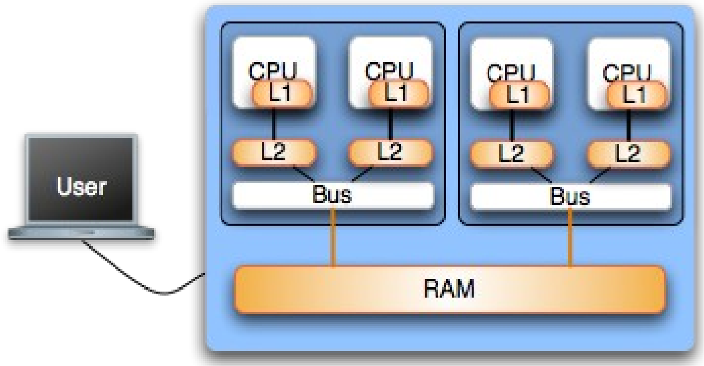
Overview

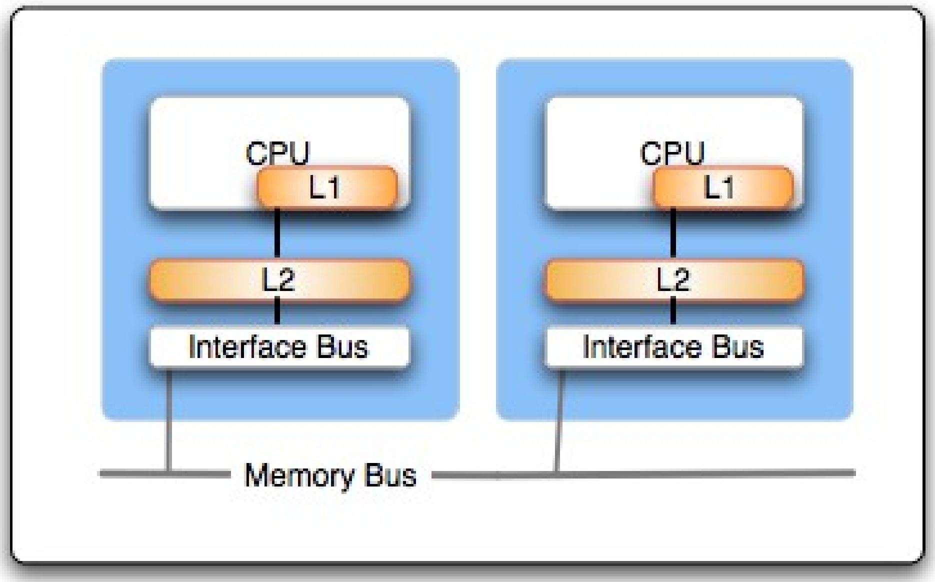
- Shared vs Distributed memory models
- Why OpenMP
- How OpenMP works
- Basic examples
- How to execute the executable

Hardware considerations







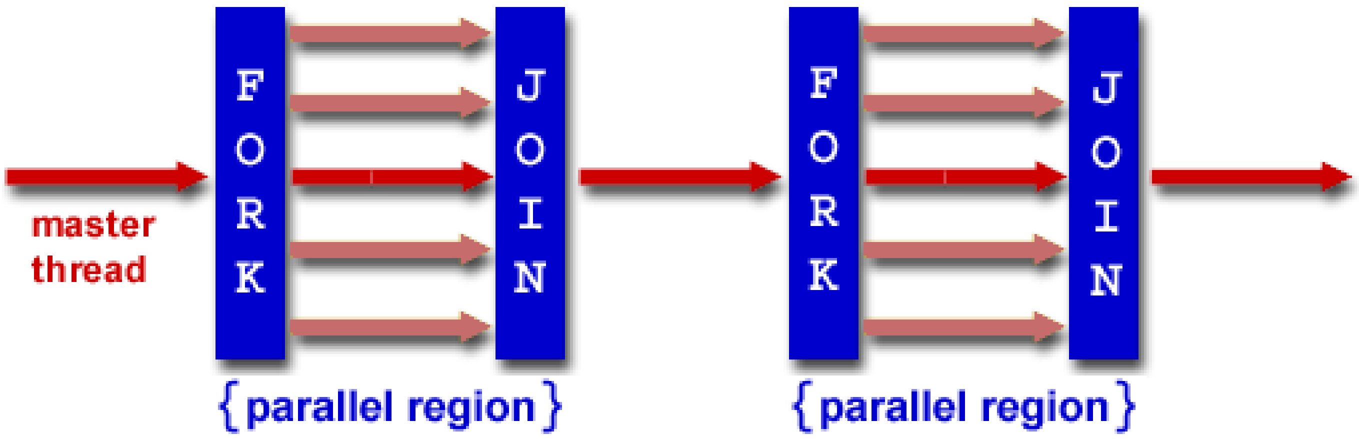


Introduction to OpenMP

- API extension to C/C++ and Fortran languages
  - Most compilers support OpenMP
    - GNU, IBM, Intel, PGI, PathScale, Open64 …
- Extensively used for writing programs for shared memory architectures over the past decade
- Thread (process) communication is implicit and uses variables pointing to shared memory locations; this is in contrast with MPI which uses explicit messages passed among each process

Threaded parallel programming (openMP)

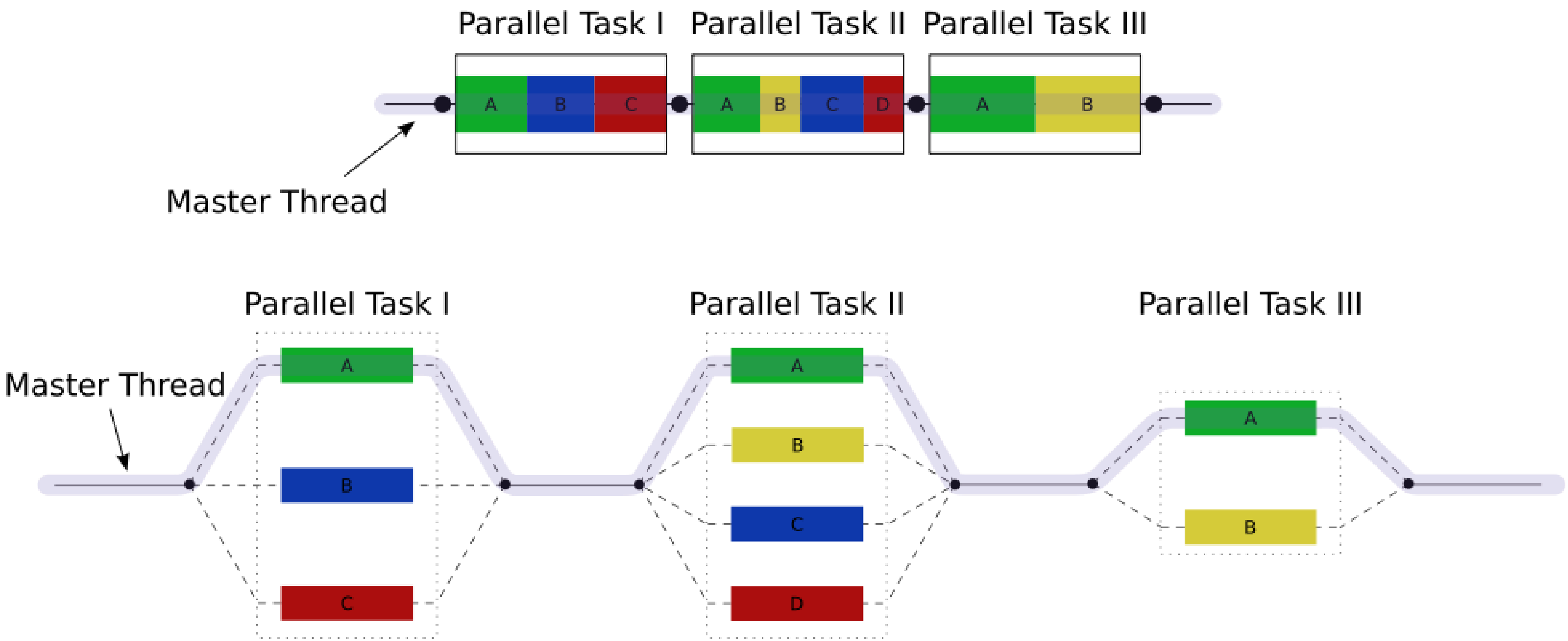
- openMP is based on a fork - join model
  - Master - worker threads



Use of directives and pragmas within source code

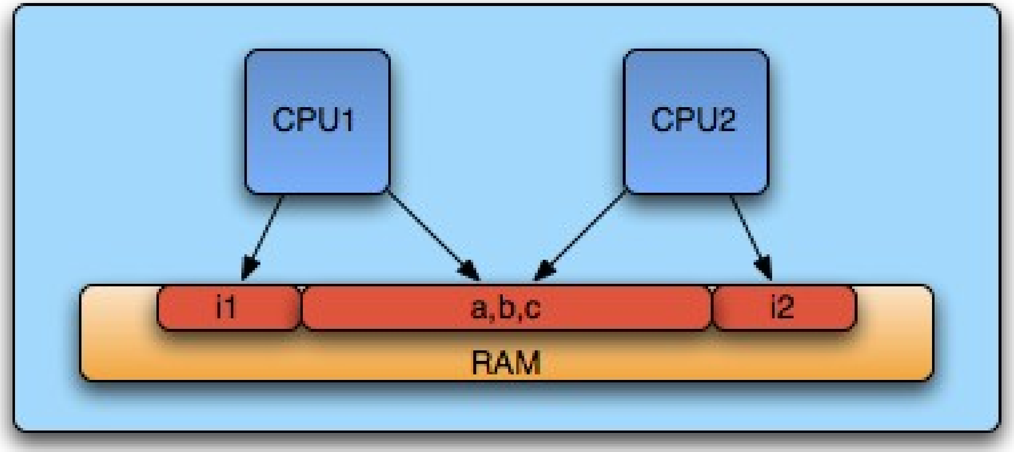
Approach towards parallelism

- From serial to parallel with OpenMP



Memory issues

- Threads have access to the same address space
  - Communication is implicit
- Programmer needs to define
  - local data
  - shared data



Yet another hello world example

```fortran
      PROGRAM HELLO

      INTEGER NTHREADS, TID, OMP_GET_NUM_THREADS,
     +        OMP_GET_THREAD_NUM

!     Fork a team of threads giving them their own copies of variable:
!$OMP PARALLEL PRIVATE(TID)

!     Obtain thread number
      TID = OMP_GET_THREAD_NUM()
      PRINT *, 'Hello World from thread = ', TID

!     Only master thread does this
      IF (TID .EQ. 0) THEN
        NTHREADS = OMP_GET_NUM_THREADS()
        PRINT *, 'Number of threads = ', NTHREADS
      END IF

!     All threads join master thread and disband
!$OMP END PARALLEL

      END
```

```cpp
#include <iostream>
#include <omp.h>

using namespace std;

int main(int argc, char* argv[])
{
  #pragma omp parallel
  {
    printf("Hello World! This is thread %d out of %d\n",
           omp_get_thread_num(), omp_get_num_threads());
  }
  return 0;
}
```

Environment variable
OMP_NUM_THREADS

Common API calls

Call	Description
int omp_get_num_threads()	Returns the number of threads in the concurrent team
int omp_get_thread_num()	Returns the id of the thread inside the team
int omp_get_num_procs()	Returns the number of processors in the machine
int omp_get_max_threads()	Returns maximum number of threads that will be used in the next parallel region
double omp_get_wtime()	Returns the number of seconds since a time in the past
bool omp_in_parallel()	1 if in parallel region, 0 otherwise

Common API calls example

```
#include <iostream>
#include <omp.h>

using namespace std;

int main(int argc, char* argv[])
{
  double start = omp_get_wtime();
  if( !omp_in_parallel() )
  {
    printf("Number of processors is: %d\n", omp_get_num_procs());
    printf("Number of max threads is: %d\n", omp_get_max_threads());
  }
  sleep(1);
  double end = omp_get_wtime();
  printf("start = %.16g\nend = %.16g\ndiff = %.16g\n",
              start, end, end - start);
  return 0;
}
```

Data scoping

- For each parallel region the data environment is constructed through a number of clauses
  - shared (variable is common among threads)
  - private (variable inside the construct is a new variable)
  - firstprivate (variable is new but initialized to its original value)
  - default (used to set overall defaults for construct)
  - lastprivate (variable's last value is copied outside construct)
  - reduction (variable's value is reduced at the end)

A few examples

```
int x=1;
#pragma omp parallel shared(x) num_threads(2)
{
   x++;
   printf("%d\n",x);
}
printf("%d\n",x);
```

x = 3
x = 2
x = 3

or

x = 2
x = 3
x = 3

```
int x=1;
#pragma omp parallel private(x) num_threads(2)
{
   x++;
   printf("%d\n",x);
}
printf("%d\n",x);
```

Will print anything and then x=1

```
int x=1;
#pragma omp parallel firstprivate(x) num_threads(2)
{
   x++;
   printf("%d\n",x);
}
printf("%d\n",x);
```

x = 2
x = 2
x = 1

Synchronization

- OpenMP provides several synchronization mechanisms
  - barrier (synchronizes all threads inside the team)
  - master (only the master thread will execute the block)
  - critical (only one thread at a time will execute)
  - atomic (same as critical but for one memory location)

Synchronization examples

```
int x=1;
#pragma omp parallel num_threads(2)
{
   x++;
   #pragma omp barrier
   foo(x);
}
```

foo(3), foo(3)

```
int x=1;
#pragma omp parallel num_threads(2)
{
   #pragma omp master
   {
      x++;
   }
   foo(x);
}
```

foo(2), foo(2) or foo(1), foo(2)

```
int x=1;
#pragma omp parallel num_threads(2)
{
  #pragma omp critical
  {
    x++;
    foo(x);
  }
}
```

foo(2), foo(3)

Data parallelism

- Worksharing constructs
  - Threads cooperate in doing some work
  - Thread identifiers are not used explicitly
  - Most common use case is loop worksharing
  - Worksharing constructs may not be nested
- DO/for directives are used in order to determine a parallel loop region

The for loop directive

```
#pragma omp for  [clauses]
for (iexpr ; test ; incr)
```

- Where clauses may be
  - private, firstprivate, lastprivate
  - Reduction
  - Schedule
  - Nowait
- Loop iterations must be independent
- Can be merged with parallel constructs
- Default data sharing attribute is shared

```
int i,j;
#pragma omp parallel
#pragma omp for private(j)
for(i=0; i<N; i++)
{
    for(j=0; j<N; j++)
        m[i][j] = f(i,j);
}
```

j must be declared private explicitly

i is privatized automatically

Implicit synchronization point at the end of for loop

The schedule clause

- Schedule clause may be used to determine the distribution of computational work among threads
  - static, chunk; The loop is equally divided among pieces of size chunk which are evenly distributed among threads in a round robin fashion
  - dynamic, chunk; The loop is equally divided among pieces of size chunk which are distributed for execution dynamically to threads. If no chunk is specified chunk=1
  - guided; similar to dynamic with the variation that chunk size is reduced as threads grab iterations
- Configurable globally via OMP_SCHEDULE
  - i.e. setenv OMP_SCHEDULE "dynamic,4"

Adding two vectors

```
#include <iostream>
#include <omp.h>

using namespace std;

int main(int argc, char **argv)
{
  int n = atoi(argv[1]);
  double *x, *y;

  x = new double [n]; for(int i=0; i<n; i++) x[i] = (double) (i+2);
  y = new double [n]; for(int i=0; i<n; i++) y[i] = (double) (i*3);

  double start = omp_get_wtime();
  #pragma omp parallel for
    for (int i=0; i<n; i++) x[i] = x[i] + y[i];
  double end = omp_get_wtime();
  printf("diff = %.16g\n", end - start);

  return 0;
}
```

Reduction clause

- Useful in the case one variable’s value is accumulated within a loop
- Using the reduction clause
  - A private copy per thread is created and initialized
  - At the end of the region the compiler safely updates the shared variable
  - Operators may be +, *, -, /, &, ^, |, &&, ||

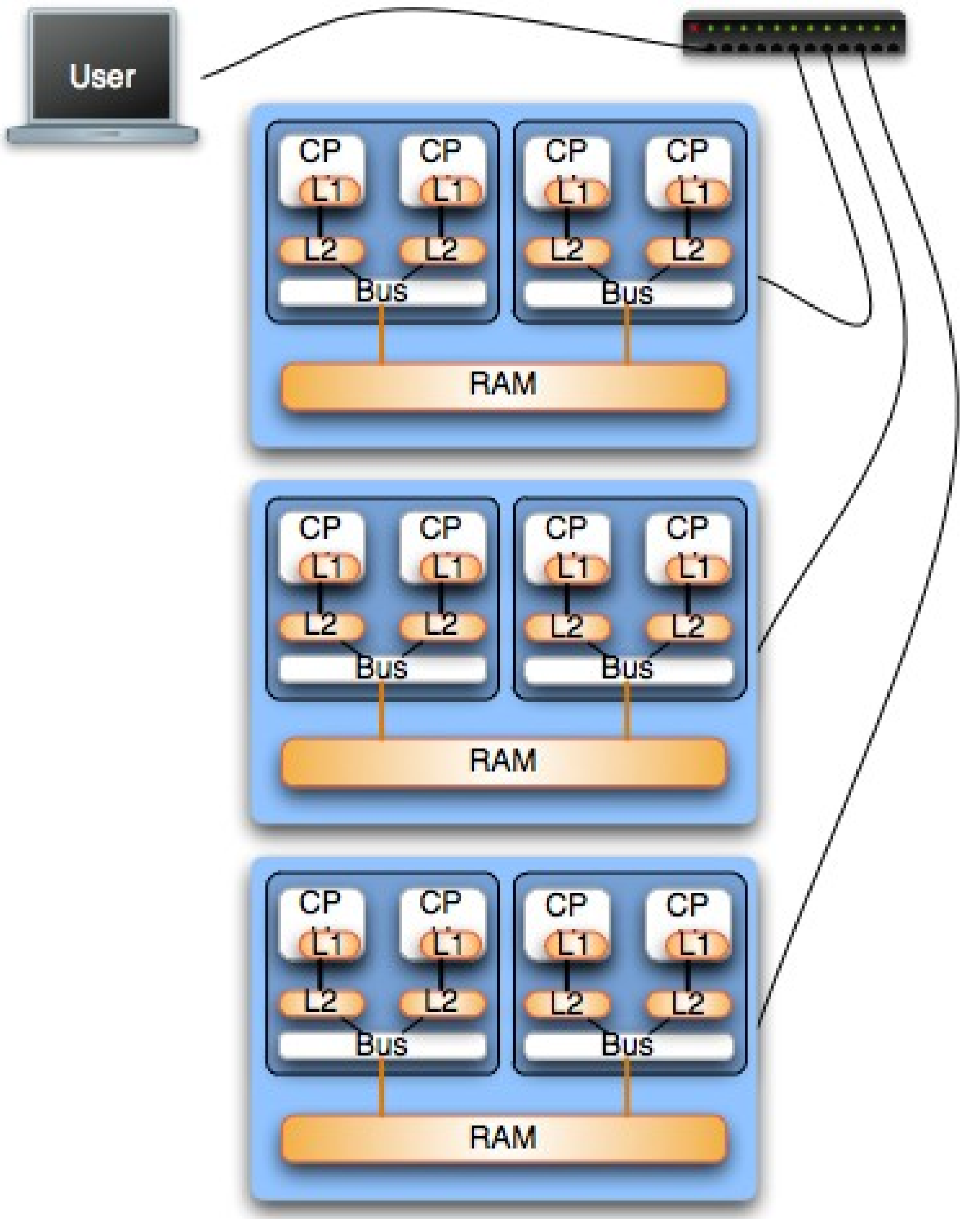
Reduction clause example

```
#include <iostream>
#include <cmath>
#include <vector>
#include <omp.h>

using namespace std;

int main(int argc, char* argv[])
{
        // declerations
        int i,N=atoi(argv[1]);
        vector <double> A(N);
        double s;
        // calculations
        #pragma omp parallel for shared(A,N) private(i)
        for(i=0; i<N; i++)
        {
                A[i] = pow(cos((double) i),2)/3.0 - 1.0/sqrt((double) (i+1));
        }
        #pragma omp parallel for shared(A,N) private(i) reduction(+:s)
        for(i=0; i<N; i++)
        {
                s += A[i];
        }
        cout << "Total sum is s = "<< s << endl;
        return 0;
}
```

Mixing MPI and OpenMP



- Hybrid architectures
  - Clusters on SMPs
  - HPC Platforms
    - IBM BlueGene (i.e. Jugene)
    - IBM P6 (i.e. Huygens)
- Good starting point
  - Mapping of MPI on nodes (interconnection layer)
  - Multithreading with OpenMP inside SMPs