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SUMMIT

Parallel Programming with GCC

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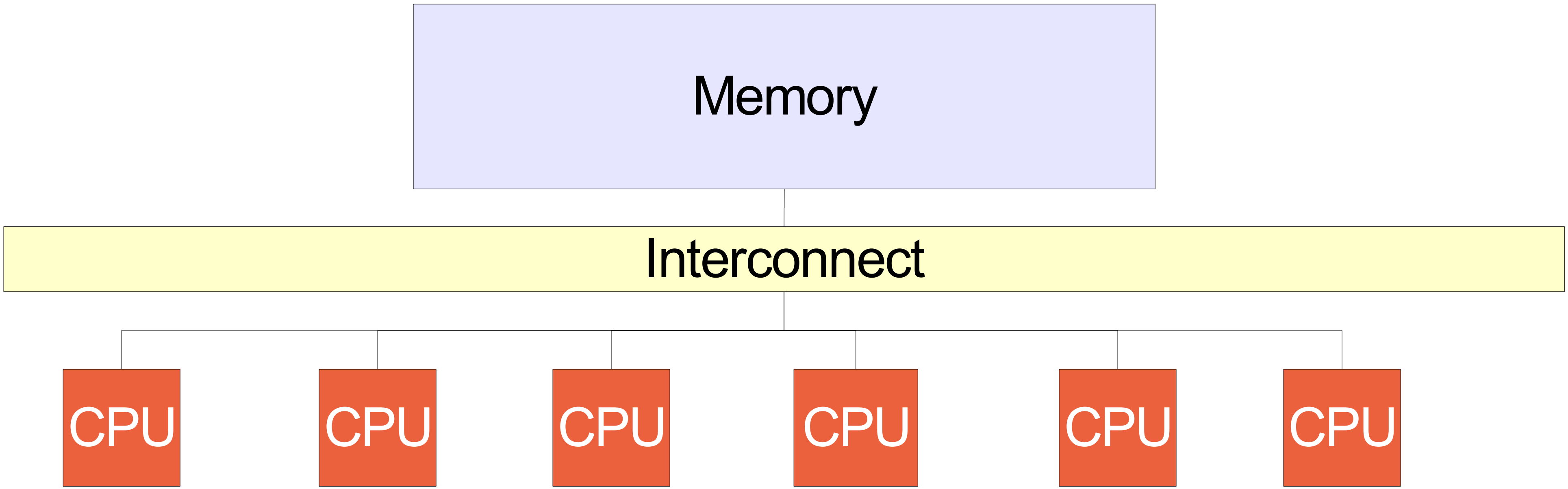
Outline

- Introduction to parallel computing
- Parallel programming models
  - Automatic parallelization
  - Shared memory
  - Message passing
- Vectorization in GCC
- Introduction to OpenMP
- Status and Conclusions

Parallel Computing

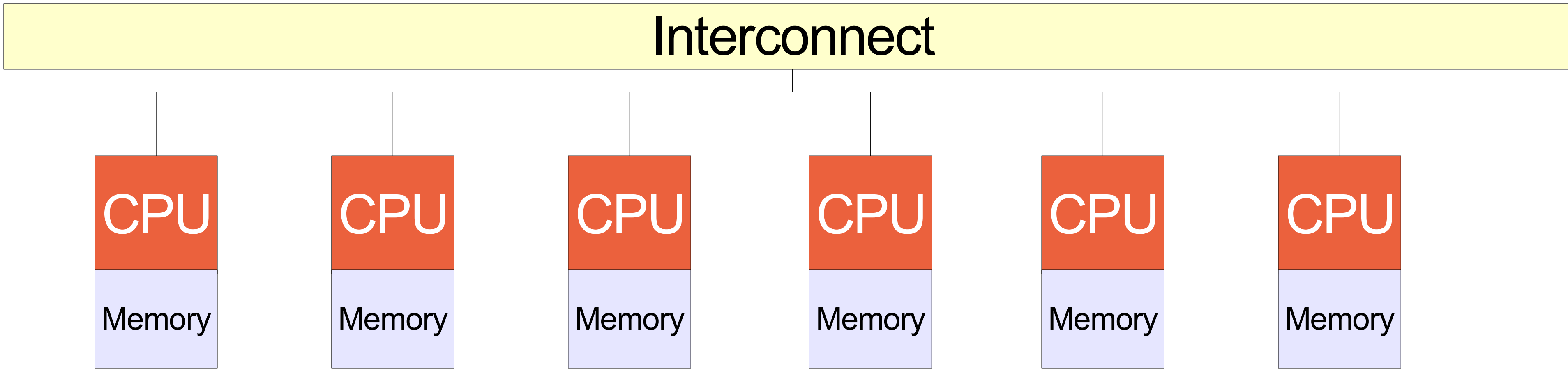
- Use hardware concurrency for increased
  - Performance
  - Problem size
- Two main models
  - Shared memory
  - Distributed memory
- Nature of problem dictates
  - Computation/communication ratio
  - Hardware requirements

Shared Memory



- Processors share common memory
- Implicit communication
- Explicit synchronization
- Simple to program but hidden side-effects

Distributed Memory



- Each processor has its own private memory
- Explicit communication
- Explicit synchronization
- Difficult to program but no/few hidden side-effects

Programming Models

- Shared/Distributed memory often combined
  - Networks of multi-core nodes
  - Parallelism available at various levels
- Additional requirements over sequential
  - Task creation
  - Communication
  - Synchronization
- How do we program these systems?

Automatic Parallelization

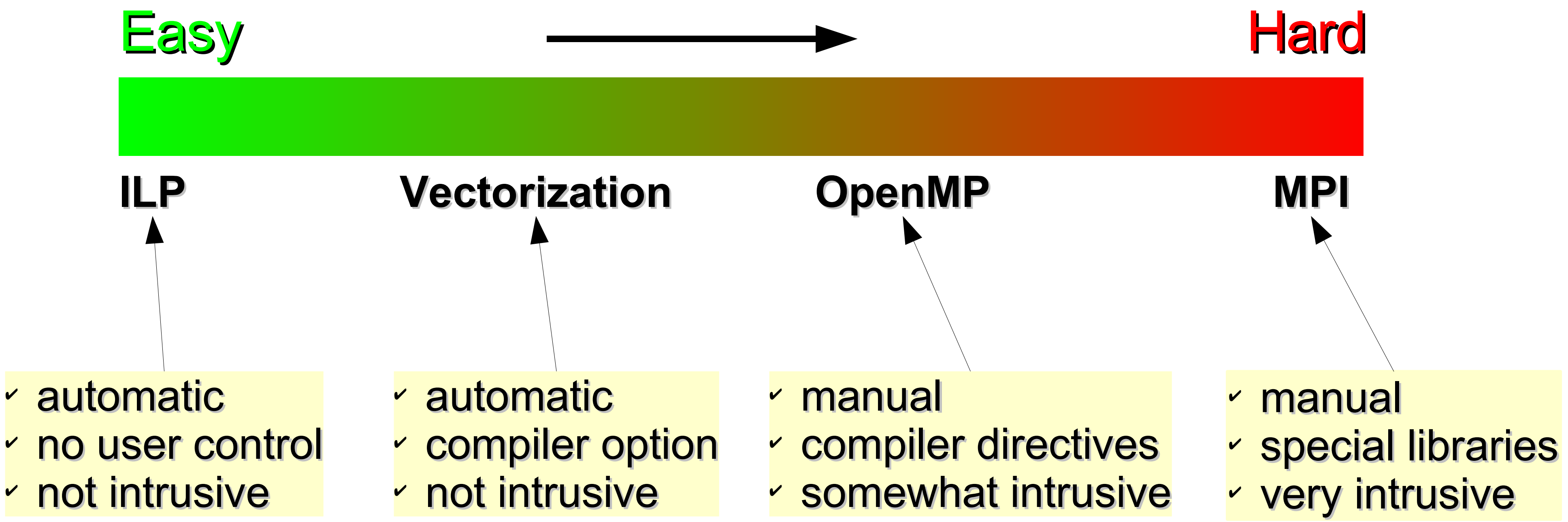
- Holy grail for a long time
- Limited success
- Hampered by need to preserve sequential semantics
- Useful in certain application domains
  - Loop intensive codes
  - No “complex” data dependencies across iterations
- Vectorization, instruction-level parallellism (ILP), loop parallelism

Explicit Parallelism

- User controls: Tasks, communication and synchronization
- Increased programming complexity
  - Often require different algorithms
- Many different approaches
  - Parallel languages or language extensions: HPF, Occam, Java
  - Compiler annotations: OpenMP
  - Libraries: Pthreads, MPI

Parallelism in GCC

GCC supports four concurrency models



Ease of use not necessarily related to speedups!

Vectorization

- Perform multiple array computations at once
- Two distinct phases
  - Analysis → high-level
  - Transformation → low-level
- Successful analysis depends on
  - Data dependency analysis
  - Alias analysis
  - Pattern matching
- Suitable only on loop intensive code

Vectorization

- Enable vectorizer

```
$ gcc -ftree-vectorize -O2 prog.c
```

- Additional **-m** flags on some architectures
  - PowerPC → **-maltivec**
  - x86 → **-msse2**
- Speedups depend greatly on
  - Regular, compute-intensive loops
  - Data size and alignment
  - “Simple” code patterns in inner loops
  - Aliasing

Vectorization

- Debugging
  - `-fdump-tree-vect` enables dump
  - `-ftree-vectorizer-verbose=[0-7]` controls verbosity
- Features and limitations
  - Multi-platform vectorization: x86, ppc, ia64, etc
  - Recognized patterns grow with each release
  - Only works on loops (straight-line code in progress)

Vectorization

```
int a[256], b[256], c[256];

foo ()
{
  for (i = 0; i < 256; i++)
   a[i] = b[i] + c[i];
}
```

Vectorized

(~2x on P4)

```
.L2:
        movdqa  c(%eax), %xmm0
        paddd   b(%eax), %xmm0
        movdqa  %xmm0, a(%eax)
        addl    $16, %eax
        cmpl    $1024, %eax
        jne     .L2
```

Scalar

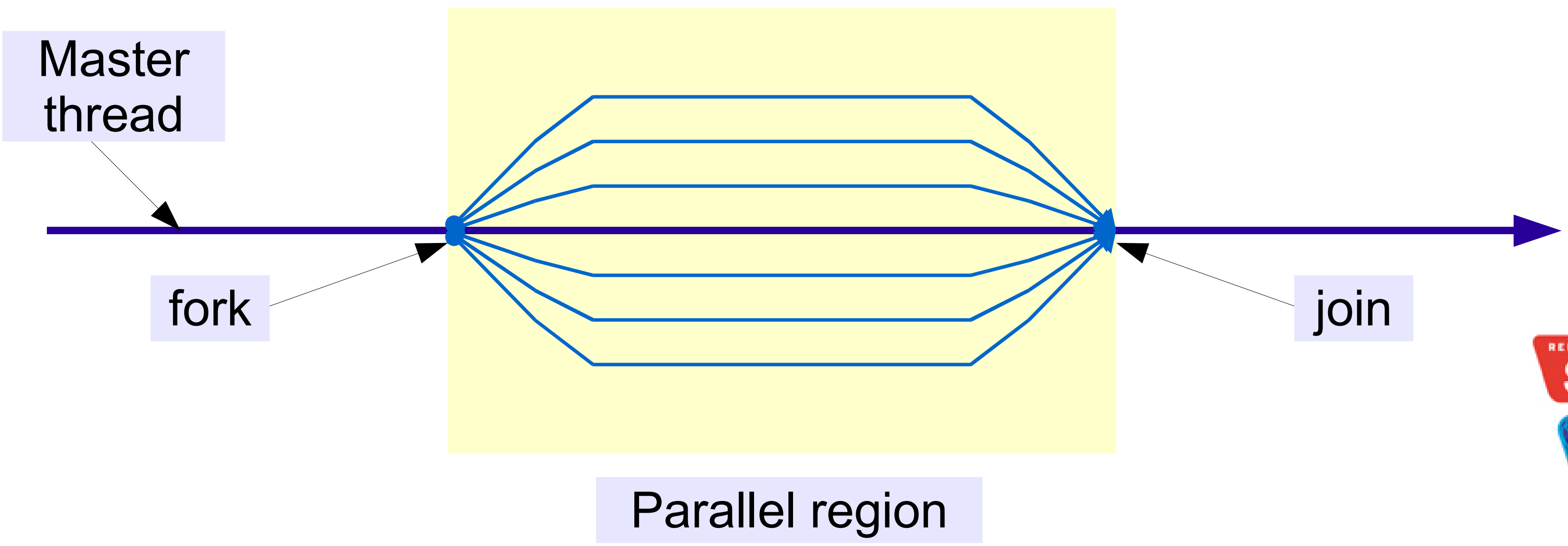
```
.L2:
        movl    c(,%edx,4), %eax
        addl    b(,%edx,4), %eax
        movl    %eax, a(,%edx,4)
        addl    $1, %edx
        cmpl    $256, %edx
        jne     .L2
```

OpenMP - Introduction

- Language extensions for shared memory concurrency
- Supports C, C++ and Fortran
- Embedded directives specify
  - Parallelism
  - Data sharing semantics
  - Work sharing semantics
- Standard and increasingly popular

OpenMP – Programming Model

- Based on fork/join semantics
  - Master thread spawns teams of children threads
  - All threads share common memory
- Allows sequential and parallel execution



OpenMP - Programming Model

- Compiler directives via pragmas (C, C++) or comments (Fortran).
- Compiler replaces directives with calls to runtime library (`libgomp`)
- Runtime controls available via library API and environment variables
- Environment variables control parallelism

OMP_NUM_THREADS	**OMP_SCHEDULE**
OMP_DYNAMIC	**OMP_NESTED**

OpenMP – Programming Model

- Explicit sharing and synchronization
- Threads interact via shared variables
  - Several ways for specifying shared data
  - Sharing always at the variable level
- Programmer responsible for synchronization
  - Unintended sharing leads to “data races”
  - Use synchronization directives and library API
  - Synchronization is expensive

OpenMP - Hello World

```c
#include <omp.h>
main()
{
  #pragma omp parallel
  printf ("[%d] Hello\n", omp_get_thread_num());
}
```

```
$ gcc -fopenmp -o hello hello.c
$ ./hello
[2] Hello
[3] Hello
[0] Hello    ← Master thread
[1] Hello
```

```
$ gcc -o hello hello.c
$ ./hello
[0] Hello
```

OpenMP – Directives and Clauses

- Directives are the main OpenMP construct
- Clauses provide modifiers and attributes to the directives
- General syntax is
  - C/C++

```
#pragma omp directive [ clause [ clause ] ... ]
```

  - Fortran

```
c$omp directive [ clause [ clause ] ... ]
!$omp directive [ clause [ clause ] ... ]
*$omp directive [ clause [ clause ] ... ]
```

OpenMP – Directives and Clauses

- Directives are enabled with **`-fopenmp`**
- Most directives only apply to structured blocks
  - No early exits except program termination
- Directives control
  - Thread creation
  - Work sharing
  - Synchronization
- Clauses control data sharing

OpenMP – Thread creation

- Exactly **one** way to specify parallelism

```
#pragma omp parallel [ clauses ]
   structured-block
```

- Every thread executes the block
- Number of threads created depends on
  - Environment variable **OMP_NUM_THREADS**
  - Clauses **num_threads** and **if**
  - Library function **omp_set_num_threads**

OpenMP – Thread creation

- Number of threads involved may be dynamic
  - Environment variable **`OMP_DYNAMIC`**
  - Library function **`omp_set_dynamic`**
- No implicit synchronization between threads
- At end of parallel region all children threads disappear
- Every thread has a unique ID starting at 0
  - Useful for distributing work (*work sharing*)

OpenMP – Work Sharing

- Different threads should work on different parts of a problem
- Distribution can be specified manually using thread IDs
- Directives for common work sharing patterns
  - Data parallel loops

```
#pragma omp for [ clauses ]
```

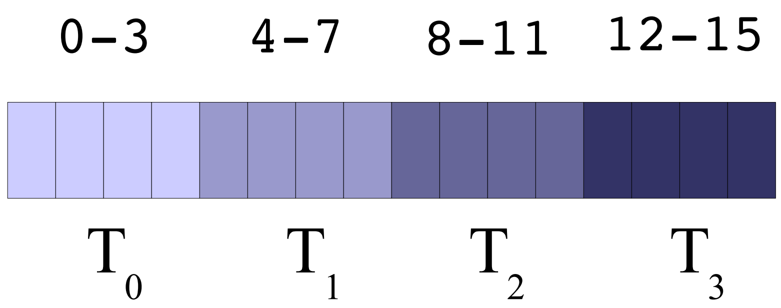
  - cobegin/coend

```
#pragma omp sections [ clauses ]
```

OpenMP – Parallel loops

- Most common work sharing mechanism
- Threads execute subset of iteration space

```
#pragma omp parallel
#pragma omp for
for (i = 0; i < 16; i++)
  a[i] = i;
```



- Scheduling determines distribution of chunks
- No synchronization other than implicit barrier at the end of the loop

OpenMP – Parallel loops

- `#pragma omp for schedule(type[, chunk])`
- Schedule type is
  - `static` Static round-robin distribution
  - `dynamic` First-come, first-serve queue
  - `guided` Same as dynamic but varying chunk size proportional to outstanding iterations
  - `runtime` Taken from environment `OMP_SCHEDULE`.
- Dynamic and guided schedules may achieve better load balancing
- Runtime useful to avoid re-compiling.

OpenMP – Parallel sections

- **`#pragma omp sections`**
- cobegin/coend parallelism
- Sections delimited with **`#pragma omp section`**
- Each section is executed by a different thread

```
#pragma omp parallel sections
{
  #pragma omp section
  t1();
  #pragma omp section
  t2();
  #pragma omp section
  t3();
}
```

Can be combined

OpenMP – Fortran arrays

- **`#pragma omp workshare`**
- Distributes execution of Fortran FORALL, WHERE and array assignments
- Distribution of units of work is up to the compiler

```
integer :: a (10), b (10)
!$omp parallel workshare
  a = 10
  b = 20
  a(1:5) = max (a(1:5), b(1:5))
!$omp end parallel workshare
```

OpenMP – Data sharing

- Sharing specified at variable level
- **`#pragma omp [ ... ] shared (x,y)`**
  - All threads access the same variable
- **`#pragma omp [ ... ] private (x,y)`**
  - All threads have their own copy
- **`#pragma omp [ ... ] firstprivate (x,y)`**
  - Private with initial value taken from master thread

OpenMP – Data sharing

- `#pragma omp [ ... ] lastprivate (x,y)`
  - Private with last value taken from last iteration or lexically last section
  - Only valid for parallel loops and sections
- `#pragma omp [ ... ]reduction (op:x)`
  - Apply reduction operator ***op*** to private copy of **`x`** and update original at the end
  - C/C++ → `+ * - & | ^ && ||`
  - Fortran → `+ * - .and. .or. .eqv. .neqv. max min iand ior ieor`

OpenMP – Data sharing

- **`#pragma omp single copyprivate (x)`**
  - Broadcast private **`x`** to all the threads that did not enter the region
- **`#pragma omp threadprivate (x, y)`**
  - Global variables **`x`** and **`y`** are private to each thread
- **`#pragma omp [...] copyin(x, y)`**
  - Initialize threadprivate variables with the value from the master thread.

OpenMP – Data sharing

- Various rules to determine default/implicit sharing properties
  - Globals and heap allocated variables are shared
  - Locals declared outside a directive body are shared
  - Locals declared inside a directive body are private
  - Loop iteration variables for parallel loops are private

OpenMP – Synchronization

- With few exceptions user is ultimately responsible for preventing data races using OpenMP directives
- **`#pragma omp single`**
  - Only one thread in thread team enters block
- **`#pragma omp master`**
  - Only master thread enters block
- **`#pragma omp critical`**
  - Mutual exclusion

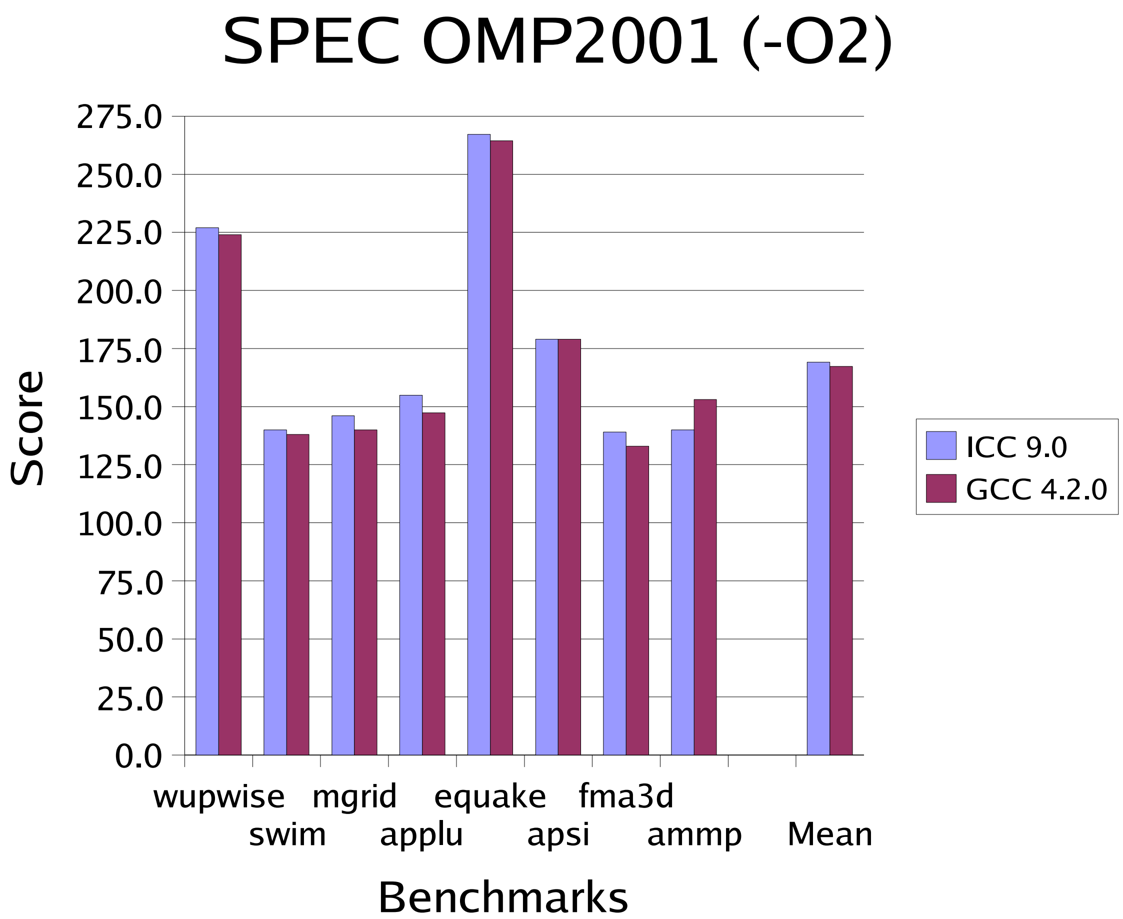
OpenMP – Synchronization

- **`#pragma omp barrier`**
- **`#pragma omp atomic`**
  - Atomic storage update: `x` *`op`*`= expr`, `x++`, `x--`
- **`#pragma omp ordered`**
  - Used in loops, threads enter in loop iteration order.

Status and Future Work

- Vectorization support started in 4.0 series
  - New patterns added with every release
  - Use on loop-intensive code
- OpenMP will be released with 4.2 later this year
- Implementation available in Fedora Core 5
- Automatic parallelism planned using OpenMP infrastructure

Status and Future Work



SPEC OMP2001 scores on dual-core EM64T

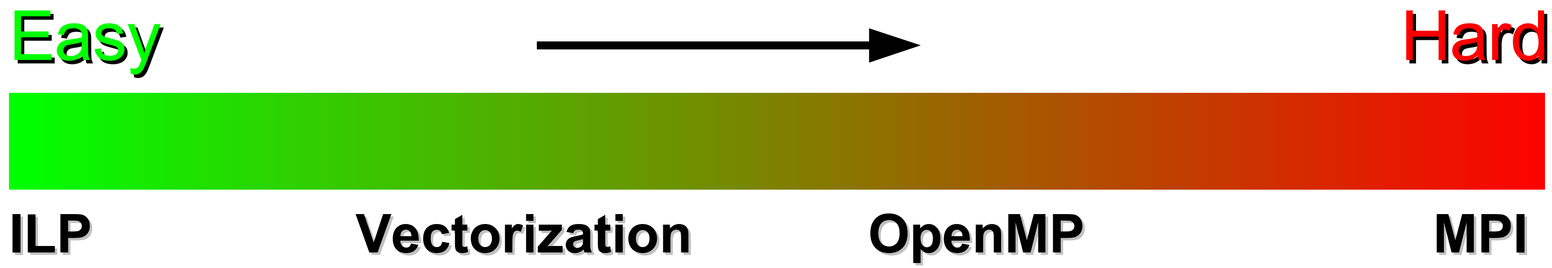
Message Passing

- Completely library based
- No special compiler support required
- The “assembly language” of parallel programming
  - Ultimate control
  - Ultimate pain when things go wrong
  - Computation/communication ratio must be high
- Message Passing Interface (MPI) most popular model

Message Passing

- Separate address spaces
  - It may also be used on a shared memory machine
- Heavy weight processes
- Communication explicit via network messages
  - User responsible for marshalling, sending and receiving

Conclusions



- There is no "right" choice
  - Granularity of work main indicator
  - Evaluate complexity ↔ speedup trade-offs
- Combined approach for complex applications
- Algorithms matter!
- Good sequential algorithms may make bad parallel ones