SICSA Int. Summer School on Advances in Programming Languages

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OpenMP Multicore Programming

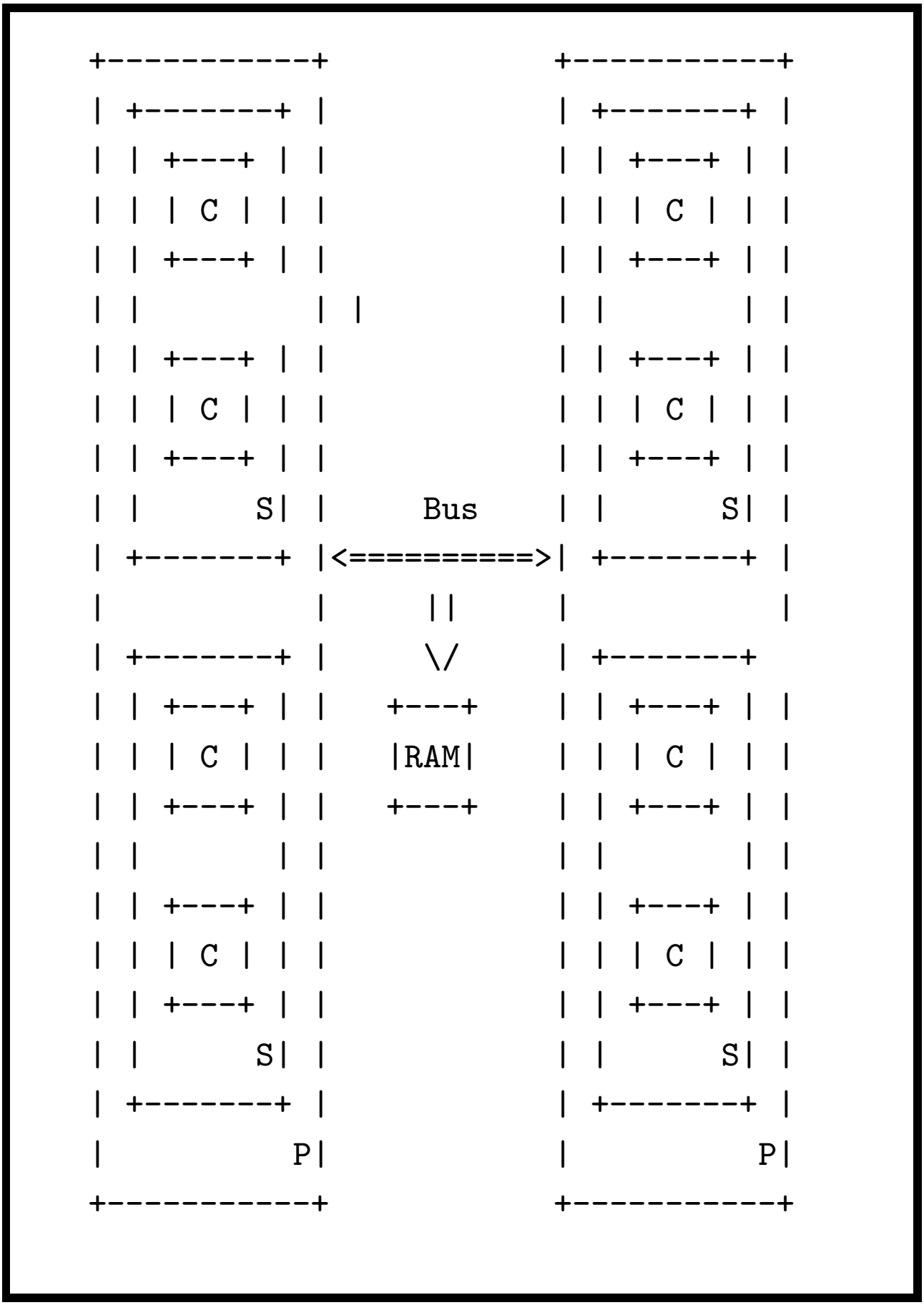
Reading Materials

Numerous Tutorials on the web
Chapters of Multicore Programming Textbooks
Wikipedia article

Parts of this lecture are adapted from
`computing.llnl.gov/tutorials/openMP/`

Multicore Architectures

- Physical limits of semiconductor technology and improved manufacturing technologies make multicores the dominant *Central* processor (CPU) technology
- Of course there are still lots of unicores, e.g. in embedded systems
- The architectures are shared-memory, and cores share some level of cache
- The terminology is (deliberately?) confused: cores (C) may reside on the same
  - (S)ilicon Chip
  - (P)ackage
  - Board, connected by a synchronising bus


C
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Multicore Architectures

- These components are often combined e.g. the '8-core' Dell PowerEdge machines comprise a pair of quad cores in 2 packages.
- Major performance issues are
  - *cache coherence* - ensuring that each core's caches are consistent after memory writes
  - *contention* - synchronising memory read/writes between cores
- The trend is towards more cores: many cores

Multicore Programming

- The architectures encourages a programming model with lightweight threads (sometimes called filaments)
- Stateful programming (e.g. assignment) causes problems with cache coherence
- **Caution**: much threaded code is not safe for parallel execution!
- There are a number of programming models being explored, e.g.
  - Concurrent Collection libraries, e.g. java.util.concurrent
  - High-level Parallelism, e.g. JaSkel, GpH, Erlang
  - Thread-based models, e.g. Intel Thread Library, **OpenMP**

What is OpenMP?

- Open Multi-Processing
- An API for multi-threaded, shared memory parallelism
- API components:
  1. Compiler Directives
  2. Runtime Library Routines
  3. Environment Variables
- Available for
  - C, C++ and Fortran(s)
  - Unix & some Windows platforms

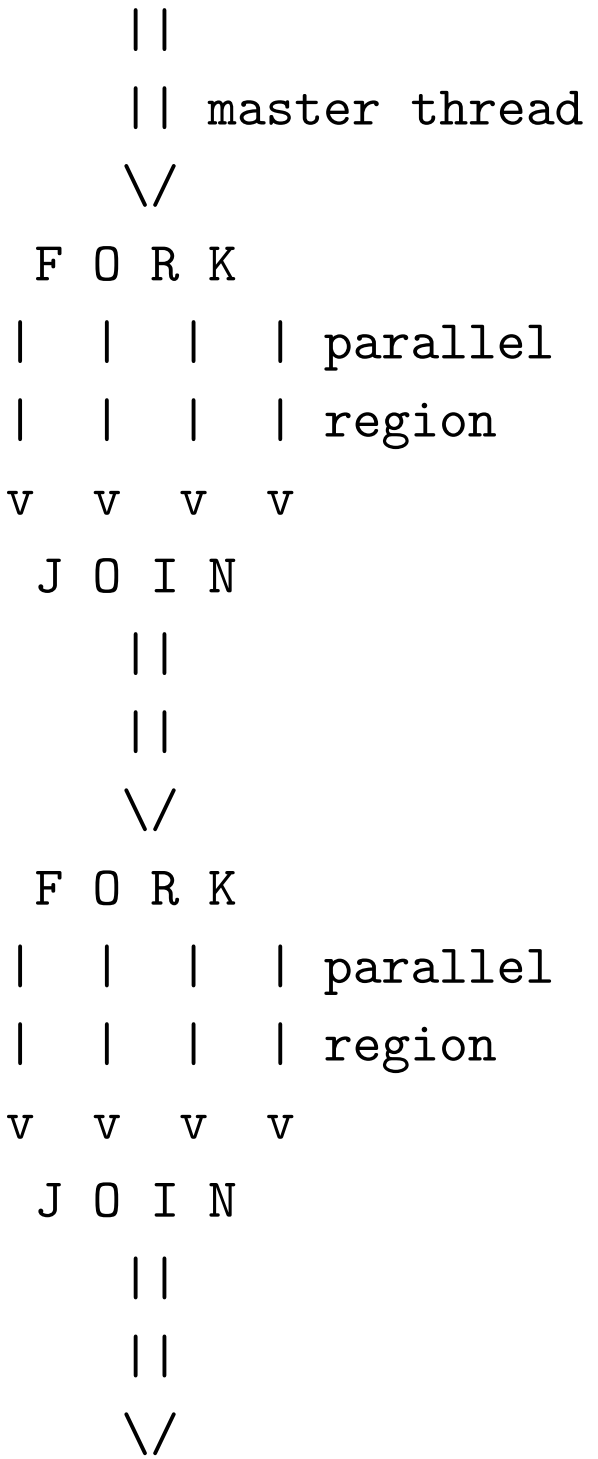
OpenMP Does Not

- Guarantee efficient use of shared memory
- Check for data dependencies, data conflicts, race conditions, or deadlocks
- Guarantee that I/O (e.g. to the same file) is synchronous

History

- Developed by a consortium of companies: HP, Intel, IBM, ...
- 1997 1st Standard
- 2008 OpenMP 3.0

Fork/Join Pattern



Code Structure

```
#include <omp.h>

main ()  {
int var1, var2, var3;
Serial code
      .
      .
Beginning of parallel section. Fork a team of
threads and specify variable scoping

#pragma omp parallel private(var1, var2) shared(var3)
  {

  Parallel section executed by all threads
        .
        .
  All threads join master thread and disband
  }

Resume serial code
      .
      .
}
```

1. Compiler Directives

- `#pragma omp` directive [clause, clause, ...]
- A directive typically applies to the following structured block
- No. threads determined by:
  - Setting of the NUM_THREADS clause
  - Use of the omp_set_num_threads() library function
  - Setting of the OMP_NUM_THREADS environment variable
  - Implementation default - usually the number of cores, though it could be dynamic
  - others ...

```
#include <omp.h>

main ()  {

int nthreads, tid;

/* Fork a team of threads with each thread having
   a private tid variable */
#pragma omp parallel private(tid)
  {

  /* Obtain and print thread id */
  tid = omp_get_thread_num();
  printf("Hello World from thread = %d\n", tid);

  /* Only master thread does this */
  if (tid == 0)
    {
    nthreads = omp_get_num_threads();
    printf("Number of threads = %d\n", nthreads);
    }
  }  /* All threads join master thread and terminate */
}
```

Dual Core execution:

```
jove% helloPar
Hello World from thread = 1
Hello World from thread = 0
Number of threads = 2
jove%
```

8-core execution:

```
lxpara3% helloPar
Hello World from thread = 4
Hello World from thread = 3
Hello World from thread = 5
Hello World from thread = 1
Hello World from thread = 6
Hello World from thread = 2
Hello World from thread = 0
Number of threads = 8
Hello World from thread = 7
lxpara3%
```

Data Parallelism: `for` Directive

```
#pragma omp for [clause ...]}
                schedule (type [,chunk])
                ordered
                collapse
                nowait
                reduction (operator: list)
                ...
```

- `schedule` specifies how loop iterations are divided amongst threads
  - `static` iterations of size `chunk` are statically assigned
  - `dynamic` iterations of size `chunk` are assigned, and when a thread finshes it dynamically collects the next chunk
  - `auto` scheduling delegated to compiler/runtim
  - ...
- `nowait` threads don't synchronise at the end of the loop

- `ordered` loop iterations must be executed in the same order as in a sequential program
- `reduction` Performs a reduction on all scalar variables in `list` using the specified operator, e.g. `reduction(+:sum)`. It is analogous to the `fold` or `reduce` patterns found in other languages like MPI, `mapreduce` etc.

  A private copy of each variable in `list` is created for each thread. At the end of the statement block, the final values of all private copies of the reduction variables are combined using the operator, and the result is placed back into the shared reduction variable.
- ...

```
#include <omp.h>
#define CHUNKSIZE 100
#define N     1000

main ()
{
int i, chunk;
float a[N], b[N], c[N];

/* Some initializations */
for (i=0; i < N; i++)
  a[i] = b[i] = i * 1.0;
chunk = CHUNKSIZE;

#pragma omp parallel shared(a,b,c,chunk) private(i)
  {
  #pragma omp for schedule(dynamic,chunk) nowait
  for (i=0; i < N; i++)
    c[i] = a[i] + b[i];
  }  /* end of parallel section */
}
```

Control Parallelism: `sections` Directive

```
#pragma omp sections [clause ...]
                     reduction (operator: list)
                     nowait
```

- Create threads to evaluate different control structures in a program

```
include <omp.h>
#define N     1000

main () {
int i;
float a[N], b[N], c[N], d[N];

for (i=0; i < N; i++) { /* Initialise */
  a[i] = i * 1.5;
  b[i] = i + 22.35;
}
#pragma omp parallel shared(a,b,c,d) private(i)
  {
  #pragma omp sections nowait
    {
    #pragma omp section
    for (i=0; i < N; i++)
      c[i] = a[i] + b[i];

    #pragma omp section
    for (i=0; i < N; i++)
      d[i] = a[i] * b[i];
    }  /* end of sections */
  }  /* end of parallel section */
}
```

Synchronisation Constructs

- `#pragma omp critical` [name] structured_block
  If a thread is executing in a `critical` region, any other thread reaching the region blocks until the first thread exits
- `#pragma omp barrier`
  A thread reaching a barrier waits until *all* other threads have reached the barrier. Thereafter all threads resume parallel execution.
- ...

Data Sharing Clauses

- As OpenMP is a shared memory paradigm variables are `shared` by default
- However it is important for each thread to keep a `private` copy of some variables, including loop index variables, thread id, etc.
- See previous programs for examples

2. Run-Time Library Functions

Library functions support

- Querying the number of threads/ processors, setting number of threads
- Semaphores
- Portable wall clock timing
- Setting execution environment for functions

Example functions

- Getting and setting number of threads:

```
void omp_set_num_threads(int num_threads)
int omp_get_num_threads(void)
```

- Get thread Id (see 1st example program):

```
int omp_get_thread_num(void)
```

- Get no. processors:

```
int omp_get_num_procs(void)
```

- Set/Unset locks

```
void omp_set_lock(omp_lock_t *lock)
void omp_unset_lock(omp_lock_t *lock)
```

- Get wallclock time

```
double omp_get_wtime(void)
```

3. Environment Variables

- OpenMP parallel evaluation can be controlled from the environment, for example:
- To control parallel `for` loops:
  `export OMP_SCHEDULE="dynamic"`
- To set the maximum number of threads to use during execution:
  `export OMP_NUM_THREADS=6`

  For example:

```
lxpara3%  export OMP_NUM_THREADS=4
lxpara3% helloPar
Hello World from thread = 2
Hello World from thread = 3
Hello World from thread = 1
Hello World from thread = 0
Number of threads = 4
lxpara3%
```

- ...

Critique of OpenMP

- Provides high-level parallelism compared with MPI
- Programmer must
  - identify paradigm(s) and introduce them e.g. data parallelism, control parallelism
  - control thread granularity
  - identify shared and private variables
  - synchronise on shared variables
- The directives are:
  - elaborate - how do you chose the best ones?
  - a fixed set: there's no way to introduce a new directive
  - there are only fixed ways of combining directives. Other coordination notations allow coordination constructs to be combined, e.g. sequenced, composed, or passed as arguments.