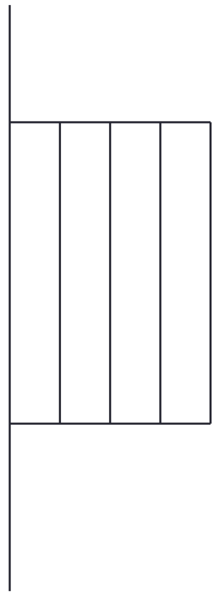
Advanced OpenMP

Other threading APIs

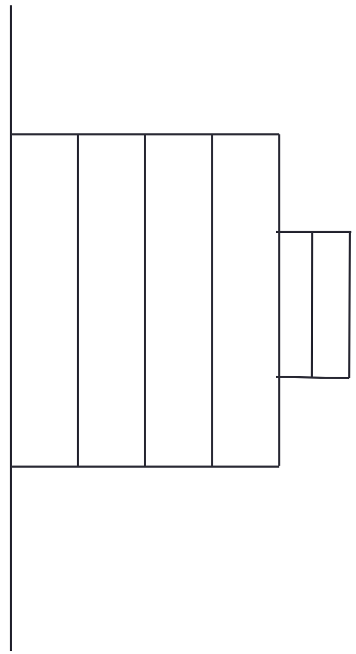
What’s wrong with OpenMP?

- OpenMP is designed for programs where you want a fixed number of threads, and you always want the threads to be consuming CPU cycles.
  - cannot arbitrarily start/stop threads
  - cannot put threads to sleep and wake them up later
- OpenMP is good for programs where each thread is doing (more-or-less) the same thing.
- Although OpenMP supports C++, it’s not especially OO friendly
  - though it is gradually getting better.
- OpenMP doesn’t support other popular base languages
  - e.g. Java, Python

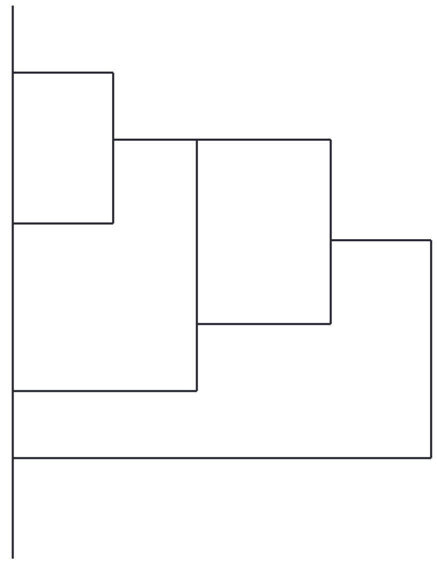
What’s wrong with OpenMP? (cont.)



Can do this



Can do this



Can’t do this

Threaded programming APIs

- Essential features
  - a way to create threads
  - a way to wait for a thread to finish its work
  - a mechanism to support thread private data
  - some basic synchronisation methods
    - at least a mutex lock, or atomic operations
- Optional features
  - support for tasks
  - more synchronisation methods
    - e.g. condition variables, barriers,...
  - higher levels of abstraction
    - e.g. parallel loops, reductions

What are the alternatives?

- POSIX threads
- C++ threads
- Intel TBB
- Cilk
- OpenCL
- Java

(not an exhaustive list!)

POSIX threads

- POSIX threads (or Pthreads) is a standard library for shared memory programming without directives.
  - Part of the ANSI/IEEE 1003.1 standard (1996)
- Interface is a C library
  - no standard Fortran interface
  - can be used with C++, but not OO friendly
- Widely available
  - even for Windows
  - typically installed as part of OS
  - code is pretty portable
- Lots of low-level control over behaviour of threads
- Lacks a proper memory consistency model

Thread forking

```
#include <pthread.h>

int pthread_create(
          pthread_t *thread,
          const pthread_attr_t *attr,
          void*(*start_routine, void*),
          void *arg)
```

- Creates a new thread:
  - first argument returns a pointer to a thread descriptor.
  - can set attributes.
  - new thread will execute `start_routine(arg)`
  - return value is error code.

Thread joining

```
#include <pthread.h>

int pthread_join(
         pthread_t thread,
         void **value_ptr)
```

- Waits for the specified thread to finish.
  - thread finishes when **start_routine** exits
  - second argument holds return value from **start_routine**

Synchronisation

- Barriers
  - need to specify how many threads will check in
- Mutex locks
  - behaviour is essentially the same as the OpenMP lock routines.
- Condition variables
  - allows a thread to put itself to sleep and be woken up by another thread at some point in the future
  - not especially useful in HPC applications
  - c.f. wait/notify in Java

Hello World

```
#include <pthread.h>
#define NTHREADS 5
int i, threadnum[NTHREADS];
pthread_t tid[NTHREADS];

for (i=0; i<NTHREADS; i++) {
  threadnum[i]=i;
  pthread_create(&tid[i], NULL, hello, &threadnum[i]);
}

for (i=0; i<NTHREADS; i++)
   pthread_join(tid[i], NULL);
```

Hello World (cont.)

```
void* hello (void *arg) {
   int myid;

   myid = *(int *)arg;
   printf("Hello world from thread %d\n", myid);

   return (0);
}
```

C++11 threads

- Library for multithreaded programming built in to C++11 standard
- Similar functionality to POSIX threads
  - but with a proper OO interface
  - based quite heavily on BOOST threads library
- Portable
  - depends on C++11 support, OK in gcc, Intel, clang, MS
- Threads are C++ objects
  - call a constructor to create a thread
- Synchronisation
  - mutex locks
  - condition variables
  - C++11 atomics

Hello world

```
#include <thread>
#include <iostream>
#include <vector>

void hello(){
  std::cout << "Hello from thread " << std::this_thread::get_id() <<
  std::endl;
}
int main(){
  std::vector<std::thread> threads;
  for(int i = 0; i < 5; ++i){
        threads.push_back(std::thread(hello));
  }
  for(auto& thread : threads){
        thread.join();
  }
}
```

Intel Thread Building Blocks (TBB)

- C++ library for multithreaded programming
- Offers somewhat higher level of abstraction that POSIX/C++11 threads
  - notion of tasks rather that explicit threads
  - support for parallel loops and reductions
  - mutexs and atomic operations, concurrency on containers
- Moderately portable
  - support for Intel and gcc compilers on Linux and Mac OS X, Intel and Visual C++ on Windows
  - no build required to install

Hello World

```
#include <iostream>
#include <tbb/parallel_for.h>

using namespace tbb;

class Hello
{
public:
void operator()(int x) const {
std::cout << "Hello world\n";
}
};

int main()
{
// parallelizing:
// for(int i = 0; i < 2; ++i) { ... }
parallel_for(0, 2, 1, Hello());

return 0;
}
```

Cilk

- Very minimal API which supports spawning and joining of tasks
  - C/C++ with a few extra keywords
- Commercial implementation by Intel
  - Intel Cilk Plus, built in to Intel C++ compiler
  - not very portable
- Support for parallel loops and reductions
  - No locks, but can use pthread or TBB mutexes.
- Still unclear whether it is really useful for real-world applications!

Hello World

```
#include <stdio.h>
#include <cilk/cilk.h>

static void hello(){
   printf("Hello ");
}

int main(){
   cilk_spawn hello();
   cilk_sync;
}
```

OpenCL

- API designed for programming heterogeneous systems (GPUs, DSPs, etc).
  - but can also execute on regular CPUs
- Open standard administered by Khronos Group
- Based on C99 with some extra keywords, large set of runtime library routines
- CPU implementations from Intel, IBM
- Very low level (c.f. CUDA), lots of boiler-plate code required
- Performance (and performance portability) not convincingly demonstrated....

OpenCL

- Quite a different model from other threaded APIs
- Execute host code on CPU which launches kernels to execute on a device (typically GPU, but could be the CPU)
- Need to explicitly transfer data from host to device (and back again)
- Kernel executes on multiple threads
  - can get a thread identifier
- Limited ability to synchronise between threads
  - barrier only inside a “workgroup”
  - atomics
- Can specify orderings between kernels

Hello World

```
__kernel void hello(__global char* string)
{
string[0] = 'H';
string[1] = 'e';
string[2] = 'l';
string[3] = 'l';
string[4] = 'o';
string[5] = ',';
string[6] = ' ';
string[7] = 'W';
string[8] = 'o';
string[9] = 'r';
string[10] = 'l';
string[11] = 'd';
string[12] = '!';
string[13] = '\0';
}
```

```
#include <stdio.h>
#include <stdlib.h>
#include <CL/cl.h>

#define MEM_SIZE (128)
#define MAX_SOURCE_SIZE (0x100000)

int main()
{
cl_device_id device_id = NULL;
cl_context context = NULL;
cl_command_queue command_queue = NULL;
cl_mem memobj = NULL;
cl_program program = NULL;
cl_kernel kernel = NULL;
cl_platform_id platform_id = NULL;
cl_uint ret_num_devices;
cl_uint ret_num_platforms;
cl_int ret;

char string[MEM_SIZE];

FILE *fp;
char fileName[] = "./hello.cl";
char *source_str;
size_t source_size;
```

```
/* Load the source code containing
the kernel*/
fp = fopen(fileName, "r");
if (!fp) {
fprintf(stderr, "Failed to load
kernel.\n");
exit(1);
}
source_str =
(char*)malloc(MAX_SOURCE_SIZE);
source_size = fread(source_str, 1,
MAX_SOURCE_SIZE, fp);
fclose(fp);
/* Get Platform and Device Info */
ret = clGetPlatformIDs(1,
&platform_id, &ret_num_platforms);
ret = clGetDeviceIDs(platform_id,
CL_DEVICE_TYPE_DEFAULT, 1, &device_id,
&ret_num_devices);
```

```
/* Create OpenCL context */
context = clCreateContext(NULL, 1,
&device_id, NULL, NULL, &ret);
/* Create Command Queue */
command_queue =
clCreateCommandQueue(context,
device_id, 0, &ret);
/* Create Memory Buffer */
memobj = clCreateBuffer(context,
CL_MEM_READ_WRITE,MEM_SIZE *
sizeof(char), NULL, &ret);
/* Create Kernel Program from the
source */
program =
clCreateProgramWithSource(context, 1,
(const char **)&source_str,
(const size_t *)&source_size, &ret);
```

```
/* Build Kernel Program */
ret = clBuildProgram(program, 1,
&device_id, NULL, NULL, NULL);
/* Create OpenCL Kernel */
kernel = clCreateKernel(program,
"hello", &ret);
/* Set OpenCL Kernel Parameters */
ret = clSetKernelArg(kernel, 0,
sizeof(cl_mem), (void *)&memobj);
/* Execute OpenCL Kernel */
ret = clEnqueueTask(command_queue,
kernel, 0, NULL,NULL);
/* Copy results from the memory buffer
*/
ret =
clEnqueueReadBuffer(command_queue,
memobj, CL_TRUE, 0,
MEM_SIZE * sizeof(char),string, 0,
NULL, NULL);
```

```
/* Display Result */
puts(string);
/* Finalization */
ret = clFlush(command_queue);
ret = clFinish(command_queue);
ret = clReleaseKernel(kernel);
ret = clReleaseProgram(program);
ret = clReleaseMemObject(memobj);
ret =
clReleaseCommandQueue(command_queue);
ret = clReleaseContext(context);
free(source_str);
return 0;
}
```

Java threads

- Built in to the Java language specification
  - highly portable

- Threads are Java objects
  - created by calling a constructor

- Synchronisation
  - synchronised blocks and methods
    - act as a critical region
    - specify an object to synchronise on
    - every object has an associated lock
  - also explicit locks, atomic classes, barriers, semaphores, wait/notify

Hello World

```
class Example {
   public static void main(String args[]){
     Thread thread_object [] = new Thread[nthread];
     for(int i=0; i<nthread; i++){
       thread_object[i] = new Thread(new MyClass(i));
       thread_object[i].start();
     }
     for(int i=0; i<nthread; i++){
       try{
         thread_object[i].join();
       }catch (InterruptedException x){}
     }
   }
}
```

Hello World (cont.)

```
class MyClass implements Runnable {
   int id;

   public MyClass(int id) {
     this.id = id;
   }

   public void run() {
     System.out.println("Hello World from Thread" + id);
   }
}
```

Java Tasks

- Create an Executor Service with a pool of threads

```
ExecutorService ex = Executors.newFixedThreadPool(nthreads);
```

- Submitting tasks
  - Submit method submits a task for execution and returns a Future representing that task

```
Future ft = ex.submit(new Myclass(i));
```

  - Future
    - Represents the status and result of an asynchronous computation
    - Provides methods to check if computation is complete, to wait for completion and, if appropriate, retrieve the result of the computation