Shared Memory Programming

Arvind Krishnamurthy
Fall 2004

Parallel Programming Overview

Basic parallel programming problems:

1. Creating parallelism & managing parallelism
   - Scheduling to guarantee parallelism and load-balance
2. Communication between processors
   - Building shared data structures
3. Synchronization
   - Point-to-point or “pairwise”
   - Global synchronization (barriers)

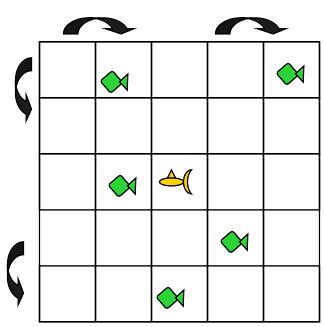
- Make use of a running example, “Sharks and Fish”

A Model Problem: Sharks and Fish

- Illustration of parallel programming
  - Original version (discrete event only) proposed by Geoffrey Fox
  - Called WATOR
    - Sharks and fish living in a 2D toroidal ocean
- We can imagine several variations to show different physical phenomenon
- Basic idea: sharks and fish living in an ocean
  - rules for movement
  - breeding, eating, and death
  - forces in the ocean
  - forces between sea creatures

Sharks and Fish as Discrete Event System

- Ocean modeled as a 2D toroidal grid
- Each cell occupied by at most one sea creature



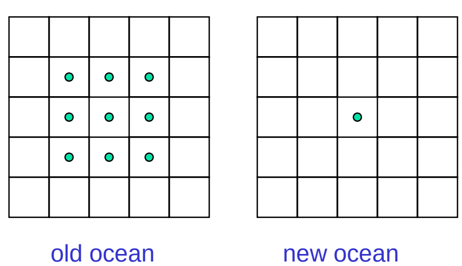
Fish-only: the Game of Life

- A new fish is born if
  - a cell is empty
  - exactly 3 (of 8) neighbors contain fish
- A fish dies (of overcrowding) if
  - cell contains a fish
  - 4 or more neighboring cells are full
- A fish dies (of loneliness) if
  - cell contains a fish
  - less than 2 neighboring cells are full
- Other configurations are stable

- The original Wator problem adds fish-eating sharks

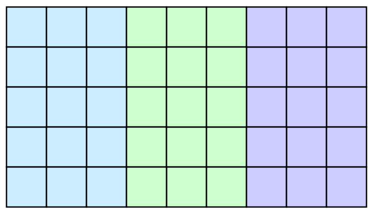
Parallelism in Sharks and Fish

- The activities in this system are discrete events
- The simulation is synchronous
  - use two copies of the grid (old and new)
  - the value of each new grid cell in new depends only on the 9 cells (itself plus neighbors) in old grid
    - Each grid cell update is independent: reordering or parallelism OK
  - simulation proceeds in timesteps, where (logically) each cell is evaluated at every timestep



Parallelism in Sharks and Fish

- Parallelism is straightforward
  - ocean is regular data structure
  - even decomposition across processors gives load balance
- Locality is achieved by using large patches of the ocean
  - boundary values from neighboring patches are needed → communication (either explicit or implicit as in cache transfers)



- Advanced optimization: visit only occupied cells (and neighbors) → load balance is more difficult

Language Notions of Thread Creation

- cobegin/coend

```
cobegin
    job1(a1);
    job2(a2);
coend
```

- •Statements in block may run in parallel
- •cobegins may be nested
- •Scoped, so you cannot have a missing coend

- fork/join

```
tid1 = fork(job1, a1);
job2(a2);
join tid1;
```

- •Forked function runs in parallel with current thread
- •join waits for completion (may be in different function)

- cobegin cleaner, but fork is more general

Programming with Threads

Several Thread Libraries

- PTHREADS is the Posix Standard
  - Solaris threads are very similar
  - Relatively low level
  - Portable but sometimes slow
- P4 (Parmacs) is a widely used portable package
  - Higher level than Pthreads http://www.netlib.org/p4/index.html
- OpenMP is newer standard
  - Support for scientific programming on shared memory http://www.openMP.org
- User-level vs. kernel level threads
  - User-level threads cannot make use of multi-processors!
  - Kernel-level threads have more overhead
  - Kernel-level threads better integrated with OS actions (page-faults etc.)

Forking Posix Threads

Signature:

```
int pthread_create(pthread_t *,
                   const pthread_attr_t *,
                   void * (*)(void *),
                   void *);
```

Example call:

```
errcode = pthread_create(&thread_id; &thread_attribute
                         &thread_fun; &fun_arg);
```

- thread_id is the thread id or handle (used to halt, etc.)
- thread_attribute various attributes
  - standard default values obtained by passing a NULL pointer
- thread_fun the function to be run (takes and returns void*)
- fun_arg an argument can be passed to thread_fun when it starts
- errorcode will be set nonzero if the create operation fails

Posix Thread Example

```
#include <pthread.h>
void print_fun( void *message ) {
    printf("%s \n", message);
}

main() {
    pthread_t thread1, thread2;
    char *message1 = "Hello";
    char *message2 = "World";

    pthread_create( &thread1,
          NULL,
          (void*)&print_fun,
          (void*) message1);
    pthread_create(&thread2,
          NULL,
          (void*)&print_fun,
          (void*) message2);
    return(0);
}
```

Compile using gcc –lpthread

Note: There is a race condition in the print statements

Loop Level Parallelism

- Many scientific application have parallelism in loops
  - With threads:

```
… ocean [n][n];
for (int i = 0; i < n; i++)
  for (int j = 0; j < n; j++)
    … pthread_create (update_cell, …, ocean);
```

Also needs i & j

- What's wrong with this approach?

SPMD Parallelism with Threads

Creating a fixed number of threads is common:

```
pthread_t threads[NTHREADS];  /* thread info */
int errcode;                  /* error code */
int *status;                  /* return code */
```

```
for (int worker=0; worker<NTHREADS; worker++) {
  ids[worker]=worker;
  errcode=pthread_create(&threads[worker],
                         NULL, work,
                         &ids[worker]));
  if (errcode) { . . . }
}
```

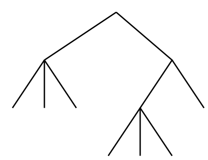
```
for (worker=0; worker<NTHREADS; worker++) {
   errcode=pthread_join(threads[worker],
                        (void *) &status));
   if (errcode !! *status != worker) { . . . }
}
```

Loop Level Parallelism

- Many scientific application have parallelism in loops
  - degree may be fixed by data, either
    - start p threads and partition data (SPMD style)
    - start a thread per loop iteration
- Parallel degree may be fixed, but not work
  - self-scheduling: have each processor grab the next fixed-sized chunk of work
    - want this to be larger than 1 array element
  - guided self-scheduling: decrease chunk size as a remaining work decreases [Polychronopoulos]
- How to do this:
  - With threads, create a data structure to keep track of chunks

Dynamic Parallelism

- Divide-and-Conquer problems are task-parallel
  - classic example is search (recursive function)
  - arises in numerical algorithms, dense as well as sparse
  - natural style is to create a thread at each divide point
    - **too much parallelism at the bottom**
    - **thread creation time too high**
- Stop splitting at some point to limit overhead
- Use a "task queue" to schedule
  - have a pool of worker threads
  - place root in a bag (unordered queue)
  - at each divide point, put children
  - this isn't this the same as forking them



Shared Data and Threads

- Variables declared outside of main are shared
- Object allocated on the heap may be shared (if pointer is passed)
- For Sharks and Fish, natural to share 2 oceans
  - Also need indices i and j, or range of indices to update
- Often done by creating a large "thread data" struct
  - Passed into all threads as argument

Synchronization in Sharks and Fish

- We use 2 copies of the ocean mesh to avoid synchronization of each element
- Need to coordinate
  - Every processor must be done updating one grid before using it
  - Also useful to swap old/new to avoid overhead of allocation
    - Need to make sure done with old before making into new
- Global synchronization of this kind is very common
  - Timesteps, iterations in solvers, etc.

Basic Types of Synchronization: Barrier

Barrier -- global synchronization

- fork multiple copies of the same function “work”
  - SPMD “Single Program Multiple Data”
- simple use of barriers -- threads hit the same one

```
work_on_my_subgrid();
barrier;
read_neighboring_values();
barrier;
```

- more complicated -- barriers on branches (or loops)

```
if (tid % 2 == 0) {
    work1();
    barrier
} else { barrier }
```

- barriers are not provided in many thread libraries

Pairwise Synchronization

- Sharks and Fish example needs only barriers
- Imagine other variations in which pairs of processors would synchronization:
  - World divided into independent “ponds” with creatures rarely moving between them
    - Producer-consumer model of parallelism
  - All processors updating some global information, such as total population count asynchronously
    - Mutual exclusion needed

Basic Types of Synchronization: Mutexes

Mutexes -- mutual exclusion aka locks

- threads are working mostly independently
- need to access common data structure

```
lock *l = alloc_and_init();    /* shared */
acquire(l);
  access data
release(l);
```

- Java and other languages have lexically scoped synchronization
  - similar to cobegin/coend vs. fork and join
- Semaphores are locks plus shared counters and can be used for mutual exclusion
- Locks only affect processors using them:
  - pair-wise synchronization

Pthreads Locks

- Steps: declare a lock and initialize it; make sure it is locked before doing something critical
- Standard locks semantics: only one can thread can have it

```
pthread_mutex_t    pond_lock[n];                 //  declaration
pthread_mutex_init(&pond_lock[i], NULL);   //  initialization
```

```
pthread_mutex_lock(&pond_lock[i]);
pthread_mutex_lock(&pond_lock[j]);
move_fish(fish, pond[i], pond[j]);
pthread_mutex_unlock(&pond_lock[j]);
pthread_mutex_unlock(&pond_lock[i]);
```

Locking Issues

- Repeated locking of the same lock
  - Linux has "fast" vs. "recursive" locks
- Reader/writer locks: allow multiple readers to own a lock at any time, but not allow any readers if there is a writer
- pthread_mutex_trylock is non-blocking ("non-committal")
- Deadlock issues:
  - Example: T1 locks pond1 followed by pond2, T2 locks pond2 followed by pond1
  - Deadlocks can be analyzed with the "waits-for" graph
  - T1 is waiting for T2 (to release pond2), and T2 is waiting for T1 (to release pond1), and a cycle in this graph implies deadlock
  - Deadlock avoidance: order locks, and each thread obtains the locks it needs in increasing order of relevance → no cycles!

Condition Variables

- Allows for threads to wait for a condition to be satisfied
- Used along with a mutex lock
- pthread_cond_wait puts a thread to sleep waiting for a pthread_cond_signal to be issued by another thread
- Example: producer-consumers interaction, wake up a consumer when there is a task available

```
pthread_mutex_lock(&mut);
while (tasks_left == 0) {
    pthread_cond_wait(&cv, &mut);
}
pthread_mutex_unlock(&mut);
```

```
pthread_mutex_lock(&mut);
if (tasks_left != 0) {
    pthread_cond_signal(&cv, &mut);
}
pthread_mutex_unlock(&mut);
```

Condition Variable Issues

- Programming discipline: always obtain the lock before signaling or waiting on a condition variable
- Makes sure that no signals are lost
- pthread_cond_wait implicitly relinquishes the lock and obtains it back when woken up
- pthread_cond_signal wakes up exactly one waiting thread, pthread_cond_broadcast wakes up all waiting threads
- signal could be used without locking
- A thread could wake up and reset the program level criteria; broadcast does not imply all threads are runnable