Pthreads: A Shared Memory Programming Model

- POSIX standard shared-memory multithreading interface
- Not just for parallel programming, but for general multithreaded programming
- Provides primitives for process management and synchronization

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What does the user have to do?

- Decide how to decompose the computation into parallel parts
- Create (and destroy) processes to support that decomposition
- Add synchronization to make sure dependences are covered

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General Thread Structure

- Typically, a thread is a concurrent execution of a function or a procedure
- So, your program needs to be restructured such that parallel parts form separate procedures or functions

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General Program Structure

- Encapsulate parallel parts in functions.
- Use function arguments to parametrize what a particular thread does.
- Call pthread_create() with the function and arguments, save thread identifier returned.
- Call pthread_join() with that thread identifier.

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Synchronization Primitives in Pthreads

- Mutexes
- Reader-writer locks
- Condition variables
- Semaphores
- Barriers

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Sequential SOR

```
for some number of timesteps/iterations {
  for (i=0; i<n; i++ )
        for( j=1, j<n, j++ )
              temp[i][j] = 0.25 *
                    ( grid[i-1][j] + grid[i+1][j]
                    grid[i][j-1] + grid[i][j+1] );
  for( i=0; i<n; i++ )
        for( j=1; j<n; j++ )
              grid[i][j] = temp[i][j];
}
```

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Barrier Synchronization

- A wait at a barrier causes a thread to wait until all threads have performed a wait at the barrier.
- At that point, they all proceed
- Use instead of creating and destroying threads multiple times to achieve the same global synchronization with lower overhead

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Implementing Barriers in Pthreads

- Count the number of arrivals at the barrier.
- Wait if this is not the last arrival.
- Make everyone unblock if this is the last arrival.
- Since the arrival count is a shared variable, enclose the whole operation in a mutex lock-unlock.

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Implementing Barriers in Pthreads

```
void barrier()
{
   pthread_mutex_lock(&mutex_arr);
   arrived++;
   if (arrived<N) {
          pthread_cond_wait(&cond, &mutex_arr);
   }
   else {
          pthread_cond_broadcast(&cond);
          arrived=0; /* be prepared for next barrier */
   }
   pthread_mutex_unlock(&mutex_arr);
}
```

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Monitor

- Synchronization construct that provides mutual exclusion and the ability to wait on one or more conditions
  - Hoare style: signaler must leave/give up the monitor to the thread being woken up
    - E.g., Hansen's Concurrent Pascal
  - Mesa style: thread being woken up may return to the monitor at a later time
    - E.g., Java and C#

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Implications: Parallel TSP: Condition Synchronization

```
de_queue() {
   pthread_mutex_lock(&queue);
   while( (q is empty) and (not done) ) {
          waiting++;
          if( waiting == p ) {
                 done = true;
                 pthread_cond_broadcast(&empty);
          }
          else {
                 pthread_cond_wait(&empty, &queue);
                 waiting--;
          }
   }
   if( done )
          return null;
   else
          remove and return head of the queue;
   pthread_mutex_unlock(&queue);
}
```

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Parallel SOR with Barriers (1 of 2)

```
void* sor (void* arg)
{
   int slice = (int)arg;
   int from = (slice * (n-1))/p + 1;
   int to = ((slice+1) * (n-1))/p + 1;

   for some number of iterations { … }
}
```

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Parallel SOR with Barriers (2 of 2)

```
for (i=from; i<to; i++)
  for (j=1; j<n; j++)
        temp[i][j] = 0.25 * (grid[i-1][j] + grid[i+1][j]
                     + grid[i][j-1] + grid[i][j+1]);
barrier();
for (i=from; i<to; i++)
  for (j=1; j<n; j++)
        grid[i][j]=temp[i][j];
barrier();
```

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Parallel SOR with Barriers: main

```
int main(int argc, char *argv[])
{
  pthread_t *thrd[p];
  /* Initialize mutex and condition variables */
  for (i=0; i<p; i++)
        pthread_create (&thrd[i], &attr, sor, (void*)i);
  for (i=0; i<p; i++)
        pthread_join (thrd[i], NULL);
  /* Destroy mutex and condition variables */
}
```

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Busy Waiting

- Not an explicit part of the API
- Available in any general shared memory programming environment

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Busy Waiting

initially: flag = 0;

P1: produce data;
flag = 1;

P2: while(!flag) ;
consume data;

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Use of Busy Waiting

- On the surface, simple and efficient
- In general, not a recommended practice
- Often leads to messy and unreadable code (blurs data/synchronization distinction)
- On some architectures, may be inefficient or may not even work as intended (depending on consistency model)

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Private Data in Pthreads

- To make a variable private in pthreads, you need to make an array out of it
- Index the array by thread identifier, which you can get by the pthread_self() call
- An alternative is to declare the variable on the stack
- Not very elegant or efficient

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Other Primitives in Pthreads

- Set the attributes of a thread
- Set the attributes of a mutex lock
- Set scheduling parameters

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Thread Creation Syntax

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Programming in Parallel

- Explicitly concurrent languages – e.g., Occam, SR, Java, Ada, UPC, C++11
- Compiler-supported extensions – e.g., HPF, Cilk
- Library packages outside the language proper – e.g., pthreads, MPI

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Thread Creation Syntax

- Properly nested (can share context)
  - Co-Begin (Algol 68, Occam, SR)
  - Parallel loops (HPF, Occam, Fortran90, SR)
  - Launch-at-Elaboration (Ada, SR)
- Fork/Join (pthreads, Ada, Modula-3, Java, SR)
- Implicit Receipt (RPC systems, SR)
- Early Reply (SR)

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Co-Begin (e.g., Algol 68)

```
par begin
   p (a, b, c),
   begin
      d := q(e, f);
      r(d, g, h)
   end,
   s(i, j)
end
```

Commas: nondeterministic or concurrent semantics
Semicolons: sequential semantics

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Co-Begin in OpenMP

```
#pragma omp sections
{
#   pragma omp section
    { printf("thread 1 here\n");}
#   pragma omp section
    { printf("thread 2 here\n");
}
```

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Parallel Loops

- Examples:
  - OpenMP: # pragma omp parallel for
  - C#: Task Parallel Library

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OpenMP

For-loop parallelized using an OpenMP pragma

```
#pragma omp parallel for
for (int i=0; i<n; i++)
    c[i] = a[i] + b[i];
```

```
% cc -xopenmp source.c
% setenv OMP_NUM_THREADS 5
% a.out
```

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Parallelism in Loops (Fortran)

- FOR: sequential
- FORALL: each statement executed completely and in parallel; old values for current and subsequent statements; new values for previous statement
- DOPAR: each iteration executed in parallel; statements within each iteration executed sequentially; old values for other iterations
  - DOALL: DOPAR with no conflicts
- DOACROSS: sequential loop with dependences
- DOSINGLE: each variable assigned once, new value always used

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Initially

	0	1	2	3	4	5
a	3	3	3	3	3	3
b	1	2	3	4	5	6

Example Loop

(1) Loop i=1:4

(2) a[i] = a[i-1]+1

(3) b[i] = b[i+1] + a[i-1]

	(2) a[i-1]	(3) a[i-1]	(3) b[i+1]
for	New	New	Old
forall	Old	New	Old
dopar	Old	Old	Old
dosingle	New	New	New

Final values using for, forall, dopar, dosingle?

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Launch-at-Elaboration (e.g., Ada)

```
procedure P is
   task T is
      …
   end T;
begin – P
   …
end P;
```

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Explicit Thread Creation Syntax

- Fork/Join (pthreads, Ada, Modula-3, Java, SR)
- Implicit Receipt (RPC systems, SR)
- Early Reply (SR – fork a thread on a local procedure, reply early, and continue execution after returning/replying to caller)

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CILK

```
cilk int fib (int n) {
      if (n < 2) return n;
      else {
          int x, y;
          x = spawn fib (n-1);
          y = spawn fib (n-2);
          sync;
          return (x+y);
      }
}
```

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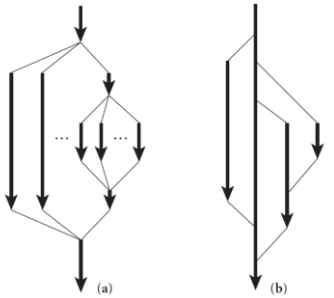
Nested vs. General Parallelism



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Sequential SOR

```
for (k = 0; k < 100; k++) {

    for (j = 1; j < M-1; j++)
        for (i = 1; i < M-1; i++)
            a[j][i] = (b[j][i-1] + b[j][i+1] +
                       b[j-1][i] + b[j+1][i])/4;

    for (j = 1; j < M-1; j++)
        for (i = 1; i < M-1; i++)
            b[j][i] = a[j][i];
}
```

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Shared Memory Version

```
for (k = 0; k < 100; k++) {

    for (j = begin; j < end; j++)
        for (i = 1; i < M-1; i++)
            a[j][i] = (b[j][i-1] + b[j][i+1] +
                       b[j-1][i] + b[j+1][i])/4;
    barrier();

    for (j = begin; j < end; j++)
        for (i = 1; i < M-1; i++)
            b[j][i] = a[j][i];
    barrier();
}
```

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Data Parallel Version of SOR (OpenMP)

```
for (k = 0; k < 100; k++) {

#pragma parallel shared(a, b) private(i,j)
{
   #pragma omp parallel for
   for (j = 1; j < M-1; j++)
      for (i = 1; i < M-1; i++)
         a[j][i] = (b[j][i-1] + b[j][i+1] +
                    b[j-1][i] + b[j+1][i])/4;
}

#pragma parallel shared(a, b) private(i, j)
{
   #pragma omp parallel for
   for (j = 1; j < M-1; j++)
      for (i = 1; i < M-1; i++)
         b[j][i] = a[j][i];
}
}
```

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SOR in HPF (Fortran D)

```
      real a (1000, 1000), b(1000, 1000)
C     decomposition d(1000, 1000)
C     align a, b with d
C     distribute d(:, block)
      do k = 1, 1000
        do j = 2, 999
          do I = 2, 999
             a(i,j) = F(b(i-1,j),b(i+1,j),b(i,j-1),b(I,j+1))
          enddo
        enddo
        second loop (b(i,j) = a(i,j)
      enddo
```

Data distribution: block, cyclic, or block-cyclic

Compiler applies owner-computes rule

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Thread Implementation

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Processes or Threads

- A process or thread is a potentially-active execution context
- Processes/threads can come from
  - Multiple CPUs
  - Kernel-level multiplexing of single physical CPU (kernel-level threads or processes)
  - Language or library-level multiplexing of kernel-level abstraction (user-level threads)
- Threads can run
  - Truly in parallel (on multiple CPUs)
  - Unpredictably interleaved (on a single CPU)
  - Run-until-block (coroutine-style)

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Processes Vs. Threads

- Process
  - Single address space
  - Single thread of control for executing program
  - State information
    - Page tables, swap images, file descriptors, queued I/O requests, saved registers
- Threads
  - Separate notion of execution from the rest of the definition of a process
  - Other parts potentially shared with other threads
  - Program counter, stack of activation records, control block (e.g., saved registers/state info for thread management)
  - Kernel-level (lightweight process) handled by the system scheduler
  - User-level handled in user mode

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Thread Implementation Requirements

- Data structures
  - Program counter
  - Stack
  - Control block (state for thread management)
  - Run queue

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Thread Scheduling: Transferring Context Blocks

Coroutines

transfer(other)

save all callee-saves registers on stack, including ra and fp

*current := sp

current := other

sp := *current

pop all callee-saves registers (including ra, but NOT sp!)

return (into different coroutine!)

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Uniprocessor Scheduling

- Use Ready List to reschedule voluntarily (cooperative threading)

reschedule:
  - t : cb := dequeue(ready_list)
  - transfer(t)

yield:
  - enqueue(ready_list, current)
  - reschedule

sleep_on(q):
  enqueue(q, current)
  reschedule

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Preemption

- Use timer interrupts or signals to trigger involuntary yields
- Protect scheduler data structures by disabling/reenabling prior to/after rescheduling

yield:
  disable_signals
  enqueue(ready_list, current)
  reschedule
  re-enable_signals

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Multiprocessor Scheduling

- Disabling signals not sufficient
- Acquire scheduler lock when accessing any scheduler data structure, e.g.,

yield:
  disable_signals
  acquire(scheduler_lock) // spin lock
  enqueue(ready_list, current)
  reschedule
  release(scheduler_lock)
  re-enable_signals

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Thread Management

- Creation
- Startup
- Block
- Signal
- Resume
- Finish

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Performance Measures

- Latency
  - Cost of thread management under the best case assumption of no contention for locks
- Throughput
  - Rate at which threads can be created, started, and finished when there is contention

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Thread Management Data Structures?

- Control blocks
- Stacks
- Ready queue

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Anderson et al.

- Raises issues of
  - Locality (per-processor data structures)
  - Granularity of scheduling tasks
  - Lock overhead
  - Tradeoff between throughput and latency
    - Large critical sections are good for best-case latency (low locking overhead) but bad for throughput (low parallelism)

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Optimizations

- Allocate stacks lazily
- Store deallocated control blocks and stacks in free lists
- Create per-processor ready lists
- Create local free lists for locality
- Queue of idle processors (in addition to queue of waiting threads)

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Ready List Management

- Single lock for all data structures
- Multiple locks, one per data structure
- Local freelists for control blocks and stacks, single shared locked ready list
- Queue of idle processors with preallocated control block and stack waiting for work
- Local ready list per processor, each with its own lock

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