Lecture 20b: Implementing Parallel Runtimes, Part 2

Parallel Computer Architecture and Programming
CMU 15-418/15-618, Spring 2019
Objectives

- What are the costs of using parallelism APIs?
- How do the runtimes operate?
Basis of Lecture

- This lecture is based on runtime and source code analysis of Intel’s open source parallel runtimes
  - OpenMP – https://www.openmp.org/
  - Cilk – https://bitbucket.org/intelcilkruntime/intel-cilk-runtime

- And using the LLVM compiler
  - OpenMP – part of LLVM as of 3.8
  - Cilk - http://cilkplus.github.io/
OpenMP and Cilk

- What do these have in common?
  - pthreads

- What benefit does abstraction versus implementation provide?
Simple OpenMP Loop Compiled

- What is this code doing?
- What do the OpenMP semantics specify?
- How might you accomplish this?

```c
extern float foo( void );
int main (int argc, char** argv) {
    int i;
    float r = 0.0;
    #pragma omp parallel for schedule(dynamic) reduction(+:r)
    for ( i = 0; i < 10; i ++ ) {
        r += foo();
    }
    return 0;
}
```

Example from OpenMP runtime documentation
```c
extern float foo(void);
int main(int argc, char** argv) {
    static int zero = 0;
    auto int gtid;
    auto float r = 0.0;
    __kmpc_begin(&loc3, 0);
    gtid = __kmpc_global_thread_num(&loc3);
    __kmpc_fork_call(&loc7, 1, main_7_parallel_3, &r);
    __kmpc_end(&loc0);
    return 0;
}
```

Call a function in parallel with the argument(s)
Simple OpenMP Loop Compiled

- **OpenMP “microtask”**
  - Each thread runs the task
- Initializes local iteration bounds and reduction
- Each iteration receives a chunk and operates locally
- After finishing all chunks, combine into global reduction

```c
struct main_10_reduction_t_5 { float r_10_rpr; }

void main_7_parallel_3( int *gtid, int *btid, float *r_7_shp ) {
    auto int i_7_pr;
    auto int lower, upper, liter, incr;
    auto struct main_10_reduction_t_5 reduce;
    reduce.r_10_rpr = 0.F;
    liter = 0;
    __kmpc_dispatch_init_4( &loc7, *gtid, 35, 0, 9, 1, 1 );
    while ( __kmpc_dispatch_next_4( &loc7, *gtid, &liter, &lower, &upper, &incr ) ) {
        for( i_7_pr = lower; upper >= i_7_pr; i_7_pr ++ )
            reduce.r_10_rpr += foo();
    }
    switch( __kmpc_reduce_nowait( &loc10, *gtid, 1, 4,
                                  &reduce, main_10_reduce_5, &lck ) ) {
      case 1:
        *r_7_shp += reduce.r_10_rpr;
        __kmpc_end_reduce_nowait( &loc10, *gtid, &lck);
        break;
      case 2:
        __kmpc_atomic_float4_add( &loc10, *gtid,
                                  r_7_shp, reduce.r_10_rpr );
        break;
      default:;
    }
}
```

Example from OpenMP runtime documentation
Simple OpenMP Loop Compiled

- All code combined

```c
extern float foo( void );
int main (int argc, char** argv) {
    static int zero = 0;
    auto int gtid;
    auto float r = 0.0;
    __kmpc_begin( &loc3, 0 );
    gtid = __kmpc_global_thread_num( &loc3 );
    __kmpc_fork_call( &loc7, 1, main_7_parallel_3, &r );
    __kmpc_end( &loc0 );
    return 0;
}

struct main_10_reduction_t_5 {
    float r_10_rpr;
};
static kmp_critical_name lck = { 0 };
static ident_t loc10;

void main_10_reduce_5( struct main_10_reduction_t_5 *reduce_lhs, 
                        struct main_10_reduction_t_5 *reduce_rhs )
{
    reduce_lhs->r_10_rpr += reduce_rhs->r_10_rpr;
}

void main_7_parallel_3( int *gtid, int *btid, float *r_7_shp ) {
    auto int i_7_pr;
    auto int lower, upper, liter, incr;
    auto struct main_10_reduction_t_5 reduce;
    reduce.r_10_rpr = 0.F;
    liter = 0;
    __kmpc_dispatch_init_4( &loc7,*gtid, 35, 0, 9, 1, 1 );
    while ( __kmpc_dispatch_next_4( &loc7, *gtid, &liter, 
                                    &lower, &upper, &incr ) ) {
        for( i_7_pr = lower; upper >= i_7_pr; i_7_pr ++ )
            reduce.r_10_rpr += foo();
    }
    switch( __kmpc_reduce_nowait( &loc10, *gtid, 1, 4, 
                                  &reduce, main_10_reduce_5, &lck ) ) {
    case 1:
        *r_7_shp += reduce.r_10_rpr;
        __kmpc_end_reduce_nowait( &loc10, *gtid, &lck);
        break;
    case 2:
        __kmpc_atomic_float4_add( &loc10, *gtid, r_7_shp, 
                                  reduce.r_10_rpr );
        break;
    default:
        break;
    }
}
```

Example from OpenMP runtime documentation
Fork Call

- “Forks” execution and calls a specified routine (microtask)
- Determine how many threads to allocate to the parallel region
- Setup task structures
- Release allocated threads from their idle loop
Iteration Mechanisms

- Static, compile time iterations
  - __kmp_for_static_init
  - Compute one set of iteration bounds

- Everything else
  - __kmp_dispatch_next
  - Compute the next set of iteration bounds
OMP Barriers

- Two phase -> gather and release
  - Gather non-master threads pass, master waits
  - Release is opposite

- Barrier can be:
  - Linear
  - Tree
  - Hypercube
  - Hierarchical
OMP Atomic

- Can the compiler do this in a read-modify-write (RMW) op?

- Otherwise, create a compare-and-swap loop

```c
T* val;
T update;
#pragma omp atomic
    *val += update;
```

If T is int, this is “lock add …”.
If T is float, this is “lock cmpxchg …”

Why?
OMP Tasks

- \#pragma omp task depend (inout:x) ...

- Create microtasks for each task
  - Track dependencies by a list of address / length tuples
Cilk

- Covered in Lecture 6
- We discussed the what and why, now the how
Simple Cilk Program Compiled

- What is this code doing?
- What do the Cilk semantics specify?
- Which is the child? Which is the continuation?

```c
int fib(int n) {
  if (n < 2)
    return n;
  int a = cilk_spawn fib(n-1);
  int b = fib(n-2);
  cilk_sync;
  return a + b;
}
```
How to create a continuation?

- Continuation needs all of the state to continue
  - Register values, stack, etc.

- What function allows code to jump to a prior point of execution?

- `Setjmp(jmp_buf env)`
  - Save stack context
  - Return via `longjmp(env, val)`
  - `Setjmp` returns 0 if saving, `val` if returning via `longjmp`
Basic Block

- **Unit of Code Analysis**

- **Sequence of instructions**
  - Execution can only enter at the first instruction
    - Cannot jump into the middle
  - Execution can only exit at the last instruction
    - Branch or Function Call
    - Or the start of another basic block (fall through)
Simple Cilk Program Revisited

entry → setjmp → fib(n-2)

Save Continuation

fib(n-1) → fib1 + fib2 → ret

!0 → fib(n-2)

0 → fib(n-1)

setjmp → Is sync?

!0 → ret

0 → cilkrts_sync

parallel

serial

maybe
Cilk Workers

- While there may be work
  - Try to get the next item from our queue
  - Else try to get work from a random queue
  - If there is no work found, wait on semaphore

- If work item is found
  - Resume with the continuation’s stack
Thread Local Storage

- Linux supports thread local storage
  - **New: C11 - _Thread_local** keyword
    - one global instance of the variable per thread
  - Compiler places values into .tbss
  - OS provides each thread with this space

- Since Cilk and OpenMP are using pthreads
  - These values are in the layer below them
DEMO