

Lecture 27:

Implementing Parallel Runtimes, Part 2

**Parallel Computer Architecture and Programming
CMU 15-418/15-618, Fall 2020**

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?**
 - **pthread**
- **What benefit does abstraction versus implementation provide?**
- **Recall that OpenMP and Cilk try to be annotations**
 - **Removing these annotations leaves correct serial code**

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**

Simple OpenMP Loop Compiled

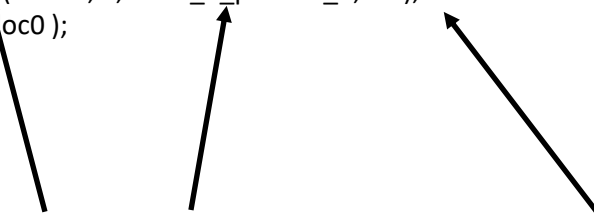
- What is this code doing?
- What do the OpenMP semantics specify?
- How might you accomplish this?

```
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;  
}
```

Simple OpenMP Loop Compiled

```
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**

```
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::;
    }
}
```


Simple OpenMP Loop Compiled

■ All code combined

```
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;;
    }
}
```

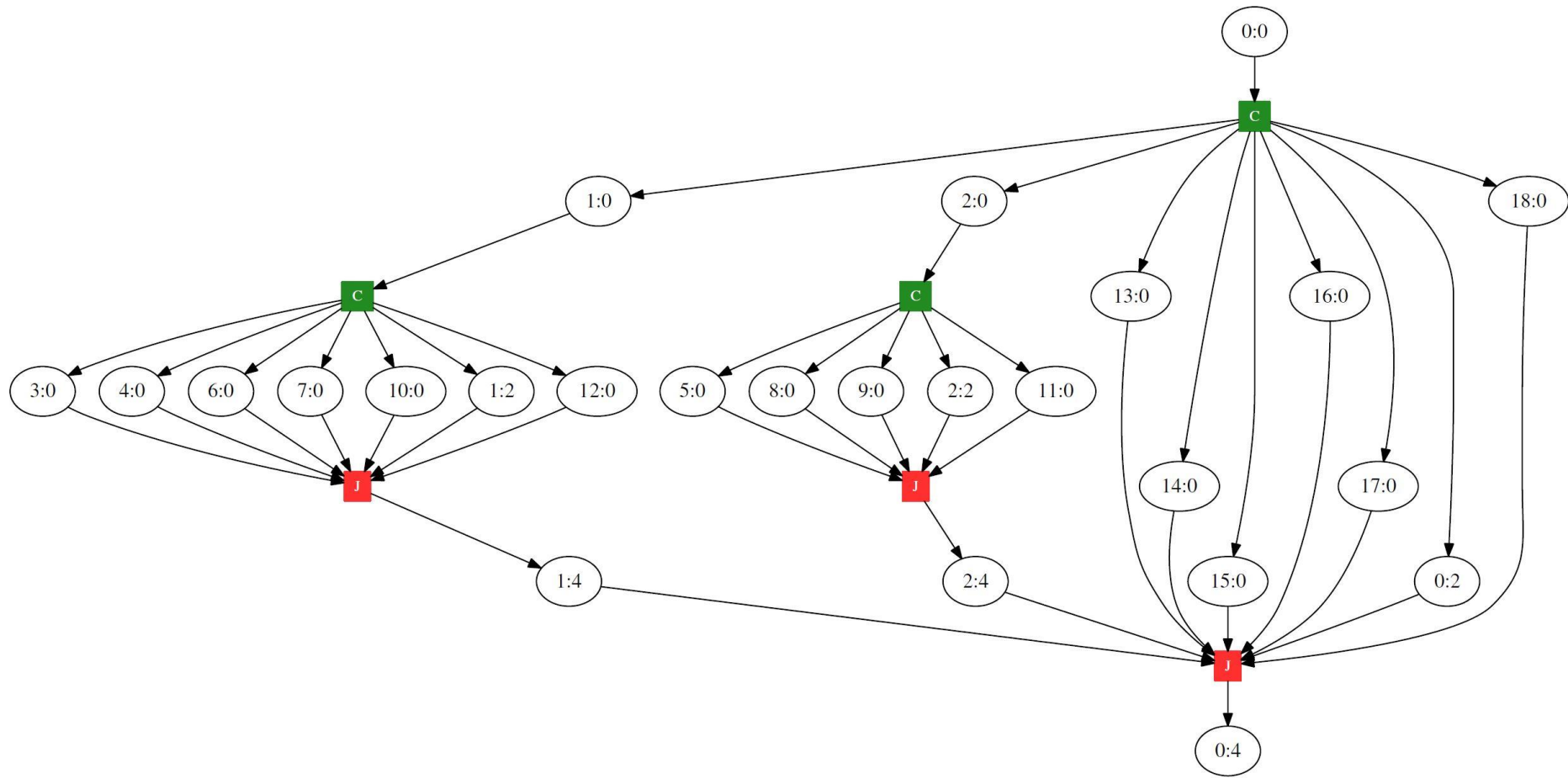
Fork Call

- **“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**

OpenMP Example



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

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

If T is int, this is “lock add ...”.

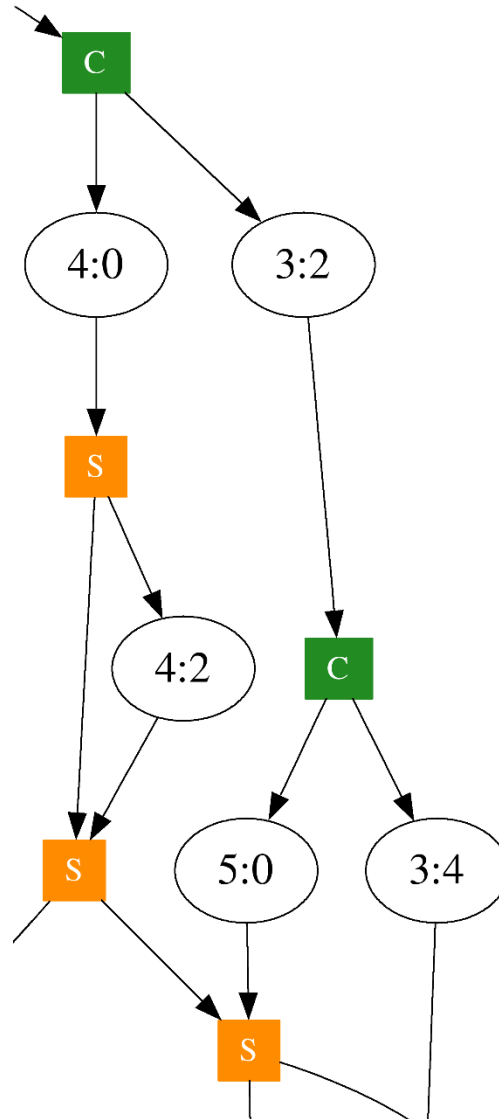
If T is float, this is “lock cmpxchg ...”

Why?

OMP Tasks

- **#pragma omp task depend (inout:x) ...**
- **Create microtasks for each task**
 - **Track dependencies by a list of address / length tuples**

OMP Tasks



Cilk

- **Covered in Lecture 5**
- **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?**
- **How many continuation points are there?**

```
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;  
}
```

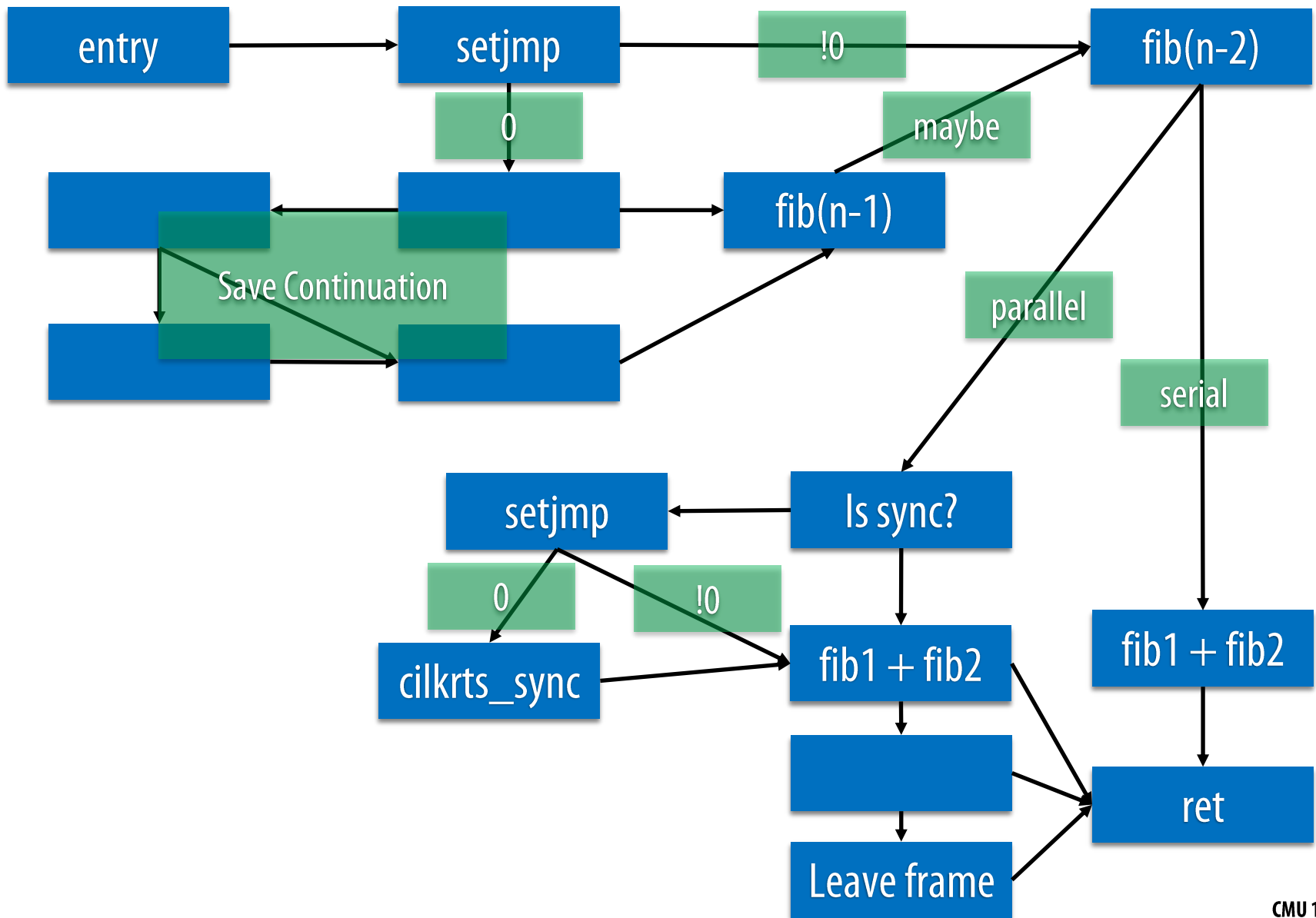
How to create a continuation?

- 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



Cilk Workers

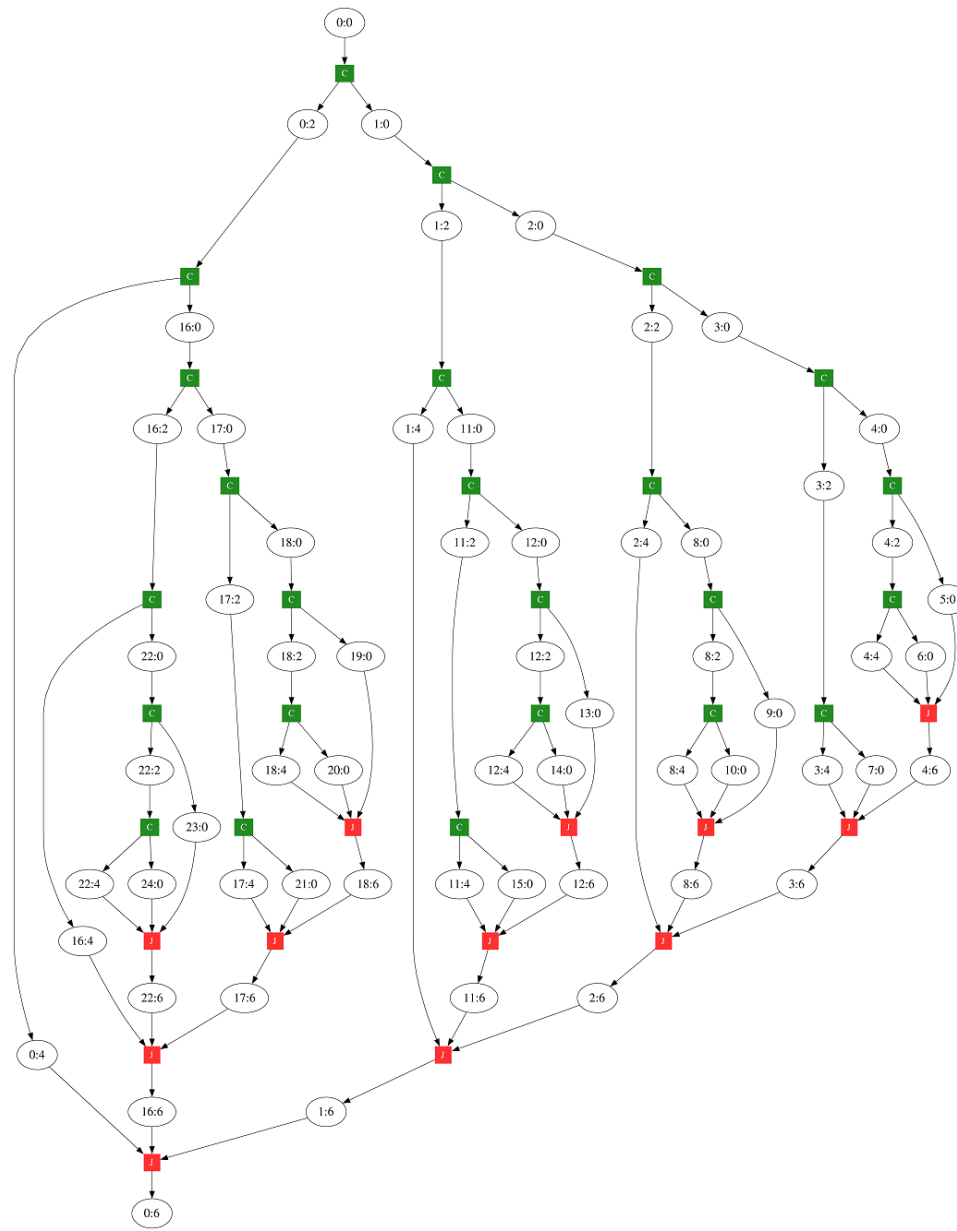
- **While there may be work**
 - **Try to get the next item from our queue**
 - **Else try to get work from a random queue**
 - **If there is no work found, wait on semaphore**
- **If work item is found**
 - **Resume with the continuation's stack**

DEMO

Cilk Output (subset)

```
...
NE: 41 - 0x14e39d0
Attempt sync - 41 - 0x1509a80
Join: 42 - 0x1509a80
Attempt sync - 41 - 0x1509a80
NE: 41 - 0x1509a80
Exit: 41 (6) - 0x1509940
Init: 6 - 0x1507fc0
Child create: 54 (from 6) - 0x1507fc0
Init: 54 - 0x1506460
Child create: 55 (from 54) - 0x1506460
Init: 55 - 0x15064b0
Child create: 56 (from 55) - 0x15064b0
Init: 56 - 0x1506500
Child create: 57 (from 56) - 0x1506500
Init: 57 - 0x150a010
Attempt sync - 57 - 0x150a010
NE: 57 - 0x150a010
Exit: 57 (56) - 0x1506500
Init: 56 - 0x150a0c0
Attempt sync - 56 - 0x150a0c0
NE: 56 - 0x150a0c0
Attempt sync - 56 - 0x1506500
Join: 57 - 0x1506500
Attempt sync - 56 - 0x1506500
```


Cilk Taskgraph



Cilk Taskgraph

