Compiler-level Concurrency Support: OpenMP, Cilk

Chris Rossbach

Outline for Today

- Questions?
- Administrivia
  - Go go go!
- Agenda
  - Compiler supported parallelism/concurrency
  - OpenMP
  - Cilk

Faux Quiz Questions

- What is a loop-carried dependence?
- List some tradeoffs between manual and auto parallelization
- List some challenges that make auto-parallelization of C/C++ hard; do any of them go away with managed language support?
- How does spawn differ from spawn_next in Cilk? Why does the language need both?
- How does OpenMP deal with partitioning work across threads? Compare and constrast this with Cilk.

Message Passing: Motivation

- Threads have a *lot* of down-sides:
  - Tuning parallelism for different environments
  - Load balancing/assignment brittle
  - Shared state requires locks →
    - Priority inversion
    - Deadlock
    - Incorrect synchronization
  - …
- Message passing:
  - *Threads aren't the problem, shared memory is*
  - *restructure programming model to avoid communication through shared memory (and therefore locks)*

Remember this slide?

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- Compiler Parallelization:
  - *Threads and shared memory aren't the problem, the PROGRAMMER is*
  - *restructure programming model to get the compiler to write the tricky code*

A simple program

```
int main() {
    int * data = malloc(10000 * sizeof(int));
    for(int i = 0; i < 10000; i++) {
        data[i] = data[i] * data[i];
    }
}
```

A simple program

How can we parallelize this?

```
int main() {
    int * data = malloc(10000 * sizeof(int));
    for(int i = 0; i < 10000; i++) {
        data[i] = data[i] * data[i];
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```

A simple program

```c
int main() {
    int * data = malloc(10000 * sizeof(int));
    for(int i = 0; i < 10000; i++) {
        data[i] = data[i] * data[i];
    }
}
```

How can we parallelize this?

Could a compiler parallelize this? If so, how? If not, why not?

How can we parallelize this one?

```
int main() {
    int * data = …
    for(int i = 1; i < 10000; i++) {
        data[i] = data[i] * data[i-1];
    }
}
```

How can we parallelize this one?

```
int main() {
    int * data = …
    for(int i = 1; i < 10000; i++) {
        data[i] = data[i] * data[i-1];
    }
}
```

Could a compiler tell the difference?

Another simple program

```
int main() {
    int * data = …
    int * temp = …
    int * result = …
    for(int i = 0; i < 10000; i++) {
        temp[i] = pipeline_stage1(data[i]);
    }
    for(int i = 0; i < 10000; i++) {
        result[i] = pipeline_stage2(data[i]);
    }
}
```

Another simple program

```
int main() {
    int * data = …
    int * temp = …
    int * result = …
    for(int i = 0; i < 10000; i++) {
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    }
}
```

Multiple forms of parallelism—both very simple and compiler-accessible

What about this one?

```c
int fib(int n) {
    if(n == 0 || n == 1)
        return n;
    return fib(n - 1) + fib(n - 2);
}

int main() {
    return fib(1000000);
}
```

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Hopeless?

Auto- and Guided Compiler parallelization

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- Wide range of approaches:
  - partial/guided
  - Restricted programming model
  - Fully automatic
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- Core: compiler looks for parallel idioms
  - Runs static analyses to decide safety
  - Not always guaranteed to be correct/performant
- Challenges same as for human
  - Decomposition/partitioning
  - Synchronization/Communication
  - Identifying ***Dependences***

Data Dependence

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Loop dependency analysis

- Compiler detects loops that can be safely and efficiently executed in parallel
- To know whether usages of an array access the same memory location, compiler performs dependency tests: dataflow analysis

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1. Flow (True) dependence : read-after-write

   int a, b, c;

   *a = c * 10;*

   *b = 2 * a + c;*

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   int a, b, c;

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   c = b + 40;

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2. Anti Dependency: write-after-read

   int a, b, c;

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   c = b + 40;

3. Output Dependence: write-after-write

   int a, b, c;

   *a = b *c ;*

   a = b + c + 10;

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Dependency in Loops

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Two main types of dependency in loops

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Loop Independent : Dependence in same iteration

```
for (i = 2; i<= 4; i++){
    a[i] = b[i] + c[i];
    d[i] = a[i];
}
```

Dependency in Loops

Two main types of dependency in loops

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for (i = 2; i<= 4; i++){
    a[i] = b[i] + c[i];
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Loop Carried : Dependence over the iteration

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for (i = 2 ;  i< = 4; i++) {
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Loop dependency analysis

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How about this one?

```
int main() {
    int * data, temp, out = …
    for(int i = 0; i < 100; i++) {
        for(int j = 0; j < 100; j++) {
            int idx = i * 100 + j;
            temp[idx] = data[idx] + data[i];
        }
    }
    for(int i = 0; i < 100; i++) {
        for(int j = 0; j < 100; j++) {
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            out[idx] = data[idx] + data[i];
        }
    }
}
```

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    for(int i = 0; i < 100; i++) {
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            out[idx] = data[idx] + data[i];
        }
    }
}
```

Super parallel. Has data parallelism, nested parallelism, pipeline…
How to partition?

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        }
    }
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        }
    }
}
```

Super parallel. Has data parallelism, nested parallelism, pipeline…
How to partition?

In general, compiler can’t do this arbitrarily without *hints*

OpenMP

- Standard for shared memory programming
  - Target: scientific applications.
- Specific support for scientific application needs
  - unlike Pthreads
- API is a set of compiler directives
  - Programmer inserts in the source program
  - Plus a few library functions
- Ideally, compiler directives do not affect sequential code.
  - pragma's in C / C++ .
  - (special) comments in Fortran code.
  - If the compiler ignores them → correct single-threaded program

OpenMP API Example

Sequential code:

```
statement1;
statement2;
statement3;
```

We want to execute:

- statement 2 in parallel
- statement 1 and 3 sequentially.

OpenMP API Example

OpenMP parallel code:

```
statement 1;
#pragma <specific OpenMP directive>
statement2;
statement3;
```

Statement 2 (may be) executed in parallel.

Statement 1 and 3 are executed sequentially.

OpenMP API Example

OpenMP parallel code:

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statement 1;
#pragma <specific OpenMP directive>
statement2;
statement3;
```

Statement 2 (may be) executed in parallel.

Statement 1 and 3 are executed sequentially.

- By giving a parallel directive, the user asserts that the program will remain correct if the statement is executed in parallel.
- OpenMP compiler does not check correctness.

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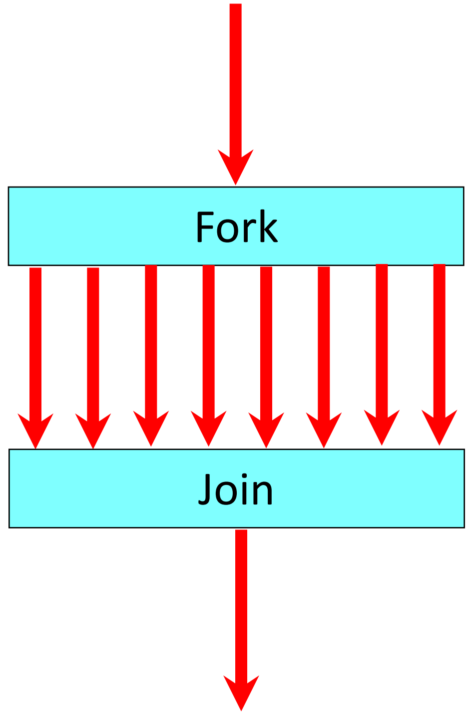
- Master and slaves execute parallel code.



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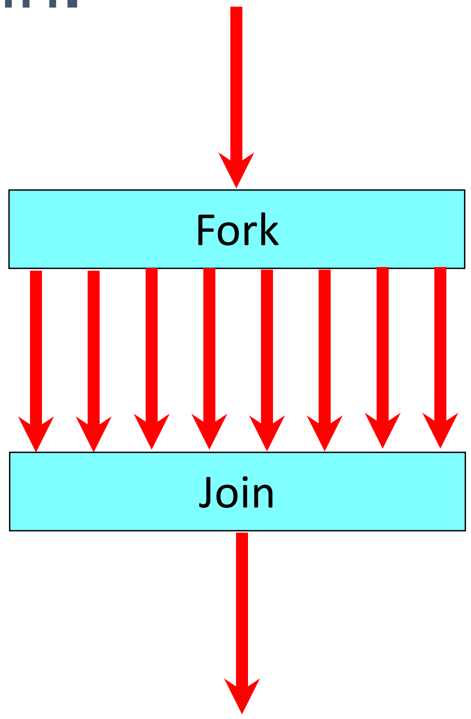
- Note: very similar to fork-join:



API Semantics

- Master thread executes sequential code.
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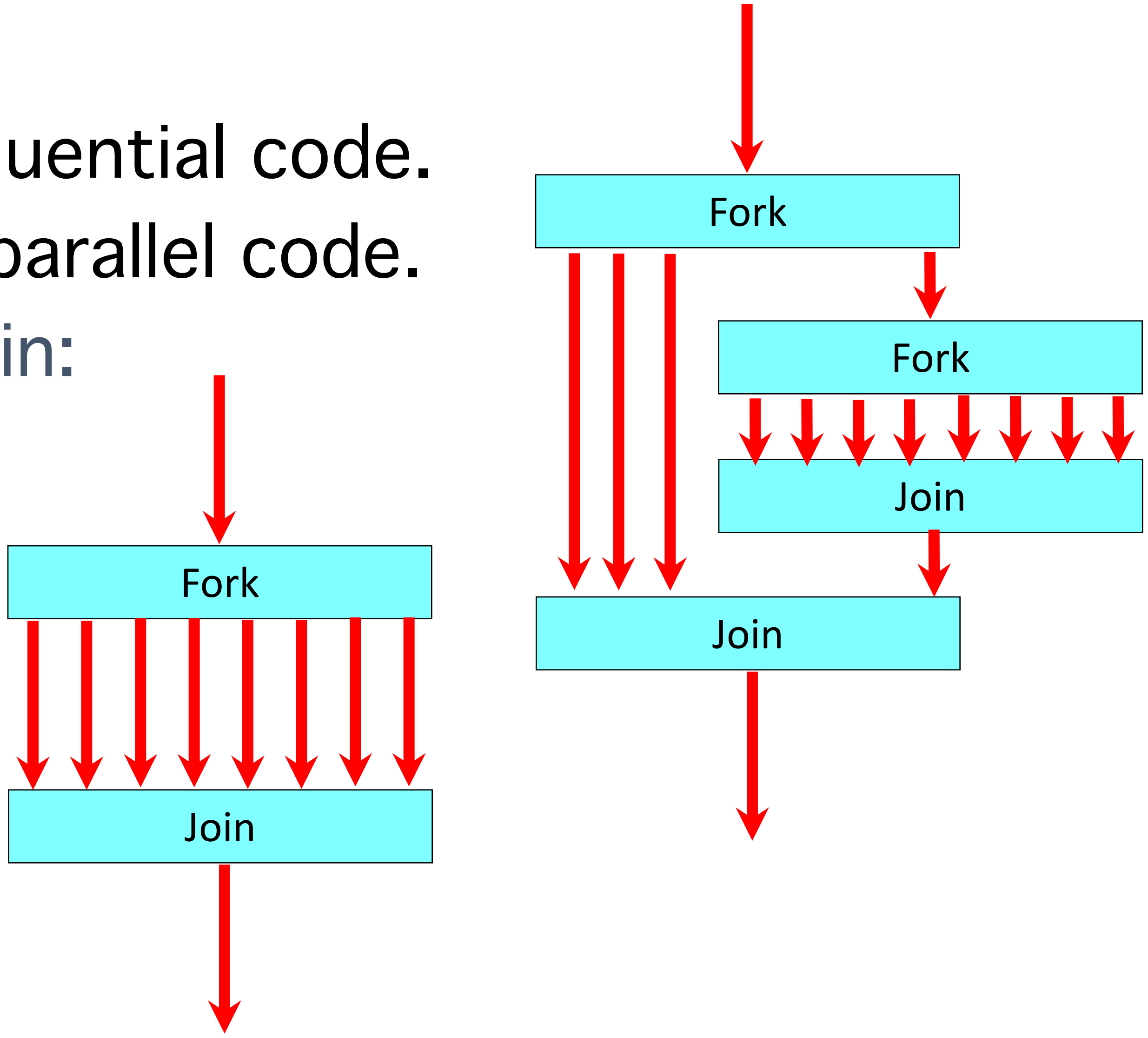
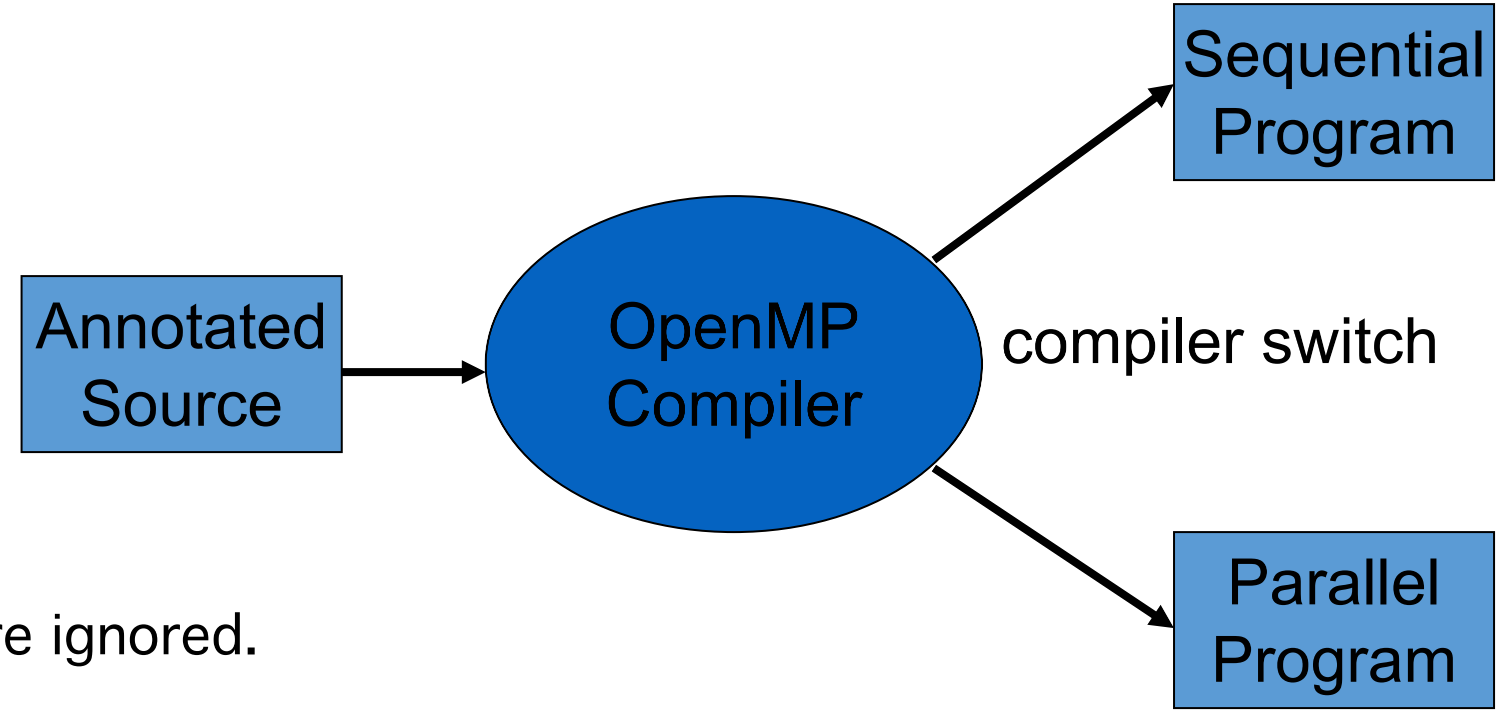
- Note: very similar to fork-join:
- But allows nesting!



OpenMP Compiler



- Sequential switch →
  - comments and pragmas are ignored.
- Parallel switch →
  - translation into parallel program.
- *One source for sequential and parallel!*

OpenMP Directives

- Always apply to the next statement
  - must be a structured block.
- Examples
  - #pragma omp …
    statement
  - #pragma omp …
    { statement1; statement2; statement3; }

OpenMP Directives

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  - parallel region
  - parallel for

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- Synchronization directives:
  - barrier, critical

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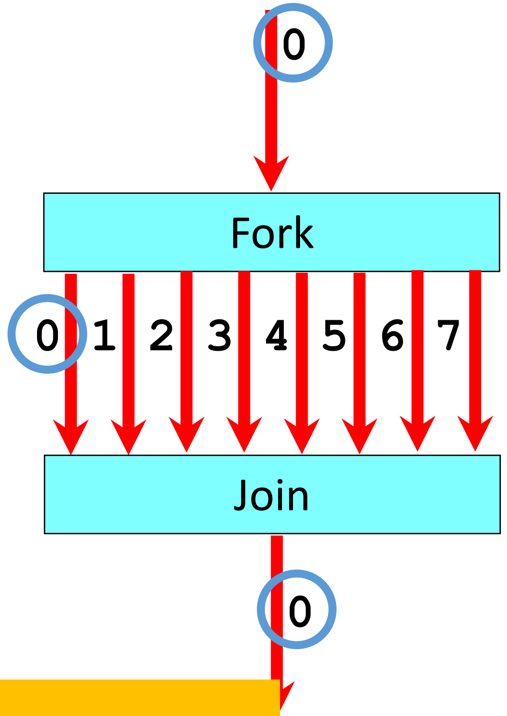
- How to get threads to do different things?
    - Through explicit thread identification (as in Pthreads).
    - ...and work-sharing directives.

Thread Identification

int omp_get_thread_num()
int omp_get_num_threads()

- Library function (not annotation)
- Gets the thread id.
- Gets the total number of threads.




```
#pragma omp parallel
{
  if( !omp_get_thread_num() )
    master();
  else
    slave();
}
```

Work Sharing Directives

- Always occur within a parallel region directive.
- Two principal ones are
  - parallel for
  - parallel section

OpenMP Parallel For

```
#pragma omp parallel
  #pragma omp for
  for( ... ) { ... }
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```
#pragma omp parallel for
for( i=0; i<n; i++ )
  for( j=0; j<n; j++ ) {
        c[i][j] = 0.0;
        for( k=0; k<n; k++ )
                c[i][j] += a[i][k]*b[k][j];
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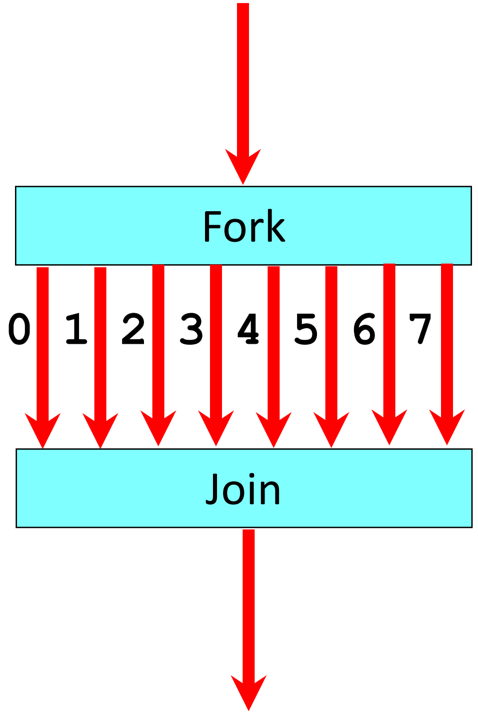

Multiple Work Sharing Directives

- May occur within a single parallel region

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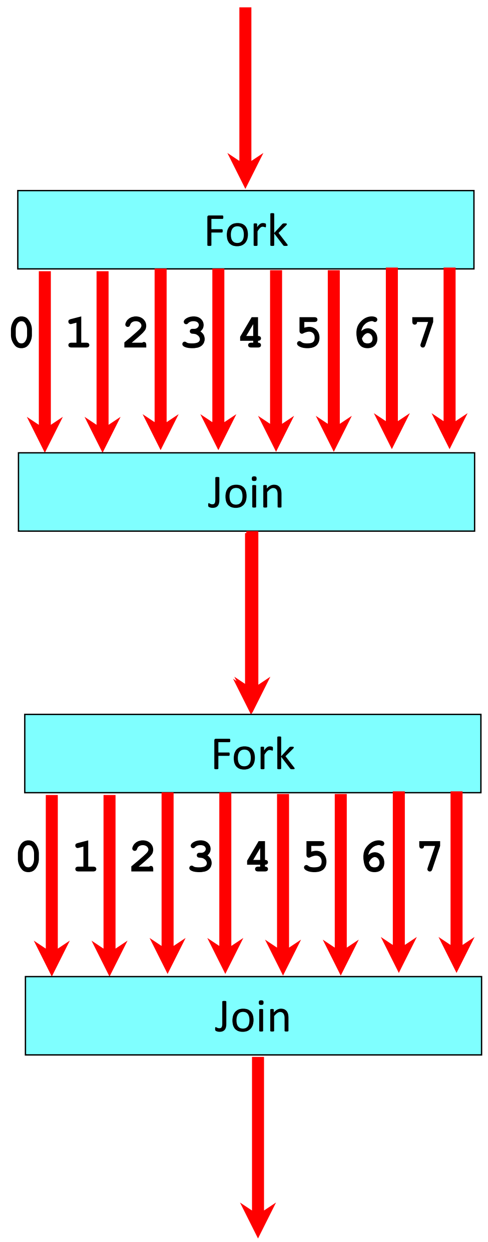

Conditional Parallelism

```
#pragma omp parallel if( expression )
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- Execute in parallel if expression, otherwise sequential

Conditional Parallelism

- Parallelism only useful for large problem size

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```

- Execute in parallel if ex

```
for( i=0; i<n; i++ )
  #pragma omp parallel for if( n-i > 100 )
  for( j=i+1; j<n; j++ )
    for( k=i+1; k<n; k++ )
          a[j][k] = a[j][k] - a[i][k]*a[i][j] / 
  a[j][j]
```

Scheduling of Iterations

- Scheduling: assigning iterations to a thread.
- Default is block scheduling.
- OpenMP allows other scheduling strategies:
  - Cyclic, block, gss (guided self-scheduling), dynamic…

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```
#pragma omp parallel for schedule(<sched>)
```

- <sched> can be one of
  - block (default)
  - cyclic
  - Gss
  - Etc.

Example

```c
#define THREADS 16
#define N 100000000

int main ( ) {
  int i;

  printf("Running %d iterations on %d threads guided.\n", N, THREADS);
  #pragma omp parallel for schedule(guided) num_threads(THREADS)
  for (i = 0; i < N; i++) {
    /* a loop that doesn't take very long */

  }

  /* all threads done */
  printf("All done!\n");
  return 0;
}
```

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```

chunk size changes as the program runs. It begins with big chunks, but then adjusts to smaller chunk sizes if the workload is imbalanced

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- All variables are by default shared.
- One exception: the loop variable of a parallel for is private.
- Data directives:
    - Private
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        for( k=0; k<n; k++ )
              c[i][j] +=
  a[i][k]*b[k][j];
  }
```

- a, b, c are shared
- i, j, k are private

Private Variables

```
#pragma omp parallel for private( list )
```

- Private copy for each thread for each variable in the list.

```
for( i=0; i<n; i++ ) {
   tmp = a[i];
   a[i] = b[i];
   b[i] = tmp;
}
```

- Swaps the values in a and b.
- Loop-carried dependence on tmp.
- Easily fixed by privatizing tmp.

```
#pragma omp parallel for private( tmp )
for( i=0; i<n; i++ ) {
   tmp = a[i];
   a[i] = b[i];
   b[i] = tmp;
}
```

- Removes dependence

Reduction Variables

```
#pragma omp parallel for reduction( op:list )
```

- op is one of +, *, -, &, ^, |, &&, or ||
- The variables in list must be used with this operator in the loop.
- The variables are automatically initialized to sensible values.

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```
#pragma omp parallel for reduction( +:sum )
for( i=0; i<n; i++ )
  sum += a[i];
```

- Sum is automatically initialized to zero.

OpenMP synchronization

Implicit Barrier

– beginning and end of `parallel` constructs

– end of all other control constructs

– implicit synchronization can be removed with **`nowait`** clause

- Explicit

`critical`

OpenMP critical directive

Enclosed code

– executed by all threads, but

– **restricted to only one thread at a time**

• C/C++:

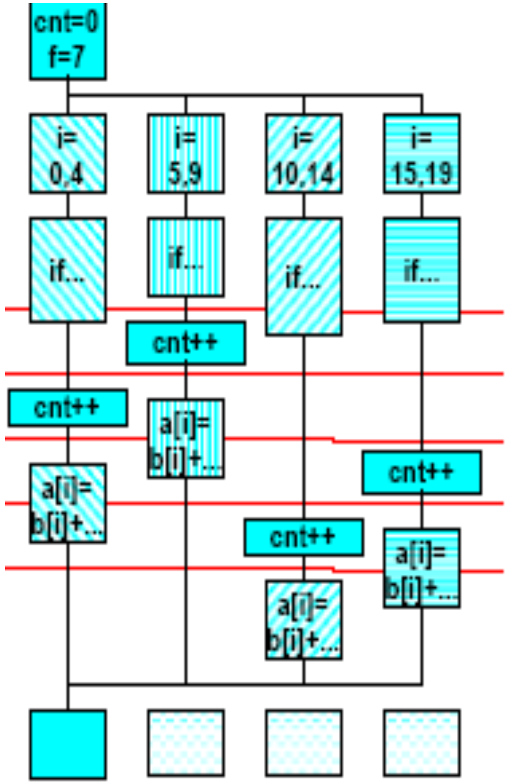
`#pragma omp critical` [(name)] new-line

structured-block

• A thread waits at the beginning of a critical region until no other thread in the team is executing a critical region with the same name. All unnamed `critical` directives map to the same unspecified name.

OpenMP critical

C / C++: cnt = 0;
f=7;
#pragma omp parallel
{
#pragma omp for
   for (i=0; i<20; i++) {
            if (b[i] == 0) {
#pragma omp critical
                        cnt ++;
            } /* endif */
   a[i] = b[i] + f * (i+1);
   } /* end for */
} /*omp end parallel */



OpenMP Fibonacci

```
int main(){
   int nthreads, tid;
   int n = 8;
   #pragma omp parallel num_threads(4) private(tid)
   {
      #pragma omp single
      {
         tid = omp_get_thread_num();
         printf("Hello world from (%d)\n", tid);
         printf("Fib(%d) = %d by %d\n", n, fib(n), tid);
      }
   } // all threads join master thread and terminates
}

Static int fib(int n){
   int i, j, id;
   if(n < 2)
      return n;
   #pragma omp task shared (i) private (id)
   {
      i = fib(n-1);
   }
   #pragma omp task shared (j) private (id)
   {
      j = fib(n-2);
    }
   return (i+j);
}
```

OpenMP Summary

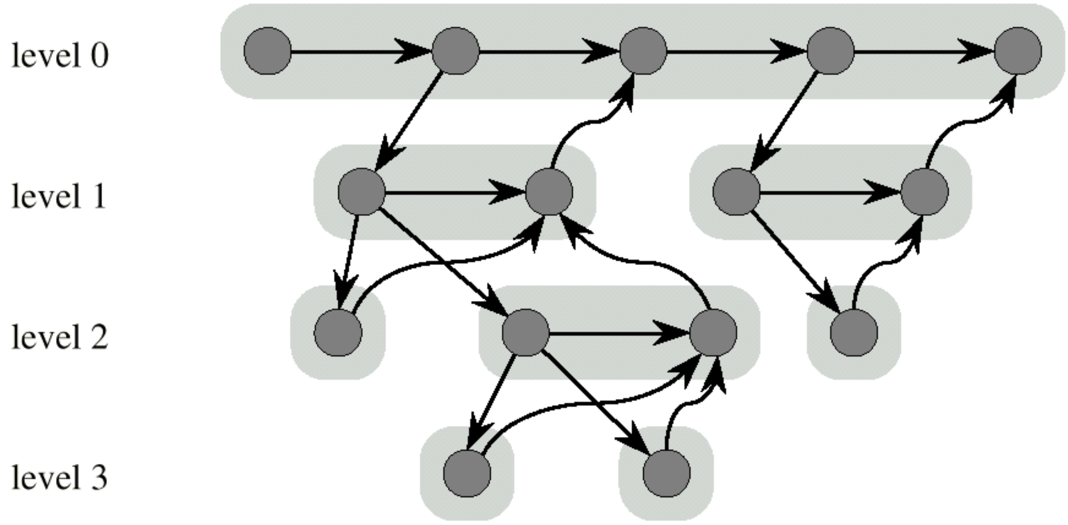
- Programmer gives the compiler hints
- Compiler auto-parallizes based on those hints
- Seems to require a lot of hints, no?
- What do you think?

Cilk

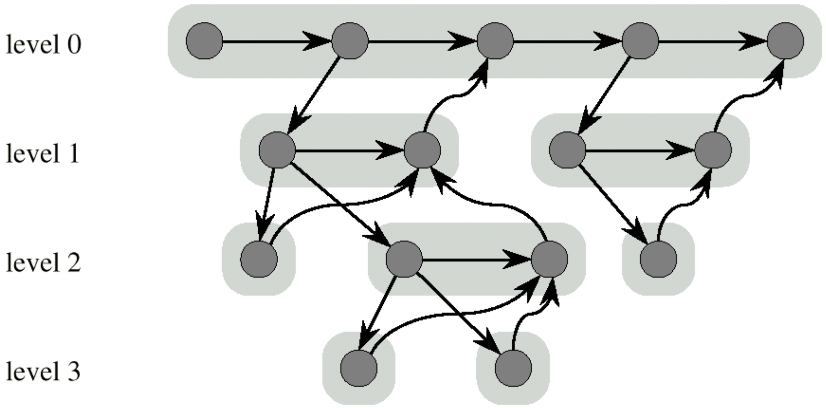
- Goal:

  To implement dynamic, asynchronous, concurrent programs.

- Cilk programmer optimizes:
  - total work
  - critical path
- A Cilk computation:
  - dynamic, directed acyclic graph (dag)

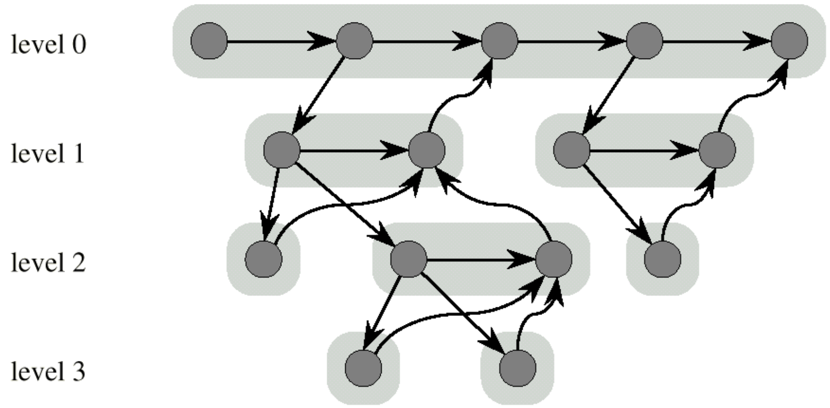


Cilk Terms



- Cilk *program* is a set of procedures
- A *procedure* is a *sequence* of threads
- Cilk *threads* are:
  - represented by nodes in the dag
  - **Non-blocking**: run to completion: **no** waiting or suspension: **atomic** units of execution

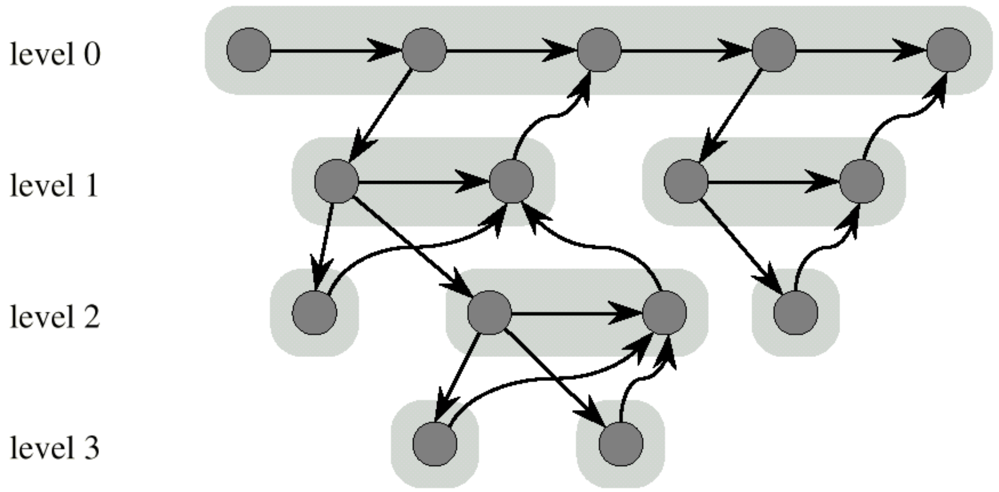
Programming Model



- Threads can *spawn* child threads
  - downward edges connect a parent to its children
- A child & parent can run concurrently.
  - Non-blocking threads ➔ a child cannot return a value to its parent.
  - The parent spawns a *successor* that receives values from its children

Programming Model

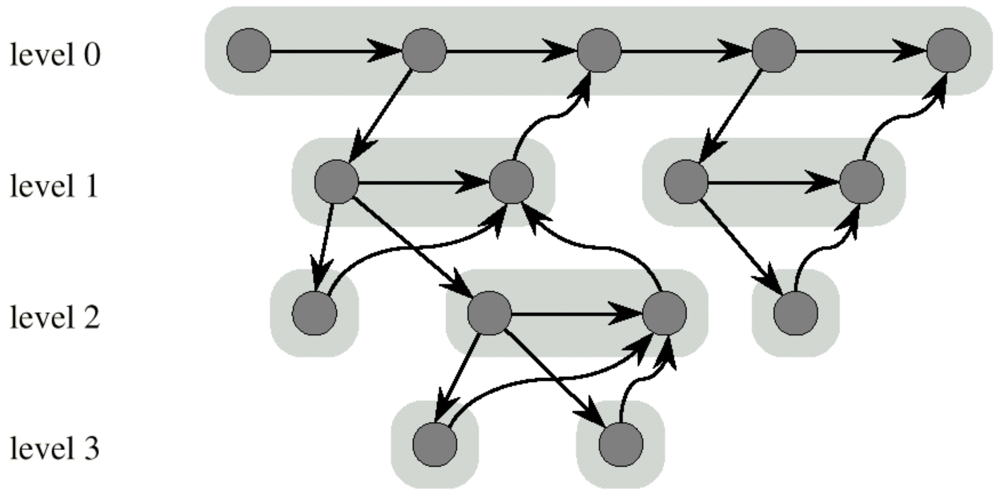
- Thread & successor: parts of the same Cilk procedure.
  - connected by horizontal arcs
- Children's returned values:
  - received before their successor begins
  - They constitute data dependencies.
  - Connected by curved arcs



Execution Time & Scheduling

- Execution time of a Cilk program using P cores depends on:
  - Work (T_1): time for Cilk program with 1 processor to complete.
  - Critical path (T_∞): the time to execute the longest directed path in the dag.
  - $T_P >= T_1 / P$ (not true for some searches)
  - $T_P >= T_\infty$

- Cilk uses run time scheduling: work stealing.
- For "fully strict" programs
  - asymptotic optimality for:
  - space, time, & communication



Cilk Language

- Cilk is an extension of C
- Cilk programs are:
  - preprocessed to C
  - linked with a runtime library

- Declaring a thread:

thread T (<args>) { <stmts> }

- T is preprocessed
  - C function of 1 argument
  - return type void.
- The 1 argument is a pointer to a *closure*

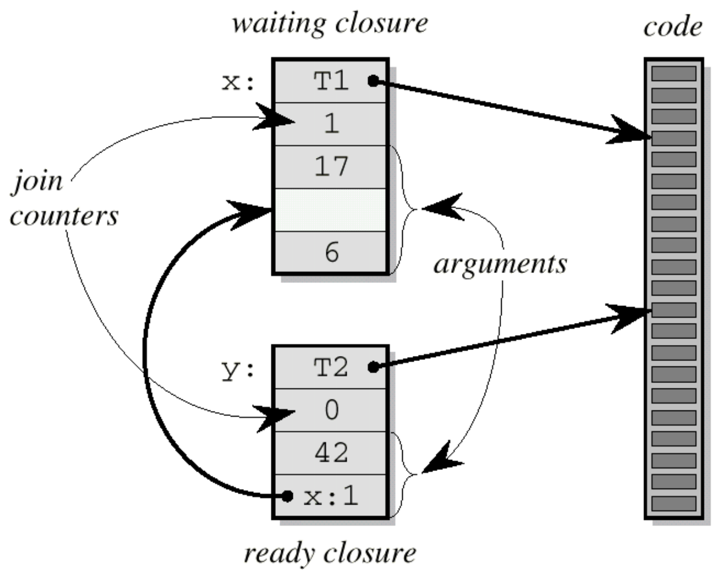
Environment: Closures and Continuations

- A *closure* is a data structure that has:
  - a pointer to the C function for T
  - a slot for each argument (inputs & continuations)
  - a **join counter**: count of the missing argument values
- A closure is ready when join counter == 0.
- A closure is waiting otherwise.
- They are allocated from a runtime heap

- *Continuation* is a data type,

```
cont int x;
```

- Global reference to an *empty slot of a closure*.
- It is implemented as 2 items:
  - a pointer to the closure; (what thread)
  - an int value: the slot number. (what input)



Creating Parallel Work

- To *spawn* a child, a thread creates its closure:

  spawn T (<args>)

  - creates child's closure
  - sets available arguments
  - sets join counter

- To specify a missing argument, prefix with a "?"

  spawn T (k, ?x);

- A *successor* thread spawned the same way
- except the keyword spawn_next is used:

  spawn_next T(k, ?x)

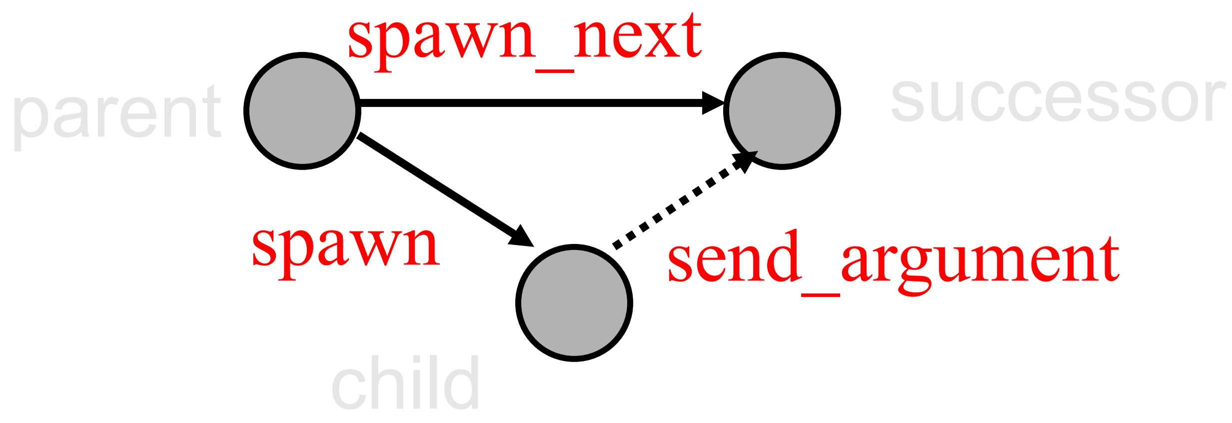
- Children typically have no missing arguments; successors do.

Explicit continuation passing

- Nonblocking threads ➔ a parent cannot block on children's results.
- It spawns a successor thread.
- Paradigm called *explicit continuation passing*.
- Cilk provides a primitive to *send a value* from one closure to another.

send_argument(k, value)

sends value to the argument slot of a waiting closure specified by continuation k.



Cilk Procedure for computing a Fibonacci number

```
thread int fib ( cont int k, int n ) {
   if ( n < 2 ) send_argument( k, n );
   else { cont int x, y;
            spawn_next sum ( k, ?x, ?y );
            spawn fib ( x, n  - 1 );
            spawn fib ( y, n - 2 );
           }
}
thread sum ( cont int k, int x, int y ) {
  send_argument ( k, x + y );
}
```

Nonblocking Threads: Pros, Cons

- *Shallow call stack*. (for us: fault tolerance)
- Simplify runtime system:

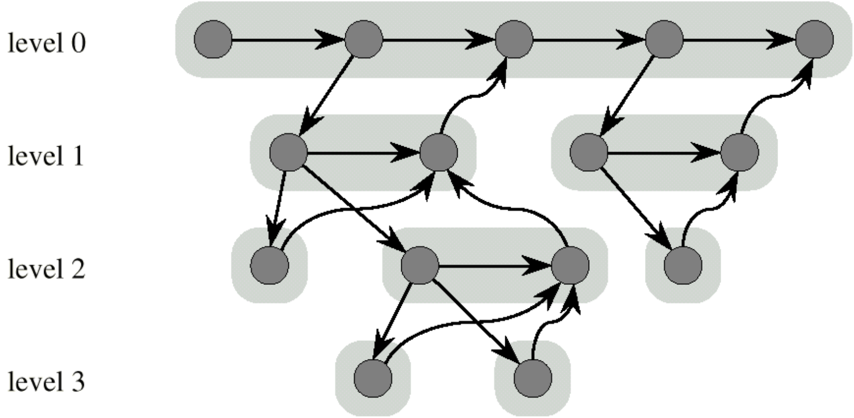
  Completed threads leave C runtime stack empty.

- Portable runtime implementation

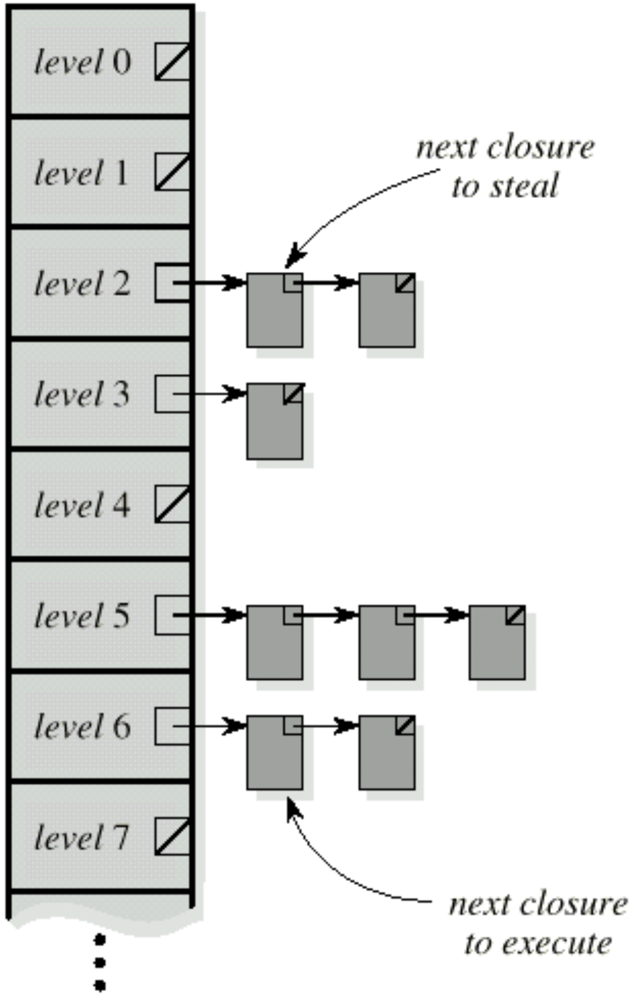
Con: Burdens programmer with explicit continuation passing.

Stealing Work: The Ready Deque

- Work-stealing:
  - Process with no work selects a victim
  - Gets shallowest thread in victim's spawn tree.
- Thieves choose victims *randomly*.
- Each closure has a level:
  - level(child) = level(parent) + 1
  - level(successor) = level(parent)
- Each processor keeps a ready deque:
  - Contains ready closures
  - The **L**th element contains the list of all ready closures whose level is **L**.



Ready deque



if (! readyDeque .isEmpty())

take deepest thread

else

steal shallowest thread from readyDeque of *randomly selected* victim

Why Steal Shallowest closure?

- Shallow threads *probably* produce more work, therefore, reduce communication.
- Shallow threads *more likely to be* on critical path.