

CSE 613: Parallel Programming

Lectures 3 & 4

(The Cilk++ Concurrency Platform)

(inspiration for many slides comes from talks given
by Charles Leiserson and Matteo Frigo)

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The Cilk++ Concurrency Platform

- Supports *dynamic multithreading*
- Includes a small set of *linguistic extensions* to C++ to support *fork-join* parallelism
- Based on multithreaded language technology developed at MIT and MIT spin-off *Cilk Arts* (acquired by *Intel* in 2009)
- Includes
 - A provably efficient scheduler
 - Hyperobject library for parallelizing code with global variables
 - Race detector (*Cilkscreen*)
 - Scalability analyzer (*Cilkview*)

The Cilk++ Concurrency Platform

Download URL

- MIT Cilk Project:

<http://supertech.csail.mit.edu/cilk/>

- Intel® Cilk++ SDK:

<http://software.intel.com/en-us/articles/download-intel-cilk-sdk/>

- Intel® Cilk Plus:

<http://software.intel.com/en-us/articles/intel-cilk-plus/>

- Intel® C++ Composer XE 2013:

<http://software.intel.com/en-us/non-commercial-software-development>

**Serial to Parallel
using
Three Keywords**

Nested Parallelism in Cilk++

$${}^n C_r = {}^{n-1} C_{r-1} + {}^{n-1} C_r$$

```
int comb ( int n, int r )
{
    if ( r > n ) return 0;
    if ( r == 0 || r == n ) return 1;

    int x, y;

    x = comb( n - 1, r - 1 );
    y = comb( n - 1, r );

    return ( x + y );
}
```

Serial C++ code

Control cannot pass this point until all spawned children have returned.

Grant permission to execute the called (spawned) function in parallel with the caller.

```
comb ( int n, int r )
{
    if ( r > n ) return 0;
    if ( r == 0 || r == n ) return 1;

    int x, y;

    x = cilk_spawn comb( n - 1, r - 1 );
    y = comb( n - 1, r );

    cilk_sync;

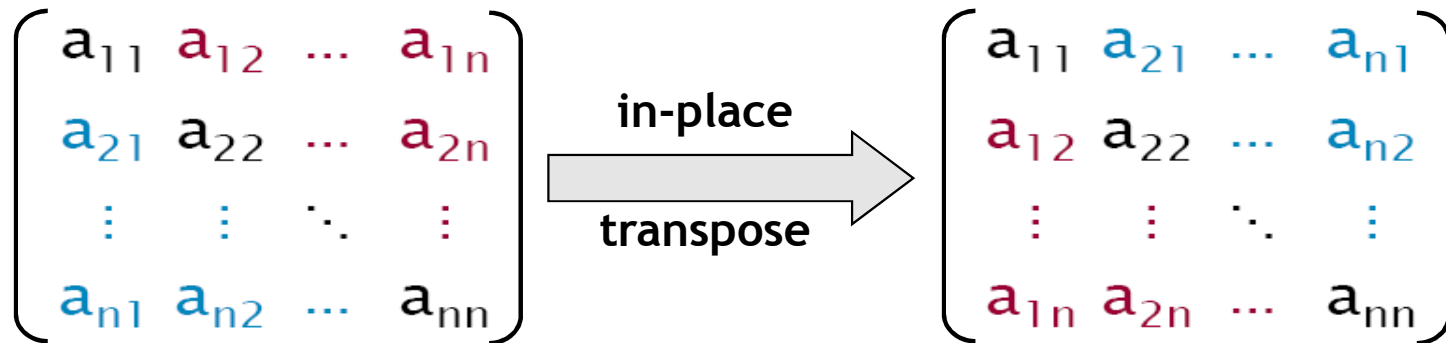
    return ( x + y );
}
```

Function return enforces implicit synchronization.

Oblivious of the number of cores / processors!

Cilk++ code

Loop Parallelism in Cilk++



```
for ( int i = 1; i < n; ++i )
  for ( int j = 0; j < i; ++j )
  {
    double t = A[ i ][ j ];
    A[ i ][ j ] = A[ j ][ i ];
    A[ j ][ i ] = t;
  }
```

Allows all iterations of the loop to be executed in parallel.

Converted to spawns and syncs using recursive divide-and-conquer.

Serial C++ code

```
cilk_for ( int i = 1; i < n; ++i )
  for ( int j = 0; j < i; ++j )
  {
    double t = A[ i ][ j ];
    A[ i ][ j ] = A[ j ][ i ];
    A[ j ][ i ] = t;
  }
```

Cilk++ code

Measuring Parallel Performance

Cilk++ Execution Model

```
int comb ( int n, int r )
{
    if ( r > n ) return 0;
    if ( r == 0 || r == n ) return 1;

    int x, y;

    x = cilk_spawn comb( n - 1, r - 1 );
    y = comb( n - 1, r );

    cilk_sync;

    return ( x + y );
}
```


Cilk++ Execution Model

```
int comb ( int n, int r )
{
    if ( r > n ) return 0;
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    int x, y;

    x = cilk_spawn comb( n - 1, r - 1 );
    y = comb( n - 1, r );

    cilk_sync;

    return ( x + y );
}
```

1

(4, 2)



Cilk++ Execution Model

```
int comb ( int n, int r )
{
  if ( r > n ) return 0;
  if ( r == 0 || r == n ) return 1;

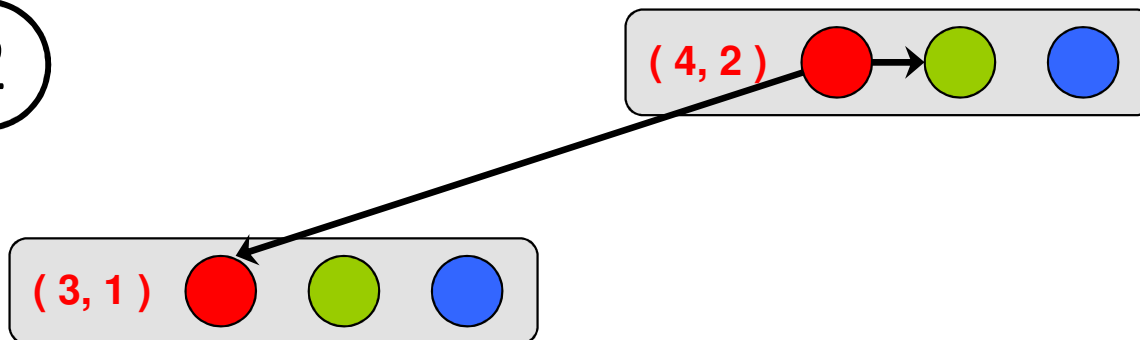
  int x, y;

  x = cilk_spawn comb( n - 1, r - 1 );
  y = comb( n - 1, r );

  cilk_sync;

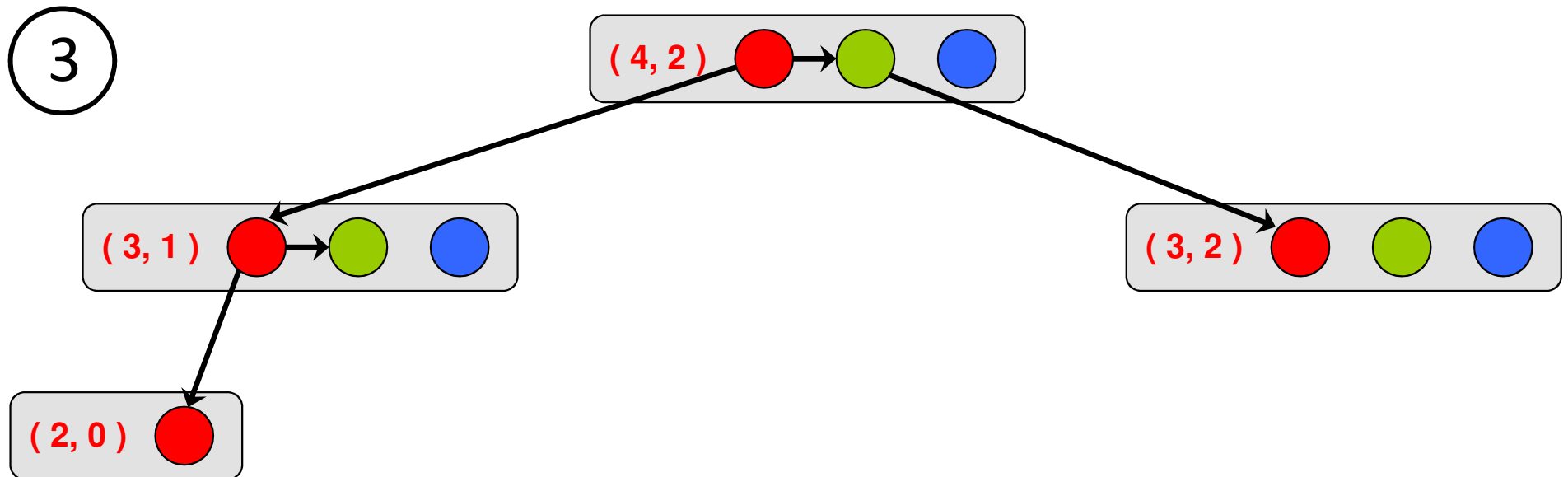
  return ( x + y );
}
```

2



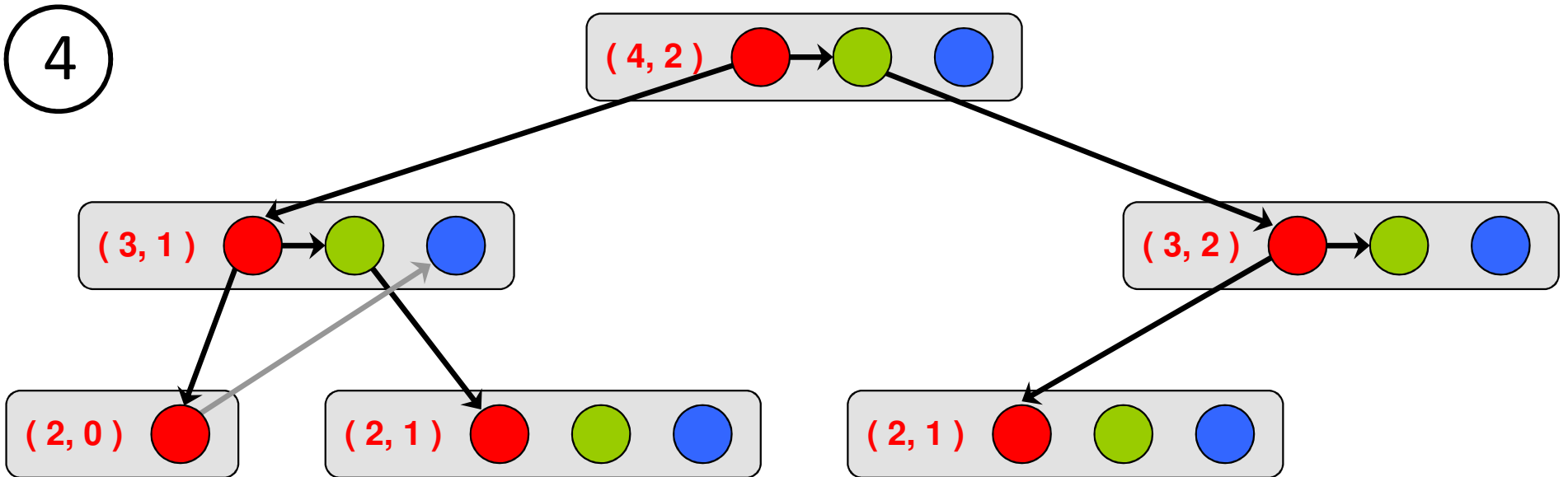
Cilk++ Execution Model

```
int comb ( int n, int r )  
{  
    if ( r > n ) return 0;  
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    int x, y;  
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    y = comb( n - 1, r );  
    cilk_sync;  
    return ( x + y );  
}
```



Cilk++ Execution Model

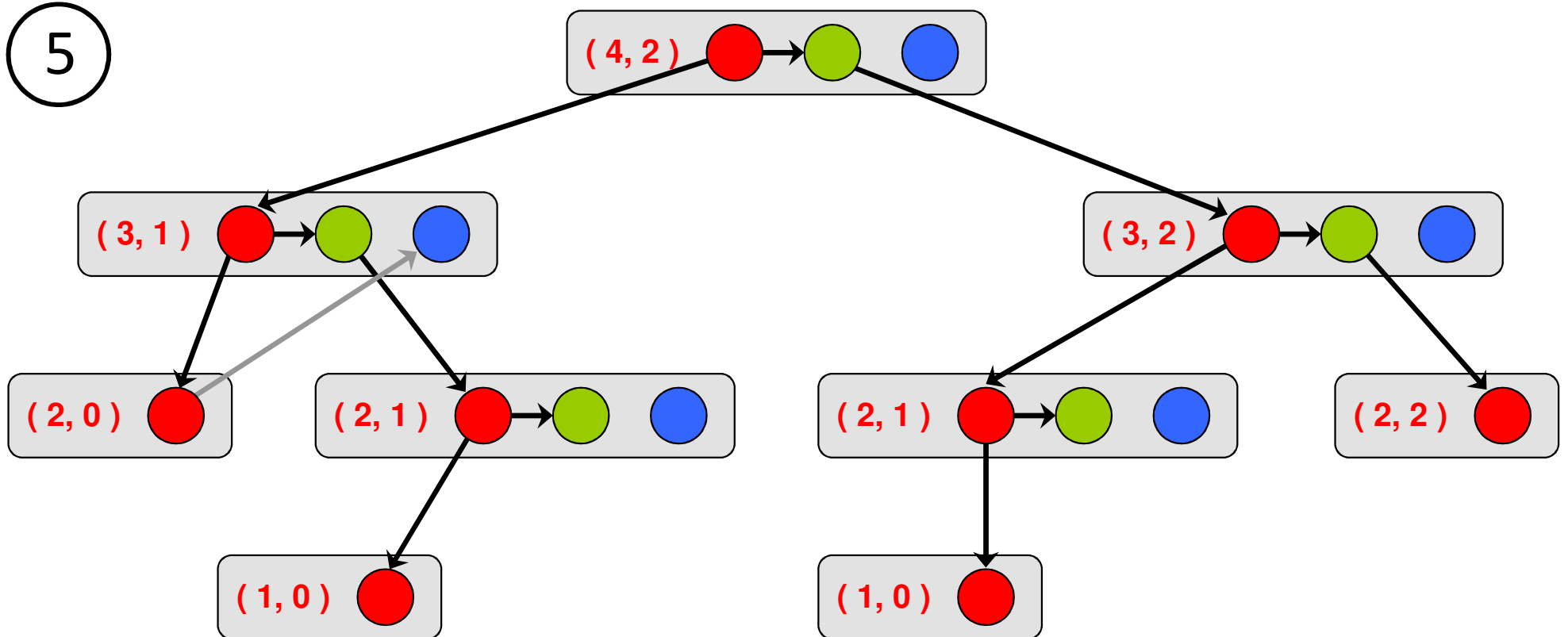
```
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    if ( r > n ) return 0;  
    if ( r == 0 || r == n ) return 1;  
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    y = comb( n - 1, r );  
    cilk_sync;  
    return ( x + y );  
}
```



Cilk++ Execution Model

```
int comb ( int n, int r )  
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    cilk_sync;  
    return ( x + y );  
}
```

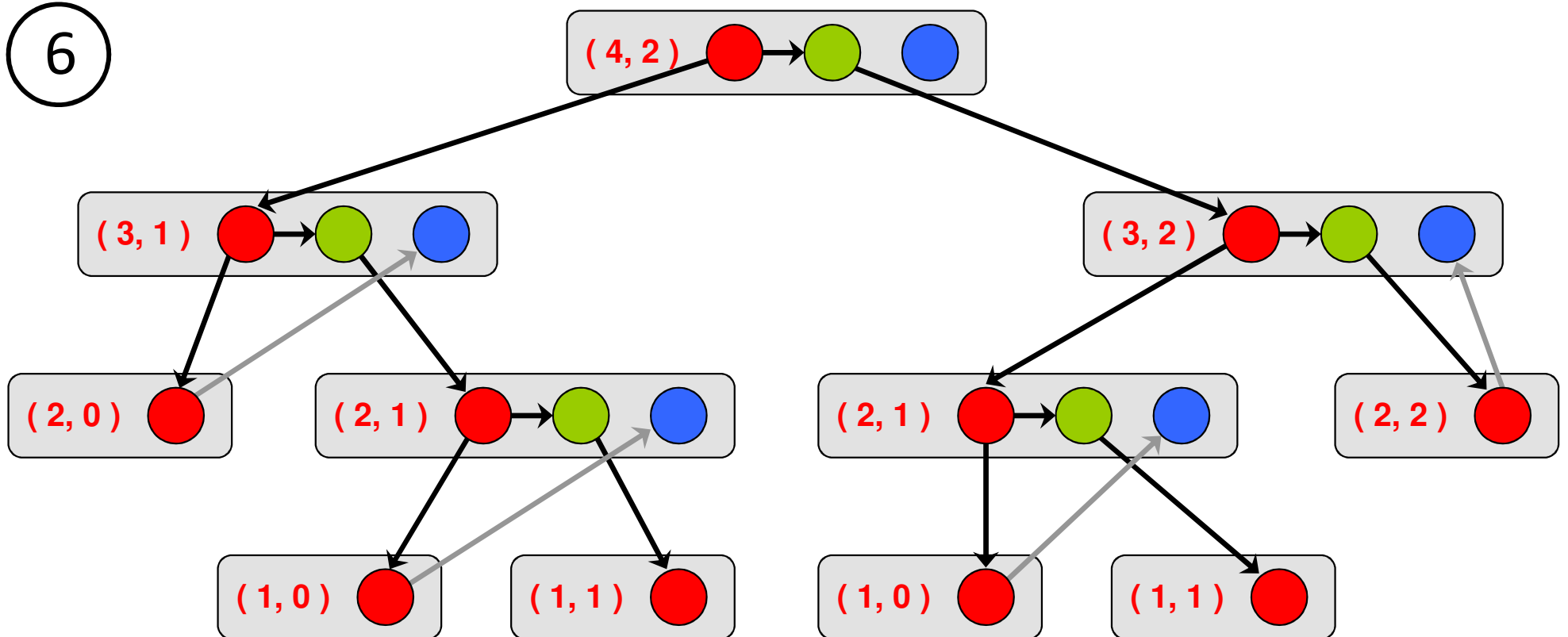
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Cilk++ Execution Model

```
int comb ( int n, int r )  
{  
    if ( r > n ) return 0;  
    if ( r == 0 || r == n ) return 1;  
    int x, y;  
    x = cilk_spawn comb( n - 1, r - 1 );  
    y = comb( n - 1, r );  
    cilk_sync;  
    return ( x + y );  
}
```

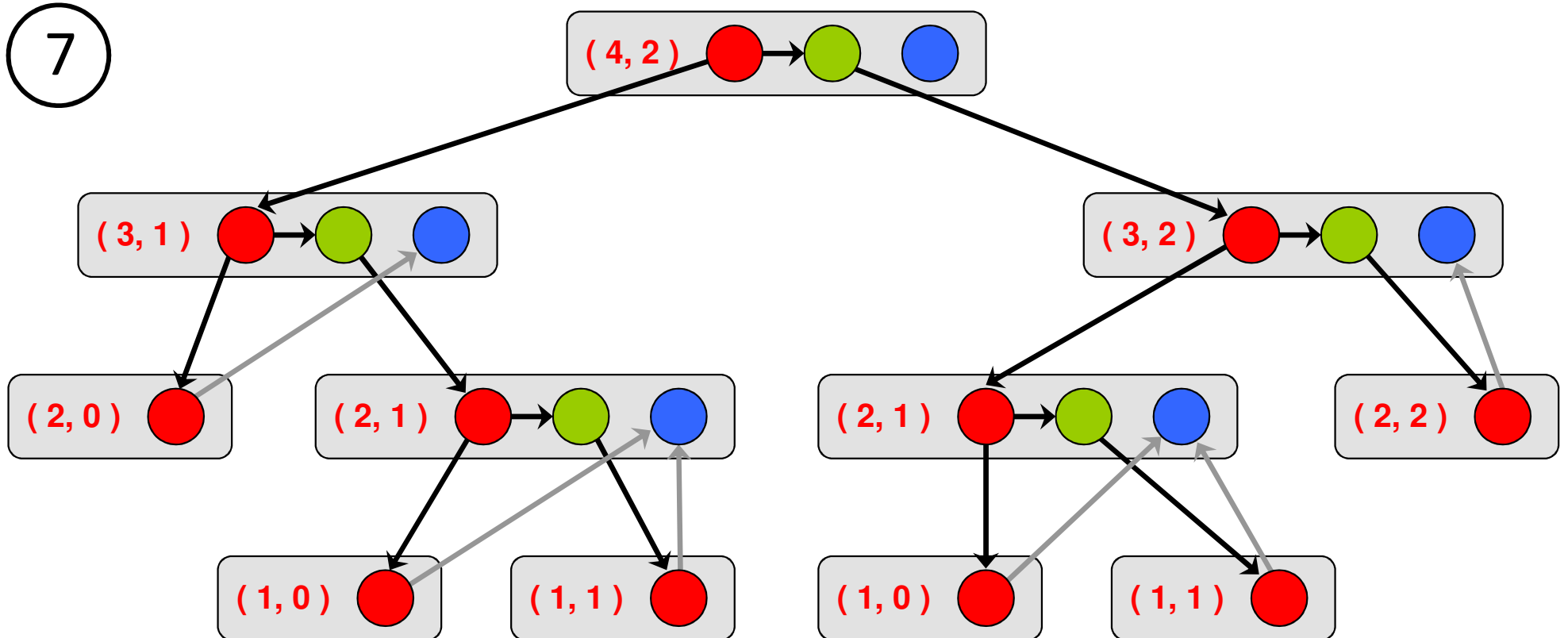
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Cilk++ Execution Model

```
int comb ( int n, int r )  
{  
    if ( r > n ) return 0;  
    if ( r == 0 || r == n ) return 1;  
    int x, y;  
    x = cilk_spawn comb( n - 1, r - 1 );  
    y = comb( n - 1, r );  
    cilk_sync;  
    return ( x + y );  
}
```

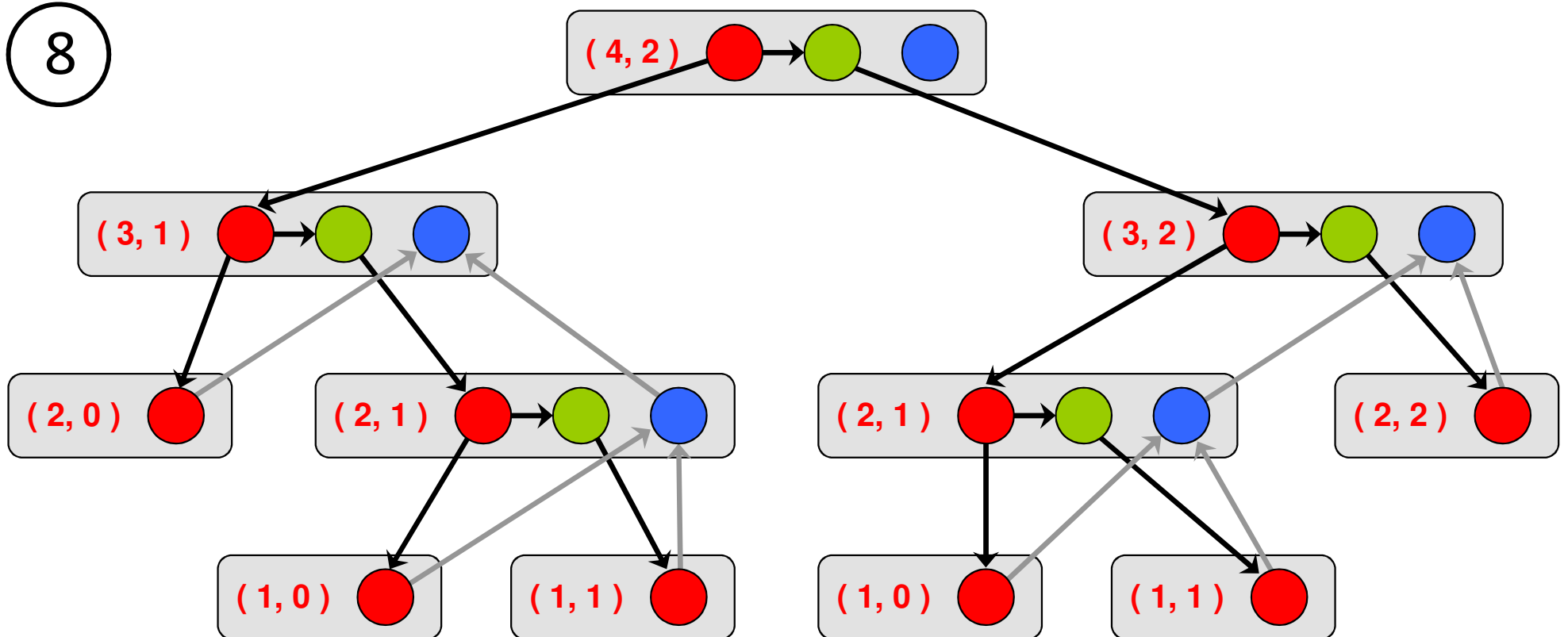
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Cilk++ Execution Model

```
int comb ( int n, int r )  
{  
    if ( r > n ) return 0;  
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    int x, y;  
    x = cilk_spawn comb( n - 1, r - 1 );  
    y = comb( n - 1, r );  
    cilk_sync;  
    return ( x + y );  
}
```

8



Cilk++ Execution Model

```
int comb ( int n, int r )
{
  if ( r > n ) return 0;
  if ( r == 0 || r == n ) return 1;

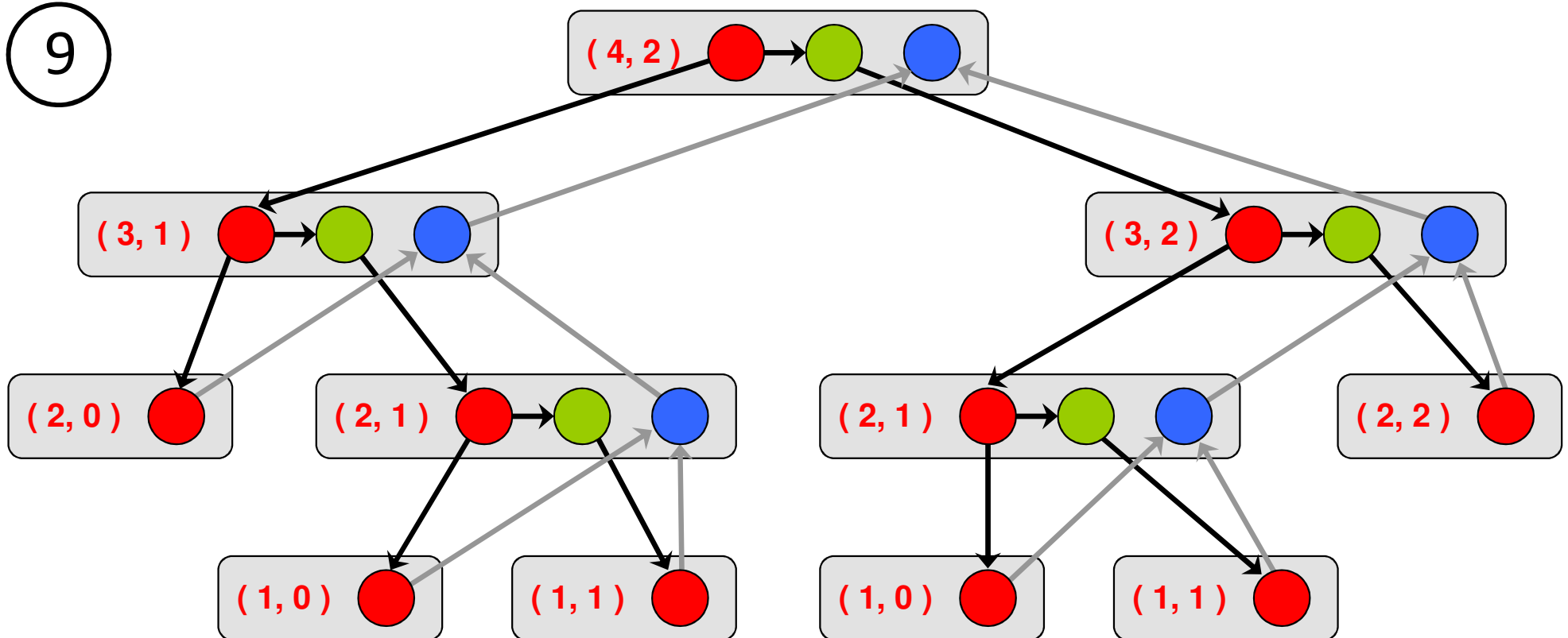
  int x, y;

  x = cilk_spawn comb( n - 1, r - 1 );
  y = comb( n - 1, r );

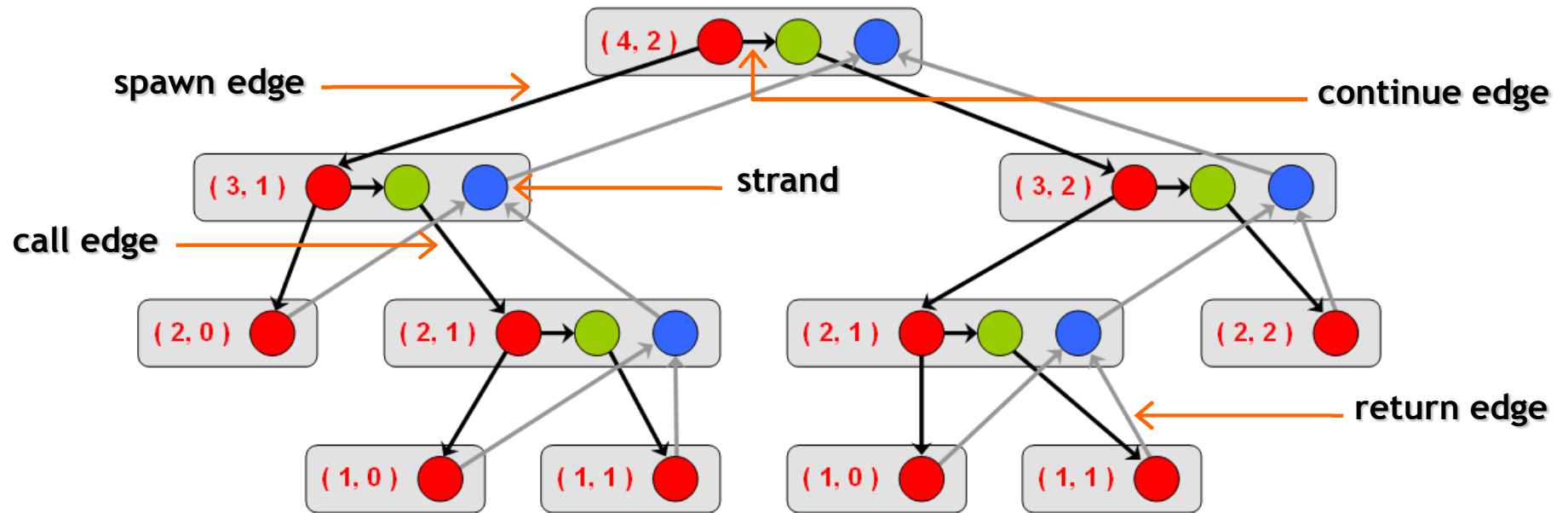
  cilk_sync;

  return ( x + y );
}
```

9

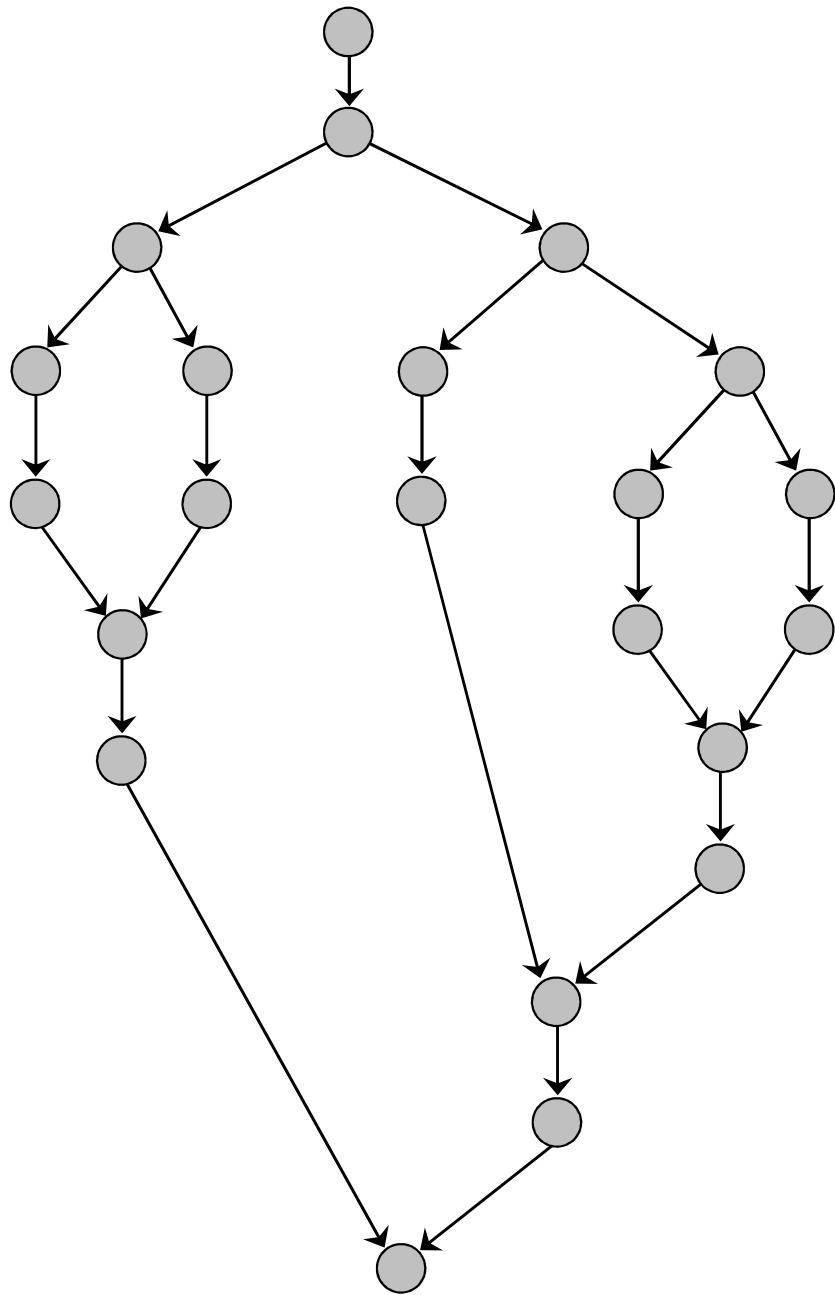


Computation DAG



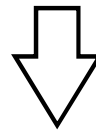
- A parallel instruction stream is represented by a DAG $G = (V, E)$.
- Each vertex $v \in V$ is a *strand* which is a sequence of instructions without a spawn, call, return or exception.
- Each edge $e \in E$ is a *spawn*, *call*, *continue* or *return* edge.

Parallel Performance



T_p = execution time on p cores

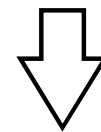
work = T_1



Work Law

$$T_p \geq T_1 / p$$

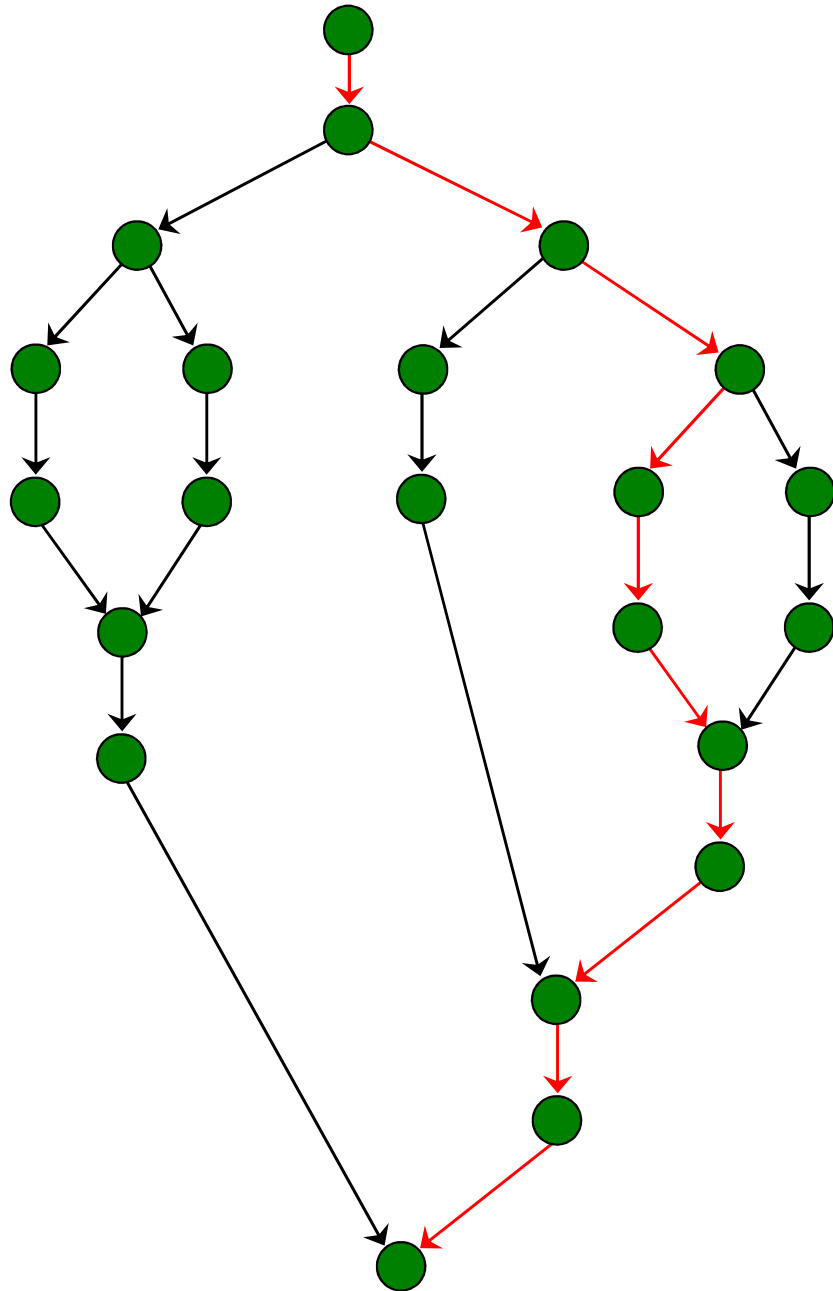
span = T_∞



Span Law

$$T_p \geq T_\infty$$

Speedup & Parallelism



T_p = execution time on p cores

$$\text{work} = T_1$$

$$\text{span} = T_\infty$$

Work Law

Span Law

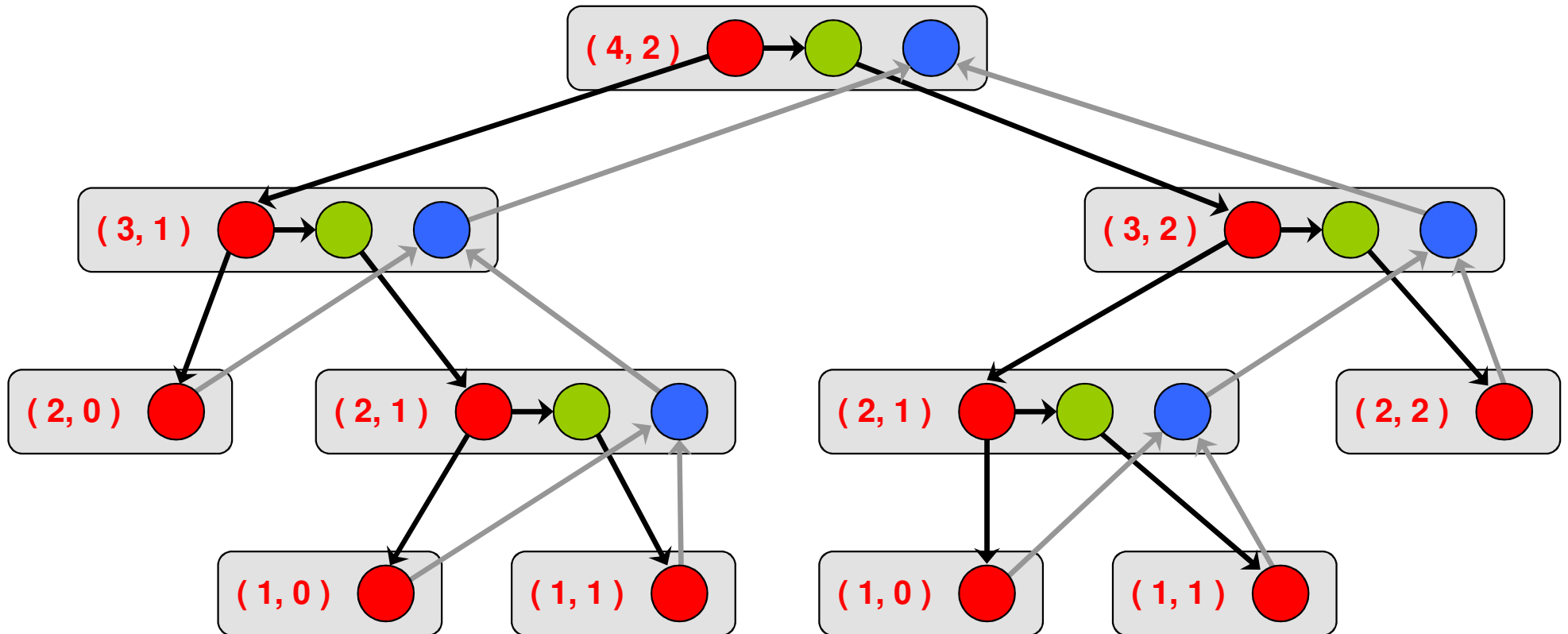
$$T_p \geq T_1 / p$$

$$T_p \geq T_\infty$$

$$\text{speedup} = T_1 / T_p$$

$$\text{parallelism} = T_1 / T_\infty$$

Parallelism in comb(4, 2)



work: $T_1 = 21$

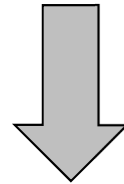
span: $T_\infty = 9$

Only marginal performance gains with more than 2 cores!

parallelism = $T_1 / T_\infty = 21 / 9 \approx 2.33$

Implementation of Parallel Loops in Cilk++

```
cilk_for ( int i = s; i < t; ++i )  
    BODY( i );
```

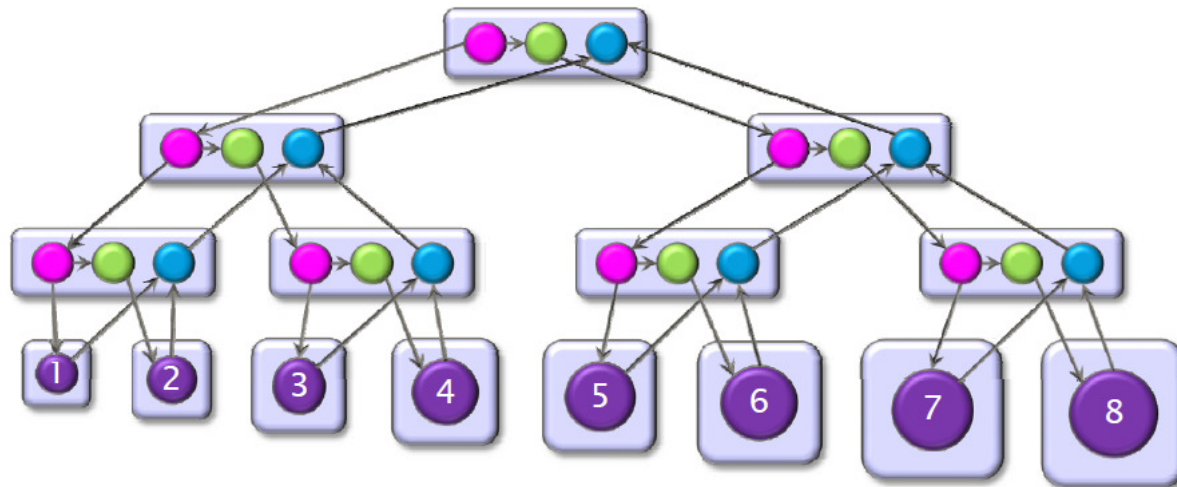


divide-and-conquer
implementation

```
void recur( int lo, int hi )  
{  
    if ( hi - lo > GRAINSIZE )  
    {  
        int mid = lo + ( hi - lo ) / 2;  
        cilk_spawn recur( lo, mid );  
        recur( mid, hi );  
    }  
    else  
    {  
        for ( int i = lo; i < hi; ++i )  
            BODY( i );  
    }  
}  
  
recur( s, t );
```

Analysis of Parallel Loops

```
cilk_for ( int i = 1; i < n; ++i )  
  for ( int j = 0; j < i; ++j )  
  {  
    double t = A[ i ][ j ];  
    A[ i ][ j ] = A[ j ][ i ];  
    A[ j ][ i ] = t;  
  }
```



Source: Charles Leiserson

- Span of loop control = $\Theta(\log n)$
- Maximum span of an iteration = $\Theta(n)$
- Work, $T_1(n) = \Theta(n^2)$
- Span, $T_\infty(n) = \Theta(n + \log n) = \Theta(n)$
- Parallelism = $\frac{T_1(n)}{T_\infty(n)} = \Theta(n)$

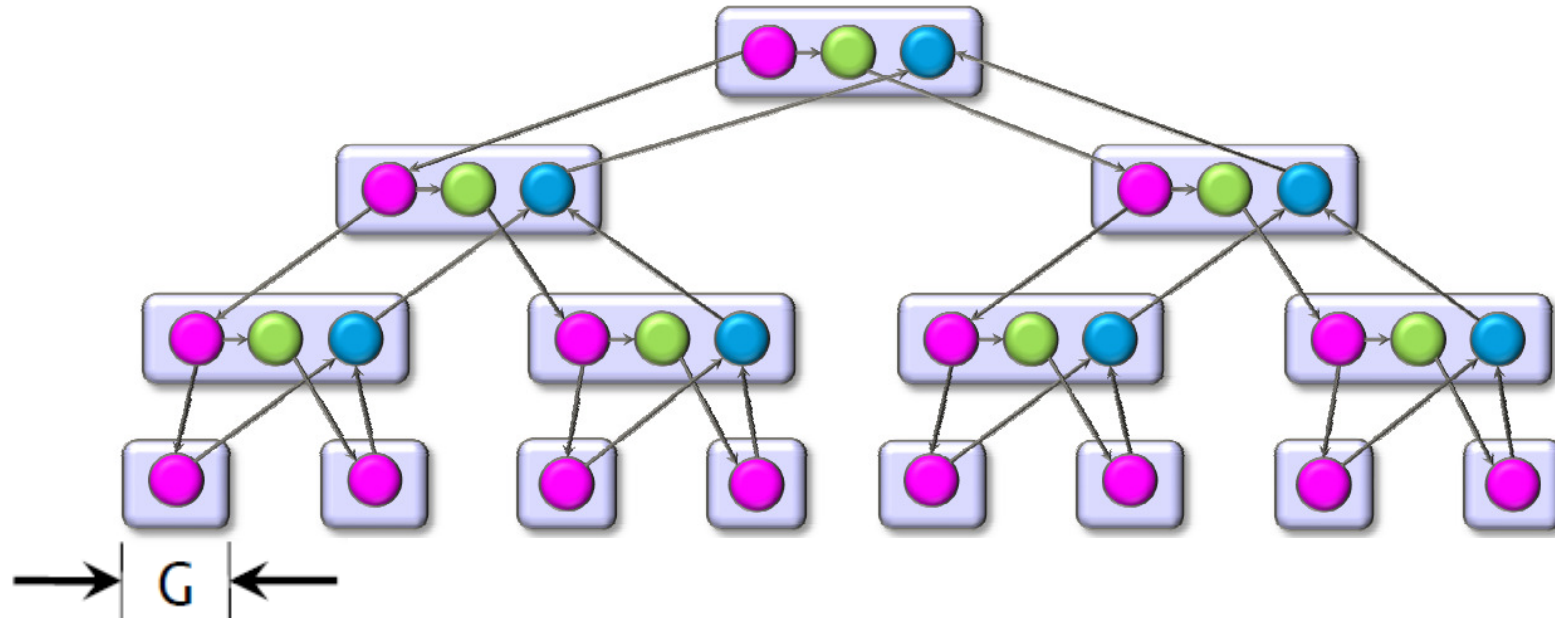
Analysis of Parallel Loops

```
cilk_for ( int i = 1; i < n; ++i )
  cilk_for ( int j = 0; j < i; ++j )
  {
    double t = A[ i ][ j ];
    A[ i ][ j ] = A[ j ][ i ];
    A[ j ][ i ] = t;
  }
```

- Span of outer loop control = $\Theta(\log n)$
- Maximum span of inner loop control = $\Theta(\log n)$
- Span of body = $\Theta(1)$
- Work, $T_1(n) = \Theta(n^2)$
- Span, $T_\infty(n) = \Theta(\log n)$
- Parallelism = $\frac{T_1(n)}{T_\infty(n)} = \Theta\left(\frac{n^2}{\log n}\right)$

Analysis of Parallel Loops

```
#pragma cilk_grainsize = G
cilk_for ( int i = 0; i < n; ++i )
    A[ i ] += B[ i ];
```



Source: Charles Leiserson

– Work, $T_1(n) = n \cdot t_{iter} + \frac{n}{G} \cdot t_{spawn}$

– Span, $T_\infty(n) = G \cdot t_{iter} + \log\left(\frac{n}{G}\right) \cdot t_{spawn}$

– Parallelism = $\frac{T_1(n)}{T_\infty(n)} = \frac{n}{G} \cdot \frac{1 + \frac{r}{G}}{1 + \frac{r}{G} \cdot \log\left(\frac{n}{G}\right)}$, where, $r = \frac{t_{spawn}}{t_{iter}}$

Implementation of Parallel Loops in Cilk++

Default **GRAINSIZE**: $\min \left\{ \frac{N}{8p}, 512 \right\}$

- p = number of processing elements
- N = number of loop iterations
- Works well for loops that are reasonably balanced

```
void cilk_for_custom_grainsize( int s, int t )
{
    int p = cilk::current_worker_count( );
    #pragma cilk_grainsize = ( t - s ) / ( 4 * p )
    cilk_for ( int i = s; i < t; ++i )
        BODY( i );
}
```

Custom **GRAINSIZE**

- small \Rightarrow high overhead
- large \Rightarrow less parallelism

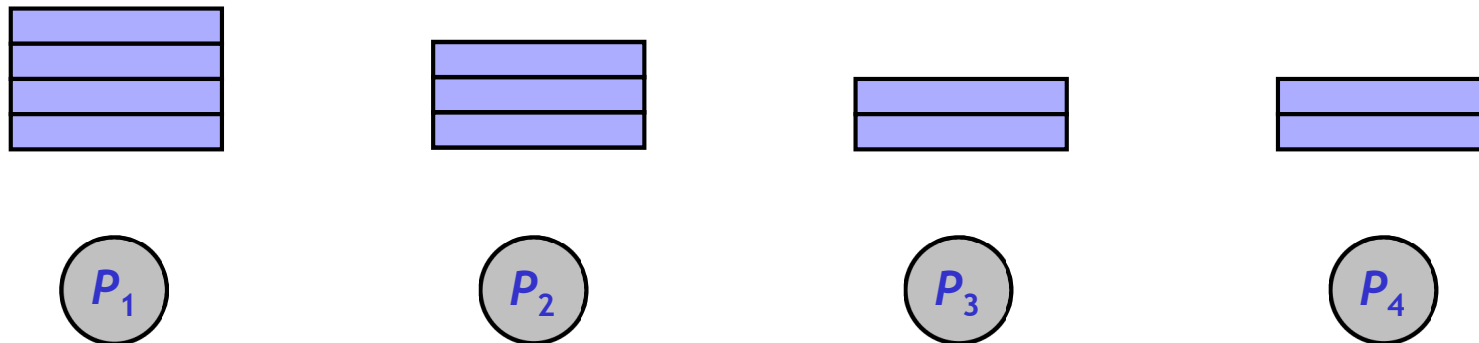
Cilk++'s Work-Stealing Scheduler

Cilk++'s Work-Stealing Scheduler

- A *randomized distributed* scheduler
- Achieves
 - $T_p = \frac{T_1}{p} + O(T_\infty)$ time (provably)
 - $T_p \approx \frac{T_1}{p} + T_\infty$ time (empirically)
- Near-perfect linear speedup as long as parallelism, $\frac{T_1}{T_\infty} \gg p$
- Uses at most p times the space used by a serial execution
- Has provably good *cache performance*

Cilk++'s Work-Stealing Scheduler

- Each core maintains a *work dqueue* of ready threads
- A core manipulates the bottom of its dqueue like a stack
 - Pops ready threads for execution
 - Pushes new/spawned threads
- Whenever a core runs out of ready threads it *steals* one from the top of the dqueue of a *random* core



The Cilkview Scalability Analyzer

Cilkview Scalability Analyzer

- ❑ Measures *work* and *span* using *dynamic instrumentation*.
- ❑ Derives *upper bounds* on parallel performance using work and span.
- ❑ Estimates *scheduling overhead* to compute a *burdened span* for lower bounds.

Cilkview Scalability Analyzer

```
template < typename T >
void qsort( T p, T r )
{
    if ( p != r )
    {
        T q = partition( p, r, bind2nd( less< typename
            iterator_traits< T >::value_type >( ), *p ) );

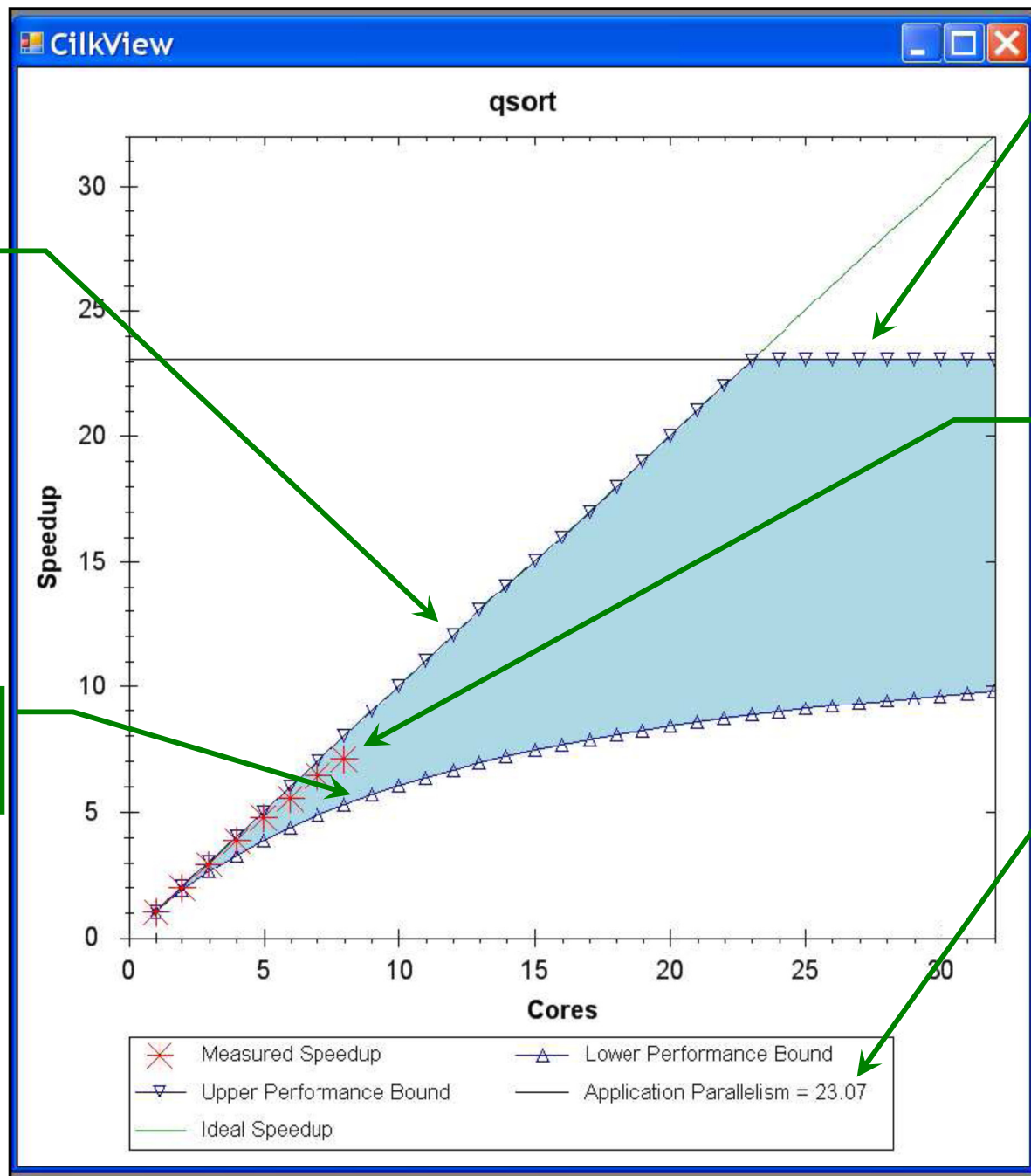
        cilk_spawn qsort( p, q );
        qsort( max( p + 1, q ), r );
        cilk_sync;
    }
}

int cilk_main( )
{
    int n = 10000000;
    double a[ n ];

    cilk::cilkview cv;
    cilk_for ( int i = 0; i < n; i++ )
        a[ i ] = sin( ( double ) i );
    cv.start( );
    qsort( a, a + n );
    cv.stop( );
    cv.dump( ``qsort'' );

    return 0;
}
```


Cilkview Scalability Analyzer



Work Law
(linear speedup)

Span Law

Measured Speedup

Burdened Parallelism
(scheduling overhead)

Parallelism

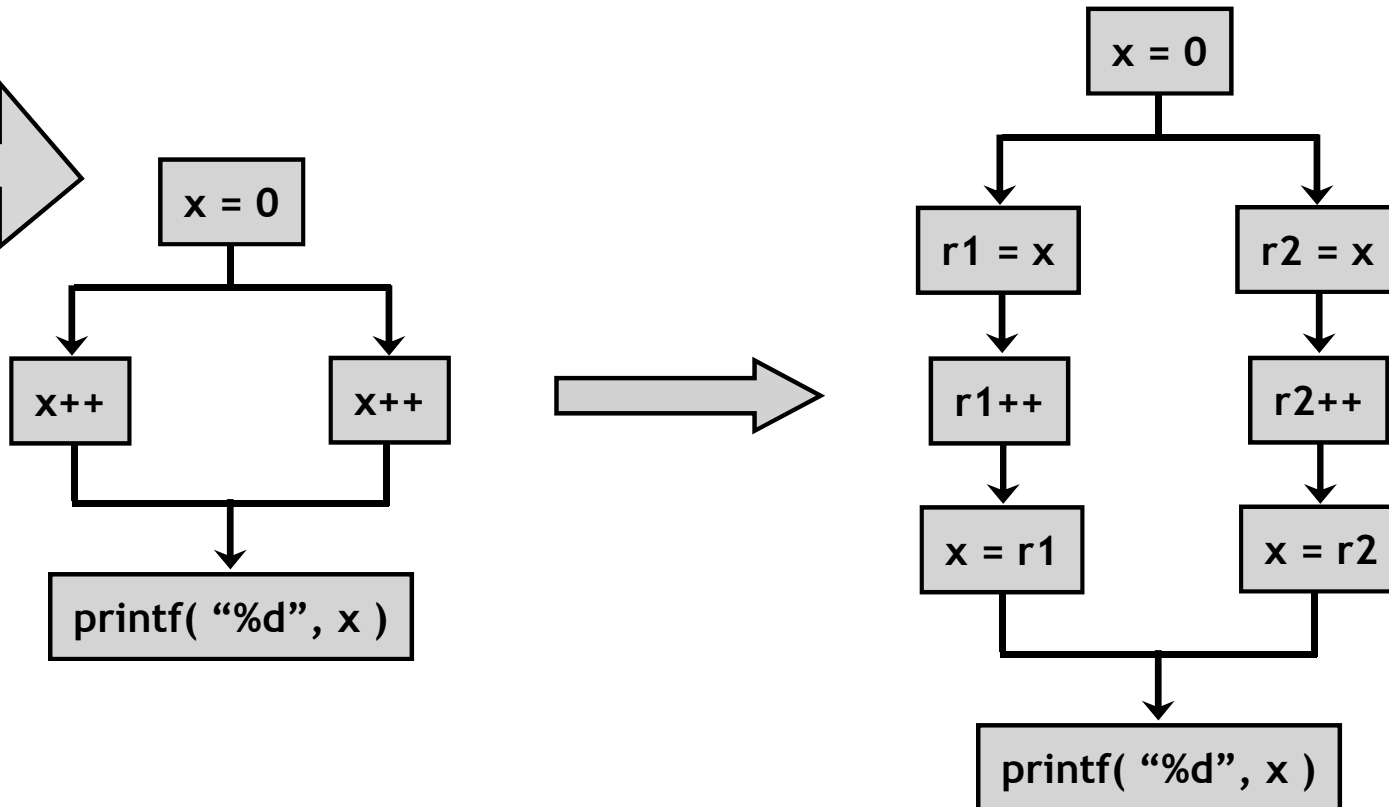
Source: He, Leiserson & Leiserson, 2009

**Race Bugs
and
the Cilkscreen Race Detector**

Race Bugs

A *determinacy race* occurs if two logically parallel instructions access the same memory location and at least one of them performs a write.

```
int x = 0;  
cilk_for ( int i = 0; i < 2; i++ )  
    x++;  
printf( "%d", x );
```



Critical Sections and Mutexes

```
int r = 0;  
  
cilk_for ( int i = 0; i < n; i++ )  
  r += eval( x[ i ] );
```

race

```
cilk::mutex mtx;  
  
cilk_for ( int i = 0; i < n; i++ )  
  mtx.lock( );  
  r += eval( x[ i ] );  
  mtx.unlock( );
```

critical section
two or more strands
must not access
at the same time

mutex (mutual exclusion)

an attempt by a strand
to lock an already locked mutex
causes that strand to block (i.e., wait)
until the mutex is unlocked

Problems

- lock overhead
- lock contention

Critical Sections and Mutexes

race

```
int r = 0;
cilk_for ( int i = 0; i < n; i++ )
  r += eval( x[ i ] );
```

```
cilk::mutex mtx;
cilk_for ( int i = 0; i < n; i++ )
  mtx.lock( );
  r += eval( x[ i ] );
  mtx.unlock( );
```

```
cilk::mutex mtx;
cilk_for ( int i = 0; i < n; i++ )
  int y = eval( x[ i ] );
  mtx.lock( );
  r += y;
  mtx.unlock( );
```

- slightly better solution
- but lock contention can still destroy parallelism

Cilkscreen Race Detector

- If determinacy data races exist in an ostensibly deterministic program (e.g., a program with no mutexes), *Cilkscreen* guarantees to find such a race.
- Uses *regression tests* on user-provided test inputs
- *Reports* filenames, line and variables involved in races as well as stack traces.
- Runs the binary executable using *dynamic instrumentation*.
- Runs about 20 times *slower* than real-time.

**Race Bugs
and
the Cilk++ Reducers**

Race Bugs and Cilk++ Reducer Hyperobjects

- Cilk++ provides *reducer hyperobjects* to mitigate data races on nonlocal variables without locks and code restructuring
- A variable x can be declared a Cilk++ *reducer* over an *associative* operation such as addition, list concatenation etc.
- Strands can update x as if it were an ordinary local variable, but x is, in fact, maintained as a collection of different *views*.
- Cilk++ runtime system coordinates the views and combines them when appropriate.

a summing
reducer over int

updates are resolved automatically
without races or contention

at the end the
final int value
can be extracted

```
cilk::reducer_opadd< int > r;  
cilk_for ( int i = 0; i < n; i++ )  
    r += eval( x[ i ] );  
cout << r.get_value( );
```


Race Bugs and Cilk++ Reducer Hyperobjects

original

```
x = 0;  
x += 2;  
x++;  
x += 3;  
x += 4;  
x += 7;  
x += 5;  
x += 4;  
x += 2;  
x++;  
x += 6;  
x += 9;  
x += 3;  
x++;  
x += 8;
```

raceless
parallel
execution

equivalent

```
x1 = 0;  
x1 += 2;  
x1++;  
x1 += 3;  
x1 += 4;  
x1 += 7;  
x1 += 5;  
x1 += 4;  
x2 = 0;  
x2 += 2;  
x2++;  
x2 += 6;  
x2 += 9;  
x2 += 3;  
x2++;  
x2 += 8;
```

$x = x1 + x2;$

equivalent

```
x1 = 0;  
x1 += 2;  
x1++;  
x1 += 3;  
x1 += 4;  
x2 = 0;  
x2 += 7;  
x2 += 5;  
x2 += 4;  
x2 += 2;  
x2++;  
x3 = 0;  
x3 += 6;  
x3 += 9;  
x3 += 3;  
x3++;  
x3 += 8;
```

$x = x1 + x2 + x3;$

raceless
parallel
execution

If you do not need to look at intermediate values the result is *determinate* because addition is *associative*.

Cilk++ Reducer Library

- Many commonly used reducers
 - `reducer_list_append`
 - `reducer_list_prepend`
 - `reducer_max`
 - `reducer_max_index`
 - `reducer_min`
 - `reducer_min_index`
 - `reducer_opadd`
 - `reducer_ostream`
 - `reducer_basic_string`
 - ...
- One can also make one's own reducers using `cilk::monoid_base` and `cilk::reducer`

Some Concluding Remarks

Cilk++ seems to have several major advantages

- very easy to use (compared to DIY platforms like pthreads)
- portable code (e.g., core-/processor-oblivious)
- produces efficient executables
(efficient scheduler, cache-efficiency)
- useful toolkit (cilkview, cilkscreen)