Software
Performance
Engineering

LECTURE 9

Scheduling Theory and Task-Parallel Algorithms I

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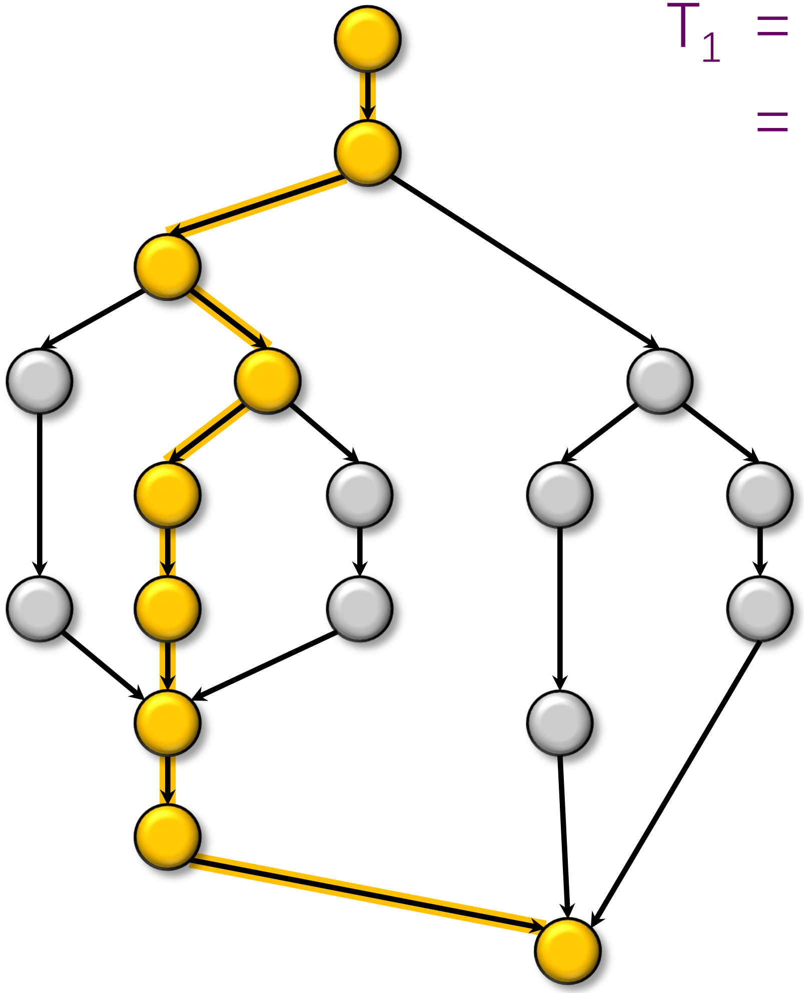
Performance Measures

T_P = execution time on P processors



T_1 = work

= 18

T_∞ = span

= 9

WORK LAW

- $T_P \geqslant T_1/P$

SPAN LAW

- $T_P \geqslant T_\infty$

Parallelism

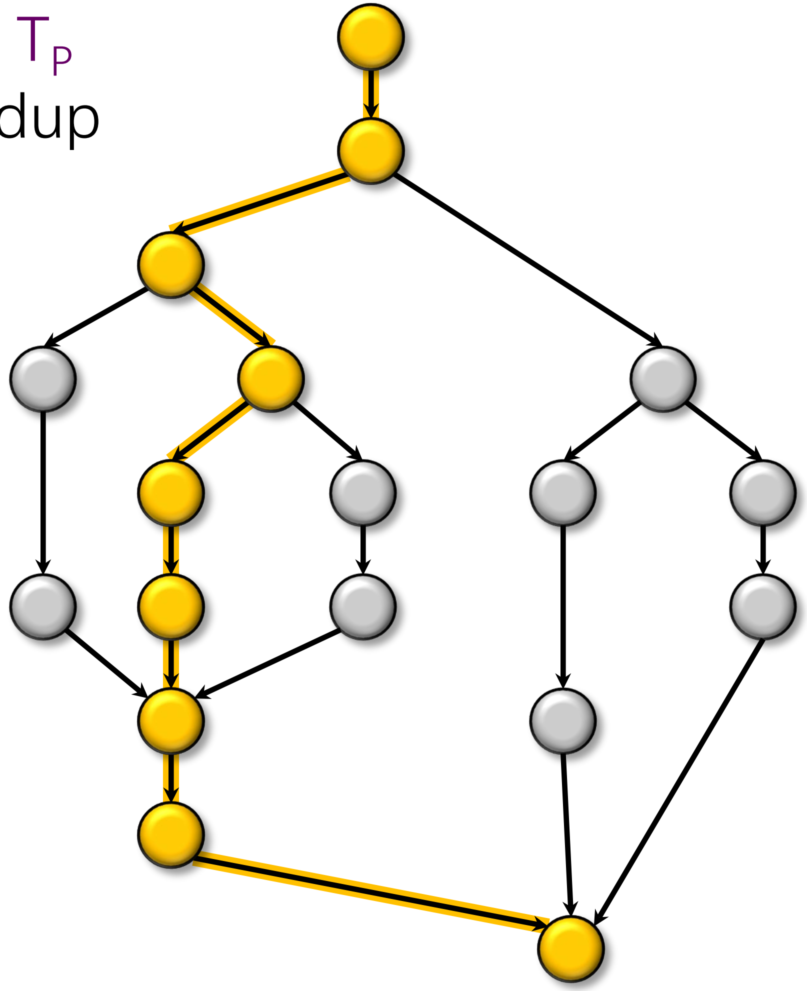
Because the SPAN LAW dictates that $T_P \geqslant T_\infty$, the maximum possible speedup given T_1 and T_∞ is

T_1/T_∞ = parallelism

= the average amount of work per step along the span

= 18/9

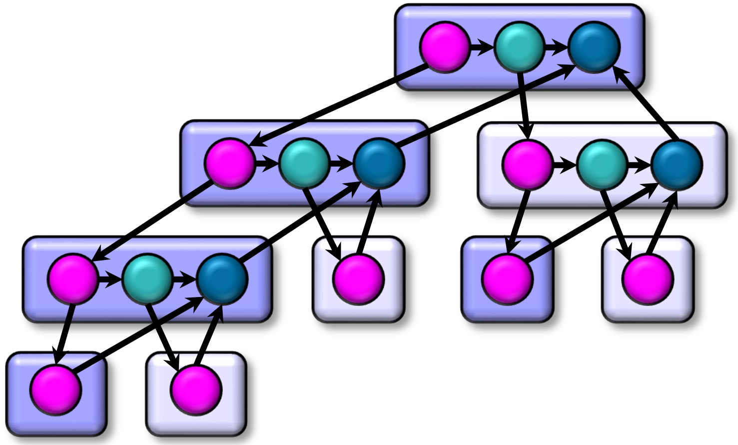
= 2 .

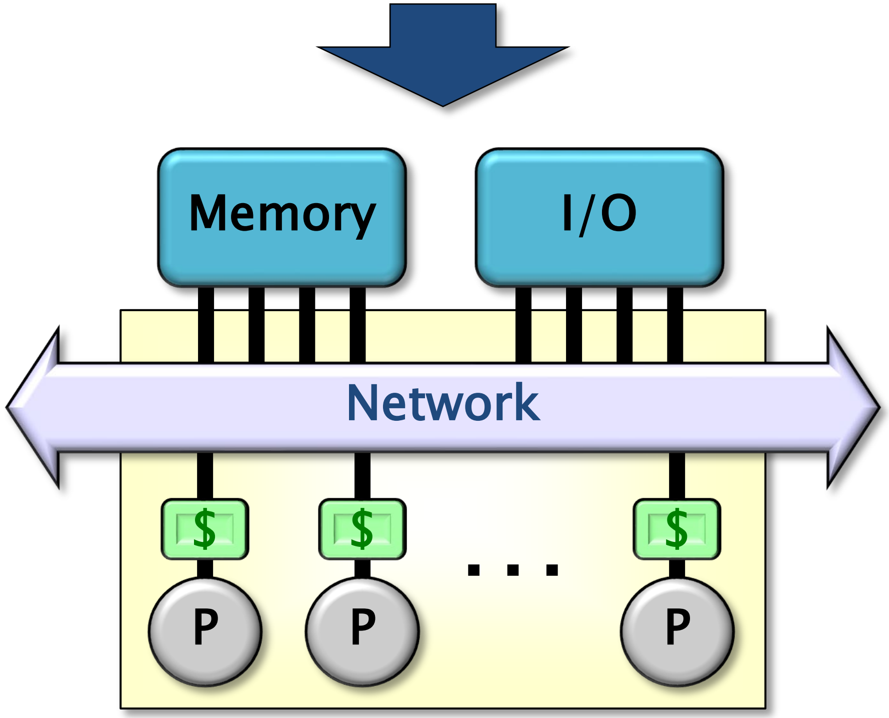


SCHEDULING THEORY

Scheduling

- Cilk allows the programmer to express potential parallelism in an application
- The Cilk scheduler maps strands onto processors dynamically at runtime
- Since the theory of distributed schedulers is complicated, we'll explore the ideas with a simple, centralized scheduler

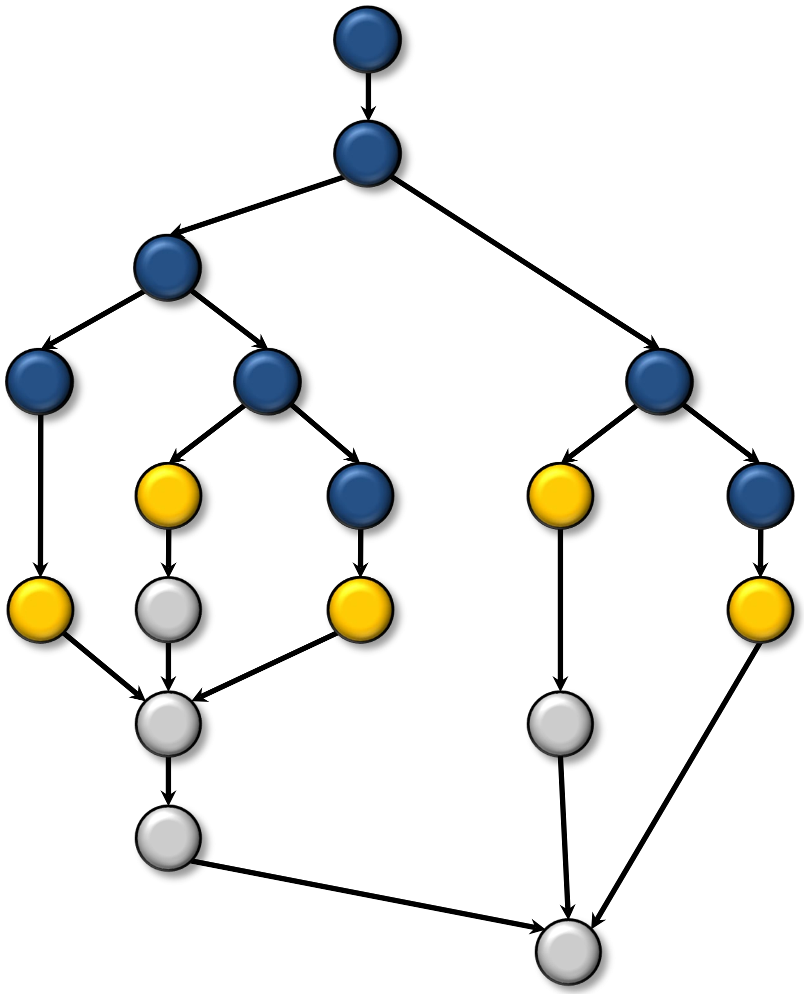




Greedy Scheduling

IDEA: Do as much as possible on every step.

Definition. A strand is ready if all its predecessors have executed.



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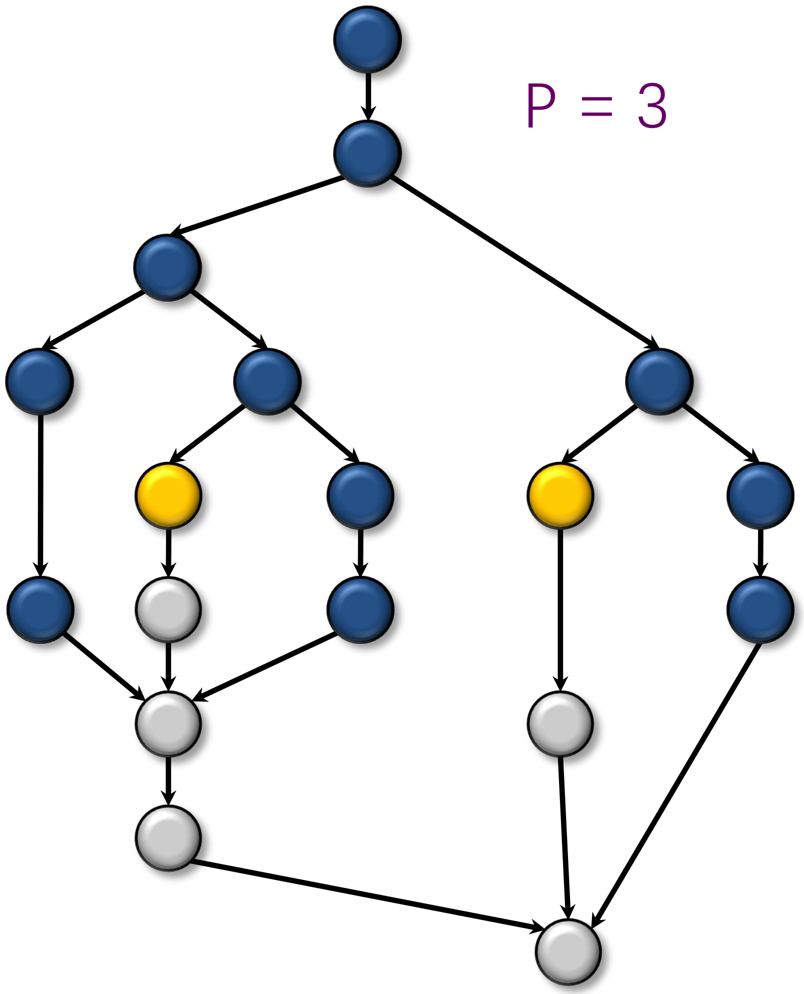

Complete step

- $\geqslant P$ strands ready.
- Run any P.

Greedy Scheduling

IDEA: Do as much as possible on every step.

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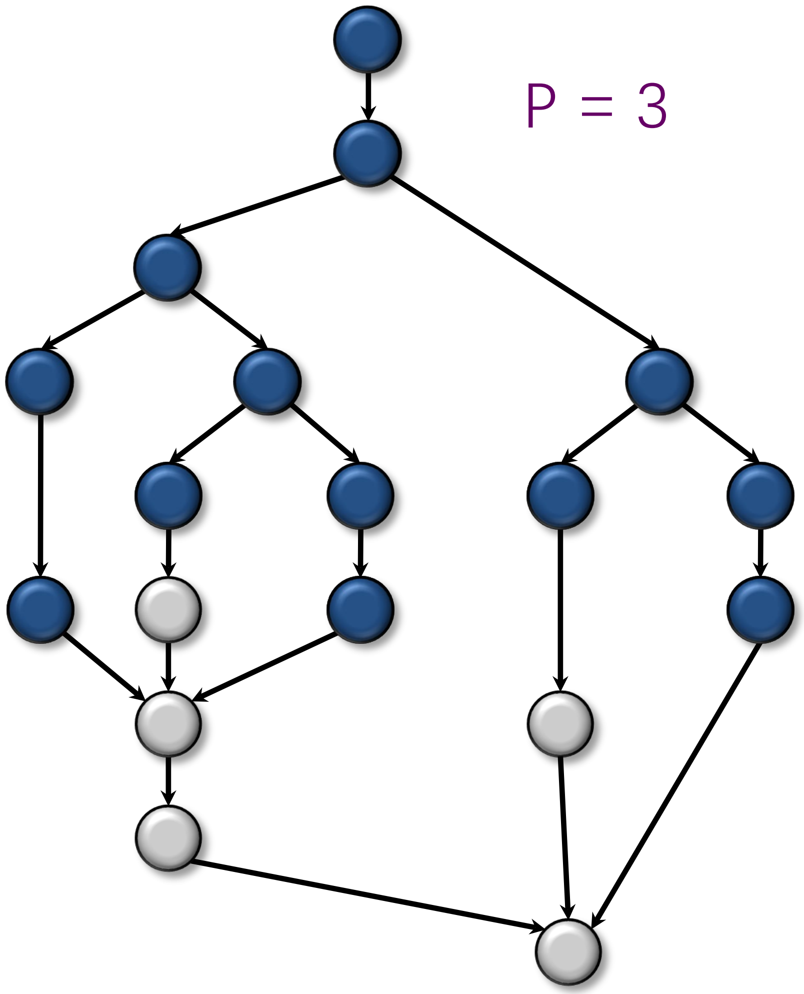


Complete step

- $\geqslant$ P strands ready.
- Run any P.

Incomplete step

- $<$ P strands ready.
- Run all of them.

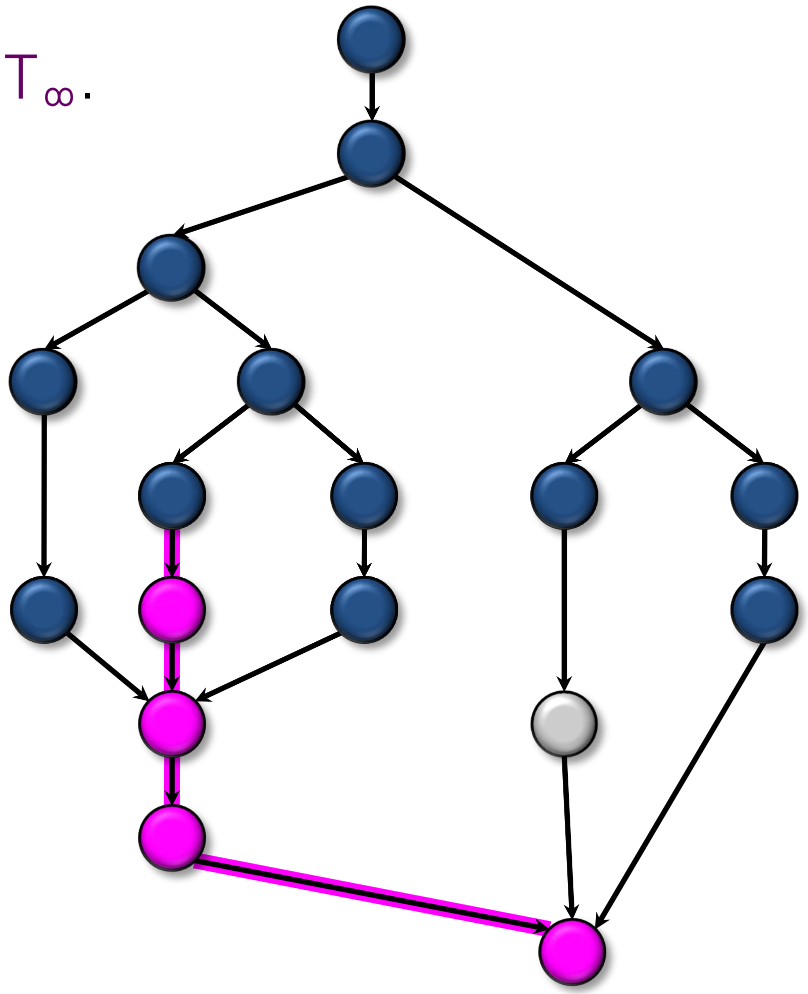
Analysis of Greedy

Greedy Scheduling Theorem [G68, B75, EZL89]. Any greedy scheduler achieves

$$T_P \leqslant T_1/P + T_\infty.$$

Proof.

- \# complete steps $\leqslant T_1/P$ since each complete step performs P work.
- \# incomplete steps $\leqslant T_\infty$ since each incomplete step reduces the span of the unexecuted dag by 1. ■



Optimality of Greedy

Corollary. Any greedy scheduler achieves within a factor of 2 of optimal.

Proof. Let $T_P{*}$ be the execution time produced by the optimal scheduler. Since $T_P{*} \geqslant \max\{T_1/P, T_\infty\}$ by the WORK and SPAN LAWS, we have

$$\begin{aligned} T_P &\leqslant T_1/P + T_\infty \\ &\leqslant 2\cdot\max\{T_1/P, T_\infty\} \\ &\leqslant 2T_P{*}\ . \quad \blacksquare \end{aligned}$$

Linear Speedup

Corollary. Any greedy scheduler achieves near-perfect linear speedup whenever $T_1/T_\infty \gg P$.

Proof. Since $T_1/T_\infty \gg P$ is equivalent to $T_\infty \ll T_1/P$, the Greedy Scheduling Theorem gives us

$$\begin{aligned} T_P &\leqslant T_1/P + T_\infty \\ &\approx T_1/P\,. \end{aligned}$$

Thus, the speedup is $T_1/T_P \approx P$. ■

Definition. The quantity $(T_1/T_\infty)/P = T_1/PT_\infty$ is called the parallel slackness.

Cilk Performance

- Cilk's randomized work-stealing scheduler achieves
  - $T_P = T_1/P + O(T_\infty)$ expected time (provably);
  - $T_P \approx T_1/P + T_\infty$ time (empirically).
- Near-perfect linear speedup as long as $P \ll T_1/T_\infty$.
- Instrumentation in Cilkscale allows you to measure T_1 and T_∞ .

Cilk Loops

Loop Parallelism in Cilk

Example:
In-place matrix transpose

$$\underset{A}{\begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix}} \Rightarrow \underset{A^T}{\begin{pmatrix} a_{11} & a_{21} & \cdots & a_{n1} \\ a_{12} & a_{22} & \cdots & a_{n2} \\ \vdots & \vdots & \ddots & \vdots \\ a_{1n} & a_{2n} & \cdots & a_{nn} \end{pmatrix}}$$

The iterations of a `cilk_for` loop execute in parallel.

```
// indices run from 0, not 1
for (int i=1; i<n; ++i) {
  for (int j=0; j<i; ++j) {
    double temp = A[i][j];
    A[i][j] = A[j][i];
    A[j][i] = temp;
  }
}
```

Loop Parallelism in Cilk

Example: In-place matrix transpose

$$A = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix} \Rightarrow A^T = \begin{pmatrix} a_{11} & a_{21} & \cdots & a_{n1} \\ a_{12} & a_{22} & \cdots & a_{n2} \\ \vdots & \vdots & \ddots & \vdots \\ a_{1n} & a_{2n} & \cdots & a_{nn} \end{pmatrix}$$

The iterations of a `cilk_for` loop execute in parallel.

```
// indices run from 0, not 1
cilk_for (int i=1; i<n; ++i) {
  for (int j=0; j<i; ++j) {
    double temp = A[i][j];
    A[i][j] = A[j][i];
    A[j][i] = temp;
  }
}
```

Implementation of Parallel Loops

```
// indices run from 0, not 1
cilk_for (int i=1; i<n; ++i) {
  for (int j=0; j<i; ++j) {
    double temp = A[i][j];
    A[i][j] = A[j][i];
    A[j][i] = temp;
  }
}
```

Original code

Compiler-generated recursion

```
void p_loop(int lo, int hi)  //half open
{
  if (hi > lo + 1) {
    int mid = lo + (hi - lo)/2;
    cilk_scope {
      cilk_spawn p_loop(lo, mid);
      p_loop(mid, hi);
    }
    return;
  }
  int i = lo;
  for (int j=0; j<i; ++j) {
    double temp = A[i][j];
    A[i][j] = A[j][i];
    A[j][i] = temp;
  }
}
⋮
p_loop(1, n);
```

Divide-and-conquer

The OpenCilk compiler implements `cilk_for` loops using divide and conquer at optimization levels `-O1` and higher.

Implementation of Parallel Loops

```
// indices run from 0, not 1
cilk_for (int i=1; i<n; ++i) {
  for (int j=0; j<i; ++j) {
    double temp = A[i][j];
    A[i][j] = A[j][i];
    A[j][i] = temp;
  }
}
```

Original code

Compiler-generated recursion

```
void p_loop(int lo, int hi)  //half open
{
  if (hi > lo + 1) {
    int mid = lo + (hi - lo)/2;
    cilk_scope {
      cilk_spawn p_loop(lo, mid);
      p_loop(mid, hi);
    }
    return;
  }
  int i = lo;
  for (int j=0; j<i; ++j) {
    double temp = A[i][j];
    A[i][j] = A[j][i];
    A[j][i] = temp;
  }
}
⋮
p_loop(1, n);
```

Divide-and-conquer

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Implementation of Parallel Loops

```
// indices run from 0, not 1
cilk_for (int i=1; i<n; ++i) {
  for (int j=0; j<i; ++j) {
    double temp = A[i][j];
    A[i][j] = A[j][i];
    A[j][i] = temp;
  }
}
```

cilk_for
loop control

```
void p_loop(int lo, int hi) //half open
{
  if (hi > lo + 1) {
    int mid = lo + (hi - lo)/2;
    cilk_scope {
      cilk_spawn p_loop(lo, mid);
      p_loop(mid, hi);
    }
    return;
  }
  int i = lo;
  for (int j=0; j<i; ++j) {
    double temp = A[i][j];
    A[i][j] = A[j][i];
    A[j][i] = temp;
  }
}
⋮
p_loop(1, n);
```

Implementation of Parallel Loops

```
// indices run from 0, not 1
cilk_for (int i=1; i<n; ++i) {
  for (int j=0; j<i; ++j) {
    double temp = A[i][j];
    A[i][j] = A[j][i];
    A[j][i] = temp;
  }
}
```

```
void p_loop(int lo, int hi)  //half open
{
  if (hi > lo + 1) {
    int mid = lo + (hi - lo)/2;
    cilk_scope {
      cilk_spawn p_loop(lo, mid);
      p_loop(mid, hi);
    }
    return;
  }
  int i = lo;
  for (int j=0; j<i; ++j) {
    double temp = A[i][j];
    A[i][j] = A[j][i];
    A[j][i] = temp;
  }
}
⋮
p_loop(1, n);
```

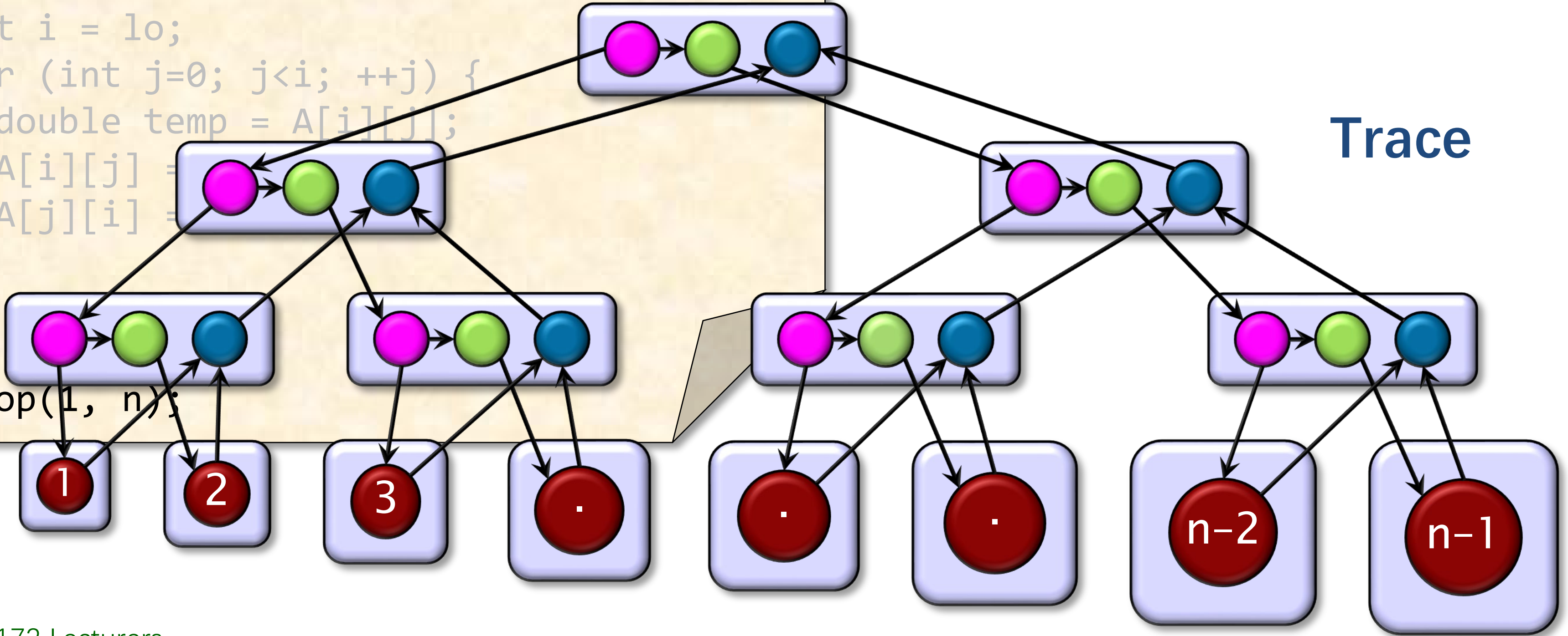
lifted
loop body

Execution of Parallel Loops

```
void p_loop(int lo, int hi)  //half open
{
  if (hi > lo + 1) {
    int mid = lo + (hi - lo)/2;
    cilk_scope {
      cilk_spawn p_loop(lo, mid);
      p_loop(mid, hi);
    }
    return;
  }
  int i = lo;
  for (int j=0; j<i; ++j) {
    double temp = A[i][j];
    A[i][j] =
    A[j][i] =
  }
}
⋮
p_loop(1, n);
```

Divide-and-conquer implementation

cilk_for loop control (internal nodes)



Trace

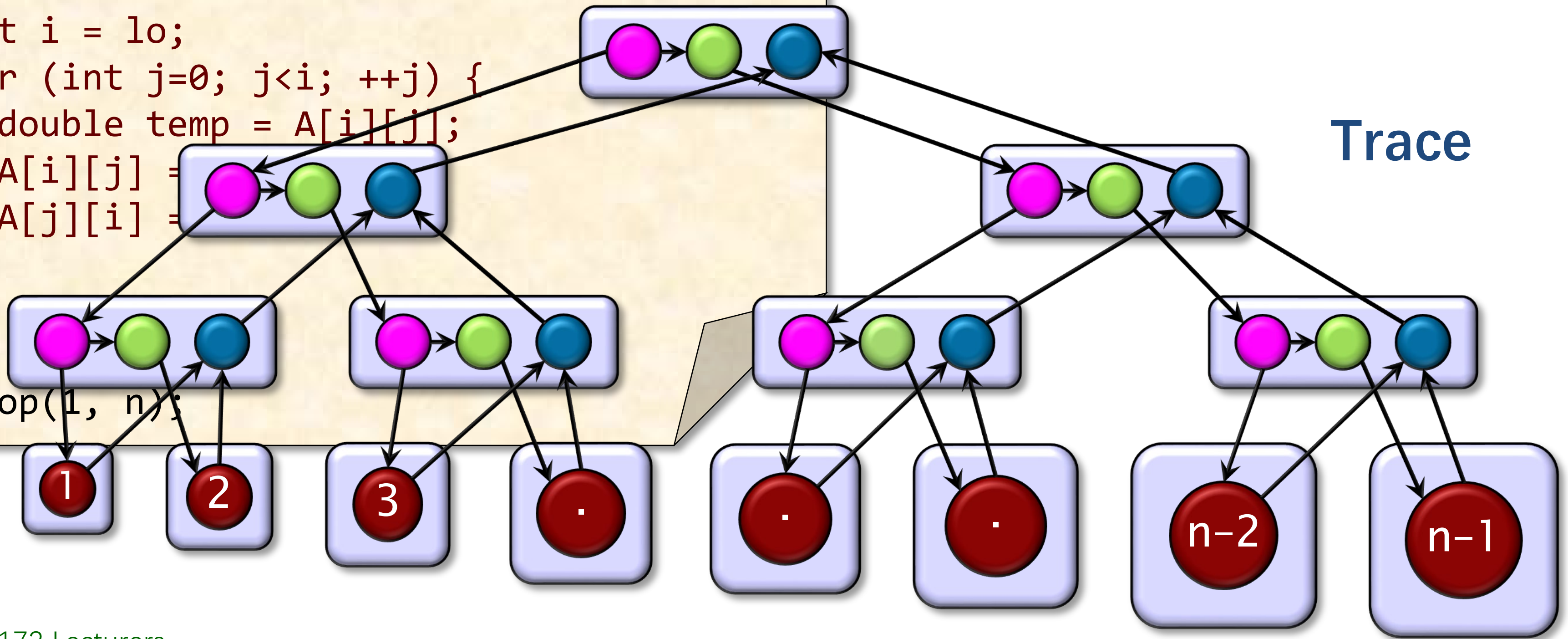
Execution of Parallel Loops

```
void p_loop(int lo, int hi)  //half open
{
  if (hi > lo + 1) {
    int mid = lo + (hi - lo)/2;
    cilk_scope {
      cilk_spawn p_loop(lo, mid);
      p_loop(mid, hi);
    }
    return;
  }
  int i = lo;
  for (int j=0; j<i; ++j) {
    double temp = A[i][j];
    A[i][j] =
    A[j][i] =
  }
}
⋮
p_loop(1, n);
```

Divide-and-conquer implementation

cilk_for body (leaves)

Trace

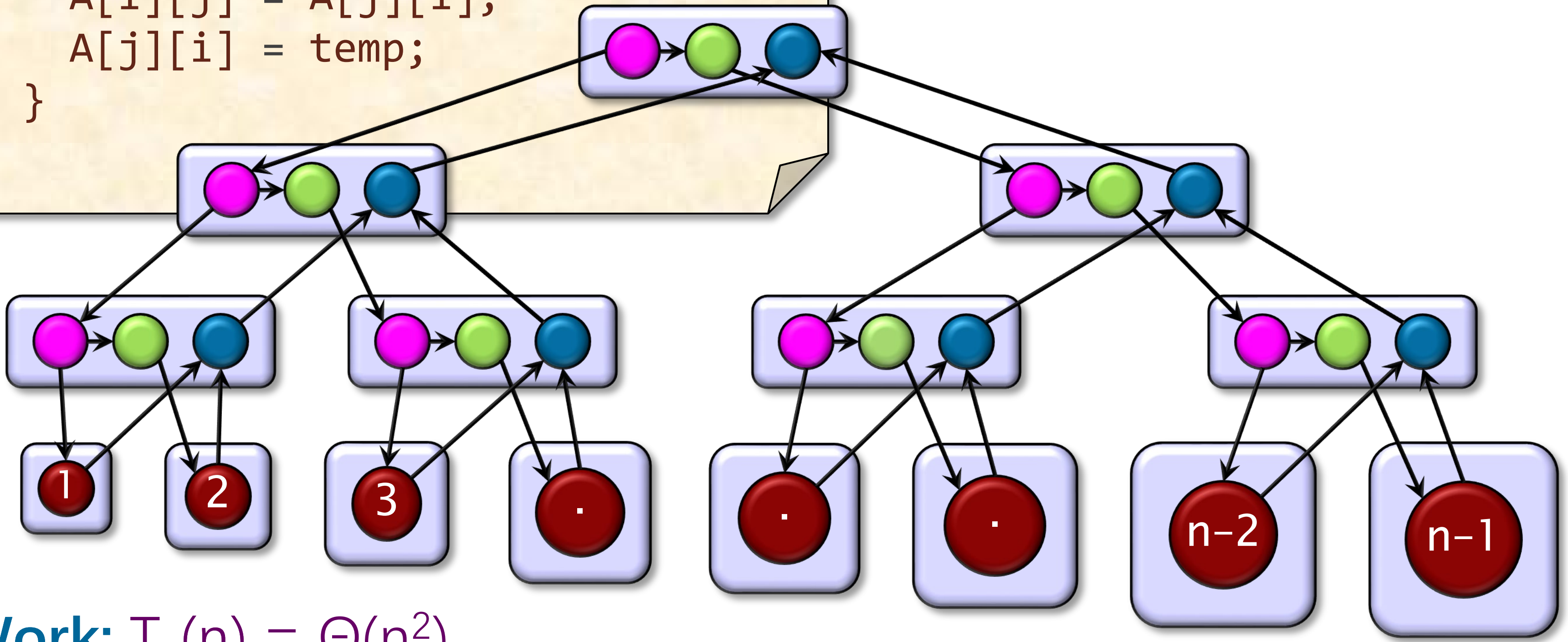


Analysis of Parallel Matrix Transpose

```
// indices run from 0, not 1
cilk_for (int i=1; i<n; ++i) {
  for (int j=0; j<i; ++j) {
    double temp = A[i][j];
    A[i][j] = A[j][i];
    A[j][i] = temp;
  }
}
```

Span of loop control = $\Theta(\lg n)$.

Max span of body = $\Theta(n)$.



Work: $T_1(n) = \Theta(n^2)$

Span: $T_\infty(n) = \Theta(n + \lg n) = \Theta(n)$

Parallelism: $T_1(n)/T_\infty(n) = \Theta(n^2)/\Theta(n) = \Theta(n)$

Analysis of Nested Parallel Loops

```
// indices run from 0, not 1
cilk_for (int i=1; i<n; ++i) {
  cilk_for (int j=0; j<i; ++j) {
    double temp = A[i][j];
    A[i][j] = A[j][i];
    A[j][i] = temp;
  }
}
```

Span of outer loop control = $\Theta(\lg n)$

Max span of inner loop control = $\Theta(\lg n)$

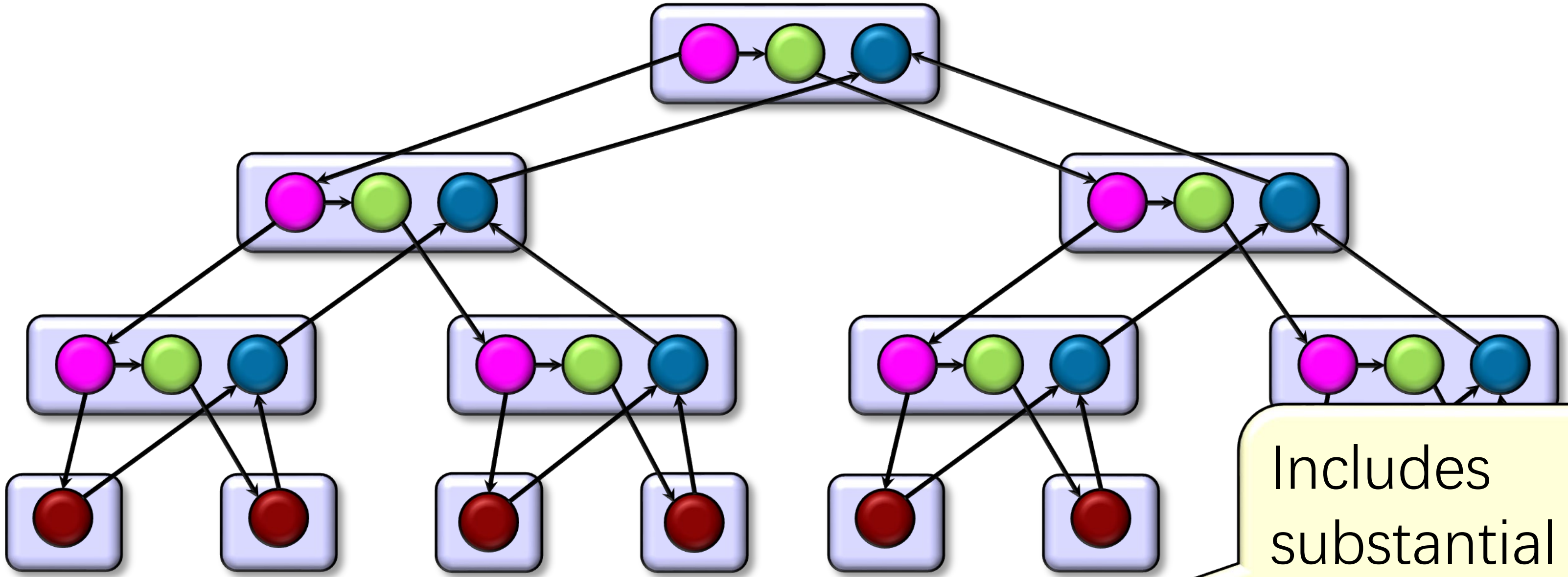
Span of body = $\Theta(1)$

Work: $T_1(n) = \Theta(n^2)$
Span: $T_\infty(n) = \Theta(\lg n)$
Parallelism: $T_1(n)/T_\infty(n) = \Theta(n^2/\lg n)$

A Closer Look at Parallel Loops

Vector addition

```
cilk_for (int i=0; i<n; ++i) {
  A[i] += B[i];
}
```



Includes substantial overhead!

Work: $T_1 = \Theta(n)$
Span: $T_\infty = \Theta(\lg n)$
Parallelism: $T_1/T_\infty = \Theta(n/\lg n)$

Optimizing Parallel-Loop Control

```
cilk_for (int i=0; i<n; ++i) {
  A[i] += B[i];
}
```

Original code

Compiler-generated recursion

```
void p_loop(int lo, int hi) { //half open
  if (hi > lo + 1) {
    int mid = lo + (hi - lo)/2;
    cilk_scope {
      cilk_spawn p_loop(lo, mid);
      p_loop(mid, hi);
    }
    return;
  }
  for (int i=lo; i<hi; ++i) {
    A[i] += B[i];
  }
}
⋮
p_loop(0, n);
```

Coarsening Parallel Loops

```
#pragma cilk grainsize G
cilk_for (int i=0; i<n; ++i) {
  A[i] += B[i];
}
```

If a grain-size pragma is not specified, the Cilk runtime system heuristically guesses G to minimize overhead.

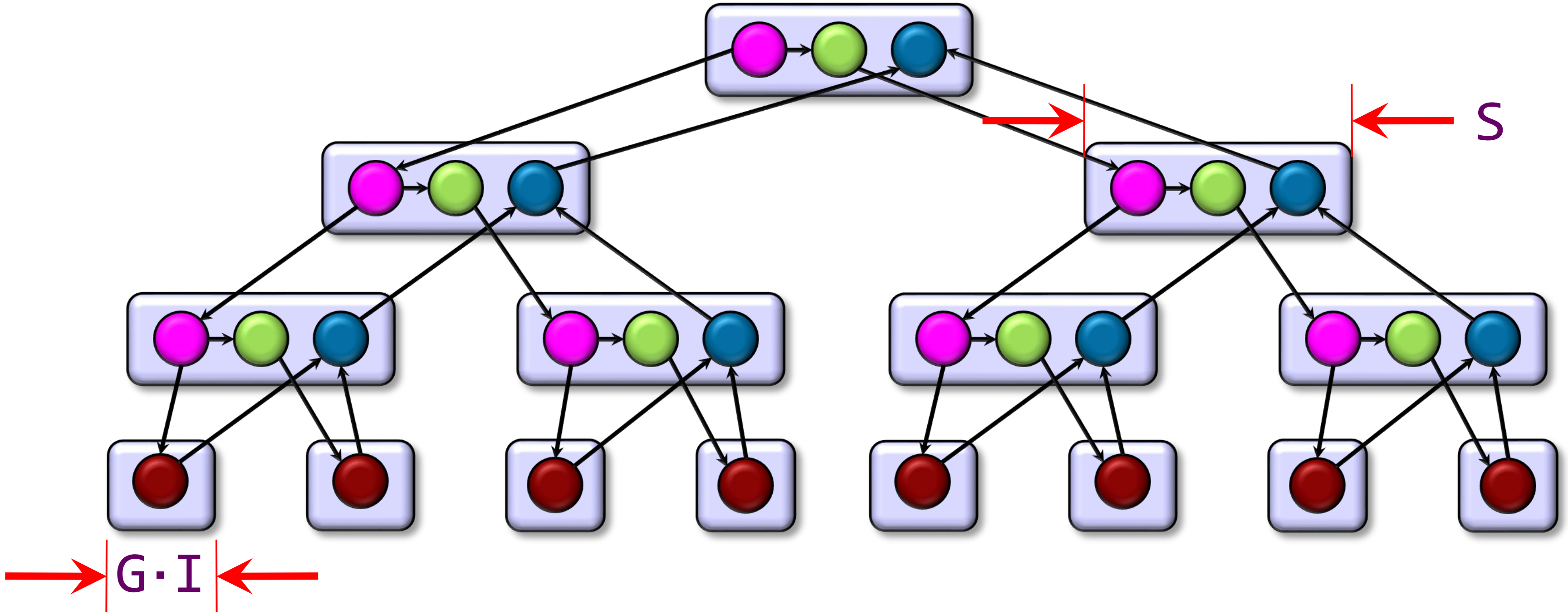
Compiler-generated recursion

```
void p_loop(int lo, int hi) { //half open
  if (hi > lo + G) {
    int mid = lo + (hi - lo)/2;
    cilk_scope {
      cilk_spawn p_loop(lo, mid);
      p_loop(mid, hi);
    }
    return;
  }
  for (int i=lo; i<hi; ++i) {
    A[i] += B[i];
  }
}
⋮
p_loop(0, n);
```

Loop Grain Size

Vector addition

```
#pragma cilk grainsize G
cilk_for (int i=0; i<n; ++i) {
  A[i] += B[i];
}
```



Let I be the time for one iteration of the loop body.
Let S be the time to perform a level of the recursion.

Loop Grain Size

Vector addition

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#pragma cilk grainsize G
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  A[i] += B[i];
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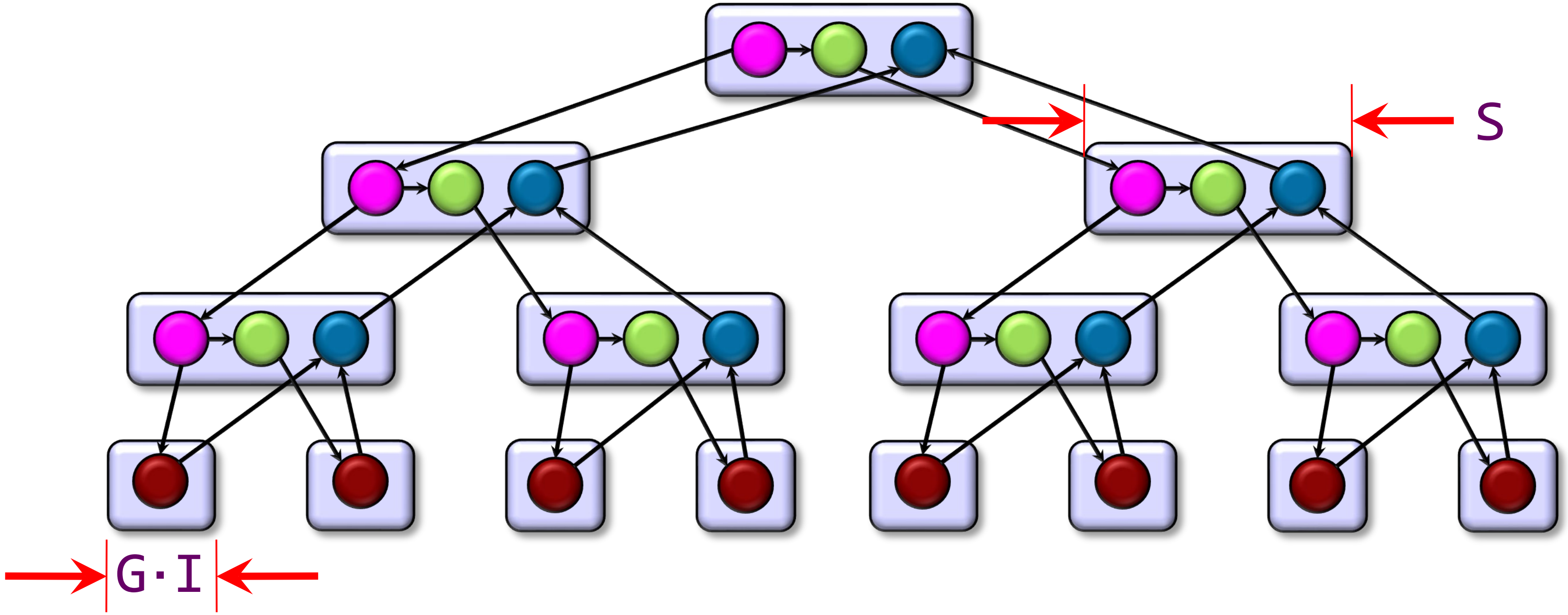

Work: $T_1 = n \cdot I + (n/G - 1) \cdot S$

Loop Grain Size

Vector addition

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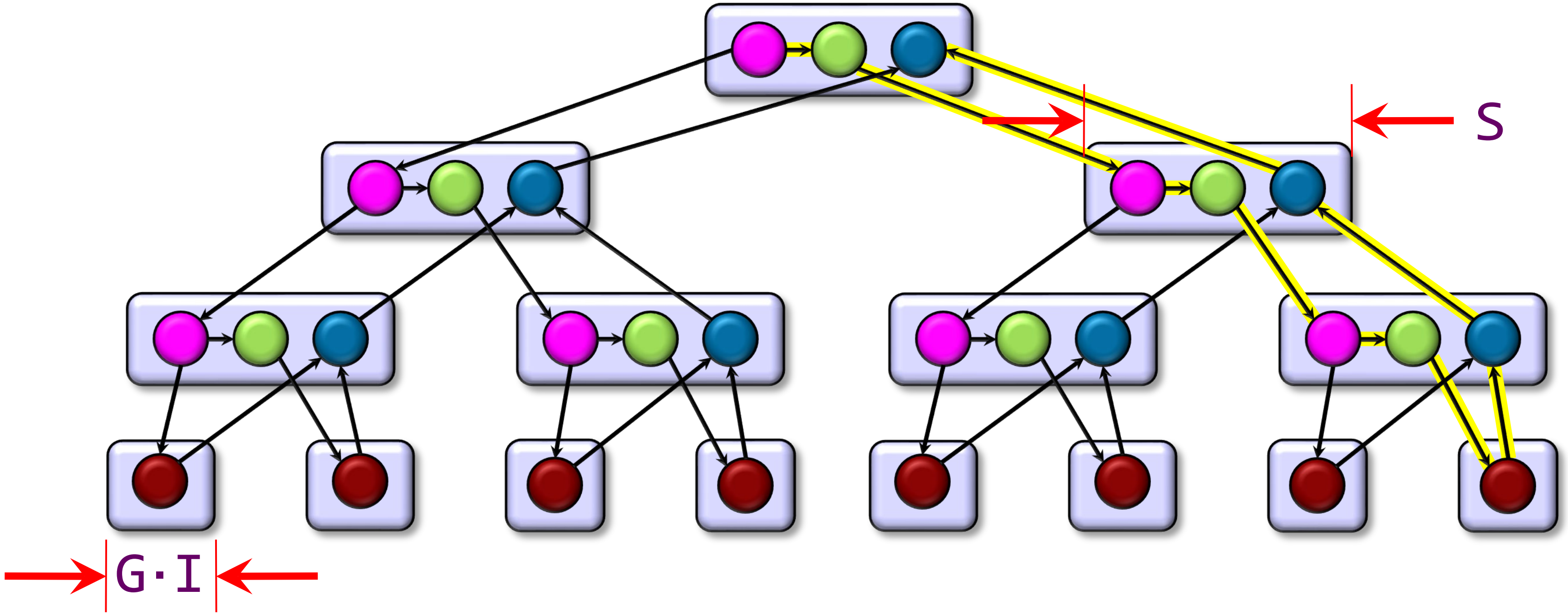
#pragma cilk grainsize G
cilk_for (int i=0; i<n; ++i) {
  A[i] += B[i];
}
```



Work: $T_1 = n \cdot I + (n/G - 1) \cdot S$

Span: $T_\infty = G \cdot I + \lg(n/G) \cdot S$

Loop Grain Size

Vector addition

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#pragma cilk grainsize G
cilk_for (int i=0; i<n; ++i) {
  A[i] += B[i];
}
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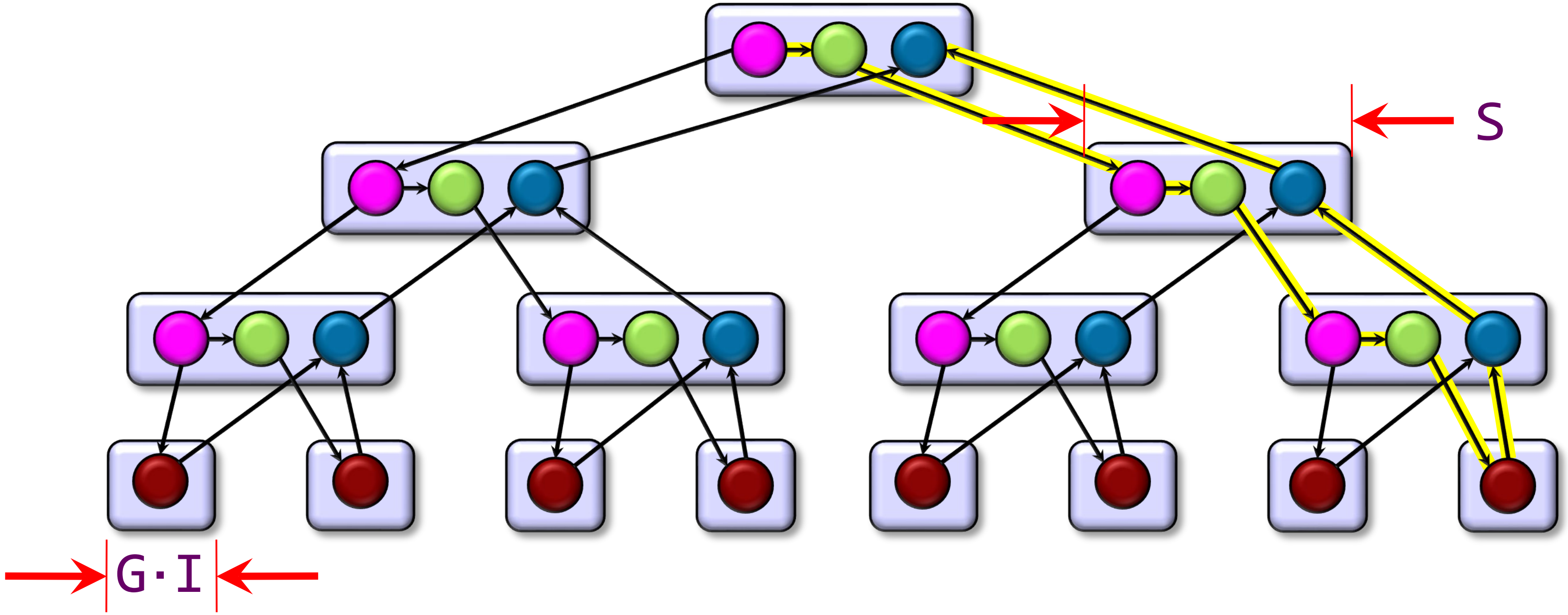

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Loop Grain Size

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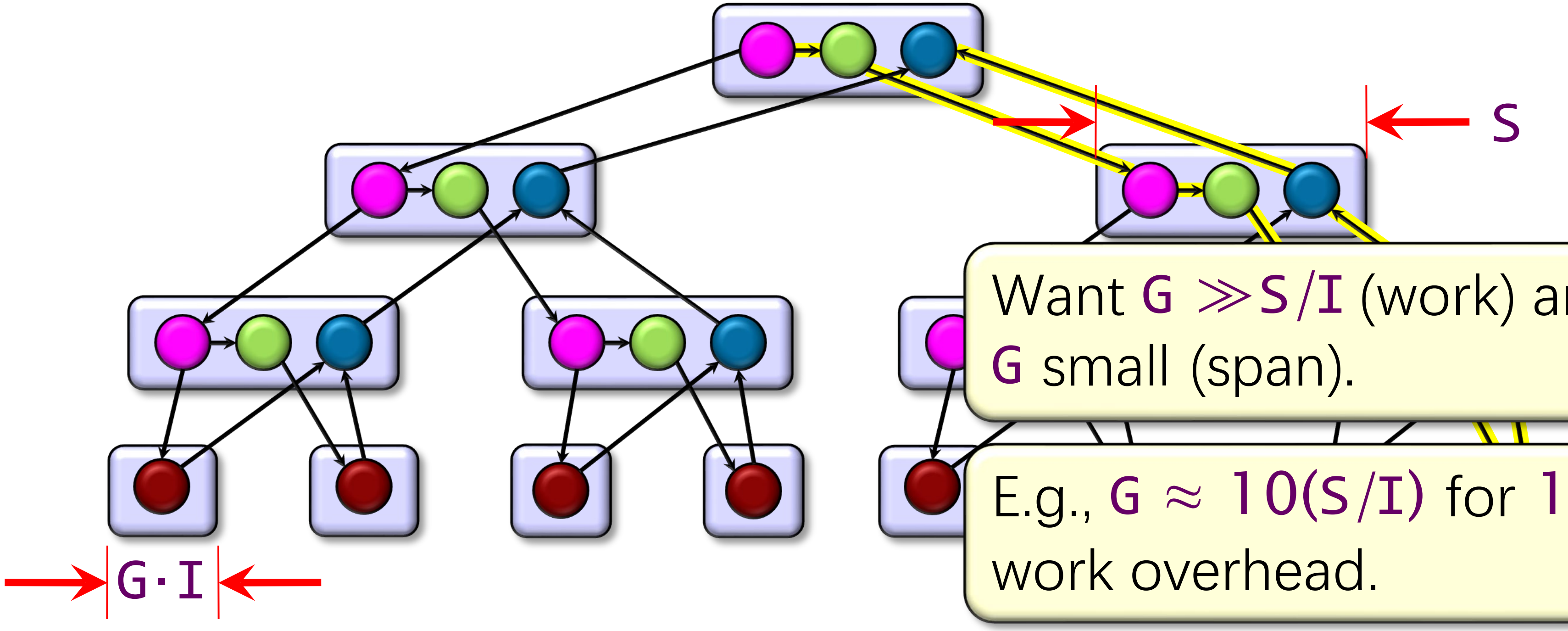


Work: $T_1 = n \cdot I + (n/G - 1) \cdot S$

Span: $T_\infty = G \cdot I + \lg(n/G) \cdot S$

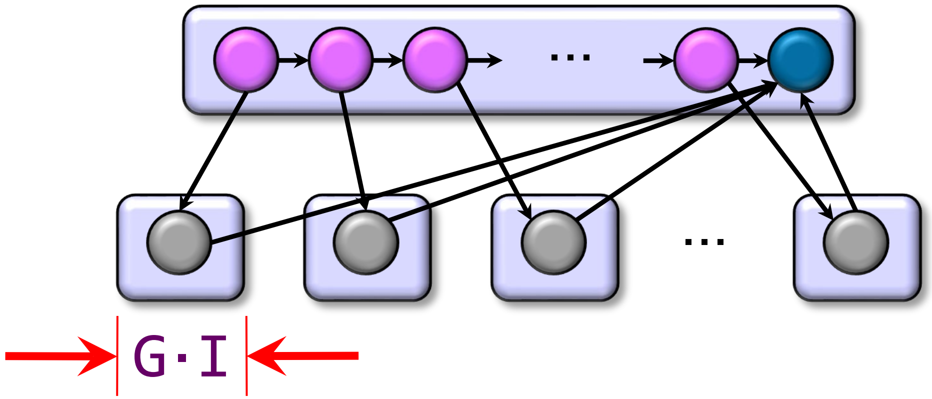
Want $G \gg S/I$ (work) and G small (span).

E.g., $G \approx 10(S/I)$ for 10% work overhead.

Parallelism:
$T_1/T_\infty \approx \Theta(n/\lg n)/(S/I)$.

Another Implementation

```
void vadd (double *A, double *B, int n){
  cilk_scope {
    for (int j=0; j<n; j+=G) {
      cilk_spawn {
        for (int i=j; i<MIN(j+G,n); i++)
          A[i] += B[i];
} } } }
```



Assume that **G** = 1.

Work: $T_1 = \Theta(n)$

Span: $T_\infty =$

Another Implementation

```
void vadd (double *A, double *B, int n){
  cilk_scope {
    for (int j=0; j<n; j+=G) {
      cilk_spawn {
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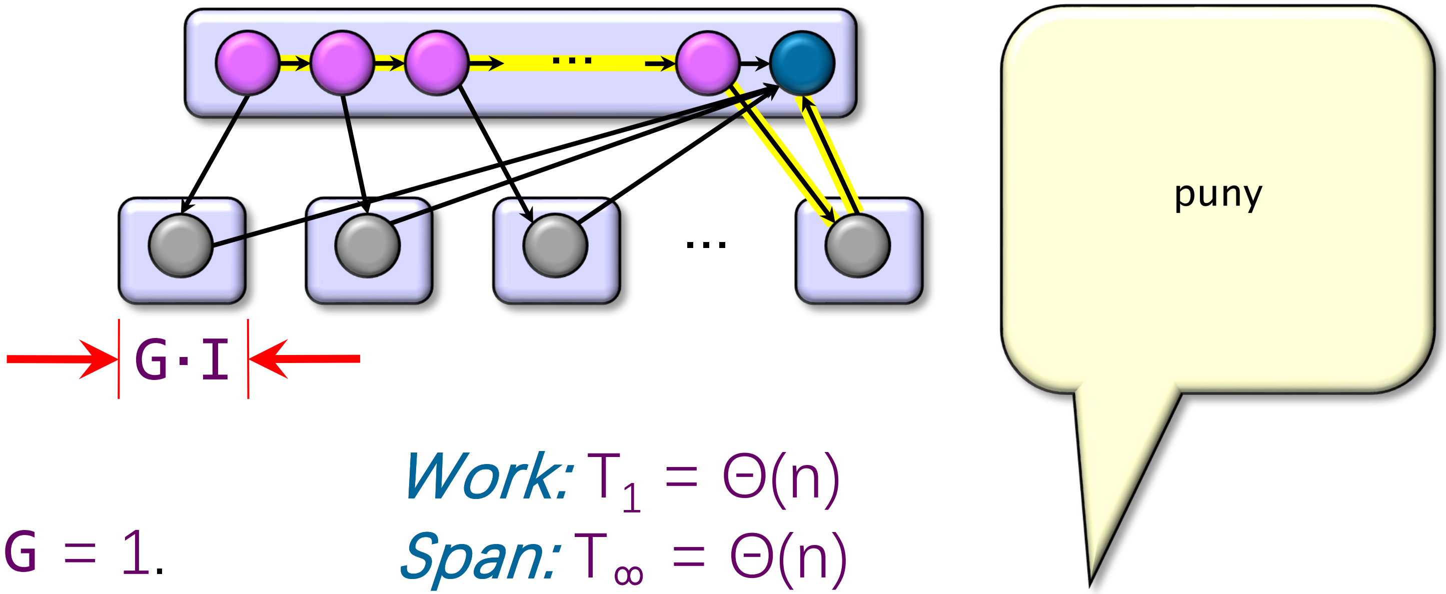

Assume that $\mathbf{G} = 1$.

Work: $T_1 = \Theta(n)$

Span: $T_\infty = \Theta(n)$

Parallelism: $T_1/T_\infty = \Theta(1)$

Another Implementation

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void vadd (double *A, double *B, int n){
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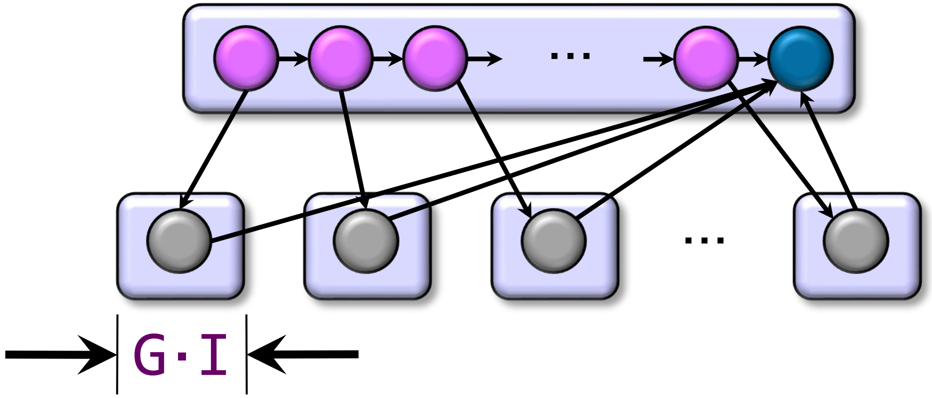

Choose $G = \sqrt{n}$ to minimize.

Analysis in terms of G

Work: $T_1 = \Theta(n)$

Span: $T_\infty = \Theta(G + n/G) = \Theta(\sqrt{n})$

Parallelism: $T_1/T_\infty = \Theta(\sqrt{n})$

Quiz on Parallel Loops

Question: Let $P \ll n$ be the number of workers on the system. How does the asymptotic parallelism of Code A compare to that of Code B? (Differences highlighted.)

Code A

```
#pragma cilk grainsize 1
cilk_for (int i=0; i<n; i+=32) {
  for (int j=i; j<MIN(i+32, n); ++j)
    A[j] += B[j];
}
```

Work:

Span:

Parallelism:

Code B

```
#pragma cilk grainsize 1
cilk_for (int i=0; i<n; i+=n/P) {
  for (int j=i; j<MIN(i+n/P, n); ++j)
    A[j] += B[j];
}
```

Work:

Span:

Parallelism:

Three Performance Tips

1. Minimize the span to maximize parallelism. Try to generate 10 times more parallelism than processors for near-perfect linear speedup.
2. If you have plenty of parallelism, try to trade some of it off to reduce work overhead.
3. Use divide-and-conquer recursion or parallel loops rather than spawning one small thing after another.

Do this:

```
cilk_for (int i=0; i<n; ++i) {
  foo(i);
}
```

Not this:

```
cilk_scope {
  for (int i=0; i<n; ++i) {
    cilk_spawn foo(i);
} }
```

And Three More

4. Ensure that work/#spawns is sufficiently large.
   - Coarsen by using function calls and inlining near the leaves of recursion, rather than spawning.
5. Parallelize outer loops, as opposed to inner loops, if you're forced to make a choice.
6. Watch out for scheduling overheads.

Do this:

```
cilk_for (int i=0; i<2; ++i) {
  for (int j=0; j<n; ++j)
    f(i,j);
}
```

Not this:

```
for (int j=0; j<n; ++j) {
  cilk_for (int i=0; i<2; ++i)
    f(i,j);
}
```

Take-Aways

- Any greedy scheduler provides linear speedup on computations having sufficient parallel slackness.
- The OpenCilk runtime system incorporates a randomized work-stealing scheduler that has strong theoretical bounds on its running time similar to those for greedy scheduling.
- Loops in Cilk are synthesized using divide-and-conquer spawning, which incurs linear work and logarithmic span.
- Coarsening recursion can lower loop overhead.