CS528
Cilk

Slides are adopted from
http://supertech.csail.mit.edu/cilk/
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Cilk

- Developed by **Leiserson at CSAIL, MIT**
  - **Chapter 27, Multithreaded Algorithm, Introduction to Algorithm, Coreman, Leiserson and Rivest**
- Initiated a startup: Cilk Plus
  - Added Cilk_for Keyword, Cilk Reduction features
  - Acquired by Intel, Intel uses Cilk Scheduler
- Addition of 6 keywords to standard C
  - Easy to install in linux system
  - With gcc and pthread

Cilk

- In 2008, ACM SIGPLAN awarded **Best influential paper of Decade**
  - **The Implementation of the Cilk-5 Multithreaded Language**, PLDI 1998
- PLDI 2008 Best paper Award
  - Reducers and Other Cilk++ Hyperobjects , PLDI 2008

Cilk : Biggest principle

- Programmer should be responsible for
  - Exposing the parallelism,
  - Identifying elements that can safely be executed in parallel
- Work of run-time environment (scheduler) to
  - Decide during execution how to actually divide the work between processors
- Work Stealing Scheduler
  - Proved to be good scheduler
  - Now also in GCC, Intel CC, **Intel acquire Cilk++**

Fibonacci

```
int fib (int n) {
if (n<2) return (n);
  else {
    int x,y;
    x = fib(n-1);
    y = fib(n-2);
    return (x+y);
  }
}
```

C elision

Cilk code

```
cilk int fib (int n) {
  if (n<2) return (n);
  else {
    int x,y;
    x = spawn fib(n-1);
    y = spawn fib(n-2);
    sync;
    return (x+y);
  }
}
```

Cilk is a ***faithful*** extension of C. A Cilk program's ***serial elision*** is always a legal implementation of Cilk semantics. Cilk provides *no* new data types.

Basic Cilk Keywords

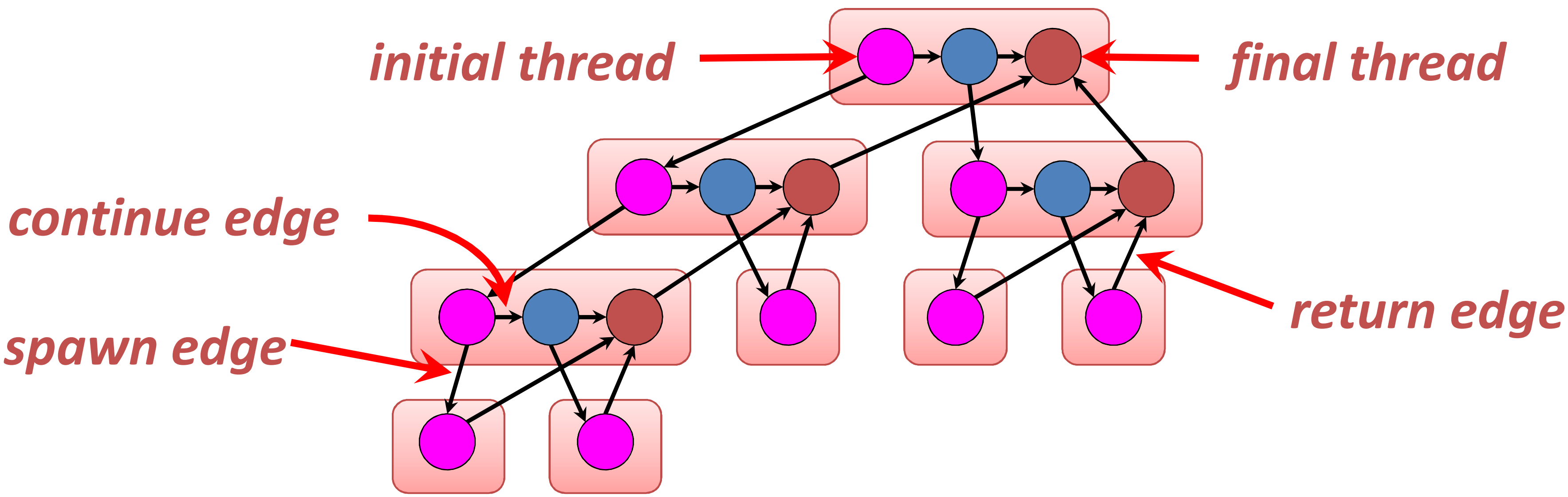
```
cilk int fib (int n) {
  if (n<2) return (n);
  else {
    int x,y;
    x = spawn fib(n-1);
    y = spawn fib(n-2);
    sync;
    return (x+y);
  }
}
```

Identifies a function as a ***Cilk procedure***, capable of being spawned in parallel.

The named ***child*** Cilk procedure can execute in parallel with the ***parent*** caller.

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

Multithreaded Computation

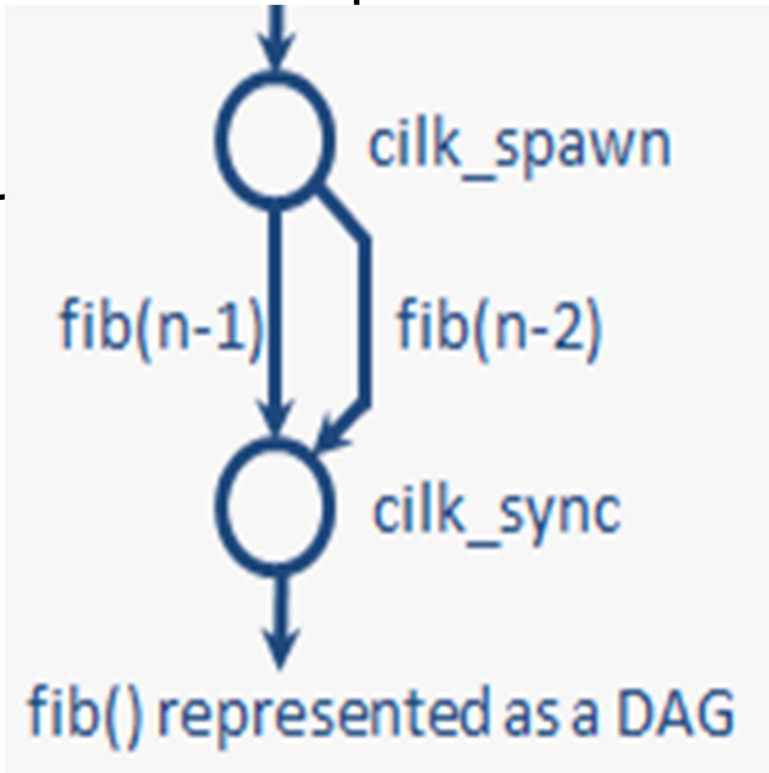


- The dag $G = (V, E)$ represents a parallel instruction stream.
- Each vertex v 2 V represents a ***(Cilk) thread***: a maximal sequence of instructions not containing parallel control (**`spawn`**, **`sync`**, **`return`**).
- Every edge e 2 E is either a ***spawn*** edge, a ***return*** edge, or a ***continue*** edge.

Fib: Cilk++ Version

```
int fib(int n) {
    if (n < 2) return n;
    int x=cilk_spawn fib(n-1);
    int y = fib(n-2);
    cilk_sync;
    return x + y;
}
```

Not available in Cilk



For loop in Cilk

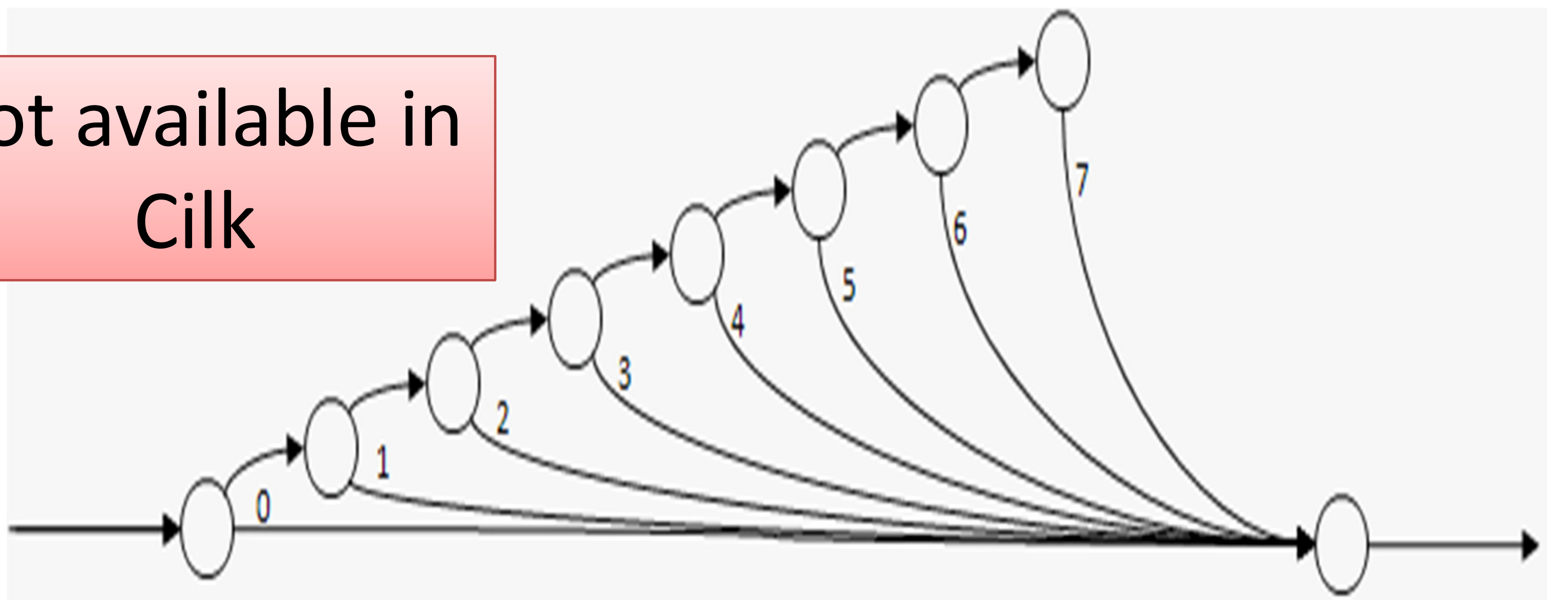
```
for (int i = 0; i < 8; ++i)
    do_work(i);
```

Serial

```
for (int i = 0; i < 8; ++i)
    cilk_spawn do_work(i);
cilk_sync;
```

Parallel

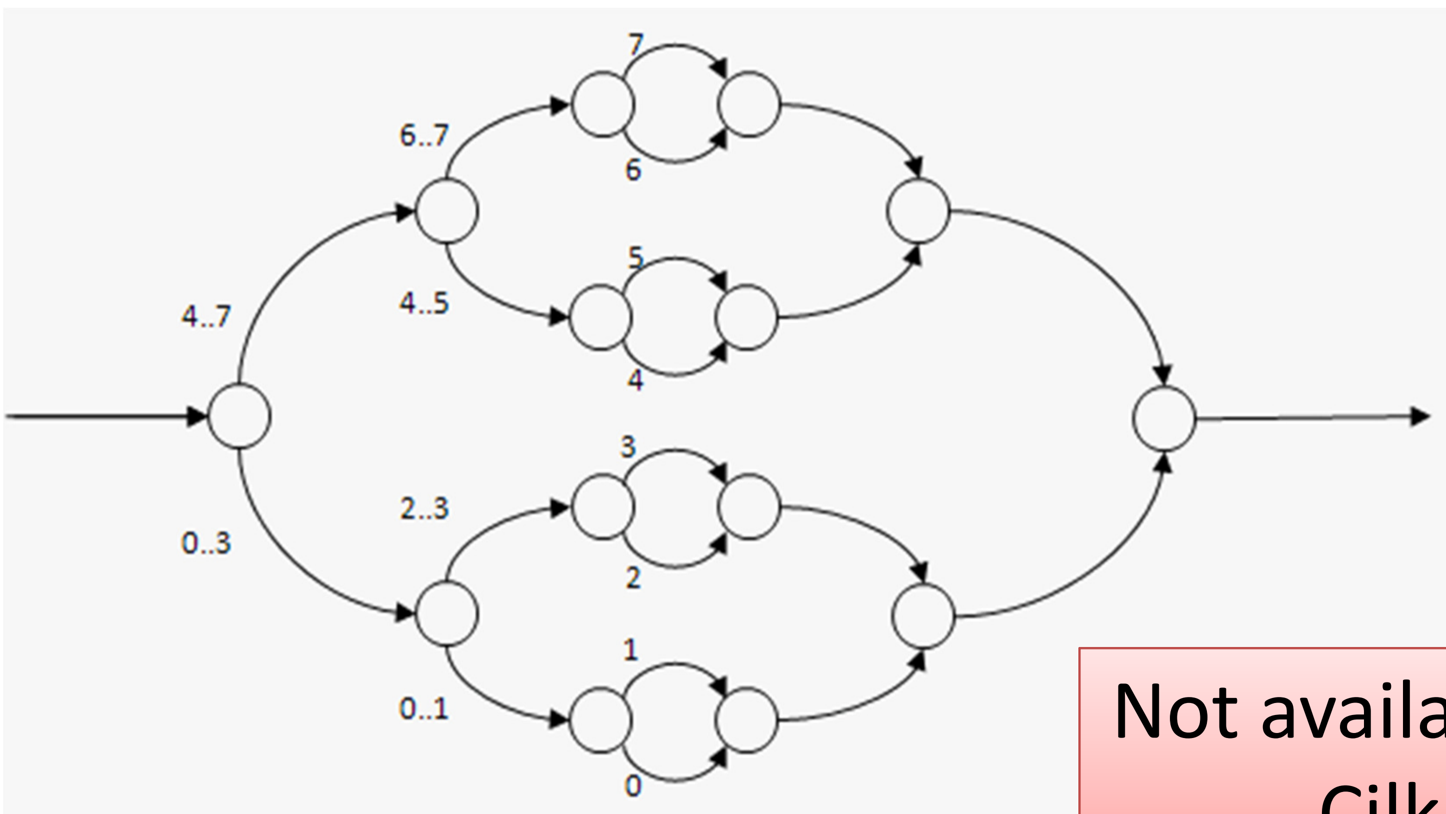
Not available in Cilk



Loop_for in Cilk++

```
cilk_for (int i=0;i<8;++i){
     do_work(i);
}// No sync required; auto sync
```

Parallel



Not available in Cilk

Cilk Run Time Scheduler

- Distributed load balancing
  - Receiver initiated
- Work stealing : Free processor steal a task of busy processor
- When ever a process spawns a new process,
  - This processor starts executing the spawned one
  - Parent goes to waiting/suspend mode
  - Parent can be transferred to other processor

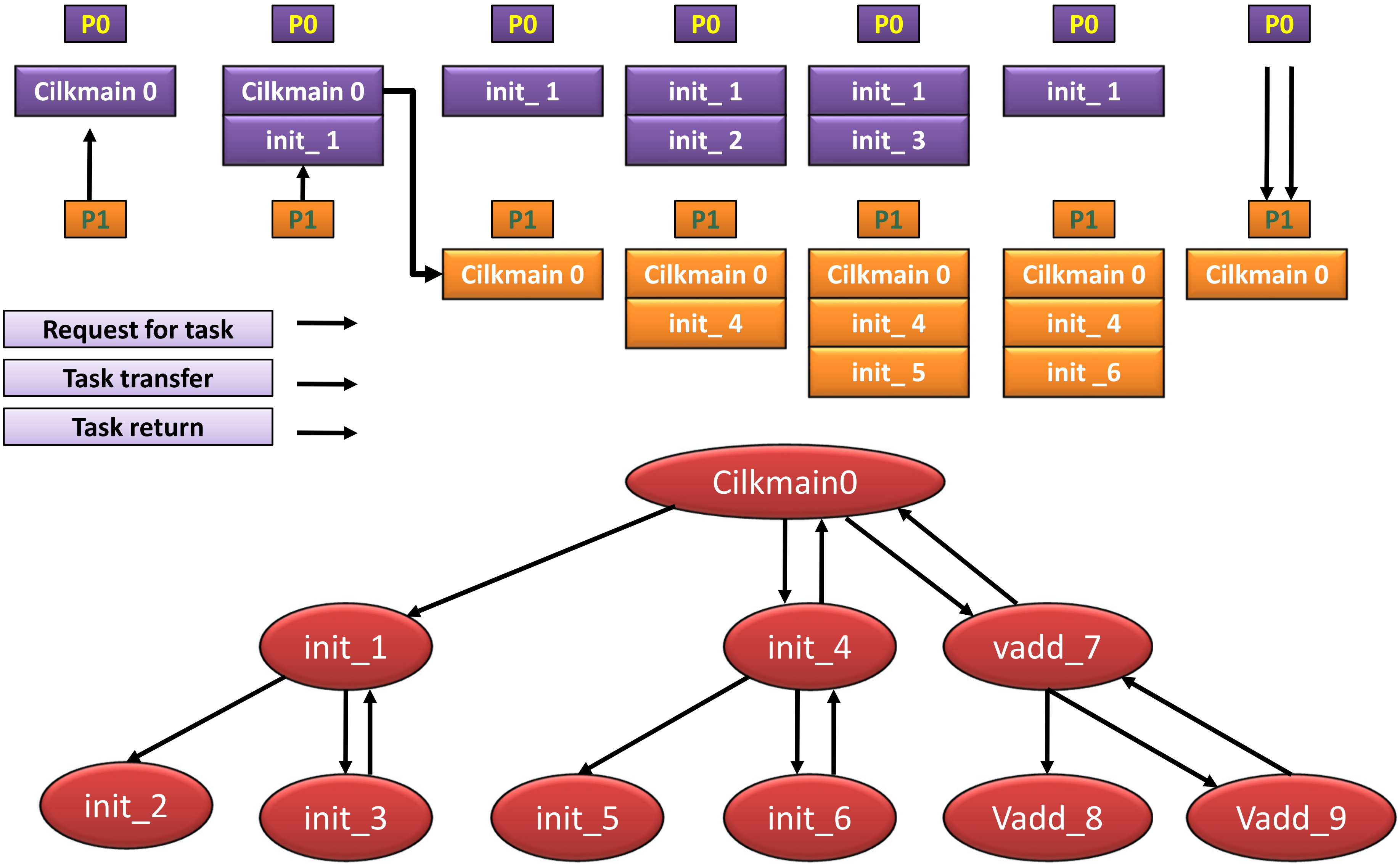
Work stealing

- Work stealing algorithm is receiver initiated algorithm
- Technique commonly used for load balancing
- Thief processor (Idle processor)
  - Steal work from other processor
  - Victim is selected randomly
- Victim processor (From a set of busy processor)
  - Work is stolen from these processor

Work stealing

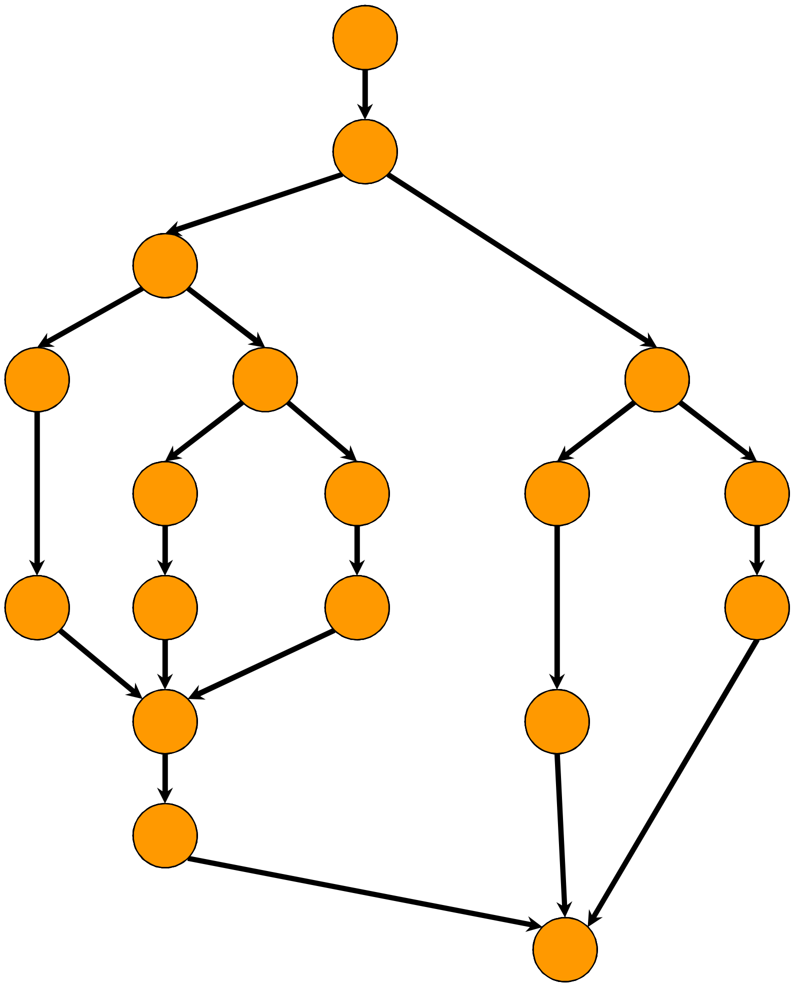
- Optimal algorithm for load balancing
  - If select victim randomly algorithm is Optimal **Proved**
- Basic assumption in work stealing
  - All the memory access are take same time
  - **UMA (Uniform Memory Access): shared memory**
  - Can be feasible iff
    - Task transfer time is same for all pair of processors
    - Communication bandwidth is same for all pair of processors

Cilk Run Time Scheduler



Algorithmic Complexity Measures

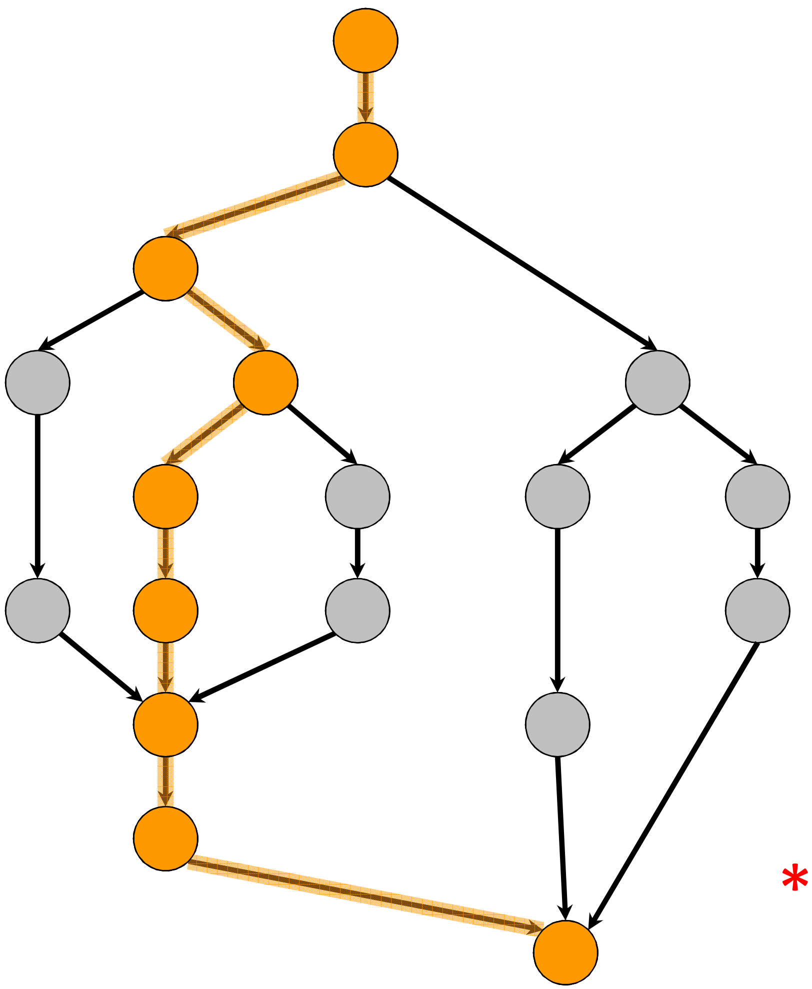
T_P = execution time on P processors



T_1 = ***work***

Algorithmic Complexity Measures

T_P = execution time on P processors



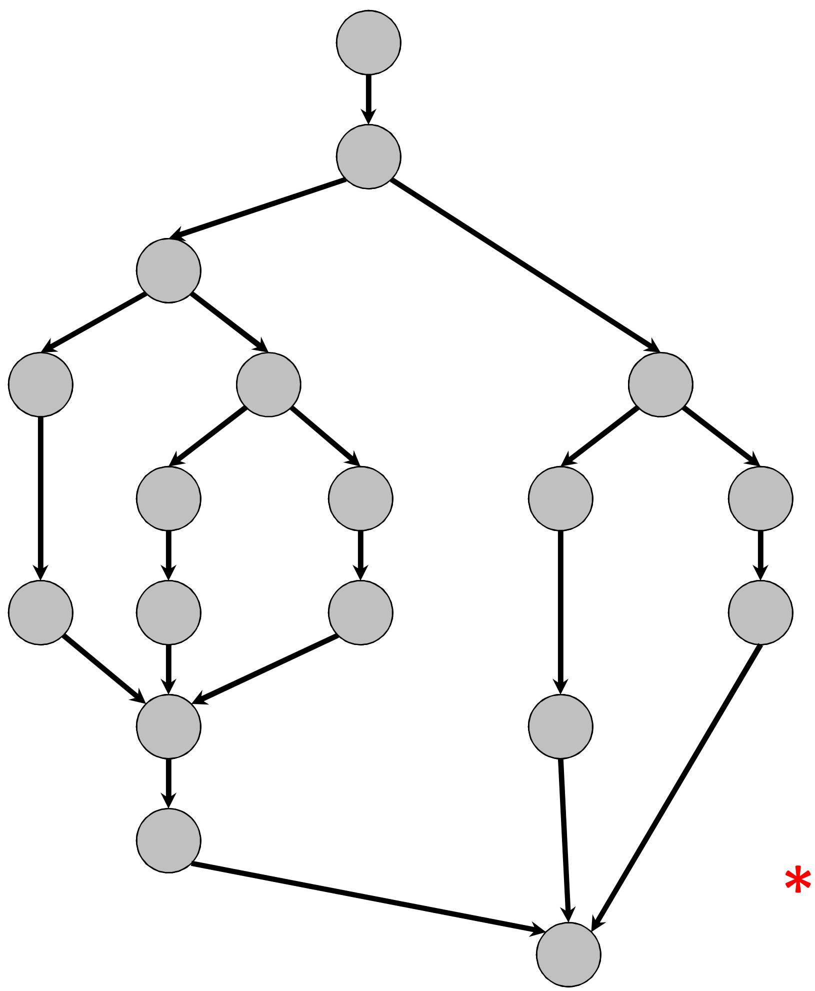
T_1 = ***work***

T_∞ = ***span****

* Also called ***critical-path length*** or ***computational depth***.

Algorithmic Complexity Measures

T_P = execution time on P processors



T_1 = ***work***

T_∞ = ***span****

LOWER BOUNDS

- $T_P \geq T_1/P$
- $T_P \geq T_\infty$

*Also called ***critical-path length*** or ***computational depth***.

Speedup

Definition: T_1/T_P = ***speedup*** on P processors.

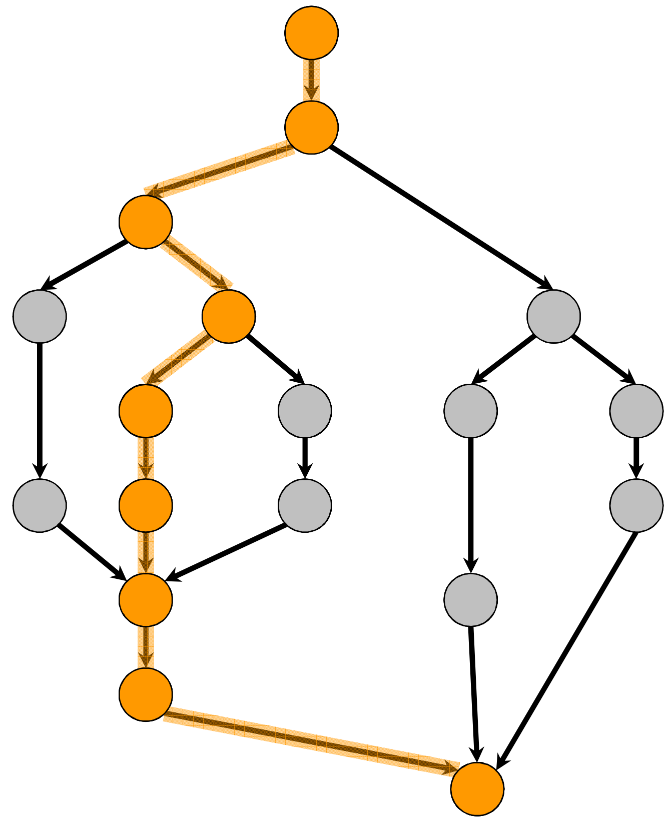
If $T_1/T_P = \Theta(P) \cdot P$, we have ***linear speedup***;
$= P$, we have ***perfect linear speedup***;
$> P$, we have ***superlinear speedup***,
which is not possible in our model, because of the lower bound $T_P \geq T_1/P$.

Parallelism

Because we have the lower bound $T_P \geq T_\infty$, the maximum possible speedup given T_1 and T_∞ is

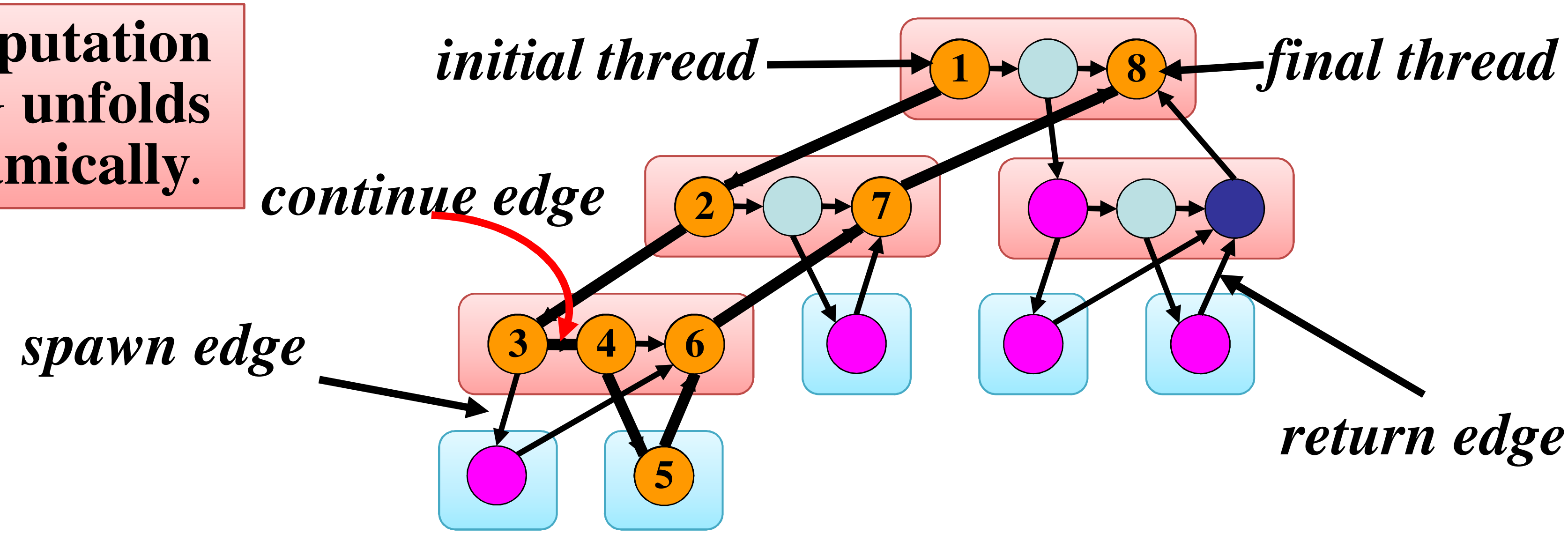
T_1 / T_∞ = ***parallelism***

= the average amount of work per step along the span.



CILK Example: Fib(4)

Computation DAG unfolds dynamically.



Assume for simplicity that each Cilk thread in `fib()` takes unit time to execute.

Work: $T_1 = 17$

Span: $T_\infty = 8$

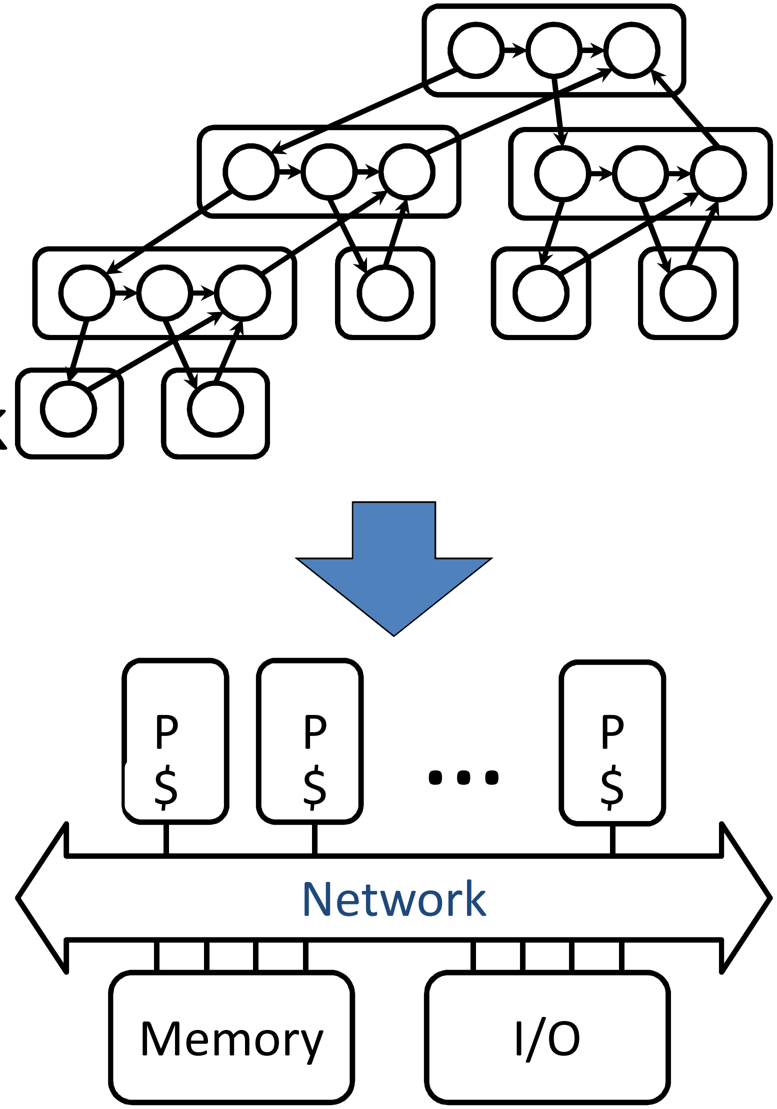
Parallelism: $T_1/T_\infty = 2.125$

Using many more than **2** processors makes little sense.

Ref1:The Cilk System for Parallel Multithreaded Computing, MIT Phd Thesis
Ref2:The Implementation of the Cilk-5 Multithreaded Language, 1998 ACM SIGPLAN

Scheduling

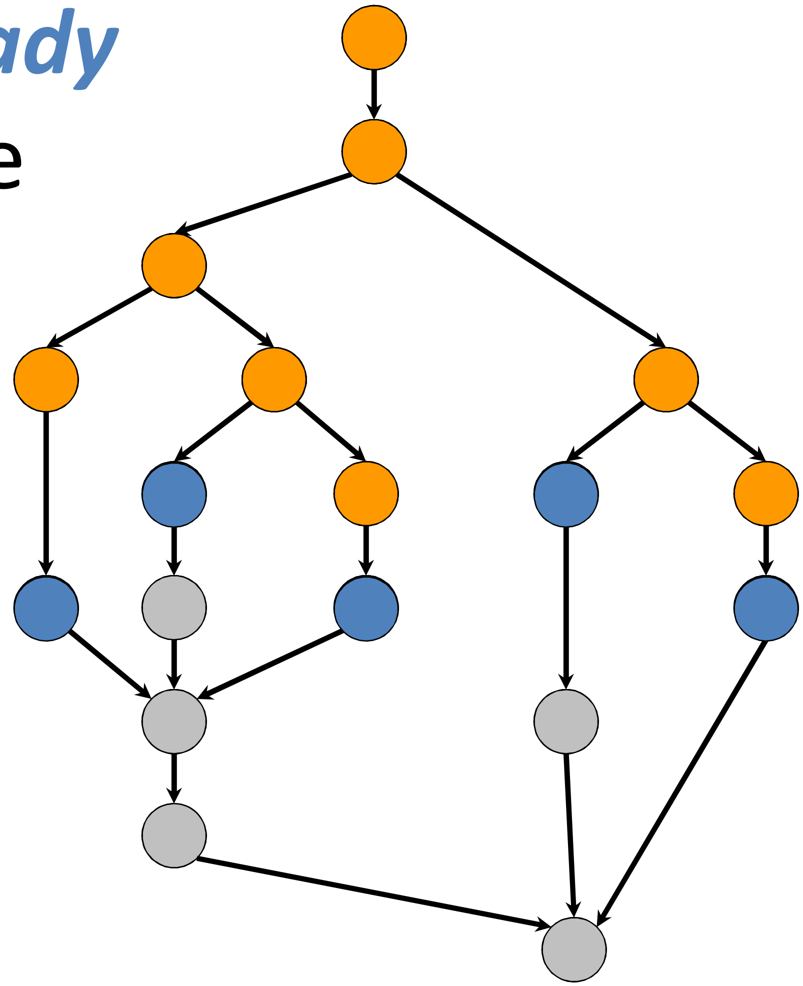
- Cilk allows the programmer to express *potential* parallelism in an application.
- The Cilk ***scheduler*** maps Cilk threads onto processors dynamically at runtime.
- Since ***on-line*** schedulers are complicated, we'll illustrate the ideas with an ***off-line*** scheduler.



Greedy Scheduling

IDEA: Do as much as possible on every step.

Definition: A thread is ***ready*** if all its predecessors have ***executed***.



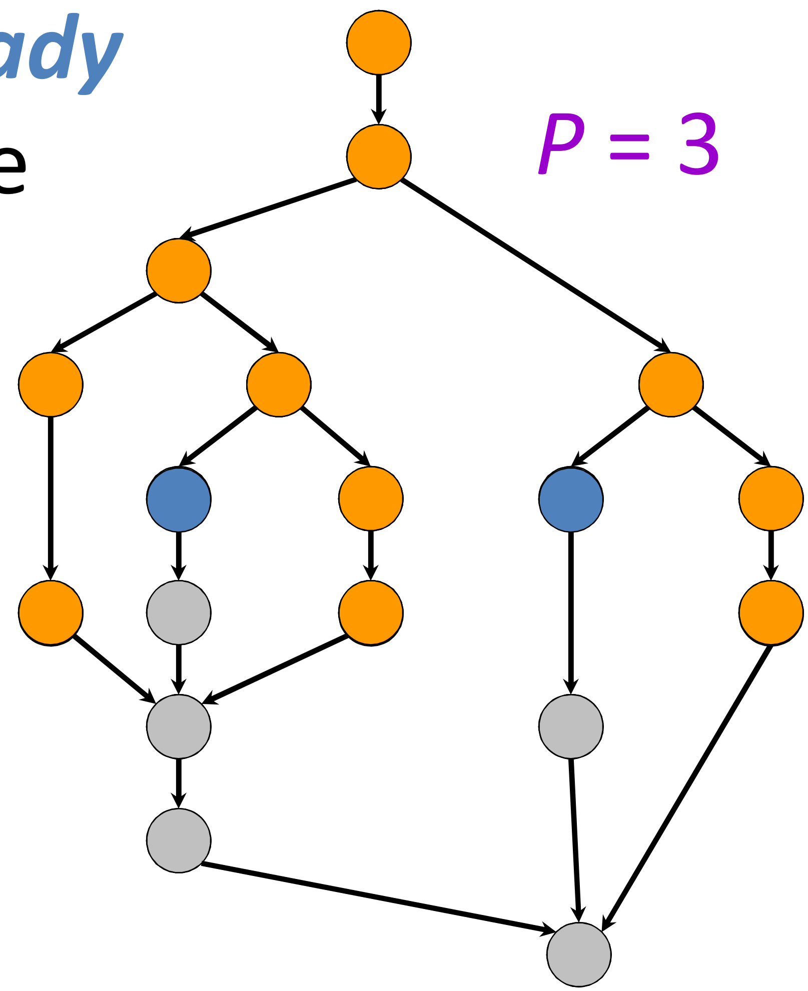
Greedy Scheduling

IDEA: Do as much as possible on every step.

Definition: A thread is ***ready*** if all its predecessors have ***executed***.

Complete step

- $\geq P$ threads ready.
- Run any P.



Greedy Scheduling

IDEA: Do as much as possible on every step.

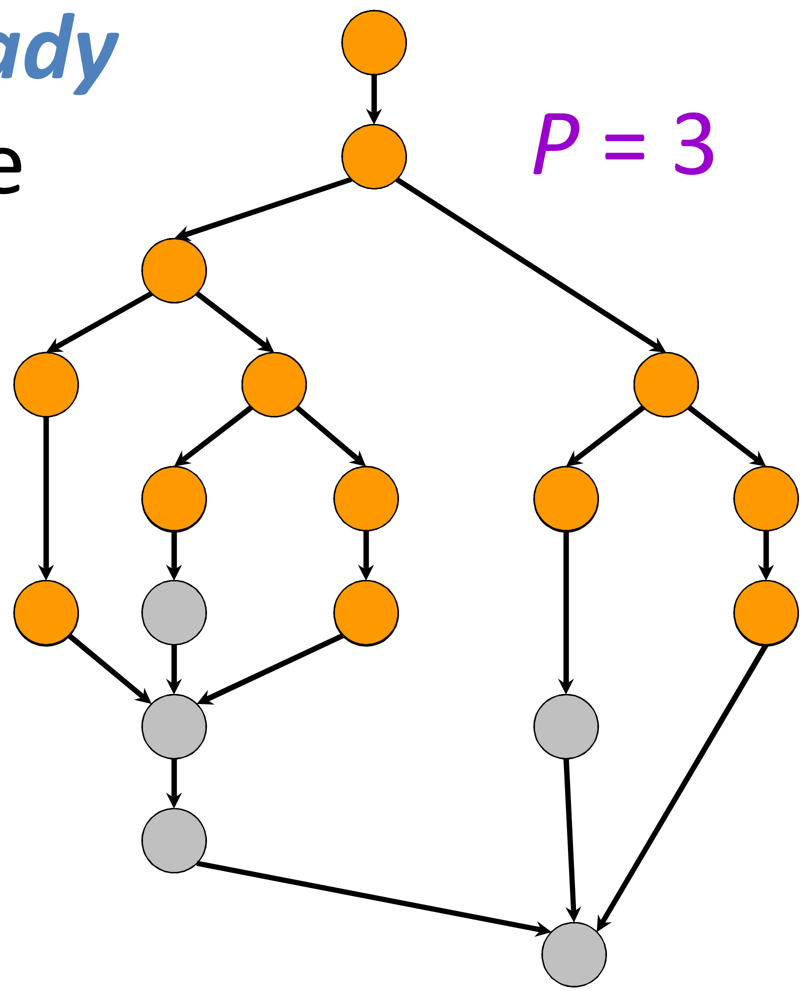
Definition: A thread is ***ready*** if all its predecessors have ***executed***.

Complete step

- ≥ P threads ready.
- Run any P.

Incomplete step

- < P threads ready.
- Run all of them.

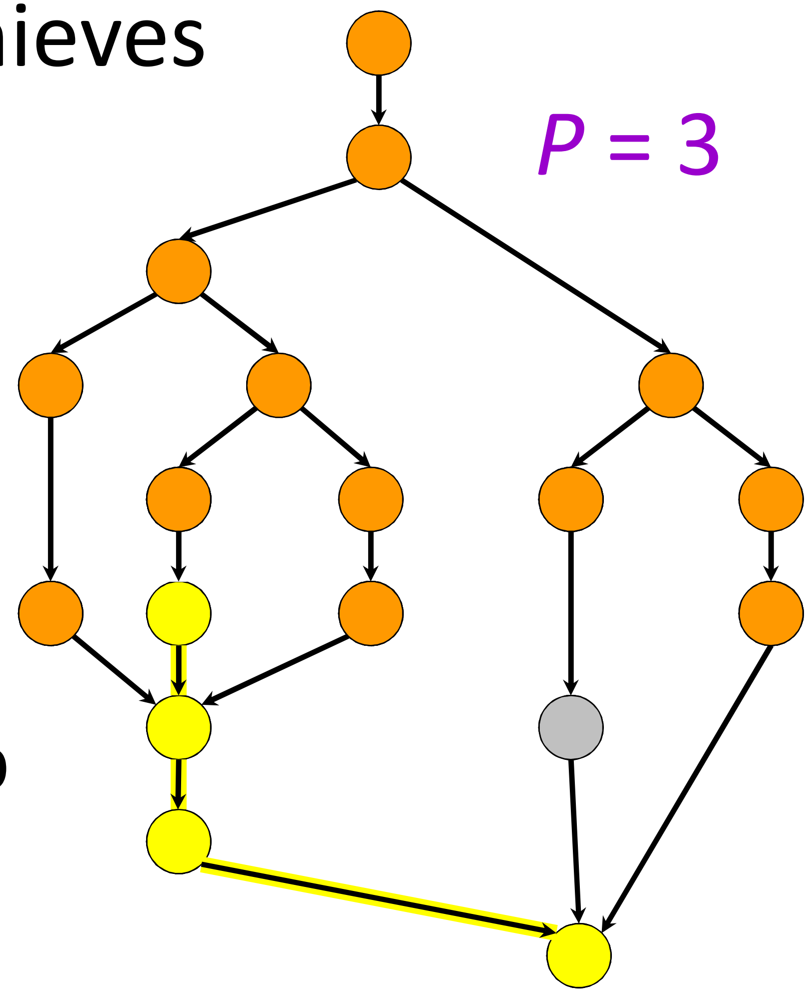


Greedy-Scheduling Theorem

Theorem [Graham '68 & Brent '75].

Any greedy scheduler achieves

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



$P = 3$

Proof.

- # complete steps $\leq T_1/P$, since each complete step performs P work.
- # incomplete steps $\leq T_\infty$, 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 $T_P{}^* \geq \max\{T_1/P, T_\infty\}$ (lower bounds), we have

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

Linear Speedup

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

Proof. Since $T_1/T_\infty \gg P \;\rightarrow\; T_\infty \ll T_1/P$, the Greedy Scheduling Theorem gives us

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

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

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

Cilk Performance

- Cilk's "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 if $P \ll T_1/T_\infty$.
- Instrumentation in Cilk allows the user to determine accurate measures of T_1 and T_∞ .
- The average cost of a `spawn` in Cilk-5 is only 2–6 times the cost of an ordinary C function call, depending on the platform.

Parallelizing Vector Addition

C

```
void vadd(float *A, float *B, int N)
    int i; for (i=0; i<n; i++) A[i]+=B[i];
}
```

Parallelization strategy:

1. Convert loops to recursion.

Parallelizing Vector Addition

C

```
void vadd(float *A, float *B, int N)
    int i; for (i=0; i<n; i++) A[i]+=B[i];
}
```

C

```
     void vadd(float *A, float *B, int N){

  if (n<=BASE) {
    int i; for (i=0; i<n; i++) A[i]+=B[i];
  } else {
                  vadd (A, B, n/2);
                  vadd (A+n/2, B+n/2, n/2);

}
```

Parallelization strategy:

1. Convert loops to recursion.
2. Insert Cilk keywords.

Parallelizing Vector Addition

C

```
void vadd(float *A, float *B, int N)
    int i; for (i=0; i<n; i++) A[i]+=B[i];
}
```

Cilk

```
cilk void vadd(float *A, float *B, int N){

  if (n<=BASE) {
    int i; for (i=0; i<n; i++) A[i]+=B[i];
  } else {
        spawn  vadd (A, B, n/2);
        spawn  vadd (A+n/2, B+n/2, n/2);
        sync;
}
```

Parallelization strategy:

1. Convert loops to recursion.
2. Insert Cilk keywords.

Parallelizing Vector Addition

C

```
void vadd(float *A, float *B, int N)
    int i; for (i=0; i<n; i++) A[i]+=B[i];
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        spawn  vadd (A+n/2, B+n/2, n/2);
        sync;
}
```

Parallelization strategy:

1. Convert loops to recursion.
2. Insert Cilk keywords.

Side benefit:

D&C is generally good for caches!

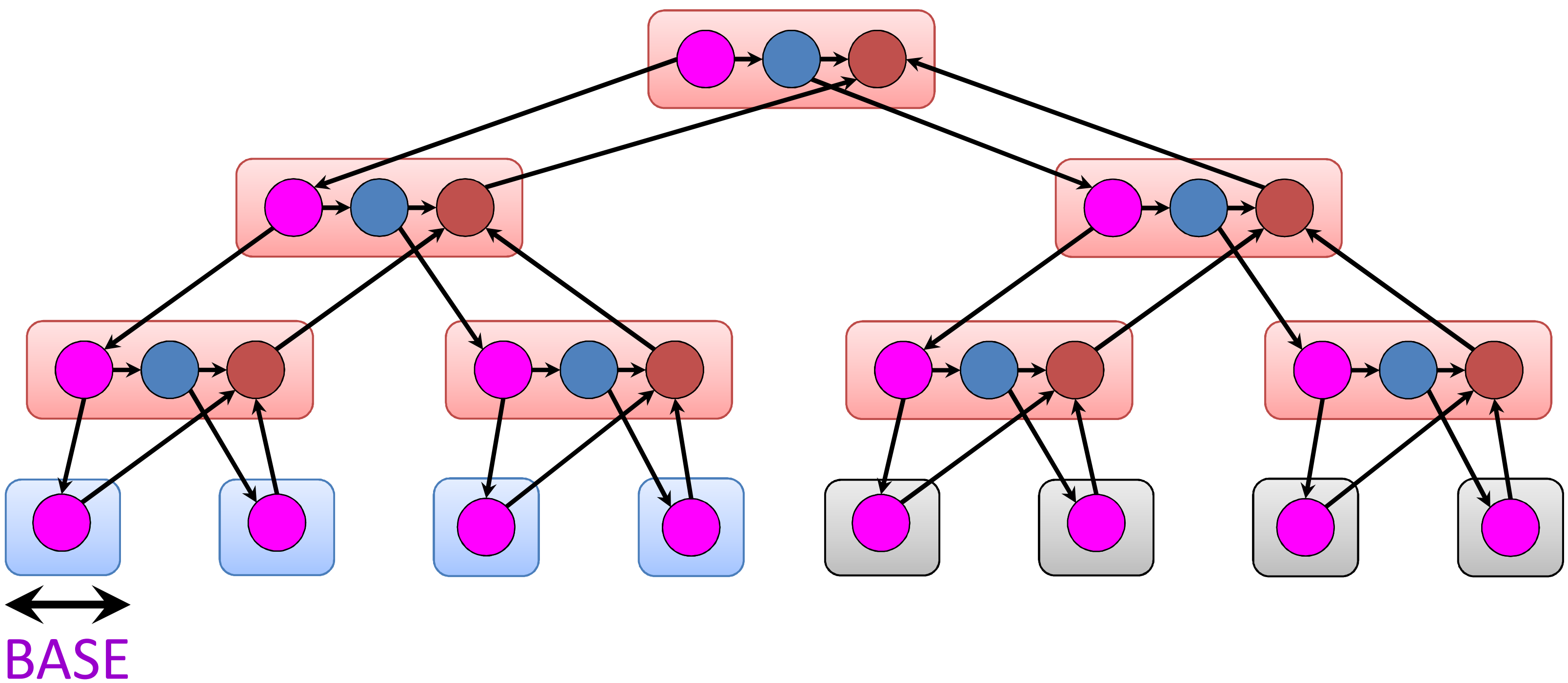
Vector Addition Analysis

To add two vectors of length n, where BASE = $\Theta(1)$:

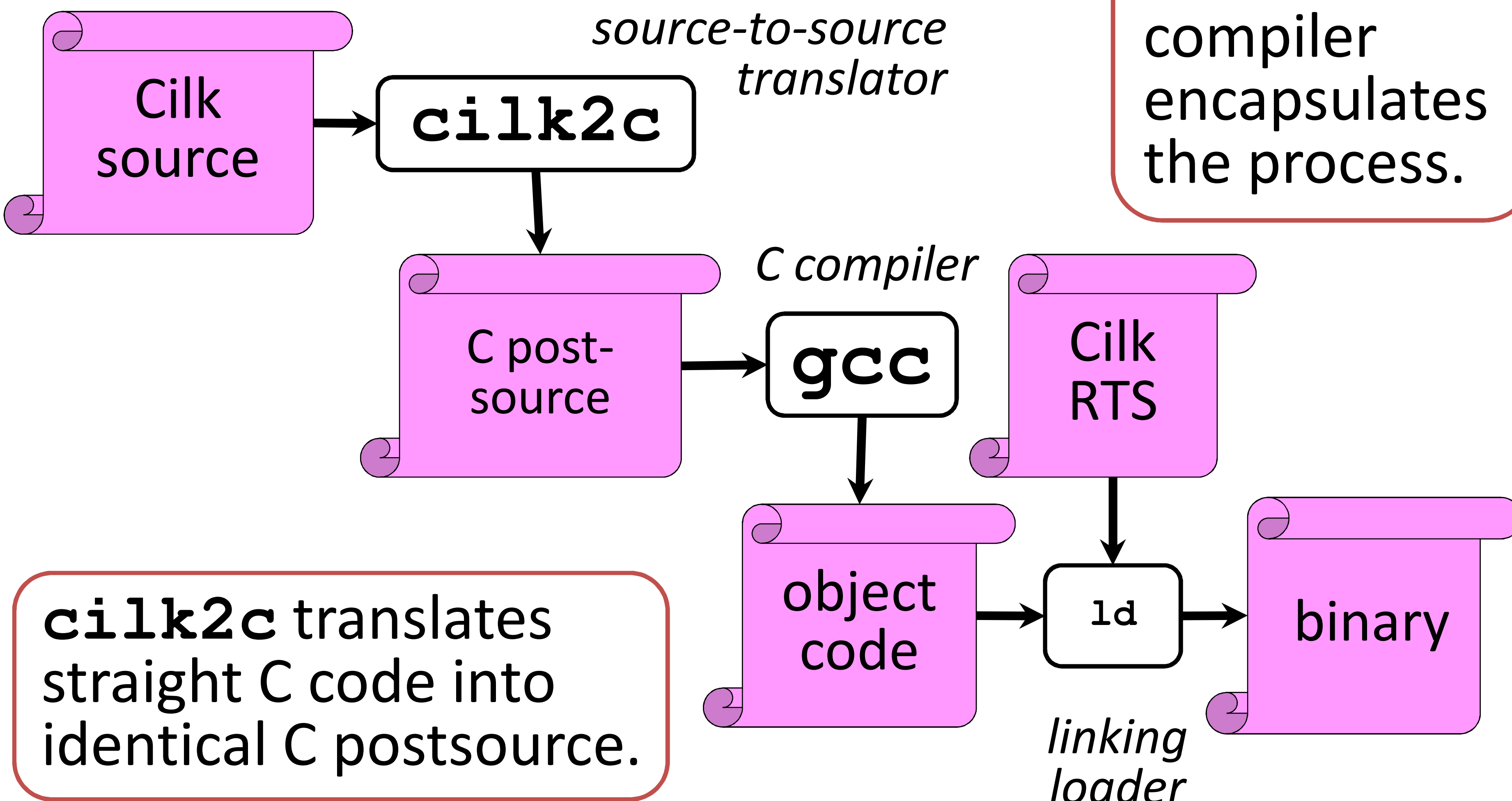
Work: T_1 = ? $\Theta(n)$

Span: T_1 = ? $\Theta(\lg n)$

Parallelism: T_1/T_1 = ? $\Theta(n/\lg n)$



Compiling Cilk Program



The **`cilkc`** compiler encapsulates the process.

`cilk2c` translates straight C code into identical C postsource.

```
$ cilkc fib.cilk –o fib
$ ./fib  -proc 4  5  // run using  4 threads
```

Square-Matrix Multiplication

$$\begin{pmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ c_{n1} & c_{n2} & \cdots & c_{nn} \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix} \times \begin{pmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{n1} & b_{n2} & \cdots & b_{nn} \end{pmatrix}$$

C $\qquad$ A $\qquad$ B

$$c_{ij} = \sum_{k=1}^{n} a_{ik} b_{kj}$$

Assume for simplicity that $n = 2^k$.

Recursive Matrix Multiplication

Divide and conquer —

$$\begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \text{X} \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix}$$

$$= \begin{bmatrix} A_{11}B_{11} & A_{11}B_{12} \\ A_{21}B_{11} & A_{21}B_{12} \end{bmatrix} + \begin{bmatrix} A_{12}B_{21} & A_{12}B_{22} \\ A_{22}B_{21} & A_{22}B_{22} \end{bmatrix}$$

8 multiplications of $(n/2)$ X $(n/2)$ matrices.
1 addition of n *X* n matrices.

Matrix Multiply in Pseudo-Cilk

```
cilk void Mult(*C, *A, *B, n) {
  float *T = Cilk_alloca(n*n*sizeof(float));
  h base case & partition matrices i
  spawn Mult(C11,A11,B11 n/2);
  spawn Mult(C12,A11,B12 /2);
  spawn Mult(C22,A21,B12, /2);
  spawn Mult(C21,A21,B11, 2);
  spawn Mult(T11,A12,B21,n );
  spawn Mult(T12,A12,B22,n ;
  spawn Mult(T22,A22,B22,n/
  spawn Mult(T21,A22,B21,n/
  sync;
  spawn Add(C,T,n);
  sync;
  return;
}
```

C = A X B

Absence of type declarations.

Matrix Multiply in Pseudo-Cilk

```
cilk void Mult(*C, *A, *B, n) {
  float *T = Cilk_alloca(n*n*sizeof(float));
  h base case & partition matrices i
  spawn Mult(C11,A11,B11,n/2);
  spawn Mult(C12,A11,B12,n/2);
  spawn Mult(C22,A21,B12,n/2);
  spawn Mult(C21,A21,B11,n/2);
  spawn Mult(T11,A12,B21,n/2);
  spawn Mult(T12,A12,B22,n/2);
  spawn Mult(T22,A22,B22,n/2);
  spawn Mult(T21,A22,B21,n/2);
  sync;
  spawn Add(C,T,n);
  sync;
  return;
}
```

Coarsen base cases for efficiency.

$C = A \times B$

Matrix Multiply in Pseudo-Cilk

```
cilk void Mult(*C, *A, *B, n) {
  float *T = Cilk_alloca(n*n*sizeof(float));
  h base case & partition matrices i
  spawn Mult(C11,A11,B11,n/2);
  spawn Mult(C12,A11,B12,n/2)
  spawn Mult(C22,A21,B12,n/2)
  spawn Mult(C21,A21,B11,n/2)
  spawn Mult(T11,A12,B21,n/2)
  spawn Mult(T12,A12,B22,
  spawn Mult(T22,A22,B22,n
  spawn Mult(T21,A22,B21,n/
  sync;
  spawn Add(C,T,n);
  sync;
  return;
}
```

Also need a row-size argument for array indexing.

Submatrices are produced by pointer calculation, not copying of elements.

C = A X B