Shared-memory Parallel Programming with Cilk Plus

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What is a Thread?

- **Thread: an independent flow of control**
  - —software entity that executes a sequence of instructions
- **Thread requires**
  - —program counter
  - —a set of registers
  - —an area in memory, including a call stack
  - —a thread id
- **A process consists of one or more threads that share**
  - —address space
  - —attributes including user id, open files, working directory, ...

An Abstract Example of Threading

A sequential program for matrix multiply

```
for (row = 0; row < n; row++)
  for (col = 0; col < n; col++)
    c[row][col] =
      dot_product(get_row(a, row), get_col(b, col))
```

can be transformed to use multiple threads

```
for (row = 0; row < n; row++)
  for (col = 0; col < n; col++)
    c[row][col] =
      spawn dot_product(get_row(a, row), get_col(b, col))
```

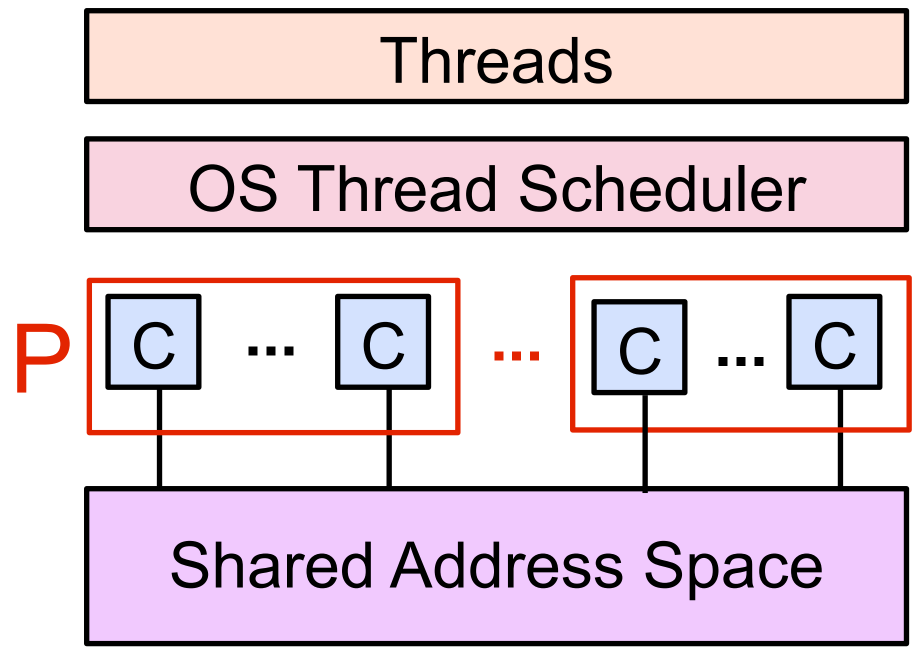
Why Threads?

Well matched to multicore hardware

- **Employ parallelism to compute on shared data**
  - —boost performance on a fixed memory footprint (strong scaling)
- **Useful for hiding latency**
  - —e.g. latency due to I/O, memory latency, communication latency
- **Useful for scheduling and load balancing**
  - —especially for dynamic concurrency
- **Relatively easy to program**
  - —easier than message-passing? you be the judge!

Threads and Memory

- All memory is globally accessible to every thread
- Each thread's stack is treated as local to the thread
- Additional local storage can be allocated on a per-thread basis
- Idealization: treat all memory as equidistant



Schema for SMP Node

Targets for Threaded Programs

Shared-memory parallel systems

- **Multicore processor**
- **Workstations or cluster nodes with multiple processors**
- **Xeon Phi accelerator**
  - —~240 threads
- **SGI UV: scalable shared memory system**
  - —up to 4096 threads

Threaded Programming Models

- **Library-based models**
  - —all data is shared, unless otherwise specified
  - —examples: Pthreads, Intel Threading Building Blocks, Java Concurrency, Boost, Microsoft .Net Task Parallel Library
- **Directive-based models, e.g., OpenMP**
  - —shared and private data
  - —pragma syntax simplifies thread creation and synchronization
- **Programming languages**
  - —Cilk Plus (Intel, GCC)
  - —CUDA (NVIDIA)
  - —Habanero-Java (Rice)

Toward Standard Threading for C/C++

At last month's meeting of the C standard committee, WG14 decided to form a study group to **produce a proposal for language extensions for C to simplify parallel programming**. This proposal is expected to **combine the best ideas from Cilk and OpenMP, two of the most widely-used and well-established parallel language extensions for the C language family.**

As the chair of this new study group, named CPLEX (C Parallel Language Extensions), I am announcing its organizational meeting:

June 17, 2013 10:00 AM PDT, 2 hours

Interested parties should join the group's mailing list, to which further information will be sent:

http://www.open-std.org/mailman/listinfo/cplex

Questions can be sent to that list, and/or to me directly.

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Clark Nelson — Vice chair, PL22.16 (ANSI C++ standard committee)
Intel Corporation — Chair, SG10 (WG21 study group for C++ feature-testing)
clark.nelson@intel.com — Chair, CPLEX
(WG14 study group for C parallel language extensions)

Outline for Today

- **Why multithreaded programming models?**
- **Threaded programming models**
- **Cilk Plus**
  - —tasks
  - —algorithmic complexity measures
  - —scheduling
  - —performance and granularity
  - —task parallelism examples
    - – vector addition using divide and conquer
    - – nqueens: exploratory search

Cilk Plus Programming Model

- A simple and powerful model for writing multithreaded programs
- Extends C/C++ with three new keywords
  - —cilk_spawn: invoke a function (potentially) in parallel
  - —cilk_sync: wait for a procedure's spawned functions to finish
  - —cilk_for: execute a loop in parallel
- Cilk Plus programs specify logical parallelism
  - —what computations can be performed in parallel, i.e., tasks
  - —<u>not</u> mapping of work to threads or cores
- Faithful language extension
  - —if Cilk Plus keywords are elided → C/C++ program semantics
- Availability
  - —Intel compilers
  - —GCC 4.9 (except cilk_for)

Cilk Plus Tasking Example: Fibonacci

Fibonacci sequence

0 + 1 + 1 + 2 + 3 + 5 + 8 + 13 … 21 … 34 55 89 144 233 377 610 987

- **Computing Fibonacci recursively**

```
int fib(int n)  {
  if (n < 2) return n;
  else {
    int n1, n2;
    n1 = fib(n-1);
    n2 = fib(n-2);
   return (n1 + n2);
  }
}
```

Cilk Plus Tasking Example: Fibonacci

Fibonacci sequence

0 + 1 + 1 + 2 + 3 + 5 + 8 + 13 ... 21 34 55 89 144 233 377 610 987 ...

- **Computing Fibonacci recursively in parallel with Cilk Plus**

```
int fib(int n)  {
  if (n < 2) return n;
  else {
    int n1, n2;
    n1 = cilk_spawn fib(n-1);
    n2 = fib(n-2);
    cilk_sync;
    return (n1 + n2);
  }
}
```

Cilk Plus Terminology

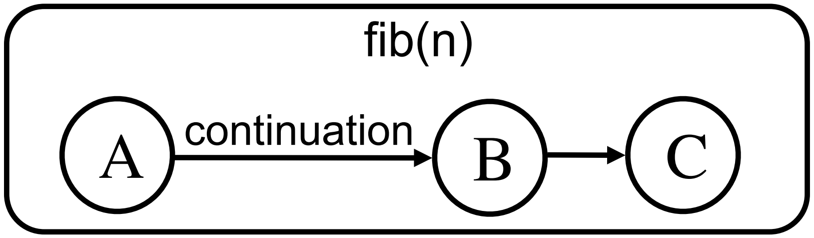
- Parallel control
  - cilk_spawn, cilk_sync
  - return from spawned function
- Strand
  - maximal sequence of instructions not containing parallel control

```
int fib(n)  {
  if (n < 2) return n;
  else {
   int n1, n2;
   n1 = cilk_spawn fib(n - 1);
   n2 = cilk_spawn fib(n - 2);
   cilk_sync;
  return (n1 + n2);
  }
}
```

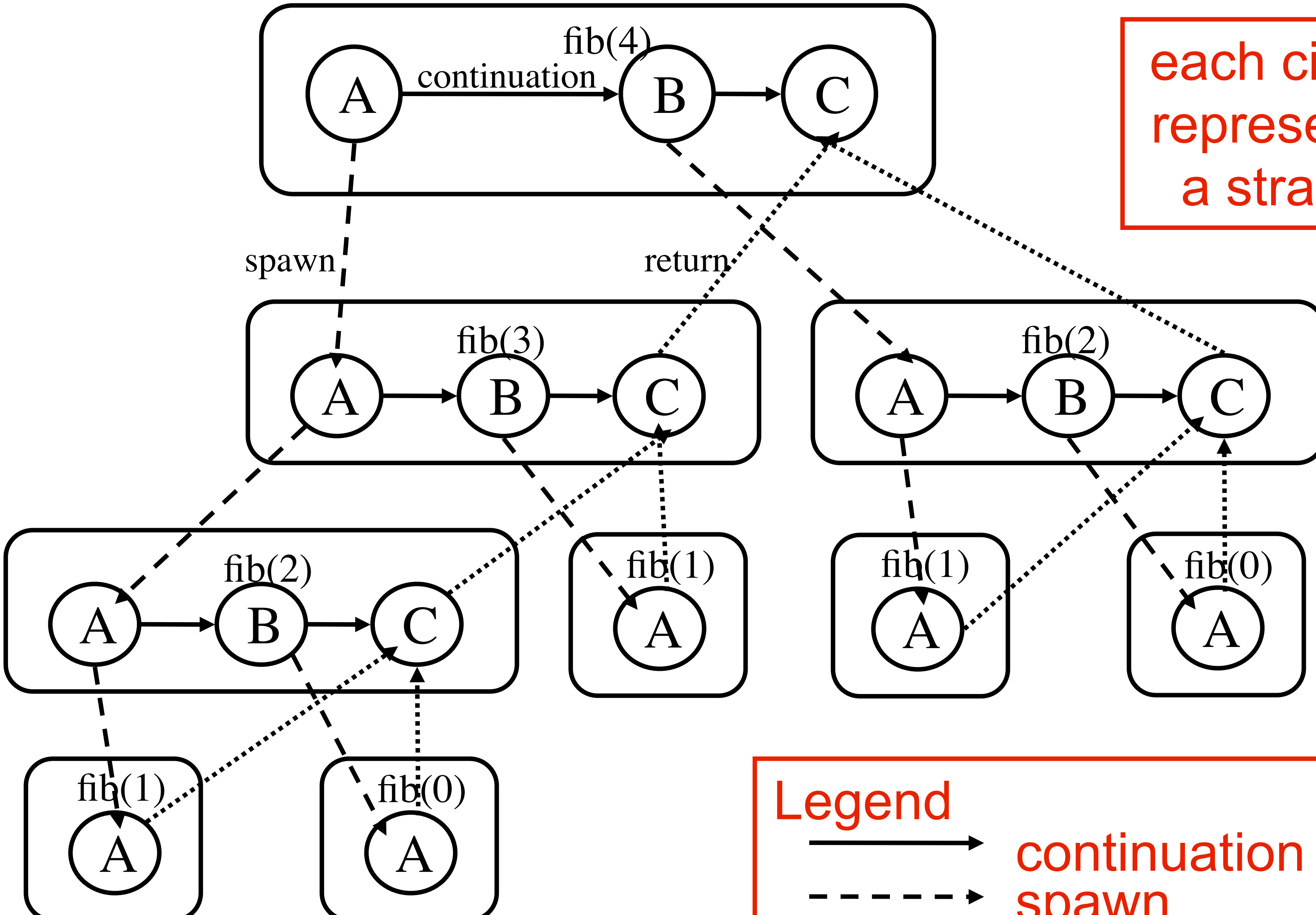
Strand A: code before first spawn

Strand B: compute n-2 before 2nd spawn

Strand C: n1+ n2 before the return



Cilk Program Execution as a DAG

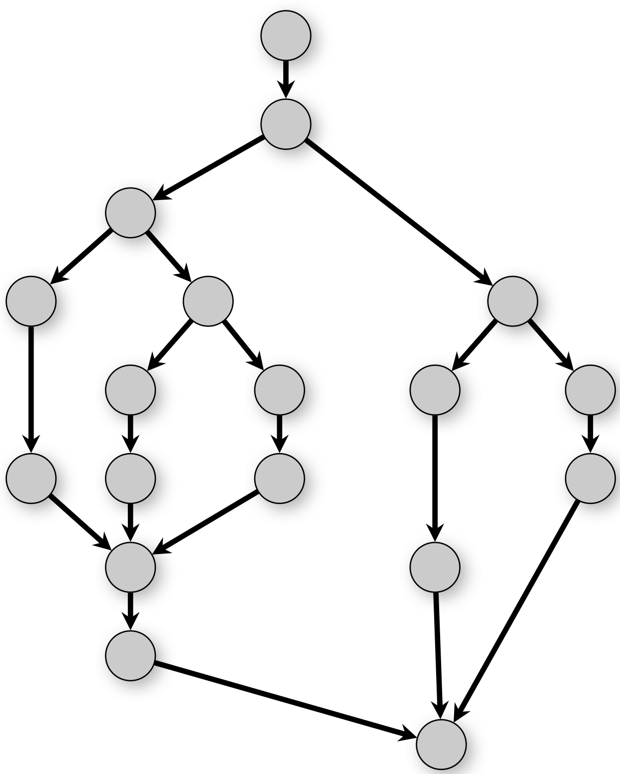


each circle represents a strand

Legend
continuation
spawn
return

Algorithmic Complexity Measures

T_P = execution time on P processors



PROC_0 . . . PROC_{P-1}

Computation graph abstraction:

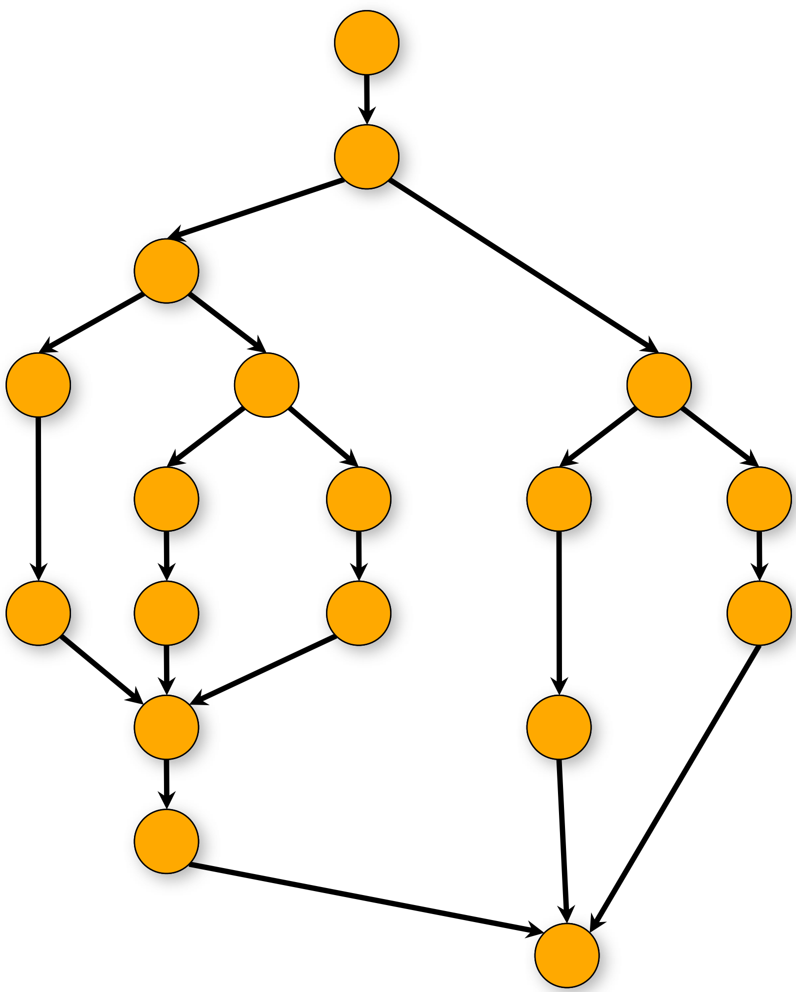
- node = arbitrary sequential computation
- edge = dependence (successor node can only execute after predecessor node has completed)
- Directed Acyclic Graph (DAG)

Processor abstraction:

- P identical processors
- each processor executes one node at a time

Algorithmic Complexity Measures

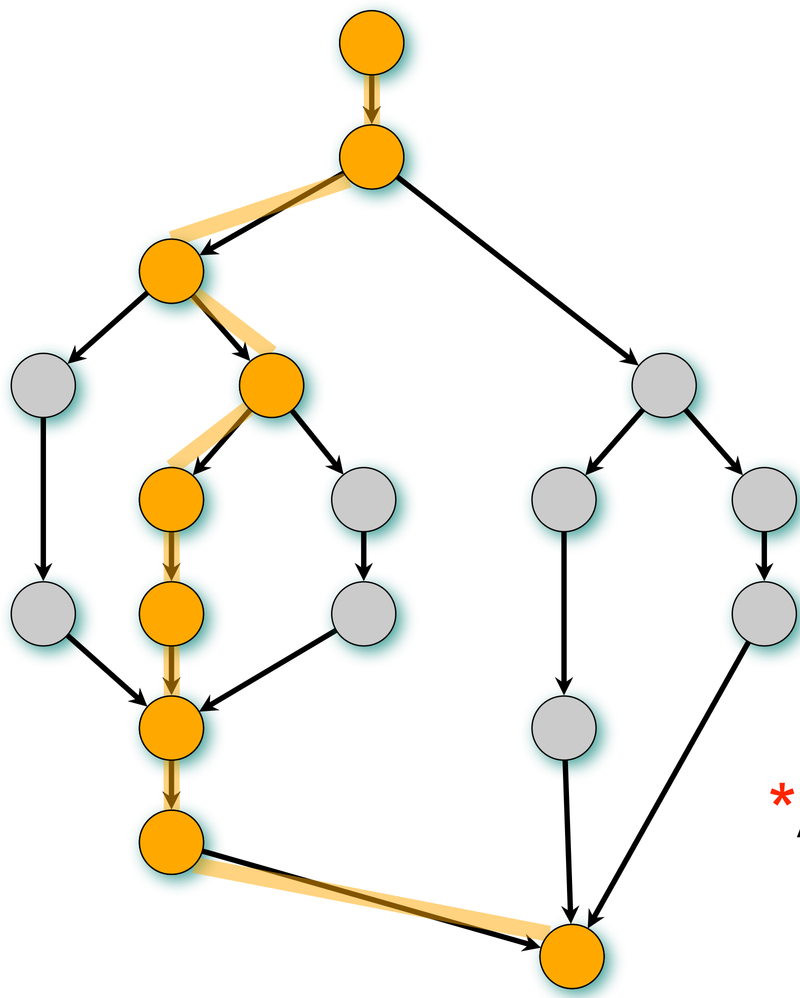
T_P = execution time on P processors



T_1 = *work*

Algorithmic Complexity Measures

T_P = execution time on P processors



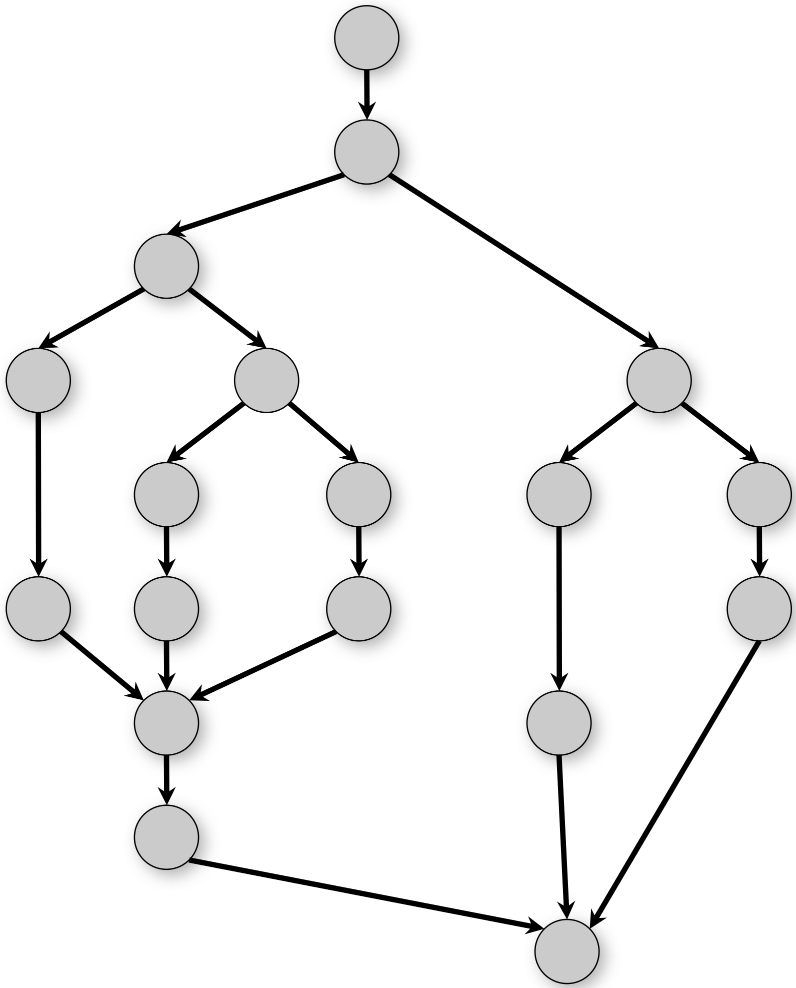
T_1 = *work*

T_∞ = *span**

*Also called *critical-path length*

Algorithmic Complexity Measures

T_P = execution time on P processors



T_1 = *work*

T_∞ = *span*

LOWER BOUNDS

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

Speedup

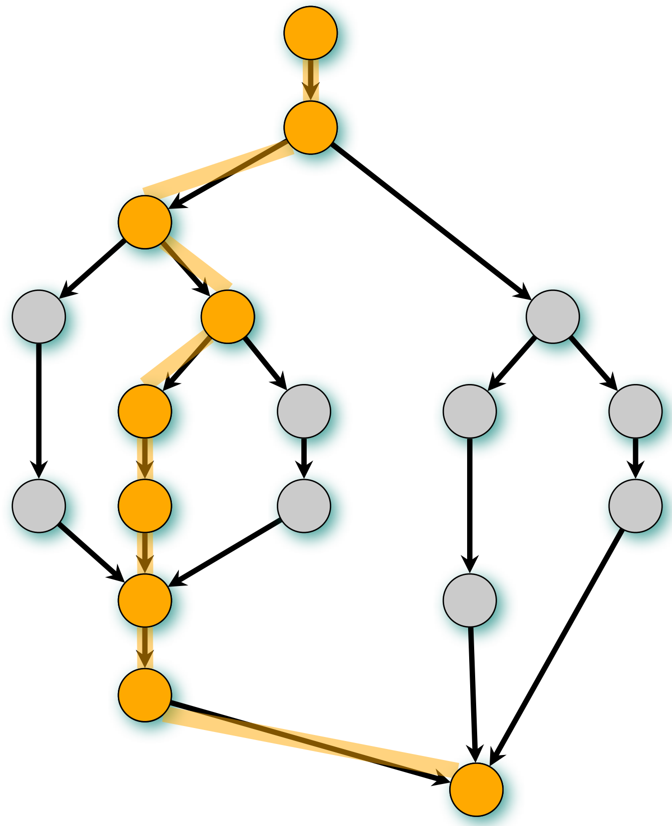
Definition: T_1/T_P = ***speedup*** **on** P **processors**

If $T_1/T_P = \Theta(P)$, we have *linear speedup*;
$= P$, we have *perfect linear speedup*;
$> P$, we have *superlinear speedup*,

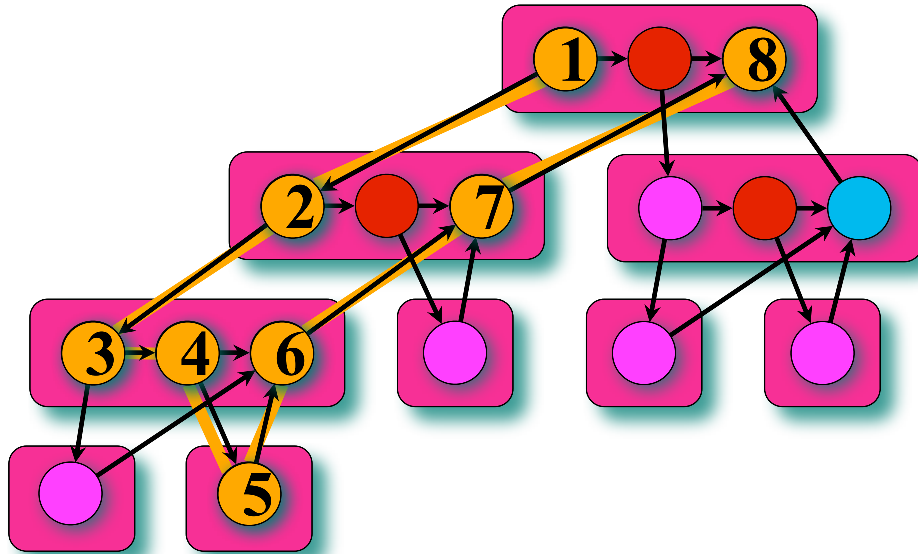
Superlinear speedup is not possible in this model because of the lower bound $T_P \geq T_1/P$, but it can occur in practice (e.g., due to cache effects)

Parallelism ("Ideal Speedup")

- T_P depends on the schedule of computation graph nodes on the processors
  - two different schedules can yield different values of T_P for the same P
- For convenience, define *parallelism* (or ideal speedup) as the ratio T_1/T_∞
- Parallelism is independent of P, and only depends on the computation graph
- Also define *parallel slackness* as the ratio, $(T_1/T_\infty)/P$; the larger the slackness, the less the impact of T_∞ on performance



Example: `fib(4)`

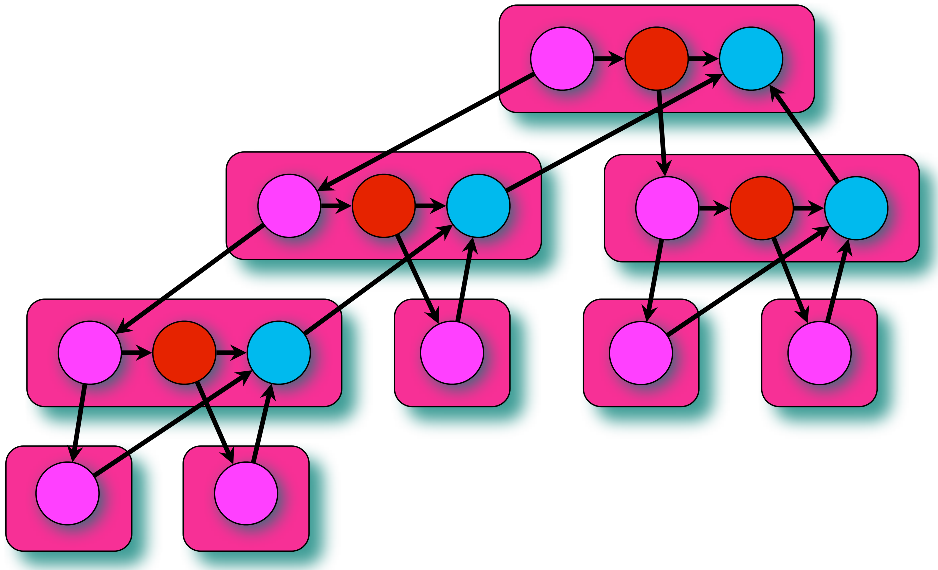


Assume for simplicity that each strand in **fib()** *takes unit time to execute.*

Work: T_1 = 17 (T_P refers to execution time on P processors)

Span: T_∞ = 8 (Span = "critical path length")

Example: `fib(4)`



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

Work: T_1 = 17

Span: T_∞ = 8

Ideal Speedup: T_1 / T_∞ = 2.125

Using more than 2 processors makes little sense

Task Scheduling in Cilk

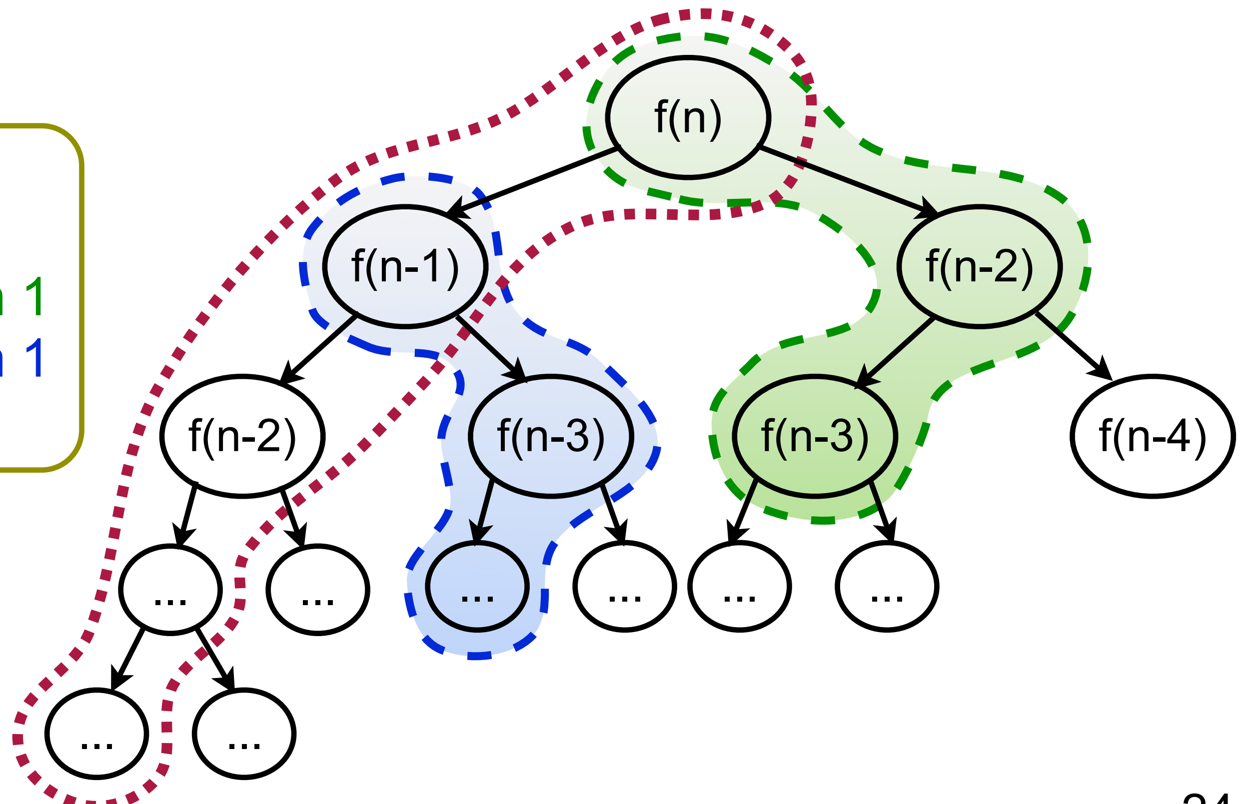
- Popular scheduling strategies
  - —work-sharing: task scheduled to run in parallel at every spawn
    - benefit: maximizes parallelism
    - drawback: cost of setting up new strands is high → should be avoided
  - —work-stealing: processor looks for work when it becomes idle
    - lazy parallelism: put off work for parallel execution until necessary
    - benefits: executes with precisely as much parallelism as needed
      minimizes the number of strands that must be set up
      runs with same efficiency as serial program on uniprocessor
- Cilk uses work-stealing rather than work-sharing

Cilk Execution using Work Stealing

- **Cilk runtime maps logical tasks to compute cores**
- **Approach:**
  - **lazy task creation plus work-stealing scheduler**
    - **`cilk_spawn`: a potentially parallel task is available**
    - **an idle thread steals tasks from a random working thread**

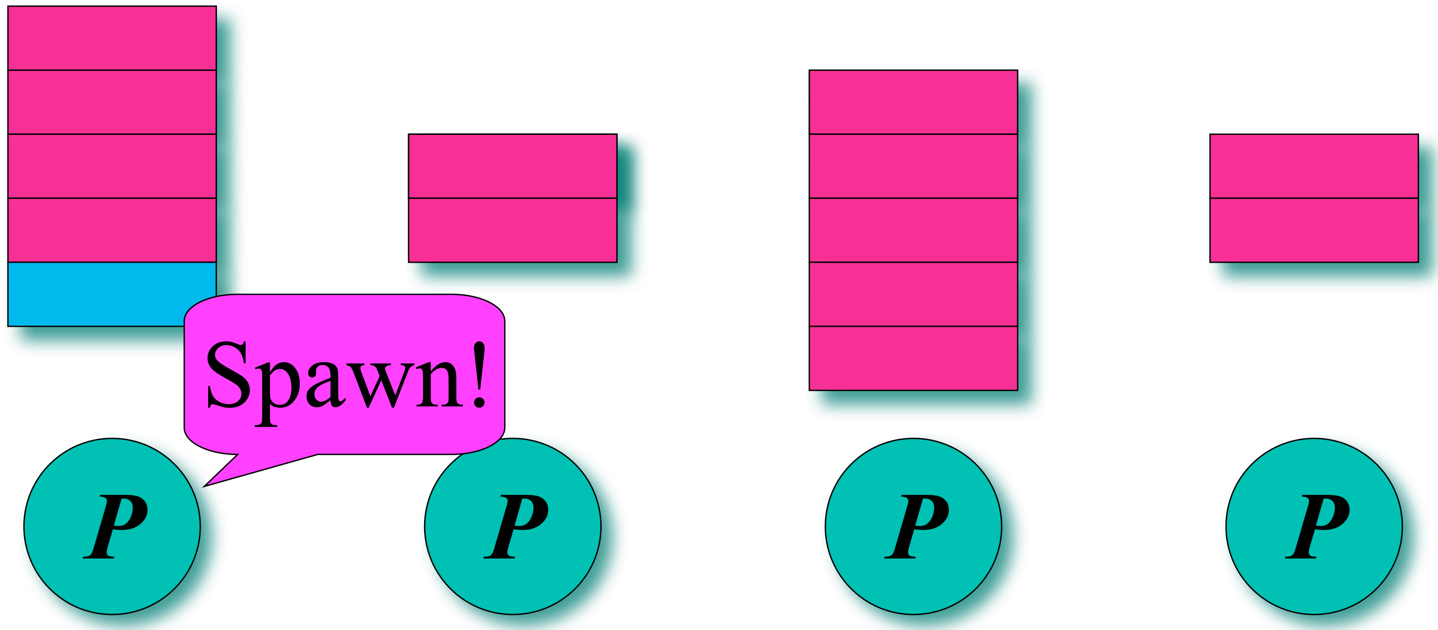
<u>Possible Execution:</u>

thread 1 begins
thread 2 steals from 1
thread 3 steals from 1
etc...



Cilk's Work-Stealing Scheduler

Each processor maintains a ***work deque*** of ready threads, and it manipulates the bottom of the deque like a stack.



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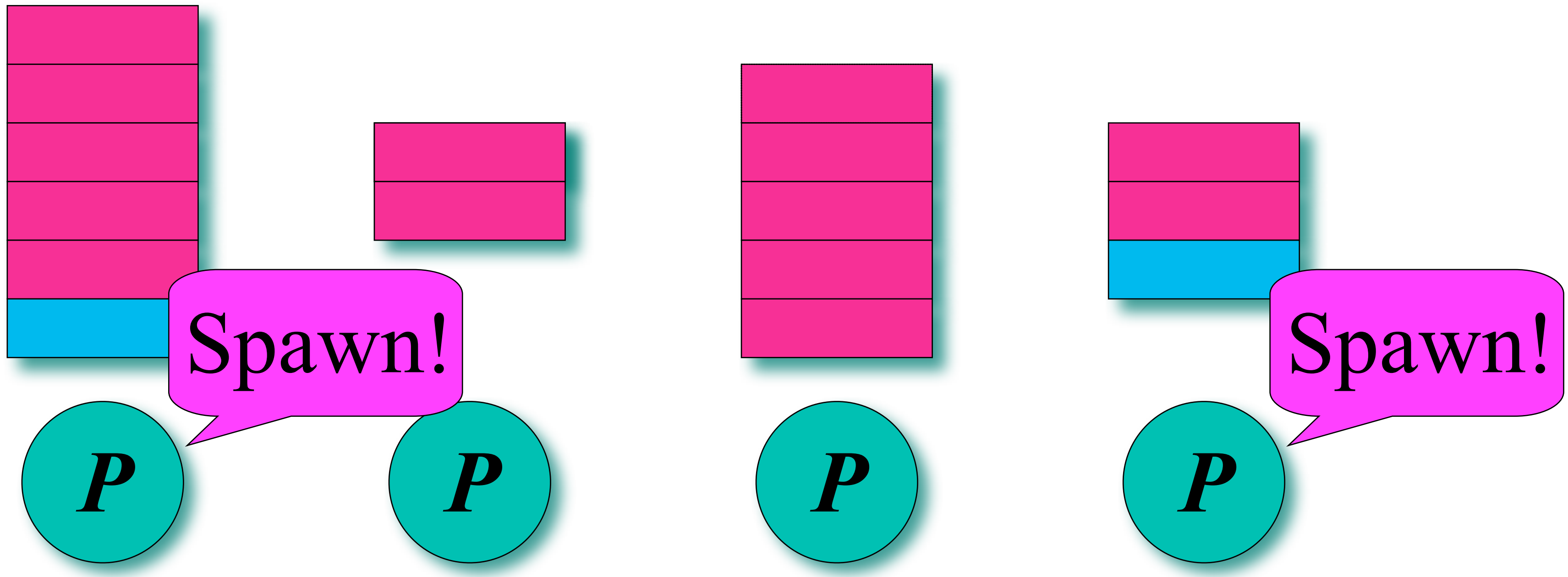

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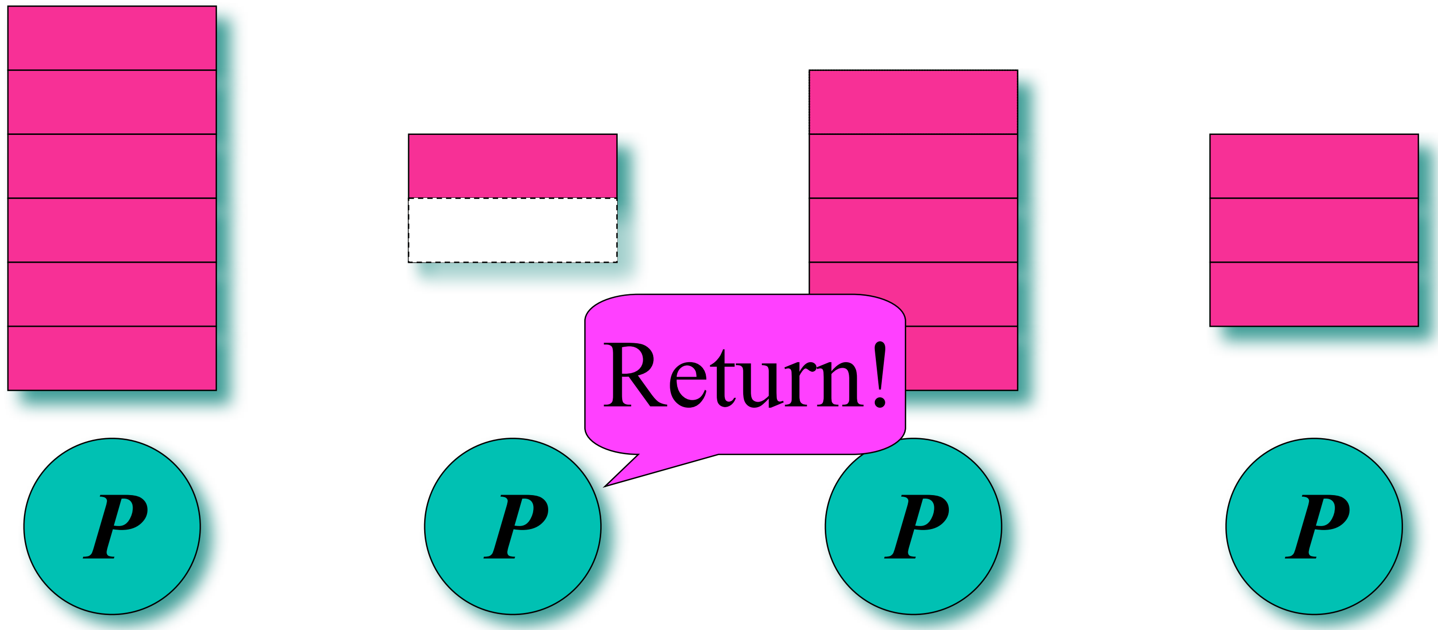

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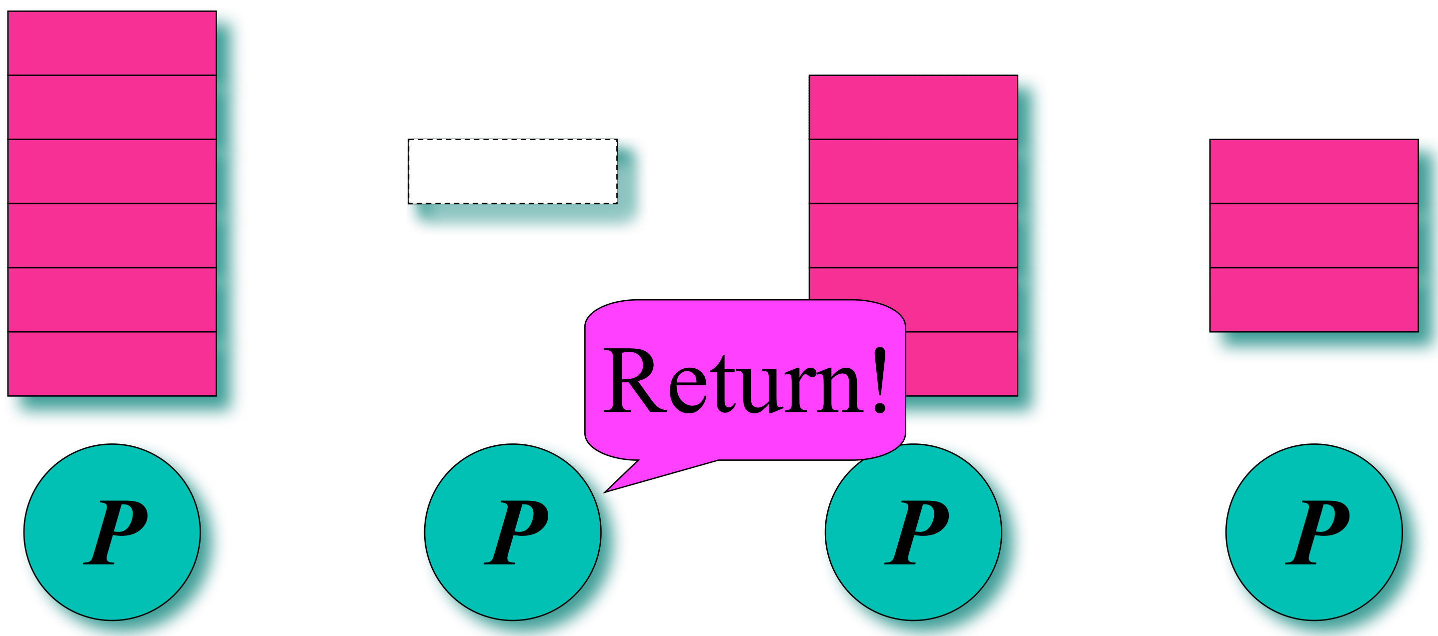

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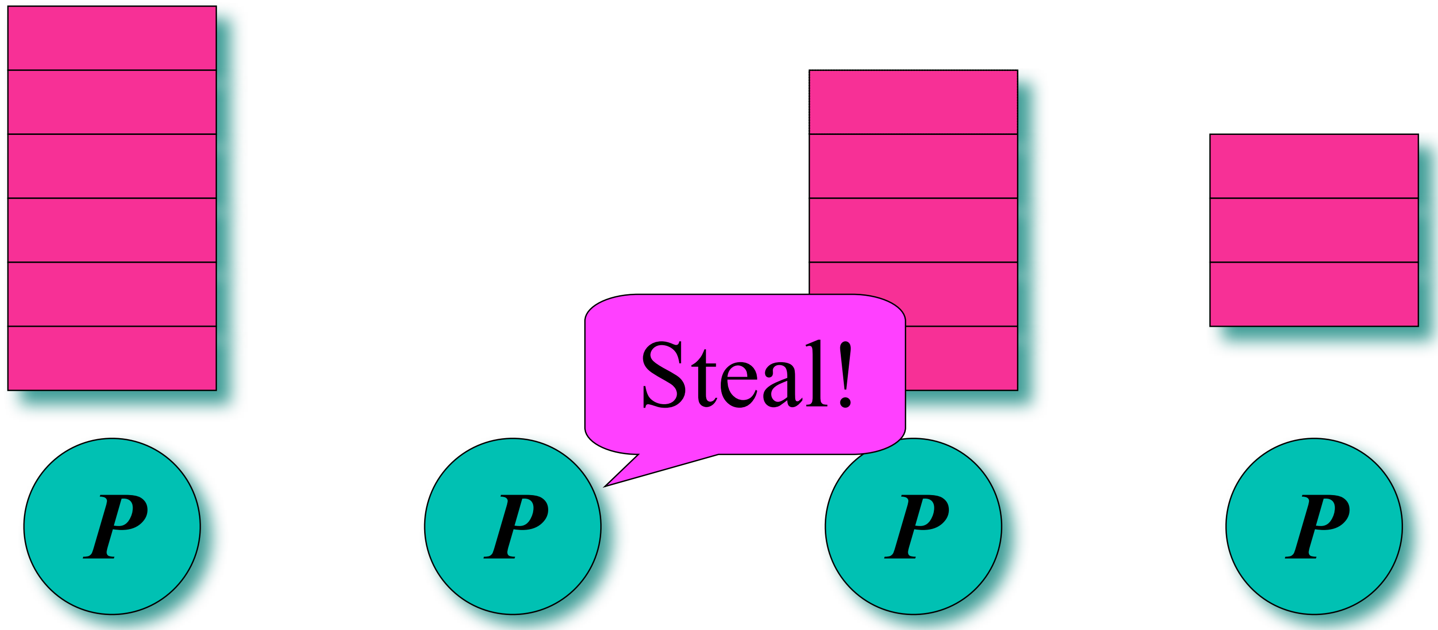
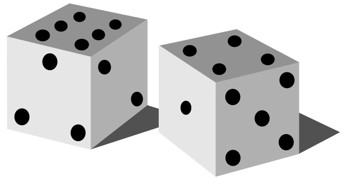


When a processor runs out of work, it ***steals*** a thread from the top of a ***random*** victim's deque



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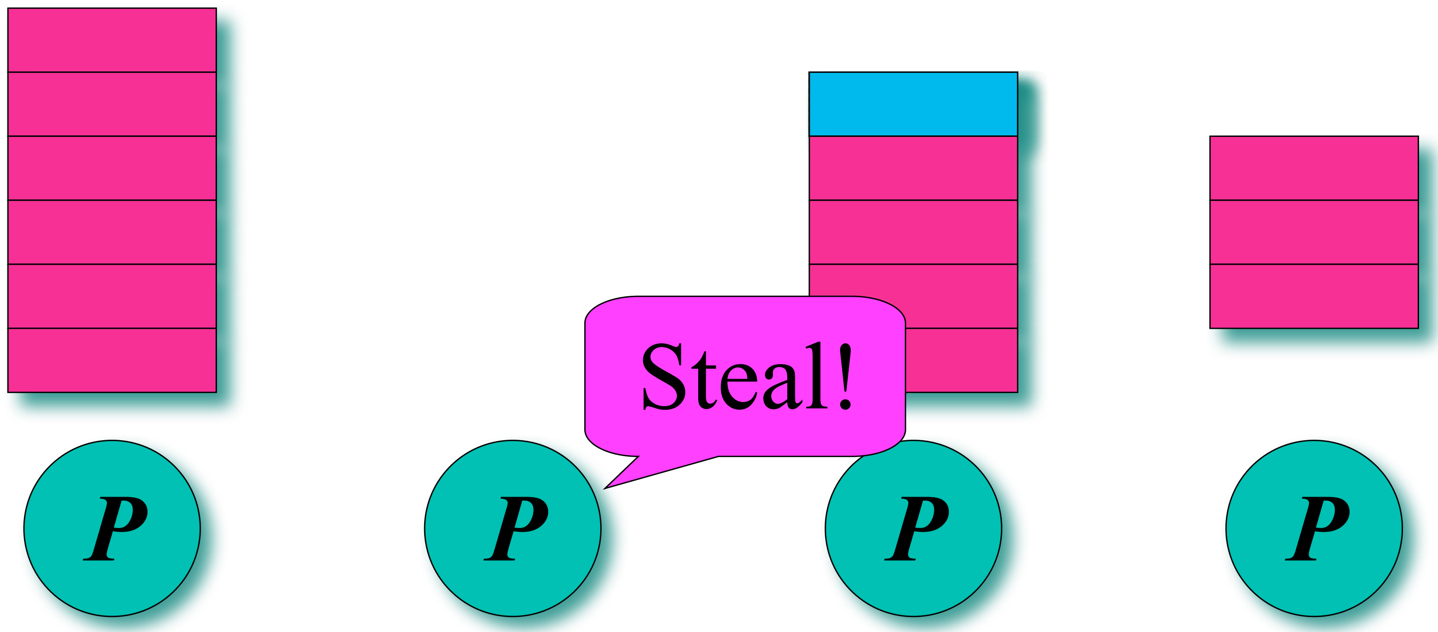

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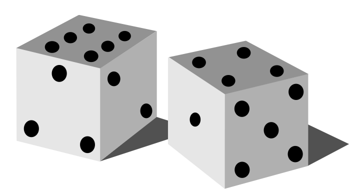

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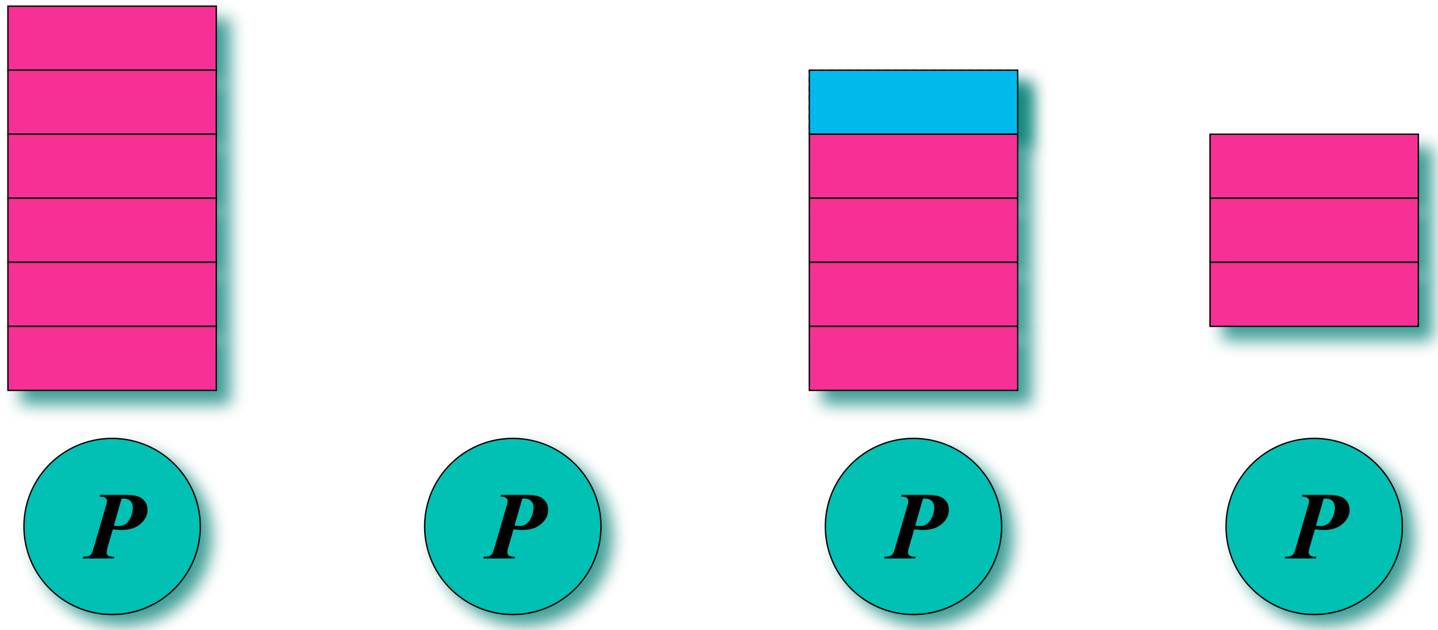

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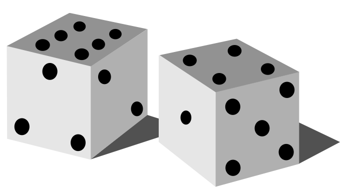

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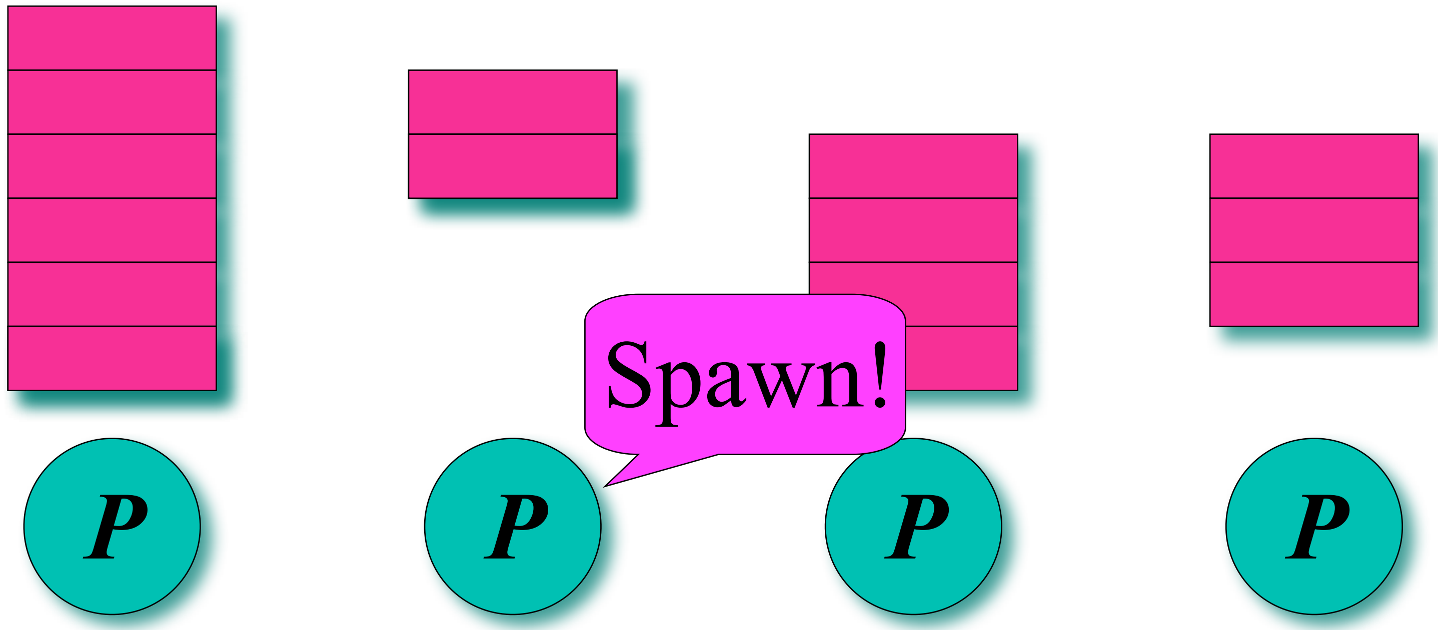

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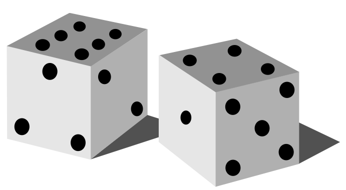


Performance of Work-Stealing

Theorem: Cilk's work-stealing scheduler achieves an expected running time of $T_P \leq T_1/P + O(T_\infty)$ on P processors

Greedy Scheduling Theorem

- Types of schedule steps
  - complete step
    - at least P operations ready to run
    - select any P and run them
  - incomplete step
    - strictly < P operation ready to run
    - greedy scheduler runs them all

Theorem: On P processors, a greedy scheduler executes any computation G with work T_1 and critical path of length T_∞ in time $T_p \leq T_1/P + T_\infty$

Proof sketch

- only two types of scheduler steps: complete, incomplete
- cannot be more than T_1/P complete steps, else work $> T_1$
- every incomplete step reduces remaining critical path length by 1
  - no more than T_∞ incomplete steps

Parallel Slackness Revisited

critical path overhead = smallest constant c_∞ such that

$$T_p \le \frac{T_1}{P} + c_\infty T_\infty$$

$$T_p \le \left(\frac{T_1}{T_\infty P} + c_\infty\right) T_\infty = \left(\frac{\overline{P}}{P} + c_\infty\right) T_\infty$$

Let $\overline{P}$ = T_1/T_∞ = parallelism = max speedup on ∞ processors

Parallel slackness assumption

$$\overline{P}/P >> c_\infty \qquad \textbf{thus} \qquad \frac{T_1}{P} >> c_\infty T_\infty$$

$$T_p \approx \frac{T_1}{P}$$

linear speedup

"critical path overhead has little effect on performance when sufficient parallel slackness exists"

Work Overhead

$$c_1 = \frac{T_1}{T_s}$$

work overhead

"Minimize work overhead (c_1) at the expense of a larger critical path overhead (c_∞), because work overhead has a more direct impact on performance"

$$T_p \leq c_1 \frac{T_s}{P} + c_\infty T_\infty$$

$$T_p \approx c_1 \frac{T_s}{P}$$

assuming parallel slackness

You can reduce **C_1** by increasing the granularity of parallel work

Parallelizing Vector Addition

C

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

Divide and Conquer

- **An effective parallelization strategy**
  - **—creates a good mix of large and small sub-problems**
- **Work-stealing scheduler can allocate chunks of work efficiently to the cores, as long as**
  - **—not only a few large chunks**
    - **if work is divided into just a few large chunks, there may not be enough parallelism to keep all the cores busy**
  - **—not too many very small chunks**
    - **if the chunks are too small, then scheduling overhead may overwhelm the benefit of parallelism**

Parallelizing Vector Addition

C

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

C

```
void vadd (real *A, real *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-n/2);
  }
}
```

Parallelization strategy:

1. Convert loops to recursion.

Parallelizing Vector Addition

C

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

Cilk Plus

```
void vadd (real *A, real *B, int n){
  if (n<=BASE) {
    int i; for (i=0; i<n; i++) A[i]+=B[i];
  } else {
    cilk_spawn vadd (A, B, n/2);
    vadd (A+n/2, B+n/2, n-n/2);
  } cilk_sync;
}
```

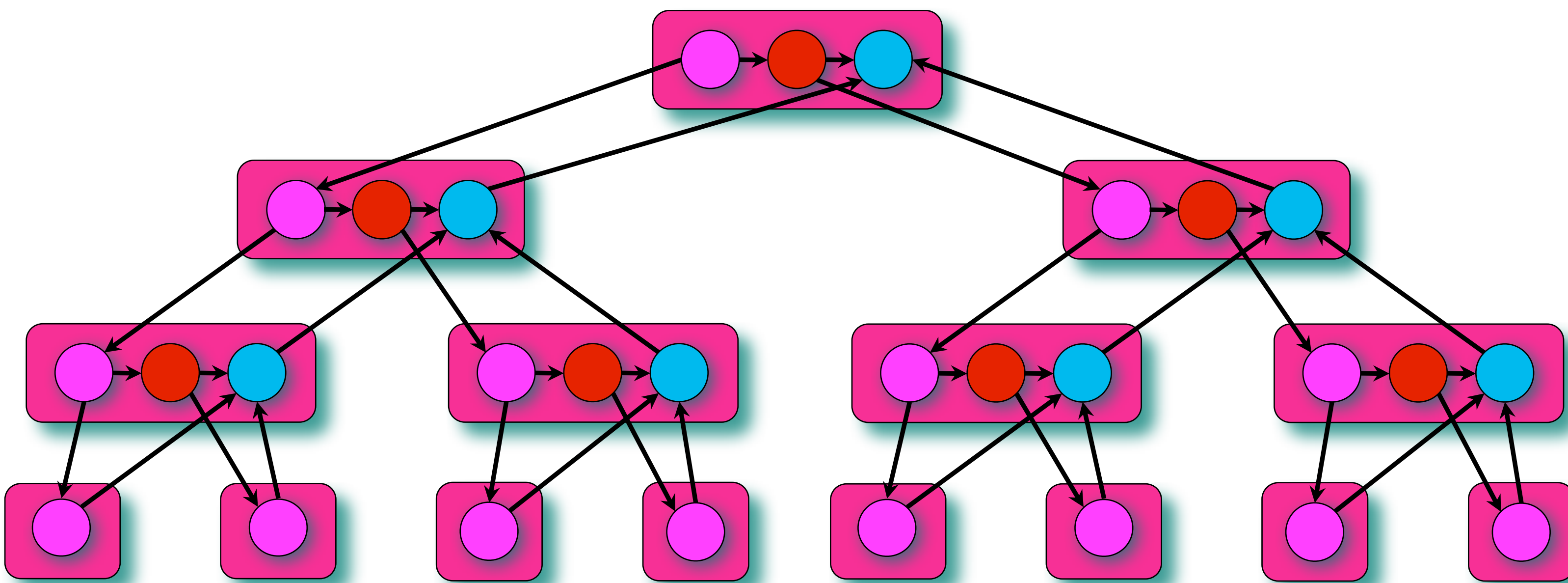
Parallelization strategy:

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

Side benefit:
D&C is generally good for caches!

Vector Addition

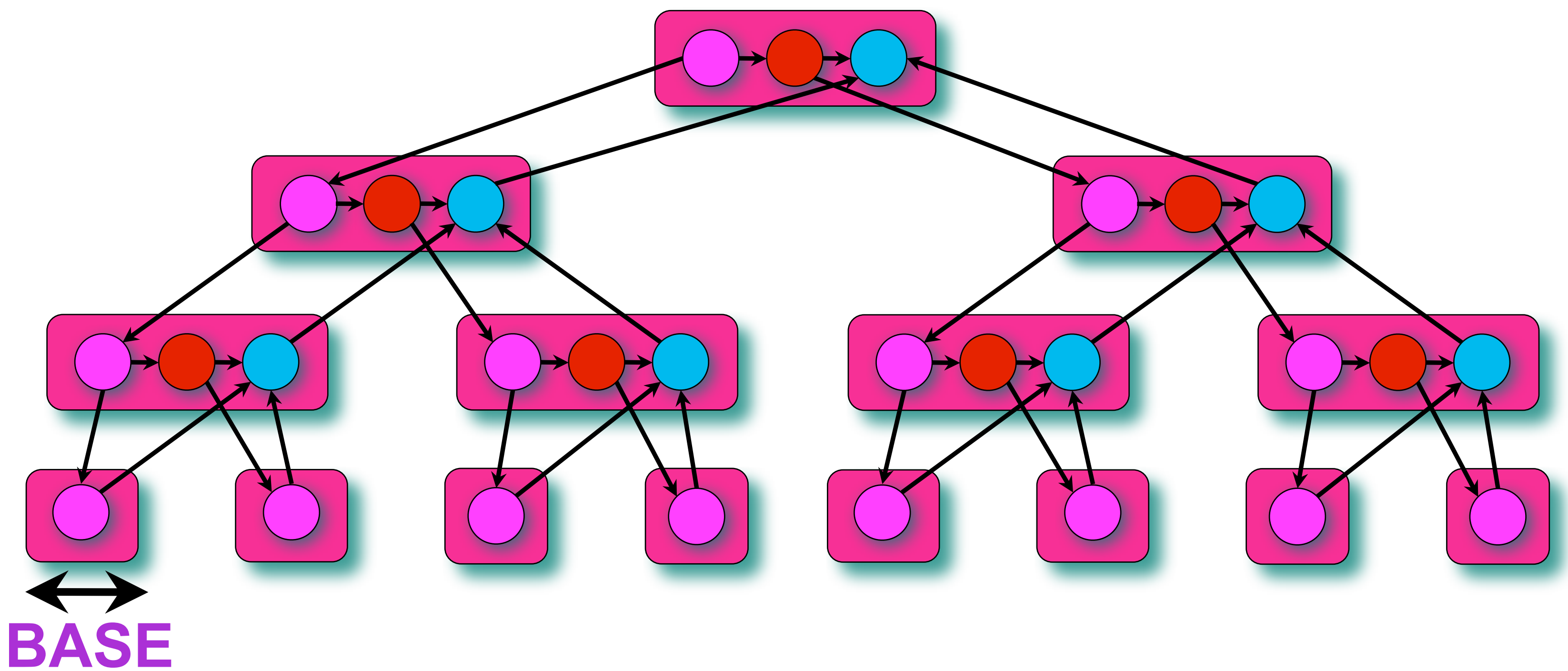
```
void vadd (real *A, real *B, int n){
  if (n<=BASE) {
    int i; for (i=0; i<n; i++) A[i]+=B[i];
  } else {
    cilk_spawn vadd (A, B, n/2);
    vadd (A+n/2, B+n/2, n-n/2);
    cilk_sync;
  }
}
```



Vector Addition Analysis

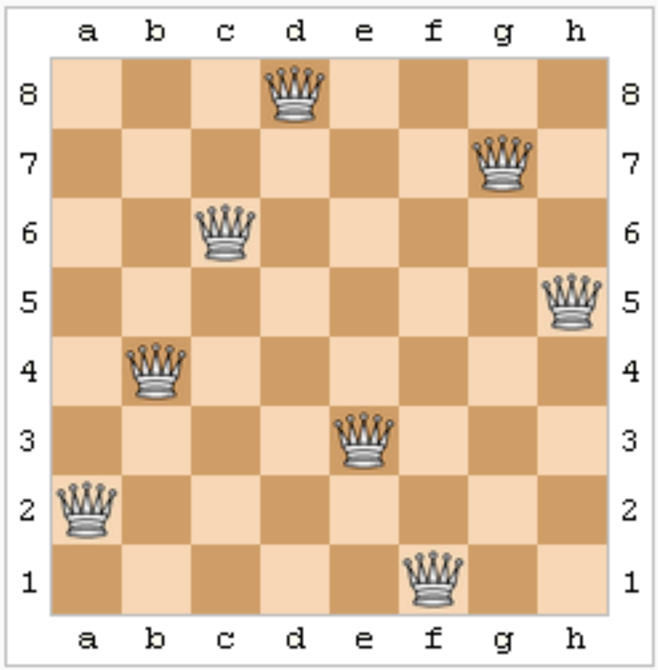
To add two vectors of length *n*, where BASE = Θ(1):

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



Example: N Queens

- **Problem**
  - **—place N queens on an N x N chess board**
  - **—no 2 queens in same row, column, or diagonal**
- **Example: a solution to 8 queens problem**



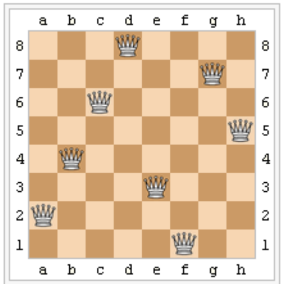
One possible solution

Image credit: http://en.wikipedia.org/wiki/Eight_queens_puzzle

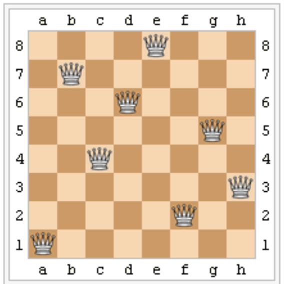
N Queens: Many Solutions Possible

Example: 8 queens

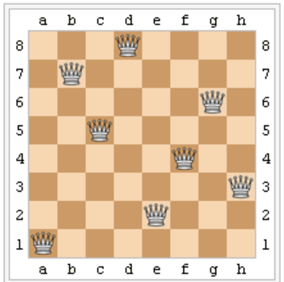
- 92 distinct solutions
- 12 unique solutions; others are rotations & reflections



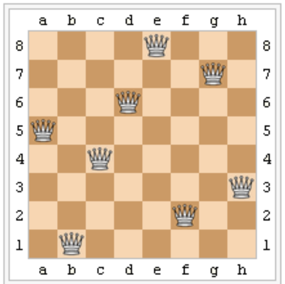
Unique solution 1



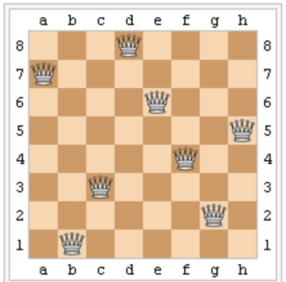
Unique solution 2



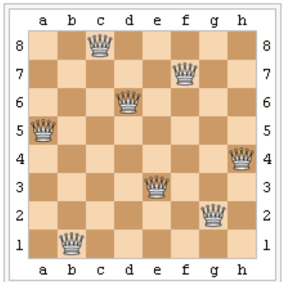
Unique solution 3



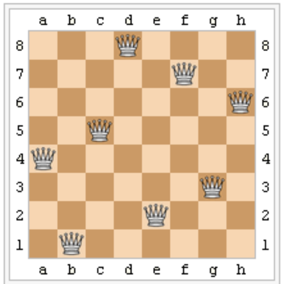
Unique solution 7



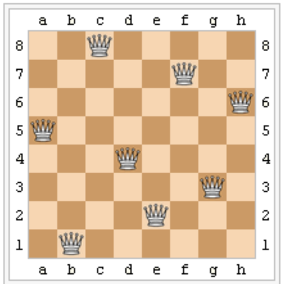
Unique solution 8



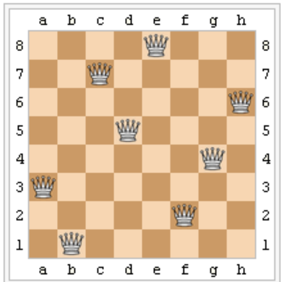
Unique solution 9



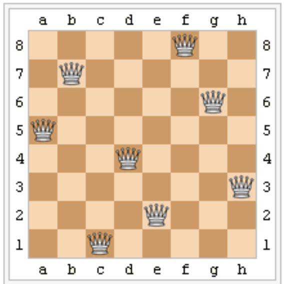
Unique solution 4



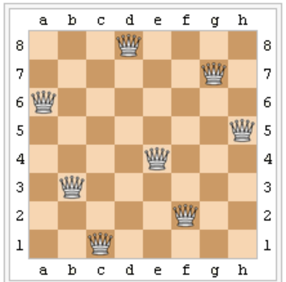
Unique solution 5



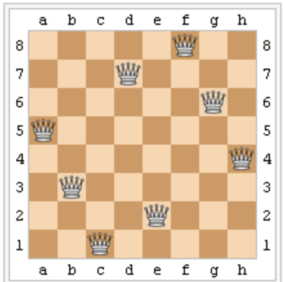
Unique solution 6



Unique solution 10



Unique solution 11



Unique solution 12

Image credit: http://en.wikipedia.org/wiki/Eight_queens_puzzle

N Queens Solution Sketch

Sequential Recursive Enumeration of All Solutions

```
int nqueens(n, j, placement) {
    // precondition: placed j queens so far
    if (j == n)  { print placement; return; }
   for (k = 0; k < n; k++)
     if putting j+1 queen in kth position in row j+1 is legal
         add queen j+1 to placement
         nqueens(n, j+1, placement)
         remove queen j+1 from placement
}
```

- Where’s the potential for parallelism?
- What issues must we consider?

Parallel N Queens Solution Sketch

```
void nqueens(n, j, placement) {
  // precondition: placed j queens so far
  if (j == n) {  /* found a placement  */ process placement; return; }
  for (k = 1; k <= n; k++)
    if putting j+1 queen in kth position in row j+1 is legal
      copy placement into newplacement and add extra queen
      cilk_spawn nqueens(n,j+1,newplacement)
  cilk_sync
  discard placement
}
```

Issues regarding placements

- **—how can we report placements?**
- **—what if a single placement suffices?**
  - **—no need to compute all legal placements**
  - **—so far, no way to terminate children exploring alternate placement**

Approaches to Managing Placements

- **Choices for reporting multiple legal placements**
  - —count them
  - —print them on the fly
  - —collect them on the fly; print them at the end
- **If only one placement desired, can skip remaining search**

References

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