6.172 Performance Engineering of Software Systems

LECTURE 13
The Cilk Runtime System

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Recall: Cilk Programming

Cilk allows programmers to make software run faster using parallel processors.

Serial matrix multiply

```
for (int i = 0; i < n; ++i)
  for (int k = 0; k < n; ++k)
    for (int j = 0; j < n; ++j)
      C[i][j] += A[i][k] * B[k][j];
```

Running time T_S.

Cilk matrix multiply

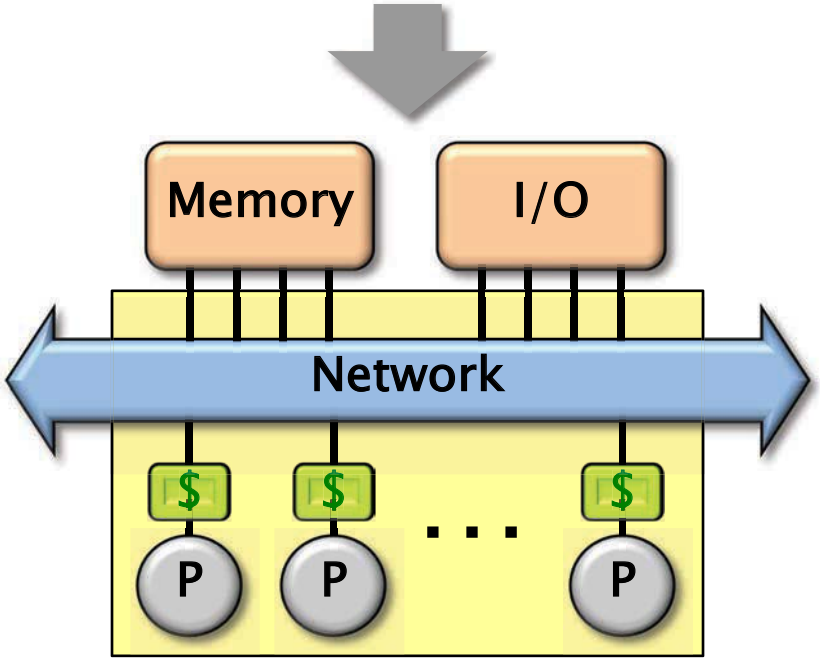
```
cilk_for (int i = 0; i < n; ++i)
  for (int k = 0; k < n; ++k)
    for (int j = 0; j < n; ++j)
      C[i][j] += A[i][k] * B[k][j];
```

Running time T_P on P processors.

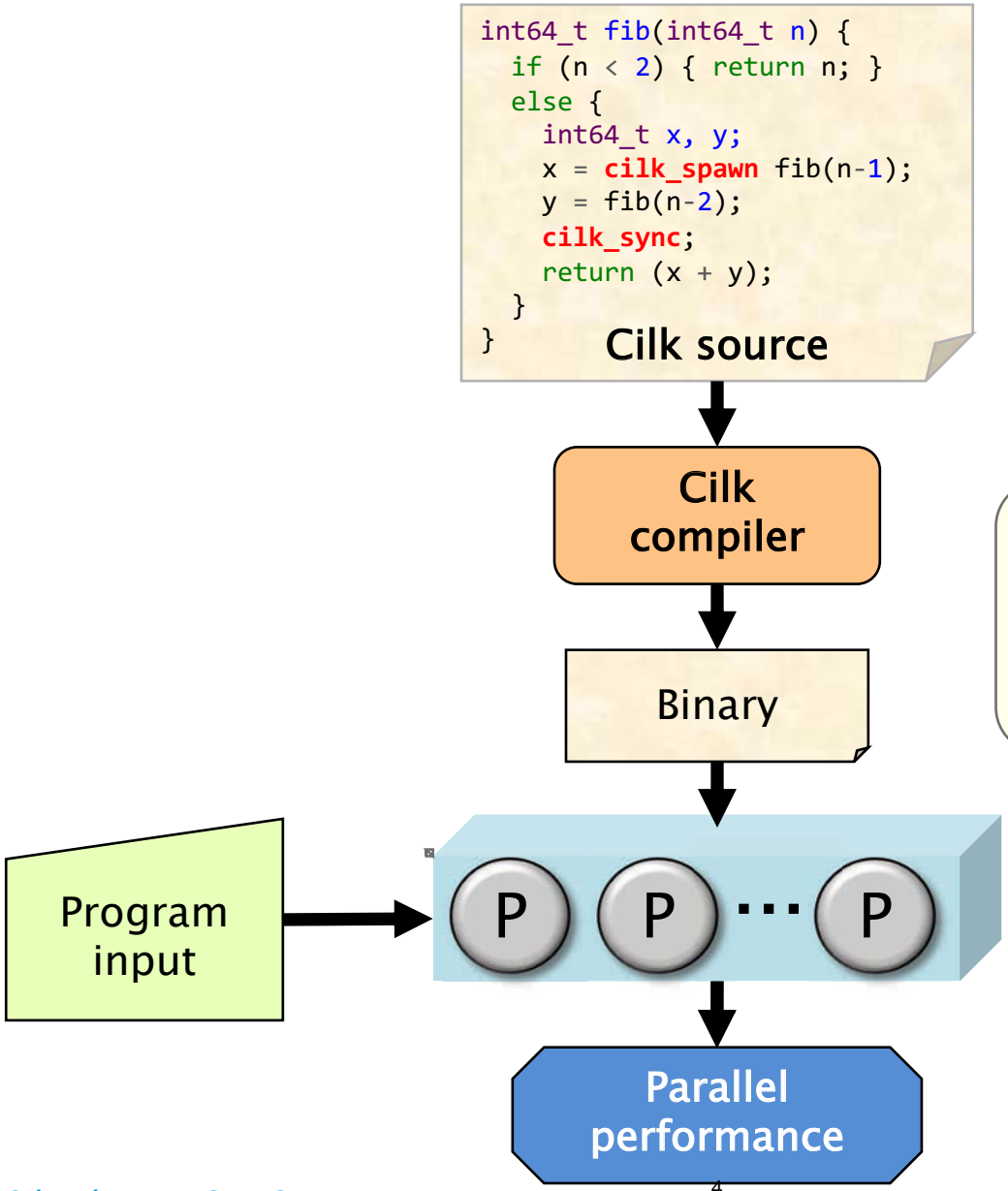
Recall: Cilk Scheduling

- The Cilk concurrency platform allows the programmer to express logical parallelism in an application.
- The Cilk scheduler maps the executing program onto the processor cores dynamically at runtime.
- Cilk's work-stealing scheduling algorithm is provably efficient.

```
int64_t fib(int64_t n) {
  if (n < 2) {
    return n;
  } else {
    int64_t x, y;
    x = cilk_spawn fib(n-1);
    y = fib(n-2);
    cilk_sync;
    return (x + y);
  }
}
```

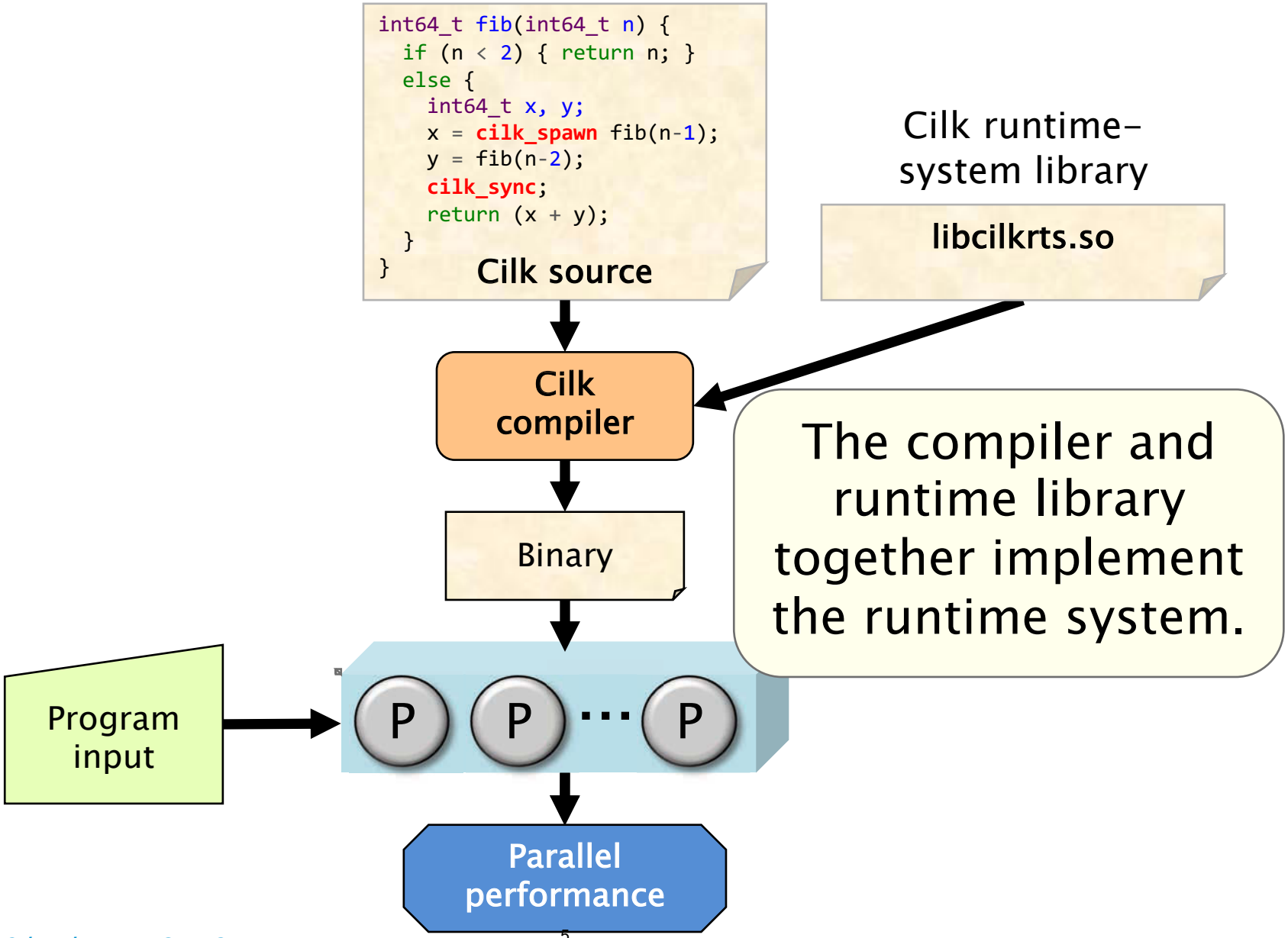


Recall: Cilk Platform



This lecture: How does Cilk work?

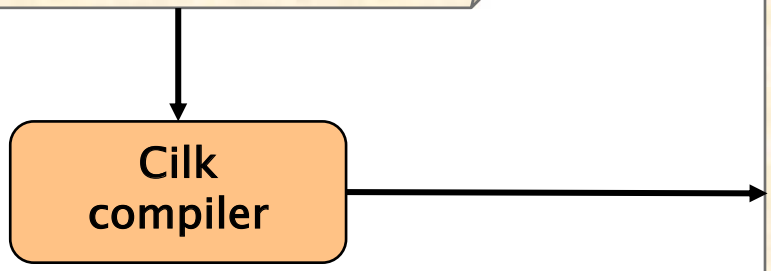
A More Accurate Picture



What the Compiler Generates

Cilk code

```
int foo(int n) {
  int x, y;
  x = cilk_spawn bar(n);
  y = baz(n);
  cilk_sync;
  return x + y;
}
```



C pseudocode of compiled result

```
int foo(int n) {
  __cilkrts_stack_frame_t sf;
  __cilkrts_enter_frame(&sf);
  int x, y;
  if (!setjmp(sf.ctx))
    spawn_bar(&x, n);
  y = baz(n);
  if (sf.flags & CILK_FRAME_UNSYNCHED)
    if (!setjmp(sf.ctx))
      __cilkrts_sync(&sf);
  int result = x + y;
  __cilkrts_pop_frame(&sf);
  if (sf.flags)
    __cilkrts_leave_frame(&sf);
  return result;
}

void spawn_bar(int *x, int n) {
  __cilkrts_stack_frame sf;
  __cilkrts_enter_frame_fast(&sf);
  __cilkrts_detach();
  *x = bar(n);
  __cilkrts_pop_frame(&sf);
  __cilkrts_leave_frame(&sf);
}
```

Outline

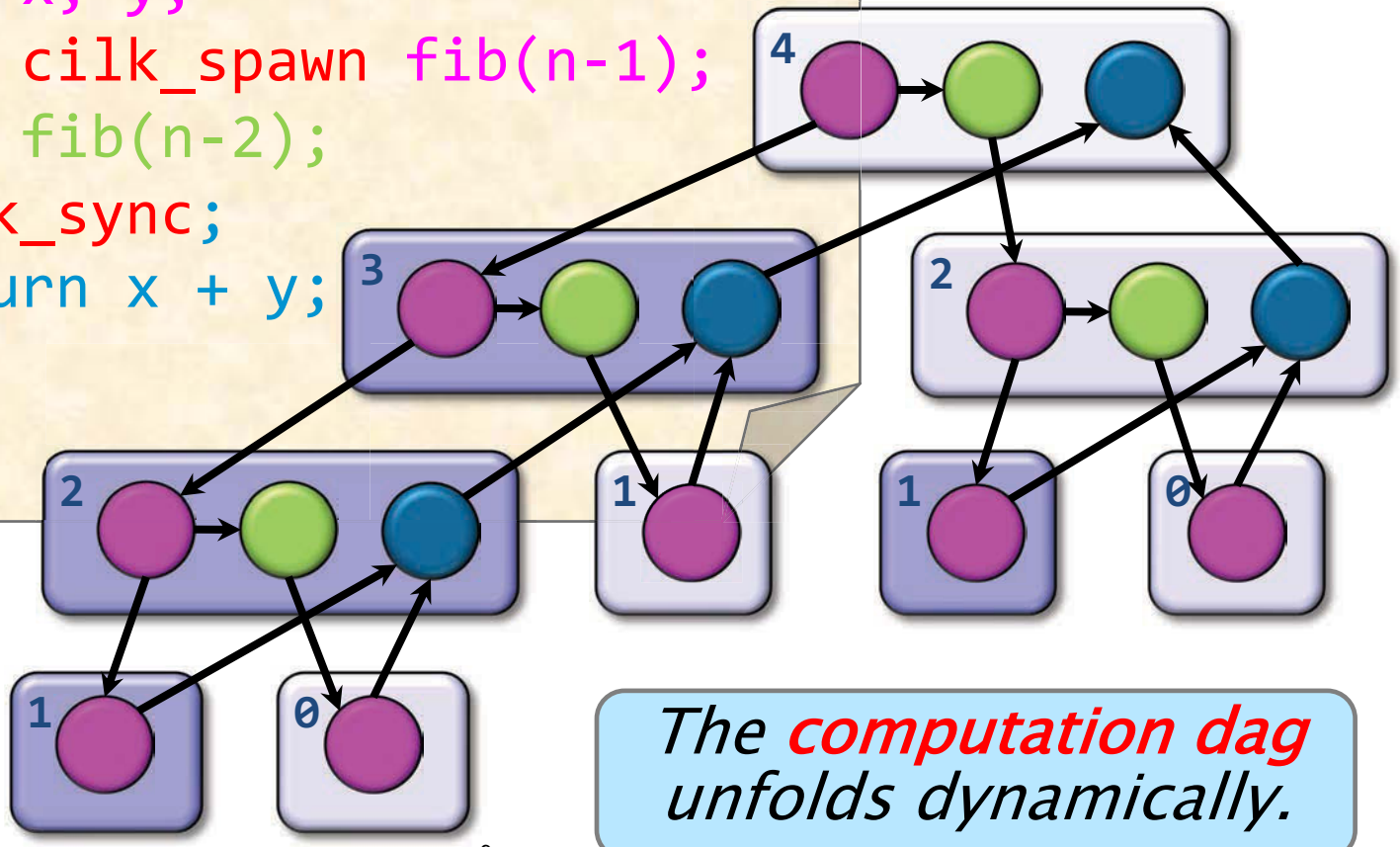
- Required Functionality
- Performance Considerations
- Implementing a Worker Deque
- Spawning Computation
- Stealing Computation
- Synchronizing Computation

Required Functionality

Recall: Execution Model

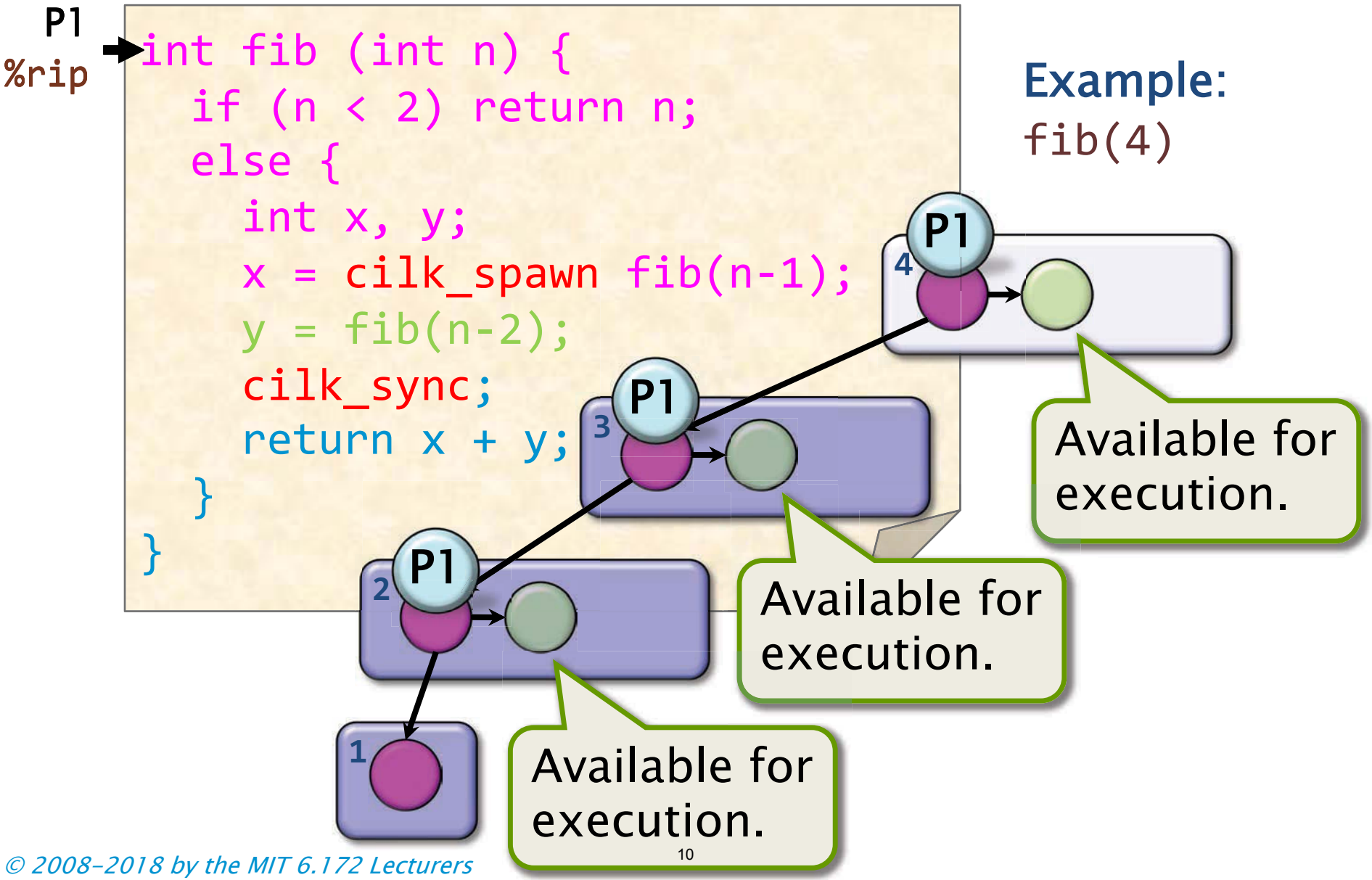
```
int fib (int n) {
  if (n < 2) return n;
  else {
    int x, y;
    x = cilk_spawn fib(n-1);
    y = fib(n-2);
    cilk_sync;
    return x + y;
  }
}
```

Example:
`fib(4)`



*The **computation dag** unfolds dynamically.*

Serial Execution



Parallel Execution: Steals

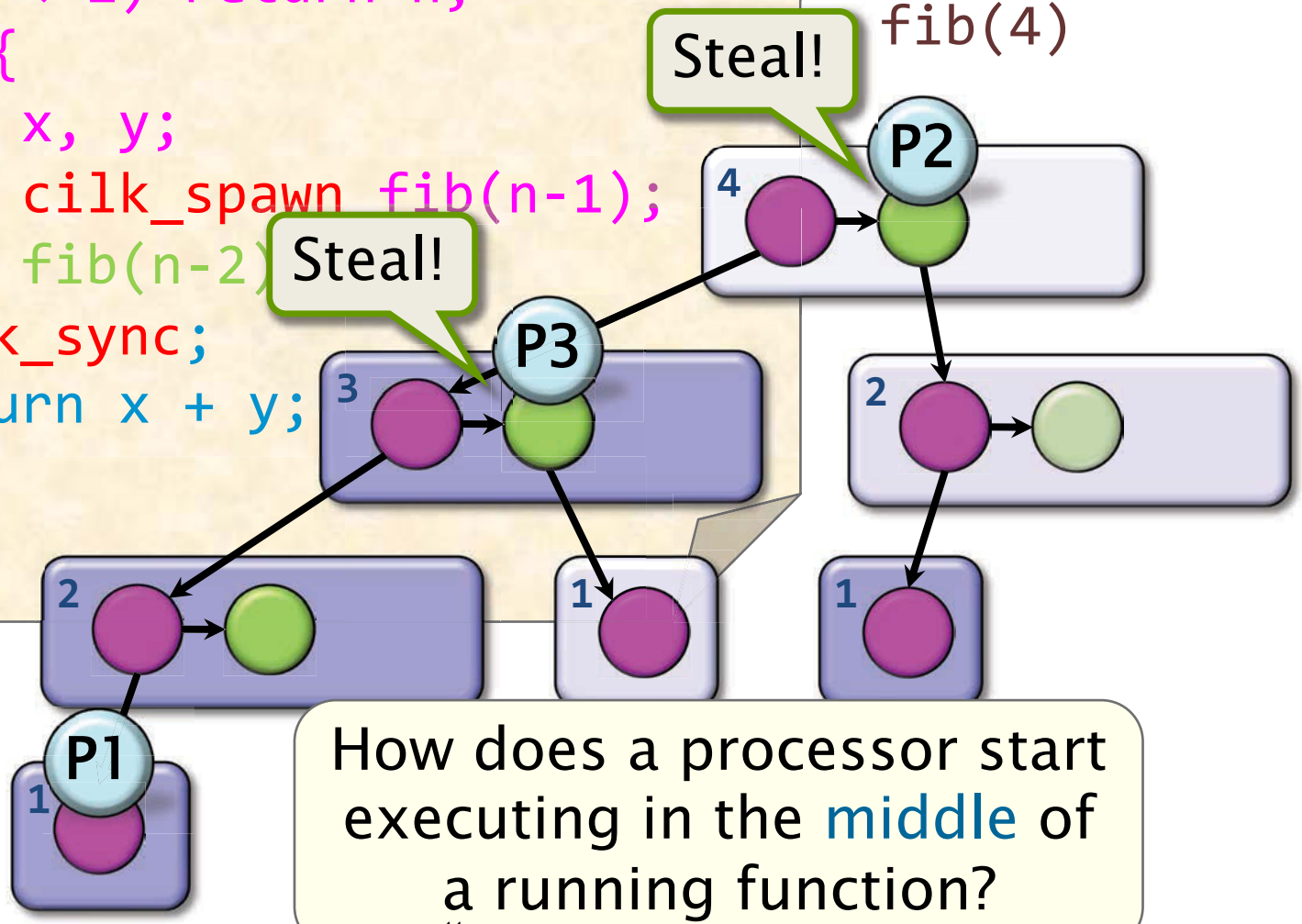
```
int fib (int n) {
  if (n < 2) return n;
  else {
    int x, y;
    x = cilk_spawn fib(n-1);
    y = fib(n-2);
    cilk_sync;
    return x + y;
  }
}
```

P2 %rip

P1 %rip

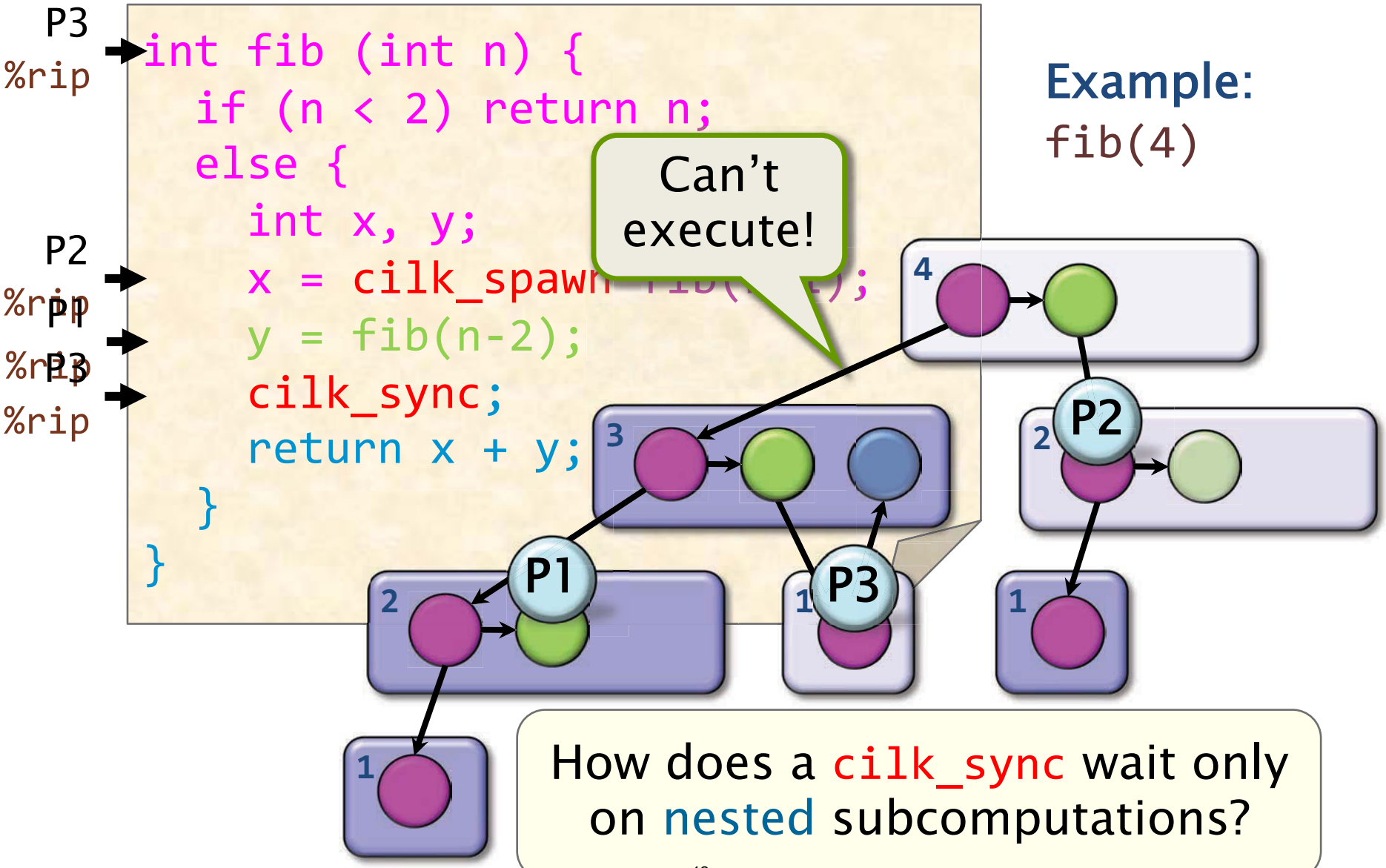
P3 %rip

Example: fib(4)



How does a processor start executing in the middle of a running function?

Parallel Execution: Syncs



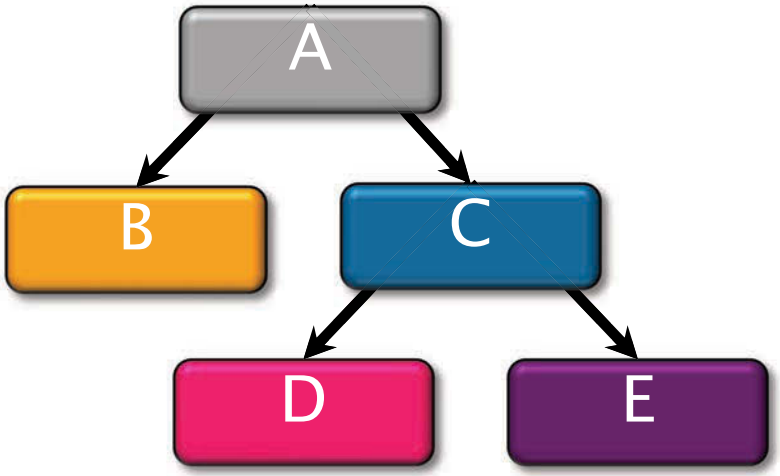
Required Functionality

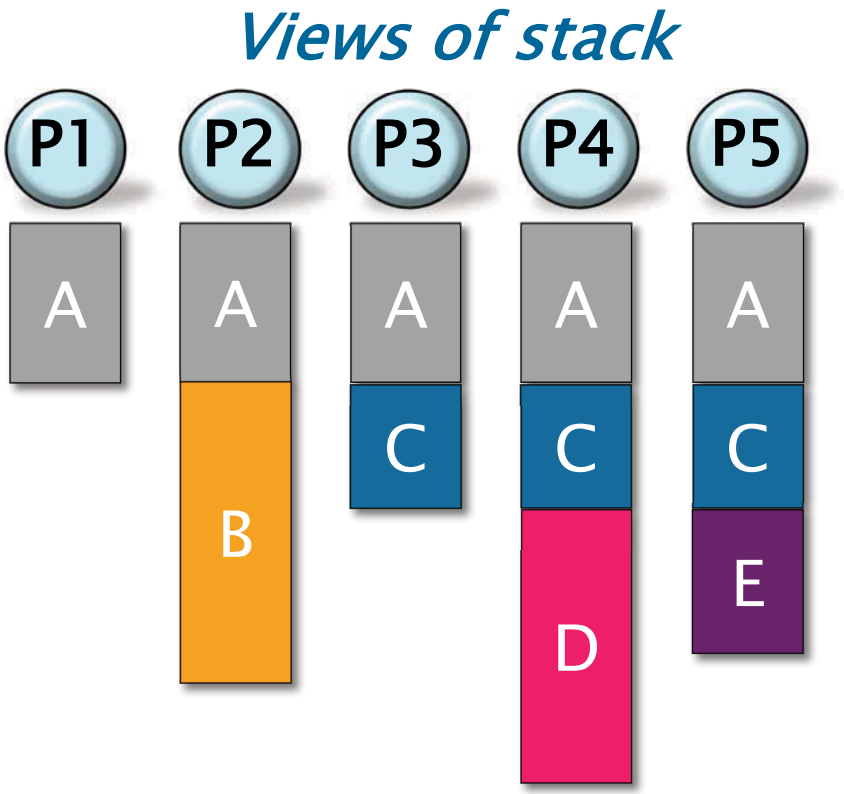
- A single worker must be able to execute the computation on its own similarly to an ordinary serial computation.
- A thief must be able to jump into the middle of an executing function to steal a continuation.
- A sync must stall a function's execution until child subcomputations complete.

What other functionality is needed?

Recall: Cactus Stack

Cilk supports C's rule for pointers: A pointer to stack space can be passed from parent to child, but not from child to parent.

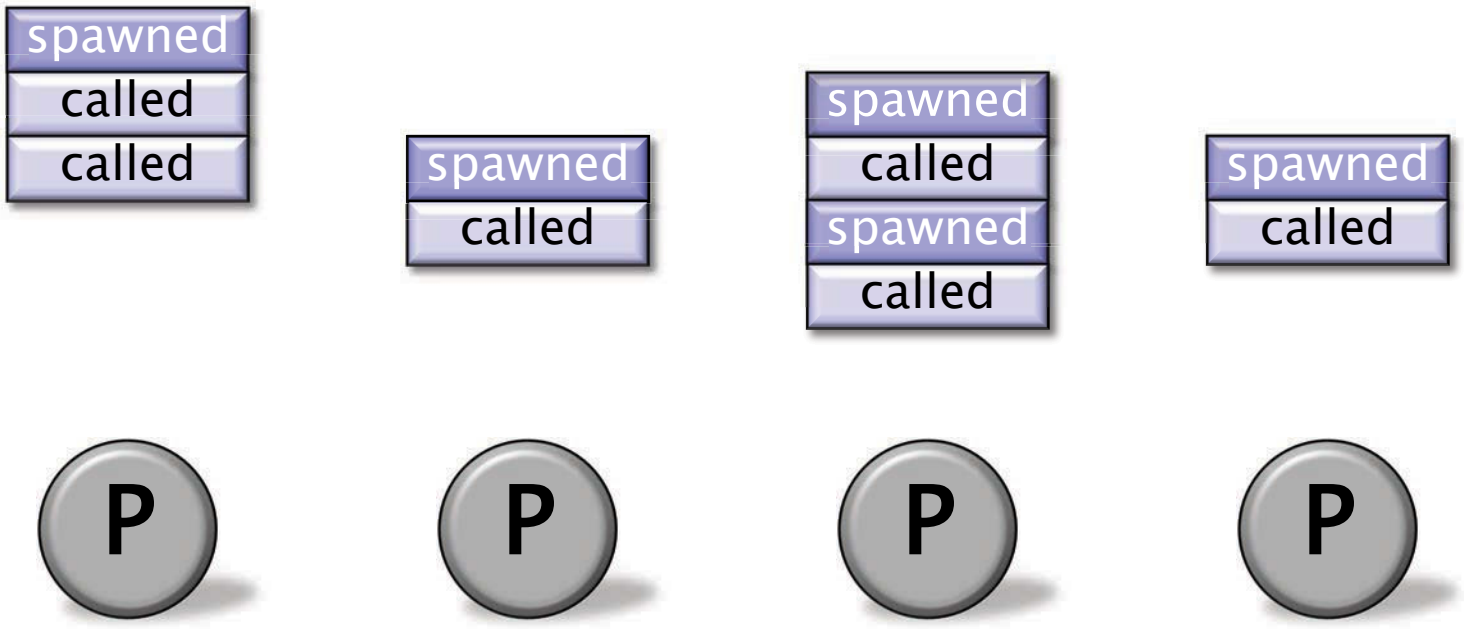




Cilk's cactus stack supports multiple views in parallel.

Recall: Work Stealing

Each worker (processor) maintains a work deque of ready strands, and it manipulates the bottom of the deque like a stack [MKH90, BL94, FLR98].



Each deque contains a mixture of spawned frames and called frames.

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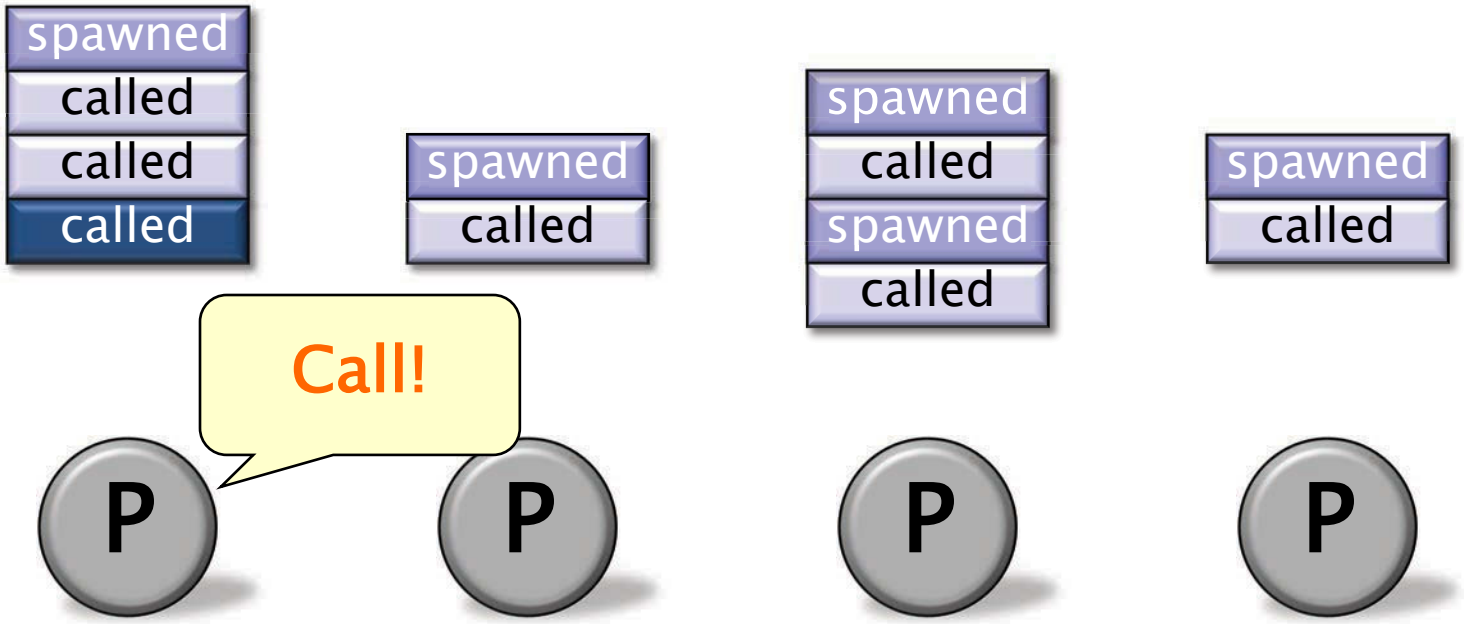

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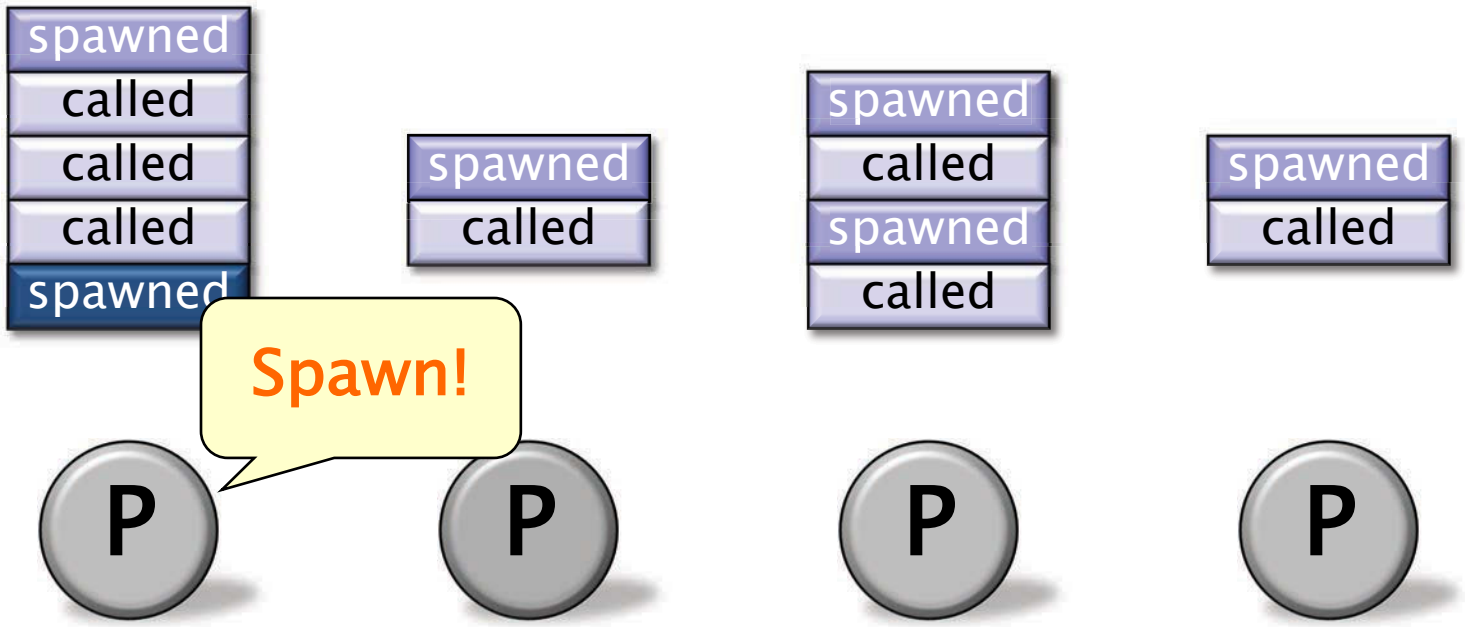

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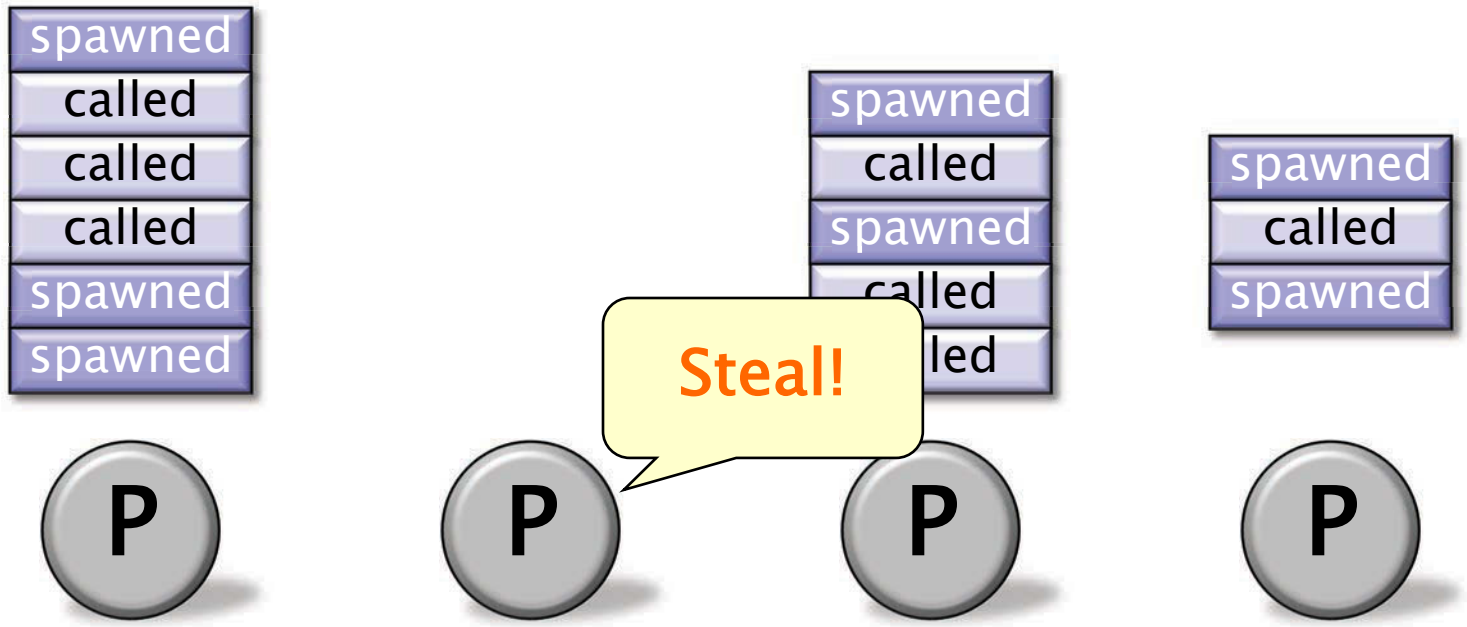
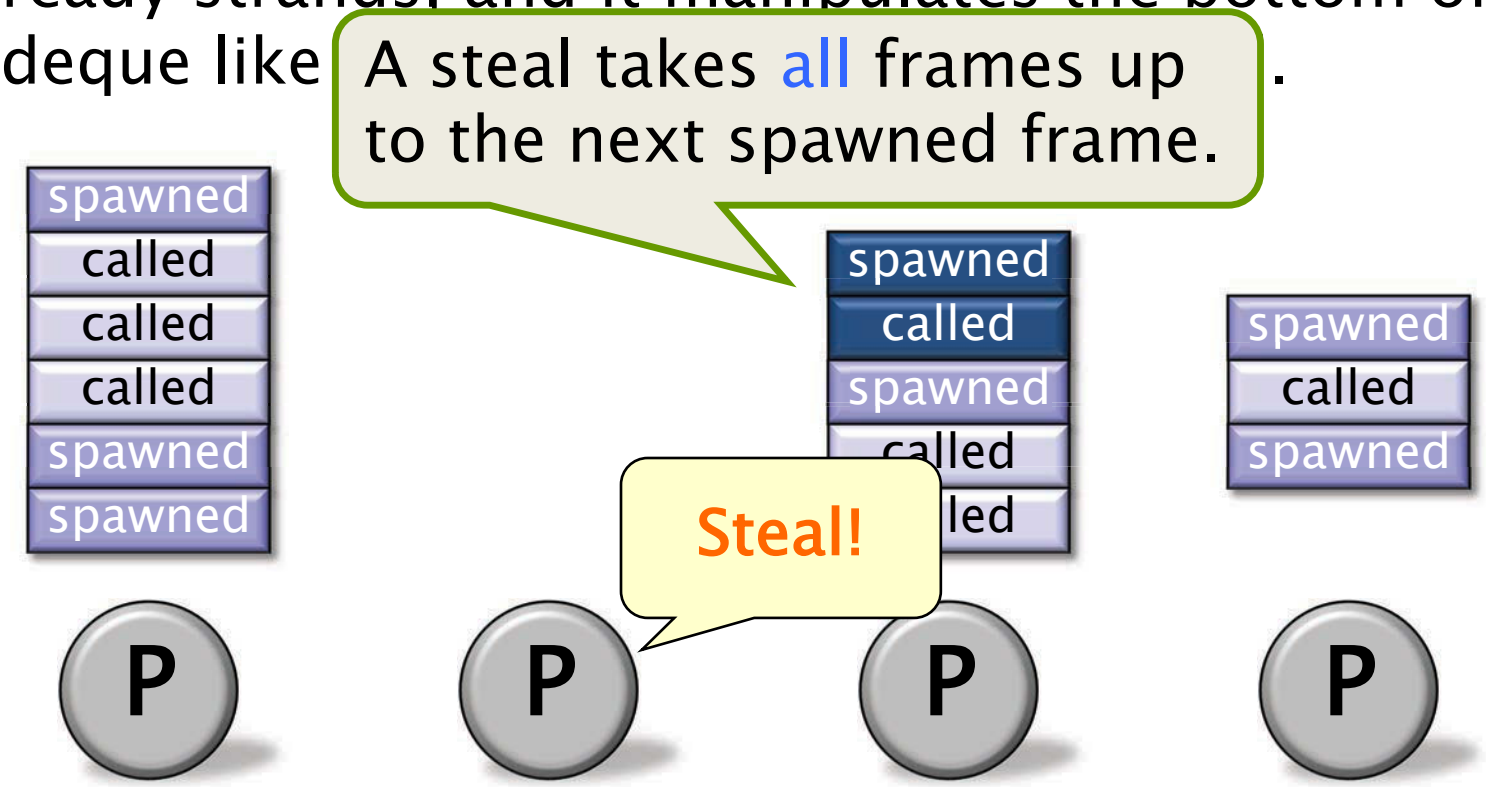


When a worker runs out of work, it steals from the top of a random victim's deque.

Recall: Work Stealing

Each worker (processor) maintains a work deque of ready strands, and it manipulates the bottom of the deque like .



When a worker runs out of work, it steals from the top of a random victim's deque.

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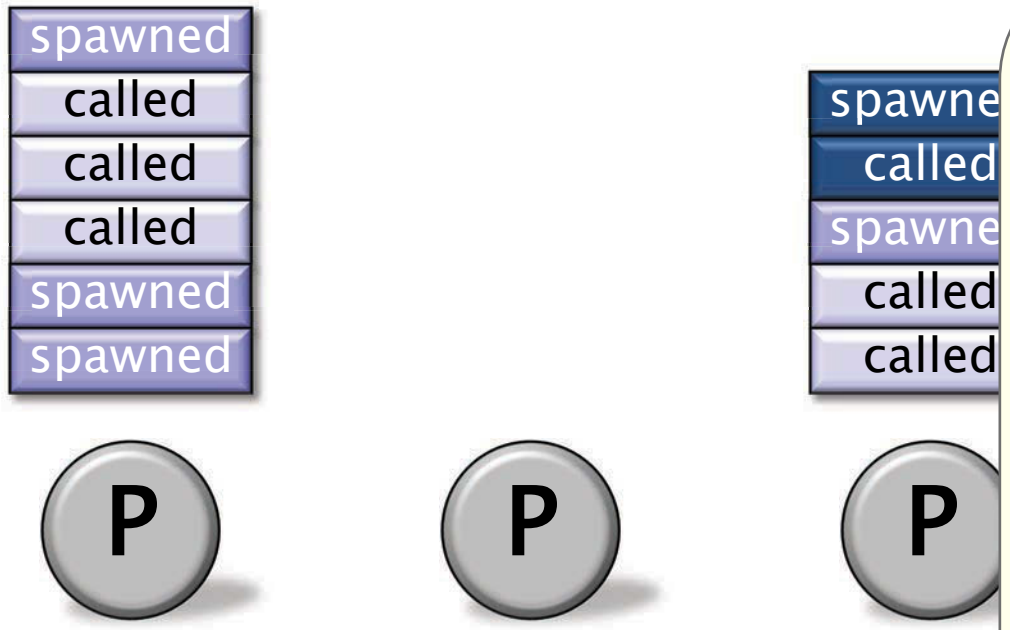
Each worker (processor) maintains a work deque of ready strands, and it manipulates the bottom of the deque like a stack [MKH90, BL94, FLR98].



What is involved in stealing frames?

- What synchronization is needed?
- What happens to the stack?
- How efficient can this be?

When a worker runs out of work, [illegible] from the top of a random victim's deque.

Required Functionality

- A single worker must be able to execute the computation on its own similarly to an ordinary serial computation.
- A thief must be able to jump into the middle of an executing function to steal a continuation.
- A sync must stall a function's execution until child subcomputations complete.
- The runtime must implement a cactus stack for its parallel workers.
- Thieves must be able to handle mixtures of called spawned functions.

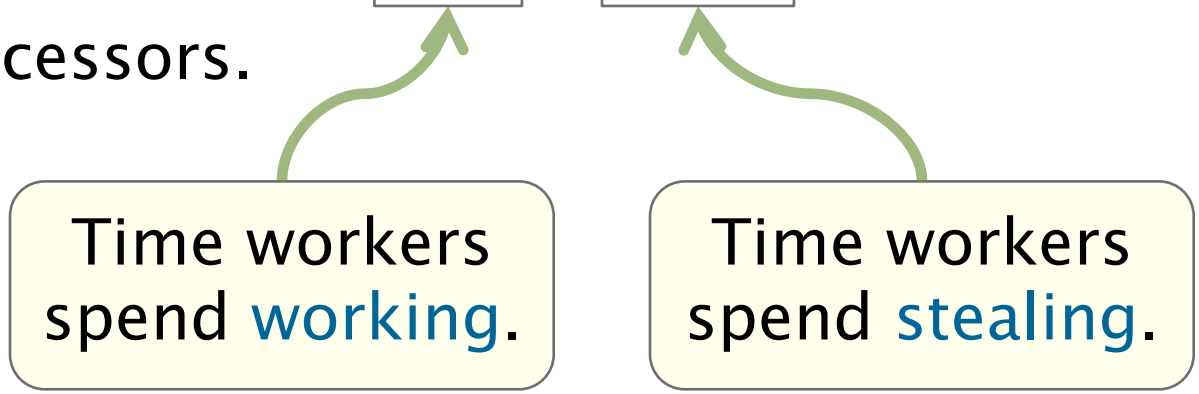
Performance Considerations

Recall: Work-Stealing Bounds

Theorem [BL94]. The Cilk work-stealing scheduler achieves expected running time

$$T_P \approx \boxed{T_1/P} + \boxed{O(T_\infty)}$$

on P processors.



If the program achieves linear speedup, then workers spend most of their time working.

Parallel Speedup

Ideally, parallelizing a serial code makes it run P times faster on P processors.

Serial matrix multiply

```
for (int i = 0; i < n; ++i)
  for (int k = 0; k < n; ++k)
    for (int j = 0; j < n; ++j)
      C[i][j] += A[i][k] * B[k][j];
```

Running time T_S.

Cilk matrix multiply

```
cilk_for (int i = 0; i < n; ++i)
  for (int k = 0; k < n; ++k)
    for (int j = 0; j < n; ++j)
      C[i][j] += A[i][k] * B[k][j];
```

With sufficient parallelism, running time is $T_P \approx T_1/P$.

Goal: $T_P \approx T_S/P$, meaning that $T_S \approx T_1$.

Work Efficiency

Let T_S denote the work of a serial program. Suppose the serial program is parallelized. Let T_1 denote the work of the parallel program, and let T_∞ denote the span of the parallel program.

To achieve linear speedup on P processors over the serial program, i.e., $T_P \approx T_S/P$, the parallel program must exhibit:

- Ample parallelism: $T_1/T_\infty \gg P$.
- High work efficiency: $T_S/T_1 \approx 1$.

The Work-First Principle

To optimize the execution of programs with sufficient parallelism, the implementation of the Cilk runtime system works to maintain high work-efficiency by abiding by the work-first principle:

> Optimize for the *ordinary serial execution*, at the expense of some additional computation in steals.

Division of Labor

The work-first principle guides the division of the Cilk runtime system between the compiler and the runtime library.

Compiler

- Uses a handful of small data structures, e.g., workers and stack frames.
- Implements optimized fast paths for execution of functions when no steals have occurred.

Runtime library

- Uses larger data structures.
- Handles slow paths of execution, e.g., when a steal occurs.

Implementing a Worker Deque

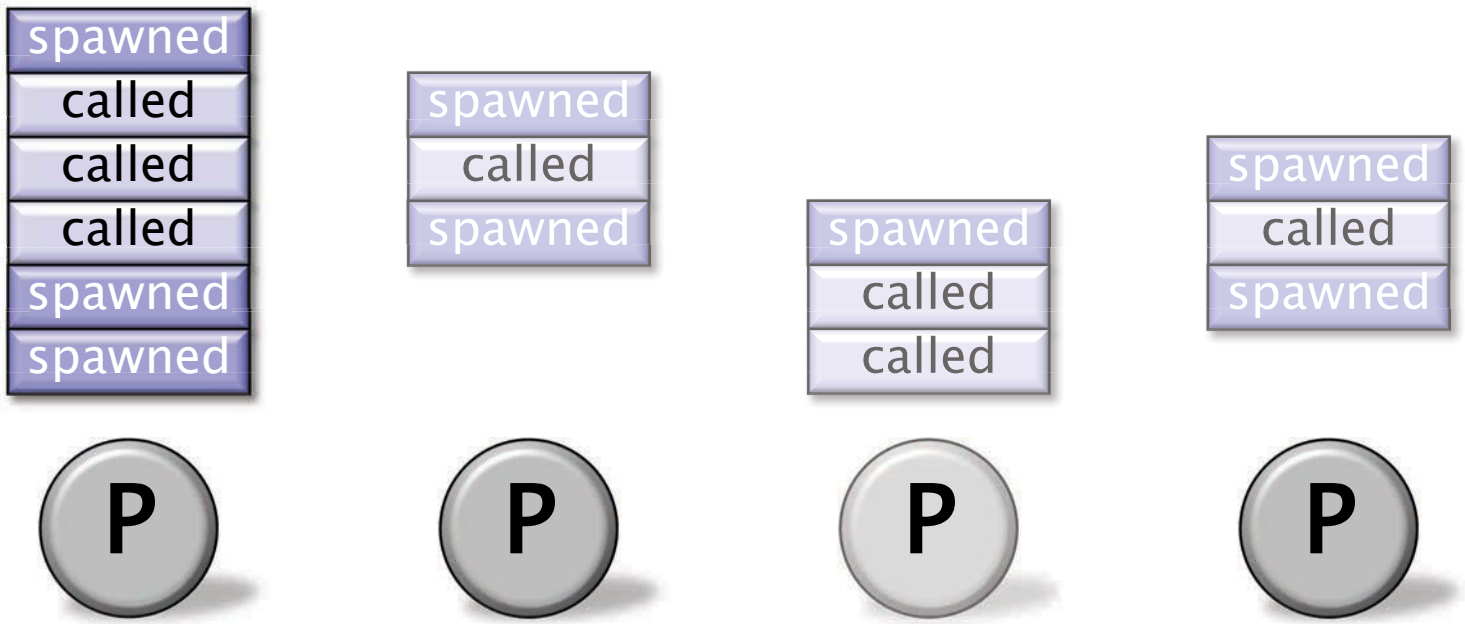
Running Example

```
int foo(int n) {
  int x, y;
  x = cilk_spawn bar(n);
  y = baz(n);
  cilk_sync;
  return x + y;
}
```

- Function `foo` is a spawning function, meaning that `foo` contains a `cilk_spawn`.
- Function `bar` is spawned by `foo`.
- The call to `baz` occurs in the continuation of the spawn.

Requirements of Worker Deques

PROBLEM: How do we implement a worker's deque?



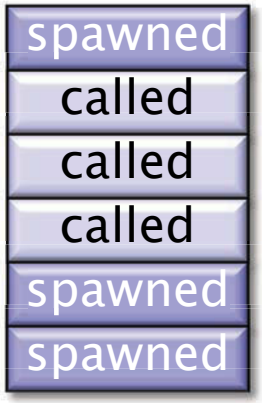
- The worker should operate its own deque like a stack.
- A steal needs to transfer ownership of several consecutive frames to a thief.
- A thief needs to be able to resume a continuation.

Basic Worker-Deque Design

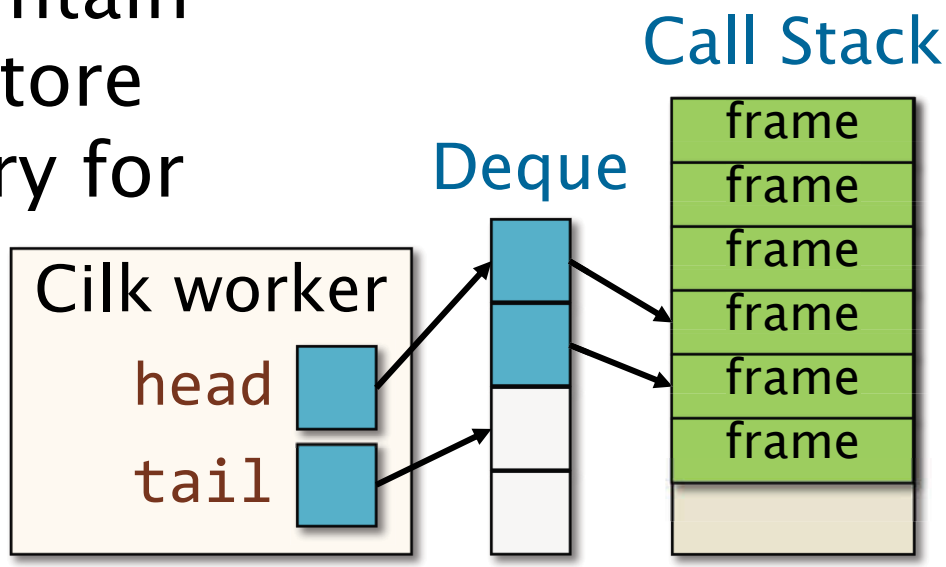
IDEA: The worker deque is an external structure with pointers to stack frames.

- A Cilk worker maintains head and tail pointers to its deque.
- Stealable frames maintain a local structure to store information necessary for stealing the frame.

Concept



Design



Implementation Details

The Intel Cilk Plus runtime elaborates on this idea as follows:

- Every spawned subcomputation runs in its own spawn-helper function.
- The runtime maintains three basic data structures as workers execute work:
  - A worker structure for every worker used to execute the program.
  - A Cilk stack-frame structure for each instantiation of a spawning function.
  - A spawn-helper stack frame for each instantiation of a `cilk_spawn`.

Spawn-Helper Functions

Cilk code

```
int foo(int n) {
  int x, y;
  x = cilk_spawn bar(n);
  y = baz(n);
  cilk_sync;
  return x + y;
}
```

Cilk compiler

C pseudocode of compiled result

```
int foo(int n) {
  __cilkrts_stack_frame_t sf;
  __cilkrts_enter_frame(&sf);
  int x, y;
  if (!setjmp(sf.ctx))
    spawn_bar(&x, n);
  y = baz(n);
  if (sf.flags & CILK_FRAME_UNSYNCHED)
    if (!setjmp(sf.ctx))
      __cilkrts_sync(&sf);
  int result = x + y;
  __cilkrts_pop_frame(&sf);
  if (sf.flags)
    __cilkrts_leave_frame(&sf);
  return result;
}

void spawn_bar(int *x, int n) {
  __cilkrts_stack_frame sf;
  __cilkrts_enter_frame_fast(&sf);
  __cilkrts_detach();
  *x = bar(n);
  __cilkrts_pop_frame(&sf);
  __cilkrts_leave_frame(&sf);
}
```

Cilk Stack-Frame Structures

```
int foo(int n) {
  __cilkrts_stack_frame_t sf;
  __cilkrts_enter_frame(&sf);
  int x, y;
  if (!setjmp(sf.ctx))
    spawn_bar(&x, n);
  y = baz(n);
  if (sf.flags & CILK_FRAME_UNSYNCHED)
    if (!setjmp(sf.ctx))
      __cilkrts_sync(&sf);
  int result = x + y;
  __cilkrts_pop_frame(&sf
  if (sf.flags)
    __cilkrts_leave_frame
  return result;
}
```

C pseudocode of compiled result

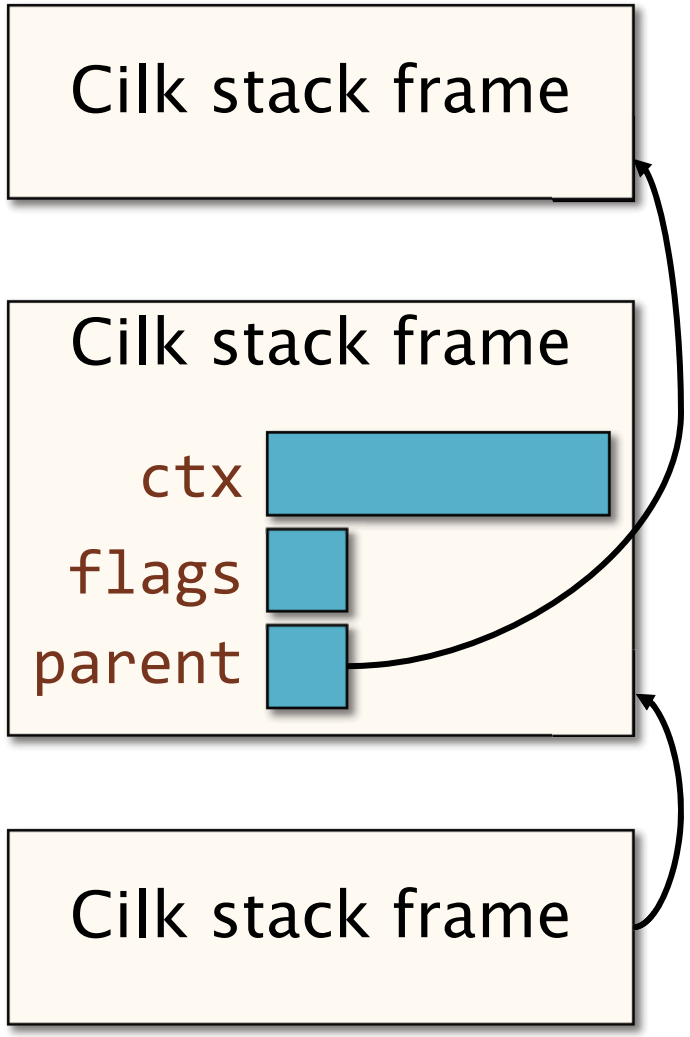
Cilk stack-frame structures

```
void spawn_bar(int *x, int n) {
  __cilkrts_stack_frame sf;
  __cilkrts_enter_frame_fast(&sf);
  __cilkrts_detach();
  *x = bar(n);
  __cilkrts_pop_frame(&sf);
  __cilkrts_leave_frame(&sf);
}
```

The Cilk Stack Frame (Simplified)

Each Cilk stack frame stores:

- A context buffer, `ctx`, which contains enough information to resume a function at a continuation, i.e., after a `cilk_spawn` or `cilk_sync`.
- An integer, `flags`, that summarizes the state of the Cilk stack frame.
- A pointer, `parent`, to its parent Cilk stack frame.

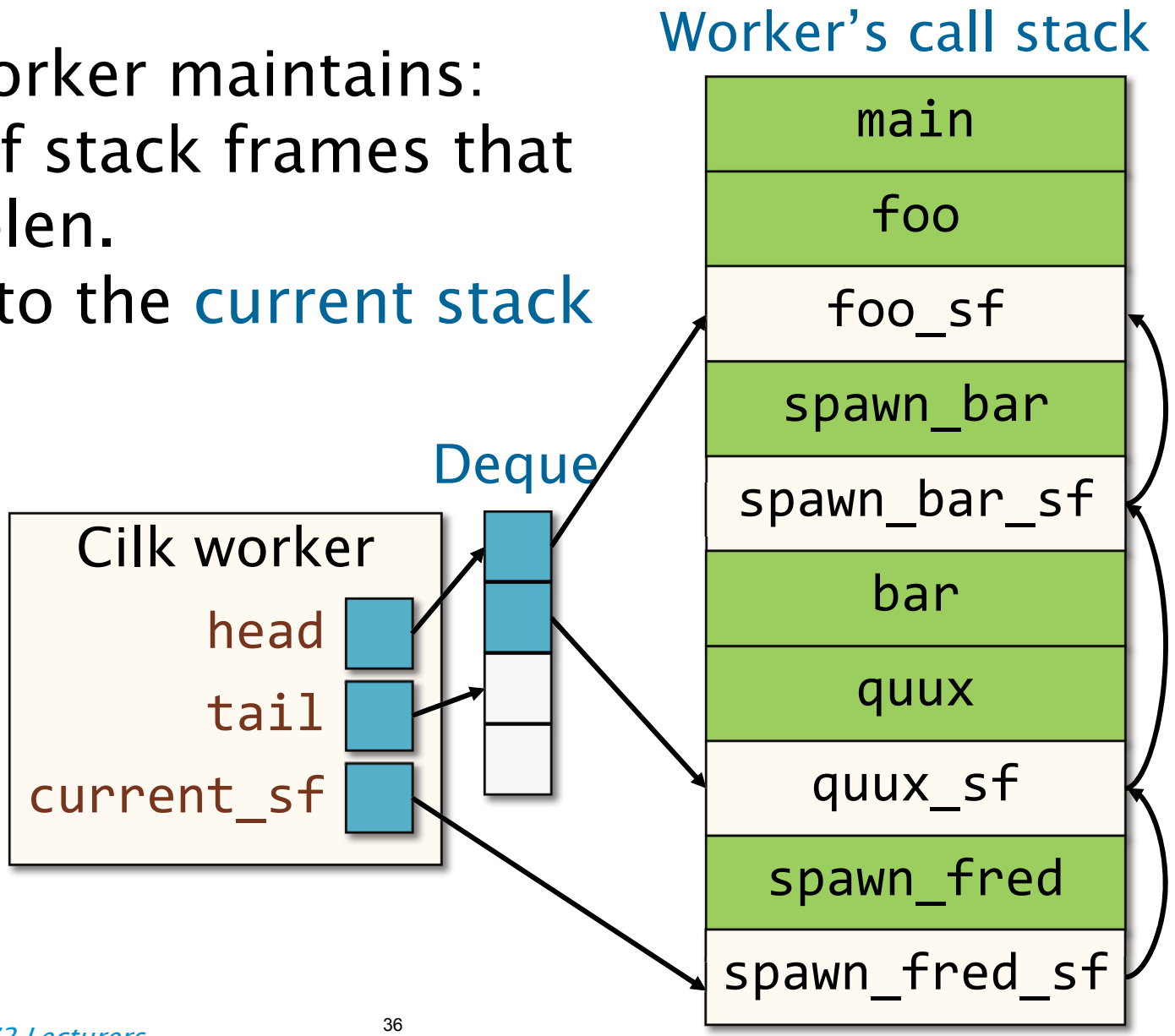


The Cilk Worker Structure (Simplified)

Each Cilk worker maintains:

- A deque of stack frames that can be stolen.
- A pointer to the current stack frame.

Example:
Function `foo` spawned `bar`, which called `quux`, which spawned `fred`.



Spawning Computation

Code for a Spawning Function

C pseudocode of a spawning function

```
int foo(int n) {
  __cilkrts_stack_frame_t sf;
  __cilkrts_enter_frame(&sf);
  int x, y;
  if (!setjmp(sf.ctx))
    spawn_bar(&x, n);
  y = baz(n);
  if (sf.flags & CILK_FRAME_UNSYNCHED)
    if (!setjmp(sf.ctx))
      __cilkrts_sync(&sf);
  int result = x + y;
  __cilkrts_pop_frame(&sf);
  if (sf.flags)
    __cilkrts_leave_frame(&sf);
  return result;
}
```

Create and initialize a Cilk stack-frame structure.

Prepare to spawn.

Invoke the spawn helper.

Perform a sync.

Clean up the Cilk stack-frame structure.

Clean up the deque.

Code for a Spawn Helper

C pseudocode of a spawn helper

```
void spawn_bar(int *x, int n) {
  __cilkrts_stack_frame sf;
  __cilkrts_enter_frame_fast(&sf);

  __cilkrts_detach();

  *x = bar(n);

  __cilkrts_pop_frame(&sf);
  __cilkrts_leave_frame(&sf);
}
```

Create and initialize a Cilk stack-frame structure.

Upate the deque to allow the parent to be stolen.

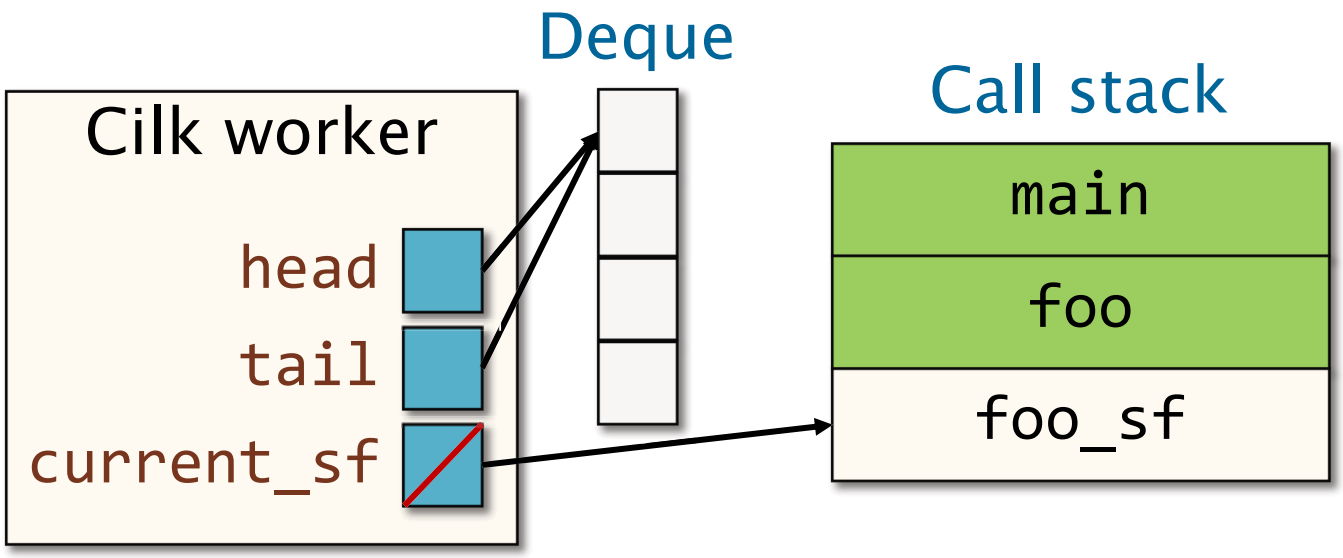
Invoke the spawned subroutine.

Clean up the Cilk stack-frame structure.

Clean up the deque and attempt to return.

Entering a Spawning Function

When execution enters a spawning function, the Cilk worker's current stack-frame structure is updated.



Preparing to Spawn

Cilk code

```
int foo(int n) {
  …
  x = cilk_spawn bar(n);
  …
}
```

C pseudocode

```
int foo(int n) {
  …
  if (!setjmp(sf.ctx))
    spawn_bar(&x, n);
  …
}
```

Cilk uses the `setjmp` function to allow thieves to steal the continuation.

The `setjmp` function stores information necessary for resuming the function at the `setjmp` into the given buffer.

QUESTION: What information needs to be saved?

ANSWER: Registers `%rip`, `%rbp`, `%rsp`, and callee-saved registers.

Spawning a Function

C pseudocode

```
int foo(int n) {
  …
  if (!setjmp(sf.ctx))
    spawn_bar(&x, n);
  …
}
void spawn_bar(int *x, int n) {
  __cilkrts_stack_frame sf;
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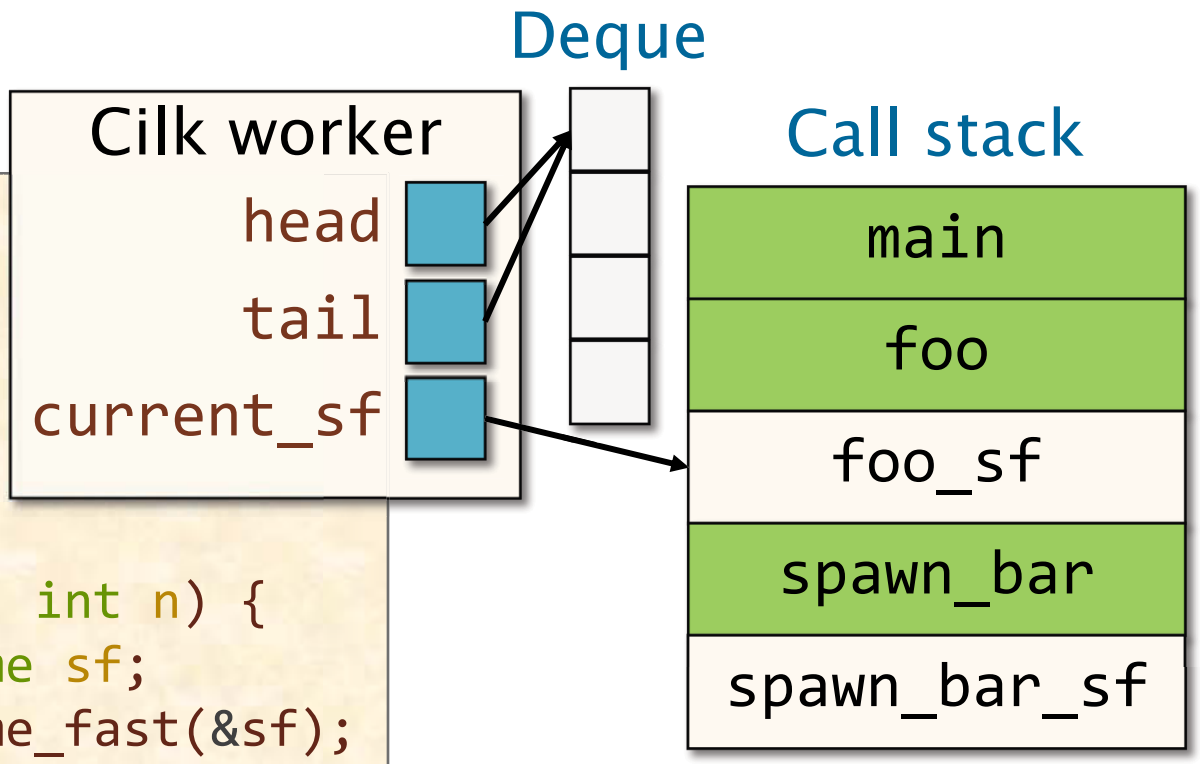
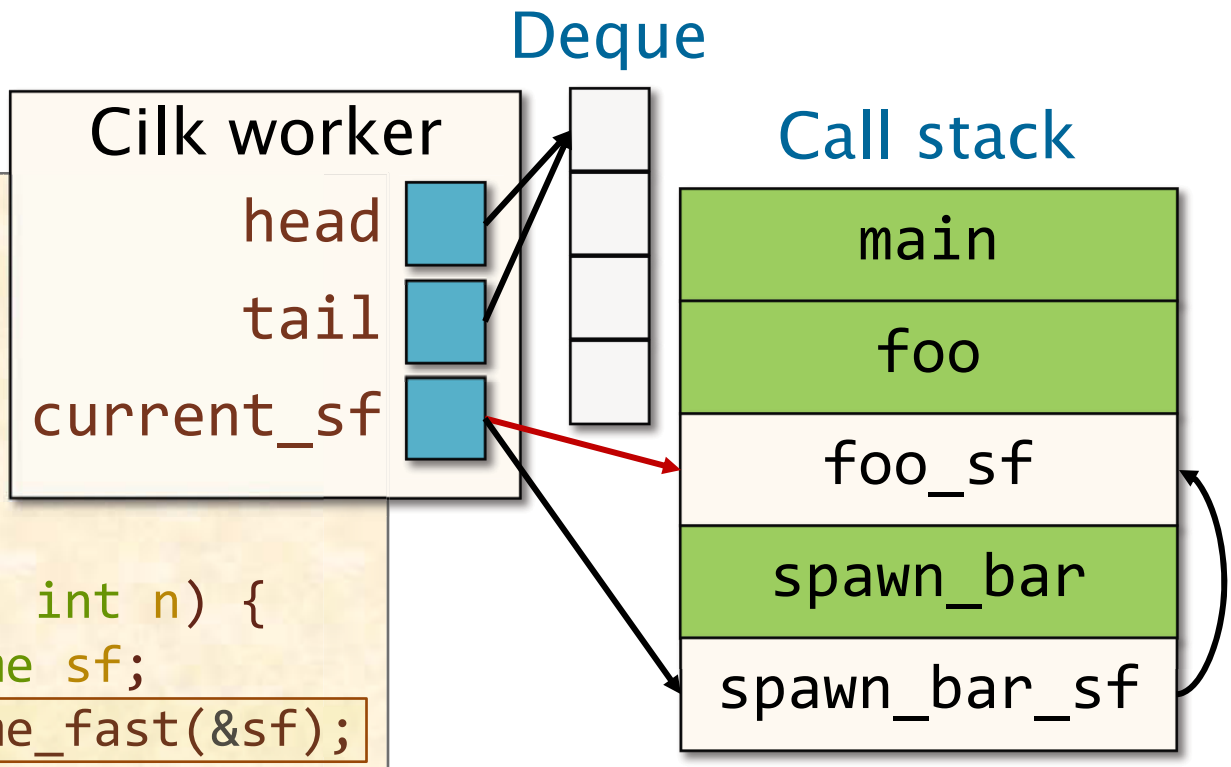
  __cilkrts_detach();
  *x = bar(n);
  …
}
```



Spawning a Function

C pseudocode

```
int foo(int n) {
  …
  if (!setjmp(sf.ctx))
    spawn_bar(&x, n);
  …
}
void spawn_bar(int *x, int n) {
  __cilkrts_stack_frame sf;
  __cilkrts_enter_frame_fast(&sf);
  __cilkrts_detach();
  *x = bar(n);
  …
}
```



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C pseudocode

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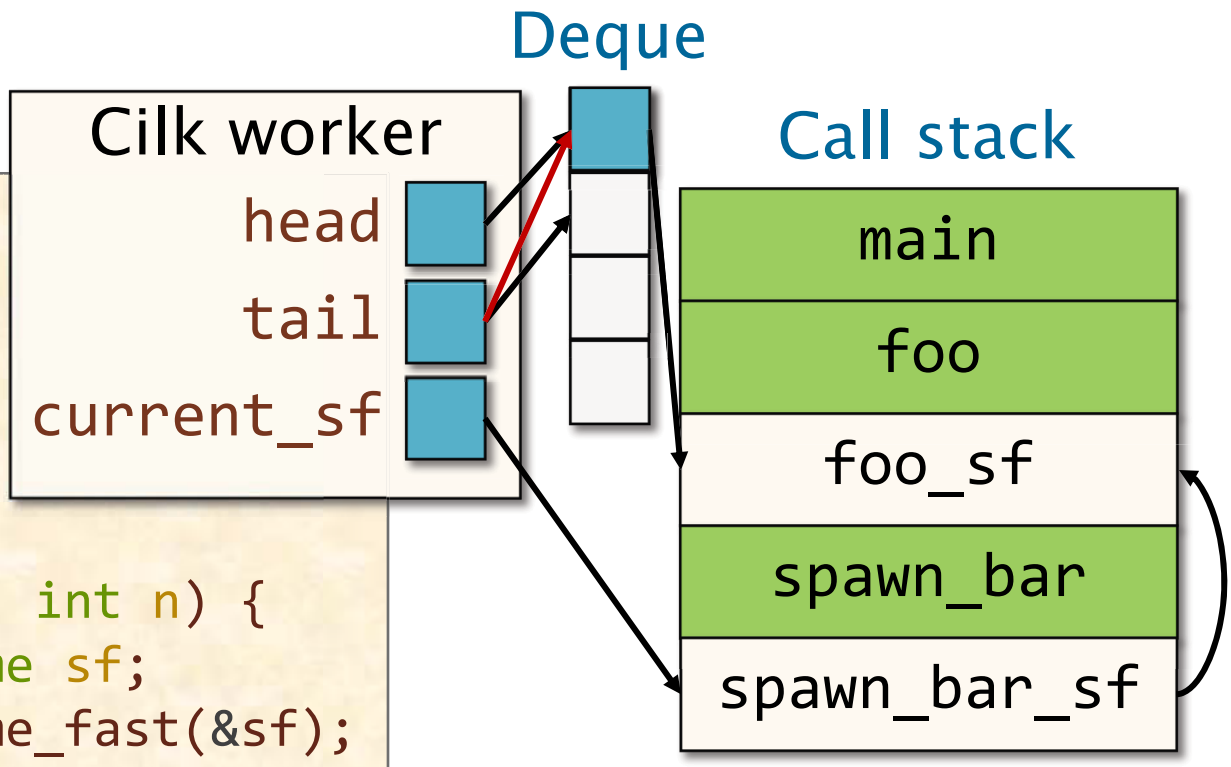
    spawn_bar(&x, n);
  …
}
void spawn_bar(int *x, int n) {
  __cilkrts_stack_frame sf;
  __cilkrts_enter_frame_fast(&sf);
  __cilkrts_detach();
  *x = bar(n);
  …
}
```



Spawning a Function

C pseudocode

```
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  …
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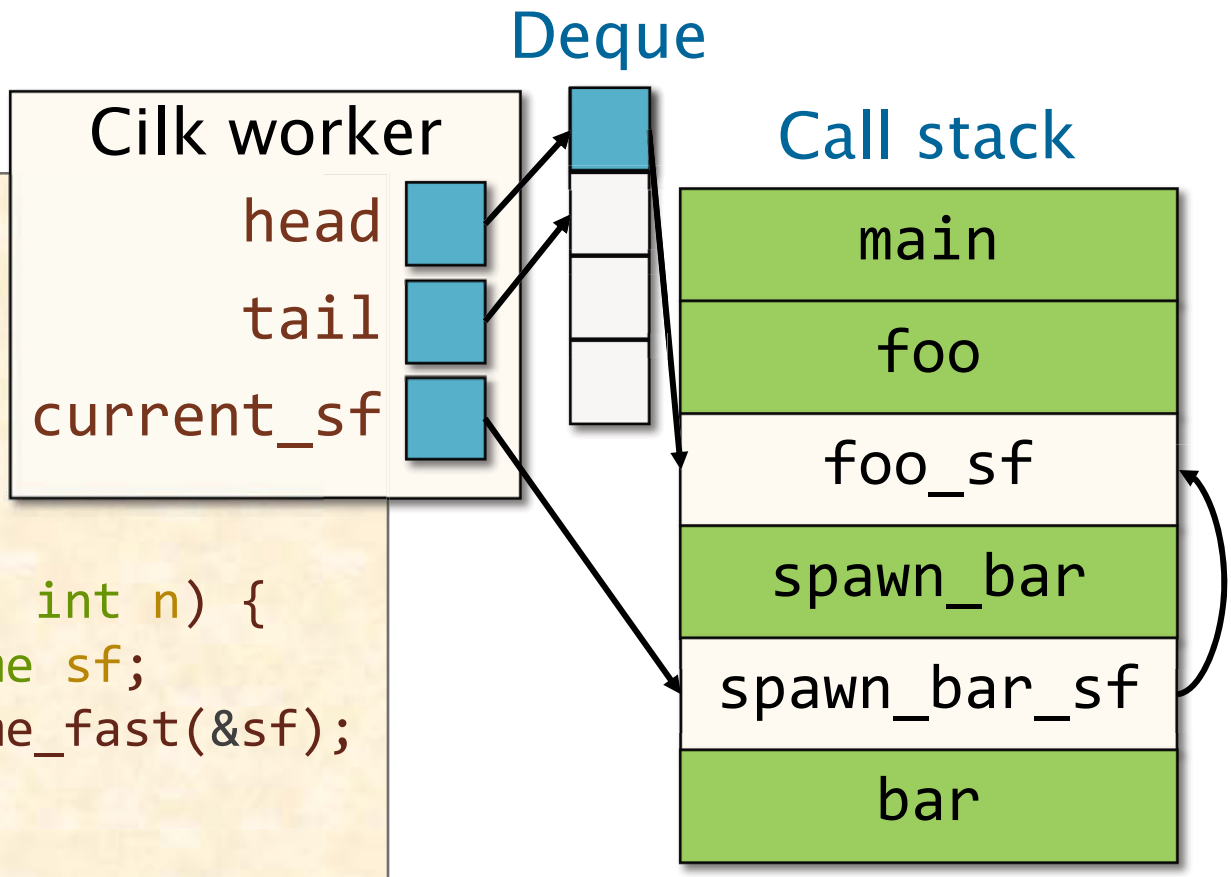
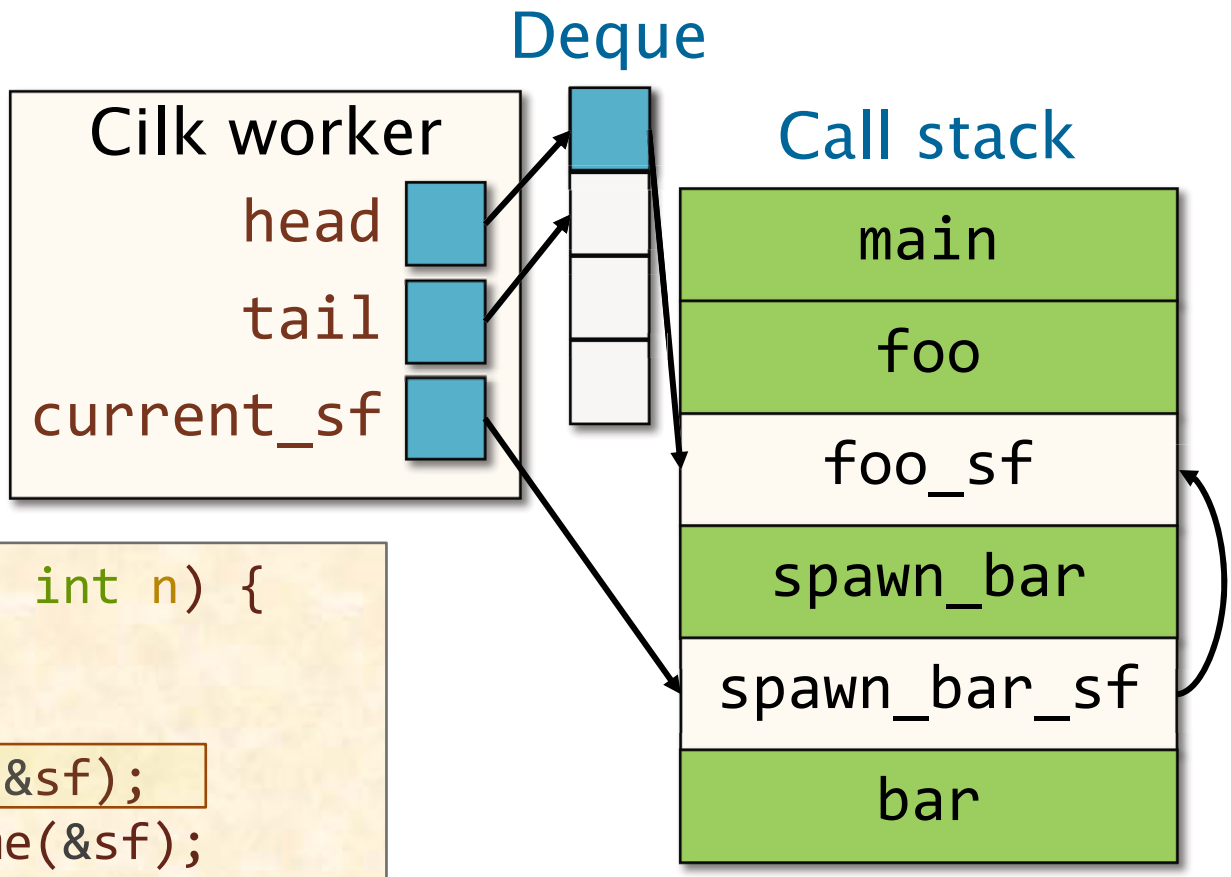
  …
}
```



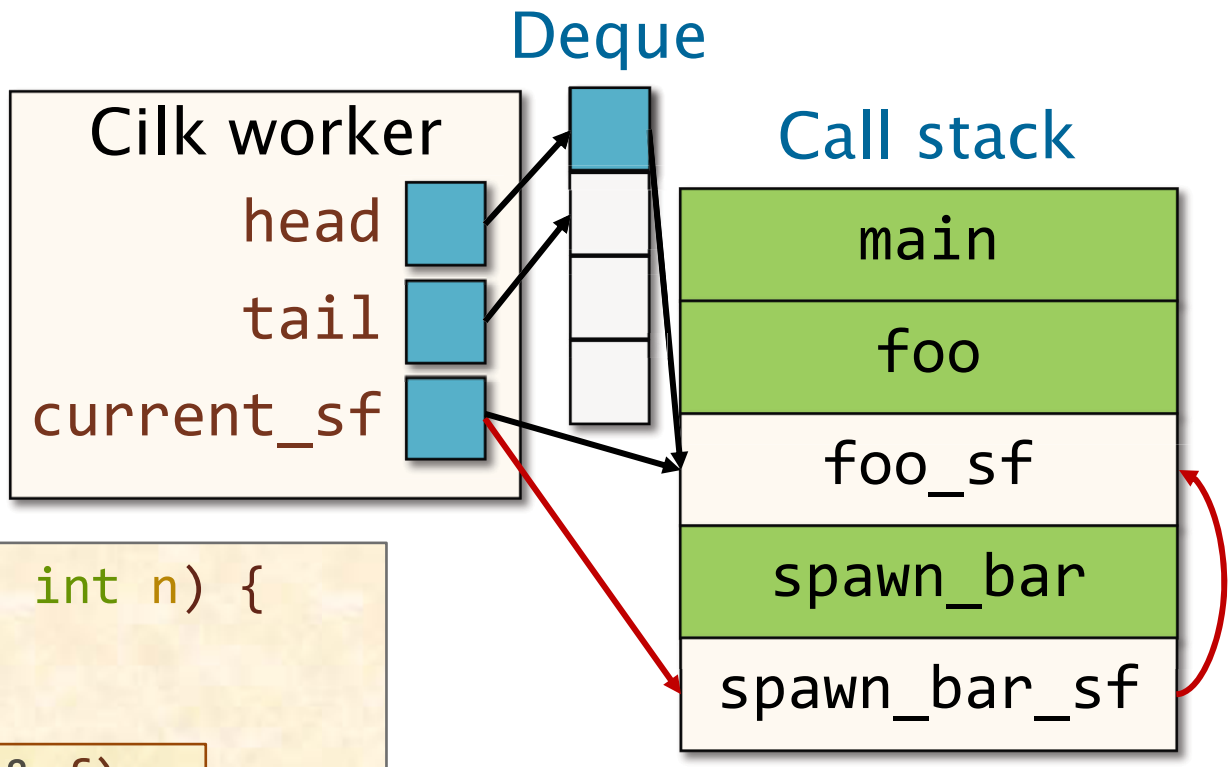
Returning from a Spawn



C pseudocode

```
void spawn_bar(int *x, int n) {
  …
  *x = bar(n);
  __cilkrts_pop_frame(&sf);
  __cilkrts_leave_frame(&sf);
}
```

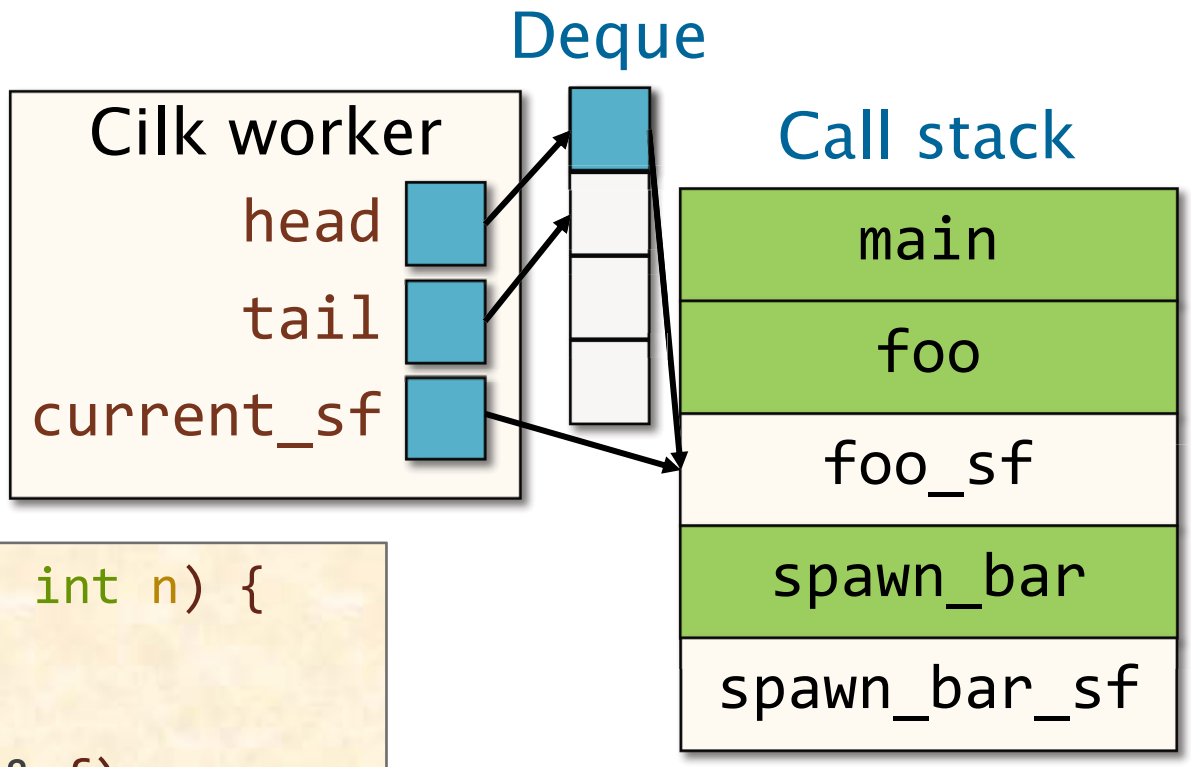
Returning from a Spawn



C pseudocode

```
void spawn_bar(int *x, int n) {
  …
  *x = bar(n);
  __cilkrts_pop_frame(&sf);
  __cilkrts_leave_frame(&sf);
}
```

Returning from a Spawn



C pseudocode

```
void spawn_bar(int *x, int n) {
  …
  *x = bar(n);
  __cilkrts_pop_frame(&sf);
  __cilkrts_leave_frame(&sf);
}
```

May or may not return, depending on what's in the worker's deque.

Popping the Deque

In `__cilkrts_leave_frame`, the worker tries to pop the stack frame from the tail of the deque. There are two possible outcomes:

1. If the pop succeeds, then the execution continues as normal.
2. If the pop fails, then the worker is out of work to do. It thus becomes a thief and tries to steal work from the top of a random victim's deque.

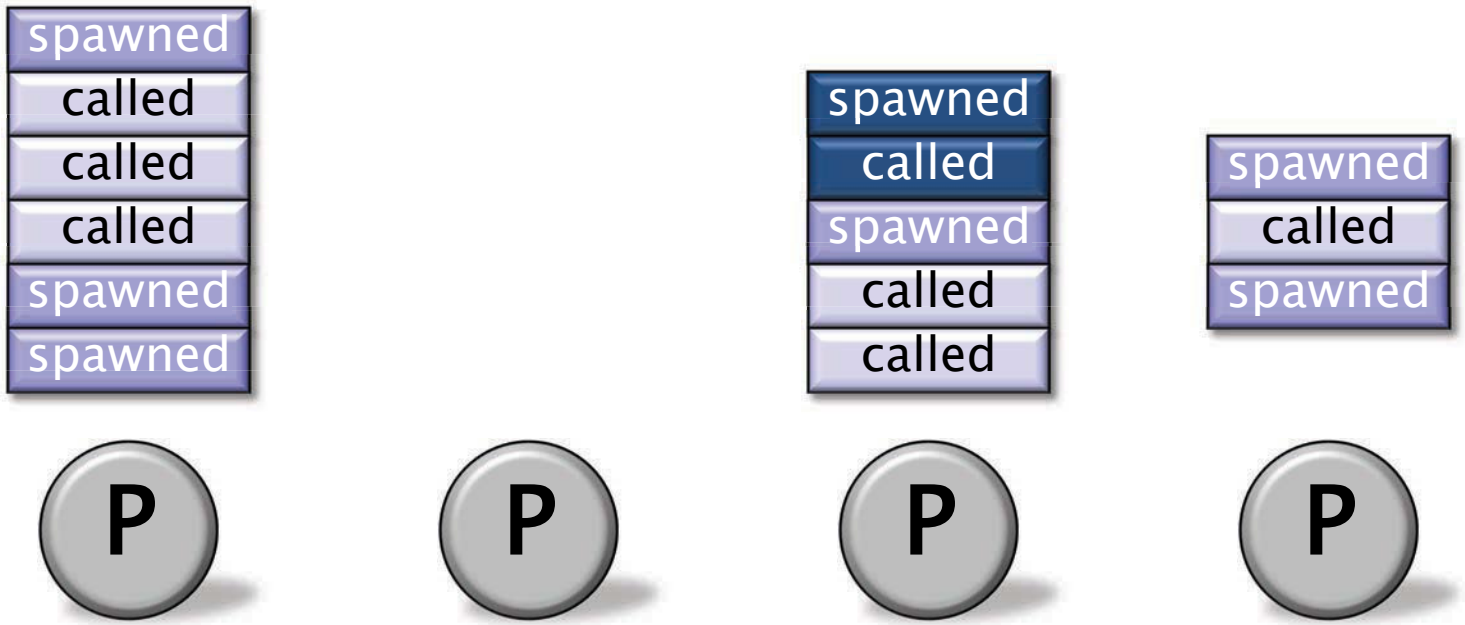
Question: Which case is more important to optimize?

Answer: Case 1.

STEALING COMPUTATION

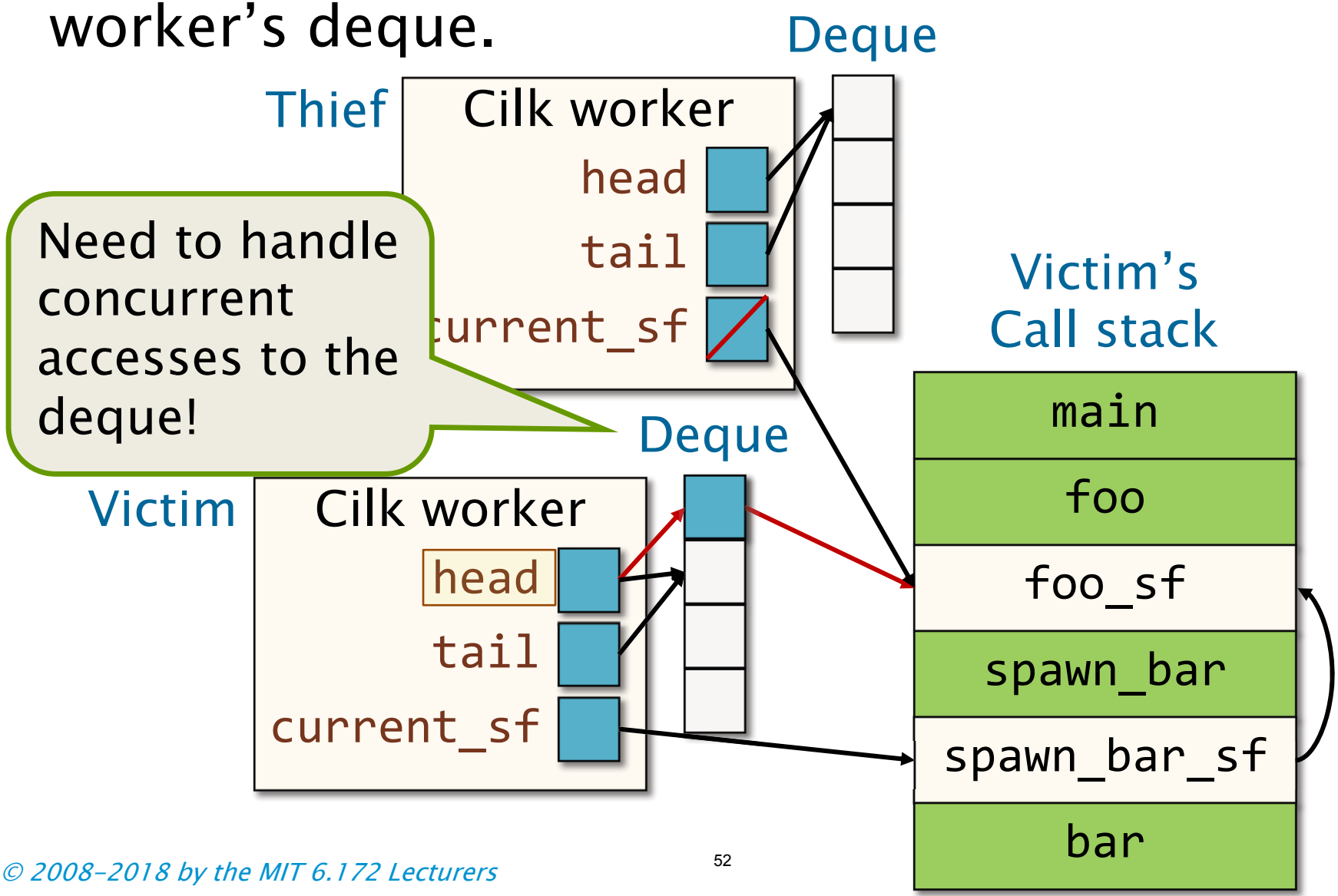
Recall: Stealing Work

Conceptually, a thief takes frames off of the top of a victim worker's deque.



Stealing a Frame

A thief steals from the head of the victim worker's deque.



Synchronizing Deque Accesses

Worker protocol

```
void push(
  tail++;
}
bool pop()
  tail--;
  if (head > tail) {
    tail++;
    lock(L);
    tail--;
    if (head > tail) {
      tail++;
      unlock(L);
      return FAILURE;
    }
```

The worker pops the optimistically.

The worker only grabs a lock if the deque appears to be empty.

e worker and thief ordinate operations the deque using e THE protocol:

Thief proto

```
bool steal(
  lock(L);
  head++;
  if (head
    head--;
    unlock(L);
    return FAILURE;
  }
  unlock(L);
  return SUCCESS;
}
```

The thief always grabs a lock before operating on the deque.

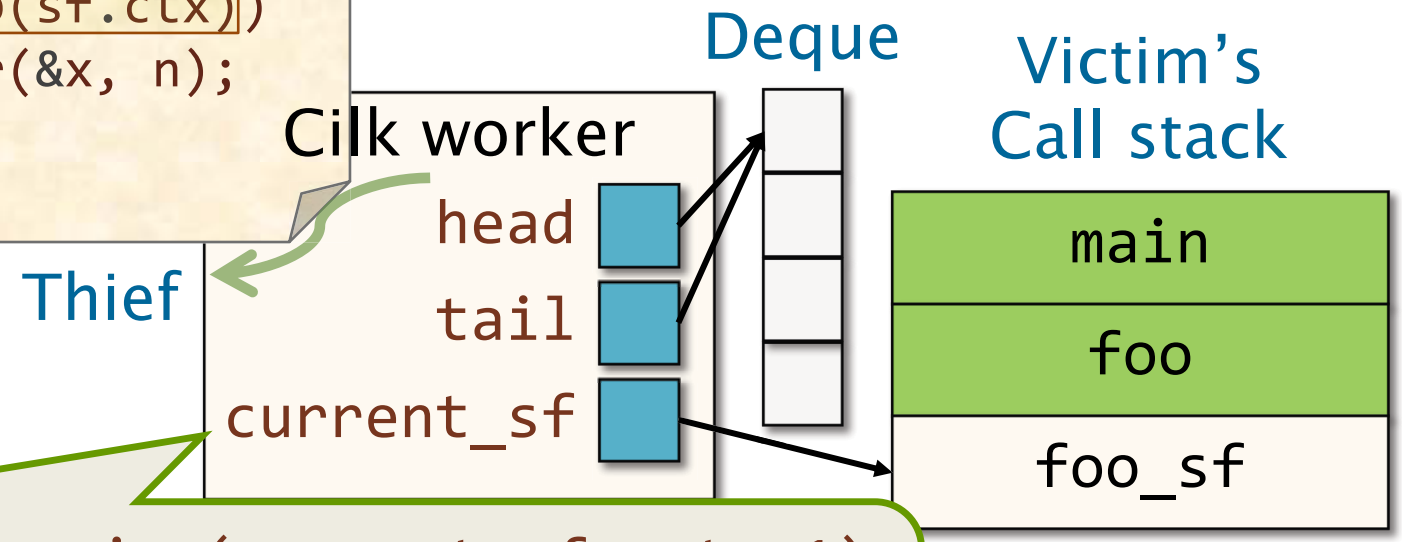
Resuming a Continuation

Cilk uses the `longjmp` function to resume a stolen continuation.

C pseudocode

```
int foo(int n) {
  …
  if (!setjmp(sf.ctx))
    spawn_bar(&x, n);
  …
}
```

Previously, the victim performed a `setjmp` to store register state in `foo_sf.ctx`.



Executing `longjmp(current_sf->ctx,1)` sets the thief's registers to start executing at the location of the `setjmp`.

Resuming a Continuation

The contract between `setjmp` and `longjmp` ensures the thief resumes the continuation.

- On its direct invocation, `setjmp(buffer)` returns `0`.
- Invoking `longjmp(buffer, x)` causes the `setjmp` to effectively return again with the integer value `x`.

C pseudocode

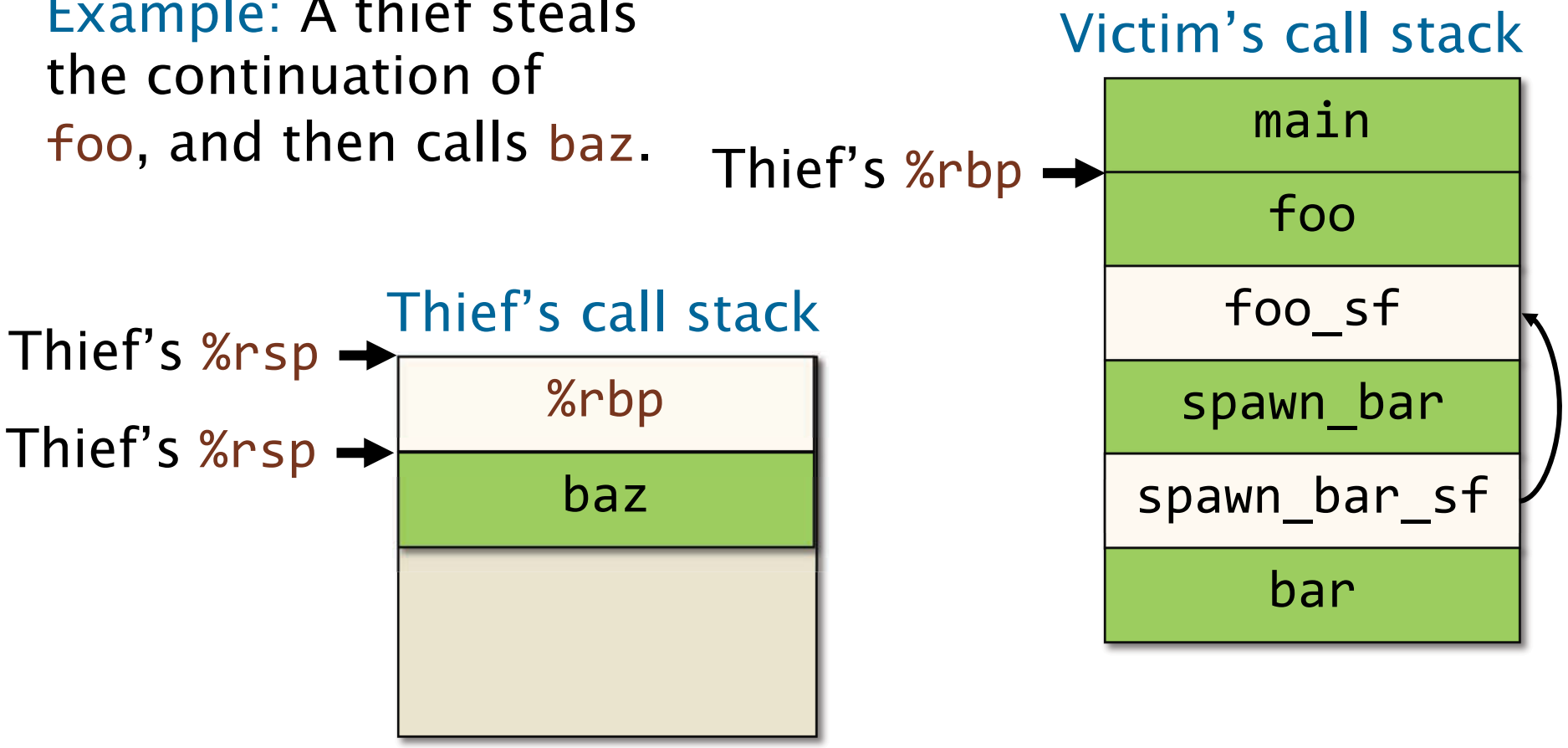
```
int foo(int n) {
  …
  if (!setjmp(sf.ctx)) {
    spawn_bar(&x, n);
  …
}
```

Because a thief reaches this point by calling `longjmp(current_sf->ctx,1)`, the condition fails, and the thief jumps to the continuation.

Implementing the Cactus Stack

Thieves maintain their own call stacks and use pointer tricks to implement the cactus stack.

Example: A thief steals the continuation of `foo`, and then calls `baz`.

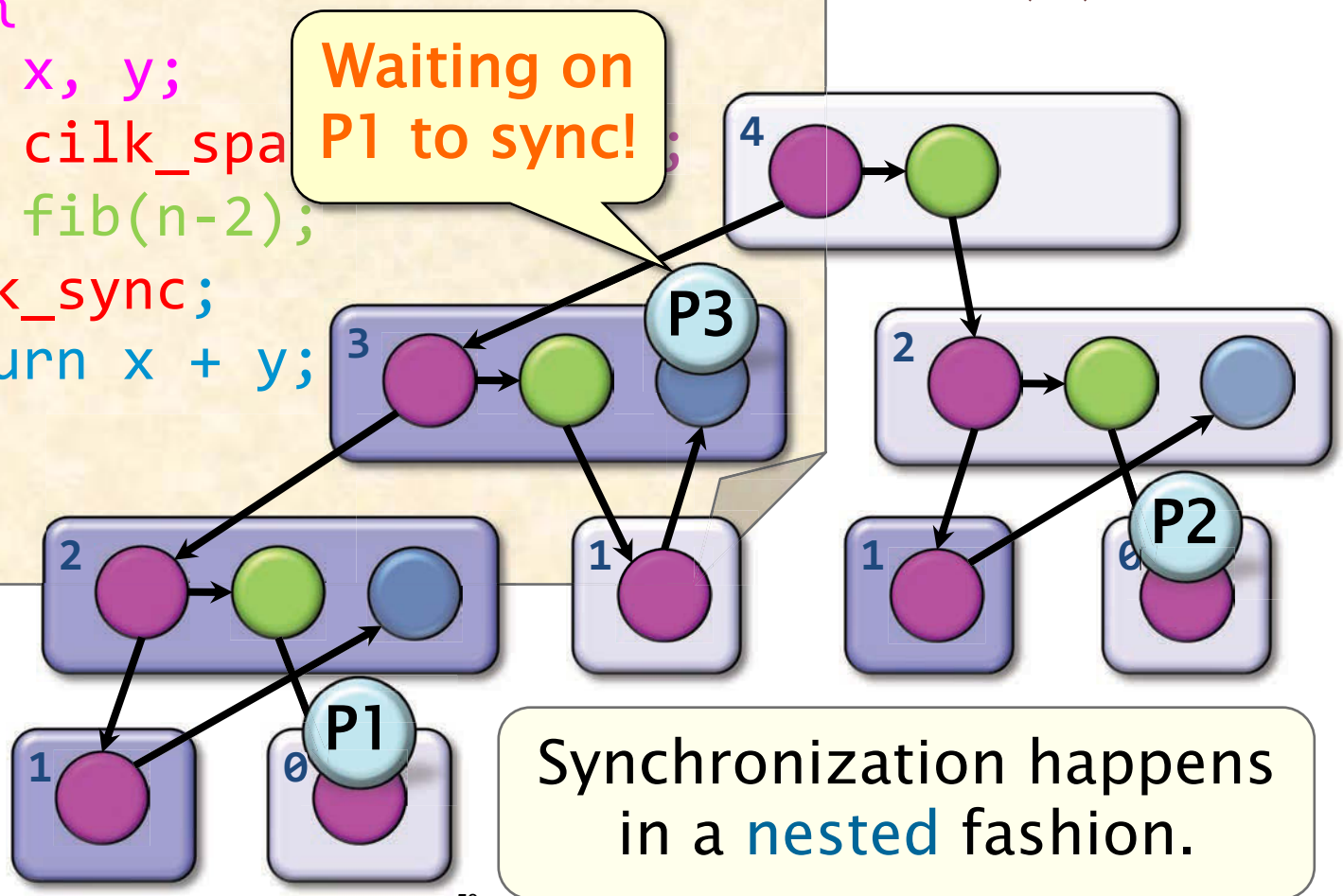


SYNCHRONIZING COMPUTATION

Recall: Nested Synchronization

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

Example:
fib(4)



Synchronization happens in a nested fashion.

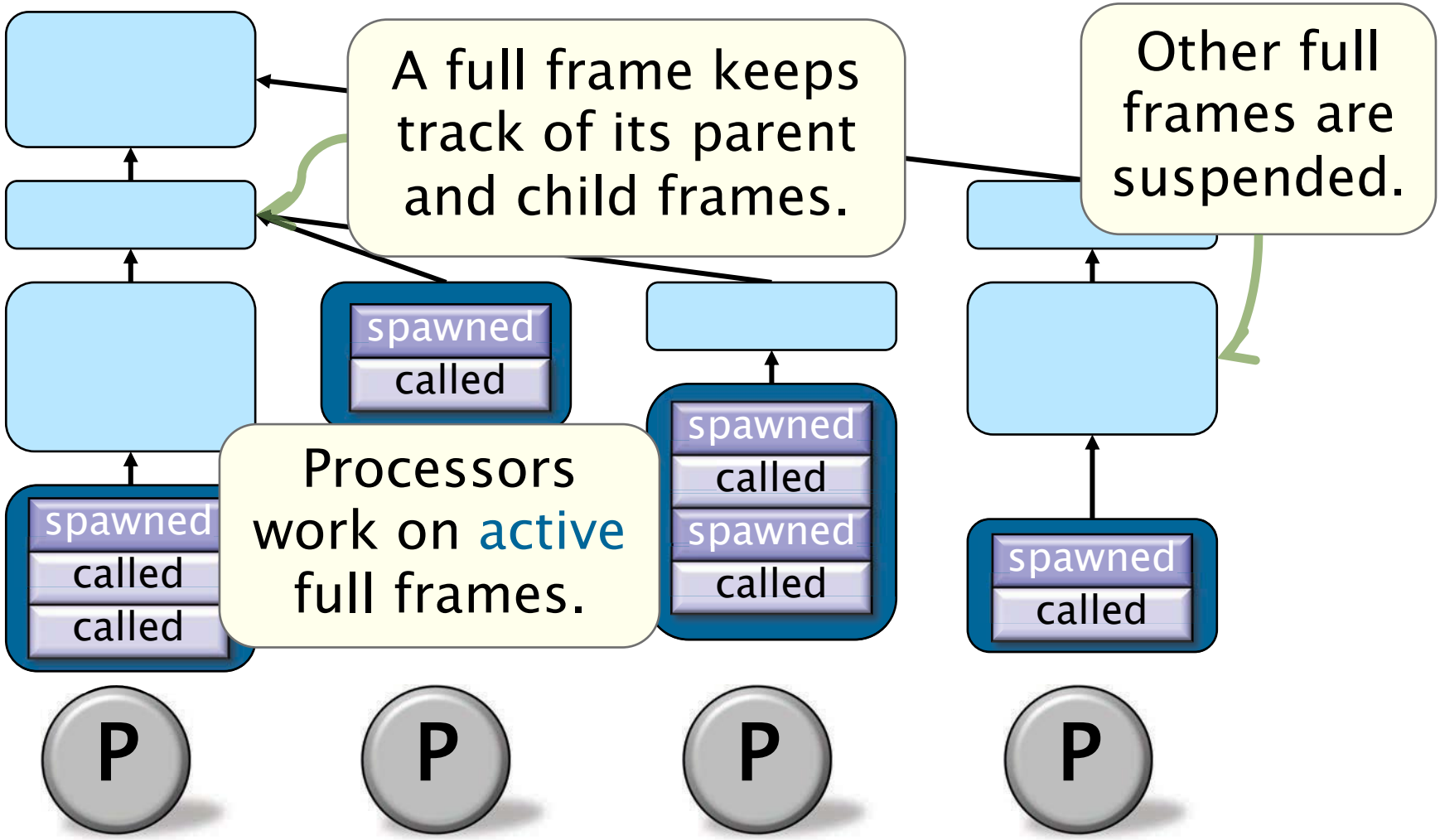
Synchronization Concerns

If a worker reaches a `cilk_sync` before all spawned subcomputations are complete, the worker should become a thief, but the worker's current function frame should not disappear!

- The existing subcomputations might access state in that frame, which is their parent frame.
- In the future, another worker must resume that frame and execute the `cilk_sync`.
- The `cilk_sync` only applies to nested subcomputations of the frame, not to all subcomputations or workers.

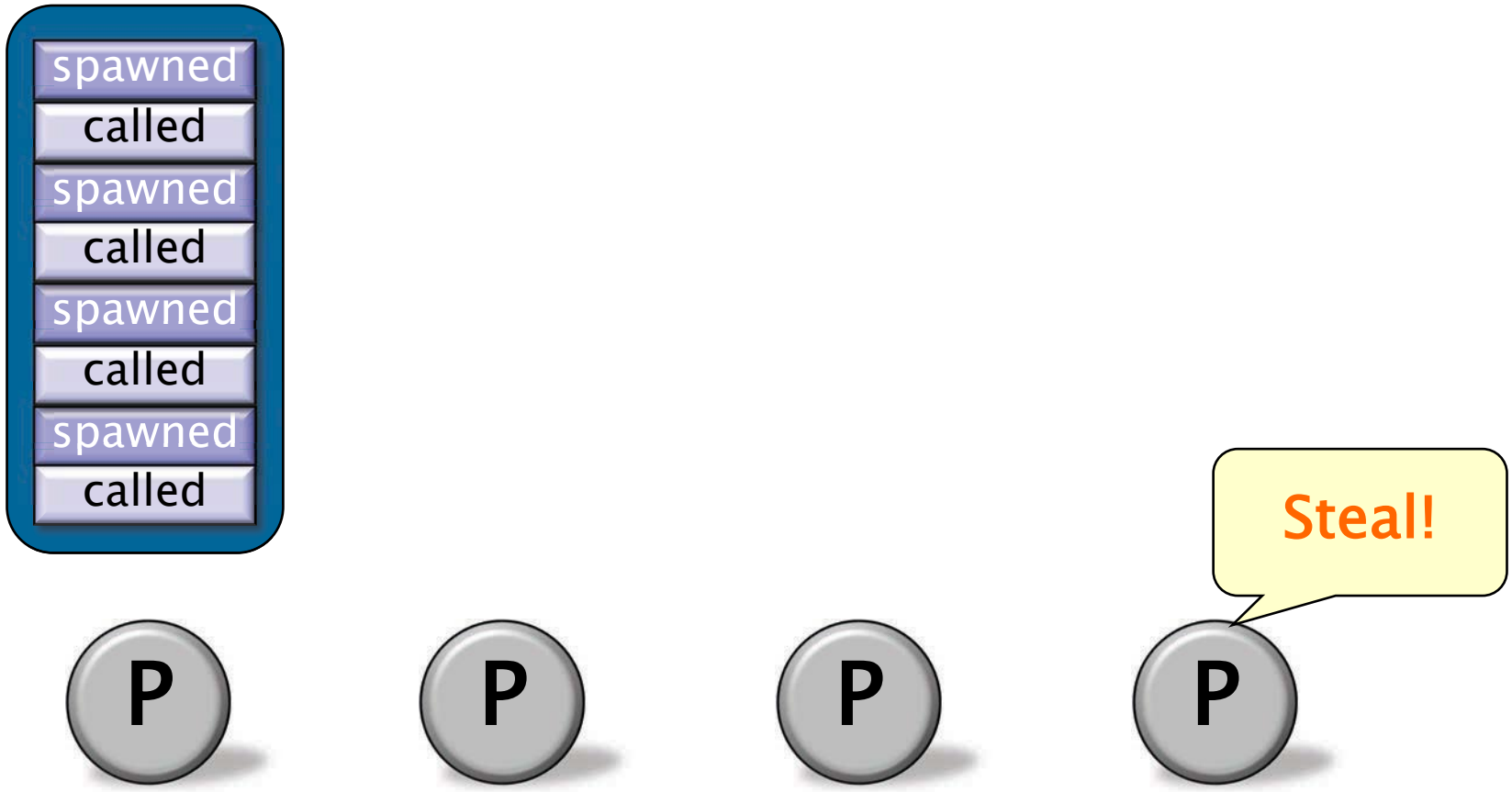
Full-Frame Tree

The Cilk runtime maintains a tree of full frames, which stores state for parallel subcomputations.



Maintaining Full Frames

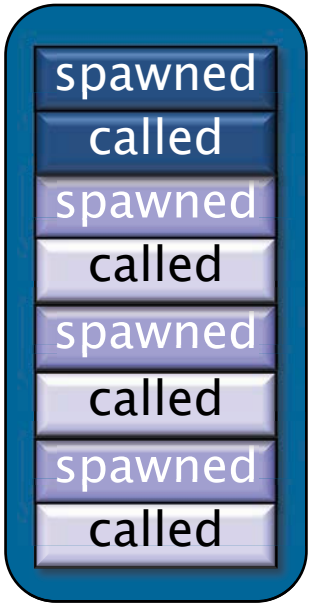
Let's see how steals can produce a tree of full frames.

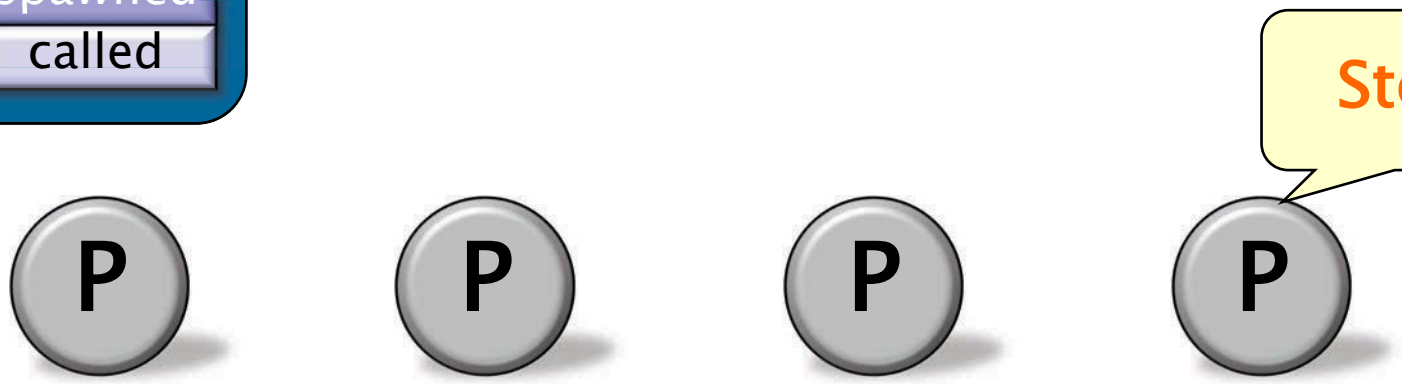


Maintaining Full Frames

Let's see how steals can produce a tree of full frames.

The thief steals the full frame and creates a new full frame for the victim.





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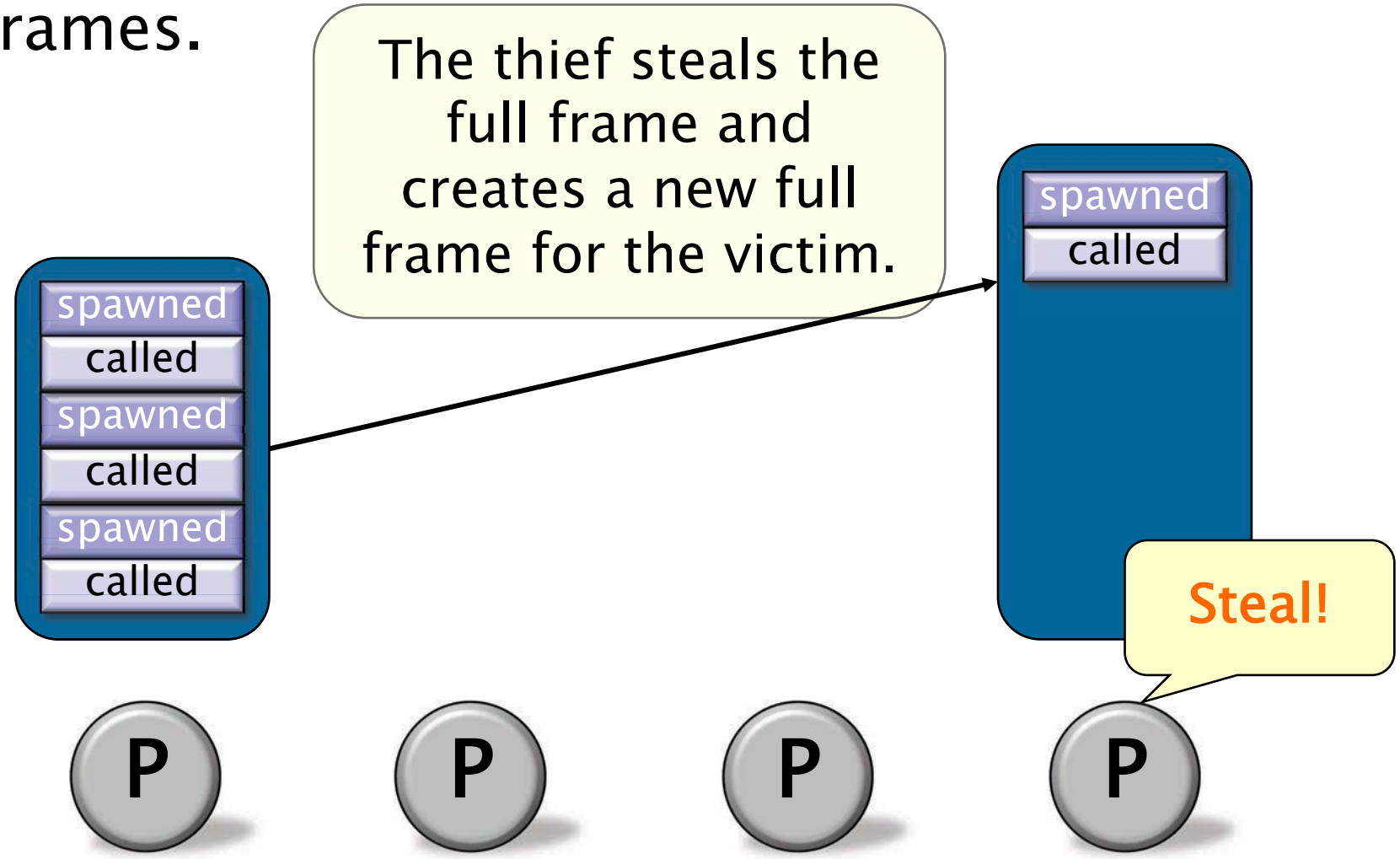

Maintaining Full Frames

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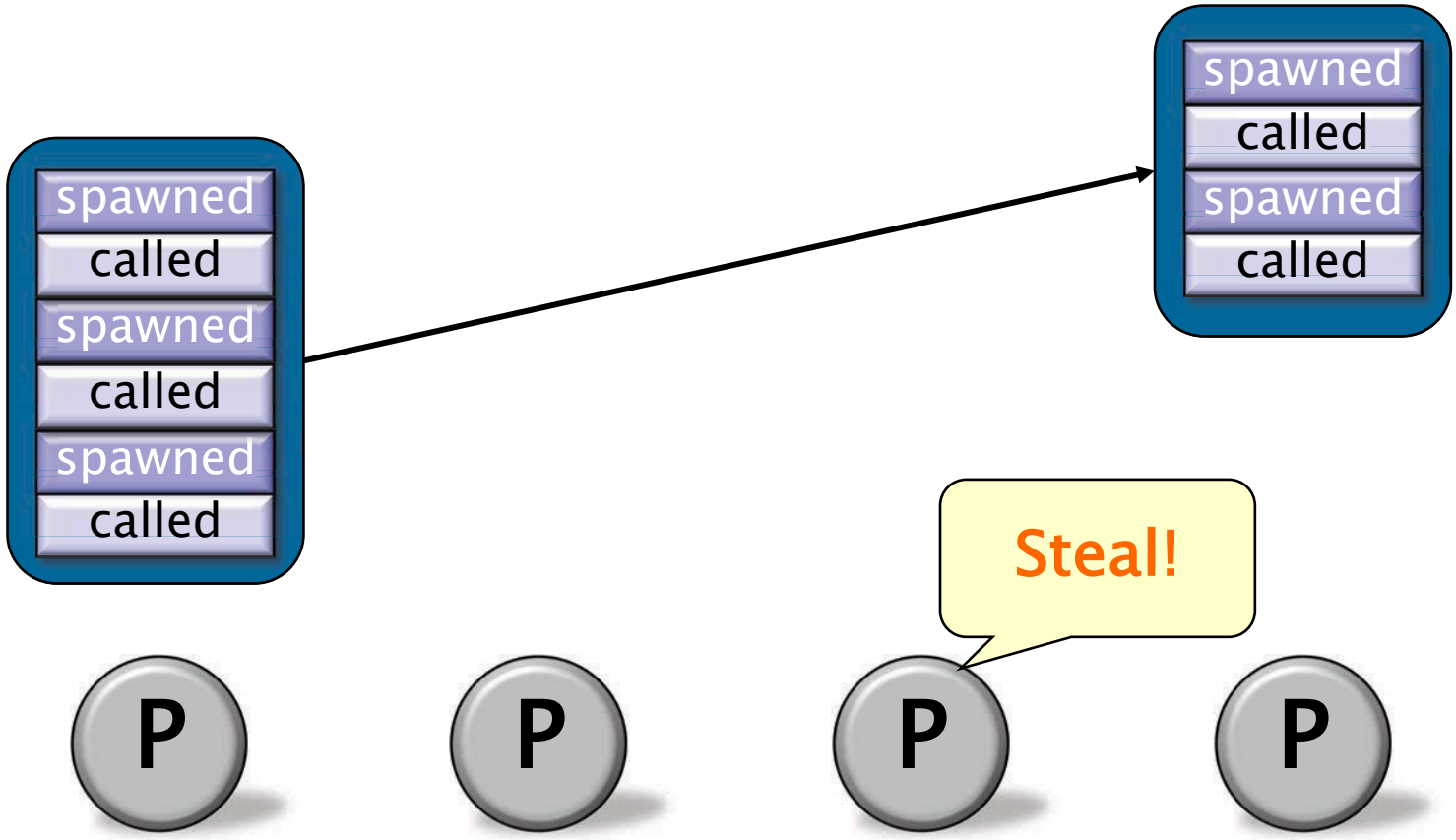
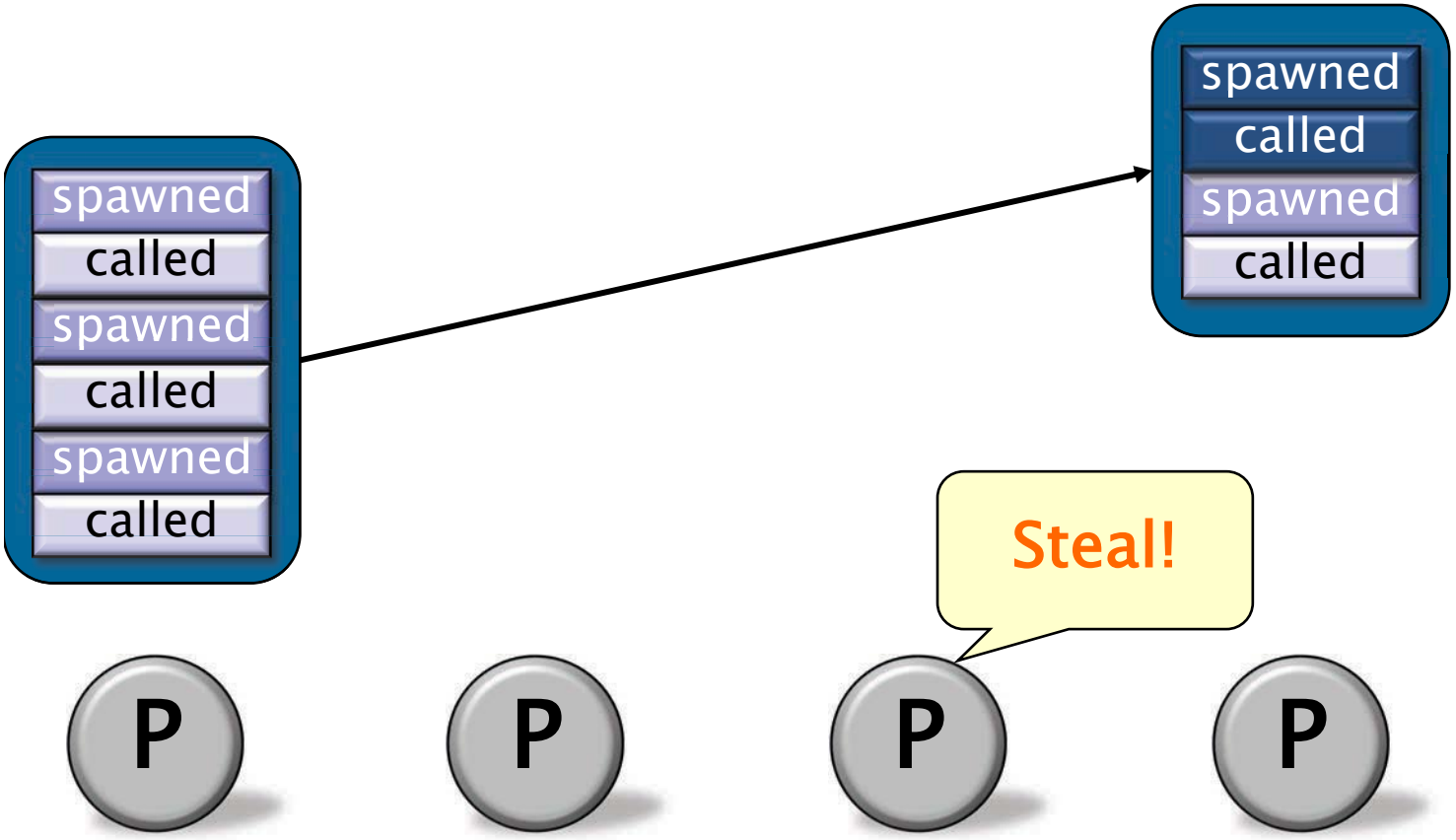


*Full-frame illustrations resized for cleanliness.

Maintaining Full Frames

Let's see how steals can produce a tree of full frames.



Maintaining Full Frames

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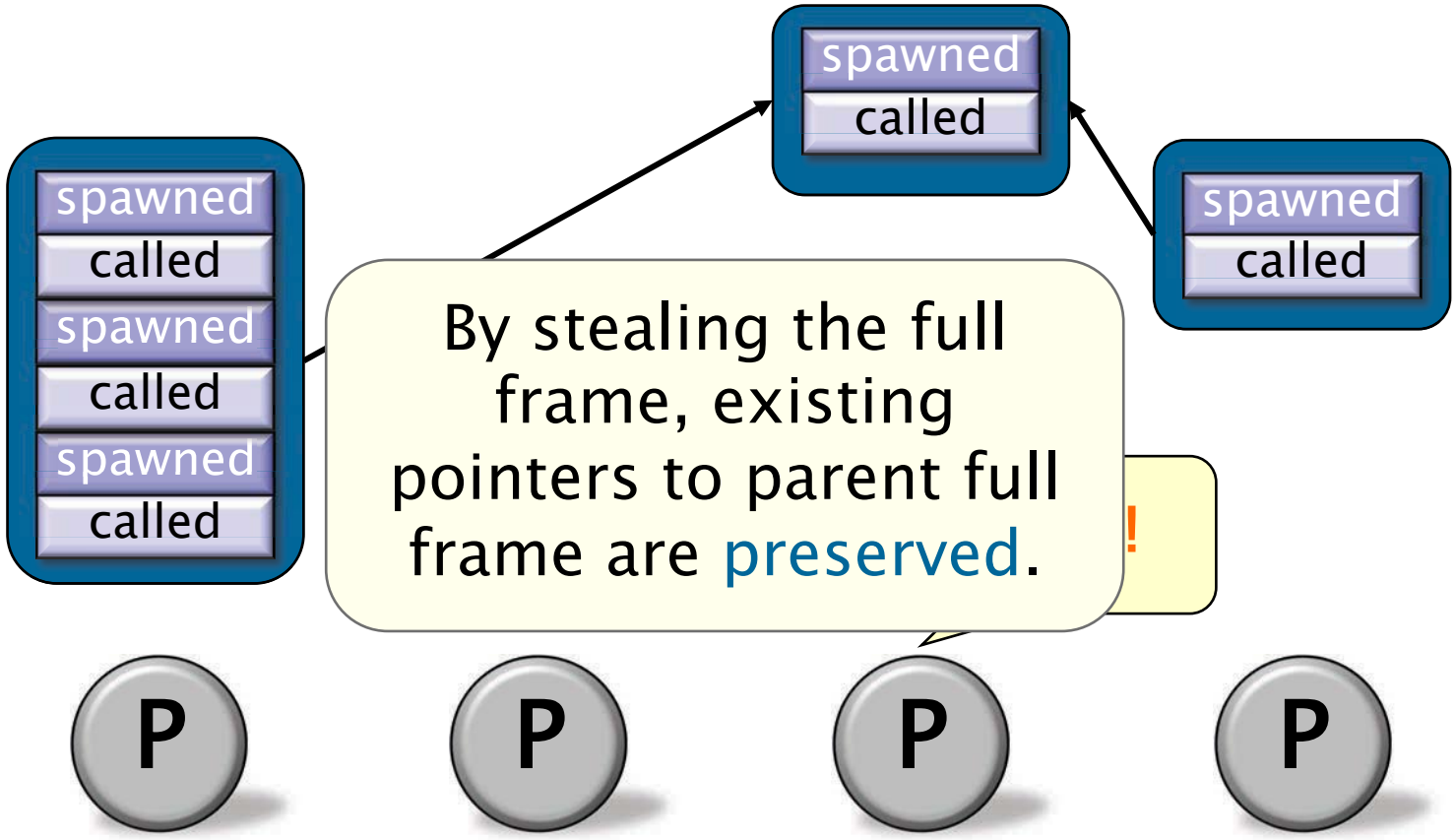

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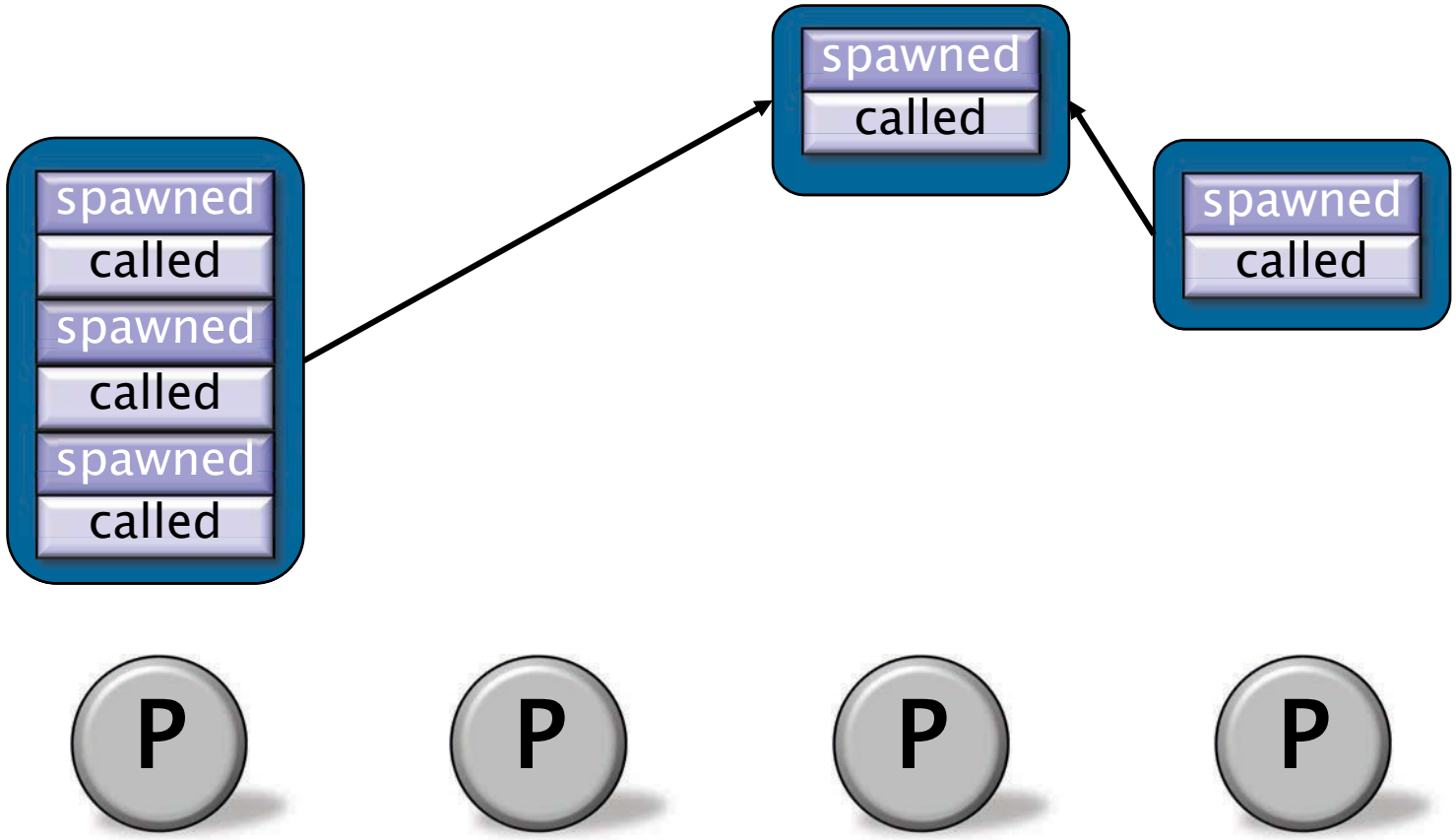

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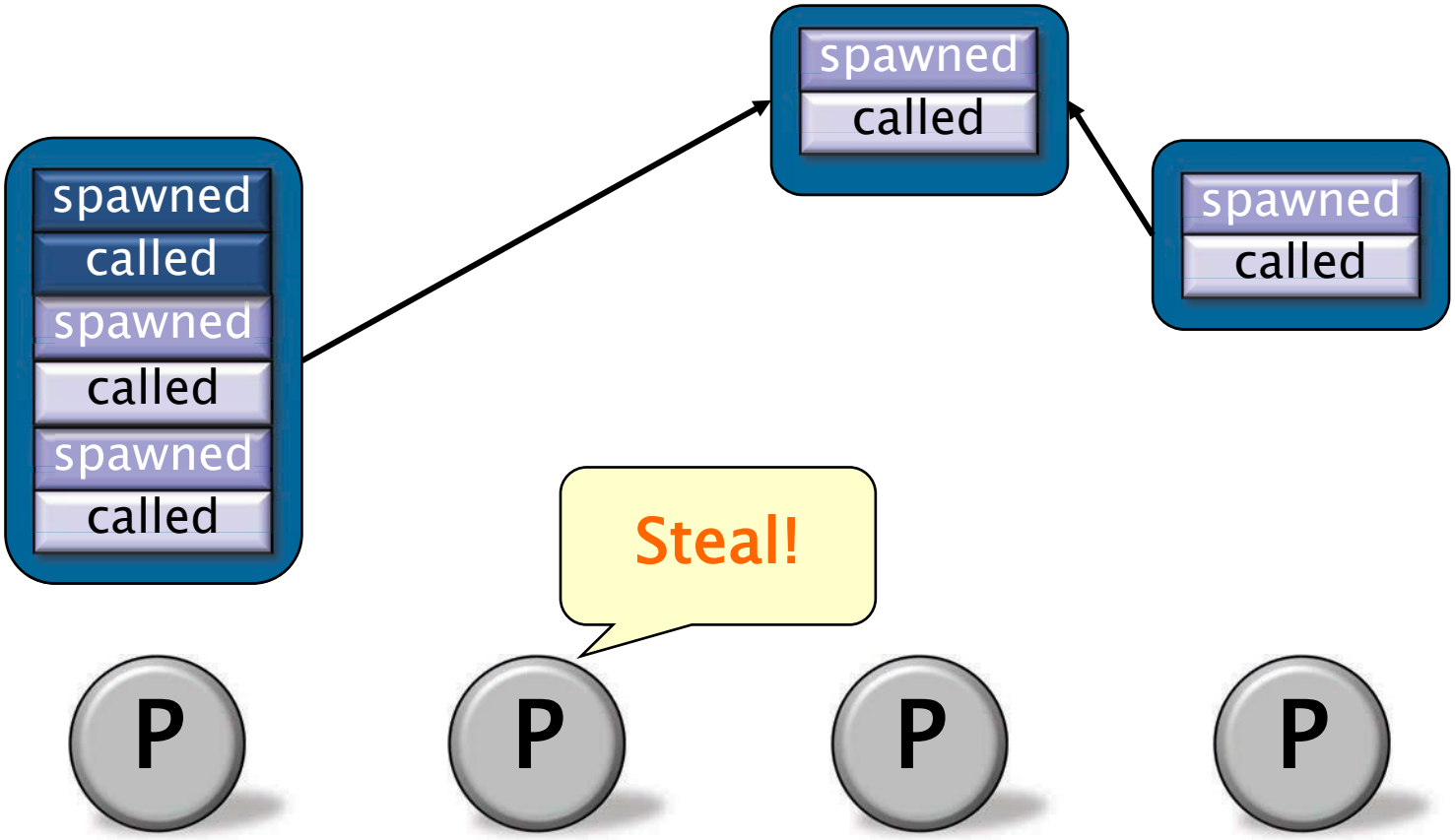

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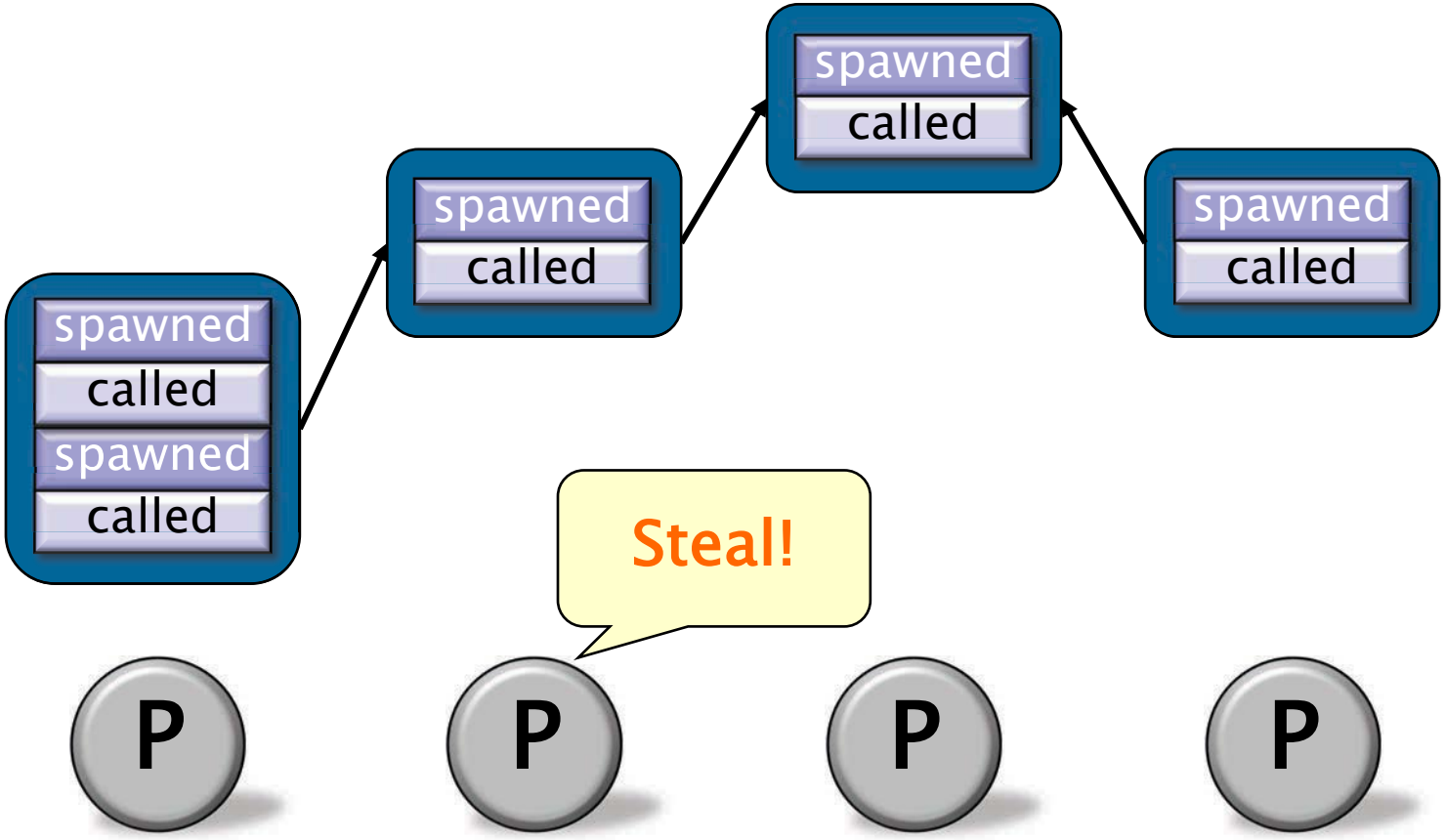
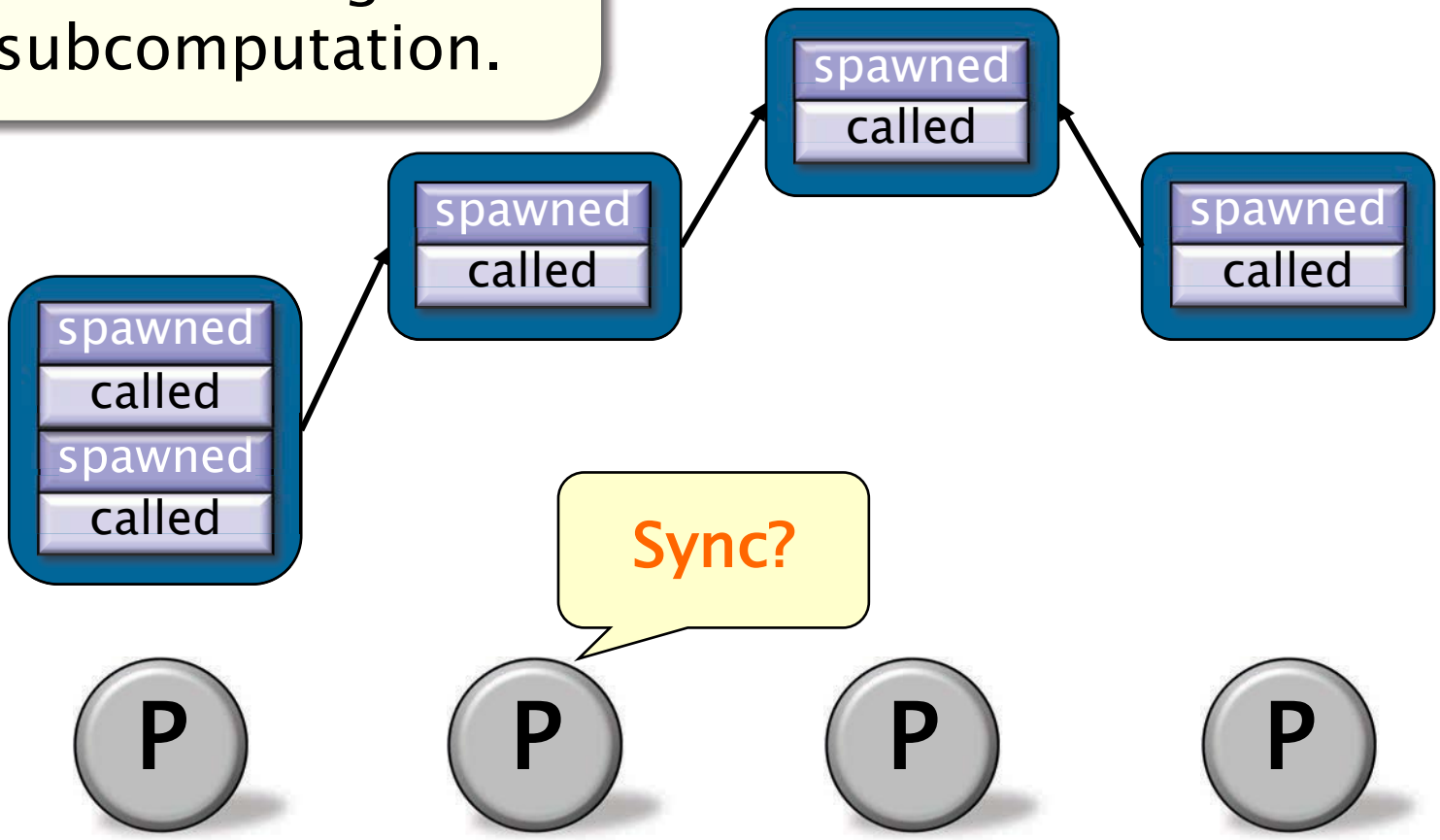


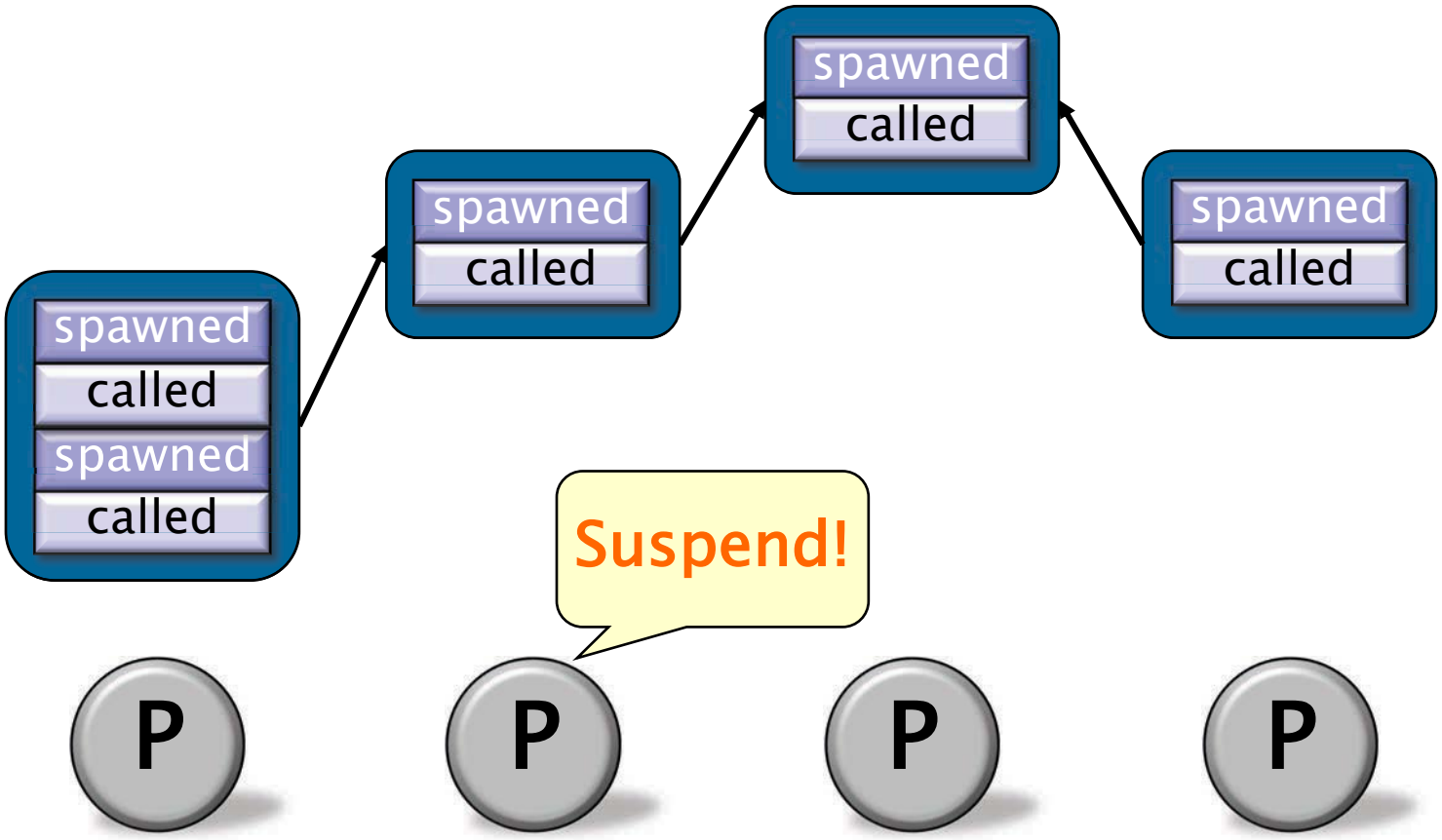
*Full-frame illustrations resized for cleanliness.

Suspending Full Frames

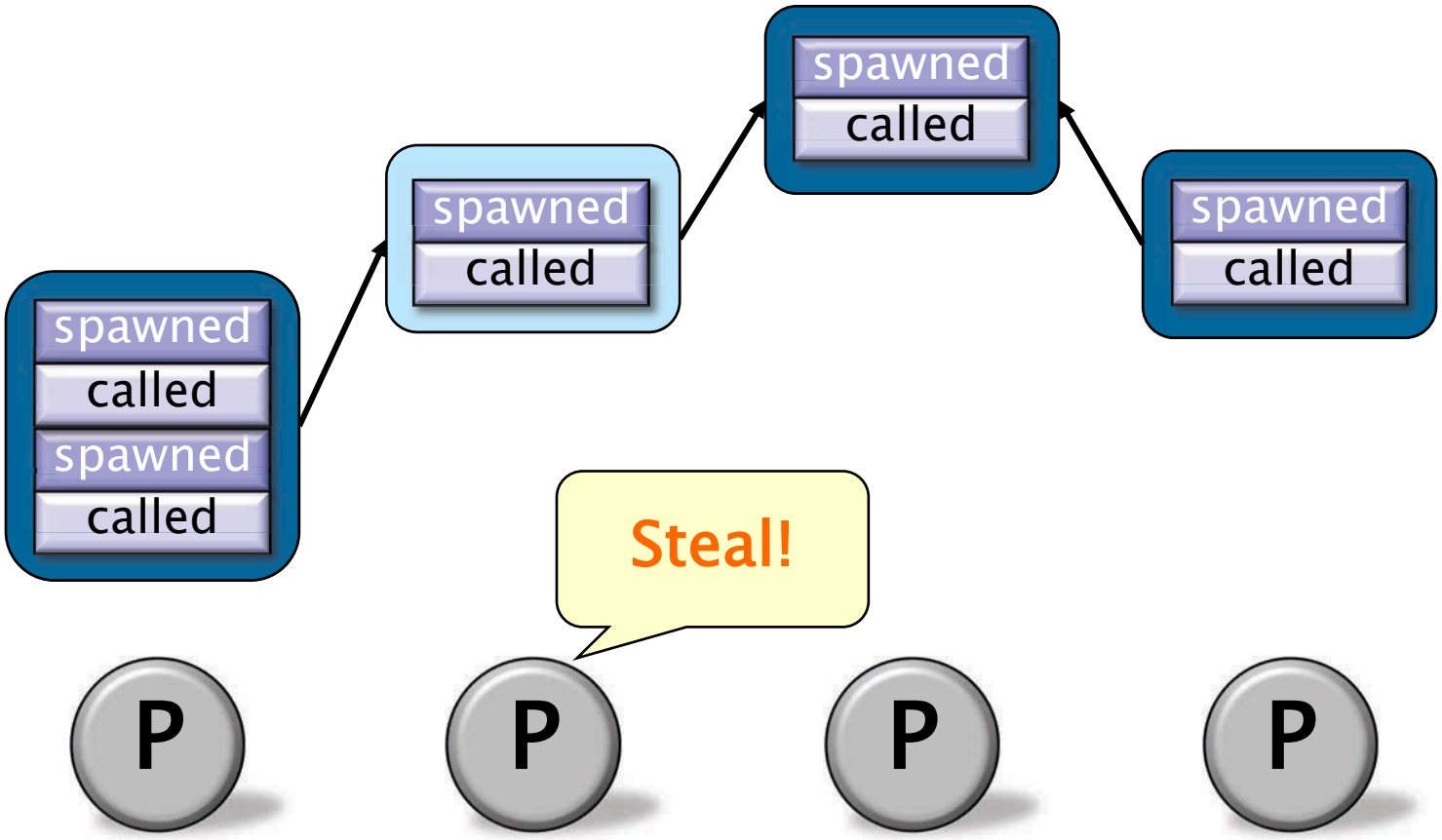
The full frame cannot sync because of the running child subcomputation.



Suspending Full Frames



Suspending Full Frames



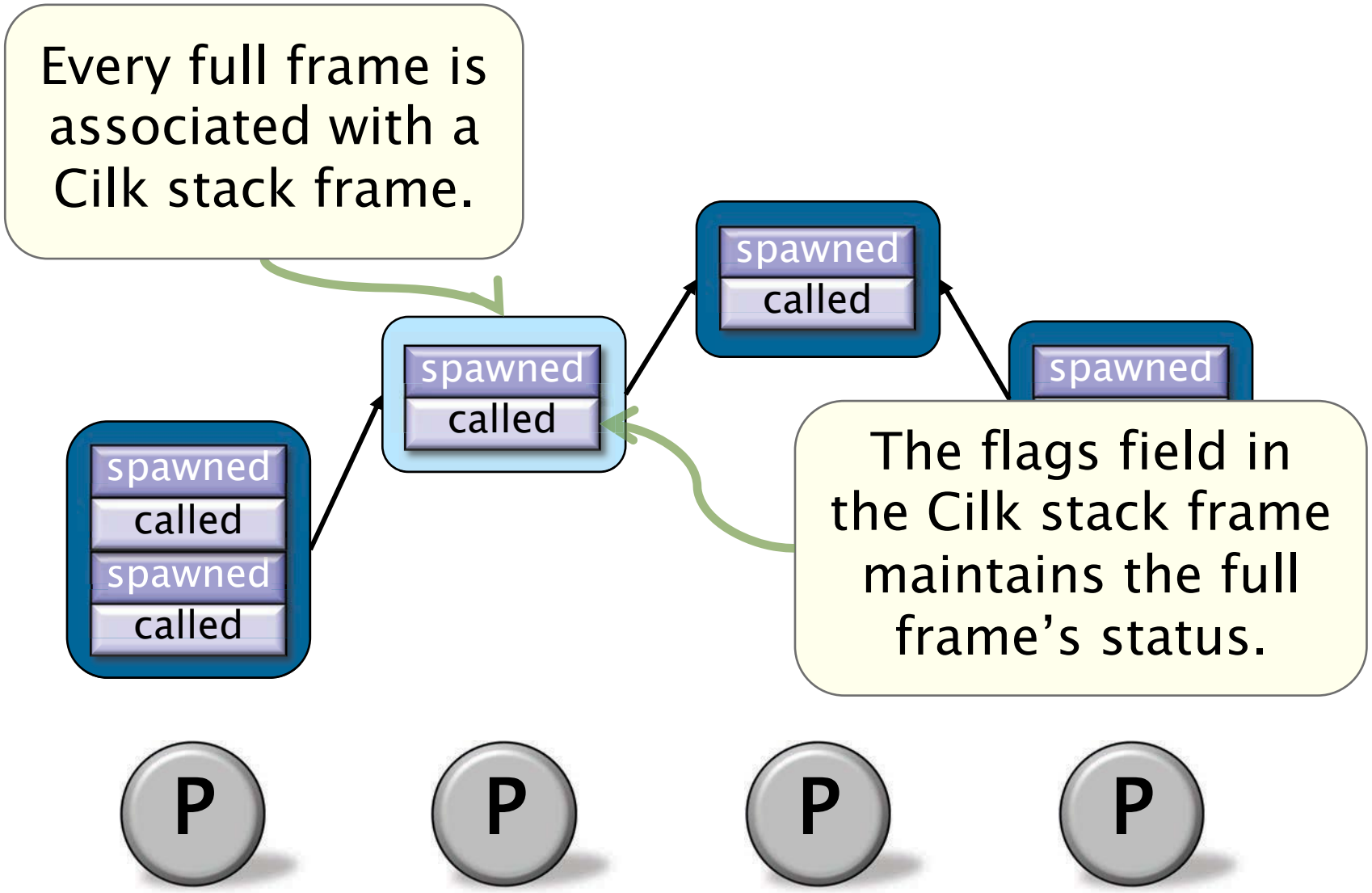
Common Case for Sync

QUESTION: If the program has ample parallelism, what do we expect will typically happen when the program execution reaches a `cilk_sync`?

ANSWER: The executing function contains no outstanding spawned children.

How does the runtime optimize for this case?

Stack Frames and Full Frames



Compiled Code for Sync

Cilk code

```
int foo(int n) {
  int x, y;
  x = cilk_spawn bar(n);
  y = baz(n);
  cilk_sync;
  return x + y;
}
```

C pseudocode

```
int foo(int n) {
  …
  if (sf.flags &
      CILK_FRAME_UNSYNCHED)
    if (!setjmp(sf.ctx))
      __cilkrts_sync(&sf);
  …
}
```

The code compiled to implement a `cilk_sync` checks the flags field before performing an expensive call to `__cilkrts_sync` in the Cilk runtime library.

More Cilk Runtime Features

The Cilk runtime system implements many other features and optimizations:

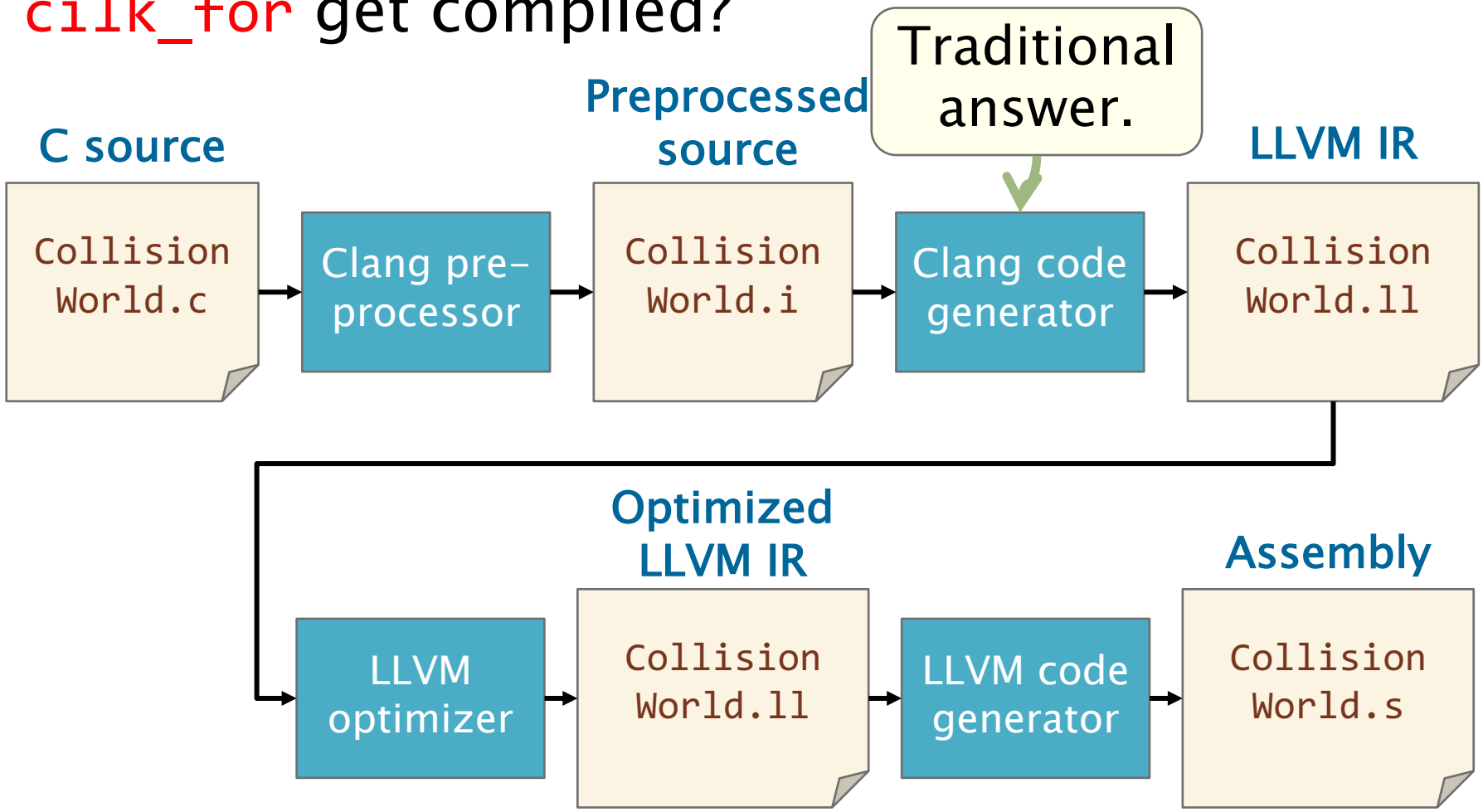
- Schemes for making the full-frame tree simpler and easier to maintain.
- Data structure and protocol enhancements to support C++ exceptions.
- Sibling pointers between full frames to support reducer hyperobjects.
- Pedigrees to assign a unique, deterministic ID to each strand efficiently in parallel.

THE TAPIR COMPILER

[SML17]

Compilation Pipeline

Question: When do `cilk_spawn`, `cilk_sync`, and `cilk_for` get compiled?



Example: Normalize

```
__attribute__((const))
double norm(const double *X, int n);

void normalize(double *restrict Y,
               const double *restrict X,
               int n) {
  for (int i = 0; i < n; ++i)
    Y[i] = X[i] / norm(X, n);
}
```

Test: Random vector of n=64M elements
Machine: AWS c4.8xlarge *Compiler:* GCC 6.2
Running time: $T_S = 0.312$ s

Optimizing the Serial Code

```
__attribute__((const))
double norm(const double *X, int n);

void normalize(double *restri
               const double *
               int n) {
  for (int i = 0; i < n; ++i)
    Y[i] = X[i] / norm(X, n);
}
```

The norm function performs $\Theta(n)$ work.

GCC can move the call to norm out of the serial loop.

Work before hoisting: $T(n) = \Theta(n^2)$

Work after hoisting: $T(n) = \Theta(n)$

GCC Compiling Cilk Code

Cilk code

```
void normalize(double *restrict Y,
               const double *restrict X, int n) {
  cilk_for (int i = 0; i < n; ++i)
    Y[i] = X[i] / norm(X, n);
}
```

Cilk

Helper function encodes the loop body.

Call into Cilk runtime library to execute a cilk_for loop.

C pseudo-code

```
void normalize(double *restrict Y,
               const double *restrict X, int n) {
  struct args_t args = { Y, X, n };
  __cilkrts_cilk_for(normalize_helper, args, 0, n);
}
void normalize_helper(struct args_t args, int i) {
  double *Y = args.Y;
  double *X = args.X;
  int n = args.n;
  Y[i] = X[i] / norm(X, n);
}
```

The compiler can't move norm out of the loop.

Performance of Parallel Normalize

```
__attribute__((const))
double norm(const double *X

void normalize(double *restrict Y,
               const double *restrict X,
               int n) {
  cilk_for (int i = 0;
    Y[i] = X[i] / norm
}
```

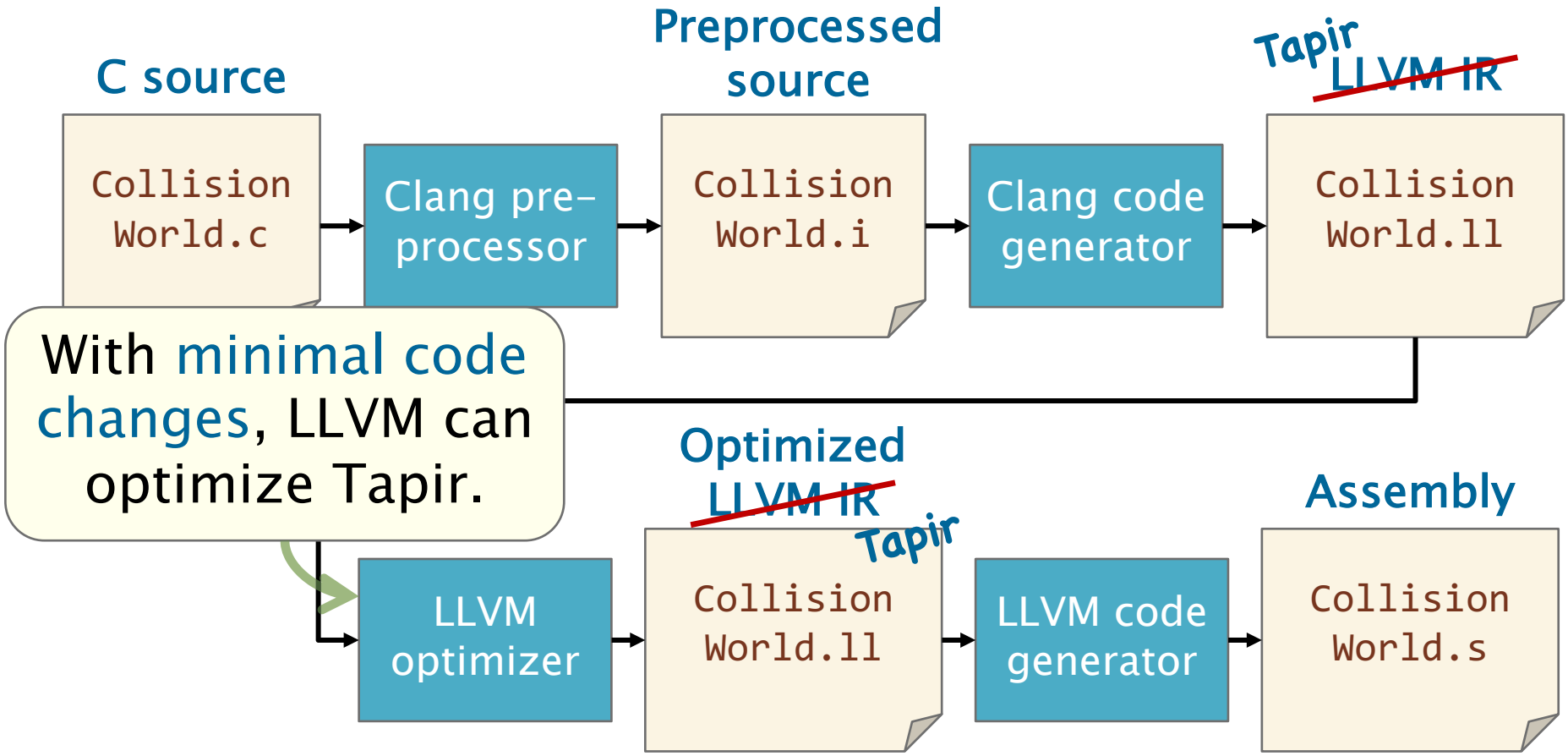
The norm function was also parallelized.

Terrible work efficiency!
$T_S/T_1 = 0.312/2600$
$\sim 1/8600$

Test: Random vector of n=64M elements
Machine: AWS c4.8xlarge *Compiler:* GCC 6.2
Running time of serial code: $T_S = 0.312$ s
18-core running time: $T_{18} = 180.657$ s
1-core running time: $T_1 = 2600.287$ s

Tapir's Compilation Pipeline

Tapir embeds fork-join parallelism into LLVM's IR.



Unsafe Optimizations

Problem: There are many examples of optimizations on serial code that cannot be safely applied to parallel code [MP90].

Cilk code

```
void foo(int n) {
  cilk_for (int i = 0; i < n; ++i)
    bar(5*i);
}
```

Incorrectly optimized Cilk code

```
void foo(int n) {
  int tmp = 0;
  cilk_for (int i = 0; i < n; ++i) {
    bar(tmp);
    tmp += 5;
  }
}
```

Unleashing LLVM on parallel programs requires some care.

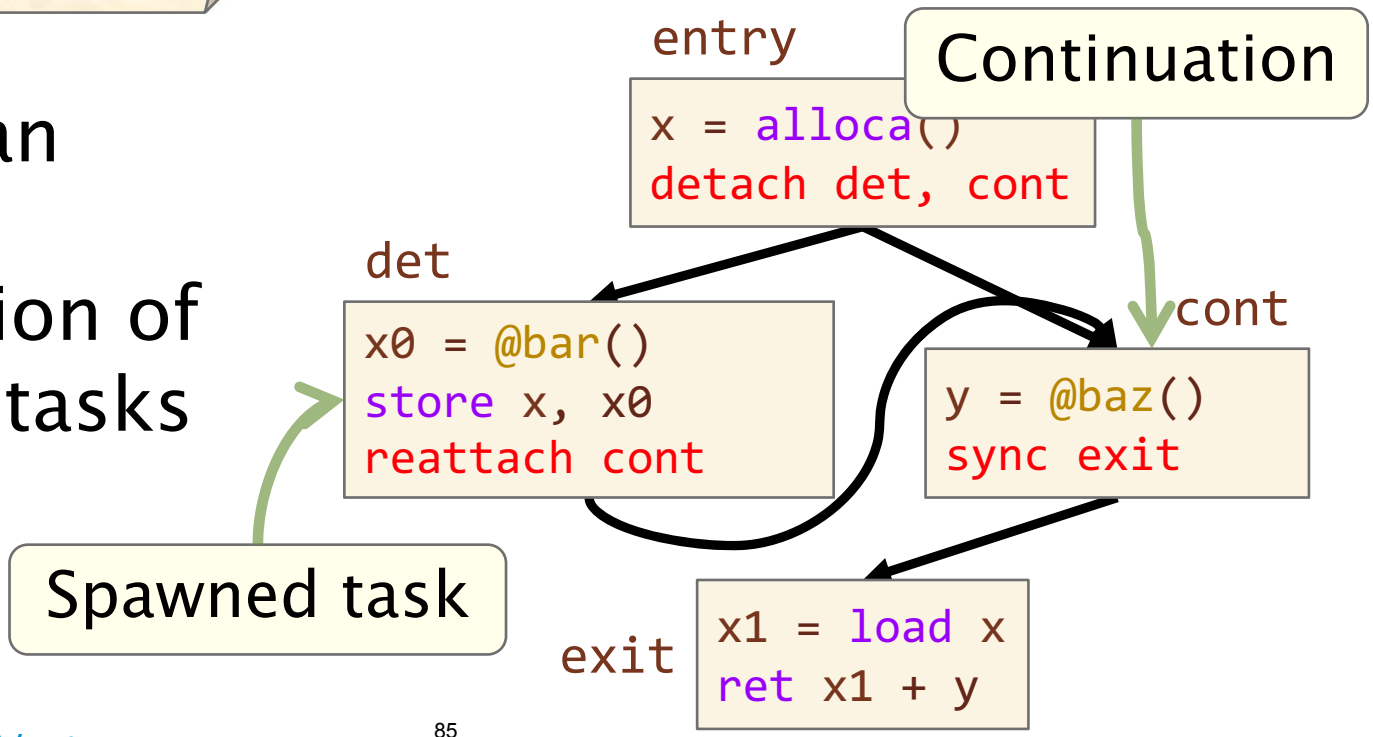
A Tapir CFG

```
int foo(int n) {
  int x, y;
  x = cilk_spawn bar(n);
  y = baz(n);
  cilk_sync;
  return x + y;
}
```

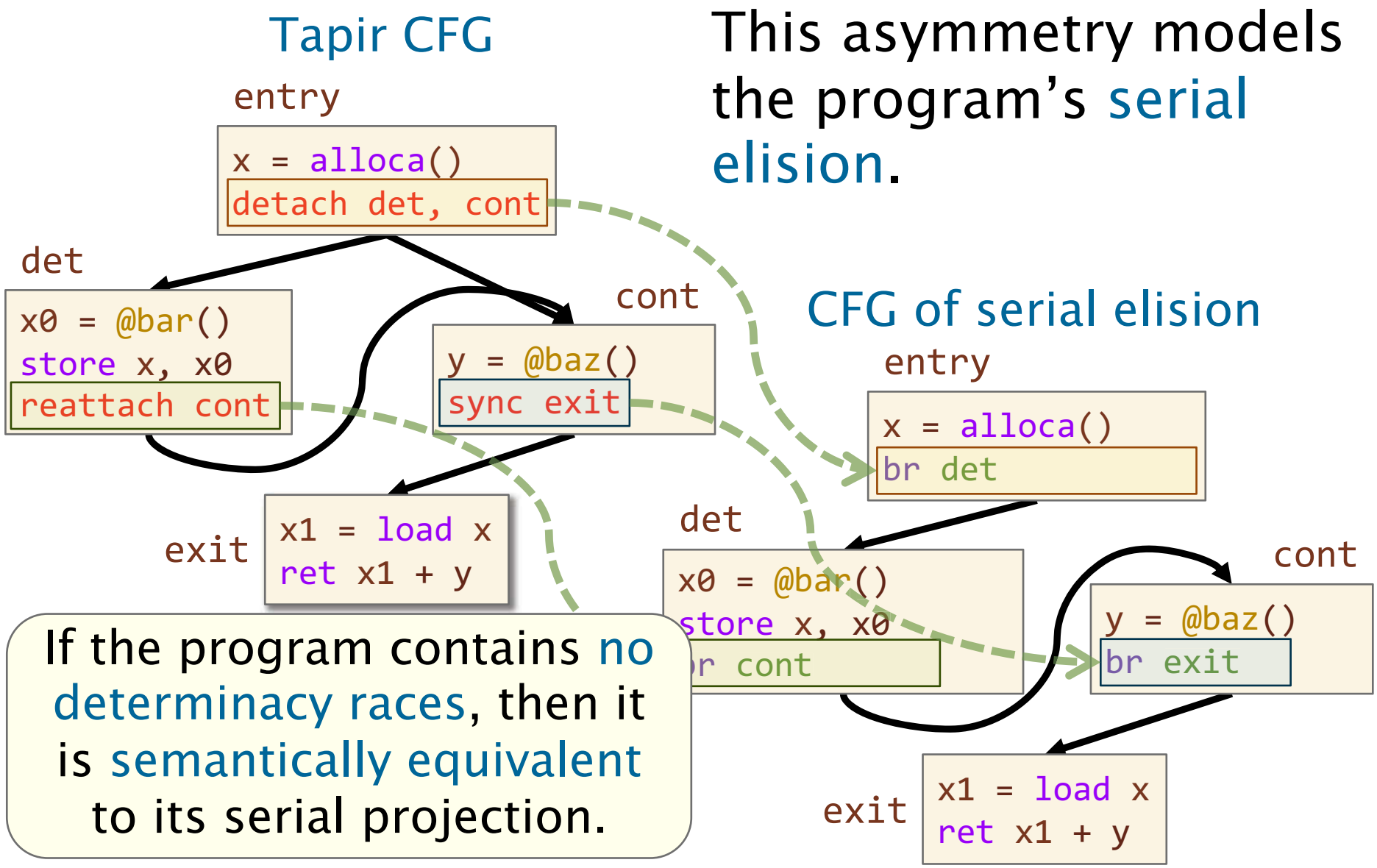
Tapir adds three constructs to LLVM's IR: detach, reattach, and sync.

Tapir uses an asymmetric representation of the parallel tasks in the CFG.

Tapir control-flow graph

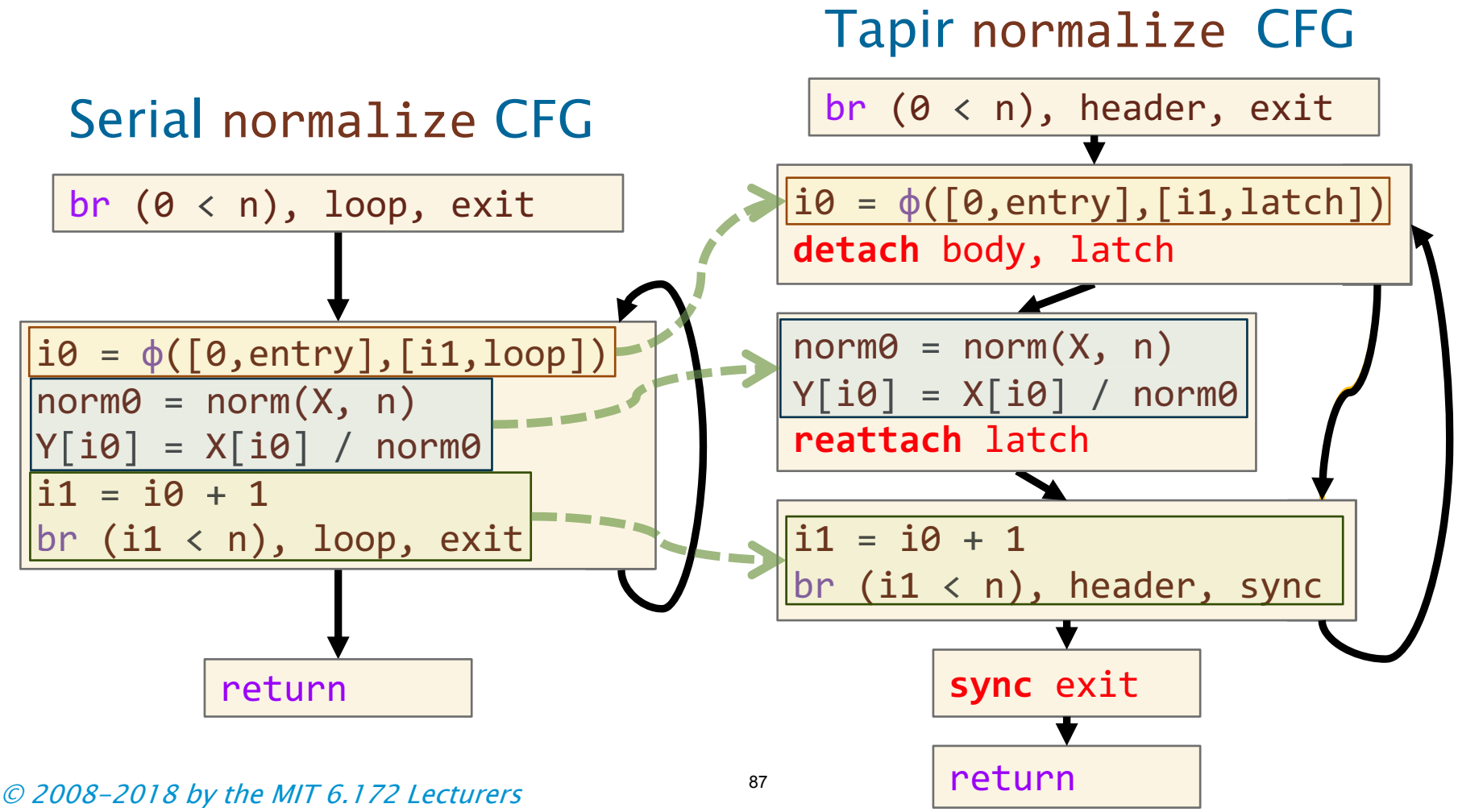


Serial Elision



Parallel Loops in Tapir

In Tapir, parallel loops look similar to serial loops, with some differences due to parallelism.



Impact on LLVM

LLVM can reason about a Tapir CFG as a relatively minor change to the CFG of the serial elision.

- Many standard compiler analyses required no changes.
- Memory analysis required a minor change to handle Tapir's constructs (~450 lines of code).
- Some optimizations, e.g., code hoisting and tail-recursion elimination, required some changes to work on Tapir CFG's.

In total, implementing Tapir involved adding or modifying ~6000 lines of LLVM's 4-million-line codebase.

Parallelize Normalize with Tapir

```
__attribute__((const))
double norm(const double *X, int n);

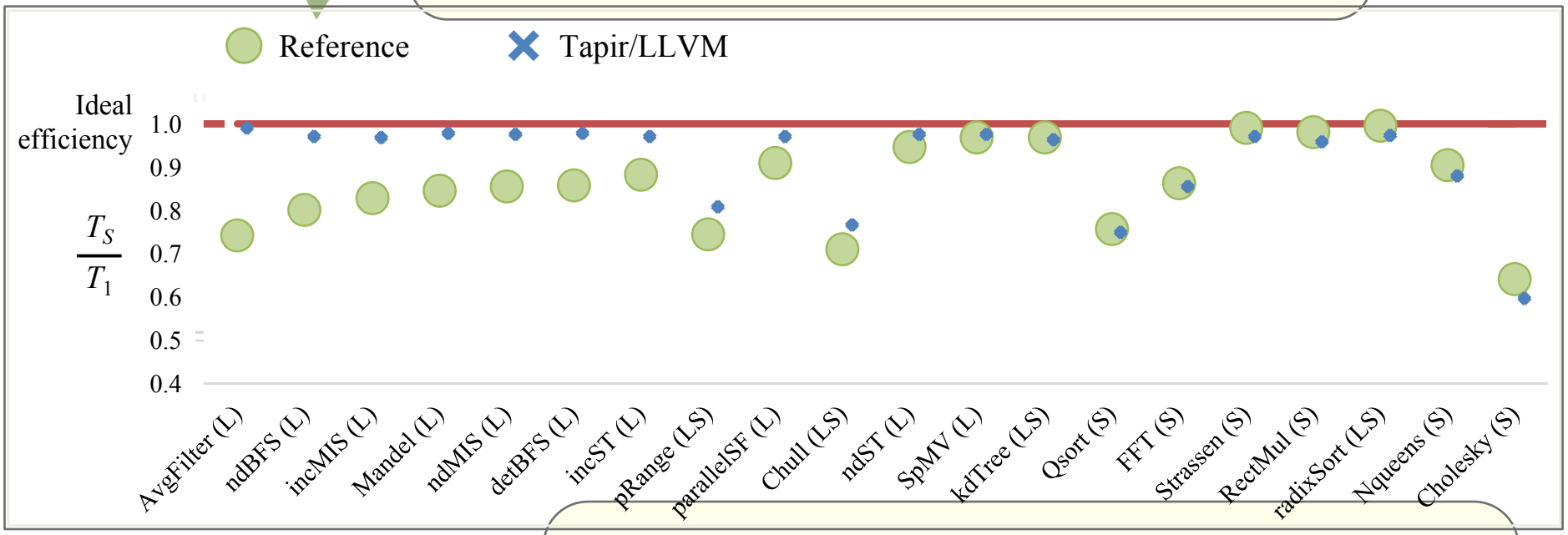
void normalize(double *restrict Y,
               const double *restrict X,
               int n) {
  cilk_for (int i = 0; i
    Y[i] = X[i] / norm(X
}
```

Good work efficiency:
$T_S/T_1 = 97\%$

Test: Random vector of n=64M elements
Machine: AWS c4.8xlarge *Compiler:* Tapir/LLVM
Running time of serial code: $T_S = 0.312$ s
1-core running time: $T_1 = 0.321$ s
18-core running time: $T_{18} = 0.081$ s

Work-Efficiency Improvement

Same as Tapir/LLVM except that Cilk constructs are compiled early.



Tapir/LLVM doesn't fix everything, but it helps parallel programs achieve good work efficiency.

CASE STUDY: OPENMP

Example: OpenMP Normalize

```
__attribute__((const))
double norm(const double *X

void normalize(double *restrict Y,
               const double *restrict X,
               int n) {
  agma omp parallel for
  (int i = 0; i < n; ++i)
[i] = X[i] / norm(X, n);
}
```

The norm function was also parallelized.

Why do we get this performance?

Good work efficiency without Tapir?

Test: Random vector of n=64M elements

Machine: AWS c4.8xlarge *Compiler:* GCC 6.2

Running time of serial code: $T_S = 0.312$ s

1-core running time: $T_1 = 0.329$ s

18-core running time: $T_{18} = 0.205$ s

Parallel speedup is not great.

GCC Compiling OpenMP Code

OpenMP code

```
void normalize(double *restrict Y,
               const double *restrict X, int n) {
  #pragma omp parallel for
  for (int i = 0; i < n; ++i)
    Y[i] = X[i] / norm(X, n);
}
```

Each processor invokes this helper method on n/P iterations.

The helper function's loop on n/P iterations can be optimized.

```
void normalize(double *restrict Y,
               const double *restrict X, int n) {
  __kmpc_fork_call(omp_outlined, n, Y, X);
}
void omp_outlined(int n, double *restrict Y,
                  const double *restrict X) {
  int local_n = n; double *local_Y = Y, *local_X = X;
  __kmpc_for_static_init(&local_n, &local_Y, &local_X);
  double tmp = norm(X, n);
  for (int i = 0; i < local_n; ++i)
    local_Y[i] = local_X[i] / tmp;
  __kmpc_for_static_fini();
}
```

Analysis of OpenMP Normalize

Each processor invokes omp_outlined on n/P iterations.

The norm function performs Θ(n) work.

The variable local_n is approximately n/P.

```
*restrict Y,
uble *restric
_outlined, n, Y, X);
}
void omp_outlined(int n, double *restrict Y,
                  const double *
  int local_n = n; double *local
  __kmpc_for_static_init(&local_
  double tmp = norm(X, n);
  for (int i = 0; i < local_n; ++i)
    local_Y[i] = local_X[i] / tmp;
  __kmpc_for_static_fini();
}
```

Work of omp_outlined: $T(n) = \Theta(n)$

Total work on P processors: $T(n) = \Theta(Pn)$

Summary of OpenMP Normalize

```
__attribute__((const))
double norm(const double *X, int n);

void normalize(double *restrict Y,
               const double *restrict X,
               int n) {
  #pragma omp parallel for
  for (int i = 0; i < n; ++i)
    Y[i] = X[i] / norm(X, n);
}
```

Work on P processors:
$T(n) = \Theta(Pn)$

- This code is only work efficient on 1 processor.
- This code can never achieve more than minimal parallel speedup.

Takeaways

The work-first principle

Optimize for *ordinary serial execution*, at the expense of some additional computation in steals.

Two more takeaways:

- Think about the performance model for your program.
- Know what your parallel runtime system is doing.