A Quick Introduction To The Intel Cilk Plus Runtime

6.S898: Advanced Performance Engineering for Multicore Applications
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Cilk Language Constructs

Cilk extends C and C++ with three keywords to expose task parallelism: `cilk_spawn`, `cilk_sync`, and `cilk_for`.

Cilk Fibonacci code

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

The child function is **spawned**: It is **allowed** (but not required) to execute in parallel with the parent caller.

Control cannot pass this point until the function is **synched:** all spawned children have returned.

Simple Cilk Example: Fib

How is a Cilk program compiled and executed in parallel?

Cilk Fibonacci code

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

1. The **compiler** takes program and generates assembly with calls to the Cilk Plus runtime library, `libcilkrts.so`.

2. When executing a program, the **runtime library** is dynamically loaded and handles scheduling of the program on multiple worker threads.

What Do the Compiler and Runtime Do?

Cilk Fibonacci code

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

→ **Compiler** →

```
int fib(int n) {
  __cilkrts_stack_frame_t sf;
  __cilkrts_enter_frame(&sf);
  if (n < 2) return n;
  int x, y;
  if (!setjmp(sf.ctx))
    spawn_fib(&x, n);
  y = fib(n-2);
  if (sf.flags & CILK_FRAME_UNSYNCHED)
    if (!setjmp(sf.ctx))
      (&sf);
  int result = x + y;
  (&sf);

    frame(&sf);
  return result;
}

void spawn_fib(int *x, int n) {
  __cilkrts_stack_frame sf;
  __cilkrts_enter_frame_fast(&sf);
  __cilkrts_detach();
  *x = fib(n-1);
  __cilkrts_pop_frame(&sf);
  if (sf.flags)
    __cilkrts_leave_frame(&sf);
}
```

Cilk runtime sche

```
// …
static cilk_fiber* worker_schedul
                                              void* wptr)
{
    __cilkrts_worker *w = (__cilkrts_worker*) wptr;
    CILK_ASSERT(current_fiber == w->l->scheduling_fiber);

    // Stage 1: Transition from executing user code to the runtime code.
    // We don't need to do this call here any more, because
    // every switch to the scheduling fiber should make this call
    // using a post_switch_proc on the fiber.
    //
    //  enter_runtime_transition_proc(w->l->scheduling_fiber, wptr);

    // After Stage 1 is complete, w should no longer have
    // an associated full frame.
    CILK_ASSERT(NULL == w->l->frame_ff);

    // Stage 2.  First do a quick check of our 1-element queue.
    full_frame *ff = pop_next_frame(w);

    if (!ff) {
        // Stage 3.  We didn't find anything from our 1-element
        // queue.  Now go through the steal loop to find work.
        ff = search_until_work_found_or_done(w);
```

Today: Dive into some of this code.

Organization of Runtime Source Code

The Intel Cilk Plus runtime source code is available online:
`https://bitbucket.org/intelcilkruntime/intel-cilk-runtime`

- Basic data structures: `include/internal/abi.h`
- Compiler-inserted runtime calls: `runtime/cilk-abi.c`
- Runtime data structures: `runtime/full_frame.h`, `runtime/full_frame.c`, `runtime/local_state.h`
- Heart of the Cilk Plus scheduler: `runtime/scheduler.c`

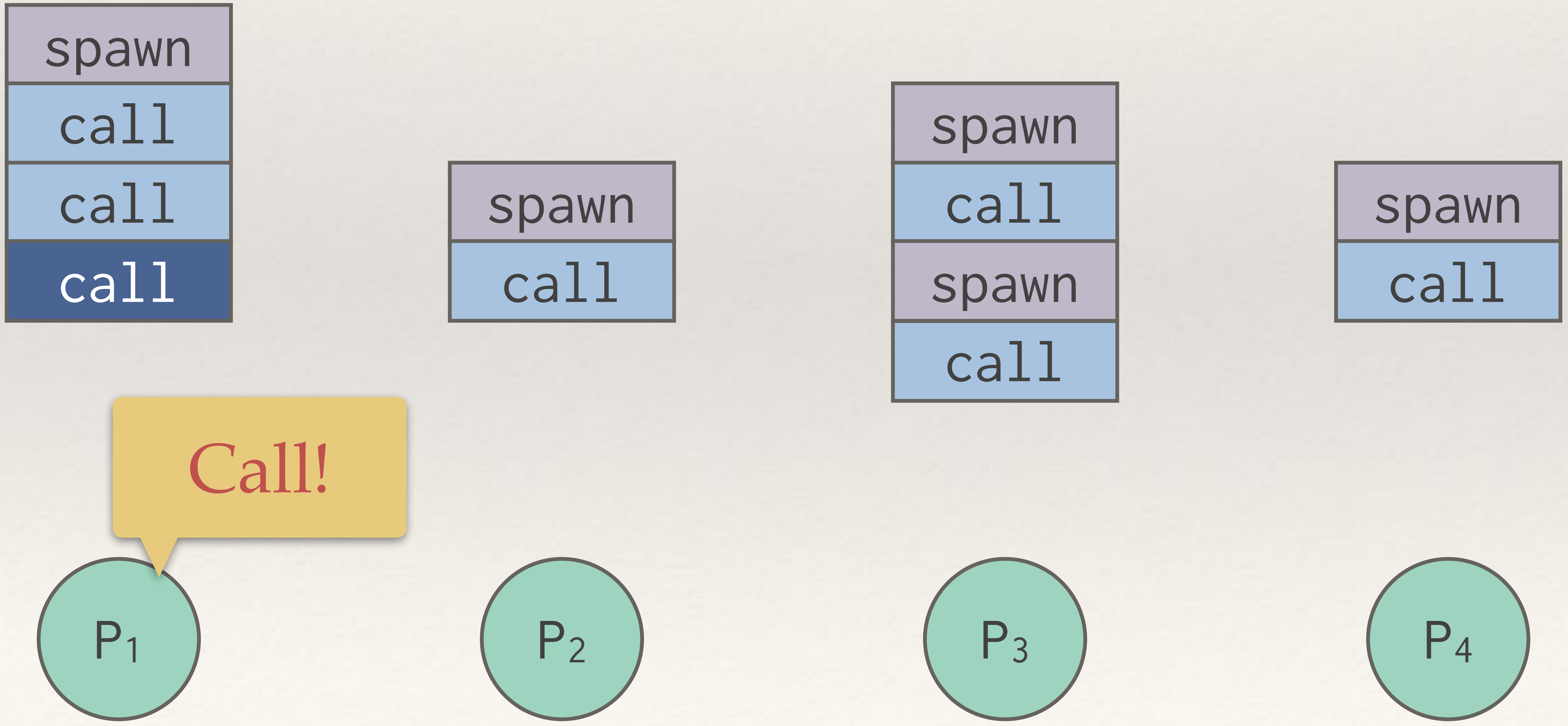
Outline

- Review of randomized work stealing
- Compiler and runtime internals
  - Fast path: executing with no steals
  - Data structures for steals
  - Steals: the ugly details

Randomized Work Stealing: Working

Each worker maintains a **work deque** of ready strands, and it manipulates the bottom of the deque like a stack

[MKH90, BL94, FLR98].



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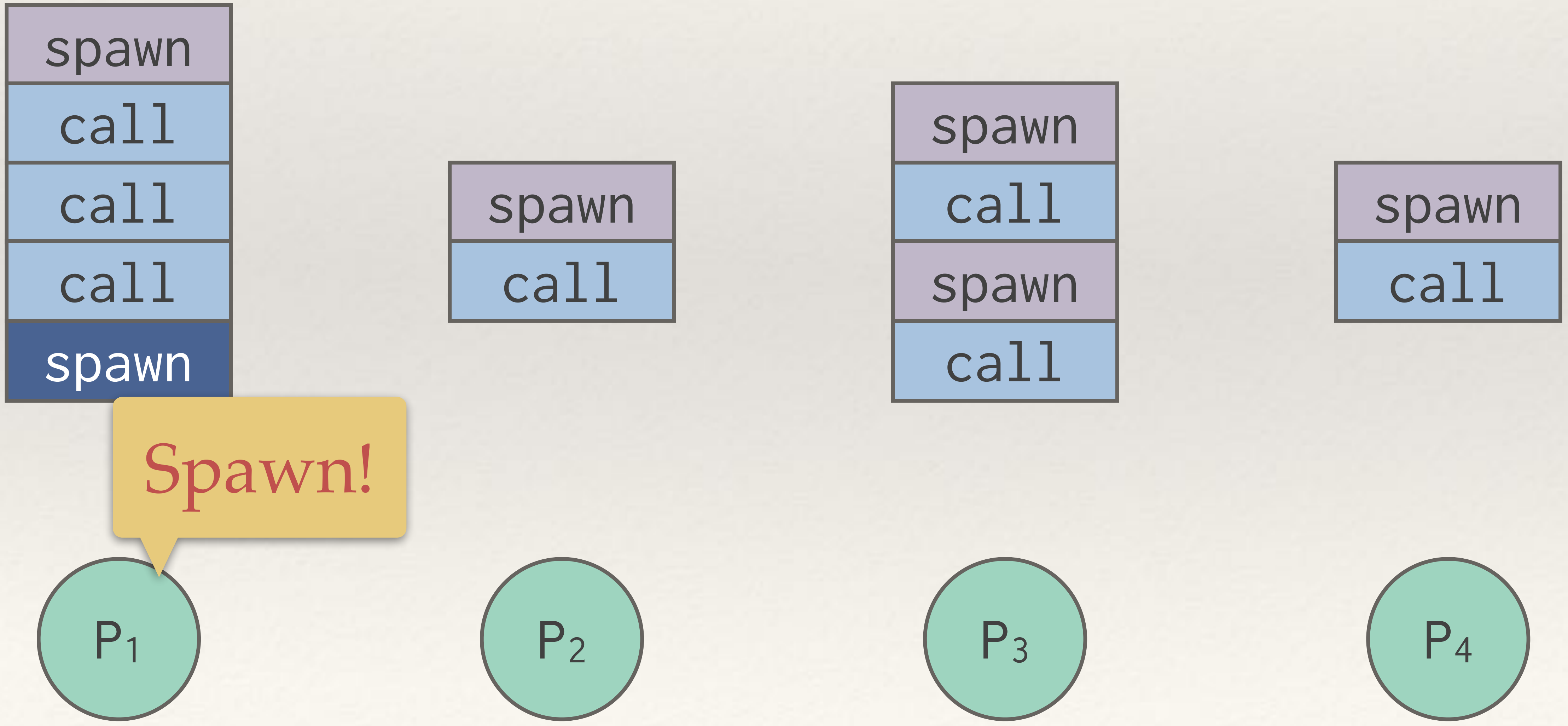

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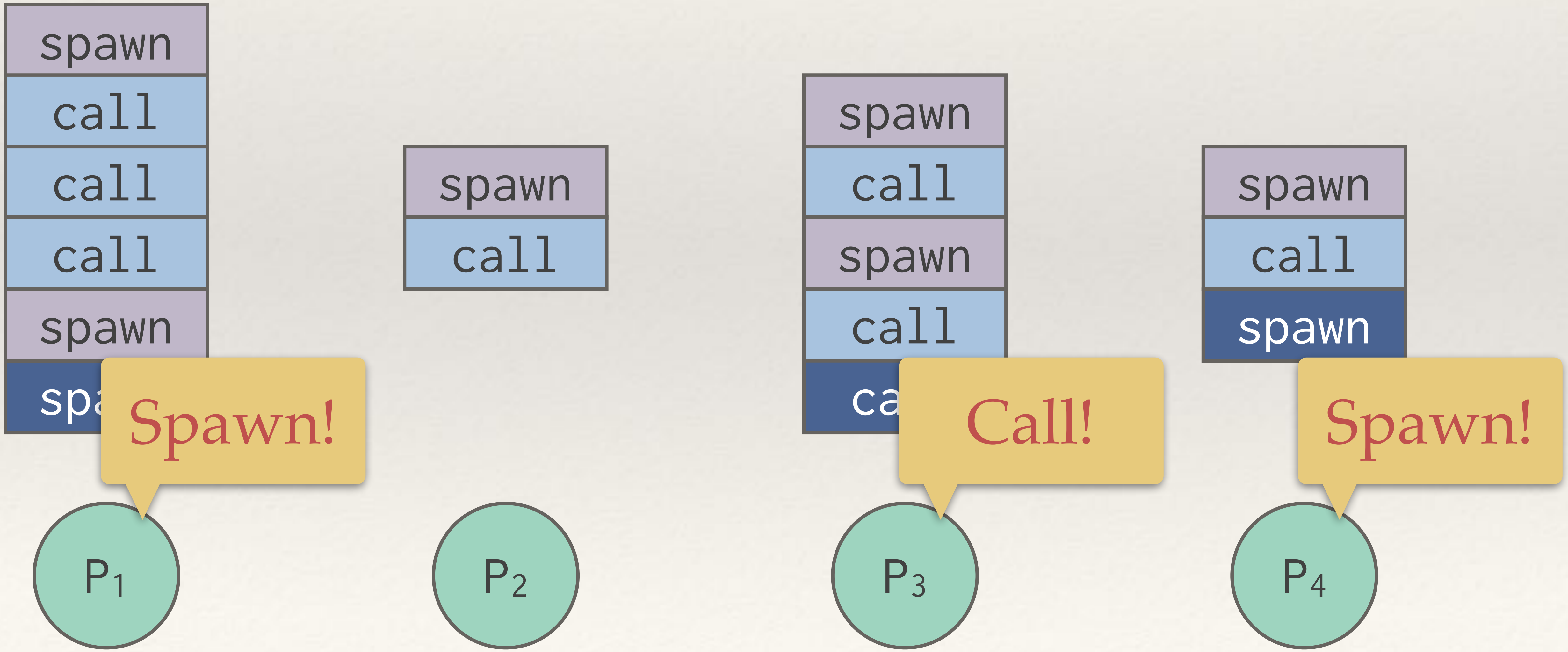

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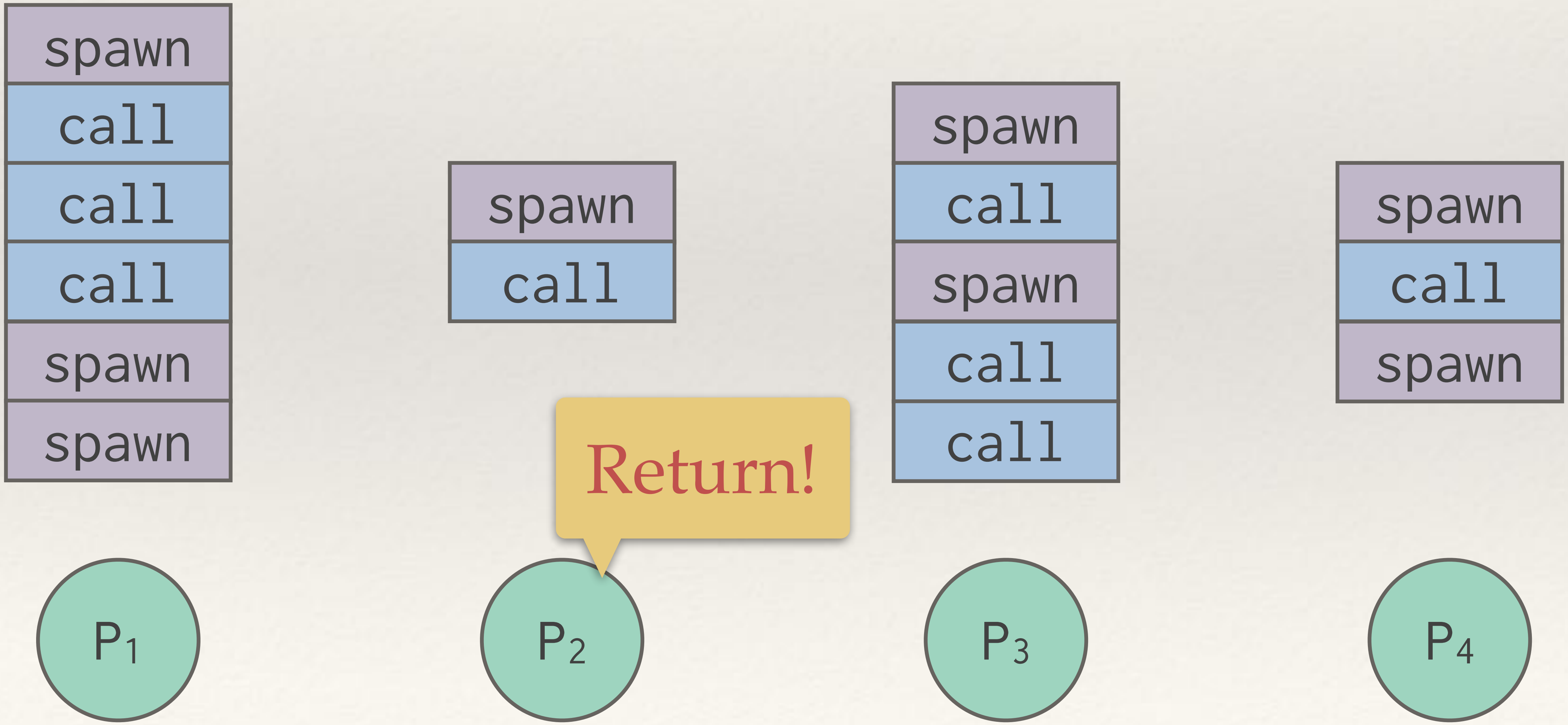

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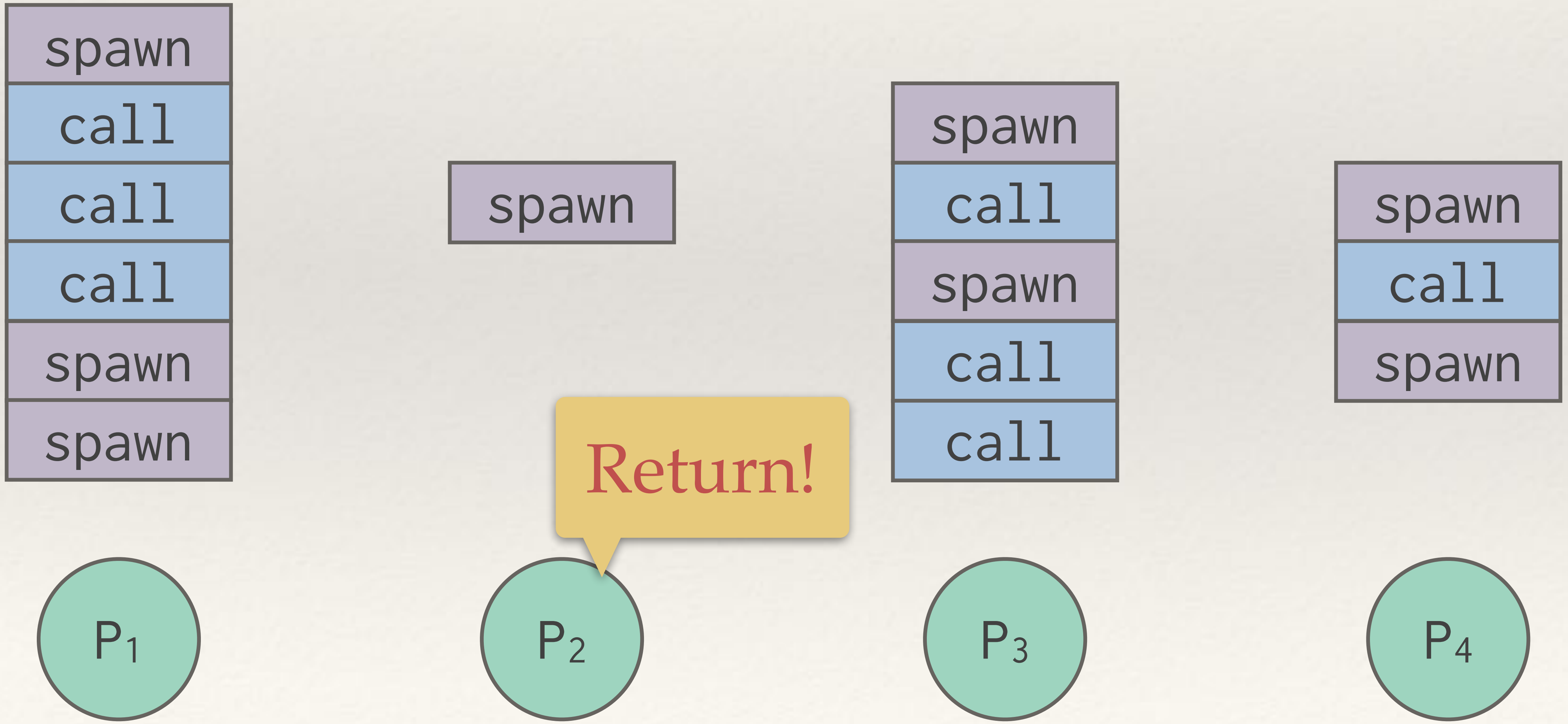
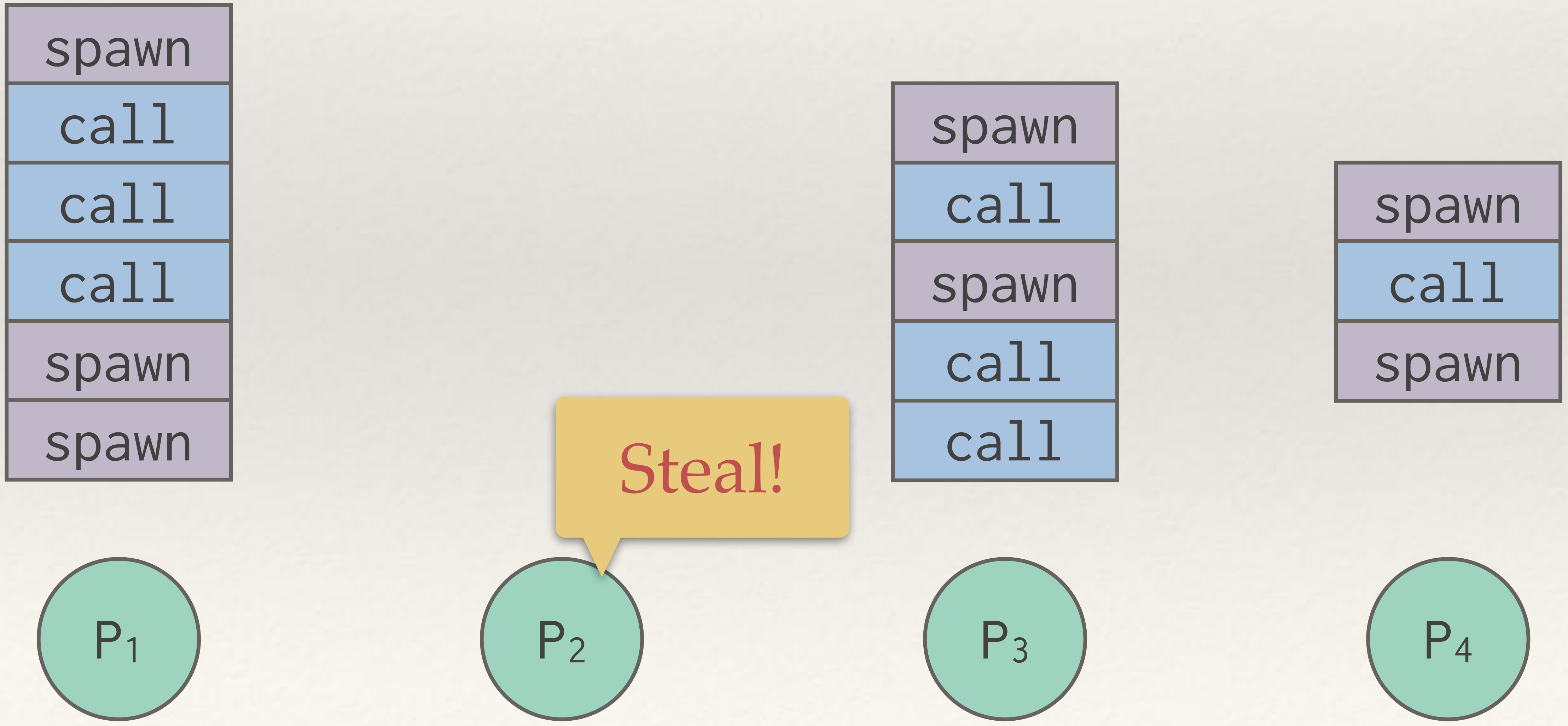


Randomized Work Stealing: Stealing

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



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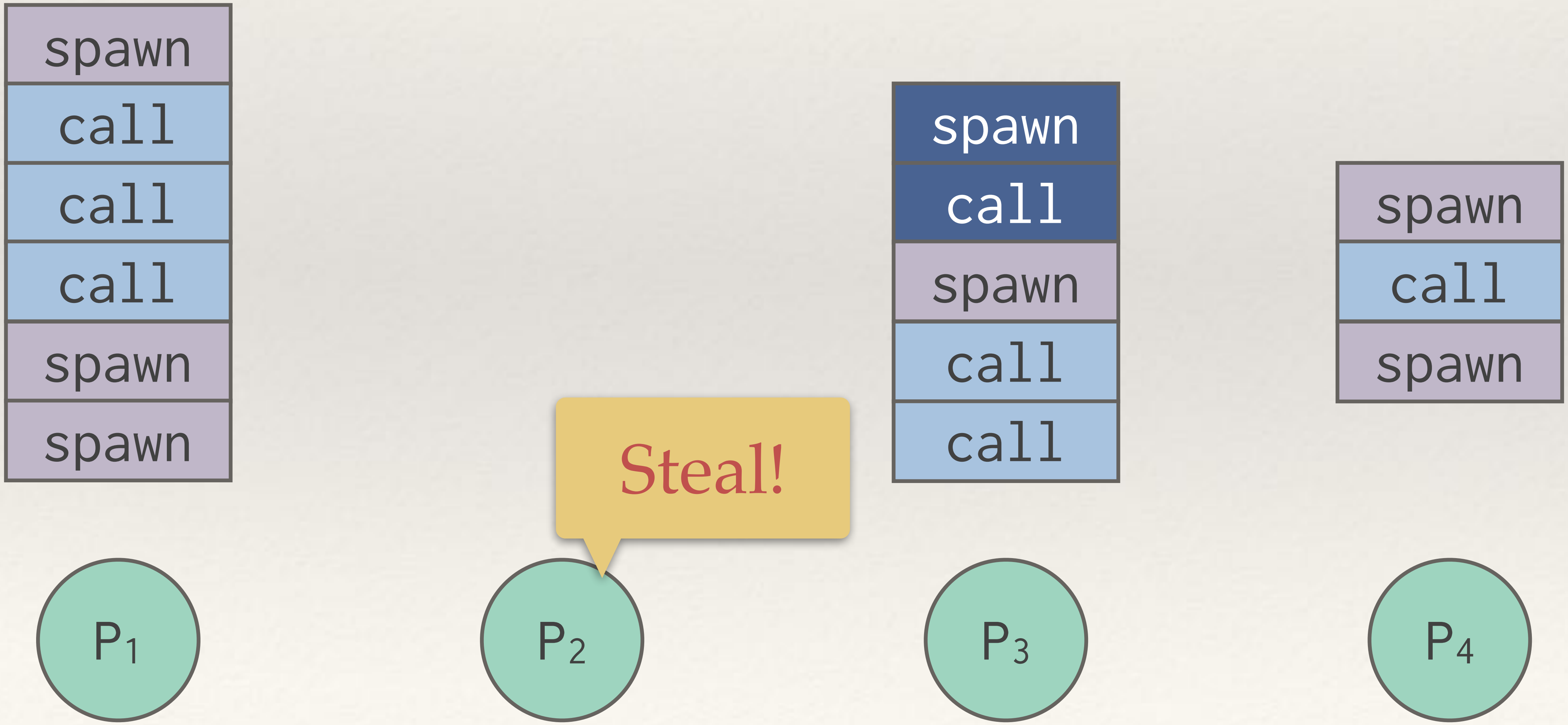
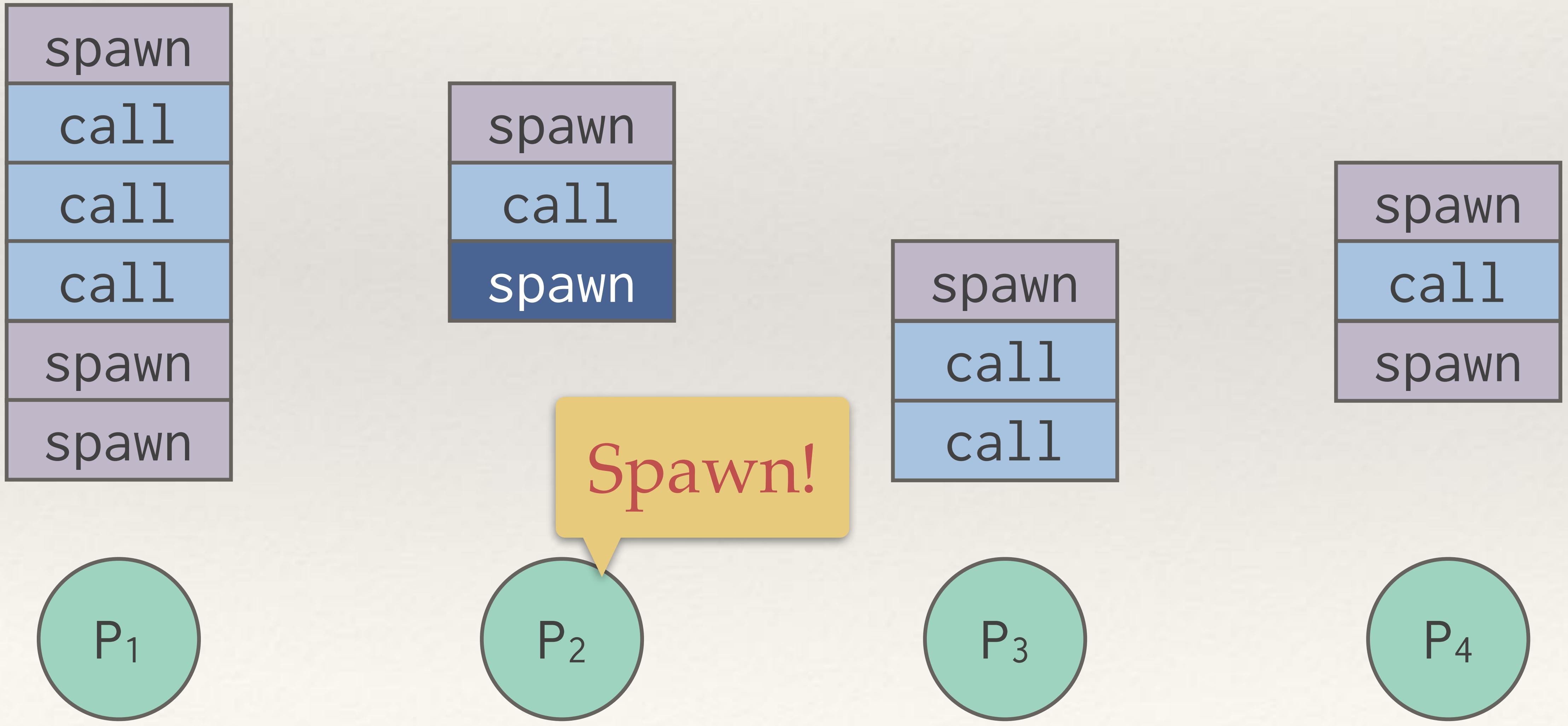


Randomized Work Stealing: Stealing

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



Work-Stealing Bounds

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

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

on P processors.

Pseudoproof: A processor is either **working** or **stealing**. The total time all processors spend working is T_1. Each steal has a $1/P$ chance of reducing the span by 1. Thus, the expected cost of all steals is $O(PT_\infty)$. Because there are P processors, the expected running time is

$$(T_1 + O(PT_\infty))/P = T_1/P + O(T_\infty) \, .$$

Work-Stealing Bounds

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

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

on P processors.

Time workers spend **working.**

Time workers spend **stealing.**

The Work-First Principle

Corollary [BL94]: A program with **sufficient parallelism** satisfies $T_1/P \gg O(T_\infty)$, meaning that workers steal infrequently and the program exhibits **linear speedup.**

To optimize the execution of programs with sufficient parallelism, the implementation of the Cilk runtime system abides by **work-first principle:** Optimize for **ordinary serial execution**, at the expense of some additional computation in steals.

Compiler/Runtime Division

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

The 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.

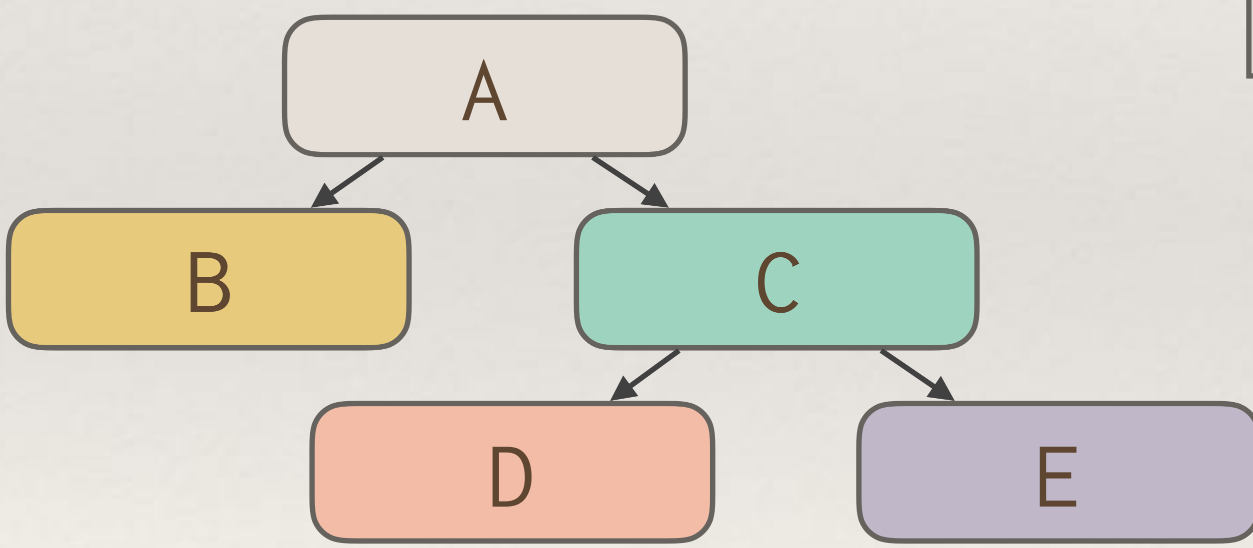
The runtime library:

- Handles **slow paths** of execution, i.e., when a steal occurs.
- Uses data structures that are generally larger.

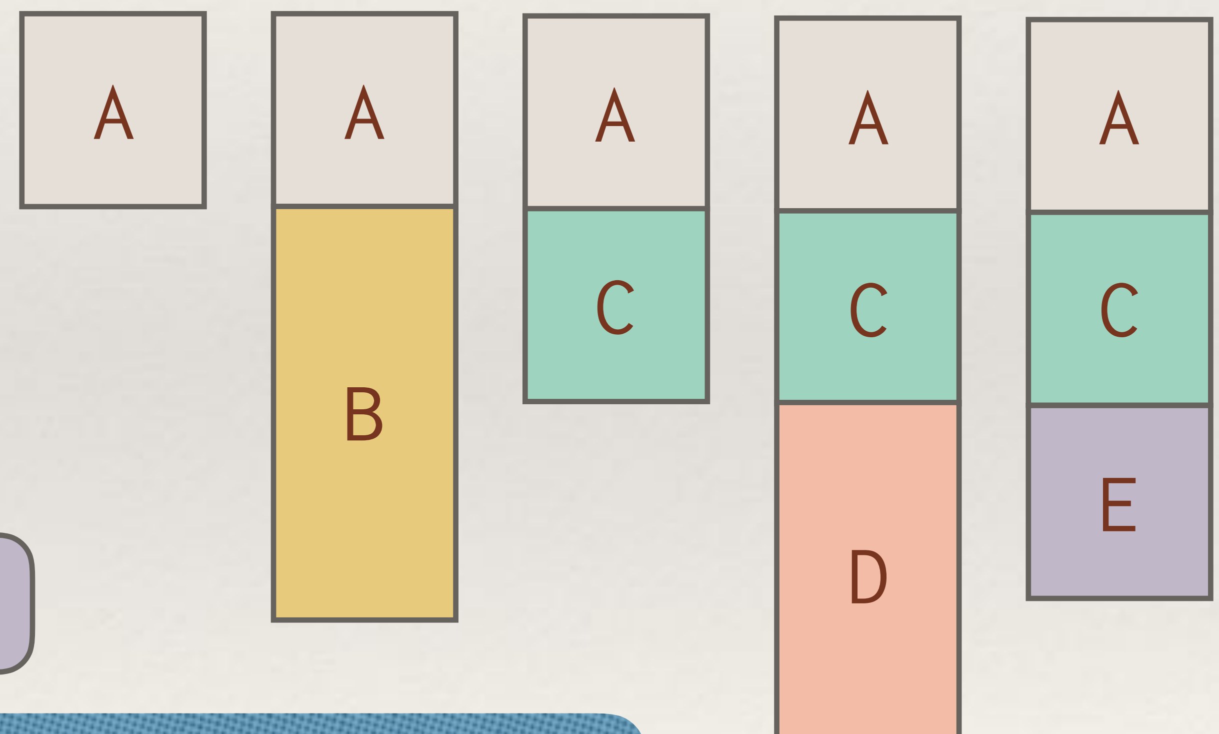
Cactus Stack

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.

Program invocation tree



Parallel views of the stack



Cilk's cactus stack supports multiple views in parallel.

Outline

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  - Steals: the ugly details

Our Running Example

Example Cilk code

```
int f(int n) {
  int x, y;
  x = cilk_spawn g(n);
  y = h(n);
  cilk_sync;
  return x + y;
}
```

Function `f` is a **spawning function**.

Function g is a **spawned** by `f`.

The call to `h` occurs in the **continuation** of `cilk_spawn g()`.

Compiler-Generated Code for Example

Example Cilk code

```
int f(int n) {
  int x, y;
  x = cilk_spawn g(n);
  y = h(n);
  cilk_sync;
  return x + y;
}
```

→ Compiler →

```
int f(int n) {
  __cilkrts_stack_frame_t sf;
  __cilkrts_enter_frame(&sf);
  int x, y;
  if (!setjmp(sf.ctx))
    spawn_g(&x, n);
  y = h(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_g(int *x, int n) {
  __cilkrts_stack_frame sf;
  __cilkrts_enter_frame_fast(&sf);
  __cilkrts_detach();
  *x = g(n);
  __cilkrts_pop_frame(&sf);
  if (sf.flags)
    __cilkrts_leave_frame(&sf);
}
```

Source: Tapir/LLVM compiler source code, `lib/Transforms/Tapir/CilkABI.cpp`.

Basic Data Structures

The Cilk Plus runtime maintains three basic data structures as workers execute work.

- Cilk Plus maintains a **worker** structure for every worker used to execute a program.
- Cilk Plus creates a **Cilk stack frame** to represent each **spawning function** — each function that contains a `cilk_spawn`.
- Cilk Plus creates a **spawn-helper (stack) frame** for each instance of a `cilk_spawn` that executes.

Our Running Example

```
int f(int n) {
  __cilkrts_stack_frame_t sf;
  __cilkrts_enter_frame(&sf);
  int x, y;
  if (!setjmp(sf.ctx))
    spawn_g(&x, n);
  y = h(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_g(int *x, int n) {
  __cilkrts_stack_frame sf;
  __cilkrts_enter_frame_fast(&sf);
  __cilkrts_detach();
  *x = g(n);
  __cilkrts_pop_frame(&sf);
  if (sf.flags)
    __cilkrts_leave_frame(&sf);
}
```

Cilk stack frame for the spawning function `f`.

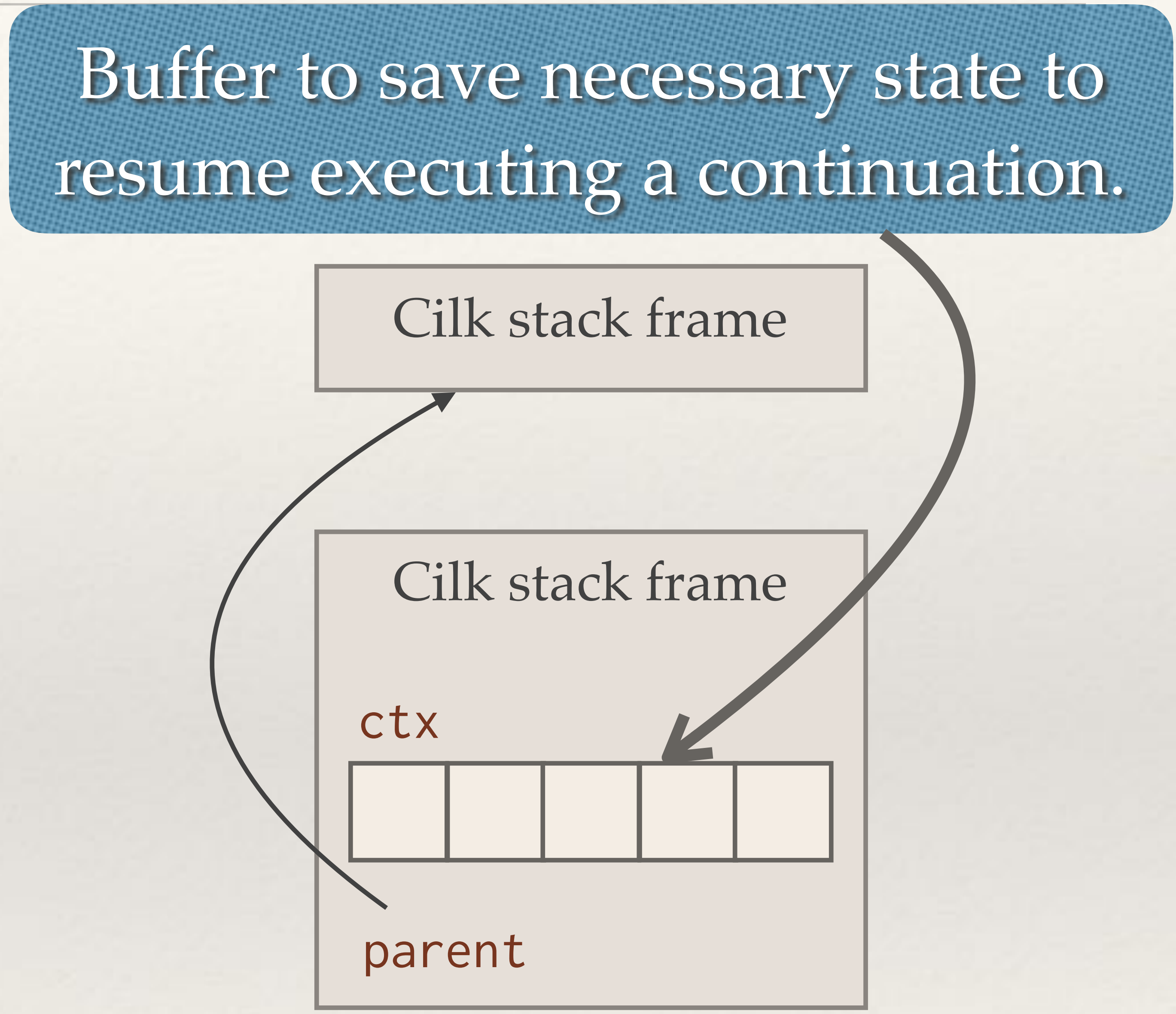
Spawn-helper function for `cilk_spawn g()`.

Cilk stack frame for the spawn-helper function.

Cilk Stack Frame

Each Cilk stack frame stores:

- A **context buffer**, which contains enough information to resume a function at a continuation, i.e., after a spawn or sync.
- A pointer to its **parent** Cilk stack frame.



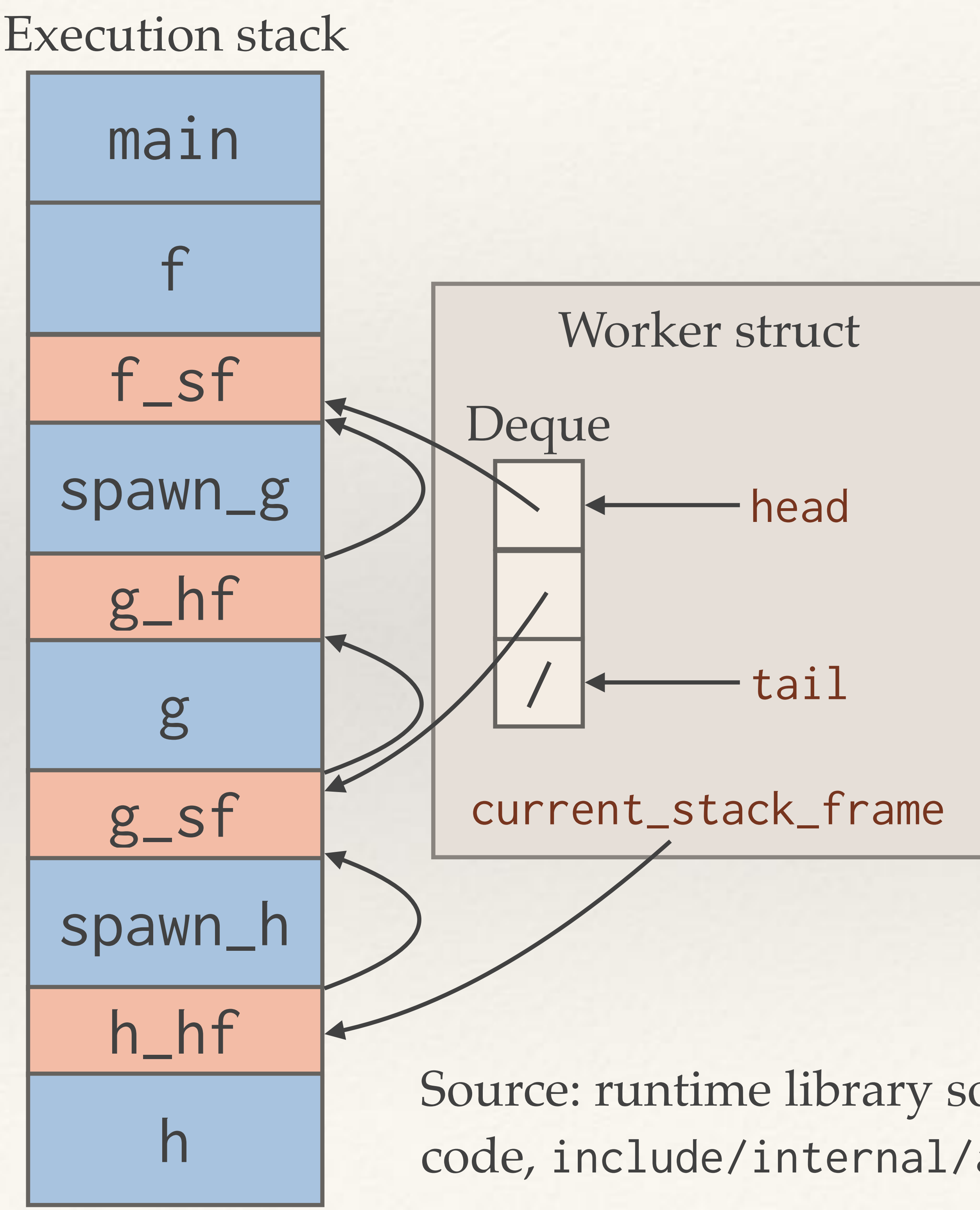
Source: runtime library source code, `include/internal/abi.h`.

Basic Worker Data Structure

For each worker `w`, the Cilk runtime system maintains:

- A chain of **Cilk stack frames**. The end of the chain is `w->current_stack_frame`.
- A **deque** of pointers to Cilk stack frames, with `w->head` and `w->tail` pointers.

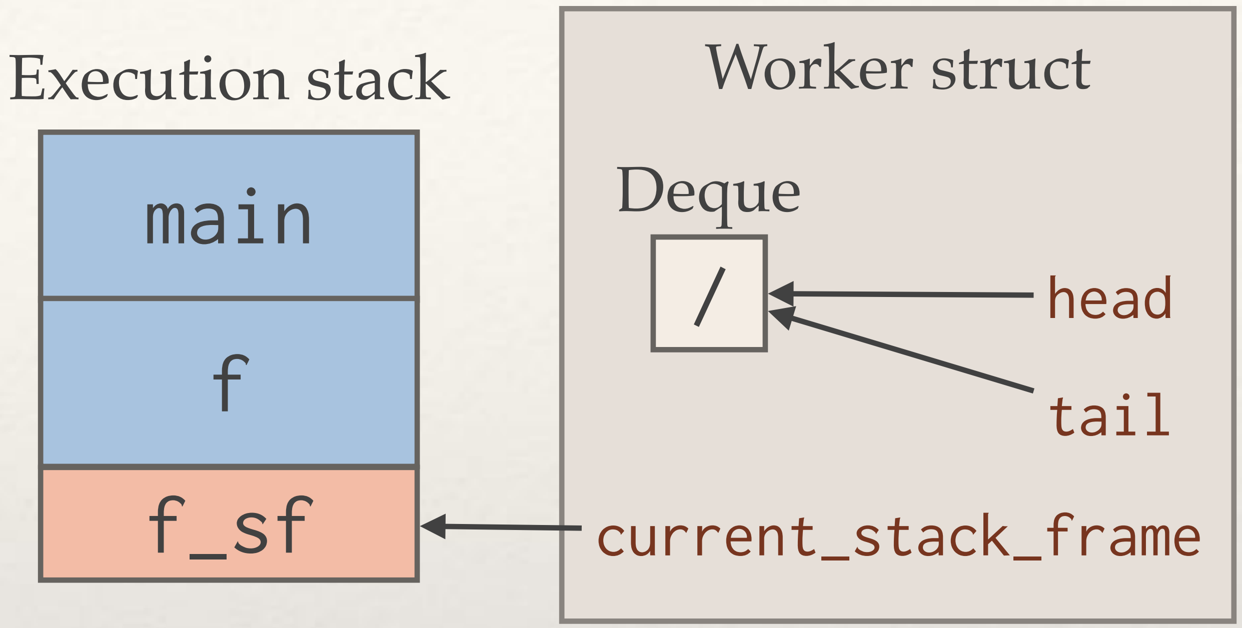
Each worker also operates on its own ordinary **execution stack**, which stores normal frame data, e.g., local variables of the function.



Source: runtime library source code, `include/internal/abi.h`.

Calling a Function That Spawns

```
int f(int n) {
  __cilkrts_stack_frame_t sf;
  __cilkrts_enter_frame(&sf);
  int x, y;
  if (!setjmp(sf.ctx))
    spawn_g(&x, n);
  y = h(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_g(int *x, int n) {
  __cilkrts_stack_frame sf;
  __cilkrts_enter_frame_fast(&sf);
  __cilkrts_detach();
  *x = g(n);
  __cilkrts_pop_frame(&sf);
  if (sf.flags)
    __cilkrts_leave_frame(&sf);
}
```



A call to f does the following.

1. Update the execution stack as normal.
2. Creates a Cilk stack frame, f_sf, on the execution stack.
3. Pushes f_sf onto the chain of Cilk stack frames.

Spawning a Function g from f

```
int f(int n) {
  __cilkrts_stack_frame_t sf;
  __cilkrts_enter_frame(&sf);
  int x, y;
  if (!setjmp(sf.ctx))
    spawn_g(&x, n);
  y = h(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_g(int *x, int n) {
  __cilkrts_stack_frame sf;
  __cilkrts_enter_frame_fast(&sf);
  __cilkrts_detach();
  *x = g(n);
  __cilkrts_pop_frame(&sf);
  if (sf.flags)
    __cilkrts_leave_frame(&sf);
}
```

Spawning g from `f` involves 5 steps:

1. Save the continuation of `f` in the Cilk stack frame.
2. Call the spawn-helper function and initialize its Cilk stack frame, g_`hf`.
3. Evaluate the arguments of g, calling any necessary C++ constructors.
4. Mark g_`hf` as **detached** and push its parent `f_sf` onto the deque.
5. Call function g.

The `setjmp` and `longjmp` Instructions

The Cilk runtime uses `setjmp` and `longjmp` to suspend and resume the execution of functions.

- `setjmp`: Save the current execution context in a specified buffer.
- `longjmp`: Restore the current execution context from the specified buffer.

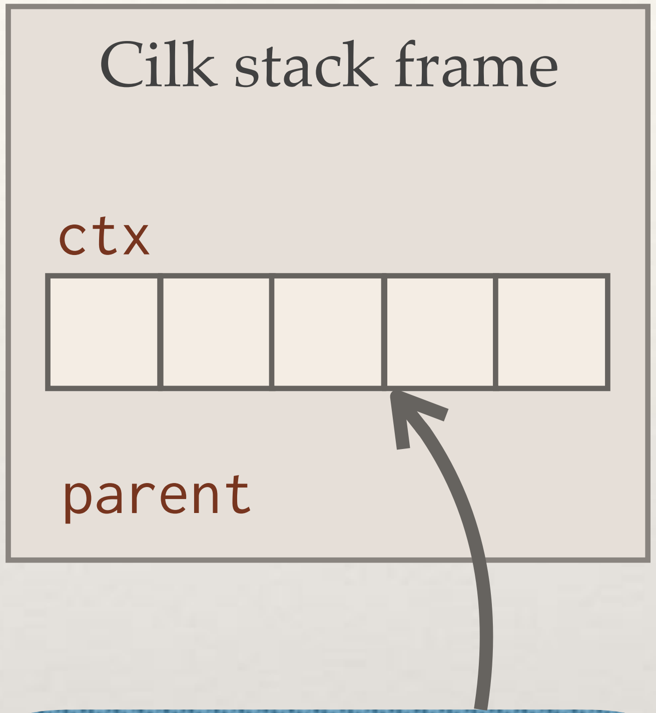
The `setjmp` instruction returns 0 or 1, depending on whether it's reached by normal execution or by a `longjmp`.

```
int f(int n) {
  __cilkrts_stack_frame_t sf;
  __cilkrts_enter_frame(&sf);
  int x, y;
  if (!setjmp(sf.ctx))
    spawn_g(&x, n);
  y = h(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_g(int *x, int n) {
  __cilkrts_stack_frame sf;
  __cilkrts_enter_frame_fast(&sf);
  __cilkrts_detach();
  *x = g(n);
  __cilkrts_pop_frame(&sf);
  if (sf.flags)
    __cilkrts_leave_frame(&sf);
}
```

The Buffer for `setjmp` and `longjmp`

The content of the jump buffer that setjmp and longjmp use depends on the **architecture** and **operating system**.

- On Linux and x86_64, this buffer just stores a few registers: the **program counter**, the **stack pointer**, the **base pointer**, and **callee-saved registers**.
- The Cilk runtime library ensures that other state (e.g., the execution stack) is maintained.



On Linux and x86_64, the context buffer takes 64 bytes of space in the Cilk stack frame.

Example: cilk_spawn of g

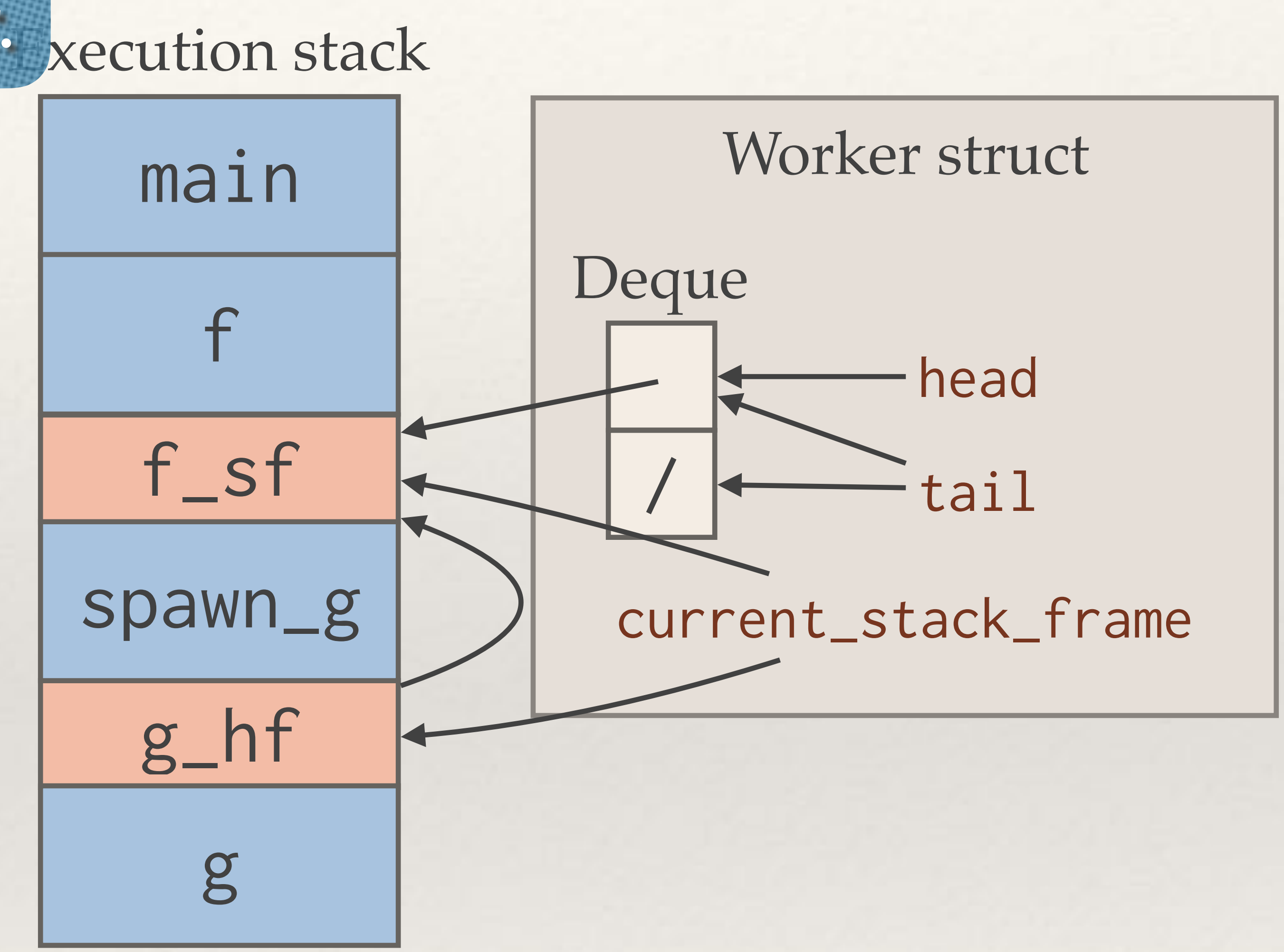
```
int f(int n) {
  __c
  __cilkrts_enter_frame(&sf);
  int x, y;
  if (!setjmp(sf.ctx))
    spawn_g(&x, n);
  y = h(n);
  if (s
    if
      _
  int r
  __cilkrts_pop_frame(&sf);
  if (sf.flags)
    __cilkrts_leave_frame(&sf);
  return result;
}

void spawn_g(int *x, int n) {
  __cilkrts_stack_frame sf;
  __cilkrts_enter_frame_f
  __cilkrts_detach();
  *x = g(n);
  __cilkrts_pop_frame(&sf
  if (sf.flags)
    __cilkrts_leave_frame
}
```

Save state of f into f_sf and call the spawn helper.

Create spawn-helper Cilk stack frame, g_hf.

Mark g_hf as detached, and push f_sf onto deque.

Call g.



Example: Return From `cilk_spawn` of g

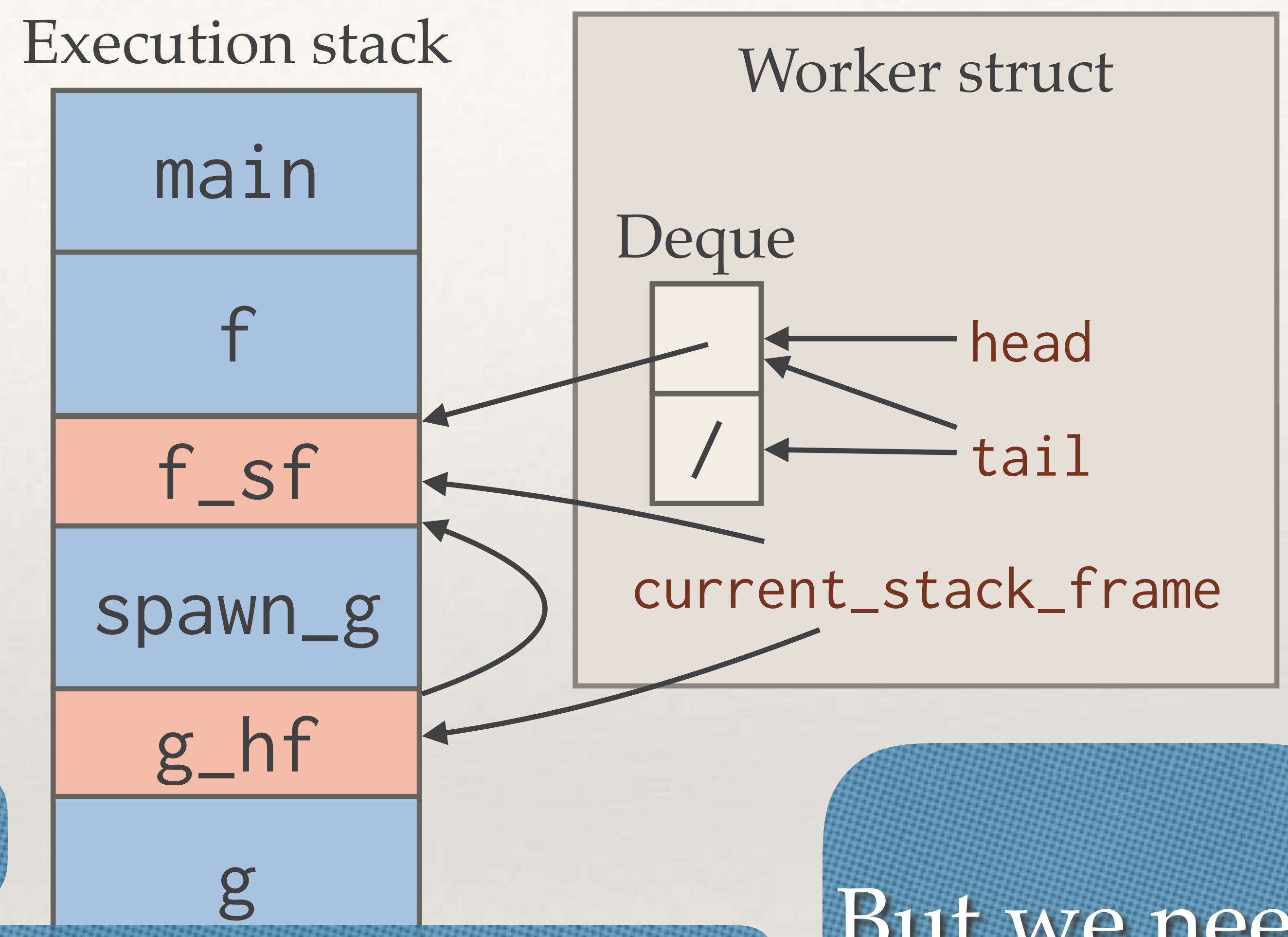
```
int f(int n) {
  __cilkrts_stack_frame_t sf;
  __cilkrts_enter_frame(&sf);
  int x, y;
  if (!setjmp(sf.ctx))
    spawn_g(&x, n);
  y = h(n);
  if (sf.flags & CILK_FRAME_UNSYNCHED)
    if (!setjmp(sf.ctx))
      __cilkrts_sync(&sf);
  int result = x + y;
  __cilkrts_pop_frame(&sf);
  if (sf.flags)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

void spawn_g(int *x, int n) {
  __cilkrts_stack_frame sf;
  __cilkrts_enter_frame_fast(&sf);
  __cilkrts_detach();
  *x = g(n);
  __cilkrts_pop_frame(&sf);
  if (sf.flags)
    __cilkrts_leave_frame(&sf);
}
```

Returning from a spawned function g involves 5 steps:

1. Return from g.
2. Copy the return value of g.
3. Call C++ destructors for any computed temporaries.
4. Undo the detach of the Cilk stack frame.
5. Leave the spawn-helper function.

Example: Return From a `cilk_spawn`

```
int f(int n) {
  __cilkrts_stack_frame_t sf;
  __cilkrts_enter_frame(&sf);
  int x, y;
  if (!setjmp(sf.ctx))
    spawn_g(&x, n);
  y = h(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_g(int *x, int n) {
  __cilkrts_stack_frame sf;
  __cilkrts_enter_frame_fast(&sf);
  __cilkrts_detach();
  *x = g(n);
  __cilkrts_pop_frame(&sf);
  if (sf.flags)
    __cilkrts_leave_frame(&sf);
}
```



Return from g.

Pop g_hf from the chain of Cilk stack frames.

Attempt to remove f_sf from the deque.

But we need to check if the parent was stolen!

The THE Protocol

The Cilk runtime system implements the **THE protocol** to synchronize updates to the deque. (See `runtime/scheduler.c`.)

Pseudocode for the simplified THE protocol:

Worker/Victim

```
void push() {
  tail++;
}

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

Thief

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

Speculatively decrement `tail` for the common case.

If the deque looks empty, lock the deque and try again.

The deque really is empty, meaning the parent continuation was stolen.

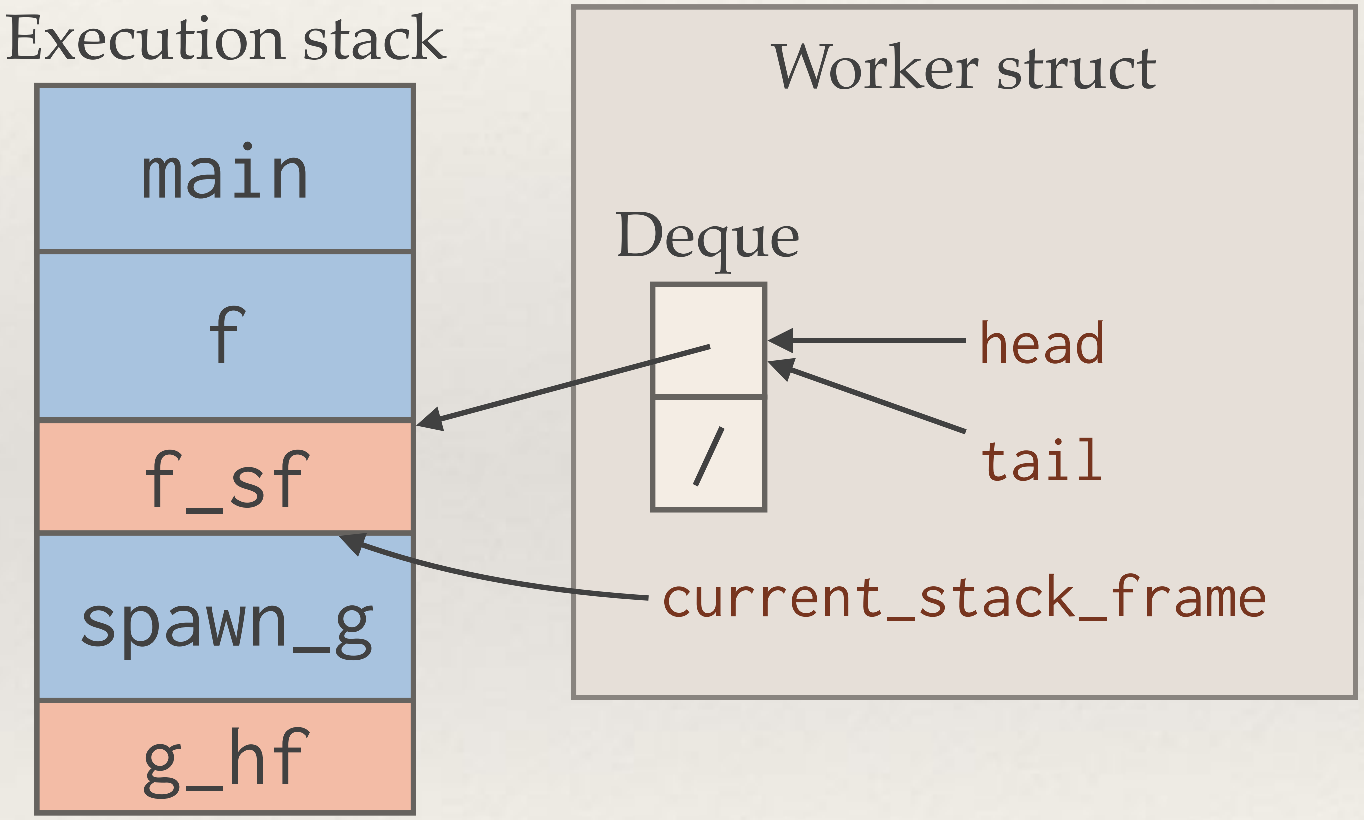
The thief always locks the deque.

Result of __cilkrts_leave_frame()

There are two possible outcomes from calling `__cilkrts_leave_frame`:

a) **Fast path:** If the continuation in `f` was not stolen then `__cilkrts_leave_frame` returns normally.

b) **Slow path:** Otherwise, control jumps into the runtime library.



Executing a `cilk_sync`

```
int f(int n) {
  __cilkrts_stack_frame_t sf;
  __cilkrts_enter_frame(&sf);
  int x, y;
  if (!setjmp(sf.ctx))
    spawn_g(&x, n);
  y = h(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_g(int *x, int n) {
  __cilkrts_stack_frame sf;
  __cilkrts_enter_frame_fast(&sf);
  __cilkrts_detach();
  *x = g(n);
  __cilkrts_pop_frame(&sf);
  if (sf.flags)
    __cilkrts_leave_frame(&sf);
}
```

The execution of a cilk_sync branches based on whether the function has **synched**.

- If so, then execution continues normally.
- Otherwise, the continuation of the `cilk_sync` is saved, and `__cilkrts_sync()` is called to transfer control into the runtime.

Returning From a Function That Spawns

```
int f(int n) {
  __cilkrts_stack_frame_t sf;
  __cilkrts_enter_frame(&sf);
  int x, y;
  if (!setjmp(sf.ctx))
    spawn_g(&x, n);
  y = h(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_g(int *x, int n) {
  __cilkrts_stack_frame sf;
  __cilkrts_enter_frame_fast(&sf);
  __cilkrts_detach();
  *x = g(n);
  __cilkrts_pop_frame(&sf);
  if (sf.flags)
    __cilkrts_leave_frame(&sf);
}
```

When the spawning function returns, `__cilkrts_leave_frame` is called to remove its Cilk stack frame.

No need to update the deque if the function did not detach.

Implementation in Practice

```
int f(int n) {
  __cilkrts_stack_frame_t sf;
  __cilkrts_enter_frame(&sf);
  int x, y;
  if (!setjmp(sf.ctx))
    spawn_g(&x, n);
  y = h(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_g(int *x, int n) {
  __cilkrts_stack_frame sf;
  __cilkrts_enter_frame_fast(&sf);
  __cilkrts_detach();
  *x = g(n);
  __cilkrts_pop_frame(&sf);
  if (sf.flags)
    __cilkrts_leave_frame(&sf);
}
```

Where are these routines implemented?

- The compiler implements and inlines `enter_frame`, `enter_frame_fast`, `detach`, and `pop_frame`.
- The runtime library implements `__cilkrts_sync` and `__cilkrts_leave_frame`. (See `runtime/cilk-abi.c`.)

Outline

- Review of randomized work stealing
- Compiler and runtime internals
  - Fast path: executing with no steals
  - Data structures for steals
  - Steals: the ugly details

Parallel Execution Stacks

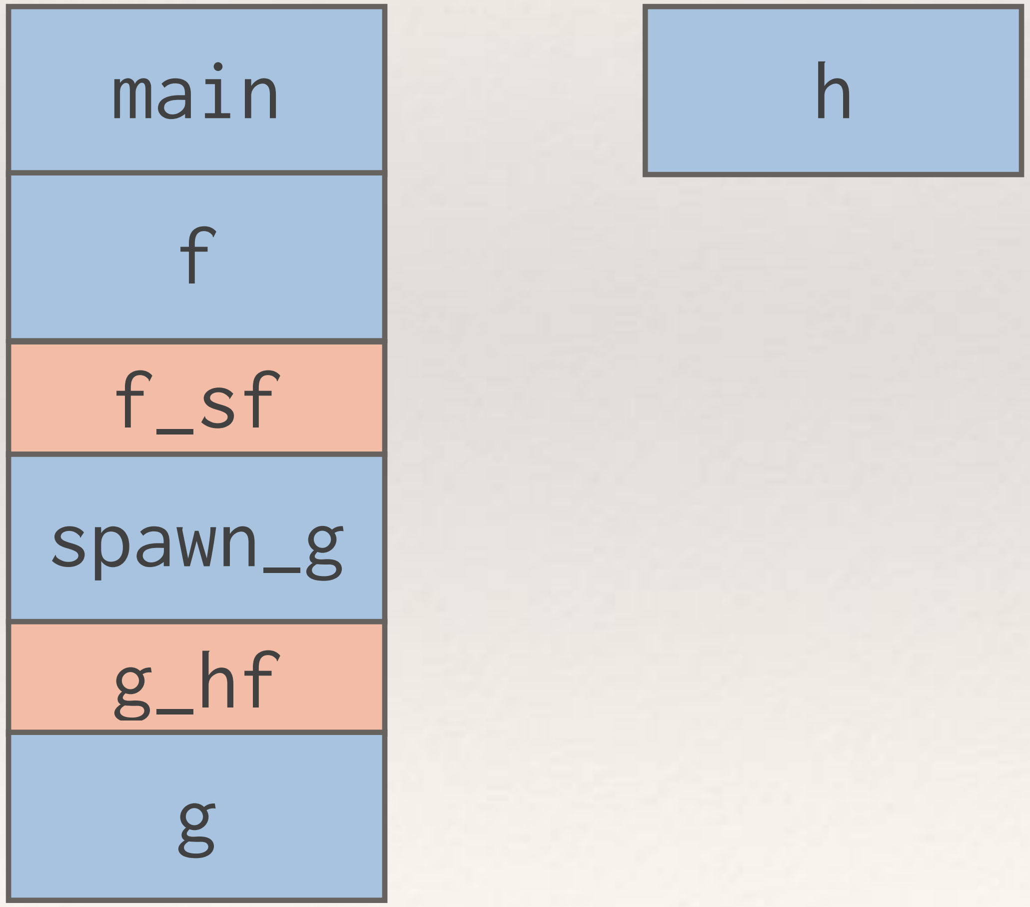
Two workers executing a spawned routine and its continuation in parallel use distinct execution stacks.

Example Cilk code

```
int f(int n) {
  int x, y;
  x = cilk_spawn g(n);
  y = h(n);
  cilk_sync;
  return x + y;
}
```

Execution stack for worker w0

Execution stack for worker w1

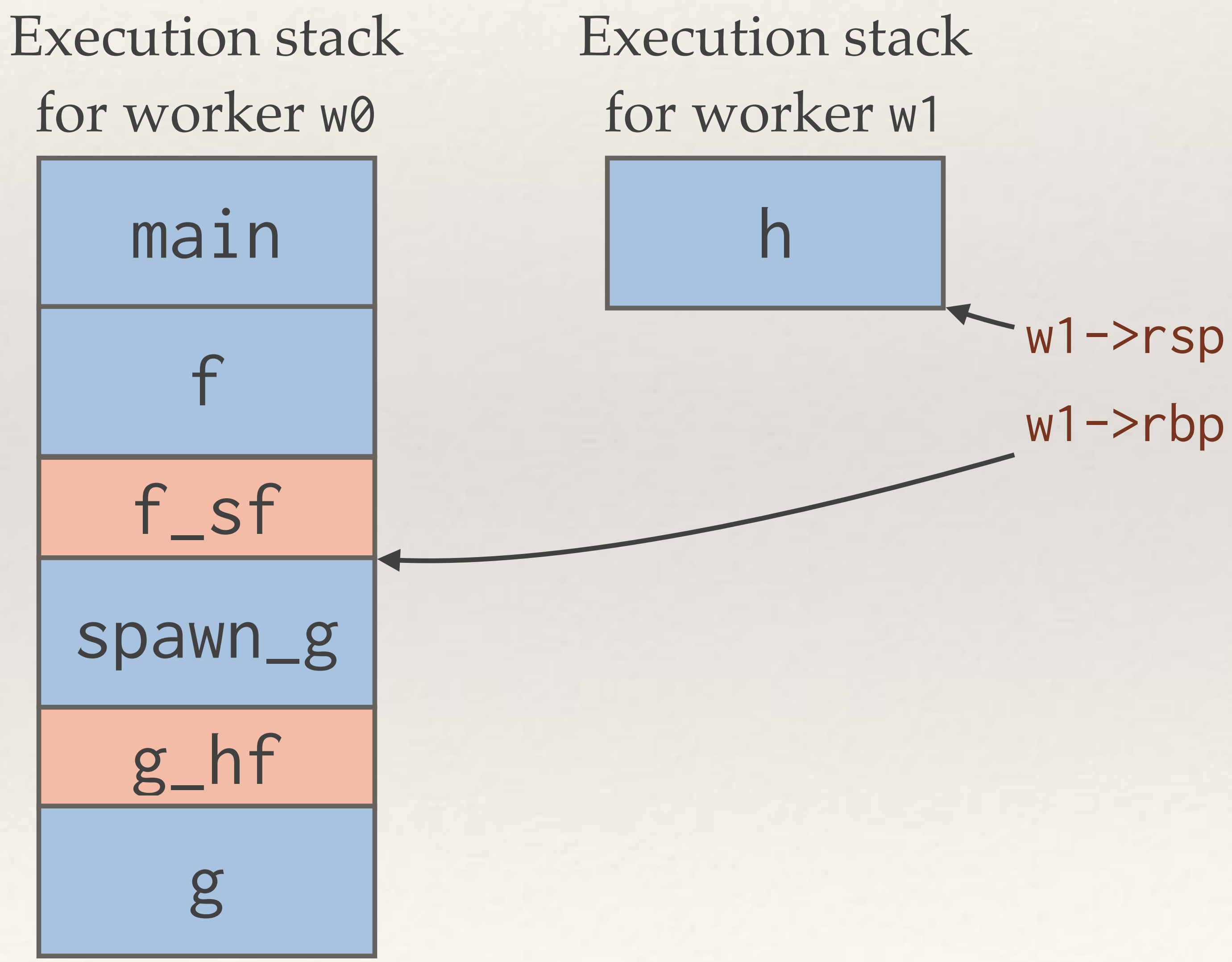


Accessing The Parent Stack Frame

After stealing, a worker can access state in its parent's stack via a separate pointer.

Example Cilk code

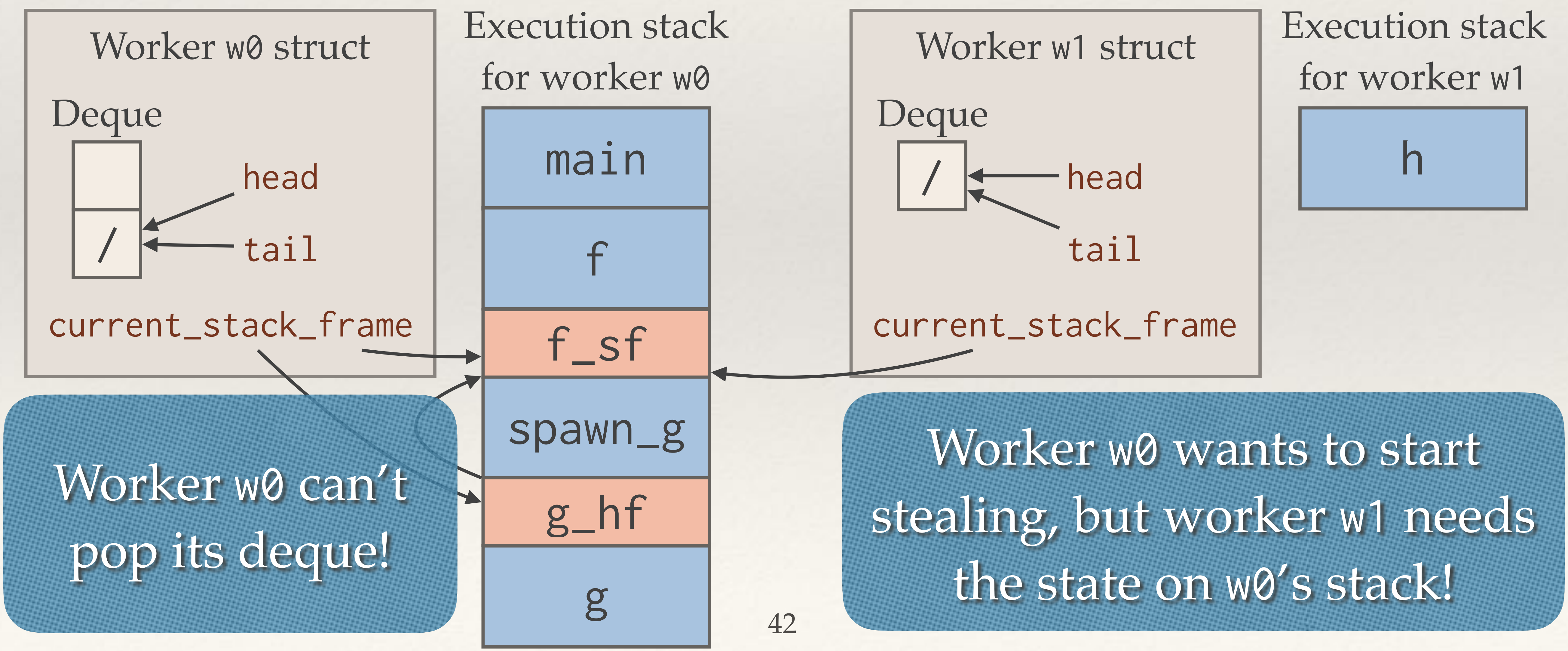
```
int f(int n) {
  int x, y;
  x = cilk_spawn g(n);
  y = h(n);
  cilk_sync;
  return x + y;
}
```



Stalling

Execution on a stack **stalls** if the worker discovers its deque to be empty.

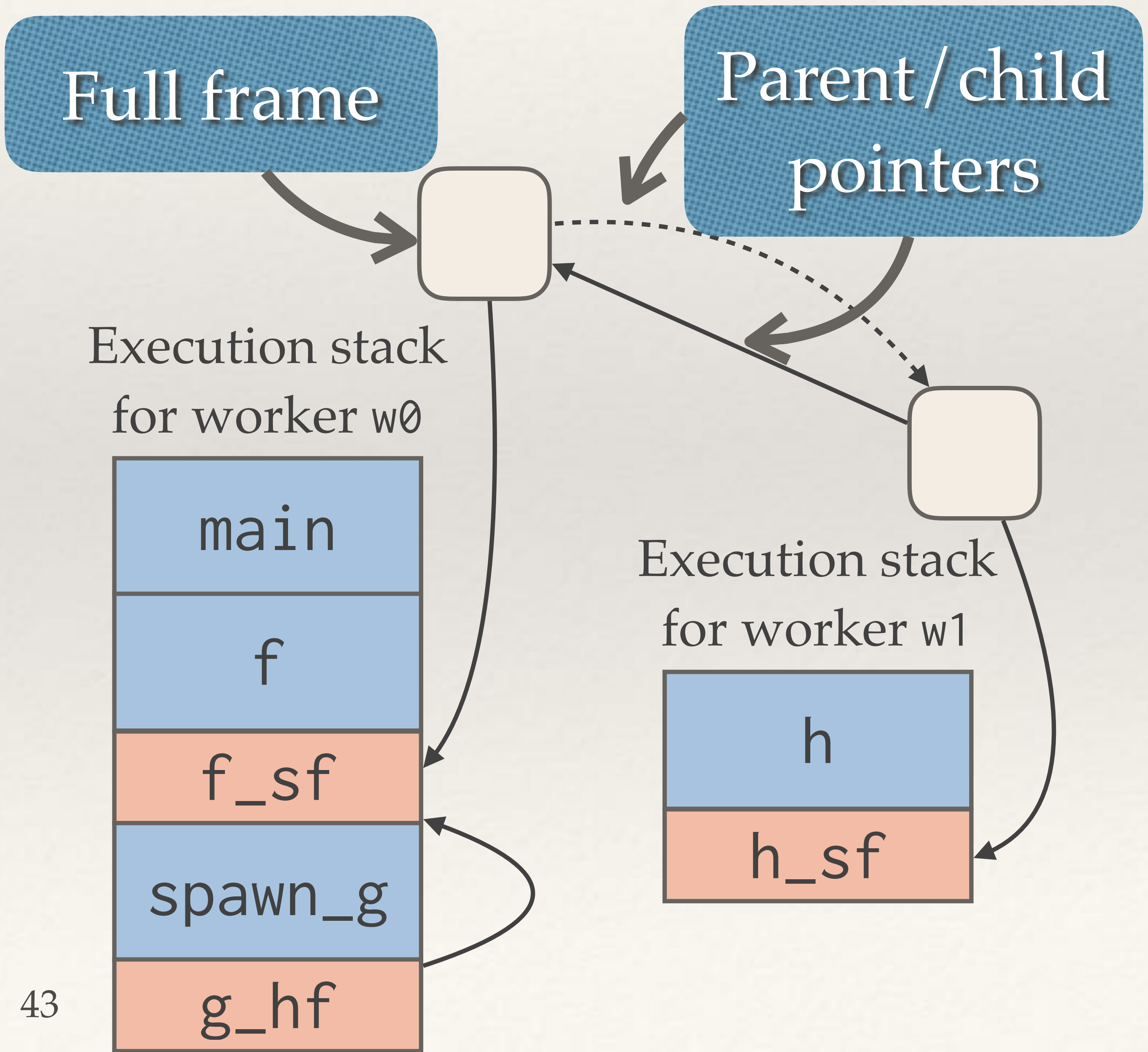
Example: Worker `w0` returns from `cilk_spawn` of g:



Full Frames

The Cilk Plus runtime system maintains **full frames** to keep track of executing and stalled function frames.

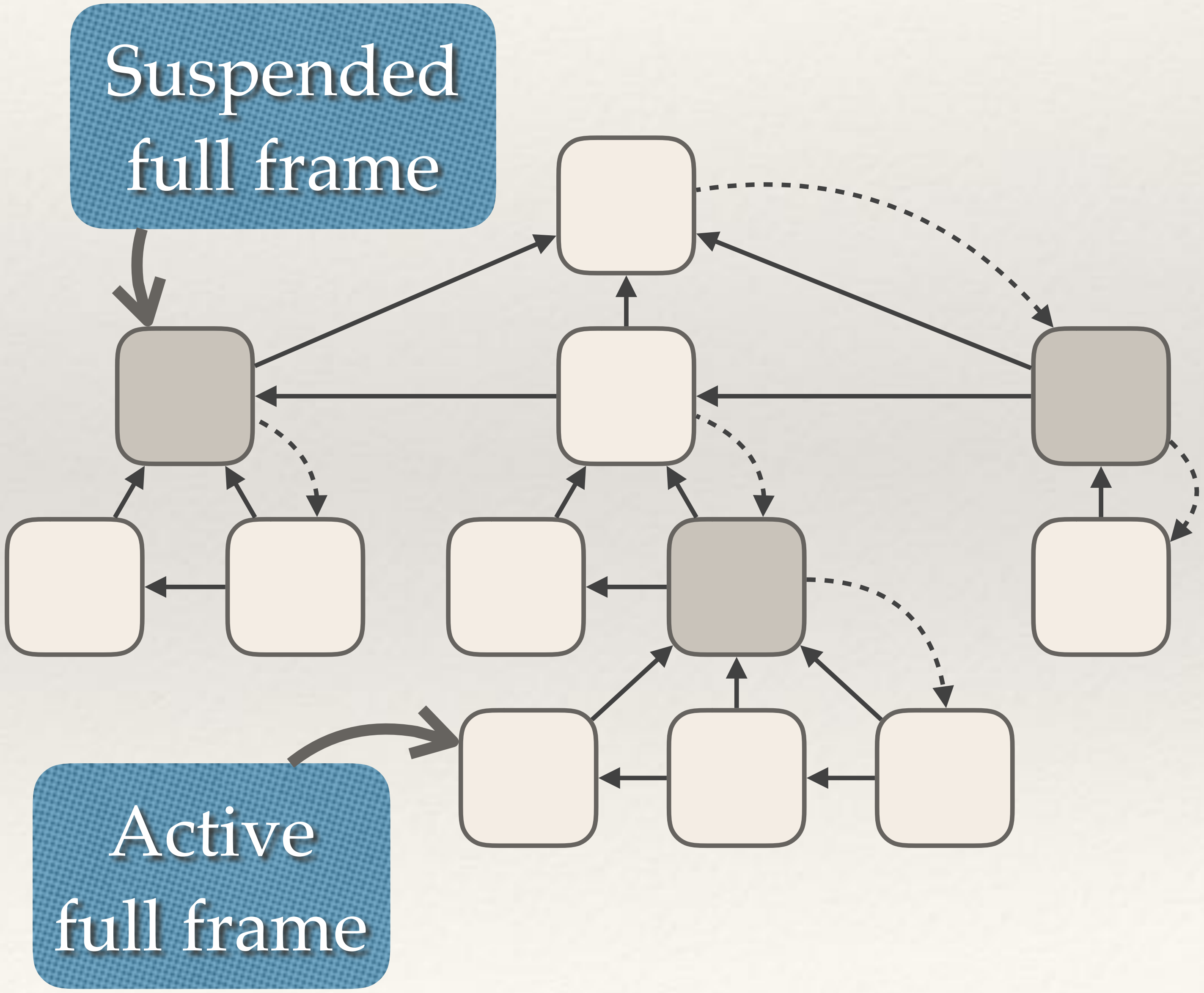
- A full frame has an associated Cilk stack frame, as well as a **lock**, a **join counter**, and other fields.
- Every worker that is executing user code has an **active** full frame.
- Other full frames are **suspended**.



The Full Frame Tree

Full frames are connected together in a **full frame tree**.

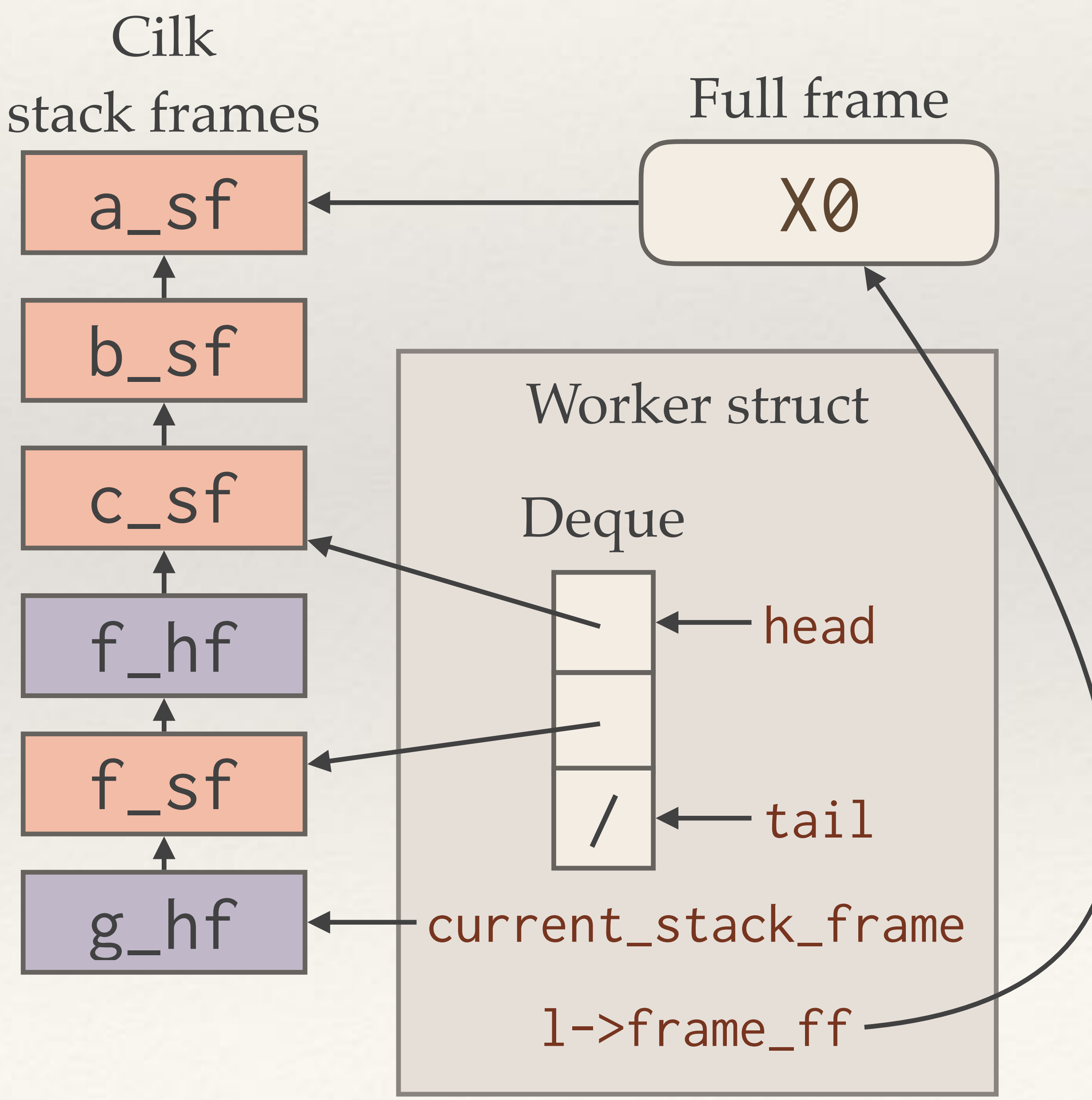
- Each full frame maintains **parent**, **right-sibling**, and **left-child** pointers.
- The tree structure reflects the relationship between stack frames.
- **Busy leaves property:** All leaves of the full frame tree are active full frames.



Workers and Full Frames

Each worker executing user code tracks its full frame in the field `l->frame_ff`.

- That full frame points to the **oldest** Cilk stack frame associated with this worker.
- The worker's pointer to its full frame is **local state** associated with the worker that the compiler doesn't care about.



Source Code for Full Frames

- The full frame data structure is defined in the runtime library, in `runtime/full_frame.h` and `runtime/full_frame.c`.
- The local state associated with a worker is defined in the runtime library, in `runtime/local_state.h` and `runtime/local_state.c`.

Outline

- Review of randomized work stealing
- Compiler and runtime internals
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  - Data structures for steals
  - Steals: the ugly details

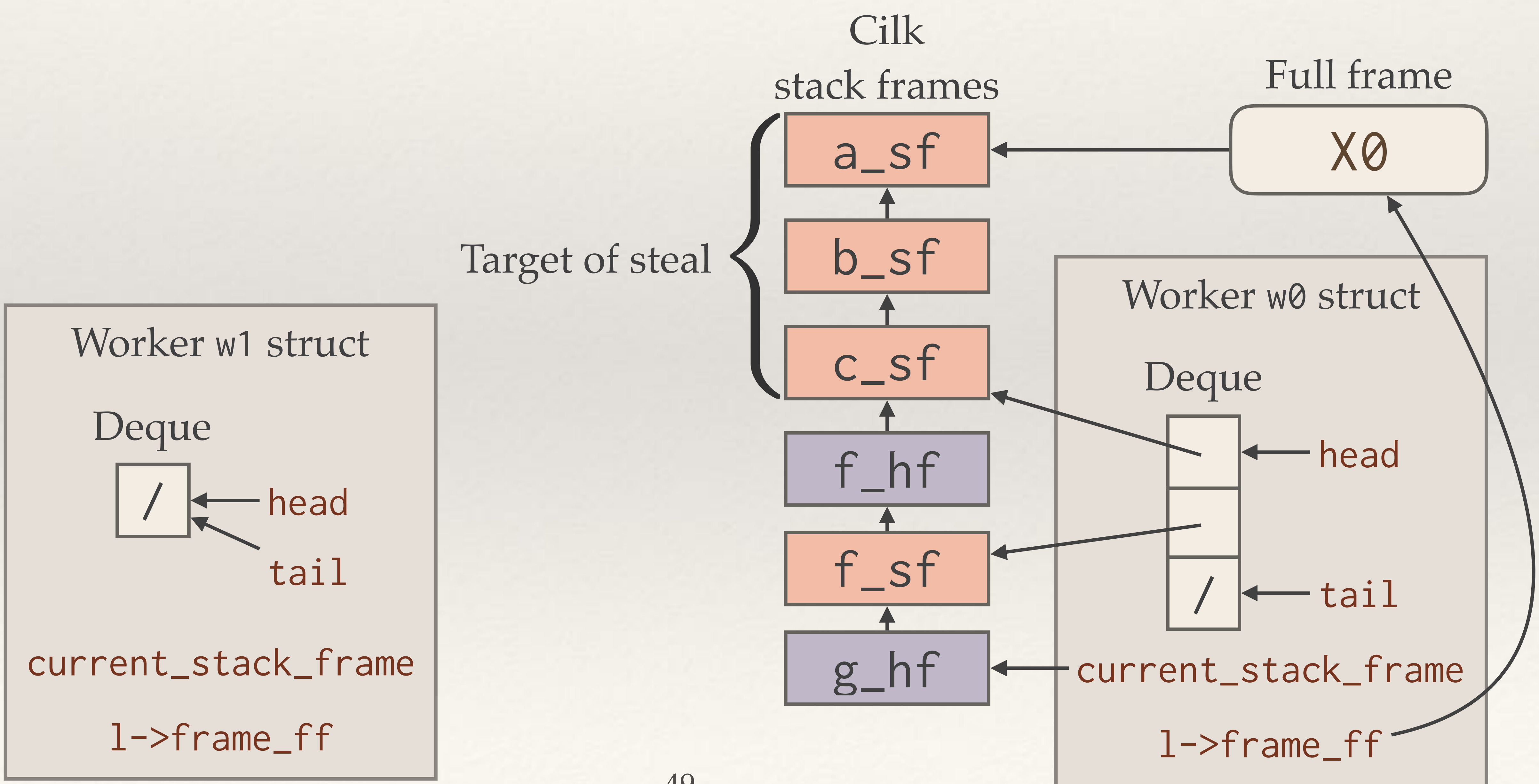
Where's The Steal Code?

The stealing algorithm is implemented in the runtime library, in `runtime/scheduler.c`.

- The method `random_steal()` implements random selection of a victim and the THE protocol for the thief.
- Management of full frames to execute a steal (i.e., "the ugly details") is implemented in `detach_for_steal()`.

Target of a Steal

When a thief worker `w1` steals from a victim worker `w0`, it steals a **chain** of stack frames.



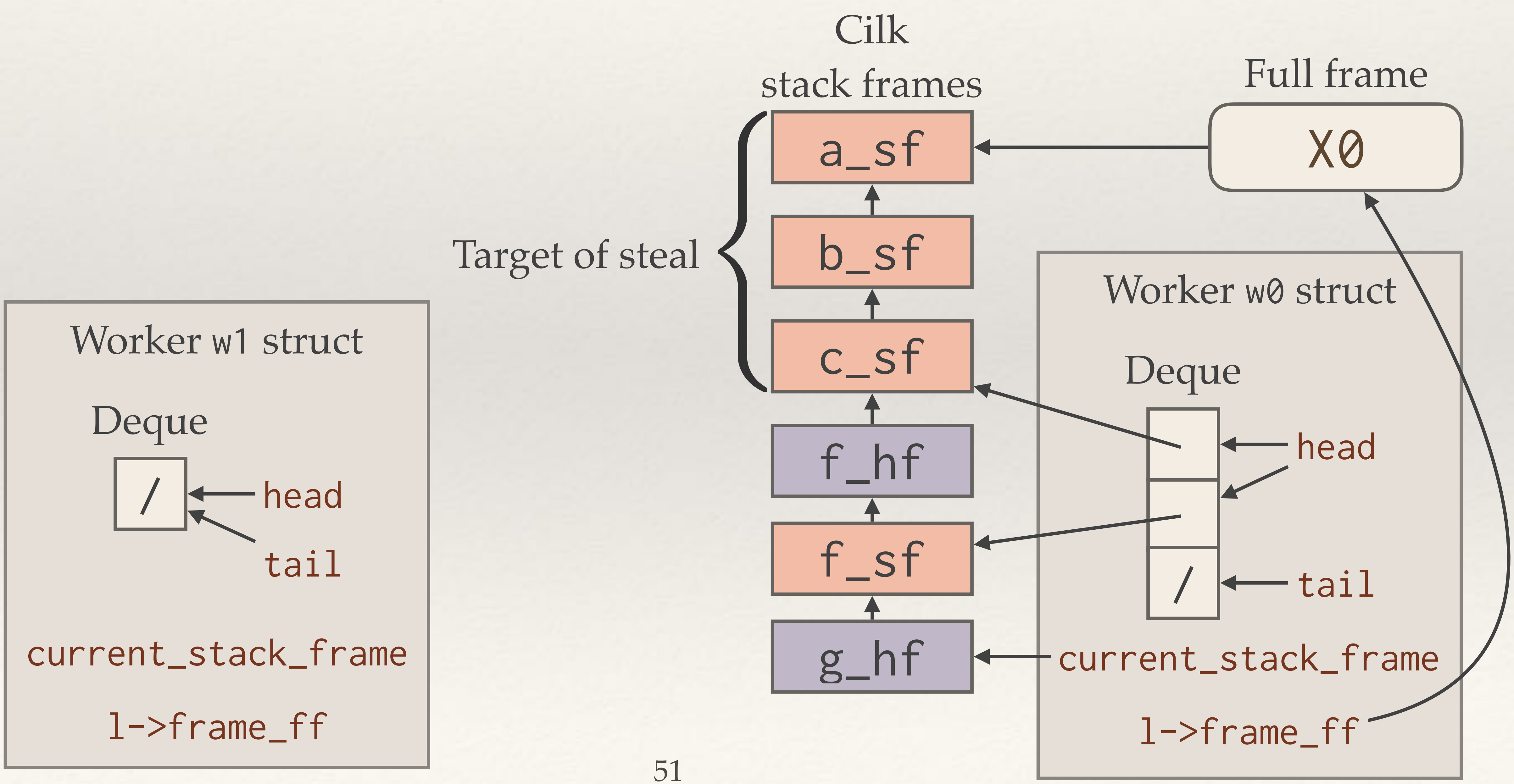
Steps to Perform a Steal

A thief steals a continuation from a victim in 5 steps.

1. Pop the victim's deque.
2. Call `unroll_call_stack()` to update the full frame tree.
3. Make the loot the thief's active frame.
4. Create a new child full frame for the victim.
5. Execute the stolen computation.

Example of a Steal: Step 1

Pop the deque of the victim, worker `w0`.

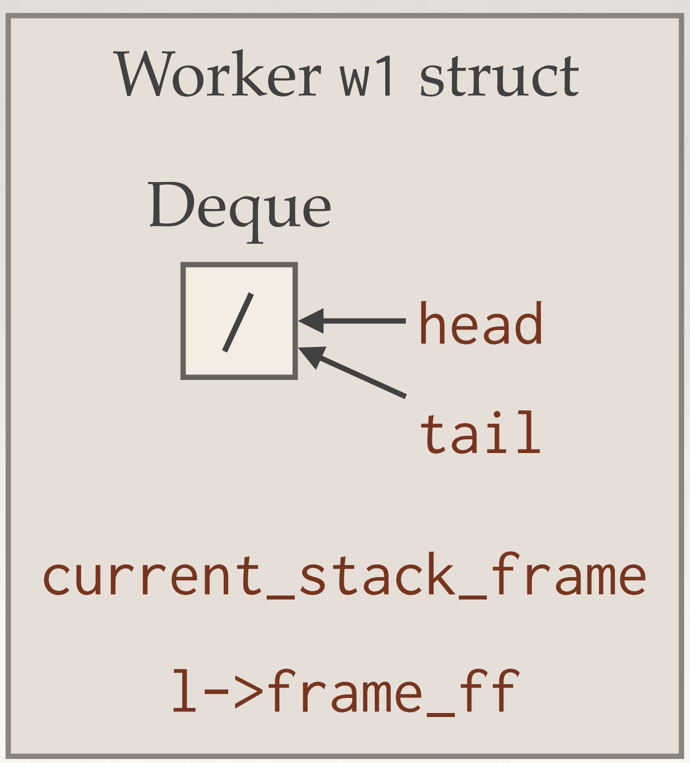


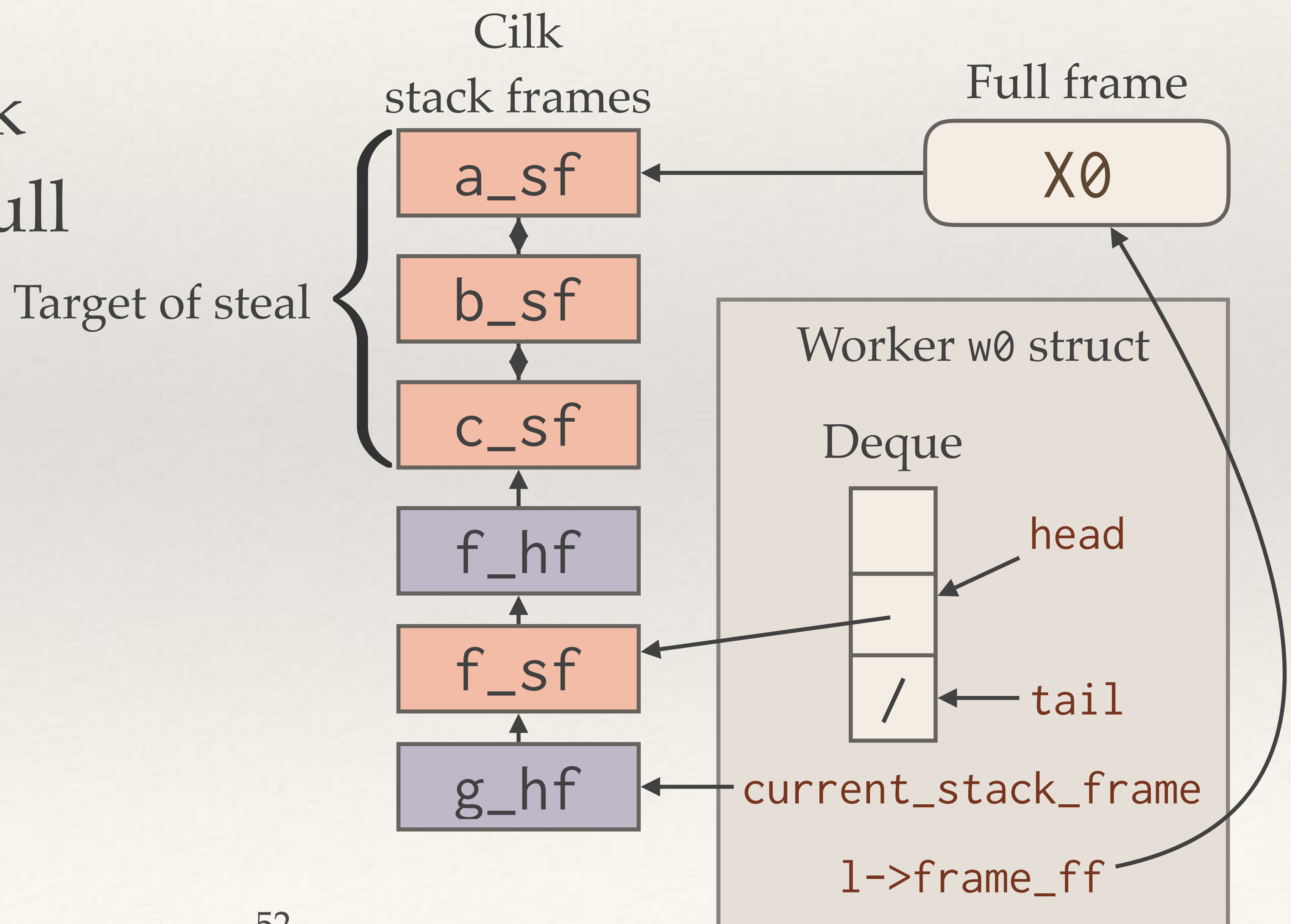
Example of a Steal: Step 2

Call `unroll_call_stack()` on the target of the steal.

a) **Reverse** the chain.

b) Promote each Cilk stack frame to a full frame.



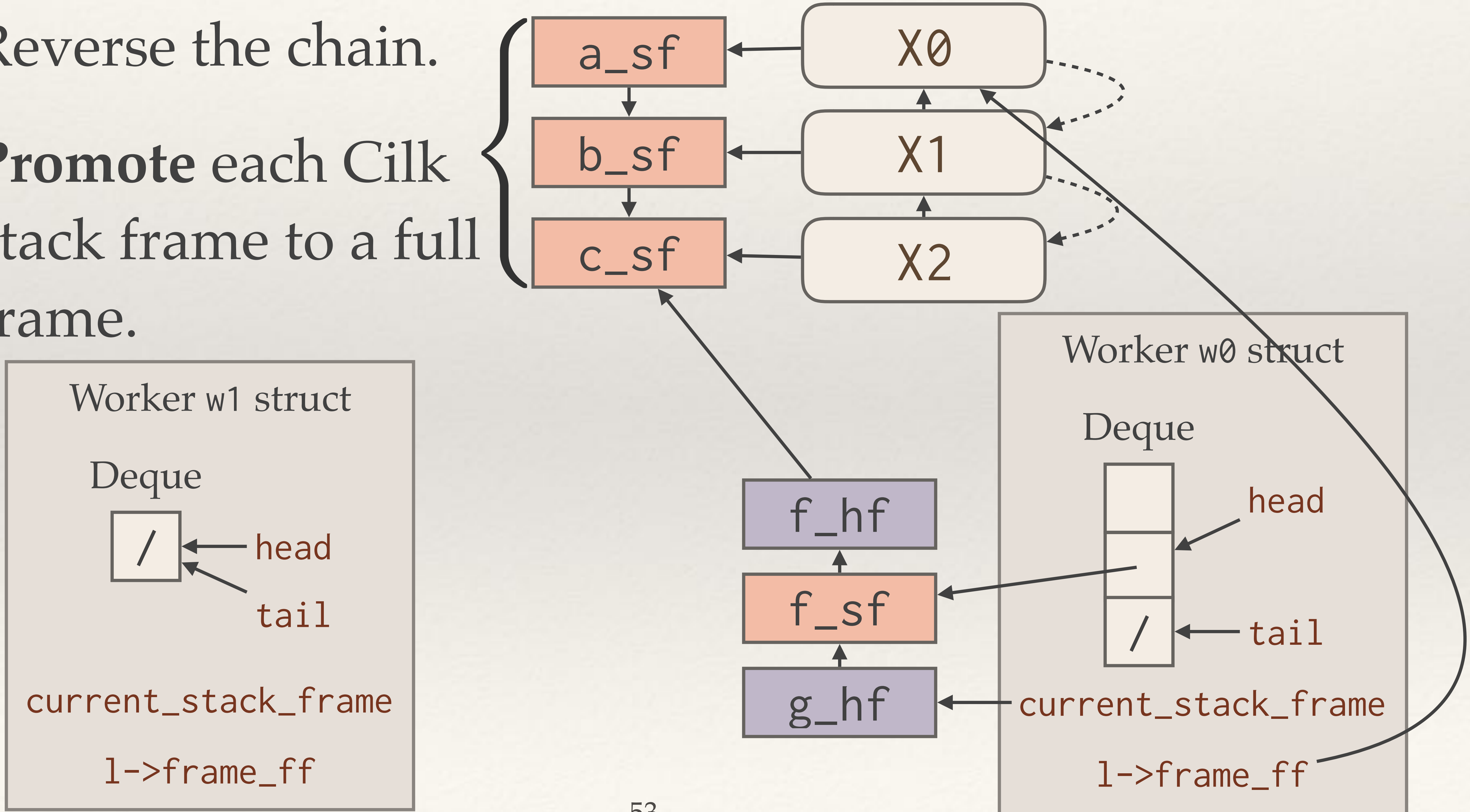


Example of a Steal: Step 2

Call `unroll_call_stack()` on the target of the steal.

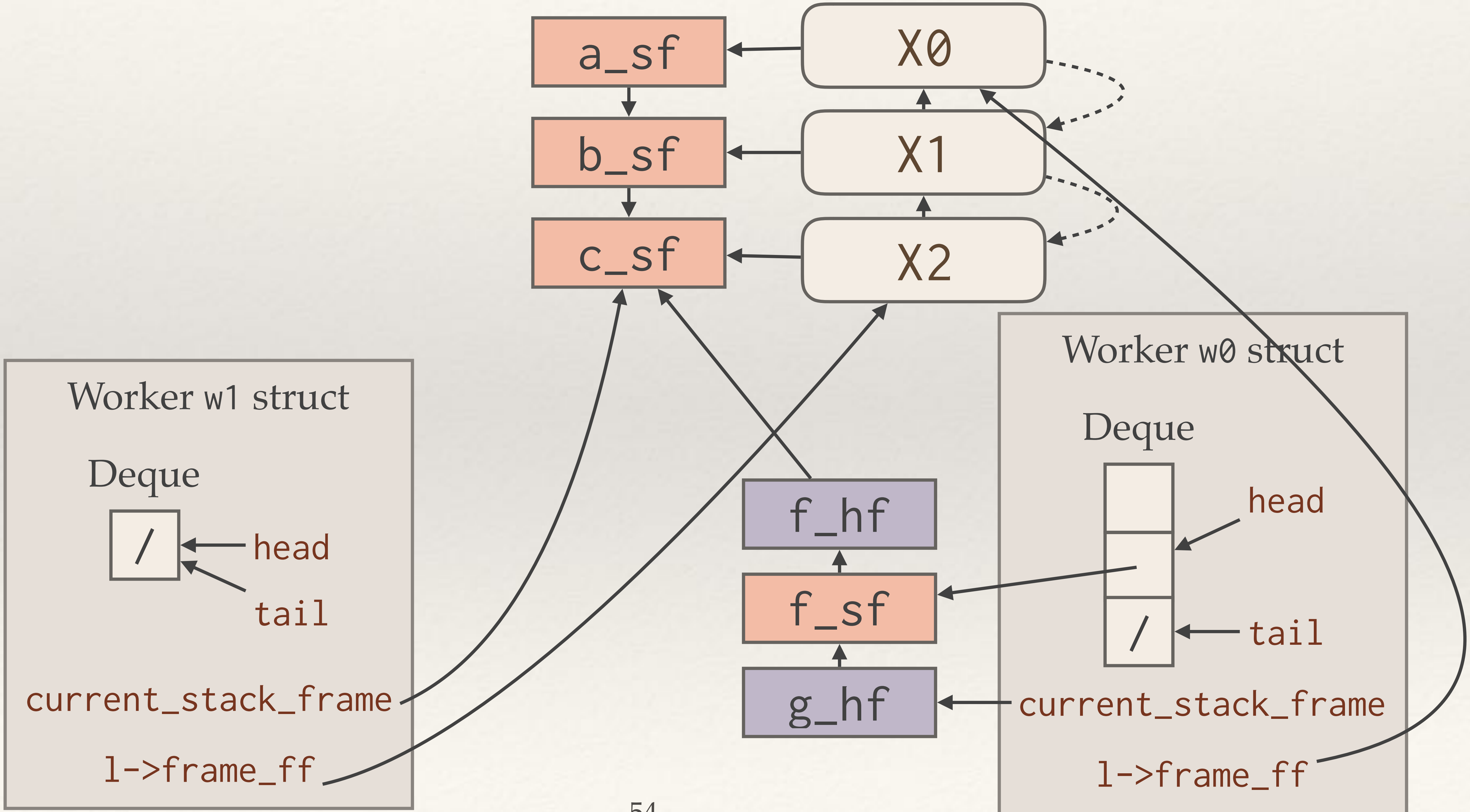
a) Reverse the chain.

b) **Promote** each Cilk stack frame to a full frame.



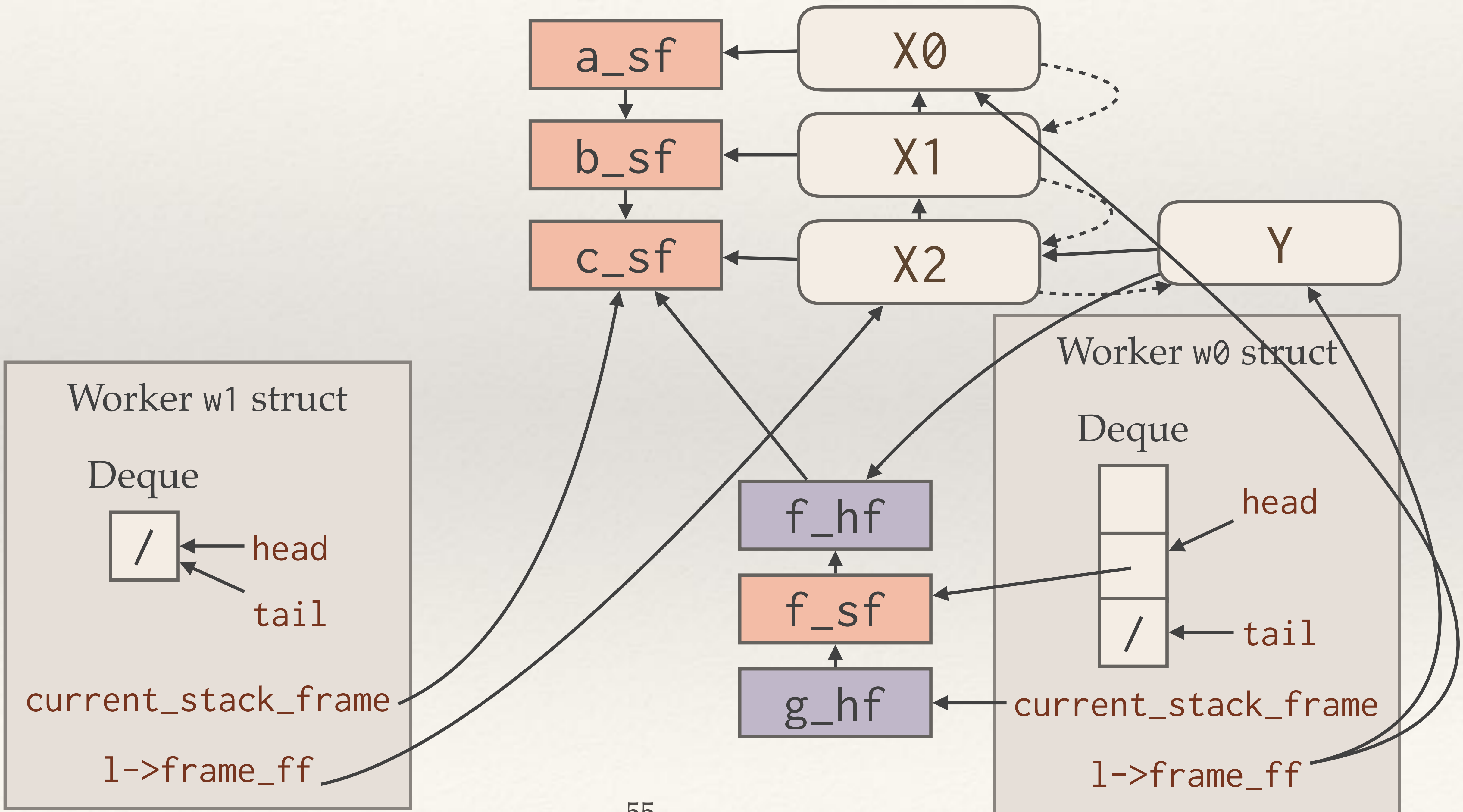
Example of a Steal: Step 3

Make the loot the active frame of the thief, worker `w1`.



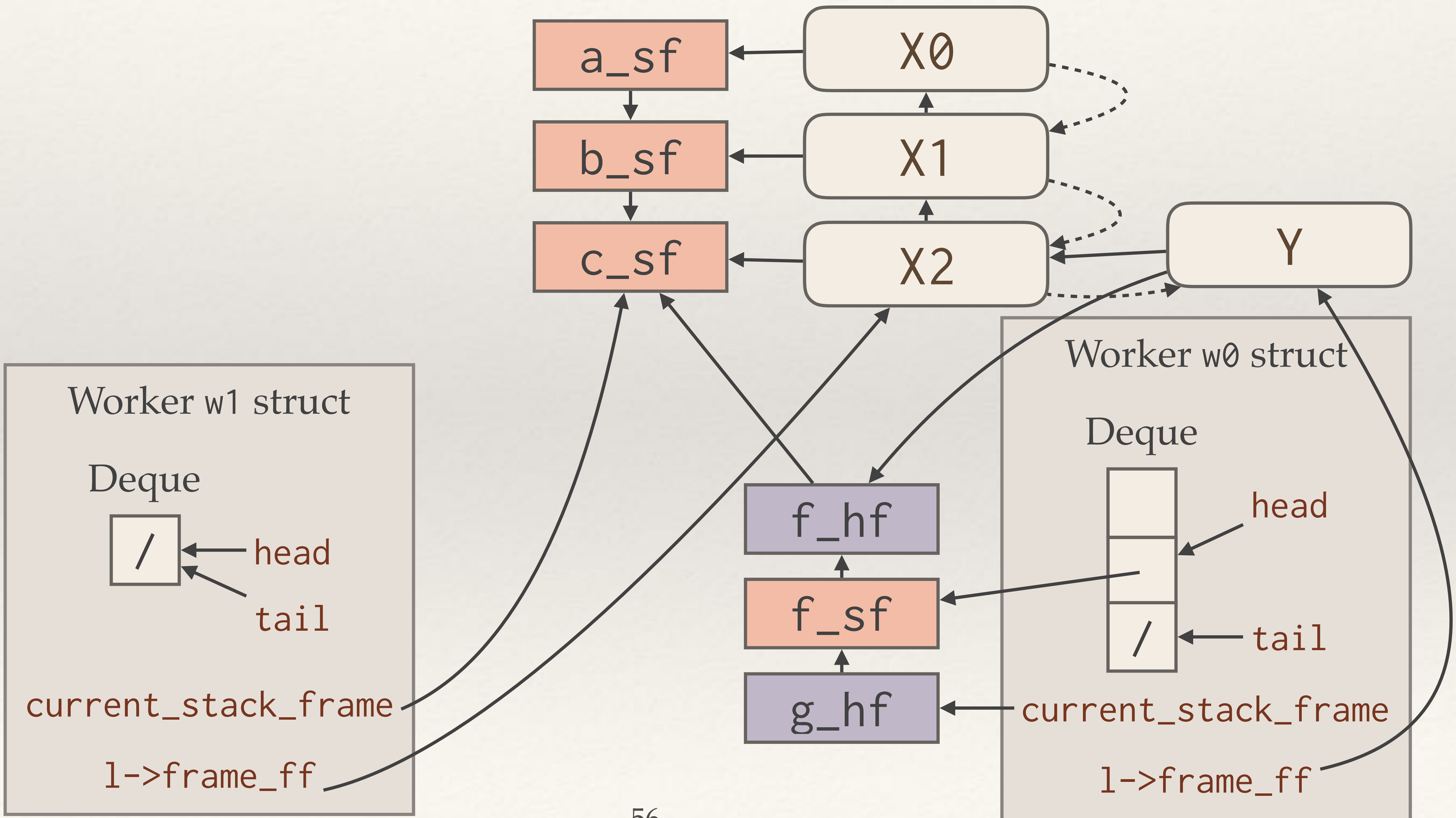
Example of a Steal: Step 4

Create a new child full frame for w0.



Example of a Steal: Step 5

Begin executing the stolen continuation.



More Cilk Features

The Cilk Plus runtime also contains support for other features.

- Reducers [FHLL09]
- Pedigrees [LSS12]
- Exception-handling
- Support for multiple user threads

For the most part, these features can be safely ignored during initial experimentation with the runtime.

Hands-On: Compiling Your Own Runtime

- Log in to the cloud machine:

```
$ ssh 6898tapir.csail.mit.edu
```

- Get the runtime source code:

```
$ git clone https://bitbucket.org/intelcilkruntime/intel-cilk-runtime
```

- Build the runtime from source:

```
$ libtoolize
$ aclocal
$ automake --add-missing
$ autoconf
$ LIBS=-ldl ./configure
$ make
```

- Compile some Cilk code to use your custom-built runtime:

```
$ clang my_cilk_prog.c -fcilkplus -L /path/to/intel-cilk-runtime/.libs \
> -o my_cilk_prog
$ LD_LIBRARY_PATH=/path/to/intel-cilk-runtime/.libs ldd ./my_cilk_prog
```

Hands-On: Generating Stats

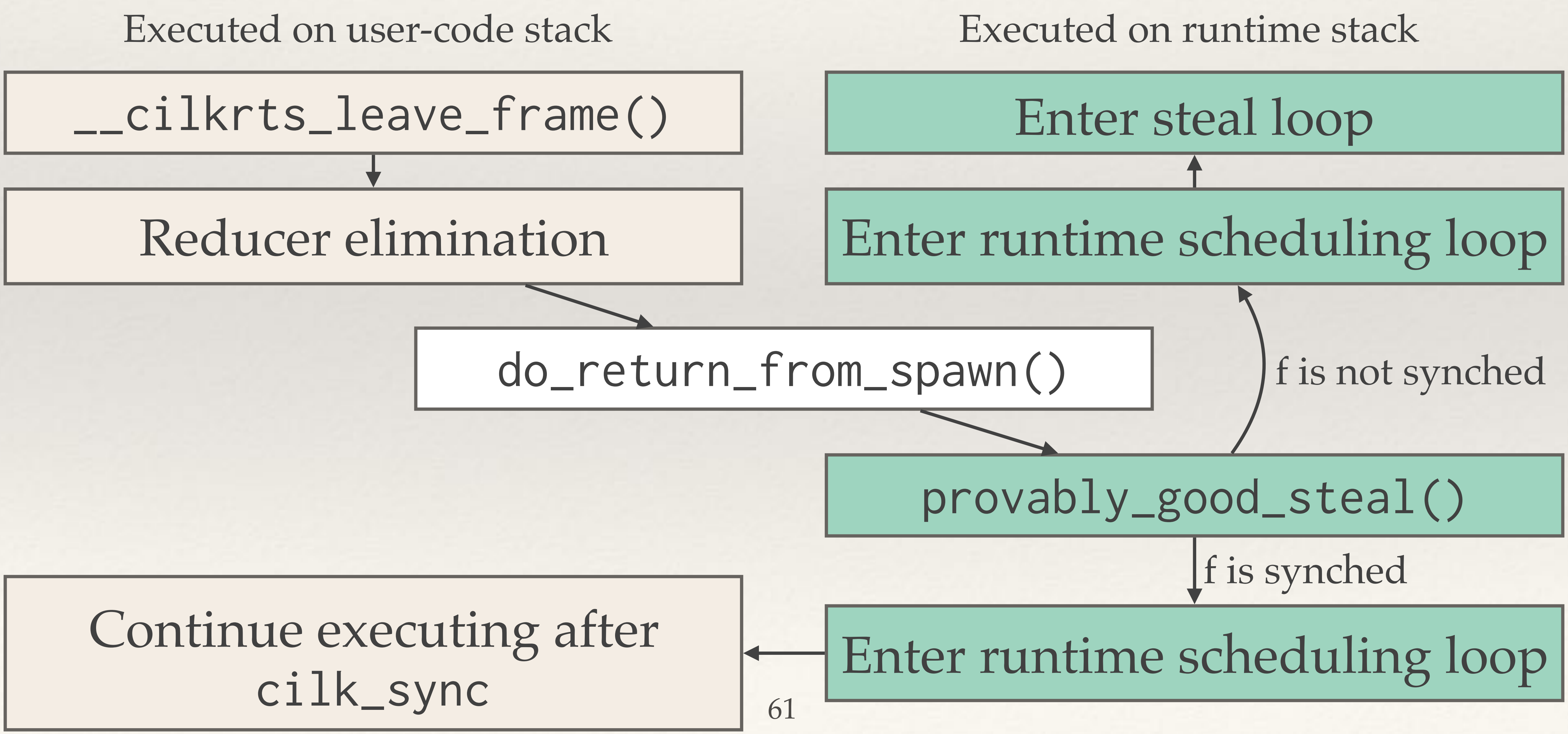
- At the top of `runtime/stats.h`, add
  `#define CILK_PROFILE 1`
- Recompile the runtime system:
  `$ make clean && make`
- Add `__cilkrts_dump_stats()` to the end of your Cilk program.
- Recompile and rerun your Cilk program, and see the runtime statistics!
- **Challenge:** Implement your own statistic.

References

- Frigo, Leiserson, Randall. "The Implementation of the Cilk-5 Multithreaded Language."
- Frigo, Halpern, Leiserson, Lewin-Berlin. "Reducers and Other Cilk++ Hyperobjects."
- Intel Corporation. "Intel Cilk Plus Application Binary Interface Specification."

Return From `cilk_spawn`: Slow Path

The slow path from returning from a `cilk_spawn` changes stacks to enter the runtime.



Return From `cilk_spawn`: Slow Path

The slow path for a cilk_sync follows a similar path.