CS111, Lecture 17

Dispatching

Optional reading:

Operating Systems: Principles and Practice (2nd Edition): Chapter 7 up through Section 7.2

Based on slides and notes created by John Ousterhout, Jerry Cain, Chris Gregg, and others.

Topic 3: Multithreading - How can we have concurrency within a single process? How does the operating system support this?

CS111 Topic 3: Multithreading

Multithreading - *How can we have concurrency within a single process?* ***How does the operating system support this?***

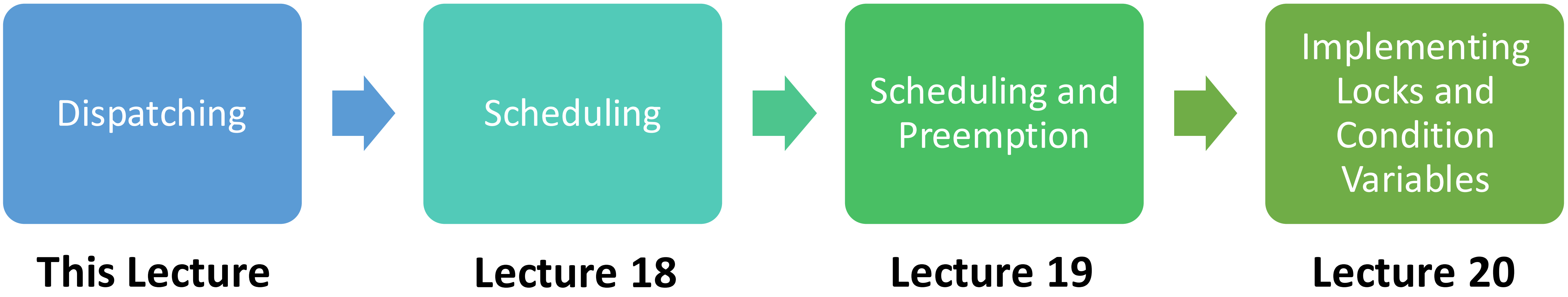
Why is answering this question important?

- Shows us what the mechanism looks like for switching between running threads (today)
- Allows us to see how threads are represented and the fairness challenges for who gets to run next / for how long (next time)
- Allows us to understand how locks and condition variables are implemented (next week)

assign5: implement your own version of **thread**, **mutex** and **condition_variable**!

CS111 Topic 3: Multithreading, Part 2

Multithreading - *How can we have concurrency within a single process? **How does the operating system support this?***



Dispatching → Scheduling → Scheduling and Preemption → Implementing Locks and Condition Variables

This Lecture — Dispatching

Lecture 18 — Scheduling

Lecture 19 — Scheduling and Preemption

Lecture 20 — Implementing Locks and Condition Variables

assign5: implement your own version of **thread**, **mutex** and **condition_variable_any**!

Learning Goals

- Learn about how the operating system keeps track of threads and processes
- Understand the general mechanisms for switching between threads and when switches occur

Plan For Today

- Overview: Dispatching and Scheduling
- Running a Thread
- Switching to Another Thread
  - Context Switch Implementation
- How do we switch what code is running?

```
cp -r /afs/ir/class/cs111/lecture-code/lect17 .
```

Plan For Today

- **Overview: Dispatching and Scheduling**
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```

Scheduling And Dispatching

We have learned how user programs can create new processes and spawn threads. But how does the operating system manage this internally? What happens when we spawn a new thread or create a new process?

Key questions we will answer:

- How does the operating system track info for threads and processes? (today)
- How does the operating system run a thread and how does it switch between threads (“dispatching”)? (today)
- **Scheduling:** How does the operating system decide which thread to run next? (next time)

Plan For Today

- Overview: Dispatching and Scheduling
- **Running a Thread**
- Switching to Another Thread
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```

Running a Thread

Threads are the “unit of execution” – processes aren’t executed, threads are.

- A processor has 1 or more “cores” - Each core contains a complete CPU capable of executing a thread
- Typically have more threads than cores, but most may not need to run at any given point in time (why? They are waiting for something)
- When the OS wants to run a thread, it loads its state (registers – more on this later!) into a core, and starts or resumes it

Problem: once we run a thread, the OS is not running anymore! (e.g. 1 core) How does it regain control?

Regaining Control

There are several ways control can switch back to the OS:

1. “Traps” (events that require OS attention):
    1. System calls (like **read** or **waitpid**)
    2. Errors (illegal instruction, address violation, etc.)
    3. Page fault (accessing memory that must be loaded in) – more later…
2. “Interrupts” (events occurring outside current thread):
    1. Character typed at keyboard
    2. Completion of disk operation
    3. Timer – to make sure OS eventually regains control

At this point, OS could then decide to run a different thread.

Plan For Today

- Overview: Dispatching and Scheduling
- Running a Thread
- **Switching to Another Thread**
  - Context Switch Implementation
- How do we switch what code is running?

```
cp -r /afs/ir/class/cs111/lecture-code/lect17 .
```

Switching to Another Thread

Key Idea: when we switch from one thread to another, we must save the current thread's state (“freeze frame”) to resume it later.

- E.g., must remember current program values it's using, and where it was executing

Key Idea #2: we must also load the thread state of the new thread in to resume it where it left off.

How can we remember this information? **We must remember the CPU core(s) register values and the thread's stack space.**

Aside: x86-64 Assembly Refresher

- A **register** is a 64-bit space inside a processor core.
- Each core has its own set of registers.
- Registers are like "scratch paper" for the processor. Data being calculated or manipulated is moved to registers first. Operations are performed on registers.
- Registers also hold parameters and return values for functions.
- Some registers have special responsibilities – e.g. **%rsp** always stores the address of the current top of the stack.

Key Idea: when we switch to a new thread, we must remember our register values – and by remembering %rsp, we also keep a reference to our stack. Then we can load them in later when we run again. But where do we put these register values?

Process and Thread State

The OS maintains a (private) **process control block (“PCB”)** for each process - a set of relevant information about its execution. Lives as long as the process does.

- Information about memory used by this process
- File descriptor table
- Info about threads in this process
- Other misc. accounting and info

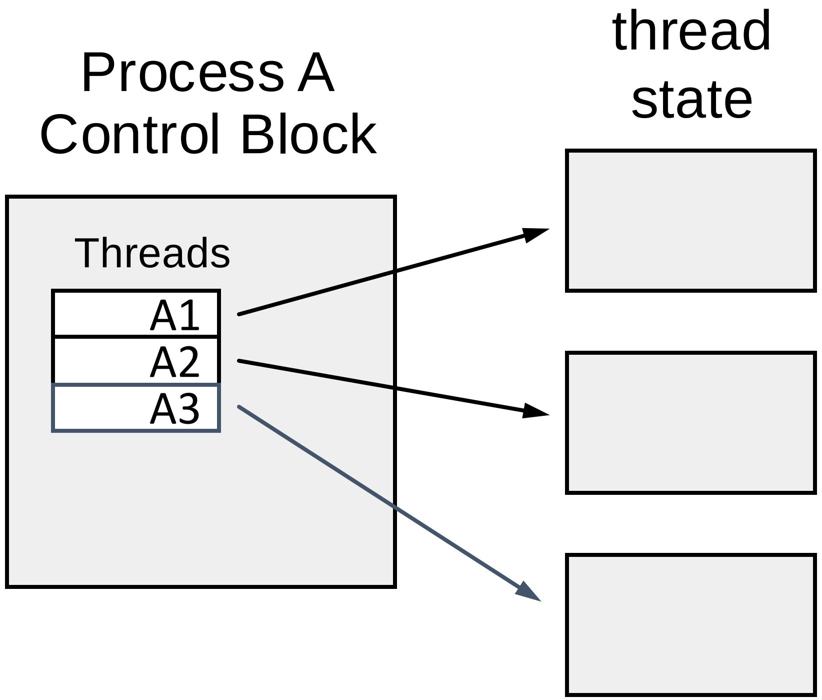
Process and Thread State

The OS maintains a (private) **process control block ("PCB")** for each process - a set of relevant information about its execution. Lives as long as the process does.

- Information about memory used by this process
- File descriptor table
- ***Info about threads in this process***
- Other misc. accounting and info

Thread State

- Every process has 1 main thread and can spawn additional threads.
- All main info in the PCB (e.g. memory info for the entire process) is relevant to all threads
- Each thread also has some of its own private info – we can use this to store thread state.
  - When we want to switch threads, store the current thread's info, and load in the new thread's info.



Switching Between Threads

The **dispatcher** is OS code that runs on each core that switches between threads

- Not a thread – code that is invoked to perform the dispatching function
- Lets a thread run, then switches to another thread, etc.
- *Context switch* – changing the thread currently running to another thread. We must save the current thread state (registers) and load in the new thread state.
- The context switch function is funky – like running a function that, as part of its execution, returns to a *completely different function in a completely different thread!!*
  - If we context switch to a new thread, we call context switch but then return to the start of the function the new thread is supposed to run.
  - If we context switch to a thread that ran before, we call context switch but then return to where *that thread called context switch previously when it was switched off*.

Demo: context-switch.cc

Plan For Today

- Overview: Dispatching and Scheduling
- Running a Thread
- **Switching to Another Thread**
    - **Context Switch Implementation**
- How do we switch what code is running?

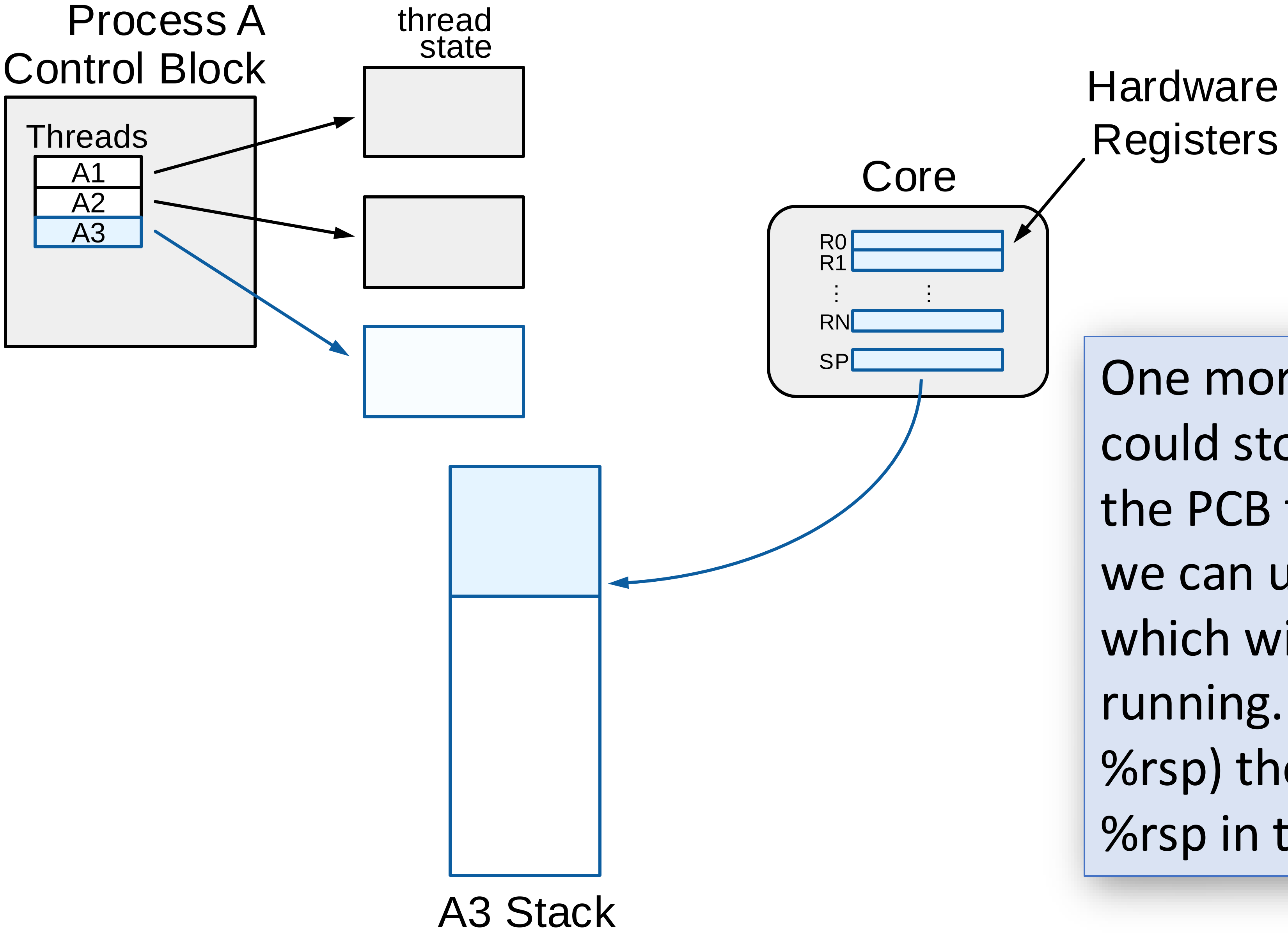
```
cp -r /afs/ir/class/cs111/lecture-code/lect17 .
```

Context Switch

```
Thread main_thread;
Thread other_thread;

void other_func() {
    cout << "Howdy! I am another thread." << endl;
    context_switch(other_thread, main_thread);
    cout << "We will never reach this line :(" << endl;
}

int main(int argc, char *argv[]) {
    // Initialize other_thread to run other_func
    other_thread = create_thread(other_func);

    cout << "Hello, world!  I am the main thread" << endl;
    context_switch(main_thread, other_thread);
    cout << "Cool, I'm back in main()!" << endl;
    return 0;
}
```

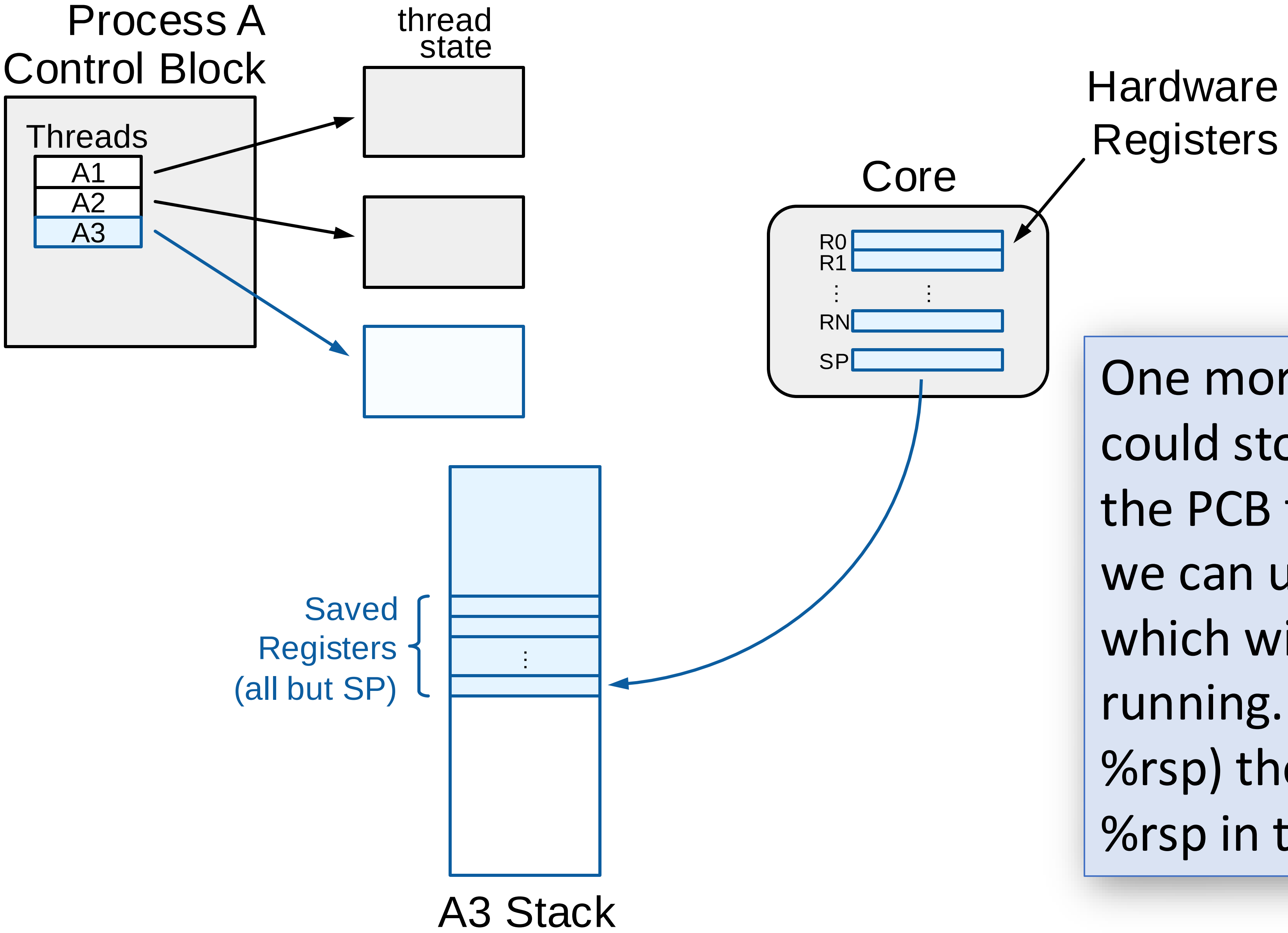
- *context_switch* is called from one function, but returns to another
- The next time we switch back to the original thread, it resumes where it left off.

Context Switching



One more key detail: while we could store *all* saved registers in the PCB thread state space, instead we can utilize the thread's stack, which will be unused while it is not running. Store all registers (except %rsp) there, and then store only %rsp in thread state space!

Context Switching



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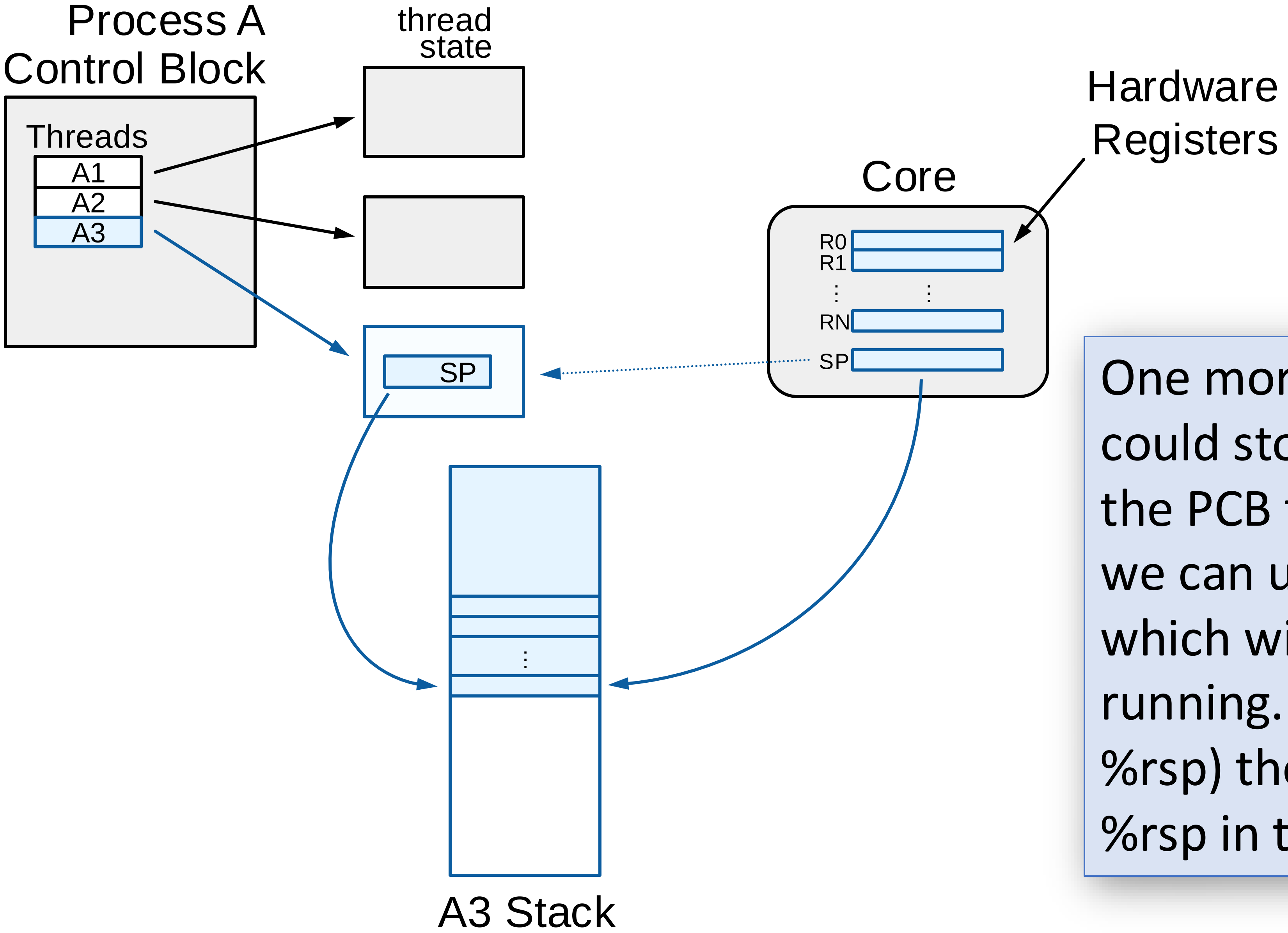
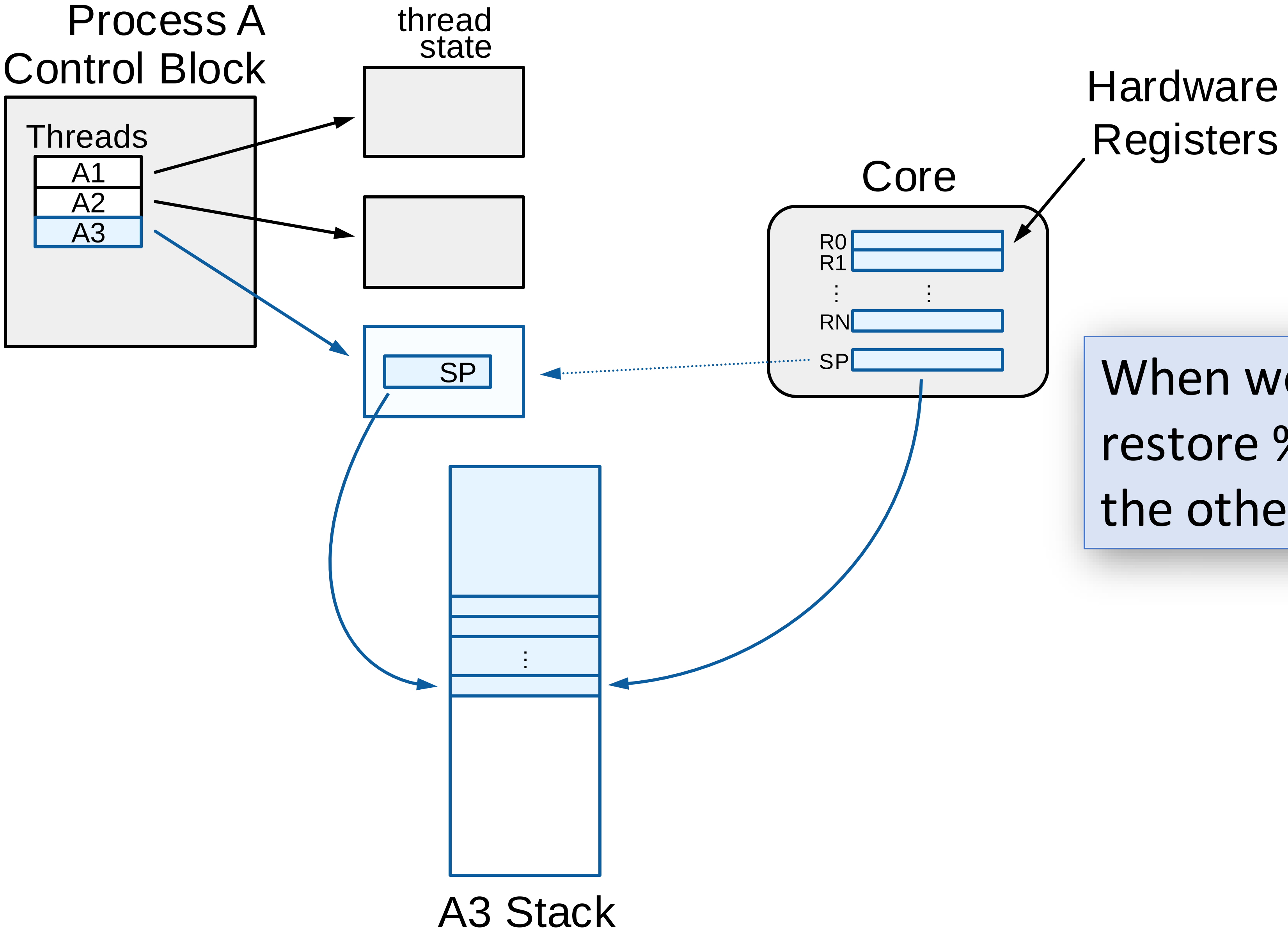
Context Switching



One more key detail: while we could store *all* saved registers in the PCB thread state space, instead we can utilize the thread's stack, which will be unused while it is not running. Store all registers (except %rsp) there, and then store only %rsp in thread state space!

Context Switching



When we switch back later, we will restore %rsp and then pop off all the other saved register values.

Context Switching

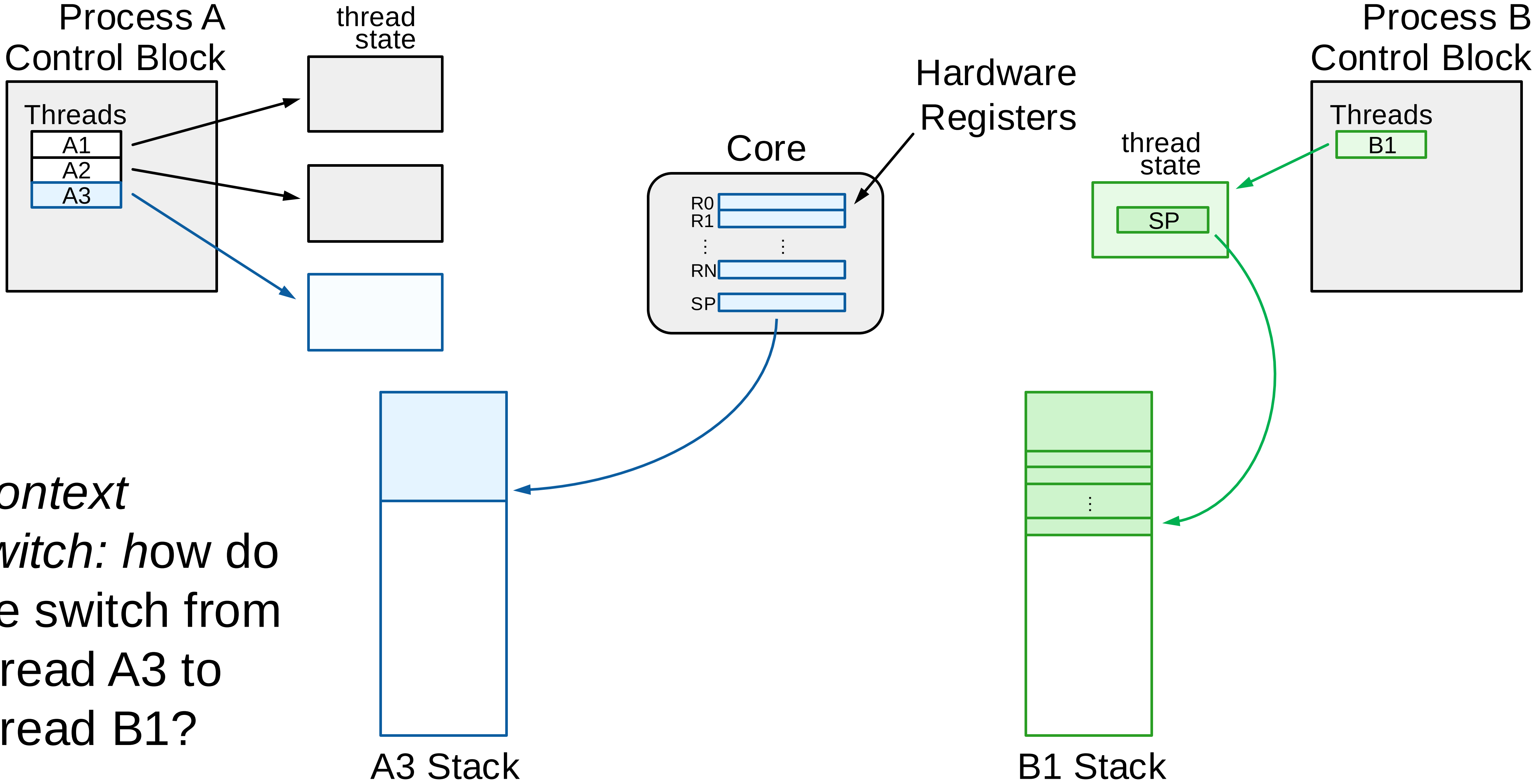
A *context switch* means changing the thread currently running to another thread. We must save the current thread state and load in the new thread state.

1. Push all registers besides stack onto current thread's stack
2. Save the current stack register (rsp) into the thread's state space
3. Load the other thread's saved stack register from its state space into rsp
4. Pop registers off the other thread's stack

Let's see an example switching from thread A3 to another already-running thread B1.

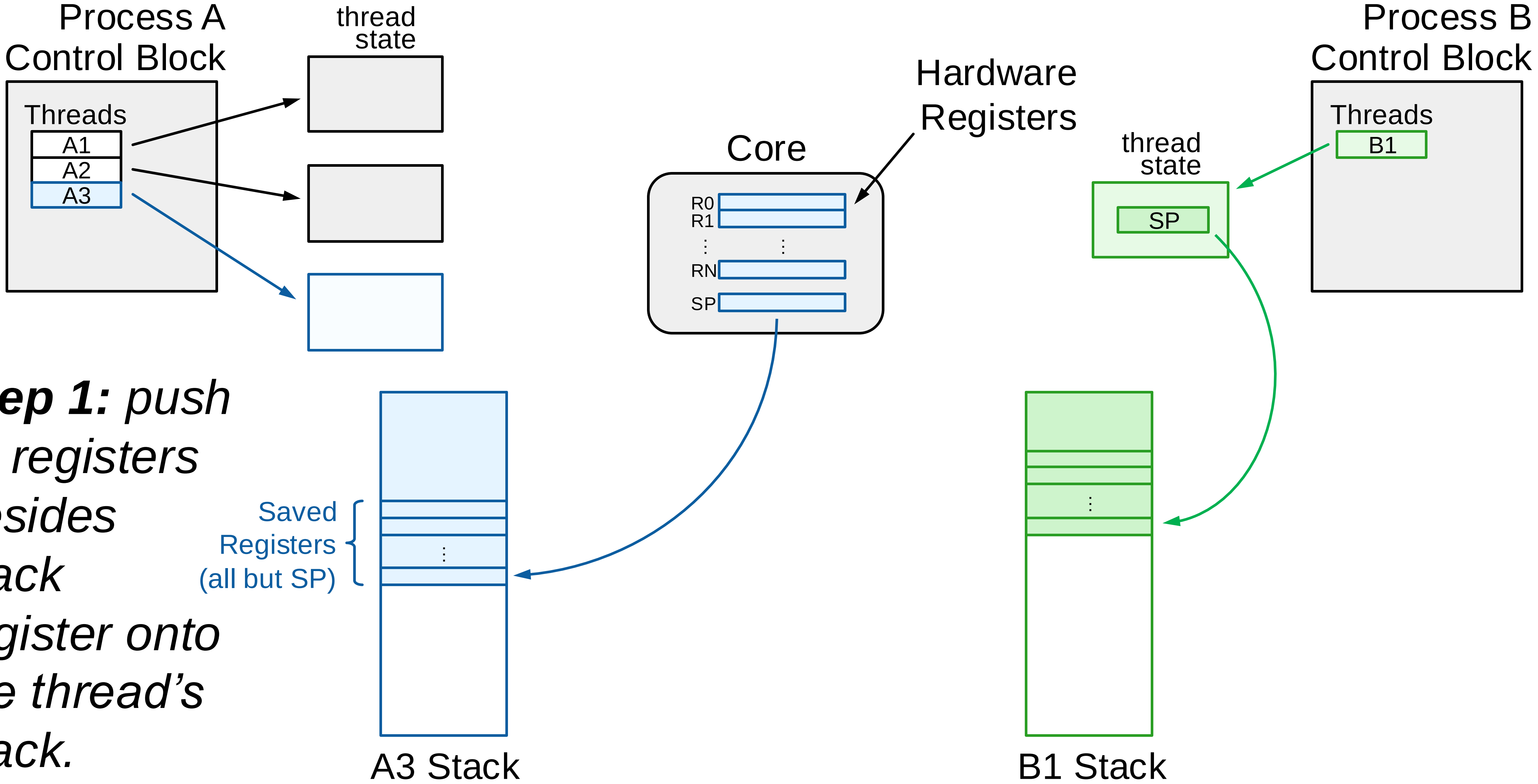
Super funky: we are calling a function from one thread's stack and execution and returning from it in **another** thread's stack and execution!

Context Switching



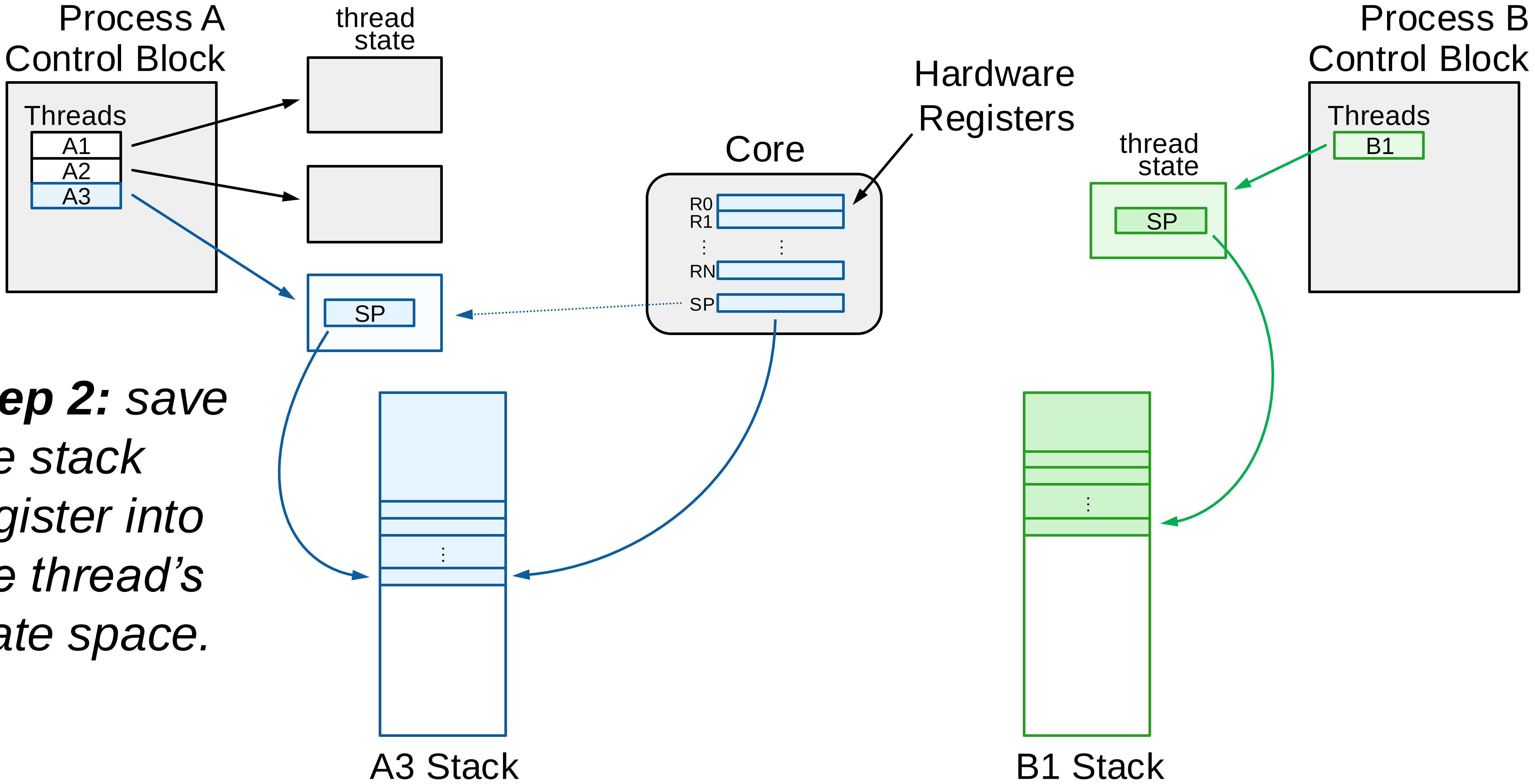
Context switch: how do we switch from thread A3 to thread B1?

Context Switching



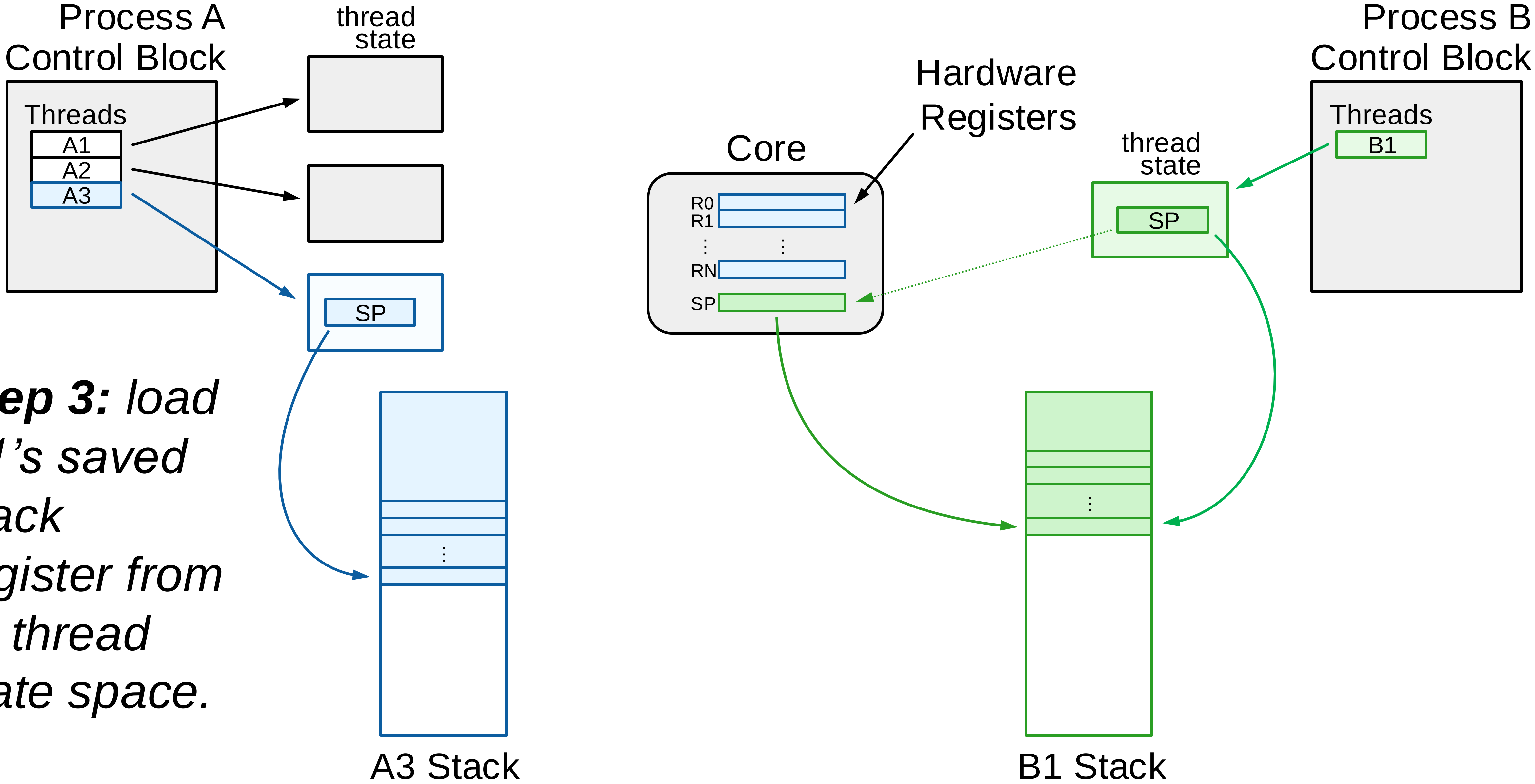
Step 1: *push all registers besides stack register onto the thread's stack.*

Context Switching



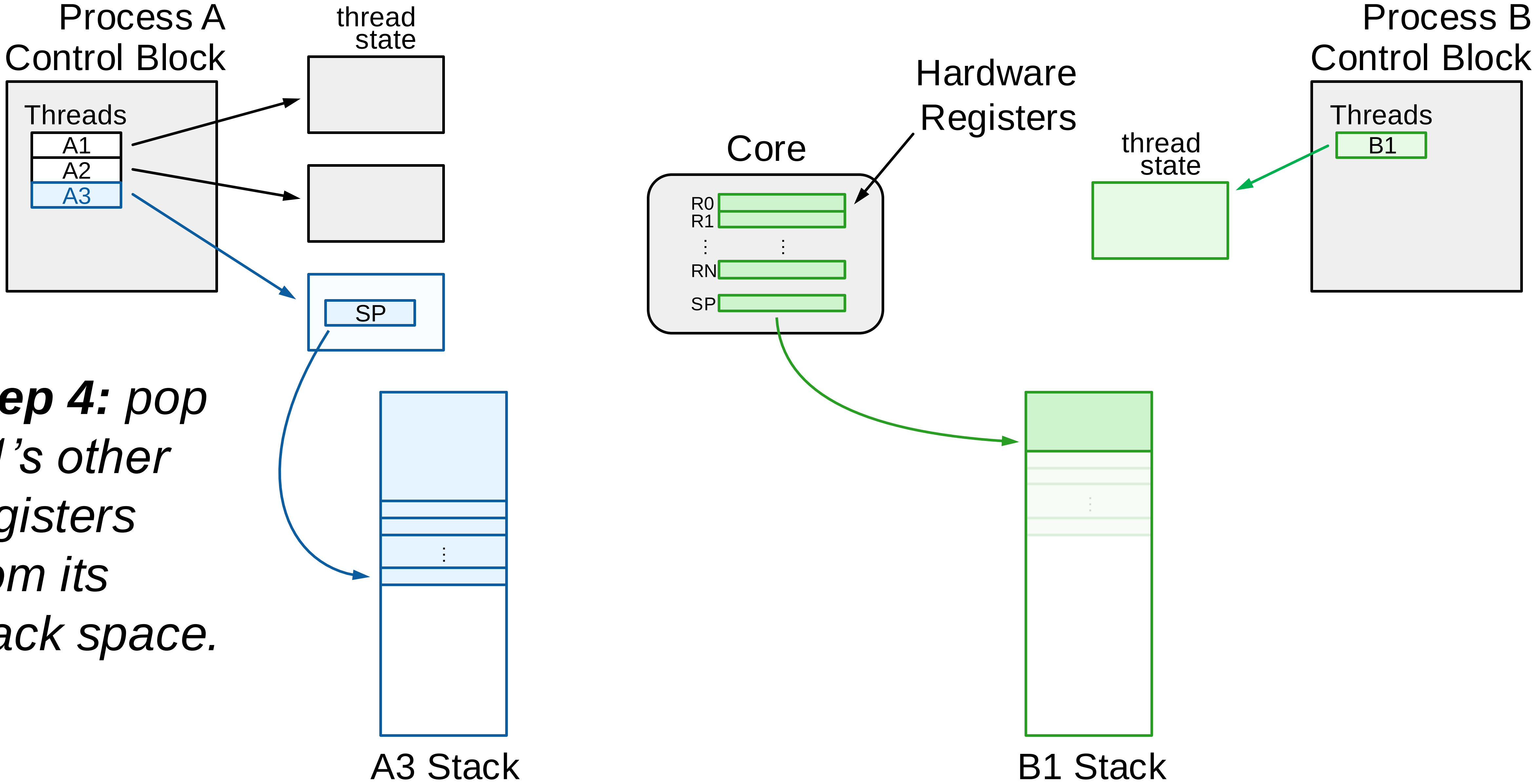
Step 2: *save the stack register into the thread's state space.*

Context Switching



Step 3: *load B1's saved stack register from its thread state space.*

Context Switching



***Step 4:** pop B1's other registers from its stack space.*

Context Switching

A *context switch* means changing the thread currently running to another thread. We must save the current thread state and load in the new thread state.

1. Push all registers besides stack onto current thread's stack
2. Save the current stack register (rsp) into the thread's state space
3. Load the other thread's saved stack register from its state space into rsp
4. Pop registers off the other thread's stack

Super funky: we are calling a function from one thread's stack and execution and returning from it in **another** thread's stack and execution!

Context Switching

```
pushq %rbp
pushq %rbx
pushq %r12
pushq %r13
pushq %r14
pushq %r15
movq %rsp,0x2000(%rdi)
movq 0x2000(%rsi),%rsp
popq %r15
popq %r14
popq %r13
popq %r12
popq %rbx
popq %rbp
ret
```

Context Switching

```
pushq %rbp
pushq %rbx
pushq %r12
pushq %r13
pushq %r14
pushq %r15
movq %rsp,0x2000(%rdi)
movq 0x2000(%rsi),%rsp
popq %r15
popq %r14
popq %r13
popq %r12
popq %rbx
popq %rbp
ret
```

1. Push all registers besides stack onto current thread's stack

Context Switching

```
pushq %rbp
pushq %rbx
pushq %r12
pushq %r13
pushq %r14
pushq %r15
movq %rsp,0x2000(%rdi)
movq 0x2000(%rsi),%rsp
popq %r15
popq %r14
popq %r13
popq %r12
popq %rbx
popq %rbp
ret
```

2. Save the current stack register (rsp) into the thread's state space

Context Switching

```
pushq %rbp
pushq %rbx
pushq %r12
pushq %r13
pushq %r14
pushq %r15
movq %rsp,0x2000(%rdi)
movq 0x2000(%rsi),%rsp
popq %r15
popq %r14
popq %r13
popq %r12
popq %rbx
popq %rbp
ret
```

3. Load the other thread’s saved stack register from its state space into rsp

Context Switching

```
pushq %rbp
pushq %rbx
pushq %r12
pushq %r13
pushq %r14
pushq %r15
movq %rsp,0x2000(%rdi)
movq 0x2000(%rsi),%rsp
popq %r15
popq %r14
popq %r13
popq %r12
popq %rbx
popq %rbp
ret
```

4. Pop registers off the other thread's stack

Context Switching

```
pushq %rbp
pushq %rbx
pushq %r12
pushq %r13
pushq %r14
pushq %r15
movq %rsp,0x2000(%rdi)
movq 0x2000(%rsi),%rsp
```

we start executing on one stack…

```
popq %r15
popq %r14
popq %r13
popq %r12
popq %rbx
popq %rbp
ret
```

and end executing on another!

Plan For Today

- Overview: Dispatching and Scheduling
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  - Context Switch Implementation
- **How do we switch what code is running?**

```
cp -r /afs/ir/class/cs111/lecture-code/lect17 .
```

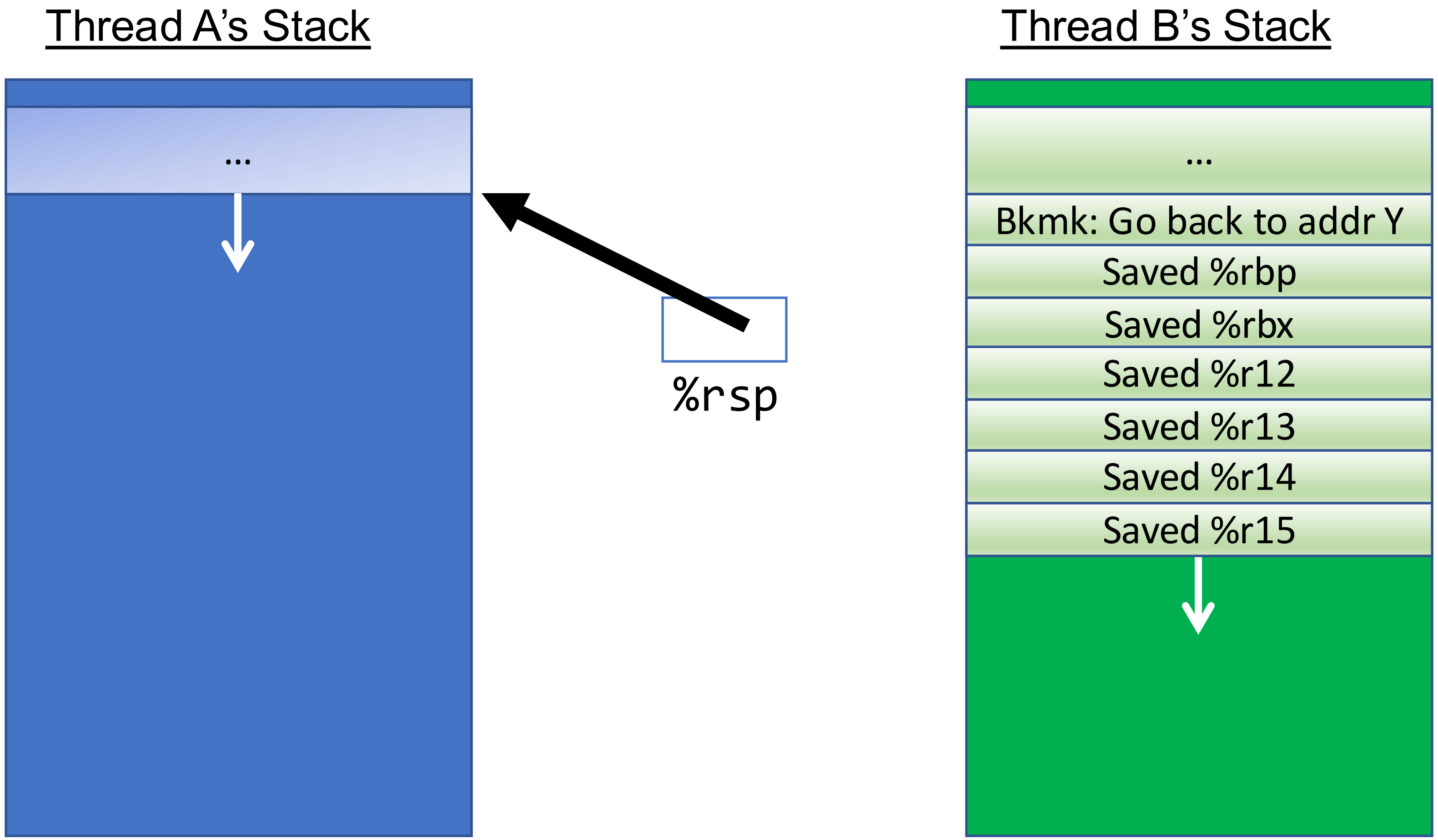
How do we switch what code is running?

It turns out information about what code to run is *also* stored in each thread's stack space, automatically! So by switching stacks, we switch code too.

Key Idea: whenever we call a function, before running that function we store info on the stack about where we should resume in the calling function when we are done. This is called the return address ("bookmark"). This includes when we call context switch.

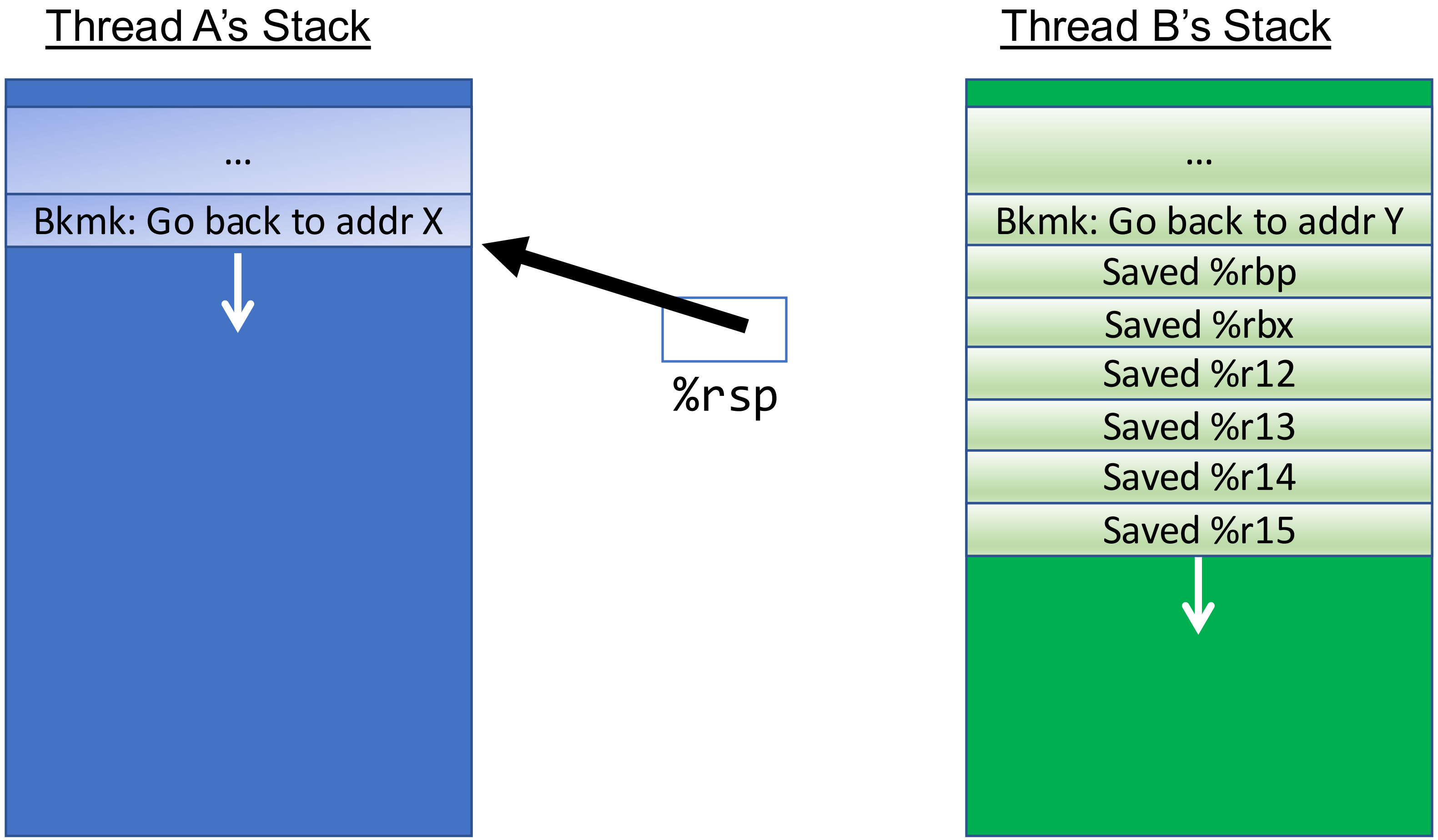
- The **callq** instruction (for calling a function) stores the return address
- The **ret** instruction pops the return address off the stack and resumes executing that code (pops value off and into the %rip register)

Context Switching



```
callq context_switch
...
pushq %rbp
pushq %rbx
pushq %r12
pushq %r13
pushq %r14
pushq %r15
movq %rsp,0x2000(%rdi)
movq 0x2000(%rsi),%rsp
popq %r15
popq %r14
popq %r13
popq %r12
popq %rbx
popq %rbp
ret
```

Context Switching



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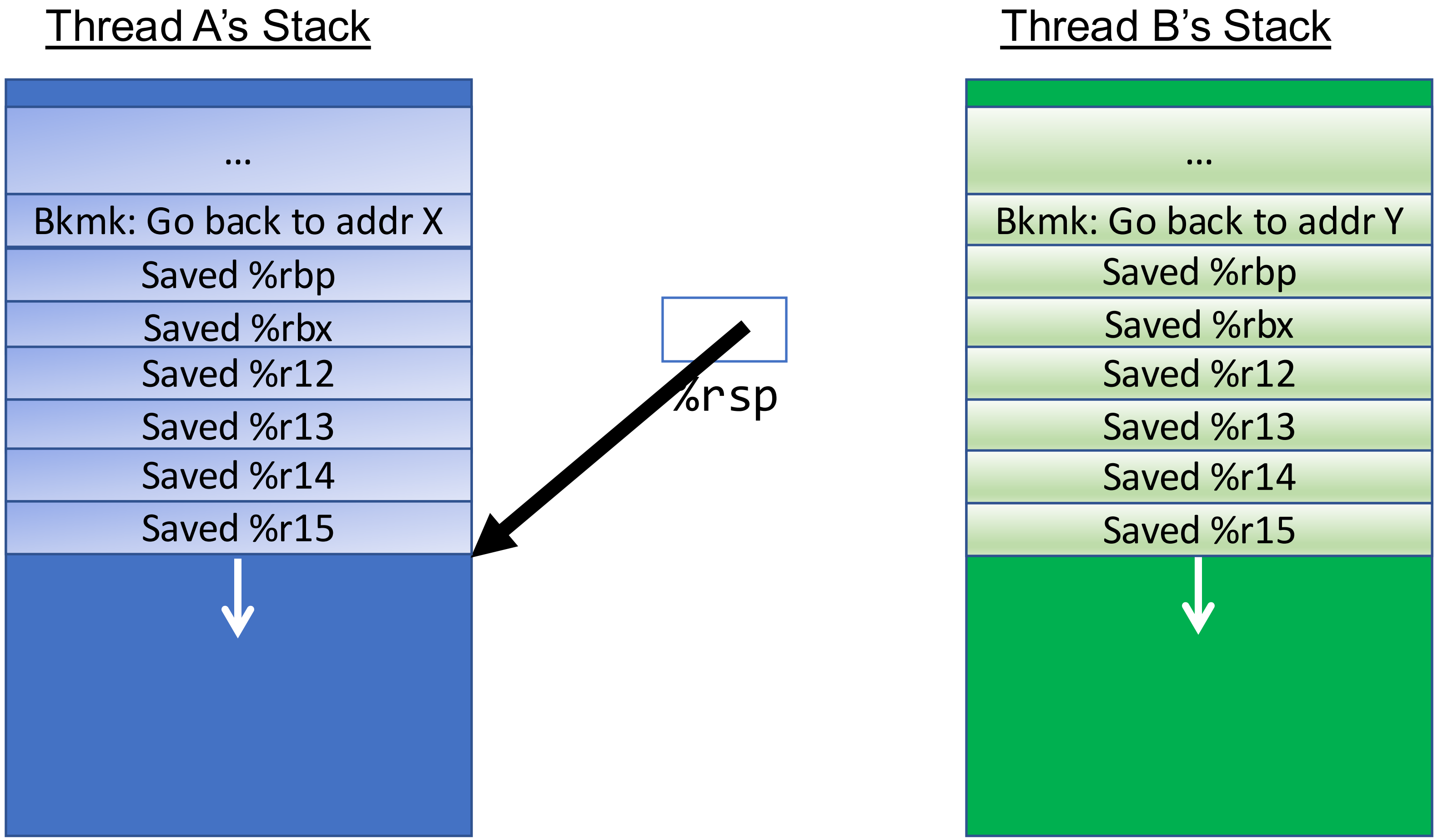
movq 0x2000(%rsi),%rsp
popq %r15
popq %r14
popq %r13
popq %r12
popq %rbx
popq %rbp
ret
```

Context Switching



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pushq %r12
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movq %rsp,0x2000(%rdi)
movq 0x2000(%rsi),%rsp
popq %r15
popq %r14
popq %r13
popq %r12
popq %rbx
popq %rbp
ret
```
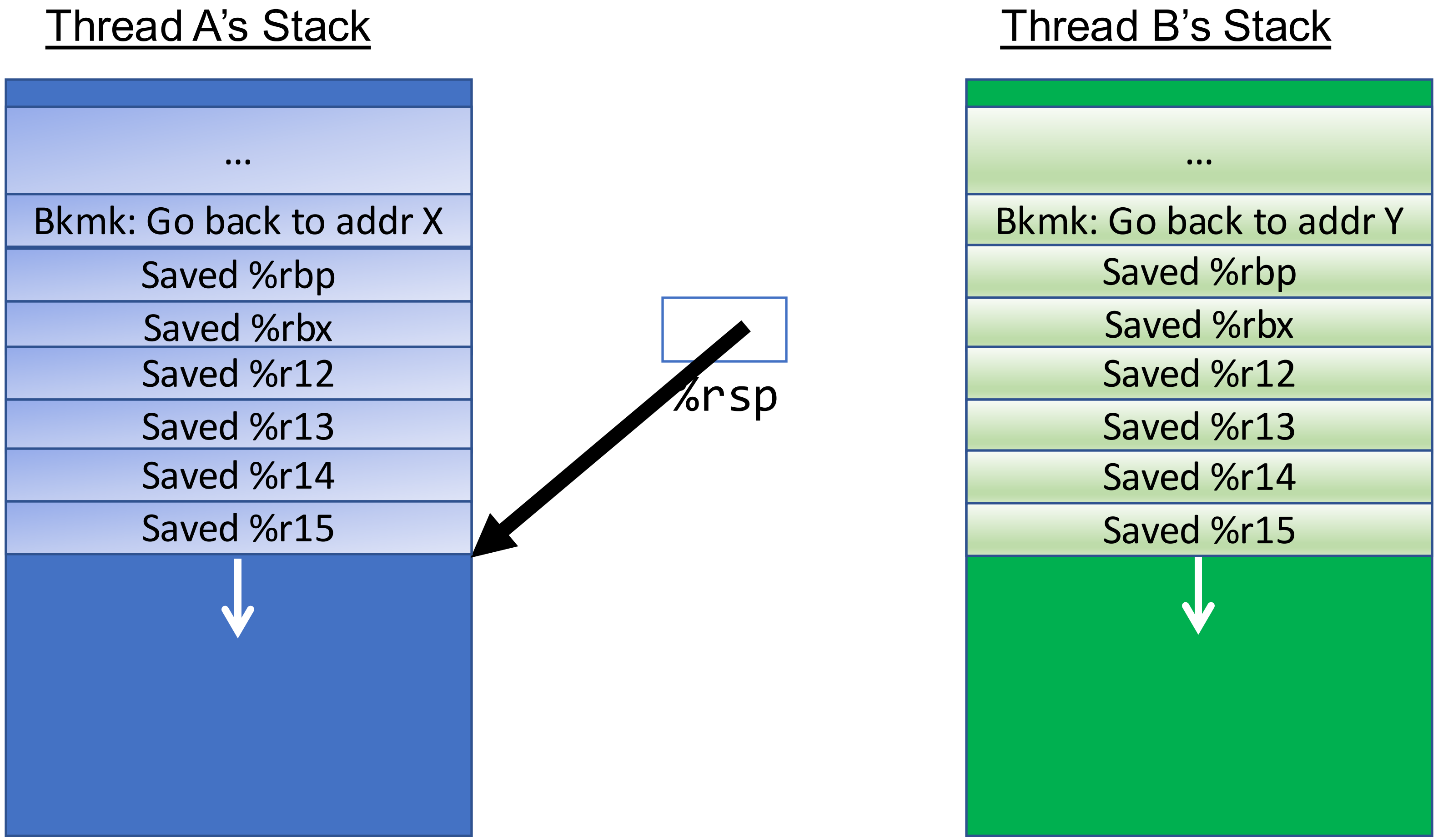

Context Switching



Thread A's Stack

…

Bkmk: Go back to addr X

Saved %rbp

Saved %rbx

Saved %r12

Saved %r13

Saved %r14

Saved %r15

%rsp

Thread B's Stack

…

Bkmk: Go back to addr Y

Saved %rbp

Saved %rbx

Saved %r12

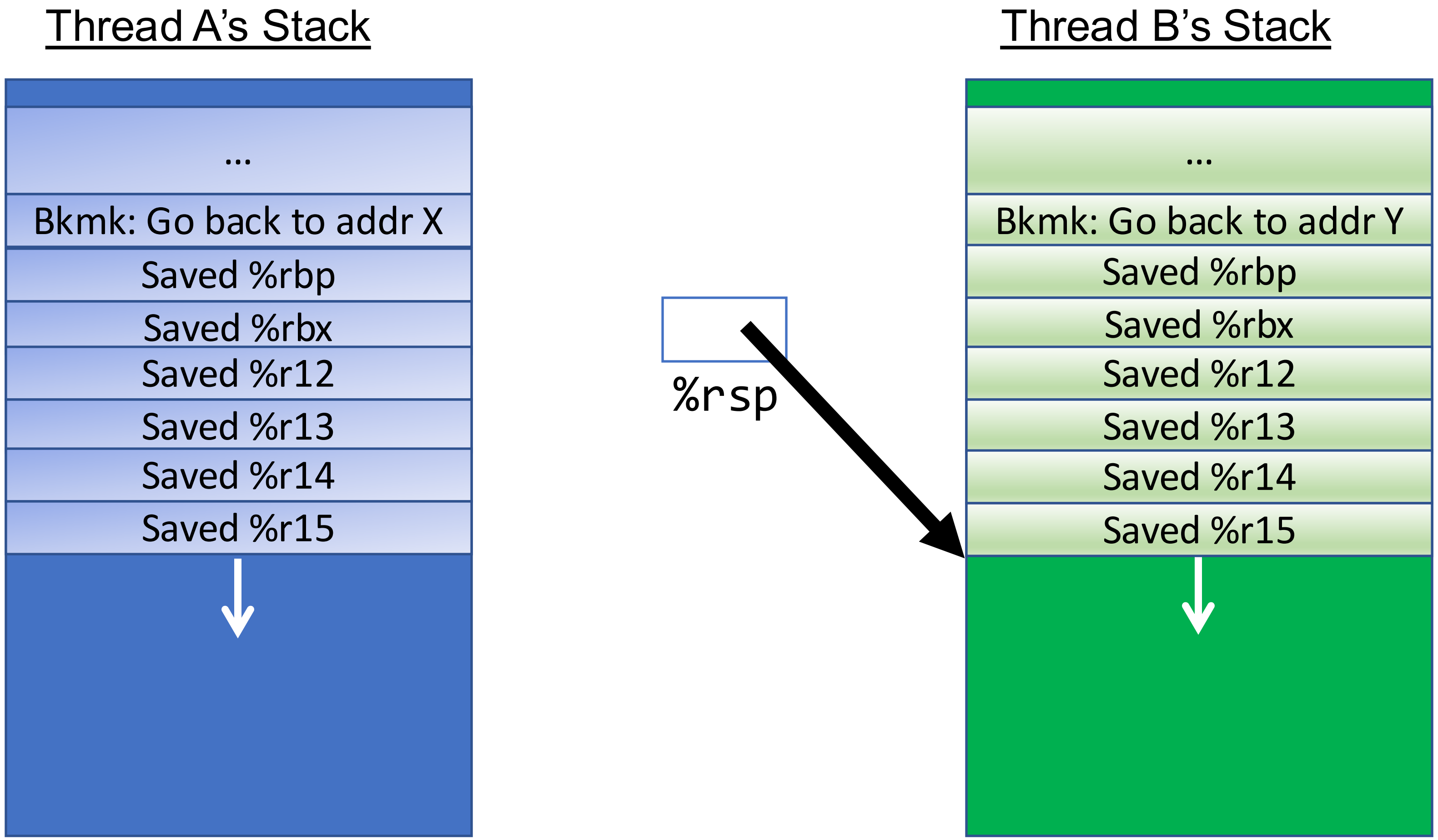
Saved %r13

Saved %r14

Saved %r15

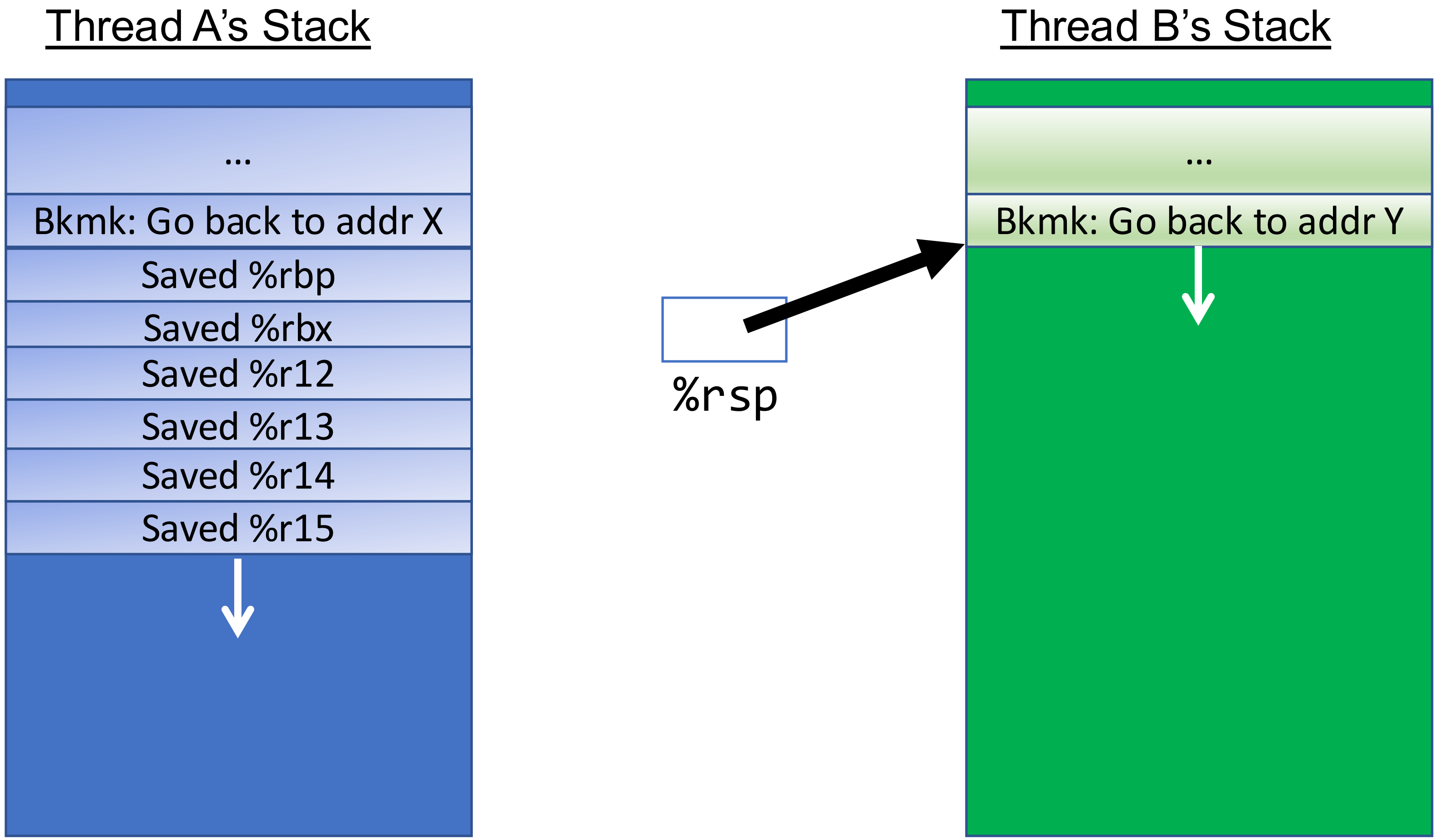
```
callq context_switch
...
pushq %rbp
pushq %rbx
pushq %r12
pushq %r13
pushq %r14
pushq %r15
movq %rsp,0x2000(%rdi)
movq 0x2000(%rsi),%rsp
popq %r15
popq %r14
popq %r13
popq %r12
popq %rbx
popq %rbp
ret
```

Context Switching



```
callq context_switch
...
pushq %rbp
pushq %rbx
pushq %r12
pushq %r13
pushq %r14
pushq %r15
movq %rsp,0x2000(%rdi)
movq 0x2000(%rsi),%rsp
popq %r15
popq %r14
popq %r13
popq %r12
popq %rbx
popq %rbp
ret
```

Context Switching



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callq context_switch
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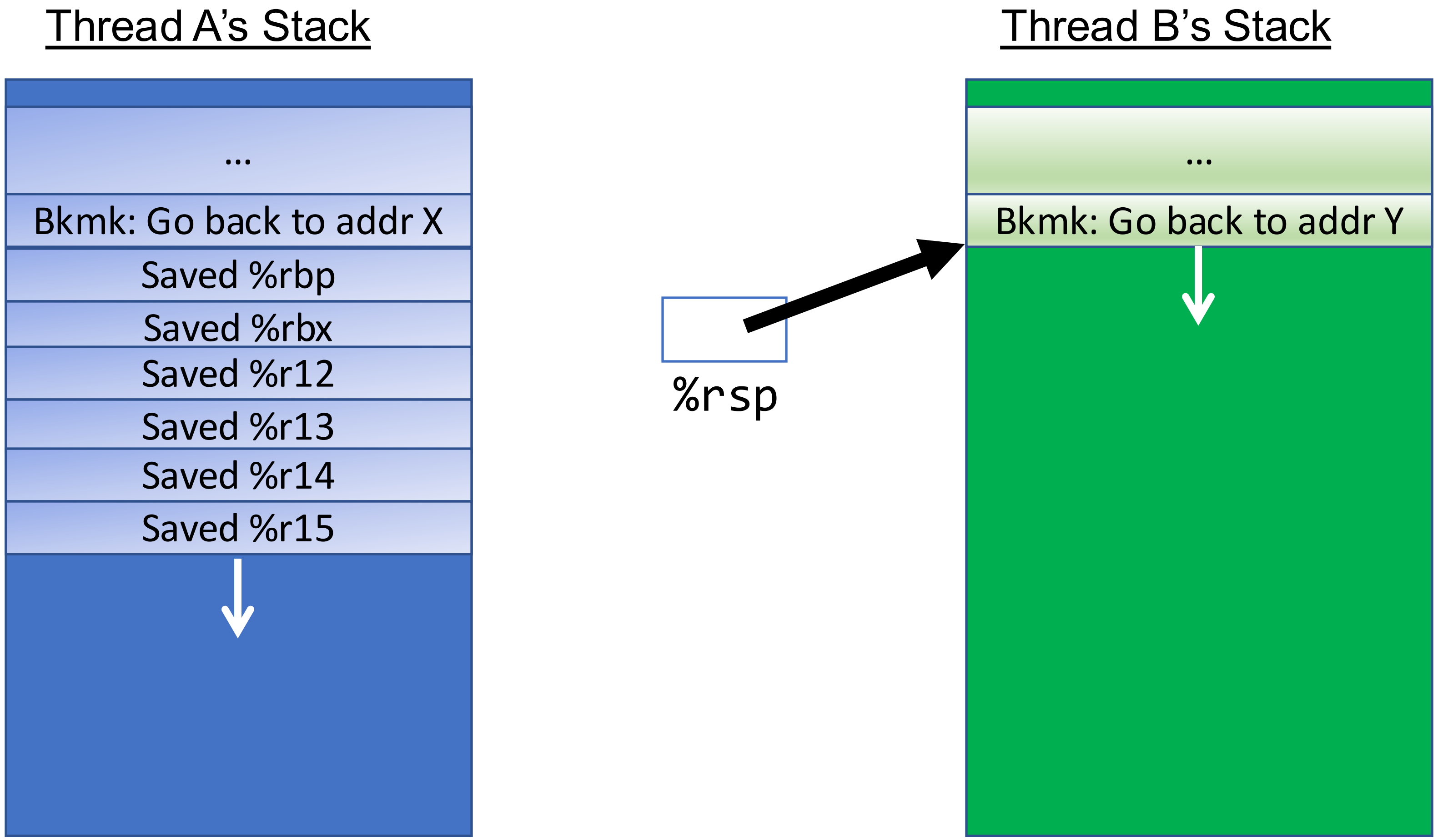
pushq %rbp
pushq %rbx
pushq %r12
pushq %r13
pushq %r14
pushq %r15
movq %rsp,0x2000(%rdi)
movq 0x2000(%rsi),%rsp
popq %r15
popq %r14
popq %r13
popq %r12
popq %rbx
popq %rbp
ret
```

Context Switching



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pushq %rbx
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pushq %r13
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pushq %r15
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movq 0x2000(%rsi),%rsp
popq %r15
popq %r14
popq %r13
popq %r12
popq %rbx
popq %rbp
ret
```
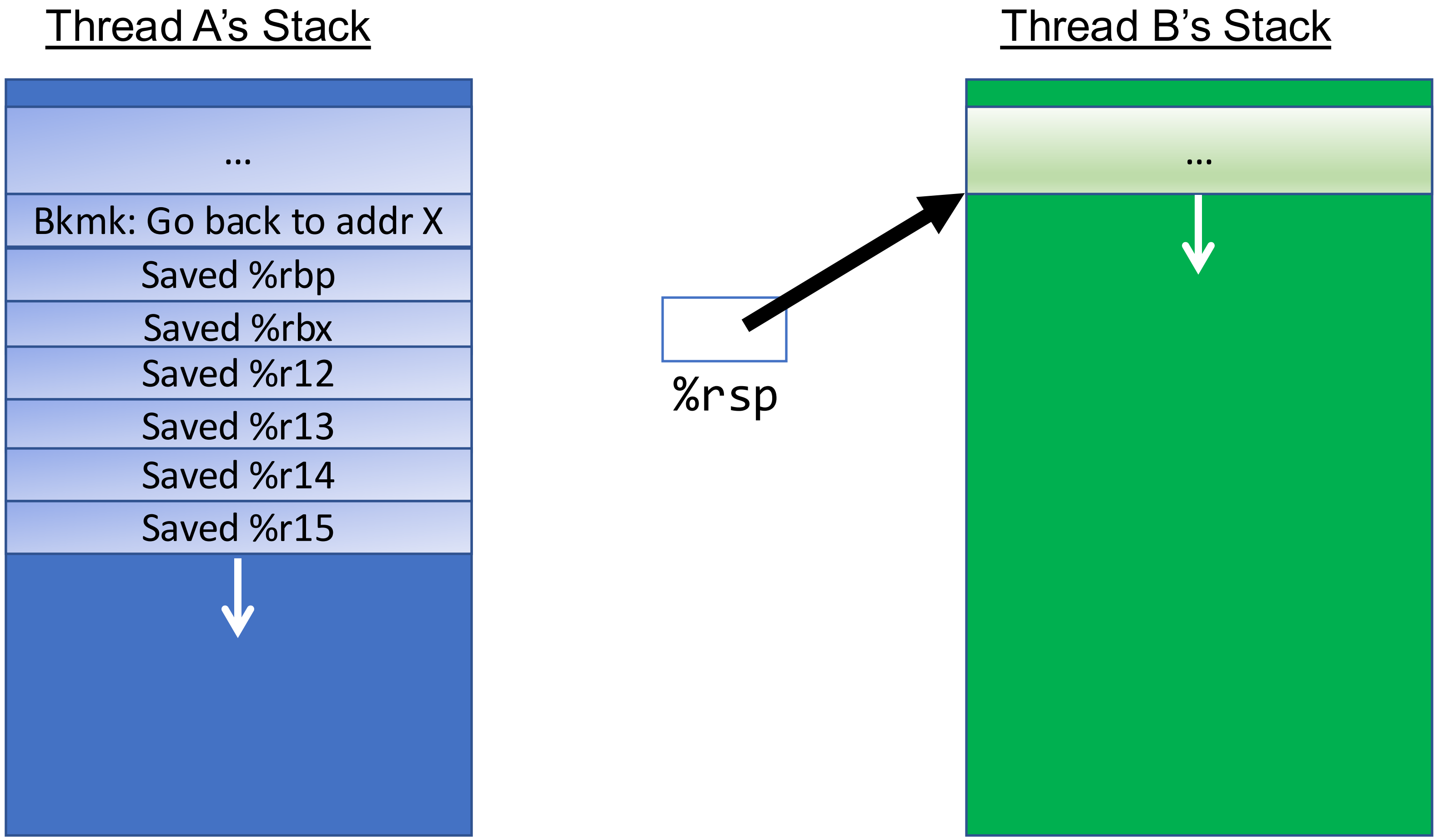

Context Switching


Thread A's Stack

…

Bkmk: Go back to addr X

Saved %rbp

Saved %rbx

Saved %r12

Saved %r13

Saved %r14

Saved %r15

%rsp

Thread B's Stack

…

```
callq context_switch
...
pushq %rbp
pushq %rbx
pushq %r12
pushq %r13
pushq %r14
pushq %r15
movq %rsp,0x2000(%rdi)
movq 0x2000(%rsi),%rsp
popq %r15
popq %r14
popq %r13
popq %r12
popq %rbx
popq %rbp
ret
```

Context Switching

```
pushq %rbp
pushq %rbx
pushq %r12
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pushq %r15
movq %rsp,0x2000(%rdi)
movq 0x2000(%rsi),%rsp
popq %r15
popq %r14
popq %r13
popq %r12
popq %rbx
popq %rbp
ret
```

we start executing on one stack…

and end executing on another!

Context Switching

We enter via a call from a function in the current thread

```
pushq %rbp
pushq %rbx
pushq %r12
pushq %r13
pushq %r14
pushq %r15
movq %rsp,0x2000(%rdi)
movq 0x2000(%rsi),%rsp
popq %r15
popq %r14
popq %r13
popq %r12
popq %rbx
popq %rbp
ret
```

We exit to a call from a function in the new thread!

Context Switch

```
Thread main_thread;
Thread other_thread;

void other_func() {
    cout << "Howdy! I am another thread." << endl;
    context_switch(other_thread, main_thread);
    cout << "We will never reach this line :(" << endl;
}

int main(int argc, char *argv[]) {
    // Initialize other_thread to run other_func
    other_thread = create_thread(other_func);

    cout << "Hello, world!  I am the main thread" << endl;
    context_switch(main_thread, other_thread);
    cout << "Cool, I'm back in main()!" << endl;
    return 0;
}
```

- *context_switch* is called from one function, but returns to another
- The next time we switch back to the original thread, it resumes where it left off.

Creating New Threads

Problem: when a thread runs for the first time, it won’t have a “freeze frame”. How does context-switching to a new thread work?

- *Key idea:* when created, we give a thread a fake “saved state” that appears as though it was frozen right before executing its first function.
- In other words; we put fake saved registers and a return address that, when ret runs, will take us "back" to the specified function it should run.

Context Switch Practice

```
Thread main_thread;
Thread other_thread;

void other_func() {
    context_switch(other_thread, main_thread);
    cout << "D" << endl;
    context_switch(other_thread, main_thread);
    cout << "A" << endl;
}

int main(int argc, char *argv[]) {
    other_thread = create_thread(other_func);
    cout << "B" << endl;
    context_switch(main_thread, other_thread);
    cout << "C" << endl;
    context_switch(main_thread, other_thread);
    return 0;
}
```

Respond on PollEv:
pollev.com/cs111

What would be outputted by this program? *Key points:*

- *context_switch* is called from one function, but returns to another
- The next time we switch back to the original thread, it resumes where it left off.
- New thread starts with ”fake” freeze frame
- These custom threads don’t run unless we explicitly context switch to them

What would be outputted by this program?

BDCA	0%
BCD	0%
BCA	0%
BCDA	0%
DBAC	0%

Context Switch Practice

```
Thread main_thread;
Thread other_thread;

void other_func() {
    context_switch(other_thread, main_thread);
    cout << "D" << endl;
    context_switch(other_thread, main_thread);
    cout << "A" << endl;
}

int main(int argc, char *argv[]) {
    other_thread = create_thread(other_func);
    cout << "B" << endl;
    context_switch(main_thread, other_thread);
    cout << "C" << endl;
    context_switch(main_thread, other_thread);
    return 0;
}
```

Answer: *BCD*

What would be outputted by this program? *Key points:*

- *context_switch* is called from one function, but returns to another
- The next time we switch back to the original thread, it resumes where it left off.
- New thread starts with ”fake” freeze frame

Recap

- Overview: Dispatching and Scheduling
- Running a Thread
- Switching to Another Thread
  - Context Switch Implementation
- How do we switch what code is running?

Lecture 17 takeaway: The OS keeps a process control block for each process and uses it to context switch between threads. To switch we must freeze frame the existing register values and load in new ones.

Next time: how do we decide which thread to run?