barkhausen institut

Microkernel Construction

Threads

Nils Asmussen

04/23/2026

- **Threads**
  - **Definition and Basics in NOVA**
  - Thread Switch
- Synchronization
- FPU Handling

What is a Thread?

- An independent flow of control inside an address space
- Communicates with other threads using IPC
- Characterized by a set of registers and the thread state
- Dispatched by the kernel according to a defined schedule

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- An independent flow of control inside an address space
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- Each thread is bound to one core at a time
- Only one thread per core is running at one point in time
- With n cores, n threads can run at once
- All other threads are inactive, waiting inside the kernel

Implementation in NOVA

Execution Context

- Register state
- Continuation
- Address Space (PD)
- UTCB (message buffer)
- IPC partner
- FPU state
- prev/next pointer

Scheduling Context

- Execution Context
- Priority
- Budget
- Remaining budget
- prev/next pointer

Thread Variants

Global Thread

- Needs a scheduling context, i.e., CPU time, to execute
- Causes exception on startup to let creator set register state

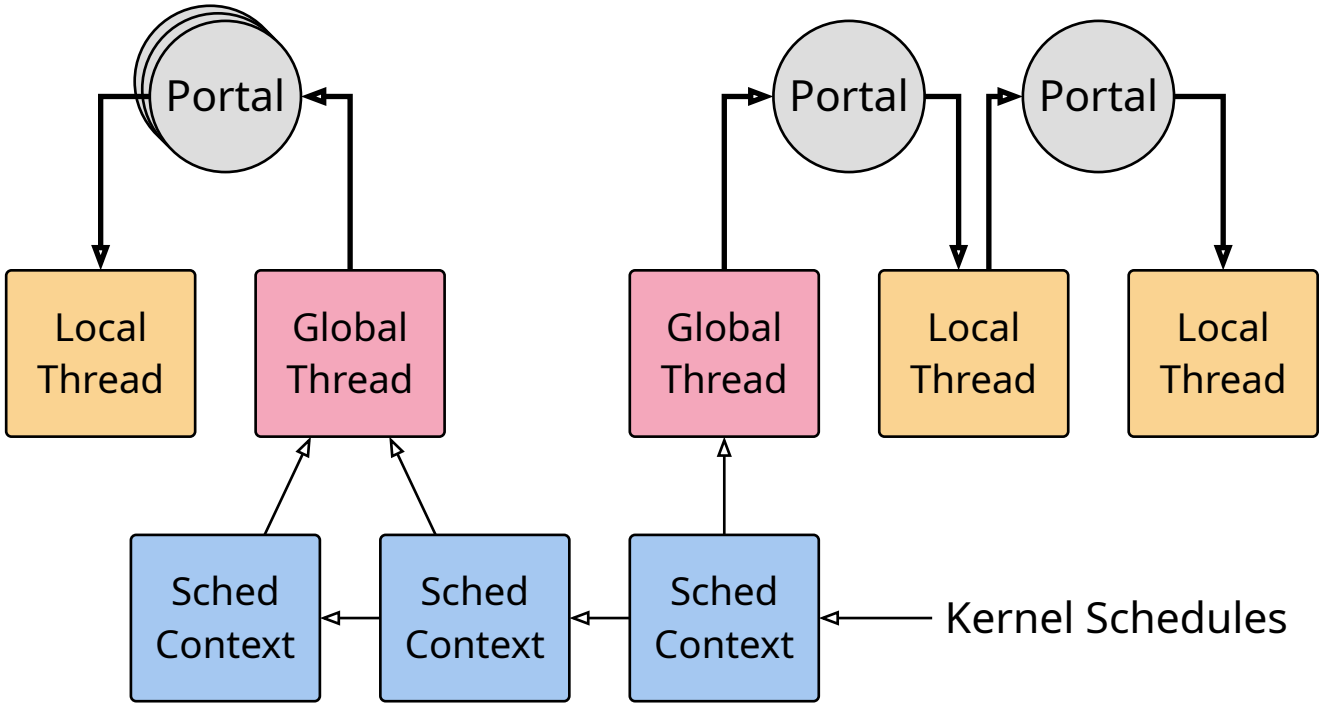
Local Thread

- Has no scheduling context
- Are only used to handle portal calls
- Waits in the kernel until someone called an associated portal

Portals

- A portal is an IPC endpoint
- Executed by local threads
- CPU time is donated from caller
- Called via system call
- Message is transferred from sender UTCB to receiver UTCB

Overview


Portal
Portal
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Local Thread
Global Thread
Global Thread
Local Thread
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Sched Context
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Kernel Schedules

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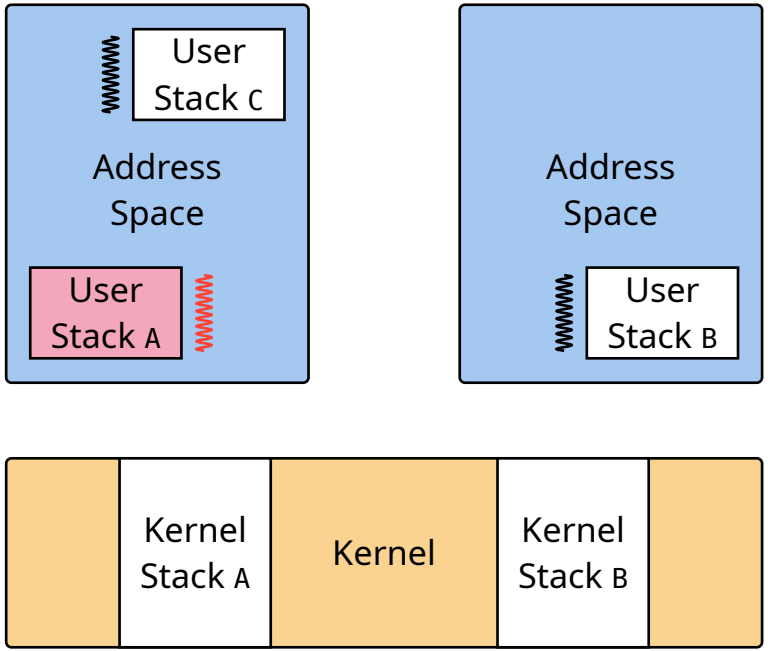
Thread Switch: Conventional



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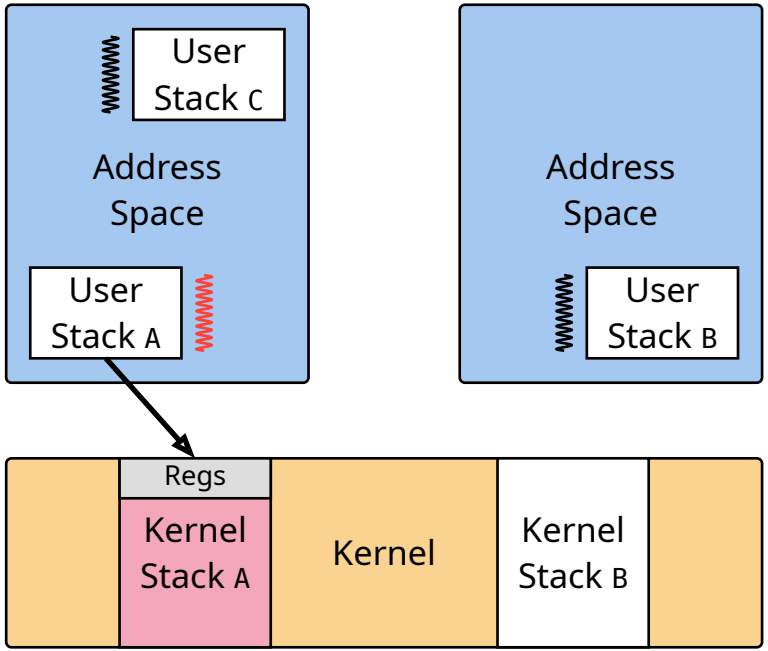

- User thread A is running
- Timer interrupt occurs
- Kernel saves register state onto kernel stack A

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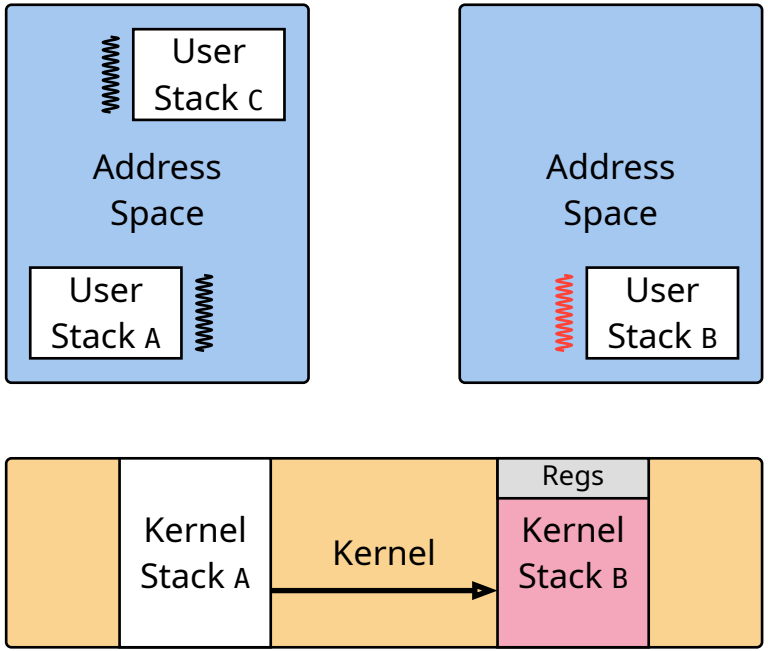
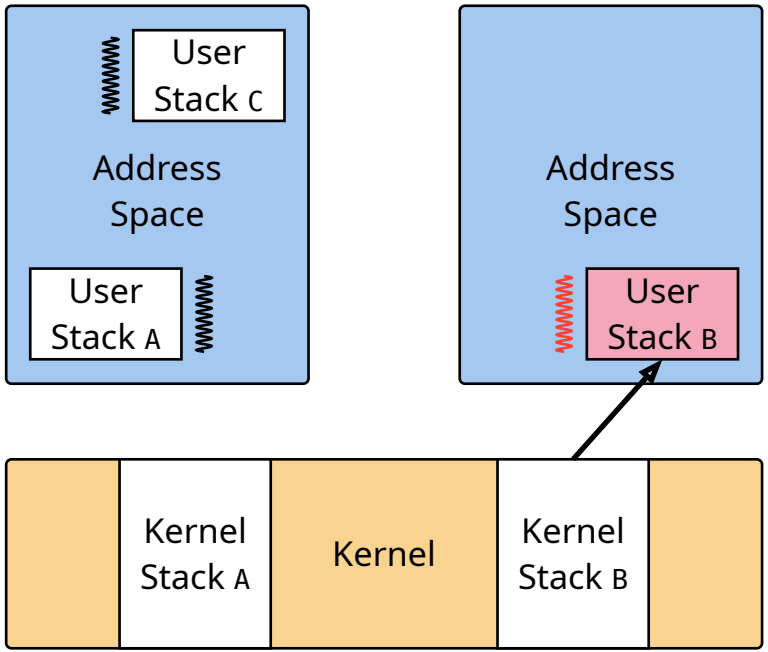


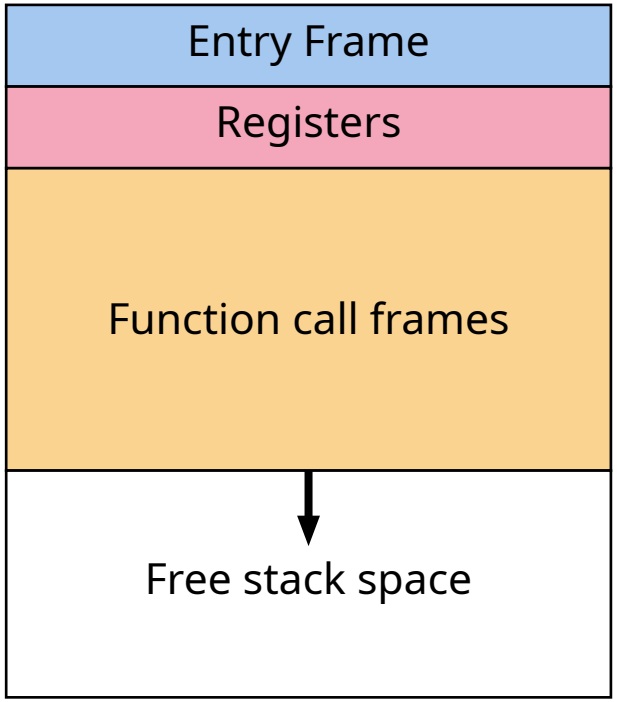
- User thread A is running
- Timer interrupt occurs
- Kernel saves register state onto kernel stack A
- Kernel switches to thread B
- Restores register state from kernel stack B

Thread Switch: Conventional



- User thread A is running
- Timer interrupt occurs
- Kernel saves register state onto kernel stack A
- Kernel switches to thread B
- Restores register state from kernel stack B
- Resumes user thread B

Thread Switch: Conventional Kernel Stack



`SS`, `RSP`, `RFLAGS`, `CS`, `RIP`

`RAX`, `RCX`, `RDX`, `RBX`, `RSP`, `RBP`, `RSI`, `RDI`, `R8`, ..., `R15`

- function arguments
- function return address
- callee-saved registers: `RBX`, `RBP`, `R12`, ..., `R15`
- local variables

Thread Switch: Conventional In-Kernel Switch

Implementation of `thread_switch(reg_t *old, reg_t *new)`

```asm
thread_switch:
    mov     %rbx,  0(%rdi)
    mov     %rsp,  8(%rdi)
    mov     %rbp, 16(%rdi)
    mov     %r12, 24(%rdi)
    mov     %r13, 32(%rdi)
    mov     %r14, 40(%rdi)
    mov     %r15, 48(%rdi)
    # load and save rflags
    pushfq
    popq    56(%rdi)
    mov     48(%rsi), %r15
    mov     40(%rsi), %r14
    mov     32(%rsi), %r13
    mov     24(%rsi), %r12
    mov     16(%rsi), %rbp
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    # restore rflags
    pushq   56(%rsi)
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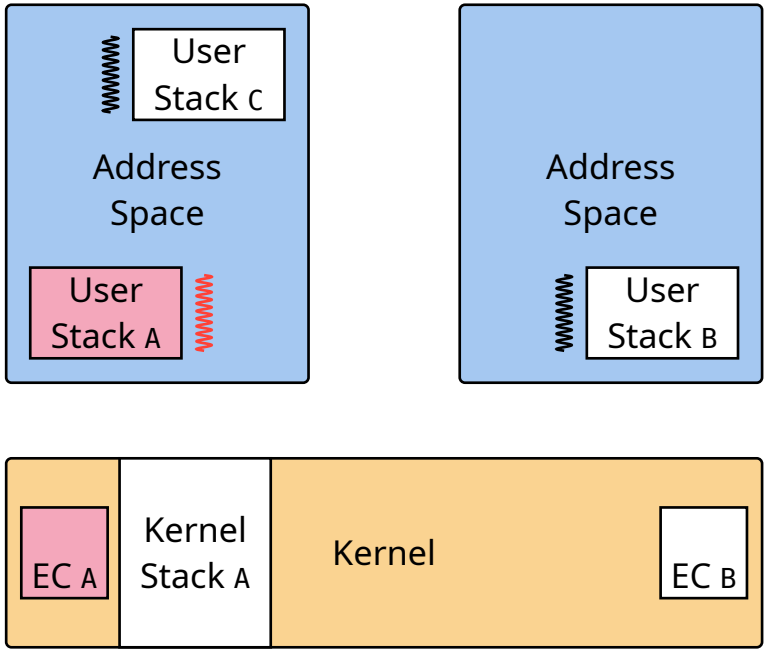
Thread Switch: Continuation Style



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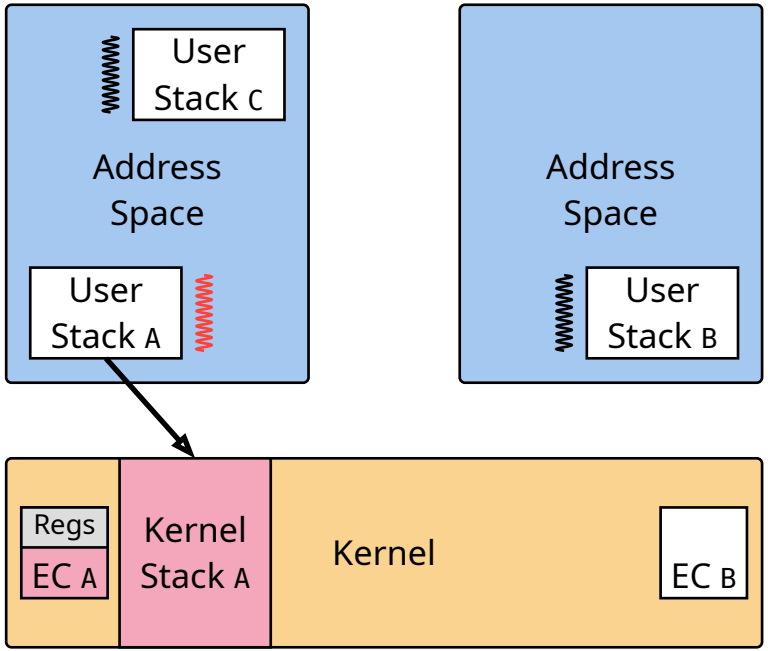

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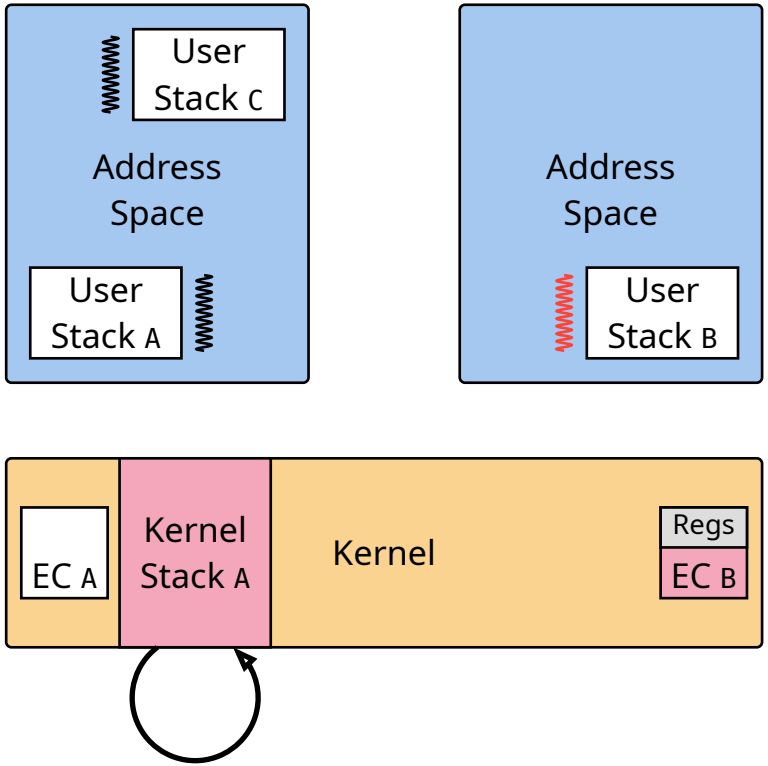

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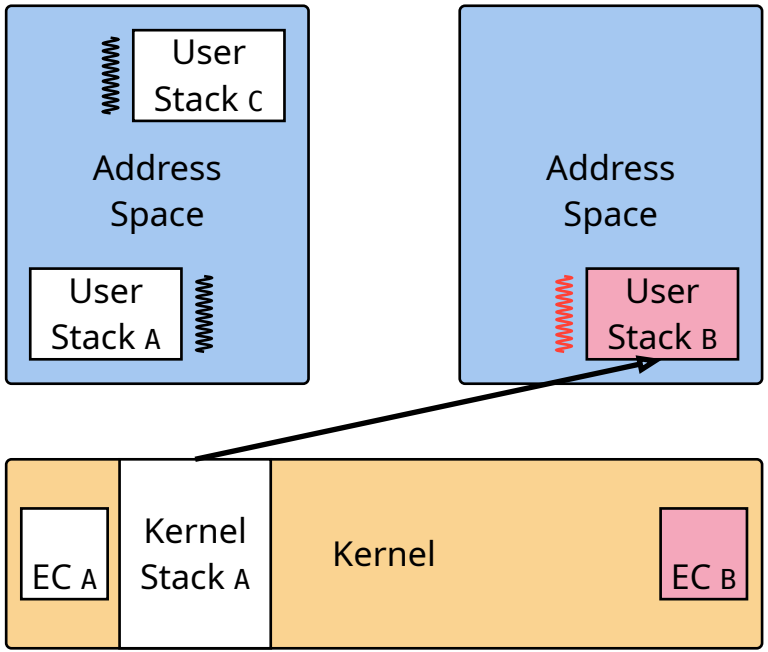

- User thread A is running
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- Kernel saves register state into thread A's TCB
- Kernel switches to thread B, starting with fresh kernel stack
- Restores register state from thread B's TCB
- Resumes user thread B

Thread Switch: In-Kernel Switch

- Traditional kernels save/restore the current CPU state
- Each thread has own stack → stack frames are kept
- In NOVA, stack frames and CPU state are lost

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Example in-kernel switch: `sys_call`

C++

```
1  current->cont = ret_user_sysexit;
2  current->set_partner (ec);
3  ec->cont = recv_user;
4  ec->regs.set_ip (pt->ip);
5  ec->regs.set_pt (pt->id);
6  ec->make_current();
```

Thread Switch: In-Kernel Switch

Switching to an Ec

C++

```
1  void Ec::make_current() {
2    current = this;
3    Tss::run.sp0 = reinterpret_cast<mword>(exc_regs());
4    pd->make_current();
5    asm volatile (
6      "mov %0, %%rsp;"
7      "jmp *%1;"
8      :
9      : "g" (CPU_LOCAL_STCK + PAGE_SIZE),
10       "rm" (cont)
11     : "memory"
12   );
13   UNREACHED;
14 }
```

Continuation Style: Pros and Cons

- 🙁 Context switches more restricted
  - thread loses all state
  - switches only possible at specific points
- 🙂 Less kernel memory usage
- 🙂 Performance
  - less cache pressure
  - less TLB pressure

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- **Synchronization**
  - **Basic Concepts**
  - Blocking Synchronization
  - Lock-Free Synchronization
  - Wait-Free Synchronization
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Synchronization Properties

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Multi-processor synchronization

- Higher synchronization effort

Preemptibility and Concurrency

No preemptibility (example: seL4)

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Restricted preemptibility (example: NOVA)

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High preemptibility (example: Linux)

- Thread can be preempted at (almost) any point in time
- State has to be consistent for all possible preemptions

Synchronization Primitives

Disabling Interrupts

- Not multi-core safe
- Core-local data structures, kernel entry/exit

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Non-blocking synchronization

- Lock-free: some thread makes progress
- Wait-free: all threads make progress

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Blocking Synchronization

Sleeping locks: Semaphores

- Suspend thread when lock is already taken
- Wake up thread when lock is released
- High overhead: suitable for long critical sections
- Not used by NOVA; only in user space

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Spinning locks: Spinlocks

- Waiting thread spins until lock is released
- Burns CPU time: suitable for short critical sections

Spinlock Variants

Test and set lock

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- Otherwise spin (reading)
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Ticket lock

- Every thread acquires a ticket
- Tickets get access in FIFO order; guarantees fairness

Ticket Lock

NOVA's ticket lock implementation

C++

```
1  void lock() {
2      uint16 tmp = 0x100; // high: reserved ticket, low: active ticket
3      asm volatile ("     lock; xadd %0, %1;  "  // reserve ticket; tmp = val; val += 0x100
4                    "1:   cmpb %h0, %b0;      "  // compare our ticket with active ticket
5                    "     je 2f;              "  // we are next? -> done
6                    "     pause;              "  // relax CPU
7                    "     movb %1, %b0;       "  // update active ticket
8                    "     jmp 1b;             "  // retry
9                    "2:                       "  // enter critical section
10                   : "+Q" (tmp), "+m" (val) : : "memory");
11 }
12 void unlock() {
13     asm volatile ("incb %0" : "=m" (val) : : "memory");
14 }
```

Problems of Locks

- Overhead
- Deadlocks
- Lock-holder preemption
- Priority inversion

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Lock-Free Synchronization

- Principle:
  - prepare data out of line
  - atomically try to exchange old data with new one
  - retry if failed
- Less overhead than locks
- Deadlock free
- *Some* thread makes progress
- Many threads may starve (see wait-free synchronization)

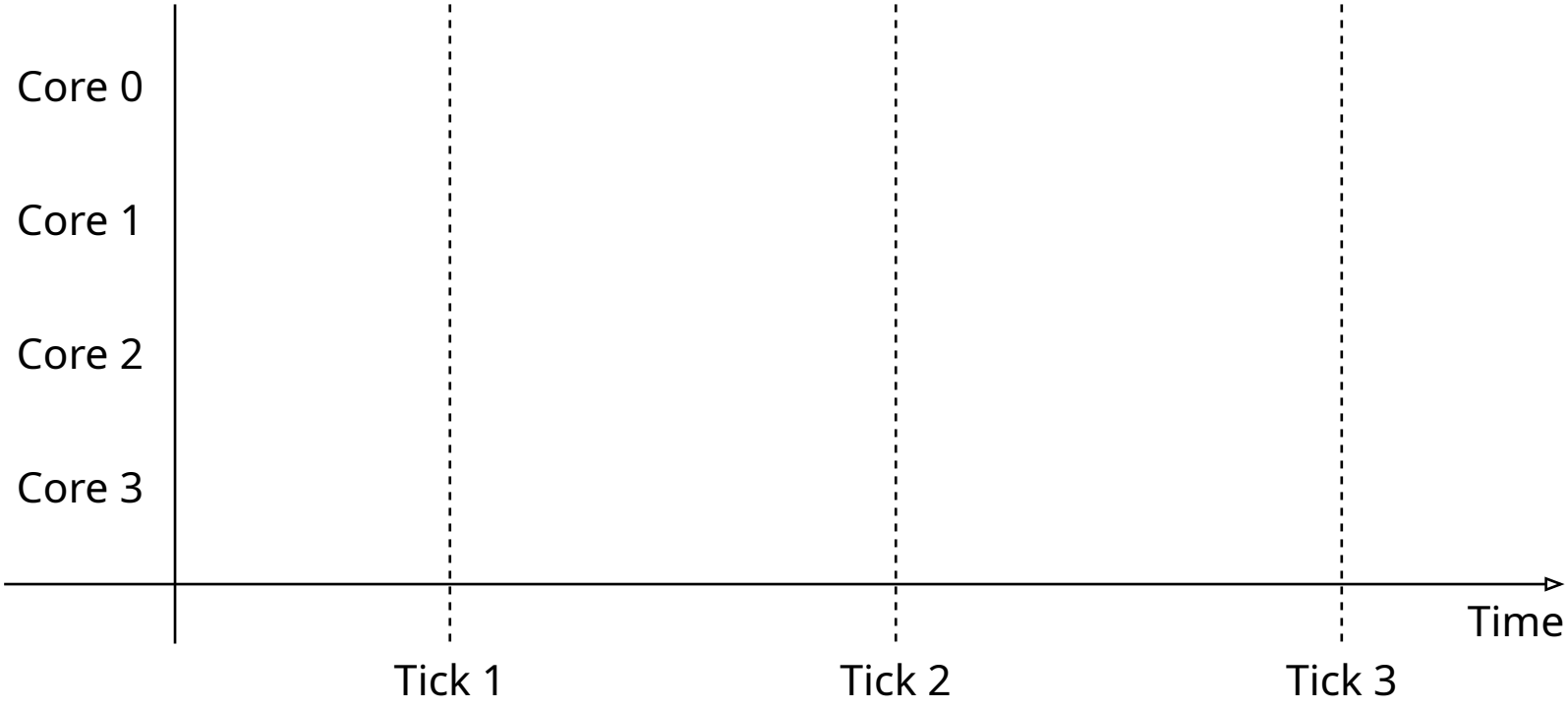
Example in NOVA: Deletion of Kernel Objects

- When revoking, kernel objects should be destructed
- But what if somebody accesses them at the same time?
- We could lock them during each access
- But this is expensive
- We don’t care that much when exactly they are destructed
- Can’t we destruct them if nobody accesses them anymore?

Read-Copy-Update (RCU)

- Basically: copy-on-write with lazy delete
- Don’t change objects, but copy them and change the copy
- Don’t delete objects immediately, but when readers are done
- In case of NOVA: no copy-on-write, but only lazy delete
- On revoke, object is removed first
- Then, the object is registered for deletion
- Timer IRQ is used to delete only if all readers are gone

RCU In Action



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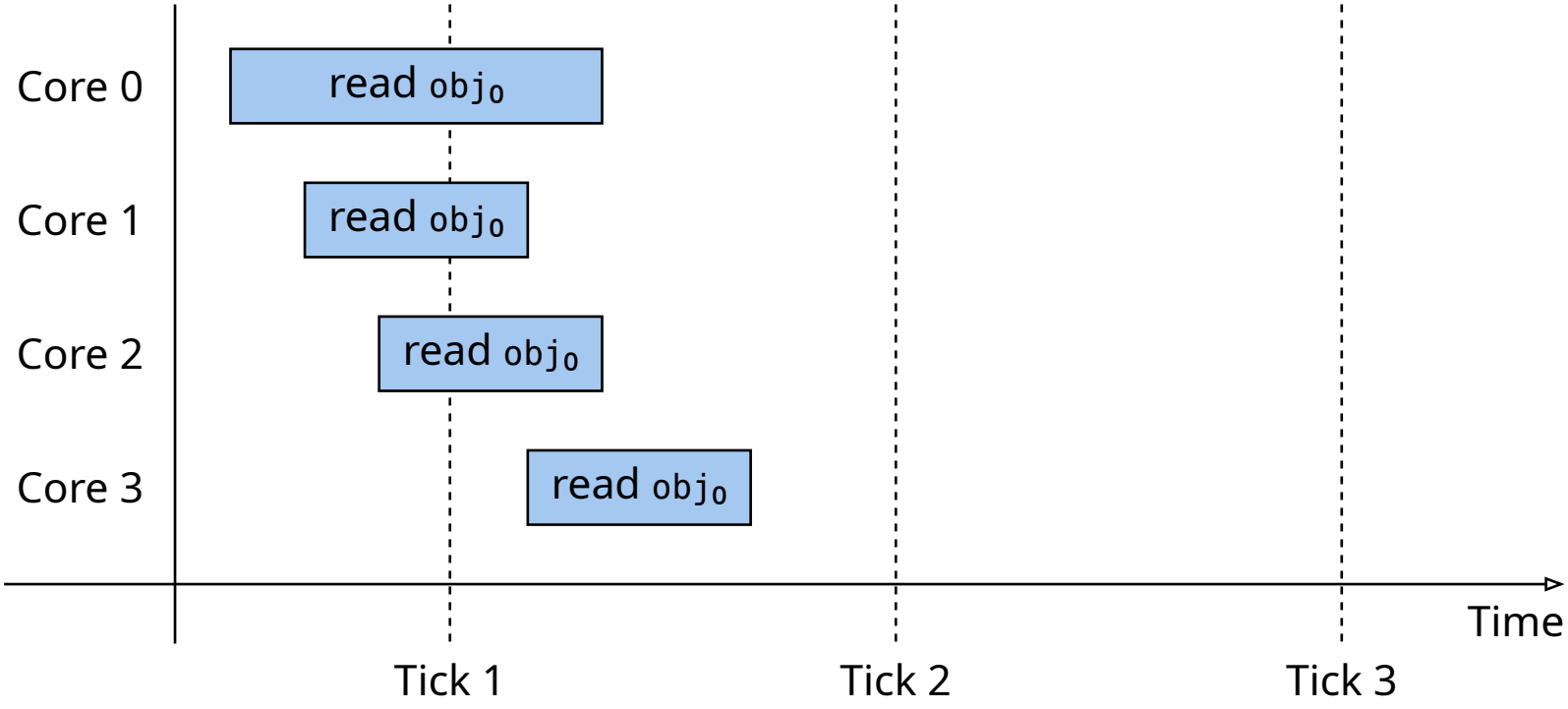

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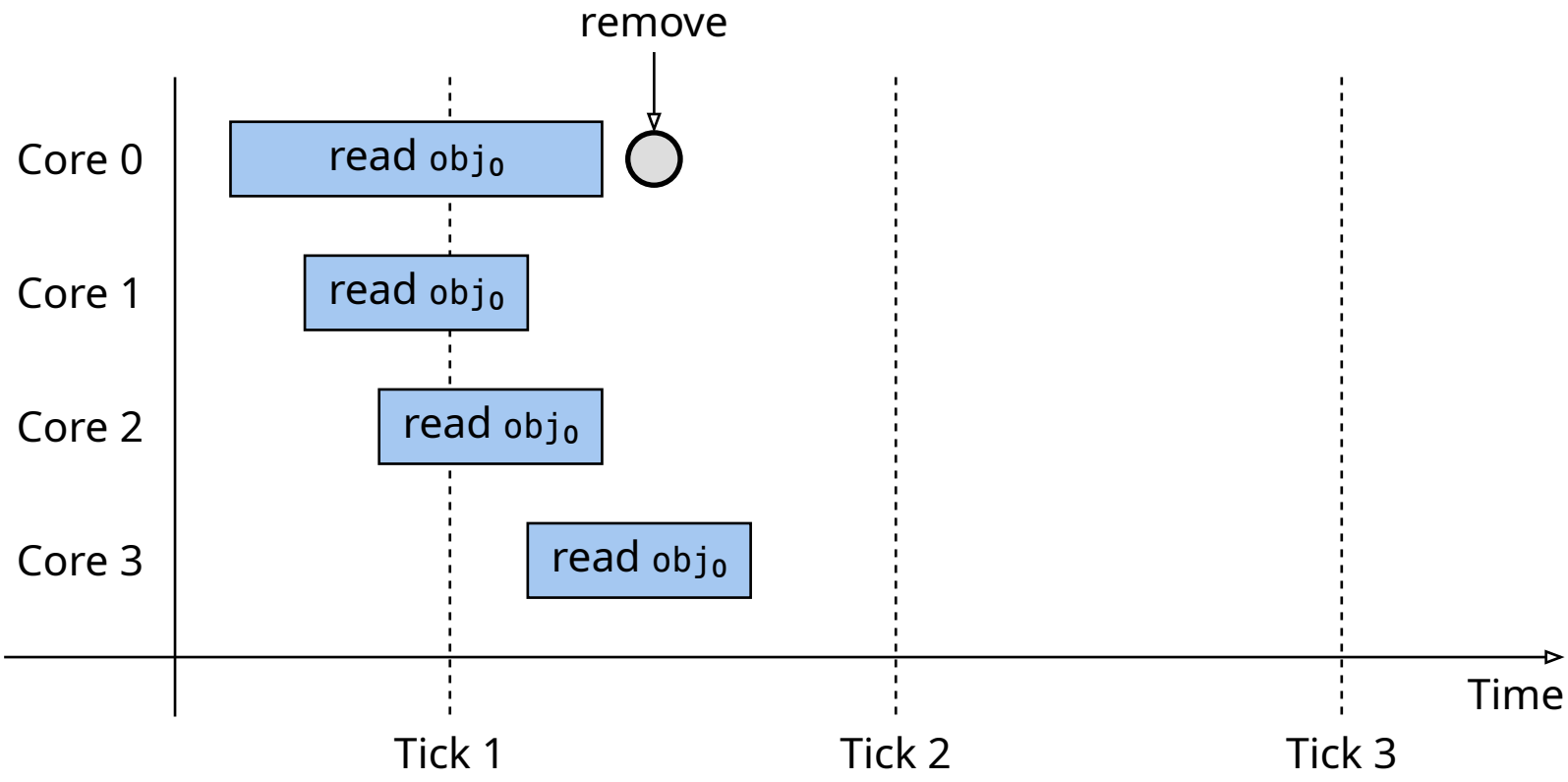

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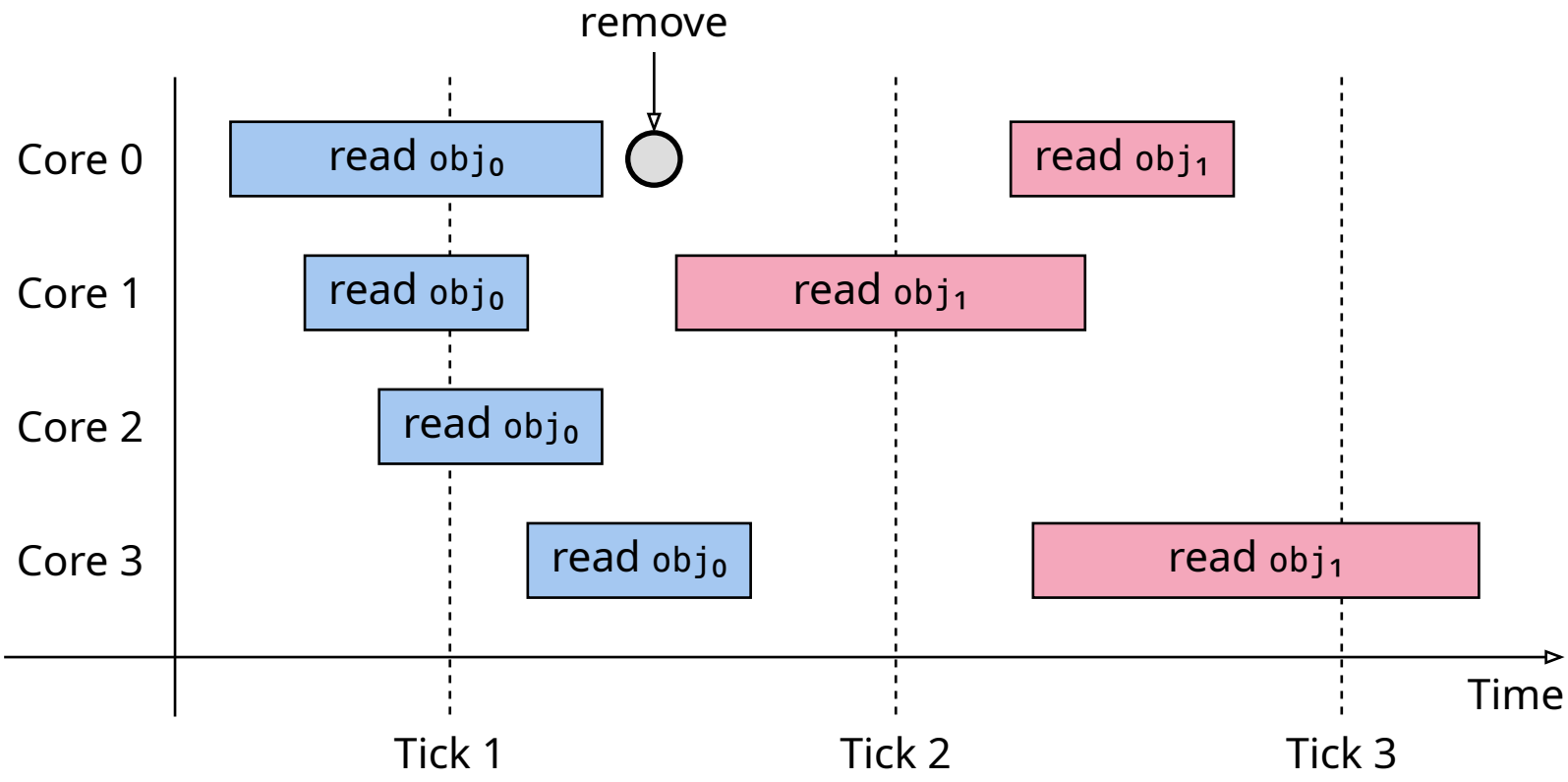

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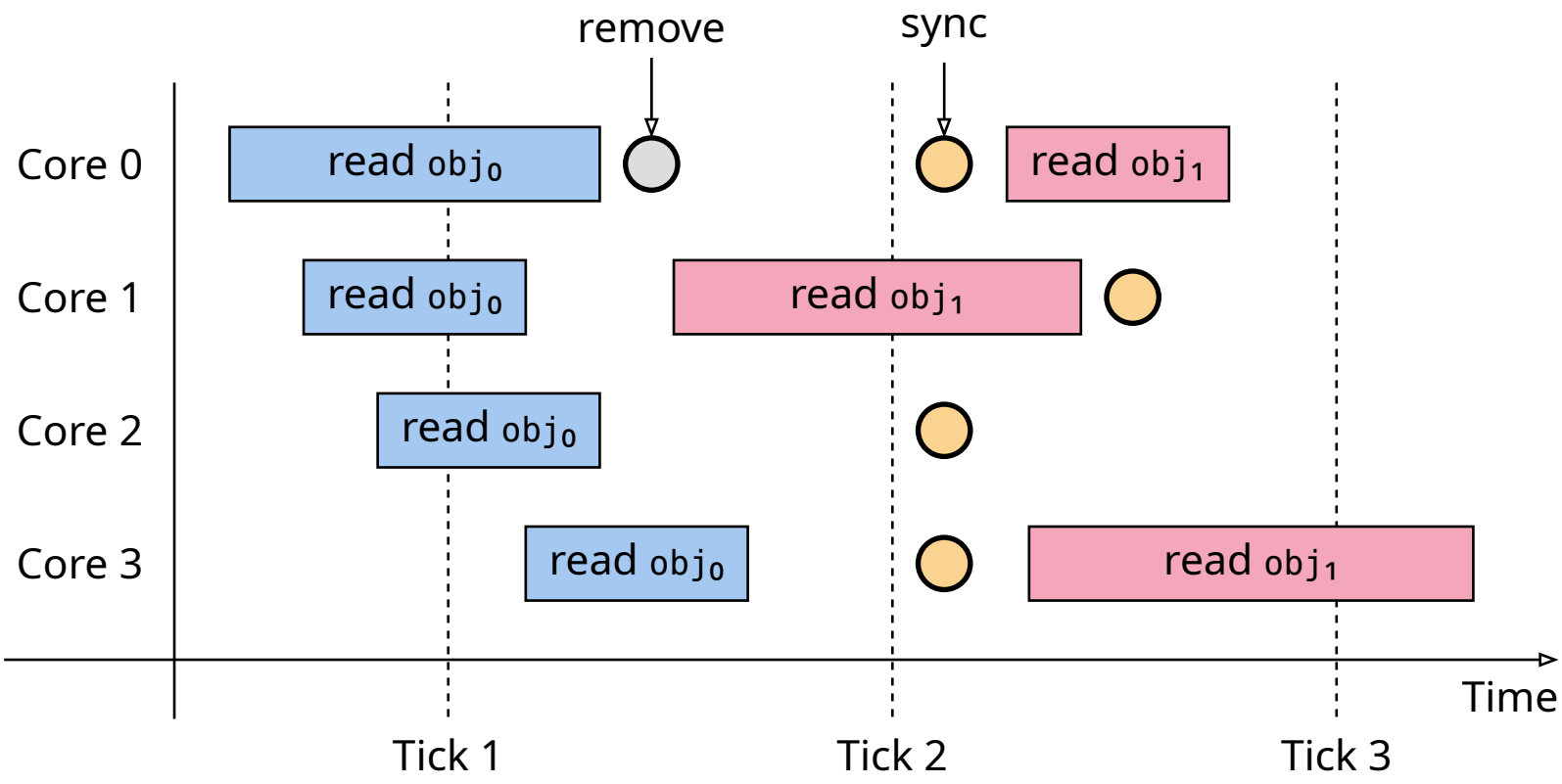

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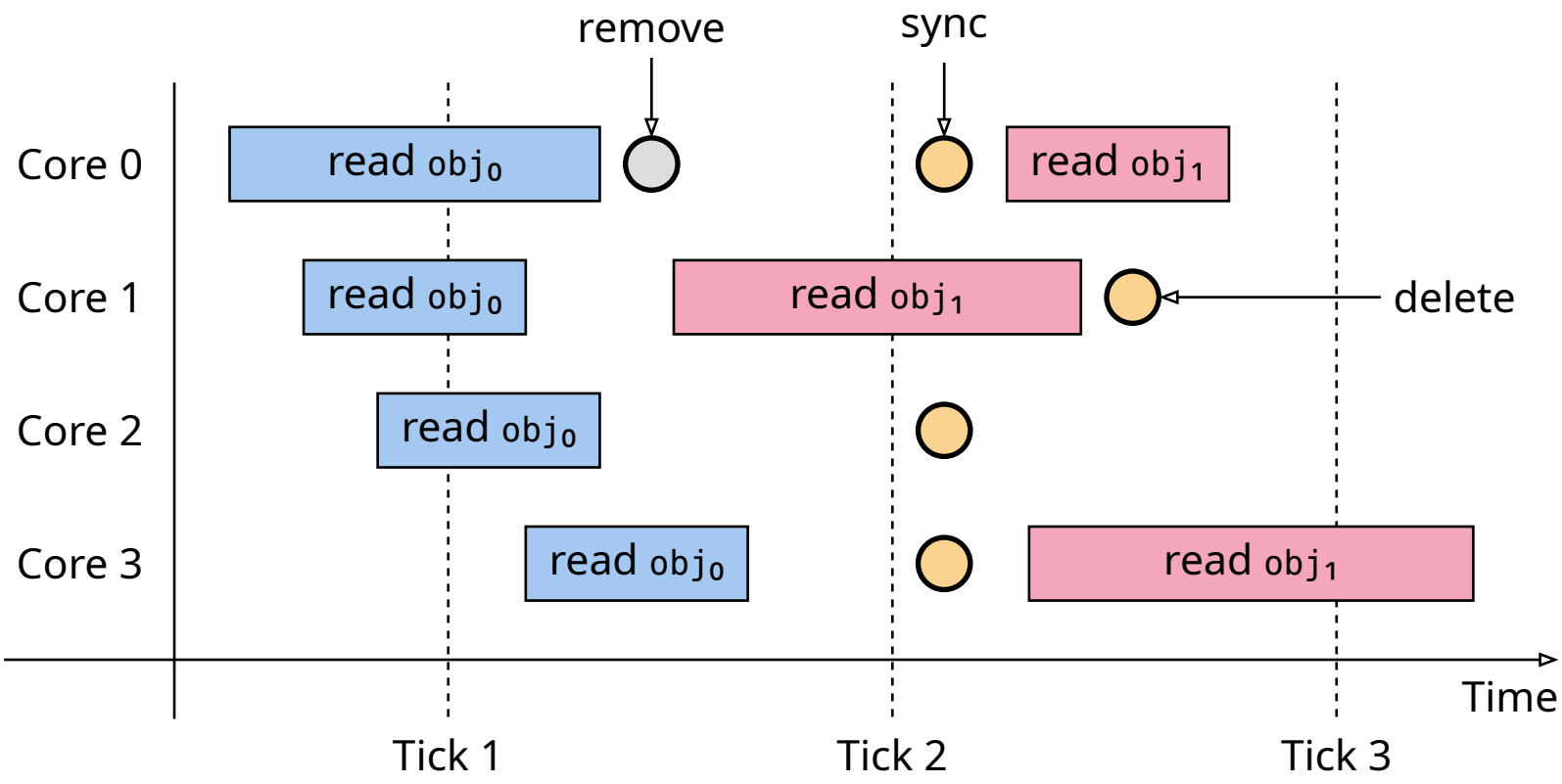

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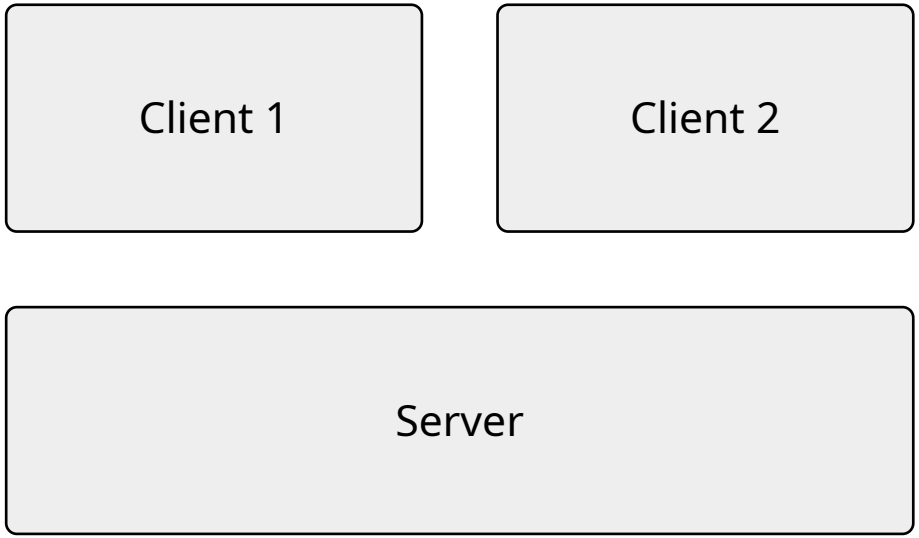
Separation of Scheduling and Execution Context



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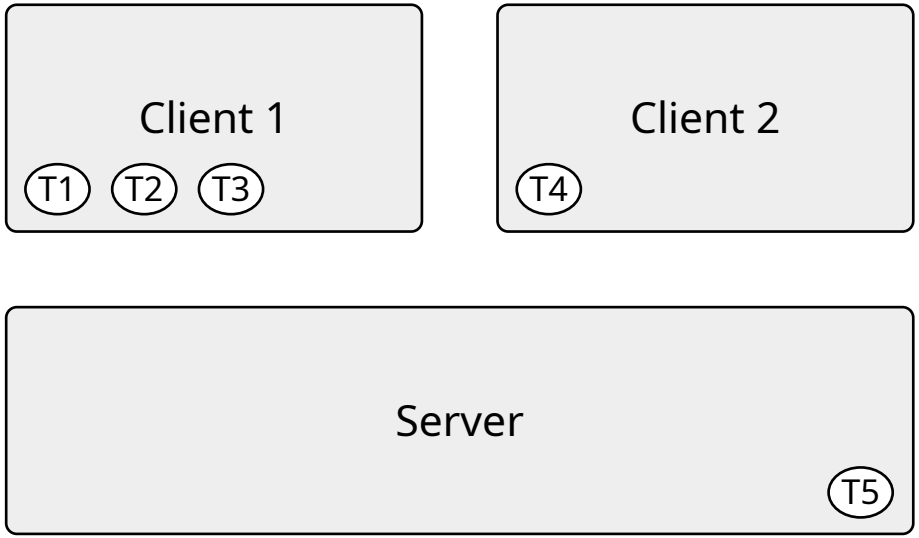

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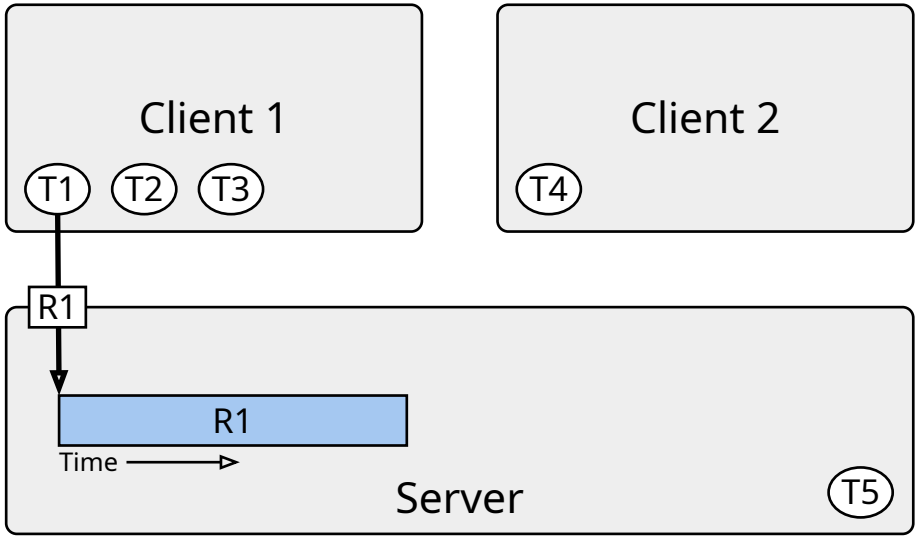

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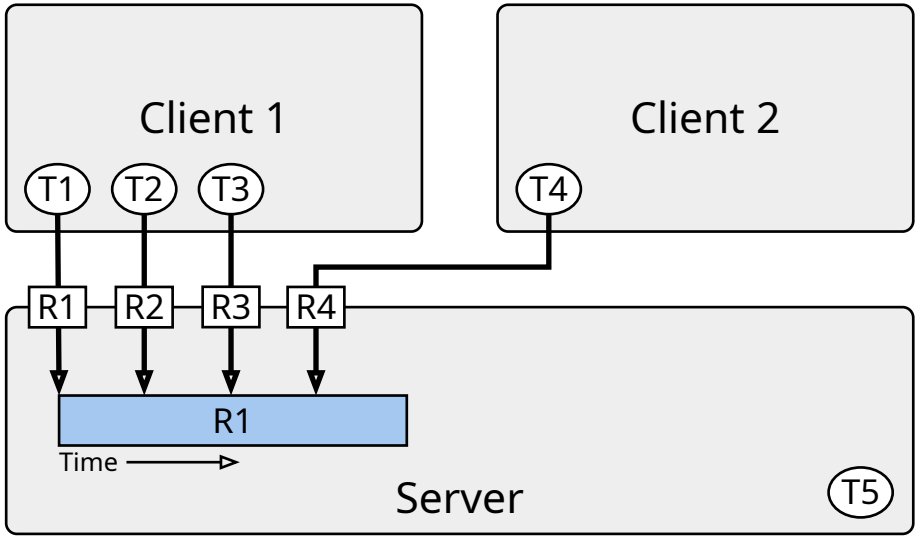

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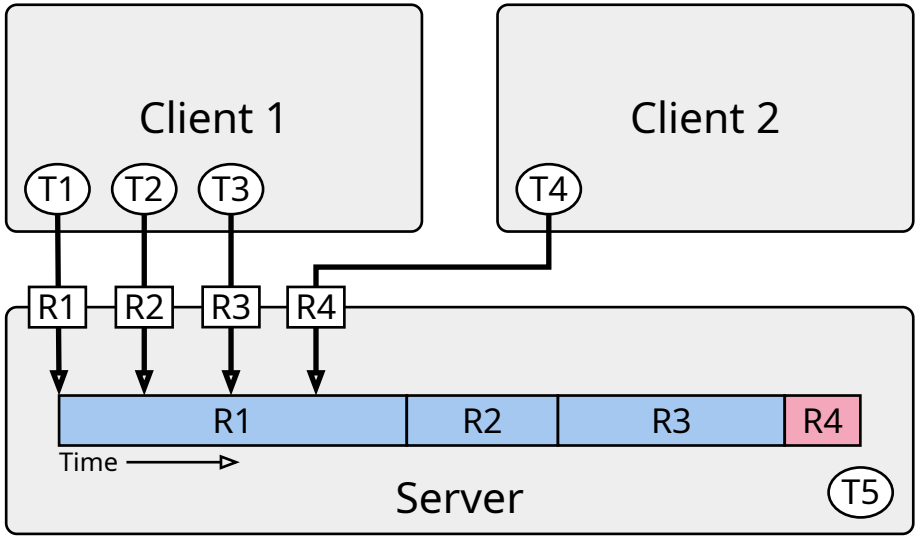

- clients that send the most and longest requests win
- how can we restrict the time budget for requests?
- how can we give clients different priorities?
- what priority should the server thread have?

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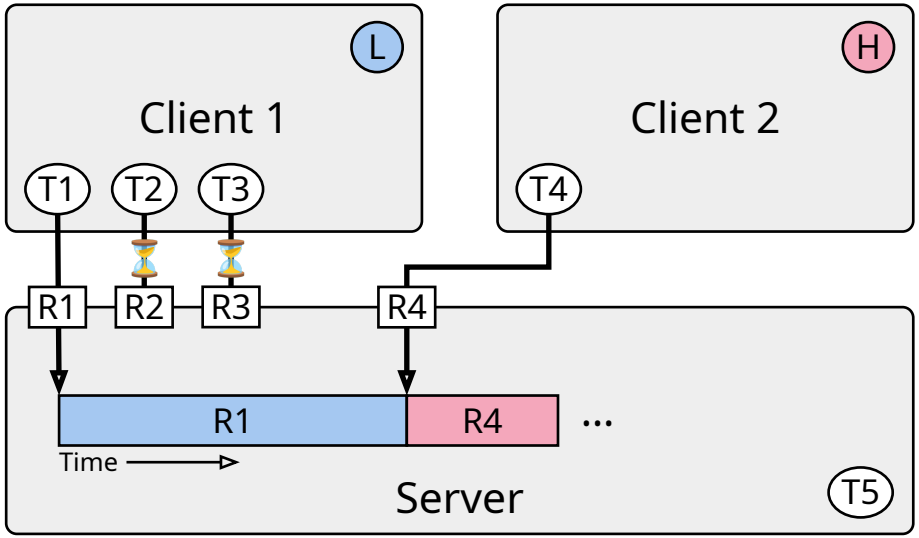

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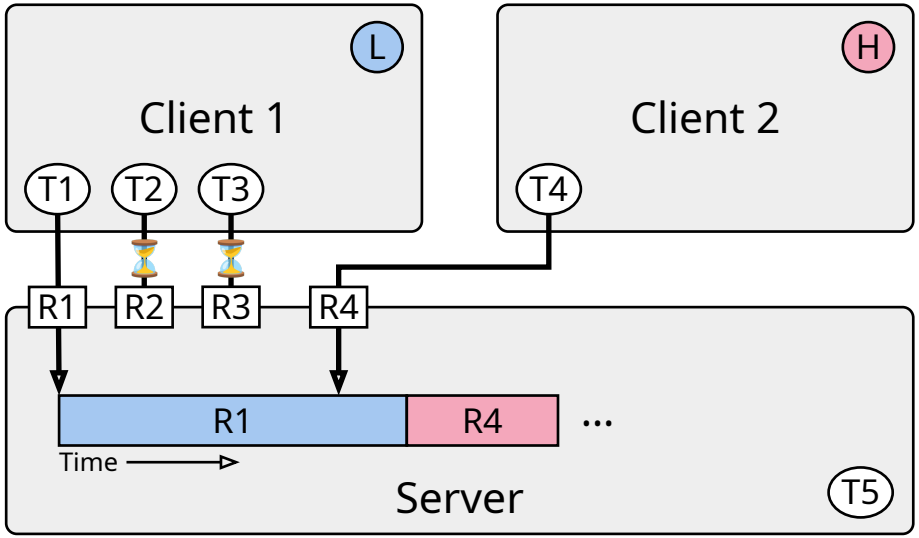

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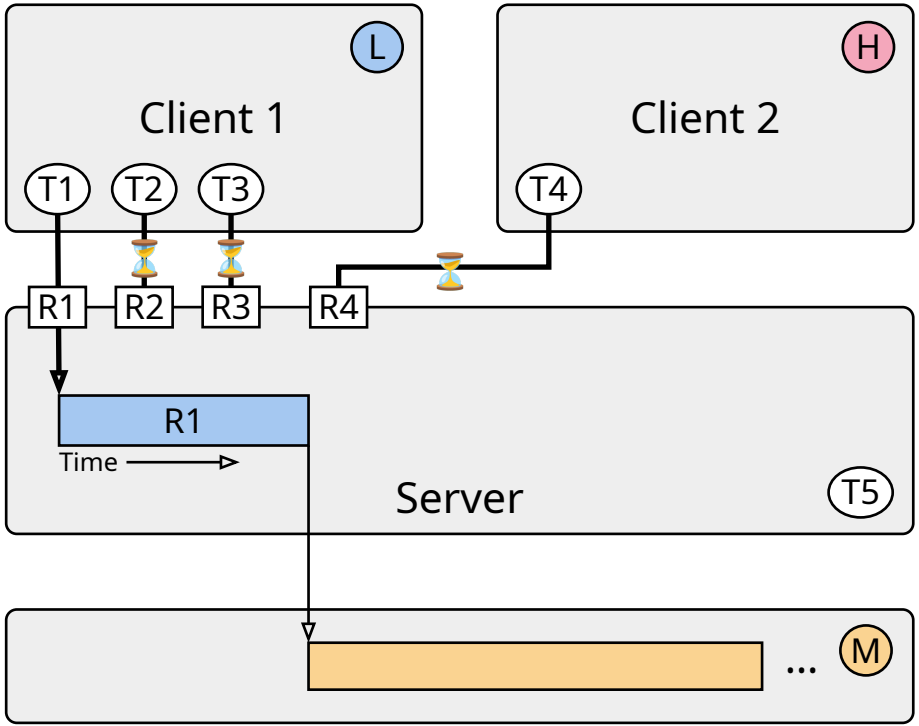

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- priority inversion?

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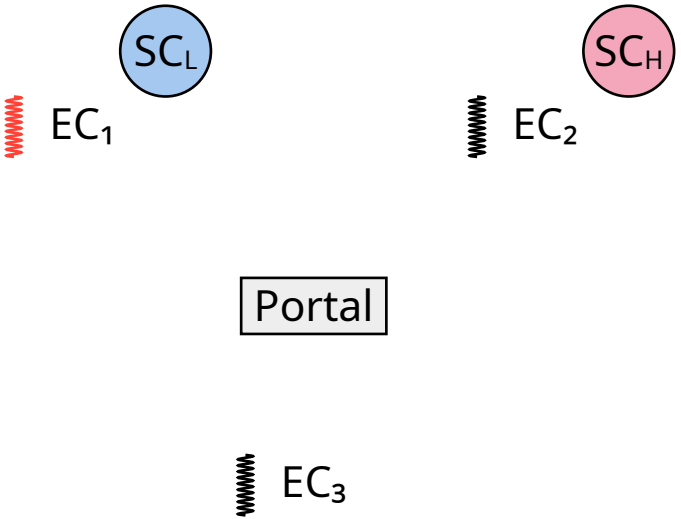

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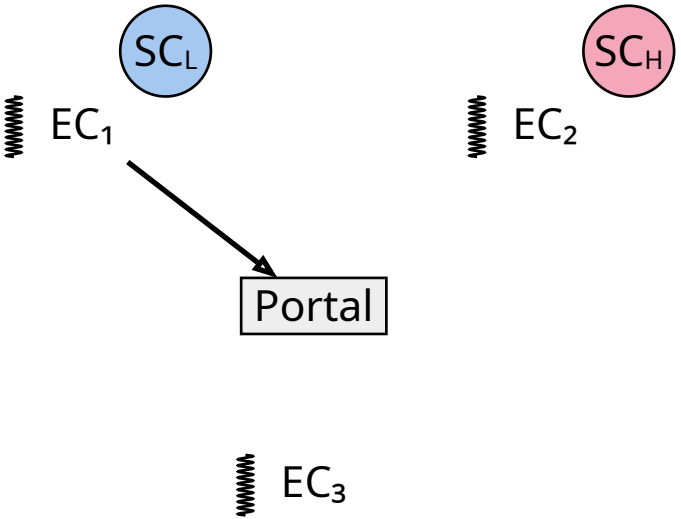

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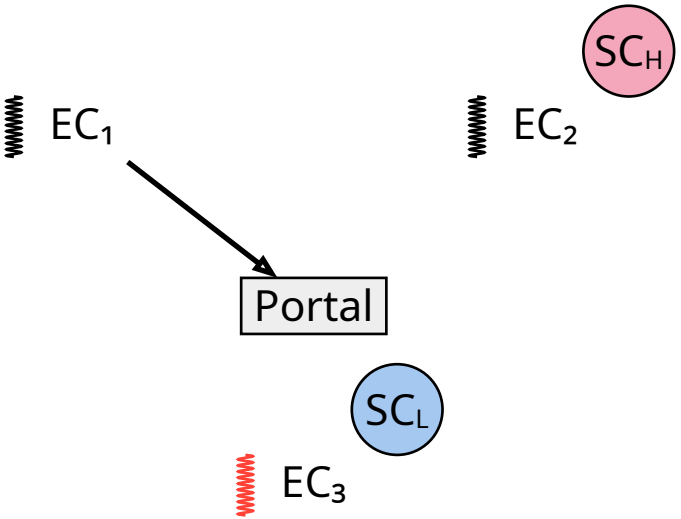

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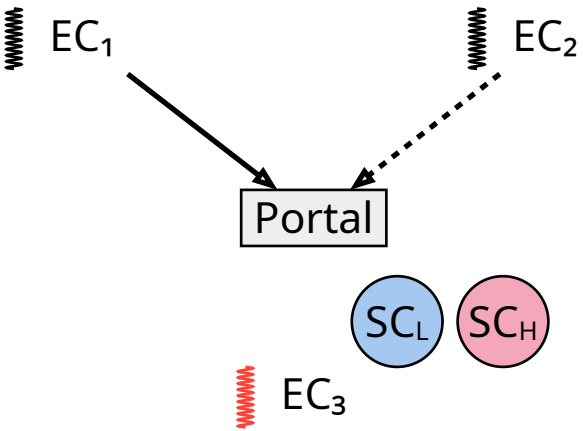

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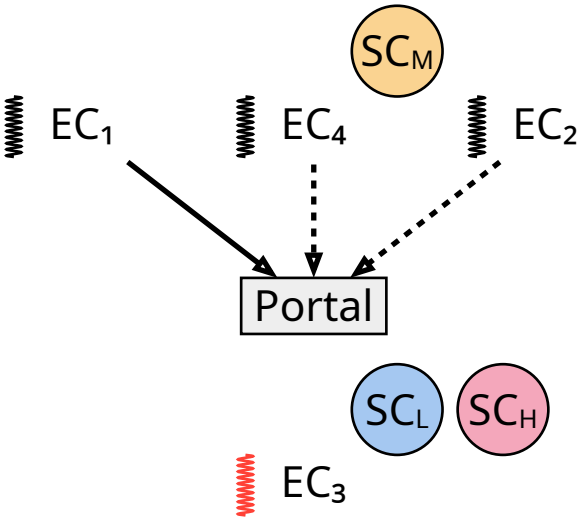

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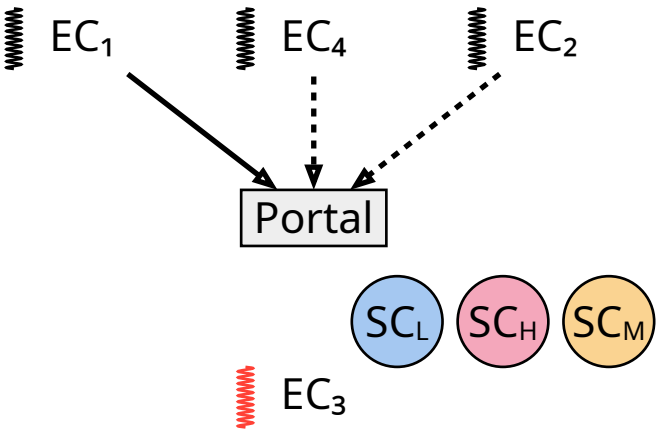
  - EC_3 runs with SC_H

Solution in NOVA: Priority Inheritance



- Timeslice donation:
  - EC_1 calls portal with SC_1
  - SC_L is donated to EC_3
- Helping:
  - if SC_L has no time left, SC_H helps EC_3
  - EC_3 runs with SC_H

Wait-Free Synchronization

- Strongest non-blocking guarantees
- *All* threads make progress
- Achieved by helping
- Priority inversion prevented by priority inheritance

- Threads
- Synchronization
- **FPU Handling**

Floating Point Unit

- CPU has dedicated functional units for FP computations
- Are accessed with specific instructions
- Have their own state, which is large (512 bytes)
- Each thread has its own FPU state

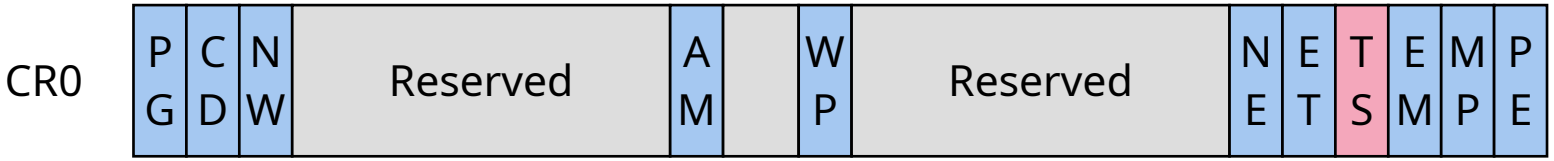
➡️ Save/restore FPU on each context switch is expensive

➡️ However, many OSes on x86 today save it on every switch (vector instructions, LazyFPU vulnerability)

FPU Switch: General Idea

- We want to know if/when a thread uses the FPU
- We only want to save the FPU state if it has been modified
- We don’t want to save the FPU state when switching from a thread that used the FPU to a thread that is not going to use the FPU and then later restore the old (unmodified) FPU state

Lazy FPU Switch on x86



`CR0.TS`

If `CR0.TS` (task switched) flag is set, FPU instructions are not executed, but cause `#NM` exception.

Implementation in NOVA

Handling the #NM exception

C++

```
1   void handle_exc_nm() {
2     CR0.TS = 0;
3     hzd |= HZD_FPU;
4     if (current == fpowner) return;
5     if (fpowner)
6       fpowner->fpu->save();
7     if (current->fpu)
8       current->fpu->load();
9     else {
10      current->fpu = new Fpu;
11      Fpu::init();
12    }
13    fpowner = current;
14  }
```

Before leaving to user

C++

```
1  void handle_hazards() {
2    if ((hzd & HZD_FPU) &&
3          current != fpowner) {
4      CR0.TS = 1;
5      hzd &= ~HZD_FPU;
6    }
7  }
```