Linux Scheduling and Kernel Synchronization

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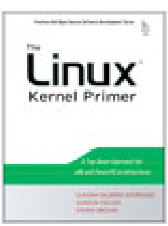
Contents Print Share This

Page 1 of 6 Next >

The Linux kernel is a multitasking kernel, which means that many processes can run as if they were the only process on the system. The way in which an operating system chooses which process at a given time has access to a system's CPU(s) is controlled by a scheduler. This chapter covers the Linux scheduler, preemption in Linux, and the Linux system clock and timers.

This chapter is from the book



Linux Kernel Primer, The: A Top-Down Approach for x86 and PowerPC Architectures

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In this chapter

- 7.1 Linux Scheduler
- 7.2 Preemption
- 7.3 Spinlocks and Semaphores
- 7.4 System Clock: Of Time and Timers
- Summary
- Exercises

The Linux kernel is a multitasking kernel, which means that many processes can run as if they were the only process on the system. The way in which an operating system chooses which process at a given time has access to a system's CPU(s) is controlled by a scheduler.

The scheduler is responsible for swapping CPU access between different processes and for choosing the order in which processes obtain CPU access. Linux, like most operating systems, triggers the scheduler by using a timer interrupt. When this timer goes off, the kernel needs to decide whether to yield the CPU to a process different than the current process and, if a yield occurs, which process gets the CPU next. The amount of time between the timer interrupt is called a timeslice.

System processes tend to fall into two types: interactive and non-interactive. Interactive processes are heavily dependent upon I/O and, as a result, do not usually use their entire timeslice and, instead, yield the CPU to another process. Non-interactive processes are heavily dependent on the CPU and typically use most, if not all, of their timeslice. The scheduler has to balance the requirements of these two types of processes and attempt to ensure every process gets enough time to accomplish its task without detrimentally affecting the execution of other processes.

Linux, like some schedulers, distinguishes between one more type of process: a real-time process. Real-time processes must execute in real time. Linux has support for real-time processes, but those exist outside of the scheduler logic. Put simply, the Linux scheduler treats any process marked as real-time as a higher priority than any other process. It is up to the developer of the real-time processes to ensure that these processes do not hog the CPU and eventually yield.

Schedulers typically use some type of process queue to manage the execution of processes on the system. In Linux, this process queue is called the run queue. The run queue is described fully in Chapter 3, "Processes: The Principal Model of Execution,"[1] but let's recap some of the fundamentals here because of the close tie between the scheduler and the run queue.

In Linux, the run queue is composed of two priority arrays:

- **Active.** Stores processes that have not yet used up their timeslice
- **Expired.** Stores processes that have used up their timeslice

From a high level, the scheduler's job in Linux is to take the highest priority active processes, let them use the CPU to execute, and place them in the expired array when they use up their timeslice. With this high-level framework in mind, let's closely look at how the Linux scheduler operates.

7.1 Linux Scheduler

The 2.6 Linux kernel introduces a completely new scheduler that's commonly referred to as the O(1) scheduler. The scheduler can perform the scheduling of a task in constant time.[2] Chapter 3 addressed the basic structure of the scheduler and how a newly created process is initialized for it. This section describes how a task is executed on a single CPU system. There are some mentions of code for scheduling across multiple CPU (SMP) systems but, in general, the same scheduling process applies across CPUs. We then describe how the scheduler switches out the currently running process, performing what is called a context switch, and then we touch on the other significant change in the 2.6 kernel: preemption.

From a high level, the scheduler is simply a grouping of functions that operate on given data structures. Nearly all the code implementing the scheduler can be found in `kernel/sched.c` and `include/linux/sched.h`. One important point to mention early on is how the scheduler code uses the terms "task" and "process" interchangeably. Occasionally, code comments also use "thread" to refer to a task or process. A task, or process, in the scheduler is a collection of data structures and flow of control. The scheduler code also refers to a `task_struct`, which is a data structure the Linux kernel uses to keep track of processes.[3]

7.1.1 Choosing the Next Task

After a process has been initialized and placed on a run queue, at some time, it should have access to the CPU to execute. The two functions that are responsible for passing CPU control to different processes are `schedule()` and `scheduler_tick()`. `scheduler_tick()` is a system timer that the kernel periodically calls and marks processes as needing rescheduling. When a timer event occurs, the current process is put on hold and the Linux kernel itself takes control of the CPU. When the timer event finishes, the Linux kernel normally passes control back to the process that was put on hold. However, when the held process has been marked as needing rescheduling, the kernel calls `schedule()` to choose which process to activate instead of the process that was executing before the kernel took control. The process that was executing before the kernel took control is called the current process. To make things slightly more complicated, in certain situations, the kernel can take control from the kernel; this is called kernel preemption. In the following sections, we assume that the scheduler decides which of two user space processes gains CPU control.

Figure 7.1 illustrates how the CPU is passed among different processes as time progresses. We see that *Process A* has control of the CPU and is executing. The system timer `scheduler_tick()` goes off, takes control of the CPU from *A*, and marks *A* as needing rescheduling. The Linux kernel calls `schedule()`, which chooses *Process B* and the control of the CPU is given to *B*.

Figure 7.1 Scheduling Processes

Process B executes for a while and then voluntarily yields the CPU. This commonly occurs when a process waits on some resource. *B* calls `schedule()`, which chooses *Process C* to execute next.

Process C executes until `scheduler_tick()` occurs, which does not mark *C* as nee rescheduling. This results in `schedule()` not being called and *C* regains control of t

Process C yields by calling `schedule()`, which determines that *Process A* should gai the CPU and *A* starts to execute again.

We first examine `schedule()`, which is how the Linux kernel decides which process next, and then we examine `scheduler_tick()`, which is how the kernel determin processes need to yield the CPU. The combined effects of these functions demonstra of control within the scheduler:


```
-----------------------------------------------------------------------
kernel/sched.c
asmlinkage void schedule(void)
{
 long *switch_count;
 task_t *prev, *next;
 runqueue_t *rq;
 prio_array_t *array;
 struct list_head *queue;
 unsigned long long now;
 unsigned long run_time;
 int idx;

 /*
 * Test if we are atomic. Since do_exit() needs to call into
 * schedule() atomically, we ignore that path for now.
 * Otherwise, whine if we are scheduling when we should not be.
 */
 if (likely(!(current->state & (TASK_DEAD | TASK_ZOMBIE)))) {
  if (unlikely(in_atomic())) {
   printk(KERN_ERR "bad: scheduling while atomic!\n ");
   dump_stack();
  }
 }

need_resched:
 preempt_disable();
```

```
2209  prev = current;
2210  rq = this_rq();
2211
2212  release_kernel_lock(prev);
2213  now = sched_clock();
2214  if (likely(now - prev->timestamp < NS_MAX_SLEEP_AVG))
2215   run_time = now - prev->timestamp;
2216  else
2217   run_time = NS_MAX_SLEEP_AVG;
2218
2219  /*
2220  * Tasks with interactive credits get charged less run_time
2221  * at high sleep_avg to delay them losing their interactive
2222  * status
2223  */
2224  if (HIGH_CREDIT(prev))
2225  run_time /= (CURRENT_BONUS(prev) ? : 1);
-----------------------------------------------------------------------
```

Lines 2213–2218

We calculate the length of time for which the process on the scheduler has been active. If the process has been active for longer than the average maximum sleep time (`NS_MAX_SLEEP_AVG`), we set its runtime to the average maximum sleep time.

This is what the Linux kernel code calls a timeslice in other sections of the code. A timeslice refers to both the amount of time between scheduler interrupts and the length of time a process has spent using the CPU. If a process exhausts its timeslice, the process expires and is no longer active. The timestamp is an absolute value that determines for how long a process has used the CPU. The scheduler uses timestamps to decrement the timeslice of processes that have been using the CPU.

For example, suppose Process A has a timeslice of 50 clock cycles. It uses the CPU for 5 clock cycles and then yields the CPU to another process. The kernel uses the timestamp to determine that Process A has 45 cycles left on its timeslice.

Lines 2224–2225

Interactive processes are processes that spend much of their time waiting for input. A good example of an interactive process is the keyboard controller—most of the time the controller is waiting for input, but when it has a task to do, the user expects it to occur at a high priority.

Interactive processes, those that have an interactive credit of more than 100 (default value), get their effective `run_time` divided by (`sleep_avg/ max_sleep_avg` * `MAX_BONUS(10)`):[4]

```
-----------------------------------------------------------------------
kernel/sched.c
2226
2227  spin_lock_irq(&rq->lock);
2228
2229  /*
2230  * if entering off of a kernel preemption go straight
2231  * to picking the next task.
2232  */
2233  switch_count = &prev->nivcsw;
2234  if (prev->state && !(preempt_count() & PREEMPT_ACTIVE)) {
2235   switch_count = &prev->nvcsw;
2236   if (unlikely((prev->state & TASK_INTERRUPTIBLE) &&
2237     unlikely(signal_pending(prev))))
2238    prev->state = TASK_RUNNING;
2239   else
2240    deactivate_task(prev, rq);
2241  }
-----------------------------------------------------------------------
```

Line 2227

The function obtains the run queue lock because we're going to modify it.

Lines 2233–2241

If we have entered `schedule()` with the previous process being a kernel preemption, we leave the previous process running if a signal is pending. This means that the kernel has preempted normal processing in quick succession; thus, the code is contained in two `unlikely()` statements.[5] If there is no further preemption, we remove the preempted process from the run queue and continue to choose the next process to run.

```
-----------------------------------------------------------------------
kernel/sched.c
2243  cpu = smp_processor_id();
2244  if (unlikely(!rq->nr_running)) {
2245   idle_balance(cpu, rq);
2246   if (!rq->nr_running) {
2247    next = rq->idle;
2248    rq->expired_timestamp = 0;
2249    wake_sleeping_dependent(cpu, rq);
2250    goto switch_tasks;
2251   }
2252  }
2253
2254  array = rq->active;
2255  if (unlikely(!array->nr_active)) {
2256   /*
2257   * Switch the active and expired arrays.
2258   */
2259   rq->active = rq->expired;
2260   rq->expired = array;
2261   array = rq->active;
2262   rq->expired_timestamp = 0;
2263   rq->best_expired_prio = MAX_PRIO;
2264  }
-----------------------------------------------------------------------
```

Line 2243

We grab the current CPU identifier via `smp_processor_id()`.

Lines 2244–2252

If the run queue has no processes on it, we set the next process to the idle process and reset the run queue's expired timestamp to 0. On a multiprocessor system, we first check if any processes are running on other CPUs that this CPU can take. In effect, we load balance idle processes across all CPUs in the system. Only if no processes can be moved from the other CPUs do we set the run queue's next process to idle and reset the expired timestamp.

Lines 2255–2264

If the run queue's active array is empty, we switch the active and expired array pointers before choosing a new process to run.

```
-----------------------------------------------------------------------
kernel/sched.c
2266  idx = sched_find_first_bit(array->bitmap);
2267  queue = array->queue + idx;
2268  next = list_entry(queue->next, task_t, run_list);
2269
2270  if (dependent_sleeper(cpu, rq, next)) {
2271   next = rq->idle;
2272   goto switch_tasks;
2273  }
2274
2275  if (!rt_task(next) && next->activated > 0) {
2276   unsigned long long delta = now - next->timestamp;
```

```
2277
2278   if (next->activated == 1)
2279    delta = delta * (ON_RUNQUEUE_WEIGHT * 128 / 100) / 128;
2280
2281   array = next->array;
2282   dequeue_task(next, array);
2283   recalc_task_prio(next, next->timestamp + delta);
2284   enqueue_task(next, array);
2285  }
next->activated = 0;
-----------------------------------------------------------------------
```

Lines 2266–2268

The scheduler finds the highest priority process to run via `sched_find_first_bit()` and then sets up `queue` to point to the list held in the priority array at the specified location. `next` is initialized to the first process in `queue`.

Lines 2270–2273

If the process to be activated is dependent on a sibling that is sleeping, we choose a new process to be activated and jump to `switch_tasks` to continue the scheduling function.

Suppose that we have Process A that spawned Process B to read from a device and that Process A was waiting for Process B to finish before continuing. If the scheduler chooses Process A for activation, this section of code, `dependent_sleeper()`, determines that Process A is waiting on Process B and chooses an entirely new process to activate.

Lines 2275–2285

If the process' activated attribute is greater than 0, and the next process is not a real-time task, we remove it from `queue`, recalculate its priority, and enqueue it again.

Line 2286

We set the process' activated attribute to 0, and then run with it.

```
-----------------------------------------------------------------------
kernel/sched.c
2287 switch_tasks:
2288  prefetch(next);
2289  clear_tsk_need_resched(prev);
2290  RCU_qsctr(task_cpu(prev))++;
2291
2292  prev->sleep_avg -= run_time;
2293  if ((long)prev->sleep_avg <= 0) {
2294   prev->sleep_avg = 0;
2295   if (!(HIGH_CREDIT(prev) || LOW_CREDIT(prev)))
2296    prev->interactive_credit--;
2297  }
2298  prev->timestamp = now;
2299
2300  if (likely(prev != next)) {
2301   next->timestamp = now;
2302   rq->nr_switches++;
2303   rq->curr = next;
2304   ++*switch_count;
2305
2306   prepare_arch_switch(rq, next);
2307   prev = context_switch(rq, prev, next);
2308   barrier();
2309
2310   finish_task_switch(prev);
2311  } else
2312   spin_unlock_irq(&rq->lock);
2313
2314  reacquire_kernel_lock(current);
2315  preempt_enable_no_resched();
2316  if (test_thread_flag(TIF_NEED_RESCHED))
2317   goto need_resched;
```

```
2318 }
-----------------------------------------------------------------------
```

Line 2288

We attempt to get the memory of the new process' task structure into the CPU's L1 cache. (See `include/linux/prefetch.h` for more information.)

Line 2290

Because we're going through a context switch, we need to inform the current CPU that we're doing so. This allows a multi-CPU device to ensure data that is shared across CPUs is accessed exclusively. This process is called read-copy updating. For more information, see http://lse.sourceforge.net/locking/rcupdate.html.

Lines 2292–2298

We decrement the previous process' `sleep_avg` attribute by the amount of time it ran, adjusting for negative values. If the process is neither interactive nor non-interactive, its interactive credit is between high and low, so we decrement its interactive credit because it had a low sleep average. We update its timestamp to the current time. This operation helps the scheduler keep track of how much time a given process has spent using the CPU and estimate how much time it will use the CPU in the future.

Lines 2300–2304

If we haven't chosen the same process, we set the new process' timestamp, increment the run queue counters, and set the current process to the new process.

Lines 2306–2308

These lines describe the assembly language `context_switch()`. Hold on for a few paragraphs as we delve into the explanation of context switching in the next section.

Lines 2314–2318

We reacquire the kernel lock, enable preemption, and see if we need to reschedule immediately; if so, we go back to the top of `schedule()`.

It's possible that after we perform the `context_switch()`, we need to reschedule. Perhaps `scheduler_tick()` has marked the new process as needing rescheduling or, when we enable preemption, it gets marked. We keep rescheduling processes (and context switching them) until one is found that doesn't need rescheduling. The process that leaves `schedule()` becomes the new process executing on this CPU.

7.1.2 Context Switch

Called from `schedule()` in `/kernel/sched.c`, `context_switch()` does the machine-specific work of switching the memory environment and the processor state. In the abstract, `context_switch` swaps the current task with the next task. The function `context_switch()` begins executing the next task and returns a pointer to the task structure of the task that was running before the call:

```
-----------------------------------------------------------------------
kernel/sched.c
/*
* context_switch - switch to the new MM and the new
* thread's register state.
*/
static inline
task_t * context_switch(runqueue_t *rq, task_t *prev, task_t *next
{
 struct mm_struct *mm = next->mm;
 struct mm_struct *oldmm = prev->active_mm;
...
  switch_mm(oldmm, mm, next);
...
 switch_to(prev, next, prev);
```

```

 return prev;
}
-----------------------------------------------------------------------
```

Here, we describe the two jobs of `context_switch`: one to switch the virtual memory mapping and one to switch the task/thread structure. The first job, which the function `switch_mm()` carries out, uses many of the hardware-dependent memory management structures and registers:

```
-----------------------------------------------------------------------
/include/asm-i386/mmu_context.h
026 static inline void switch_mm(struct mm_struct *prev,
027   struct mm_struct *next,
028   struct task_struct *tsk)
029 {
030  int cpu = smp_processor_id();
031
032  if (likely(prev != next)) {
033  /* stop flush ipis for the previous mm */
034  cpu_clear(cpu, prev->cpu_vm_mask);
035 #ifdef CONFIG_SMP
036  cpu_tlbstate[cpu].state = TLBSTATE_OK;
037  cpu_tlbstate[cpu].active_mm = next;
038 #endif
039  cpu_set(cpu, next->cpu_vm_mask);
040
041  /* Re-load page tables */
042  load_cr3(next->pgd);
043
044  /*
045  * load the LDT, if the LDT is different:
046  */
047  if (unlikely(prev->context.ldt != next->context.ldt))
048   load_LDT_nolock(&next->context, cpu);
049  }
050 #ifdef CONFIG_SMP
051  else {
-----------------------------------------------------------------------
```

Line 39

Bind the new task to the current processor.

Line 42

The code for switching the memory context utilizes the x86 hardware register `cr3`, which holds the base address of all paging operations for a given process. The new page global descriptor is loaded here from `next->pgd`.

Line 47

Most processes share the same LDT. If another LDT is required by this process, it is loaded here from the new `next->context` structure.

The other half of function `context_switch()` in `/kernel/sched.c` then calls the macro `switch_to()`, which calls the C function `__switch_to()`. The delineation of architecture *in*dependence to architecture dependence for both x86 and PPC is the `switch_to()` macro.

7.1.2.1

Following the x86 Trail of switch_to()

The x86 code is more compact than PPC. The following is the architecture-dependent code for `__switch_to()`. `task_struct` (not `thread_struct`) is passed to `__switch_to()`. The code discussed next is inline assembler code for calling the C function `__switch_to()` (line

23) with the proper `task_struct` structures as parameters.

The `context_switch` takes three task pointers: `prev`, `next`, and `last`. In addition, there is the current pointer.

Let us now explain, at a high level, what occurs when `switch_to()` is called and how the task pointers change after a call to `switch_to()`.

Figure 7.2 shows three `switch_to()` calls using three processes: A, B, and C.

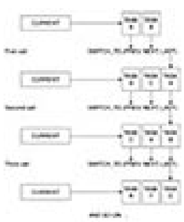

Figure 7.2 switch_to Calls

We want to switch A and B. Before, the first call we have

- Current → A
- Prev → A, next → B

After the first call:

- Current → B
- Last → A

Now, we want to switch B and C. Before the second call, we have

- Current → B
- Prev → B, next → C

After the second call:

- Current → C
- Last → B

Returning from the second call, current now points to task (C) and last points to (B).

The method continues with task (A) being swapped in once again, and so on.

The inline assembly of the `switch_to()` function is an excellent example of assembly magic in the kernel. It is also a good example of the `gcc` C extensions. See Chapter 2, "Exploration Toolkit," for a tutorial featuring this function. Now, we carefully walk through this code block.

```
-----------------------------------------------------------------------
/include/asm-i386/system.h
012 extern struct task_struct * FASTCALL(__switch_to(struct task_struct
 struct task_struct *next));

015 #define switch_to(prev,next,last) do {   \
016  unsigned long esi,edi;    \
017  asm volatile("pushfl\n\t"    \
018  "pushl %%ebp\n\t"    \
019  "movl %%esp,%0\n\t" /* save ESP */  \
020  "movl %5,%%esp\n\t" /* restore ESP */  \
021  "movl $1f,%1\n\t"  /* save EIP */  \
022  "pushl %6\n\t"  /* restore EIP */  \
023  "jmp __switch_to\n"    \
```

```
023  "1:\t"     \
024  "popl %%ebp\n\t"    \
025  "popfl"     \
026  :"=m" (prev->thread.esp),"=m" (prev->thread.eip), \
027  "=a" (last),"=S" (esi),"=D" (edi)   \
028  :"m" (next->thread.esp),"m" (next->thread.eip),  \
029  "2" (prev), "d" (next));    \
030 } while (0)
----------------------------------------------------------------------
```

Line 12

The `FASTCALL` macro resolves to `__attribute__ regparm(3)`, which forces the parameters to be passed in registers rather than stack.

Lines 15–16

The `do {} while (0)` construct allows (among other things) the macro to have local the variables `esi` and `edi`. Remember, these are just local variables with familiar names.

> **Current and the Task Structure**
>
> As we explore the kernel, whenever we need to retrieve or store information on the task (or process) which is *currently* running on a given processor, we use the global variable `current` to reference its task structure. For example, `current->pid` holds the process ID. Linux allows for a quick (and clever) method of referencing the current task structure.
>
> Every process is assigned 8K of contiguous memory when it is created. (With Linux 2.6, there is a compile-time option to use 4K instead of 8K.) This 8K segment is occupied by the task structure and the kernel stack for the given process. Upon process creation, Linux puts the task structure at the low end of the 8K memory and the kernel stack pointer starts at the high end. The kernel stack pointer (especially for x86 and r1 for PPC) decrements as data is pushed onto the stack. Because this 8K memory region is page-aligned, its starting address (in hex notation) always ends in 0x000 (multiples of 4k bytes).
>
> As you might have guessed, the clever method by which Linux references the current task structure is to AND the contents of the stack pointer with 0xffff_f000. Recent versions of the PPC Linux kernel have taken this one step further by dedicating General Purpose Register 2 to holding the current pointer.

Lines 17 and 30

The construct `asm volatile ()`[6] encloses the inline assembly block and the volatile keyword assures that the compiler will not change (optimize) the routine in any way.

Lines 17–18

Push the `flags` and `ebp` registers onto the stack. (Note: We are still using the stack associated with the `prev` task.)

Line 19

This line saves the current stack pointer `esp` to the `prev` task structure.

Line 20

Move the stack pointer from the next task structure to the current processor `esp`.

> **NOTE**
>
> By definition, we have just made a context switch.

We are now with a new kernel stack and thus, any reference to current is to the new (`next`) task structure.

Line 21

Save the return address for `prev` into its task structure. This is where the `prev` task resumes when it is restarted.

Line 22

Push the return address (from when we return from `__switch_to()`) onto the stack. This is the `eip` from `next`. The `eip` was saved into its task structure (on line 21) when it was stopped, or preempted the last time.

Line 23

Jump to the C function `__switch_to()` to update the following:

- The next thread structure with the kernel stack pointer
- Thread local storage descriptor for this processor
- `fs` and `gs` for `prev` and `next`, if needed
- Debug registers, if needed
- I/O bitmaps, if needed

`__switch_to()` then returns the updated `prev` task structure.

Lines 24–25

Pop the base pointer and flags registers from the new (next task) kernel stack.

Lines 26–29

These are the output and input parameters to the inline assembly routine. See the "Inline Assembly" section in Chapter 2 for more information on the *constraints* put on these parameters.

Line 29

By way of assembler magic, `prev` is returned in `eax`, which is the third positional parameter. In other words, the input parameter `prev` is passed out of the `switch_to()` macro as the output parameter last.

Because `switch_to()` is a macro, it was executed inline with the code that called it in `context_switch()`. It does not return as functions normally do.

For the sake of clarity, remember that `switch_to()` passes back `prev` in the `eax` register, execution then continues in `context_switch()`, where the next instruction is `return prev` (line 1074 of `kernel/sched.c`). This allows `context_switch()` to pass back a pointer to the last task running.

7.1.2.2

Following the PPC context_switch()

The PPC code for `context_switch()` has slightly more work to do for the same results. Unlike the `cr3` register in x86 architecture, the PPC uses hash functions to point to context environments. The following code for `switch_mm()` touches on these functions, but Chapter 4, "Memory Management," offers a deeper discussion.

Here is the routine for `switch_mm()` which, in turn, calls the routine `set_context()`.

```
-----------------------------------------------------------------------
/include/asm-ppc/mmu_context.h
155 static inline void switch_mm(struct mm_struct *prev, struct
mm_struct *next,struct task_struct *tsk)
```

```
156 {
157  tsk->thread.pgdir = next->pgd;
158  get_mmu_context(next);
159  set_context(next->context, next->pgd);
160 }
-----------------------------------------------------------------------
```

Line 157

The page global directory (segment register) for the new thread is made to point to the `next->pgd` pointer.

Line 158

The `context` field of the `mm_struct` (`next->context`) passed into `switch_mm()` is updated to the value of the appropriate context. This information comes from a global reference to the variable `context_map[]`, which contains a series of bitmap fields.

Line 159

This is the call to the assembly routine `set_context`. Below is the code and discussion of this routine. Upon execution of the `blr` instruction on line 1468, the code returns to the `switch_mm` routine.

```
-----------------------------------------------------------------------
/arch/ppc/kernel/head.S
1437 _GLOBAL(set_context)
1438 mulli r3,r3,897 /* multiply context by skew factor */
1439 rlwinm r3,r3,4,8,27 /* VSID = (context & 0xfffff) << 4 */
1440 addis r3,r3,0x6000 /* Set Ks, Ku bits */
1441 li r0,NUM_USER_SEGMENTS
1442 mtctr r0
...
1457 3: isync
...
1461 mtsrin r3,r4
1462 addi r3,r3,0x111 /* next VSID */
1463 rlwinm r3,r3,0,8,3 /* clear out any overflow from VSID field */
1464 addis r4,r4,0x1000 /* address of next segment */
1465 bdnz 3b
1466 sync
1467 isync
1468 blr
-----------------------------------------------------------------------
```

Lines 1437–1440

The `context` field of the `mm_struct` (`next->context`) passed into `set_context()` by way of `r3`, sets up the hash function for PPC segmentation.

Lines 1461–1465

The `pgd` field of the `mm_struct` (`next->pgd`) passed into `set_context()` by way of `r4`, points to the segment registers.

Segmentation is the basis of PPC memory management (refer to Chapter 4). Upon returning from `set_context()`, the `mm_struct` next is initialized to the proper memory regions and is returned to `switch_mm()`.

7.1.2.3 Following the PPC Trail of switch_to()

The result of the PPC implementation of `switch_to()` is necessarily identical to the x86 call; it takes in the `current` and `next` task pointers and returns a pointer to the previously running task:

```
-----------------------------------------------------------------------
include/asm-ppc/system.h
88 extern struct task_struct *__switch_to(struct task_struct *,
89  struct task_struct *);
90 #define switch_to(prev, next, last)
((last) = __switch_to((prev), (next)))
91
92 struct thread_struct;
93 extern struct task_struct *_switch(struct thread_struct *prev,
94     struct thread_struct *next);
-----------------------------------------------------------------------
```

On line 88, `__switch_to()` takes its parameters as `task_struct` type and, at line 93, `_switch()` takes its parameters as thread_`struct`. This is because the thread entry within `task_struct` contains the architecture-dependent processor register information of interest for the given thread. Now, let us examine the implementation of `__switch_to()`:

```
-----------------------------------------------------------------------
/arch/ppc/kernel/process.c
200 struct task_struct *__switch_to(struct task_struct *prev,
  struct task_struct *new)
201 {
202  struct thread_struct *new_thread, *old_thread;
203  unsigned long s;
204  struct task_struct *last;
205  local_irq_save(s);
...
247  new_thread = &new->thread;
248  old_thread = &current->thread;
249  last = _switch(old_thread, new_thread);
250  local_irq_restore(s);
251  return last;
252 }
-----------------------------------------------------------------------
```

Line 205

Disable interrupts before the context switch.

Lines 247–248

Still running under the context of the *old* thread, pass the pointers to the thread structure to the `_switch()` function.

Line 249

`_switch()` is the assembly routine called to do the work of switching the two thread structures (see the following section).

Line 250

Enable interrupts after the context switch.

To better understand what needs to be swapped within a PPC thread, we need to examine the `thread_struct` passed in on line 249.

Recall from the exploration of the x86 context switch that the switch does not officially occur until we are pointing to a new kernel stack. This happens in `_switch()`.

Tracing the PPC Code for _switch()

By convention, the parameters of a PPC C function (from left to right) are held in `r3`, `r4`, `r5`, ...`r12`. Upon entry into `switch()`, `r3` points to the `thread_struct` for the current task and `r4` points to the `thread_struct` for the new task:

```
-----------------------------------------------------------------------
/arch/ppc/kernel/entry.S
437 _GLOBAL(_switch)
438  stwu r1,-INT_FRAME_SIZE(r1)
439  mflr r0
440  stw r0,INT_FRAME_SIZE+4(r1)
441  /* r3-r12 are caller saved -- Cort */
442  SAVE_NVGPRS(r1)
443  stw r0,_NIP(r1) /* Return to switch caller */
444  mfmsr r11
...
458 1: stw r11,_MSR(r1)
459  mfcr r10
460  stw r10,_CCR(r1)
461  stw r1,KSP(r3) /* Set old stack pointer */
462
463  tophys(r0,r4)
464  CLR_TOP32(r0)
465  mtspr SPRG3,r0/* Update current THREAD phys addr */
466  lwz r1,KSP(r4) /* Load new stack pointer */
467  /* save the old current 'last' for return value */
468  mr r3,r2
469  addi r2,r4,-THREAD /* Update current */
...
478  lwz r0,_CCR(r1)
479  mtcrf 0xFF,r0
480  REST_NVGPRS(r1)
481
482  lwz r4,_NIP(r1) /* Return to _switch caller in new task */
483  mtlr r4
484  addi r1,r1,INT_FRAME_SIZE
485  blr
-----------------------------------------------------------------------
```

The byte-for-byte mechanics of swapping out the previous `thread_struct` for the new is left as an exercise for you. It is worth noting, however, the use of `r1`, `r2`, `r3`, SPRG3, and `r4` in `_switch()` to see the basics of this operation.

Lines 438–460

The environment is saved to the current stack with respect to the current stack pointer, `r1`.

Line 461

The entire environment is then saved into the current `thread_struct` pointer passed in by way of `r3`.

Lines 463–465

SPRG3 is updated to point to the thread structure of the new task.

Line 466

KSP is the offset into the task structure (`r4`) of the new task's kernel stack pointer. The stack pointer `r1` is now updated with this value. (This is the point of the PPC context switch.)

Line 468

The current pointer to the previous task is returned from `_switch()` in `r3`. This represents the last task.

Line 469

The current pointer (`r2`) is updated with the pointer to the new task structure (`r4`).

Lines 478–486

Restore the rest of the environment from the new stack and return to the caller with the previous task structure in `r3`.

This concludes the explanation of `context_switch()`. At this point, the processor has swapped the two processes `prev` and `next` as called by `context_switch` in `schedule()`.

```
-----------------------------------------------------------------------
kernel/sched.c
prev = context_switch(rq, prev, next);
-----------------------------------------------------------------------
```

prev now points to the process that we have just switched away from and next points to the current process.

Now that we've discussed how tasks are scheduled in the Linux kernel, we can examine how tasks are told to be scheduled. Namely, what causes schedule() to be called and one process to yield the CPU to another process?

7.1.3 Yielding the CPU

Processes can voluntarily yield the CPU by simply calling schedule(). This is most commonly used in kernel code and device drivers that want to sleep or wait for a signal to occur.[7] Other tasks want to continually use the CPU and the system timer must tell them to yield. The Linux kernel periodically seizes the CPU, in so doing stopping the active process, and then does a number of timer-based tasks. One of these tasks, scheduler_tick(), is how the kernel forces a process to yield. If a process has been running for too long, the kernel does not return control to that process and instead chooses another one. We now examine how scheduler_tick()determines if the current process must yield the CPU:

```
-----------------------------------------------------------------------
kernel/sched.c
1981 void scheduler_tick(int user_ticks, int sys_ticks)
1982 {
1983  int cpu = smp_processor_id();
1984  struct cpu_usage_stat *cpustat = &kstat_this_cpu.cpustat;
1985  runqueue_t *rq = this_rq();
1986  task_t *p = current;
1987
1988  rq->timestamp_last_tick = sched_clock();
1989
1990  if (rcu_pending(cpu))
1991  rcu_check_callbacks(cpu, user_ticks);
-----------------------------------------------------------------------
```

Lines 1981–1986

This code block initializes the data structures that the scheduler_tick() function needs. cpu, cpu_usage_stat, and rq are set to the processor ID, CPU stats and run queue of the current processor. p is a pointer to the current process executing on cpu.

Line 1988

The run queue's last tick is set to the current time in nanoseconds.

Lines 1990–1991

On an SMP system, we need to check if there are any outstanding read-copy updates to perform (RCU). If so, we perform them via rcu_check_callback().

```
-----------------------------------------------------------------------
kernel/sched.c
/* note: this timer irq context must be accounted for as well */
if (hardirq_count() - HARDIRQ_OFFSET) {
 cpustat->irq += sys_ticks;
 sys_ticks = 0;
} else if (softirq_count()) {
 cpustat->softirq += sys_ticks;
 sys_ticks = 0;
}
```

```
2001
2002  if (p == rq->idle) {
2003   if (atomic_read(&rq->nr_iowait) > 0)
2004    cpustat->iowait += sys_ticks;
2005   else
2006    cpustat->idle += sys_ticks;
2007   if (wake_priority_sleeper(rq))
2008    goto out;
2009   rebalance_tick(cpu, rq, IDLE);
2010   return;
2011  }
2012  if (TASK_NICE(p) > 0)
2013   cpustat->nice += user_ticks;
2014  else
2015   cpustat->user += user_ticks;
2016  cpustat->system += sys_ticks;
---------------------------------------------------------------------
```

Lines 1994–2000

`cpustat` keeps track of kernel statistics, and we update the hardware and software interrupt statistics by the number of system ticks that have occurred.

Lines 2002–2011

If there is no currently running process, we atomically check if any processes are waiting on I/O. If so, the CPU I/O wait statistic is incremented; otherwise, the CPU idle statistic is incremented. In a uniprocessor system, `rebalance_tick()` does nothing, but on a multiple processor system, `rebalance_tick()` attempts to load balance the current CPU because the CPU has nothing to do.

Lines 2012–2016

More CPU statistics are gathered in this code block. If the current process was `niced`, we increment the CPU `nice` counter; otherwise, the user tick counter is incremented. Finally, we increment the CPU's system tick counter.

```
---------------------------------------------------------------------
kernel/sched.c
2019  if (p->array != rq->active) {
2020   set_tsk_need_resched(p);
2021   goto out;
2022  }
2023  spin_lock(&rq->lock);
---------------------------------------------------------------------
```

Lines 2019–2022

Here, we see why we store a pointer to a priority array within the `task_struct` of the process. The scheduler checks the current process to see if it is no longer active. If the process has expired, the scheduler sets the process' rescheduling flag and jumps to the end of the `scheduler_tick()` function. At that point (lines 2092–2093), the scheduler attempts to load balance the CPU because there is no active task yet. This case occurs when the scheduler grabbed CPU control before the current process was able to schedule itself or clean up from a successful run.

Line 2023

At this point, we know that the current process was running and not expired or nonexistent. The scheduler now wants to yield CPU control to another process; the first thing it must do is take the run queue lock.

```
---------------------------------------------------------------------
kernel/sched.c
```

```
2024  /*
2025  * The task was running during this tick - update the
2026  * time slice counter. Note: we do not update a thread's
2027  * priority until it either goes to sleep or uses up its
2028  * timeslice. This makes it possible for interactive tasks
2029  * to use up their timeslices at their highest priority levels.
2030  */
2031  if (unlikely(rt_task(p))) {
2032   /*
2033   * RR tasks need a special form of timeslice management.
2034   * FIFO tasks have no timeslices.
2035   */
2036   if ((p->policy == SCHED_RR) && !--p->time_slice) {
2037    p->time_slice = task_timeslice(p);
2038    p->first_time_slice = 0;
2039    set_tsk_need_resched(p);
2040
2041    /* put it at the end of the queue: */
2042    dequeue_task(p, rq->active);
2043    enqueue_task(p, rq->active);
2044   }
2045   goto out_unlock;
2046 }
-----------------------------------------------------------------------
```

Lines 2031–2046

The easiest case for the scheduler occurs when the current process is a real-time task. Real-time tasks always have a higher priority than any other tasks. If the task is a FIFO task and was running, it should continue its operation so we jump to the end of the function and release the run queue lock. If the current process is a round-robin real-time task, we decrement its timeslice. If the task has no more timeslice, it's time to schedule another round-robin real-time task. The current task has its new timeslice calculated by `task_timeslice()`. Then the task has its first timeslice reset. The task is then marked as needing rescheduling and, finally, the task is put at the end of the round-robin real-time tasklist by removing it from the run queue's active array and adding it back in. The scheduler then jumps to the end of the function and releases the run queue lock.

```
-----------------------------------------------------------------------
kernel/sched.c
2047  if (!--p->time_slice) {
2048   dequeue_task(p, rq->active);
2049   set_tsk_need_resched(p);
2050   p->prio = effective_prio(p);
2051   p->time_slice = task_timeslice(p);
2052   p->first_time_slice = 0;
2053
2054   if (!rq->expired_timestamp)
2055    rq->expired_timestamp = jiffies;
2056   if (!TASK_INTERACTIVE(p) || EXPIRED_STARVING(rq)) {
2057    enqueue_task(p, rq->expired);
2058    if (p->static_prio < rq->best_expired_prio)
2059     rq->best_expired_prio = p->static_prio;
2060   } else
2061    enqueue_task(p, rq->active);
2062  } else {
-----------------------------------------------------------------------
```

Lines 2047–2061

At this point, the scheduler knows that the current process is not a real-time process. It decrements the process' timeslice and, in this section, the process' timeslice has been exhausted and reached 0. The scheduler removes the task from the active array and sets the process' rescheduling flag. The priority of the task is recalculated and its timeslice is reset. Both of these operations take into account prior process activity.[8] If the run queue's expired timestamp is 0, which usually occurs when there are no more processes on the run queue's active array, we set it to jiffies.

Jiffies

Jiffies is a 32-bit variable counting the number of ticks since the system has been booted. This is approximately 497 days before the number wraps around to 0 on a 100HZ system. The macro on line 20 is the suggested method of accessing this value as a u64. There are also macros to help detect wrapping in `include/jiffies.h`.

```
-------------------------------------------------------------------
include/linux/jiffies.h
017 extern unsigned long volatile jiffies;
020 u64 get_jiffies_64(void);
-------------------------------------------------------------------
```

We normally favor interactive tasks by replacing them on the active priority array of the run queue; this is the `else` clause on line 2060. However, we don't want to starve expired tasks. To determine if expired tasks have been waiting too long for CPU time, we use `EXPIRED_STARVING()` (see EXPIRED_STARVING on line 1968). The function returns true if the first expired task has been waiting an "unreasonable" amount of time or if the expired array contains a task that has a greater priority than the current process. The unreasonableness of waiting is load-dependent and the swapping of the active and expired arrays decrease with an increasing number of running tasks.

If the task is not interactive or expired tasks are starving, the scheduler takes the current process and enqueues it onto the run queue's expired priority array. If the current process' static priority is higher than the expired run queue's highest priority task, we update the run queue to reflect the fact that the expired array now has a higher priority than before. (Remember that high-priority tasks have low numbers in Linux, thus, the (<) in the code.)

```
-----------------------------------------------------------------------
kernel/sched.c
2062  } else {
2063   /*
2064   * Prevent a too long timeslice allowing a task to monopolize
2065   * the CPU. We do this by splitting up the timeslice into
2066   * smaller pieces.
2067   *
2068   * Note: this does not mean the task's timeslices expire or
2069   * get lost in any way, they just might be preempted by
2070   * another task of equal priority. (one with higher
2071   * priority would have preempted this task already.) We
2072   * requeue this task to the end of the list on this priority
2073   * level, which is in essence a round-robin of tasks with
2074   * equal priority.
2075   *
2076   * This only applies to tasks in the interactive
2077   * delta range with at least TIMESLICE_GRANULARITY to requeue.
2078   */
2079   if (TASK_INTERACTIVE(p) && !((task_timeslice(p) -
2080    p->time_slice) % TIMESLICE_GRANULARITY(p)) &&
2081    (p->time_slice >= TIMESLICE_GRANULARITY(p)) &&
2082    (p->array == rq->active)) {
2083
2084    dequeue_task(p, rq->active);
2085    set_tsk_need_resched(p);
2086    p->prio = effective_prio(p);
2087    enqueue_task(p, rq->active);
2088   }
```

```
2089  }
2090 out_unlock:
2091  spin_unlock(&rq->lock);
2092 out:
2093  rebalance_tick(cpu, rq, NOT_IDLE);
2094 }
-----------------------------------------------------------------------
```

Lines 2079–2089

The final case before the scheduler is that the current process was running and still has timeslices left to run. The scheduler needs to ensure that a process with a large timeslice doesn't hog the CPU. If the task is interactive, has more timeslices than `TIMESLICE_GRANULARITY`, and was active, the scheduler removes it from the active queue. The task then has its reschedule flag set, its priority recalculated, and is placed back on the run queue's active array. This ensures that a process at a certain priority with a large timeslice doesn't starve another process of an equal priority.

Lines 2090–2094

The scheduler has finished rearranging the run queue and unlocks it; if executing on an SMP system, it attempts to load balance.

Combining how processes are marked to be rescheduled, via `scheduler_tick()` and how processes are scheduled, `via schedule()` illustrates how the scheduler operates in the 2.6 Linux kernel. We now delve into the details of what the scheduler means by "priority."

7.1.3.1 Dynamic Priority Calculation

In previous sections, we glossed over the specifics of how a task's dynamic priority is calculated. The priority of a task is based on its prior behavior, as well as its user-specified `nice` value. The function that determines a task's new dynamic priority is `recalc_task_prio()`:

```
-----------------------------------------------------------------------
kernel/sched.c
static void recalc_task_prio(task_t *p, unsigned long long now)
{
 unsigned long long __sleep_time = now - p->timestamp;
 unsigned long sleep_time;

 if (__sleep_time > NS_MAX_SLEEP_AVG)
  sleep_time = NS_MAX_SLEEP_AVG;
 else
  sleep_time = (unsigned long)__sleep_time;

 if (likely(sleep_time > 0)) {
  /*
  * User tasks that sleep a long time are categorised as
  * idle and will get just interactive status to stay active &
  * prevent them suddenly becoming cpu hogs and starving
  * other processes.
  */
  if (p->mm && p->activated != -1 &&
   sleep_time > INTERACTIVE_SLEEP(p)) {
    p->sleep_avg = JIFFIES_TO_NS(MAX_SLEEP_AVG -
      AVG_TIMESLICE);
    if (!HIGH_CREDIT(p))
     p->interactive_credit++;
  } else {
   /*
   * The lower the sleep avg a task has the more
   * rapidly it will rise with sleep time.
   */
   sleep_time *= (MAX_BONUS - CURRENT_BONUS(p)) ? : 1;

   /*
   * Tasks with low interactive_credit are limited to
   * one timeslice worth of sleep avg bonus.
   */
```

```
415    if (LOW_CREDIT(p) &&
416    sleep_time > JIFFIES_TO_NS(task_timeslice(p)))
417     sleep_time = JIFFIES_TO_NS(task_timeslice(p));
418
419    /*
420    * Non high_credit tasks waking from uninterruptible
421    * sleep are limited in their sleep_avg rise as they
422    * are likely to be cpu hogs waiting on I/O
423    */
424    if (p->activated == -1 && !HIGH_CREDIT(p) && p->mm) {
425     if (p->sleep_avg >= INTERACTIVE_SLEEP(p))
426      sleep_time = 0;
427     else if (p->sleep_avg + sleep_time >=
428       INTERACTIVE_SLEEP(p)) {
429      p->sleep_avg = INTERACTIVE_SLEEP(p);
430      sleep_time = 0;
431     }
432    }
433
434    /*
435    * This code gives a bonus to interactive tasks.
436    *
437    * The boost works by updating the 'average sleep time'
438    * value here, based on ->timestamp. The more time a
439    * task spends sleeping, the higher the average gets -
440    * and the higher the priority boost gets as well.
441    */
442    p->sleep_avg += sleep_time;
443
444    if (p->sleep_avg > NS_MAX_SLEEP_AVG) {
445     p->sleep_avg = NS_MAX_SLEEP_AVG;
446     if (!HIGH_CREDIT(p))
447      p->interactive_credit++;
448    }
449   }
450  }
452
452  p->prio = effective_prio(p);
453 }
------------------------------------------------------------------------
```

Lines 386–389

Based on the time `now`, we calculate the length of time the process `p` has slept for and assign it to `sleep_time` with a maximum value of `NS_MAX_SLEEP_AVG`. (`NS_MAX_SLEEP_AVG` defaults to 10 milliseconds.)

Lines 391–404

If process `p` has slept, we first check to see if it has slept enough to be classified as an interactive task. If it has, when `sleep_time` > `INTERACTIVE_SLEEP(p)`, we adjust the process' sleep average to a set value and, if `p` isn't classified as interactive yet, we increment `p`'s `interactive_credit`.

Lines 405–410

A task with a low sleep average gets a higher sleep time.

Lines 411–418

If the task is CPU intensive, and thus classified as non-interactive, we restrict the process to having, at most, one more timeslice worth of a sleep average bonus.

Lines 419–432

Tasks that are not yet classified as interactive (not `HIGH_CREDIT`) that awake from uninterruptible sleep are restricted to having a sleep average of `INTERACTIVE()`.

Lines 434–450

We add our newly calculated `sleep_time` to the process' sleep average, ensuring it doesn't go over `NS_MAX_SLEEP_AVG`. If the processes are not considered interactive but have slept for the maximum time or longer, we increment its interactive credit.

Line 452

Finally, the priority is set using `effective_prio()`, which takes into account the newly calculated `sleep_avg` field of p. It does this by scaling the sleep average of `0 .. MAX_SLEEP_AVG` into the range of -5 to +5. Thus, a process that has a static priority of 70 can have a dynamic priority between 65 and 85, depending on its prior behavior.

One final thing: A process that is not a real-time process has a range between 101 and 140. Processes that are operating at a very high priority, 105 or less, cannot cross the real-time boundary. Thus, a high priority, highly interactive process could never have a dynamic priority of lower than 101. (Real-time processes cover `0..100` in the default configuration.)

7.1.3.2 Deactivation

We already discussed how a task gets inserted into the scheduler by forking and how tasks move from the active to expired priority arrays within the CPU's run queue. But, how does a task ever get removed from a run queue?

A task can be removed from the run queue in two major ways:

- The task is preempted by the kernel and its state is not running, and there is no signal pending for the task (see line 2240 in `kernel/sched.c`).
- On SMP machines, the task can be removed from a run queue and placed on another run queue (see line 3384 in `kernel/sched.c`).

The first case normally occurs when `schedule()` gets called after a process puts itself to sleep on a wait queue. The task marks itself as non-running (`TASK_INTERRUPTIBLE`, `TASK_UNINTERRUPTIBLE`, `TASK_STOPPED`, and so on) and the kernel no longer considers it for CPU access by removing it from the run queue.

The case in which the process is moved to another run queue is dealt with in the SMP section of the Linux kernel, which we do not explore here.

We now trace how a process is removed from the run queue via `deactivate_task()`:

```
-----------------------------------------------------------------------
kernel/sched.c
507 static void deactivate_task(struct task_struct *p, runqueue_t *rq)
508 {
509  rq->nr_running--;
510  if (p->state == TASK_UNINTERRUPTIBLE)
511   rq->nr_uninterruptible++;
512  dequeue_task(p, p->array);
513  p->array = NULL;
514 }
-----------------------------------------------------------------------
```

Line 509

The scheduler first decrements its count of running processes because p is no longer running.

Lines 510–511

If the task is uninterruptible, we increment the count of uninterruptible tasks on the run queue. The corresponding decrement operation occurs when an uninterruptible process wakes up (see `kernel/sched.c` line 824 in the function `try_to_wake_up()`).

Line 512–513

Our run queue statistics are now updated so we actually remove the process from the run queue. The kernel uses the `p->array` field to test if a process is running and on a run queue. Because it no longer is either, we set it to `NULL`.

There is still some run queue management to be done; let's examine the specifics of dequeue_task():

```
-----------------------------------------------------------------------
kernel/sched.c
303 static void dequeue_task(struct task_struct *p, prio_array_t *array
304 {
305  array->nr_active--;
306  list_del(&p->run_list);
307  if (list_empty(array->queue + p->prio))
308   __clear_bit(p->prio, array->bitmap);
309 }
-----------------------------------------------------------------------
```

Line 305

We adjust the number of active tasks on the priority array that process p is on—either the expired or the active array.

Lines 306–308

We remove the process from the list of processes in the priority array at p's priority. If the resulting list is empty, we need to clear the bit in the priority array's bitmap to show there are no longer any processes at priority `p->prio()`.

`list_del()` does all the removal in one step because `p->run_list` is a `list_head` structure and thus has pointers to the previous and next entries in the list.

We have reached the point where the process is removed from the run queue and has thus been completely deactivated. If this process had a state of `TASK_INTERRUPTIBLE` or `TASK_UNINTERRUPTIBLE`, it could be awoken and placed back on a run queue. If the process had a state of `TASK_STOPPED`, `TASK_ZOMBIE`, or `TASK_DEAD`, it has all of its structures removed and

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