CS350: Operating Systems

Lecture 3: Threads

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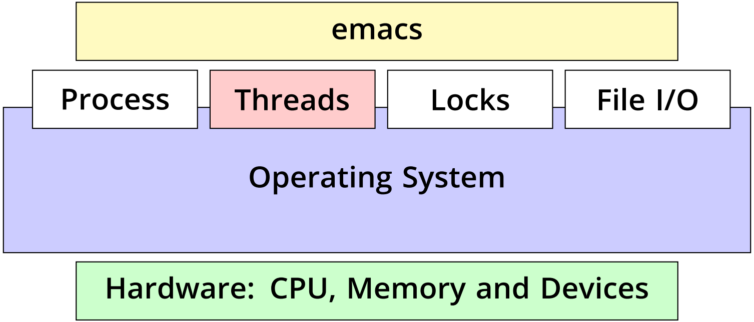
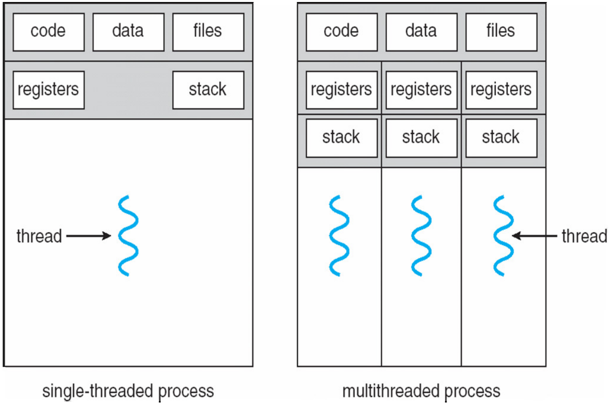
Today: Threads



Outline

1. Threads
2. Case Study: Go Language and Runtime
3. How to implement threads in OS/161

Threads



- A thread is a schedulable execution context
  - Program counter, registers, stack (local variables) ...
- Multi-threaded programs share the address space (global variables, heap, ...)

Why threads?

- Most popular abstraction for concurrency
  - Lighter-weight abstraction than processes
  - All threads in one process share memory, file descriptors, etc.
- Allows one process to use multiple CPUs or cores
- Allows program to overlap I/O and computation
  - Same benefit as OS running `emacs` & `gcc` simultaneously
  - E.g., threaded web server services clients simultaneously:

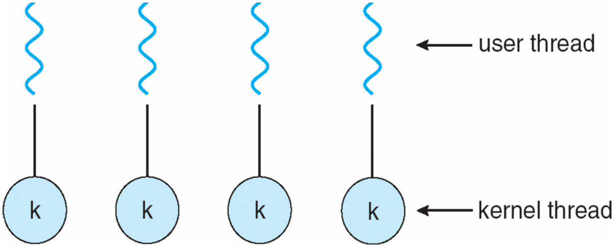
```
for (;;) {
  fd = accept_client ();
  thread_create (service_client, &fd);
}
```

- Most kernels have threads, too
  - Typically at least one kernel thread for every process

POSIX thread API

- `int pthread_create (pthread_t *thr, pthread_attr_t *attr, void *(*fn)(void *), void *arg);`
  - Create a new thread identified by `thr` with optional attributes, run `fn` with `arg`
- `void pthread_exit(void *return_value);`
  - Destroy current thread and return a pointer
- `int pthread_join(pthread_t thread, void **return_value);`
  - Wait for thread `thread` to exit and receive the return value
- `void pthread_yield();`
  - Tell the OS scheduler to run another thread or process
- Plus lots of support for synchronization (next Lecture and see [Birell])

Kernel threads

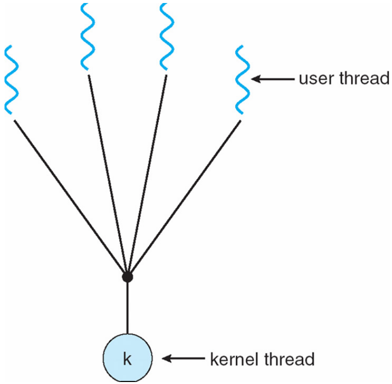


- Can implement `pthread_create` as a system call
- To add `pthread_create` to an OS:
  - Start with process abstraction in kernel
  - `pthread_create` like process creation with features stripped out
    - Keep same address space, file table, etc., in new process
    - `rfork`/`clone` syscalls actually allow individual control
- Faster than a process, but still very heavy weight

Limitations of kernel-level threads

- Every thread operation must go through kernel
  - create, exit, join, synchronize, or switch for any reason
  - Syscall takes 100 cycles, function call 2 cycles
  - Result: threads $10\times$–$30\times$ slower when implemented in kernel
  - Worse today because of SPECTRE/Meltdown mitigations
- One-size fits all thread implementation
  - Kernel threads must please all people
  - Maybe pay for fancy features (priority, etc.) you don't need
- General heavy-weight memory requirements
  - E.g., requires a fixed-size stack within kernel
  - Other data structures designed for heavier-weight processes

User threads



- An alternative: implement in user-level library
  - One kernel thread per process
  - `pthread_create`, `pthread_exit`, etc., just library functions

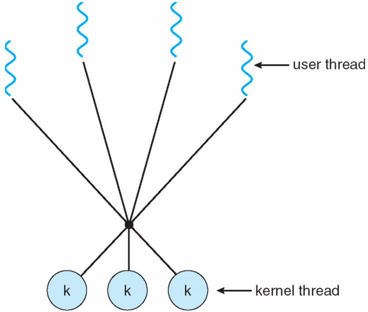
Implementing user-level threads

- Allocate a new stack for each `pthread_create`
- Keep a queue of runnable threads
- Replace blocking system calls (`read`/`write`/etc.)
  - If operation would block, switch and run different thread
- Schedule periodic timer signal (`setitimer`)
  - Switch to another thread on timer signals (preemption)
- Multi-threaded web server example
  - Thread calls `read` to get data from remote web browser
  - "Fake" `read` *function* makes `read` *syscall* in non-blocking mode
  - No data? schedule another thread
  - On timer or when idle check which connections have new data

Limitations of user-level threads

- Can't take advantage of multiple CPUs or cores
- A blocking system call blocks all threads
  - Can replace `read` to handle network connections
  - But usually OSes don't let you do this for disk
  - So one uncached disk read blocks all threads
- A page fault blocks all threads
- Possible deadlock if one thread blocks on another
  - May block entire process and make no progress
  - [More on deadlock in future lectures.]

User threads on kernel threads



- User threads implemented on kernel threads
  - Multiple kernel-level threads per process
  - `thread_create`, `thread_exit` still library functions as before
- Sometimes called $n : m$ threading
  - Have n user threads per m kernel threads
    (Simple user-level threads are $n : 1$, kernel threads $1 : 1$)

Limitations of $n : m$ threading

- Many of same problems as $n : 1$ threads
  - Blocked threads, deadlock, ...
- Hard to keep same # ktrheads as available CPUs
  - Kernel knows how many CPUs available
  - Kernel knows which kernel-level threads are blocked
  - Tries to hide these things from applications for transparency
  - User-level thread scheduler might think a thread is running while underlying kernel thread is blocked
- Kernel doesn't know relative importance of threads
  - Might preempt kthread in which library holds important lock

Lessons

- Threads best implemented as a library
  - But kernel threads not best interface on which to do this
- Better kernel interfaces have been suggested
  - See Scheduler Activations [Anderson et al.]
  - Maybe too complex to implement on existing OSes (some have added then removed such features, now Windows is trying it)
- Today shouldn't dissuade you from using threads
  - Standard user or kernel threads are fine for most purposes
  - Use kernel threads if I/O concurrency main goal
  - Use $\mathrm{n}:\mathrm{m}$ threads for highly concurrent (e.g,. scientific applications) with many thread switches
- ...though concurrency/synchronization lectures may
  - Concurrency greatly increases the complexity of a program!
  - Leads to all kinds of nasty race conditions

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Go Routines

- Go routines are very light-weight
  - Running 100k go routines is practical
  - Custom compiler enables stack segmentation, preemption, and garbage collection
  - Runs on segmented stack – stack allocated on demand to avoid memory use
  - OS thread typically allocate 2 MiB fixed stacks
- Go routines on top of Kernel threads (n:m Model)
  - Multi-core scalability and efficient user-level threads
  - One pthread (kernel-level thread) per CPU core
  - Supports many user-level threads as you like

Go Routine Continued

- Each kernel-level thread finds and runs a go routine (user-level thread)
- Every logical core is owned by a kernel thread when running
- Convert blocking system calls (when possible):
  - Converted to non-blocking by in the runtime yielding the CPU to another core
  - Cores poll using kernel event API `poll`, `epoll`, or `kqueue`
- Blocking system calls:
  - Release the "CPU" to another kernel-level thread before the call
  - Let the kernel thread sleep
  - Regain the "CPU" thread when done

Go Channels

- Go routine communicate and synchronize through *channels*

```
func worker(done chan bool) {
    // Notify the main routine
    done <- true
}

func main() {
    // Create a channel to notify us
    done := make(chan bool, 1)

    // Create go routine
    go worker(done)

    // Block until we receive a message
    <-done
}
```

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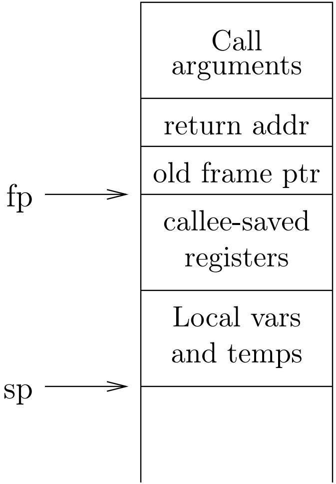
Background: MIPS calling conventions

- Registers divided into 2 groups
  - Functions free to clobber *caller-saved* regs (`%t0`–`%t9` on MIPS)
  - But must restore *callee-saved* ones to original value upon return (`%s0`–`%s7`, `%fp`)
- `%sp` register always base of stack
  - Frame pointer (`%fp`) is old `%sp`
- Local variables stored in registers and on stack
- Function arguments go in caller-saved regs and on stack
  - First four arguments in `%a0`–`%a3`
  - Remaining arguments on stack
- Return value `%v0` and `%v1`



Background: procedure calls

save active caller registers
call foo → saves used callee registers
...do stuff...
restores callee registers
jumps back to pc
restore caller regs

- Some state saved on stack
  - Return address, caller-saved registers
- Some state not saved
  - Callee-saved regs, global variables, stack pointer

Threads vs. procedures

- Threads may resume out of order:
  - Cannot use LIFO stack to save state
  - General solution: one stack per thread
- Threads switch less often:
  - Don't partition registers (why?)
- Threads can be involuntarily interrupted:
  - Synchronous: procedure call can use compiler to save state
  - Asynchronous: thread switch code saves all registers
- More than one than one thread can run at a time:
  - Procedure call scheduling obvious: Run called procedure
  - Thread scheduling: What to run next and on which CPU?

OS/161 Kernel Threads

- OS/161 supports fork, exec, exit, and wait
  - You will implement these functions in Assignments 2a/2b
- One thread per process

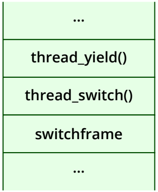
```
int thread_fork(const char *name,
  struct proc *proc,
  void (*entrypoint)(void *data1, unsigned long data2),
  void *data1, unsigned long data2);
```

- OS/161 supports kernel threads (no user-level threading)
- Create a kernel thread with: `thread_fork()`
- Bad nameing: Not `fork()` this is actually pthread_create!

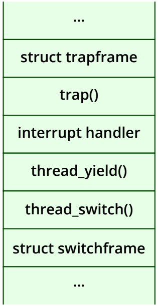
Switching Threads

- **All thread switches go through** `thread_yield()` **and** `thread_switch()`
- `thread_switch()` **calls** `switchframe_switch` **generates** `switchframe`
- `switchframe_switch switches from one stack to other`

General (from Kernel)



Hardware Interrupt (typically Timer)



OS/161 switchframe_switch – save old thread

From OS/161 kern/arch/mips/thread/switch.S

```
switchframe_switch:
  /* a0: switchframe pointer to old thread */
  /* a1: switchframe pointer to new thread */
  /* Allocate space for saving 10 registers. 10*4 = 40 */
  addi sp, sp, -40

  sw ra, 36(sp) /* Save callee save registers */
  sw gp, 32(sp) /* Caller saved registers saved by thread_switch() */
  sw s8, 28(sp)
  sw s6, 24(sp)
  sw s5, 20(sp)
  sw s4, 16(sp)
  sw s3, 12(sp)
  sw s2, 8(sp)
  sw s1, 4(sp)
  sw s0, 0(sp)

  /* Store the old stack pointer in the old thread */
  sw sp, 0(a0)
```

OS/161 switchframe_switch – restore new thread

```
/* Get the new stack pointer from the new thread */
lw sp, 0(a1)
nop /* Delay slot for load */

lw s0, 0(sp) /* Now, restore callee saved registers */
lw s1, 4(sp) /* Caller saved registers restored by thread_switch() */
lw s2, 8(sp)
lw s3, 12(sp)
lw s4, 16(sp)
lw s5, 20(sp)
lw s6, 24(sp)
lw s8, 28(sp)
lw gp, 32(sp)
lw ra, 36(sp)
nop /* Delay slot for load */

j ra /* jump register to return address. */
addi sp, sp, 40 /* Fix sp in delay slot for j */
```