Process Management II

Operating Systems

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Lecture 3

Normal Process Termination

- a process can be killed by itself, some other process, or the kernel
- normal termination — `exit(3)`
  - may return data to parent
  - returning from `main()` is equivalent to `exit(3)`
  - all resources are deallocated
    - call all handlers registered with `atexit(3)`
    - close all standard I/O streams, etc.
    - release memory
  - `_exit(2)` is called by `exit(3)` to take care of OS-specific details

Abnormal Process Termination

- abnormal termination — `abort(3)`
  - invoked by another process, typically parent
  - calling process needs to know the `pid` (`fork(2)` returns the child's `pid` to the parent)
  - a special case of a signal — `SIGABRT`
  - reasons:
    - resource usage exceeded
    - task no loner needed,
    - parent is exiting (cascading termination)

Process Termination: Details I

- parent must be notified
  - for normal termination `exit(3)` or `_exit(2)` are called with an “exit status” argument
    - “exit status” is converted to “termination status” by the kernel when `_exit(2)` is called
  - for abnormal termination the kernel generates the “termination status”
  - parent can obtain the termination status using `wait(2)` or `waitpid(2)` (handler for `SIGCHLD`)

Process Termination: Details II

- what if parent terminates before child?
  - cascading termination (VMS) — child cannot exist if parent is terminated (normally or abnormally)
  - UNIX — every process has a parent, if parent terminates the kernel changes the `ppid` to `1` (`init`) for all the children
- what if a child terminates before the parent?
  - the kernel must keep minimal information (`pid`, status, usage statistics) for every terminated process
  - the process becomes a “zombie”
  - `init` periodically calls one of the `wait()` functions to prevent clogging by “zombies”

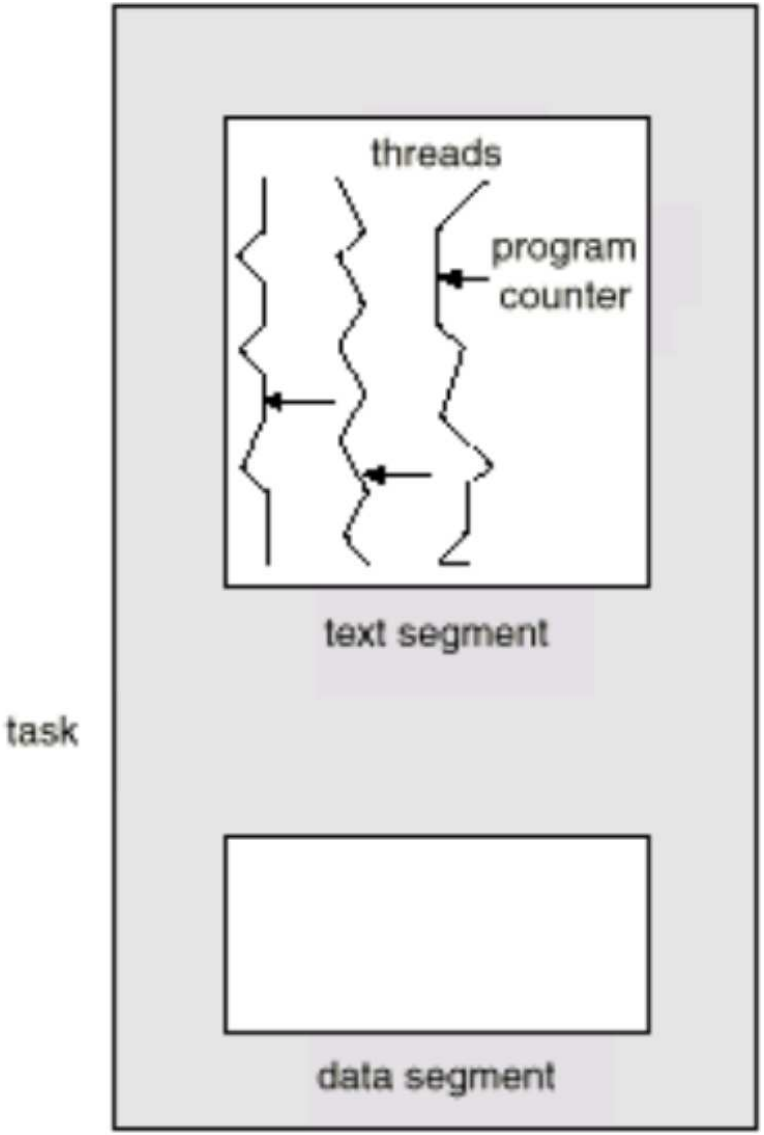
Terminating Processes: Windows

- `TerminateProcess()` is not a substitute for `kill(2)`
  - not all DLL's call their exit routines
  - use only in extreme circumstances
  - use `WM_CLOSE` message instead
- remember: no concept of parent
  - if the parent was created with `CREATE_NEW_PROCESS_GROUP` flag set, the children can be grouped
  - `GenerateConsoleCtrlEvt()` can send Control-C or Control-Break signals to the group
  - only the children who share a console with parent will receive the signal

Threads

- a thread (a.k.a. “lightweight process”) is a basic unit of CPU utilization
- a thread consists of
  - program counter
  - register set
  - stack
- a thread must belong to exactly one task (or process)
- threads in one task share all resources except CPU:
  - code section
  - data section
  - OS resources
- a traditional process is a task with one thread

Multiple Threads in a Process



Threads vs. Processes: Similarities

- both share the CPU
  - only one thread (of one process) may be running
- same (similar) states
  - ready, blocked, running, terminated
- can create children
- block on system calls
  - if one thread is blocked another can run

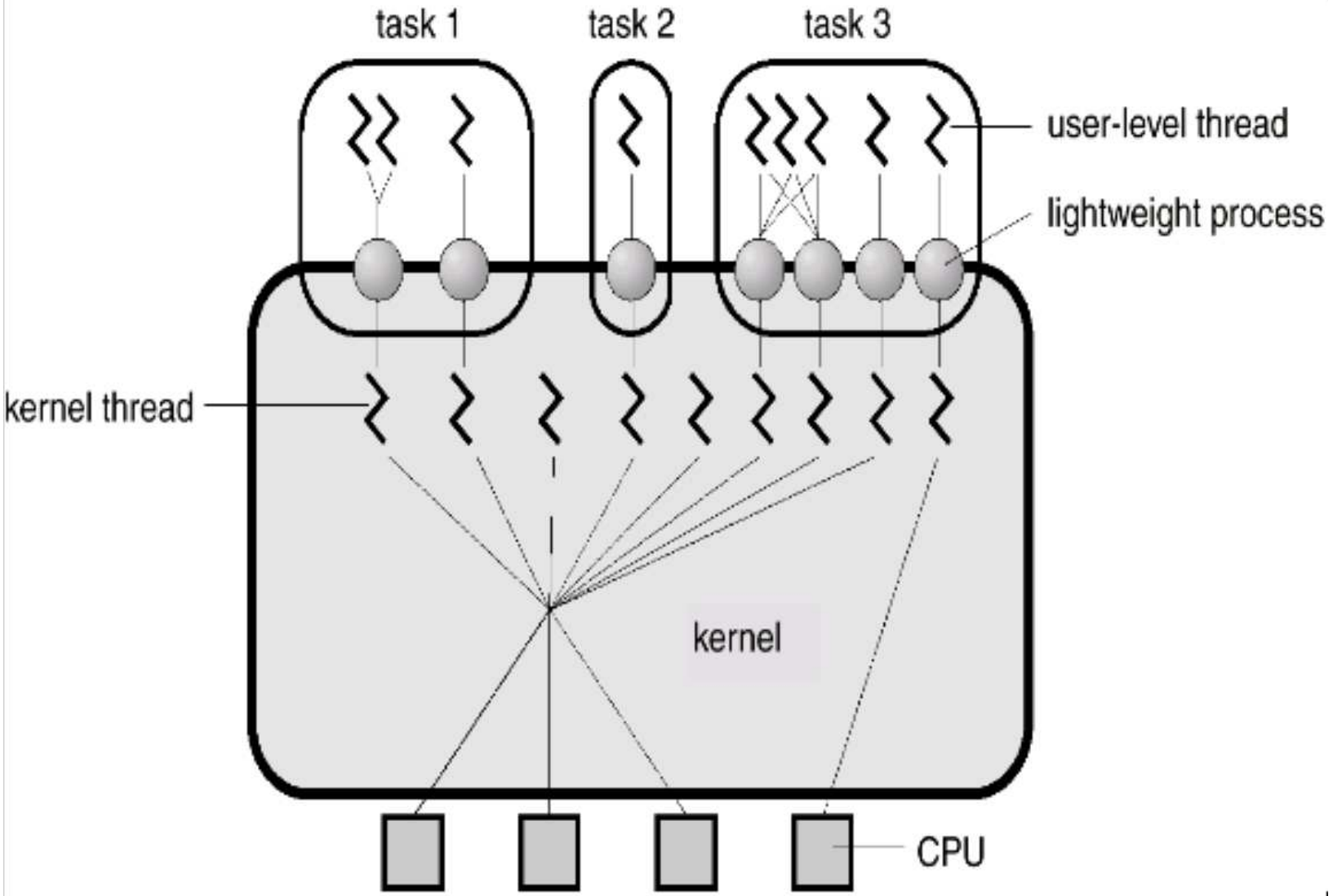
Threads vs. Processes: Differences

- threads have access to all the memory space of the task
  - can read from and write to each other's stacks
  - do not have — or require — mutual protection
- processes are useful to parallelize unrelated, independent tasks
- threads are useful to parallelize operations on shared resources
  - cooperation of multiple threads in the same task leads to higher throughput, improved performance
  - applications that require sharing common data (e.g., the buffer in producer-consumer) benefit from threads

Implementing Threads

- user-level threads
  - fast switching
  - write your own scheduler
    - but the OS can take the CPU away from the task
    - unfair scheduling since the OS allocates the CPU to tasks regardless of the number of threads
  - will not work with single-threaded kernels
    - imagine a thread executing a system call
- kernel supported threads
  - more expensive switching
  - fair scheduling is possible
  - a process can execute concurrent system calls
- hybrid (user-level and kernel-level) — Solaris 2

Solaris Threads



Cooperating Processes

- independent and cooperating processes
  - independent processes cannot affect each other's execution
  - cooperating processes can affect or be affected by the execution of another process
- what for?
  - information sharing
  - speedup
    - overlap CPU and I/O
    - use several processors
  - modularity
  - convenience

Cooperating Processes: Classic Models

- producer-consumer: one process produces information that it consumed by another
  - bounded-buffer — a buffer of fixed size is assumed
  - unbounded-buffer — no practical limit is placed on the buffer size
- reader-writer: a number of processes read from and write to a shared location in memory
- environment
  - shared memory
    - read and write atomicity
    - serial consistency: read returns the value stored by the latest write
  - message passing (distributed environments)

Shared Memory Bounded-Buffer

```
/* shared data */
item_t buffer[LENGTH];
/* in - next free position;
   out - first full */
int in, out /* from 0 to LENGTH */
/* circular buffer implementation */
int empty(void) { return (in == out); }
int full(void) {
    return (((in+1) % LENGTH) == out);
}
/* assume the following are defined */
void produce(item_t *next);
void consume(const item_t *next);
void copy_item(item_t *dst, const item_t *src);
```

Circular Buffer Producer-Consumer

```
void producer(void) {
    item_t next;
    while (1) {
        produce(&next);
        while (full()) /* wait */;
        copy_item(&(buffer[in]),&next);
        in = (in+1) % LENGTH; } }

void consumer(void) {
    item_t next;
    while (1) {
        while (empty()) /* wait */;
        copy_item(&next,&(buffer[out]));
        out = (out+1) % LENGTH;
        consume(&next); } }
```

Critical Sections

- parts of the program in which shared variables are manipulated
- mutual exclusion is used to avoid races
- a variety of algorithms and hardware support
- conditions for a good solution
  - no assumption about speed or number of CPUs
  - no two processes can simultaneously be inside their critical section (exclusion)
  - no process running outside its critical section may block other processes and the selection of who enters can't be postponed indefinitely (progress)
  - no process should have to wait forever to enter its critical section (bounded waiting or no starvation)

Mutual Exclusion with Busy Waiting

- brute force solution: disable interrupts
  - cannot be used in userspace
  - does not work with more than one CPU
- lock variables do not prevent races

```
..
while (lock == 1); /* busy-wait */
lock = 1;
critical_section();
lock = 0;
noncritical_section();
..
```

Busy Waiting: Strict Alternation

rocess 0:

```
hile (1) {
    while (turn != 0) /* wait */;
    critical_section();
    turn = 1;
    noncritical_section(); }
```

rocess 1:

```
hile (1) {
    while (turn != 1) /* wait */;
    critical_section();
    turn = 0;
    noncritical_section(); }
```

f one of the processes is slower than the other the progress condition is violated

Busy Waiting: Peterson's Solution

```
#define N 2
int turn, interested[N]

void enter_critical_region(int process) {
    int other = 1 - process;
    interested[process] = TRUE;
    turn = other;
    while (turn == other &&
           interested[other] == TRUE);
}

void leave_critical_region(int process) {
    interested[process] = FALSE;
}
```

Hardware Support: Test and Set Lock

- atomic `TSL` instruction
  - `tsl register,lock`
  - copies `lock` to `register` and stores a non-zero value in `lock`
- fictitious assembly code:

```
enter_region:
    tsl register,lock // test and set to 1
    cmp register,#0   // is the lock zero?
    jnz enter_region  // loop if non-zero
    ret               // return to caller
leave_region:
    mov lock,#0       // set lock to zero
    ret               // return to caller
```

Synchronization Hazards

- busy-waiting wastes CPU cycles
- race conditions — see above
- priority inversion
  - a low priority process L grabs a lock and enters a critical section
  - a high priority process H busy-waits on the lock
  - a medium priority process M grabs the CPU while L is in the critical section
  - net result: M runs most of the time, sometimes L runs, H is stuck...
- deadlocks...

Deadlocks

Process 1:

```
acquire(lock1);
acquire(lock2);
..
release(lock1);
release(lock2);
```

Process 2:

```
acquire(lock2);
acquire(lock1);
...
release(lock2);
release(lock1);
```

- necessary conditions for deadlock:
  - at least one exclusive resource is held
  - a process is holding a resource and waiting for another resource held by another process
  - no preemption: resources can only be released voluntarily
  - circular wait

Dealing with Deadlocks

- protocols ensuring the system will never enter a deadlock state
  - deadlock prevention — ensure that (some of) the necessary conditions do not hold
  - deadlock avoidance — require additional info about resource requests, analyze dynamically
- detecting and recovering from deadlocks
  - may involve killing some processes
- ignore, pretend deadlocks do not exist
  - this is what most OS do, including UNIX/Linux
  - OS is about mechanisms, not policies
  - users' responsibility

Avoiding Busy-Wait: Sleep/Wakeup I

```
#define N 100    /* buffer size */
int count = 0;   /* tracks items in buffer */

void producer(void)
{
  item_t item;
  while (1) {
    produce_item(&item);
    if (count == N) sleep(); /* buffer full */
    put_item(&item);
    count++;
    if (count == 1) wakeup(consumer);
  }
}
```

Avoiding Busy-Wait: Sleep/Wakeup II

```
void consumer(void)
{
  item_t item;
  while (1) {
    if (count == 0) sleep(); /*buffer empty*/
    get_item(&item); /* removes from buffer*/
    count--;
    if (count == N-1) wakeup(producer);
    consume_item(&item);
  }
}
```

- can you see a race here?

Sleep/Wakeup Synchronyzation

- race condition on `count` — “lost wakeup”
  - the buffer is empty — consumer reads `count == 0`
  - scheduler switches to producer
  - producer puts an item into the buffer, increments `count`, wakes consumer
  - consumer thinks `count == 0` and goes to sleep!
  - producer fills the buffer and goes to sleep, too!
- quick fix — “wakeup waiting bit”
  - set when wakeup is sent to a process that is not sleeping
  - `sleep()` will test the bit, turn it off, remain awake
  - for more than 2 processes more than 1 bit is needed, the problem exists in principle

Semaphores

- Dijkstra (1965) — generalization of sleep/wakeup
- two atomic operations — `up()` and `down()` (P and V, according to Dijkstra)
- a counter that controls a shared resource
- `down()` checks the value
  - if positive, the process can use the resource, the semaphore is decremented (indicates that the process is using a "unit" of the resource)
  - if `0`, the process goes to sleep
- when the process is done with the resource, `up()` increments the value, processes waiting for the semaphore are awakened
- binary semaphores — `0` or `1`

Semaphore Implementation

- `up()` and `down()` must be atomic — kernel support is needed
- typically implemented via system calls that disable interrupts briefly
- for multiple CPUs a (busy-wait) lock is needed to ensure that only one CPU at a time can access the semaphore — `TSL` will help here
- note that this busy-wait is only for the duration of `up()` and `down()`, not for the duration of the critical section
- POSIX and SysV semaphores — the latter are much more complicated (more details during the drill session)

Semaphore Usage

- mutual exclusion
  - guarantees that protected resource will not be corrupted by simultaneous access
- synchronization
  - guarantees that certain events will or will not occur
    - producer stops running when the buffer is full
    - consumer stops running when the buffer is empty
- very important: as any lock, semaphores protect data, not code!
  - never ask what parts of code are critical — always ask what data items must be protected or synchronized, and the critical sections will become obvious

Producer/Consumer with Semaphores

```
semaphore mutex = 1, empty = N, full = 0;

void producer(void)
{
  item_t item;
  while (1) {
    produce(&item);
    down(&empty);
    down(&mutex);
    put_item(&item);
    up(&mutex);
    up(&full);
  }
}
```

```
void consumer(void)
{
  item_t item;
  while (1) {
    down(&full) ;
    down(&mutex);
    get_item(&item);
    up(&mutex);
    up(&empty);
    consume(&item);
  }
}
```

Mutexes

- a viariable with two states: locked (0) and unlocked (1)
- basic operations
  - `mutex_lock(&mutex)`
  - `mutex_unlock(&mutex)`
- `mutex_lock()` is like `enter_critical_region()`
  - but does not busy-wait
  - if it fails to acquire the mutex it gives up the CPU (using `sched_yield(2)` or similar)
- featuritis: `mutex_trylock(&mutex)`
  - acquires the mutex or returnes an error code
  - lets the caller decide whether to yield the CPU or do something else

Semaphore and Mutex Hazards

- both semaphores and mutexes are very prone to programming errors
- many subtle timing issues
- very difficult to avoid
  - enough for one process to be buggy, and everybody suffers
- very difficult to debug (“heisenbugs”)
- some trivial examples
  - `up()` called before `down()` — no exclusion
  - two `down()`’s — deadlock
  - either `up()` or `down()` is not called

Reader/Writer Problem

- a multiprocess (multithreaded) application where processes can read and write the same data
  - several can read simultaneously
  - only one can write at a time
- practical importance: transaction systems, filesystems, etc.
- two types of locks: shared for readers, exclusive for writers
  - when an exclusive lock is held, no one else can acquire access in any form
  - when a shared lock is held, others can acquire the shared lock, but no one can acquire an exclusive lock

Reader/Writer Flavours

- reader preferred
  - if a reader runs and no one is currently writing, the reader proceeds even if there are writers waiting for access
- writer preferred
  - if a new writer runs in can proceed as soon as possible
- both solutions suffer from possible starvation

Synchronization Performance

- busy-waiting ("spinning" — we'll discuss spinlocks later)
  - wastes cycles, but if the resource is available or will be available soon avoids a context switch
- blocking (semaphores and mutexes)
  - let other processes run while we wait
  - incurs the overhead of one or more context switches
- hybrid, "adaptive mutexes"
  - start spinning, if the resource is not available spin for a limited time, then go to sleep
  - check if the thread holding the lock is running — it may be likely to release the lock soon (never on UP!)
- reader/writer locks are efficient if reads are much more frequent than writes