Operating Systems Design
6. Synchronization

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1

Concurrency

Concurrent threads/processes (informal)
- Two processes are concurrent if they run at the same time or if their execution is interleaved *in any order*

Asynchronous
- The processes require occasional synchronization

Independent
- They do not have any reliance on each other

Synchronous
- Frequent synchronization with each other – order of execution is guaranteed

Parallel
- Processes run at the same time on separate processors

2

Race Conditions

A race condition is a bug:
- The outcome of concurrent threads are unexpectedly dependent on a specific sequence of events.

Example
- Your current bank balance is $1,000.
- Withdraw $500 from an ATM machine while a $5,000 direct deposit is coming in

Withdrawal	Deposit
• Read account balance	• Read account balance
• Subtract 500	• Add 5000
• Write account balance	• Write account balance

Possible outcomes:
Total balance = $5500, $500, $6000

3

Synchronization

Synchronization deals with developing techniques to avoid race conditions

Something as simple as

x = x + 1;

May have have a race condition:

```
movl  _x (%rip), %eax
addl  $1, %eax
movl  %eax, _x (%rip)
```

Potential points of preemption for a race condition

4

Mutual Exclusion

Critical section:
- Region in a program where race conditions can arise

Mutual exclusion:
- Allow only one thread to access a critical section at a time

Deadlock:
- A thread is perpetually blocked (circular dependency on resources)

Starvation:
- A thread is perpetually denied resources

Livelock:
- Threads run but no progress in execution

5

Controlling critical section access: locks

- Grab and release locks around critical sections
- Wait if you cannot get a lock

	Withdrawal	Deposit	
Enter Critical Section	• Acquire(transfer_lock)	• Acquire(transfer_lock)	Enter Critical Section
Critical Section	• Read account balance • Subtract 500 • Write account balance	• Read account balance • Add 5000 • Write account balance	Critical Section
Exit Critical Section	• Release(transfer_lock)	• Release(transfer_lock)	Exit Critical Section

6

The Critical Section Problem

Design a protocol to allow threads to enter a critical section

7

Conditions for a solution

- Mutual exclusion: No threads may be inside the same critical sections simultaneously
- Progress: If no thread is executing in its critical section but one or more threads want to enter, the selection of a thread cannot be delayed indefinitely.
  - If one thread wants to enter, it should be permitted to enter.
  - If multiple threads want to enter, exactly one should be selected.
- Bounded waiting: No thread should wait forever to enter a critical section
- No thread running outside its critical section may block others
- A good solution will make no assumptions on:
  - No assumptions on # processors
  - No assumption on # threads/processes
  - Relative speed of each thread

8

Critical sections & the kernel

- Multiprocessors
  - Multiple processes on different processors may access the kernel simultaneously
  - Interrupts may occur on multiple processors simultaneously
- Preemptive kernels
  - Preemptive kernel: process can be preempted while running in kernel mode
  - Nonpreemptive kernel: processes running in kernel mode cannot be preempted (but interrupts can still occur!)
- Single processor, nonpreemptive kernel: free from race conditions

9

Solution #1: Disable Interrupts

Disable all system interrupts before entering a critical section and re-enable them when leaving

Bad!

- Gives the thread too much control over the system
- Stops time updates and scheduling
- What if the logic in the critical section goes wrong?
- What if the critical section has a dependency on some other interrupt, thread, or system call?
- What about multiple processors? Disabling interrupts affects just one processor

Advantage

- Simple, guaranteed to work
- Was often used in the uniprocessor kernels

10

Solution #2: Software Test & Set Locks

Keep a shared lock variable:

```
while (locked) ;
locked = 1;
/* do critical section */
locked = 0;
```

Disadvantage:

- Buggy! There's a race condition in setting the lock

Advantage:

- Simple to understand. It's been used for things such as locking mailbox files

11

Solution #3: Lockstep Synchronization

Take turns

Thread 0	Thread 1
`while (turn != 0);`	`while (turn != 1);`
`critical_section();`	`critical_section();`
`turn = 1;`	`turn = 0;`

Disadvantages:

- Tight loop that spins waiting for a turn: **busy waiting** or **spin lock**
- Forces strict alternation; if thread 2 is really slow, thread 1 is slowed down with it

12

Software solutions for mutual exclusion

- Peterson's solution (page 221 of text)
- Others
- Disadvantages:
  - Difficult to implement correctly – have to rely on `volatile` data types to ensure that compilers don't make the wrong optimizations
  - Relies on busy waiting

13

Let's turn to hardware for help

14

Help from the processor

Atomic (indivisible) CPU instructions that help us get locks

- Test-and-set
- Compare-and-swap
- Fetch-and-Increment

15

Test & Set

Test-and-set

ATOMIC

```
int test_and_set(int *x) {
    last_value = *x;
    *x = 1;
    return last_value;
}
```

Set the lock but get told if it already was set (in which case you don't have it)

```
while (test_and_set(&lock)) ;
/* do critical section */
lock = 0;
```

16

Compare & swap (CAS)

Compare the value of a memory location with an old value. If they match then replace with a new value

ATOMIC

```
int compare_and_swap(int *x, int old, int new) {
    int save = *x;
    if (save == old)
        *x = new;
    return save;  /* always return location contents */
}
```

Avoid the race condition.
Set *locked* to 1 only if *locked* is still set to 0.

```
while (compare_and_swap(&locked, 0, 1) != 0) ;
          /* spin until locked == 0 */
/* if we got here, locked got set to 1 and we have it */
/* do critical section */
locked = 0;  /* release the lock */
```

17

Fetch & Increment

Increment a memory location; return previous value

ATOMIC

```
int fetch_and_increment(int *x) {
    last_value = *x;
    *x = *x + 1;
    return last_value;
}
```

18

Fetch & Increment

Check that it's your turn for the critical section

```
ticket = 0; turn = 0;
...
myturn = fetch_and_increment(&ticket);
while (turn != myturn) ;
/* do critical section */
fetch_and_increment(&turn);
```

ticket

turn

19

Spin locks

- All these techniques rely on spin locks
- Wastes CPU cycles
- The process with the lock may not be allowed to run!
  - Lower priority process obtained a lock
  - Higher priority process is always ready to run but loops on trying to get the lock
  - Scheduler always schedules the higher-priority process
  - Priority inversion
    - If the low priority process would get to run & release its lock, it would then accelerate the time for the high priority process to get a chance to get the lock and do useful work
    - Try explaining that to a scheduler!

20

Priority Inheritance

- Technique to avoid priority inversion
- Increase the priority of any process to the maximum of any process waiting on any resource for which the process has a lock
- When the lock is released, the priority goes to its normal level

21

Spin locks aren't great

Can we block until we can get the critical section?

22

How about this?

```
public class Lock
{
    private int val = UNLOCKED;
    private ThreadQueue waitQueue = new ThreadQueue();

    public void acquire() {
        Thread me = Thread.currentThread();
        while (TestAndSet(val) == LOCKED) {
            waitQueue.waitForAccess(me);  // Put self in queue
            Thread.sleep();         // Put self to sleep
        }
        // Got the lock
    }
    public void release() {
        Thread next = waitQueue.nextThread();
        val = UNLOCKED;
        if (next != null)
            next.ready(); // Wake up a waiting thread
    }
}
```

23

Sorry…

- Accessing the wait queue is a critical section
  - Need to add mutual exclusion
- Need extra lock check in *acquire*
  - Thread may find the lock busy
  - Another thread may release the lock but before the first thread enqueues itself

24

Semaphores

- Count # of wake-ups saved for future use
- Two atomic operations:

```
down(sem s) {
   if (s > 0)
      s = s – 1;
   else
      sleep on event s
}
up(sem s) {
   if (someone is waiting on s)
      wake up one of the threads
   else
      s = s + 1;
}
```

```
//initialize
mutex = 1;

down(&mutex)

// critical section

up(&mutex)
```

Binary semaphore

25

Semaphores

Count the number of threads that may enter a critical section at any given time.

- Each *down* decreases the number of future accesses
- When no more are allowed, processes have to wait
- Each *up* lets a waiting process get in

26

Producer-Consumer example

- Producer
  - Generates items that go into a buffer
  - Maximum buffer capacity = N
  - If the producer fills the buffer, it must wait (sleep)
- Consumer
  - Consumes things from the buffer
  - If there's nothing in the buffer, it must wait (sleep)
- This is also known as the *Bounded-Buffer Problem*

27

Producer-Consumer example

```
sem mutex=1, empty=N, full=0;
producer() {
    for (;;) {
        produce_item(&item);   /* produce something */
        down(&empty);          /* decrement empty count */
        down(&mutex);          /* start critical section */
        enter_item(item);      /* put item in buffer */
        up(&mutex);            /* end critical section */
        up(&full);             /* +1 full slot */
    }
}
consumer() {
    for (;;) {
        down(&full);           /* one less item */
        down(&mutex);          /* start critical section */
        remove_item(item);     /* get the item from the buffer */
        up(&mutex);            /* end critical section */
        up(&empty);            /* one more empty slot */
        consume_item(item);    /* consume it */
    }
}
```

28

Readers-Writers example

- Shared data store (e.g., database)
- Multiple processes can read concurrently
- Only one process can write at a time
  - And no readers can read while the writer is writing

29

Readers-Writers example

```
sem mutex=1; /* critical sections used only by the reader */
sem canwrite=1;  /* critical section for N readers vs. 1 writer */
int readcount = 0; /* number of concurrent readers */

writer() {
   for (;;) {
      down(&canwrite);          /* block if we cannot write */
      // write data
      up(&canwrite);            /* end critical section */
   }
}
```

30

Readers-Writers example

```
sem mutex=1; /* critical sections used only by the reader */
sem canwrite=1;  /* critical section for N readers vs. 1 writer */
int readcount = 0; /* number of concurrent readers */


reader() {
   for (;;) {
      down(&mutex);
      readcount++;
      if (readcount == 1)
         down(canwrite);  /* sleep or disallow the writer from writing */
      up(&mutex);
      // do the read
      down(&mutex);
      readcount--;
      if (readcount == 0)
         up(writer);      /* no more readers! Allow the writer access */
      up(&mutex);
      // other stuff
   }
}
```

critical section

critical section

31

Event Counters

Avoid race conditions without using mutual exclusion

Three operations:

- *read(E)*: return the current value of event counter *E*
- *advance(E)*: increment *E* (atomically)
- *await(E, v)*: wait until *E* has a value ≥ *v*

32

Producer-Consumer example

```
#define N 4          /* four slots in the buffer */
event_counter in=0;     /* number of items inserted into buffer */
event_counter out=0;    /* number of items removed from buffer */

producer() {
    int item, sequence=0;
    for (;;) {
        produce_item(&item);    /* produce something */
        sequence++;             /* item # of item produced */
        await(out, sequence-N); /* wait until there's room */  (0≥-3), (0≥-2), …
        enter_item(item);       /* put item in buffer */
        advance(&in);        /* let consumer know there's one more item */
    }
}
consumer() {
    int item, sequence=0;
    for (;;) {
        sequence++;             /* item # we want to consume */
        await(in, sequence);    /* wait until that item is present */(0≥1)
        remove_item(item);      /* get the item from the buffer */
        advance(&out);          /* let producer know item's gone */
        consume_item(item);     /* consume it */
    }
}
```

33

Producer-Consumer example

```
#define N 4          /* four slots in the buffer */
event_counter in=0;     /* number of items inserted into buffer */
event_counter out=0;    /* number of items removed from buffer */
producer() {
    int item, sequence=0;
    for (;;) {
        produce_item(&item);    /* produce something */
        sequence++;             /* item # of item produced */
        await(out, sequence-N); /* wait until there's room */  (0≥-3), (0≥-2), …
        enter_item(item);       /* put item in buffer */
        advance(&in);        /* let consumer know there's one more item */
    }
}
```

Suppose the producer runs for a while and the consumer does not:

Iteration 1: sequence=1, out=0 *await*(0, 1-4): continue since 0 ≥ -3, in=1
Iteration 2: sequence=2, out=0 *await*(0, 2-4): continue since 0 ≥ -2, in=2
Iteration 3: sequence=3, out=0 *await*(0, 3-4): continue since 0 ≥ -1, in=3
Iteration 4: sequence=4, out=0 *await*(0, 4-4): continue since 0 ≥ 0, in=4
Iteration 5: sequence=5, out=0 *await*(0, 5-4): wait since 0 < 1

34

Producer-Consumer example

```
#define N 4          /* four slots in the buffer */
event_counter in=0;     /* number of items inserted into buffer */
event_counter out=0;    /* number of items removed from buffer */

consumer() {
    int item, sequence=0;
    for (;;) {
        sequence++;             /* item # we want to consume */
        await(in, sequence);    /* wait until that item is present */(0≥1)
        remove_item(item);      /* get the item from the buffer */
        advance(&out);          /* let producer know item's gone */
        consume_item(item);     /* consume it */
    }
}
```

Suppose the consumer runs first:

Iteration 1: sequence = 1, *await*(0, 1): sleep since 0 < 1

When the producer runs its first iteration, it will increment *in*
The consumer's *await* will wake up since it's now *await*(1,1) and 1 ≥ 1

35

Condition Variables / Monitors

- Higher-level synchronization primitive
- Implemented by the programming language / APIs
- Two operations:
  - *wait (condition_variable)*
    - Block until *condition_variable* is "signaled"
  - *signal(condition_variable)*
    - Wake up one process that is waiting on the condition variable
    - Also called *notify*

36

Synchronization
Part II: Inter-Process Communication

37

Communicating processes

- Must:
  - Synchronize
  - Exchange data
- Message passing offers:
  - Data communication
  - Synchronization (via waiting for messages)
  - Works with processes on different machines

38

Message passing

- Two primitives:
  - *send*(destination, message)
  - *receive*(source, message)
- Operations may or may not be blocking

39

Producer-consumer example

```
#define N 4      /* number of slots in the buffer */

consumer() {
    int item, i;
    message m;

    for (i=0; i < N; ++i)
        send(producer, &m);   /* send N empty messages */
    for (;;) {
        receive(producer, &m) /* get a message with the item */
        extract_item(&m, &item)   /* take item out of message */
        send(producer, &m);   /* send an empty reply */
        consume_item(item);   /* consume it */
    }
}
producer() {
    int item;
    message m;

    for (;;) {
        produce_item(&item);      /* produce something */
        receive(consumer, &m);        /* wait for an empty message */
        build_message(&m, item);  /* construct the message */
        send(consumer, &m);       /* send it off */
    }
}
```

40

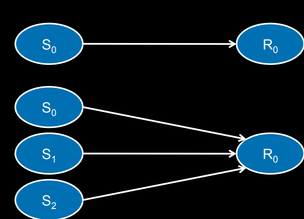
Messaging: Rendezvous

- Sending process blocked until receive occurs
- Receive blocks until a send occurs
- Advantages:
  - No need for message buffering if on same system
  - Easy & efficient to implement
  - Allows for tight synchronization
- Disadvantage:
  - Forces sender & receiver to run in lockstep

41

Messaging: Direct Addressing

- Sending process identifies receiving process
- Receiving process can identify sending process
  - Or can receive it as a parameter



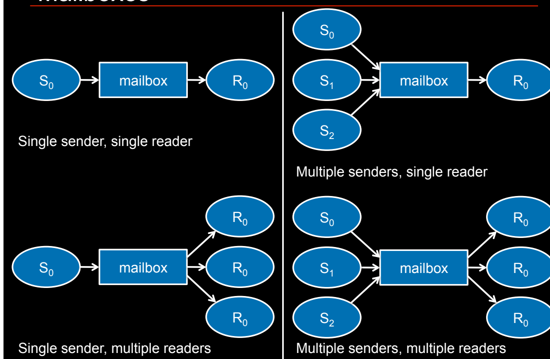
42

Messaging: Indirect Addressing

- Messages sent to an intermediary data structure of FIFO queues
- Each queue is a *mailbox*
- Simplifies multiple readers

43

Mailboxes



44

Example: What you find in the world

IPC mechanisms in Windows

- Clipboard: central repository for sharing data among apps
- Dynamic Data Exchange (DDE) – [older] allows apps to exchange data in various formats; extension of clipboard
- COM: automatically start another app to access data via interfaces
- Data Copy: Windows messaging – two cooperating processes can copy data
- File Mapping: Memory mapped files
- Mailslots: one-way communication of short messages (including network)
- Anonymous pipes: for I/O redirection
- Named pipes
- RPC (remote procedure call)
- Sockets
- Semaphore objects

45

Linux

IPC Mechanisms in Linux

- Signals
- Pipes
- Named pipes (FIFOs)
- Semaphores
- Message queues: one or more writers & one or more readers
- Shared memory
- Memory-mapped files
- RPC (remote procedure calls)
- Sockets

46

Deadlocks

Four conditions must hold

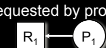
1. Mutual exclusion
2. Hold and wait
3. Non-preemption of resources
   - Resources can only be released voluntarily
4. Circular wait

47

Deadlocks

- Resource allocation graph
  - Resource R_1 is allocated to process P1: assignment edge

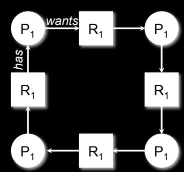
  - Resource R_1 is requested by process P_1: request edge



- Deadlock is present when the graph has cycles

48

Deadlock example



Circular dependency among four processes and four resources

49

Dealing with deadlock

- Deadlock prevention
  - Ensure that at least one of the necessary conditions cannot hold
- Deadlock avoidance
  - Provide advance information to the OS on which resources a process will request.
  - OS can then decide if the process should wait
- Ignore the problem
  - Let the user deal with it (most common solution)

50

The End

51