

Operating Systems Design

6. Synchronization

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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

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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

<p><u>Withdrawal</u></p> <ul style="list-style-type: none"> Read account balance Subtract 500 Write account balance 	<p><u>Deposit</u></p> <ul style="list-style-type: none"> Read account balance Add 5000 Write account balance
--	---

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

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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

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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

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Controlling critical section access: locks

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

<p style="text-align: center;"><u>Withdrawal</u></p> <p>Enter Critical Section</p> <ul style="list-style-type: none"> Acquire(transfer_lock) <p style="text-align: center;">Critical Section</p> <ul style="list-style-type: none"> Read account balance Subtract 500 Write account balance <p>Exit Critical Section</p> <ul style="list-style-type: none"> Release(transfer_lock) 	<p style="text-align: center;"><u>Deposit</u></p> <p>Enter Critical Section</p> <ul style="list-style-type: none"> Acquire(transfer_lock) <p style="text-align: center;">Critical Section</p> <ul style="list-style-type: none"> Read account balance Add 5000 Write account balance <p>Exit Critical Section</p> <ul style="list-style-type: none"> Release(transfer_lock)
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The Critical Section Problem

Design a protocol to allow threads to enter a critical section

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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

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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

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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

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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

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Solution #3: Lockstep Synchronization

Take turns

Thread 0	Thread 1
<code>while (turn != 0);</code>	<code>while (turn != 1);</code>
<code>critical_section();</code>	<code>critical_section();</code>
<code>turn = 1;</code>	<code>turn = 0;</code>

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

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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

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Let's turn to hardware for help

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Help from the processor

Atomic (indivisible) CPU instructions that help us get locks

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

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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;

```

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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 */

```

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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;
    }
}

```

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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);
```



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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!

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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

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Spin locks aren't great

Can we block until we can get the critical section?

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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
    }
}
```

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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

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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

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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

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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**

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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 */
    }
}

```

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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

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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 */
    }
}

```

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

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 $\geq v$

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++;
    → 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 */
  }
}
    
```

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++;
    → 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

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

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**

Synchronization Part II: Inter-Process Communication

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Communicating processes

- Must:
 - Synchronize
 - Exchange data

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

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Message passing

- Two primitives:
 - *send*(destination, message)
 - *receive*(source, message)

- Operations may or may not be blocking

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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 */
    }
}
    
```

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Messaging: Rendezvous

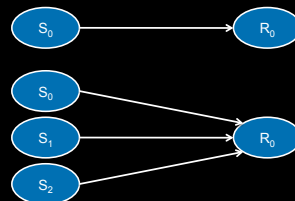
- Sending process blocked until receive occurs
- Receive blocks until a send occurs

- 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

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Messaging: Direct Addressing

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



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Messaging: Indirect Addressing

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

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Mailboxes

Single sender, single reader

Multiple senders, single reader

Single sender, multiple readers

Multiple senders, multiple readers

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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

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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

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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

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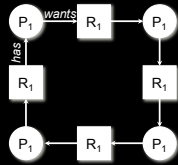
Deadlocks

- Resource allocation graph
 - Resource R_1 is allocated to process P_1 : *assignment edge*- Resource R_1 is requested by process P_1 : *request edge*

- Deadlock is present when the graph has *cycles*

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Deadlock example



Circular dependency among four processes and four resources

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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)

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The End

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