Concurrent systems

Lecture 3: CCR, monitors, and concurrency in practice

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Reminder from last time

- Implementing mutual exclusion: hardware support for atomicity and inter-processor interrupts
- Semaphores for mutual exclusion, condition synchronisation, and resource allocation
- Two-party and generalised producer-consumer relationships
- Invariants and locks

From last time: Semaphores summary

- Powerful abstraction for implementing concurrency control:
  - mutual exclusion & condition synchronization
- Better than read-and-set()… but correct use requires considerable care
  - e.g. forget to wait(), can corrupt data
  - e.g. forget to signal(), can lead to infinite delay
  - generally get more complex as add more semaphores
- Used internally in some OSes and libraries, but generally deprecated for other mechanisms…

Semaphores are a low-level implementation primitive – they say what to do, rather than describe programming goals

This time

- Multi-Reader Single-Writer (MRSW) locks
  - Starvation and fairness
- Alternatives to semaphores/locks:
  - Conditional critical regions (CCRs)
  - Monitors
  - Condition variables
  - Signal-and-wait vs. signal-and-continue semantics
- Concurrency primitives in practice
- Concurrency primitives wrap-up

Multiple-Readers Single-Writer (MRSW)

- Another common synchronisation paradigm is MRSW
  - Shared resource accessed by a set of threads
    - e.g. cached set of DNS results
  - Safe for many threads to read simultaneously, but a writer (updating) must have exclusive access
  - MRSW locks have read lock and write lock operations
  - Mutual exclusion vs. data stability
- Simple implementation uses a two semaphores
- First semaphore is a mutual exclusion lock (mutex)
  - Any writer must wait to acquire this
- Second semaphore protects a reader count
  - Reader count incremented whenever a reader enters
  - Reader count decremented when a reader exits
  - First reader acquires mutex; last reader releases mutex

Simplest MRSW solution

```
int nr = 0;                    // number of readers
rSem   = new Semaphore(1);     // protects access to nr
wSem   = new Semaphore(1);     // protects writes to data
```

```
// a writer thread
wait(wSem);
.. perform update to data
signal(wSem);
```

```
// a reader thread
wait(rSem);
nr = nr + 1;
if (nr == 1)   // first in
  wait(wSem);
signal(rSem);
.. read data
wait(rSem);
nr = nr - 1;
if (nr == 0) // last out
  signal(wSem);
signal(rSem);
```

Code for writer is simple…

.. but reader case more complex: must track number of readers, and acquire or release overall lock as appropriate

Simplest MRSW solution

- Solution on previous slide is “correct”
  - Only one writer will be able to access data structure, but – providing there is no writer – any number of readers can access it
- However writers can starve
  - If readers continue to arrive, a writer might wait forever (since readers will not release wSem)
  - Would be fairer if a writer only had to wait for all current readers to exit…
  - Can implement this with an additional semaphore

A fairer MRSW solution

```
int nr = 0;                       // number of readers
rSem    = new Semaphore(1);       // protects access to nr
wSem    = new Semaphore(1);       // protects writes to data
turn    = new Semaphore(1);       // write is awaiting a turn
```

Once a writer tries to enter, it will acquire turn…

… which prevents any further readers from entering

```
// a writer thread
wait(turn);
wait(wSem);
.. perform update to data
signal(turn);
signal(wSem);
```

```
// a reader thread
wait(turn);
signal(turn);
wait(rSem);
nr = nr + 1;
if (nr == 1)   // first in
  wait(wSem);
signal(rSem);
.. read data
wait(rSem);
nr = nr - 1;
if (nr == 0) // last out
  signal(wSem);
signal(rSem);
```

Conditional Critical Regions

- Implementing synchronisation with locks is difficult
  - Only the developer knows what data is protected by which locks
- One early (1970s) effort to address this problem was CCRs
  - Variables can be explicitly declared as ‘shared’
  - Code can be tagged as using those variables, e.g.

```
shared int A, B, C;
region A, B {
    await( /* arbitrary condition */);
    // critical code using A and B
}
```

- Compiler automatically declares and manages underlying primitives for mutual exclusion or synchronization
  - e.g. wait/signal, read/await/advance, …
- Easier for programmer (c/f previous implementations)

CCR example: Producer-Consumer

```
shared int buffer[N];
shared int in = 0; shared int out = 0;
```

```
// producer thread
while(true) {
  item = produce();
  region in, out, buffer {
    await((in-out) < N);
    buffer[in % N] = item;
    in = in + 1;
  }
}
```

```
// consumer thread
while(true) {
  region in, out, buffer {
    await((in-out) > 0);
    item = buffer[out % N];
    out  = out + 1;
  }
  consume(item);
}
```

- Explicit (scoped) declaration of critical sections
  - automatically acquire mutual exclusion lock on region entry
- Powerful await(): any evaluable predicate

CCR pros and cons

- On the surface seems like a definite step up
  - Programmer focuses on variables to be protected, compiler generates appropriate semaphores (etc)
  - Compiler can also check that shared variables are never accessed outside a CCR
  - (still rely on programmer annotating correctly)
- But await(<expr>) is problematic…
  - What to do if the (arbitrary) <expr> is not true?
  - very difficult to work out when it becomes true?
  - Solution was to leave region & try to re-enter: this is busy waiting, which is very inefficient…

Monitors

- Monitors are similar to CCRs (implicit mutual exclusion), but modify them in two ways
  - Waiting is limited to explicit condition variables
  - All related routines are combined together, along with initialization code, in a single construct
- Idea is that only one thread can ever be executing 'within' the monitor
  - If a thread calls a monitor method, it will block (enqueue) if another thread is holding the monitor
  - Hence all methods within the monitor can proceed on the basis that mutual exclusion has been ensured
- Java's synchronized primitive implements monitors

Example Monitor syntax

```
monitor <foo> {

 // declarations of shared variables

 // set of procedures (or methods)
 procedure P1(...) { ... }
 procedure P2(...) { ... }
 ...
 procedure PN(...) { ... }

 {
    /* monitor initialization code */
 }

}
```

All related data and methods kept together

Shared variables only accessible from within monitor methods

Invoking any procedure causes an [implicit] mutual exclusion lock to be taken

Shared variables can be initialized here

Condition Variables

- Mutual exclusion not always sufficient
  - Condition synchronization -- e.g., wait for a condition to occur
- Monitors allow condition variables
  - Explicitly declared and managed by programmer
  - NB: No integrated counter – not a stateful semaphore!
  - Support three operations:

```
wait(cv) {
   suspend thread and add it to the queue for CV,
   release monitor lock;
}
signal(cv) {
   if any threads queued on CV, wake one thread;
}
broadcast(cv) {
   wake all threads queued on CV;
}
```

Monitor Producer-Consumer solution?

```
monitor ProducerConsumer {
 int in, out, buffer[N];
 condition notfull = TRUE, notempty = FALSE;

 procedure produce(item) {
   if ((in-out) == N) wait(notfull);
   buffer[in % N] = item;
   if ((in-out) == 0) signal(notempty);
   in = in + 1;
 }
 procedure int consume() {
   if ((in-out) == 0) wait(notempty);
   item = buffer[out % N];
   if ((in-out) == N) signal(notfull);
   out = out + 1;
   return(item);
 }
 /* init */ { in = out = 0; }
}
```

If buffer is full, wait for consumer

If buffer was empty, signal the consumer

If buffer is empty, wait for producer

If buffer was full, signal the producer

Does this work?

- Depends on implementation of wait() & signal()
- Imagine two threads, T1 and T2
  - T1 enters the monitor and calls wait(C) – this suspends T1, places it on the queue for C, and unlocks the monitor
  - Next T2 enters the monitor, and invokes signal(C)
  - Now T1 is unblocked (i.e. capable of running again)…
  - … but can only have one thread active inside a monitor!
- If we let T2 continue (signal-and-continue), T1 must queue for re-entry to the monitor
  - And no guarantee it will be next to enter
- Otherwise T2 must be suspended (signal-and-wait), allowing T1 to continue…

Signal-and-Wait (“Hoare Monitors”)

- Consider a queue E to enter monitor
  - If monitor is occupied, threads are added to E
  - May not be FIFO, but should be fair
- If thread T1 waits on C, added to queue C
- If T2 enters monitor & signals, waking T1
  - T2 is added to a new queue S “in front of” E
  - T1 continues and eventually exits (or re-waits)
- Some thread on S chosen to resume
  - Only admit a thread from E when S is empty

Signal-and-Wait pros and cons

- We call signal() exactly when condition is true, then directly transfer control to waking thread
  - Hence condition will still be true!
- But more difficult to implement…
- And can be complex to reason about (a call to signal may or may not result in a context switch)
  - Hence we must ensure that any invariants are maintained at time we invoke signal()
- With these semantics, our example is broken:
  - We signal() before incrementing in/out

Same code as slide 11

Monitor Producer-Consumer solution?

```
monitor ProducerConsumer {
 int in, out, buf[N];
 condition notfull = TRUE, notempty = FALSE;

 procedure produce(item) {
   if ((in-out) == N) wait(notfull);
   buffer[in % N] = item;
   if ((in-out) == 0) signal(notempty);
   in = in + 1;
 }
 procedure int consume() {
   if ((in-out) == 0) wait(notempty);
   item = buffer[out % N];
   if ((in-out) == N) signal(notfull);
   out = out + 1;
   return(item);
 }
 /* init */ { in = out = 0; }
}
```

Race

Race

If buffer is full, wait for consumer

If buffer was empty, signal the consumer

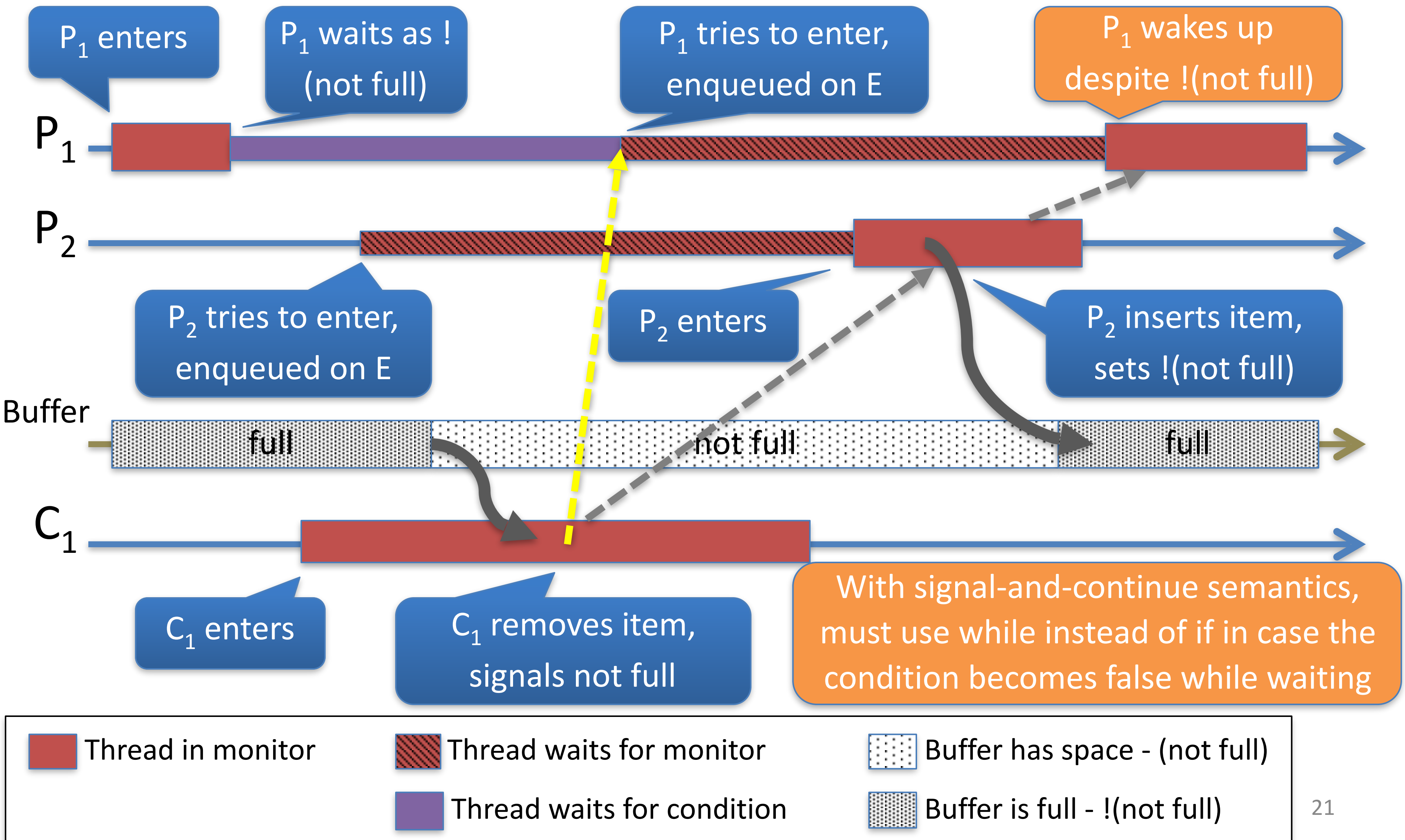
If buffer is empty, wait for producer

If buffer was full, signal the producer

Signal-and-Continue

- Alternative semantics introduced by Mesa programming language (Xerox PARC)
- An invocation of signal() moves a thread from the condition queue C to the entry queue E
  - Invoking threads continues until exits (or waits)
- Simpler to build… but now not guaranteed that condition is true when resume!
  - Other threads may have executed after the signal, but before you continue

Signal-and-Continue example (1)



Signal-and-Continue example (2)

- Consider multiple producer-consumer threads
  1. P1 enters. Buffer is full so blocks on queue for C
  2. C1 enters.
  3. P2 tries to enter; occupied, so queues on E
  4. C1 continues, consumes, and signals C (“notfull”)
  5. P1 unblocks; monitor occupied, so queues on E
  6. C1 exits, allowing P2 to enter
  7. P2 fills buffer, and exits monitor
  8. P1 resumes and tries to add item – BUG!
- Hence must re-test condition:
  - i.e. while((in - out) == N) wait(not full);

if() replaced with while() for conditions

Monitor Producer-Consumer solution?

```
monitor ProducerConsumer {
 int in, out, buf[N];
 condition notfull = TRUE, notempty = FALSE;

 procedure produce(item) {
   while ((in-out) == N) wait(notfull);
   buf[in % N] = item;
   if ((in-out) == 0) signal(notempty);
   in = in + 1;
 }
 procedure int consume() {
   while ((in-out) == 0) wait(notempty);
   item = buf[out % N];
   if ((in-out) == N) signal(notfull);
   out = out + 1;
   return(item);
 }
 /* init */ { in = out = 0; }
}
```

While buffer is full, wait for consumer

If buffer was empty, signal the consumer

While buffer is empty, wait for producer

If buffer was full, signal the producer

With signal-and-continue semantics, increment after signal does not race

Monitors: summary

- Structured concurrency control
  - groups together shared data and methods
  - (today we'd call this object-oriented)
- Considerably simpler than semaphores, but still perilous in places
- May be overly conservative sometimes:
  - e.g. for MRSW cannot have >1 reader in monitor
  - Typically must work around with entry and exit methods (BeginRead(), EndRead(), BeginWrite(), etc)
- Exercise: sketch a MRSW monitor implementation

Concurrency in practice

- Seen a number of abstractions for concurrency control
  - Mutual exclusion and condition synchronization
- Next let's look at some concrete examples:
  - POSIX pthreads (C/C++ API)
  - FreeBSD kernels
  - Java

Example: pthreads

- Standard (POSIX) threading API for C, C++, etc
  - mutexes, condition variables, and barriers
- Mutexes are essentially binary semaphores:

```
int pthread_mutex_init(pthread_mutex_t *mutex, ...);
int pthread_mutex_lock(pthread_mutex_t *mutex);
int pthread_mutex_trylock(pthread_mutex_t *mutex);
int pthread_mutex_unlock(pthread_mutex_t *mutex);
```

- A thread calling lock() blocks if the mutex is held
  – trylock() is a non-blocking variant: returns immediately; returns 0 if lock acquired, or non-zero if not.

Example: pthreads

- Condition variables are Mesa-style:

```
int pthread_cond_init(pthread_cond_t *cond, ...);
int pthread_cond_wait(pthread_cond_t *cond,
                      pthread_mutex_t *mutex);
int pthread_cond_signal(pthread_cond_t *cond);
int pthread_cond_broadcast(pthread_cond_t *cond);
```

- No proper monitors: must manually code e.g.

```
pthread_mutex_lock(&M);
while (!condition)
    pthread_cond_wait(&C,&M);
// do stuff
if (condition)
    pthread_cond_broadcast(&C);
pthread_mutex_unlock(&M);
```

Notice: while() and not if() due to signal-and-continue semantics

Example: pthreads

- Barriers: explicit synchronization mechanism
  - Wait until all threads reach some point
- E.g., in discrete event simulation, all parallel threads must complete one epoch before any begin on the next

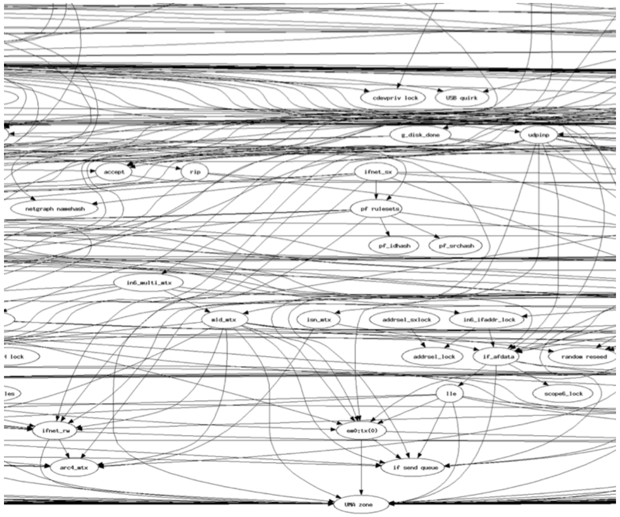
```
int pthread_barrier_init(pthread_barrier_t *b, ...,  N);
int pthread_barrier_wait(pthread_barrier_t *b);
```

```
pthread_barrier_init(&B, ..., NTHREADS);
for(i=0; i<NTHREADS; i++)
   pthread_create(..., worker, ...);

worker() {
   while(!done) {
     // do work for this round
     pthread_barrier_wait(&B);
   }
}
```

Example: FreeBSD kernel

- Kernel provides spin locks, mutexes, conditional variables, reader-writer + read-mostly locks
  - Semantics (roughly) modeled on POSIX threads
- A variety of deferred work primitives
  - "Fully preemptive" and highly threaded (e.g., interrupt processing in threads)
- Interesting debugging tools such as DTrace, lock contention measurement, lock-order checking
- Concurrency case study for our last lecture



Example: Java synchronization (1)

- Inspired by monitors – objects have intrinsic locks
- Synchronized methods:

```
public synchronized void myMethod() throws ...{
    // This code runs with the intrinsic lock held.
}
```

- Synchronized statements:

```
public void myMethod() throws ...{
    synchronized(this) {
        // This code runs with the intrinsic lock held.
}}
```

- Method return / statement exit release lock
- Locks are reentrant: a single thread can reenter synchronized statements/methods without waiting
- synchronized() can accept other objects than this

Example: Java synchronization (2)

- Objects have condition variables for guarded blocks
- wait() puts the thread to sleep:

```
public synchronized void waitDone() {
    while (!done) {
        wait();
    }
}
```

- notify() and notifyAll() wake threads up:

```
public synchronized void notifyDone() {
    done = true;
    notifyAll();
}
```

- As with Mesa, signal-and-continue semantics
- As with locks, can name object (thatObject.wait())

Example: Java synchronization (3)

- Java also specifies memory consistency and atomicity properties that make some lock-free concurrent access safe – if used very carefully
  - We will consider lock-free structures later in the term
- java.util.concurrent (especially as of Java 8) includes many higher-level primitives –for example, thread pools, concurrent collections, semaphores, cyclic barriers, …
- Because Java is a type-safe, managed language, it is a much safer place to experiment with concurrent programming than (for example) C

Concurrency Primitives: Summary

- Concurrent systems require means to ensure:
  - Safety (mutual exclusion in critical sections), and
  - Progress (condition synchronization)
- Spinlocks (busy wait); semaphores; MRSWs, CCRs, and monitors
  - Hardware primitives for synchronisation
  - Signal-and-Wait vs. Signal-and-Continue
- Many of these are used in practice
  - Subtle minor differences can be dangerous
  - Much care required to avoid bugs
  - E.g., "lost wakeups" – signal w/o waiter
- More detail on implementation in our case study

Summary + next time

- Multi-Reader Single-Writer (MRSW) locks
- Alternatives to semaphores/locks:
  - Conditional critical regions (CCRs)
  - Monitors
  - Condition variables
  - Signal-and-wait vs. signal-and-continue semantics
- Concurrency primitives in practice
- Concurrency primitives wrap-up

- Next time:
  - Problems with concurrency: deadlock, livelock, priorities
  - Resource allocation graphs; deadlock {prevention, detection, recovery}
  - Priority and scheduling; priority inversion; priority inheritance