Lecture 8: Synchronization exercises

601.418/618 Operating Systems

David Hovemeyer

February 14, 2024

Agenda

- Readers/Writers (using semaphore)
- Bounded Buffer (using semaphores)
- Readers/Writers (as a monitor with condition variables)

Acknowledgments: These slides are shamelessly adapted from Prof. Ryan Huang's Fall 2022 slides, which in turn are based on Prof. David Mazières's OS lecture notes.

Using semaphores

We've looked at a simple example for using synchronization

- Mutual exclusion while accessing a bank account

Now let's use semaphores to look at more interesting examples

- Readers/Writers
- Bounded Buffers

Readers/Writers Problem

Readers/Writers Problem:

- An object is shared among several threads
- Some threads only read the object, others only write it
- We can allow multiple readers but only one writer
  - Let `#r` be the number of readers, `#w` be the number of writers
  - Safety: $(\texttt{\#r} \geq 0) \wedge (0 \leq \texttt{\#w} \leq 1) \wedge ((\texttt{\#r} > 0) \implies (\texttt{\#w} = 0))$

How can we use semaphores to implement this protocol?

Start with. . .

- Semaphore `w_or_r` – exclusive writing or reading

Readers/Writers

Is this correct? Are we done?

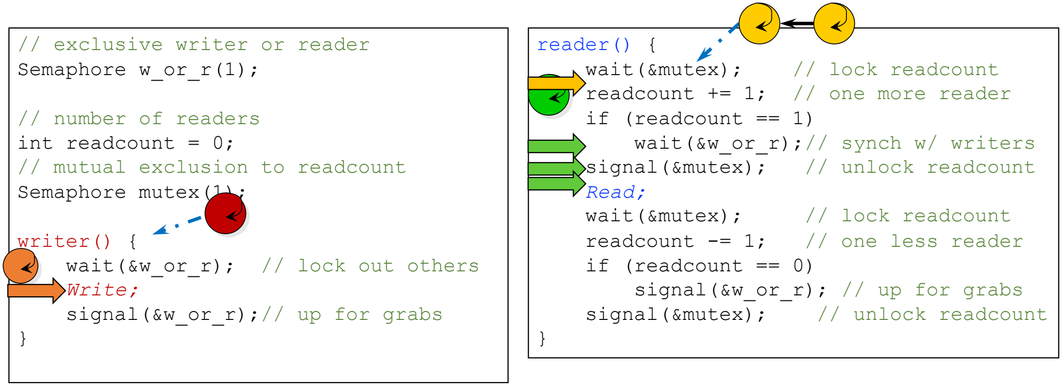
```
// exclusive writer or reader
Semaphore w_or_r(1);

// number of readers
int readcount = 0;
// mutual exclusion to readcount
Semaphore mutex(1);

writer() {
    wait(&w_or_r);  // lock out others
    Write;
    signal(&w_or_r);// up for grabs
}
```

```
reader() {
    wait(&mutex);    // lock readcount
    readcount += 1;  // one more reader
    if (readcount == 1)
        wait(&w_or_r);// synch w/ writers
    signal(&mutex);   // unlock readcount
    Read;
    wait(&mutex);     // lock readcount
    readcount -= 1;   // one less reader
    if (readcount == 0)
        signal(&w_or_r); // up for grabs
    signal(&mutex);    // unlock readcount
}
```

Readers/Writers



```
// exclusive writer or reader
Semaphore w_or_r(1);

// number of readers
int readcount = 0;
// mutual exclusion to readcount
Semaphore mutex(1);

writer() {
    wait(&w_or_r);  // lock out others
    Write;
    signal(&w_or_r);// up for grabs
}
```

```
reader() {
    wait(&mutex);    // lock readcount
    readcount += 1;  // one more reader
    if (readcount == 1)
        wait(&w_or_r);// synch w/ writers
    signal(&mutex);   // unlock readcount
    Read;
    wait(&mutex);     // lock readcount
    readcount -= 1;   // one less reader
    if (readcount == 0)
        signal(&w_or_r); // up for grabs
    signal(&mutex);    // unlock readcount
}
```

Readers/Writers Notes

`w_or_r` provides mutex between readers and writers

- writer wait/signal, reader wait/signal when `readcount` goes from 0 to 1 or from 1 to 0.

If a writer is writing, where will readers be waiting?

Once a writer exits, all readers can fall through

- Which reader gets to go first?
- Is it guaranteed that all readers will fall through?

If readers and writers are waiting, and a writer exits, who goes first?

Why do readers use `mutex`?

Why don't writers use `mutex`?

What if the signal is above "`if (readcount == 1)`"?

Bounded Buffer

Problem: a set of buffers shared by producer and consumer threads

- *Producer* inserts resources into the buffer set
  - Output, disk blocks, memory pages, processes, etc.
- *Consumer* removes resources from the buffer set
- Whatever is generated by the producer

Producer and consumer execute at different rates

- No serialization of one behind the other
- Tasks are independent (easier to think about)
- The buffer set allows each to run without explicit handoff

Safety:

- Sequence of consumed values is prefix of sequence of produced values
- If nc is number consumed, np number produced, and N the size of the buffer, then $0 \leq np - nc \leq N$

Bounded Buffer (2)

$$0 \leq np - nc \leq N \iff 0 \leq (nc - np) + N \leq N$$

Use three semaphores:

- **empty**: number of empty buffers
  - Counting semaphore
  - empty $= (nc - np) + N$
- **full**: number of full buffers
  - Counting semaphore
  - full $= np - nc$
- **mutex**: mutual exclusion to shared set of buffers
  - Binary semaphore

Bounded Buffer (3)

```
Semaphore mutex(1);  // mutual exclusion to shared set of buffers
Semaphore empty(N);  // count of empty buffers (all empty to start)
Semaphore full(0);   // count of full buffers (none full to start)
```

```
producer() {
  while (1) {
    Produce new resource;
    wait(&empty); // wait for empty buffer
    wait(&mutex); // lock buffer list
    Add resource to an empty buffer;
    signal(&mutex); // unlock buffer list
    signal(&full);  // note a full buffer
  }
}
```

```
consumer() {
  while (1) {
    wait(&full);  // wait for a full buffer
    wait(&mutex); // lock buffer list
    Remove resource from a full buffer;
    signal(&mutex); // unlock buffer list
    signal(&empty); // note an empty buffer
    Consume resource;
  }
}
```

Bounded Buffer (4)

Why do we need the mutex at all?

Where are the critical sections?

What has to hold for deadlock to occur?

- empty $=0$ and full $=0$
- $(nc-np)+N=0$ and $np-nc=0$
- N $=0$

What happens if operations on mutex and full/empty are switched around?

- The pattern of signal/wait on full/empty is a common construct often called an interlock

Readers/Writers and Bounded Buffer are classic synchronization problems

Monitor Readers and Writers

Using Mesa monitor semantics.

Will have four methods: `StartRead`, `StartWrite`, `EndRead` and `EndWrite`

Monitored data: nr (# of readers) and nw (# of writers) with monitor invariant

$$(nr \geq 0) \wedge (0 \leq nw \leq 1) \wedge ((nr > 0) \implies (nw = 0))$$

Two conditions:

- `canRead`: $nw = 0$
- `canWrite`: $(nr = 0) \wedge (nw = 0)$

Monitor Readers and Writers

Try #1

- Will be safe, maybe not live: why?

```
Monitor RW {
  int nr = 0, nw = 0;
  Condition canRead, canWrite;

  void StartRead () {
    while (nw != 0) wait(canRead);
    nr++;
  }

  void EndRead () {
    nr--;
  }
```

```
  void StartWrite {
    while (nr != 0 || nw != 0) wait(canWrite);
    nw++;
  }

  void EndWrite () {
    nw--;
  }
} // end monitor
```

Monitor Readers and Writers

Need to add `signal()` and `broadcast()`

```
Monitor RW {
  int nr = 0, nw = 0;
  Condition canRead, canWrite;

  void StartRead () {
    while (nw != 0) wait(canRead);
    nr++;
  }

  void EndRead () {
    nr--;
    if (nr == 0) signal(canWrite);
  }
```

can we put a signal here?

```
  void StartWrite () {
    while (nr != 0 || nw != 0) wait(canWrite);
    nw++;
  }

  void EndWrite () {
    nw--;
    broadcast(canRead);
    signal(canWrite);
  }
} // end monitor
```

can we put a signal here?

Monitor Readers and Writers

Is there any priority between readers and writers?

What if you wanted to ensure that a waiting writer would have priority over new readers?

Monitor Bounded Buffer

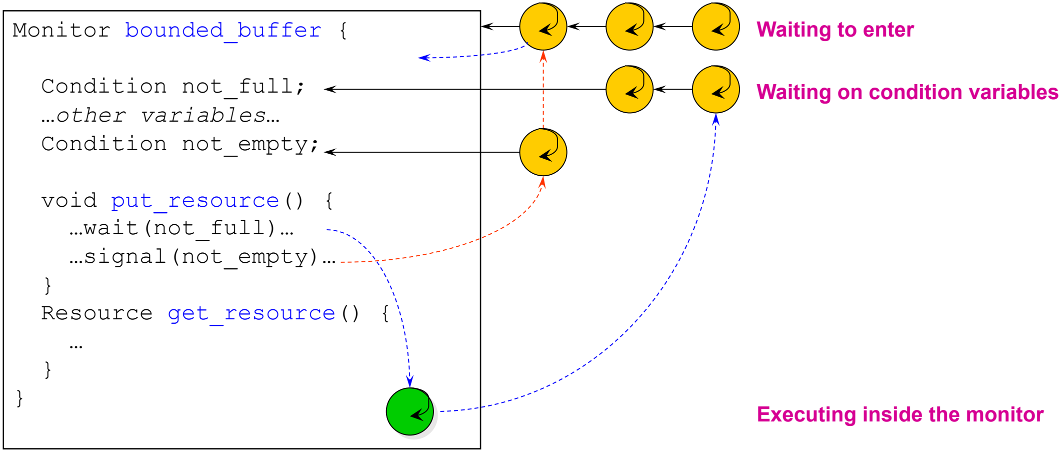
```
Monitor bounded_buffer {
  Resource buffer[N];
  // Variables for indexing buffer
  // monitor invariant involves these vars
  Condition not_full; // space in buffer
  Condition not_empty; // value in buffer

  void put_resource (Resource R) {
    while (buffer array is full)
        wait(not_full);
    Add R to buffer array;
    signal(not_empty);
  }
```

```
  Resource get_resource() {
    while (buffer array is empty)
        wait(not_empty);
    Get resource R from buffer array;
    signal(not_full);
    return R;
  }
} // end monitor
```

What happens if no threads are waiting when signal is called?

Monitor Queues



```
Monitor bounded_buffer {

  Condition not_full;
  …other variables…
  Condition not_empty;

  void put_resource() {
    …wait(not_full)…
    …signal(not_empty)…
  }
  Resource get_resource() {
    …
  }
}
```

Waiting to enter

Waiting on condition variables

Executing inside the monitor

Next time

Deadlock (!)