15-410
“My computer is 'modern'!”

Synchronization #1
Feb. 1, 2019

Dave Eckhardt
Brian Railing
Notice

Me vs. OSC Chapter 6
- I will cover 6.3 much more than the text does...
  - ...even more than the previous edition did...
  - This is a good vehicle for understanding race conditions

Me vs. OS:P+P Chapter 5
- Philosophically very similar
- Examples and focus are different
Notice

Not in the book

- "Atomic sequences vs. voluntary de-scheduling"
  - "Sim City" example

Textbook recommended!

- We will spend ~4 lectures on one chapter (~7 on two)
- This is important stuff
  - Getting a “second read” could be very useful
Outline

An intrusion from the “real world”
Two fundamental operations
Three necessary critical-section properties
Two-process solution
N-process “Bakery Algorithm”
Mind your P's and Q's

Imagine you wrote this code:

```python
choosing[i] = true;
number[i] =
    max(number[0], number[1], ...) + 1;
choosing[i] = false;
```
Mind your P's and Q's

Imagine you wrote this code:

```c
choosing[i] = true;
number[i] =
    max(number[0], number[1], ...) + 1;
choosing[i] = false;
```

Imagine what is sent out over the memory bus is:

```c
number[i] = 11;
choosing[i] = false;
```

Is that ok?
Mind your P's and Q's

Imagine you wrote this code:

choosing[i] = true;
number[i] =
    max(number[0], number[1], ...) + 1;
choosing[i] = false;

How about this??

choosing[i] = false;
number[i] = 11;

Is my computer broken???
- “Computer Architecture for $200, Dave”...
Is my computer broken?!

No, your computer is “modern”
- Processor “write pipe” queues memory stores
- ...and coalesces “redundant” writes!

Crazy?
- Not if you're pounding out pixels!

---

CPU

choosing[i] false

number[i] 11

choosing[i] true

Memory
My Computer is Broken?!

Magic “memory barrier” instructions available...
  • ...stall processor until write pipe is empty

Ok, now I understand
  • Probably not!
    • http://www.cs.umd.edu/~pugh/java/memoryModel/
      » see “Double-Checked Locking is Broken” Declaration
  • See also “release consistency”

Textbook mutual exclusion algorithm memory model
  • ...is “what you expect” (pre-“modern”)
  • Ok to use simple model for homework, exams, P2
    • But it's not right for multi-processor Pentium-4 systems...
Synchronization Fundamentals

Two fundamental operations

- Atomic instruction sequence
- Voluntary de-scheduling

Multiple implementations of each

- Uniprocessor vs. multiprocessor
- Special hardware vs. special algorithm
- Different OS techniques
- Performance tuning for special cases

Be very clear on features, differences

- The two operations are more “opposite” than “the same”
Synchronization Fundamentals

Multiple client abstractions use the two operations

Textbook prefers

- “Critical section”, semaphore, monitor

Very relevant

- Mutex/condition variable (POSIX pthreads)
- Java “synchronized” keyword (3 flavors)
Synchronization Fundamentals

Two Fundamental operations

- Atomic instruction sequence
- Voluntary de-scheduling
Atomic Instruction Sequence

**Problem domain**

- *Short* sequence of instructions
- Nobody else may interleave same sequence
  - or a “related” sequence
- “Typically” nobody is competing
Non-interference

Multiprocessor simulation (think: “Sim City”)
- Coarse-grained “turn” (think: hour)
- Lots of activity within each turn
- Think: M:N threads, M=objects, N=#processors

Most cars don't interact in a game turn...
- Must model those that do
- So street intersections can't generally be “processed” by multiple cars at the same time
Commerce

<table>
<thead>
<tr>
<th>Customer 0</th>
<th>Customer 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>cash = store-&gt;cash;</td>
<td>cash = store-&gt;cash;</td>
</tr>
<tr>
<td>cash += 50;</td>
<td>cash += 20;</td>
</tr>
<tr>
<td>wallet -= 50;</td>
<td>wallet -= 20;</td>
</tr>
<tr>
<td>store-&gt;cash = cash;</td>
<td>store-&gt;cash = cash;</td>
</tr>
</tbody>
</table>

Should the store call the police?
Is deflation good or bad for the economy?
Commerce – Observations

Instruction sequences are “short”

- Ok to “mutually exclude” competitors (make them wait)

Probability of collision is “low”

- Many non-colliding invocations per second
  - (lots of stores in the city)
- Must not use an expensive anti-collision approach!
  - “Just make a system call” is not an acceptable answer
- Common (non-colliding) case must be fast
Synchronization Fundamentals

Two Fundamental operations

- Atomic instruction sequence
- Voluntary de-scheduling
Voluntary De-scheduling

Problem domain
- “Are we there yet?”
- “Waiting for Godot”

Example - “Sim City” disaster daemon

```c
while (date < 1906-04-18) cwait(date);
while (hour < 5) cwait(hour);
for (i = 0; i < max_x; i++)
    for (j = 0; j < max_y; j++)
        wreak_havoc(i,j);
```
Voluntary De-scheduling

Anti-atomic

- We *want* to be “maximally interleaved against”

Running and making others wait is *wrong*

- Wrong for them – we won't be ready for a while
- Wrong for us – we can't be ready until *they* progress

We don't *want* exclusion

We *want* others to run - they *enable* us

CPU *de*-scheduling is an OS service!
Voluntary De-scheduling

Wait pattern

LOCK WORLD
while (!(ready = scan_world())){
  UNLOCK WORLD
  WAIT_FOR(progress_event)
  LOCK WORLD
}

Your partner-competitor will

SIGNAL(progress_event)
Standard Nomenclature

“Traditional CS” code skeleton / naming

```c
do {
    entry section
    critical section:
        ...computation on shared state...
    exit section
    remainder section:
        ...private computation...
} while (1);
```
Standard Nomenclature

What's muted by this picture?

- What's in that critical section?
  - Quick atomic sequence?
  - Need to block for a while?

For now...

- Pretend critical section is a brief atomic sequence
- Study the entry/exit sections
Three Critical Section Requirements

**Mutual Exclusion**
- At most one thread is executing each critical section

**Progress**
- Choosing protocol must have bounded time
  - Common way to fail: choosing next entrant cannot wait for non-participants

**Bounded waiting**
- Cannot wait forever once you begin entry protocol
- ...bounded number of entries by others
  - not necessarily a bounded number of *instructions*
Notation For 2-Process Protocols

Assumptions
- Multiple threads (1 CPU with timer, or multiple CPU's)
- Shared memory, but no locking/atomic instructions
- No thread “runs at zero speed”

Thread $i = \text{“us”}$

Thread $j = \text{“the other thread”}$

$i,j$ are thread-local variables
- $\{i,j\} = \{0,1\}$
- $j = 1 - i$

This notation is “odd”
- But it may well appear in an exam question
Idea #1 - “Taking Turns”

```c
int turn = 0;

while (turn != i)
    continue;
...critical section...
turn = j;
```
Idea #1 - “Taking Turns”

```c
int turn = 0;

while (turn != i)
    continue;
...critical section...
turn = j;
```

Mutual exclusion – yes (make sure you see it)
Idea #1 - “Taking Turns”

```c
int turn = 0;

while (turn != i)
    continue;
...critical section...
turn = j;
```

Mutual exclusion – yes (make sure you see it)

Progress - **no**

- *Strict* turn-taking is fatal
- If T0 never tries to enter, T1 will wait forever
  - Violates the “depends on non-participants” rule
Idea #2 - “Registering Interest”

```java
boolean want[2] = {false, false};

want[i] = true;
while (want[j])
    continue;
...critical section...
want[i] = false;
```
## Mutual Exclusion (Intuition)

<table>
<thead>
<tr>
<th>Thread 0</th>
<th>Thread 1</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>want[0] = true;</code></td>
<td></td>
</tr>
<tr>
<td><code>while (want[1]) ;</code></td>
<td></td>
</tr>
<tr>
<td>...enter...</td>
<td><code>want[1] = true;</code></td>
</tr>
<tr>
<td></td>
<td><code>while (want[0]) ;</code></td>
</tr>
<tr>
<td></td>
<td><code>while (want[0]) ;</code></td>
</tr>
<tr>
<td><code>want[0] = false;</code></td>
<td><code>while (want[0]) ;</code></td>
</tr>
<tr>
<td></td>
<td>...enter...</td>
</tr>
</tbody>
</table>
### Mutual Exclusion (Intuition)

<table>
<thead>
<tr>
<th>Thread 0</th>
<th>Thread 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>want[0] = true;</td>
<td></td>
</tr>
<tr>
<td>while (want[1]) ;</td>
<td>want[1] = true;</td>
</tr>
<tr>
<td>...enter...</td>
<td></td>
</tr>
<tr>
<td>want[0] = false;</td>
<td>while (want[0]) ;</td>
</tr>
<tr>
<td></td>
<td>while (want[0]) ;</td>
</tr>
<tr>
<td></td>
<td>while (want[0]) ;</td>
</tr>
<tr>
<td></td>
<td>...enter...</td>
</tr>
</tbody>
</table>
Mutual Exclusion (Intuition)

<table>
<thead>
<tr>
<th>Thread 0</th>
<th>Thread 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>want[0] = true;</td>
<td>want[1] = true;</td>
</tr>
<tr>
<td>while (want[1]);</td>
<td>while (want[0]);</td>
</tr>
</tbody>
</table>

It works for every *other* interleaving!
“Peterson's Solution” (1981)

(“Taking turns when necessary”)

```java
boolean want[2] = {false, false};
int turn = 0;

want[i] = true;
turn = j;
while (want[j] && turn == j)
    continue;
...critical section...
want[i] = false;
```
Proof Sketch of Exclusion

Assume contrary: two threads in critical section
Both in c.s. implies want[i] == want[j] == true
Thus both while loops exited because “turn != j”
Cannot have (turn == 0 && turn == 1)
  ▪ So one exited first
w.l.o.g., T0 exited first because “turn ==1” failed
  ▪ So turn==0 before turn==1
  ▪ So T1 had to set turn==0 before T0 set turn==1
  ▪ So T0 could not see turn==0, could not exit loop first!
Proof Sketch Hints

want[i] == want[j] == true

“want[]” fall away, focus on “turn”

turn[] vs. loop exit...

What really happens here?

<table>
<thead>
<tr>
<th>Thread 0</th>
<th>Thread 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>turn = 1;</td>
<td>turn = 0;</td>
</tr>
<tr>
<td>while (turn == 1) ;</td>
<td>while (turn == 0) ;</td>
</tr>
</tbody>
</table>
Bakery Algorithm (Lamport)

More than two processes?
- Generalization based on bakery/deli counter
  - Get monotonically-increasing ticket number from dispenser
  - Wait until monotonically-increasing “now serving” == you
    » You have lowest number ⇒ all people with smaller numbers have already been served

Multi-process version
- Unlike “reality”, two people can get the same ticket number
- Sort by “ticket number with tie breaker”:
  - (ticket number, process number) tuple
Bakery Algorithm (Lamport)

Phase 1 – Pick a number
- Look at all presently-available numbers
- Add 1 to highest you can find

Phase 2 – Wait until you hold *lowest* number
- Not strictly true: processes may have same number
- Use process-id as a tie-breaker
  - (ticket 7, process 99) > (ticket 7, process 45)
- Your turn when you hold lowest (t,pid)
Bakery Algorithm (Lamport)

```java
boolean choosing[n] = { false, ... };
int number[n] = { 0, ... };
```
Bakery Algorithm (Lamport)

Phase 1: Pick a number

choosing[i] = true;

number[i] =
    max(number[0], number[1], ...) + 1;

choosing[i] = false;

Worst case: everybody picks same number!

But at least next wave of arrivals will pick a larger number...
Bakery Algorithm (Lamport)

Phase 2: Sweep “proving” we have lowest number

```c
for (j = 0; j < n; ++j) {
    while (choosing[j])
        continue;
    while (((number[j] != 0) &&
            ((number[i], i) > (number[j], j)))
        continue;
}
...critical section...
number[i] = 0;
```
Summary

Memory is *weird*

Two fundamental operations - understand!

- *Brief exclusion* for atomic sequences
- *Long-term yielding* to get what you want

Three necessary critical-section properties

Understand these “exclusion algorithms” (which are also race-condition parties)

- Two-process solution
- N-process “Bakery Algorithm”