15-410
“*My computer is 'modern'!*”

Synchronization #1
Feb. 1, 2017

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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:

```plaintext
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:

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

Imagine what is sent out over the memory bus is:

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

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

Imagine you wrote this code:

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

How about this??

```java
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!
My Computer is Broken?!

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

Ok, now I understand
  - Probably not!
      » 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><strong>Customer 0</strong></th>
<th><strong>Customer 1</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><code>cash = store-&gt;cash;</code></td>
<td><code>cash = store-&gt;cash;</code></td>
</tr>
<tr>
<td><code>cash += 50;</code></td>
<td><code>cash += 20;</code></td>
</tr>
<tr>
<td><code>wallet -= 50;</code></td>
<td><code>wallet -= 20;</code></td>
</tr>
<tr>
<td><code>store-&gt;cash = cash;</code></td>
<td><code>store-&gt;cash = cash;</code></td>
</tr>
</tbody>
</table>

Should the store call the police?
Is deflation good for the economy?
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

```plaintext
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**

```c
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 \textit{in} that critical section?
  - Quick atomic sequence?
  - Need for a long sleep?

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

Thread $i$ = “us”

Thread $j$ = “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”

```java
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>want[0] = true;</td>
<td>want[1] = true;</td>
</tr>
<tr>
<td>while (want[1]) ;</td>
<td>while (want[0]) ;</td>
</tr>
<tr>
<td>…enter…</td>
<td>while (want[0]) ;</td>
</tr>
<tr>
<td></td>
<td>while (want[0]) ;</td>
</tr>
<tr>
<td>want[0] = false;</td>
<td>while (want[0]) ;</td>
</tr>
<tr>
<td></td>
<td>…enter…</td>
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</table>
Mutual Exclusion (Intuition)

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<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><code>while (want[0]);</code></td>
<td></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>
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</table>

How about progress?
## Failing “Progress”

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

    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”