Thread Synchronization: Too Much Milk

Implementing Critical Sections in Software Hard

- The following example will demonstrate the difficulty of providing mutual exclusion with memory reads and writes
    - Hardware support is needed
- The code must work *all* of the time
    - Most concurrency bugs generate correct results for *some* interleavings
- Designing mutual exclusion in software shows you how to think about concurrent updates
    - Always look for what you are checking and what you are updating
    - A meddlesome thread can execute between the check and the update, the dreaded race condition

Thread Coordination

Too much milk!

Jack

- Look in the fridge; out of milk
- Go to store
- Buy milk
- Arrive home; put milk away

Jill

- Look in fridge; out of milk
- Go to store
- Buy milk
- Arrive home; put milk away
- Oh, no!

Fridge and milk are shared data structures

Formalizing "Too Much Milk"

- Shared variables
  - "Look in the fridge for milk" – check a variable
  - "Put milk away" – update a variable

- Safety property
  - At most one person buys milk

- Liveness
  - Someone buys milk when needed

- How can we solve this problem?

How to think about synchronization code

- Every thread has the same pattern
  - Entry section: code to attempt entry to critical section
  - Critical section: code that requires isolation (e.g., with mutual exclusion)
  - Exit section: cleanup code after execution of critical region
  - Non-critical section: everything else
- There can be multiple critical regions in a program
  - Only critical regions that access the same resource (e.g., data structure) need to synchronize with each other

```
while(1) {
   Entry section
   Critical section
   Exit section
   Non-critical section
}
```

The correctness conditions

- Safety
  - Only one thread in the critical region
- Liveness
  - Some thread that enters the entry section eventually enters the critical region
  - Even if some thread takes forever in non-critical region
- Bounded waiting
  - A thread that enters the entry section enters the critical section within some bounded number of operations.
- Failure atomicity
  - It is OK for a thread to die in the critical region
  - Many techniques do not provide failure atomicity

```
while(1) {
    Entry section
    Critical section
    Exit section
    Non-critical section
}
```

Too Much Milk: Solution #0

```
while(1) {
  if (noMilk) {          // check milk (Entry section)
     if (noNote) {       // check if roommate is getting milk
        leave Note;      //Critical section
        buy milk;
        remove Note; // Exit section
     }
   // Non-critical region
}
```

- Is this solution
  - 1. Correct
  - 2. Not safe
  - 3. Not live
  - 4. No bounded wait
  - 5. Not safe and not live

What if we switch the order of checks?

- It works sometime and doesn't some other times
  - Threads can be context switched between checking and leaving note
  - Live, note left will be removed
  - Bounded wait ('buy milk' takes a finite number of steps)

Too Much Milk: Solution #1

```
turn := Jill  // Initialization
```

```
while(1) {
   while(turn ≠ Jack) ; //spin
   while (Milk) ; //spin
   buy milk;        // Critical section
   turn := Jill  // Exit section
   // Non-critical section
}
```

```
while(1) {
   while(turn ≠ Jill) ; //spin
   while (Milk) ; //spin
   buy milk;
   turn := Jack
   // Non-critical section
}
```

- Is this solution
  - 1. Correct
  - 2. Not safe
  - 3. Not live
  - 4. No bounded wait
  - 5. Not safe and not live

- *At least it is safe*

Solution #2 (a.k.a. Peterson's algorithm): combine ideas of 0 and 1

Variables:

- in_i: thread T_i is executing , or attempting to execute, in CS
- *turn*: id of thread allowed to enter CS if multiple want to

Claim: We can achieve mutual exclusion if the following invariant holds before thread i enters the critical section:

$$\{(\neg in_j \lor (in_j \land turn = i)) \land in_i\}$$

$$((\neg in_0 \lor (in_0 \land turn = 1)) \land in_1) \land$$
$$((\neg in_1 \lor (in_1 \land turn = 0)) \land in_0)$$
$$\Longrightarrow$$
$$((turn = 0) \land (turn = 1)) = false$$

Intuitively: j doesn't want to execute or it is i's turn to execute

Peterson's Algorithm

$in_0 = in_1 = false;$

```
Jack
while (1) {
    $in_0$:= true;
    turn := Jill;
    while (turn == Jill
        && $in_1$) ;//wait
    Critical section
    $in_0$ := false;
    Non-critical section
}
```

```
Jill
while (1) {
    $in_1$:= true;
    turn := Jack;
    while (turn == Jack
        && $in_0$);//wait
    Critical section
    $in_1$ := false;
    Non-critical section
}
```

Spin!

turn=Jack, in_0 = false, in_1:= true

Safe, live, and bounded waiting

But, only 2 participants

Too Much Milk: Lessons

- Peterson’s works, but it is really unsatisfactory
  - Limited to two threads
  - Solution is complicated; proving correctness is tricky even for the simple example
  - While thread is waiting, it is consuming CPU time
- How can we do better?
  - Use hardware to make synchronization faster
  - Define higher-level programming abstractions to simplify concurrent programming