Announcements

- Extra Office Hour: tomorrow at 11am

- Slides for today are posted
- Slides from Friday are posted
- Homework is due April 13, not April 11
  - This includes extra credit

- All graduating seniors should have received a PTA for the new section. If you are a graduating senior and did not, please contact the Undergraduate Advisors ***immediately!!!!!***

Interprocess Synchronization and Communication

Solutions in Software

- Last class' solution was Peterson's Solution
- Lamport's bakery algorithm solves the *n*-process problem

Lamport’s Bakery Algorithm

```
var choosing: shared array[0..n-1] of boolean;
    number: shared array[0..n-1] of integer;
    ...
repeat
    choosing[i] <- true;            / ... eEntry section
    number[i] <- max(number[0],number[1],...,number[n-1]) + 1;
    choosing[i] := false;
    for j := 0 to n-1 do begin
            while choosing[j] do
                    (* nothing *);
            while number[j] ≠ 0 and (number[j], j) < (number[i],i) do
                    (* nothing *);
    end;
                                    / ... critical section
    number[i] := 0;                 / ... exit section
    until false;
```

Explanation

- *choosing*[*i*]: true if process *i* is choosing a number
- *number*[*i*]: number that process *i* will use to enter the critical section; 0 if process *i* is not trying to enter its critical section

Entry section:

- Process *i* signals it is choosing a number
- Process *i* tries to get a unique number
  - May not happen due to race
- Process *i* indicates it is done

Explanation

Which process goes in:

- Process *i* waits until it has the lowest number of all the processes waiting to enter the critical section.
  - If two processes have the same number, the one with the smaller name (like *i*) goes in
  - If another process is choosing a number when process *i* tries to look at it, process *i* waits until it has done so before looking.

Exit section

- Process *i* no longer interested in entering its critical section, so it sets *number*[*i*] to 0.

Proof It Is a Solution

- Mutual exclusion: Suppose process i is in critical section. Some other process k ($k \neq i$) gets $number[k] \neq 0$. Assume $i < k$; then

  $$(number[i],i) < (number[k],k).$$

  Suppose process k wants to enter the critical section, and process i is in the critical section. When process k is in the for loop, and $j = i$, then $number[i] \neq 0$ and $(number[i],i) < (number[k],k)$, so it loops in second **while** statement

- Are bounded wait and progress satisfied? Yes, as processes enter the critical section on FIFO basis.

Hardware Indivisible Test-and-Set Instruction

- This is atomic, and cannot be interrupted:

```
function TaS(var Lock: boolean): boolean
begin
  TaS: = Lock;
  Lock = True;
end;
```

- It sets `Lock` to true and returns the previous value of `Lock`

Test-and-Set *n* Process Solution: Variables

```
var waiting: shared array [0..n-1] of Boolean <- false;
      Lock: shared Boolean <- false;
      j: 0..n-1;
      key: boolean;
```

- *Waiting*, *Lock* are shared by all *n* processes
- *j*, *key* are local variables

Test-and-Set *n* Process Solution: Entry Section

```
repeat (* process Pi *)
      waiting[i] := true;
      key := true;
      while waiting[i] and key do
            key := TaS(Lock);
      waiting[i] := false;
```

- Process *i* indicates it wants to go into critical section
- If *Lock* is true, then *key* will be true and process *i* loops at the **while** statement
- When it can enter *key* is false, so it resets *waiting*[*i*] and enters. Note the *TaS*(*Lock*) that sets *key* to false also sets *Lock* to true

Test-and-Set *n* Process Solution: Exit Section

```
        j := i + 1 mod n;
        while (j <> i) and not waiting[j] do
              j := j + 1 mod n;
        if j = i then Lock := false
        else waiting[j] := false;
until false;
```

- Process *i* exits and must choose who goes next
- If one (process *j*) is waiting, process *i* lets it proceed by setting *waiting*[*j*] to true; note *Lock* remains true.
- If none are waiting, *Lock* is set to false

Problems of All These

- Busy waiting; the CPU does nothing in such a way that no-one else can use it while the process is waiting
- Not easily generalizable
  - For example, Peterson's solution does not easily generalize to *n* processes
- So look for other solutions . . .

Semaphores

- Non-negative integer variable *sem* that has 3 allowed operations:
  - Initialization: initial value set atomically, as in

    sem <- *n*
  - signal*:* increment value of *sem* by 1, as in

    sem <- sem + 1
  - wait: block until value of *sem* is non-zero; then decrement value by 1, as in

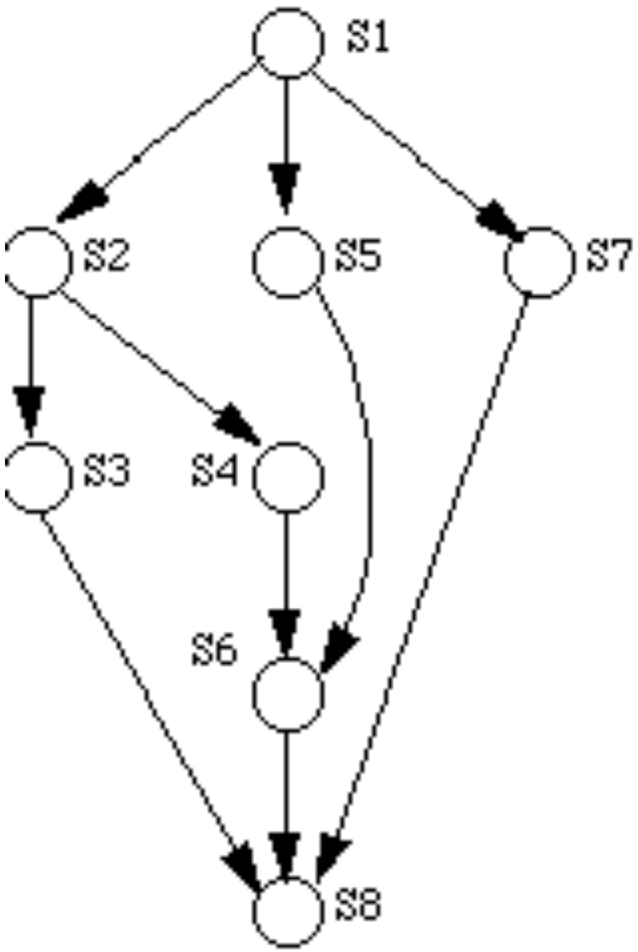
    while *sem* = 0 **do block**

    sem <- *sem* – 1

Blocking

- Each semaphore has an associated blocking (or waiting) queue
- When a process blocks, it goes into a queue
- When semaphore is non-zero, first process in queue is moved to the ready queue
- Processes normally are removed from the queue in FIFO order

Example




```
S1;
parbegin
   begin S2; signal(a); signal(b); end;
   begin wait(a); S3; signal( c); end;
   begin wait(b); S4; signal(d); end;
   begin S5; signal( e); end;
   begin wait(d); wait( e); S6; signal(f); end;
   begin S7; signal(g); end;
   begin wait( c); wait(f); wait(g); S8; end;
parend;
```

Semaphore Solution to Critical Section

- Initialize semaphore (call it *mutex*) to 1
- Then *wait* at the beginning of the critical section
- On exit, *signal*

```
semaphore mutex <- 1;

repeat
     wait(mutex);
     // critical section
     signal(mutex);
until false;
```

Process Synchronization Using Semaphores

```
semaphore mutex <- 0;
```

Process 1

```
repeat
    …
    wait(mutex);
    …
until false;
```

Process 2

```
repeat
    …
    signal(mutex);
    …
until false;
```

Producers-Consumers Problem

- Initialize *full* to 0
- Initialize *empty* to *n* (size of buffer)
- Initialize *mutex* to 1 – used to enforce mutual exclusion for access to the buffer
- Producer:

  wait(*empty*); *wait*(*mutex*); item into buffer; *signal*(*mutex*); *signal*(*full*)
- Consumer:

  wait(*full*); *wait*(*mutex*); item from buffer; *signal*(*mutex*); *signal*(*empty*)

Demonstration

- Suppose *empty* is *n*, meaning the buffer is empty
- Consumer wants an item, but blocks at *wait*(*full*)
- Producer wants to produce item, so at *wait*(*empty*), it decrements *empty*, puts item into buffer, and signals *full* to indicate there is an item in buffer
- Now, if buffer is full, *empty* is 0 and *full* is *n*
- Producer wants to produce an item, but has to wait for buffer to have an empty spot; so it blocks on *empty*
- When consumer wants to take an item, at *wait*(*full*) it decrements *full*, consumes the item, and signals *empty* to indicate there is an empty space in buffer

Readers-Writers Problem

- Processes share a file
- Some processes want to read it (the *readers*)
- Others want to write it (the *writers*)
- Rules:
  - Any number of readers can access the file simultaneously
  - When a writer is accessing the file, no other process (reader or writer) can access the file

Versions

- First version: readers have priority
  - Even if a writer wants to access the file, it must wait until all readers are finished with the file *and* no readers want access to the file
  - Note: writers may never be able to access the file (said as “writers may *starve*”)
- Second version: writers have priority
  - Once a writer wants access to the file, no readers may obtain access
  - Any readers with access continue to have access

Demonstration (First Readers-Writers)

- Reader wants to read the file
  - Sets mutual exclusion
  - Adds that another reader wants to go in
  - Release mutual exclusion
  - If no other readers in critical section, wait for any writers
  - If other readers in critical section, or no writers, enter critical section
  - On exit, set mutual exclusion
  - Decrement number of readers; if last one, signal any writers they can proceed
  - Release mutual exclusion
- Summary
  - Add 1 to the number of readers in, or wanting to enter, critical section
  - If other readers in critical section, or no writers, enter critical section; otherwise, wait
  - On exit, subtract 1 from the number of readers in or wanting to enter
  - If no more readers, signal any writers

Demonstration (First Readers-Writers)

- Writer wants to write the file
  - Block until no readers and no other writers are in the critical section
  - Set mutual exclusion for the critical section
  - Enter
  - Release mutual exclusion
- Summary
  - Block until no other process is in the critical section
  - Enter the critical section
  - Unblock any waiting processes
- Note: mutual exclusion for critical section is *not* the same as for incrementing or decrementing the number of readers wanting to enter the critical section

Dining Philosophers Problem

- Five philosophers are dining at a circular table
- There are five plate, one in front of each philosopher
- There are five forks, one between each plate
- Philosophers alternate between thinking and using both their right and left forks to eat
- Problem: prevent starvation and deadlock

Possible Solution

- Each philosopher picks the fork on their left

```
var fork: array [0..4] of semaphore: = 1,1,1,1,1
repeat (* philosopher i *)
     wait(fork[i]);
     wait(fork[(i + 1) mod 5]);
     (* eat *)
     signal(fork[i]);
     signal(fork[(i + 1) mod 5]);
     (* think *)
until false
```

Do You See the Problem?

- Suppose all philosophers want to eat
- Each picks up their left fork (`wait(fork[i])`)
- All now want to pick up their right fork (`wait(fork[(i + 1) mod 5]))`
- Oops . . . All right forks are the left forks of the philosophers to the right
- So all philosophers wait until the one to their right begins to think
- . . . ***Deadlock***!

Problem

- Like fork/join/quit, semaphores are too low level
- Combine blocking with counting
  - Really two separate operations, and should be treated as such
- Hard to debug
  - Easy to make mistakes
  - Think of typing wait when you meant to type signal
  - Original name for wait (P), signal (V) even easier to mistype
    - P from the Dutch *passering* ("passing")
    - V from the Dutch *verhogen* ("increase")
    - Taken from railroad signals