Synchronization II

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Today's Topics

Spinlock is not enough

- What if a lock is held by others?
- What if a condition is not met inside the critical section?

Higher-level synchronization mechanisms

- Semaphores
- Monitors

Higher-level Synchronization

Motivation

- Spinlocks and disabling interrupts are useful only for very short and simple critical sections
  - Wasteful otherwise
  - These primitives are "primitive" - don't do anything besides mutual exclusion
- Need higher-level synchronization primitives that
  - Block waiters
  - Leave interrupts enabled within the critical section
- Two common high-level primitives:
  - Semaphores: binary (mutex) and counting
  - Monitors: mutexes and condition variables
- We'll use our "atomic" locks as primitives to implement them

Semaphores (1)

Semaphores

- A synchronization primitive higher level than locks
- Invented by Dijkstra in 1968, as part of the "THE" OS
- Does not require busy waiting
- Manipulated atomically through two operations:
  - Wait (S): decrement, block until semaphore is open
    = P(), after Dutch word for test, also called down()
  - Signal (S): increment, allow another to enter
    = V(), after Dutch word for increment, also called up()

Semaphores (2)

Blocking in semaphores

- Each semaphore has an associated queue of processes/threads
- When wait() is called by a thread,
  - If semaphore is "open", thread continues
  - If semaphore is "closed", thread blocks, waits on queue
- signal()
  - Opens the semaphore
  - If thread(s) are waiting on a queue, one thread is unblocked
- In other words, semaphore has history
  - The history is a counter
  - If counter falls below 0, then the semaphore is closed
  - wait() decreases the counter while signal() increases it

Implementing Semaphores

```
typedef struct {
   int value; // 1 or N
   struct process *L;
} semaphore;

void wait (semaphore S)  {
   S.value--;
   if (S.value < 0)   {
      add this process to S.L;
      block ();
   }
}

void signal (semaphore S)  {
   S.value++;
   if (S.value <= 0)  {
      remove a process P from S.L;
      wakeup (P);
   }
}
```

wait() / signal() are critical sections!
Hence, they must be executed atomically

HOW??

Algorithm

H/W instruction

Interrupt disable/enable

Types of Semaphores

Binary semaphore (a.k.a mutex)

- Guarantees mutually exclusive access to resource
- Only one thread/process allowed entry at a time
- Counter is initialized to 1

Counting semaphore

- Represents a resource with many units available
  - e.g., 5 printers
- Allows threads/processes to enter as long as more units are available
- Counter is initialized to N (=units available)

Deadlock and Starvation

Deadlock

- Two or more processes are waiting indefinitely for an event that can be caused by only one of the waiting processes
- Let S and Q be two semaphores initialized to 1

P_0	P_1
wait (S);	wait (Q);
wait (Q);	wait (S);
...	...
...	...
signal (S);	signal (Q);
signal (Q);	signal (S);

Starvation

- Indefinite blocking
- A process may never be removed from the semaphore queue in which it is suspended

Priority Inversion

- Scheduling problem when lower-priority process holds a lock needed by higher-priority process
- Solved via priority-inheritance protocol

Classical Problems of Synchronization

Classical problems used to test newly-proposed synchronization schemes

- Bounded-Buffer Problem
- Dining-Philosophers Problem

- Readers and Writers Problem
- ...
- ...

Bounded Buffer Problem (1)

Producer/consumer problem

- There is a set of resource buffers shared by producer and consumer
- Producer inserts resources into the buffer
  - Output, disk blocks, memory pages, etc.
- Consumer removes resources from the buffer
- Producer and consumer execute in different rates
  - No serialization of one behind the other
  - Tasks are independent

Bounded Buffer Problem (2)

No synchronization

Producer

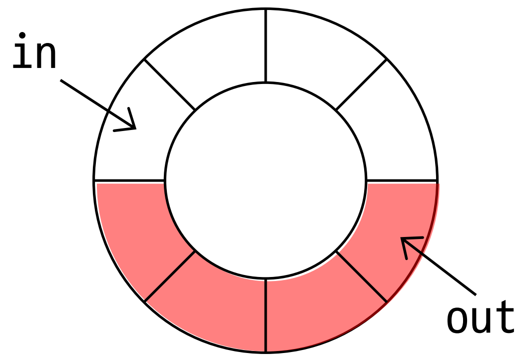
```
void produce(data)
{

  while (count==N);
  buffer[in] = data;
  in = (in+1) % N;
  count++;

}
```

```
int count;
```

```
struct item buffer[N];
int in, out;
```



Consumer

```
void consume(data)
{

  while (count==0);
  data = buffer[out];
  out = (out+1) % N;
  count--;

}
```

Bounded Buffer Problem (3)

counter++ could be implemented as

- register1 = count
- register1 = register1 + 1
- count = register1

counter-- could be implemented as

- register2 = count
- register2 = register2 - 1
- count = register2

Consider this execution interleaving with "count = 5" initially:

1. P: register1 = count {register1 = 5}
2. P: register1 = register1 + 1 {register1 = 6}
3. C: register2 = count {register2 = 5}
4. C: register2 = register2 - 1 {register2 = 4}
5. P: count = register1 {count = 6}
6. C: count = register2 {count = 4}

Dining Philosopher (1)

Dining philosopher problem

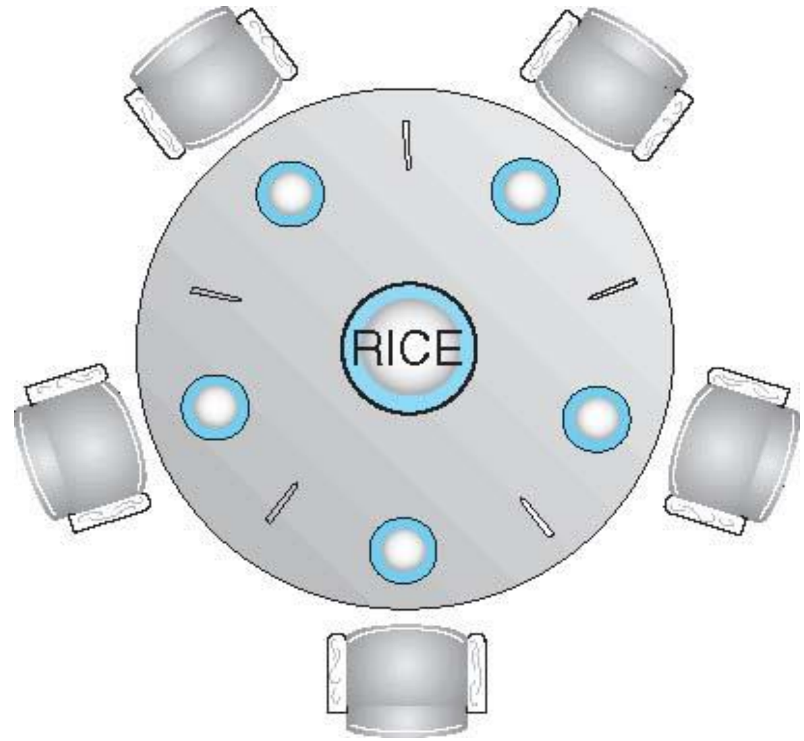
- Dijkstra, 1965
- Life of a philosopher
  - Repeat forever:

    Thinking

    Getting hungry

    Getting two chopsticks

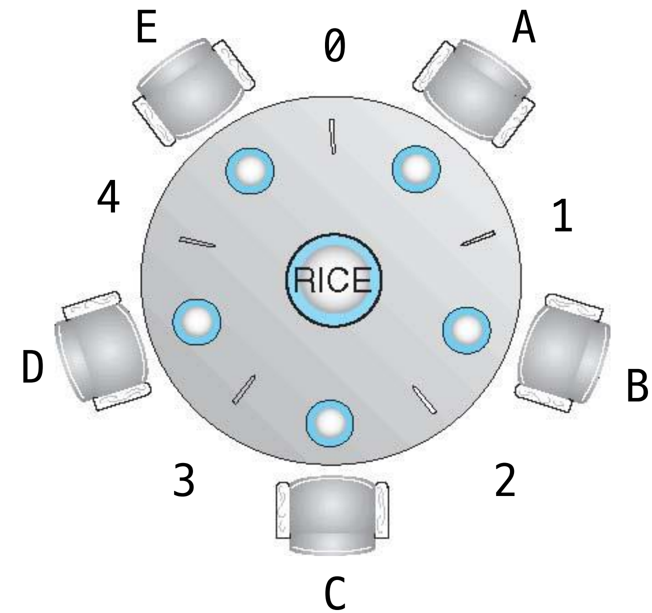
    Eating



Dining Philosopher (2)

A simple solution

```
Semaphore chopstick[N];  // initialized to 1
void philosopher (int i)
{
    while (1)  {
        think ();
        wait (chopstick[i]);
        wait (chopstick[(i+1) % N];
        eat ();
        signal (chopstick[i]);
        signal (chopstick[(i+1) % N];
    }
}
```



Problems with Semaphores

Drawbacks

- They are essentially shared global variables
  - Can be accessed from anywhere (bad software engineering)
- Used for both critical sections (mutual exclusion) and for coordination (scheduling)
- No control over their use, no guarantee of proper usage
- Incorrect use of semaphore operations:
  - signal (mutex) ... wait (mutex)
  - wait (mutex) ... wait (mutex)
  - Omitting of wait (mutex) or signal (mutex) (or both)
- Deadlock and starvation

Thus, hard to use and prone to bugs

- Another approach: use programming language support

Monitors (1)

Monitor

- A programming language construct that supports controlled access to shared data
  - Synchronization code added by compiler, enforced at runtime
  - Allows the safe sharing of an abstract data type among concurrent processes
- A monitor is a software module that encapsulates
  - Shared data structures
  - Procedures that operate on the shared data
  - Synchronization between concurrent processes that invoke those procedures
- Monitor protects the data from unstructured access
  - Guarantees only access data through procedures, hence in legitimate ways

Monitors (2)

Monitor example

- In Java, "synchronized" keyword

```
class A extends Thread {
        static int x;
        public void run() {
                add1();
                sub1();
        }
        void add1() {
                x=x+1;
        }
        void sub1() {
                x=x-1;
        }
}
```

```
class A extends Thread {
        static int x;
        public void run() {
                add1();
                sub1();
        }
        synchronized void add1() {
                x=x+1;
        }
        synchronized void sub1() {
                x=x-1;
        }
}
```

Synchronization Mechanisms

Spinlocks

- Busy waiting

H/W support

- TestAndSet
- SWAP

Disabling interrupts

Semaphores

- Binary semaphore = mutex (≅lock)
- Counting semaphore

Monitors

- Language construct with condition variables