Sistemi in tempo reale

Semaphores

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Outline

A general mechanism for blocking tasks

- The semaphore mechanism was first proposed by Dijkstra
- A semaphore is an abstract data type that consists of
  - a counter
  - a blocking queue
  - operation wait
  - operation signal
- The operations on a semaphore must be atomic
  - the OS makes them atomic by appropriate low-level mechanisms

Semaphore definition

- semaphores are a basic mechanisms for providing synchronization
- it has been shown that every kind of synchronization and mutual exclusion can be implemented by using sempahores
- we will analyze possible implementation of the semaphore mechanism later

```
class Semaphore {
  <blocked queue> blocked;
  int counter;
public:
  Semaphore (int n) : count (n) {...}
  void wait();
  void signal();
};
```

Wait and signal

- a wait operation has the following behavior:
  - if `counter == 0`, the requiring thread is blocked;
    - it is removed from the ready queue and inserted in the blocked queue;
  - if `counter > 0`, then `counter--`;
- a signal operation has the following behavior:
  - if `counter == 0` and there is some blocked thread, unblock it;
    - the thread is removed from the blocked queue and inserted in the ready queue
  - otherwise, increment counter;

Pseudo-code for wait and signal

```
class Semaphore {
  <blocked queue> blocked;
  int counter;
public:
  Semaphore (int n) : counter (n) {...}
  void wait() {
    if (counter == 0)
      <block the thread>
    else counter--;
  }
  void signal() {
    if (<some blocked thread>)
      <unblock the thread>
    else counter++;
  }
};
```

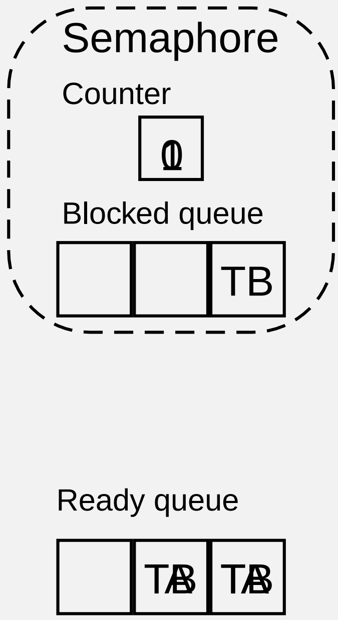
Mutual exclusion with semaphores

- To use a semaphore for mutual exclusions:
  - define a semaphore initialized to 1
  - before entering the critical section, perform a wait
  - after leaving the critical section, perform a signal

```
void *threadA(void *)
{
  ...
  s.wait();
  <critical section>
  s.signal();
  ...
}
```

```
void *threadB(void *)
{
  ...
  s.wait();
  <critical section>
  s.signal();
  ...
}
```

Mutual exclusion: example



example1.c

```
s.wait();                 (TA)
```

example1.c

```
s.wait();                 (TA)
<critical section (1)>    (TA)
```

example1.c

```
s.wait();                 (TA)
<critical section (1)>    (TA)
s.wait();                 (TB)
```

example1.c

```
s.wait();                 (TA)
<critical section (1)>    (TA)
s.wait();                 (TB)
<critical section (2)>    (TA)
```

example1.c

```
s.wait();                 (TA)
```

Synchronization with semaphores

- How to use a semaphore for synchronizing two or more threads
  - define a sempahore initialized to 0
  - at the syncronization point, the task to be blocked performs a `wait`
  - at the synchronization point, the other task performs a signal
- Example: thread A must block if it arrives at the synch point before thread B

```
Semaphore s(0);
```

```
void *threadA(void *) {
  ...
  s.wait();
  ...
}
```

```
void *threadB(void *) {
  ...
  s.signal();
  ...
}
```

Problem 1

- How to make each thread wait for the other one?
  - The first one that arrives at the synchronization point waits for the other one.
- Solution: use two semaphores!

```
Semaphore sa(0), sb(0);
```

```
void *threadA(void *) {
  ...
  sa.signal();
  sb.wait();
  ...
}
```

```
void *threadB(void *) {
  ...
  sb.signal();
  sa.wait();
  ...
}
```

Problem 2

- Generalize the previous synchronization problem to N threads
  - The first N-1 threads must block waiting for the last one
- First solution (more elegant)
- Second solution (more practical)

Producer / Consumer

- We now want ot implement a mailbox with a circular array
- avoiding busy wait
  - The producer must be blocked when the mailbox is full
  - The consumer must be blocked when the mailbox is empty
  - We use appropriate semaphores to block these threads
- Initially we consider only one producer and one consumer

Implementation

circulararray1.c

```
#define N 10

class CA {
    int array[N];
    int head(0);
    int tail(0);

    Semaphore empty(0);
    Semaphore full(N);
public:
    void insert(int elem);
    void extract(int &elem);
};
```

circulararray1.c

```
void CA::insert(int elem)
{
    full.wait();
    array[head++] = elem;
    head = head % N;
    empty.signal();
}

void CA::extract(int &elem)
{
    empty.wait();
    elem = array[tail++];
    tail = tail % N;
    full.signal();
}
```

Proof of correctness

- when the number of elements in the queue is between 1 and 9, there is no problem;
  - insert and extract work on different variables (head and tail respectively) and different elements of the array;
  - The value of full and empty is always greater than 0, so neither the producer nor the consumer can block;
- when there is no element in the queue, head = tail, counter of empty = 0, counter of full = N;
  - If the extract begins before the end of an insert, it will be blocked
  - After an insert, there is an element in the queue, so we are in the previous case
- For symmetry, the same holds for the case of N elements in the queue. Again, head = tail, counter of empty = N, counter of full = 0;
  - If the insert begins before the end of an extract, it will be blocked
  - After an extract, we fall back in the previous case

Multiple producers/consumers

- Suppose now there are mamy producers and many consumers;
- all producers will act on the same variable head, and all consumers on tail;
- If one producer preempts another producer, an inconsistency can arise
  - Exercise: prove the above sentence
- Therefore, we need to combine synchronization and mutual exclusion

First solution

circulararray-wrong.c

```
#define N 10

class CA {
    int array[N];
    int head(0);
    int tail(0);

    Semaphore empty(0);
    Semaphore full(N);
    Semaphore mutex(1);
public:
    void insert(int elem);
    void extract(int &elem);
};
```

circulararray-wrong.c

```
void CA::insert(int elem)
{
    mutex.wait();
    full.wait();
    array[head++] = elem;
    head = head % N;
    empty.signal();
    mutex.signal();
}

void CA::extract(int &elem)
{
    mutex.wait();
    empty.wait();
    elem = array[tail++];
    tail = tail % N;
    full.signal();
    mutex.signal();
}
```

Wrong solution

- The previous solution is wrong!
- Counter example:
  - A consumer thread executes first, locks the mutex and blocks on the empty semaphore
  - All other threads (producers or consumers) will block on the mutex
- Lesson learned: never block inside a mutex!

Deadlock

- Deadlock situation
  - A thread executes mutex.wait() and then blocks on a synchronisation semaphore
  - To be unblocked another thread must enter a critical section guarded by the same mutex semaphore
  - So, the first thread cannot be unblocked and free the mutex
  - The situation cannot be solved

Correct solution

circulararray-correct.c

```
#define N 10

class CA {
    int array[N];
    int head(0);
    int tail(0);

    Semaphore empty(0);
    Semaphore full(N);
    Semaphore mutex(1);
public:
    void insert(int elem);
    void extract(int &elem);
};
```

circulararray-correct.c

```
void CA::insert(int elem)
{
    full.wait();
    mutex.wait();
    array[head++] = elem;
    head = head % N;
    mutex.signal();
    empty.signal();
}

void CA::extract(int &elem)
{
    empty.wait();
    mutex.wait();
    elem = array[tail++];
    tail = tail % N;
    mutex.signal();
    full.signal();
}
```

Exercises

- Solve the previous exercise with two mutex (one for the consumers and one for the producers)
  - Prove the solution is correct
- Suppose there are one producer and N consumer. Every message has to be received by each consumer.
  - Write the data structure, the insert and extract functions
  - Suppose that extract() takes an additional arguments that specifies the consumer ID (between 0 and N-1).

First solution to problem 2

Elegant solution. Uses many semaphores! (with the pthread interface)

prob2-solution1.c

```
#include <stdio.h>
#include <pthread.h>
#include <semaphore.h>
#define N 8

sem_t s[N][N];

void init()
{
    int i, j;
    for (i=0; i<N; i++)
        for(j=0; j<N; j++)
            sem_init(&s[i][j], 0, 0);
}

void *thread(void *arg)
{
    int k = *((int *) arg); int j;
    printf("TH%d: before synch\n", k);
    for (j=0; j<N; j++)
        if (j!=k) sem_post(&s[k][j]);
    for (j=0; j<N; j++)
        if (j!=k) sem_wait(&s[j][k]);
    printf("TH%d: after synch\n", k);
    return 0;
}
```

prob2-solution1.c

```
int main()
{
    pthread_t tid[N];
    int i;
    int args[N];

    init();

    for (i=0; i<N; i++) {
        args[i] = i;
        pthread_create(&tid[i], 0, thread,
                       (void *)&args[i]);
    }
```

Second solution to problem 2

Practical solution. We need a mutex semaphore, a counter, and a semaphore to block threads. (with the pthread interface)

solution2.c

```
struct synch {
  int count;
  sem_t m; // mutex
  sem_t b; // blocked
  int N;   // number of threads
};

void initsynch(struct synch *s, int n)
{
  int i;
  s->count = 0;
  sem_init(&s->m, 0, 1);
  sem_init(&s->b, 0, 0);
  s->N = n;
}
```

solution2.c

```
void my_synch(struct synch *s)
{
  int i;
  sem_wait(&s->m);
  if (++s->count < s->N) {
    sem_post(&s->m);
    sem_wait(&s->b);
  }
  else {
    for (i=0; i < s->N - 1; i++)
      sem_post(&s->b);
    sem_post(&s->m);
  }
}

struct synch sp;

void *thread(void *arg)
{
  ...
  mysynch(&sp);
  ...
}
```