Semaphores (week 3)

INF4140 - Models of concurrency

Semaphores, lecture 3

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Overview

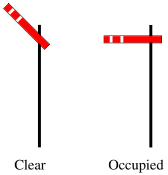
- Last lecture: Locks and Barriers (complex techniques)
    - No clear difference between variables for synchronization and variables for compute results.
    - Busy waiting.
- This lecture: Semaphores (synchronization tool)
    - Used easely for mutual exclusion and condition synchronization.
    - A way to implement signaling and (scheduling).
    - Can be implemented in many ways.

Outline

- Semaphores: Syntax and semantics
- Synchronization examples:
    - Mutual exclusion (Critical Section).
    - Barriers (signaling events).
    - Producers and consumers (split binary semaphores).
    - Bounded buffer (resource counting).
    - Dining philosophers (mutual exclusion - deadlock).
    - Reads and writers (condition synchronization - passing the baton).

Semaphores

- Introduced by Dijkstra in 1968
- “inspired” by railroad traffic synchronization
- railroad semaphore indicates whether the track ahead is clear or occupied by another train



Properties

- Semaphores in concurrent programs work in a similar way
- Used to implement mutex and condition synchronization
- Included in most standard libraries for concurrent programming
- also: system calls in e.g., Linux kernel, similar in Windows etc.

Concept

- semaphore: special kind of shared program variable (with built-in sync. power)
- value of a semaphore: a *non-negative* integer
- can *only* be manipulated by the following two atomic operations:[1]
  - **P:** (Passeren) Wait for signal - want to pass
    - effect: wait until the value is greater than zero, and decrease the value by one
  - **V:** (Vrijgeven) Signal an event - release
    - effect: increase the value by one
- nowadays, for libraries or sys-calls: other names are preferred (up/down, wait/signal, . . .)
- different "flavors" of semaphores (binary vs. counting)
- a mutex: basically used as synonym for binary semaphore

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[1] There are different stories about what Dijkstra actually wanted V and P stand for.

Syntax and semantics

- declaration of semaphores:
  - sem s; default initial value is zero
  - sem s = 1;
  - sem s[4] = ([4] 1);
- semantics[2] (via "implementation"):

P-operation P(s)

$\langle \texttt{await}(s > 0)\ s := s - 1 \rangle$

V-operation V(s)

$\langle s := s + 1 \rangle$

Important: No direct access to the value of a semaphore.
E.g. a test like

if *(s = 1)* ***then*** *....* ***else***

is *not* allowed!

---

[2] meaning

Kinds of semaphores

- Kinds of semaphores

  General semaphore: possible values — all non-negative integers

  Binary semaphore: possible values — 0 and 1

Fairness

- as for await-statements.
- In most languages: FIFO (“waiting queue”): processes delayed while executing P-operations are awaken in the order they where delayed

Example: Mutual exclusion (critical section)

Mutex[3] implemented by a binary semaphore

```
sem mutex := 1;
process CS[i = 1 to n] {
  while (true) {
    P(mutex);
      criticalsection;
    V(mutex);
    noncriticalsection;
}
```

Note:

- The semaphore is initially 1
- Always P before V → (used as) binary semaphore

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[3] As mentioned: "mutex" is also used to refer to a data-structure, basically the same as binary semaphore itself.

Example: Barrier synchronization

Semaphores may be used for signaling events

```
sem arrive1 = 0, arrive2 = 0;
process Worker1 {
                  ...
      V(arrive1);       reach the barrier
      P(arrive2);       wait for other processes
                  ...
}
process Worker2 {
                  ...
      V(arrive2);       reach the barrier
      P(arrive1);       wait for other processes
                  ...
}
```

Note:

- signalling semaphores: usually initialized to 0 and
- signal with a V and then wait with a P

Split binary semaphores

split binary semaphore

A set of semaphores, whose sum ≤ 1

mutex by split binary semaphores

- initialization: one of the semaphores =1, all others $= 0$
- discipline: all processes call P on a semaphore, before calling V on (another) semaphore

⇒ code between the P and the V

  - all semaphores $= 0$
  - code executed in mutex

Example: Producer/consumer with split binary semaphores

```
  T buf;  # one element buffer, some type T
sem empty := 1;
sem  full := 0;
```

```
process Producer {
  while (true) {
     P(empty);
    buff := data;
     V(full);
  }
}
```

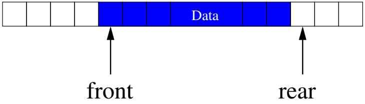
```
process Consumer {
  while (true) {
     P(full);
    buff := data;
     V(empty);
  }
}
```

Note:

- remember also P/C with await + exercise 1
- `empty` and `full` are both binary semaphores, together they form a split binary semaphore.
- solution works with several producers/consumers

Increasing buffer capacity

- previous example: strong coupling, the producer must wait for the consumer to empty the buffer before it can produce a new entry.
- easy to generalize to a buffer of size n.
- loose coupling/asynchronous communcation ⇒ “buffering”
  - ring-buffer, typically represented
    - by an array
    - + two integers `rear` and `front`.
  - semaphores to keep track of the number of free slots



Increasing buffer capacity

- previous example: strong coupling, the producer must wait for the consumer to empty the buffer before it can produce a new entry.
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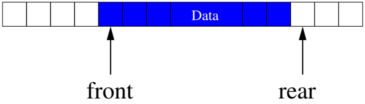


Producer/consumer: increased buffer capacity

```
T buf[n]                        # array, elements of type T
int front = 0, rear := 0; # ''pointers''
sem empty := n,
sem full = 0;
```

```
process Producer {                    process Consumer {
  while (true) {                        while (true) {
     P(empty);                             P(full);
     buff[rear] := data;                   result := buff[front];
     rear := (rear + 1) % n;               front  := (front + 1) % n
     V(full);                              V(empty);
  }                                     }
}                                     }
```

Producer/consumer: increased buffer capacity

```
T buf[n]                         # array, elements of type T
int front = 0, rear := 0;        # ''pointers''
sem empty := n,
sem full = 0;
```

```
process Producer {
  while (true) {
    P(empty);
    buff[rear] := data;
    rear := (rear + 1) % n;
    V(full);
  }
}
```

```
process Consumer {
  while (true) {
    P(full);
    result := buff[front];
    front  := (front + 1) % n
    V(empty);
  }
}
```

several producers or consumers?

Increasing the number of processes

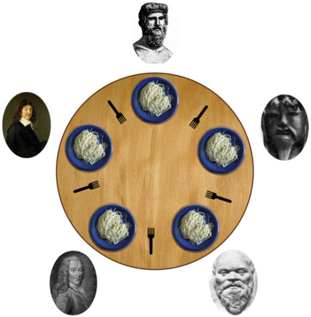
- several producers and consumers.
- New synchronization problems:
  - Avoid that two producers deposits to `buf[rear]` before `rear` is updated
  - Avoid that two consumers fetches from `buf[front]` before `front` is updated.
- Solution: 2 binary semaphores for protection
  - `mutexDeposit` to deny two producers to deposit to the buffer at the same time.
  - `mutexFetch` to deny two consumers to fetch from the buffer at the same time.

Example: Producer/consumer with several processes

```
T buf[n]                                  # array, elem's of type T
int front = 0, rear := 0;                 # ''pointers''
sem empty := n,
sem full = 0;
sem mutexDeposit, mutexFetch := 1;        # protect the data stuct.
```

```
process Producer {                        process Consumer {
  while (true) {                            while (true) {
    P(empty);                                 P(full);
    P(mutexDeposit);                          P(mutexFetch);
     buff[rear] := data;                       result := buff[front];
     rear := (rear + 1) % n;                   front  := (front + 1) % n
    V(mutexDeposit);                          V(mutexFetch);
    V(full);                                  V(empty);
  }                                         }
}                                         }
```

Problem: Dining philosophers introduction



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[4] image from wikipedia.org

Problem: Dining philosophers introduction

- famous sync. problem (Dijkstra)
- Five philosophers sit around a circular table.
- one fork placed between each pair of philosophers
- philosophers alternates between thinking and eating
- philosopher needs two forks to eat (and none for thinking)

---

[4] image from wikipedia.org

Dining philosophers: sketch

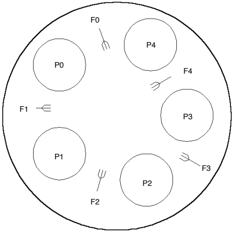
```
process Philosopher [i = 0 to 4] {
  while true {
    think;
    acquire forks;
    eat;
    release forks;
  }
}
```

now: program the actions `acquire forks` and `release forks`

Dining philosophers: 1st attempt

- forks as semaphores
- let the philosophers pick up the left fork first

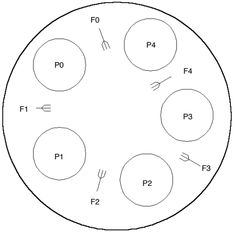
```
process Philosopher [i = 0 to 4] {
  while true {
    think;
    acquire forks;
    eat;
    release forks;
  }
}
```



Dining philosophers: 1st attempt

- forks as semaphores
- let the philosophers pick up the left fork first

```
sem fork[5] := ([5] 1);
process Philosopher [i = 0 to 4] {
  while true {
    think;
    P(fork[i];
    P(fork[(i+1)%5]);
    eat;
    V(fork[i];
    V(fork[(i+1)%5]);
  }
}
```



ok solution?

Example: Dining philosophers 2nd attempt

breaking the symmetry

To avoid deadlock, let 1 philospher (say 4) grab the right fork first

```
process Philosopher [i = 0 to 3] {
  while true {
    think;
    P(fork[i];
    P(fork[(i+1)%5]);
    eat;
    V(fork[i];
    V(fork[(i+1)%5]);
  }
}
```

```
process Philosopher4 {
  while true {
    think;
    P(fork[4];
    P(fork[0]);
    eat;
    V(fork[4];
    V(fork[0]);
  }
}
```

Example: Dining philosophers 2nd attempt

breaking the symmetry

To avoid deadlock, let 1 philospher (say 4) grab the right fork first

```
process Philosopher [i = 0 to 3] {
  while true {
    think;
    P(fork[i];
    P(fork[(i+1)%5]);
    eat;
    V(fork[i];
    V(fork[(i+1)%5]);
  }
}
```

```
process Philosopher4 {
  while true {
    think;
    P(fork[0]);
    P(fork[4];
    eat;
    V(fork[4];
    V(fork[0]);
  }
}
```

Dining philosphers

- important illustration of problems with concurrency:
  - deadlock
  - but also other aspects: liveness and fairness etc.
- resource access
- connection to mutex/critical sections

Example: Readers/Writers overview

- Classical synchronization problem
- Reader and writer processes, sharing access to a database
    - readers: read-only from the database
    - writers: update (and read from) the database

Example: Readers/Writers overview

- Classical synchronization problem
- Reader and writer processes, sharing access to a database
    - readers: read-only from the database
    - writers: update (and read from) the database
- R/R access unproblematic, W/W or W/R: interference
    - writers need mutually exclusive access
    - When no writers have access, many readers may access the database

Readers/Writers approaches

- Dining philosophers: Pair of processes compete for access to “forks”
- Readers/writers: Different classes of processes competes for access to the database
  - Readers compete with writers
  - Writers compete both with readers and other writers

- General synchronization problem:
  - readers: must wait until no writers are active in DB
  - writers: must wait until no readers or writers are active in DB

- here: two different approaches
  1. Mutex: easy to implement, but unfair
  2. Condition synchronization:
     - Using a split binary semaphore
     - Easy to adapt to different scheduling strategies

Readers/writers with mutex (1)

sem rw := 1

```
process Reader [i=1 to M] {
  while (true) {
    ...
    P(rw);

    read from DB

    V(rw);
  }
}
```

```
process Writer [i=1 to N] {
  while (true) {
    ...
    P(rw);

    write to DB

    V(rw);
  }
}
```

Readers/writers with mutex (1)

sem rw := 1

```
process Reader [i=1 to M] {
  while (true) {
    ...
    P(rw);

   read from DB

    V(rw);
  }
}
```

```
process Writer [i=1 to N] {
  while (true) {
    ...
    P(rw);

   write to DB

    V(rw);
  }
}
```

- safety ok
- but: unnessessarily cautious
- We want more than one reader simultaneously.

Readers/writers with mutex (2)

Initially:

```
int nr := 0;    # nunber of active readers
sem rw := 1     # lock for reader/writer mutex
```

```
process Reader [i=1 to M] {
  while (true) {
     ...
    < nr := nr + 1;
      if (n=1)  P(rw) > ;

    read from DB

    < nr := nr - 1;
      if (n=0)  V(rw) > ;
  }

}
```

```
process Writer [i=1 to N] {
  while (true) {
     ...

      P(rw);

    write to DB


      V(rw);
  }

}
```

Readers/writers with mutex (2)

Initially:

```
int nr := 0;    # nunber of active readers
sem rw := 1     # lock for reader/writer mutex
```

```
process Reader [i=1 to M] {
  while (true) {
    ...
   < nr := nr + 1;
     if (n=1)  P(rw) > ;

  read from DB

   < nr := nr - 1;
     if (n=0)  V(rw) > ;
  }

}
```

```
process Writer [i=1 to N] {
  while (true) {
    ...

    P(rw);

  write to DB


    V(rw);
  }

}
```

Semaphore inside await statement?

Readers/writers with mutex (3)

```
int     nr = 0;   # number of      active readers
sem     rw = 1;   # lock for reader/writer exclusion
sem mutexR = 1;   # mutex for readers

process Reader [i=1 to M] {
  while (true) {
    ...
      P(mutexR)
      nr := nr + 1;
      if (n=1)  P(rw);
      V(mutexR)

   read from DB

      P(mutexR)
     nr := nr - 1;
      if (n=0)  V(rw);
      V(mutexR)
  }
}
```

Readers/writers with mutex (3)

```
int      nr = 0;  # number of      active readers
sem      rw = 1;  # lock for reader/writer exclusion
sem mutexR = 1;   # mutex for readers

process Reader [i=1 to M] {
  while (true) {
    ...
      P(mutexR)
      nr := nr + 1;
      if (n=1)  P(rw);
      V(mutexR)

    read from DB

      P(mutexR)
     nr := nr - 1;
      if (n=0)  V(rw);
      V(mutexR)
  }
}
```

“Fairness”

What happens if we have a constant stream of readers?

Readers/writers with condition synchronization: overview

- mutex solution solved two separate synchronization problems
  - Reader vs. writer for access to the database
  - Reader vs. reader for access to the counter

- Now: a solution based on **condition synchronization**

Invariant

reasonable invariant[a]

- When a writer access the DB, no one else can
- When no writers access the DB, one or more readers may

---

[a] 2nd point: not technically an invariant.

- introduce two counters:
  - `nr`: number of active readers
  - `nw`: number of active writers

The invariant may be:

RW: $(nr = 0 \text{ or } nw = 0) \text{ and } nw \leq 1$

Code for "counting" readers and writers

Reader:

```
< nr := nr + 1; >
read from DB
< nr := nr - 1; >
```

Writer:

```
< nw := nw + 1; >
write to DB
< nw := nw - 1; >
```

- maintain invariant ⇒ add sync-code
- decrease counters: not dangerous
- before increasing though:
    - before increasing `nr`: `nw = 0`
    - before increasing `nw`: `nr = 0 and nw = 0`

condition synchronization/without semaphores

Initially:

```
int nr := 0;    # nunber of active readers
int nw := 0;    # number of active writers
sem rw := 1     # lock for reader/writer mutex

## Invariant RW: (nr = 0 or nw = 0) and nw <= 1
```

```
process Reader [i=1 to M]{
  while (true) {
    ...
    < await (nw=0)
      nr := nr+1>;
    read from DB;
    < nr := nr - 1>
  }
}
```

```
process Writer [i=1 to N]{
  while (true) {
    ...
    < await (nr = 0 or nw = 0)
      nw := nw+1>;
    write to DB;
    < nw := nw - 1>
  }
}
```

condition synchr.: converting to split binary semaphores

implementation of `awaits`: may be done by split binary semaphores

- May be used to implement different synchronization problems with different guards $\mathtt{B}_1$, $\mathtt{B}_2$...
- entry semaphore (`e`) initialized to 1
- For each guard $\mathtt{B}_i$:
  - associate 1 counter and
  - 1 delay-semaphore

  both initialized to 0
  - semaphore: delay the processes waiting for $\mathtt{B}_i$
  - counter: count the number of processes waiting for $\mathtt{B}_i$

⇒ for readers/writers problem: 3 semaphores and 2 counters:

```
sem e = 1;
sem r = 0; int dr = 0;     # condition reader:  nw == 0
sem w = 0; int dw = 0;     # condition writer:  nr == 0 and nw == 0
```

Condition synchr.: converting to split binary semaphores (2)

- `e`, `r` and `w` form a split binary semaphore.
- All execution paths starts with a P-operation and ends with a V-operation → Mutex
- We need a signal mechanism `SIGNAL` to pick which semaphore to signal.
- `SIGNAL` must make sure the invariant holds
- B_i holds when a process enters CR because either:
  - the process checks
  - the process is only signaled if B_i holds
- Avoid deadlock by checking the counters before the delay semaphores are signaled.
  - `r` is not signalled (`V(r)`) unless there is a delayed reader
  - `w` is not signalled (`V(w)`) unless there is a delayed writer

Condition synchr.: Reader

```
     int nr := 0, nw = 0;        # condition variables (as before)
     sem e := 1;                 # delay semaphore
     int dr := 0; sem r := 0;    # delay counter + sem for reader
     int dw := 0; sem w := 0;    # delay counter + sem for writer
   # invariant RW: (nr = 0 ∨ nw = 0 ) ∧ nw ≤ 1

process Reader [i=1 to M]{   # entry condition: nw = 0
  while (true) {
     ...
       P(e);
       if (nw > 0) { dr := dr + 1;      # < await (nw=0)
                     V(e);              #     nr:=nr+1 >
                     P(r)};
       nr:=nr+1; SIGNAL;

       read from DB;

       P(e); nr:=nr -1; SIGNAL;       # < nr:=nr−1 >
  }
}
```

With condition synchronization: Writer

```
process Writer [i=1 to N]{  # entry condition: nw = 0 and nr = 0
  while (true) {
    ...
      P(e);                       # < await (nr=0 ∧ nw=0)
      if (nr > 0 or nw > 0) {     #     nw:=nw+1 >
          dw := dw + 1;
          V(e);
          P(w) };
      nw:=nw+1; SIGNAL;

      write to DB;

      P(e);1nw:=nw −1; SIGNAL      # < nw:=nw−1>
  }
}
```

With condition synchronization: Signalling

- SIGNAL

```
if (nw = 0 and dr > 0) {
      dr := dr −1; V(r);                          # awaken reader
  }
elseif (nr = 0 and nw = 0 and dw > 0) {
      dw := dw −1; V(w);                          # awaken writer
  }
else
      V(e);                                       # release entry lock
```

[1] G. R. Andrews.
Foundations of Multithreaded, Parallel, and Distributed Programming.
Addison-Wesley, 2000.

[2] E. W. Dijkstra.
Solution of a problem in concurrent programming control.
Communications of the ACM, 8(9):569, 1965.