Concurrency: Mutual Exclusion and Synchronization

Chapter 5

Problems with concurrent execution

- Concurrent processes (or threads) often need to share data (maintained either in shared memory or files) and resources
- If there is no controlled access to shared data, some processes will obtain an inconsistent view of this data
- The action performed by concurrent processes will then depend on the order in which their execution is interleaved

An example

- Process P1 and P2 are running this same procedure and have access to the same variable "a"
- Processes can be interrupted anywhere
- If P1 is first interrupted after user input and P2 executes entirely
- Then the character echoed by P1 will be the one read by P2 !!

```
static char a;

void echo()
{
   cin >> a;
   cout << a;
}
```

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The critical section problem

- When a process executes code that manipulates shared data (or resource), we say that the process is in it's critical section (CS) (for that shared data)
- The execution of critical sections must be mutually exclusive: at any time, only one process is allowed to execute in its critical section (even with multiple CPUs)
- Then each process must request the permission to enter it's critical section (CS)

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The critical section problem

- The section of code implementing this request is called the entry section
- The critical section (CS) might be followed by an exit section
- The remaining code is the remainder section
- The critical section problem is to design a protocol that the processes can use so that their action will not depend on the order in which their execution is interleaved (possibly on many processors)

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Framework for analysis of solutions

- Each process executes at nonzero speed but no assumption on the relative speed of n processes
- General structure of a process:

```
repeat
  entry section
   critical section
  exit section
   remainder section
forever
```

- many CPU may be present but memory hardware prevents simultaneous access to the same memory location
- No assumption about order of interleaved execution
- For solutions: we need to specify entry and exit sections

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Requirements for a valid solution to the critical section problem

- **Mutual Exclusion**
  - At any time, at most one process can be in its critical section (CS)
- **Progress**
  - Only processes that are in their entry section can be selected to enter their CS. This selection cannot be postponed indefinitely

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Requirements for a valid solution to the critical section problem

- **Bounded Waiting**
  - After a process has made a request to enter it's CS, there is a bound on the number of times that the other processes are allowed to enter their CS
    - otherwise the process will suffer from starvation

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Types of solutions

- **Software solutions**
  - algorithms who’s correctness does not rely on any other assumptions (see framework)
- **Hardware solutions**
  - rely on some special machine instructions
- **Operation System solutions**
  - provide some functions and data structures to the programmer

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Software solutions

- **We consider first the case of 2 processes**
  - Algorithm 1 and 2 are incorrect
  - Algorithm 3 is correct (Peterson’s algorithm)
- **Then we generalize to n processes**
  - the bakery algorithm
- **Notation**
  - We start with 2 processes: P0 and P1
  - When presenting process Pi, Pj always denotes the other process (i != j)

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Algorithm 1

- The shared variable turn is initialized (to 0 or 1) before executing any Pi
- Pi's critical section is executed iff turn = i
- Pi is busy waiting if Pj is in CS: mutual exclusion is satisfied
- Progress requirement is not satisfied since it requires strict alternation of CSs
- Ex: if turn=0 and P0 is in it's RS, P1 can never enter it's CS

```
Process Pi:
repeat
  while(turn!=i){};
     CS
  turn:=j;
     RS
forever
```

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Algorithm 2

- Keep 1 Bool variable for each process: flag[0] and flag[1]
- Pi signals that it is ready to enter it's CS by: flag[i]:=true
- Mutual Exclusion is satisfied but not the progress requirement
- If we have the sequence:
  - T0: flag[0]:=true
  - T1: flag[1]:=true
- Both process will wait forever to enter their CS: we have a deadlock

```
Process Pi:
repeat
  flag[i]:=true;
  while(flag[j]){};
     CS
  flag[i]:=false;
     RS
forever
```

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Algorithm 3 (Peterson's algorithm)

- Initialization:
  flag[0]:=flag[1]:=false
  turn:= 0 or 1
- Willingness to enter CS specified by flag[i]:=true
- If both processes attempt to enter their CS simultaneously, only one `turn` value will last
- Exit section: specifies that Pi is unwilling to enter CS

```
Process Pi:
repeat
  flag[i]:=true;
  turn:=j;
  do {} while
  (flag[j]and turn=j);
     CS
  flag[i]:=false;
     RS
forever
```

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Algorithm 3: proof of correctness

- **Mutual exclusion is preserved since:**
  - P0 and P1 are both in CS only if flag[0] = flag[1] = true and only if turn = j for each Pi (impossible)
- **We now prove that the progress and bounded waiting requirements are satisfied:**
  - Pi cannot enter CS only if stuck in while() with condition flag[j] = true and turn = j.
  - If Pj is not ready to enter CS then flag[j] = false and Pi can then enter its CS

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Algorithm 3: proof of correctness (cont.)

- If Pj has set flag[j]=true and is in its while(), then either turn=i or turn=j
- If turn=i, then Pi enters CS. If turn=j then Pj enters CS but will then reset flag[j]=false on exit: allowing Pi to enter CS
- but if Pj has time to reset flag[j]=true, it must also set turn=i
- since Pi does not change value of turn while stuck in while(), Pi will enter CS after at most one CS entry by Pj (bounded waiting)

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n-process solution: bakery algorithm

- **Before entering their CS, each Pi receives a number. Holder of smallest number enter CS (like in bakeries, ice-cream stores...)**
- **When Pi and Pj receives same number:**
  - if i<j then Pi is served first, else Pj is served first
- **Pi resets its number to 0 in the exit section**
- **Notation:**
  - (a,b) < (c,d) if a < c or if a = c and b < d
  - max(a0,...ak) is a number b such that
    - b >= ai for i=0,..k

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The bakery algorithm (cont.)

- **Shared data:**
  - choosing: array[0..n-1] of boolean;
    - initialized to false
  - number: array[0..n-1] of integer;
    - initialized to 0
- **Correctness relies on the following fact:**
  - If Pi is in CS and Pk has already chosen its number[k]!= 0, then (number[i],i) < (number[k],k)
  - but the proof is somewhat tricky...

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The bakery algorithm (cont.)

```
Process Pi:
repeat
  choosing[i]:=true;
  number[i]:=max(number[0]..number[n-1])+1;
  choosing[i]:=false;
  for j:=0 to n-1 do {
    while (choosing[j]) {};
    while (number[j]!=0
       and (number[j],j)<(number[i],i)){};
  }
  CS
  number[i]:=0;
  RS
forever
```

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Drawbacks of software solutions

- Processes that are requesting to enter in their critical section are busy waiting (consuming processor time needlessly)
- If CSs are long, it would be more efficient to block processes that are waiting...

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Hardware solutions: interrupt disabling

- On a uniprocessor: mutual exclusion is preserved but efficiency of execution is degraded: while in CS, we cannot interleave execution with other processes that are in RS
- On a multiprocessor: mutual exclusion is not preserved
- Generally not an acceptable solution

```
Process Pi:
repeat
  disable interrupts
   critical section
  enable interrupts
   remainder section
forever
```

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Hardware solutions: special machine instructions

- Normally, access to a memory location excludes other access to that same location
- Extension: designers have proposed machines instructions that perform 2 actions atomically (indivisible) on the same memory location (ex: reading and testing)
- The execution of such an instruction is mutually exclusive (even with multiple CPUs)
- They can be used simply to provide mutual exclusion but need more complex algorithms for satisfying the 3 requirements of the CS problem

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The test-and-set instruction

- A C++ description of test-and-set:

```
bool testset(int& i)
{
  if (i==0) {
    i=1;
    return true;
  } else {
    return false;
  }
}
```

- An algorithm that uses testset for Mutual Exclusion:
- Shared variable b is initialized to 0
- Only the first Pi who sets b enter CS

```
Process Pi:
repeat
  repeat{}
  until testset(b);
     CS
  b:=0;
     RS
forever
```

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The test-and-set instruction (cont.)

- Mutual exclusion is preserved: if Pi enter CS, the other Pj are busy waiting
- When Pi exit CS, the selection of the Pj who will enter CS is arbitrary: no bounded waiting. Hence starvation is possible
- Processors (ex: Pentium) often provide an atomic xchg(a,b) instruction that swaps the content of a and b.
- But xchg(a,b) suffers from the same drawbacks as test-and-set

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Using xchg for mutual exclusion

- Shared variable b is initialized to 0
- Each Pi has a local variable k
- The only Pi that can enter CS is the one who finds b=0
- This Pi excludes all the other Pj by setting b to 1

```
Process Pi:
repeat
  k:=1
  repeat xchg(k,b)
  until k=0;
     CS
  b:=0;
     RS
forever
```

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Semaphores

- Synchronization tool (provided by the OS) that do not require busy waiting
- A semaphore S is an integer variable that, apart from initialization, can only be accessed through 2 atomic and mutually exclusive operations:
  - wait(S)
  - signal(S)
- To avoid busy waiting: when a process has to wait, it will be put in a blocked queue of processes waiting for the same event

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Semaphores

- Hence, in fact, a semaphore is a record (structure):

```
type semaphore = record
                   count: integer;
                   queue: list of process
                 end;
var S: semaphore;
```

- When a process must wait for a semaphore S, it is blocked and put on the semaphore’s queue
- The signal operation removes (acc. to a fair policy like FIFO) one process from the queue and puts it in the list of ready processes

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Semaphore's operations (atomic)

```
wait(S):
  S.count--;
  if (S.count<0) {
    block this process
    place this process in S.queue
  }
signal(S):
  S.count++;
  if (S.count<=0) {
    remove a process P from S.queue
    place this process P on ready list
  }
```

`S.count may be initialized to a nonnegative value (often = 1)`

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Semaphores: observations

- When S.count >=0: the number of processes that can execute wait(S) without being blocked = S.count
- When S.count<0: the number of processes waiting on S is = |S.count|
- Atomicity and mutual exclusion: no 2 process can be in wait(S) and signal(S) (on the same S) at the same time (even with multiple CPUs)
- This is a critical section problem: the critical sections are the blocks of code defining wait(S) and signal(S)

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Semaphores: observations

- **Hence: the critical sections here are very short: typically 10 instructions**
- **Solutions:**
  - uniprocessor: disable interrupts during these operations (ie: for a very short period). This does not work on a multiprocessor machine.
  - multiprocessor: use previous software or hardware schemes. The amount of busy waiting should be small.

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Using semaphores for solving critical section problems

- **For n processes**
- **Initialize S.count to 1**
- **Then only 1 process is allowed into CS (mutual exclusion)**
- **To allow k processes into CS, we initialize S.count to k**

```
Process Pi:
repeat
  wait(S);
   CS
  signal(S);
   RS
forever
```

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Using semaphores to synchronize processes

- We have 2 processes: P1 and P2
- Statement S1 in P1 needs to be performed before statement S2 in P2
- Then define a semaphore "synch"
- Initialize synch to 0
- Proper synchronization is achieved by having in P1:

```
S1;
signal(synch);
```

- And having in P2:

```
wait(synch);
S2;
```

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The producer/consumer problem

- A producer process produces information that is consumed by a consumer process
  - Ex1: a print program produces characters that are consumed by a printer
  - Ex2: an assembler produces object modules that are consumed by a loader
- We need a buffer to hold items that are produced and eventually consumed
- A common paradigm for cooperating processes

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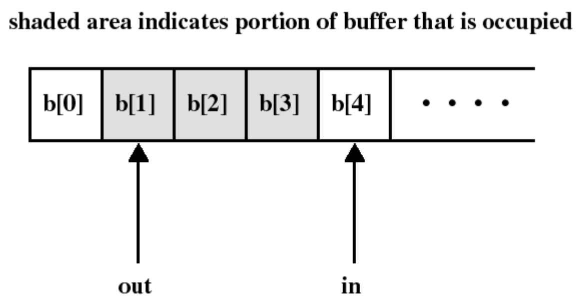
P/C: unbounded buffer

- We assume first an unbounded buffer consisting of a linear array of elements
- `in` points to the next item to be produced
- `out` points to the next item to be consumed



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P/C: unbounded buffer

- We need a semaphore S to perform mutual exclusion on the buffer: only 1 process at a time can access the buffer
- We need another semaphore N to synchronize producer and consumer on the number N (= in - out) of items in the buffer
  - an item can be consumed only after it has been created

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P/C: unbounded buffer

- The producer is free to add an item into the buffer at any time: it performs wait(S) before appending and signal(S) afterwards to prevent customer access
- It also performs signal(N) after each append to increment N
- The consumer must first do wait(N) to see if there is an item to consume and use wait(S)/signal(S) to access the buffer

Solution of P/C: unbounded buffer

```
Initialization:
  S.count:=1;
  N.count:=0;
  in:=out:=0;
```

```
append(v):
b[in]:=v;
in++;

take():
w:=b[out];
out++;
return w;
```

```
Producer:
repeat
  produce v;
  wait(S);
  append(v);
  signal(S);
  signal(N);
forever
```

```
Consumer:
repeat
  wait(N);
  wait(S);
  w:=take();
  signal(S);
  consume(w);
forever
```

■ critical sections

P/C: unbounded buffer

- **Remarks:**
  - Putting signal(N) inside the CS of the producer (instead of outside) has no effect since the consumer must always wait for both semaphores before proceeding
  - The consumer must perform wait(N) before wait(S), otherwise deadlock occurs if consumer enter CS while the buffer is empty
- **Using semaphores is a difficult art...**

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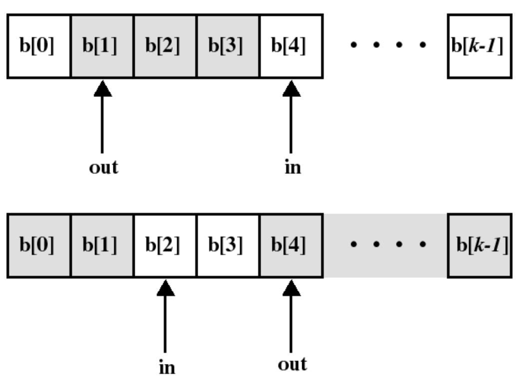
P/C: finite circular buffer of size k



- **can consume only when number N of (consumable) items is at least 1 (now: N!=in-out)**
- **can produce only when number E of empty spaces is at least 1**

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P/C: finite circular buffer of size k

- **As before:**
  - we need a semaphore S to have mutual exclusion on buffer access
  - we need a semaphore N to synchronize producer and consumer on the number of consumable items
- **In addition:**
  - we need a semaphore E to synchronize producer and consumer on the number of empty spaces

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Solution of P/C: finite circular buffer of size k

```
Initialization: S.count:=1;
                N.count:=0;
                E.count:=k;
```

```
append(v):
b[in]:=v;
in:=(in+1)
     mod k;

take():
w:=b[out];
out:=(out+1)
      mod k;
return w;
```

```
Producer:
repeat
  produce v;
  wait(E);
  wait(S);
  append(v);
  signal(S);
  signal(N);
forever
```

```
Consumer:
repeat
  wait(N);
  wait(S);
  w:=take();
  signal(S);
  signal(E);
  consume(w);
forever
```

- critical sections

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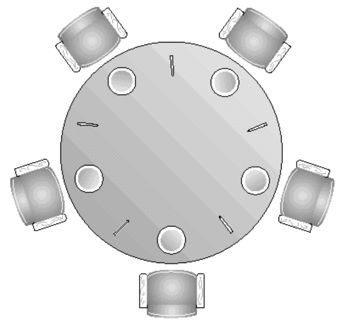
The Dining Philosophers Problem

- 5 philosophers who only eat and think
- each need to use 2 forks for eating
- we have only 5 forks
- a classical synchronization problem
- illustrates the difficulty of allocating resources among process without deadlock and starvation



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The Dining Philosophers Problem

- Each philosopher is a process
- One semaphore per fork:
  - fork: array[0..4] of semaphores
  - Initialization: fork[i].count:=1 for i:=0..4
- A first attempt:
- Deadlock if each philosopher start by picking his left fork!

```
Process Pi:
repeat
 think;
 wait(fork[i]);
 wait(fork[i+1 mod 5]);
 eat;
 signal(fork[1+1 mod 5]);
 signal(fork[i]);
forever
```

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The Dining Philosophers Problem

- A solution: admit only 4 philosophers at a time that tries to eat
- Then 1 philosopher can always eat when the other 3 are holding 1 fork
- Hence, we can use another semaphore T that would limit at 4 the numb. of philosophers "sitting at the table"
- Initialize: T.count:=4

```
Process Pi:
repeat
 think;
 wait(T);
 wait(fork[i]);
 wait(fork[i+1 mod 5]);
 eat;
 signal(fork[1+1 mod 5]);
 signal(fork[i]);
 signal(T);
forever
```

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Problems with Semaphores

- Semaphores provide a powerful tool for enforcing mutual exclusion and coordinate processes
- But wait(S) and signal(S) are scattered among several processes. Hence, difficult to understand their effects
- Usage must be correct in all the processes
- One bad (or malicious) process can fail the entire collection of processes

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Monitors

- **Are high-level language constructs that provide equivalent functionality to that of semaphores but are easier to control**
- **Found in many concurrent programming languages**
  - Concurrent Pascal, Modula-3, uC++, Java...
- **Can be implemented by semaphores...**

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Monitor

- **Is a software module containing:**
  - one or more procedures
  - an initialization sequence
  - local data variables
- **Characteristics:**
  - local variables accessible only by monitor's procedures
  - a process enters the monitor by invoking one of it's procedures
  - only one process can be in the monitor at any one time

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Monitor

- **The monitor ensures mutual exclusion: no need to program this constraint explicitly**
- **Hence, shared data are protected by placing them in the monitor**
  - The monitor locks the shared data on process entry
- **Process synchronization is done by the programmer by using condition variables that represent conditions a process may need to wait for before executing in the monitor**

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Condition Variables

- **are local to the monitor (accessible only within the monitor)**
- **can be access and changed only by two functions:**
  - cwait(a): blocks execution of the calling process on condition (variable) a
  - csignal(a): resume execution of some process blocked on condition (variable) a.
    - If several such process exists: choose any one
    - If no such process exists: do nothing

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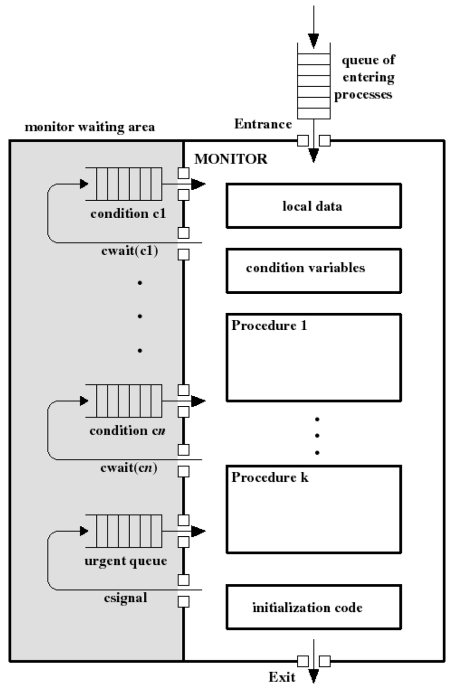
Monitor

- Awaiting processes are either in the entrance queue or in a condition queue
- A process puts itself into condition queue cn by issuing cwait(cn)
- csignal(cn) brings into the monitor 1 process in condition cn queue
- Hence csignal(cn) blocks the calling process and puts it in the urgent queue (unless csignal is the last operation of the monitor procedure)



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Producer/Consumer problem

- Two processes:
  - ◆ producer
  - ◆ consumer
- Synchronization is now confined within the monitor
- append(.) and take(.) are procedures within the monitor: are the only means by which P/C can access the buffer
- If these procedures are correct, synchronization will be correct for all participating processes

```
Producer:
repeat
  produce v;
  append(v);
forever

Consumer:
repeat
  take(v);
  consume v;
forever
```

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Monitor for the bounded P/C problem

- **Monitor needs to hold the buffer:**
  - buffer: array[0..k-1] of items;
- **needs two condition variables:**
  - notfull: true when buffer is not full
  - notemty: true when buffer is not empty
- **needs buffer pointers and counts:**
  - nextin: points to next item to be appended
  - nextout: points to next item to be taken
  - count: holds the number of items in buffer

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Monitor for the bounded P/C problem

```
Monitor boundedbuffer:
  buffer: array[0..k-1] of items;
  nextin, nextout, count: integer;
  notfull, notempty: condition;

  append(v):
    while (count=k) cwait(notfull);
    buffer[nextin]:= v;
    nextin:= nextin+1 mod k;
    count++;
    csignal(notempty);

  take(v):
    while (count=0) cwait(notempty);
    v:= buffer[nextout];
    nextout:= nextout+1 mod k;
    count--;
    csignal(notfull);
```

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Message Passing

- **Is a general method used for interprocess communication (IPC)**
  - for processes inside the same computer
  - for processes in a distributed system
- **Yet another mean to provide process synchronization and mutual exclusion**
- **We have at least two primitives:**
  - send(destination, message)
  - received(source, message)
- **In both cases, the process may or may not be blocked**

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Synchronization in message passing

- **For the sender: it is more natural not to be blocked after issuing send(.,.)**
  - can send several messages to multiple dest.
  - but sender usually expect acknowledgment of message receipt (in case receiver fails)
- **For the receiver: it is more natural to be blocked after issuing receive(.,.)**
  - the receiver usually needs the info before proceeding
  - but could be blocked indefinitely if sender process fails before send(.,.)

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Synchronization in message passing

- **Hence other possibilities are sometimes offered**
- **Ex: blocking send, blocking receive:**
  - both are blocked until the message is received
  - occurs when the communication link is unbuffered (no message queue)
  - provides tight synchronization (*rendez-vous*)

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Addressing in message passing

- **direct addressing:**
  - when a specific process identifier is used for source/destination
  - but it might be impossible to specify the source ahead of time (ex: a print server)
- **indirect addressing (more convenient):**
  - messages are sent to a shared mailbox which consists of a queue of messages
  - senders place messages in the mailbox, receivers pick them up

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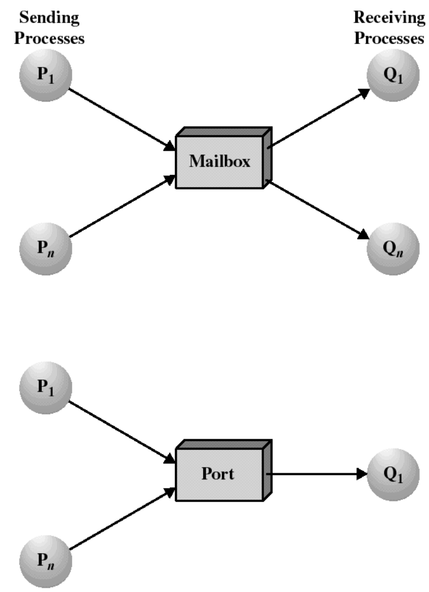
Mailboxes and Ports

- **A mailbox can be private to one sender/receiver pair**
- **The same mailbox can be shared among several senders and receivers**
  - the OS may then allow the use of message types (for selection)
- **Port: is a mailbox associated with one receiver and multiple senders**
  - used for client/server applications: the receiver is the server



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Ownership of ports and mailboxes

- **A port is usually owned and created by the receiving process**
- **The port is destroyed when the receiver terminates**
- **The OS creates a mailbox on behalf of a process (which becomes the owner)**
- **The mailbox is destroyed at the owner's request or when the owner terminates**

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Enforcing mutual exclusion with message passing

- **create a mailbox** *mutex* **shared by n processes**
- **send() is non blocking**
- **receive() blocks when** *mutex* **is empty**
- **Initialization: send(***mutex***, "go");**
- **The first Pi who executes receive() will enter CS. Others will be blocked until Pi resends msg.**

```
Process Pi:
var msg: message;
repeat
  receive(mutex,msg);
  CS
  send(mutex,msg);
  RS
forever
```

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The bounded-buffer P/C problem with message passing

- **We will now make use of messages**
- **The producer place items (inside messages) in the mailbox** *mayconsume*
- *mayconsume* **acts as our buffer: consumer can consume item when at least one message is present**
- **Mailbox** *mayproduce* **is filled initially with k null messages (k= buffer size)**
- **The size of** *mayproduce* **shrinks with each production and grows with each consumption**
- **can support multiple producers/consumers**

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The bounded-buffer P/C problem with message passing

```
Producer:
var pmsg: message;
repeat
  receive(mayproduce, pmsg);
  pmsg:= produce();
  send(mayconsume, pmsg);
forever

Consumer:
var cmsg: message;
repeat
  receive(mayconsume, cmsg);
  consume(cmsg);
  send(mayproduce, null);
forever
```

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