Concurrency and Synchronisation

1

Learning Outcomes

- Understand concurrency is an issue in operating systems and multithreaded applications
- Know the concept of a *critical region*.
- Understand how mutual exclusion of critical regions can be used to solve concurrency issues
    - Including how mutual exclusion can be implemented correctly and efficiently.
- Be able to identify and solve a *producer consumer bounded buffer* problem.
- Understand and apply standard synchronisation primitives to solve synchronisation problems.

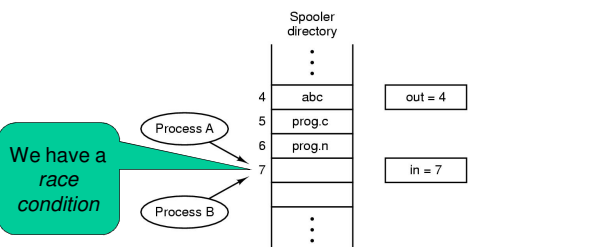2

Textbook

- Sections 2.3 - 2.3.7 & 2.5

3

Concurrency Example

`count` is a global variable shared between two threads.

After increment and decrement complete, what is the value of count?

```
void increment ()              void decrement ()
{                              {
   int t;                         int t;
   t = count;                     t = count;
   t = t + 1;                     t = t - 1;
   count = t;                     count = t;
}                              }
```
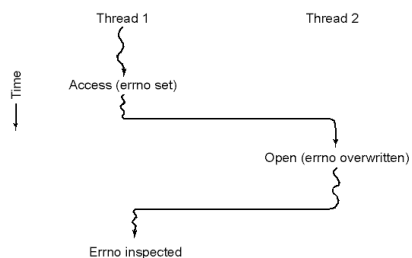
4

Inter- Thread and Process Communication

We have a *race condition*

Two processes want to access shared memory at same time

5

# Making Single-Threaded Code Multithreaded

Conflicts between threads over the use of a global variable

1

Critical Region

- We can control access to the shared resource by controlling access to the code that accesses the resource.
- ⇒ A *critical region* is a region of code where shared resources are accessed.
  - Variables, memory, files, etc…
- Uncoordinated entry to the critical region results in a race condition
  - ⇒ Incorrect behaviour, deadlock, lost work,…

Critical Regions
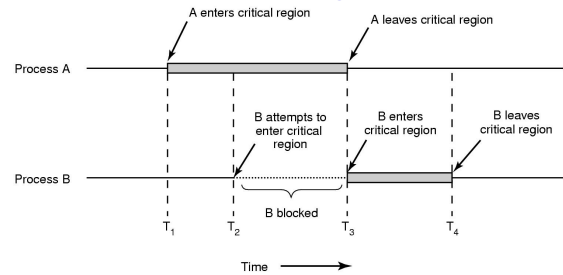
Mutual exclusion using critical regions

Identifying critical regions

- Critical regions are regions of code that:
  - Access a shared resource,
  - And correctness relies on the shared resource not being concurrently modified by another thread/process/entity.

Example critical regions

```
struct node {
    int data;
    struct node *next;
};
struct node *head;

void init(void)
{
    head = NULL;
}
```

- Simple last-in-first-out queue implemented as a linked list.

```
void insert(struct *item)
{
    item->next = head;
    head = item;
}

struct node *remove(void)
{
    struct node *t;
    t = head;
    if (t != NULL) {
        head = head->next;
    }
    return t;
}
```

Example Race

```
void insert(struct *item)
{
    item->next = head;
    head = item;
}
```

```
void insert(struct *item)
{
    item->next = head;
    head = item;
}
```

Example critical regions

```
struct node {
    int data;
    struct node *next;
};
struct node *head;

void init(void)
{
    head = NULL;
}
```

- Critical sections

```
void insert(struct *item)
{
    item->next = head;
    head = item;
}

struct node *remove(void)
{
    struct node *t;
    t = head;
    if (t != NULL) {
        head = head->next;
    }
    return t;
}
```

2

Critical Regions Solutions

Also called *critical sections*
Conditions required of any solution to the critical region problem
- Mutual Exclusion:
  - No two processes simultaneously in critical region
- No assumptions made about speeds or numbers of CPUs
- Progress
  - No process running outside its critical region may block another process
- Bounded
  - No process waits forever to enter its critical region

A solution?

- A lock variable
  - If lock == 1,
    - somebody is in the critical section and we must wait
  - If lock == 0,
    - nobody is in the critical section and we are free to enter

A solution?

```
while(TRUE) {              while(TRUE) {
  while(lock == 1);          while(lock == 1);
  lock = 1;                  lock = 1;
  critical();                critical();
  lock = 0                   lock = 0
  non_critical();            non_critical();
}                          }
```

A problematic execution sequence

```
while(TRUE) {
                          while(TRUE) {
                            while(lock == 1);
  while(lock == 1);
  lock = 1;
                            lock = 1;
  critical();    <——>      critical();
  lock = 0
  non_critical();
}                           lock = 0
                            non_critical();
                          }
```

Observation

- Unfortunately, it is usually easier to show something does not work, than it is to prove that it does work.
  - Easier to provide a counter example
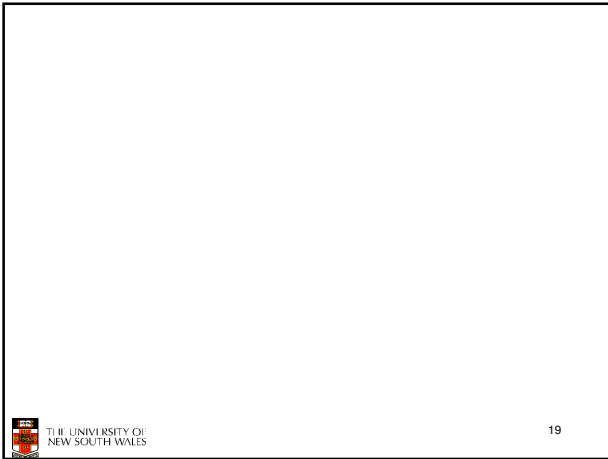 - Ideally, we'd like to prove, or at least informally demonstrate, that our solutions work.

Mutual Exclusion by Taking Turns

```
while (TRUE) {                    while (TRUE) {
  while (turn != 0)   /* loop */ ;   while (turn != 1)   /* loop */ ;
  critical_region();                 critical_region();
  turn = 1;                          turn = 0;
  noncritical_region();              noncritical_region();
}                                  }

        (a)                                (b)
```

Proposed solution to critical region problem
(a) Process 0.   (b) Process 1.

Mutual Exclusion by Taking Turns

- Works due to *strict alternation*
  - Each process takes turns
- Cons
  - Busy waiting
  - Process must wait its turn even while the other process is doing something else.
    - With many processes, must wait for everyone to have a turn
      - Does not guarantee progress if a process no longer needs a turn.
    - Poor solution when processes require the critical section at differing rates

Peterson's Solution

- See the textbook

Mutual Exclusion by Disabling Interrupts

- Before entering a critical region, disable interrupts
- After leaving the critical region, enable interrupts
- Pros
  - simple
- Cons
  - Only available in the kernel
  - Blocks everybody else, even with no contention
    - Slows interrupt response time
  - Does not work on a multiprocessor

Hardware Support for mutual exclusion

- Test and set instruction
  - Can be used to implement lock variables correctly
    - It loads the value of the lock
    - If lock == 0,
      - set the lock to 1
      - return the result 0 – we acquire the lock
    - If lock == 1,
      - return 1 – another thread/process has the lock
  - Hardware guarantees that the instruction executes atomically.
    - Atomically: As an indivisible unit.

Mutual Exclusion with Test-and-Set

```
enter_region:
    TSL REGISTER,LOCK        | copy lock to register and set lock to 1
    CMP REGISTER,#0          | was lock zero?
    JNE enter_region         | if it was non zero, lock was set, so loop
    RET | return to caller; critical region entered


leave_region:
    MOVE LOCK,#0             | store a 0 in lock
    RET | return to caller
```

Entering and leaving a critical region using the TSL instruction

Test-and-Set

- Pros
  - Simple (easy to show it's correct)
  - Available at user-level
    - To any number of processors
    - To implement any number of lock variables
- Cons
  - Busy waits (also termed a *spin lock*)
    - Consumes CPU
    - Livelock in the presence of priorities
      - If a low priority process has the lock and a high priority process attempts to get it, the high priority process will busy-wait forever.
    - Starvation is possible when a process leaves its critical section and more than one process is waiting.

25

Tackling the Busy-Wait Problem

- Sleep / Wakeup
  - The idea
    - When process is waiting for an event, it calls sleep to block, instead of busy waiting.
    - The event happens, the event generator (another process) calls wakeup to unblock the sleeping process.
   - Waking a ready/running process has no effect.

26

The Producer-Consumer Problem

- Also called the *bounded buffer* problem
- A producer produces data items and stores the items in a buffer
- A consumer takes the items out of the buffer and consumes them.

Producer

Consumer

27
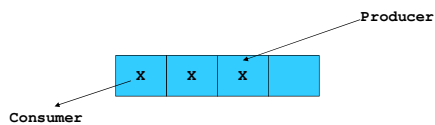
Issues

- We must keep an accurate count of items in buffer
  - Producer
    - can sleep when the buffer is full,
    - and wakeup when there is empty space in the buffer
      - The consumer can call wakeup when it consumes the first entry of the full buffer
  - Consumer
    - Can sleep when the buffer is empty
    - And wake up when there are items available
      - Producer can call wakeup when it adds the first item to the buffer

Producer

Consumer

28
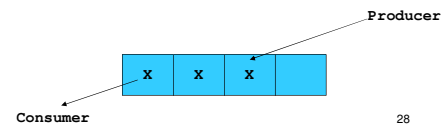
Pseudo-code for producer and consumer

```
int count = 0;
#define N 4 /* buf size */
prod() {
   while(TRUE) {
      item = produce()
      if (count == N)
            sleep();
      insert_item();
      count++;
      if (count == 1)
            wakeup(con);
   }
}
```

```
con() {
   while(TRUE) {
      if (count == 0)
            sleep();
      remove_item();
      count--;
      if (count == N-1)
            wakeup(prod);
   }
}
```

29

Problems

```
int count = 0;
#define N 4 /* buf size */
prod() {
   while(TRUE) {
      item = produce()
      if (count == N)
            sleep();
      insert_item();
      count++;
      if (count == 1)
            wakeup(con);
   }
}
```

```
con() {
   while(TRUE) {
      if (count == 0)
            sleep();
      remove_item();
      count--;
      if (count == N-1)
            wakeup(prod);
   }
}
```

Concurrent uncontrolled access to the buffer

30

5

Problems

```
int count = 0;
#define N 4 /* buf size */
prod() {
    while(TRUE) {
        item = produce()
        if (count == N)
            sleep();
        insert_item();
        count++;
        if (count == 1)
            wakeup(con);
    }
}
```

```
con() {
    while(TRUE) {
        if (count == 0)
            sleep();
        remove_item();
        count--;
        if (count == N-1)
            wakeup(prod);
    }
}
```

Concurrent uncontrolled access to the counter

Proposed Solution

- Lets use a locking primitive based on test-and-set to protect the concurrent access

---

Proposed solution?

```
int count = 0;
#define N 4 /* buf size */
prod() {
    while(TRUE) {
        item = produce()
        if (count == N)
            sleep();
        acquire_lock()
        insert_item();
        count++;
        release_lock()
        if (count == 1)
            wakeup(con);
    }
}
```

```
con() {
    while(TRUE) {
        if (count == 0)
            sleep();
        acquire_lock()
        remove_item();
        count--;
        release_lock();
        if (count == N-1)
            wakeup(prod);
    }
}
```

Problematic execution sequence

```
                                    con() {
                                        while(TRUE) {
                                            if (count == 0)
prod() {
    while(TRUE) {
        item = produce()
        if (count == N)
            sleep();
        acquire_lock()
        insert_item();
        count++;
        release_lock()
        if (count == 1)
            wakeup(con);
                                            sleep();
                                        acquire_lock()
                                        remove_item();
                                        count--;
                                        release_lock();
                                        if (count == N-1)
                                            wakeup(prod);
    }                               }
}                               }
```

wakeup without a matching sleep is lost

Problem

- The test for *some condition* and actually going to sleep needs to be atomic
- The following does not work:

The lock is held while asleep ⇒ count will never change

```
acquire_lock()
if (count == N)
        sleep();
release_lock()
```

```
acquire_lock()
if (count == 1)
            wakeup();
release_lock()
```

Semaphores

- Dijkstra (1965) introduced two primitives that are more powerful than simple sleep and wakeup alone.
  - P(): *proberen,* from Dutch *to test.*
  - V(): *verhogen,* from Dutch *to increment.*
  - Also called *wait* & *signal, down* & *up.*

How do they work

- If a resource is not available, the corresponding semaphore blocks any process waiting for the resource
- Blocked processes are put into a process queue maintained by the semaphore (avoids busy waiting!)
- When a process releases a resource, it signals this by means of the semaphore
- Signalling resumes a blocked process if there is any
- Wait and signal operations cannot be interrupted
- Complex coordination can be implemented by multiple semaphores

37

Semaphore Implementation

- Define a semaphore as a record

```
typedef struct {
    int count;
    struct process *L;
} semaphore;
```

- Assume two simple operations:
  - **sleep** suspends the process that invokes it.
  - **wakeup(P)** resumes the execution of a blocked process **P**.

38

- Semaphore operations now defined as

  wait(S):
```
        S.count--;
        if (S.count < 0) {
                add this process to S.L;
                sleep;
        }
```

  signal(S):
```
        S.count++;
        if (S.count <= 0) {
                remove a process P from S.L;
                wakeup(P);
        }
```
- Each primitive is atomic
  - E.g. interrupts are disabled for each

39

Semaphore as a General Synchronization Tool

- Execute B in P_j only after A executed in P_i
- Use semaphore *count* initialized to 0
- Code:

P_i	P_j
⋮	⋮
A	*wait*(*flag*)
signal(*flag*)	B

40

Semaphore Implementation of a Mutex

- Mutex is short for Mutual Exclusion
  - Can also be called a lock

```
semaphore mutex;
mutex.count = 1; /* initialise mutex */

wait(mutex); /* enter the critcal region */

Blahblah();

signal(mutex); /* exit the critical region */
```
Notice that the initial count determines how many waits can progress before blocking and requiring a signal ⇒ mutex.count initialised as 1

41

Solving the producer-consumer problem with semaphores

```
#define N = 4

semaphore mutex = 1;

/* count empty slots */
semaphore empty = N;

/* count full slots */
semaphore full = 0;
```

42

Solving the producer-consumer problem with semaphores

```
prod() {                        con() {
   while(TRUE) {                   while(TRUE) {
      item = produce()                wait(full);
      wait(empty);                    wait(mutex);
      wait(mutex)                     remove_item();
      insert_item();                  signal(mutex);
      signal(mutex);                  signal(empty);
      signal(full);                }
   }                            }
}
```

Summarising Semaphores

- Semaphores can be used to solve a variety of concurrency problems
- However, programming with then can be error-prone
  - E.g. must *signal* for every *wait* for mutexes
    - Too many, or too few signals or waits, or signals and waits in the wrong order, can have catastrophic results

Monitors

- To ease concurrent programming, Hoare (1974) proposed *monitors.*
  - A higher level synchronisation primitive
  - Programming language construct
- Idea
  - A set of procedures, variables, data types are grouped in a special kind of module, a *monitor.*
    - Variables and data types only accessed from within the monitor
  - Only one process/thread can be in the monitor at any one time
    - Mutual exclusion is implemented by the compiler (which should be less error prone)

Monitor

- When a thread calls a monitor procedure that has a thread already inside, it is queued and it sleeps until the current thread exits the monitor.
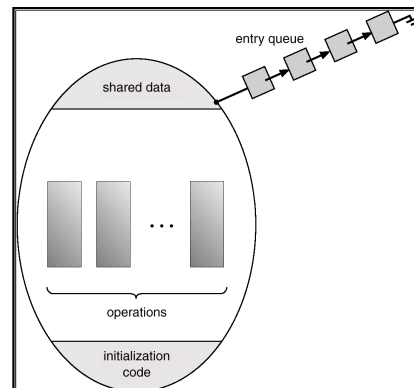
Monitors

```
monitor example
    integer i;
    condition c;

    procedure producer( );
    .
    .
    .
    end;

    procedure consumer( );
    .
    .
    .
    end;
end monitor;
```

Example of a monitor

Simple example

```
monitor counter {
  int count;
  procedure inc() {
     count = count + 1;
  }
  procedure dec() {
     count = count -1;
  }
}
```

Note: "paper" language
- Compiler guarantees only one thread can be active in the monitor at any one time
- Easy to see this provides mutual exclusion
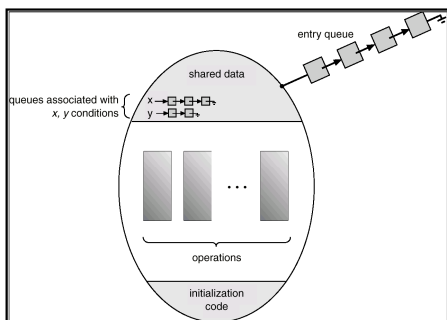 - No race condition on **count**.

How do we block waiting for an event?

- We need a mechanism to block waiting for an event (in addition to ensuring mutual exclusion)
  - e.g., for producer consumer problem when buffer is empty or full
- *Condition Variables*

49

Condition Variable

- To allow a process to wait within the monitor, a **condition** variable must be declared, as

  condition x, y;
- Condition variable can only be used with the operations **wait** and **signal**.
  - The operation
    x.wait();
    means that the process invoking this operation is suspended until another process invokes
    x.signal();
  - The **x.signal** operation resumes exactly one suspended process. If no process is suspended, then the **signal** operation has no effect.

50

Condition Variables

51

Monitors

- Outline of producer-consumer problem with monitors
  - only one monitor procedure active at one time
  - buffer has *N* slots

OS/161 Provided Synchronisation Primitives

- Locks
- Semaphores
- Condition Variables

53

Locks

- **Functions to create and destroy locks**

```
struct lock *lock_create(const char *name);
void        lock_destroy(struct lock *);
```

- **Functions to acquire and release them**

```
void        lock_acquire(struct lock *);
void        lock_release(struct lock *);
```

54

Example use of locks

```
int count;
struct lock *count_lock

main() {
   count = 0;
   count_lock =
      lock_create("count
lock");
   if (count_lock == NULL)
      panic("I'm dead");
   stuff();
}
```

```
procedure inc() {
   lock_acquire(count_lock);
   count = count + 1;
   lock_release(count_lock);
}
procedure dec() {
   lock_acquire(count_lock);
   count = count -1;
   lock_release(count_lock);
}
```

Semaphores

```
struct semaphore *sem_create(const char *name, int
                             initial_count);
void           sem_destroy(struct semaphore *);

void           P(struct semaphore *);
void           V(struct semaphore *);
```

Example use of Semaphores

```
int count;
struct semaphore
  *count_mutex;

main() {
   count = 0;
   count_mutex =
      sem_create("count",
              1);
   if (count_mutex == NULL)
      panic("I'm dead");
   stuff();
}
```

```
procedure inc() {
   P(count_mutex);
   count = count + 1;
   V(count_mutex);
}
procedure dec() {
   P(count_mutex);
   count = count -1;
   V(count_mutex);
}
```

Condition Variables

```
struct cv *cv_create(const char *name);
void      cv_destroy(struct cv *);

void      cv_wait(struct cv *cv, struct lock *lock);
```
   – Releases the lock and blocks
   – Upon resumption, it re-acquires the lock
     • Note: we must recheck the condition we slept on

```
void      cv_signal(struct cv *cv, struct lock *lock);
void      cv_broadcast(struct cv *cv, struct lock *lock);
```
   – Wakes one/all, does not release the lock
   – First "waiter" scheduled after signaller releases the lock will re-acquire the lock

Note: All three variants must hold the lock passed in.

Condition Variables and Bounded Buffers

Non-solution
```
lock_acquire(c_lock)

if (count == 0)
        sleep();

remove_item();

count--;

lock_release(c_lock);
```

Solution
```
lock_acquire(c_lock)

while (count == 0)
  cv_wait(c_cv, c_lock);

remove_item();

count--;

lock_release(c_lock);
```

A Producer-Consumer Solution Using OS/161 CVs

```
int count = 0;
#define N 4 /* buf size */
prod() {                          con() {
   while(TRUE) {                     while(TRUE) {
      item = produce()                  lock_aquire(l)
      lock_aquire(l)                    while (count == 0)
      while (count == N)                   cv_wait(empty,l);
         cv_wait(full,l);               item = remove_item();
      insert_item(item);                count--;
      count++;                          if (count == N-1)
      if (count == 1)                      cv_signal(full,l);
         cv_signal(empty,l);           lock_release(l);
      lock_release(l)                  consume(item);
   }                                 }
}                                 }
```

Dining Philosophers

- Philosophers eat/think
- Eating needs 2 forks
- Pick one fork at a time
- How to prevent deadlock
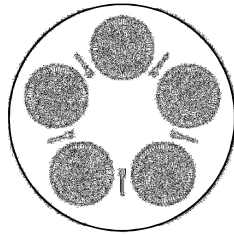
Dining Philosophers

```
#define N            5              /* number of philosophers */
#define LEFT         (i+N−1)%N      /* number of i's left neighbor */
#define RIGHT        (i+1)%N        /* number of i's right neighbor */
#define THINKING     0              /* philosopher is thinking */
#define HUNGRY       1              /* philosopher is trying to get forks */
#define EATING       2              /* philosopher is eating */
typedef int semaphore;             /* semaphores are a special kind of int */
int state[N];                      /* array to keep track of everyone's state */
semaphore mutex = 1;               /* mutual exclusion for critical regions */
semaphore s[N];                    /* one semaphore per philosopher */

void philosopher(int i)            /* i: philosopher number, from 0 to N−1 */
{
    while (TRUE) {                 /* repeat forever */
        think( );                  /* philosopher is thinking */
        take_forks(i);             /* acquire two forks or block */
        eat( );                    /* yum-yum, spaghetti */
        put_forks(i);              /* put both forks back on table */
    }
}
```

Solution to dining philosophers problem (part 1)

Dining Philosophers

```
#define N 5                         /* number of philosophers */

void philosopher(int i)             /* i: philosopher number, from 0 to 4 */
{
    while (TRUE) {
        think( );                   /* philosopher is thinking */
        take_fork(i);               /* take left fork */
        take_fork((i+1) % N);       /* take right fork; % is modulo operator */
        eat( );                     /* yum-yum, spaghetti */
        put_fork(i);                /* put left fork back on the table */
        put_fork((i+1) % N);        /* put right fork back on the table */
    }
}
```

A <u>non</u>solution to the dining philosophers problem

Dining Philosophers

```
void take_forks(int i)              /* i: philosopher number, from 0 to N−1 */
{
    down(&mutex);                   /* enter critical region */
    state[i] = HUNGRY;              /* record fact that philosopher i is hungry */
    test(i);                        /* try to acquire 2 forks */
    up(&mutex);                     /* exit critical region */
    down(&s[i]);                    /* block if forks were not acquired */
}

void put_forks(i)                   /* i: philosopher number, from 0 to N−1 */
{
    down(&mutex);                   /* enter critical region */
    state[i] = THINKING;            /* philosopher has finished eating */
    test(LEFT);                     /* see if left neighbor can now eat */
    test(RIGHT);                    /* see if right neighbor can now eat */
    up(&mutex);                     /* exit critical region */
}

void test(i)                        /* i: philosopher number, from 0 to N−1 */
{
    if (state[i] == HUNGRY && state[LEFT] != EATING && state[RIGHT] != EATING) {
        state[i] = EATING;
        up(&s[i]);
    }
}
```

Solution to dining philosophers problem (part 2)

The Readers and Writers Problem

- Models access to a database
  - E.g. airline reservation system
  - Can have more than one concurrent reader
    - To check schedules and reservations
  - Writers must have exclusive access
    - To book a ticket or update a schedule

The Readers and Writers Problem

```
typedef int semaphore;              /* use your imagination */
semaphore mutex = 1;                /* controls access to 'rc' */
semaphore db = 1;                   /* controls access to the database */
int rc = 0;                         /* # of processes reading or wanting to */

void reader(void)
{
     while (TRUE) {                 /* repeat forever */
          down(&mutex);             /* get exclusive access to 'rc' */
          rc = rc + 1;              /* one reader more now */
          if (rc == 1) down(&db);   /* if this is the first reader ... */
          up(&mutex);               /* release exclusive access to 'rc' */
          read_data_base( );        /* access the data */
          down(&mutex);             /* get exclusive access to 'rc' */
          rc = rc - 1;              /* one reader fewer now */
          if (rc == 0) up(&db);     /* if this is the last reader ... */
          up(&mutex);               /* release exclusive access to 'rc' */
          use_data_read( );         /* noncritical region */
     }
}

void writer(void)
{
     while (TRUE) {                 /* repeat forever */
          think_up_data( );         /* noncritical region */
          down(&db);                /* get exclusive access */
          write_data_base( );       /* update the data */
          up(&db);                  /* release exclusive access */
     }
}
```

A solution to the readers and writers problem