Part III
Synchronization
Monitors

You cannot build (or understand) a modern operating system unless you know the principles of concurrent programming.

Per Brinch Hansen

What Will Be Covered?

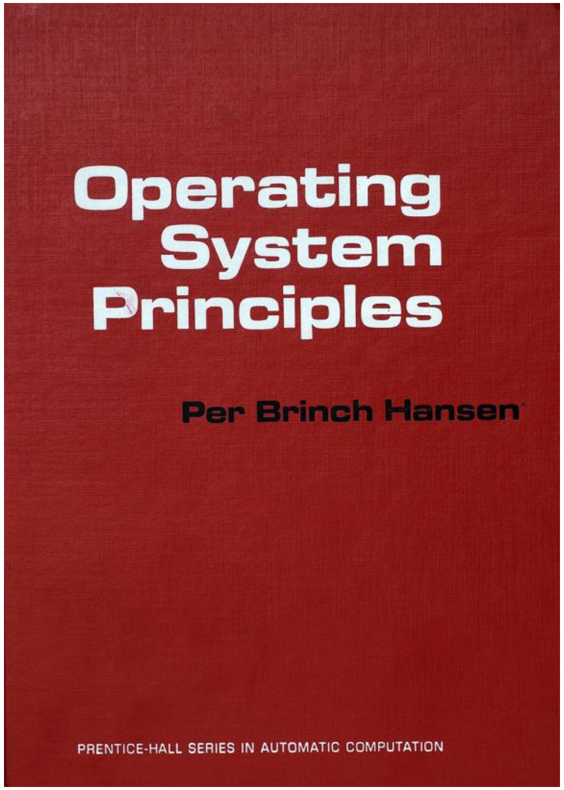
- **Some historical remarks**
- **Monitor Basics**
- **What is a condition variable?**
- **Condition variable `wait` and `signal`**
- **Two Types of monitors: Hoare and Mesa**
- **Examples**
- **Hoare type vs. Mesa type and Semaphores vs. Monitors**
- **ThreadMentor Monitor Programming**
- **ThreadMentor Monitor Visualization**

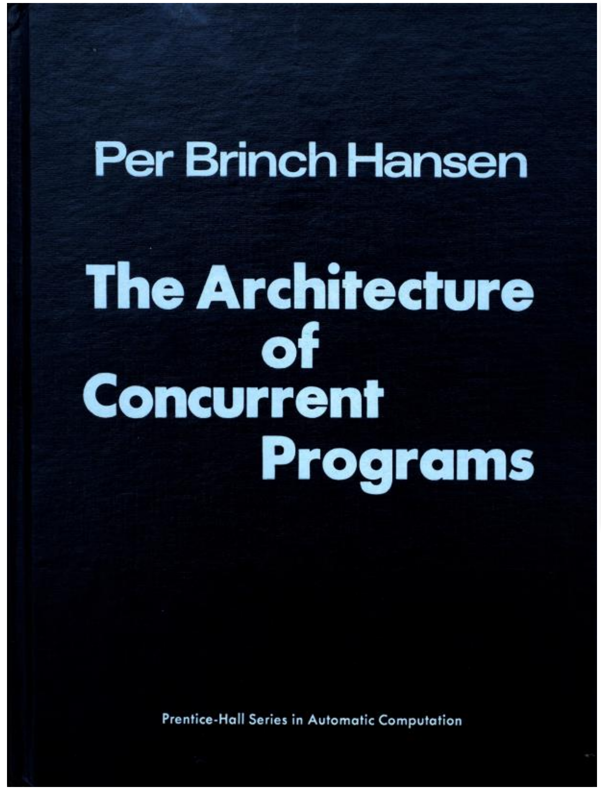
Some Historical Remarks: 1/2

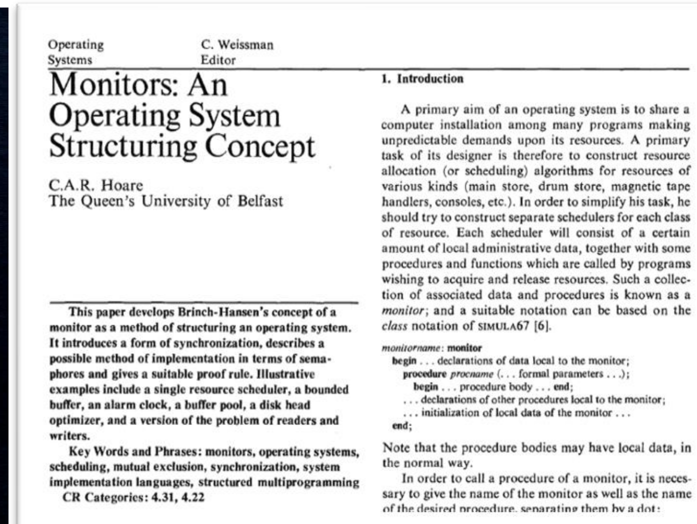
- The concept of a monitor was invented by Per Brinch Hansen in early 1970s.
- Per Brinch Hansen used the concept of class in Simula 67 and defined a shared class as the beginning of today's monitor.
- C. A. R. Hoare refined Hansen's work to become today's monitor in 1974.
- Hansen is also considered as a pioneer of concurrent programming. His *Concurrent Pascal* language used monitors for synchronization.

Per Brinch Hansen, *Operating System Principles*, Prentice-Hall, 1973 (Section 7.2)
Per Brinch Hansen, The Programming Language Concurrent Pascal,
IEEE Transactions on Software Engineering, Vol. 1 (1975), No. 2 (June), pp. 210-217.
C. A. R. Hoare, Monitors: An Operating System Structuring Concept,
Communications of the ACM, Vol. 17 (1974), No. 10, pp. 549-557.

Some Historical Remarks: 2/2







Operating Systems — C. Weissman, Editor

Monitors: An Operating System Structuring Concept

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This paper develops Brinch-Hansen's concept of a monitor as a method of structuring an operating system. It introduces a form of synchronization, describes a possible method of implementation in terms of semaphores and gives a suitable proof rule. Illustrative examples include a single resource scheduler, a bounded buffer, an alarm clock, a buffer pool, a disk head optimizer, and a version of the problem of readers and writers.

Key Words and Phrases: monitors, operating systems, scheduling, mutual exclusion, synchronization, system implementation languages, structured multiprogramming

CR Categories: 4.31, 4.22

1. Introduction

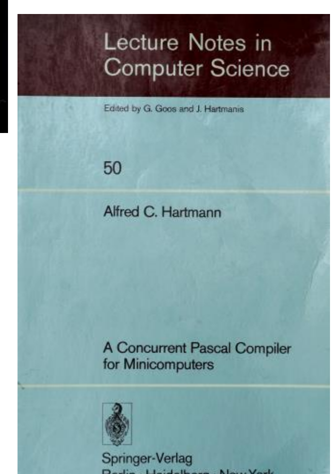
A primary aim of an operating system is to share a computer installation among many programs making unpredictable demands upon its resources. A primary task of its designer is therefore to construct resource allocation (or scheduling) algorithms for resources of various kinds (main store, drum store, magnetic tape handlers, consoles, etc.). In order to simplify his task, he should try to construct separate schedulers for each class of resource. Each scheduler will consist of a certain amount of local administrative data, together with some procedures and functions which are called by programs wishing to acquire and release resources. Such a collection of associated data and procedures is known as a *monitor*; and a suitable notation can be based on the *class* notation of SIMULA67 [6].

```
monitorname: monitor
  begin ... declarations of data local to the monitor;
    procedure procname (... formal parameters ...);
      begin ... procedure body ... end;
    ... declarations of other procedures local to the monitor;
    ... initialization of local data of the monitor ...
  end;
```

Note that the procedure bodies may have local data, in the normal way.

In order to call a procedure of a monitor, it is necessary to give the name of the monitor as well as the name of the desired procedure, separating them by a dot:

Hoare's work on refining the concept of monitor was published in 1974.



Hansen's landmark book *Operating System Principles* (Section 7.2) in 1973

Hansen's another landmark book *The Architecture of Concurrent Programs* (1977) in which the concept of monitor and his Concurrent Pascal were clearly defined and discussed.

A Concurrent Pascal Compiler for minicomputers

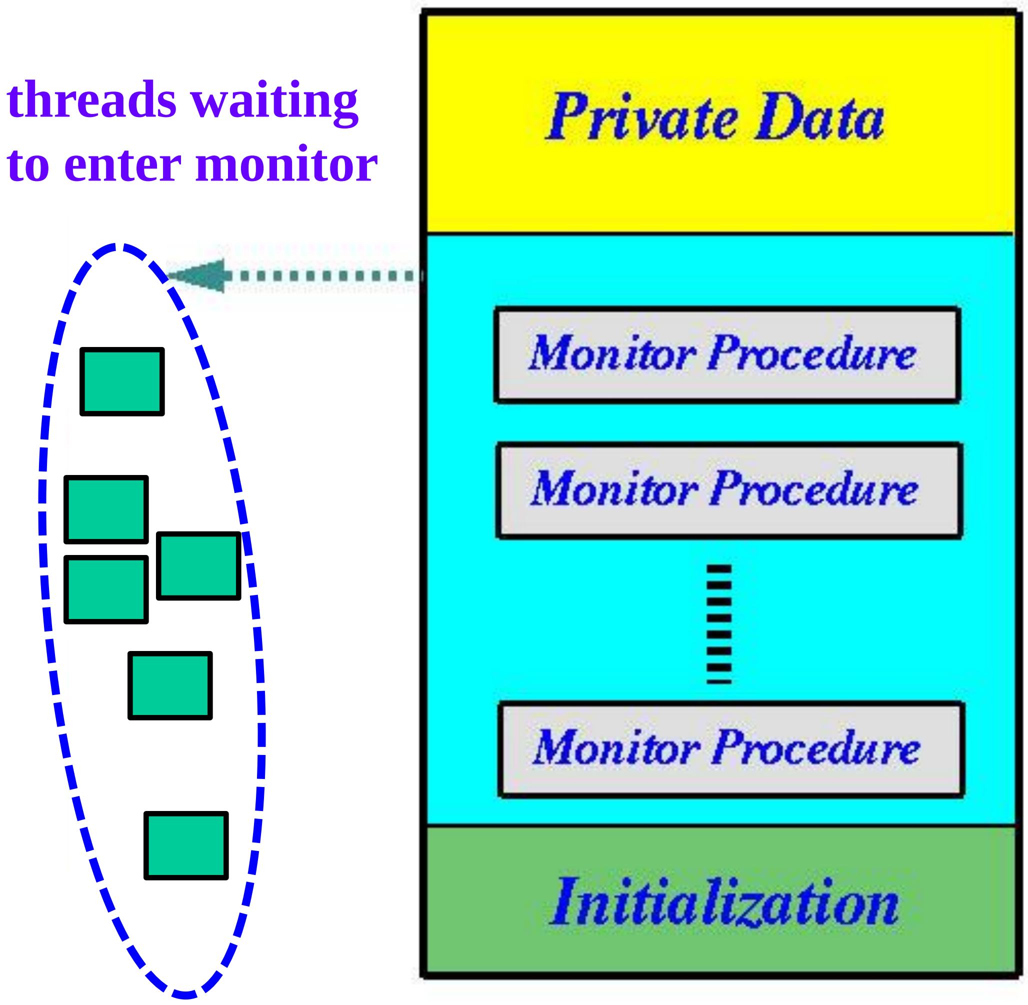
What Is a Monitor? - Basics

- **Monitor is a highly structured programming language construct. It consists of**
  - **private variables and private procedures that can only be used within a monitor.**
  - **constructors that initialize the monitor.**
  - **A number of (public) monitor procedures that are available to the users.**
- **Note that monitors have no public data.**
- **A monitor is a mini-OS with monitor procedures as system calls.**

Monitor: Mutual Exclusion 1/2

- **No more than one thread** can be executing *in* a monitor. Thus, mutual exclusion is automatically guaranteed in a monitor.
- When a thread calls a monitor procedure and enters the monitor successfully, it is the **only** thread ***executing*** in the monitor.
- When a thread calls a monitor procedure and the monitor has a thread executing, the caller is blocked outside of the monitor.

Monitor: Mutual Exclusion 2/2



- If there is a thread executing in a monitor, any thread that calls a monitor procedure is blocked **outside** of the monitor.
- When the monitor has no executing thread, one waiting thread will be let in.

Monitor: Syntax

```
monitor Monitor-Name
{
    local variable declarations;

    Procedure1(…)
    { // statements };
    Procedure2(…)
    { // statements };
    // other procedures
    {
      // initialization
    }
}
```

- All variables are **private**. **Why? Exercise!**
- **Monitor procedures are public**; however, some procedures may be private so that they can only be used within a monitor.
- **Initialization procedures** (i.e., **constructors**) execute only once when the monitor is created.

Monitor: A Very Simple Example

```
monitor IncDec
{
   int  count;
   void Increase(void)
   { count++; }

   void Decrease(void)
   { count--; }

   int GetData(void)
   {  return count; }

   {  count = 0; }
}
```

initialization

thread Increment

```
while (1) {
   // do something
   IncDec.Increase();
   cout <<
     IncDec.GetData();
   // do something
}
```

Is the printed value the one just updated?

Condition Variables

- **Mutual exclusion is an easy task with monitors.**
- **While a thread is executing in a monitor, it may have to wait until an event occurs.**
- **Each programmer-defined event is conceptually represented by a condition variable.**
- **A condition variable, or a condition, has a private waiting list, and two public methods: `signal` and `wait`.**
- **Note that a condition variable has no value and cannot be modified.**

Condition wait

- Let `cv` be a condition variable. The use of methods `signal` and `wait` on `cv` are `cv.signal()` and `cv.wait()`.
- Condition wait and condition signal can only be used **in a monitor**.
- A thread that executes a condition wait blocks immediately and is put into the waiting list of that condition variable. The monitor becomes "empty" (i.e., no executing thread inside).
- This means that this thread is waiting for the indicated event to occur.

Condition signal

- **Condition `signal` is used to indicate an event has occurred.**
- **If there are threads waiting on the signaled condition variable, one of them will be released.**
- **If there is no waiting thread waiting on the signaled condition variable, this signal is lost as if it never happens.**
- **Consider the released thread (from the signaled condition) and the thread that signals. There are two threads executing in the monitor, and mutual exclusion is violated! Something has to be done to fix this problem.**

Two Types of Monitors

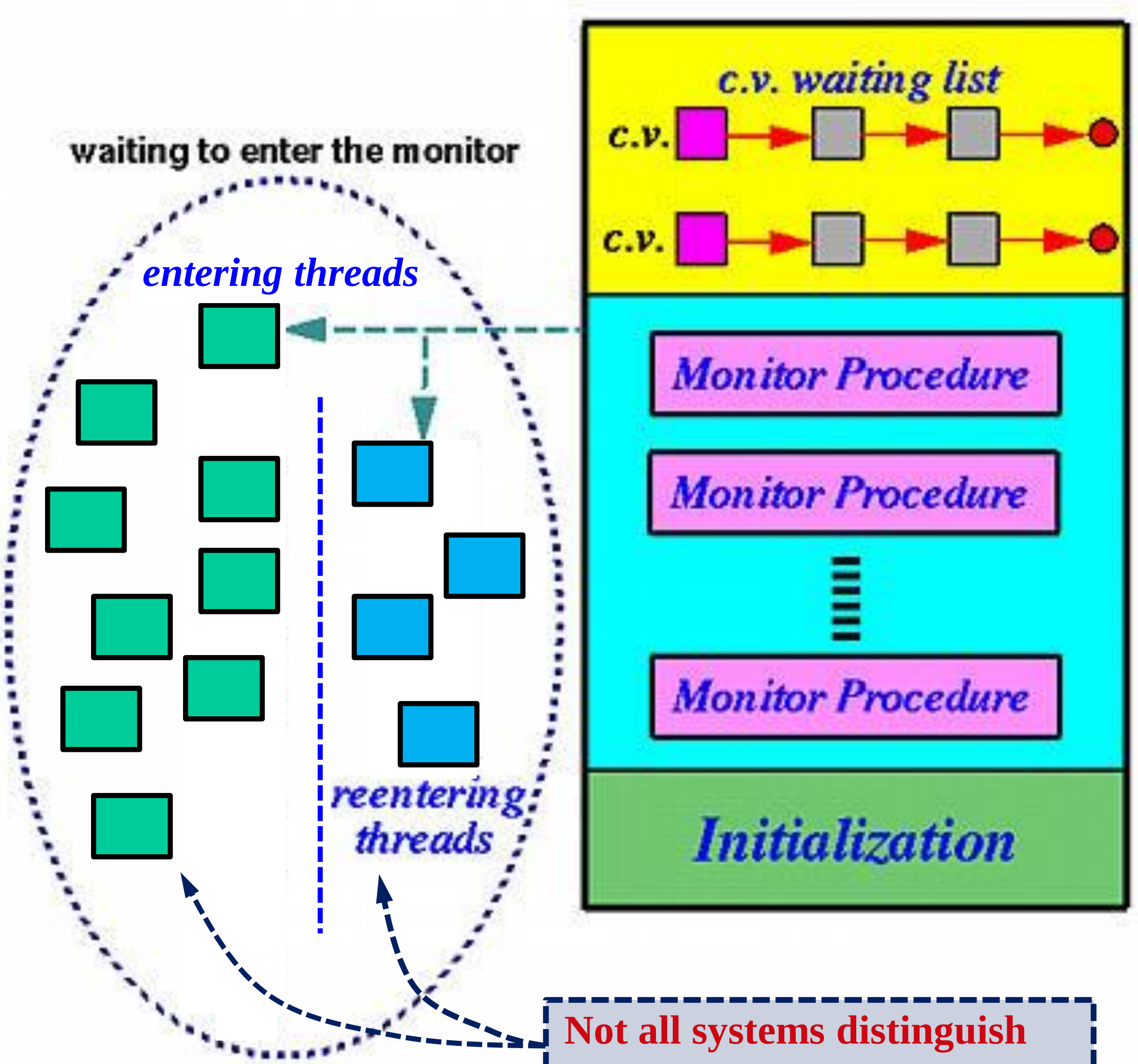
- After a signal, the released thread and the signaling thread may be executing in the monitor.
- There are two approaches to address this issue:
  - **Hoare Type** (proposed by C. A. R. Hoare)[1]: The released thread takes the monitor and the signaling thread waits somewhere.
  - **Mesa Type** (proposed by Lampson and Redell)[2]: The released thread waits somewhere and the signaling thread continues to use the monitor. This is also used in Java.

1. C. A. R. Hoare, Monitors: An Operating System Structuring Concept, Communications of the ACM, Vol. 17 (1974), No. 10 (October), pp. 549-557.
2. Butler W. Lampson and David D. Redell, Experience with Process and Monitor in Mesa, Communications of the ACM, Vol. 23 (1980), No. 2 (February), pp. 105-117.

What Do You Mean by "Waiting Somewhere"?

- **The signaling thread (Hoare type) or the released thread (Mesa type) must wait somewhere.**
- **You could consider there is a waiting bench for these threads to wait.**
- **Hence, each thread that involves in a monitor call may be in one of the four states:**
  - **Active: The running one.**
  - **Entering: Those blocked by the monitor.**
  - **Waiting: Those waiting on a condition variable.**
  - **Inactive: Those waiting on the waiting bench.**

Monitor with Condition Variables



Not all systems distinguish entry and re-entry threads

- Threads blocked due to signal/wait are in the **re-entry** list (*i.e.*, waiting bench).
- When the monitor is free, a thread is released from either **entry** or **re-entry** .

What Is the Major Difference?

```
Condition  UntilHappen;

// Hoare Type
if (!event)
   UntilHappen.wait();

// Mesa Type
while (!event)
   UntilHappen.wait();
```

With Hoare type, once a signal arrives, the signaler yields the monitor to the released thread and the condition is not changed. Thus, an `if` is sufficient.

With Mesa type, the released thread may be waiting for a while before it runs. During this period, other threads may be in the monitor and change the condition. It is better to check the condition again with a `while`!

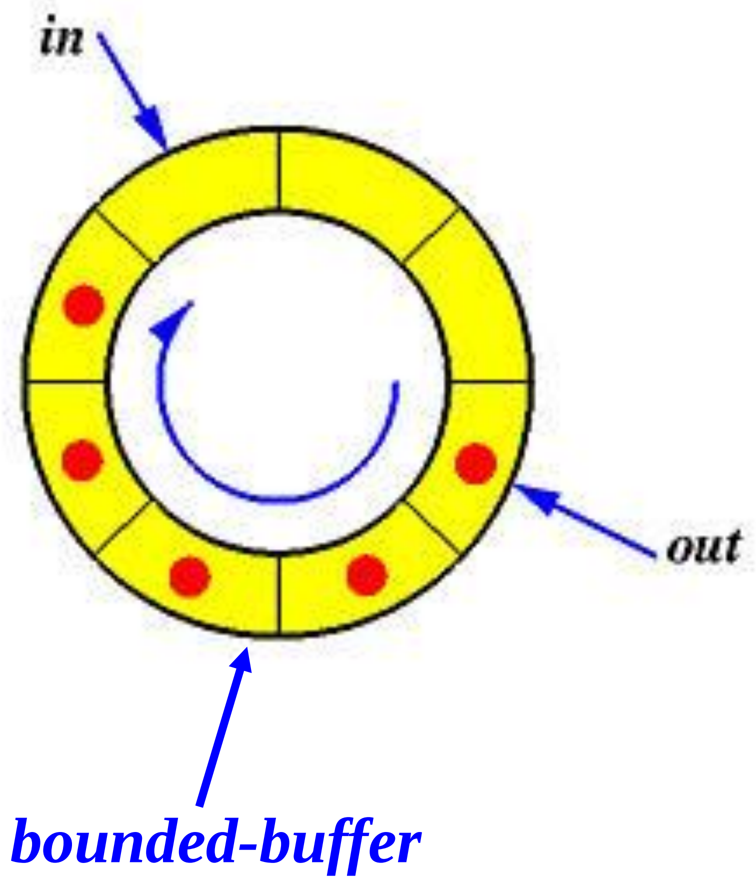
Unless stated otherwise, we only use the Hoare type monitors in this course.

Examples

- Producer/Consumer
- Dining Philosophers
- Alarm Clock
- Readers-Writers (Reader Priority)
- Readers-Writers (Take Turns)

We use the Hoare type monitors unless stated otherwise

Monitor: Producer/Consumer




```
monitor ProdCons
{
   int count, in, out;
   int Buf[SIZE];
   condition
      UntilFull,
      UntilEmpty;

   procedure PUT(int);
   procedure GET(int *);
   { count = 0}
}
```

Monitor: PUT() and GET()

```
void PUT(int X)
{
  if (count == SIZE)
    UntilEmpty.wait();
  Buf[in] = X;
  in = (in+1)%SIZE;
  count++;
  if (count == 1)
    UntilFull.signal();
}
```

```
void GET(int *X)
{
  if (count == 0)
    UntilFull.wait();
  *X = Buf[out];
  out=(out+1)%SIZE;
  count--;
  if (count == SIZE-1)
    UntilEmpty.signal();
}
```

Run This Solution with Mesa?

Buffer Size = 2

P_1	P_2	P_3	P_4	C_1	Count
					0
Add 1 item		buffer is full			1
	Add 1 item				2
		Wait `UntilEmpty`			2
				Take 1 item	1
				Signal `UntilEmpty`	1
			Add 1 item		2
					2
		No space!			2

if it is a Hoare monitor, P_3 runs immediately

signaling thread continues and exits

By the time P3 finally runs, there is no space!

Under Mesa, C_1 continues. Upon exit, the monitor becomes empty and selects P_4 to enter

monitor is empty. allow one to enter.

Dining Philosophers, Again!

- **Let us look at another solution to the dining philosophers problem.**
- **Recall that slides 138-139 of `08-Semaphores.pdf` discussed a solution suggested by Dijkstra. This solution requires that a philosopher can eat only if he can get BOTH chopsticks at the same time.**
- **This solution can be implemented using a monitor easily.**

Monitor Definition

```
monitor philosopher
{
   enum { THINKING,HUNGRY,
          EATING} state[5];
   condition  self[5];
   private: CanEat(int);

   procedure GET(int);  // get BOTH chopsticks
   procedure PUT(int);  // release chopsticks

   { for (i=0;i<5;i++)
        state[i] = THINKING;
   }
}
```

The CanEat() Procedure

checking whether philosopher *k* can eat

the left and right neighbors of philosopher *k* are not eating

```
void  CanEat(int k)
{
   if ((state[(k+4)%5] != EATING) &&
       (state[k] == HUNGRY) &&
       (state[(k+1)%5] != EATING)) {
          state[k] = EATING;
          self[k].signal();
   }
}
```

philosopher *k* is hungry

- **If the left and right neighbors of philosopher *k* are not eating and philosopher *k* is hungry, then philosopher *k* can eat. Thus, release him!**

The GET() and PUT() Procedures

I am hungry

see if I can eat

If I could not eat, block myself

```
void GET(int i)
{
   state[i] = HUNGRY;
   CanEat(i);
   if (state[i] != EATING)
      self[i].wait();
}
```

I finished eating

Let my neighbors eat

```
void PUT(int i)
{
   state[i] = THINKING;
   CanEat((i+4) % 5);
   CanEat((i+1) % 5);
}
```

How about Deadlock?

```
void CanEat(int k)
{
  if ((state[(k+4)%5] != EATING) &&
      (state[k] == HUNGRY) &&
      (state[(k+1)%5] != EATING)) {
         state[k] = EATING;
         self[k].signal();
  }
}
```

- **This solution does not cause deadlock, because**
  1. **The only place where eating permission is granted is in procedure `CanEat()`, and**
  2. **Philosopher *k* can eat only if he could get both chopsticks (i.e., no hold-and- wait and no circular waiting).**

How about Bounded Waiting?

```
void CanEat(int k)
{
  if ((state[(k+4)%5] != EATING) &&
      (state[k] == HUNGRY) &&
      (state[(k+1)%5] != EATING)) {
        state[k] = EATING;
        self[k].signal();
  }
}
```

- **Question**: The Progress condition is meet and could be proved easily. How about the **Bounded Waiting** condition? More precisely, is it possible that some philosophers can continue the process of thinking and eating and block some others indefinitely? **Exercise**.

A Simple Alarm Clock: 1/4

- **A set of Sleeper threads wish to Slumber for various times and set an alarm clock to wake them when it is time to get up.**
- **Unfortunately, their alarm clock is a little primitive:**
  - **Every hour it squirts cold water at the nearest sleeper, who immediately prods the next sleeper.**
  - **Each sleeper checks the time: if it is not the time for him/her to go to work, then he/she goes back to sleep.**
- **An external thread calls a monitor procedure every hour to initiate this waking up operation.**

This example is due to C. A. R. Hoare, Monitors: an Operating System Structuring Concept, *Communication of ACM*, Vol. 17 (1974), No. 10, pp. 549-557.

A Simple Alarm Clock: 2/4

Monitor Definition

```
monitor AlarmClock
{
   condition  Wake;              // sleepers sleep here
   int        Now = 0;           // hour counting

   procedure Tick();
   procedure Slumber(int n);  // n is the # of hours the
                              //   caller needs to sleep
}
```

A Simple Alarm Clock: 3/4

Procedure Tick

```
void  Tick(void)    // called by an external timer
                    //   every hour
{
   Now = Now + 1;   // This is internal hour count
   Wake.signal();   // wake up a sleeper
}
```

A Simple Alarm Clock: 4/4

Procedure Slumber

```
void  Slumber(int n)              // n = sleeping hours
{
   int  AlarmCall;                // time to wake up

   AlarmCall = Now + n;           // update my alarm clock
   while (Now < AlarmCall) {      // as long as I can sleep
      Wake.Wait();                //    sleep
      Wake.signal();              //    wake up the next
   }
}
```

- The `while` loop controls the number of hours a Slumber can sleep.
- The `Tick()` procedure updates the time and wakes up the first slumber.
- This Slumber wakes up the next one. The `Signal` is lost if no one there.
- This is referred to as cascading release/signal.
- Cascading release can release all waiting threads even though the # is unknown.

The Readers-Writers Problem Reader Priority

- We still need a reading reader count `reading` and a waiting reader count `readers`.
- Two condition variables are needed: `OK_to_Read` and `OK_to_Write`:
  - `OK_to_Read` : readers wait here if they cannot read because a writer is writing.
  - `OK_to_Write`: writers wait here if they cannot write because a writer is writing, or readers are reading.

Monitor Definition

```
monitor reader-writer
{
  int  reading = 0;  // reading readers
  int  readers = 0;  // waiting readers
  Bool busy = FALSE; // writer is writing

  condition  OK_to_Read, OK_to_Write;

  procedure read_REQUEST(void);
  procedure read_RELEASE(void);
  procedure write_REQUEST(void);
  procedure write_RELEASE(void);
}
```

Readers and Writers

Reader

```
while (1)
{
    // do something
    read_REQUEST();
    // reading
    read_RELEASE();
    // do something
}
```

Writer

```
while (1)
{
    // do something
    write_REQUEST();
    // writing
    write_RELEASE();
    // do something
}
```

Monitor Code for Readers

Reader Priority:
If there is a writer writing,
this reader waits!

```
void read_REQUEST()
{
  if (busy) {                // if a writer is writing
    readers++;               //   this reader must wait
    OK_to_Read.wait();       //   wait on OK_to_read
    readers--;               //   released!
  }
  reading++;                 // if not busy or released
  OK_to_Read.signal();       //   let the next reader to go
}
```

```
void read_RELEASE()
{
  reading--;                // a reader has done reading
  if (reading == 0)         // is this reader the last one?
    OK_to_Write.signal();   // YES, allow a writer to go
}
```

if there is no reader reading, yield to a writer

Monitor Code for Writers

```
void write_REQUEST()
{
  if (busy || reading != 0)  // if a writer is writing
                             //   or readers are reading
    OK_to_Write.wait();      // this writer must wait
  busy = TRUE;               // otherwise, start to write
}
```

Reader Priority:
As long as there is a reader reading, writers wait.

```
void write_RELEASE()
{
  busy = FALSE;              // a writer done writing
  if (readers != 0)          // if some waiting readers
    OK_to_Read.signal();     //   allow a reader to go
  else                       // otherwise
    OK_to_Write.signal();    //   allow a writer to go
}
```

If there is no readers reading. yield to a writer

Monitor Code: Summary

```
void read_REQUEST()
{
  if (busy) {
    readers++;
    OK_to_Read.wait();
    readers--;
  }
  reading++
  OK_to_Read.signal();
```

readers only block here

cascading release

```
void write_REQUEST()
{
  if (busy || reading != 0)
    OK_to_Write.wait();
  busy = TRUE;
}
```

the exiting writer releases a writer only if there is no waiting readers

Only if there

the exiting writer releases a waiting reader

```
void read_RELEASE()
{
  reading--;
  if (reading == 0)
    OK_to_Write.signal();
}
```

the last reader releases a waiting writer

```
void write_RELEASE()
{
  busy = FALSE;
  if (readers != 0)
    OK_to_Read.signal();
  else
    OK_to_Write.signal();
}
```


only if there is no readers waiting or reading, a writer is released

The Reader-Writer Problem: Again!

- **Let us add a minor modification to the readers-writers (priority version) problem to make it a bit more realistic:**
  - **If a writer is waiting, the new readers should yield to a writer.**
  - **Upon the exit of a reader,**
    - ✓ **If there are waiting writers, let one go**
  - **Upon the exit of a writer,**
    - ✓ **If there are waiting readers, let one go**
    - ✓ **If there are waiting writers, let one go**
  - **So, the readers and writers take turns.**

Monitor Definition

```
monitor reader-writer
{
   int readers = 0;  // waiting readers
   int reading = 0;  // reading readers
   int writing = 0;  // writing writers
   int writers = 0;  // waiting writers

   condition  OK_to_Read, OK_to_Write;

   procedure read_REQUEST(void);
   procedure read_RELEASE(void);
   procedure write_REQUEST(void);
   procedure write_RELEASE(void);
}
```

Monitor Code for Readers

If there are WAITING WRITERS or
a writer is writing,
this reader waits!

```
void read_REQUEST()
{
  if (writing > 0 || writers > 0) {// if a writer writing
                            // or there are waiting writers
    readers++;
    OK_to_Read.wait();      // this reader waits
    readers--;              // this reader is released
  }
  reading++;                // one more reading reader
  OK_to_Read.signal();      // allow other readers to read
}
```

```
void read_RELEASE()
{
  if (--reading == 0)    // if this is the last reader
    OK_to_Write.signal();  // let a writer go
}
```

Monitor Code for Writers

Same as the Reader Priority version

```
void write_REQUEST()
{
  if (writing > 0 || readers > 0) {// if a writer writing
    writers++;                   // or there are waiting readers
    OK_to_Write.wait();          //    this writer waits
    writers--;                   //    this writer is released
  }
  writing = 1;                   // this writer starts writing
}
```

```
void write_RELEASE()
{
  writing = 0;                  // this writer finishes writing
  if (readers > 0)              // if there are readers waiting
    OK_to_Read.signal();         //   let a reader to go
  else                           // otherwise
    OK_to_Write.signal();        //   let a writer to go
}
```

Monitor Code: Summary

readers→ writer → readers→ writer → ... (Taking Turns)

```
void read_REQUEST()
{  wait if writers are waiting or writing
  if (writing > 0
         || writers > 0) {
    readers++;
    OK_to_Read.wait();
    readers--;
  }
  reading++;
  OK_to_Read.signal();
}
```

cascading release

```
void write_REQUEST()
{wait if writer writing or readers waiting
  if (writing > 0
         || readers > 0) {
    writers++;
    OK_to_Write.wait();
    writers--;
  }
  writing = 1;
}
```

the exiting writer releases a waiting reader

```
void read_RELEASE()
{   the last reader releases a writer
  if (--reading == 0)
    OK_to_Write.signal();
}
```

if there is no waiting writers, these signals are lost!

```
void write_RELEASE()
{
  writing = 0;
  if (readers > 0)
    OK_to_Read.signal();
  else
    OK_to_Write.signal();
}
```

no waiting readers let a writer go

The Reader-Writer Problem Exercise...

- **Consider a solution that only uses a single condition, `Take_Turn`, rather than two: `OK_to_Read` and `OK_to_Write`.**
- **A reader waits on `Take_Turn` until there are no waiting writers, and then waits on `Take_Turn` again until there is no writer writing. In this case, this reader is safe to read.**
- **A writer waits on `Take_Turn` if there are readers reading or a writer writing.**
- **A reader or writer signals `Take_Turn` when they finish reading or writing.**

Monitor Definition

```
monitor reader-writer
{
  int reading = 0;  // reading readers
  int writing = 0;  // writing writers
  int writers = 0;  // waiting writers

  condition  Take_Turn;

  procedure read_REQUEST(void);
  procedure read_RELEASE(void);
  procedure write_REQUEST(void);
  procedure write_RELEASE(void);
}
```

Monitor Code for Readers

```
void read_REQUEST()
{
  if (writers > 0)     // if there are writers waiting,
    Take_Turn.wait();  //    wait until released
  if (writing > 0)     // if there is a writer writing,
    Take_Turn.wait();  //    wait, of course
  reading++;           // because no writer is writing,
}                      //    a reader can read

void read_RELEASE()
{
  reading--;           // a reader has done reading
  Take_Turn.signal();  // let one reader/writer to go
}
```

no writers waiting

no writer writing

Monitor Code for Writers

this means reading or writing being non-zero

```
void write_REQUEST()
{
  writers++;                  // one more write request
  if (reading || writing) // if there are readers reading
    Take_Turn.wait();   //    or a writer writing, wait
  writing++;                  // if no readers reading and no
}                             //    writer writing, then go!

void write_RELEASE()
{
  writing--;                  // reduce writing count
  writers--;                  // reduce writer count
  Take_Turn.signal();   // let some one to proceed
}
```

The Reader-Writer Problem Question…

- **Is this solution correct?**
- **If you think that this solution is correct, please prove that this solution does implement the requirements correctly (*i.e.*, taking turns correctly).**
- **If you think that this solution is incorrect, then**
  - **Explain what the problems are and use execution sequences to show that this solution fails to implement taking turns correctly.**
  - **And, modify this solution to make it working!**

Three Extensions

`empty()`, Priority `wait()`, `broadcast` (*i.e.*, `signal_all`)

The Reader-Writer: Again and Again!

- **Some monitor implementations may have additional features. For example, in addition to `wait()` and `signal()`, a condition variable may have one more function `empty()`, which returns `TRUE` if the condition variable has no waiting threads.**
- **C. A. R. Hoare proposed the following version:**
  - **A new reader should not be permitted to start if there is a waiting writer;**
  - **At the end of a write operation, waiting readers are given preference over waiting writers.**
- **We have seen this previously.**

Monitor Definition

```
monitor reader-writer
{
  int  reading = 0;      // reading readers
  Bool writing = FALSE; // writing?

  condition  OKtoRead,  // readers wait here
             OKtoWrite; // writers wait here

  procedure read_REQUEST(void);
  procedure read_RELEASE(void);
  procedure write_REQUEST(void);
  procedure write_RELEASE(void);
}
```

Monitor Code for Readers

not all systems have `empty()`

```
void read_REQUEST()
{
  if (writing || !empty(OKtoWrite))  // if writing or
    OKtoRead.wait();  // writer queue not empty, wait!
  reading++;          // then this reader can read
  OKtoRead.signal();  // allow a waiting reader to go
}                     // cascading release here!

void read_RELEASE()
{
  reading--;          // a reader has done reading
  if (reading == 0)
    OKtoWrite.signal();
}
```

because of `empty()`, a waiting writers count is eliminated

Monitor Code for Writers

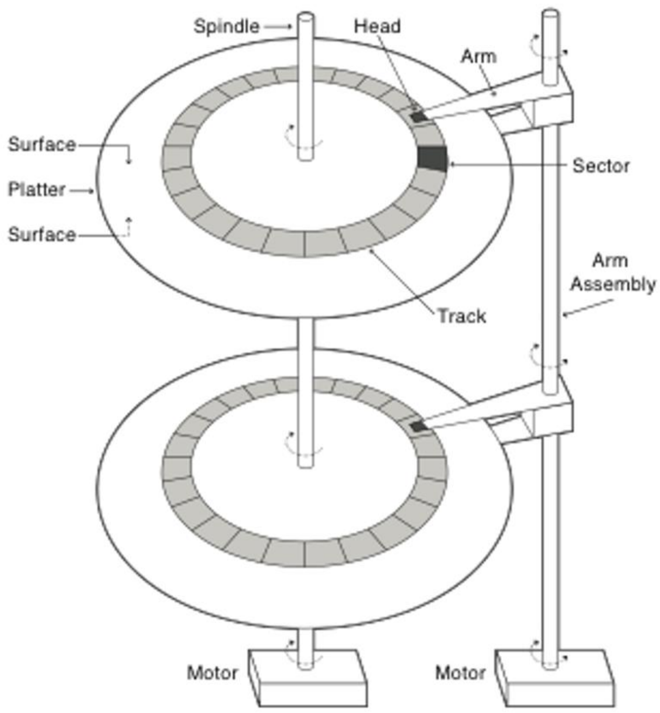
```
void write_REQUEST()
{
  if (writing || reading > 0)  // if someone writing
    OKtoWrite.wait();          // or readers waiting, wait here
  writing = TRUE;              // after released, write!
}

void write_RELEASE()
{
  writing = FALSE;             // finished writing
  if (!empty(OKtoRead))        // if there are waiting readers
    OKtoRead.signal();         //   let one go (cascading!)
  else
    OKtoWrite.signal();        // or let a waiting writer go
}                              // if there is no waiting
                               //   writer, this signal is lost.
```

not all systems have empty()

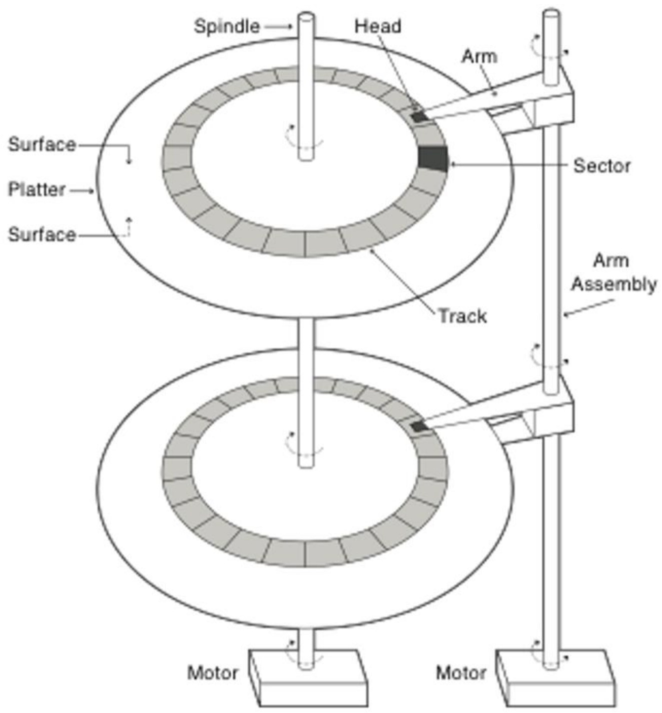
because of empty(), a waiting readers count is eliminated

Disk Organization: 1/2



- The information stored on the disk is organized into a series of *cylinders*, each of which consists of several *tracks*, and each track consists of several *sectors* or *blocks*.
- When a read/write request comes, the disk head assembly is moved to the correct cylinder, the head corresponding to the required track is selected, and the information may be read or written when the required sector passes the head as the disk rotates.
- The time to move the head assembly to a track is referred to as the *seek* time, which is mechanical and time consuming.
- Because there are many cylinders to be accessed, how can we *minimize the total seek time*?

Disk Organization: 2/2



- **Instead accessing the cylinders based on the incoming order, it would be more efficient and probably cause less mechanical strain on the device if *the requests could be handled by making continuous sweeps across the disk surfaces, first in one direction and the other*.**
- **Some systems have an extended `wait()` method.**
- **The `wait(Priority)` has an integer argument `Priority`.**
- **When a condition variable is signaled, the thread with the highest priority is released. A smaller value of `Priority` usually means a higher priority. WARNING: check the system for the details.**

Monitor Definition

```
monitor Disk_Scheduler
{
  int  Head = 0;           // initially at cylinder 0
  int  Dir  = IN;          // thus, IN sweep first
  int  MAX  = …;           // highest cylinder number
  Bool Busy = FALSE;       // initially the disk is free

  condition  IN_Sweep,     // IN sweep queue
             OUT_Sweep;    // OUT sweep queue

  procedure Request(int Cy); // request to use cylinder Cy
  procedure Release(void);   // release cylinder Cy
}
```

The Use of `Disk_Scheduler`

```
Request(Cylinder);    // request to move the
                      //   disk assembly to
                      //   cylinder Signal all
```

activate the desired track

read or write the needed sector/block

```
Release();            // release the cylinder
                      //    after the access
```

Monitor Code for Request

```
void Request(int Cy) // request to access Cylinder Cy
{
   if (Busy) {                        // if disk is busy, wait!
      if ((Head < Cy) ||              // if beyond the current pos
          (Head == Cy && Dir == IN))  //    or at the current pos
                                      //       & direction is IN
         IN_Sweep.Wait(Cy);           //    wait on IN sweep CV
      else                            // Otherwise, wait for OUT
         OUT_Sweep.Wait(MAX - Cy);    //    sweep using a reversed
   }                                  //    priority order
   Busy = TRUE;                       // Once get out, can access
   Head = Cy;                         // the disk head is at Head
}
```

When the disk head moves inward, cylinders are accessed in an ascending order.
Thus, a smaller cylinder number means a higher priority.

When the disk head moves outward, cylinders are accessed in a descending order.
Thus, a smaller cylinder number means a lower priority, and `MAX - Cy` is used.

Monitor Code for `Release`

```
void Release(void)                // request to release
{
   Busy = FALSE;                  // done using cylinder Cy
   if (Dir == IN) {               // IN sweep?
      if (!IN_Sweep.empty())      // if there are waiting in IN
         IN_Sweep.signal();       //    release one of them
      else {                      // no one waiting in IN
         Dir = OUT;               //    switch direction to OUT
         OUT_Sweep.signal();      //    release one of them
      }
                                     symmetric for IN and OUT
   else  {                        // current OUT sweep
      if (!OUT_Sweep.empty())     // if there are waiting in OUT
         OUT_Sweep.signal();      //    release one of them
      else {                      // no one waiting in OUT
         Dir = IN;                //    switch direction to IN
         IN_Sweep.signal();       //    release one of them
      }
   }
}
```

The Broadcast/Signal_all Method

- **In some systems, each condition variable may have a `broadcast` or `signal_all` method.**
- **Let `cv` be a condition variable. `cv.broadcast()` or `cv.signal_all()` releases all waiting threads on condition `cv` with a single signal call.**
- **When `cv.broadcast()` (or `cv.signal_all()`) is called, all waiting threads on condition variable `cv` are released and changed to inactive/re-entry.**
- **This will save the use of a cascading release.**

A Simple Alarm Clock

Procedures Tick & Slumber

```
void  Tick(void)    // called by an external timer
                    //   every hour
{
   Now = Now + 1;   // This is internal hour count
   Wake.broadcast(); // wake up all sleepers
}
```

```
void  Slumber(int n)               // n = sleeping hours
{
   int  AlarmCall;                 // time to wake up
                          cascading release is not needed
   AlarmCall = Now + n;            // update my alarm clock
   while (Now < AlarmCall) {       // as long as I can sleep
      Wake.Wait();                 //   sleep
      Wake.signal();               //   no more needed
   }
}
```

Readers-Writers (Reader Priority)

```
void read_REQUEST()
{
  if (busy) {
    readers++;
    OK_to_Read.wait();
    readers--;
  }
  reading++
  OK_to_Read.signal();
}
```

cascading release
no more needed

cascading release
is no more needed

```
void read_RELEASE()
{
  reading--;
  if (reading == 0)
    OK_to_Write.signal();
}
```

the last reader releases
a waiting writer

```
void write_REQUEST()
{
  if (busy || reading != 0)
    OK_to_Write.wait();
  busy = TRUE;
}
```

the exiting writer releases a writer
only if there is no waiting readers

the exiting writer releases
a waiting reader

```
void write_RELEASE()
{
  busy = FALSE;
  if (readers != 0)
    OK_to_Read.broadcast();
  else
    OK_to_Write.signal();
}
```

release ALL
waiting readers

Readers-Writers: Taking Turns

```
void read_REQUEST()
{
  if (writing > 0
        || writers > 0) {
    readers++;
    OK_to_Read.wait();
    readers--;
  }
  reading++;
  OK_to_Read.signal();
}
```

cascading release no more needed

cascading release is no more needed

```
void read_RELEASE()
{
  if (--reading == 0)
    OK_to_Write.signal();
}
```

```
void write_REQUEST()
{
  if (writing > 0
        || readers > 0) {
    writers++;
    OK_to_Write.wait();
    writers--;
  }
  writing =  1;
}
```

```
void write_RELEASE()
{
  writing = 0;
  if (readers > 0)
    OK_to_Read.broadcast();
  else
    OK_to_Write.signal();
}
```

release ALL waiting readers

An Important Note

- `cv.broadcast()` is not the same as

```
while (!cv.empty())
    cv.signal();
```

- In each iteration of the `while` loop, a waiting thread is released, and this released thread gets the monitor (Hoare type) while the signaling thread becomes inactive/re-entry.
- When the released thread exits, the monitor mechanism picks a thread to enter. If the picked one is the signaling thread, the situation is fine.
- Otherwise, the newcomer could cause problems.

Example: Barrier 1/8

- Monitor `Barrier` has an initial value `n` > 0 and a `Barrier_wait()` method.
- A thread that calls `Barrier_wait()` blocks if the number of blocked threads is less than `n` – 1.
- When the `n`-th thread calls `Barrier_wait()`, it releases all waiting `n`-1 threads.
- In other words, barrier `Barrier` blocks the first `n`-1 threads that calls `Barrier_wait()` and the `n`-th one releases all waiting threads. Thus, all `n` threads would act in a single group.

Example: Barrier 2/8

```
monitor Barrier
{
   int  n;                        // the maximum threads to be queued
   int  count = 0;                // counting the current # queued

   condition barrier;             // queue threads here

   procedure Barrier_wait()       // method for threads to call
   {
      count++;                    // one more thread entering barrier
      if (count < n) {            // is this the last one?
         barrier.wait();          //   no! queue this thread
         barrier.signal();        //   when released, releases the next
      }
      else {                      // this is the n-th thread …
         count = 0;               // reset the counter
         barrier.signal();        // releases a waiting one and cascades
      }
   }
}
```

cascading release

must be before the signal()

NOTE: This is a Hoare type monitor

Example: Barrier 3/8

- **What if the order of `count=0` and `barrier.signal()` is switched as follows?**

```
barrier.signal();
count = 0;
```

- **Does this solution work? In other words, after switching the two statements in the `else` part, can the `n`-th thread correctly release the waiting `n`-1 threads?**

Example: Barrier 4/8

- **NO, this does not work properly.**
- Suppose `n` = 3. We may have the following scenario:
  - T_1 calls `Barrier_wait()` and waits (`count` = 1)
  - T_2 calls `Barrier_wait()` and waits (`count` = 2)
  - T_3 calls `Barrier_wait()` and executes the `else`:
    - ✓ T_3 calls `barrier.signal()` (currently `count` = 3) and assume that T_1 is released. T_3 yields the monitor.
    - ✓ T_1 is active and calls `barrier.signal()`. This releases T_2.
    - ✓ T_2 calls `barrier.signal()` and exits.
    - ✓ Who will enter? If it is the signaling threads T_3, it is OK. Otherwise, a new thread enters, sees `count < 3` being `FALSE` and go to `else` and start another `signal()`. This is a wrong program logic.

Example: Barrier 5/8

```
monitor Barrier
{
   int  n;                         // the maximum threads to be queued
   int  count = 0;                 // counting the current # queued

   condition barrier;              // queue threads here

   procedure Barrier_wait()        // method for threads to call
   {
      count++;                     // one more thread entering barrier
      if (count < n) {             // is this the last one?
         barrier.wait();           //   no! queue this thread
         barrier.signal();
      }
      else {                       // this is the n-th thread …
         count = 0;                // reset the counter
         barrier.broadcast();      // releases a waiting one and cascades
      }
   }
}
```

all threads waiting here are released
and cascading release is not needed

NOTE: This is a Hoare type monitor

Example: Barrier 6/8

```
monitor Barrier
{
   int  n;                       // the maximum threads to be queued
   int  count = 0, i;            // counting the current # queued

   condition barrier;            // queue threads here

   procedure Barrier_wait()      // method for threads to call
   {
      count++;                   // one more thread entering barrier
      if (count < n)             // is this the last one?
         barrier.wait();         //    no! queue this thread
      else {                     // this is the n-th thread …
         count = 0;              // reset the counter
         for (i = 1; i <= n-1; i++)  // releases the threads using for
            barrier.signal();    //        one at a time
      }
   }
}
```

if this is the n-th thread, there are n-1 threads waiting

NOTE: This is a Hoare type monitor. This is wrong!

Example: Barrier 7/8

T_1	T_2	$T_{`3}$	barrier	count	i
			$\varnothing$	0	
`count++`			$\varnothing$	1	
`wait()`			T_1	1	
	`count++`		T_1	2	
	`wait()`		T_1, T_2	2	
T_1 is released		`count++`	T_1, T_2	3	
		`count = 0`	T_1, T_2	0	
	T_1 comes back fast	`signal()`	T_2	0	1
continue & exit			T_2	0	1
come back fast			T_2	0	1
`count++`			T_2	1	1
`wait()`	T_1 is released again!		T_1, T_2	1	1
		`signal()`	T_1, T_2	1	2
continue			T_2	1	2

Example: Barrier 8/8

- **If you use a Hoare type monitor, try to use cascading release if it is possible.**
- **If `broadcast()` is available, this is a good alternative of cascading release.**
- **Do not use a `for` or a `while` loop to release the blocked threads on a condition.**
- **QUESTION: Is the `for`/`while` version working correctly under a MESA monitor?**
- **QUESTION: Are cascading and `broadcast` releases work correctly under a MESA monitor?**

Semaphore and Monitor Equivalence

Semaphore and Monitor Equivalence

- **In terms of expressive power, semaphores and monitors are equivalent.**
- **A semaphore can easily be implemented with a monitor.**
- **Conversely, a monitor and its condition variables can also be implemented with multiple semaphores, although this is a bit tedious.**
- **Therefore, semaphores and monitors are equivalent because one may be implemented by the other.**

Semaphore Implementation Using a Monitor

Semaphores in Hoare Type: 1/2

- On the right is a possible implementation of a semaphore using a Hoare type monitor.
- `count` is the semaphore counter.
- `c` is a condition variable for blocking a thread that must wait.
- **Does it work?**

```
monitor Hoare_Sem
{
    int         count = 0;
    condition   c;

    P(void)     // wait
    {
        count--;
        if (count < 0)
            c.wait();
    }

    V(void)     // signal
    {
        count++;
        c.signal();
    }
}
```

there is no `if` statement here

Semaphores in Hoare Type: 2/2

- **Why is there no `if`?**
- Recall that `abs(count)` is the number of waiting threads on that semaphore.
- It `count++` is not positive, there are waiting threads and `c.signal()` will release one.
- If `count++` is positive, no waiting threads on `c` and `c.signal()` is lost.

```
monitor Hoare_Sem
{
    int          count = 0;
    condition    c;

    P(void)      // wait
    {
        count--;
        if (count < 0)
            c.wait();
    }

    V(void)      // signal
    {
        count++;
        c.signal();
    }
}
```

Semaphores in Mesa Type: 1/2

- Now let us try the same implementation using the Mesa type monitor.
- `count` is the semaphore counter.
- `c` is a condition variable for blocking a thread that has to wait.
- **Does it work?**

```
monitor Mesa_Sem
{
    int          count = 0;
    condition    c;

    P(void)      // wait
    {
        count--;
        while (count < 0)
            c.wait();
    }

    V(void)      // signal
    {
        count++;
        c.signal();
    }
}
```

there is no `if` statement here

Semaphores in Mesa Type: 2/2

T_1	T_2	T_3	`count`	Comment
			0	
`count--`			-1	T_1 calls `P()`
`while (…)`			-1	
`c.wait`			-1	T_1 blocks
	`count++`		0	T_2 calls `V()`
	`c.signal`		0	T_1 released
waiting to	T_2 exit	`count--`	-1	T_3 calls `P()`
re-enter		`while (…)`	-1	
		`c.wait`	-1	T_3 blocks
`while (…)`			-1	T_1 re-enters
`c.wait`			-1	T_1 blocks
			-1	T_1 and T_3 both blocked

Because of the Mesa type, T_2 continues after signaling. Upon exit, T_3 (rather than T_1) gets the control of monitor.

T_1 and T_3 are both blocked

A correct signal fails to release a waiting thread properly.

Hoare Monitor Implementation Using Semaphores

Simulating a Hoare Monitor
Using Semaphores: 1/4

- Because the boundary of a monitor must be mutually exclusive, a **mutex lock** is needed.
- Let this mutex lock be `Mutex`.
- Because the signaling thread must yield the monitor and wait, a semaphore `Suspended`, initialized to 0, is needed for this purpose.
- Threads waiting on `Suspended` are inactive ones.
- `Suspended_count` counts the number of threads suspended on semaphore `Suspended`.

Simulating a Hoare Monitor

Using Semaphores: 2/4

- Each monitor procedure has the following form:

```
Mutex.wait();                     // wait to enter
   .........
   // procedure body
   .........
   if (Suspended_count > 0)       // there are inactive ones
      Suspended.signal();         //     let one go
   else
      Mutex.signal();             // or release the monitor
```

- If there are inactive/re-entry threads, let one go!
- The baton, `Mutex`, is given to the released thread.
- Therefore, this is in favor of the **inactive/re-entry** threads.

Simulating a Hoare Monitor
Using Semaphores: 3/4

- For condition `cv`, a semaphore `cv_Sem` and a counter `cv_Count` are needed, initialized to 0.

cv.wait():

```
cv_Count++;                   // one more waiting
if (Suspended_count > 0)      // some inactive waiting
   Suspended.signal();        //    let one go
else                          // otherwise, no inactive
   Mutex.signal();            //    release the monitor
cv_Sem.wait();                // condition wait
cv_Count--;                   // cv signal received
                              // cv count decreases
```

- Before a thread waits on a `cv`, an inactive/re-entry thread is released if there is one.
- Otherwise, it releases the `Mutex`.
- Then, wait on the `cv`.

Simulating a Hoare Monitor

Using Semaphores: 4/4

- Here is `cv.signal()`:

cv.signal():

```
if (cv_Count > 0) {       // some waiting threads
   Suspended_count++;     // this one becomes inactive
   cv_Sem.signal();       // releases a waiting thread
   Suspended.wait();      // block the signaling one,
                          //    yielding the monitor
   Suspended_count--;     // signaling is back
}
// if no inactive, no action!
```

- **Before the signaling thread yields the monitor to the released one, the signaling thread signals `cv_Sem` to release a waiting thread on that `cv`.**
- **If there is no inactive thread, this signal is considered never happened.**

Simulating a Mesa Monitor
Using Semaphores

- We have seen the simulation of a Hoare type monitor using semaphores.
- It is certainly possible to simulate the Mesa type monitor using semaphores.
- Please think this over and do it as an exercise.
- The implementation discussed earlier gives inactive/re-entry threads higher priority to enter a monitor. What if there is no such requirement? In other words, an inactive/re-entry thread is pushed outside of the monitor and waits alongside other entering threads?

Comparisons

Hoare Type vs. Mesa Type

- When a signal occurs, a Hoare type monitor uses two context switches, one switching the signaling thread out and the other switching the released in. However, a Mesa type monitor uses one.
- Thread scheduling must be very reliable with Hoare type monitors to ensure once the signaling thread is switched out the next one to execute in the monitor must be the released thread.
- With Mesa type monitors, a condition may be evaluated multiple times. However, incorrect signals will do less harm because every thread checks its own condition.

Semaphores vs. Monitors

Semaphores	Monitors
Can be used anywhere, but should not be in a monitor	Can only be accessed with monitor procedure calls
No connection between the semaphore and the data this semaphore protects	Data and access procedures are in the same place (i.e., a monitor)
Semaphores are low level assembly language-like instructions	Monitors are well-structured higher-level construct
Not easy to use and prone to bugs	Easy of use and good protection of vital data

Semaphores vs. Conditions

Semaphores	Condition Variables
Can be used anywhere, but not in a monitor	Can only be used in monitors
`wait()` does not always block its caller	`wait()` always blocks its caller
`signal()` either releases a thread, or increases the semaphore counter	`signal()` either releases a thread, or the signal is lost as if it never occurs
If `signal()` releases a thread, the caller and the released *both continue*	If `signal()` releases a thread, either the caller or the released continues, but *not both*

Remarks

Reminder 1

- It is suggested that a `signal()` should be the last executed statement before exiting a monitor procedure. We have seen this in many examples.
- **Why?**
  - Whether this monitor is a Hoare type or Mesa type, the difference does not matter.
  - If this is a Hoare type, the signaling thread will not do anything even though it is inactive.
  - If this is a Mesa type, the signaling thread will exit immediately.
  - Therefore, this is a safer approach.

Reminder 2

- **Why is using semaphores in a monitor a bad idea?**
  - **If a thread *T* is executing in monitor A, monitor A is "occupied" by thread *T*.**
  - **What if thread *T* calls a semaphore wait in monitor A and is blocked?**
  - **Because thread *T* is executing in monitor A, if it waits on a semaphore in monitor A, monitor A cannot be used as monitor A is occupied by the thread *T*.**
  - **Therefore, using semaphores in a monitor is not a good idea.**

Reminder 3

- **Why is calling a monitor procedure in another monitor from this monitor a bad idea?**
  - **If a thread *T* is executing in monitor A, monitor A is "occupied" by thread *T*.**
  - **If thread *T* successfully enters another monitor B, monitor A is not empty and cannot be used by any thread. This is inefficient!**
  - **Worse, what if thread *T* waits on a condition variable in monitor B? Then, monitor A could not be used for a long time until thread *T* returns from monitor B and exits.**

Monitors with ThreadMentor

ThreadMentor does not support `empty()`, Priority `wait()` and `broadcast()` or `signal_all()`

Monitor: Definition

```
class MyMon::public Monitor
{
  public:
    MyMon(); // constructor
    MonitorProcedure-1();
    MonitorProcedure-2();
    // other procedures
  private:
    // variables used in
    // this monitor
};
```

- **A monitor must be a derived class of class `Monitor`.**
- **The initialization part should be in constructors.**
- **Make monitor procedures `public`.**
- **Local variables should be `private`/`protected`.**

Monitor: Monitor Procedures

```
int MyMon::MonProc(...)
{
   MonitorBegin();
   // other statements
   // of this procedure
   MonitorEnd();
}
```

`MonitorBegin()` *locks the monitor and* `MonitorEnd()` *unlocks it. Thus, mutual exclusion is guaranteed.*

- **Monitor procedures are C/C++ functions.**
- **Before you do anything, call** `MonitorBegin()`**.**
- **Before exit, call** `MonitorEnd()`**.**
- **The following is wrong:**

```
int MyMon::MonProc()
{
   MonitorBegin();
   // other stuffs
   return 0;
   MonitorEnd();
}
```

Monitor: A Simple Example

```
Class Count
      ::public Monitor
{
  public:
    int  Inc();
    int  Dec();
    Count();
  private:
    int  Counter;
}

Count::Count(void)
{ Counter = 0; }
```

```
int Count::Inc()
{
   MonitorBegin();
      Counter++;
   MonitorEnd();
   return Counter;
}
int Count::Dec()
{
   MonitorBegin();
      Counter--;
   MonitorEnd();
   return Counter;
}
```

Monitor: Condition Variables

```
Condition  Event;

Event.Wait();

Event.Signal();
```

- `Condition` is a class and has two methods, `Wait()` and `Signal()`.
- Waiting on a condition variable means waiting for that event to occur.
- Signaling a condition variable means that the event has occurred.

Philosopher Monitor Definition

condition variable pointers, one for each philosopher

```
class Mon::public Monitor
{
   public:
      Mon();
      GET(int); PUT(int);
   private:
      Condition Self[5];
      int  State[5];
      int  CanEat(int);
};
```

get and put chopsticks

```
Mon::Mon()
{  int i;
   for (i=0; i < 5; i++){
     State[i] = THINKING;
}
```

are both chopsticks available?

state of each philosopher

Philosopher Monitor Implementation

```
int Mon::CanEat(int k)
{
 if ((state[(k+4)%5] !=
        EATING)
    &&(state[k] ==
        HUNGRY)
    && (state[(k+1)%5] !=
        EATING)) {
     state[k] = EATING;
     self[k].Signal();
}
```

```
void Mon::GET(int k)
{
   MonitorBegin();
   state[k] = HUNGRY;
   CanEat(k);
   if (state[k] != EATING)
     self[k].Wait();
   MonitorEnd();
}
```

if I cannot eat, wait

check to see if I can eat

Specifying a Monitor Type

```
MyMonitor::MyMonitor(char *Name)
            : Monitor(Name, HOARE)
{
   // initialization here
}
```

Replace HOARE with MESA if you wish to use a Mesa type monitor.

- A monitor type must be specified in your monitor constructor.
- Use HOARE or MESA for Hoare type and Mesa type monitors.

The End