Monitors
Condition Variables

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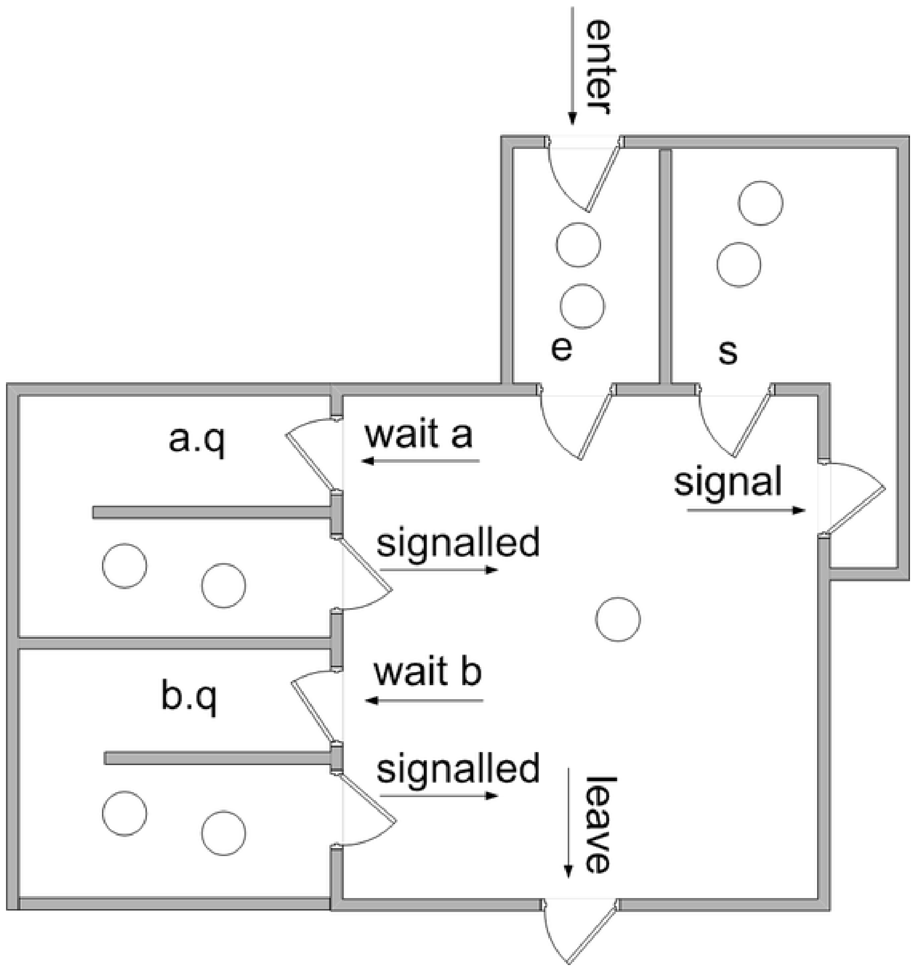
Monitor: Higher Abstraction Level Mechanism

- Idea by Brinch-Hansen 1973 in the textbook “Operating System Principles”
    - Structure an OS into a set of modules each implementing a resource scheduler
- Tony Hoare – 1974
    - Combine together in each module
        - Mutex
        - Shared data
        - Access methods to shared data
        - Condition synchronization
        - Local code and data

Basic Components

- *Monitor procedures* are **mutually exclusive**
  - called/executed by threads (monitor is implemented by all threads, data variables are shared)
  - “called” by processes (without shared address space) is also possible (HOW?)
- Conditon “variables” (*declared by user*)
  - just a naming of wait queues
  - select a meaningful name (good programming practice)
- Wait (cond_var_name) (*called by monitor procedures)*
  - calling thread will unconditionally be removed as *current* and inserted into the named waiting queue
    - then the OS kernel scheduler must select another process from the ready_queue to become the new *current*
- Signal (cond_var_name) (*called by monitor procedures)*
  - resume (wakeup) a blocked thread

Blocking Condition Variables (Hoare style)



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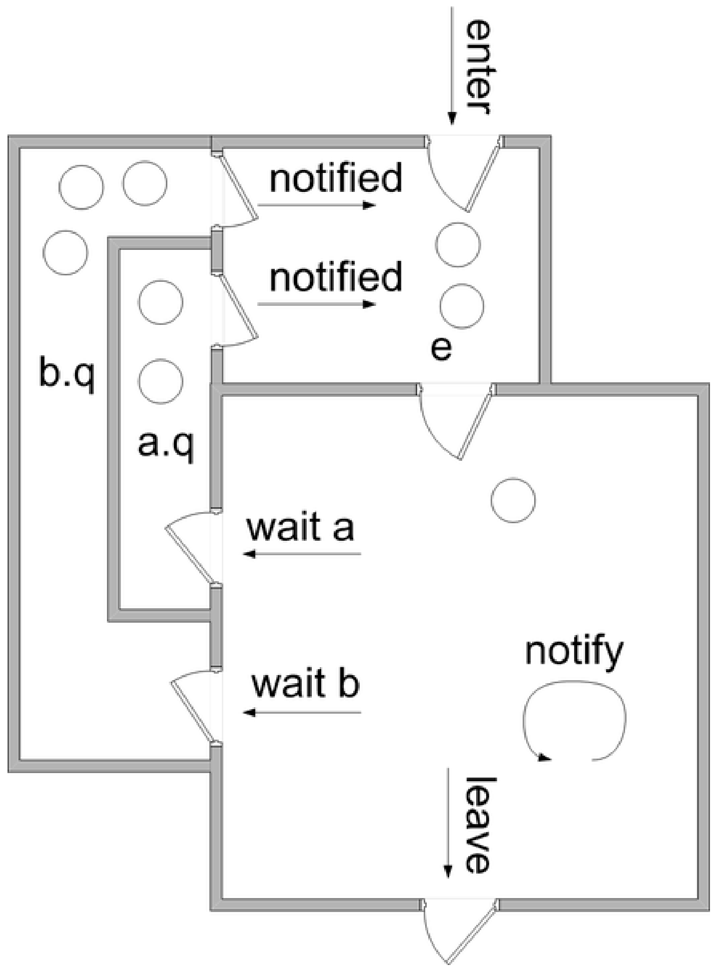
Non-Blocking (Mesa style)



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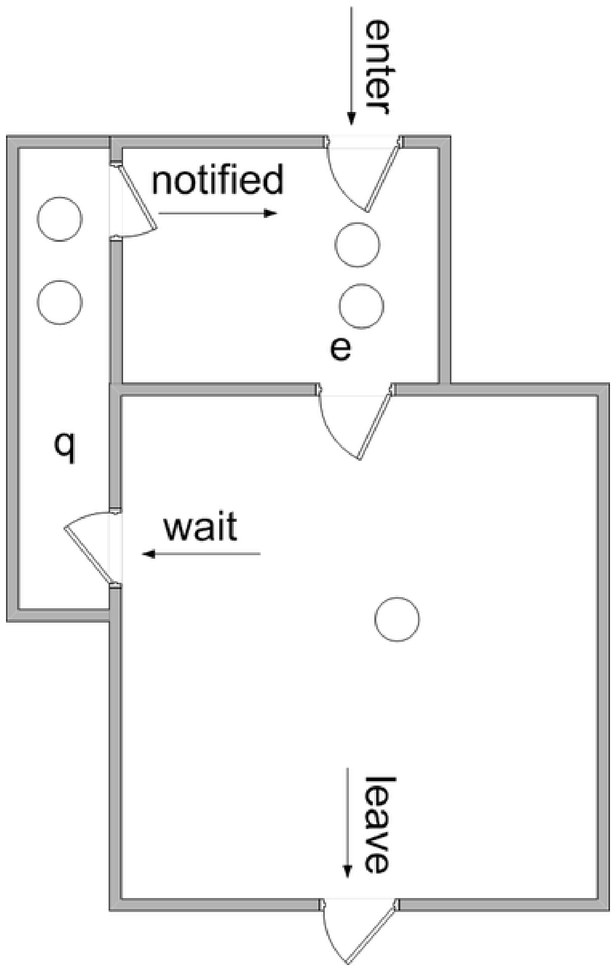
Implicit Condition Variables (Java style)



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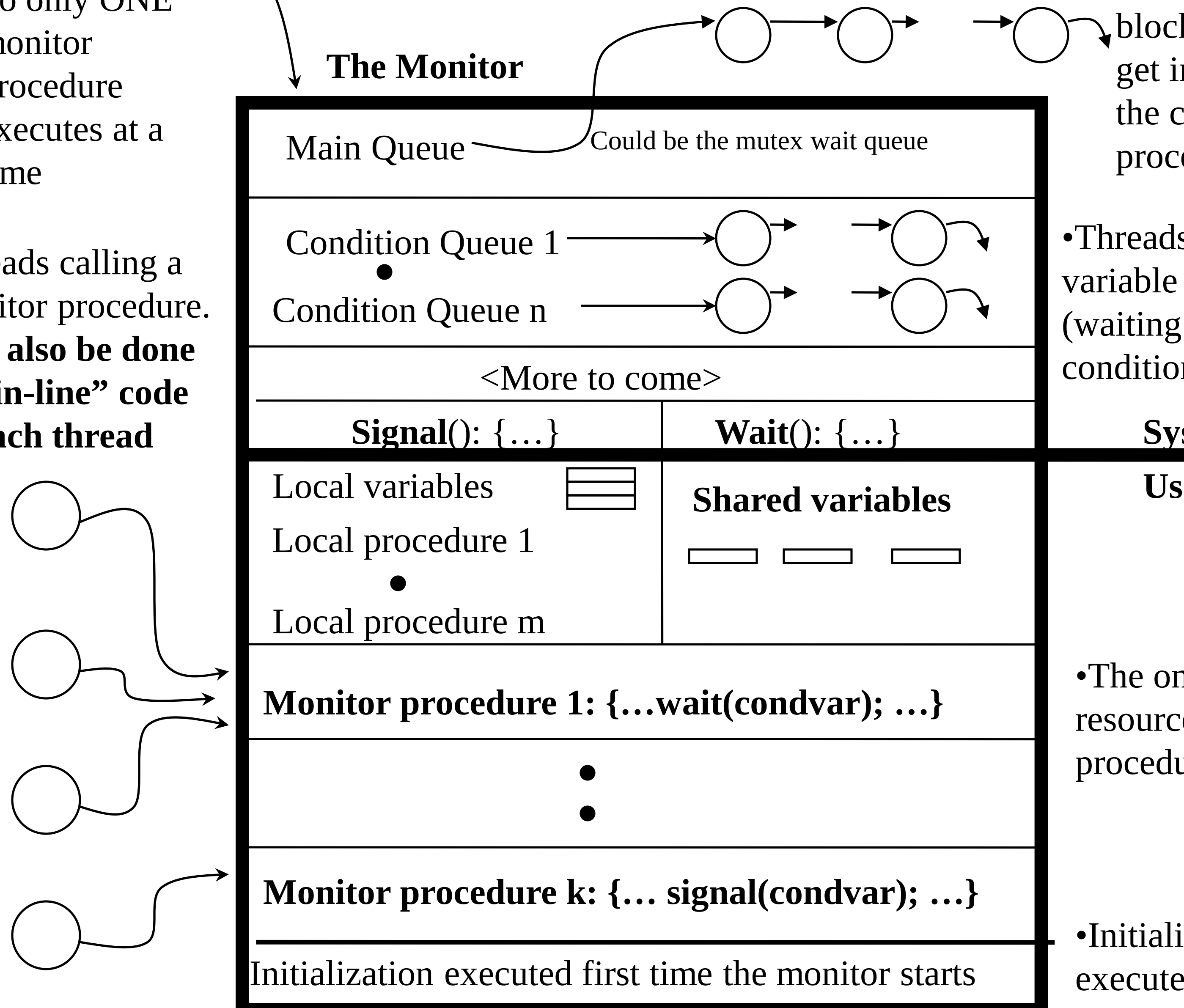
The Structure of a Monitor

MUTEX
So only ONE monitor procedure executes at a time

Proposal*: P(mname); <mon> V(name)*



•After calling, threads get blocked and are waiting to get in and start executing the called monitor procedure

Threads calling a monitor procedure. **Can also be done as “in-line” code in each thread**

•Threads waiting on a condition variable for a condition to be true (waiting for a signal on the condition variable)

System implementation

User implementation

•The only way to access shared resources is by calling a monitor procedure

•Initialization of state variables, executed ONCE at startup of monitor

Signal and Wait

- Wait (cond)
  - Insert(caller, cond_queue)
  - **Block** this instance of the monitor procedure
  - open MUTEX to get next call (for instance from the waiting queue to get in (get next call from Main_Queue))

- Signal (cond)
  - **Stop** monitor procedure calling signal (***stop??)***
  - Start first in cond_queue, or just return if empty

Implementation of the Monitor Concept

- As a primitive in a language (Mesa, Java)
- By using semaphores (in any language)
- As a thread or as a process
  - Need a way to interact with the **thread**
    - through shared variables to deliver the parameters and name of called monitor procedure
  - Need a way to interact with the **process**
    - kernel support of shared variables across address spaces
    - using another mechanism like message passing to pass parameters and name of procedure
- **At user level**
  - **use condition variables (the queues)**
  - **wait(), signal() implemented by**
    - **the operating system kernel**
    - **a thread package (Pthreads)**
  - **mutex by P-V or a special keyword like *synchronized()***

Single Resource Monitor

All threads must follow the pattern:

Reserve;

<use shared resource>

Release;

Observe

•the shared variable

•the naming of the condition variable

•the wait and signal calls

•implements a binary semaphore (s=0,1)

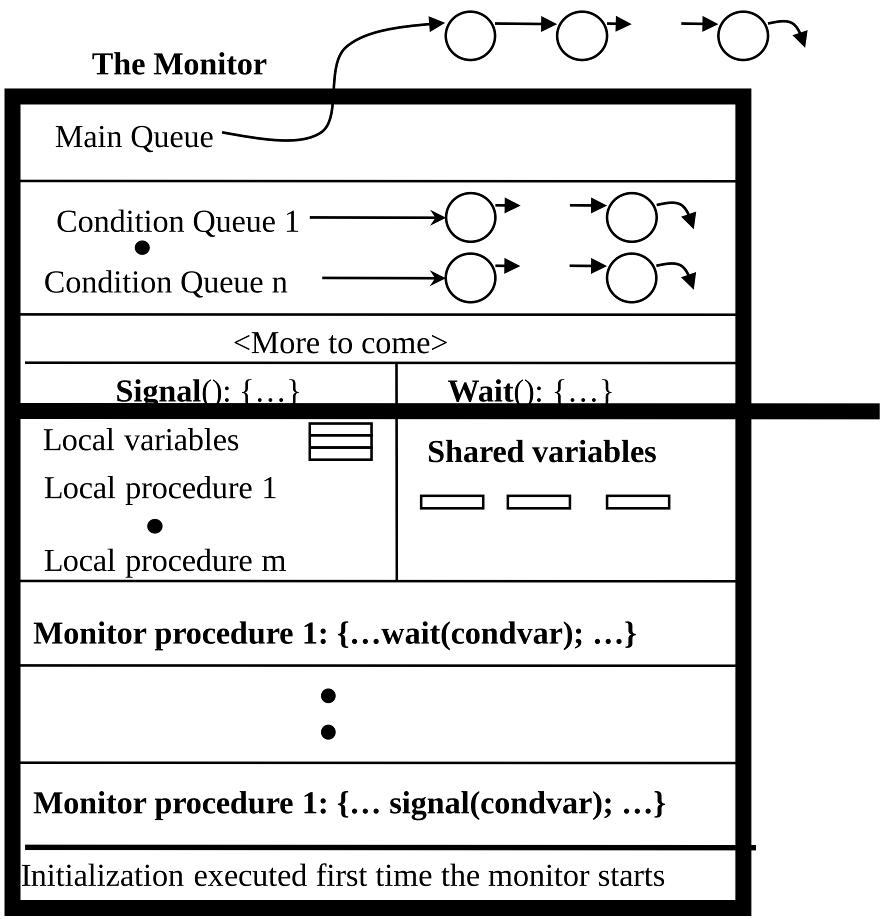
/*Local functions, variables*/
<none needed>
/*Shared variable*/
Boolean **busy**;
/*Condition variable*/
Condition **nonbusy**;

Reserve:
{
if (busy) **wait** (nonbusy);
busy:=TRUE;
}

Release:
{
busy:=FALSE;
signal (nonbusy);
}

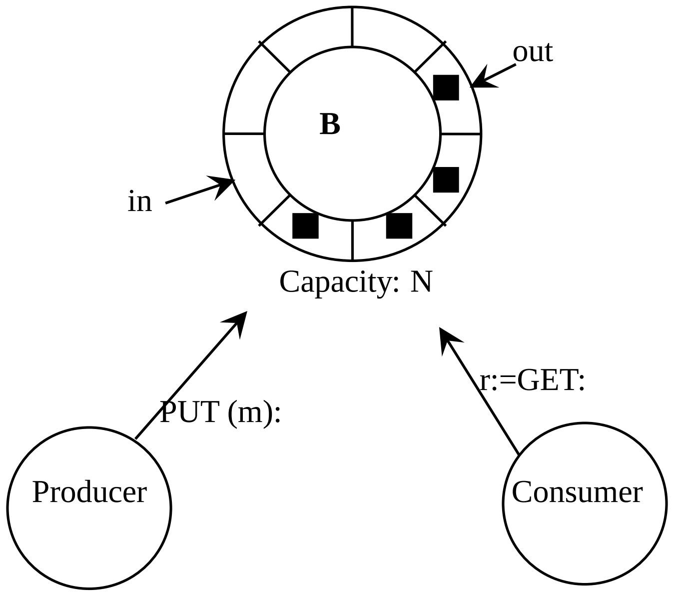
/* Initialization code*/
busy:=FALSE;
nonbusy:=EMPTY;

What is a Condition Variable?



- No "value"
- Waiting queue
- Used to represent a condition we need to wait for to be TRUE
- Initial "non-value" is EMPTY :-)

Bounded Buffer Monitor



Rules for the buffer B:

- No Get when empty
- No Put when full
- B shared, so must have mutex between Put and Get

One condition variable for each condition:

- nonempty
- nonfull
- MUTEX is already provided by the monitor

/*Local functions, variables*/
int in, out;
/*Shared variable*/
int **B(0..n-1), count**;
/*Condition variable*/
Condition **nonfull, nonempty**;

Put (int m):
{ if (count=n) **wait** (nonfull);
B(in):=m;
in:=in+1 MOD n; /* MOD is % */
count++;
signal (nonempty); }

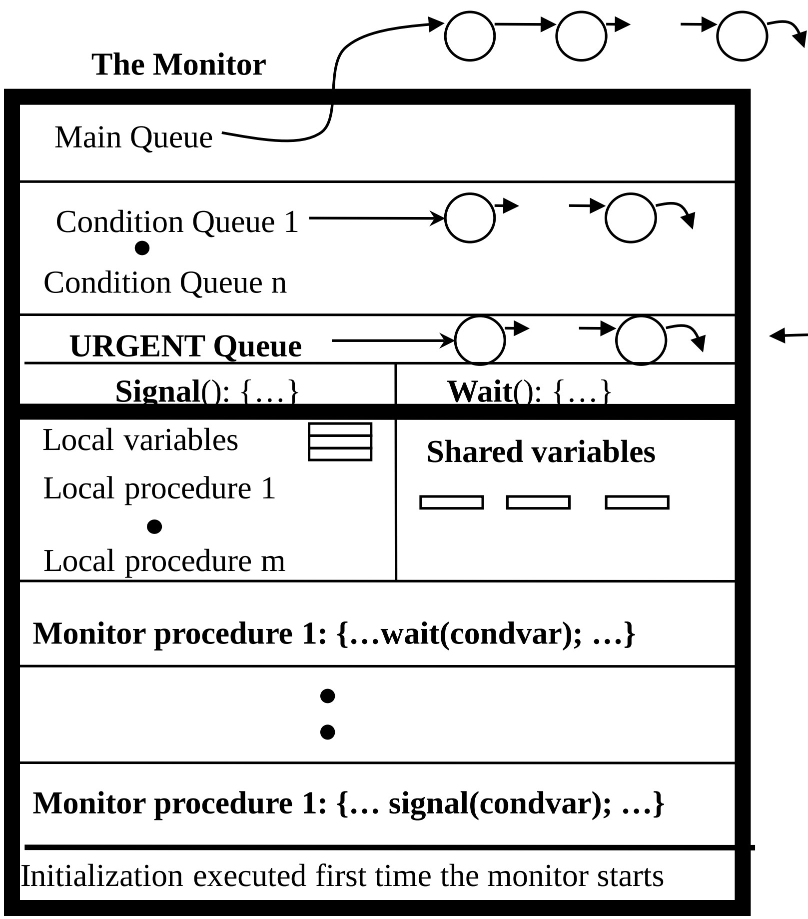
int Get:
{ if (count=0) **wait** (nonempty);
Get:=B(out);
out:=out+1 MOD n;
count--;
signal (nonfull); }

/* Initialization code*/
in:=out:=count:=0;
nonfull, nonempty:=EMPTY;

What will happen when a signal() is executed?

- Assume we have threads in Main_Queue and in a condition queue
- Main_Queue has lower "priority" than the signaled condition queue:
  - signal() => Take first from condition queue and start it from its next instruction after the wait() which blocked it
  - The signaled thread now executes
    - … until a wait(): block it, and take new from Main_Queue
    - … until a signal():
    - … until finished: take new from Main_Queue

Where to allow a call to signal()?



- Look at the two monitors we have analyzed! Where is the signal() operation?
- What if we called signal somewhere else?
  - The calling function instance must be blocked, awaiting return from signal()
    - Need a queue for the temporary halted thread
      - URGENT QUEUE
- In Hoare's monitors the signal operation must IMMEDIATELY start the signaled thread in order for the condition that it signals about **still to be guaranteed true** when the thread starts

Options of the Signaler

- Run the signaled monitor procedure (or thread) *immediately* (must suspend the current one right away) (**Hoare**)
  - If the signaler has other work to do, life gets complex
  - It is difficult to make sure there is nothing more to do because the signal implementation is not aware how it is used (where it is called)
  - It is easier to prove things
- Exit the monitor (**Hansen)**
  - Just let signal be the last statement before return from a monitor procedure
- Continues its execution (**Mesa)**
  - Easy to implement
  - But, the condition may not be true when the awaken process actually gets a chance to run

Condition Variables and Signal Semantics

Monitor Style	**Max # Cond. Variables**	**Signal Semantics**
Brinch-Hansen	More	Implicitly Enforces “Signal and Leave”
Hoare	More	“Signal and Block”
Mesa	More	“Signal and Continue”
Java	One (implicit)	“Signal and Continue”

(Mutex between monitor procedures?)

- Hoare: Yes
- But not needed if we have no shared variables
  - But **signal** and **wait** must be atomic because they can access the same condition variable
    - So no gain?
      - Finer granularity (is good)
      - Makes life harder (is bad)
- Should be possible to Put and Get at each end of a buffer?
  - Try it

Performance problems of Monitors?

- Getting in through Main_Queue
    - Many can be in Main_Queue and in a condition queue waiting for a thread to execute a monitor procedure calling a signal.
        - Can take a long time before the signaler gets in
    - Need one Wait_Main_Queue and one Signal_Main_Queue?
        - But difficult when all procedures call both wait and signal
- The monitor is a potential bottleneck ("Bottleneck OS"? :))
    - Use several to avoid hot spots
- Signal must start the signaled thread immediately, so must switch thread context and save our own
    - Can have nested calls
    - Even worse for process context switches
    - Solution?
        - **Avoid starting the signaled thread immediately**
        - But then race conditions can happen so must be careful

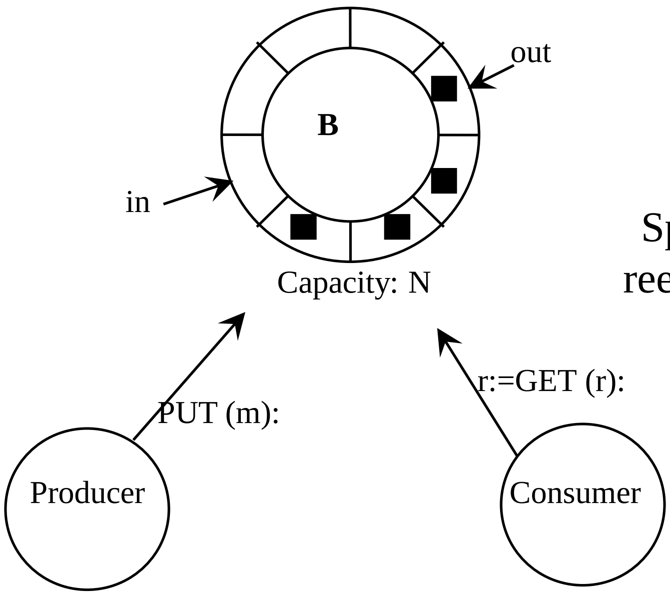
Mesa Style "Monitor" (Birrell's Paper)

- Condition variables are always associated with a mutex
- Wait(**mutex**, condition)
  - Atomically unlock the mutex and enqueue on the condition variable (block the thread)
  - Re-lock the lock when it is awaken
- Signal(condition)

Is really a NOTIFY or a HINT

  - No-op if there is no thread blocked on the condition variable
  - Wake up at **some** convenient time **at least one** (if there are threads blocked)
- Broadcast(condition)
  - Wake up **all** threads waiting on the condition

Bounded Buffer Mesa Monitors



Spins to reevaluate

Wait will UNLOCK

```
/*Local  functions, variables*/
int in, out, count;
/*Shared variable*/
int B(0..n-1);
/* Mutex */
mutex_t bb_mutex;
/*Condition variable*/
Condition nonfull, nonempty;

Put (int m):
LOCK bb_mutex {
   {  while (count=n) wait (bb_mutex, nonfull);
      B(in):=m;
      in:=in+1 MOD n;
      count++;
      signal (nonempty);    }
}

int Get:
LOCK bb_mutex {
   {  while (count=0) wait (bb_mutex, nonempty);
      Get:=B(out);
      out:=out+1 MOD n;
      count--;
      signal (nonfull);  }
}

/* Initialization code*/
in:=out:=count:=0;
nonfull, nonempty:=EMPTY;
```

Rules for the buffer B:

- No Get when empty
- No Put when full
- B shared, so must have mutex between Put and Get

One condition for each condition:

- nonempty
- nonfull
- MUTEX is locked by LOCK and unlocked by Wait

Mesa-Style vs. Hoare-Style Monitor

- Mesa-style
  - Signaler keeps lock and CPU
  - Waiter simply put on ready queue, with no special priority
    - Must then spin and reevaluate!
  - No costly context switches immediately
  - No constraints on when the waiting thread/process must run after a “signal”
  - Simple to introduce a broadcast: wake up all
    - Good when one thread frees resources, but does not know which other thread can use them (“who can use j bytes of memory?”)
  - Can easily introduce a watch dog timer: if timeout then insert waiter in Ready_Queue and let waiter reevaluate
    - Will guard a little against bugs in other signaling processes/threads causing starvation because of a “lost” signal
- Hoare-style
  - Signaler gives up lock and waiter runs immediately
  - Waiter (now executing) gives lock and CPU back to signaler when it exits critical section or if it waits again

Instead of LOCK and UNLOCK…

```
static count = 0;
static Cond full, empty;
static Mutex lock;
```

```
Enter(Item item) {
  Acquire(lock);
  while (count==N)
    Wait(lock, full);
  insert item into buffer
  count++;
  if (count==1)
    Signal(empty);
  Release(lock);
}
```

```
Remove(Item item) {
  Acquire(lock);
  while (!count)
    Wait(lock, empty);
  remove item from buffer
  count--;
  if (count==N-1)
    Signal(full);
  Release(lock);
}
```

Can we replace “while” with “if?”

Think about the performance benefit of this solution

Programming Idiom

- Waiting for a resource

```
Acquire(mutex);
while (no resource)
  wait(mutex, cond);
  use the resource
Release(mutex);
```

- Make resource available

```
Acquire(mutex);
  make resource
Signal(cond);
Release(mutex);
```

Implementing Semaphores with Mesa-Monitors

```
P( s )
{
    Acquire( s.mutex );
    --s.value;
    if (s.value < 0 )
      wait( s.mutex, s.cond );
    Release( s.mutex);
}
```

```
V( s )
{
    Acquire( s.mutex );
    ++s.value;
    if (s.value >= 0 )
      signal( s.cond );
    Release( s.mutex);
}
```

Assume that Signal wakes up exactly one awaiting thread.

Semaphore vs. Monitor

Semaphore

P(s) means WAIT if s=0
And s--

V(s) means start a waiting thread and REMEMBER that a V call was made: s++

Assume s=0 when V(s) is called: If there is no thread to start this time, the next thread to call P(s) will get through P(s)

Monitor

Wait(cond) means unconditional WAIT

Signal(cond) means start a waiting thread. But no memory!

Assume that the condition queue is empty when signal() is called. The next thread to call Wait(cond) (by executing a monitor procedure!) will block because the signal() operation did not leave any trace of the fact that it was executed on an empty condition waiting queue.

Equivalence

- Semaphores
  - Good for signaling
  - Not good for mutex because it is easy to introduce a bug
- Monitors
  - Good for scheduling and mutex
  - Too (maybe?) costly for simple signaling

History of Monitors

- Brinch-Hansen ('73) & Tony Hoare ('74)
  - Concept – No implementation
  - Requires Signal to be last action (Hansen)
  - Requires relinquishing CPU to signaler (Hoare)
- Mesa language ('77)
  - Monitor in language, but signaler keeps mutex & CPU
  - Waiter simply put on ready-queue
- Modula 2+ ('84) & Modula 3 ('88)
  - Explicit LOCK primitive
  - Mesa style monitor
- Pthreads ('95)
  - Started standardization ~'89
  - Defined by ANSI/POSIX Runtime Library
- Java threads
  - Gosling, early '90s without threads
  - Use most of Pthreads primitives