Operating Systems CSCI 3150

Lecture 6: Synchronization (II) -- Semaphores and Monitors

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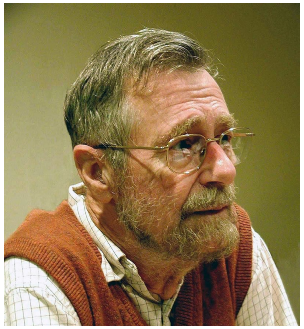
Higher-Level Synchronization

- We looked at using locks to provide mutual exclusion
- Locks work, but they have some drawbacks when critical regions are long
  - Spinlocks – inefficient
  - Disabling interrupts – can miss or delay important events
- Instead, we want synchronization mechanisms that
  - Block waiters
  - Leave interrupts enabled inside the critical section
- Look at two common high-level mechanisms
  - Semaphores: binary (mutex) and counting
  - Monitors: mutexes and condition variables
- Use them to solve common synchronization problems

Semaphores

- *Semaphores are an abstract data type that provide mutual exclusion to critical region*
- Semaphores can also be used as atomic counters
  - More later
- Semaphores are **integers** that support two operations:
  - wait(semaphore): decrement, block until semaphore is open
    - Also **P**(), after the Dutch word for test, or down()
  - signal(semaphore): increment, allow another thread to enter
    - Also **V**() after the Dutch word for increment, or up()
  - That's it! No other operations – not even just reading its value – exist
- P and V are probably the most unintuitive names you encounter in this course
  - *and you have Edsger W. Dijkstra to thank to LOL*
- Semaphore safety property: the semaphore value is always greater than or equal to 0



Dijkstra

Blocking in Semaphores

- Associated with each semaphore is a queue of waiting processes/threads
- When P() is called by a thread:
  - If semaphore is open (> 0), thread continues
  - If semaphore is closed, thread blocks on queue
- Then V() opens the semaphore:
  - If a thread is waiting on the queue, the thread is unblocked
    - *What if multiple threads are waiting on the queue?*
  - If no threads are waiting on the queue, the signal is remembered for the next thread
    - In other words, V() has "history" (c.f., condition vars later)
    - This "history" is a counter

Semaphores in OS161

```
P(sem) {
  Disable interrupts;
  while (sem->count == 0) {
    thread_sleep(sem); /* current thread
                    will sleep on this sem */
  }
  sem->count--;
  Enable interrupts;
}
```

```
V(sem) {
  Disable interrupts;
  sem->count++;
  thread_wakeup (sem); /* this will wake
      up all the threads waiting on this
      sem. Why wake up all threads? */
  Enable interrupts;
}
```

- thread_sleep() assumes interrupts are disabled
  - Note that interrupts are disabled only to enter/leave critical section
  - How can it sleep with interrupts disabled?
- What happens if "while (sem->count ==0)" is an "if (sem->count != 0)"?

Semaphore Types

- Semaphores come in two types
- Mutex semaphore (or binary semaphore)
  - Represents single access to a resource
  - Guarantees mutual exclusion to a critical section
- Counting semaphore (or general semaphore)
  - Represents a resource with many units available, or a resource that allows certain kinds of unsynchronized concurrent access (e.g., reading)
  - Multiple threads can pass the semaphore (P)
  - Number of threads determined by the semaphore “count”
    - mutex has count = 1, counting has count = N

Using Semaphores

- Use is similar to our locks, but semantics are different

```
struct Semaphore {
    int value;
    Queue q;
} S;
withdraw (account, amount) {
    P(S);
    balance = get_balance(account);
    balance = balance – amount;
    put_balance(account, balance);
    V(S);
    return balance;
}
```

Threads block

critical section

```
P(S);
balance = get_balance(account);
balance = balance – amount;
```

```
P(S);
```

```
P(S);
```

```
put_balance(account, balance);
V(S);
```

```
…
V(S);
```

```
…
V(S);
```

It is undefined which thread runs after a signal

Possible Deadlocks with Semaphores

Example:

share two mutex semaphores S and Q

S:= 1; Q:=1;

Thread 1:

P(S);
P(Q);
.. ..
V(Q);
V(S);

Thread 2:

P(Q);
P(S);
.. ..
V(S);
V(Q);

Deadlock?

Semaphore Summary

- Semaphores can be used to solve any of the traditional synchronization problems
- However, they have some drawbacks
  - They are essentially shared global variables
    - Can potentially be accessed anywhere in program
  - No connection between the semaphore and the data being controlled by the semaphore
  - No control or guarantee of proper usage
- Sometimes hard to use and prone to bugs
  - Another approach: Use programming language support

Monitors

- A monitor is a programming language construct that controls access to shared data
  - Synchronization code added by compiler, enforced at runtime
  - Why is this an advantage?
- A monitor is a module that encapsulates
  - Shared data structures
  - Procedures that operate on the shared data structures
  - Synchronization between concurrent threads that invoke the procedures
- A monitor protects its data from unstructured access
- It guarantees that threads accessing its data through its procedures interact only in legitimate ways

Monitor Semantics

- A monitor guarantees mutual exclusion
  - Only one thread can execute any monitor procedure at any time (the thread is "in the monitor")
  - If a second thread invokes a monitor procedure when a first thread is already executing one, it blocks
    - So the monitor has to have a wait queue…
  - If a thread within a monitor blocks, another one can enter
    - Condition Variable
- What are the implications in terms of parallelism in monitor?

Account Example

```
Monitor account {
  double balance;

  double withdraw(amount) {
    balance = balance – amount;
    return balance;
  }
}
```

Threads block waiting to get into monitor

```
withdraw(amount)
  balance = balance – amount;
```

```
withdraw(amount)
```

```
withdraw(amount)
```

```
  return balance (and exit)
```

```
  balance = balance – amount
  return balance;
```

```
  balance = balance – amount;
  return balance;
```

When first thread exits, another can enter. Which one is undefined.

- Hey, that was easy
- But what if a thread wants to wait inside the monitor?

Condition Variables

- A condition variable is associated with a condition needed for a thread to make progress once it is in the monitor.

```
Monitor M {
  ... monitored variables
  Condition c;

  void enter_mon (...) {
    if (extra property not true) wait(c);        waits outside of the monitor's mutex
    do what you have to do
    if (extra property true) signal(c);          brings in one thread waiting on condition
  }
```

Condition Variables

- Condition variables support three operations:
  - Wait – release monitor lock, wait for C/V to be signaled
    - So condition variables have wait queues, too
  - Signal – wakeup one waiting thread
  - Broadcast – wakeup all waiting threads
- Condition variables *are not* boolean objects
  - "if (condition_variable) then" … does not make sense
  - "if (num_resources == 0) then wait(resources_available)" does
  - An example will make this more clear

Condition Vars != Semaphores

- Condition variables != semaphores
  - However, they each can be used to implement the other
- Access to the monitor is controlled by a lock
  - wait() blocks the calling thread, and gives up the lock
    - To call wait, the thread has to be in the monitor (hence has lock)
    - Semaphore::P just blocks the thread on the queue
  - signal() causes a waiting thread to wake up
    - If there is no waiting thread, the signal is lost
    - Semaphore::V increases the semaphore count, allowing future entry even if no thread is waiting
    - Condition variables have no history

Locks and Condition Vars

- A C.V. allows a thread to be signaled when some condition is satisfied. By itself, mutex (and lock) doesn't do this.
- A queue of items to work on
  - Use a lock to ensure mutex to access the queue
  - Need C.V. to tell a consumer thread that the queue is non-empty or empty
    - Otherwise, threads have to poll the queue…

Using Semaphores

- We've looked at a simple example for using synchronization
  - Mutual exclusion while accessing a bank account
- Now we're going to use semaphores to look at more interesting examples
  - Readers/Writers
  - Bounded Buffers (after we discuss Monitor)

Readers/Writers Problem

- Readers/Writers Problem:
  - An object is shared among several threads
  - Some threads only read the object, others only write it
  - We can allow multiple readers but only one writer
    - Let #r be the number of readers, #w be the number of writers
    - Safety: $(\#r \geq 0) \land (0 \leq \#w \leq 1) \land ((\#r > 0) \Rightarrow (\#w = 0))$
- How can we use semaphores to control access to the object to implement this protocol?

First write operational code

```
reader {
  read;
}

writer {
  Write;
}
```

- Does it work?
- Why?

First attempt: one mutex semaphore

```
// exclusive writer or reader
Semaphore w_or_r = 1;

reader {
   P(w_or_r); // lock out writers
   read;
   V(w_or_r); // up for grabs
}

writer {
    P(w_or_r); // lock out readers
    Write;
    V(w_or_r); // up for grabs
}
```

- Does it work?
- Why?
- Which condition is satisfied and which is not?

$(\#r \geq 0)$

$(0 \leq \#w \leq 1)$

$((\#r > 0) \Rightarrow (\#w = 0))$

Second attempt: add a counter

```
int readcount = 0; // record #readers
Semaphore w_or_r = 1; // mutex semaphore

reader {
  readcount++;
  if (readcount == 1){
     P(w_or_r); // lock out writers
  }
  read;
  readcount--;
  if (readcount == 0){
    V(w_or_r); // up for grabs
  }
}

writer {
   P(w_or_r); // lock out readers
   Write;
   V(w_or_r); // up for grabs
}
```

- Does it work?
- *readcount is a shared variable, who protects it?*

Thread 1:	***Thread 2:***
reader {	
readcount++;	
	reader {
	readcount++;
	if (readcount == 1){
	P(w_or_r);
	}
if (readcount == 1){	
P(w_or_r);	
}	

context switch

A context switch can happen, a writer can come in since no reader locked the semaphore!

Readers/Writers Real Solution

- Use three variables
  - int readcount – number of threads reading object
  - Semaphore mutex – control access to readcount
  - Semaphore w_or_r – exclusive writing or reading

Readers/Writers

```
// number of readers
int readcount = 0;
// mutual exclusion to readcount
Semaphore mutex = 1;
// exclusive writer or reader
Semaphore w_or_r = 1;

writer {
   P(w_or_r); // lock out readers
   Write;
   V(w_or_r); // up for grabs
}
```

```
reader {
   P(mutex);     // lock readcount
   readcount += 1; // one more reader
   if (readcount == 1)
      P(w_or_r); // synch w/ writers
   V(mutex);   // unlock readcount
   Read;
   P(mutex);     // lock readcount
   readcount -= 1; // one less reader
   if (readcount == 0)
      V(w_or_r); // up for grabs
   V(mutex);   // unlock readcount}
}
```

- Why do readers use mutex?
- What if the V(mutex) is above “if (readcount == 1)”?

But it still has a problem…

```
// number of readers
int readcount = 0;
// mutual exclusion to readcount
Semaphore mutex = 1;
// exclusive writer or reader
Semaphore w_or_r = 1;

writer {
   P(w_or_r); // lock out readers
   Write;
   V(w_or_r); // up for grabs
}
```

```
reader {
   P(mutex);      // lock readcount
   readcount += 1; // one more reader
   if (readcount == 1)
      P(w_or_r); // synch w/ writers
   V(mutex);   // unlock readcount
   Read;
   P(mutex);      // lock readcount
   readcount -= 1; // one less reader
   if (readcount == 0)
      V(w_or_r); // up for grabs
   V(mutex);   // unlock readcount}
}
```

Problem: Starvation

- What if a writer is waiting, but readers keep coming, the writer is starved

Semaphore Questions

- Are there any problems that can be solved with counting semaphores that cannot be solved with mutex semaphores?
- If a system provides only mutex semaphores, can you use it to implement a counting semaphores?
- When to use counting semaphore?
  - Problem needs a counter
  - The maximum value is known (bounded)

Monitor Readers and Writers

- Will have four methods: StartRead, StartWrite, EndRead and EndWrite
- Monitored data: nr (number of readers) and nw (number of writers) with the monitor invariant

$$(nr \geq 0) \land (0 \leq nw \leq 1) \land ((nr > 0) \Rightarrow (nw = 0))$$

- Two conditions:
  - canRead: $nw = 0$
  - canWrite: $(nr = 0) \land (nw = 0)$

Monitor Readers and Writers

```
Monitor RW {
  int nr = 0, nw = 0;
  Condition canRead, canWrite;

  void StartRead () {
    while (nw != 0) do wait(canRead);
    nr++;
  }

  void EndRead () {
    nr--;
   if (nr == 0) signal(canWrite);
}
```

```
  void StartWrite {
    while (nr != 0 || nw != 0) do wait(canWrite);
    nw++;
  }

  void EndWrite () {
    nw--;
    broadcast(canRead);
    signal(canWrite);
  }
} // end monitor
```

Monitor Readers and Writers

- Is there any priority between readers and writers?
- What if you wanted to ensure that a waiting writer would have priority over new readers?

Bounded Buffer

- Problem: There is a set of resource buffers shared by producer and consumer threads
  - Producer inserts resources into the buffer set
    - Output, disk blocks, memory pages, processes, etc.
  - Consumer removes resources from the buffer set
    - Whatever is generated by the producer

- Producer and consumer execute at different rates
  - No serialization of one behind the other
  - Tasks are independent (easier to think about)
  - The buffer set allows each to run without explicit handoff

- Safety:
  - Sequence of consumed values is prefix of sequence of produced values
  - If *nc* is number consumed, *np* number produced, and N the size of the buffer, then $0 \leq np - nc \leq N$

Bounded Buffer (2) – functional code

```
producer {
  while (1) {
    Produce new resource;
    Add resource to an empty buffer;
  }
}
```

```
consumer {
  while (1) {
    Remove resource from a full buffer;
    Consume resource;
  }
}
```

Bounded Buffer (3)

- Use three semaphores:
  - empty – count of empty buffers
    - Counting semaphore
    - empty = N – (np – nc)
  - full – count of full buffers
    - Counting semaphore
    - *np* - *nc* = full
  - mutex – mutual exclusion to shared set of buffers
    - Binary semaphore

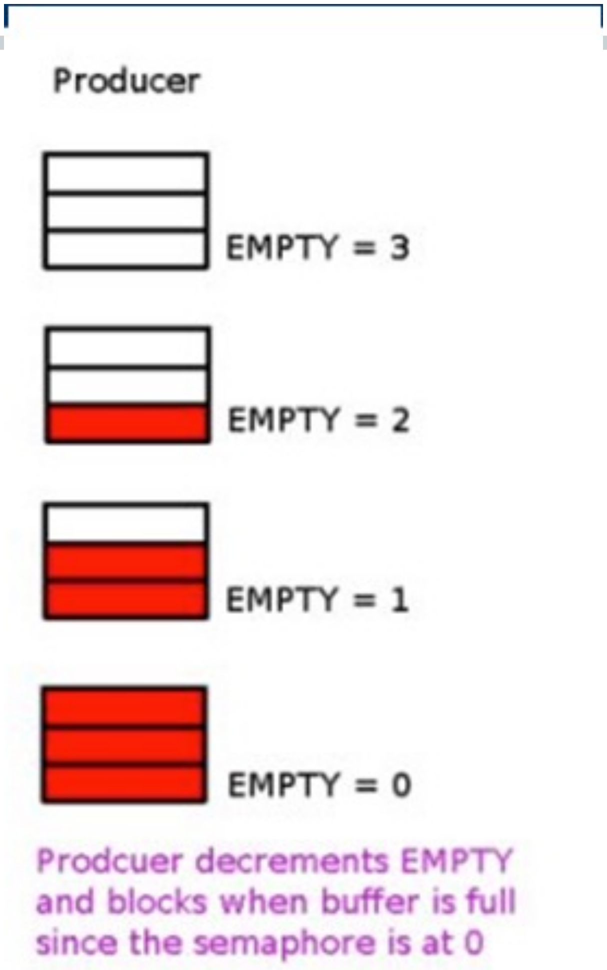
Bounded Buffer (4)

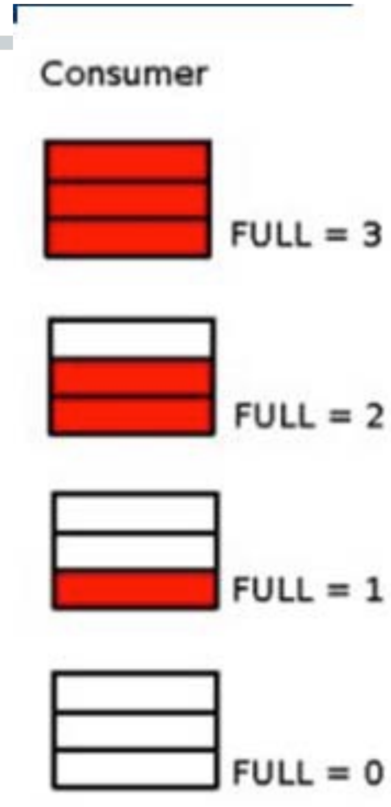
```
Semaphore mutex = 1;   // mutual exclusion to shared set of buffers
Semaphore empty = N;   // count of empty buffers (all empty to start)
Semaphore full = 0;    // count of full buffers (none full to start)
```

```
producer {
  while (1) {
    Produce new resource;
    P(empty); // wait for empty buffer
    P(mutex); // lock buffer list
    Add resource to an empty buffer;
    V(mutex); // unlock buffer list
    V(full);  // note a full buffer
  }
}
```

```
consumer {
  while (1) {
    P(full);   // wait for a full buffer
    P(mutex);  // lock buffer list
    Remove resource from a full buffer;
    V(mutex);  // unlock buffer list
    V(empty);  // note an empty buffer
    Consume resource;
  }
}
```

Bounded Buffer (5)





Consumer decrements FULL and blocks when buffer has no item since the semaphore FULL is at 0

Bounded Buffer (6)

Why we need both "empty" and "full" semaphores?

```
Semaphore mutex = 1;   // mutual exclusion to shared set of buffers
Semaphore empty = N;   // count of empty buffers (all empty to start)
```
~~Semaphore full = 0;   // count of full buffers (none full to start)~~

```
producer {
  while (1) {
    Produce new resource;
    P(empty); // wait for empty buffer
    P(mutex); // lock buffer list
    Add resource to an empty buffer;
    V(mutex); // unlock buffer list
```
~~V(full);   // note a full buffer~~
```
  }
}
```

```
consumer {
  while (1) {
```
~~P(full);   // wait for a full buffer~~
```
    P(mutex);   // lock buffer list
    Remove resource from a full buffer;
    V(mutex); // unlock buffer list
    V(empty); // note an empty buffer
    Consume resource;
  }
}
```

More consumers "remove resource" than actually produced!

Monitor Bounded Buffer

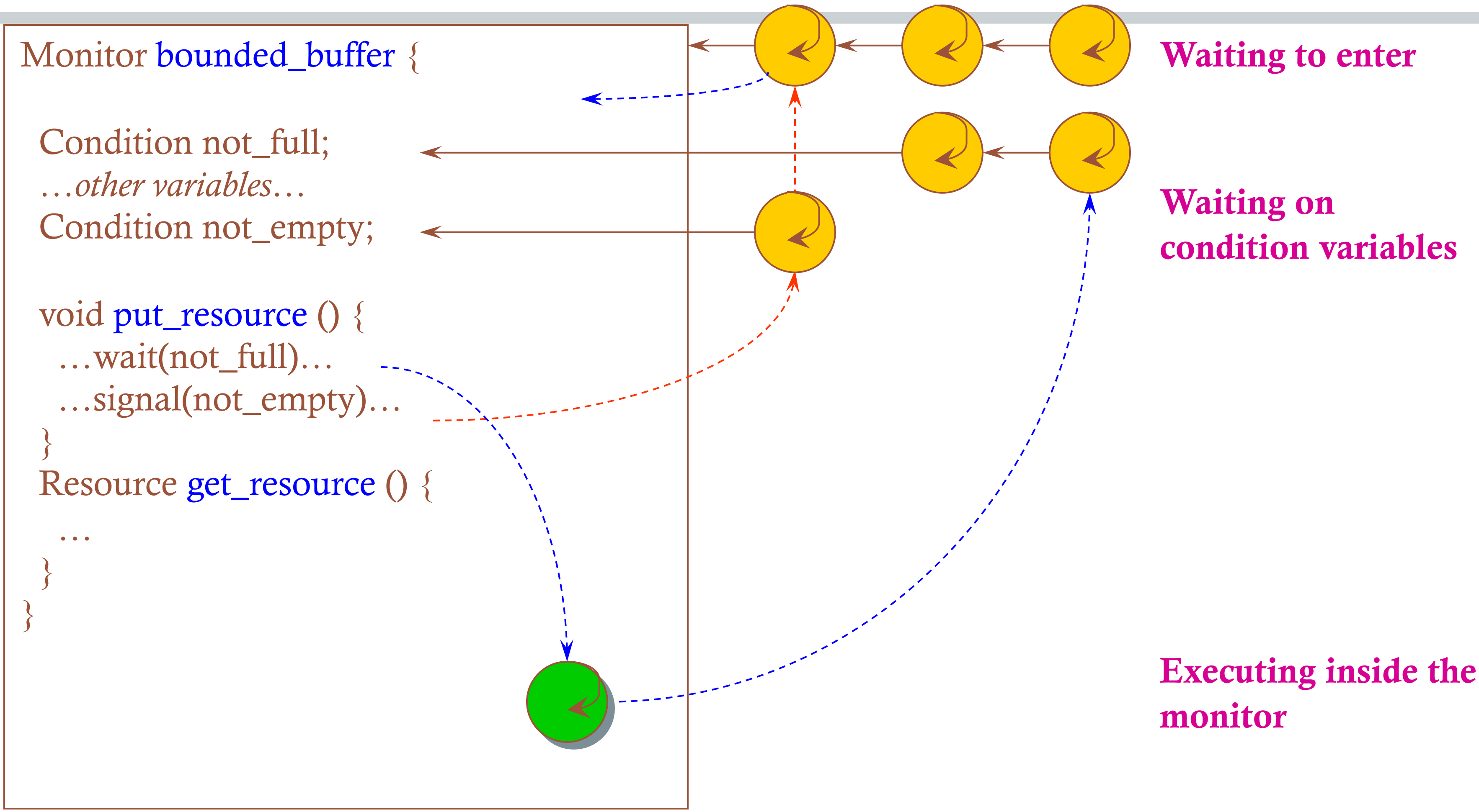
```
Monitor bounded_buffer {
  Resource buffer[N];
  // Variables for indexing buffer
  // monitor invariant involves these vars
  Condition not_full; // space in buffer
  Condition not_empty; // value in buffer

  void put_resource (Resource R) {
    while (buffer array is full)
        wait(not_full);
    Add R to buffer array;
    signal(not_empty);
  }
```

```
  Resource get_resource() {
    while (buffer array is empty)
        wait(not_empty);
    Get resource R from buffer array;
    signal(not_full);
    return R;
  }
} // end monitor
```

- What happens if no threads are waiting when signal is called?
  - Signal is lost

Monitor Queues



Summary

- Semaphores
  - P()/V() implement blocking mutual exclusion
  - Also used as atomic counters (counting semaphores)
  - Can be inconvenient to use
- Monitors
  - Synchronizes execution within procedures that manipulate encapsulated data shared among procedures
    - Only one thread can execute within a monitor at a time
  - Relies upon high-level language support
- Condition variables
  - Used by threads as a synchronization point to wait for events
  - Inside monitors

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