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Limitations of Wait- and Lock-Free Algorithms

Wait-/Lock-Free algorithms are severely limited in terms of their computation:

- restricted to the semantics of a *single* atomic operation
- set of atomic operations is architecture specific, but often includes
  - exchange of a memory cell with a register
  - compare-and-swap of a register with a memory cell
  - fetch-and-add on integers in memory
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⇝ only very simple algorithms can be implemented, for instance

binary semaphores : a flag that can be acquired (set) if free (unset) and released

counting semaphores : an integer that can be decreased if non-zero and increased

mutex : ensures mutual exclusion using a binary semaphore

monitor : ensures mutual exclusion using a binary semaphore, allows other threads to block until the next release of the resource

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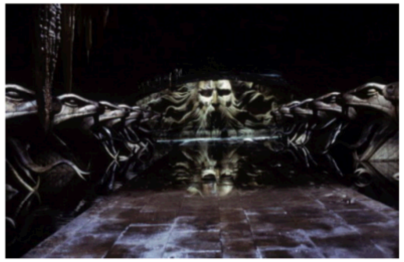
We will collectively refer to these data structures as *locks*.

Locks

 $\Rightarrow$ 

A lock is a data structure that

- protects a *critical section*: a piece of code that may produce incorrect results when executed concurrently from several threads
- it ensures *mutual exclusion*: no two threads execute at once
- *block* other threads as soon as one thread executes the critical section
- can be *acquired* and *released*
- may *deadlock* the program

Semaphores and Mutexes

A (counting) *semaphore* is an integer s with the following operations:

```
void signal() {
  atomic { s = s + 1; }
}
```

```
void wait() {
  bool avail;
  do {
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      avail = s>0;
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- a thread requiring a resource executes `wait()`
- if a resource is still available, `wait()` returns
- once a thread finishes using a resource, it calls `signal()`

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Special case: initializing with $\boxed{s = 1}$ gives a *binary* semaphore:

- can be used to block and unblock a thread
- can be used to protect a single resource
  - in this case the data structure is also called *mutex*

Implementation of Semaphores

A *semaphore* does not have to wait busily:

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void signal() {
  atomic { s = s + 1; }
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```
void wait() {
  bool avail;
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```

Busy waiting is avoided by placing waiting threads into queue:

- a thread failing to decrease s executes `de_schedule()`
- `de_schedule()` enters the operating system and inserts the current thread into a queue of threads that will be woken up when `s` becomes non-zero, usually by *monitoring writes* to `&s`
- once a thread calls `signal()`, the first thread t waiting on `&s` is extracted
- the operating system lets t return from its call to `de_schedule()`

Practical Implementation of Semaphores

Certain optimisations are possible:

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In general, the implementation is more complicated

- `wait()` may busy wait for a few iterations
  - saves de-scheduling if the lock is released frequently
  - better throughput for semaphores that are held for a short time
- `signal()` might have to inform the OS that `s` has been written

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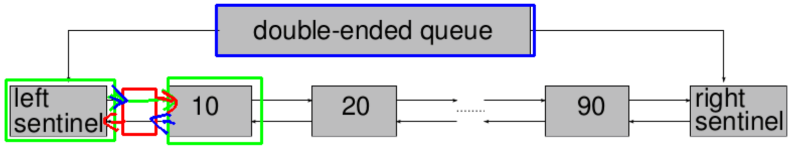
⇝ using a semaphore with a single thread reduces to `if (s) s--; s++;`

Making a Queue Thread-Safe

Consider a double ended queue:



double-ended queue: adding an element

```
void PushLeft(DQueue* q, int val) {
  QNode *qn = malloc(sizeof(QNode));
  qn->val = val;
  // prepend node qn
  QNode* leftSentinel = q->left;
  QNode* oldLeftNode = leftSentinel->right;
  qn->left = leftSentinel;
  qn->right = oldLeftNode;
  leftSentinel->right = qn;
  oldLeftNode -> left = qn;
}
```


Mutexes

One common use of semaphores is to guarantee mutual exclusion.

- in this case, a binary semaphore is also called a *mutex*
- add a lock to the double-ended queue data structure
- decide what needs protection and what not

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double-ended queue: thread-safe version

```
void PushLeft(DQueue* q, int val) {
  QNode *qn = (QNode*) malloc(sizeof(QNode));
  qn->val = val;
  QNode* leftSentinel = q->left;
  wait(q->s); // wait to enter the critical section
  QNode* oldLeftNode = leftSentinel->right;
  qn->left = leftSentinel;
  qn->right = oldLeftNode;
  leftSentinel->right = qn;
  oldLeftNode -> left = qn;
  signal(q->s); // signal that we're done
}
```


Implementing the Removal

By using the same lock `q->s`, we can write a thread-safe `PopRight`:

double-ended queue: removal

```
int PopRight(DQueue* q) {
  QNode* oldRightNode;
  QNode* leftSentinel = q->left;
  QNode* rightSentinel = q->right;
  wait(q->s); // wait to enter the critical section
  oldRightNode = rightSentinel->left;
  if (oldRightNode==leftSentinel) { signal(q->s); return -1; }
  QNode* newRightNode = oldRightNode->left;
  newRightNode->right = rightSentinel;
  rightSentinel->left = newRightNode;
  signal(q->s); // signal that we're done
  int val = oldRightNode->val;
  free(oldRightNode);
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  int val = oldRightNode->val;
  free(oldRightNode);
  return val;
}
```

- error case complicates code ⇝ semaphores are easy to get wrong
- abstract common concept: take lock on entry, release on exit

Monitors: An Automatic, Re-entrant Mutex

Often, a data structure can be made thread-safe by

- acquiring a lock upon entering a function of the data structure
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Locking each procedure body that accesses a data structure:

1. is a re-occurring pattern, should be generalized
2. becomes problematic in recursive calls: it blocks
3. if a thread t waits for a data structure to be filled:
   - t will call e.g. `PopRight` and obtain `-1`
   - t then has to call again, until an element is available
   - ⚠ t is busy waiting and produces contention on the lock

Implementation of a Basic Monitor

A monitor contains a mutex `s` and the thread currently occupying it:

```
typedef struct monitor mon_t;
struct monitor { int tid; int count; };
void monitor_init(mon_t* m) { memset(m, 0, sizeof(mon_t)); }
```

Define `monitor_enter` and `monitor_leave`:

- ensure mutual exclusion of accesses to `mon_t`
- track how many times we called a monitored procedure recursively

```
void monitor_enter(mon_t *m) {
  bool mine = false;
  while (!mine) {
    atomic {
      mine = thread_id()==m->tid;
      if (mine) m->count++; else
        if (m->tid==0) {
          mine = true; m->count=1;
          m->tid = thread_id();
        }
    };
    if (!mine) de_schedule(&m->tid);}}
```

```
void monitor_leave(mon_t *m) {
  atomic {
    m->count--;
    if (m->count==0) {
      // wake up threads
      m->tid=0;
    }
  }
}
```

Rewriting the Queue using Monitors

Instead of the mutex, we can now use monitors to protect the queue:

double-ended queue: monitor version

```
void PushLeft(DQueue* q, int val) {
  monitor_enter(q->m);
  ...
  monitor_leave(q->m);
}
void ForAll(DQueue* q, void* data, void (*callback)(void*,int)){
  monitor_enter(q->m);
  for (QNode* qn = q->left->right; qn!=q->right; qn=qn->right)
    (*callback)(data, qn->val);
  monitor_leave(q->m);
}
```

Recursive calls possible:

- the function passed to `ForAll` can invoke `PushLeft`
- example: `ForAll(q,q,&PushLeft)` duplicates entries
- using monitor instead of mutex ensures that recursive call does not block

Condition Variables

✓ Monitors simplify the construction of thread-safe resources.
Still: Efficiency problem when using resource to synchronize:

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Idea: create a *condition variable* on which to block while waiting:

```
struct monitor { int tid; int count; int cond; };
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Idea: create a *condition variable* on which to block while waiting:

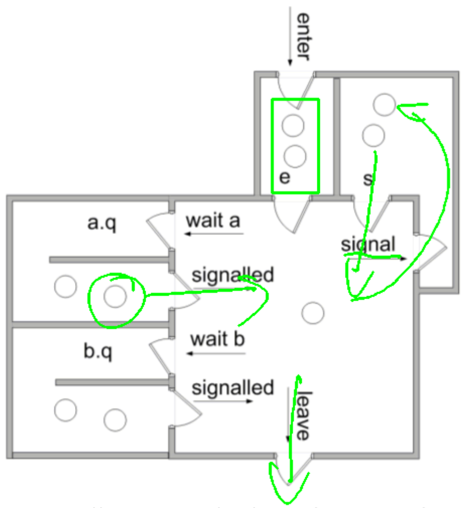
```
struct monitor { int tid; int count; int cond; };
```

Define these two functions:

1. `wait` for the condition to become true
   - called while being *inside* the monitor
   - temporarily *releases* the monitor and blocks
   - when *signalled*, re-acquires the monitor and returns
2. `signal` waiting threads that they may be able to proceed
   - one/all waiting threads that called *wait* will be woken up, two possibilities:
     - *signal-and-urgent-wait*: the *signalling* thread suspends and continues once the *signalled* thread has released the monitor
     - *signal-and-continue* the *signalling* thread continues, any *signalled* thread enters when the monitor becomes available

Signal-And-Urgent-Wait Semantics

Requires one queues for each condition c and a suspended queue s:

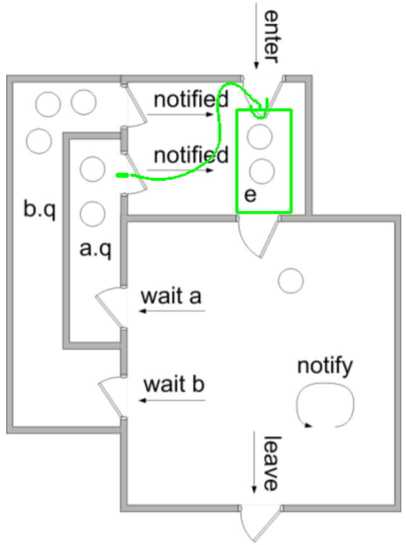


source: http://en.wikipedia.org/wiki/Monitor_(synchronization)

- a thread who tries to enter a monitor is added to queue e if the monitor is occupied
- a call to `wait` on condition a adds thread to the queue $a.q$
- a call to `signal` for a adds thread to queue s (suspended)
- one thread form the a queue is woken up
- `signal` on a is a no-op if $a.q$ is empty
- if a thread leaves, it wakes up one thread waiting on s
- if s is empty, it wakes up one thread from e

Signal-And-Continue Semantics

Here, the `signal` function is usually called `notify`.



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- a call to `wait` on condition a adds thread to the queue $a.q$
- a call to `notify` for a adds one thread from $a.q$ to e (unless $a.q$ is empty)
- if a thread leaves, it wakes up one thread waiting on e

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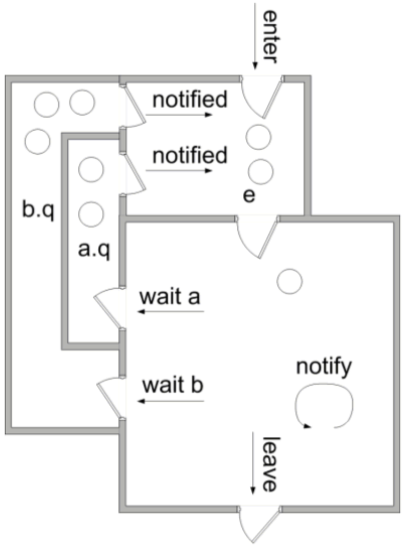

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- a call to `wait` on condition a adds thread to the queue $a.q$
- a call to `notify` for a adds one thread from $a.q$ to e (unless $a.q$ is empty)
- if a thread leaves, it wakes up one thread waiting on e

⇝ signalled threads compete for the monitor

- assuming FIFO ordering on e, threads who tried to enter between `wait` and `notify` will run first
- need additional queue s if waiting threads should have priority

Implementing Condition Variables

We implement the simpler *signal-and-continue* semantics:

- a *notified* thread is simply woken up and competes for the monitor

```
void cond_wait(mon_t *m) {
  assert(m->tid==thread_id());
  int old_count = m->count;
  m->tid = 0;
  wait(m->cond);
  bool next_to_enter;
  do {
    atomic {
      next_to_enter = m->tid==0;
      if (next_to_enter) {
        m->tid = thread_id();
        m->count = old_count;
      }
    }
    if (!next_to_enter) de_schedule(&m->tid);
  } while (!next_to_enter);}
```

```
void cond_notify(mon_t *m) {
  // wake up other threads
  signal(m->cond);
}
```

A Note on Notify

With *signal-and-continue* semantics, two notify functions exist:

1. `notify`: wakes up exactly one thread waiting on condition variable
2. `notifyAll`: wakes up all threads waiting on a condition variable

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⇝ programmer should assume that thread is not the only one woken up

What about the priority of notified threads?

- a notified thread is likely to block immediately on `&m->tid`
- ⇝ notified threads compete for the monitor with other threads
- if OS implements FIFO order: notified threads will run *after* threads that tried to enter since `wait` was called
- giving priority to waiting threads requires more complex implementation (queue data structure for signaled threads)

Implementing `PopRight` with Monitors

We use the monitor `q->m` and the condition variable `q->c`. `PopRight`:

double-ended queue: removal

```
int PopRight(DQueue* q, int val) {
  QNode* oldRightNode;
  monitor_enter(q->m); // wait to enter the critical section
L: QNode* rightSentinel = q->right;
  oldRightNode = rightSentinel->left;
  if (oldRightNode==leftSentinel) { cond_wait(q->c); goto L; }
  QNode* newRightNode = oldRightNode->left;
  newRightNode->right = rightSentinel;
  rightSentingel->left = newRightNode;
  monitor_leave(q->m); // signal that we're done
  int val = oldRightNode->val;
  free(oldRightNode);
  return val;
}
```

Monitor versus Semaphores

A monitor can be implemented using semaphores:

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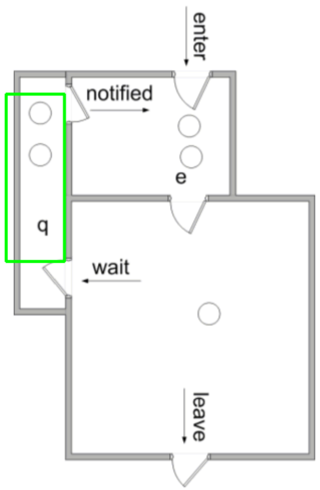
A semaphore can be implemented using a monitor:

- protect the semaphore variable s with a monitor
- implement `wait` by calling `cond_wait` if $s = 0$

Monitors with a Single Condition Variable

Monitors with a single condition variable are built into *Java* and *C#*:



source: http://en.wikipedia.org/wiki/Monitor_(synchronization)

```
class C {
  public synchronized void f() {
    // body of f
}}
```

Synchronized(o)

is equivalent to

```
class C {
  public void f() {
    monitor_enter();
    // body of f
    monitor_leave();
}}
```

with `Object` containing:

```
private int mon_var;
private int mon_count;
private int cond_var;
protected void monitor_enter();
protected void monitor_leave();
```


Deadlocks with Monitors

Definition (Deadlock)

A deadlock is a situation in which two processes are waiting for the respective other to finish, and thus neither ever does.

(The definition generalizes to a set of actions with a cyclic dependency.)