Script generated by TTT

Title: Simon: Programmiersprachen (16.11.2012)

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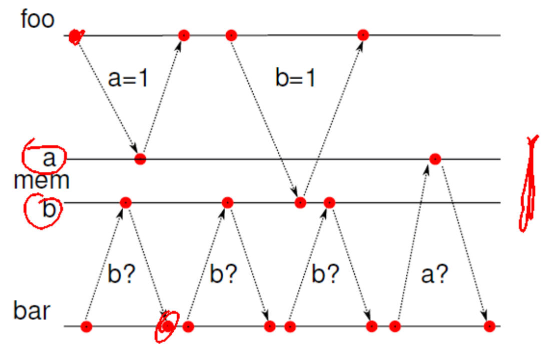
Sequential Consistency

Note: there is no observable change if calculations on different memory locations can happen in parallel.

- model each memory location as different process



Some observations:

- the accesses of `foo` to `a` occurs before `b`
- the first two read accesses to `b` are in parallel to `a=1`

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

Semaphores and Mutexes

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

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void signal() {
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- the operating system lets t return from its call to `de_schedule()`

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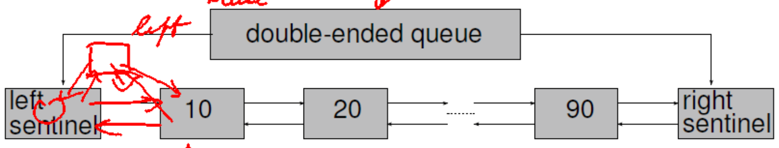
⇝ using a semaphore with a single thread reduces to `if (s) s--; s++;`

- using semaphores in sequential code has no or little penalty
- program with concurrency in mind?

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;
}
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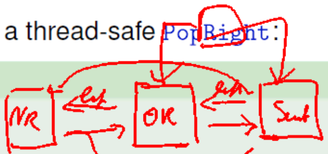
- add a lock to the double-ended queue data structure
- decide what needs protection and what not

double-ended queue: thread-safe version

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

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- acquiring a lock upon entering a function of the data structure
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⇝ need a way to release the lock after the return of the last recursive call

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 s; 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->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:

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- the function passed to `ForAll` can invoke `PushLeft`
- example: `ForAll(q,q,&PushLeft)` duplicates entries

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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 s; int tid; int count; int cond; };
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Define these two functions:

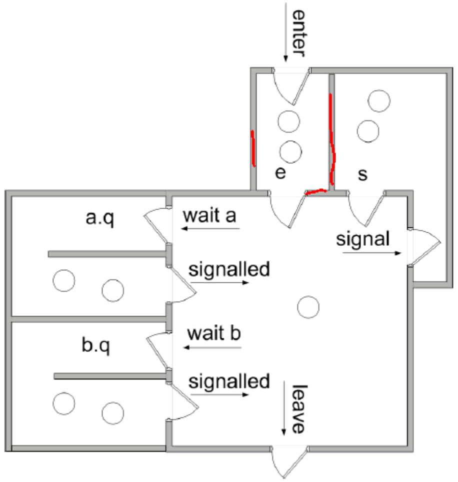
1. `wait` for the condition to become true
   - called while being *inside* the monitor
   - temporarily *releases* the monitor and blocks
   - when *signalled*, re-acquires the monitor and returns
2. `signal` waiting threads that they may be able to proceed
   - one/all waiting threads that called *wait* 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:



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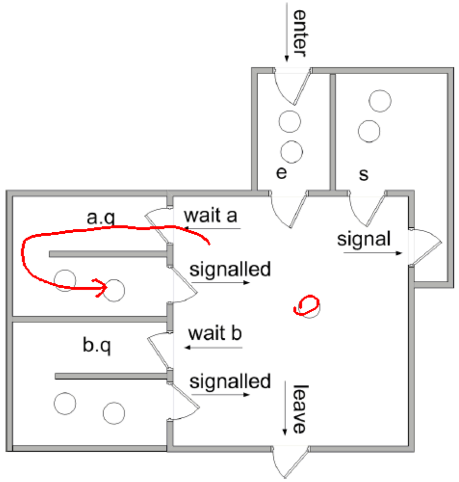

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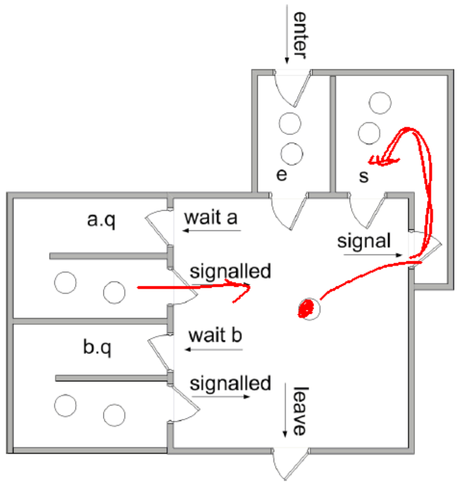

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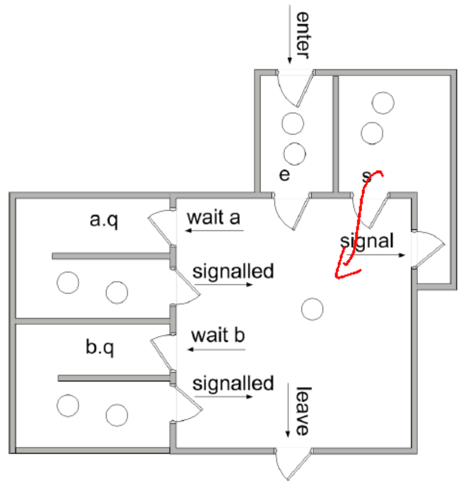

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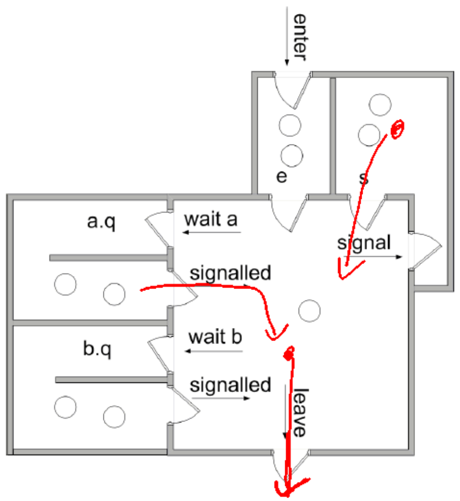

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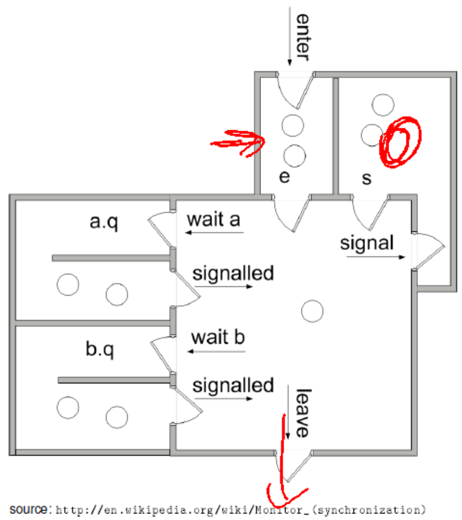

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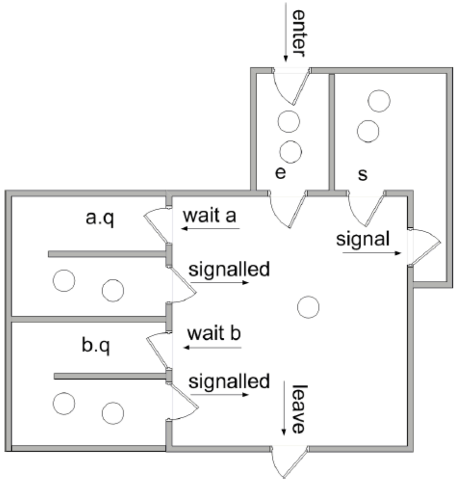

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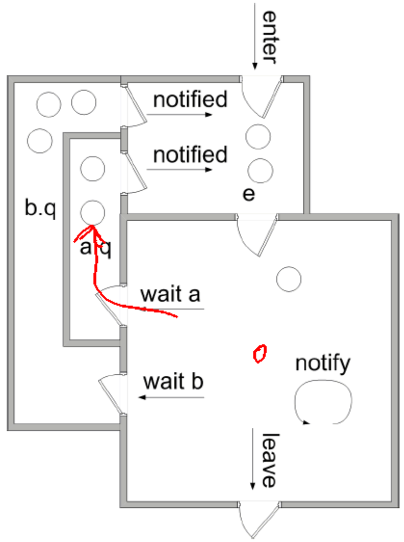
⇝ queue s has priority over e

Signal-And-Continue Semantics

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



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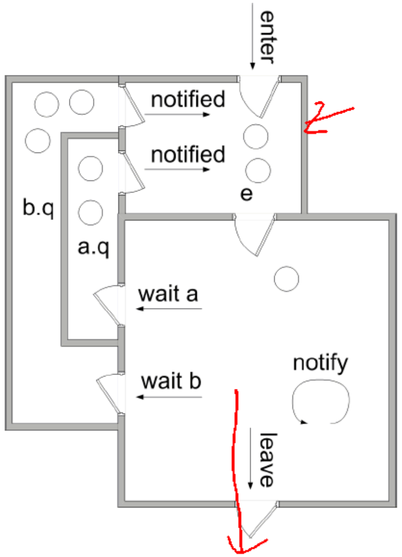

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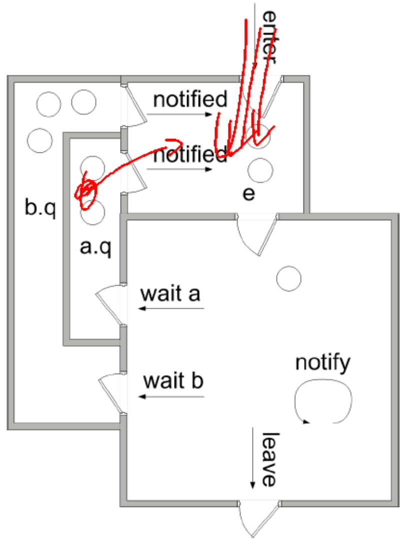

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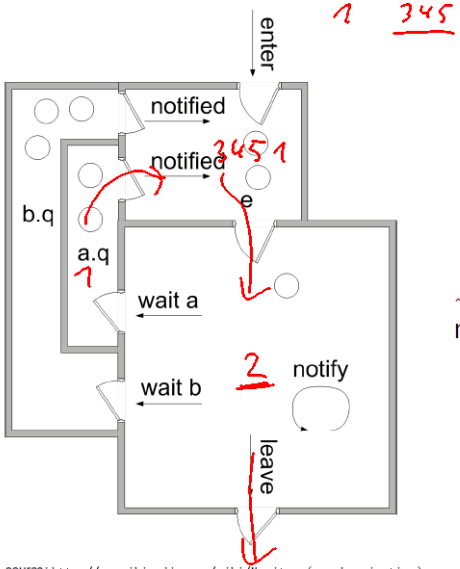

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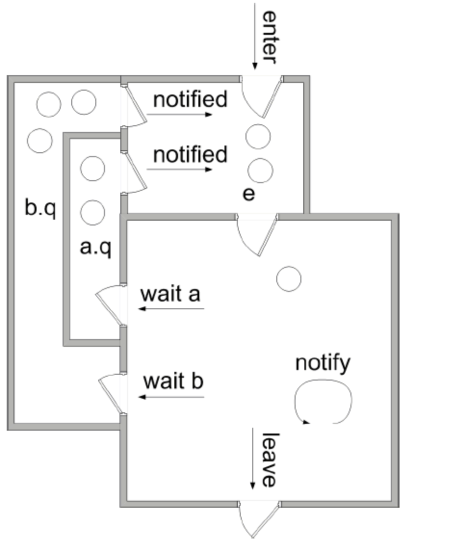

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- need additional queue s if waiting threads should have priority

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->count = 0; m->tid = 0;
  de_schedule(&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
  m->cond = 1;
}
```


A Note on Notify

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

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- giving priority to waiting threads requires better interface to OS

Implementing PopRight with Monitors

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

double-ended queue: removal

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  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; }
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- if the queue is empty, wait on `q->c`
- use a loop, in case the thread is woken up spuriously

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A note on the history of monitors:

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A semaphore can be implemented using a monitor:

- protect the semaphore variable s with a monitor
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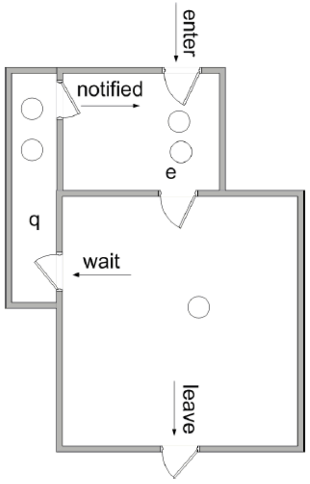
  - $\leadsto$ wake up thread and have it check the predicate itself
- create condition variable for each set of threads with the same p
  - notify variable if the predicate may have changed
- or, simpler: notify all threads each time any predicate changes

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
  }}
```

is equivalent to

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

with `Object` containing:

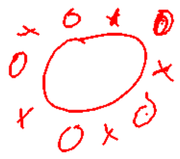
```
private int mon_var;
private int mon_count;
private int cond_var;
protected void monitor_enter();
protected void monitor_leave();
```


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.)



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class Foo {
  public Foo other = null;
  public synchronized void bar() {
    ... if (*) other.bar(); ...
  }
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and two instances:

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Foo a = new Foo();
Foo b = new Foo();
a.other = b; b.other = a;
// in parallel:
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Sequence leading to a deadlock:

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- `a.bar()` acquires the monitor of `a`
- `b.bar()` acquires the monitor of `b`
- A happens to execute `other.bar()`
- A blocks on the monitor of b
- B happens to execute `other.bar()`

Treatment of Deadlocks

Deadlocks occur if the following four conditions hold [1]:

1. *mutual exclusion*: processes require exclusive access
2. *wait for*: a process holds resources while waiting for more
3. *no preemption*: resources cannot be taken away form processes
4. *circular wait*: waiting processes form a cycle

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⇝ *prevention* is the only safe approach on standard operating systems

- can be achieve using *lock-free* algorithms
- but what about algorithms that require locking?

Deadlock Prevention through Partial Order

Observation: A cycle cannot occur if locks can be *partially ordered*.

Definition (lock sets)

Let L denote the set of locks. We call $\lambda(p) \subseteq L$ the lock set at p, that is, the set of locks that may be in the “acquired” state at program point p.

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We require the transitive closure σ^+ of a relation σ:

Definition (transitive closure)

Let $\sigma \subseteq X \times X$ be a relation. Its transitive closure is $\sigma^+ = \bigcup_{i \in \mathbb{N}} \sigma^i$ where

$$\begin{aligned} \sigma^0 &= \sigma \\ \sigma^{i+1} &= \sigma^i \cup \{\langle x_1, x_3 \rangle \mid \exists x_2 \in X \,.\, \langle x_1, x_2 \rangle \in \sigma^i \wedge \langle x_2, x_3 \rangle \in \sigma^i\} \end{aligned}$$

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