Script **generated by TTT**

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TECHNISCHE UNIVERSITÄT MÜNCHEN
FAKULTÄT FÜR INFORMATIK

19.11. there is a lecture

Programming Languages

Concurrency: Atomic Executions, Locks and Monitors

Dr. Axel Simon and Dr. Michael Petter

Winter term 2014

Why Memory Barriers are not Enough

Communication via memory barriers has only specific applications:

- coordinating state transitions between threads
- for systems that require minimal overhead (and no de-scheduling)

Often certain pieces of memory may only be modified by one thread at once.

- can use barriers to implement automata that ensure *mutual exclusion*
- ⇝ generalize the re-occurring concept of enforcing mutual exclusion

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);
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Recursive calls possible:

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- 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:

- 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

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```
struct monitor { 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:

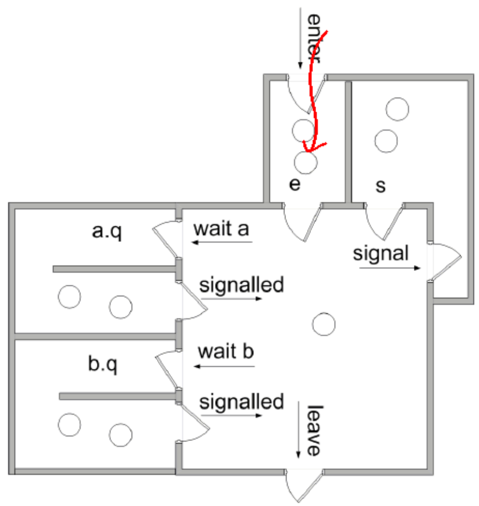
     signal-and-urgent-wait : the *signalling* thread suspends and continues once the *signalled* thread has released the monitor

     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:

- a thread who tries to enter a monitor is added to queue e if the monitor is occupied



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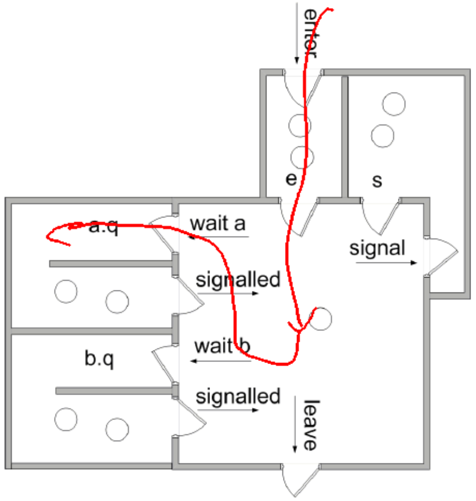

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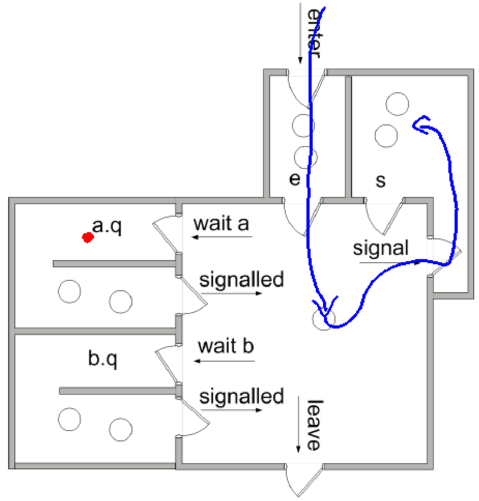

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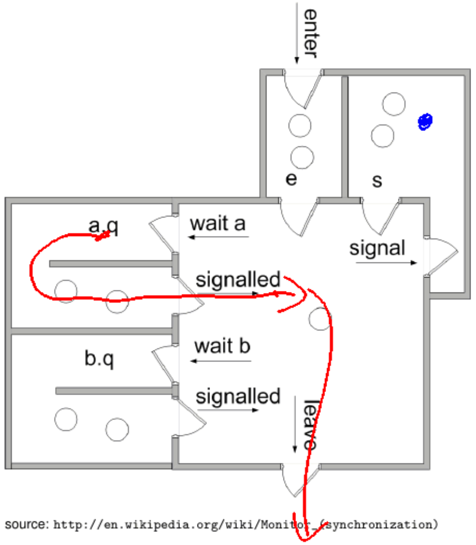

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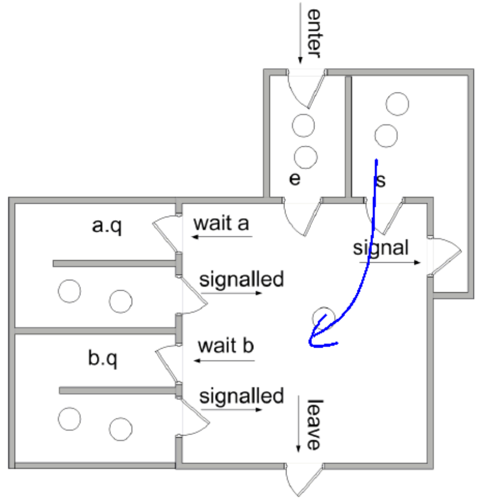

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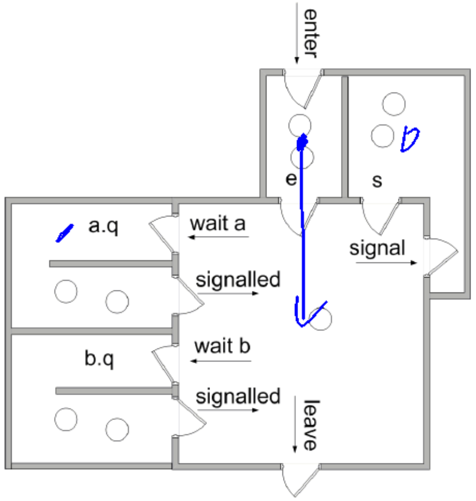

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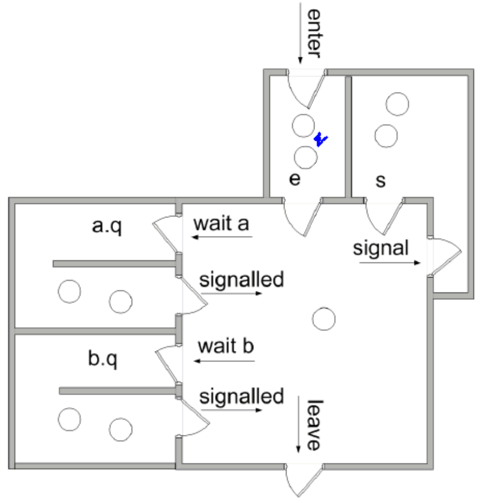

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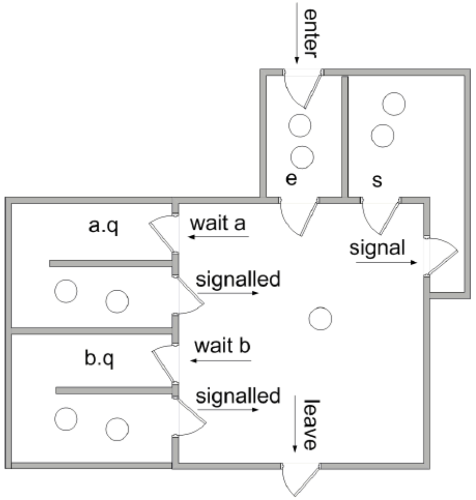

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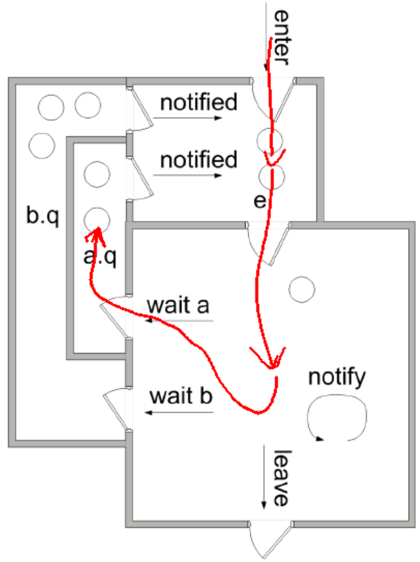

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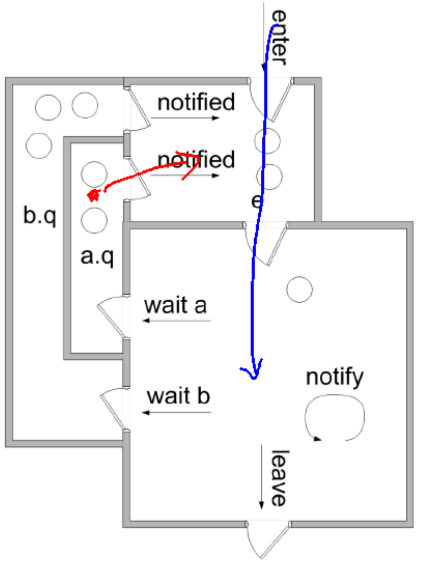

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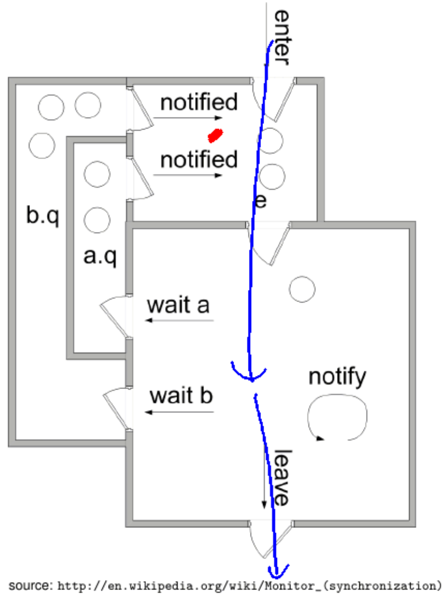

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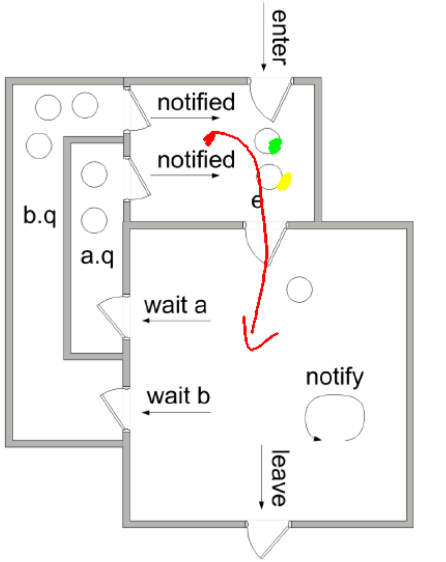

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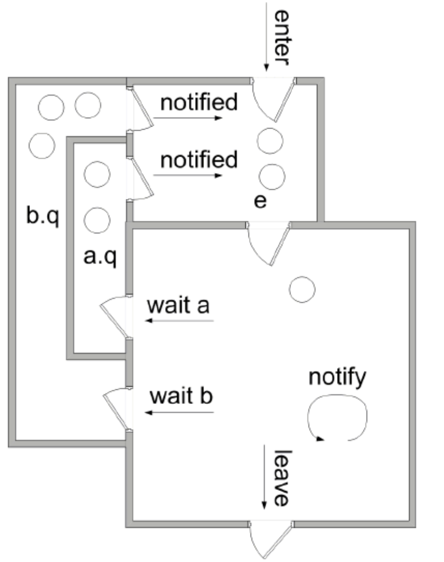

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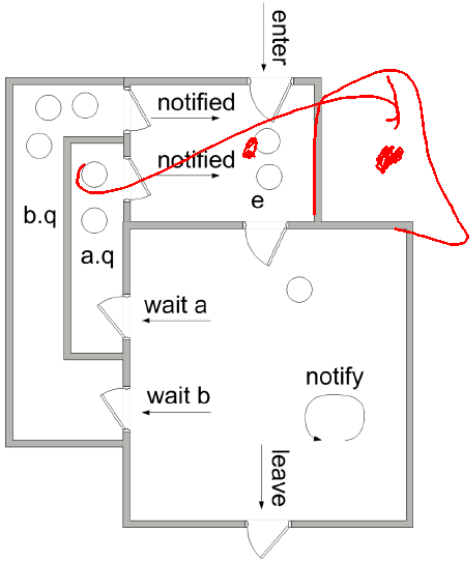

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- assuming FIFO ordering on e, threads who tried to enter between `wait` and `notify` will run first
- need additional queue s if waiting threads should have priority

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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
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- ⇝ 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

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);
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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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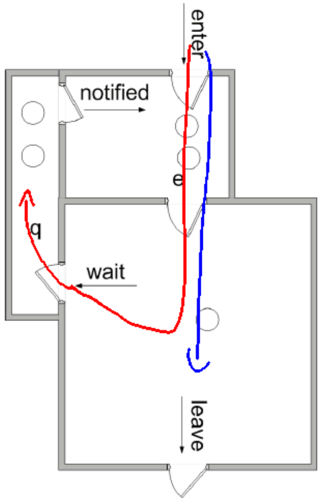
  - $\rightsquigarrow$ wake up thread and have it check the predicate itself
- create condition variable for each set of threads with the same p
  - notify variable if the predicate may have changed
- or, simpler: notify all threads each time any predicate changes
  - $\rightsquigarrow$ without predicates, a single condition variable suffices!

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:

```
  Foo a = new Foo();
  Foo b = new Foo();
  a.other = b; b.other = a;
  // in parallel:
  a.bar() || b.bar();
```

Sequence leading to a deadlock:

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- threads A and B execute a.bar() and b.bar()
- 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()
- $\rightsquigarrow$ both *block* indefinitely

Treatment of Deadlocks

Deadlocks occur if the following four conditions hold [Coffman et al.(1971)Coffman, Elphick, and Shoshani]:

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
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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*.

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

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Each time a lock is acquired, we track the lock set at p:

Definition (lock order)

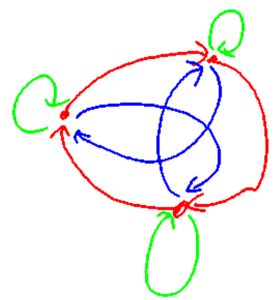
Define $\triangleleft \subseteq L \times L$ such that $l \triangleleft l'$ iff $l \in \lambda(p)$ and the statement at p is of the form `wait(l')` or `monitor_enter(l')`. Define the strict lock order $\prec = \triangleleft^+$.

Freedom of Deadlock

The following holds for a program with mutexes and monitors:

Theorem (freedom of deadlock)

If there exists no $a \in L$ with $a \prec a$ then the program is free of deadlocks.



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If $\forall a \in L_S . a \not\prec a$ and $\forall a \in L_M, b \in L . a \prec b \wedge b \prec a \Rightarrow a = b$ then the program is free of deadlocks.

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Note: the set L contains *instances* of a lock.

- the set of lock instances can vary at runtime
- if we statically want to ensure that deadlocks cannot occur:
  - summarize every lock/monitor that may have several instances into one
  - a summary lock/moitor $\bar{a} \in L_M$ represents several concrete ones
  - thus, if $\bar{a} \prec \bar{a}$ then this might not be a self-cycle
  - $\leadsto$ require that $\bar{a} \not\prec \bar{a}$ for all summarized monitors $\bar{a} \in L_M$

Avoiding Deadlocks in Practice

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⚠ What to do when lock order contains cycle?

- determining which locks may be acquired at each program point is undecidable $\leadsto$ lock sets are an approximation
- an array of locks in L_S: lock in increasing array index sequence
- if $l \in \lambda(P)$ exists $l' \prec l$ is to be acquired $\leadsto$ change program: release l, acquire l', then acquire l again $\leadsto$ inefficient
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an example for the latter is the `Foo` class: two instances of the same class call each other

Refining the Queue: Concurrent Access

Add a second lock `s->t` to allow concurrent removal:

double-ended queue: removal

```
int PopRight(DQueue* q) {
  QNode* oldRightNode;
  wait(q->t); // wait to enter the critical section
  QNode* rightSentinel = q->right;
  oldRightNode = rightSentinel->left;
  if (oldRightNode==leftSentinel) { signal(q->t); return -1; }
  QNode* newRightNode = oldRightNode->left;
  int c = newRightNode==leftSentinel;
  if (c) wait(q->s);
  newRightNode->right = rightSentinel;
  rightSentinel->left = newRightNode;
  if (c) signal(q->s);
  signal(q->t); // signal that we're done
  int val = oldRightNode->val;
  free(oldRightNode);
  return val;
}
```


Example: Deadlock freedom

Is the example deadlock free? Consider its skeleton:

double-ended queue: removal

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void PopRight() {
  ...
  wait(q->t);
  ...
  if (*) { signal(q->t); return; }
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```

- in `PushLeft`, the lock set for s is empty
- here, the lock set of s is $\{t\}$
- $t \lhd s$ and transitive closure is $t \prec s$
- $\leadsto$ the program cannot deadlock

Atomic Execution and Locks

Consider replacing the specific locks with `atomic` annotations:

double-ended queue: removal

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- nested `atomic` blocks still describe one atomic execution
- ⇝ locks convey additional information over `atomic`
- locks cannot easily be recovered from `atomic` declarations

Outlook

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Idea of mutexes: Implement `atomic` sections with locks:

- a single lock could be use to protect all `atomic` blocks
- more concurrency is possible by using several locks
  - see the `PushLeft`, `PopRight` example
- some statements might modify variables that are never read by other threads ⇝ no lock required
- statements in one `atomic` block might access variables in a different order to another `atomic` block ⇝ deadlock possible with locks implementation
- creating too many locks can decrease the performance, especially when required to release locks in $\lambda(l)$ when acquiring l

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language	barriers	wait-/lock-free	semaphore	mutex	monitor
C,C++	✓	✓	✓	✓	(a)
Java,C#	-	-	(b)	✓	✓

(a) some pthread implementations allow a *reentrant* attribute

(b) simulate semaphores using an object with two `synchronized` methods

Summary

Classification of concurrency algorithms:

- wait-free, lock-free, locked
- next on the agenda: transactional

Wait-free algorithms:

- never block, always succeed, never deadlock, no starvation
- very limited in what they can do

Lock-free algorithms:

- never block, may fail, never deadlock, may starve
- invariant may only span a few bytes (8 on Intel)

Locking algorithms:

- can guard arbitrary code
- can use several locks to enable more fine grained concurrency
- may deadlock
- semaphores are not re-entrant, monitors are

⇝ use algorithm that is best fit