Script generated by TTT

Title: Petter: Programmiersprachen (09.11.2016)

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Implementation of a Basic Monitor

A monitor contains a mutex `count` and the id of the thread `tid` 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;
    }
  }
}
```


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. `pop()` 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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Idea: create a *condition variable* on which to block while waiting:

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struct monitor { int tid; int count; int cond; int cond2;... };
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Idea: create a *condition variable* on which to block while waiting:

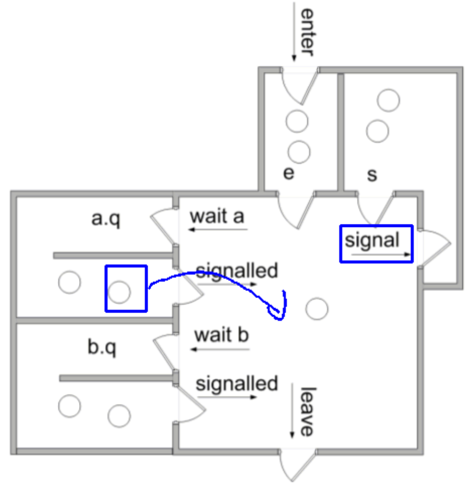
```
struct monitor { int tid; int count; int cond; int cond2;... };
```

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:

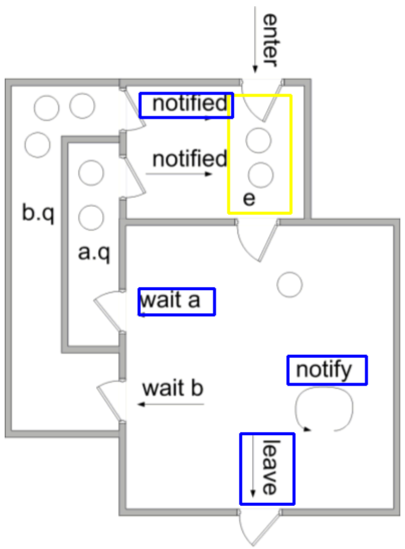


source: http://en.wikipedia.org/wiki/Monitor_(synchronization)

- 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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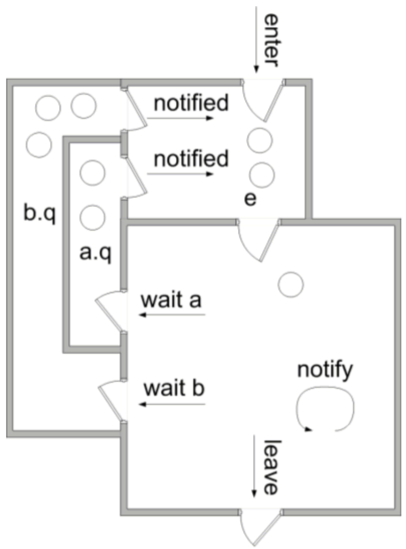

- a call to `wait` on condition a adds thread to the queue $a.q$
- a call to `notify` for a adds one thread from $a.q$ to e (unless $a.q$ is empty)
- if a thread leaves, it wakes up one thread waiting on e

⇝ 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

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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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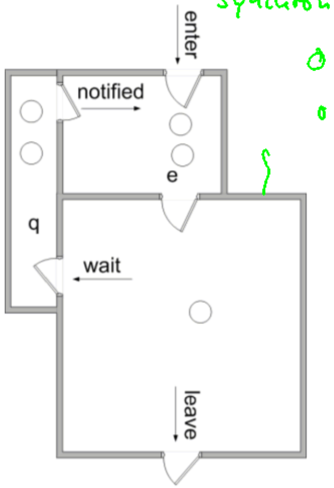
What about the priority of notified threads?

- 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)

Monitors with a Single Condition Variable

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



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```
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

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.

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Consider this Java class:

```
class Foo {
  public Foo other = null;
  public synchronized void bar() {
    ... if (*) other.bar(); ...
  }
}
```

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:

- 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
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How can this situation be avoided?

Treatment of Deadlocks

Observation: 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
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- can be achieved using *lock-free* algorithms
- but what about algorithms that require locking?

Deadlock Prevention through Partial Order

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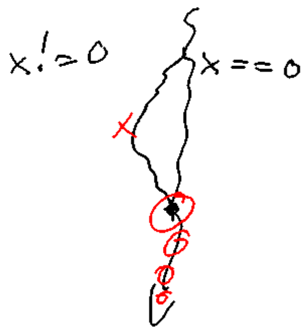

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Definition (transitive closure)

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

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

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

Definition (lock order)

Define $\lhd \subseteq L \times L$ such that $l \lhd l'$ 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 $\prec = \lhd^+$.

Freedom of Deadlock

The following holds for a program with mutexes and monitors:

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Theorem (freedom of deadlock for monitors)

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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/monitor $\bar{a} \in L_M$ represents several concrete ones
  - thus, if $\bar{a} \prec \bar{a}$ then this might not be a self-cycle
  - ⇝ require that $\bar{a} \not\prec \bar{a}$ for all summarized monitors $\bar{a} \in L_M$

Avoiding Deadlocks in Practice

How can we verify that a program contains no deadlocks?

1. identify mutex locks L_S and summarized monitor locks $L^s_M \subseteq L_M$
2. identify non-summary monitor locks $L^n_M = L_M \setminus L^s_M$
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⚠ What to do when the lock order contains a cycle?

- determining which locks may be acquired at each program point is undecidable ⇝ 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 ⇝ change program: release l, acquire l', then acquire l again ⇝ inefficient
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an example for the latter is the `Foo` class: two instances of the same class call each other

Locks Roundup

Atomic Execution and Locks

Consider replacing the specific locks with `atomic` annotations:

stack: removal

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


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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 used to protect all `atomic` blocks
- more concurrency is possible by using several locks
- 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

Concurrency across Languages

In most systems programming languages (C,C++) we have

- the ability to use *atomic* operations

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

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

(b) newer API extensions (`java.util.concurrent.atomic.*` and `System.Threading.Interlocked` resp.)

(c) 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 expressivity

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

References

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