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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:

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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
- B happens to execute `other.bar()`
- ⇝ both *block* indefinitely

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How can this situation be avoided?

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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The occurrence of deadlocks can be:

1. *ignored*: for the lack of better approaches, can be reasonable if deadlocks are rare
2. *detection*: check within OS for a cycle, requires ability to *preempt*
3. *prevention*: design programs to be deadlock-free
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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

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

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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:

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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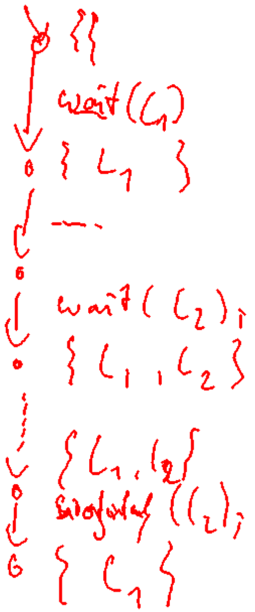

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signal(a)
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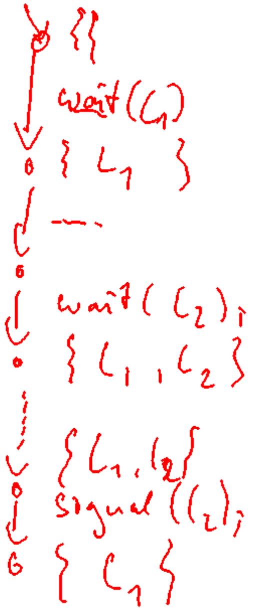

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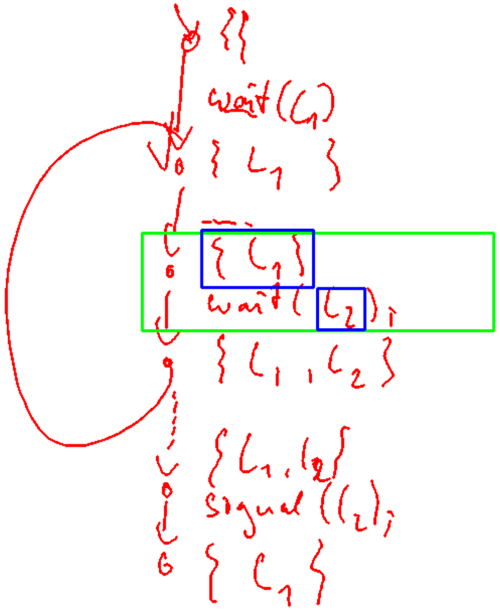

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Suppose a program blocks on semaphores (mutexes) L_S and on monitors L_M such that $L = L_S \cup L_M$.

Theorem (freedom of deadlock for monitors)

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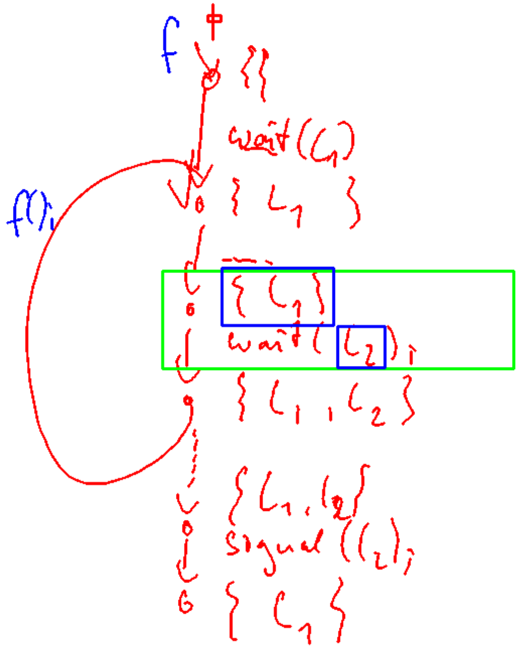
Note: the set L contains *instances* of a lock.

- 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/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 $\bar{a} \in L_M$



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Avoiding Deadlocks in Practice

How can we verify that a program contains no deadlocks?

- identify mutex locks L_S and summarized monitor locks $L_M^s \subseteq L_M$
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⚠ What to do when lock order contains 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

Refining the Queue: Concurrent Access

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

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() {
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  wait(q->t);
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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

void PopRight() {
  ...
  ~~wait(q->t);~~ atomic {
  ...
  if (*) { ~~signal(q->t)~~; return; }
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  if (c) wait(q->s); atomic {
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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
  - 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

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 what they can do

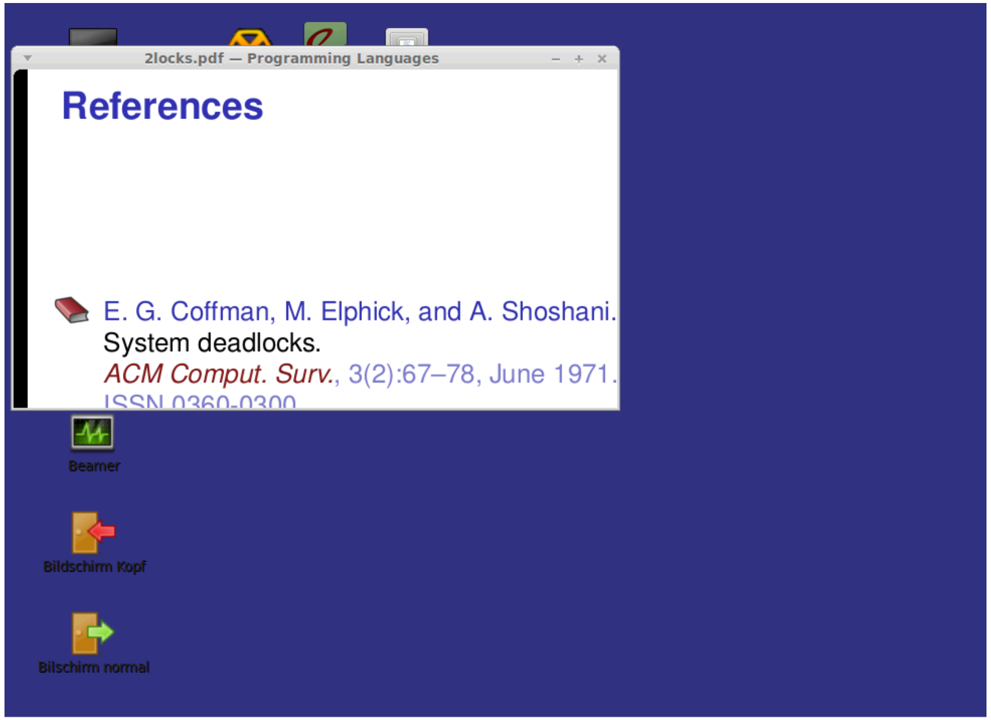
Lock-free algorithms:

- 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



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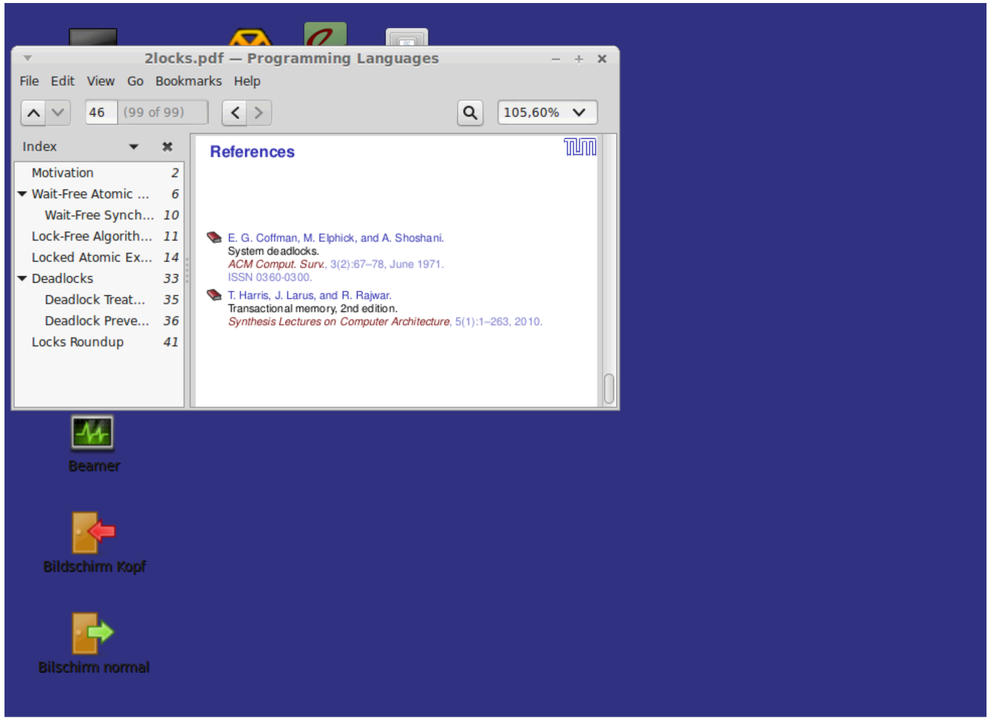

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TECHNISCHE UNIVERSITÄT MÜNCHEN
FAKULTÄT FÜR INFORMATIK

Programming Languages

Concurrency: Transactions

Dr. Michael Petter
Winter term 2015

Abstraction and Concurrency

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Consider an example:

- a linked list data structure exposes a fixed set of operations to modify the list structure, such as `PushLeft` and `ForAll`
- a set object may internally use the list object and expose a set of operations, including `PushLeft`

The `Insert` operations uses the `ForAll` operation to check if the element already exists and uses `PushLeft` if not.

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The `Insert` operations uses the `ForAll` operation to check if the element already exists and uses `PushLeft` if not.

Wrapping the linked list in a mutex does not help to make the *set* thread-safe.

⇝ wrap the two calls in `Insert` in a mutex

- but other list operations can still be called ⇝ use the *same* mutex

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Abstraction and Concurrency

Two fundamental concepts to build larger software are:

abstraction	: an object storing certain data and providing certain functionality may be used without reference to its internals
composition	: several objects can be combined to a new object without interference

Both, *abstraction* and *composition* are closely related, since the ability to compose depends on the ability to abstract from details.

Consider an example:

- a linked list data structure exposes a fixed set of operations to modify the list structure, such as `PushLeft` and `ForAll`
- a set object may internally use the list object and expose a set of operations, including `PushLeft`

The `Insert` operations uses the `ForAll` operation to check if the element already exists and uses `PushLeft` if not.

Wrapping the linked list in a mutex does not help to make the *set* thread-safe.

⇝ wrap the two calls in `Insert` in a mutex

- but other list operations can still be called ⇝ use the *same* mutex

⇝ unlike sequential algorithms, thread-safe algorithms cannot always be composed to give new thread-safe algorithms

---

Transactional Memory [2]

Idea: automatically convert `atomic` blocks into code that ensures atomic execution of the statements.

```
atomic {
  // code
  if (cond) retry;
  atomic {
    // more code
  }
  // code
}
```

Transactional Memory [2]

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atomic {
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```

Execute code as *transaction*:

- execute the code of an atomic block
- nested atomic blocks act like a single atomic block
- check that it runs without *conflicts* due to accesses from another thread
- if another thread interferes through conflicting updates:
  - undo the computation done so far
  - re-start the transaction
- provide a `retry` keyword similar to the `wait` of monitors

Managing Conflicts

Definition (Conflicts)

A conflict *occurs* when accessing the same piece of data, a conflict is *detected* when the TM system observes this, it is *resolved* when the TM system takes action (by delaying or aborting a transaction).

Design choices for transactional memory implementations:

- *optimistic vs. pessimistic concurrency control*:
  - *pessimistic*: detection/resolution when the conflict is *about to occur*
    - resolution here is usually *delaying* one transaction
    - can be implemented using *locks*: deadlock problem
  - *optimistic*: detection and resolution happen *after a conflict occurs*
    - resolution here must be *aborting* one transaction
    - need to repeat aborted transaction: livelock problem

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- *eager vs. lazy version management*: how read and written data are managed during the transaction
  - *eager*: writes modify the memory and an *undo-log* is necessary if the transaction aborts
  - *lazy*: writes are stored in a *redo-log* and modifications are done on committing