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TECHNISCHE UNIVERSITÄT MÜNCHEN
FAKULTÄT FÜR INFORMATIK

# Programming Languages

Concurrency: Atomic Executions, Locks and Monitors

Dr. Axel Simon and Dr. Michael Petter
Winter term 2014



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Communication via memory barriers has only specific applications:

- coordinating state transitions between threads
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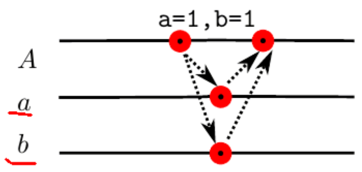
Need a mechanism to update these pieces of memory as a single *atomic execution*:




- several values of the objects are used to compute new value
- certain information form the thread flows into this computation
- certain information flows from the thread computation to the thread



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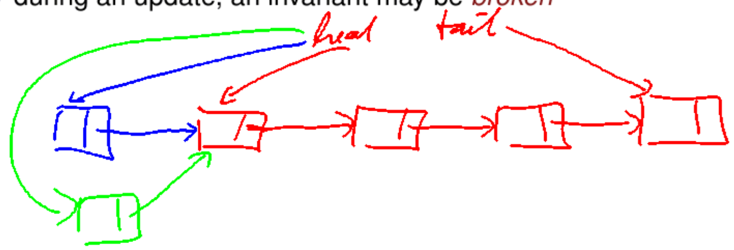




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Ideally, we want to mark a sequence of operations that update shared resources for *atomic execution* [Harris et al.(2010)Harris, Larus, and Rajwar]. This would ensure that the invariant never seem to be broken.



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**Learning Outcomes**

1. Principle of Atomic Executions
2. Wait-Free Algorithms based on Atomic Operations
3. Locks: Mutex, Semaphore, and Monitor
4. Deadlocks: Concept and Prevention



# Atomic Execution: Varieties

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These classes differ in

- *amount of data* they can access during an atomic execution
- *expressivity* of operations they allow
- *granularity* of objects in memory they require



# Wait-Free Updates

Which operations on a CPU are atomic executions? (`j` and `tmp` are registers)

**Program 1**
```
i++;
```

**Program 2**
```
j = i;
i = i+k;
```

**Program 3**
```
int tmp = i;
i = j;
j = tmp;
```

[&i] ← 0

i++

r ← [&i]   0
r ← r+1
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⚠ Without `lock`, the load and store generated by `i++` may be interleaved with a store from another processor.



# Wait-Free Bumper-Pointer Allocation

Garbage collectors often use a *bumper pointer* to allocated memory:

**Bumper Pointer Allocation**

```
char heap[2^20];
char* firstFree = &heap[0];

char* alloc(int size) {
  char* start = firstFree;
  firstFree = firstFree + size;
  if (start+size>sizeof(heap)) garbage_collect();
  return start;
}
```

first free

0

$2^{20}-1$

- `firstFree` points to the first unused byte
- each allocation reserves the next `size` bytes in `heap`



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Thread-safe implementation:

- the `alloc` function can be used from multiple threads when implemented using a `lock xadd [_firstFree],eax` instruction
- ⇝ requires inline assembler



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Rather than writing assembler: use made-up keyword `atomic`:

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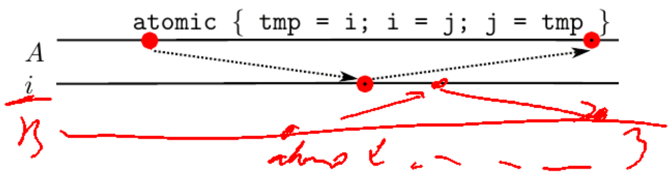
The statements in an `atomic` block execute as *atomic execution*:



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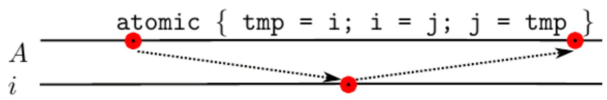


- `atomic` only translatable when a corresponding atomic CPU instruction exist
- the notion of requesting *atomic execution* is a general concept



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j; r, k registers

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atomic {
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**Program 5**
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- the first two operations can be seen as setting a flag b to $v \in \{0,1\}$ if b not already contains $v$
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$\leadsto$ use as building blocks for algorithms that can *fail*



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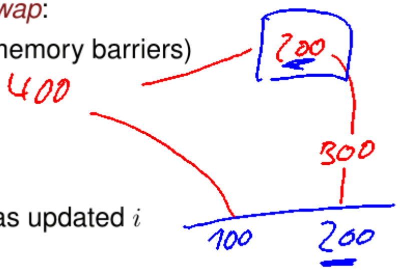


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allows the thread to enter C.S. several times



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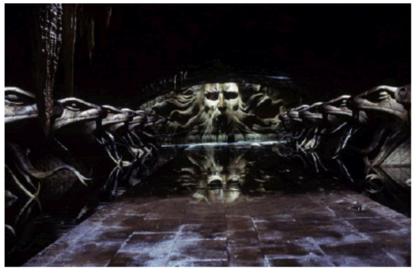
We will collectively refer to these data structures as *locks*.



## Locks

⇒



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:

s=0 lock is taken

s≥1 lock is not taken

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

```
void wait() {
  bool avail;
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  - in this case the data structure is also called *mutex*



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A *semaphore* does not have to busy wait:

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signal

returns immediately if $s == 0$

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- the operating system lets $t$ return from its call to `de_schedule()`

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Certain optimisations are possible:

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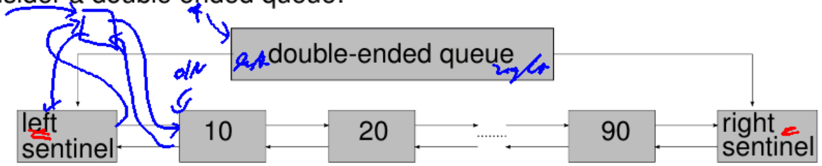
⇝ using a semaphore with a single thread reduces to if (s) s--; s++;

- 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;
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  oldLeftNode -> left = qn;
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One common use of semaphores is to guarantee mutual exclusion.

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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 = (QNode*) malloc(sizeof(QNode));
  qn->val = val;
  wait(q->s); // wait to enter the critical section
  QNode* leftSentinel = q->left;
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  qn->left = leftSentinel;
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  signal(q->s); // signal that we're done
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# 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;
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  int val = oldRightNode->val;
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- error case complicates code ⇝ semaphores are easy to get wrong
- abstract common concept: take lock on entry, release on exit



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## Monitors: An Automatic, Re-entrant Mutex

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

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$\leadsto$ 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 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;
    }
  }
}
```

atomic (m->tid == thread_id())



# 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: