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# 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

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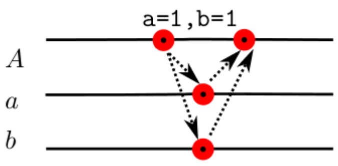
Need a mechanism to update these pieces of memory as a single *atomic execution*:



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

---

# Atomic Executions

A concurrent program consists of several threads that share common resources:

- resources are often pieces of memory, but may be an I/O entity
  - a file can be modified through a shared handle
- for each resource an *invariant* must be retained
  - a head and tail pointer must define a linked list
- an invariant may span *several* resources
- during an update, an invariant may be *broken*

⇝ several resources must be updated together to ensure the invariant

- which particular resources need to be updated may depend on the current program state

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Ideally, we would 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 seems to be broken.

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# Overview

We will address the *established* ways of managing synchronization.

- present techniques are available on most platforms
- likely to be found in most existing (concurrent) software
- techniques provide solutions to solve common concurrency tasks
- techniques are the source of common concurrency problems

Presented techniques applicable to C, C++ (pthread), Java, C# and other imperative languages.

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Presented techniques applicable to C, C++ (pthread), Java, C# and other imperative languages.

**Learning Outcomes**

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

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# Atomic Execution: Varieties

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Several classes of atomic executions exist:

*Wait-Free* : an atomic execution always succeeds and never blocks
*Lock-Free* : an atomic execution may fail but never blocks
*Locked* : an atomic execution always succeeds but may block the thread
*Transaction* : an atomic execution may fail (and may implement recovery)

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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

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# Wait-Free Atomic Executions

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## Wait-Free Updates

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

**Program 1**

```
i++;
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**Program 2**

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i = i+k;
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**Program 3**

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The programs can be atomic executions:

- `i` must be in memory (e.g. declared as volatile)
- Idea: *lock* the cache/bus for an address for the duration of an instruction; on x86:
  - Program 1 can be implemented using a `lock inc [addr_i]` instruction
  - Program 2 can be implemented using `mov eax,k; lock xadd [addr_i],eax; mov reg_j,eax`
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⚠ Without `lock`, the load and store generated by `i++` may be interleaved with a store from another processor.

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# 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;
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```

- `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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# Marking Statements as Atomic

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

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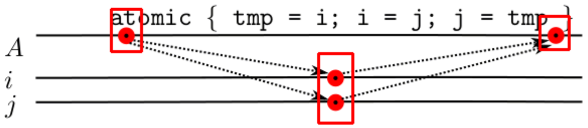
The statements in an `atomic` block execute as *atomic execution*:



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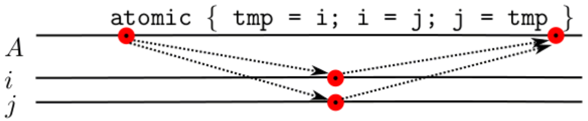

- `atomic` only translatable when a corresponding atomic CPU instruction exist
- the notion of requesting *atomic execution* is a general concept

# Wait-Free Synchronization

Wait-Free algorithms are limited to a single instruction:

- no control flow possible, no behavioral change depending on data
- often, there are instructions that execute an operation conditionally

**Program 4**

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atomic {
  r = b;
  b = 0;
}
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**Program 5**

```
atomic {
  r = b;
  b = 1;
}
```

**Program 6**

```
atomic {
  r = (k==i);
  if (r) i = j;
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```

Operations *update* a memory cell and *return* the previous value.

- the first two operations can be seen as setting a flag `b` to $v \in \{0,1\}$ if `b` not already contains $v$
  - this operation is called *modify-and-test*
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$\rightsquigarrow$ use as building blocks for algorithms that can *fail*

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Common usage pattern for *compare and swap*:

1. read the initial value in $\boxed{i \text{ into } k}$ (using memory barriers)
2. calculate a new value $\boxed{j = f(k)}$
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⇝ general recipe for *lock-free* algorithms

- given a compare-and-swap operation for $n$ bytes
- try to group variables for which an invariant must hold into $n$ bytes
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⇝ calculating new value must be *repeatable*

## 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 operation
- set of atomic operations is architecture specific, but often includes
  - exchange of a memory cell with a register
  - compare-and-swap of a register with a memory cell
  - fetch-and-add on integers in memory
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⇝ only very simple algorithms can be implemented, for instance

*binary semaphores* : a flag that can be acquired (set) if free (unset) and released

*counting semaphores* : an integer that can be decreased if non-zero and increased

*mutex* : ensures mutual exclusion using a binary semaphore

*monitor* : ensures mutual exclusion using a binary semaphore, allows other threads to block until the next release of the resource

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

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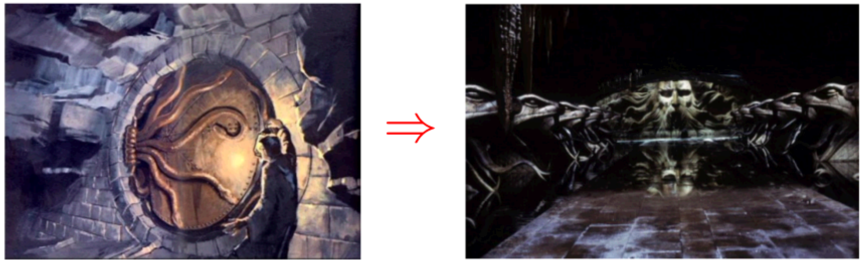
## Locks



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
- 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:

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

```
void wait() {
  bool avail;
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A counting semaphore can track how many resources are still available.

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Special case: initializing with $s = 1$ gives a *binary* semaphore:

- can be used to block and unblock a thread
- can be used to protect a single resource

⇝ in this case the data structure is also called *mutex*

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# Implementation of Semaphores

A *semaphore* does not have to wait busily:

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```

Busy waiting is avoided:

- a thread failing to decrease $s$ executes `de_schedule()`
- `de_schedule()` enters the operating system and inserts the current thread into a queue of threads that will be woken up when `s` becomes non-zero, usually by *monitoring writes* to `&s`
- once a thread calls `signal()`, the first thread $t$ waiting on `&s` is extracted
- the operating system lets $t$ return from its call to `de_schedule()`

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# Practical Implementation of Semaphores

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In general, the implementation is more complicated

- `wait()` may busy wait for a few iterations
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⇝ using a semaphore with a single core reduces to `if (s) s--; s++;`

---

# Mutexes

One common use of semaphores is to guarantee mutual exclusion.

- in this case, a binary semaphore is also called a *mutex*
- e.g. add a lock to the double-ended queue data structure

⚠ decide what needs protection and what not

## Monitors: An Automatic, Re-entrant Mutex

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

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Locking each procedure body that accesses a data structure:

1. is a re-occurring pattern, should be generalized
2. becomes problematic in recursive calls: it blocks
3. if a thread $t$ waits for a data structure to be filled:
   - $t$ will call e.g. `pop()` and obtain `-1`
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*Monitor*: a mechanism to address these problems:

1. a procedure associated with a monitor acquires a lock on entry and releases it on exit
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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 `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;
    }
  }
}
```

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# 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 tid; int count; int cond; };
```

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  - $t$ then has to call again, until an element is available
  - ⚠ $t$ is busy waiting and produces contention on the lock
Idea: create a *condition variable* on which to block while waiting:
struct monitor { int tid; int count; int cond; };

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