

A practical course on

Advanced systems programming in C/Rust

Jörg Thalheim



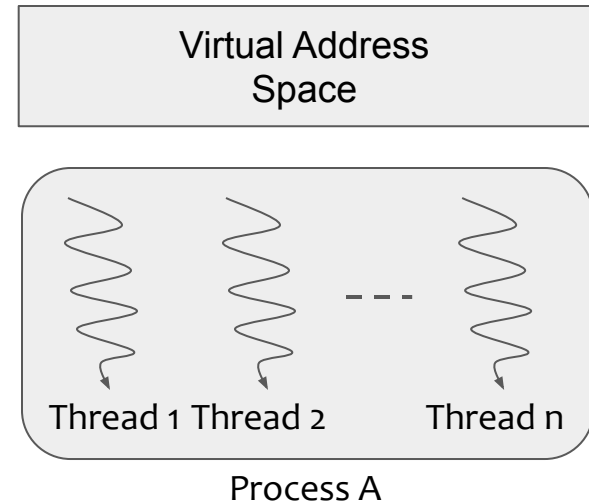
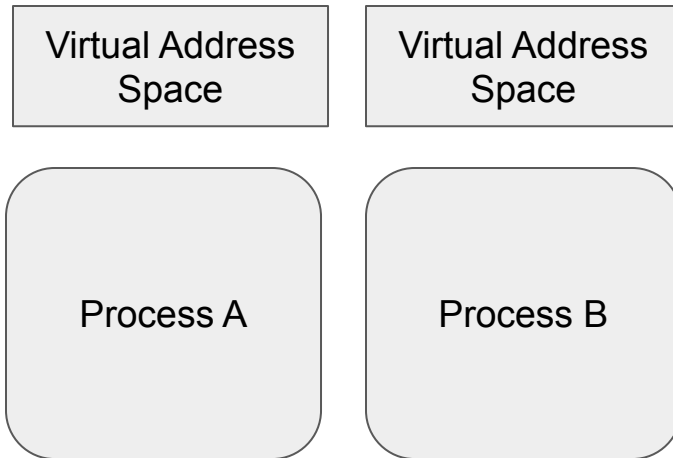
Today's topic!

Concurrency and Synchronization

Shady Issa

Processes vs Threads

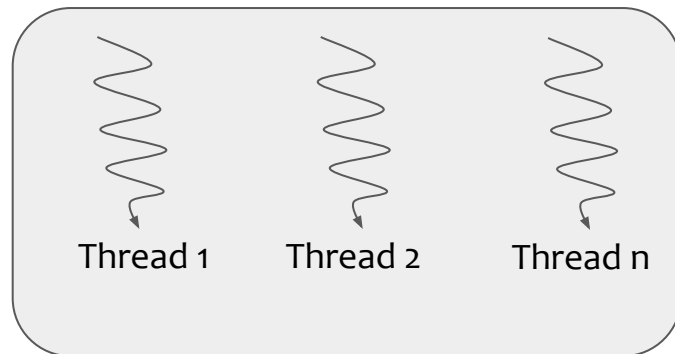
- Last lecture: inter-process parallelism
- Today: intra-process parallelism
- Intra-process parallelism is more relevant with the ubiquitous multi-core architectures
- NB: these are not mutually exclusive modes of operation



Threads

- Threads allow for dividing a program into independent units of computation
- Each thread has:
 - Program counter
 - Thread id
 - Stack
 - Set of registers
- Created using the `clone` system call

Code	Data	Files
Stack 1	Stack 2	Stack n
Registers 1	Registers 2	Registers n



- Create a thread

```
int pthread_create(pthread_t *restrict thread,  
                  const pthread_attr_t *restrict attr,  
                  void *(*start_routine)(void *),  
                  void *restrict arg);
```

- Attributes: pthread_attr_t
 - joinable vs detachable
 - stack size
- Wait for another thread to finish

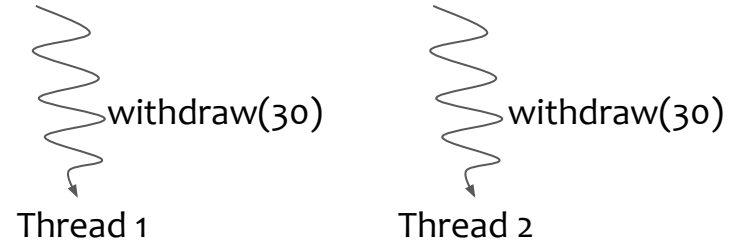
```
int pthread_join(pthread_t thread, void **retval);
```

The Need for Synchronization

- Threads share the same resources
 - heap, files, I/O
- Program correctness can not be guaranteed when two threads access the resource concurrently

```
withdraw (amount) {  
    if (balance > amount)  
        balance -= amount  
}
```

balance:
50



Threads must synchronize accesses to shared resources

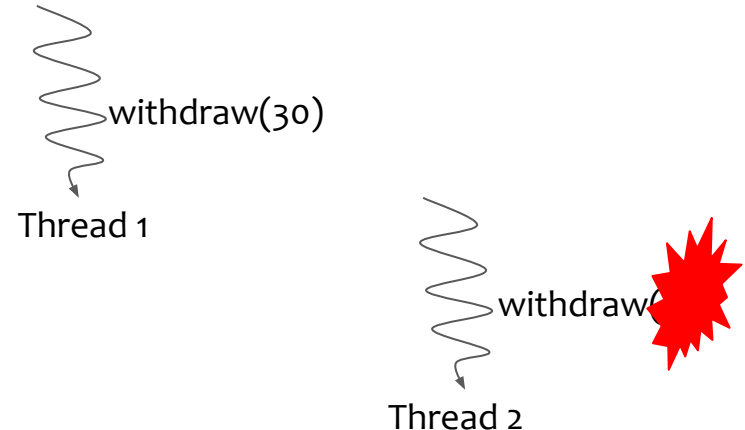
- There exists different mechanisms for synchronization
 - Mutual exclusion
 - Lock-free
 - Read-Copy-Update
 - Transactional memory

- Thread-safety

Mutual Exclusion

- To grant a thread exclusive access to a shared resource
- Mutex or a lock
 - A token that can be held by one thread at a time
 - Each thread must *acquire* the mutex *before* accessing the shared resource
 - Each thread must *release* the mutex *after* accessing the shared resource
- *Critical sections* will be executed *atomically*

```
withdraw (amount) {  
    acquire_mutex()  
    if (balance > amount)  
        balance -= amount  
    release_mutex()  
}
```



Types of Mutexes

- Mutexes and locks are usually used interchangeably
 - The same mutex can be used across different processes
- Semaphores
 - Can allow multiple threads at a time
 - They are usually used for signalling
- Read-writer locks
 - Allows readers to execute concurrently, but only one writer a time
 - e.g.: `check_balance` accesses a shared resource but does not modify it

- There is a plethora of algorithms for implementing locks
 - Test-and-set, Test-test-and-set, MCS, ticket locks, etc,
- Hardware atomic primitives
 - Read-Modify-Write
 - Atomic-Increment-Fetch

```
read_modify_write(int *var, int old_value, int new_value){  
    if (*var == old_value){  
        *var = new_value;  
    }  
    return *var;  
}
```

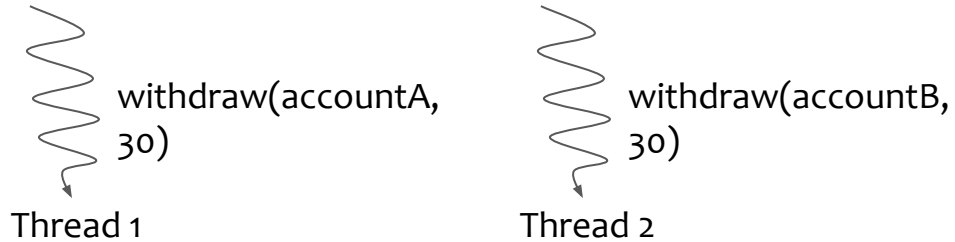
Atomic

```
acquire_mutex(){  
    while( read_modify_write(&mutex, 0, 1) != 1) ;  
}
```

- Pthreads library has several mutexes:
 - Pthread_mutex
 - threads enter sleep mode when lock is busy
 - pthread_mutex_lock, pthread_mutex_unlock, pthread_mutex_trylock
 - pthread_spinlock
 - threads keep polling the status of the lock
 - pthread_spin_lock, pthread_spin_unlock, pthread_spin_trylock
 - pthread_rwlock
 - pthread_rwlock_rdlock, pthread_rwlock_wrlock
 - sem
 - sem_post, sem_wait
- Other synchronization mechanisms:
 - pthread_cond
 - pthread_barrier

What about Performance?

```
withdraw (account, amount) {  
  acquire_mutex()  
  if (account.balance > amount)  
    balance -= amount  
  release_mutex()  
}
```

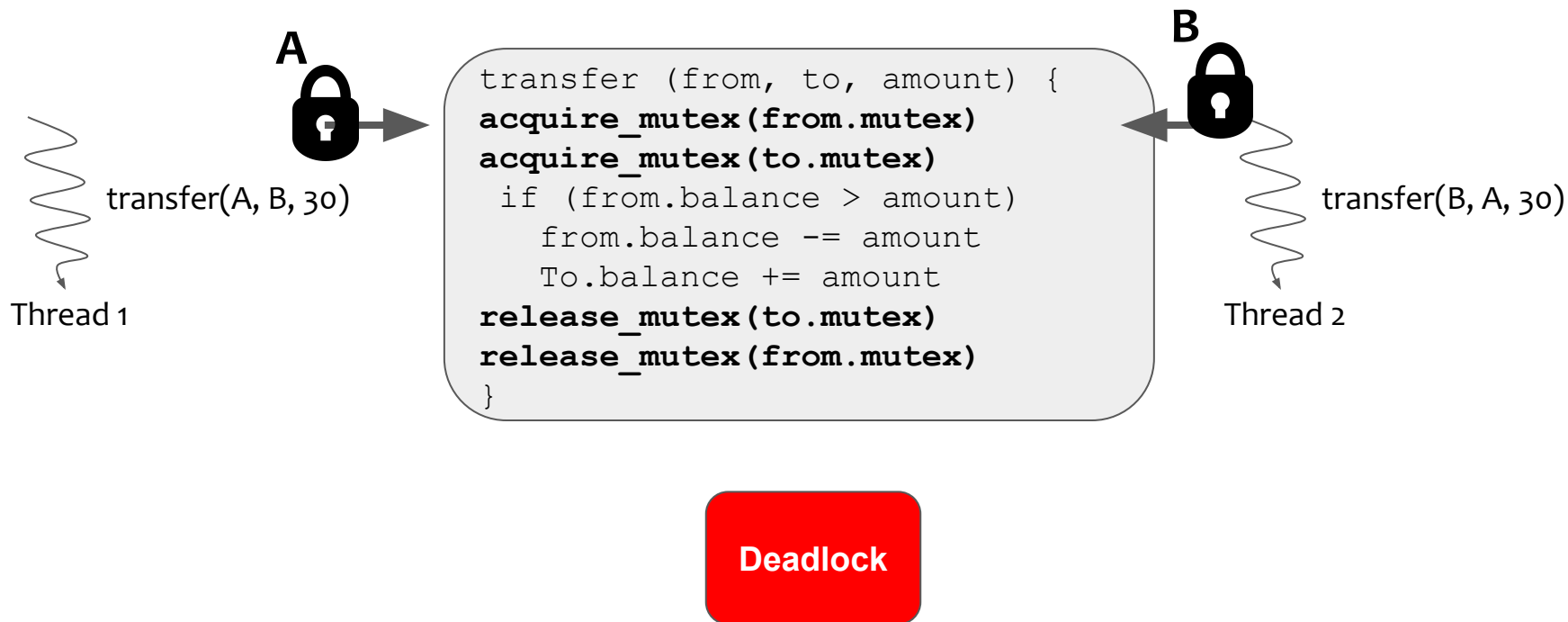


Synchronization can hamper scalability and performance

- Coarse-grained vs fine-grained locking
 - single global lock vs per-account lock
- Can allow higher parallelism
- Introduces memory overhead
 - Lock per array entry
- Challenging to design

```
withdraw (account, amount) {  
    acquire_mutex(account.mutex)  
    if (account.balance > amount)  
        balance -= amount  
    release_mutex(account.mutex)  
}
```

Scalable Synchronization

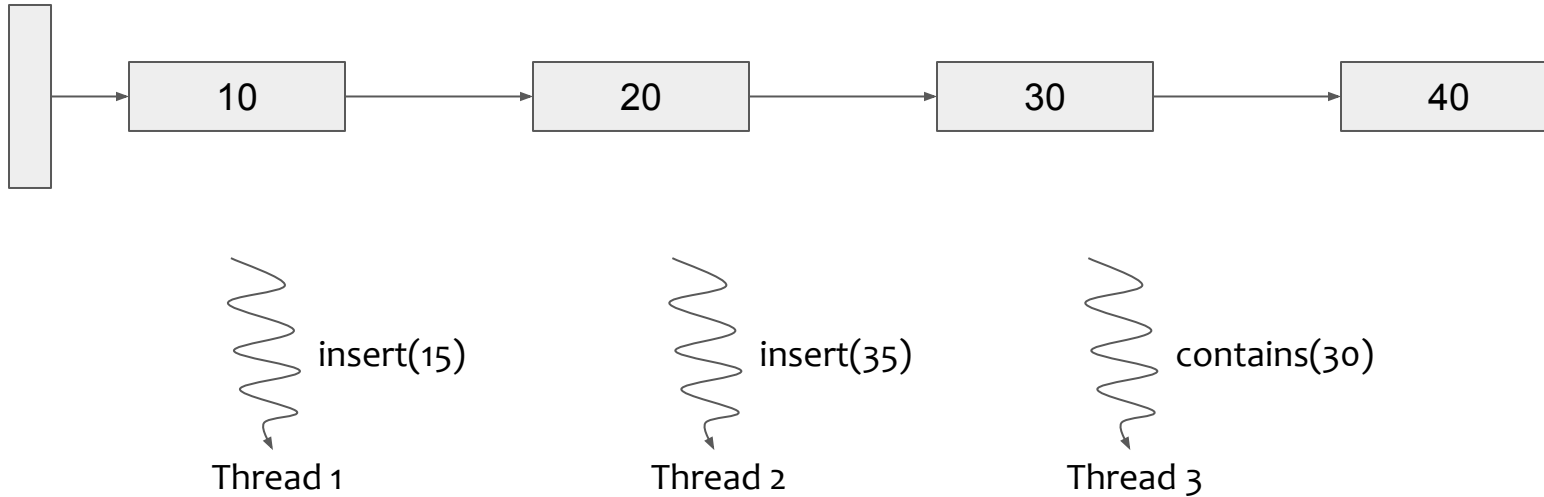


- Coarse-grained vs fine-grained locking
 - single global lock vs per-account lock
- Can allow higher parallelism
- Introduces memory overhead
 - e.g.: Lock per array entry
- Challenging to design
 - Deadlocks: threads can not make progress
 - Livelocks: threads can not make useful progress
 - Fairness and starvation

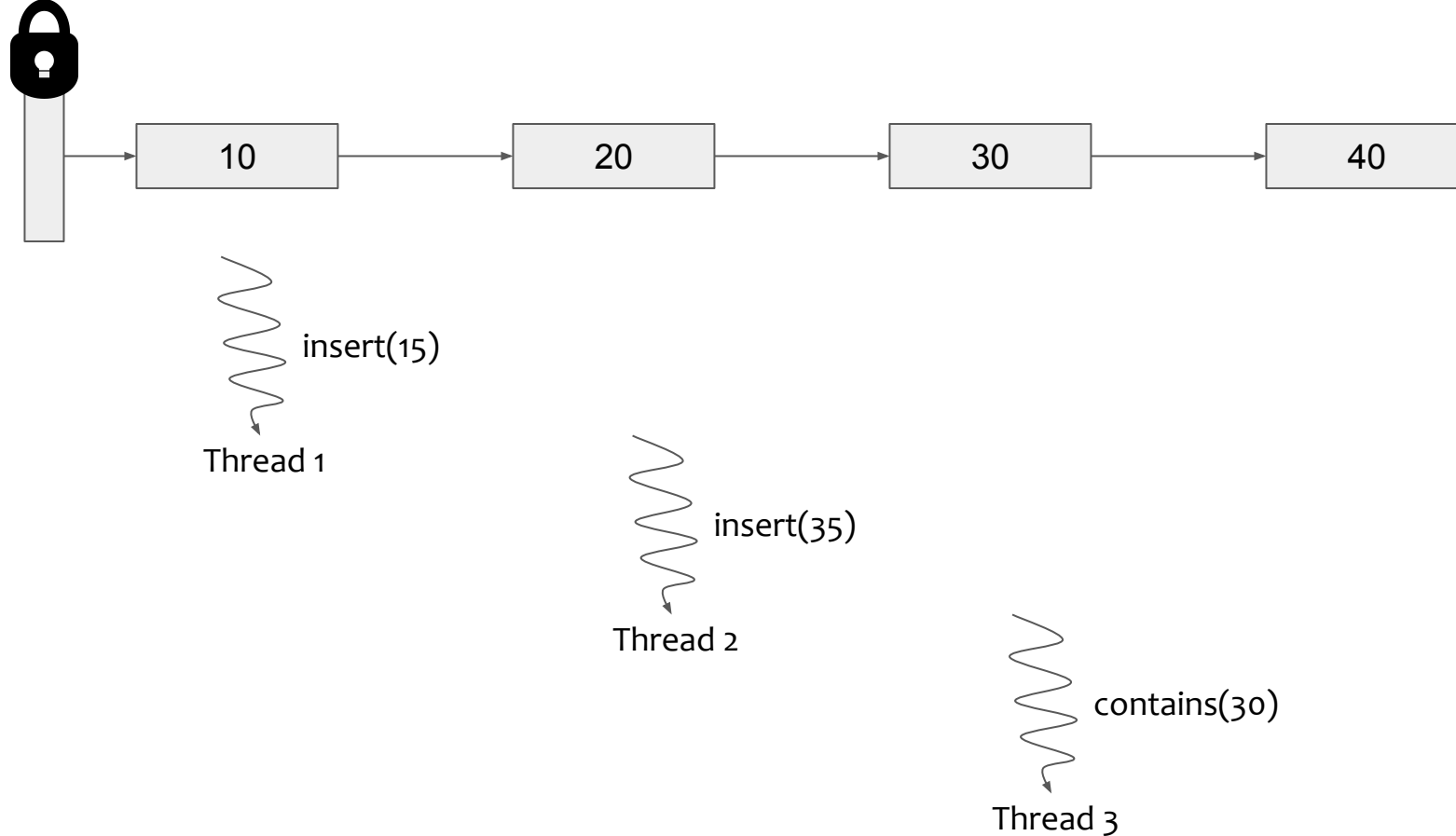
```
withdraw (account, amount) {  
    acquire_mutex(account.mutex)  
    if (account.balance > amount)  
        balance -= amount  
    release_mutex(account.mutex)  
}
```

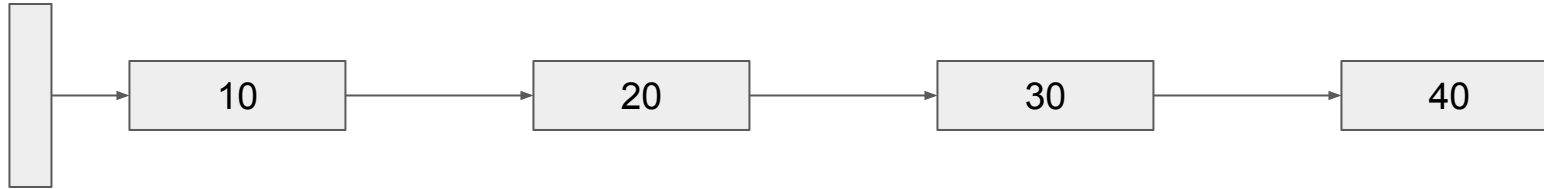
Lock-free Programming

- Avoid using locks and rely on atomic primitives
 - Threads do not have to wait for a lock to be free



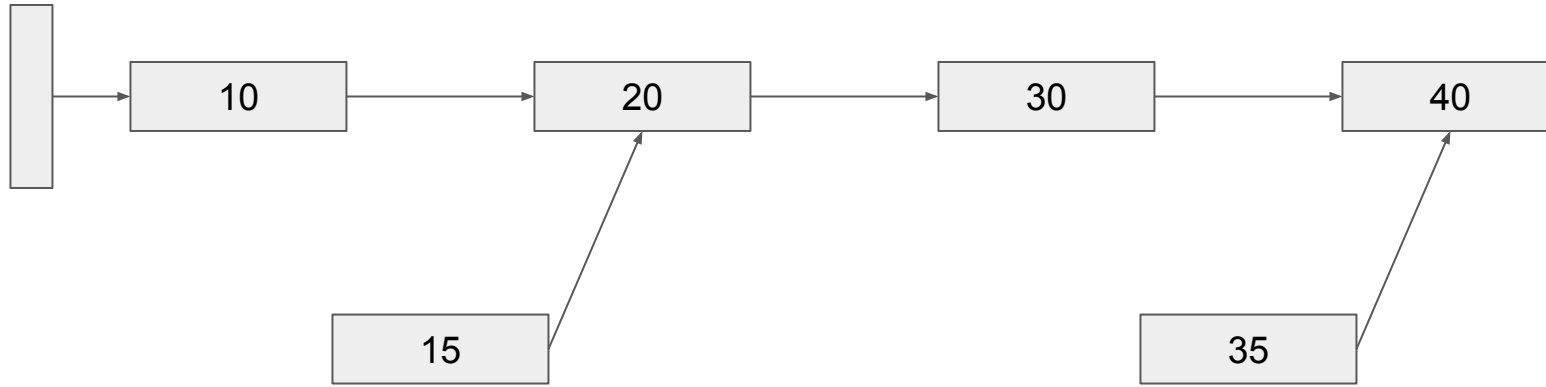
Lock-free Programming








```
insert (value) {  
    new_node.value = value  
    node = find_prev(value)  
    new_node.next = node.next  
    read_modify_write(&node.next, node.next, new_node);  
}
```

Lock-free Programming

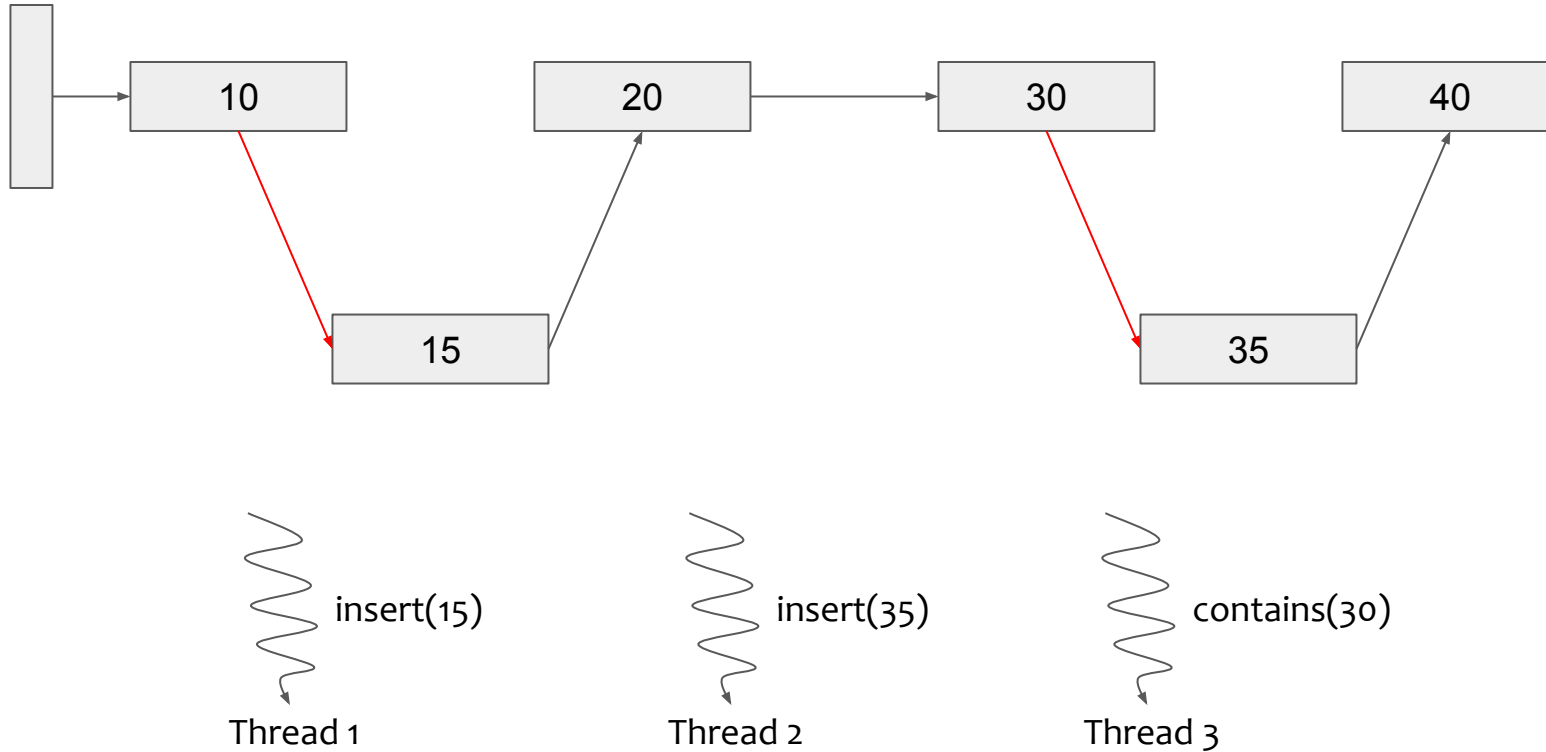


 insert(15)
Thread 1

 insert(35)
Thread 2

 contains(30)
Thread 3

Lock-free Programming



Challenges of Lock-free Programming

- Similar challenges to fine-grained locking
 - Starvation
 - Livelocks
- Memory reclamation
 - Threads can not tell if other threads are referencing some data
 - When is it safe to free an object?

- Threads allow for lightweight intra-process concurrency
- Synchronization is needed to ensure program correctness
- Hardware atomic primitives allow for implementing efficient synchronization mechanisms
- Scalable synchronization is challenging
- Lock-free algorithms can further increase performance