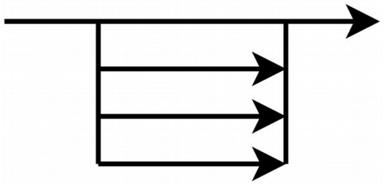
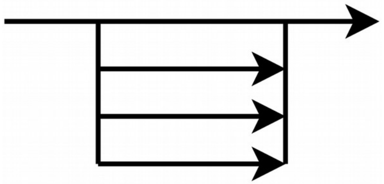
Pthreads Synchronization

Parallel Computing

Institute for Formal Models and Verification
Johannes Kepler University, Linz, Austria





The Need for Synchronization

Threads operating on *shared data* concurrently:

- scheduling determines outcome of operations → race conditions
- can lead to violations of data invariants
  - integrity of data structures: queues, buffers,...

Classical example: concurrent transactions on bank account

Thread 1	Thread 2	Balance
read balance: €1000		€1000
	read balance: €1000	€1000
	set balance: €(1000 – 200)	€800
set balance: €(1000 – 100)		€900
give out cash: €100		€900
	give out cash: €200	€900

Thread *notification*

- inform one or more threads that certain condition has become true
- example: `returnval_heap`

Basic Pthread Synchronization Mechanisms

Controlling access to shared data

- **mutex**: mutual exclusion
- special kind of semaphore
- *locking* a mutex allows mutually exclusive access to shared data
- A mutex can be locked (“owned”) by exactly one thread at a time
  - lock attempt on already locked mutex will block calling thread until mutex unlocked

Thread notification

- `pthread_join(...)`: very limited, no notification
- **condition variables:** threads block until notified that condition has become true
- <u>always</u> combined with a mutex protecting the condition's data
  - testing and setting the condition must be performed under locked mutex
- multiple threads can block on a condition variable or be notified at a time
  - e.g. multiple consumers waiting at an empty queue of items
  - e.g. producer inserts items and notifies waiting consumers

Synchronization in Java:

- `synchronized` blocks and methods, `wait()` and `notify()`,`notifyAll()`

Pthread Mutexes (1/2)

- Represented as variables of type `pthread_mutex_t`
  - never copy mutexes!
  - share mutexes by passing pointers
- Static or dynamic allocation and/or initialization
  - static initialization
    - macro `PTHREAD_MUTEX_INITIALIZER`
    - set default attributes
      - e.g. process/system-wide mutexes, real-time scheduling, priority-aware mutexes,...
      - attributes are beyond our scope
  - dynamic initialization
    - `pthread_mutex_attr_t` for setting mutex's attributes
    - `int pthread_mutex_init(pthread_mutex_t *mutex, ... *attr)`
      - pass NULL for `attr` to get default attributes
    - `int pthread_mutex_destroy(pthread_mutex_attr_t *attr)`
      - mutex becomes invalid, but can be re-initialized
  - dynamic allocation and initialization
    - allocate mutexes on heap and initialize dynamically

Pthread Mutexes (2/2)

`int pthread_mutex_lock(pthread_mutex_t *mutex)`

- mutex is currently unlocked: caller will own mutex
- mutex is currently locked: caller blocks until mutex is unlocked
  - deadlock: recursively locking a mutex (unless mutex is set to be recursive)

`int pthread_mutex_trylock(pthread_mutex_t *mutex)`

- mutex is currently unlocked: caller will own the mutex
- mutex is currently locked: caller does <u>not</u> block
  - caller can e.g. enter alternative branch

`int pthread_mutex_timedlock(...*mutex, ...*expire)`

- mutex is currently unlocked: caller will own mutex
- `struct timespec *expire`: absolute timeout for blocking

`int pthread_mutex_unlock(pthread_mutex_t *mutex)`

- among multiple blocking threads, exactly one is selected to own mutex
- error: caller does not own mutex
- error: mutex is unlocked already

Example: `sum, prodcons`

Pthread Condition Variables (1/2)

Represented as variables of type `pthread_cond_t`

- like for mutexes: analogous functions for initialization, attributes,...
  - `PTHREAD_COND_INITIALIZER, int pthread_cond_init(...),...`

Always associated with <u>exactly one</u> mutex

- but: different condition variables may use same mutex
- condition must be tested and set under protection of mutex
- mutex must be properly locked and unlocked
- suggested usage pattern:

```
mutex_lock();
while (!condition) {
  mutex_unlock();
  non_busy_wait_until_notified();
  mutex_lock();
}
/* critical region: do some work... */
mutex_unlock();
```

Managed by Pthread condition variables (similar to Java):

- set of waiting threads, (un)locking the mutex, notification of waiting threads

Pthread Condition Variables (2/2)

Waiting on a condition variable

`int pthread_cond_wait(pthread_cond_t *cond, ... *mutex)`

- caller must own mutex, will then block until notified
- mutex is <u>automatically</u> unlocked before waiting and locked again if call returns

Notifying waiting threads

`int pthread_cond_signal(pthread_cond_t *cond)`

- caller notifies one arbitrary thread waiting on `cond`
- notified thread wakes up and locks mutex (its call of `pthread_cond_wait` returns)

`int pthread_cond_broadcast(pthread_cond_t *cond)`

- caller notifies all threads waiting on `cond`
- notified threads wake up (in arbitrary order) and contend for mutex

notifying threads need not own mutex (but recommended)

`pthread_cond_timedwait(... *cond, ... *mutex, ... *expire)`

- `struct timespec *expire`: absolute timeout for waiting
- if timed out or notified: call will return with mutex locked again

Examples: `prodcons_cond, returnval_heapcond`

Pthread Barriers

Represented as variables of type `pthread_barrier_t`

Synchronizing pool of threads at a specific point

`int pthread_barrier_init(...,unsigned int cnt)`

- must be called before using barrier
- `cnt`: number of threads waiting (calls of ...`_wait(...)`) before all can continue

`int pthread_barrier_destroy(pthread_barrier_t *b)`

- reset barrier to invalid state
- must call `pthread_barrier_init(...)` before using again

`int pthread_barrier_wait(pthread_barrier_t *b)`

- Calling thread will wait (i.e. block) until `cnt` threads have called ...`_wait(...)`
- Waiting threads are then released in arbitrary order
- Returns non-zero to exactly one arbitrary thread and 0 otherwise

Example: `simple-barrier`

In Java 1.5 or higher: CyclicBarrier

Memory Visibility

When will changes of shared data be visible to other threads?

Pthreads standard guarantees basic *memory visibility rules*

- thread creation
  - memory state before calling `pthread_create(...)` is visible to created thread
- mutex unlocking (also combined with condition variables)
  - memory state before unlocking a mutex is visible to thread which locks same mutex
- thread termination (i.e. entering state “terminated”)
  - memory state before termination is visible to thread which joins with terminated thread
- condition variables
  - memory state before notifying waiting threads is visible to woke up threads

Memory barriers:

- instructions issued implicitly to ensure memory visibility rules for pthreads
- impose order on memory accesses
- all memory accesses issued before barrier must complete before any access issued after the barrier can complete

`volatile` variables do <u>not</u> guarantee memory consistency!

Hints and Pitfalls (1/4)

Always wait in a loop on a condition variable (applies to any thread library)

- condition should be re-evaluated after waking up → why?
- intercepted wakeups
  - another thread might acquire mutex before the woke up thread and reset condition
- notification on weak predicates (programmer's responsibility)
  - e.g. notify if *n* <= *value*, but “tight” condition is *n* < *value* → unnecessary notifications
- spurious wakeups
  - library: more efficient to notify multiple threads at `pthread_cond_signal(...)`
  - programming errors: notification although the condition is false
  - pthread standard does not prevent wakeups without any notifying thread [Butenhof'97]

Beware of deadlocks

- threads wait for mutexes in circular fashion
- fixed locking hierachy: always lock mutexes in fixed order
- try and back off: unlock all mutexes in a set if one lock fails, then start again later
  - can lead to starvation: thread “polls” for mutex and never waits
- Example: `deadlock_backoff`

Hints and Pitfalls (2/4)

Beware of “badly optimizing” the use of condition variables

- lost wakeups: thread waits although condition is true
  - like `prodcons_cond`: producer signals only if buffer becomes non-empty → error
- do not share condition variables between predicates
  - do not know which predicate a notified thread was waiting for

Speed/order of threads

- do not assume anything!
- adding `sleep(...)` is not a bug fix (but can “hide” synchronization problems)

Hints and Pitfalls (3/4): Performance Concerns

Number of threads:

- cost of thread creation and context switches is system-dependent

Synchronization prevents concurrency and parallelism

- best solution: do not share too much (Example: `arraysum`)

Own mutexes for shortest possible time → reduces waiting time

Massive (un)locking of mutexes is expensive

- Example: `freq-locking`

Mutexes and condition variables consume memory

- Mutex: 40 (24) bytes in 64-bit (32-bit) environment
- Condition variables: 48 bytes in 32- and 64-bit environment

Hints and Pitfalls (4/4): Performance Concerns

Fine-grain locking

- using many “small” mutexes increases concurrency and locking overhead
- Example: `locked-array/many-locks`

Coarse-grain locking

- using few “big” mutexes decreases concurrency and locking overhead
- Example: `locked-array/big-lock`

Lock chaining

- e.g. lock(m1), lock(m2), unlock(m1), lock(m3), unlock(m2),...
- e.g. concurrent linked list: locking entire list or single nodes

Read/write locks: allow concurrent reads

- multiple readers may concurrently read if no writer is active
- one writer prevents any other writer or reader from accessing

Advanced Topics

Thread-specific data

- static data where each thread has a private value associated with a key

Attributes

- for threads, mutexes and condition variables

Cancellation

- cancel threads either immediately or at special cancellation points
- held resources need to be cleaned up properly (cleanup handlers)

Realtime scheduling

- setting scheduling policy and priorities, priority-aware mutexes

Thread-safe libraries

- how to make libraries thread-safe?
- must interfaces be changed?
- often inefficient: one “big” internal mutex protecting entire functions
- problem: functions which maintain internal state across calls

Spinlocks vs. mutexes

- busy waiting vs. non-busy waiting