Solution: a lock (a/k/a mutex)

class BasicLock {
public:
    virtual void lock() = 0;
    virtual void unlock() = 0;
};
Using a lock

class Counter {
public:
    int get_and_inc() {
        lock_.lock();
        int old = count_; 
        count_ = old + 1;
        lock_.unlock();
        return old;
    }

private:
    int count_ = 0;
    Lock lock_; 
};
Using a lockRAAI-style

class Counter {
public:
    int get_and_inc()
    {
        lock_.lock();
        int old = count_;  
        count_ = old + 1;
        lock_.unlock();
        return old;
    }

private:
    int count_ = 0;
    Lock lock_;  
};

class Counter {
public:
    int get_and_inc()
    {
        auto guard = lock_.acquire();
        int old = count_;  
        count_ = old + 1;
        return old;
        // ~Guard() unlocks lock_ here
    }

private:
    int count_ = 0;
    Lock lock_;  
};
Base class for RAII-style lock

class GuardedLockBase : public BasicLock {
public:
    Guard acquire() { return Guard{*this}; }

class Guard {
    BasicLock& lock_;

public:
    Guard(BasicLock& lock) : lock_{lock} { lock_.lock(); }
    virtual ~Guard() { lock_.unlock(); }
};
How to implement the lock?

Two-thread solutions first, then $n$-thread solutions
class GuardedLockBase : public BasicLock {

  // i() is this thread:
  thread::id i() const
  {
    return this_thread::get_id();
  }

  // j() is the other thread:
  thread::id j() const
  {
    return i().other_thread();
  }

};

// i() is this thread:
thread::id i() const
{
  return this_thread::get_id();
}

// j() is the other thread:
thread::id j() const
{
  return i().other_thread();
}
An attempt

class LockOne : public GuardedLockBase {
    bool flag_[2] = {}; 
public:
    virtual void lock() override
    {
        flag_[i()] = true;
        while (flag_[j()] ) {}
    }
    virtual void unlock() override { }
};
Theorem

LockOne satisfies mutual exclusion.
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- Assume $CS_A$ overlaps $CS_B$
Theorem

LockOne satisfies mutual exclusion. **Proof by contradiction:**

- Assume $CS_A$ overlaps $CS_B$
- Consider each thread’s last read and write in `lock()` before entering its CS. For $A$ to enter, it first writes true to its flag, and then needs to read false from the other’s:
  - $\text{write}_A(\text{flag}[A] = \text{true}) \rightarrow \text{read}_A(\text{flag}[B] == \text{false}) \rightarrow CS_A$
Theorem

LockOne satisfies mutual exclusion. Proof by contradiction:

- Assume $CS_A$ overlaps $CS_B$
- Consider each thread’s last read and write in $lock()$ before entering its CS. For $A$ to enter, it first writes true to its flag, and then needs to read false from the other’s:
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And by symmetry:
  - $\text{write}_B(\text{flag}[B] = \text{true}) \rightarrow \text{read}_B(\text{flag}[A] == \text{false}) \rightarrow CS_B$

These events form a cycle, which is a contradiction.
Theorem

LockOne satisfies mutual exclusion. Proof by contradiction:

- Assume $CS_A$ overlaps $CS_B$
- Consider each thread’s last read and write in $lock()$ before entering its CS. For $A$ to enter, it first writes true to its flag, and then needs to read false from the other’s:
  - $write_A(\text{flag}[A] = \text{true}) \rightarrow read_A(\text{flag}[B] == \text{false}) \rightarrow CS_A$

And by symmetry:

- $write_B(\text{flag}[B] = \text{true}) \rightarrow read_B(\text{flag}[A] == \text{false}) \rightarrow CS_B$

Note, also, that if $A$ sees $B$’s flag as false, that must happen before $B$ writes its flag, and by symmetry for $B$ seeing $A$’s flag:

- $read_A(\text{flag}[B] == \text{false}) \rightarrow write_B(\text{flag}[B] = \text{true})$
- $read_B(\text{flag}[A] == \text{false}) \rightarrow write_A(\text{flag}[A] = \text{true})$
Theorem

LockOne satisfies mutual exclusion. Proof by contradiction:

- Assume CS\(_A\) overlaps CS\(_B\)
- Consider each thread’s last read and write in \textit{lock()} before entering its CS. For \(A\) to enter, it first writes true to its flag, and then needs to read false from the other’s:
  - \textsc{write\(_A\)}(flag[\(A\)] \(=\) true) \(\rightarrow\) \textsc{read\(_A\)}(flag[\(B\)] \(==\) false) \(\rightarrow\) CS\(_A\)

And by symmetry:

- \textsc{write\(_B\)}(flag[\(B\)] \(=\) true) \(\rightarrow\) \textsc{read\(_B\)}(flag[\(A\)] \(==\) false) \(\rightarrow\) CS\(_B\)

Note, also, that if \(A\) sees \(B\)’s flag as false, that must happen before \(B\) writes its flag, and by symmetry for \(B\) seeing \(A\)’s flag:

- \textsc{read\(_A\)}(flag[\(B\)] \(==\) false) \(\rightarrow\) \textsc{write\(_B\)}(flag[\(B\)] \(=\) true)
- \textsc{read\(_B\)}(flag[\(A\)] \(==\) false) \(\rightarrow\) \textsc{write\(_A\)}(flag[\(A\)] \(=\) true)

These events form a cycle, which is a contradiction. \(\square\)
Two other properties

Deadlock-free:

- One ill-behaved thread does not prevent other threads from locking other locks
- System as a whole makes progress
Two other properties

Deadlock-free:
- One ill-behaved thread does not prevent other threads from locking other locks
- System as a whole makes progress

Starvation-free
- Every locking thread eventually returns
- Every thread makes progress
Two other properties

Deadlock-free:

- One ill-behaved thread does not prevent other threads from locking other locks
- System as a whole makes progress
- Does LockOne enjoy deadlock freedom?

Starvation-free

- Every locking thread eventually returns
- Every thread makes progress
- Does LockOne enjoy starvation freedom?
Deadlock case for LockOne

flag_0 = true;

while (flag_1) {}

flag_1 = true;

while (flag_0) {}

(But sequentially it’s fine.)
Another attempt

class LockTwo : public GuardedLockBase {
    int waiting_; 
public:
    virtual void lock() override 
    {
        waiting_ = i();
        while (waiting_ == i()) {} 
    }
    
    virtual void unlock() override {} 
}
LockTwo claims

- Satisfies mutual exclusion
- Not deadlock-free
  - Sequential execution deadlocks
  - Concurrent execution does not (Why?)
Peterson’s algorithm

class PetersonLock : public GuardedLockBase {
    bool flag_[2];
    int waiting_;

public:
    virtual void lock() override
    {
        flag_[i()] = true;
        waiting_ = i();
        while (flag_[j()] && waiting_ == i()) {} 
    }

    virtual void unlock() override
    {
        flag_[i()] = false;
    }
};
Peterson’s Lock properties

- Mutual exclusion
  - By contradiction...
- Deadlock freedom
  - Only one thread at a time can be waiting
- Starvation freedom
  - If A finishes and tries to re-enter while B is waiting, B gets in first
Filter algorithm for $n$ threads

template <int N>
class FilterLock : public GuardedLockBase {
    int level_[N] = {0};
    int waiting_[N];

    bool exists_competition(int level)
    {
        for (auto k : thread::all_ids())
            if (k != i() && level_[k] >= level)
                return true;
        return false;
    }
};
template <int N>
class FilterLock : public GuardedLockBase {
  :
  :
public:
  virtual void lock() override
    for (int level = 1; level < N; ++level) {
      level_[i()] = level;
      waiting_[level] = i();
      while (exists_competition(level) && waiting_[level] == i())
        {
        }
    }
  }
virtual void unlock() override
  level_[i()] = 0;
};
Filter lock properties

- Mutual exclusion
  - By induction, one thread gets stuck in each level...
- Deadlock freedom
  - Like Peterson—only one thread can wait per level
- Starvation freedom
  - Like Peterson—every thread advances if any does
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