29. Parallel Programming III

Deadlock and Starvation Producer-Consumer, The concept of the monitor, Condition Variables [Deadlocks : Williams, Kap. 3.2.4-3.2.5] [Condition Variables: Williams, Kap. 4.1]

Deadlock Motivation

```
class BankAccount {
  int balance = 0;
  std::recursive_mutex m;
  using guard = std::lock_guard<std::recursive_mutex>;
public:
  ...
  void withdraw(int amount) { guard g(m); ... }
  void deposit(int amount){ guard g(m); ... }

  void transfer(int amount, BankAccount& to){
      guard g(m);
      withdraw(amount);
      to.deposit(amount);
  }
};
```

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```

Problem?

Deadlock Motivation

Suppose BankAccount instances `x` and `y`

`Thread 1: x.transfer(1,y);`

acquire lock for x

withdraw from x

acquire lock for y

`Thread 2: y.transfer(1,x);`

acquire lock for y

withdraw from y

acquire lock for x

Deadlock Motivation

Suppose BankAccount instances `x` and `y`

```
Thread 1: x.transfer(1,y);
```

acquire lock for x ⟵ 

withdraw from x

acquire lock for y

```
Thread 2: y.transfer(1,x);
```

acquire lock for y

withdraw from y

acquire lock for x

Deadlock Motivation

Suppose BankAccount instances `x` and `y`

`Thread 1: x.transfer(1,y);`

acquire lock for x ⟵ 

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Suppose BankAccount instances `x` and `y`

`Thread 1: x.transfer(1,y);`

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withdraw from x

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Deadlock Motivation

Suppose BankAccount instances `x` and `y`

`Thread 1: x.transfer(1,y);`

acquire lock for x ←

withdraw from x

acquire lock for y

`Thread 2: y.transfer(1,x);`

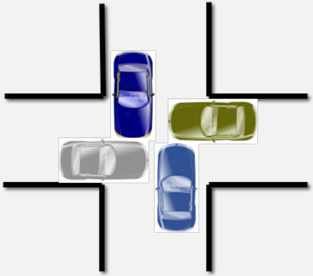
acquire lock for y ←

withdraw from y

acquire lock for x

Deadlock

Deadlock: two or more processes are mutually blocked because each process waits for another of these processes to proceed.

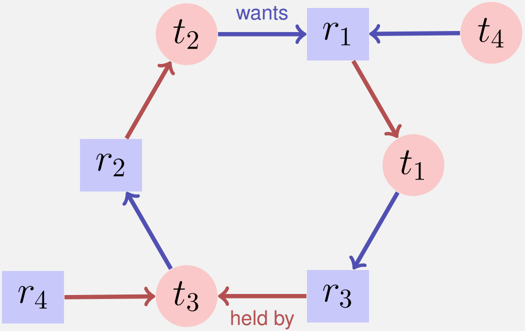


Threads and Resources

- Grafically t and Resources (Locks) r
- Thread t attempts to acquire resource a: $t \rightarrow a$
- Resource b is held by thread q: $s \leftarrow b$

Deadlock – Detection

A deadlock for threads $t_1, \ldots, t_n$ occurs when the graph describing the relation of the n threads and resources $r_1, \ldots, r_m$ contains a cycle.



Techniques

- *Deadlock detection* detects cycles in the dependency graph. Deadlocks can in general not be healed: releasing locks generally leads to inconsistent state
- *Deadlock avoidance* amounts to techniques to ensure a cycle can never arise
  - Coarser granularity “one lock for all”
  - Two-phase locking with retry mechanism
  - Lock Hierarchies
  - ...
  - Resource Ordering

Back to the Example

```
class BankAccount {
  int id; // account number, also used for locking order
  std::recursive_mutex m; ...
public:
  ...
   void transfer(int amount, BankAccount& to){
     if (id < to.id){
       guard g(m); guard h(to.m);
       withdraw(amount); to.deposit(amount);
     } else {
       guard g(to.m); guard h(m);
       withdraw(amount); to.deposit(amount);
     }
  }
};
```

C++11 Style

```
class BankAccount {
  ...
  std::recursive_mutex m;
  using guard = std::lock_guard<std::recursive_mutex>;
public:
  ...
   void transfer(int amount, BankAccount& to){
      std::lock(m,to.m); // lock order done by C++
      // tell the guards that the lock is already taken:
      guard g(m,std::adopt_lock); guard h(to.m,std::adopt_lock);
      withdraw(amount);
      to.deposit(amount);
  }
};
```

By the way...

```
class BankAccount {
  int balance = 0;
  std::recursive_mutex m;
  using guard = std::lock_guard<std::recursive_mutex>;
public:
  ...
  void withdraw(int amount) { guard g(m); ... }
  void deposit(int amount){ guard g(m); ... }

  void transfer(int amount, BankAccount& to){
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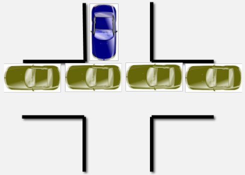
  }
};
```

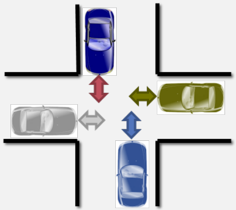
This would have worked here also. But then for a very short amount of time, money disappears, which does not seem acceptable (transient inconsistency!)

Starvation und Livelock

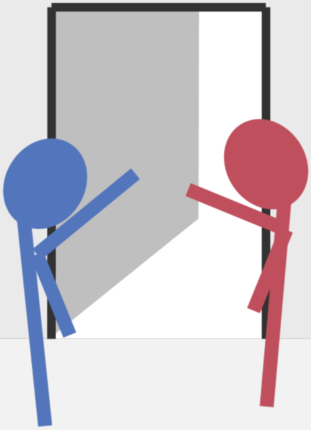
Starvation: the repeated but unsuccessful attempt to acquire a resource that was recently (transiently) free.



Livelock: competing processes are able to detect a potential deadlock but make no progress while trying to resolve it.



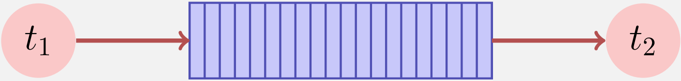
Politelock



Producer-Consumer Problem

Two (or more) processes, producers and consumers of data should become decoupled by some data structure.

Fundamental Data structure for building pipelines in software.



Sequential implementation (unbounded buffer)

```
class BufferS {
  std::queue<int> buf;
public:
    void put(int x){
        buf.push(x);
    }

    int get(){
        while (buf.empty()){} // wait until data arrive
        int x = buf.front();
        buf.pop();
        return x;
    }
};
```

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        buf.pop();
        return x;
    }
};
```

not thread-safe

How about this?

```
class Buffer {
  std::recursive_mutex m;
  using guard = std::lock_guard<std::recursive_mutex>;
  std::queue<int> buf;
public:
    void put(int x){ guard g(m);
        buf.push(x);
    }
    int get(){ guard g(m);
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        int x = buf.front();
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        while (buf.empty()){}
        int x = buf.front();
        buf.pop();
        return x;
    }
};
```

Deadlock

Well, then this?

```
void put(int x){
    guard g(m);
    buf.push(x);
}
int get(){
    m.lock();
    while (buf.empty()){
        m.unlock();
        m.lock();
    }
    int x = buf.front();
    buf.pop();
    m.unlock();
    return x;
}
```

Well, then this?

```
void put(int x){
    guard g(m);
    buf.push(x);
}
int get(){
    m.lock();
    while (buf.empty()){
        m.unlock();
        m.lock();
    }
    int x = buf.front();
    buf.pop();
    m.unlock();
    return x;
}
```

Ok this works, but it wastes CPU time.

Better?

```
void put(int x){
  guard g(m);
  buf.push(x);
}
int get(){
  m.lock();
  while (buf.empty()){
    m.unlock();
    std::this_thread::sleep_for(std::chrono::milliseconds(10));
    m.lock();
  }
  int x = buf.front(); buf.pop();
  m.unlock();
  return x;
}
```

Better?

```
void put(int x){
  guard g(m);
  buf.push(x);
}
int get(){
  m.lock();
  while (buf.empty()){
    m.unlock();
    std::this_thread::sleep_for(std::chrono::milliseconds(10));
    m.lock();
  }
  int x = buf.front(); buf.pop();
  m.unlock();
  return x;
}
```

Ok a little bit better, limits reactivity though.

Moral

We do not want to implement waiting on a condition ourselves.

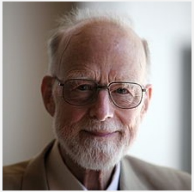
There already is a mechanism for this: *condition variables*.

The underlying concept is called *Monitor*.

Monitor

Monitor abstract data structure equipped with a set of operations that run in mutual exclusion and that can be synchronized.

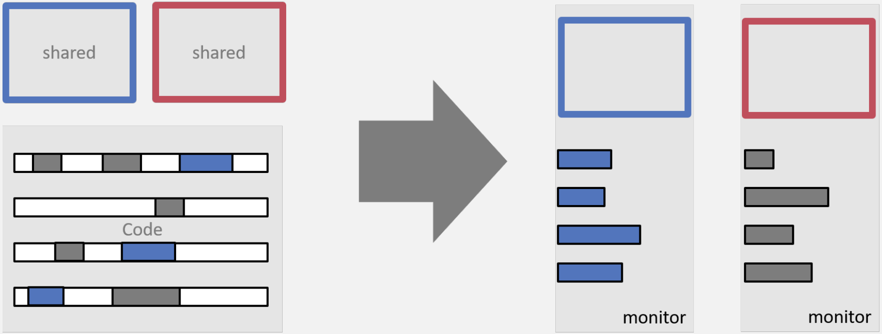
Invented by C.A.R. Hoare and Per Brinch Hansen (cf. Monitors – An Operating System Structuring Concept, C.A.R. Hoare 1974)



C.A.R. Hoare,
*1934

Per Brinch Hansen
(1938-2007)

Monitors vs. Locks



Monitor and Conditions

Monitors provide, in addition to mutual exclusion, the following mechanism:

Waiting on conditions: If a condition does not hold, then

- Release the monitor lock
- Wait for the condition to become true
- Check the condition when a signal is raised

Signalling: Thread that might make the condition true:

- Send signal to potentially waiting threads

Condition Variables

```
#include <mutex>
#include <condition_variable>
...

class Buffer {
  std::queue<int> buf;

  std::mutex m;
  // need unique_lock guard for conditions
  using guard = std::unique_lock<std::mutex>;
  std::condition_variable cond;
public:
        ...
};
```

Condition Variables

```
class Buffer {
...
public:
    void put(int x){
        guard g(m);
        buf.push(x);
        cond.notify_one();
    }
    int get(){
        guard g(m);
        cond.wait(g, [&]{return !buf.empty();});
        int x = buf.front(); buf.pop();
        return x;
    }
};
```

Technical Details

- A thread that waits using `cond.wait` runs at most for a short time on a core. After that it does not utilize compute power and "sleeps".
- The notify (or signal-) mechanism wakes up sleeping threads that subsequently check their conditions.
  - `cond.notify_one` signals *one* waiting thread
  - `cond.notify_all` signals *all* waiting threads. Required when waiting thrads wait potentially on *different* conditions.

Technical Details

- Many other programming langauges offer the same kind of mechanism. The checking of conditions (in a loop!) has to be usually implemented by the programmer.

Java Example

```
synchronized long get() {
  long x;
  while (isEmpty())
    try {
      wait ();
      } catch (InterruptedException e) { }
  x = doGet();
  return x;
}

synchronized put(long x){
  doPut(x);
  notify ();
}
```

By the way, using a bounded buffer..

```
class Buffer {
  ...
  CircularBuffer<int,128> buf; // from lecture 6
public:
    void put(int x){ guard g(m);
        cond.wait(g, [&]{return !buf.full();});
        buf.put(x);
        cond.notify_all();
    }
    int get(){ guard g(m);
        cond.wait(g, [&]{return !buf.empty();});
        cond.notify_all();
        return buf.get();
    }
};
```