

28. Parallel Programming II

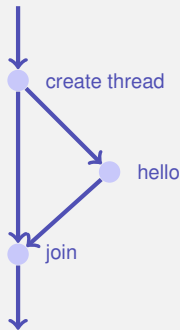
C++ Threads, Shared Memory, Concurrency, Excursion: lock algorithm (Peterson), Mutual Exclusion Race Conditions [C++ Threads: Williams, Kap. 2.1-2.2], [C++ Race Conditions: Williams, Kap. 3.1] [C++ Mutexes: Williams, Kap. 3.2.1, 3.3.3]

C++11 Threads

```
#include <iostream>
#include <thread>

void hello(){
    std::cout << "hello\n";
}

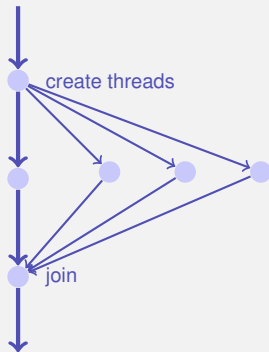
int main(){
    // create and launch thread t
    std::thread t(hello);
    // wait for termination of t
    t.join();
    return 0;
}
```



C++11 Threads

```
void hello(int id){  
    std::cout << "hello from " << id << "\n";  
}
```

```
int main(){  
    std::vector<std::thread> tv(3);  
    int id = 0;  
    for (auto & t:tv)  
        t = std::thread(hello, ++id);  
    std::cout << "hello from main \n";  
    for (auto & t:tv)  
        t.join();  
    return 0;  
}
```



Nondeterministic Execution!

One execution:

hello from main

hello from 2

hello from 1

hello from 0

Nondeterministic Execution!

One execution:

hello from main
hello from 2
hello from 1
hello from 0

Other execution:

hello from 1
hello from main
hello from 0
hello from 2

Nondeterministic Execution!

One execution:

hello from main
hello from 2
hello from 1
hello from 0

Other execution:

hello from 1
hello from main
hello from 0
hello from 2

Other execution:

hello from main
hello from 0
hello from hello from 1
2

Technical Detail

To let a thread continue as background thread:

```
void background();

void someFunction(){
    ...
    std::thread t(background);
    t.detach();
    ...
} // no problem here, thread is detached
```

More Technical Details

- With allocating a thread, reference parameters are copied, except explicitly `std::ref` is provided at the construction.
- Can also run Functor or Lambda-Expression on a thread
- In exceptional circumstances, joining threads should be executed in a catch block

More background and details in chapter 2 of the book *C++ Concurrency in Action*, Anthony Williams, Manning 2012. also available online at the ETH library.

28.2 Shared Memory, Concurrency

Sharing Resources (Memory)

- Up to now: fork-join algorithms: data parallel or divide-and-conquer
- Simple structure (data independence of the threads) to avoid race conditions
- Does not work any more when threads access shared memory.

Managing state

Managing state: Main challenge of concurrent programming.

Approaches:

- Immutability, for example constants.
- Isolated Mutability, for example thread-local variables, stack.
- Shared mutable data, for example references to shared memory, global variables

Protect the shared state

- Method 1: locks, guarantee exclusive access to shared data.
- Method 2: lock-free data structures, exclusive access with a much finer granularity.
- Method 3: transactional memory (not treated in class)

Canonical Example

```
class BankAccount {  
    int balance = 0;  
public:  
    int getBalance(){ return balance; }  
    void setBalance(int x) { balance = x; }  
    void withdraw(int amount) {  
        int b = getBalance();  
        setBalance(b - amount);  
    }  
    // deposit etc.  
};
```

(correct in a single-threaded world)

Bad Interleaving

Parallel call to `withdraw(100)` on the same account

Thread 1

```
int b = getBalance();
```

```
setBalance(b-amount);
```

Thread 2

```
int b = getBalance();
```

```
setBalance(b-amount);
```



Tempting Traps

WRONG:

```
void withdraw(int amount) {  
    int b = getBalance();  
    if (b==getBalance())  
        setBalance(b - amount);  
}
```

Bad interleavings cannot be solved with a repeated reading

Tempting Traps

also WRONG:

```
void withdraw(int amount) {  
    setBalance(getBalance() - amount);  
}
```

Assumptions about atomicity of operations are almost always wrong

Mutual Exclusion

We need a concept for mutual exclusion

Only one thread may execute the operation withdraw *on the same account* at a time.

The programmer has to make sure that mutual exclusion is used.

More Tempting Traps

```
class BankAccount {  
    int balance = 0;  
    bool busy = false;  
public:  
    void withdraw(int amount) {  
        while (busy); // spin wait  
        busy = true;  
        int b = getBalance();  
        setBalance(b - amount);  
        busy = false;  
    }  
  
    // deposit would spin on the same boolean  
};
```


More Tempting Traps

```
class BankAccount {  
    int balance = 0;  
    bool busy = false;  
public:  
    void withdraw(int amount) {  
        while (busy); // spin wait  
        busy = true;  
        int b = getBalance();  
        setBalance(b - amount);  
        busy = false;  
    }  
  
    // deposit would spin on the same boolean  
};
```

does not work!

Just moved the problem!

Thread 1



```
while (busy); //spin  
  
busy = true;  
  
int b = getBalance();  
  
setBalance(b - amount);
```

Thread 2

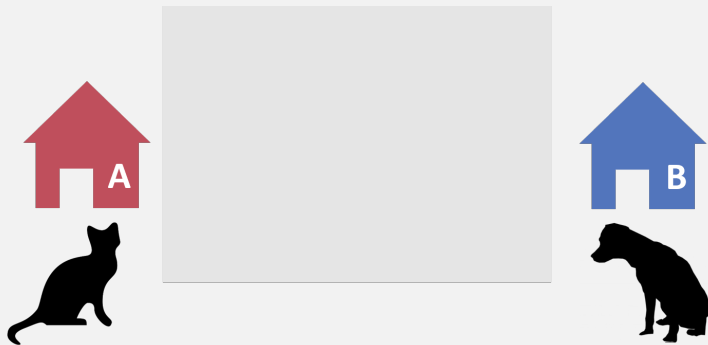
```
while (busy); //spin  
  
busy = true;  
  
int b = getBalance();  
setBalance(b - amount);
```

How ist this correctly implemented?

- We use *locks* (mutexes) from libraries
- They use hardware primitives, *Read-Modify-Write* (RMW) operations that can, in an atomic way, read and write depending on the read result.
- Without RMW Operations the algorithm is non-trivial and requires at least atomic access to variable of primitive type.

28.3 Excursion: lock algorithm

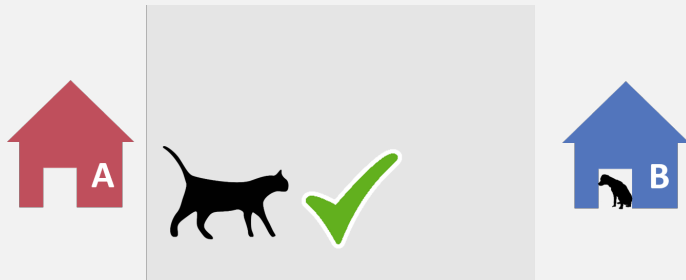
Alice's Cat vs. Bob's Dog



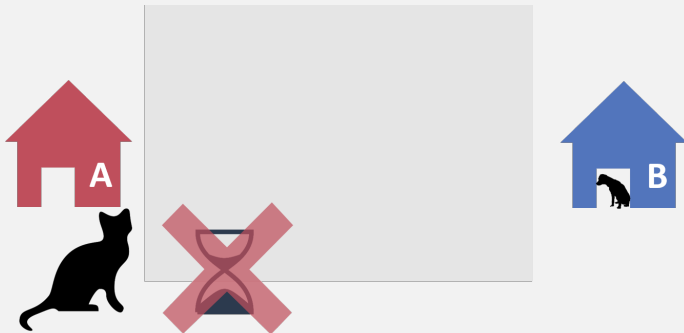
Required: Mutual Exclusion



Required: Mutual Exclusion



Required: No Lockout When Free



Communication Types

- Transient: Parties participate at the same time

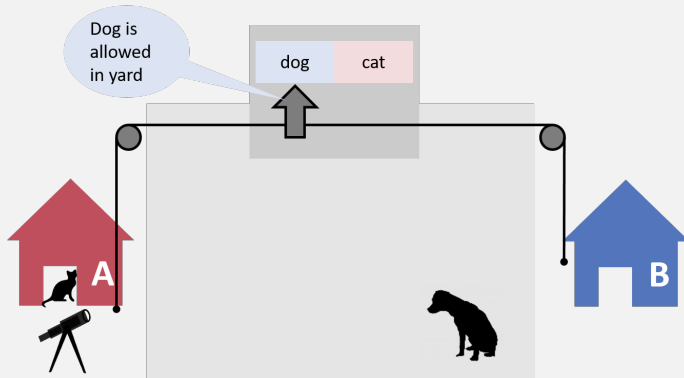


- Persistent: Parties participate at different times

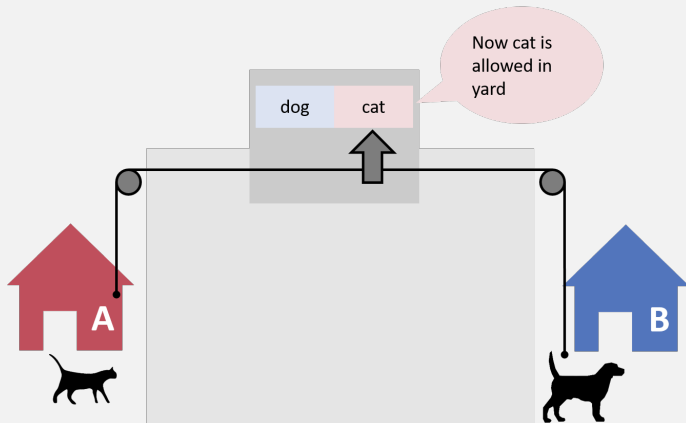


Mutual exclusion: persistent communication

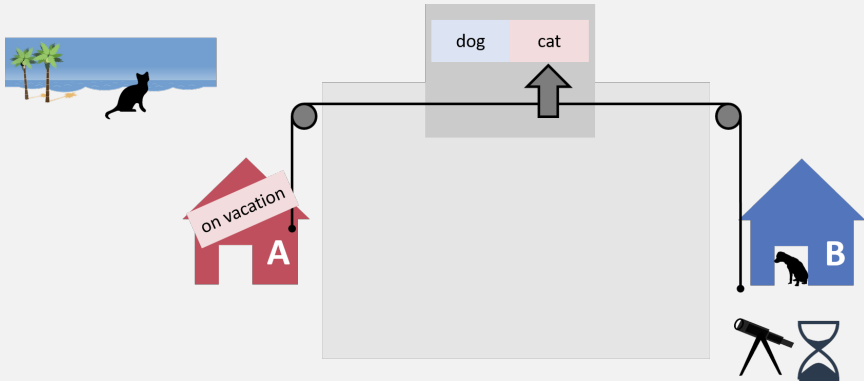
Communication Idea 1



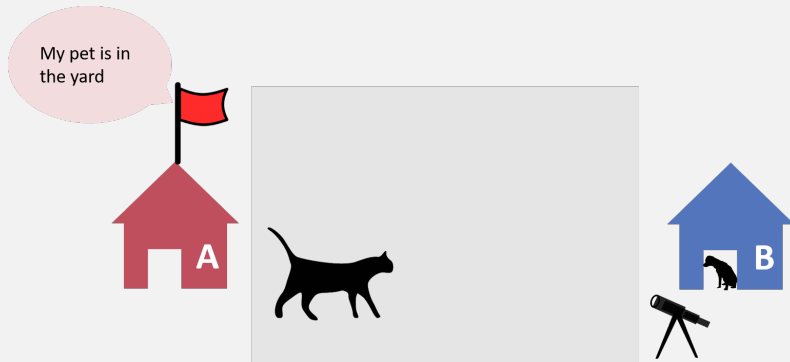
Access Protocol



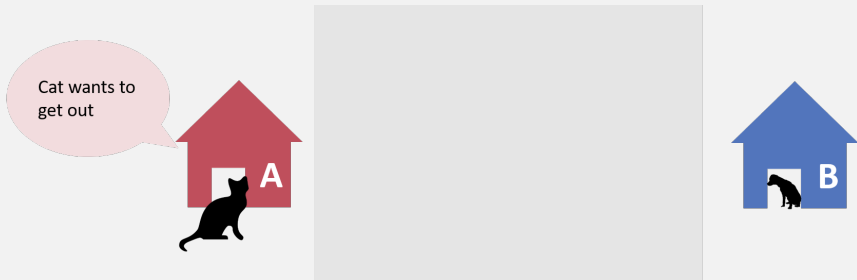
Problem!



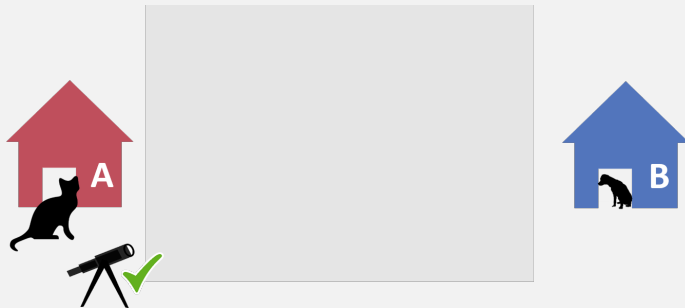
Communication Idea 2



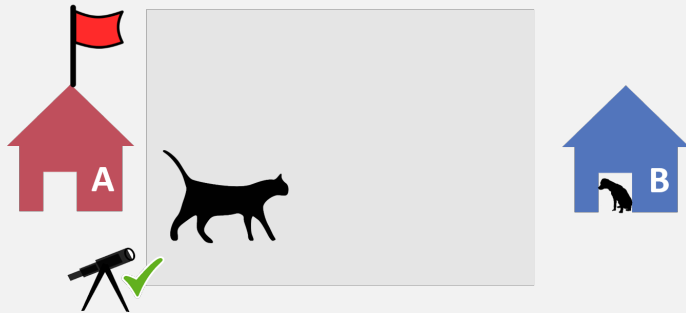
Access Protocol 2.1



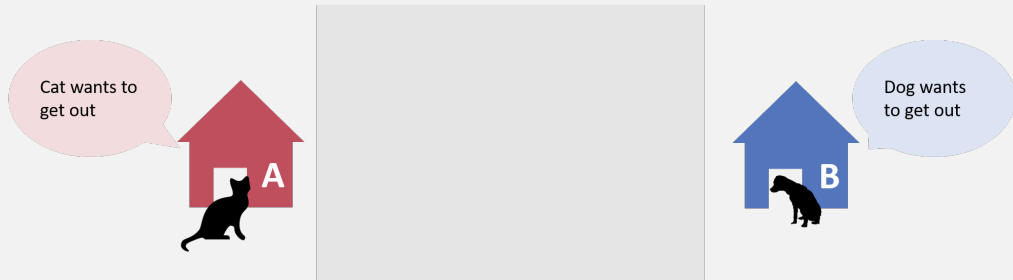
Access Protocol 2.1



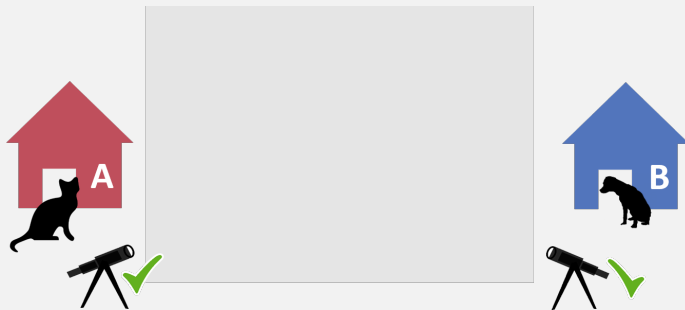
Access Protocol 2.1



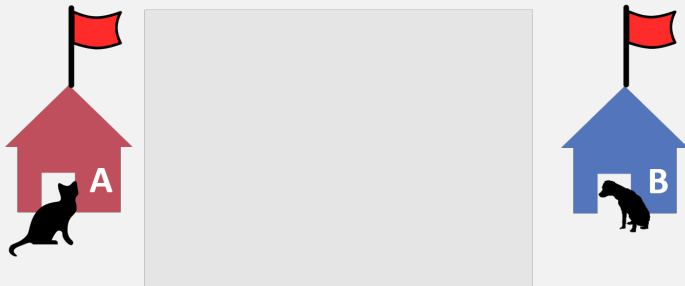
Different Scenario



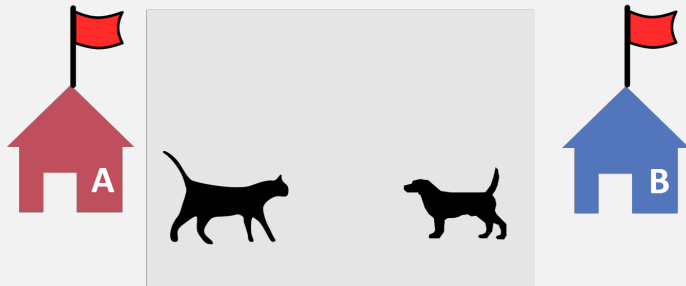
Different Scenario



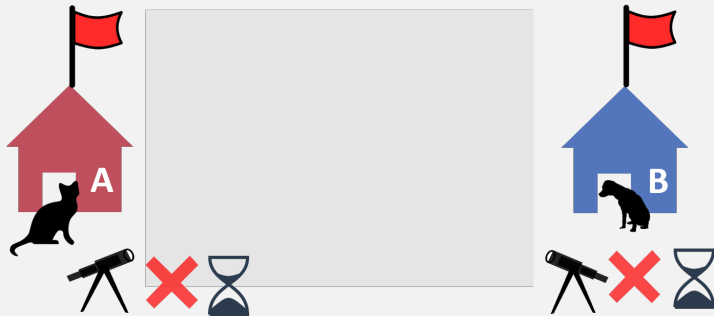
Different Scenario



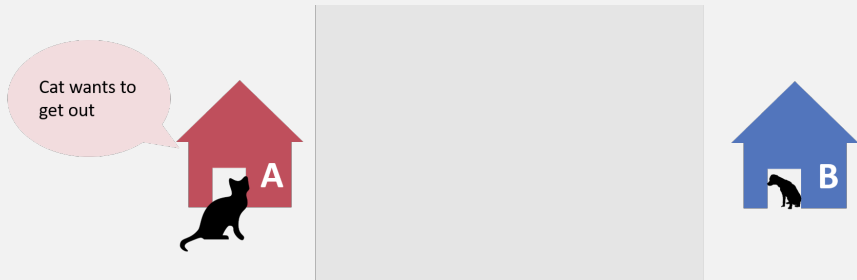
Problem: No Mutual Exclusion



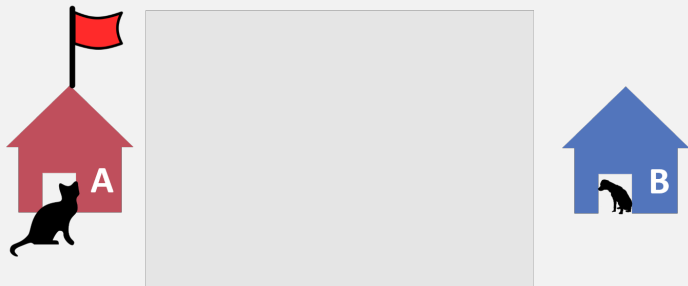
Checking Flags Twice: Deadlock



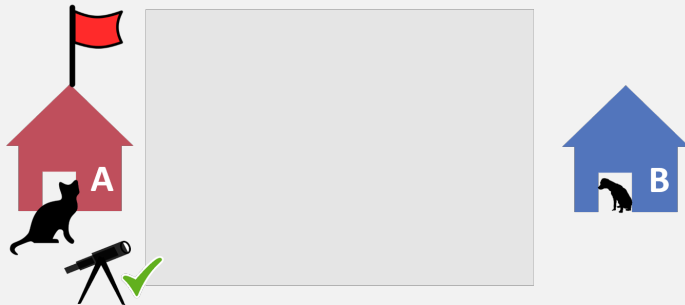
Access Protocol 2.2



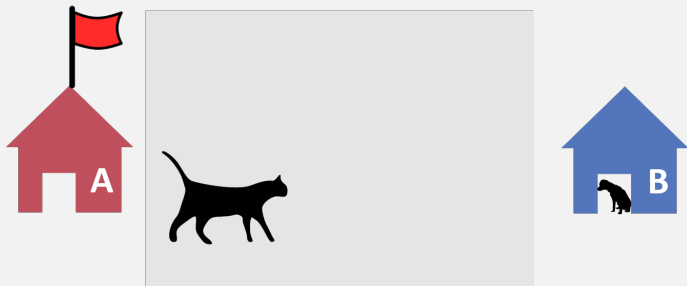
Access Protocol 2.2



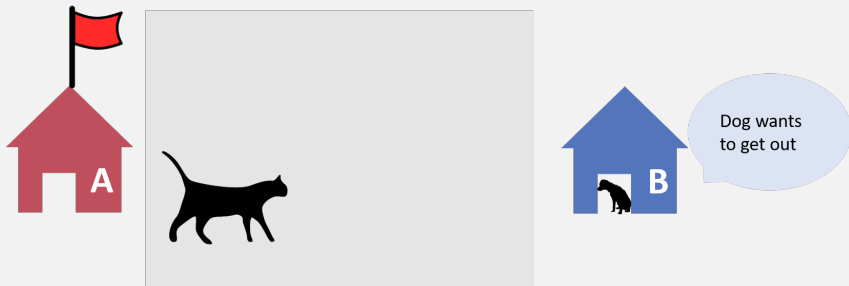
Access Protocol 2.2



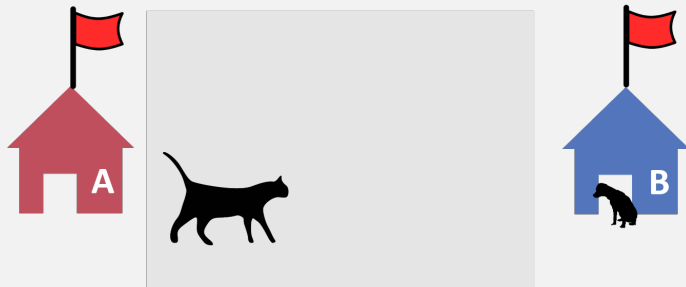
Access Protocol 2.2



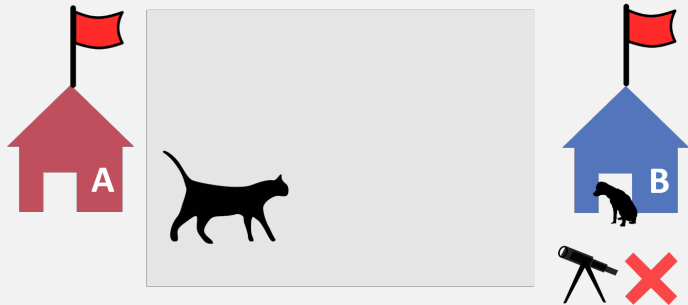
Access Protocol 2.2



Access Protocol 2.2



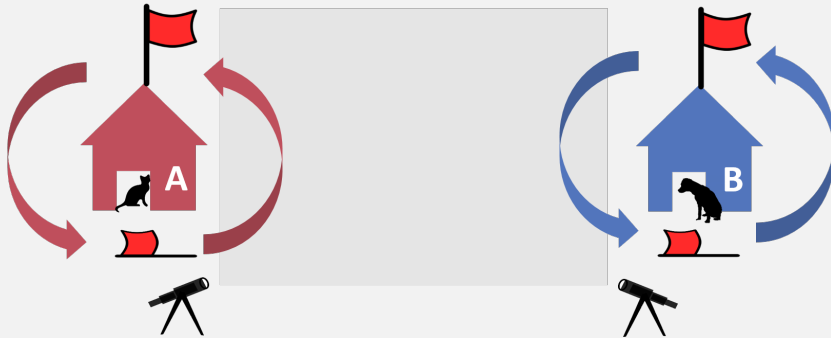
Access Protocol 2.2



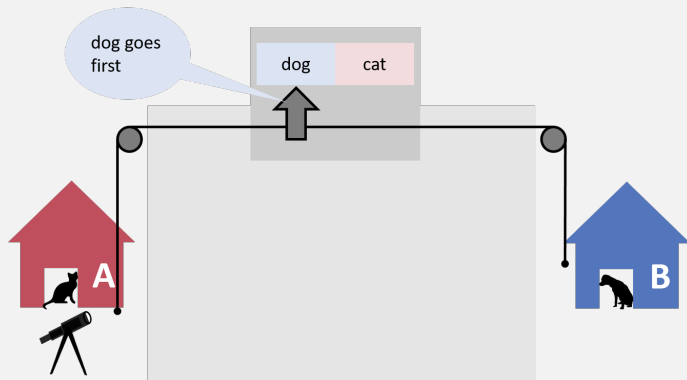
Access Protocol 2.2:provably correct



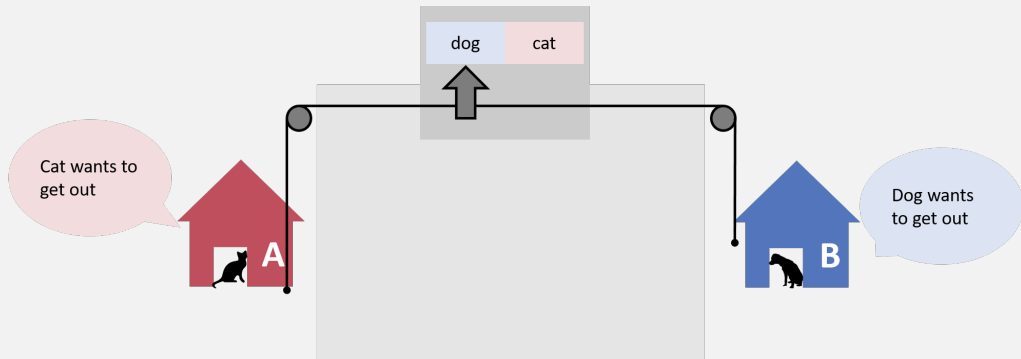
Weniger schwerwiegend: Starvation



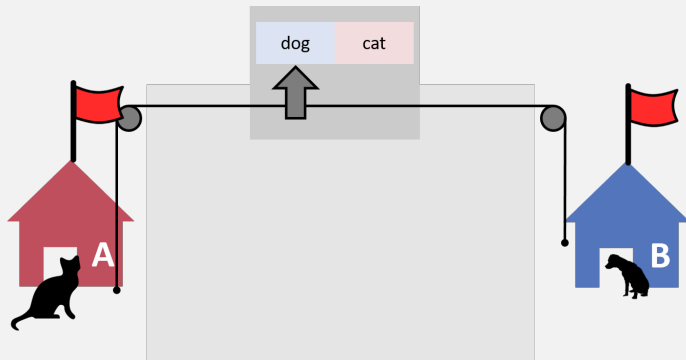
Final Solution



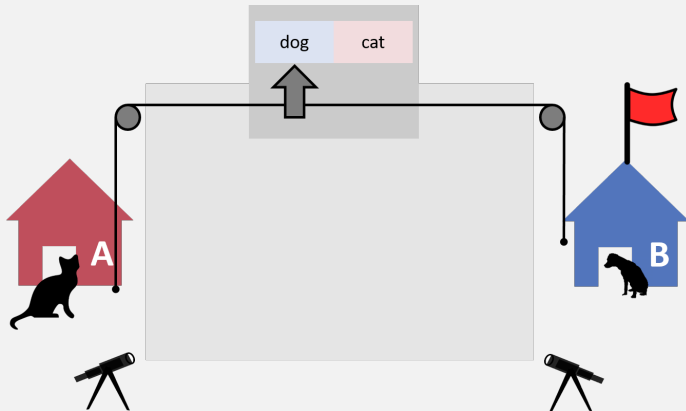
Final Solution



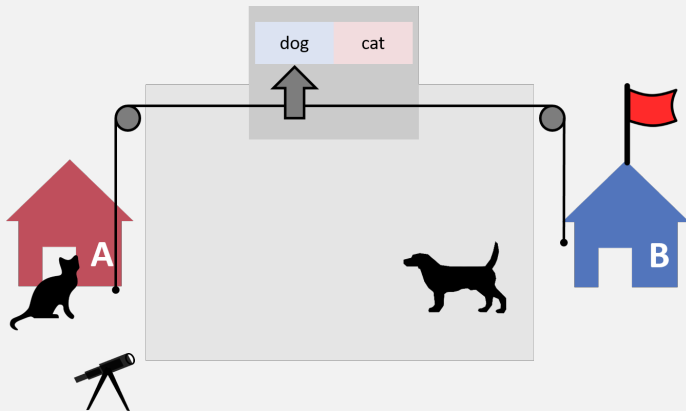
Final Solution



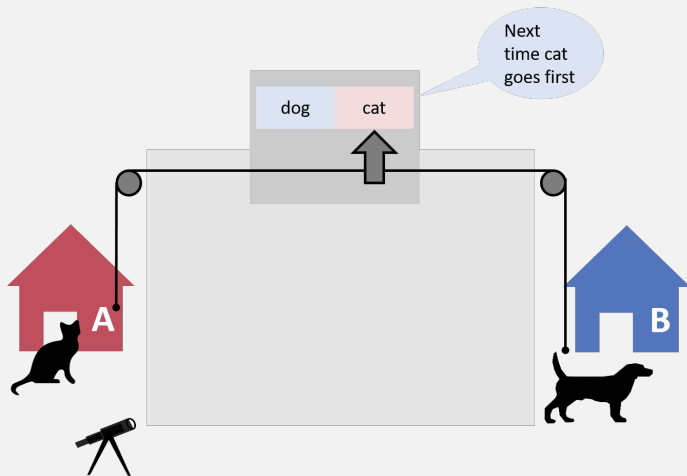
Final Solution



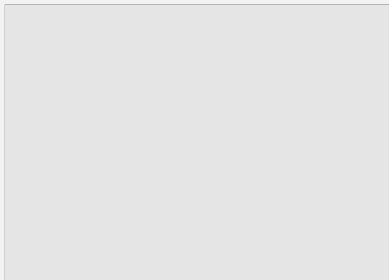
Final Solution



Final Solution



General Problem of Locking remains



Peterson's Algorithm⁴¹

for two processes is provable correct and free from starvation

non-critical section

```
flag[me] = true // I am interested
victim = me // but you go first
// spin while we are both interested and you go first:
while (flag[you] && victim == me) {};
```

critical section

```
flag[me] = false
```

⁴¹not relevant for the exam

Peterson's Algorithm⁴¹

for two processes is provable correct and free from starvation

non-critical section

```
flag[me] = true // I am interested
victim = me // but you go first
// spin while we are both interested and you go first:
while (flag[you] && victim == me) {};
```

critical section

```
flag[me] = false
```

The code assumes that the access to flag / victim is atomic and particularly linearizable or sequential consistent. An assumption that – as we will see below – is not necessarily given for normal variables. The Peterson-lock is not used on modern hardware.

⁴¹not relevant for the exam

28.4 Mutual Exclusion

Critical Sections and Mutual Exclusion

Critical Section

Piece of code that may be executed by at most one process (thread) at a time.

Mutual Exclusion

Algorithm to implement a critical section

```
acquire_mutex();    // entry algorithm\\  
...                // critical section  
release_mutex();    // exit algorithm
```

Required Properties of Mutual Exclusion

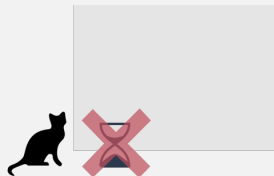
Correctness (Safety)

- At most one process executes the critical section code



Liveness

- Acquiring the mutex must terminate in finite time when no process executes in the critical section



Almost Correct

```
class BankAccount {  
    int balance = 0;  
    std::mutex m; // requires #include <mutex>  
public:  
    ...  
    void withdraw(int amount) {  
        m.lock();  
        int b = getBalance();  
        setBalance(b - amount);  
        m.unlock();  
    }  
};
```

Almost Correct

```
class BankAccount {  
    int balance = 0;  
    std::mutex m; // requires #include <mutex>  
public:  
    ...  
    void withdraw(int amount) {  
        m.lock();  
        int b = getBalance();  
        setBalance(b - amount);  
        m.unlock();  
    }  
};
```

What if an exception occurs?

RAII Approach

```
class BankAccount {  
    int balance = 0;  
    std::mutex m;  
public:  
    ...  
    void withdraw(int amount) {  
        std::lock_guard<std::mutex> guard(m);  
        int b = getBalance();  
        setBalance(b - amount);  
    } // Destruction of guard leads to unlocking m  
};
```

RAII Approach

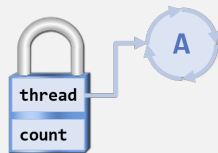
```
class BankAccount {  
    int balance = 0;  
    std::mutex m;  
public:  
    ...  
    void withdraw(int amount) {  
        std::lock_guard<std::mutex> guard(m);  
        int b = getBalance();  
        setBalance(b - amount);  
    } // Destruction of guard leads to unlocking m  
};
```

What about getBalance / setBalance?

Reentrant Locks

Reentrant Lock (recursive lock)

- remembers the currently affected thread;
- provides a counter
 - Call of lock: counter incremented
 - Call of unlock: counter is decremented. If counter = 0 the lock is released.



Account with reentrant lock

```
class BankAccount {  
    int balance = 0;  
    std::recursive_mutex m;  
    using guard = std::lock_guard<std::recursive_mutex>;  
public:  
    int getBalance(){ guard g(m); return balance;  
    }  
    void setBalance(int x) { guard g(m); balance = x;  
    }  
    void withdraw(int amount) { guard g(m);  
        int b = getBalance();  
        setBalance(b - amount);  
    }  
};
```

28.5 Race Conditions

Race Condition

- A *race condition* occurs when the result of a computation depends on scheduling.
- We make a distinction between *bad interleavings* and *data races*
- *Bad interleavings* can occur even when a mutex is used.

Example: Stack

Stack with correctly synchronized access:

```
template <typename T>
class stack{
    ...
    std::recursive_mutex m;
    using guard = std::lock_guard<std::recursive_mutex>;
public:
    bool isEmpty(){ guard g(m); ... }
    void push(T value){ guard g(m); ... }
    T pop(){ guard g(m); ...}
};
```

Peek

Forgot to implement peek. Like this?

```
template <typename T>
T peek (stack<T> &s){
    T value = s.pop();
    s.push(value);
    return value;
}
```

Peek

Forgot to implement peek. Like this?

```
template <typename T>
T peek (stack<T> &s){
    T value = s.pop();
    s.push(value);
    return value;
}
```

not thread-safe!

Peek

Forgot to implement peek. Like this?

```
template <typename T>
T peek (stack<T> &s){
    T value = s.pop();
    s.push(value);
    return value;
}
```

not thread-safe!

Despite its questionable style the code is correct in a sequential world. Not so in concurrent programming.

Bad Interleaving!

Initially empty stack s , only shared between threads 1 and 2.

Thread 1 pushes a value and checks that the stack is then non-empty. Thread 2 reads the topmost value using `peek()`.

Thread 1

```
s.push(5);
```

```
assert(!s.isEmpty());
```

Thread 2

```
int value = s.pop();
```

```
s.push(value);
```

```
return value;
```



The fix

Peek must be protected with the same lock as the other access methods

Bad Interleavings

Race conditions as bad interleavings can happen on a high level of abstraction

In the following we consider a different form of race condition: data race.

How about this?

```
class counter{
    int count = 0;
    std::recursive_mutex m;
    using guard = std::lock_guard<std::recursive_mutex>;
public:
    int increase(){
        guard g(m); return ++count;
    }
    int get(){
        return count;
    }
}
```

How about this?

```
class counter{
    int count = 0;
    std::recursive_mutex m;
    using guard = std::lock_guard<std::recursive_mutex>;
public:
    int increase(){
        guard g(m); return ++count;
    }
    int get(){
        return count;
    }
}
```

not thread-safe!

Why wrong?

It looks like nothing can go wrong because the update of count happens in a “tiny step”.

But this code is still wrong and depends on language-implementation details you cannot assume.

This problem is called *Data-Race*

Moral: *Do not introduce a data race, even if every interleaving you can think of is correct. Don't make assumptions on the memory order.*

A bit more formal

Data Race (low-level Race-Conditions) Erroneous program behavior caused by insufficiently synchronized accesses of a shared resource by multiple threads, e.g. Simultaneous read/write or write/write of the same memory location

Bad Interleaving (High Level Race Condition) Erroneous program behavior caused by an unfavorable execution order of a multithreaded algorithm, even if that makes use of otherwise well synchronized resources.


We look deeper

```
class C {  
    int x = 0;  
    int y = 0;  
public:  
    void f() {  
        x = 1;  
        y = 1;  
    }  
    void g() {  
        int a = y;  
        int b = x;  
        assert(b >= a);  
    }  
}
```


We look deeper

```
class C {  
    int x = 0;  
    int y = 0;  
public:  
    void f() {  
        ① x = 1;  
        ② y = 1;  
    }  
    void g() {  
        ③ int a = y;  
        ④ int b = x;  
        assert(b >= a);  
    }  
}
```

Can this fail?



We look deeper

```
class C {  
    int x = 0;  
    int y = 0;  
public:  
    void f() {  
        ① x = 1;  
        ② y = 1;  
    }  
    void g() {  
        ③ int a = y;  
        ④ int b = x;  
        assert(b >= a);  
    }  
}
```

Can this fail?

There is no interleaving of f and g that would cause the assertion to fail:

- A B C D ✓
- A C B D ✓
- A C D B ✓
- C A B D ✓
- C C D B ✓
- C D A B ✓

It can nevertheless fail!

One Reason: Memory Reordering

Rule of thumb: Compiler and hardware allowed to make changes that do not affect the *semantics of a sequentially* executed program

```
void f() {
```

```
    x = 1;
```

```
    y = x+1;
```

```
    z = x+1;
```

```
}
```



sequentially equivalent

```
void f() {
```

```
    x = 1;
```

```
    z = x+1;
```

```
    y = x+1;
```

```
}
```

From a Software-Perspective

Modern compilers do not give guarantees that a global ordering of memory accesses is provided as in the sourcecode:

- Some memory accesses may be even optimized away completely!
- Huge potential for optimizations – and for errors, when you make the wrong assumptions

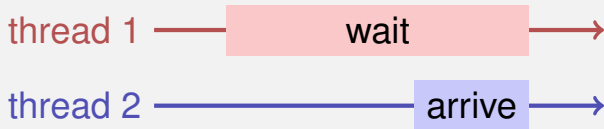
Example: Self-made Rendezvous

```
int x; // shared
```

```
void wait(){  
    x = 1;  
    while(x == 1);  
}
```

```
void arrive(){  
    x = 2;  
}
```

Assume thread 1 calls wait, later thread 2 calls arrive. What happens?



Compilation

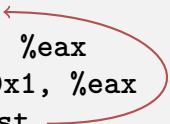
Source

```
int x; // shared
```

```
void wait(){  
    x = 1;  
    while(x == 1);  
}
```


```
void arrive(){  
    x = 2;  
}
```

Without optimisation

```
wait:  
movl $0x1, x  
test:    
mov x, %eax  
cmp $0x1, %eax  
je test
```

```
arrive:  
movl $0x2, x
```

With optimisation

```
wait:  
movl $0x1, x  
test:    
jmp test
```

```
arrive  
movl $0x2, x
```

Hardware Perspective

Modern multiprocessors do not enforce global ordering of all instructions for performance reasons:

- Most processors have a pipelined architecture and can execute (parts of) multiple instructions simultaneously. They can even reorder instructions internally.
- Each processor has a local cache, and thus loads/stores to shared memory can become visible to other processors at different times

Memory Hierarchy

Registers

fast, low latency, high cost, low capacity

L1 Cache

L2 Cache

...

System Memory

slow, high latency, low cost, high capacity

An Analogy

Anna

$C \leftarrow A \cdot C$
 n times

○

○ $C =$

1	2	3	4	5
2	3	4	5	6
3	4	5	6	7
4	5	6	7	8
5	6	7	8	9

 $A =$

1	2	3	4	5
2	3	4	5	6
3	4	5	6	7
4	5	6	7	8
5	6	7	8	9

○

Beat

○ $z = V$
 $z = A^n \cdot z$

○ $z =$

0	0	0	0	0
---	---	---	---	---

○ $A =$

1	2	3	4	5
2	3	4	5	6
3	4	5	6	7
4	5	6	7	8
5	6	7	8	9

○

V

0	1	0	2	0	0
---	---	---	---	---	---

 A

1	2	3	4	5
2	3	4	5	6
3	4	5	6	7
4	5	6	7	8
5	6	7	8	9

 ϵ

1	2	3	4	5
2	3	4	5	6
3	4	5	6	7
4	5	6	7	8
5	6	7	8	9

$h = 5$

B

1	2	3	4	5
2	3	4	5	6
3	4	5	6	7
4	5	6	7	8
5	6	7	8	9

 z

0	0	0	0	0
---	---	---	---	---

global data

Zoe

○ z

0	0	0	0	0
---	---	---	---	---

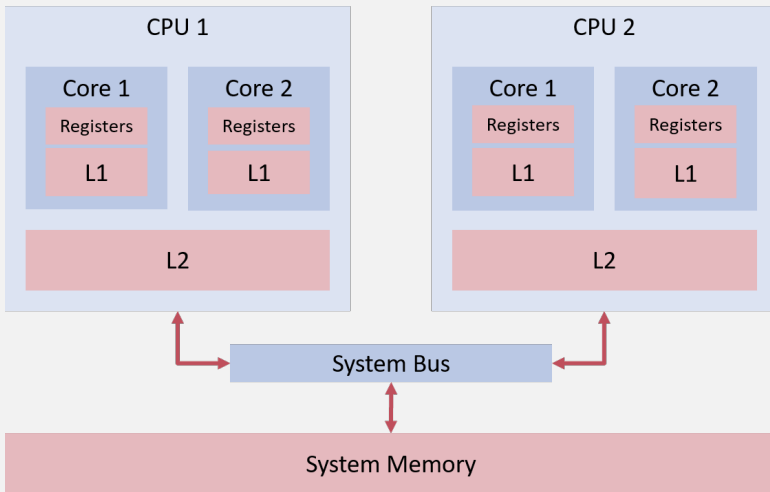
○ wait until $z \neq 0$

○ then $V = B \cdot z$

○

local data

Schematic



Memory Models

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For instance, C++ provides *guarantees when synchronisation with a mutex* is used.

Fixed

```
class C {  
    int x = 0;  
    int y = 0;  
    std::mutex m;  
public:  
    void f() {  
        m.lock(); x = 1; m.unlock();  
        m.lock(); y = 1; m.unlock();  
    }  
    void g() {  
        m.lock(); int a = y; m.unlock();  
        m.lock(); int b = x; m.unlock();  
        assert(b >= a); // cannot fail  
    }  
};
```

Atomic

Here also possible:

```
class C {  
    std::atomic_int x{0}; // requires #include <atomic>  
    std::atomic_int y{0};  
public:  
    void f() {  
        x = 1;  
        y = 1;  
    }  
    void g() {  
        int a = y;  
        int b = x;  
        assert(b >= a); // cannot fail  
    }  
};
```