# 31. Parallel Programming II

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]

## 31.1 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 **`widthdraw(100)`** on the same account

| $t$ | Thread 1 | Thread 2 |
| --- | --- | --- |
| ↓ | `int b = getBalance();` | |
| | | `int b = getBalance();` |
| | | `setBalance(b-amount);` |
| | `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);
```

$t$

# 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.

## 31.2 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
```

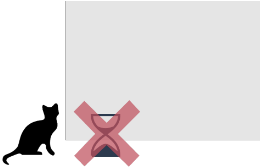
# Required Properties of Mutual Exclusion

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

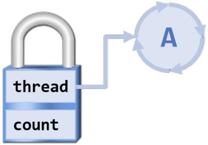
```
class BankAccount {
  int balance = 0;
  std::mutex m;
public:
  ...
  void withdraw(int amount) {
    std::lock_guard<std::mutex> guard(m);
    int b = getBalance();
    setBalance(b - amount);
  } // Destruction of guard leads to unlocking m
};
```

# 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);
  }
};
```

## 31.3 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().

| $t$ | Thread 1 | Thread 2 |
| --- | --- | --- |
| ↓ | `s.push(5);` | |
| | | `int value = s.pop();` |
| | `assert(!s.isEmpty());` | |
| | | `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() {
Ⓐ   x = 1;
Ⓑ   y = 1;
  }
  void g() {
Ⓒ   int a = y;
Ⓓ   int b = x;
    assert(b >= a);
  }
}
```

Can this fail?

# We look deeper

```
class C {
  int x = 0;
  int y = 0;
public:
  void f() {
(A)   x = 1;
(B)   y = 1;
  }
  void g() {
(C)   int a = y;
(D)   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 Resason: 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;
}
```

$\Longleftrightarrow$ 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

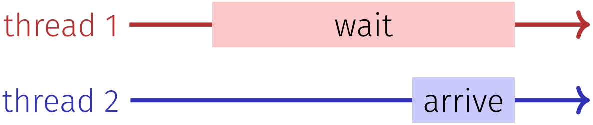
# Example: Self-made Rendevouz

```
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
```

if equal

### With optimisation

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

arrive
movl $0x2, x
```

always

# 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

L1 Cache

L2 Cache

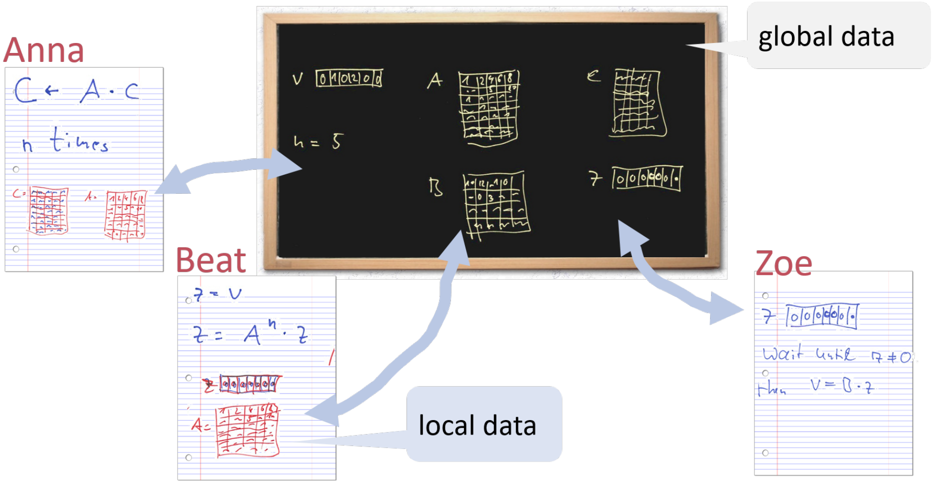
...

System Memory

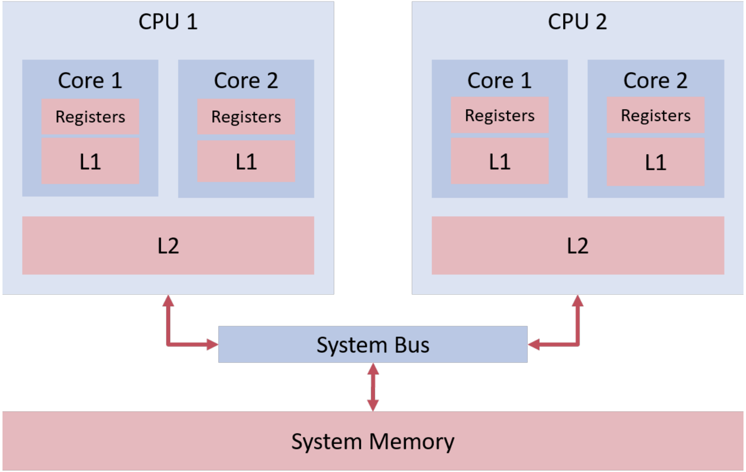
fast,low latency, high cost, low capacity

slow,high latency,low cost,high capacity

# An Analogy



# Schematic



CPU 1
Core 1
Registers
L1
Core 2
Registers
L1
L2
CPU 2
Core 1
Registers
L1
Core 2
Registers
L1
L2
System Bus
System Memory

# Memory Models

When and if effects of memory operations become visible for threads, depends on hardware, runtime system and programming language.

# Memory Models

When and if effects of memory operations become visible for threads, depends on hardware, runtime system and programming language.

A **memory model** (e.g. that of C++) provides minimal guarantees for the effect of memory operations

- leaving open possibilities for optimisation
- containing guidelines for writing thread-safe programs

# Memory Models

When and if effects of memory operations become visible for threads, depends on hardware, runtime system and programming language.

A **memory model** (e.g. that of C++) provides minimal guarantees for the effect of memory operations

- leaving open possibilities for optimisation
- containing guidelines for writing thread-safe programs

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

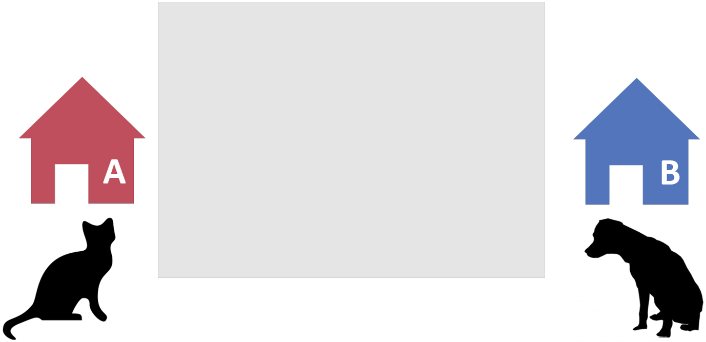
Here also possible:

```
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
  }
};
```

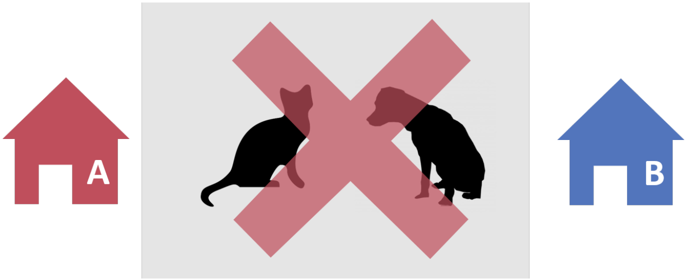
# 31.4 Appendix / Excursion: lock algorithm

not relevant for an exam

# Alice’s Cat vs. Bob’s Dog

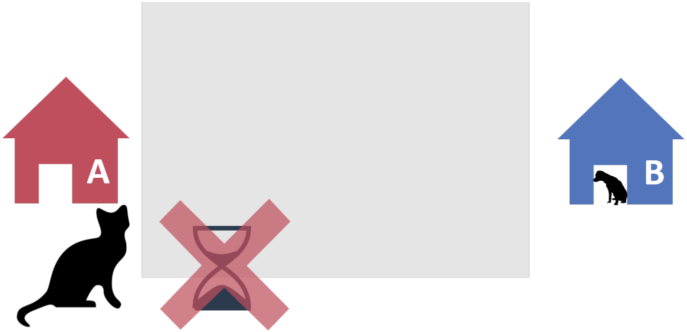


# Required: Mutual Exclusion



# Required: Mutual Exclusion

# Required: No Lockout When Free



# Communication Types

- Transient: Parties participate at the same time

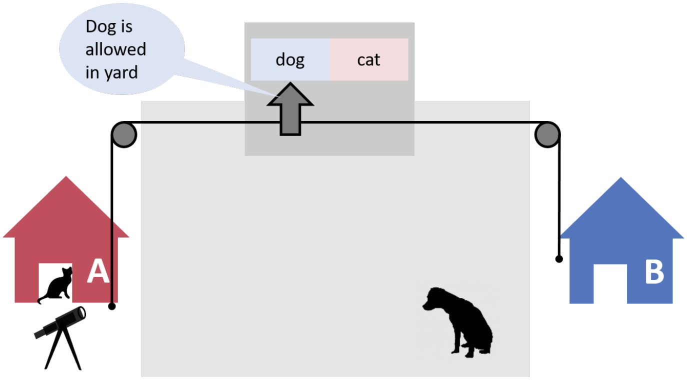


- Persistent: Parties participate at different times

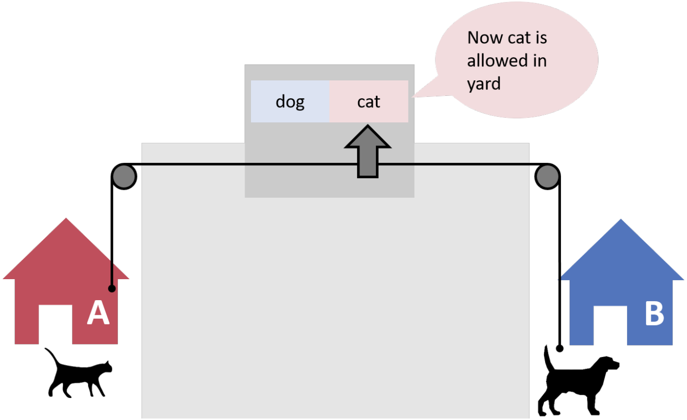


Mutual exclusion: persistent communication

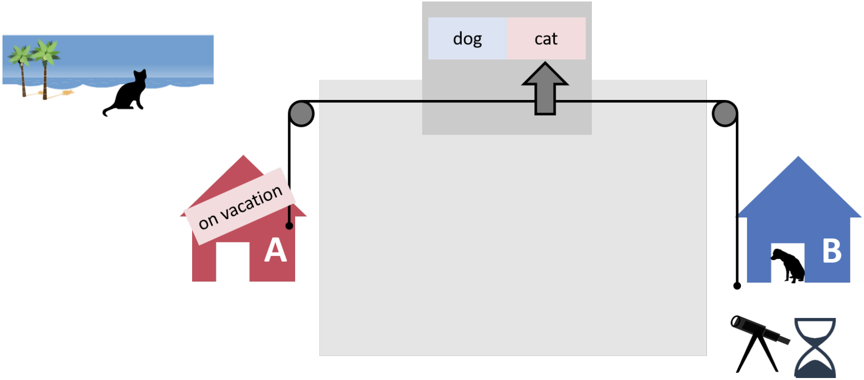
# Communication Idea 1



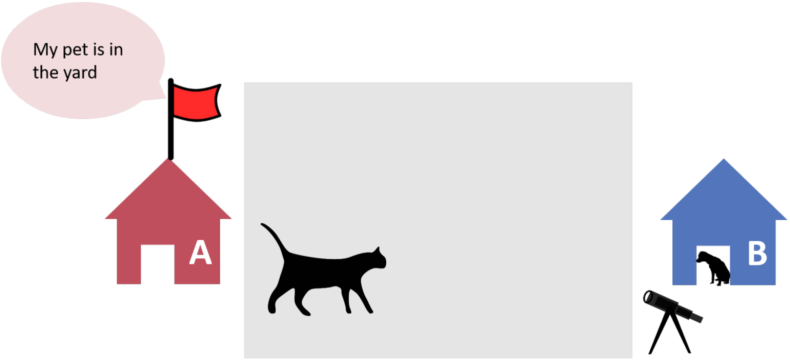
# Access Protocol



# Problem!

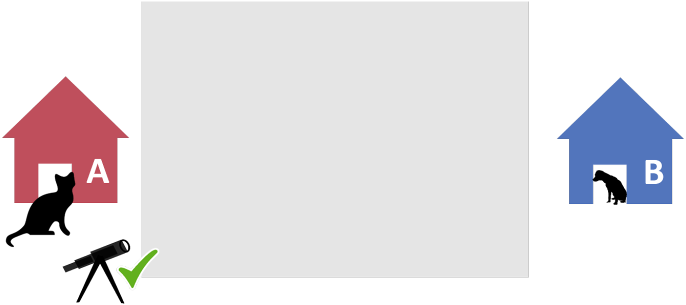


# Communication Idea 2

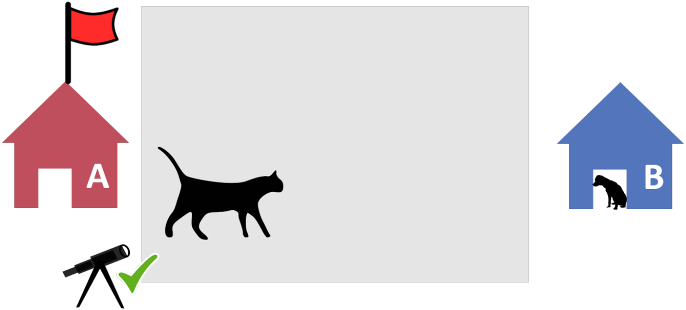


# Access Protocol 2.1

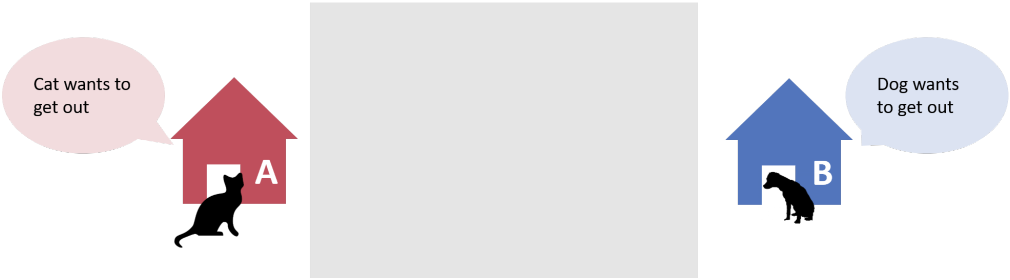
# Access Protocol 2.1



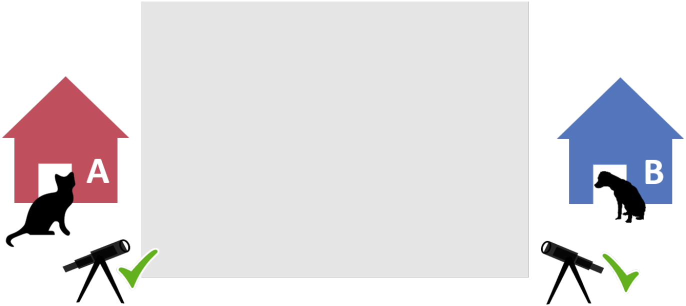
# Access Protocol 2.1



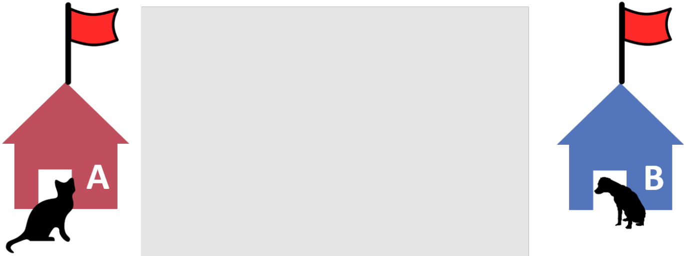
# Different Scenario



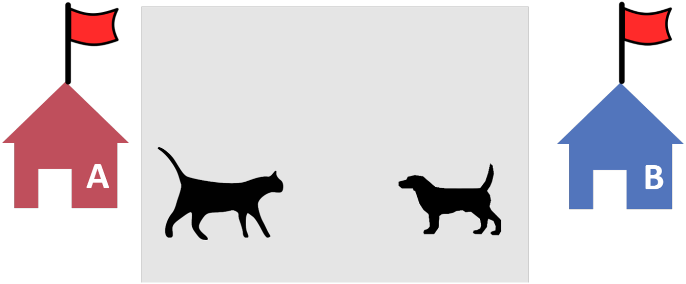
# Different Scenario



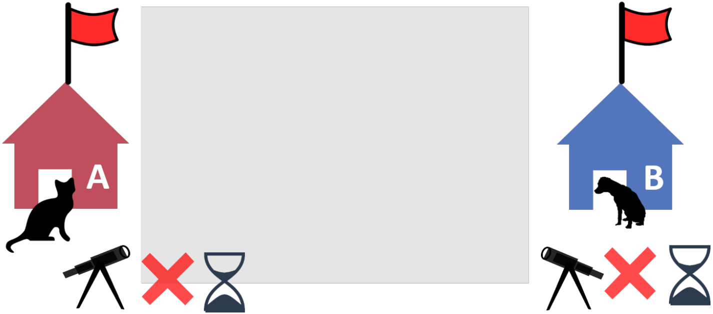
# Different Scenario



# Problem: No Mutual Exclusion

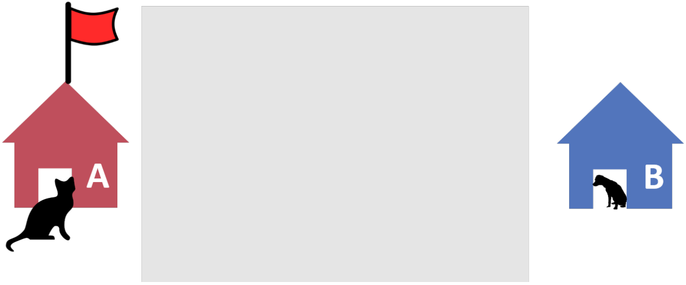


# Checking Flags Twice: Deadlock

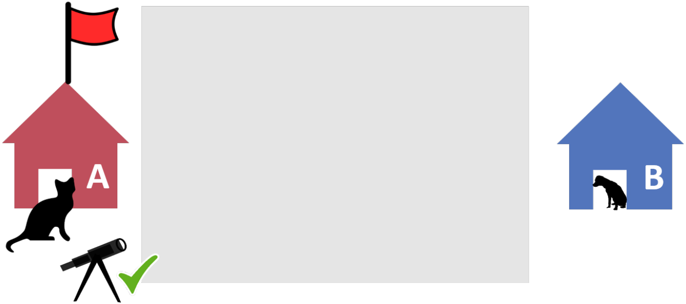


# Access Protocol 2.2

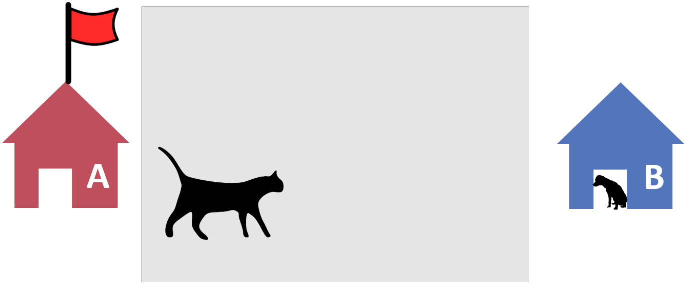
# Access Protocol 2.2



# Access Protocol 2.2

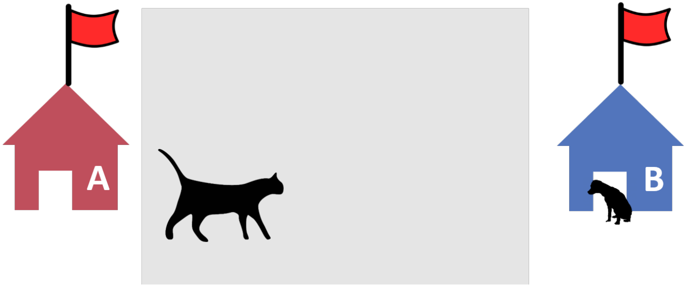


# Access Protocol 2.2

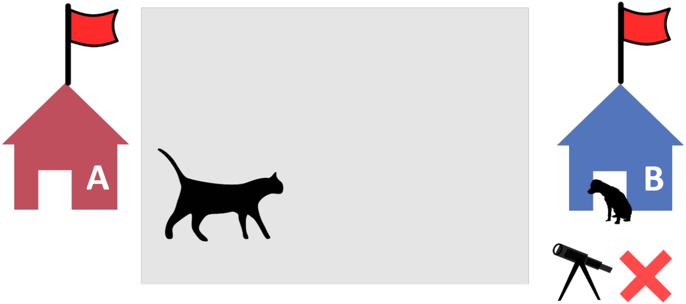


# Access Protocol 2.2

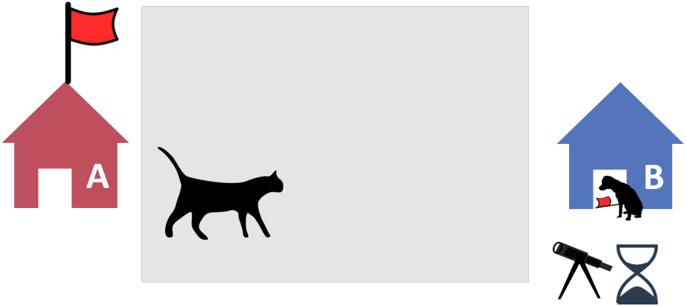
# Access Protocol 2.2



# Access Protocol 2.2

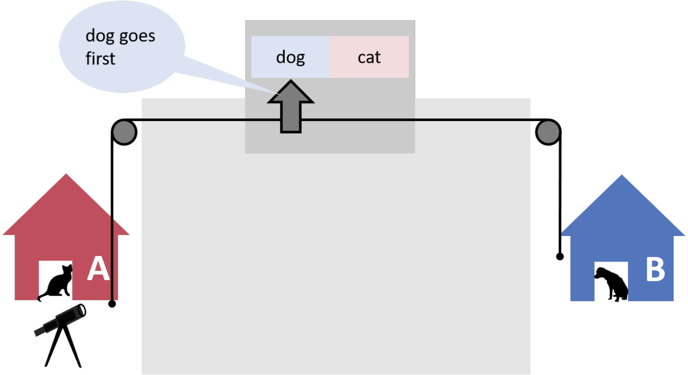


# Access Protocol 2.2:provably correct

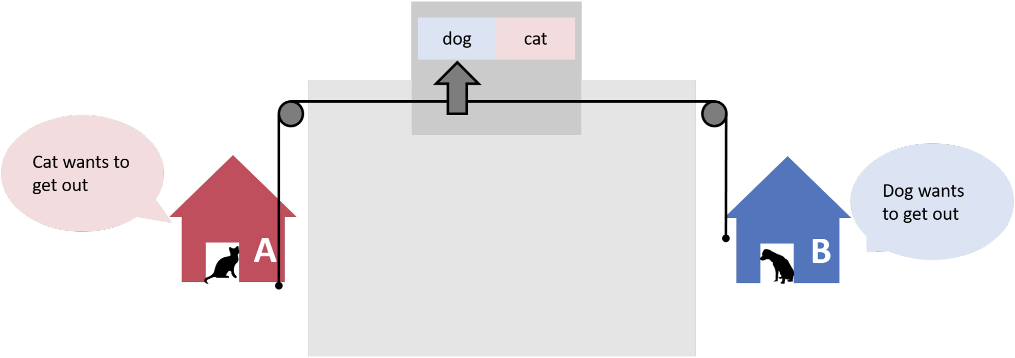


# Weniger schwerwiegend: Starvation

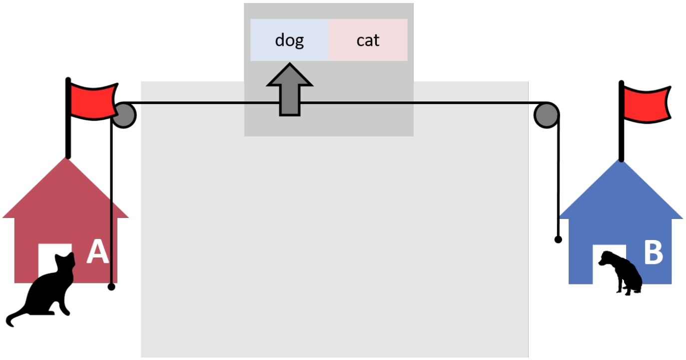
# Final Solution



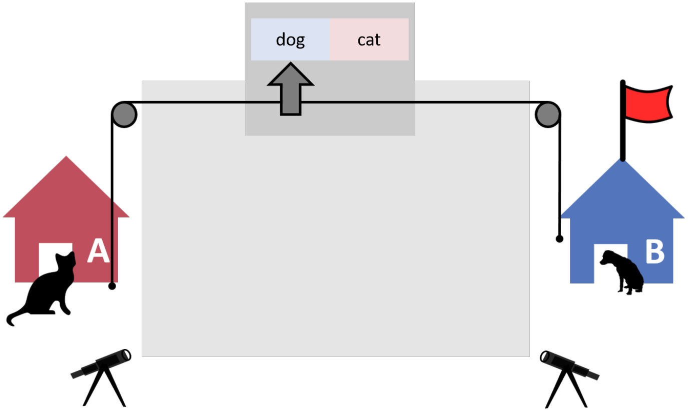
# Final Solution



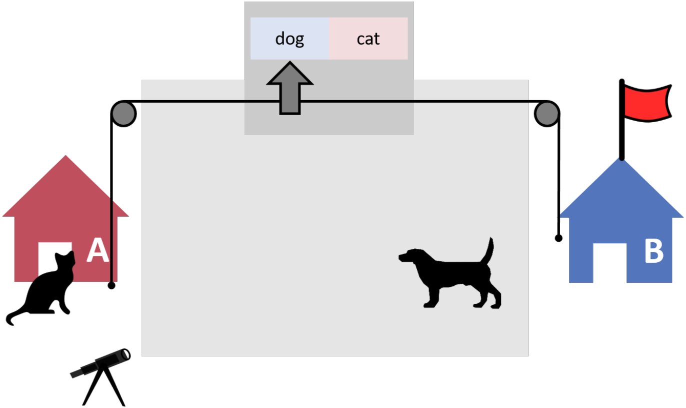
# Final Solution



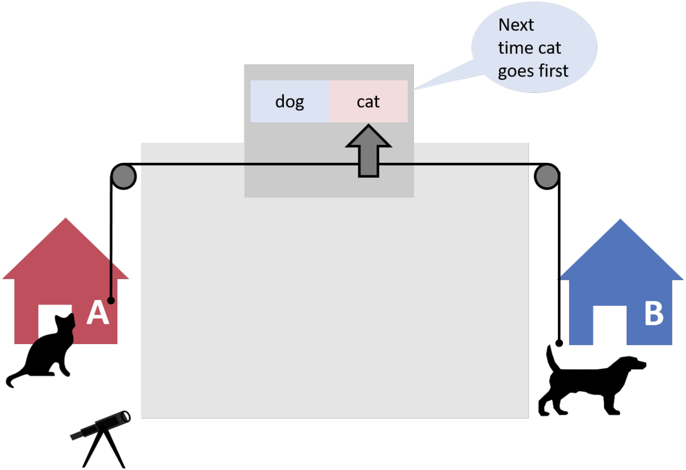
# Final Solution



# Final Solution



# Final Solution



# General Problem of Locking remains

# Peterson's Algorithm (not relevant for the exam)

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
```

# Peterson's Algorithm (not relevant for the exam)

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.