Parallel Programming

Introduction & Course Overview

SS 2024

Prof. Barbara Solenthaler

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Lecturers

Prof. Barbara Solenthaler
CNB G 102.1
solenthaler@inf.ethz.ch

Teaches Part I
Office hours: per email request

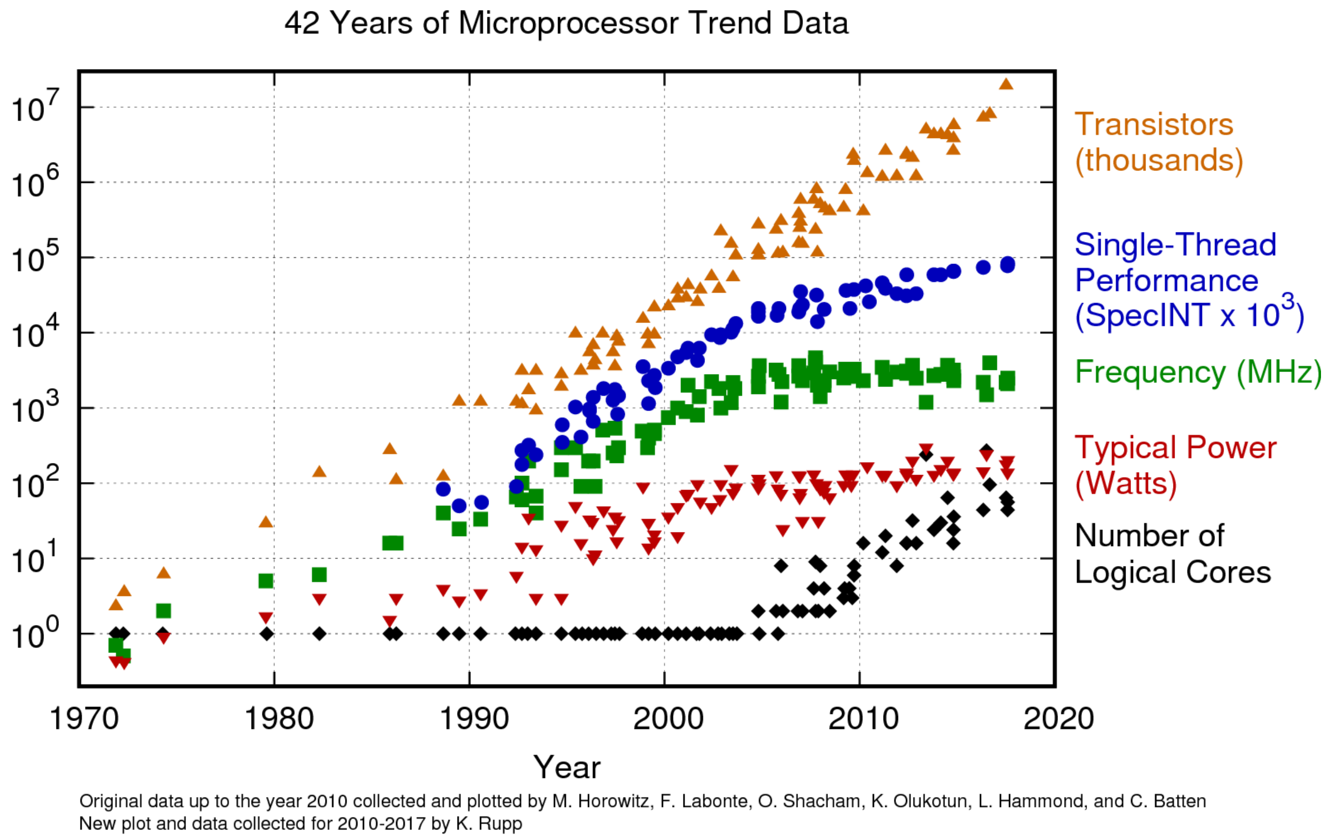
Prof. Torsten Hoefler
OAT V 15
torsten.hoefler@inf.ethz.ch

Teaches Part II
Office hours: per email request

https://spcl.inf.ethz.ch/Teaching/2024-pp/

Why This Course?

1. Parallel programming is a necessity – since 2000-ish
2. A different way of computational thinking – who said everything needs a total order?
3. Generally fun (since always) – if you like to challenge your brain



Karl Rupp's blog

Course Overview

Parallel Programming (252-0029-00L)

- 4L + 2U
- 7 ECTS Credits
- Audience: Computer Science Bachelor
  - Part of Basisprüfung

- Lecture Language: Denglisch

Course Coordination

- Lectures 2 x week:
  - Monday 10-12 HG F 5, **HG F 7**
  - Tuesday 10-12 HG F 5, **HG F 7**
- Weekly Exercise Sessions
  - Wednesday 16-18 or Friday 10-12
  - Enroll via myStudies
  - Focus groups

Course Material and Communication

Course website:

https://spcl.inf.ethz.ch/Teaching/2024-pp/

Moodle 2024:

https://moodle-app2.let.ethz.ch/course/view.php?id=22281

Lecture slides, exercises, forum

About This Course

Head TAs:

- Philine Witzig (Part I)
- Timo Schneider (Part II)

Teaching Assistants (Part I):

- Daniel Dorda
- Aurel Gruber
- Nikola Kovacevic
- Lasse Lingens
- Till Schnabel
- Agon Serifi
- Yingyan Xu
- Lingchen Yang
- Benjamin Gruzman
- Gamal Hassan
- Finn Heckman
- Sarah Kuhn
- Raphael Larisch
- Julianne Orel

Communication:

Your TA ▶ Head TA ▶ Lecturer

Grades:

- Class is part of Basisprüfung: written, centralized exam after the term
- 100% of grade determined by final exam
- Exercises not graded but essential

Academic Integrity

- Zero tolerance cheating policy (cheat = fail + being reported)
- Homework
  - Don’t look at other students code
  - Don’t copy code from anywhere
  - Ok to discuss things – but then you have to do it alone
  - Code may be checked with tools
- Don’t copy-paste
  - Code
  - Text
  - Images

Concepts and Practice

Our goal is twofold:

- Learn how to write parallel programs in practice
  - Using Java for the most part
  - And showing how it works in C
- Understand the underlying fundamental concepts
  - Generic concepts outlive specific tools
  - There are other approaches than Java's

You are Encouraged to:

- Ask questions:
  - helps us keep a good pace
  - helps you understand the material
  - let's make the course interactive
  - class or via e-mail or via forum
- Use the web to find additional information
  - Javadocs
  - Stack Overflow
- Write Code & Experiment

If there is a problem, let us know as **early as possible**!

What are Exercises for?

Learning tool

Seeing a correct solution is not enough

You should try to solve the problem yourselves

Hence, exercise sessions are

for guiding you to solve the problem

not for spoon-feeding you solutions

Class Overview

(Parallel) Programming

- Recap: Programming in Java + a bit of JVM
- Parallelism in Java (Threads)

Parallelism

- Understanding and detecting parallelism
- Intro to PC Architectures
- Formalizing parallelism
- Programming models for parallelism

Concurrency

- Shared data
- Race Conditions
- Locks, Semaphores, etc.
- Lock-free programming
- Communication across tasks and processes

Parallel Algorithms

- Useful & common algorithms in parallel
- Data structures for parallelism
- Sorting & Searching, etc.

Schedule (Part I)

Lecture

Feb 19	Introduction & Course Overview
Feb 20	Java Recap and JVM Overview
Feb 26	Introduction to Threads and Synchronization (Part I)
Feb 27	Introduction to Threads and Synchronization (Part II)
Mar 4	Introduction to Threads and Synchronization (Part II)
Mar 5	Parallel Architectures: Parallelism on the Hardware Level (Part I)
Mar 11	Basic Concepts in Parallelism
Mar 12	Divide and Conquer
Mar 18	ForkJoin Framework
Mar 19	Cilk-style bounds and Task Parallel Algorithms
Mar 25	Cilk-style bounds and Task Parallel Algorithms
Mar 26	Virtual threads
Apr 8	Shared Memory Concurrency, Locks and Data Races
Apr 9	Reserve, exam prep

Exercises

Ex 1	Introduction
Ex 2	Introduction to Multi-threading
Ex 3	Multi-threading
Ex 4	Parallel Models
Ex 5	Divide and Conquer
Ex 6	Task Parallelism
Ex 7	Synchronization and Resource Sharing

Schedule (Part II)

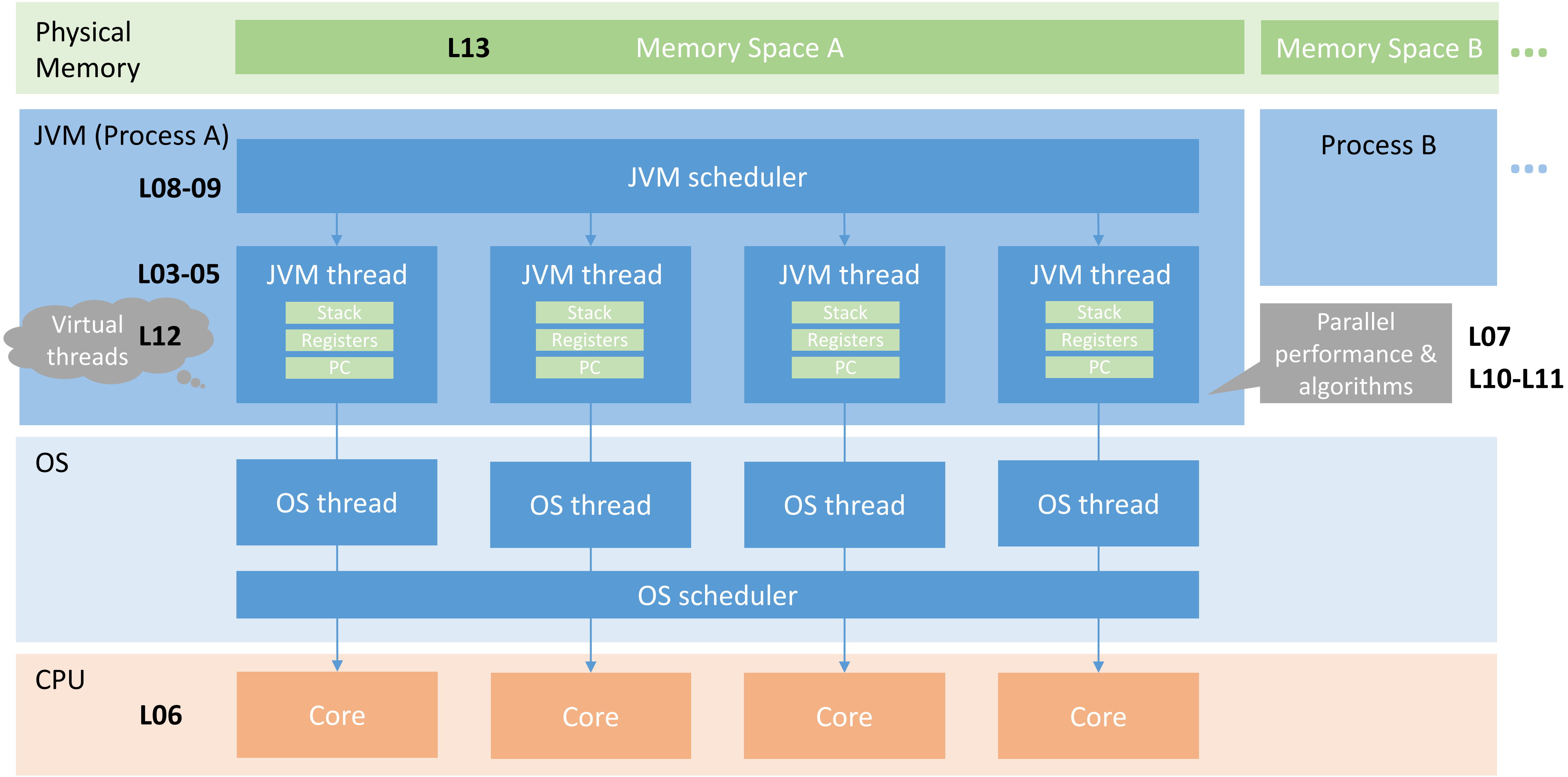
Lecture

Apr 15	Data Races - Implementing locks with Atomic Registers
Apr 16	Data Races - Implementing locks with Atomic Registers II
Apr 22	Beyond Locks I: Spinlocks, Deadlocks, Semaphores
Apr 23	Beyond Locks II: Semaphore, Barrier, Producer-/Consumer, Monitors
Apr 29	Readers/Writers Lock, Lock Granularity: Coarse Grained, Fine Grained, Optimal, and Lazy Synchronization
Apr 30	Lock tricks, skip lists, and without Locks I
May 6	Without Locks II
May 7	ABA Problem, Concurrency Theory
May 13	Sequential Consistency, Consensus, Transactional Memory
May 14	Consensus Hierarchy + Transactional Memory
May 21	Transactional Memory + Message Passing
May 27	Message Passing
May 28	Consensus Proof and Reductions
	Parallel Sorting

Exercises

Ex 8	Synchronization II
Ex 9	Reasoning about Locks / Java Memory Model Basics
Ex 10	Advanced Synchronization Mechanisms
Ex 11	Advance Synchronization Mechanisms
Ex 12	Linearizability
Ex 13	Software Transactional Memory
Ex 14	MPI + Reductions

Big Picture (Part I)



Terminology

- https://cgl.ethz.ch/teaching/parallelprog24/pages/terminology.html

Parallel Programming (1st half): Terminology

atomic
A statement or instruction is (truly) atomic if it is executed by the CPU in a single, non-interruptible step.

abstractly atomic
A statement or instruction that, at a certain level of abstraction, appears to be executed atomically. E.g. from a caller's perspective, a method `synchronized append(x)` of a queue appears to append element `x` in one step, but from the queue's perspective, this might take several steps.

Amdahl's law
Specifies the maximum amount of speedup that can be achieved for a program with a given sequential part. The pessimistic view on scalability.

bad interleaving
An interleaving that yields a problematic or otherwise undesirable computation. E.g. an incorrect result, a deadlock or non-deterministic output.

busy waiting
Occurs when a thead busily (actively) waits, e.g. by spinning in a loop, for a condition to become true. In the opposite scenario, the thread sleeps (i.e. is blocked; in Java: `join()`, `wait()`) until the condition becomes true. Trade-off: busy waiting uses up CPU time, whereas blocking may cause additional context switches.

cache coherence protocols
Hardware protocols that ensure consistency across caches, typically by tracking which locations are cached, and synchronising them if necessary.

cilk-style programming
Parallel programming idiom: To compute a program, execute code and spawn new tasks if required. Before returning, wait for all spawned tasks to complete. The system manages the eventual execution of the spawned tasks potentially in parallel. spawning and waiting on tasks creates a task graph which is a DAG.

Course Overview

aka why should you care?

How Does This Course Fit Into the CS Curriculum?

- Programming-in-the-small => Data Structures and Algorithms

Program = Algorithms + Data Structures

- Programming-in-the-large

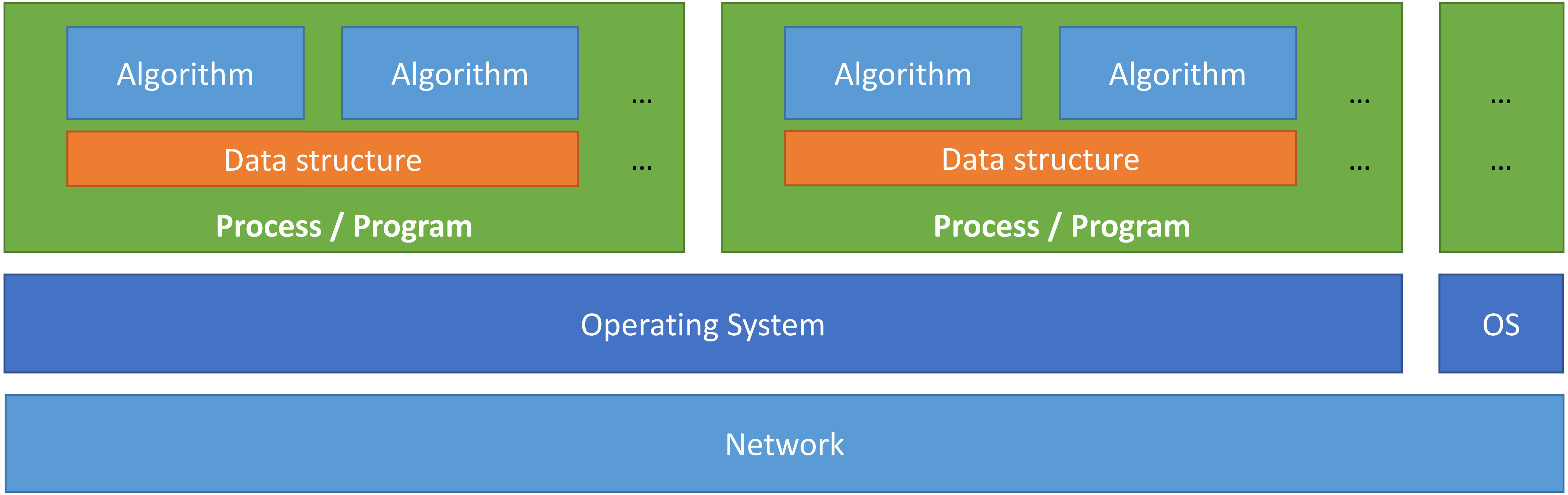
System = Processes + Objects + Communication

This class (Processes)

This class (Communication)

Intro to Programming (Objects)

How Does This Course Fit Into the CS Curriculum?



Learning Objectives

By the end of the course you should

1. have mastered fundamental concepts in parallelism
2. know how to construct parallel algorithms using different parallel programming paradigms (e.g., task parallelism, data parallelism) and mechanisms (e.g., threads, tasks, locks, communication channels).
3. be qualified to reason about correctness and performance of parallel algorithms
4. be ready to implement parallel programs for real-world application tasks (e.g. searching large data sets)

Requirements

Basic understanding of Computer Science concepts

Basic knowledge of programming concepts:

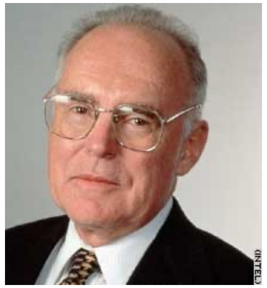
We will do a *quick* review of Java and briefly discuss JVMs

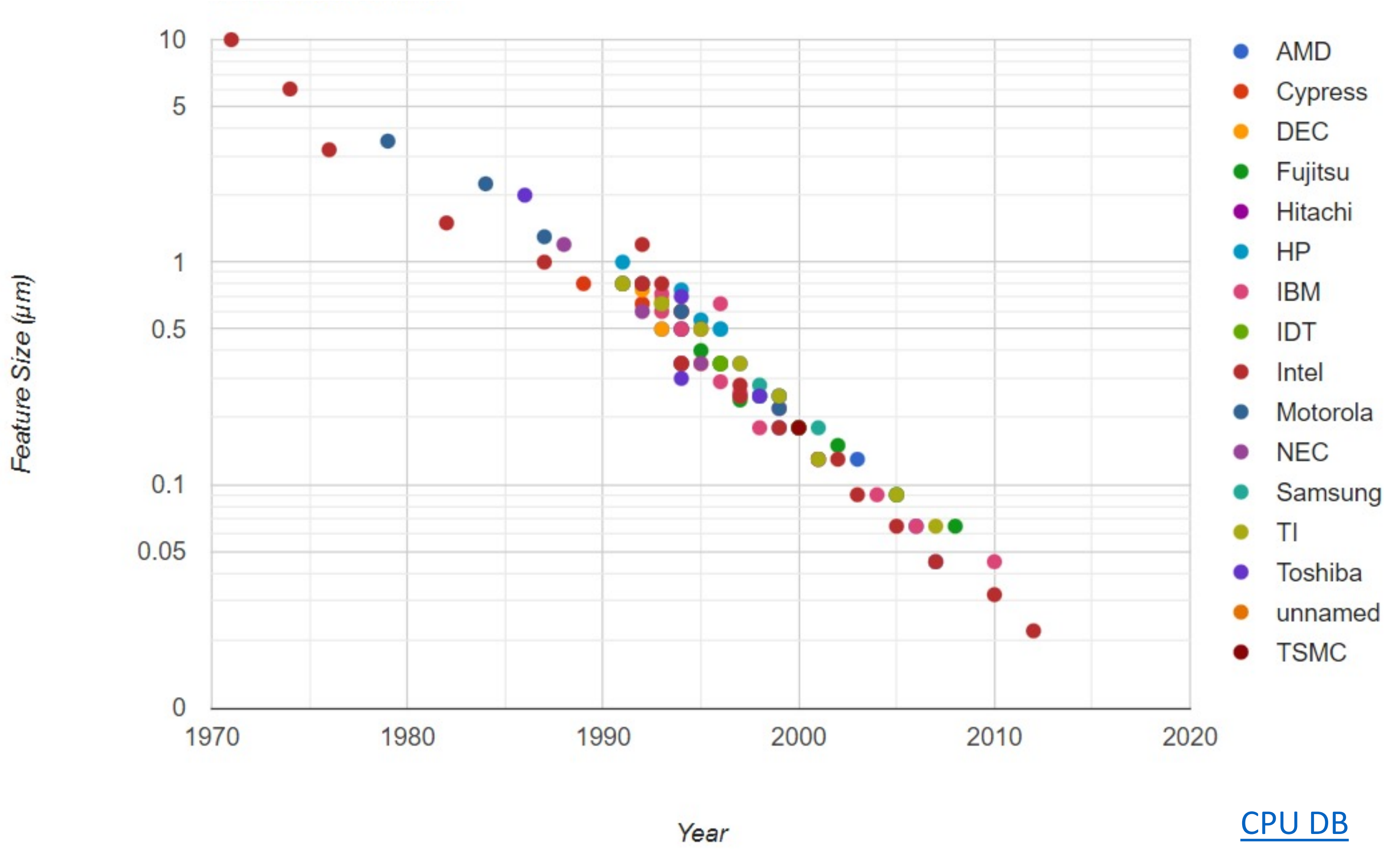
Basic understanding of computer architectures:

No detailed knowledge necessary (we will cover some)

Image source: http://jolyon.co.uk

Motivation – Why Parallelism?



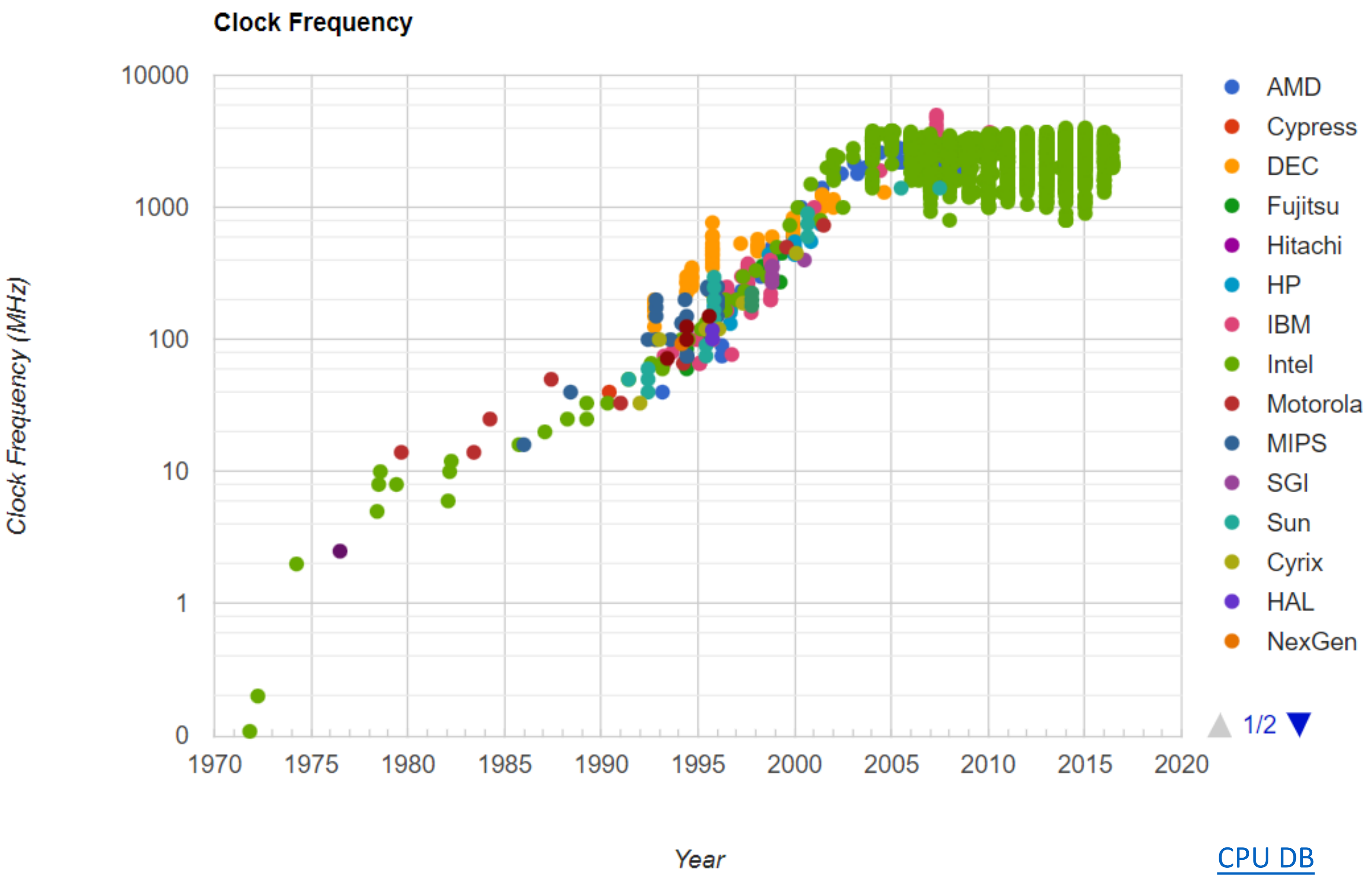


[CPU DB]

Moore’s Law Recap: Transistor counts double every two years

- Means: Smaller transistors => can put more on chip => computational power grows exponentially => your sequential program automatically gets faster.
- Also applies to RAM size and pixel densities

Motivation – Why Parallelism?



[CPU DB]

Why Don’t We Keep Increasing Clock Speeds?

Transistors have *not* stopped getting smaller + faster (Moore lives)

Heat and power have become the primary concern in modern computer architecture!

Consequence:

- Smaller, more efficient Processors in terms of power (Ops / Watt)
- More processors – often in one package

What Kind of Processors Do We Build Then?

Main design constraint today is power

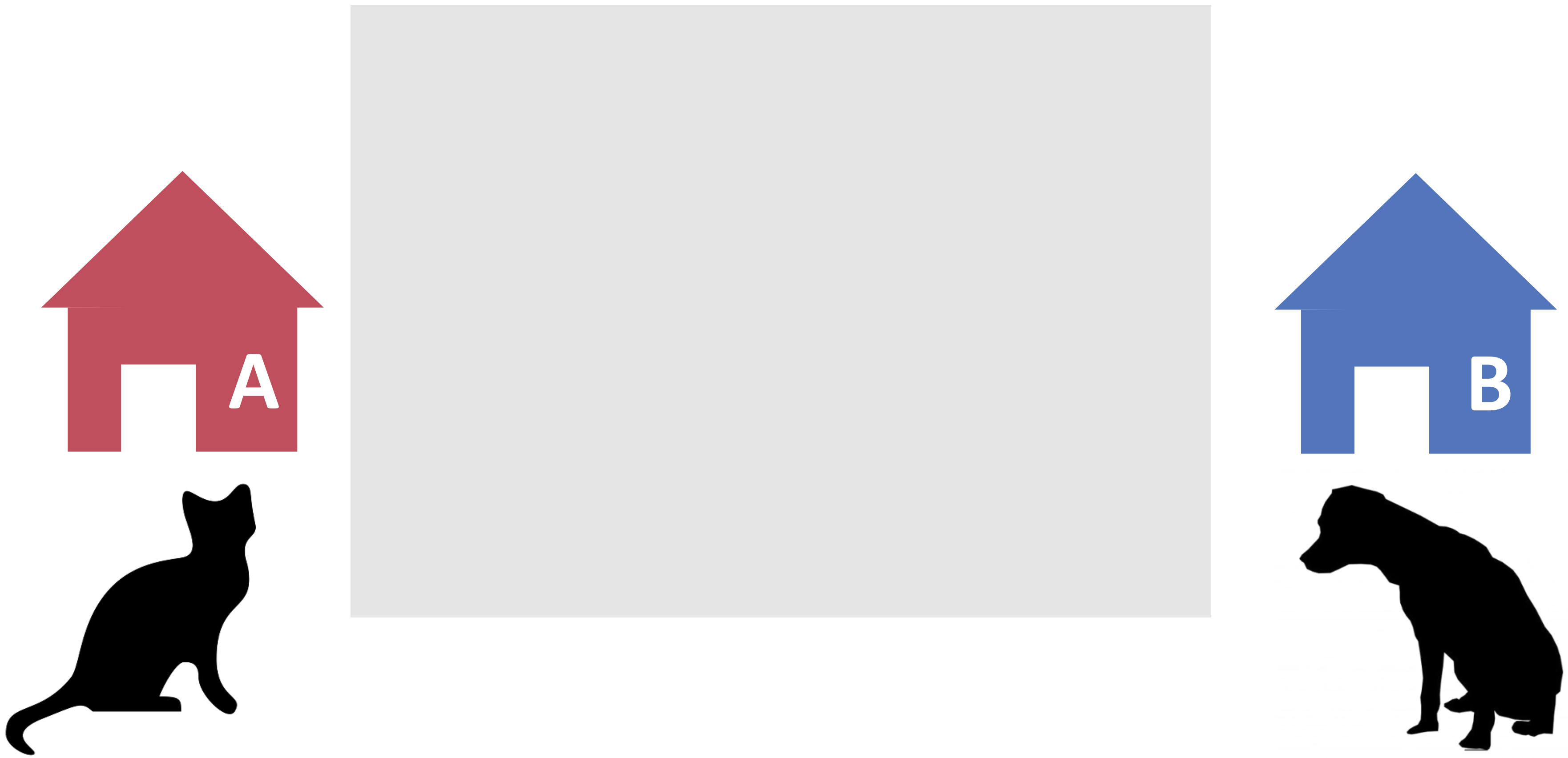
- Single-Core CPUs:
  - Complex control hardware
  - Pro: Flexibility + performance
  - Con: Expensive in terms of power (Ops / Watt)

- Many-Core/GPUs etc:
  - Simpler control hardware
  - Pro: Potentially more power efficient (Ops / Watt)
  - Con: More restrictive / complex programming models [but useful in many domains, e.g. deep learning].

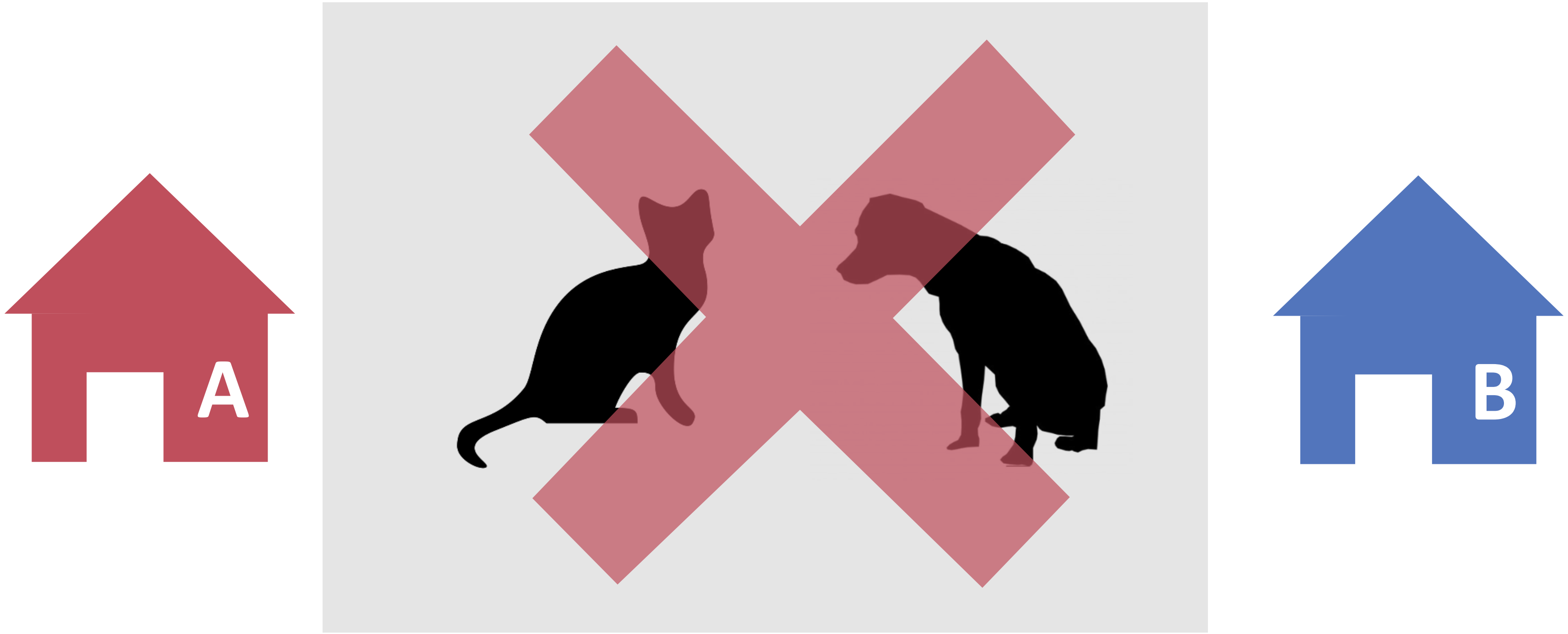
Three stories

1. MUTUAL EXCLUSION

Alice's Cat vs. Bob's Dog

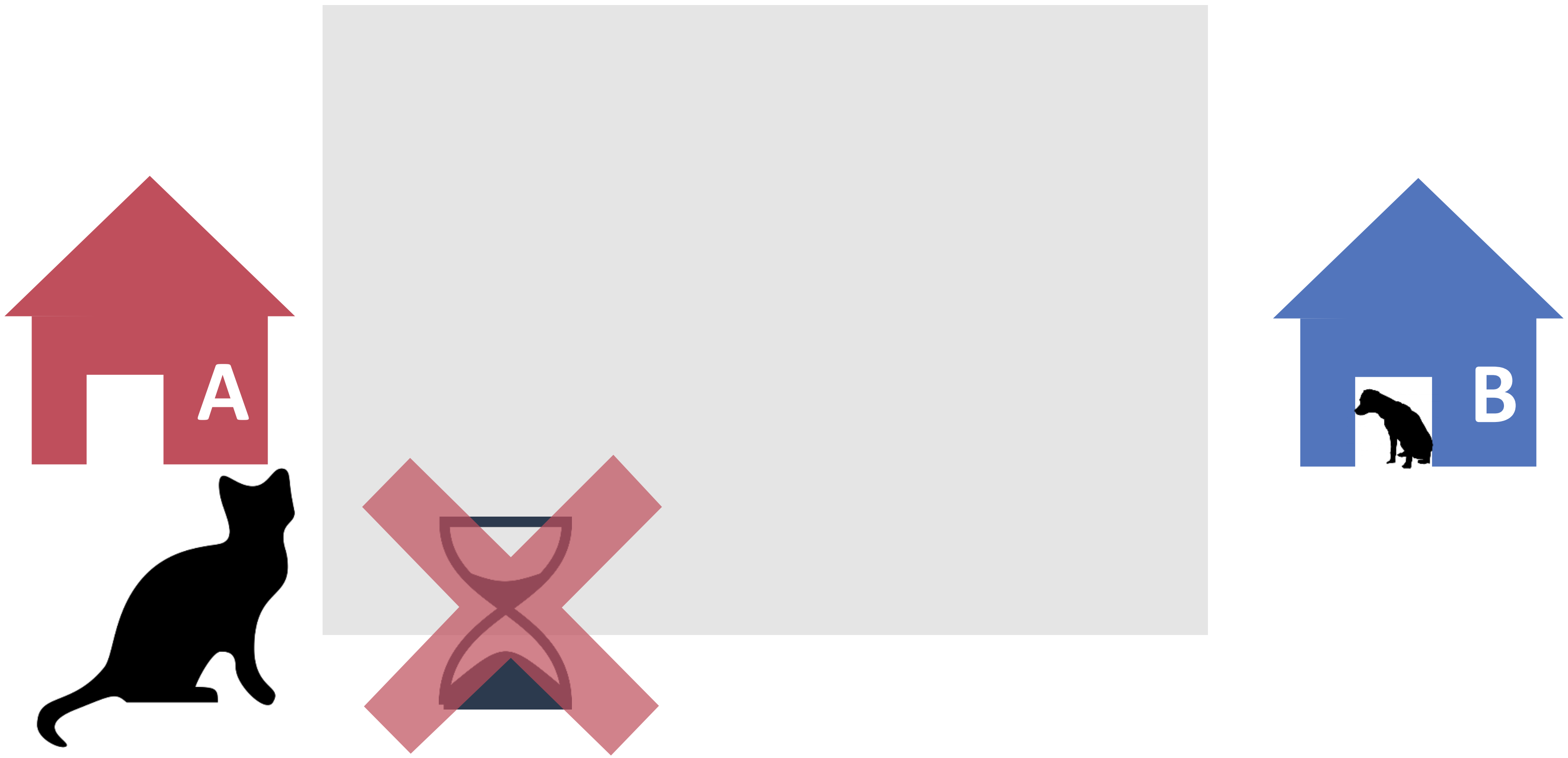


Requirement I: Mutual Exclusion !

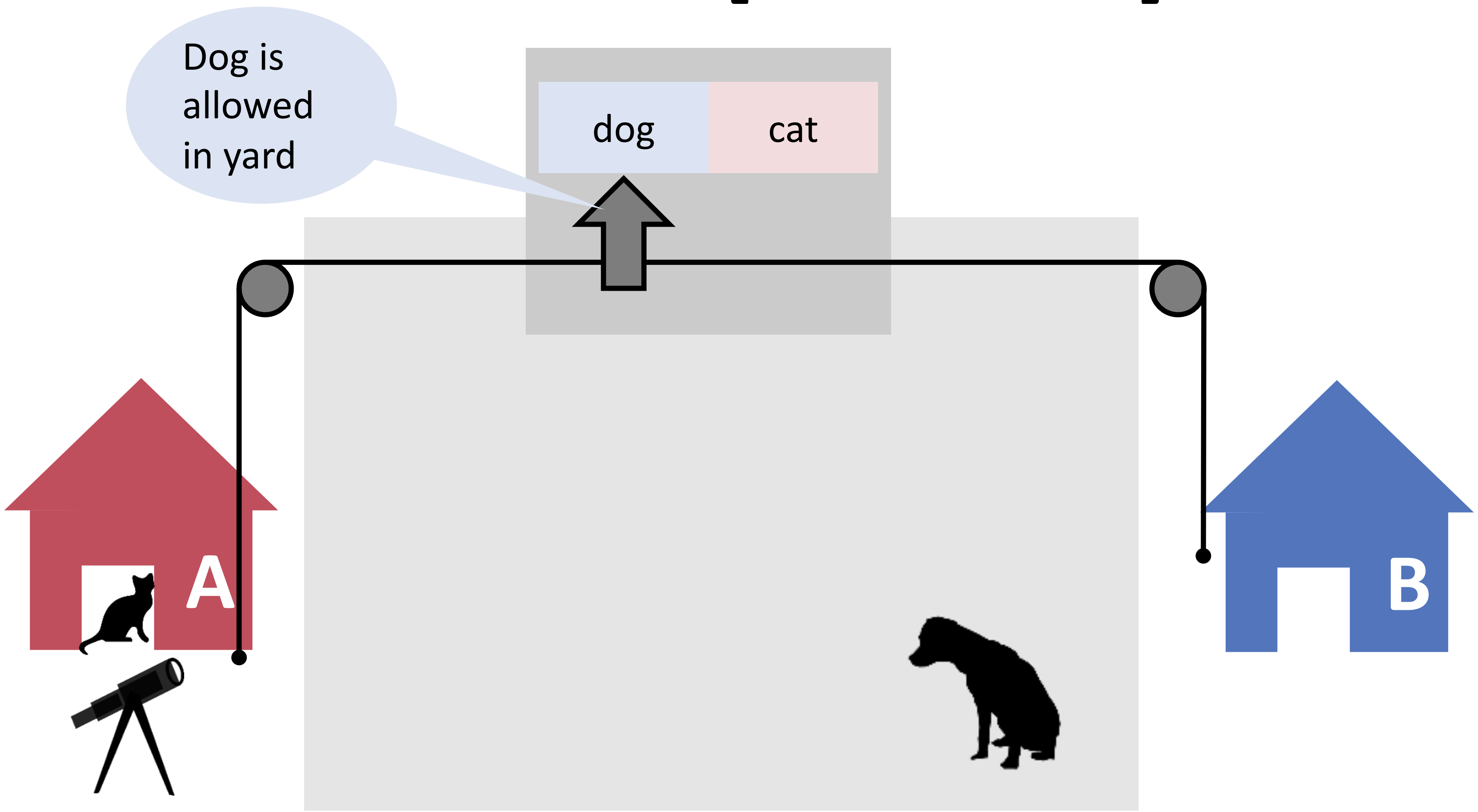



A
B

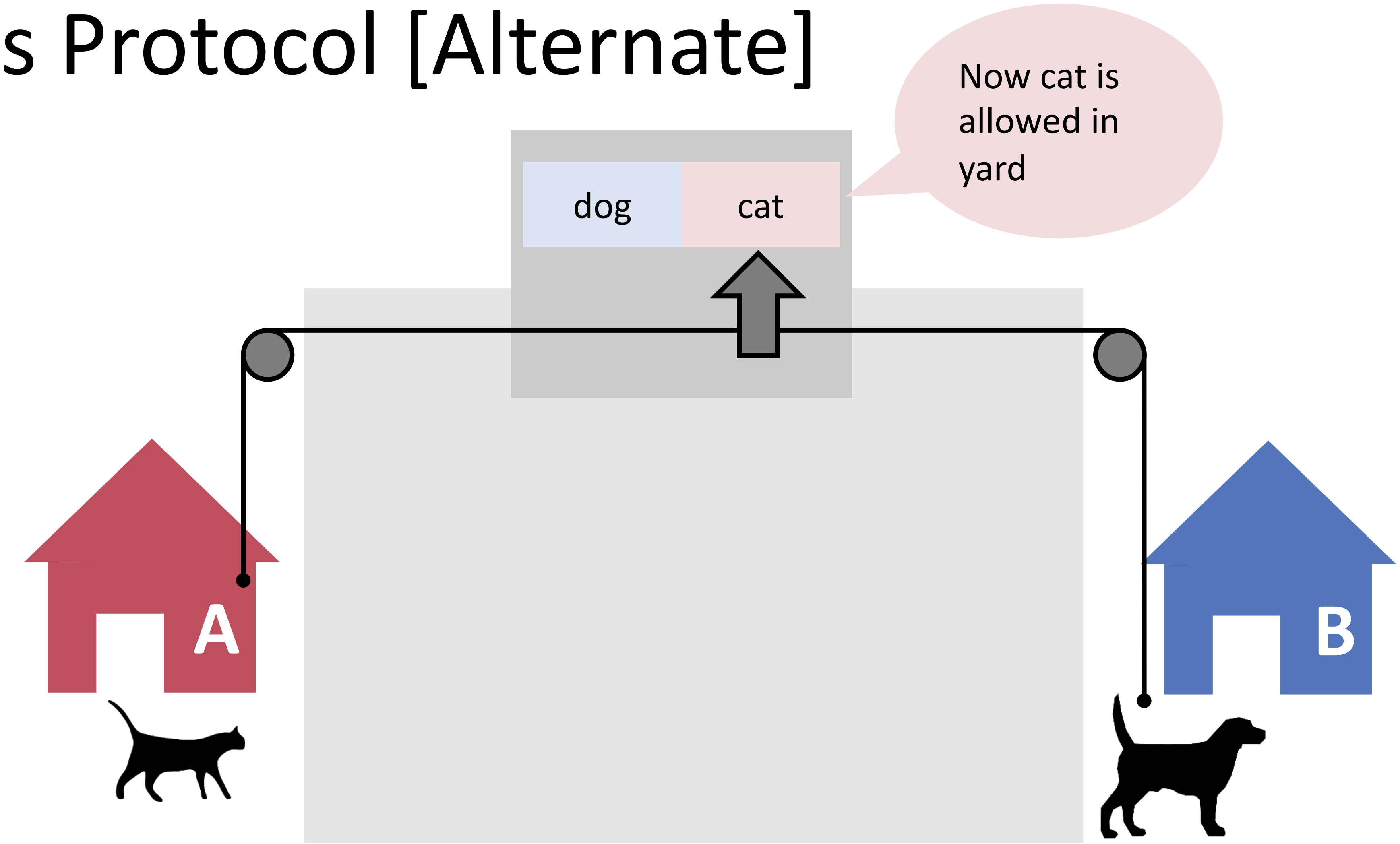
Requirement II: No Lockout when free



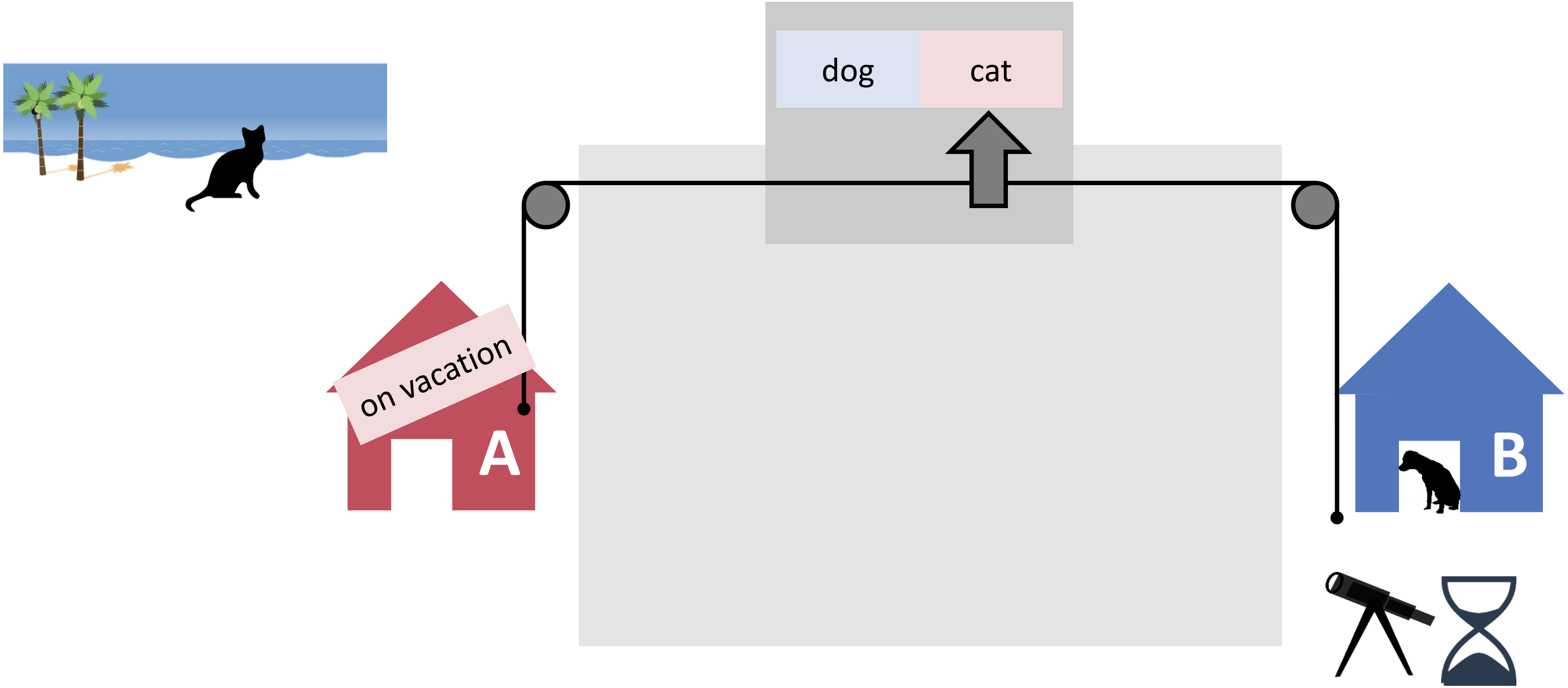
Communication: Idea 1 [Alternate]



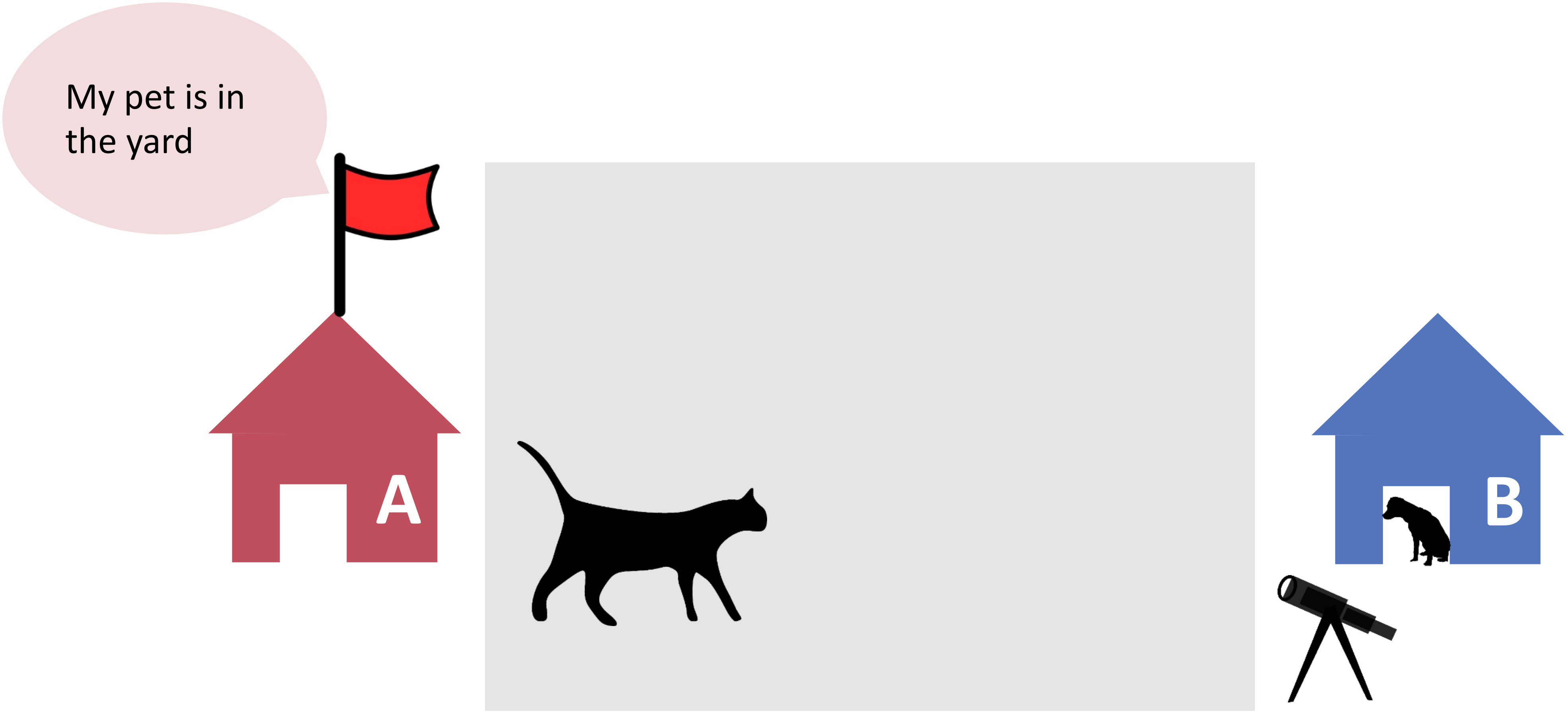
Access Protocol [Alternate]



Problem: Starvation!

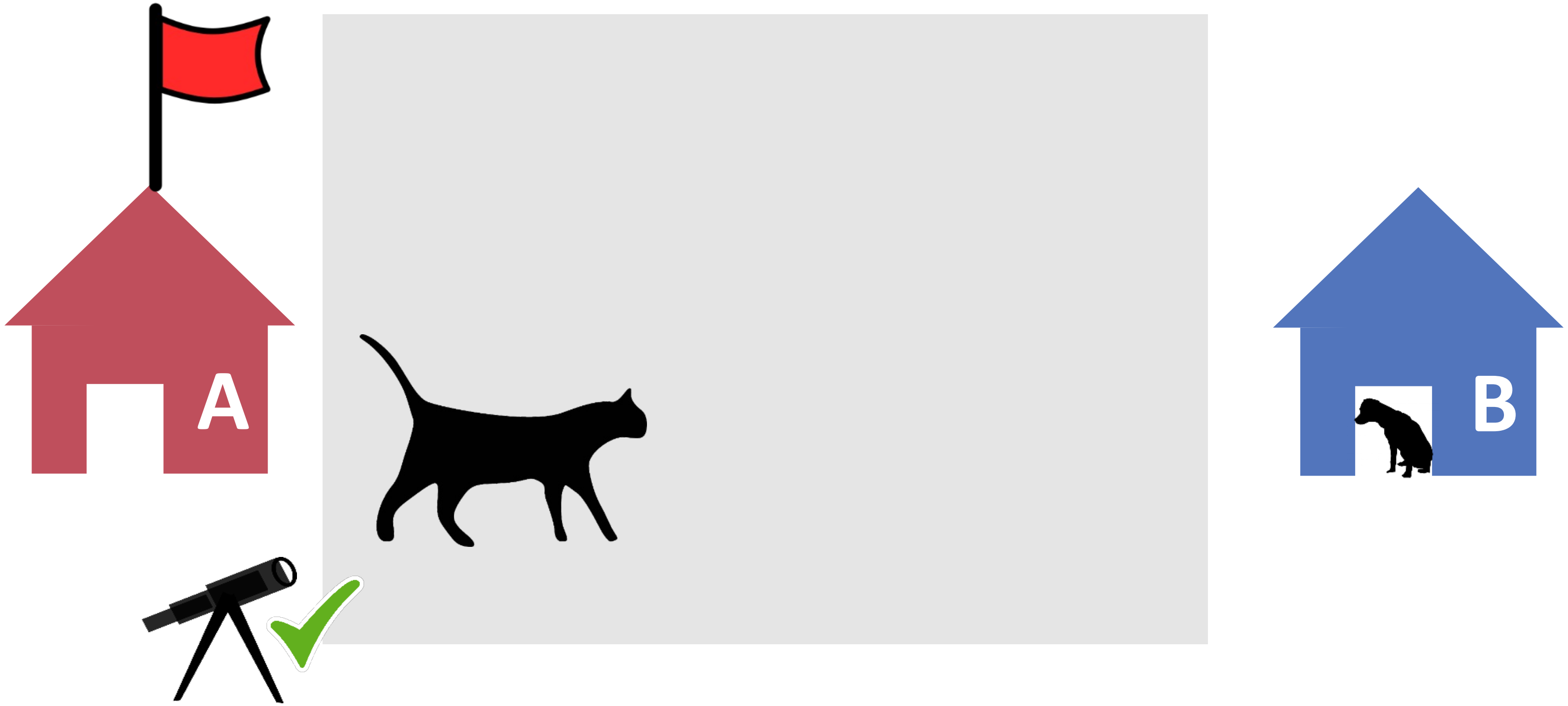


Communication: Idea 2 [Notification]

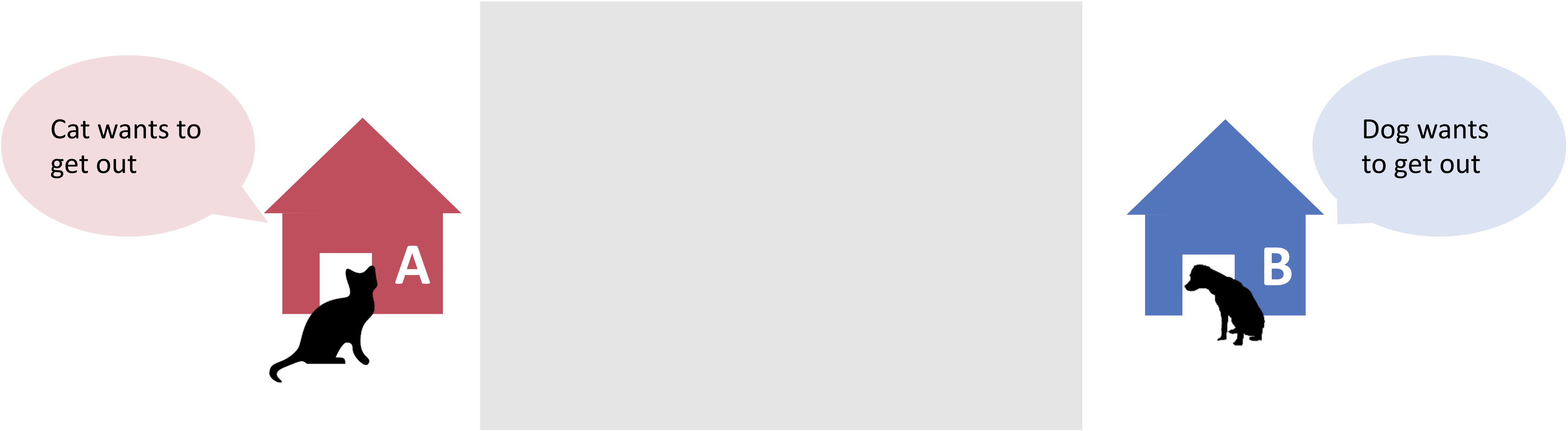


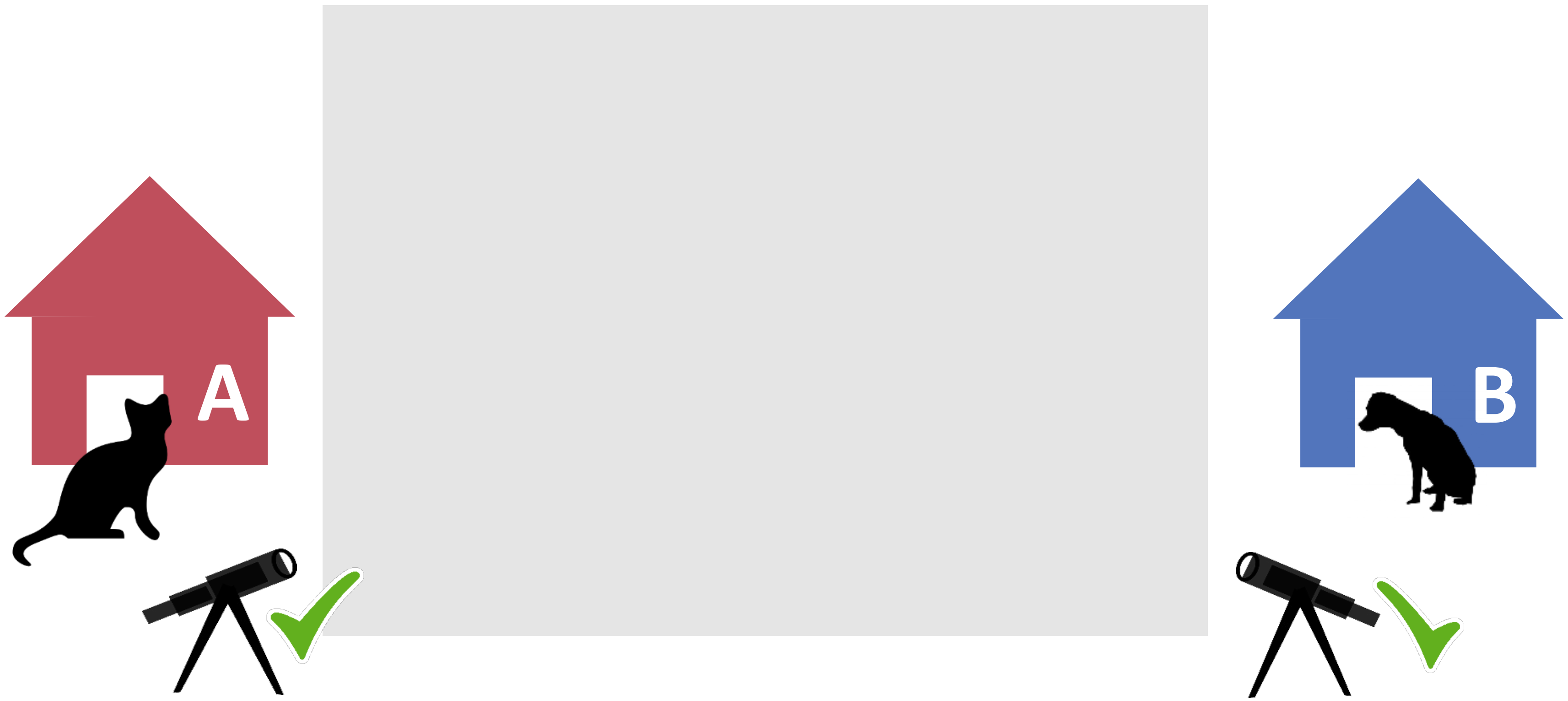
Access Protocol 2.1: Idea

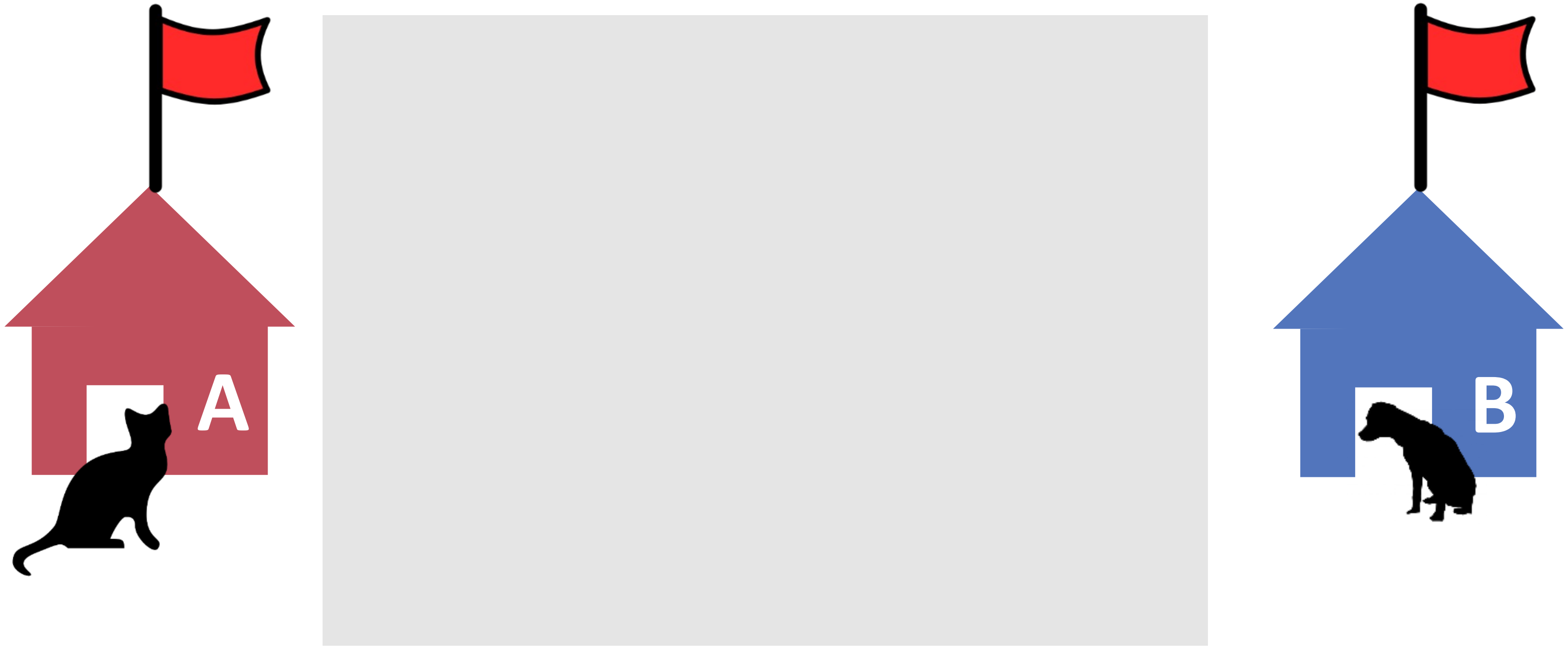

A
B


A
B

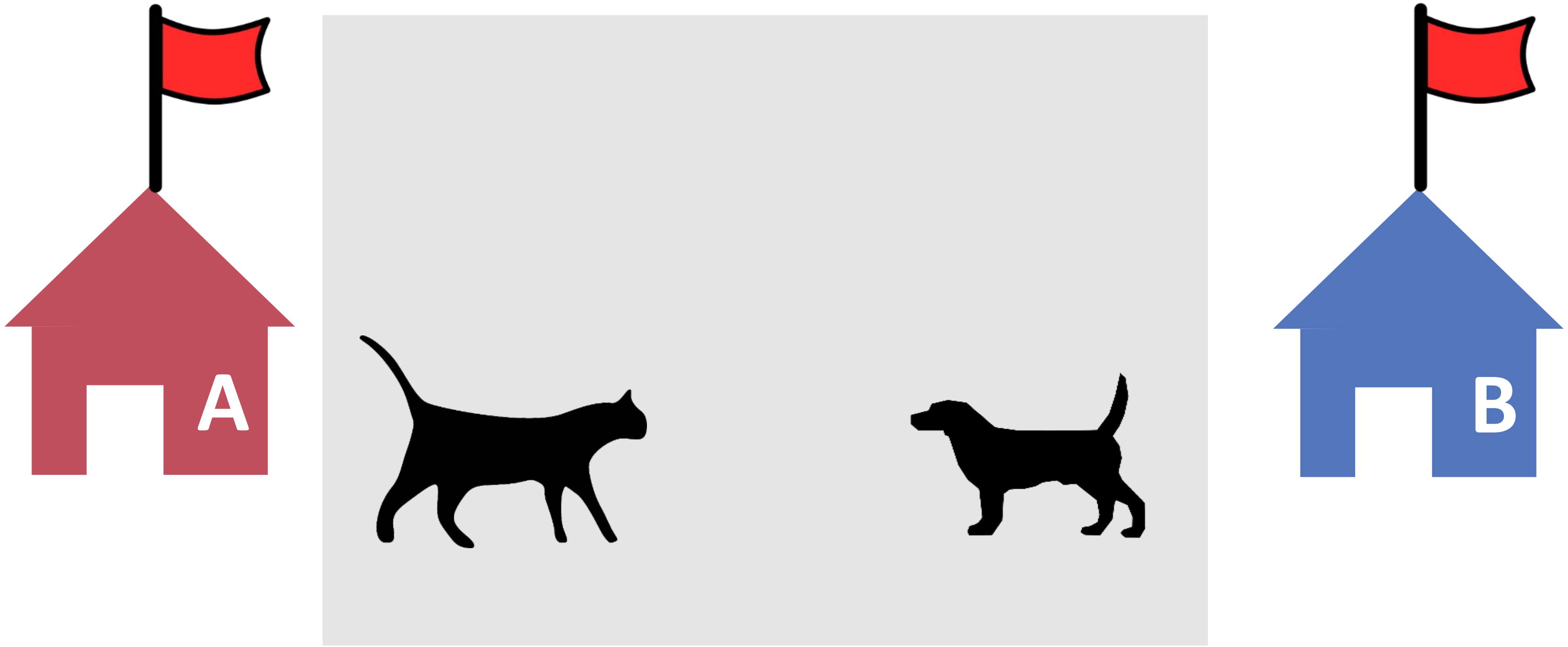
Another Scenario



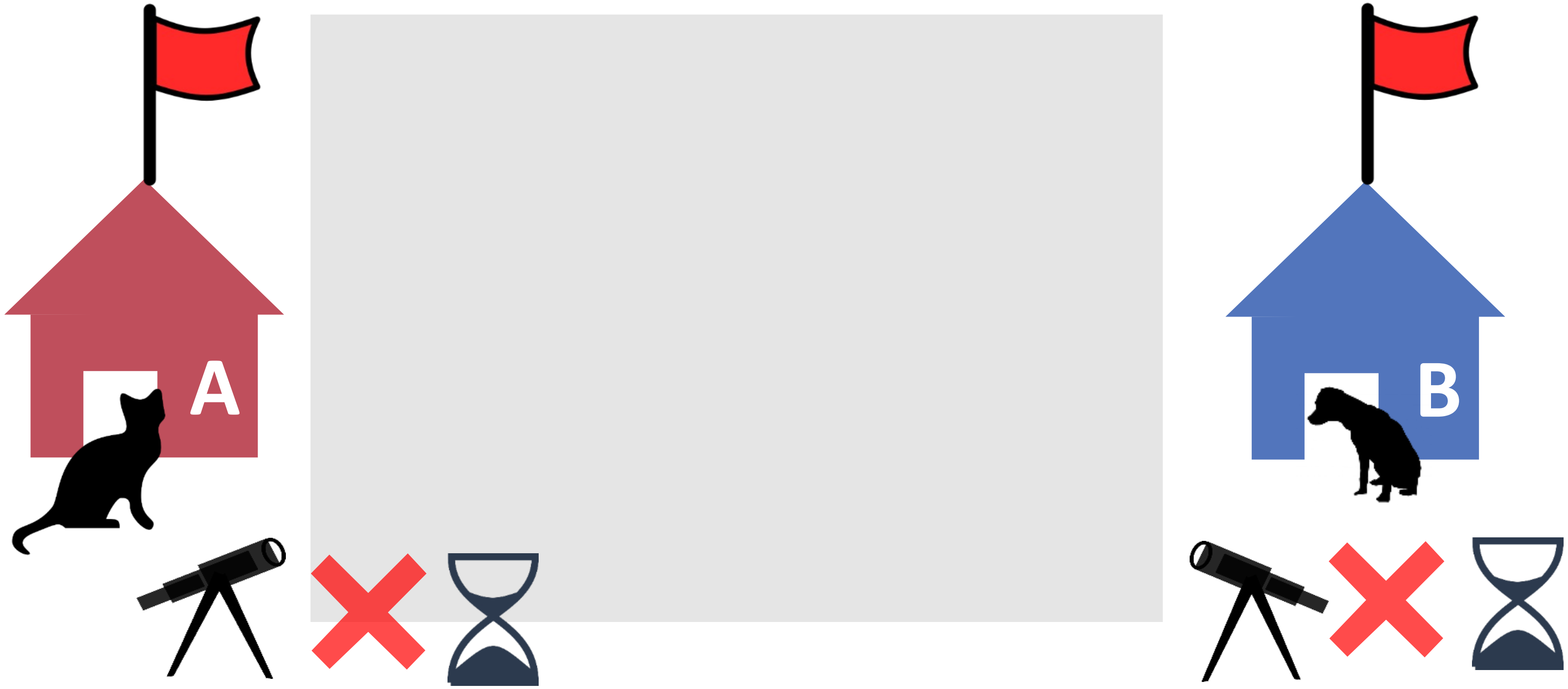

A
B


A
B

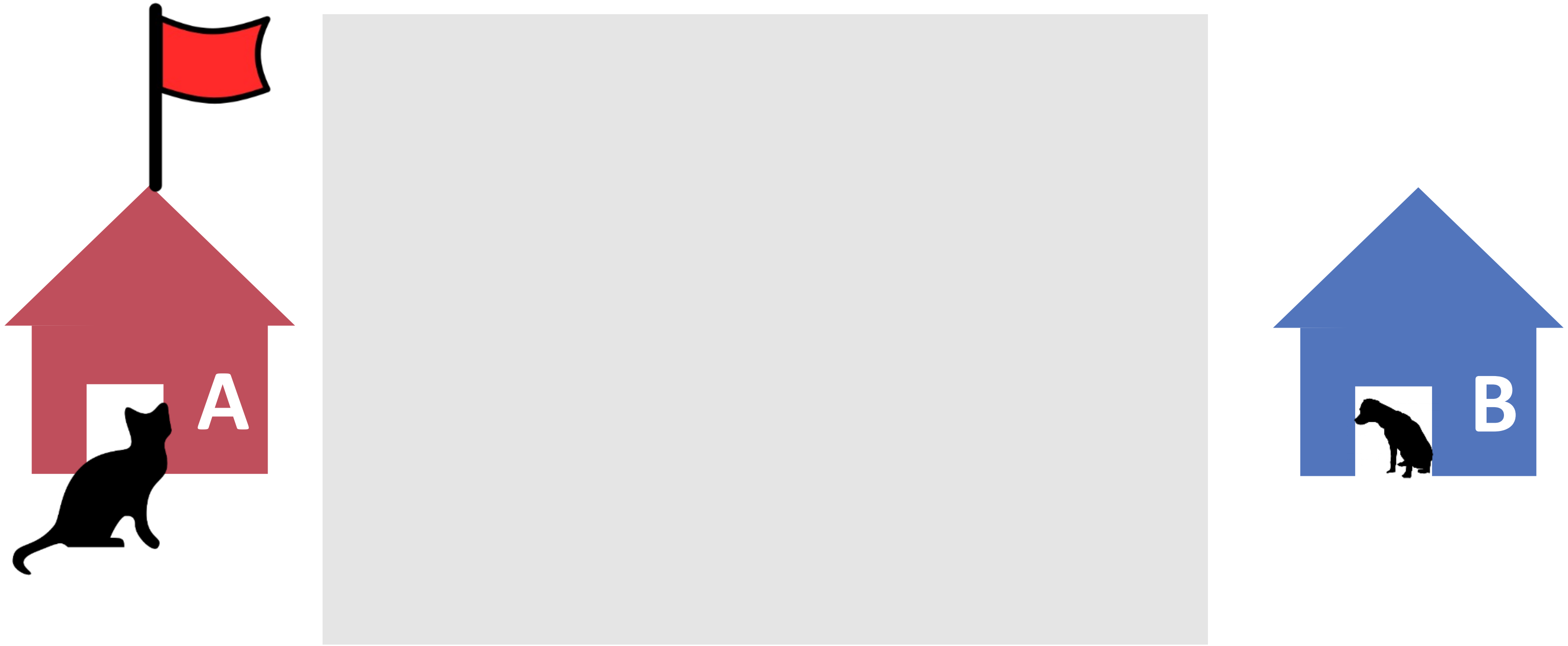
Problem: No Mutual Exclusion!

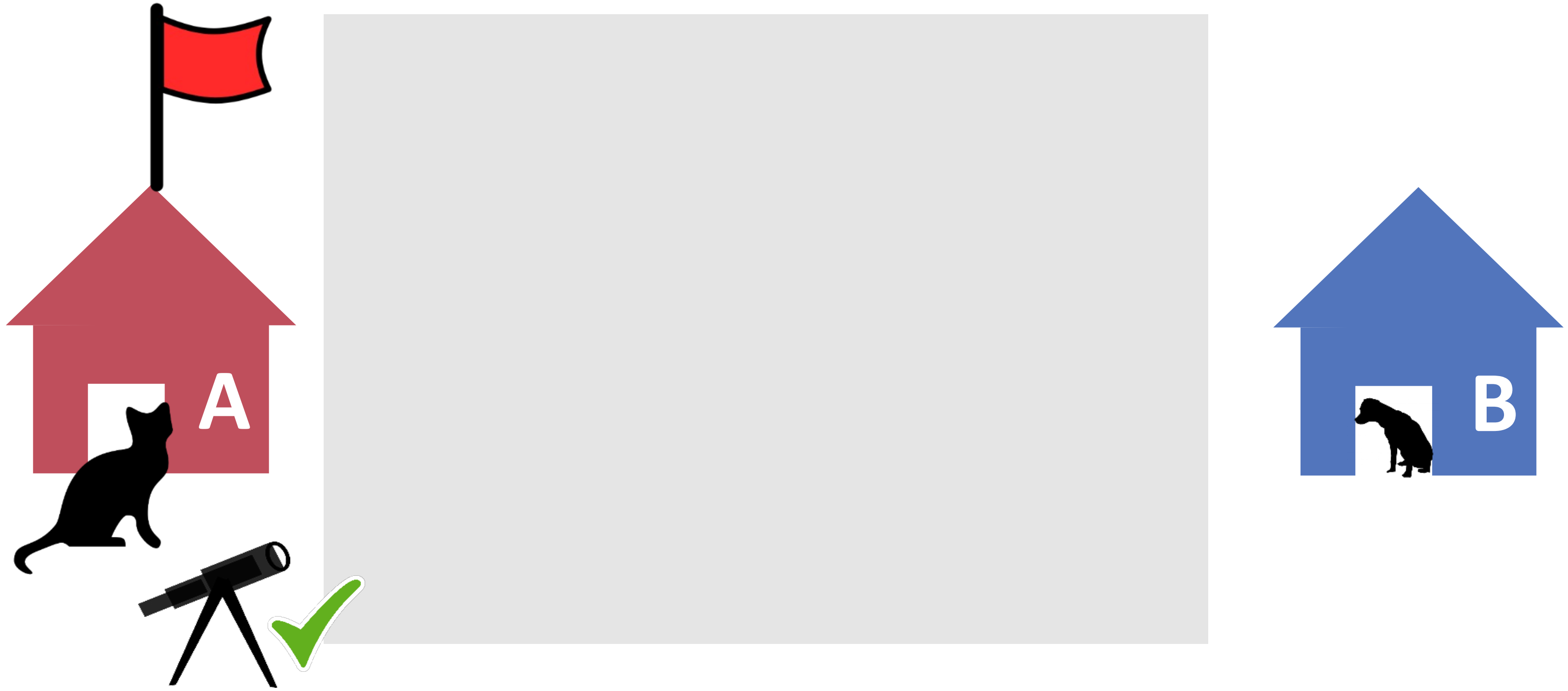


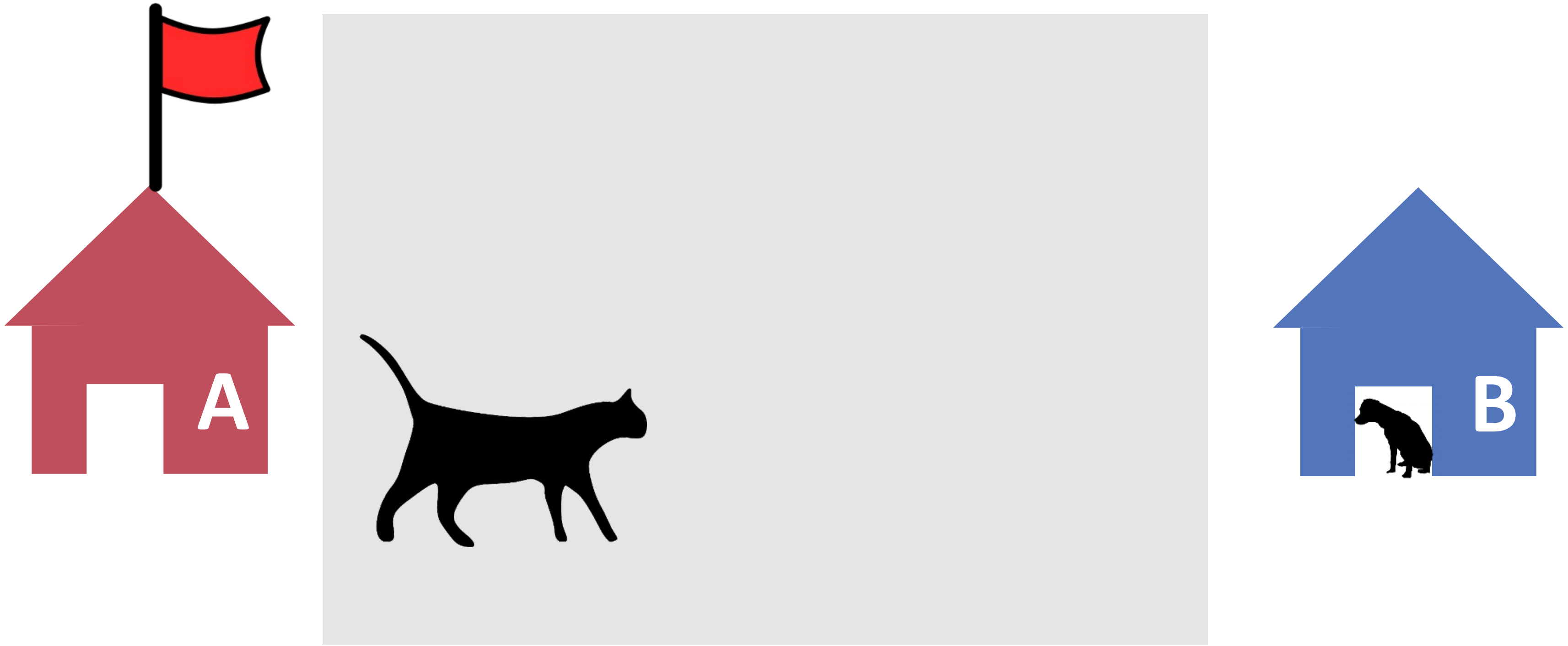
Checking Flags Twice Does Not Help: Deadlock!



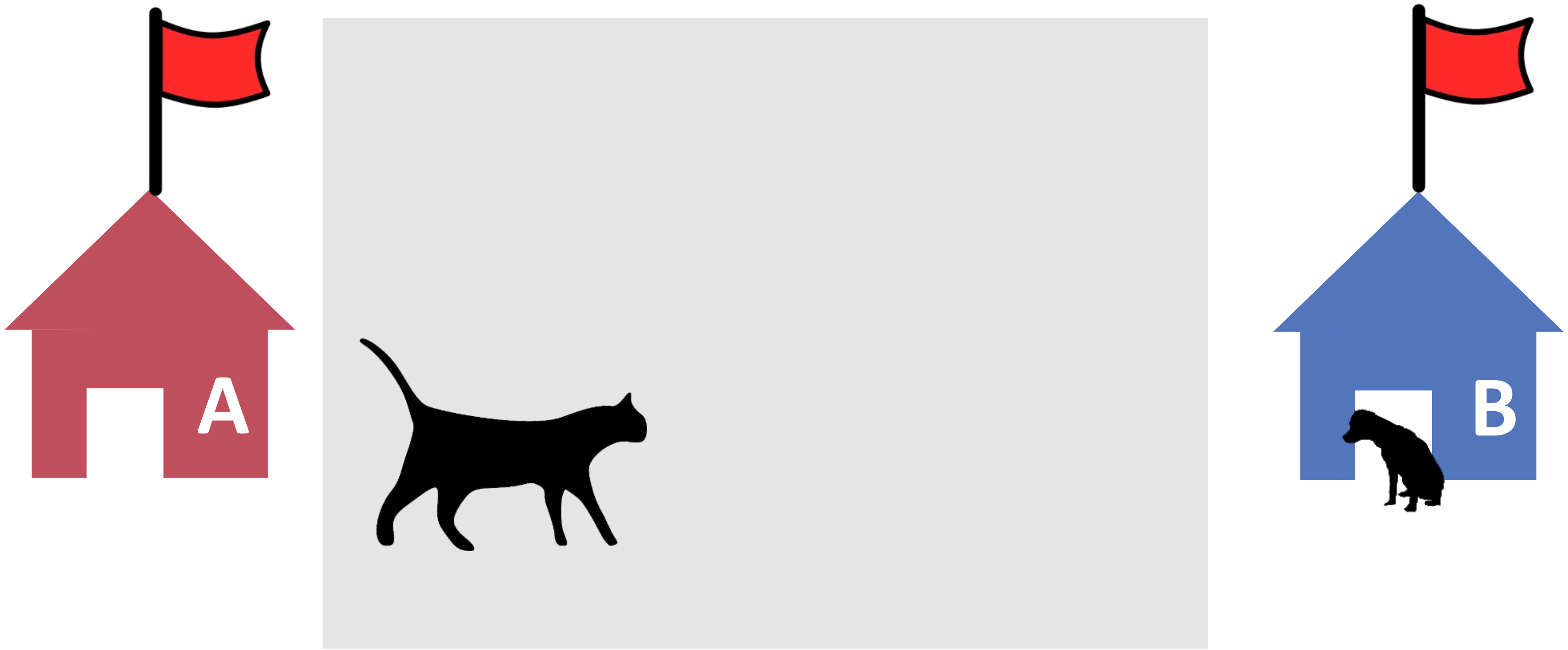
Access Protocol 2.2

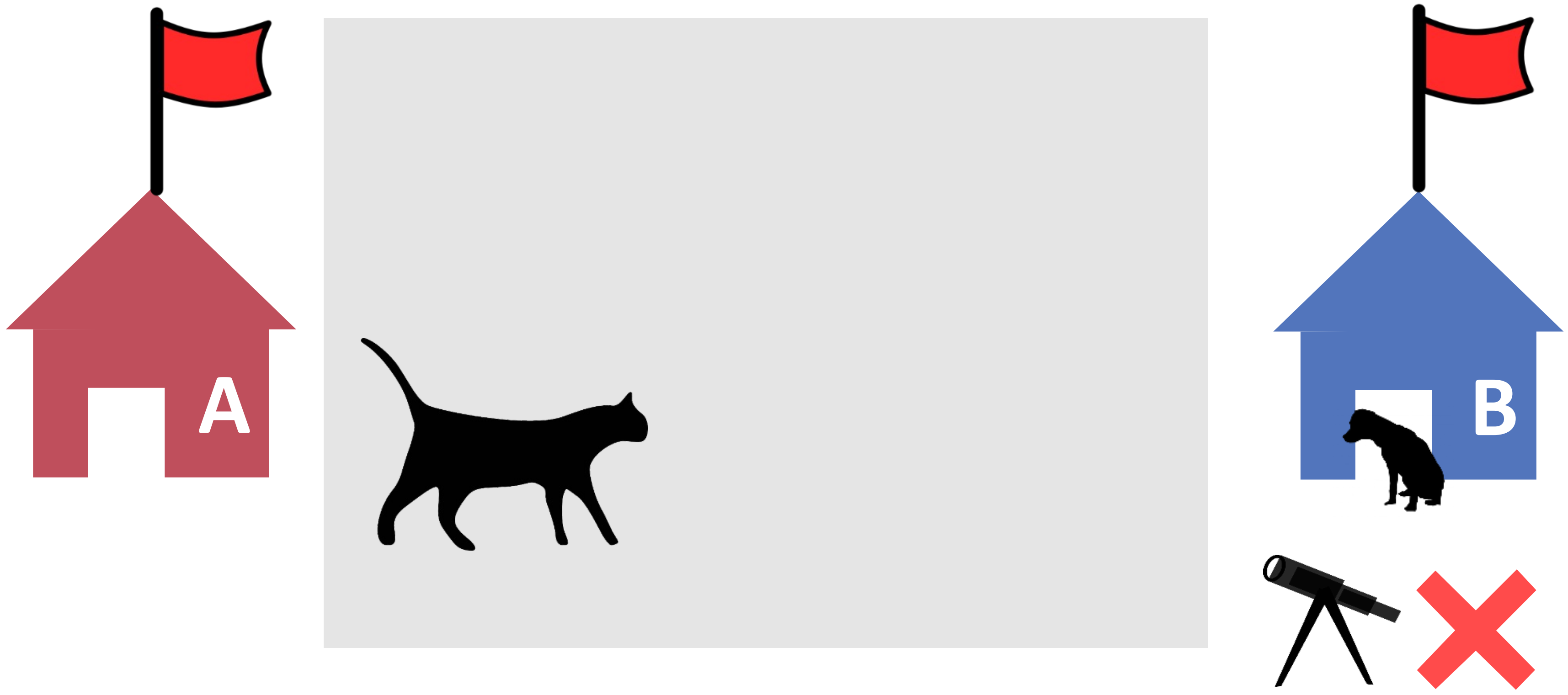

A
B


A
B

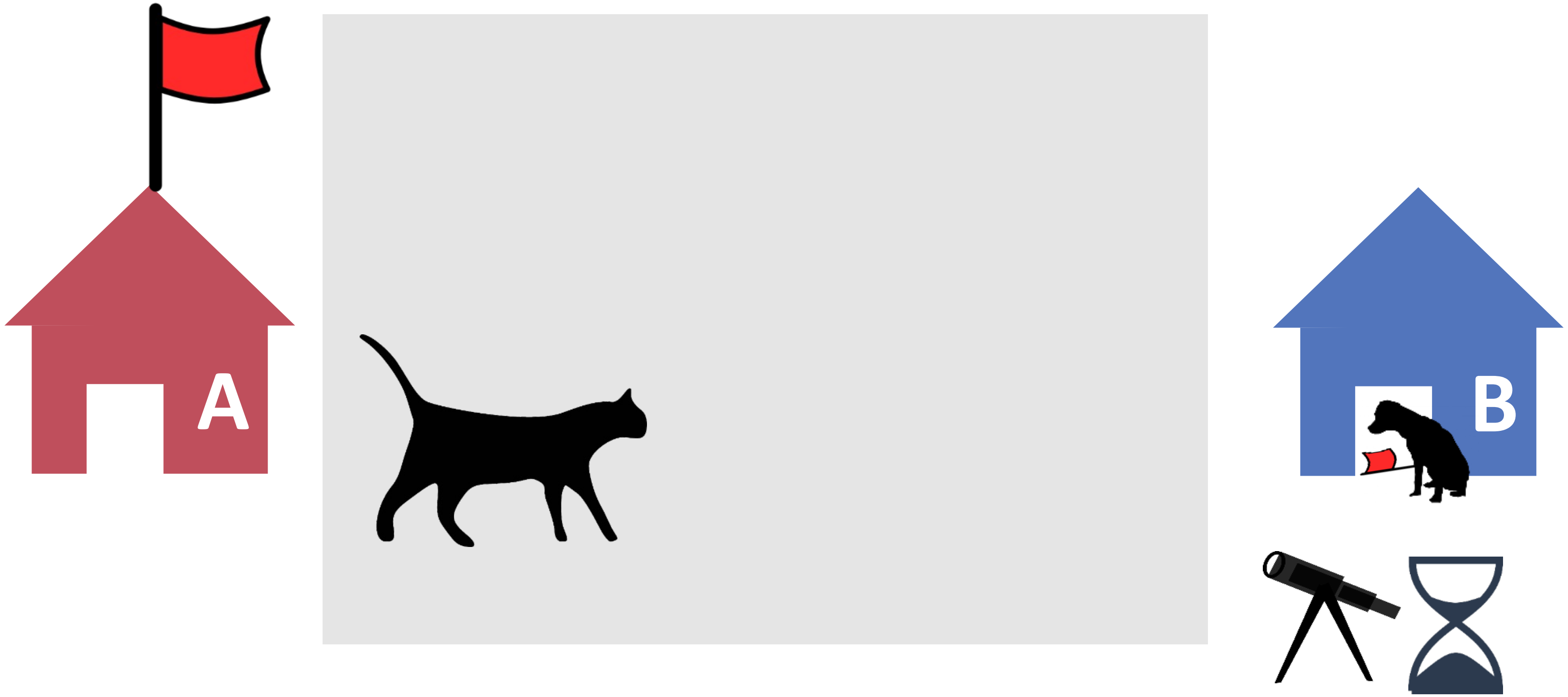

A
B


A
B
Dog wants to get out


A
B

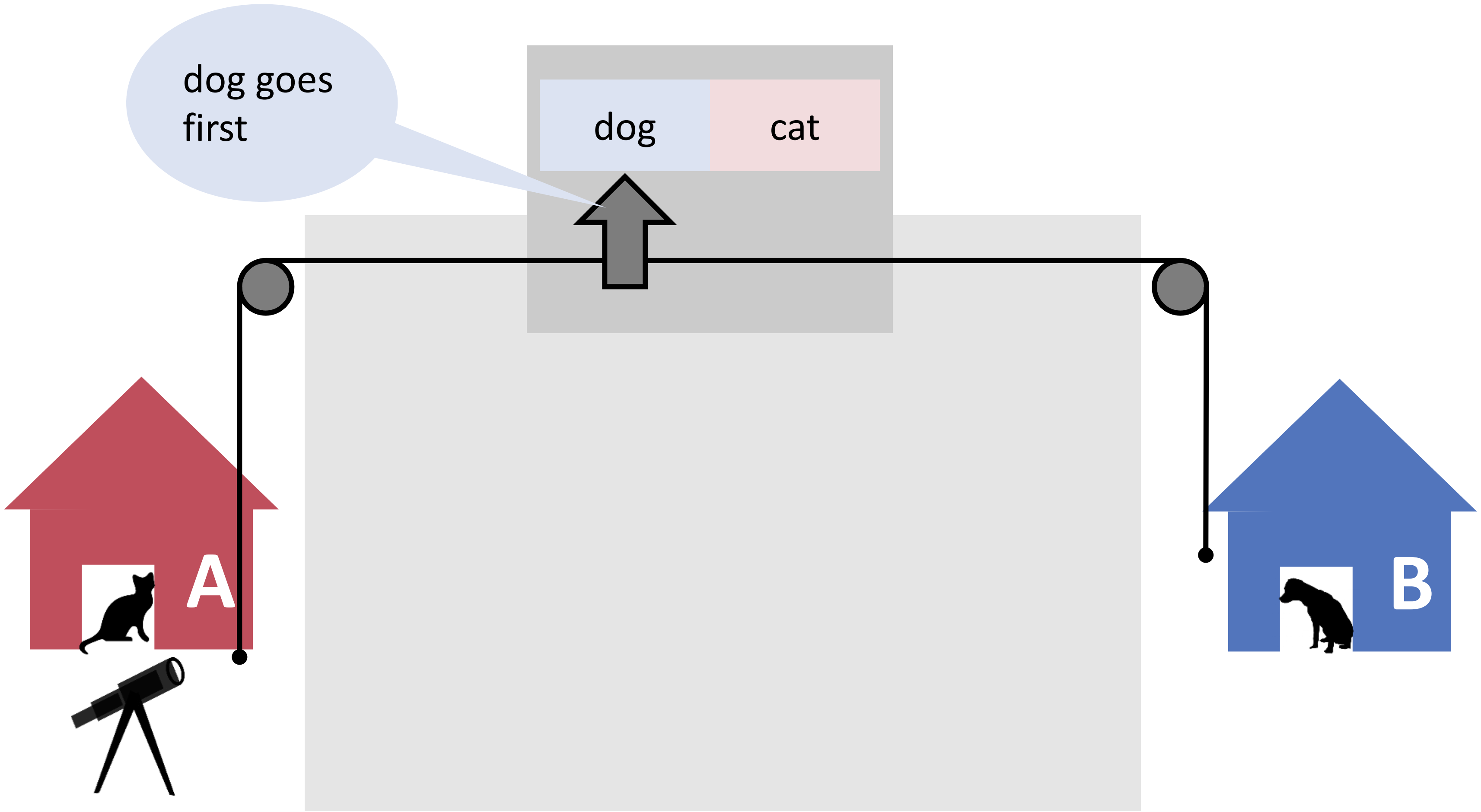

A
B

Access Protocol 2.2 is provably correct

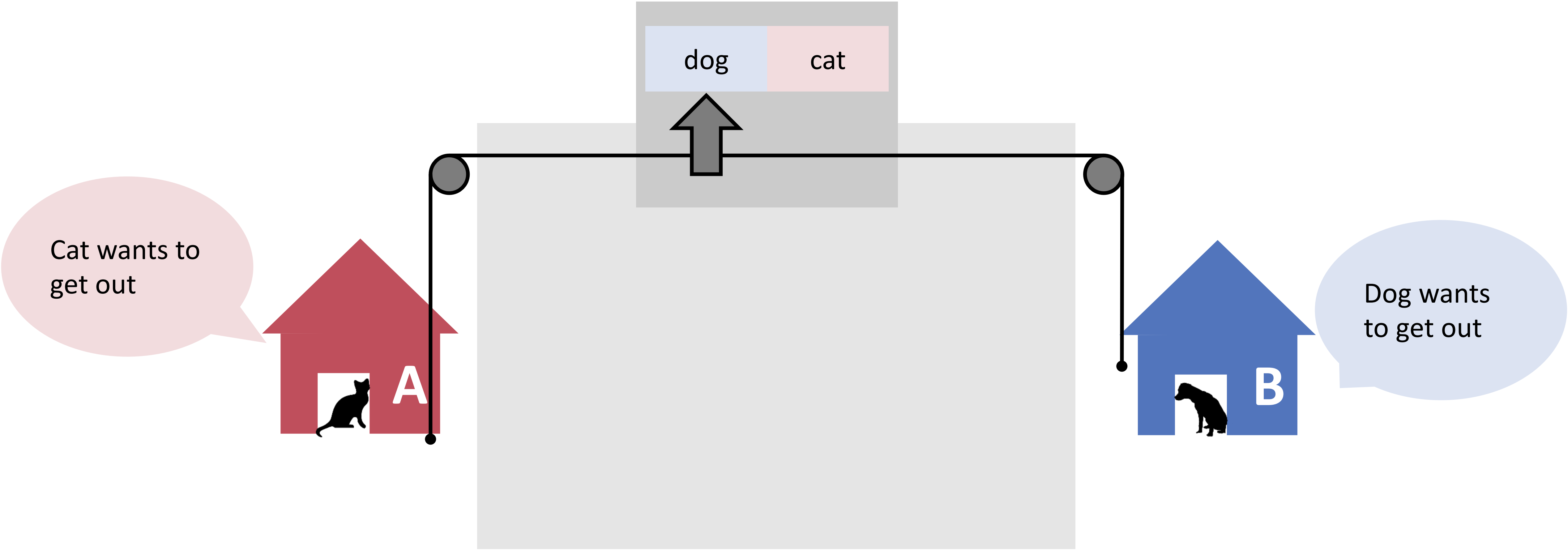


Minor (?) Problems: Livelock, Starvation

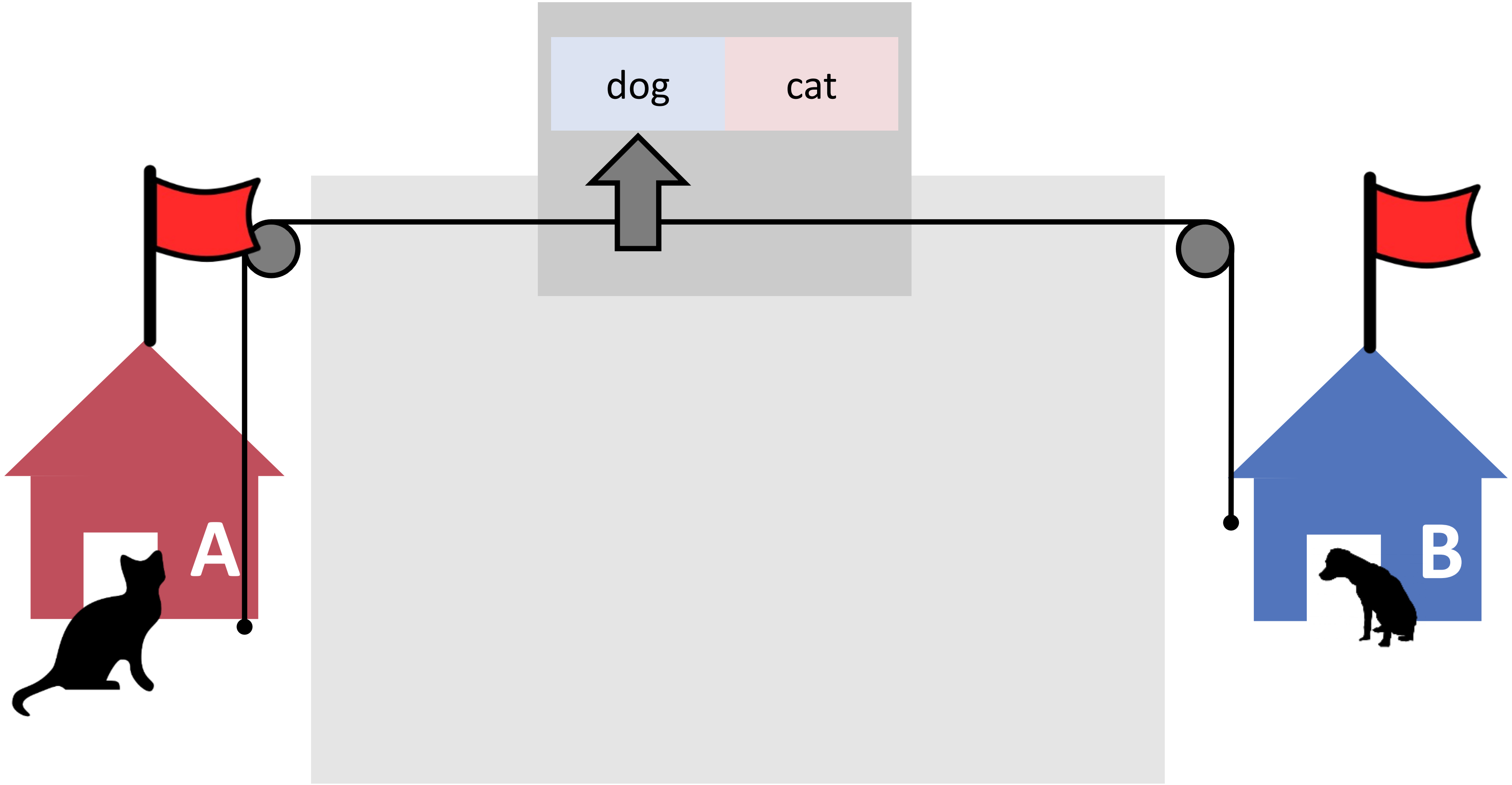
Final Solution



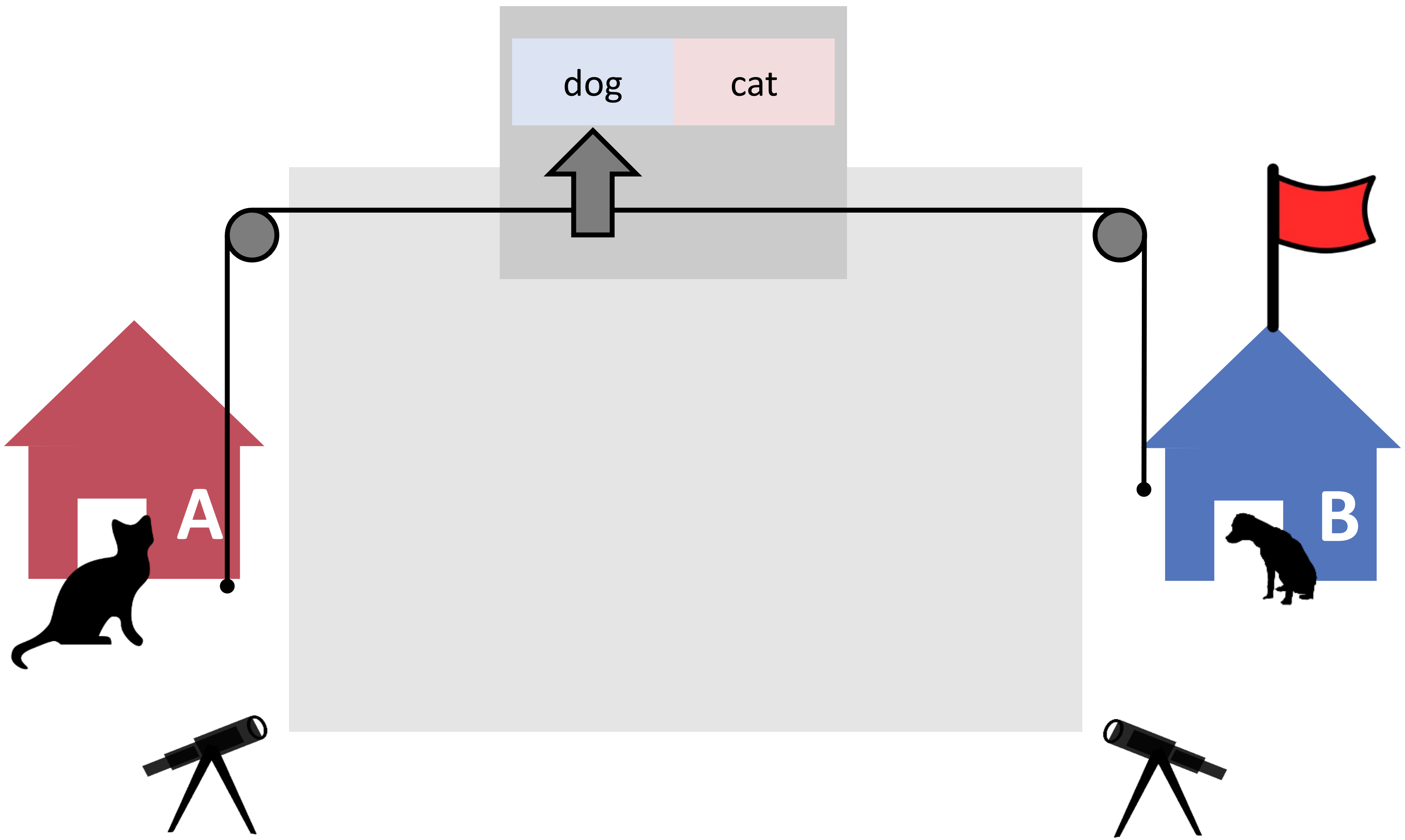
Final Solution



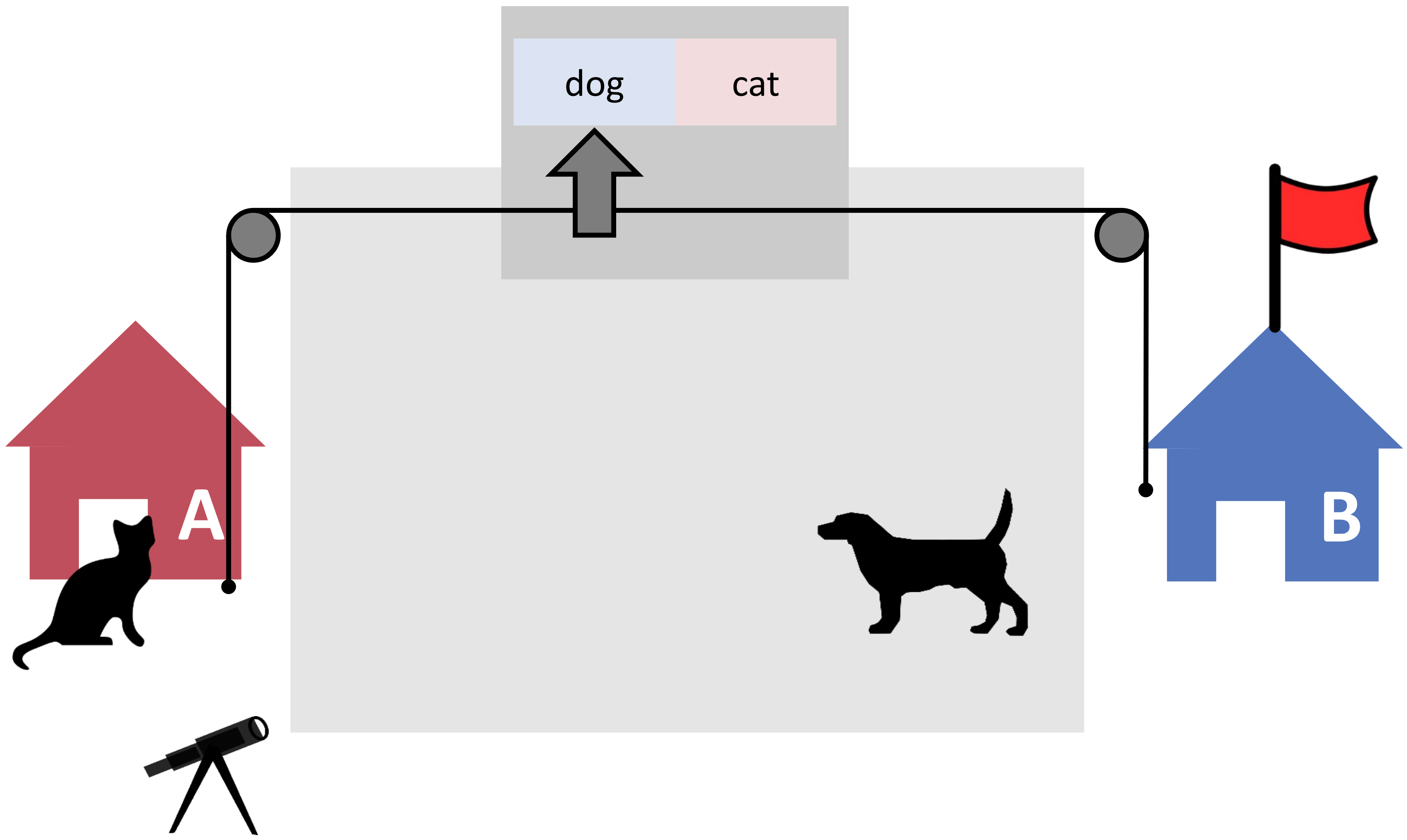
Final Solution



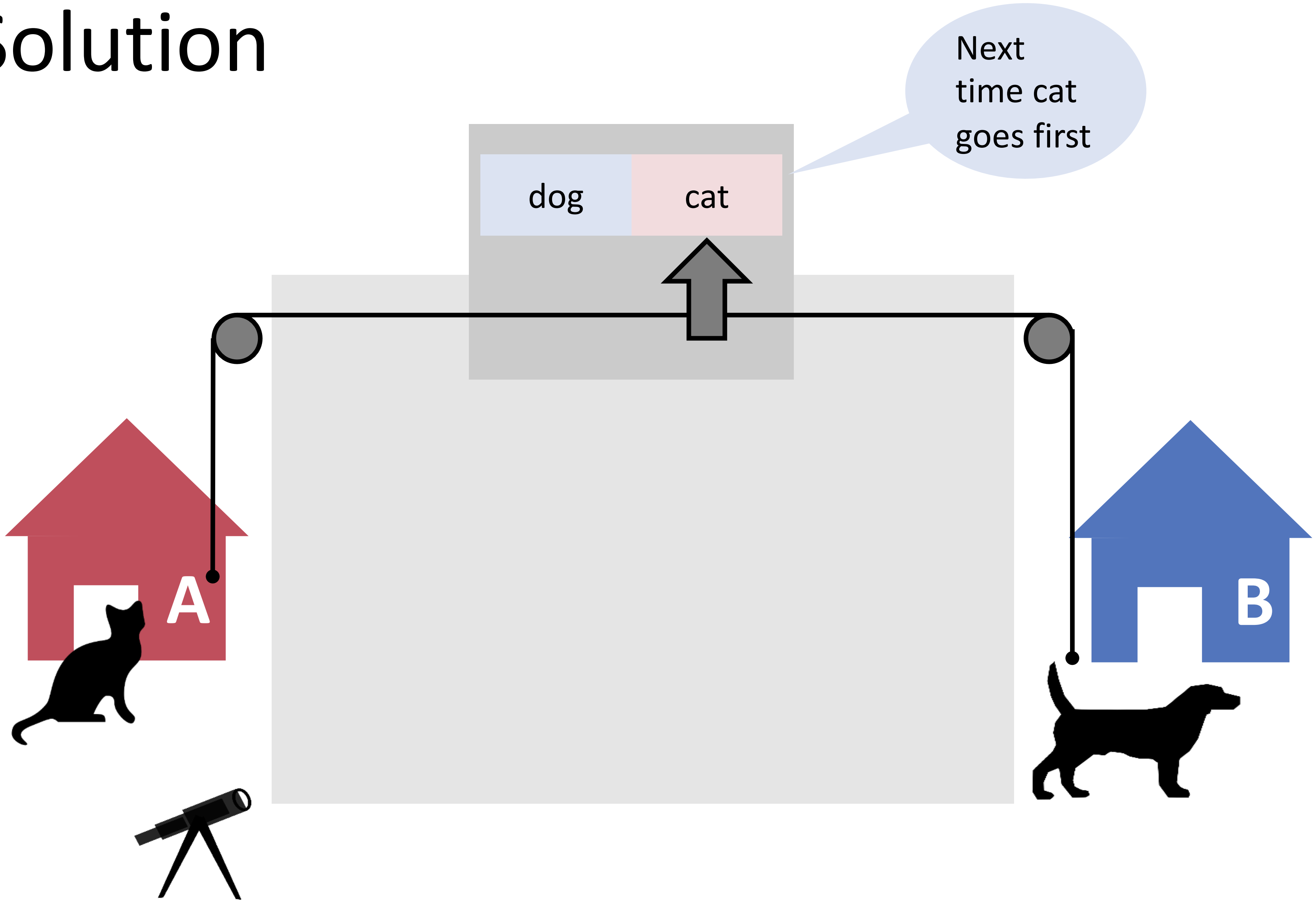
Final Solution



Final Solution



Final Solution

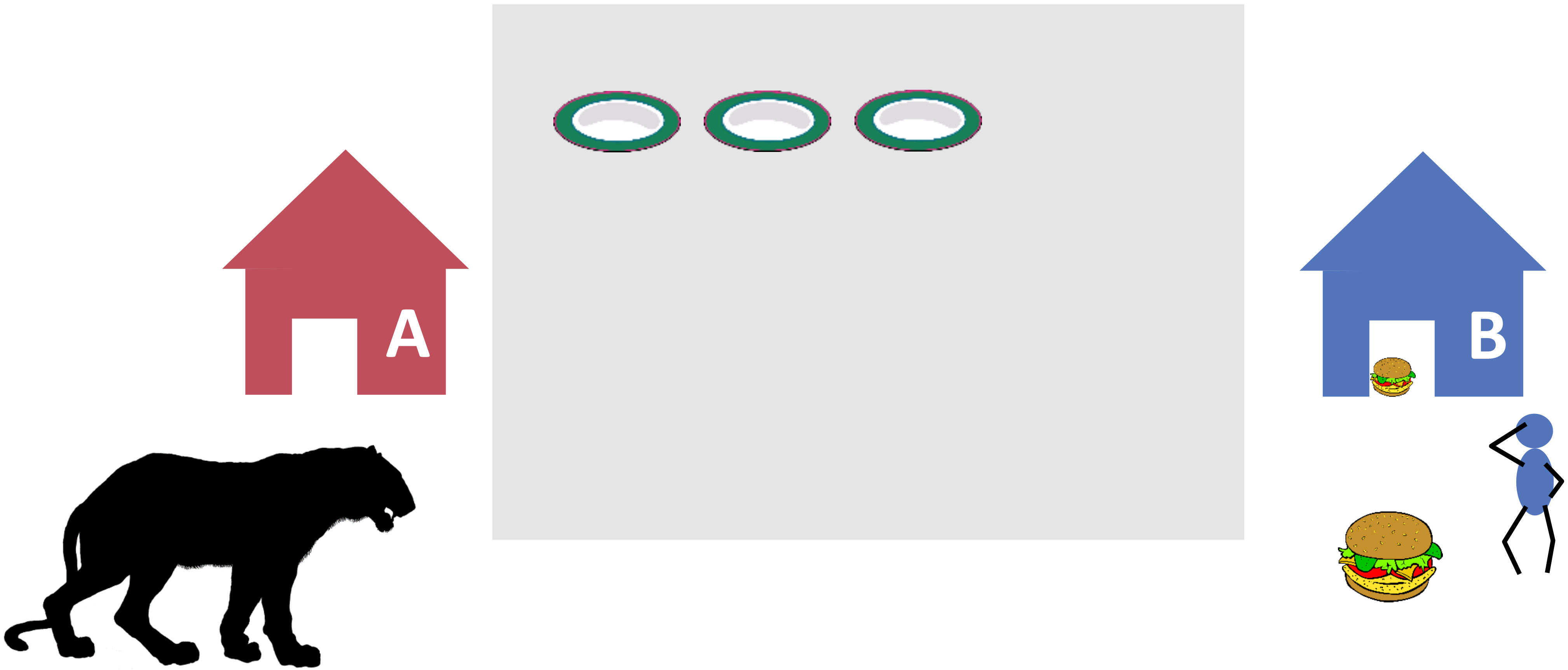


Still: General Problem of Waiting ...

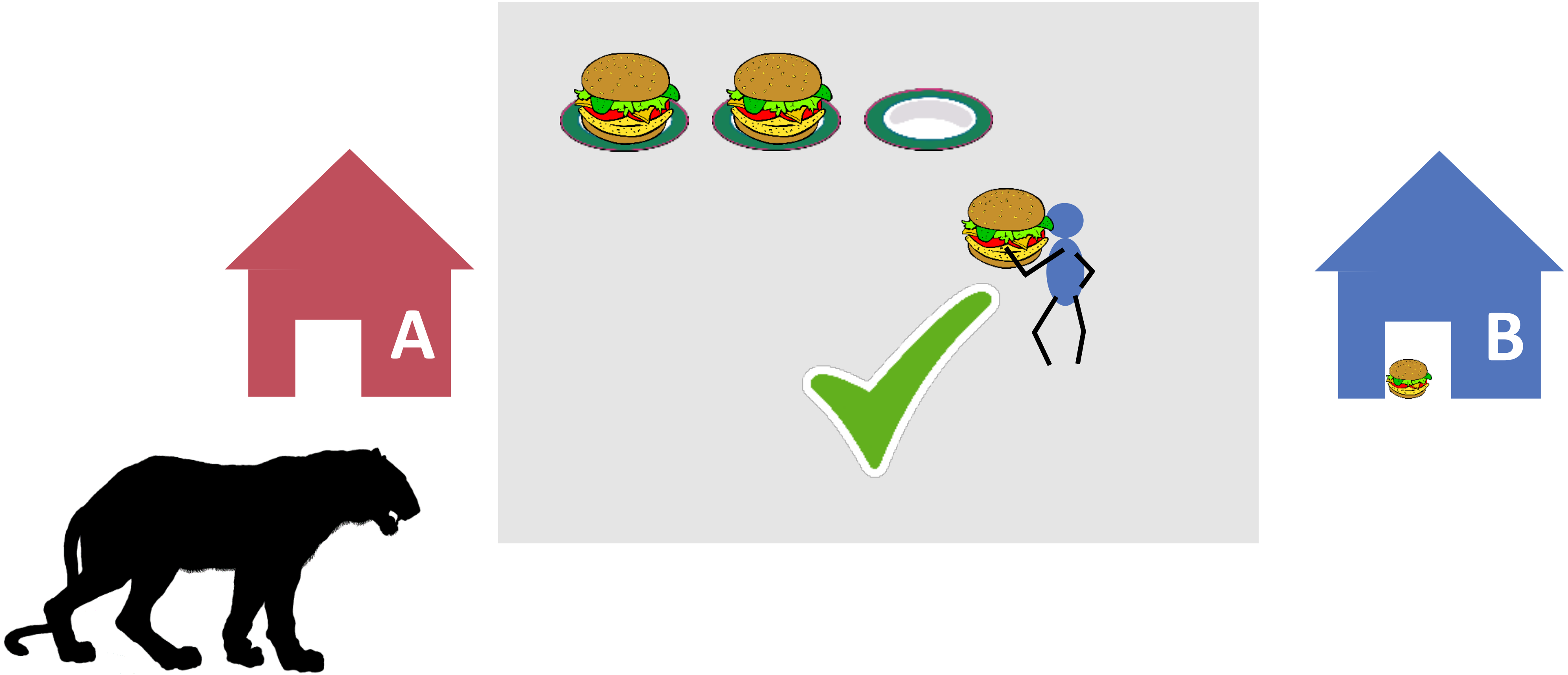
Three stories

2. PRODUCER-CONSUMER

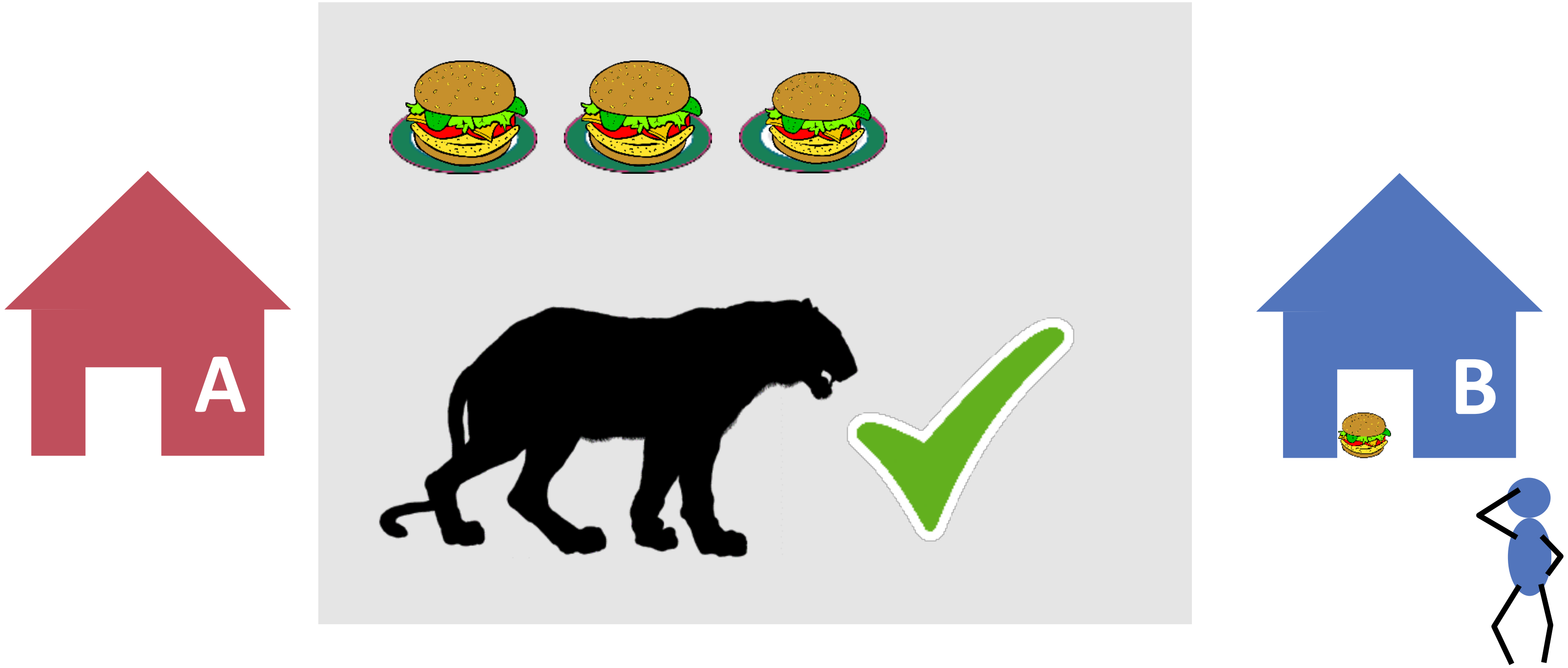
Producer-Consumer

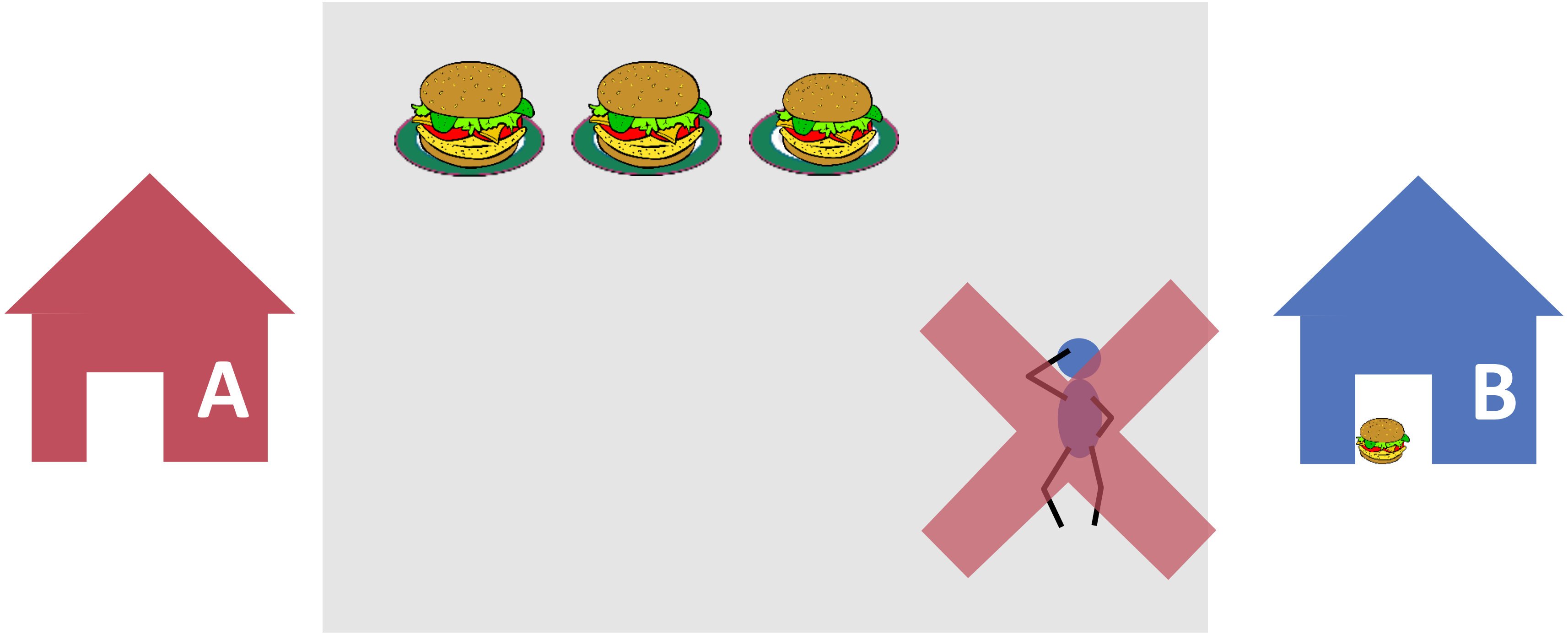


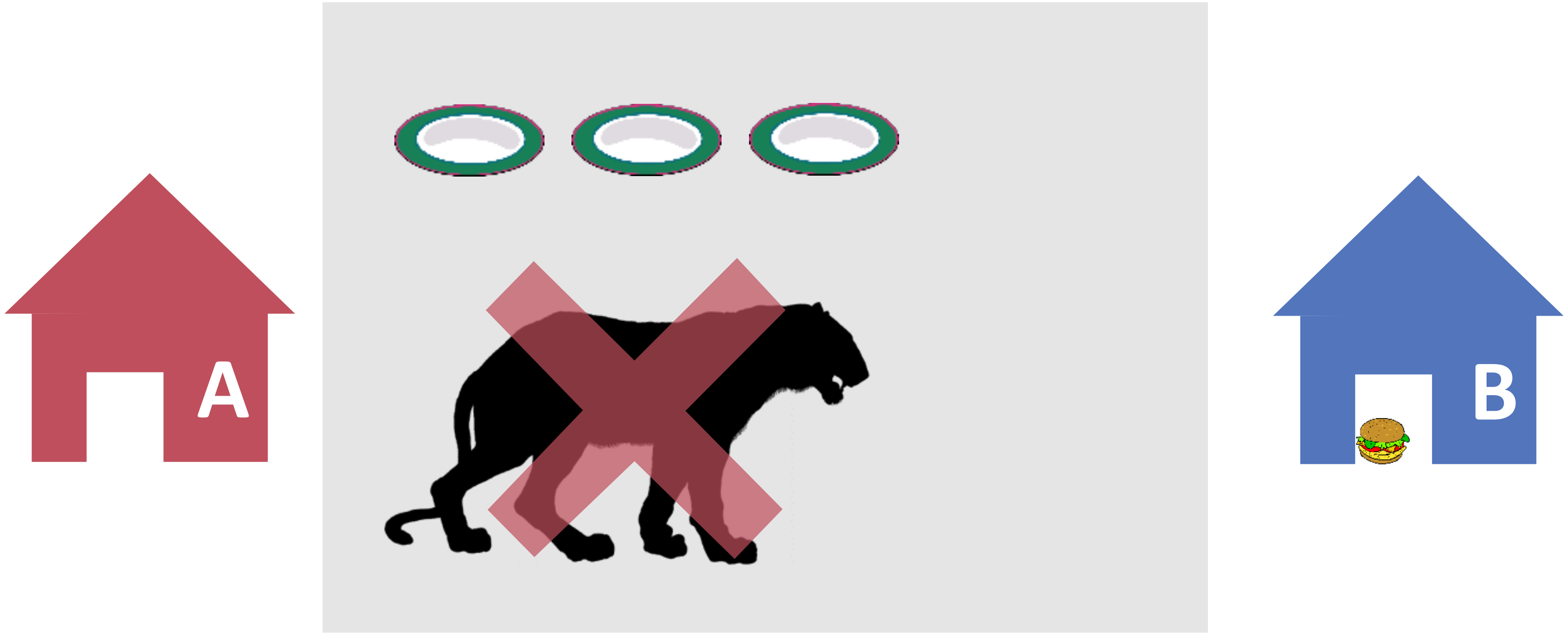
Producer-Consumer



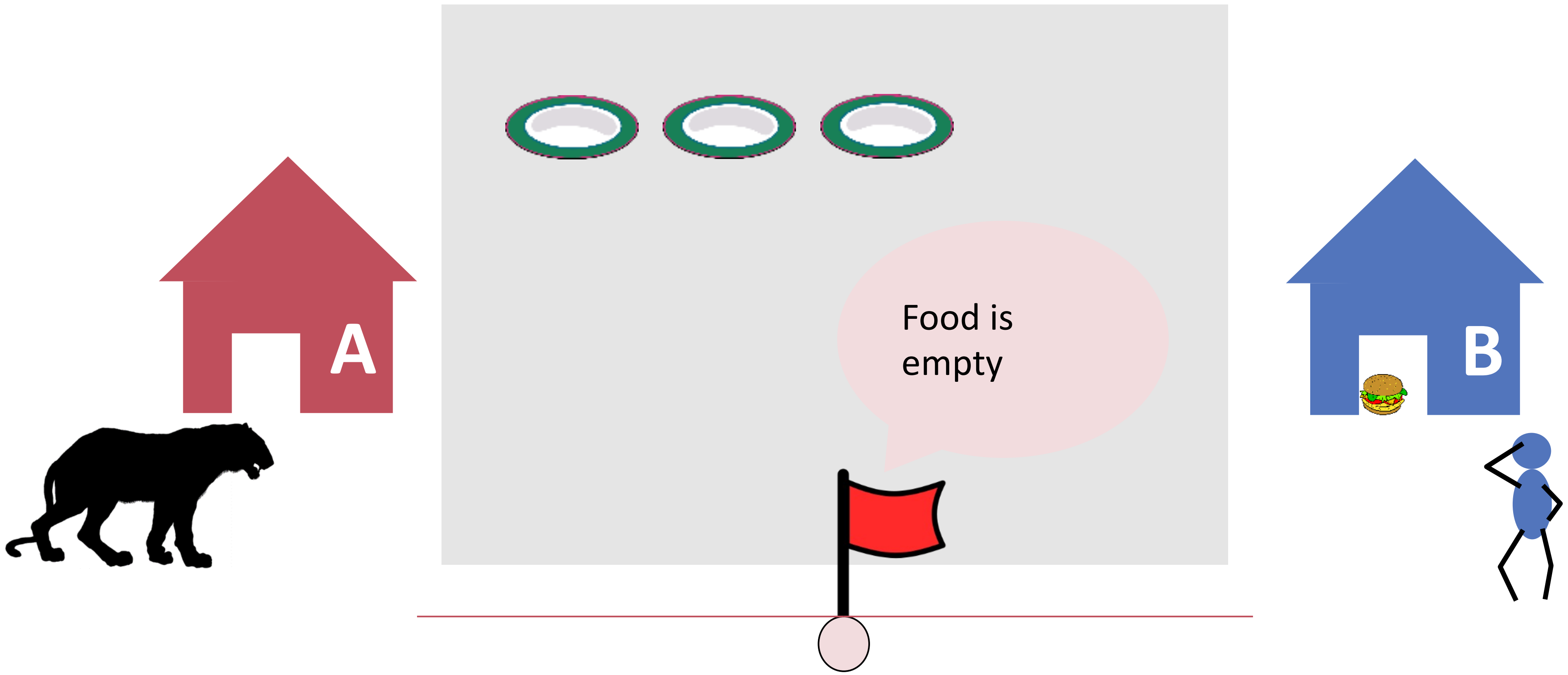
Rules



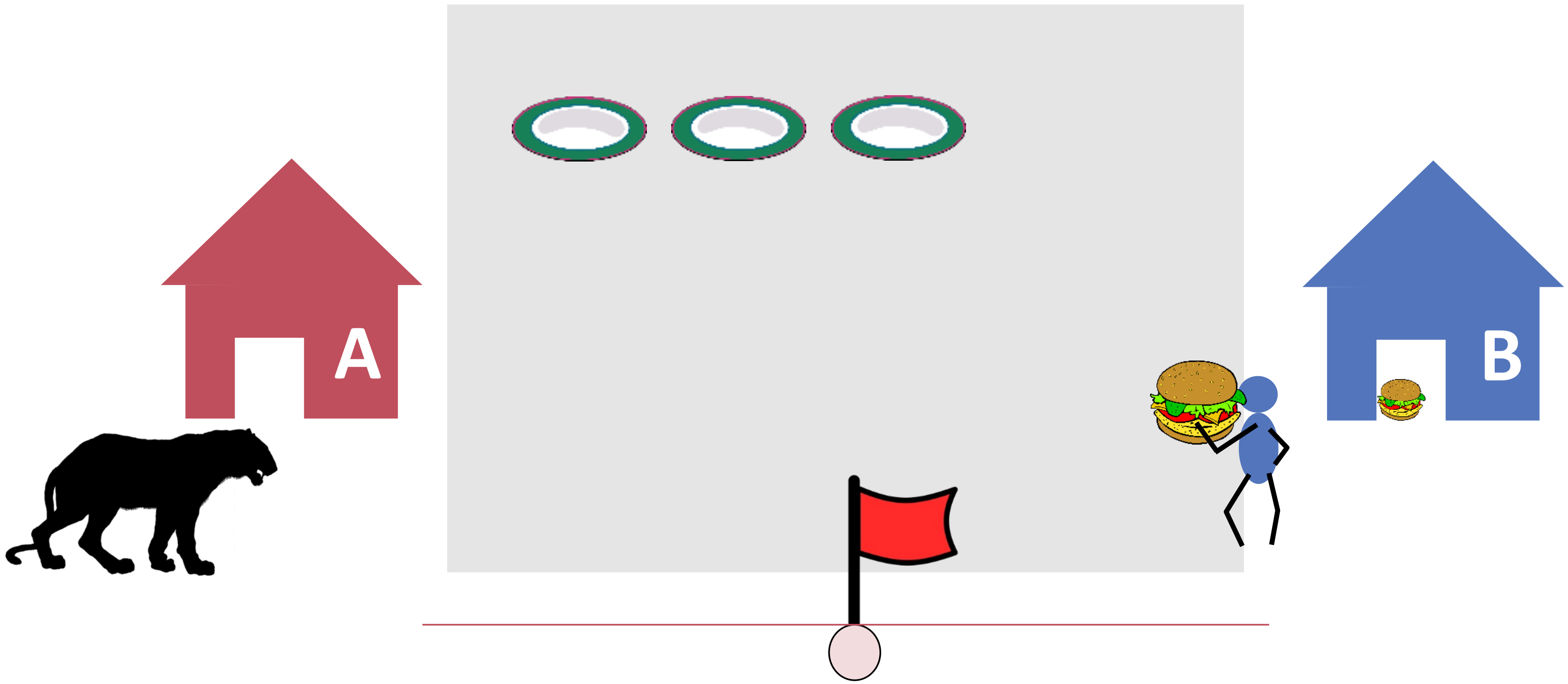

A
B

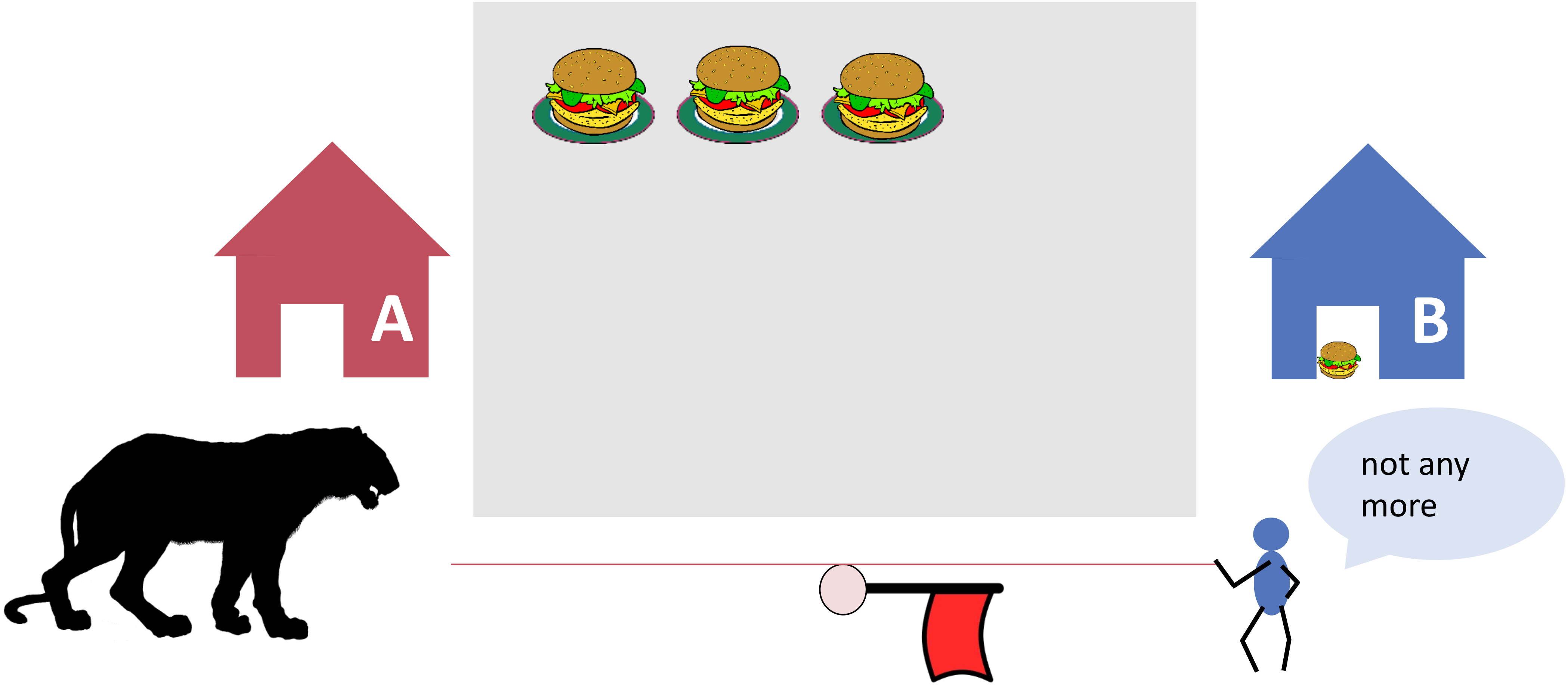

A
B

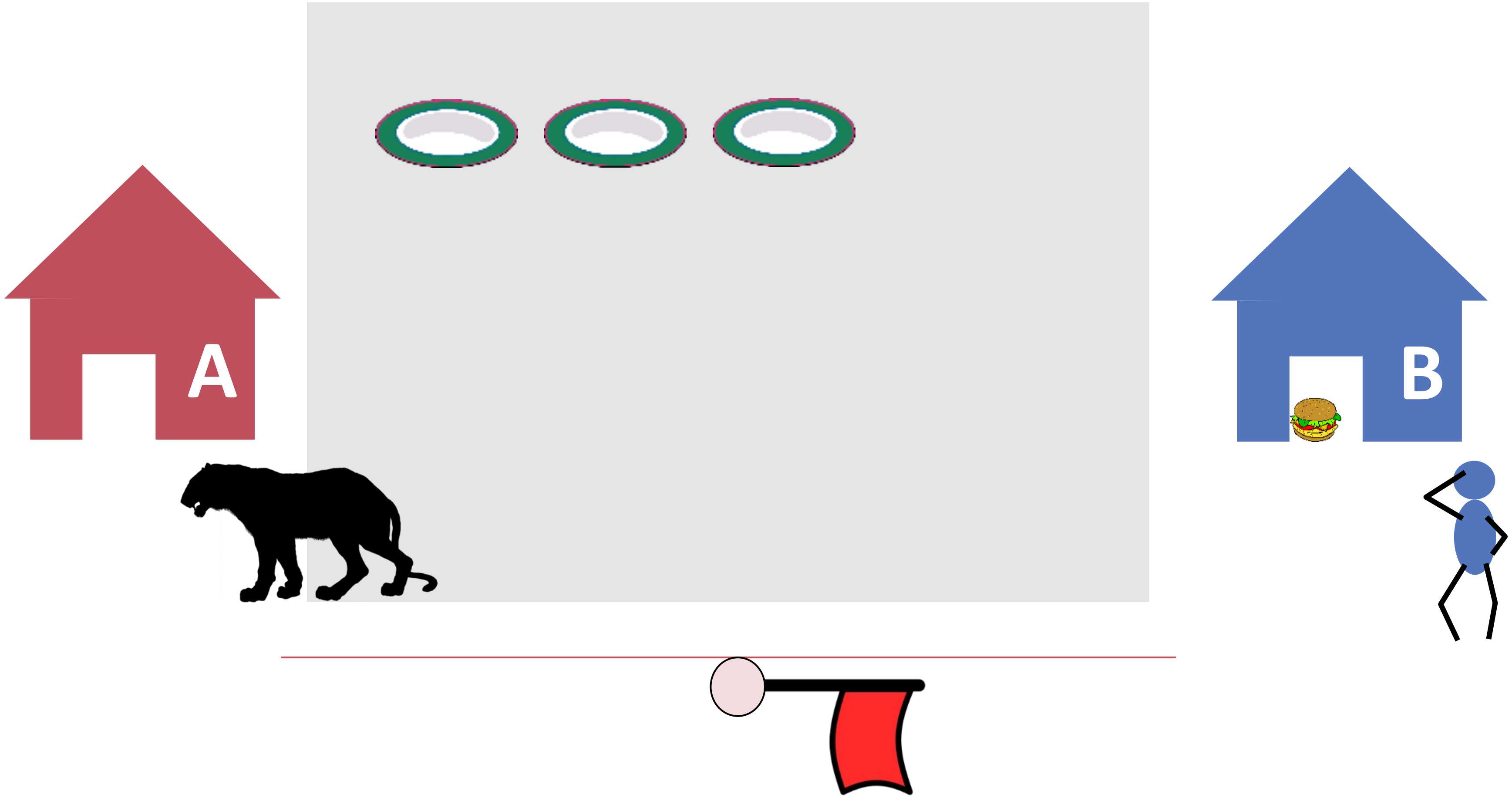
Communication

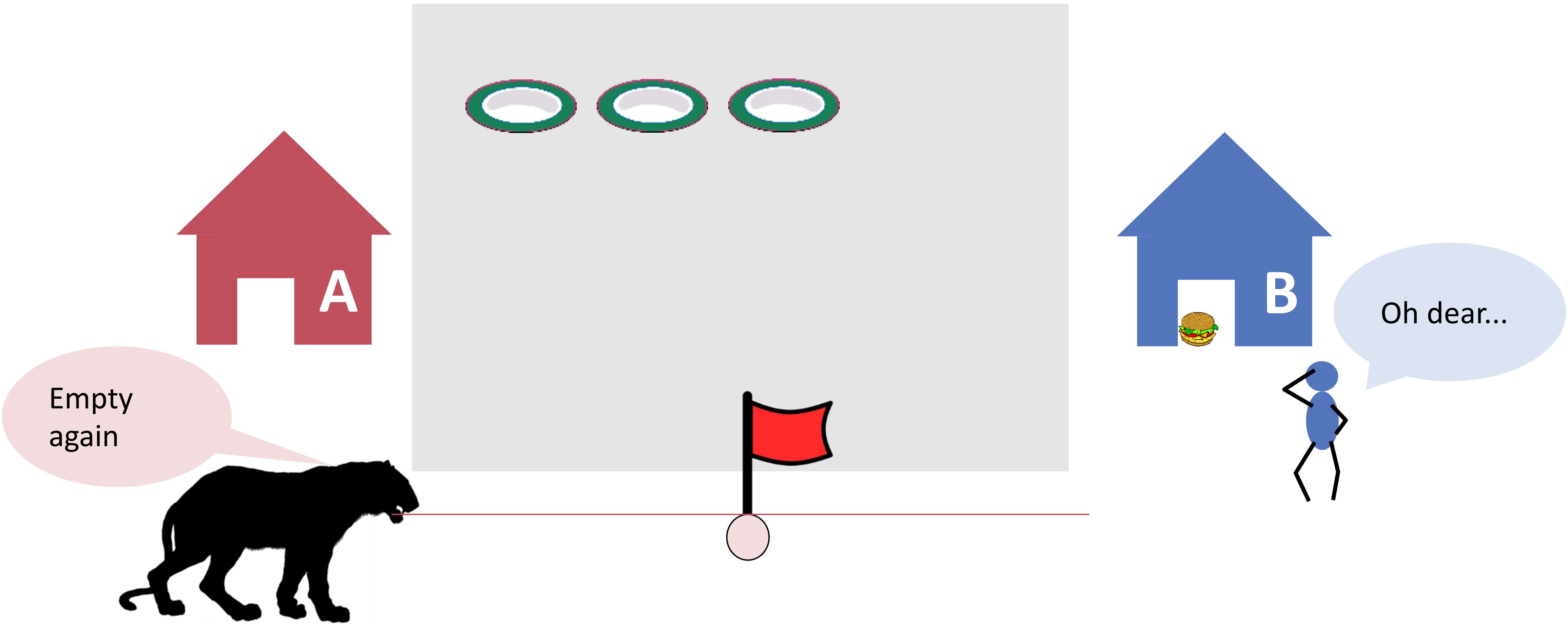


Protocol



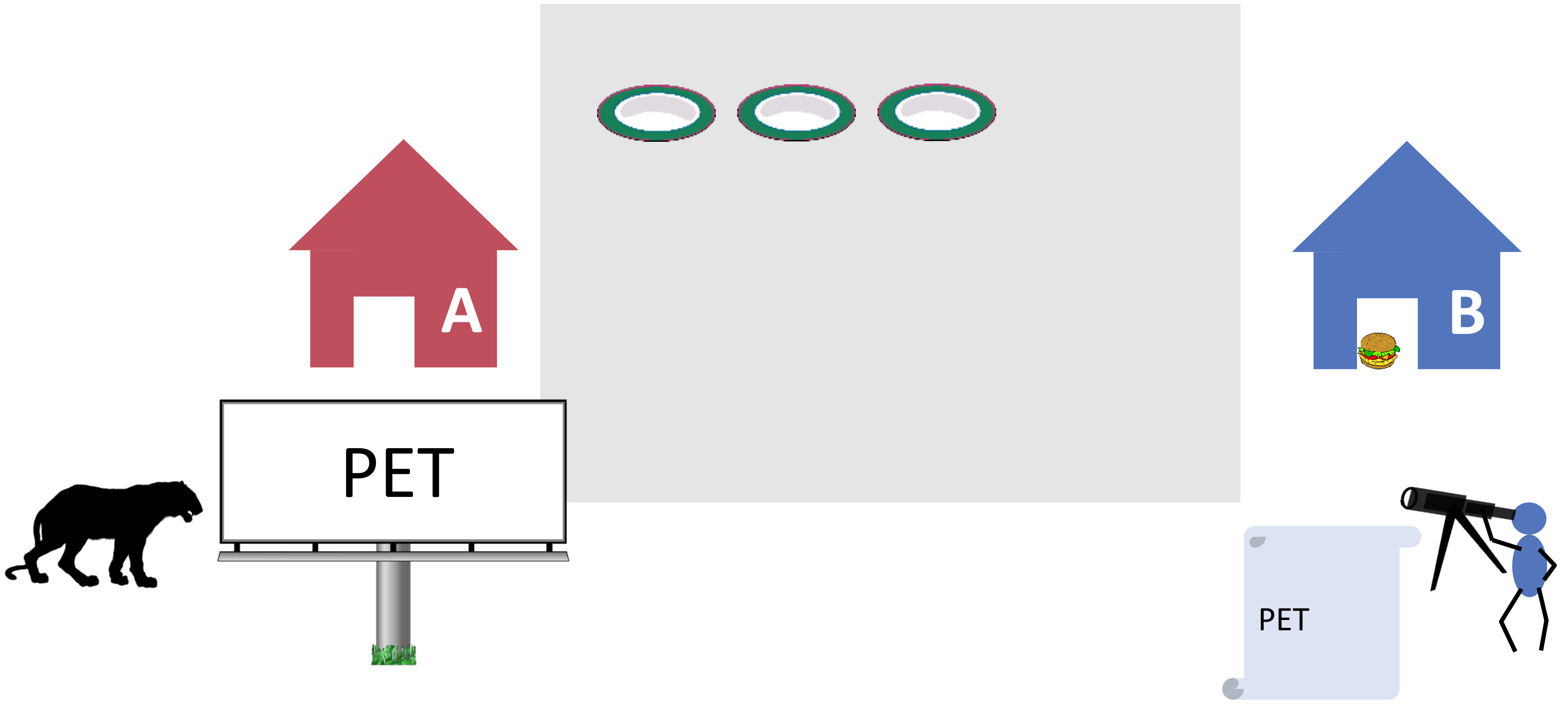

A
B
not any
more

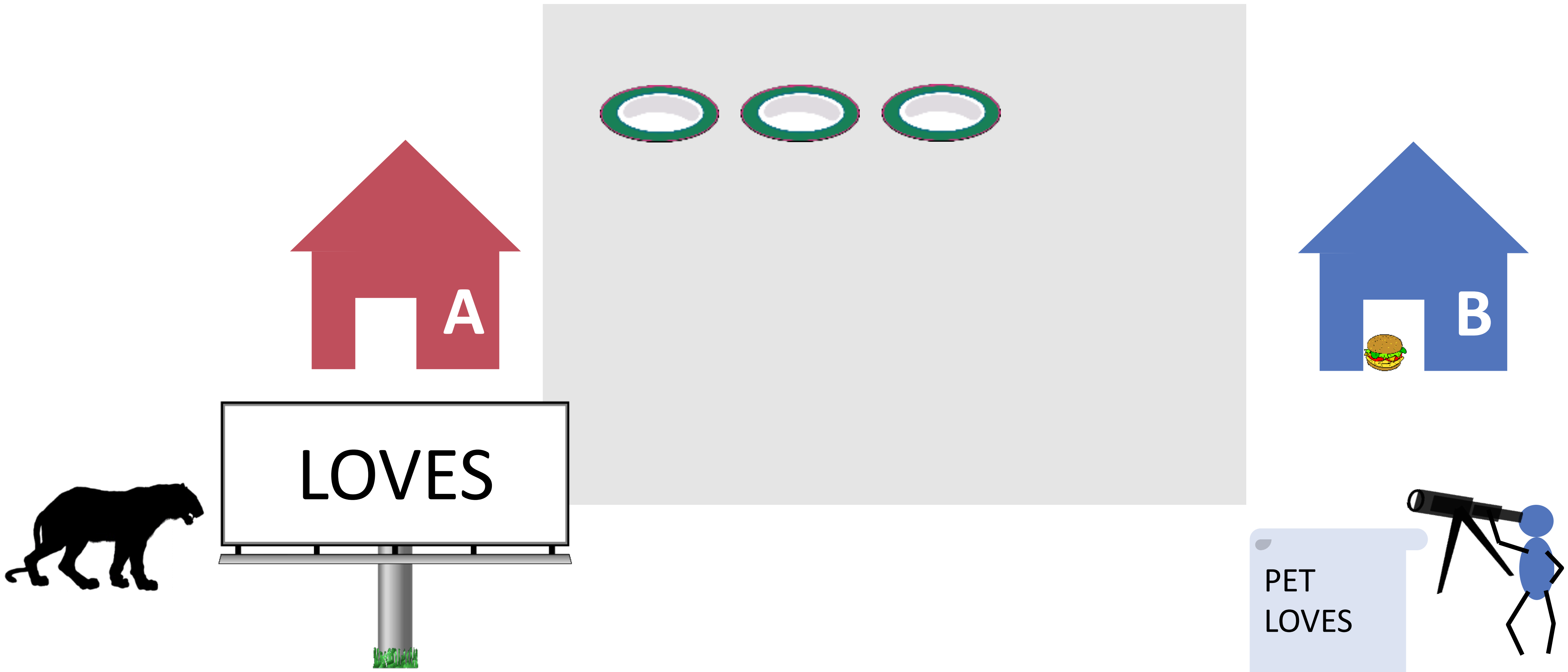

A
B

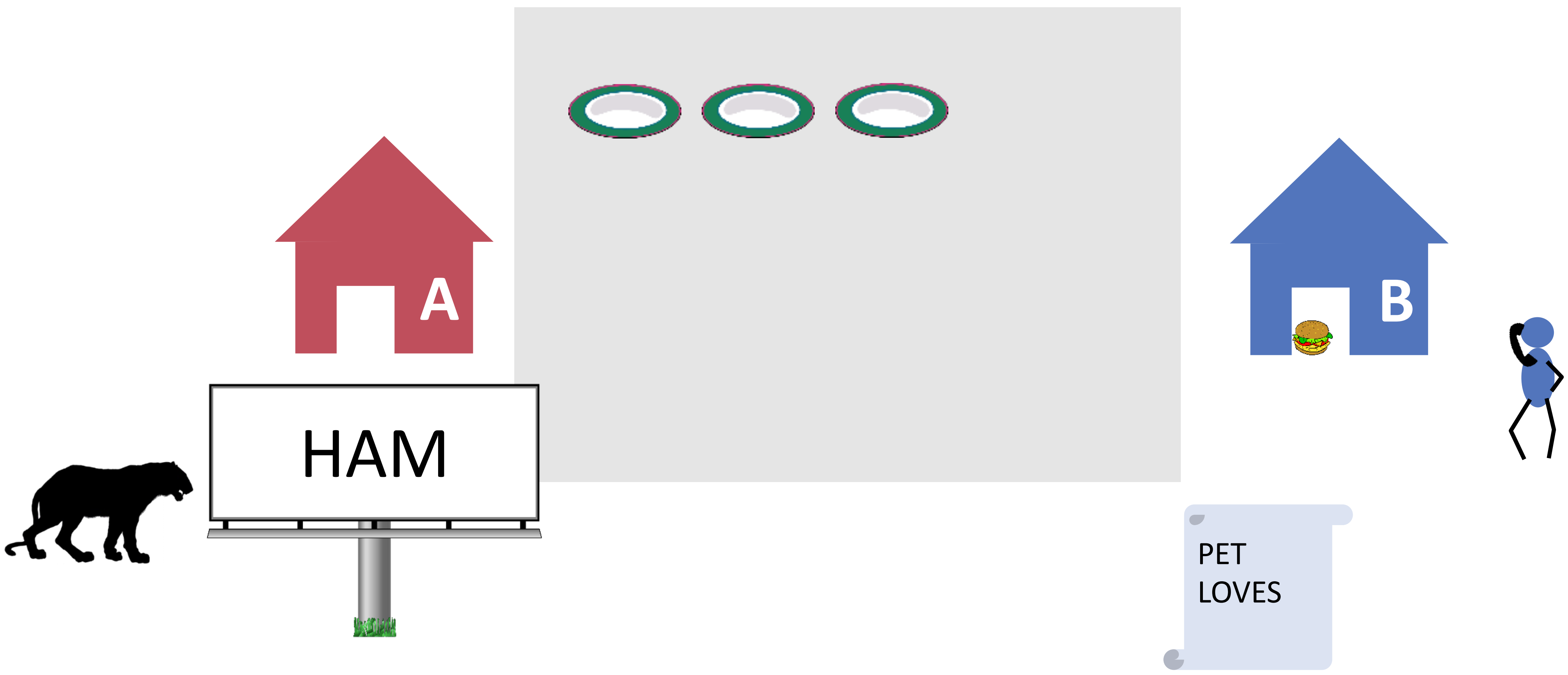

A
B
Oh dear...
Empty
again

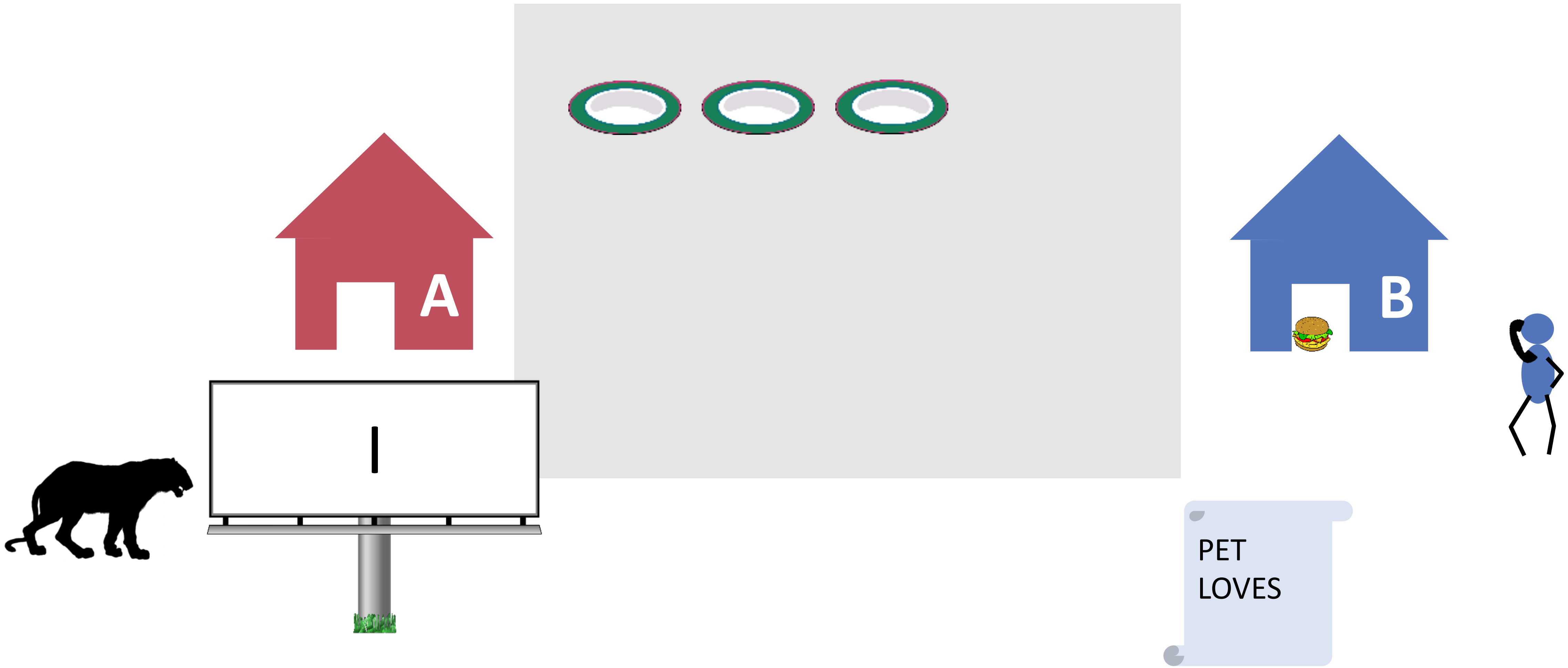
Three stories

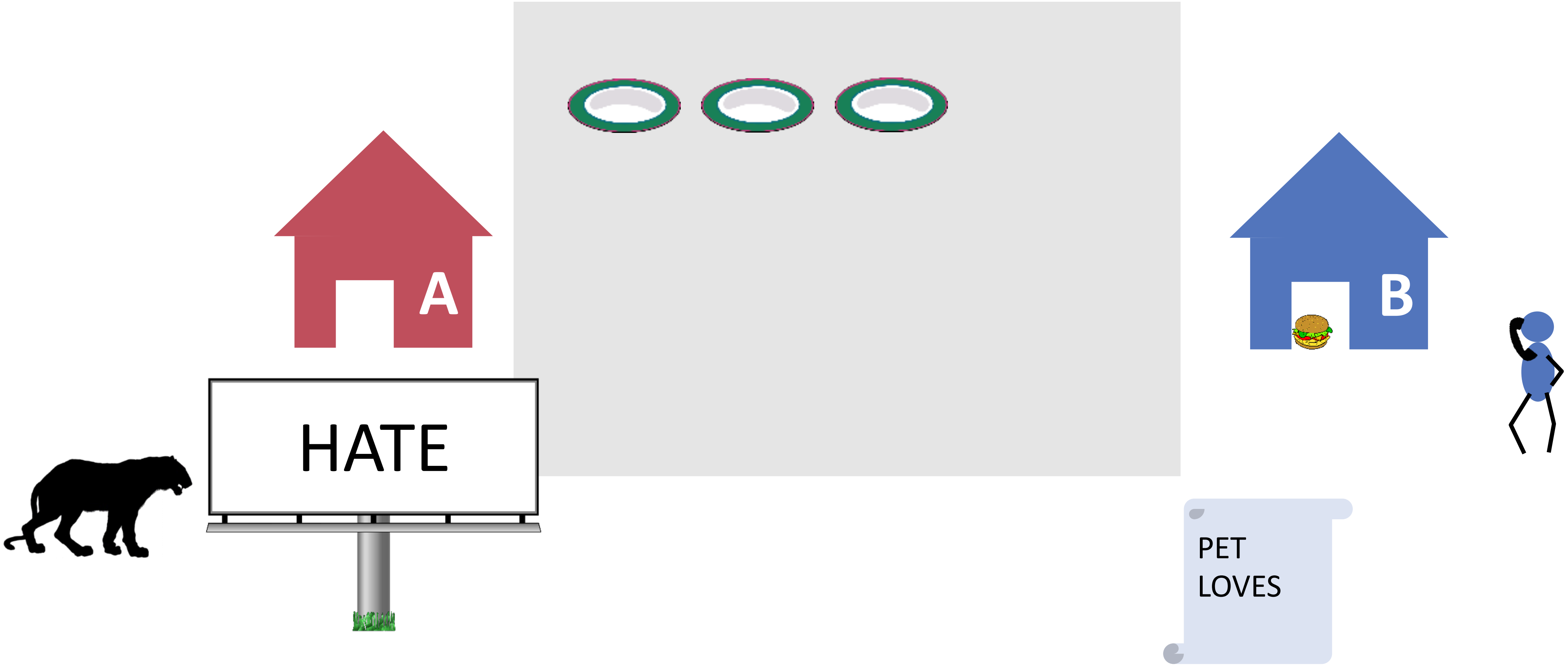
3. READERS-WRITERS

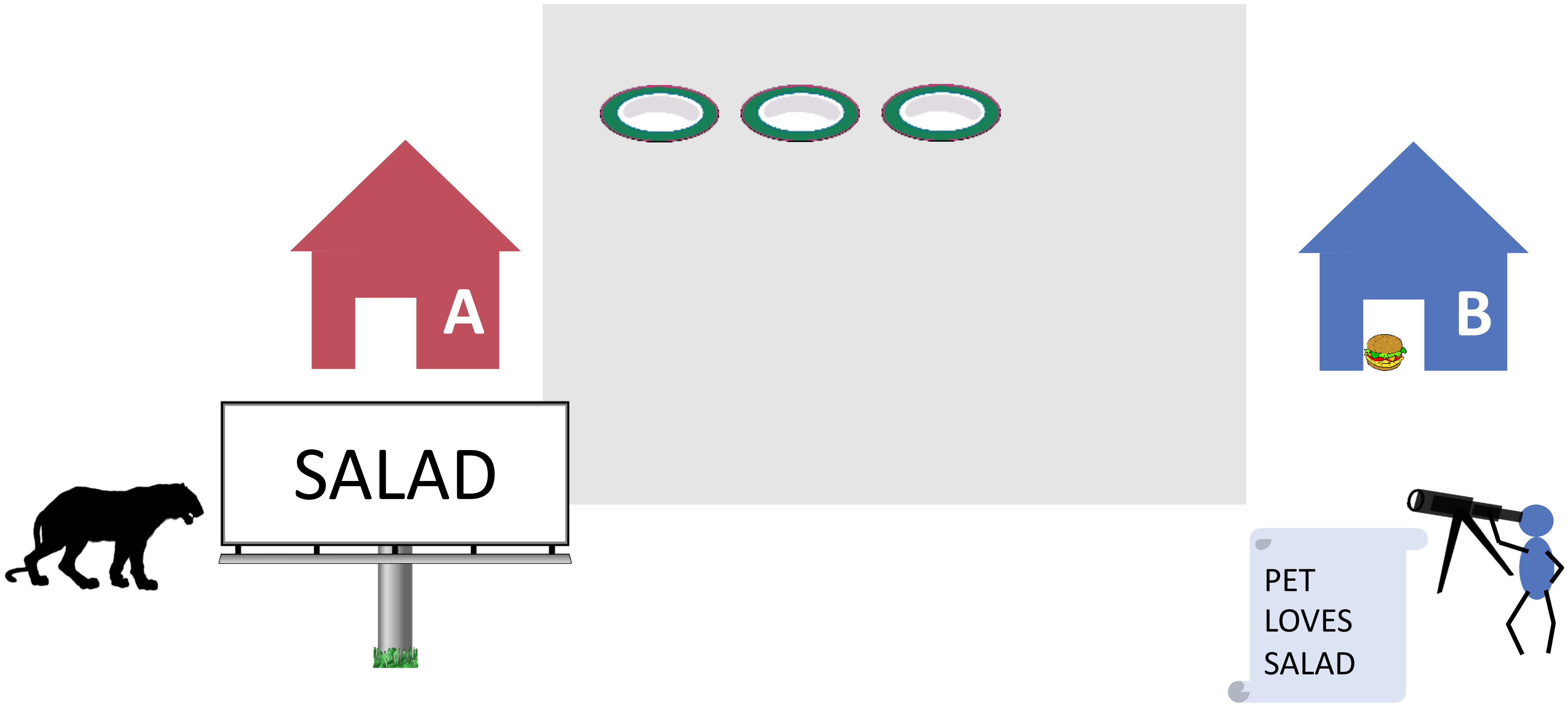

A
B
PET
PET


A
B
LOVES
PET
LOVES


A
B
HAM
PET
LOVES


A
B
I
PET
LOVES


A
B
HATE
PET
LOVES


A
B
SALAD
PET
LOVES
SALAD

The bad news

- Reality of parallel computing is **much more complicated** than this.

- The results of one action, such as the lifting of a flag by one thread, can become visible by other threads delayed or even in different order, making the aforementioned protocols even more tricky.

- Precise reasons will become clear much later in your studies. But we will understand consequences in the lectures later.

The good news

- On parallel hardware we will find an interesting tool to deal with low level concurrency issues.
- There is sufficient **abstraction** in the programming models of different programming languages.
- Later on, we will not really have to deal with such low level concurrency issues. But we should have understood them once.

Language Landscape

C, C++

Java, Kotlin, C#

Python, Ruby, Perl

Go, Rust

Haskell, OCaml

JavaScript, TypeScript

Swift, Dart

…

Why use Java?

Is ubiquitous (see oracle installer)

- Many (very useful) libraries
- Excellent online tutorials & books

Parallelism is well supported

- In the language and via frameworks

Interoperable with modern JVM languages

- E.g., Akka framework

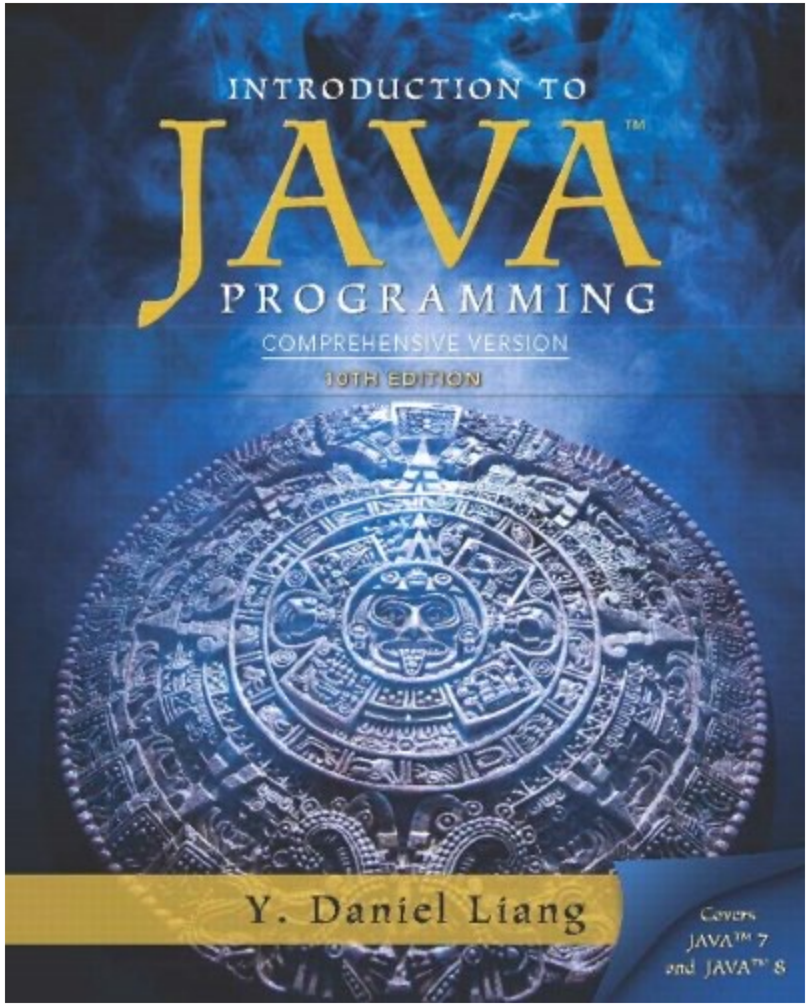
Yet, not perfect

- Tends to be verbose, lots of boilerplate code

Introduction to Java Programming

- Introduction to Java Programming, 2014.
- Daniel Liang.
- ISBN-13: 9780133813463

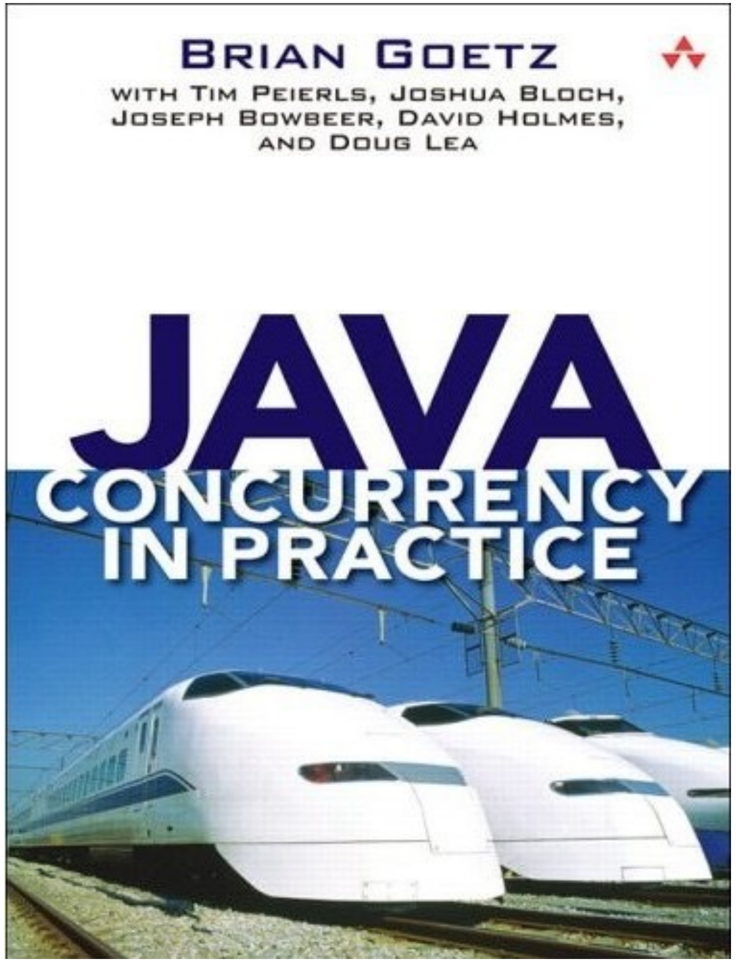
- Chapters 1-13 (with some omissions)
- Week 1-3



Java Concurrency in Practice

- Java Concurrency in Practice, 2006.
- Brian Goetz, Tim Peierls, Joshua Bloch, Joseph Bowbeer, David Holmes, Doug Lea.
- ISBN-13: 9780321349606

- Week 4-9



Theory and beyond

- Fundamental treatment of concurrency
- In particular the "Principles" part is unique
- Not easy
- In this course
  - Theory of concurrency
  - Behind locks
  - Lock-free programming