Concurrency in weak memory models

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Aim of talk

Outline memory model related differences between programming in:

- “modelling languages” like pseudocode and Promela, and
- ”real languages” like Java.

The talk is both Java specific and not Java specific:

- Java used as an example of a language with a “weak memory model”,
- but at least C/C++ similar

What to remember from this talk

In “modelling languages”, synchronization is used for:

- atomicity

In “real languages”, synchronization is used for:

- atomicity, and
- **visibility**

Outline

- What are memory models?
- Why weak memory models?
- Something about the Java memory model (as an example of a weak memory model)
- Programming in the Java memory model

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What are memory models?

- Memory model part of language semantics (what programs mean, i.e., how programs behave)

- Different memory models exist:
  - In pseudocode, sequential consistency (SC) often assumed -- one of the ”strongest” memory models

  - Java, instead, offers the Java memory model (JMM) -- one example of a ”weak” memory model

OK… but what is a memory model?

- In one sentence: Semantics of shared variables (and synchronization)
- Consider the question: What values are variable reads allowed to return?
- ???

Reading variables: Sequential programming

```
int x = 0;
int y = 0;
x = 1;
y = 1;
print(y);
print(x);
```

What value can this this read of y return?

Will *obviously* read 1 here! We always get the latest value!

Reading variables: Concurrent programming

```
bool done = false; int r = 0; // r is short for result

green_thread {
  r = 666;
  done = true;
}

blue_thread {
  if (done)
   print(r);
}
```

Assuming sequential consistency:
Just consider all possible interleavings!

What value can this this read of r return?

Reading variables: Manual reasoning

```
bool done = false; int r = 0;
```

Interleaving 1:

```
done?
r = 666;
done = true;
```

Output:

-

Interleaving 2:

```
r = 666;
done?
done = true;
```

Output:

-

Interleaving 3:

```
r = 666;
done = true;
done?
print(r);
```

Output:

666

Reading variables: Machine reasoning

```
> cat read-vars.pml
bool done = false; int r = 0;

active proctype green_proc() {
  r = 666; done = true;
}

active proctype blue_proc() {
  if
    :: done -> assert(r == 666);
    :: else
  fi
}
```

```
> spin -search read-vars.pml

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l Order Reduction

search for:
        never claim             - (none specified)
        assertion violations    +
        cycle checks            - (disabled by -DSAFETY)
        invalid end states      +

State-vector 28 byte, depth reached 5, errors: 0
       11 states, stored
        2 states, matched
       13 transitions (= stored+matche
        0 atomic steps
hash conflicts:         0 (resolved)

[…]
```

Spin is a tool that can reason about Promela programs automatically

The important part is here: 0 errors!

The same program, now written in Promela

In Promela we have SC!

What happens with the Java memory model?

Demo OutOfOrderTest.java

Reading variables: Sequential consistency (SC)

```
bool done = false; int r = 0;

green_thread {
  r = 666;
  done = true;
}

blue_thread {
  if (done)
   print(r);
}
```

Some visibility guarantees in SC:

- ”Program order” always maintained
  - In particular, `r = 666` always before `done = true` in any interleaving
- No “stale” values: Always see the latest value written to any variable
- But the above guarantees not provided by all weak memory models (e.g. JMM)!

Reading variables: Weak memory models

```
bool done = false; int r = 0;

green_thread {
  r = 666;
  done = true;
}

blue_thread {
  if (done)
   print(r);
}
```

”Interleaving-based semantics” in some sense the ”obvious” semantics for concurrency

Why make things more difficult? Why give up program order and other nice things?

Because: SC costs too much

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- What are memory models?
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Btw, the conclusion of the previous section:
You must understand the memory model you are using to understand your programs

SC cost 1: Prohibits (too many) compiler optimizations

- Aaaaah!!! Messiness! Real-world things! In pseudocode we do not have to consider ugliness such as compiler ”details” etc.

- Example: For some compiler optimizations we want to reorder writes to variables. (For whatever reason: Might improve register allocation or anything.)

SC cost 1: Prohibits (too many) compiler optimizations

- E.g., the transformation to the right "semantics preserving" in sequential setting if we only consider final state of program
- Not equivalent if we can inspect program under execution, which we can if x and y are shared variables in a concurrent setting
- Breaks illusion of "program order"!

Original program:

```
x = 1;
y = 2;
z = x + y; // x = 1, y = 2, z = 3
```

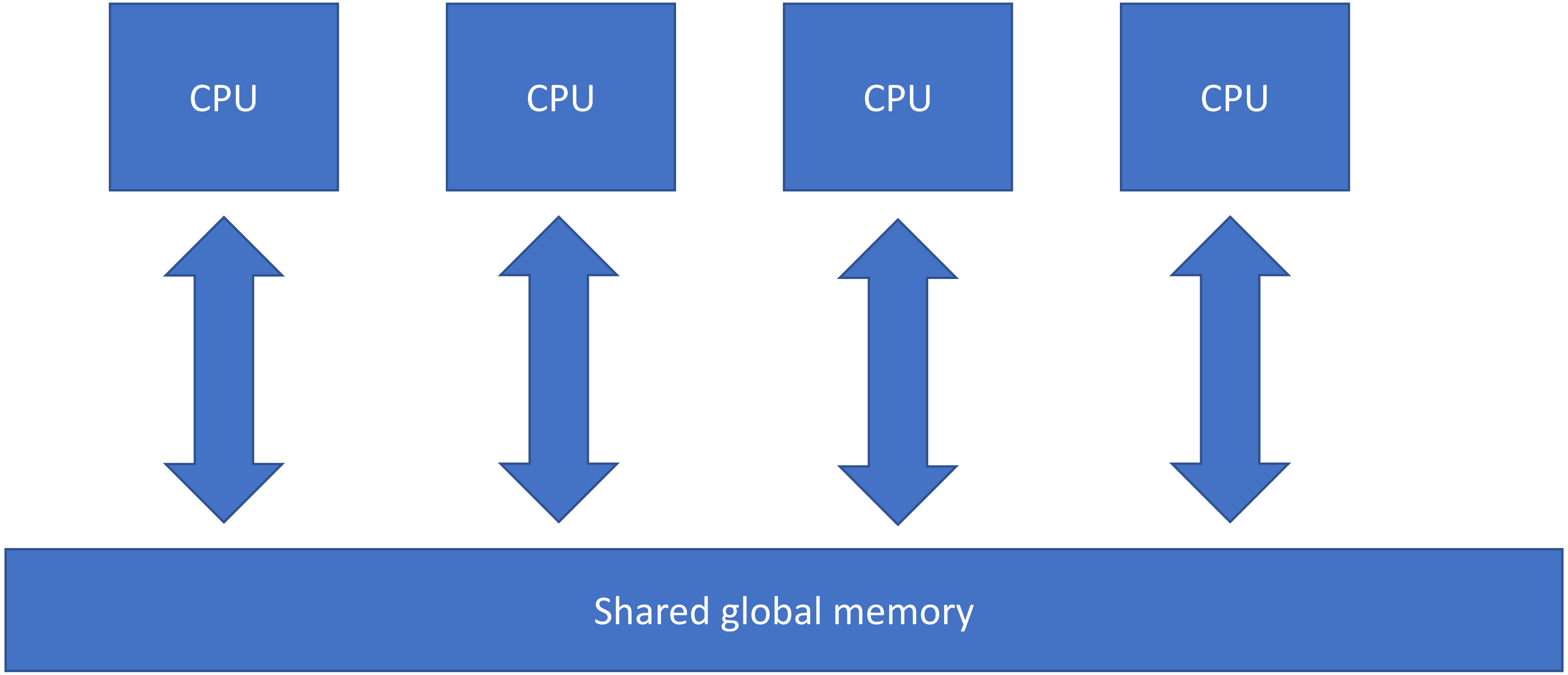
Transformed program:

```
y = 2;
x = 1;
z = x + y; // x = 1, y = 2, z = 3
```

Write order swapped

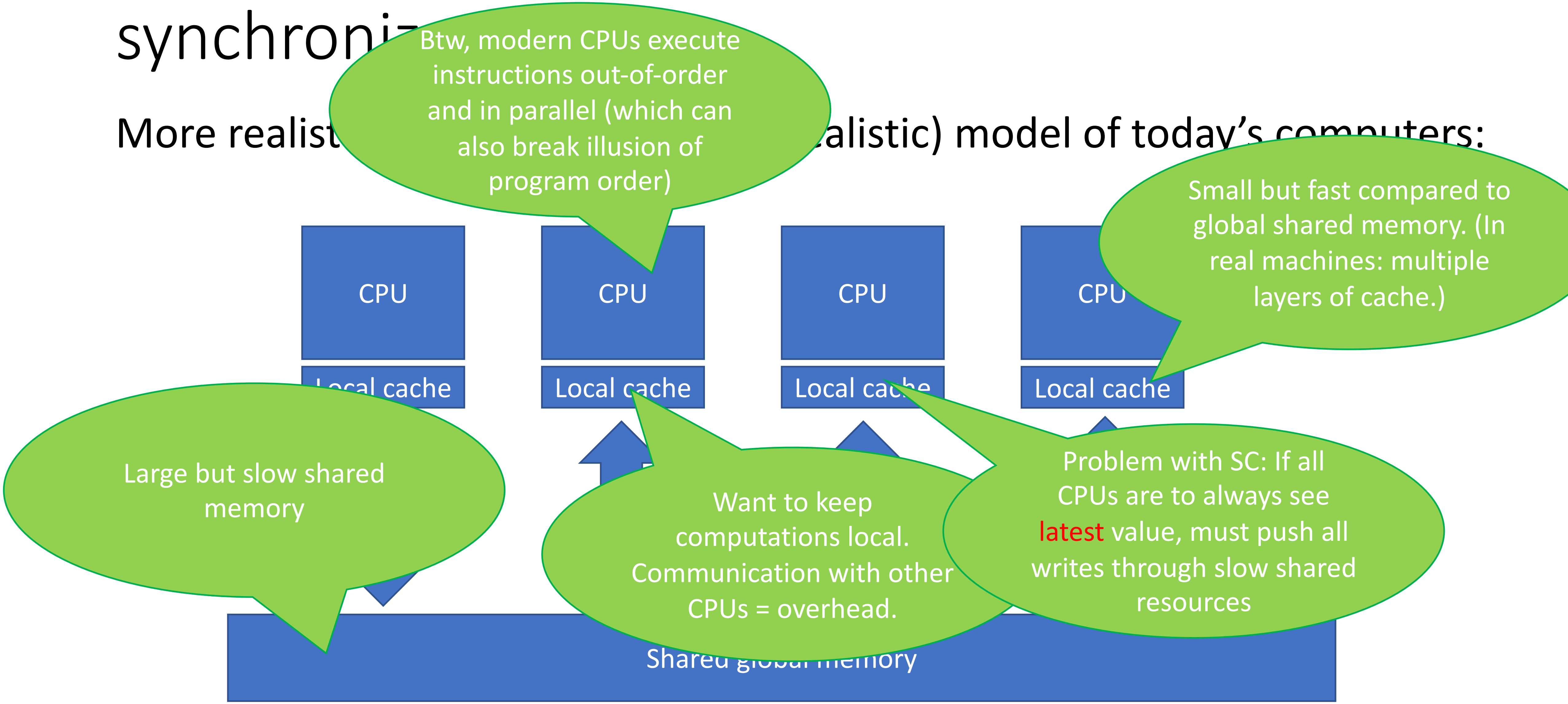
SC cost 2: Causes too much cache synchronization

Cost of SC not obvious with too simplified machine models:



SC cost 2: Causes too much cache synchroni

More realist alistic) model of today's computers:



Why not SC: Summary

- Not a complete list of reasons, just two examples!
- Anyhow, in summary:
  SC too expensive in many situations
- Solution to mentioned problems:
  Relax some guarantees offered by SC → we get weak memory models
- Weaker memory models (potentially) more performant, but more difficult to program in

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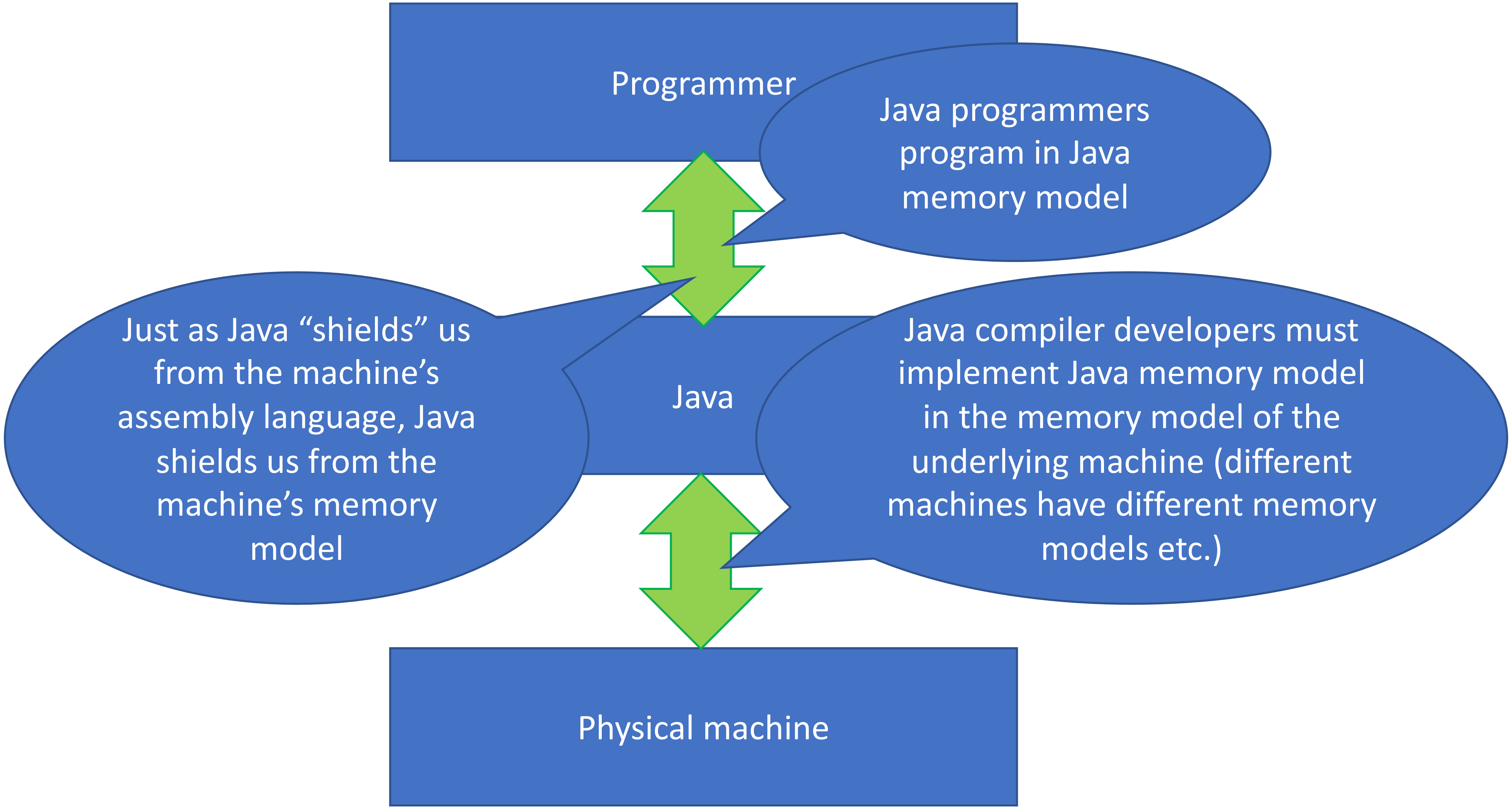
More context: Some more machine details

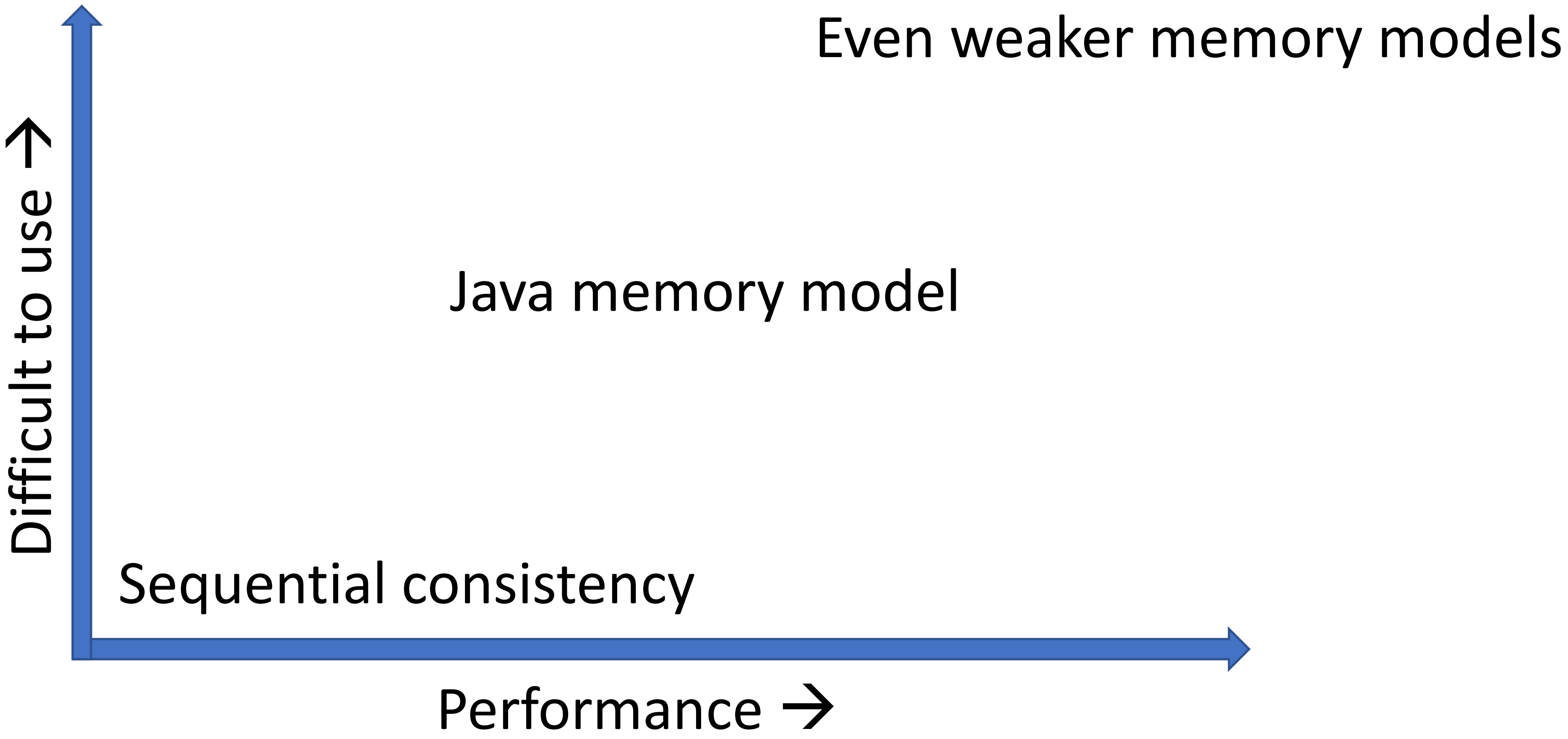


The Java memory model

- Less convenient than SC, but implementable on modern machine architectures without too much performance loss

- Opinion: Memory model part of language design, and different coordinates in the design space have different tradeoffs. As with any other language feature: No “right” answer.

Design tradeoff space



SC for data-race-free programs

- A few (C-like) languages have converged to ”sequential consistency for data-race-free programs” memory models
- Java included in this family
- Reasoning principle: If there are no data races (under SC), we can assume SC when reasoning about our program
- Important to remember definitions of data race and race conditions (many people mix them up!)

Data races

Slight variation of previous definition you seen, to fit Java better:

Def. Two memory accesses are in a data race iff

- they access the same memory location simultaneously (they are interleaved next to each other),
- at least one access is a write,
- insufficient explicit synchronization used to protect the accesses

Def. A program is data-race-free iff no SC execution of the program contain a data race

“Slight variation”? Note that we quantify over all SC executions in the second definition.

Note that data-race-freedom is a ”language-level” property!

Definition of data race surprisingly subtle

E.g., does this program contain any data races?

```
bool x = false, y = false;

t1 {
   if (x) y = true;
}

t2 {
   if (y) x = true;
}
```

No!

Race conditions

Definition from course slides:

Def. A *race condition* is a situation where the correctness of a concurrent program depends on the specific execution

Note that this is an ”application-level” property!

I.e., for a given program p, to answer the question ”is p free from race conditions?” we must have access to the specification of p.

Much confusion about these two definitions!

- Some people think *benign* data races is a thing
  - We will not be of this opinion here
  - For us, all data races are bad
- Note that some people simply mean (observable) non-determinism when they say race condition
  - With this definition of race conditions, not all race conditions are bugs
  - For us, all race conditions are bugs (since the correctness of our program will depend on how threads are scheduled when we have a race condition)

SC for data-race-free programs, again

- For Java programs, we have SC for programs without data races

- Reasoning principle in more detail:
  1. Assume SC and make sure that there are no data races
  2. If no data races, we can assume SC when reasoning about race conditions

- What about the semantics of programs *with* data races?
  - Will not be considered here (except a little at the end of the talk!)
  - In e.g. C++ data races result in undefined behavior (see C++ specification or https://en.cppreference.com/w/cpp/language/memory_model)
  - Java is supposed to be a ”safe language”, some guarantees (e.g. out-of-thin-air safety)

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What does all this mean in practice?

- I.e: How does “weak memory models” affect *my daily life as a programmer*?

- Answer: You must “annotate” your program more than with SC
  - Sprinkle additional synchronization information on top of your program
  - Variable qualifiers, synchronization mechanisms (e.g. locks), etc.
  - Exactly what “annotate” means depends on language

- Essentially, you annotate which data/actions are shared and which are not

Simple example

Simpler than initial example, only one variable here

```
bool done = false;

t1 {
    done = true;
}

t2 {
    if (done) print(33);
}
```

- Does this program contain
  - data races?
  - race conditions?
- Data race = yes, done is accessed without synchronization and one of the accesses is a write
- Race condition = depends on the specification we are to satisfy (what it means for the program to be correct)
- Race condition = even if we had a specification, we have a data race so our reasoning principle does not apply!

Simple example

```
bool done = false;

t1 {
    done = true;
}

t2 {
    if (done) print(33);
}
```

- Wait a minute!
- Are you telling me there's a problem in this program?
- From a SC perspective, everything is fine!
- No atomicity problems or anything like that… but visibility problems!

Strictly speaking if this is a problem depends on the **visibility guarantees** you make in your specification!

Simple example (fixed)

```
volatile bool done = false;

t1 {
    done = true;
}

t2 {
    if (done) print(33);
}
```

- Solution: Annotate your program. E.g., in Java `volatile` is considered synchronization.
- Does this program contain
  - data races?
  - race conditions?

Language dependent, not the case in e.g. C++

- Data race = no, in Java `volatile` accesses are considered synchronized
- Race condition = still depends on specification

Simple example (fixed)

```
volatile bool done = false;

t1 {
    done = true;
}

t2 {
    if (done) print(33);
}
```

Example specification:

- Spec = “If the program outputs something, it must output 33”
- (In other words: Spec = “Output nothing or 33”)
- Race conditions w.r.t. above specification?
- No race conditions! As correct output does not depend on specific execution/ interleaving.

Simple example (fixed)

```
volatile bool done = false;

t1 {
    done = true;
}

t2 {
    if (done) print(33);
}
```

Another example specification:

- Spec = “The program outputs 33”
- Race conditions w.r.t. above specification?
- Yes, have race condition. Some interleavings give us correct output, others do not.

Similar example, with locks

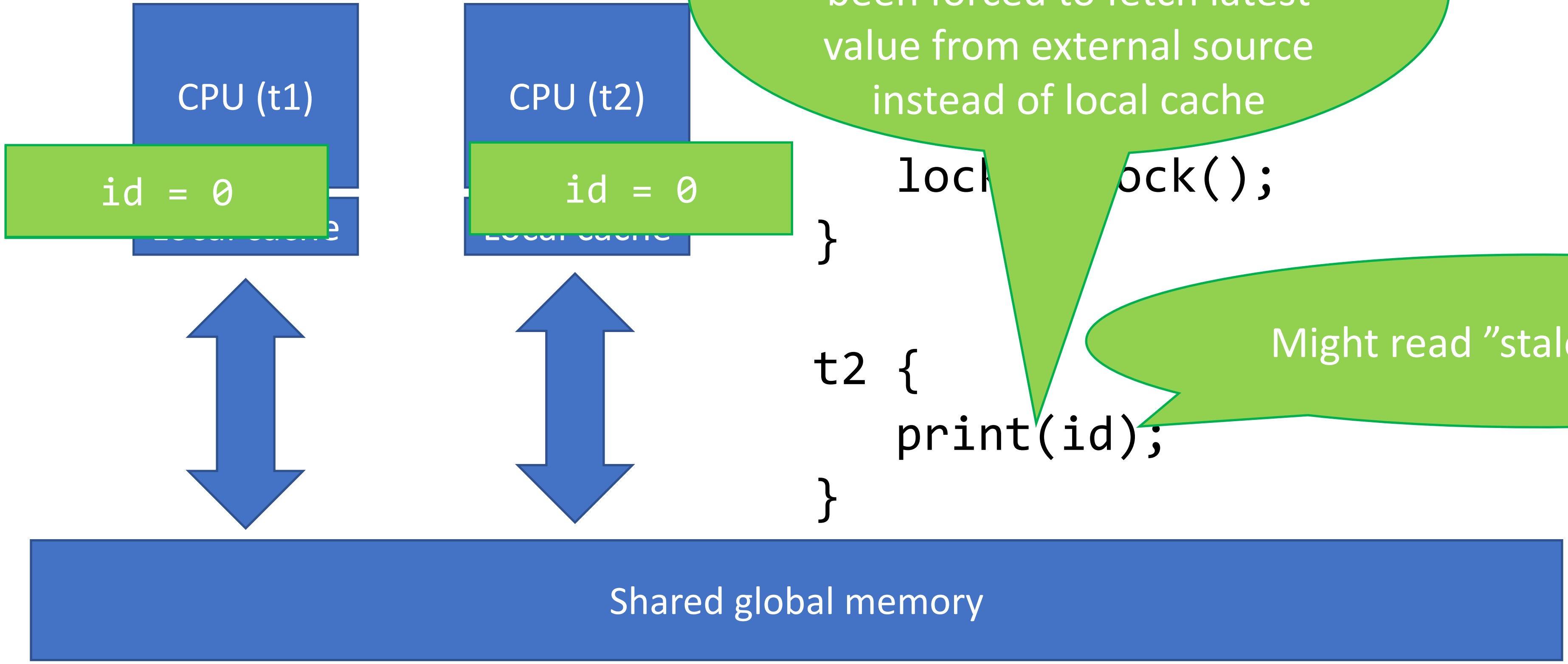
```
lock lock = new lock();
int id = 0;

t1 {
   lock.lock();
   id++;
   lock.unlock();
}

t2 {
   print(id);
}
```

Data races?

We have a race! All accesses to the shared variable done must be synchronized!

Here we have (again) atomicity, but not: visibility

id flag might exist as multiple copies…




```
lock lock = new lock();
in
    lock     ock();
}

t2 {
    print(id);
}
```

If we would have locked here, CPU would have been forced to fetch latest value from external source instead of local cache

Might read ”stale” value here

NOTE: Everything on this slide simplified, and makes unsound assumptions about JVM implementation details

Similar example, with locks (fixed)

```
lock lock = new lock();
int id = 0;

t1 {
   lock.lock();
   id++;
   lock.unlock();
}

t2 {
   lock.lock(); // new
   print(id);
   lock.unlock(); // new
}
```

This is how the program would look like with proper annotations/synchronization

No data races in sight!

The Java memory model in more detail

Module java.base

Package java.util.concurrent

Utility classes commonly useful in concurrent programming. This package includes a few small standardized extensible frameworks, as well as some classes that provide useful functionality and are otherwise tedious or difficult to implement. Here are brief descriptions of the main components. See also the `java.util.concurrent.locks` and `java.util.concurrent.atomic` packages.

Executors

Interfaces. `Executor` is a simple standardized interface for defining custom thread-like subsystems, including thread pools, asynchronous I/O, and lightweight task frameworks. Depending on which concrete Executor class is being used, tasks may execute in a newly created thread, an existing task-execution thread, or the thread calling `execute`, and may execute sequentially or concurrently. `ExecutorService` provides a more complete asynchronous task execution framework. An ExecutorService manages queuing and scheduling of tasks, and allows controlled shutdown. The `ScheduledExecutorService` subinterface and associated interfaces add support for delayed and periodic task execution. ExecutorServices provide methods arranging asynchronous execution of any function expressed as `Callable`, the result-bearing analog of `Runnable`. A `Future` returns the results of a function, allows determination of whether execution has completed, and provides a means to cancel execution. A `RunnableFuture` is a `Future` that possesses a `run` method that upon execution, sets its results.

Implementations. Classes `ThreadPoolExecutor` and `ScheduledThreadPoolExecutor` provide tunable, flexible thread pools. The `Executors` class provides factory methods for the most common kinds and configurations of Executors, as well as a few utility methods for using them. Other utilities based on `Executors` include the concrete class `FutureTask` providing a common extensible implementation of Futures, and `ExecutorCompletionService`, that assists in coordinating the processing of groups of asynchronous tasks.

Class `ForkJoinPool` provides an Executor primarily designed for processing instances of `ForkJoinTask` and its subclasses. These classes employ a work-stealing scheduler that attains high throughput for tasks conforming to restrictions that often hold in computation-intensive parallel processing.

Queues

We can also say "memory consistency model"

- they are guaranteed to traverse elements a … lect any modifications subsequent to construction.

Memory Consistency Properties

Chapter 17 of *The Java Language Specification* defines the *happens-before* relation on memory operations such as reads and writes of shared variables. The results of a write by one thread are guaranteed to be visible to a read by another thread only if the write operation *happens-before* the read operation. The `synchronized` and `volatile` constructs, as well as the `Thread.start()` and `Thread.join()` methods, can form *happens-before* relationships. In particular:

- Each action in a thread *happens-before* every action in that thread that comes later in the program's order.
- An unlock (`synchronized` block or method exit) of a monitor *happens-before* every subsequent lock (`synchronized` block or method entry) of that same monitor. And because the *happens-before* relation is transitive, all actions of a thread prior to unlocking *happen-before* all actions subsequent to any thread locking that monitor.
- A write to a `volatile` field *happens-before* every subsequent read of that same field. Writes and reads of `volatile` fields have similar memory consistency effects as entering and exiting monitors, but do *not* entail mutual exclusion locking.
- A call to `start` on a thread *happens-before* any action in the started thread.
- All actions in a thread *happen-before* any other thread successfully returns from a `join` on that thread.

The methods of all classes in `java.util.concurrent` and its subpackages extend these guarantees to higher-level synchronization. In particular:

- Actions in a thread prior to placing an object into any concurrent collection *happen-before* actions subsequent to the access or removal of that element from the collection in another thread.
- Actions in a thread prior to the submission of a `Runnable` to an `Executor` *happen-before* its execution begins. Similarly for `Callables` submitted to an `ExecutorService`.
- Actions taken by the asynchronous computation represented by a `Future` *happen-before* actions subsequent to the retrieval of the result via `Future.get()` in another thread.
- Actions prior to "releasing" synchronizer methods such as `Lock.unlock`, `Semaphore.release`, and `CountDownLatch.countDown` *happen-before* actions subsequent to a successful "acquiring" method such as `Lock.lock`, `Semaphore.acquire`, `Condition.await`, and `CountDownLatch.await` on the same synchronizer object in another thread.
- For each pair of threads that successfully exchange objects via an `Exchanger`, actions prior to the `exchange()` in each thread *happen-before* those subsequent to the corresponding `exchange()` in another thread.
- Actions prior to calling `CyclicBarrier.await` and `Phaser.awaitAdvance` (as well as its variants) *happen-before* actions performed by the barrier action, and actions performed by the barrier action *happen-before* actions subsequent to a successful return from the corresponding `await` in other threads.

Data races defined in terms of happens-before

From the Java language specification (v. 15):

Two accesses to (reads of or writes to) the same variable are said to be *conflicting* if at least one of the accesses is a write.

[…]

When a program contains two conflicting accesses (§17.4.1) that are not ordered by a happens-before relationship, it is said to contain a *data race.*

[…]

A program is *correctly synchronized* if and only if all sequentially consistent executions are free of data races.

[…]

If a program is correctly synchronized, then all executions of the program will appear to be sequentially consistent (§17.4.3).

Happens-before example

```
static int x = 1;

x = 2;
// What can be printed?
Thread t = new Thread(() ->
  System.out.println(x));
t.start();
```

- Data race because t reads x without synchronization?
- (Could argue read and write not overlapping in any SC execution.)
- x write *happens-before x read,* because *happens-before* transitive

- they are guaranteed to traverse elements as they existed upon construction exactly once, and may (but are not guaranteed to) reflect any modifications subsequent to construction.

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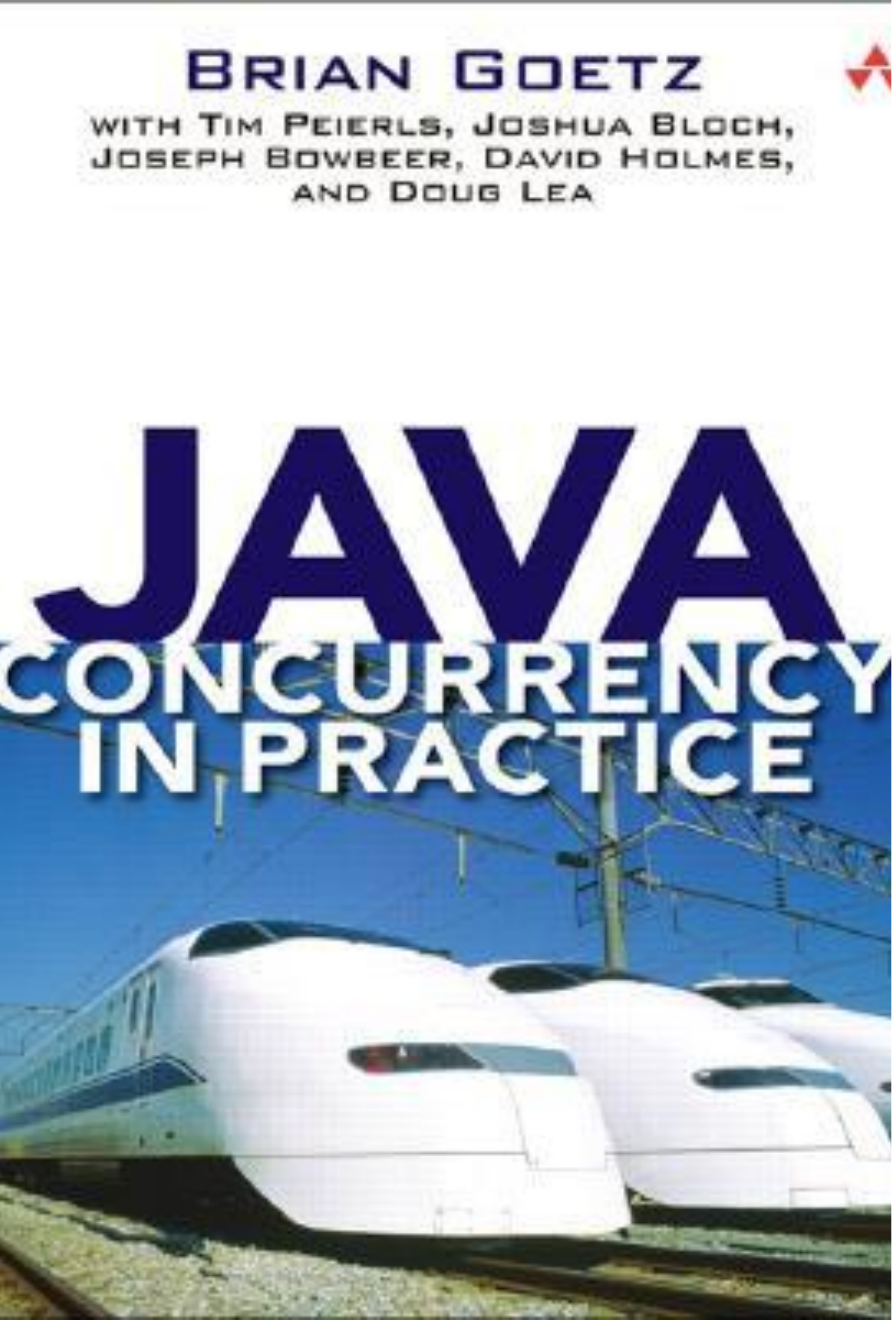
Demo OutOfOrderTest.java again



Reading suggestions

- See *Java Concurrency in Practice* (2006) if you want more of this. The book presents simplified rules you can follow to do concurrent programming in Java instead of having to learn the details of the Java memory model.
- E.g., the book provides useful “safe publication idioms”
- Also e.g.: Hans-J. Boehm, “Threads cannot be implemented as a library” (2005). (https://doi.org/10.1145/1065010.1065042)
- Also e.g.: Hans-J. Boehm and Sarita V. Adve, “You don’t know jack about shared variables or memory models” (2012). (https://doi.org/10.1145/2076450.2076465)

Advice from JCP, p. 16

If multiple threads access the same mutable state variable without appropriate synchronization, *your program is broken*. There are three ways to fix it:

Don't underestimate the two first alternatives!

- *Don't share* the state variable across threads;
- Make the state variable *immutable*; or
- Use *synchronization* whenever accessing the state variable.

Summary?

- Make sure to not have data races in your Java programs
- One way to think about all of this: Atomicity *and* visibility
- Visibility aspect new in weak memory models compared to SC!

If you only will remember one thing:

In concurrent programming in Java, not only do we have to consider atomicity, we also must consider visibility!

visibility visibility

visibility visibility visibility

v i s i b i l i t y

Ack: https://www.hboehm.info/misc_slides/10-pldi-adve-boehm-tutorial.pdf was useful when creating these slides