COMP 322: Fundamentals of Parallel Programming

Lecture 27: Parallel Design Patterns, Safety and Liveness properties

Vivek Sarkar, Shams Imam
Department of Computer Science, Rice University

Contact email: vsarkar@rice.edu, shams.imam@twosigma.com

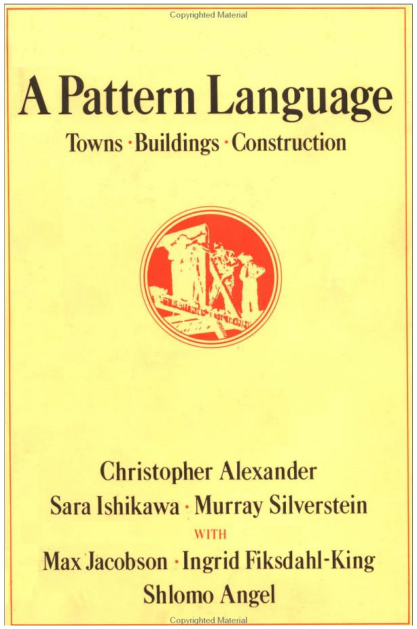
http://comp322.rice.edu/

Worksheet #26 solution: use of tryLock()

Rewrite the transferFunds() method below to use j.u.c. locks with calls to tryLock (see slide 8) instead of synchronized. Your goal is to write a correct implementation that never deadlocks, unlike the buggy version below (which can deadlock). Assume that each Account object already contains a reference to a ReentrantLock object dedicated to that object e.g., from.lock() returns the lock for the from object. Sketch your answer below using pseudocode.

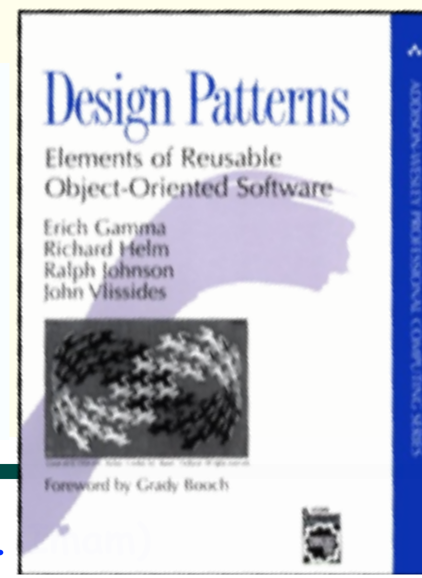
```
public void transferFunds(Account from, Account to, int amount) {
  while (true) {
    boolean fromFlag = from.lock.trylock();
    if (!fromFlag) continue; //acquire from.lock
    boolean toFlag = to.lock.trylock();
    if (!toFlag) { from.lock.unlock(); continue; }
    try { from.subtractFromBalance(amount);
          to.addToBalance(amount); break; }
    finally { from.lock.unlock(); to.lock.unlock(); }
  } // while
}
```

Design Patterns = formal discipline of design



- **Christopher Alexander's approach to (civil) architecture:**
  - **A design pattern "describes a problem which occurs over and over again in our environment, and then describes the core of the solution to that problem, in such a way that you can use this solution a million times over, without ever doing it the same way twice."** *Page x*, ***A Pattern Language,*** **Christopher Alexander, 1977**
- **A pattern language is an organized way of tackling an architectural problem using patterns**

- The Design Patterns book turned object oriented design from an "art" to a systematic design discipline.



Example of OO Design Pattern: Visitor

```
class Employee {
 private int vacationDays; private String SSN;
 public void accept(Visitor v) { v.visit(this); }
 . . .
}
abstract class Visitor {
 public abstract void visit(Employee emp);
}
class VacationVisitor extends Visitor {
 private int totalDays;
 public VacationVisitor() { total_days = 0; }
 public void visit(Employee emp) {
   totalDays += emp.getVacationDays();
 }
 public int getTotalDays() { return totalDays; }
}
. . .
VacationVisitor v = new VacationVisitor();
emp1.accept(v); emp2.accept(v); ...
... v.getTotalDays() ...
```

Patterns in Parallel Programming

- Can a pattern language/taxonomy providing guidance for the entire development process make parallel programming easier?
  - Need to identify basic patterns, along with refinements (usually for efficiency)
  - By relating HJ constructs to parallel programming patterns, you can apply HJ concepts to any parallel programming model you encounter in the future
- Algorithmic Patterns
  - Selection of task and data decompositions to solve a given problem in parallel
    - Task decomposition = identification of parallel steps
    - Data decomposition = partitioning of data into task-local vs. shared storage classes
  - Examples: Parallel Loops, Parallel Tasks, Reductions, Dataflow, Pipeline

Selecting the Right Pattern
(adapted from page 9, Parallel Programming w/ Microsoft .Net)

Application characteristics	Algorithmic pattern	Relevant HJ constructs
Sequential loop with independent iterations	1) Parallel Loop	forall, forasync
Independent operations with well-defined control flow	2) Parallel Task	async, finish
Aggregating data from independent tasks/iterations	3) Parallel Aggregation (reductions)	finish accumulators
Ordering of steps based on data flow constraints	4) Futures	futures, data-driven tasks
Divide-and-conquer algorithms with recursive data structures	5) Dynamic Task Parallelism	async, finish
Repetitive operations on data streams	6) Pipelines	phasers, actors

How to select parallel constructs in general?

1. Think of how to decompose your program into tasks
   ⇒ async, future
2. Think of how to synchronize task creation and termination
   ⇒ finish, future-get, async-await
3. Think of where multiple tasks need to operate on shared data
   ⇒ Deterministic sharing: finish accumulators
   ⇒ Nondeterministic sharing: atomic variables, isolated, actors
4. Think of how to make your program more efficient
   ⇒ Recursive tasks: seq clause (threshold condition)
   ⇒ Parallel loops: iteration grouping (chunking)
   ⇒ SPMD model: replace synchronizations in #2 by barriers/phasers
   ⇒ Isolated: use of atomic variables or object-based isolation
5. Think of when you need lower-level control beyond HJ-lib (should be rare)
   ⇒ Time-outs: Java threads and locks
   ⇒ Advanced locking: Java locks with tryLock()

Safety vs. Liveness

- In a concurrent setting, we need to specify both the safety and the liveness properties of an object
- Need a way to define
  - Safety: when an implementation is functionally correct (does not produce a wrong answer)
  - Liveness: the conditions under which it guarantees progress (completes execution successfully)

- Data race freedom is a desirable safety property for most parallel programs
- Linearizability is a desirable safety property for most concurrent objects

Liveness

- Liveness = a program's ability to make progress in a timely manner
- Is termination a requirement for liveness?
  - some applications are designed to be non-terminating
- Different levels of liveness guarantees (from weaker to stronger)
  1. Deadlock freedom
  2. Livelock freedom
  3. Starvation freedom
  4. Bounded wait

Terminating Parallel Program Executions

- A parallel program execution is terminating if all sequential tasks in the program terminate
- Example of a nondeterministic data-race-free program with a nonterminating execution

```
p.x = false;
finish {
  async { // S1
     boolean b = false; do { isolated b = p.x; } while (! b);
  }
  isolated p.x = true; // S2
} // finish
```

- Some executions of this program may be terminating, and some not
- Cannot assume in general that statement S2 will ever get a chance to execute if async S1 is nonterminating e.g., consider case when program is executed with only one worker

1. Deadlock-Free Parallel Program Executions

- A parallel program execution is *deadlock-free* if no task's execution remains incomplete due to it being blocked awaiting some condition
- Example of a program with a deadlocking execution

```
DataDrivenFuture left = new DataDrivenFuture();
DataDrivenFuture right = new DataDrivenFuture();
finish {
  async await ( left ) right.put(rightBuilder()); // Task1
  async await ( right ) left.put(leftBuilder()); // Task2
}
```

- In this case, Task1 and Task2 are in a deadlock cycle.
  - Three constructs that can lead to deadlock in HJ: async await, finish + actors, explicit phaser wait (instead of next)
  - There are many mechanisms that can lead to deadlock cycles in other programming models (e.g., thread join, synchronized, locks in Java)

2. Livelock-Free Parallel Program Executions

- A parallel program execution exhibits *livelock* if two or more tasks repeat the same interactions without making any progress (special case of nontermination)
- Livelock example:

```
// Task 1
incrToTwo(AtomicInteger ai) {
  // increment ai till it reaches 2
  while (ai.incrementAndGet() < 2);
}
```

```
// Task 2
decrToNegativeTwo(AtomicInteger ai) {
  // decrement ai till it reaches -2
  while (a.decrementAndGet() > -2);
}
```

- Many well-intended approaches to avoid deadlock result in livelock instead
- Any data-race-free HJ program without isolated/atomic-variables/actors is guaranteed to be livelock-free (may be nonterminating in a single task, however)

3. Starvation-Free Parallel Program Executions

- A parallel program execution exhibits *starvation* if some task is repeatedly denied the opportunity to make progress
  - Starvation-freedom is sometimes referred to as “lock-out freedom”
  - Starvation is possible in HJ programs, since all tasks in the same program are assumed to be cooperating, rather than competing
    - If starvation occurs in a deadlock-free HJ program, the “equivalent” sequential program must be non-terminating
- Classic source of starvation: “Priority Inversion” problem for OS threads
  - Thread A is at high priority, waiting for result or resource from Thread C at low priority
  - Thread B at intermediate priority is CPU-bound
  - Thread C never runs, hence thread A never runs
  - Fix: when a high priority thread waits for a low priority thread, boost the priority of the low-priority thread

Related Concepts: Progress Condition

- A resource is said to be *obstruction*-free if it is deadlock-free
- A resource is said to be lock-free if it is livelock-free and deadlock-free
- A resource is said to be wait-free if it is starvation-free, livelock-free, and deadlock-free
  - Question: how to bound the wait duration?

4. Bounded Wait

- A parallel program execution exhibits bounded wait if each task requesting a resource should only have to wait for a bounded number of other tasks to “cut in line” i.e., to gain access to the resource after its request has been registered.
- If bound = 0, then the program execution is fair

A metaphor for Bounded Wait

- **Progress: If no process is waiting in its critical section and several processes are trying to get into their critical section, then entry to the critical section cannot be postponed indefinitely**

- **Bounded Wait: A process requesting access to a resource should only have to wait for a bounded number of other processes to access the resource that requested access after it**

A "cut-through" could cause unbounded wait for folks in the loop!