IN5170 Models of Concurrency

Lecture 1: Introduction

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Question

Why parallel programs?

- Better? Faster?
- More natural? More abstract?

Motivation

Concurrency is Everywhere and Challenging

- Multiple computations at the same time
- Networks, programs, even single-threaded application!
- Source of serious flaws in systems: *safety*, *security*, *privacy*
- Hard or impossible to test concurrent systems – enormous amount of executions

Concurrency has Many Facets

- Programming languages use many different concurrency mechanisms
    - Multi-threading with shared state
    - Message passing, channels
    - Go-routines, async/await, futures
    - ...
- Modern languages build on these concurrency mechanisms, cf. Go, Swift, Rust, ...
- What is the essence of these mechanisms and how should we use them?

IN5170 - Models of Concurrency

Learning Outcomes

- Fundamental issues related to cooperating parallel software
- How to think when developing parallel/concurrent software
- Language mechanisms, design patterns, and paradigms for programming concurrent systems
- Examples in modern mainstream programming languages

What this course is not about . . .

- Exploiting data parallelism
- Hardware-level concurrency

General Info

Structure

- **Part 1:** Shared Memory (and Java)
- **Part 2:** Message Passing (and Go)
- **Part 3:** Analyses and Tool Support (and Rust)

Exercises, Obligs, Exam

- (Almost) weekly exercise sessions, two obligatory assignments, six optional assignments
- **Exam 28.11.2023**, check website for details

Literature

- First part: **G. R. Andrews. Foundations of Multi-threaded, Parallel, and Distributed Programming**. Addison Wesley, 2000 (Chapters 1 to 10).
- Second and third part: Slides from the lectures, supplementary material

The course is being modernized, some topics from the last years have been replaced

General Info

Rooms

- **Lectures:** 12:15 on mondays in Python
- **Exercises:** 14:15 on thursdays in Pascal
- First exercise next week

Teaching Team

For questions, contact as follows:

- **Einar Broch Johnsen** (Part 1, Exam)
- **Silvia Lizeth Tapia Tarifa** (Part 2)
- **Eduard Kamburjan** (Part 3, Organization)
- **Juliane Päßler** (Exercises, Obligs)

Today's Agenda

- Overview ✓
- Motivation and Considerations
- Critical Sections and the `await`-language

Reading material: Chapter 1 of Andrews

Shared Memory Concurrency

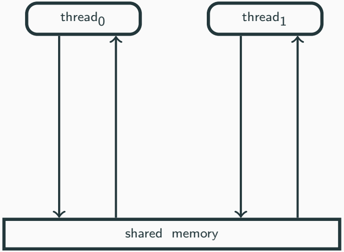
Parallel Processes

- **Sequential program:** one thread of control, full control over the whole memory
- **Parallel/concurrent program:** several threads of control, which *need to exchange information and coordinate execution*

Communication between processes

We will study two different ways to organize communication between processes:

- Reading from and writing to *shared variables* (Now)
- Communication with *messages* between processes (Part 2)



Course Overview — Part 1: Shared variables

Content

- Problems that occur in concurrent systems with shared variables
- Patterns to solve these problems

- Atomic operations
- Interference
- Deadlock, livelock, liveness, fairness
- Locks, critical sections and (active) waiting
- Semaphores and passive waiting
- Monitors
- Java: threads and synchronization
- Rust: ownership of program variables

In contrast to last year: we have removed Hoare logic and formal analysis with invariants

Why Shared Variables?

Why shared (global) variables?

- Reflected in conventional hardware architectures, e.g., multi-core systems
- Reflected in most programming languages as a default (e.g., multi-threading).

Notes

- Even with a single processor and one thread, you may want to use many processes, in order to get a natural partitioning, e.g., several active windows at the same time
- As all concurrency: potentially greater efficiency and/or better latency if several things happen/appear to happen "at the same time".
- Natural interaction for tightly coupled systems

Simple Example

Consider 3 global variables `x`, `y`, and `z` and the following program: x := x+z; y := y+z;

- Can we use parallelism here (without changing the results)?
- If operations can be performed *independently* then performance may increase
- What are the results?

Await

```
Before: {x = a & y = b & z = c}
         x := x+z; y := y+z;
After:  {x = a+c & y = b+c & z = c}
```

Pre/post-conditions

- We use brackets {...} to describe conditions before or after a statement
- These conditions are describing the state, but are not executed
- Java has `assert` that can check such conditions at runtime and the JML language to specify more complex conditions than expressions

Parallel Operator ||

- Consider shared and non-shared program variables, assignment.
- We extend the language with a construction for *parallel composition*:

Await

```
co S1 || S2 || ... || Sn oc
```

- The execution of a parallel composition happens via the *concurrent* execution of the component processes $S_1, \dots, S_n$.
- *Terminates* normally if all component processes terminate normally.

Example

Await

```
{x = a & y = b & z = c}
 x := x+z; y := y+z;
{x = a+c & y = b+c & z = c}
```

Await

```
{x = a & y = b & z = c}
 co x := x+z || y := y+z oc
{x = a+c & y = b+c & z = c}
```

Interaction Between Parallel Processes

Processes can *interact* with each other in *two* different ways:

- *Cooperation* to obtain a result
- *Competition* for common resources

To organize their interactions, we use *synchronization*

Synchronization

Synchronization *restricts* the possible interleavings of parallel processes to avoid unwanted behavior and enforce wanted behavior.

Example

- Increasing *atomicity* and *mutual exclusion* (Mutex) to introduce *critical sections* which can *not* be executed concurrently
- *Condition synchronization* enforces that processes must wait for a specific condition to be satisfied before execution can continue.

Concurrent Processes: Atomic Operations

Definition (Atomic)

An operation is atomic if it cannot be subdivided into smaller operations.

- We can ignore concurrency inside atomic operations as they cannot be interleaved
- A statement with at most one atomic operation, in addition to operations on local variables, can be considered atomic

- What is atomic depends on the language/setting: fine-grained and coarse-grained atomicity.
- Accessing global variables is atomic for this lecture. (In general, this may not be the case, e.g., for `long int`.)
- Assignments `x := e` are *not* atomic

Atomic Operations on Global Variables

Enabling atomic operations on global variables is fundamental for shared memory concurrency

- Process *communication* may be realized by variables:
  a communication channel corresponds to a variable of type vector (or similar)
- Associated with global variables is a set of *atomic operations*
- Typically: read and write, in hardware, e.g. LOAD/STORE to registers
- Channels can also be seen as global variables: *send* and *receive*
- Atomic operations on a variable x are called x-operations

Our goal:

Mutual exclusion

Make *composed* statements atomic so they cannot happen simultaneously.

. . . but observe: the more atomic we make the program, the less parallel execution can occur!

Example

Await

```
                P1                  P2
{x = 0} co x := x+1 || x := x−1 oc {?}
```

Each statement actually consists of *3* operations, e.g., P_1 is

```
read x; inc; write x;
```

Atomic x-operations:

- P1 reads value of x (R1)
- P1 writes a value into x (W1)
- P2 reads value of x (R2)
- P2 writes a value into x (W2)

What is the final state of our program?

Interleaving & Possible Execution Sequences (I)

The four operations cannot be executed in any order, the *program order* gives two constraints

- R1 must happen before W1
- R2 must happen before W2

Definition (Program Order)

- Two statements S_1, S_2 are program-ordered if they are in the same thread of the program, and S_1 occurs before S_2.
- Two operations O_1, O_2 from the same statement are program-ordered if O_1 occurs before O_2 in the translation of the statement.

In the example, `inc` and `dec` (“-1”) are process-local, so we can ignore them

Interleaving & Possible Execution Sequences (II)

Definition (Interleaving)

An interleaving of two sequences A, B is a sequence C, such that

- exactly all elements of A and B are elements of C, and
- the order of elements in A (resp. B) is respected in C

An interleaving may have additional constraints (for us, e.g, program order).

Interleavings for our example:

R1	R1	R1	R2	R2	R2
W1	R2	R2	R1	R1	W2
R2	W1	W2	W1	W2	R1
W2	W2	W1	W2	W1	W1
0	-1	1	-1	1	0

Non-determinism

- Final values for x: $\{0, 1, -1\}$
- As (post)-condition: $-1 \leq x \leq 1$
- Which one is chosen during an execution?

Await

```
{x = 0} co x := x+1 || x := x-1 oc {-1 <= x <= 1}
```

- **Non-determinism:** some choices for the program are decided during execution
- For us: the exact interleaving of instructions
- In practice, choices are not “random”, but depend on factors *outside* the program code:
  - Timing of the threads
  - Scheduler of the operating system
  - ...

Execution-space Explosion

How many interleavings of statements are possible for one given input?

- Assume that we have 3 processes, each with the same number of atomic operations, and the same starting state
- Consider executions of $P_1 \parallel P_2 \parallel P_3$

nr. of atomic op's	**nr. of executions**
2	90
3	1680
4	34 650
5	756 756

- Factorial growth!
- Different executions can lead to different final states.
- Even for simple systems: *impossible* to consider every possible execution in isolation

Factorial Explosion

The number of executions grows exponentially!

For n processes with m atomic statements each:

$$\text{number of executions} = \frac{(n * m)!}{m!^n}$$

- *n=m=5 gives 311680371562560, i.e.* $> 3 * 10^{14}$
- It would take ten million years to check, checking one execution each second!
- ... for each choice of input
- Testing hopeless as a validation technique!

How can we reduce the complexity?

The “at-most-once” Property

Fine-grained atomicity

Only the most basic operations (R/W) are atomic

- However, some non-atomic interactions appear to be atomic
- Note expressions only perform read-accesses (unlike statements)
- A *critical reference* in an expression e is a variable that is changed by another process
- An expression without critical references is evaluated as if atomic

Definition (At-most-once property)

$x := e$ satisfies the *amo*-property if either

1. e contains *no* critical reference, or
2. e contains *at most one* critical reference and x is not *referenced* by other processes

Assignments with the at-most-once property can be considered atomic!

At-most-once examples

`x`, `y` shared variables, `r`, `s` local variables

Await

```
{x=y=0} co x := x+1 || y := x+1 oc {x = 1 & (y = 1 | y = 2)}
{x=y=0} co x := y+1 || y := x+1 oc {(x,y) ∈ {(1,1),(1,2),(2,1)}}
{x=y=0} co x := y+1 || x := y+3 || y := 1 oc {y = 1 & 1<=x<=4}
{x=y=0} co r := y+1 || s := y-1 || y := 5 oc {?}
```

Beware of unintuitive behavior:

Await

```
{ x = 0 } co r := x-x || x := 5 oc { r = 0? }
{ x = 0 } co x := x || ... oc { ? }
```

A Minimal Language for Concurrency

The Await Language

- Await is used to illustrate basic ideas about concurrency without boilerplate from mainstream languages
- Their implementation in mainstream languages is shown afterwards

Features of Await

- Standard imperative constructs: sequence (;), assignment, branching, loops
- **co** .. || .. **oc** for parallel execution
- < .. > for atomic sections
- **await** for synchronization

Syntax: The Sequential Part

We use the following syntax for non-parallel control-flow

Declarations

```
int i = 3
int a[1:n]
int a[n] (= int a[0:n-1])
```

Assignments

```
x := e
a[i] := e
x++
sum +:= i
```

- **Sequential composition**
  statement; statement
- **Compound statement (block)**
  {statement}
- **Conditional**
  if (condition) statement
- **While-loop**
  while (condition) statement
- **For-loop**
  for [i=0 to n−1] statement

Parallel Statements

Await

```
co S₁ || S₂ || ... || Sₙ oc
```

- The statements S_i are executed *in parallel* with each other
- The parallel statement terminates when all S_i have terminated ("join" synchronization)

Await

```
{x = 0 & y = 0} co x := 1 || y := 1  oc; z := x+y { z = 2 }
```

Parallel Processes

For modularity, we also allow processes

Await

```
process foo {
    int sum := 0;
    for [i=1 to 10]
      sum +:= 1;
    x := sum;
  }
```

- Processes are declared globally
- All declared processes are started in the beginning and evaluated in an arbitrary order

Example

Await

```
process bar1{
  for [i = 1 to n]
    write(i);
}
```

Await

```
process bar2a{ write(1); }
process bar2b{ write(2); }
```

Await

```
process barn [i=1 to n]{
    write(i);
}
```

Starts one process

The numbers are printed in increasing order.

Starts two processes

The numbers are printed in arbitrary order because the execution order of the processes is *non-deterministic*.

Starts *n* processes

The numbers are printed in arbitrary order.

Semantic Concepts (“Interleaving Semantics”)

- A *state* in a parallel program consists of the values of the variables at a given moment in the execution.
- Each process executes independently of the others by *modifying* global variables using atomic operations.
- Do we really need to consider all interleavings to reason about possible states?
  - How to exclude some interleavings?
  - How to make reasoning modular and compositional?

Next, a first helping concept: interference

Read- and Write-variables

- $\mathcal{V}$: statement $\cup$ expression $\rightarrow \mathcal{P}$(variable): set of global variables in a statement or expression
- $\mathcal{W}$: statement $\rightarrow \mathcal{P}$(variable): set of global *write*–variables

Read-variables

$$\begin{array}{rcl}
\mathcal{V}(\mathsf{x} := \mathsf{e}) & = & \mathcal{V}(\mathsf{e}) \cup \{\mathsf{x}\} \\
\mathcal{V}(\mathsf{S}_1; \mathsf{S}_2) & = & \mathcal{V}(\mathsf{S}_1) \cup \mathcal{V}(\mathsf{S}_2) \\
\mathcal{V}(\text{if (b) then S}) & = & \mathcal{V}(b) \cup \mathcal{V}(\mathsf{S}) \\
\mathcal{V}(\text{while(b)S}) & = & \mathcal{V}(\mathsf{b}) \cup \mathcal{V}(\mathsf{S}) \\
\text{Remaining cases analogous} & &
\end{array}$$

$\mathcal{W}$ analogously, except the only difference for read-only expressions.

$$\mathcal{W}(\mathit{expression}) = \emptyset$$

Example
$\mathcal{W}(\mathsf{x} := \mathsf{e}) = \{\mathsf{x}\}$

Disjoint Processes

Interference freedom

Processes without common global variables are *interference-free*

$$\mathcal{V}(S_1) \cap \mathcal{V}(S_2) = \emptyset$$

- Statements obviously cannot perform any action that influence each other
- As all interleavings are the same, one can just run $S_1; S_2$ for analysis
- Sequence $S_1; S_2$ is of course less performant

- If variables accessed by both processes are *read-only* variables, the same holds
- Is the following *interference criterion* is sufficient?

$$\mathcal{W}(S_1) \cap \mathcal{W}(S_2) = \emptyset$$

- Write-variables are important for *race conditions*, *critical* references/amo-property, ...
- If only read-only variables are accessed, no races or critical references exist

Critical Sections and Invariants

Properties

**Read-only variables are a very coarse way to think,
how to express more specific properties?**

- A *property* is a predicate over a program, resp. its execution and reachable states
- A program has a property, if the property is true for all possible executions of the program

Classification (I)

- Safety property: program will never reach an undesirable state
- Liveness property: program will eventually reach a desirable state

Classification (II)

- *Termination*: all histories are finite.
- *Partial correctness*: *If* the program terminates, it is in a desired final state (safety property).
- *Total correctness*: The program terminates and is partially correct.

How to Check Properties of Programs?

- *Testing* or *debugging* increases confidence in a program, but gives no guarantee of correctness.
- *Operational reasoning* considers *all* executions of a program explicitly
- *Formal analyses* reason about the properties of a program without considering the executions one by one.

Dijkstra's dictum:

A test can only show errors, but never prove that a program is correct!

Properties: Invariants (I)

Definition (Invariant)

An *invariant* is a property of program states, that holds for all reachable states of a program.

- *Invariant* (adj): constant, unchanging
- Prototypical safety property
- Appropriate for non-terminating systems (does not require a final state)
- *All* reachable states often too strong

Kinds of Invariants

- Strong invariant: Holds for all reachable states
- Weak invariant: Holds for all states where an atomic block starts or ends
- Loop invariant: Holds at the start and end of a loop body
- Global invariant: Reasons about state of many processes
- Local invariant: Reasons about state of one process

Properties: Invariants (II)

- How to show that a program has a weak invariant?
- Without exploring all executions?

Induction for Invariants

One can show that a program has a weak invariant by

1. Showing that the invariant property holds initially,
2. and that each atomic statement maintains the property

Critical Sections

To enforce atomicity, we have a special construct in the language : <S> performs S atomically

Use of Critical Sections

- When the processes interfere: *synchronization* to restrict the possible interleavings
- Synchronization gives coarser grained atomic operations ("atomic blocks")
- Combines operations into an *atomic lock* where the process shall not be interrupted

Characteristics of Atomic Operations

- Internal states are *not visible* to other processes.
- Variables *cannot* be changed underway by other processes.
- *S*: executed like a *transaction*

Await

```
int x:=0; co <x:=x+1> || <x:=x−1> oc {x=0}
```

Conditional Critical Sections

Await statement

The <**await** (B) S > statement executes the statement S once the boolean condition B holds.

- Boolean condition B: *await condition*, evaluated atomically
- Body S: *critical section* executed atomically

The following delays the decrement until $y > 0$ holds – or does not terminate if it never holds

Await

```
<await (y > 0) y := y-1> { y >= 0 }
```

- Important that B has no side-effects!

Typical Pattern for Critical Sections

- One wants to avoid using atomic blocks as much as possible
- Use them in certain places to enable correct, interleaved executions

Await

```
int counter = 1;  // global variable

// start CS
< await (counter > 0) counter := counter-1; >
critical statements;
// end CS
counter := counter+1
```

- "Critical statements" *not* enclosed in atomic block
- Invariant: $0 \leq counter \leq 1$ (= counter acts as *binary lock*)
- Next lectures: patterns for correctness while minimizing atomic blocks

Example: Synchronization of Strongly Coupled Producer-Consumer System

Await

```
int buf, p := 0; c := 0;
```

Await

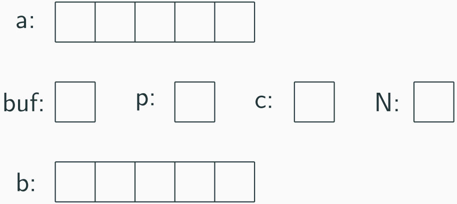
```
process Producer {
 int a[N];   ...
 while(p < N){
   <await (p = c) >;
   buf := a[p];
   p := p+1;
 }}
```

Await

```
process Consumer {
  int b[N];   ...
  while (c < N) {
    <await (p>c) >;
    b[c] := buf;
    c := c+1;
 }}
```

- `buf` as only shared variable, acting as a one element buffer
- Tasks of synchronization:
  - Coordinating the “speed” of the two processes
  - Avoiding to read data which is not yet produced

Example (Continued)



a:

buf: p: c: N:

b:

- A strong invariant holds in *all states* in *all* executions of the program.
- *Global invariant*: $\texttt{c} \leq \texttt{p} \leq \texttt{c+1}$
- *Local invariant (Producer)*: $0 \leq \texttt{p} \leq \texttt{N}$

Wrap-Up

Summary

- Shared memory
- Synchronization
- Atomic operations,
- Interleavings
- `await`-language and critical sections