INF4140 - Models of concurrency

Høsten 2013

Institutt for informatikk, Universitetet i Oslo

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Intro

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Intro, lecture 1

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Today's agenda

Introduction

- overview
- motivation: why is this course important
- simple examples and considerations

Start

a bit about

- concurrent programming with critical sections and waiting, read also Chap 1 for a little background
- interference
- the await language

What this course is about

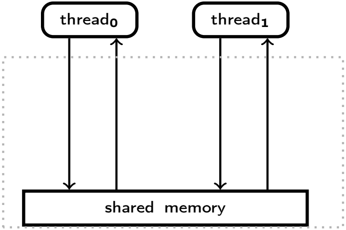
- Fundamental issues related to cooperating parallel processes
- How to think about developing parallel processes
- Various language mechanisms, design patterns, and paradigms
- Deeper understanding of parallel processes:
  - (informal and somewhat formal) analysis,
  - properties

Parallel processes

- Sequential program: one control flow thread
- Parallel program: several control flow threads

Parallel processes need to exchange information.
We will study two different ways to organize communication between processes:

- Reading from and writing to *shared variables* (part I of the course)
- Communication with *messages* between processes (part II of the course)


thread0
thread1
shared memory

course overview – part I: Shared variables

- atomic operations
- interference
- deadlock, livelock, liveness, fairness
- parallel programs with locks, critical sections and (active) waiting
- semaphores and passive waiting
- monitors
- formal analysis (Hoare logic), invariants
- Java: threads and synchronization

Course overview – part II: Communication

- asynchronous and synchronous message passing
- Basic mechanisms: RPC (remote procedure call), rendezvous, client/server setting, channels
- Java's mechanisms
- analysis using histories
- asynchronous systems

Why shared (global) variables?

- reflected in HW in conventional architectures
- Here's the situation: There may be several CPUs inside one machine.
- natural interaction for tightly coupled systems
- used in many important languages, e.g., Java's multithreading model.
- do as if one has many processes, in order to get a natural partitioning
- potentially greater efficiency if several things happen/appear to happen "at the same time"

e.g.: several active windows at the same time

Simple example

Global variables: x, y, and z. Consider the following program:

$$x := x + z; y := y + z;$$

Pre/post-condition

- executing a program (fragment) $\Rightarrow$ state-change
- the conditions describe the state of the global variables before and after a program statement
- These conditions are meant to give an understanding of the program, and are not part of the executed code.

Can we use parallelism here?

If operations can be performed *independently* of one another, then concurrency may increase performance

Simple example

Global variables: x, y, and z. Consider the following program:

pre		post
{x is a and y is b}	$x := x + z; y := y + z;$	{x is a+z and y is b+z}

Pre/post-condition

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- the conditions describe the state of the global variables before and after a program statement
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Can we use parallelism here?

If operations can be performed *independently* of one another, then concurrency may increase performance

Extend the language with a construction for *parallel composition*:

$$\text{co} \;\; S_1 \parallel S_2 \parallel \ldots \parallel S_n \;\; \text{oc}$$

Execution of a parallel composition happens via the concurrent execution of the component processes $S_1, \ldots, S_n$ and terminates normally if all component processes terminate normally.
Example Thus we can write an example as follows:

Example

$$\{ \; x \text{ is } a, \; y \text{ is } b \; \} \; x := z \; ; \;\; y := y + x; \; \{ \; x \text{ is } a + z, \; y \text{ is } b + z \; \}$$

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Example

$$\{\ x \text{ is } a,\ y \text{ is } b\ \}\ \textsf{co}\, x := z\ \parallel\ y := y{+}x;\ \textsf{oc}\ \{\ x \text{ is } a+z,\ y \text{ is } b+z\ \}$$

Interaction between processes

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

- *cooperation* to obtain a result
- *competition* for common resources

The organization of this interaction is what we will call *synchronization*.

- increasing "atomicity" and *Mutual exclusion (Mutex).*: We introduce *critical sections* of which can*not* be executed concurrently
- *Condition synchronization.* A process must wait for a specific condition to be satisfied before execution can continue.

Definition (Atomic)

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

Note

- A statement with at most one atomic operation, in addition to operations on local variables, can be considered atomic!
- We can do as if atomic operations do not happen concurrently!

- What is atomic depends on the language/setting: fine-grained and coarse-grained atomicity.
- e.g.: Reading and writing of a global variable is usually atomic.
- Some (high-level) languages: assignments $x := e$ atomic operation, others not (reading of the variables in the expression e, computation of the value e, followed by writing to x.)

Atomic operations on global variables

- fundamental for (shared var) concurrency
- also: process *communication* may be represented by variables: communication channel corresponds to a variable of type vector.
- associated to global variables: a set of *atomic operations*
- typically: read + write,
- in HW, e.g. LOAD/STORE
- channels as gobal data: *send* and *receive*
- x-operations: atomic operations on a variable x

Mutual exclusion

Atomic operations on a variable cannot happen simultaneously.

$$\{\ x = 0\ \}\quad \text{co}\ \overbrace{x := x + 1}^{P_1} \parallel \overbrace{x := x - 1}^{P_2}\ \text{oc};\quad \{?\}$$

final state? (i.e., post-condition)

- Assume:
  - each process is executed on its own processor
  - and/or: the processes run on a multi-tasking OS

  and that x is part of a shared state space, i.e. a shared var
- Arithmetic operations in the two processes can be executed simultaneously, but read and write operations on x must be performed sequentially/atomically.
- *order* of these operations: dependent on relative processor speed and/or scheduling
- outcome of such programs: *difficult* to predict!

$$\begin{array}{ccc} & P_1 & P_2 & \\ \{\, x = 0 \,\} & \mathbf{co}\; x := x + 1 & \| \; x := x - 1 \;\mathbf{oc}; & \{?\} \end{array}$$

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

4 atomic x-operations:

- P_1 reads (R1) value of x
- P_1 writes (W1) a value into x,
- P_2 reads (R2) value of x, and
- P_2 writes (W2) a value into x.

Interleaving & possible execution sequences

- "program order":[1]
  - R1 must happen before W1 and
  - R2 before W2
- `inc` and `dec` ("-1") work process-local[2]

⇒ remember (e.g.) inc ; write x behaves "as if" atomic (alternatively read x; inc)

operations can be sequenced in 6 ways ("interleaving")

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

[1] A word aside: as natural as this seems: in a number of modern architecture/modern languages & their compilers, this is not guaranteed!. cf. Java's memory model

[2] e.g.: in an arithmetic register, or a local variable (not mentioned in the code).

- final states of the program (in x): $\{0, 1, -1\}$
- Non-determinism: result can vary depending on factors *outside* the program code
  - timing of the execution
  - scheduler
- as (post)-condition:[3] $x = -1 \lor x = 0 \lor x = 1$

$$\{\ \}\quad x := 0; \mathsf{co}\ x := x + 1 \parallel x := x - 1\ \mathsf{oc};\quad \{\ x = -1 \lor x = 0 \lor x = 1\ \}$$

[3] Of course, things like $x \in \{-1, 0, 1\}$ or $-1 \leq x \leq 1$ are equally adequate formulations of the postcondition.

State-space explosion

- Assume 3 processes, each with the same number of atomic operations
- 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

- different executions can lead to different final states.
- even for simple systems: *impossible* to consider every possible execution

For n processes with m atomic statements each:

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

fine grained atomicity

only very most basic operations (R/W) atomic "by nature"

- however: some non-atomic interactions appear to be atomic.
- note: expressions do only read-access ($\neq$ statements)
- *critical reference* (in an e): a variable changed by another process
- e without critical reference $\Rightarrow$ evaluation of e as if atomic

Definition (At-most-once property)

$x := e$ satisfies the "amo"-property if

1. e contains *no* crit. reference
2. e with *at most one* crit. reference & x not *referenced*[a] by other proc's

[a] or just read

assigments with at-most-once property can be considered atomic

The "at-most-once" property

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At most once examples

- In all examples: initially $x = y = 0$. And r, r' etc: local var's (registers)
- co and oc around $\dots \parallel \dots$ omitted

$$x := x + 1 \parallel y := x + 1$$
$$x := y + 1 \parallel y := x + 1 \qquad \{ (x, y) \in \{(1,1),(1,2),(2,1)\} \}$$
$$x := y + 1 \parallel x := y + 3 \parallel y := 1 \qquad \{y = 1 \wedge x = 1, 2, 3, 4\}$$
$$r := y + 1 \parallel r' := y - 1 \parallel y := 5$$
$$r := x - x \parallel \dots \qquad \{\text{is r now 0?}\}$$
$$x := x \parallel \dots \qquad \{\text{same as skip?}\}$$
$$\texttt{if } y > 0 \texttt{ then } y := y - 1 \texttt{ fi} \parallel \texttt{if } y > 0 \texttt{ then } y := y - 1 \texttt{ fi}$$

The course's first programming language: the await-language

- the usual sequential, imperative constructions such as assignment, if-, for- and while-statements
- cobegin-construction for parallel activity
- processes
- critical sections
- await-statements for (active) waiting and conditional critical sections

We use the following syntax for non-parallel control-flow[4]

Declarations	Assignments
`int i = 3;`	`x := e;`
`int a[1:n];`	`a[i] := e;`
`int a[n];`[5]	`a[n]++;`
`int a[1:n] = ([n] 1);`	`sum +:= i;`

Seq. composition	*statement*; *statement*
Compound statement	`{statements}`
Conditional	`if` *statement*
While-loop	`while` (*condition*) *statement*
For-loop	`for` $[i = 0$ `to` $n - 1]$*statement*

[4] The book uses more C/Java kind of conventions, like = for assignment and == for logical equality.

[5] corresponds to: `int a[0:n-1]`

Parallel statements

$$\text{co } S_1 \parallel S_2 \parallel \ldots \parallel S_n \text{ oc}$$

- The statement(s) of each arm S_i are executed *in parallel* with thos of the other arms.
- Termination: when all "arms" S_i have terminated ("join" synchronization)

Parallel processes

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

- Processes evaluated in arbitrary order.
- Processes are declared (as methods/functions)
- side remark: the convention "declaration = start process" is *not* used in practice.[6]

[6] one typically separates declaration/definition from "activation" (with good reasons). Note: even *instantiation* of a runnable interface in Java starts a process. Initialization (filling in initial data into a process) is tricky business.

Example

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

Starts one process.

The numbers are printed in increasing order.

```
process bar2[i=1 to n] {
write(i);
}
```

Starts n processes.

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

Read- and write-variables

- $\mathcal{V}$: *statement* $\longrightarrow$ *variable set*: set of global variables in a statement (also for expressions)
- $\mathcal{W}$: *statement* $\longrightarrow$ *variable set* set of *write*–variables

$$
\begin{array}{rcl}
\mathcal{V}(x := e) & = & \mathcal{V}(e) \cup \{x\} \\
\mathcal{V}(S_1; S_2) & = & \mathcal{V}(S_1) \cup \mathcal{V}(S_2) \\
\mathcal{V}(\texttt{if}\ \ b\ \texttt{then}\ S) & = & \mathcal{V}(b) \cup \mathcal{V}(S) \\
\mathcal{V}(\texttt{while}\ (b)S) & = & \mathcal{V}(b) \cup \mathcal{V}(S)
\end{array}
$$

$\mathcal{W}$ analogously, except the most important difference:

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

- note: expressions side-effect free

Disjoint processes

- Parallel processes without common (=shared) global variables: without *interference*

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

- *read-only* variables: no interference.
- The following *interference criterion* is thus sufficient:

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

- cf. notion of *race* (or *race condition*)
- remember also: *critical* references/amo-property
- programming practice: `final` variables in Java

Semantic concepts

- A *state* in a parallel program consists of the values of the global variables at a given moment in the execution.
- Each process executes independently of the others by *modifying* global variables using atomic operations.
- An execution of a parallel program can be modelled using a *history*, i.e. a sequence of operations on global variables, or as a sequence of states.
- For non-trivial parallel programs there are *very many possible histories*.
- synchronization: conceptually used to *limit* the possible histories/interleavings.

Properties

- property = predicate over programs, resp. their histories
- A (true) *property* of a program[7] is a predicate which is true for all possible histories of the program.
- Two types:
  - *safety* property: program will not reach an undesirable state
  - *liveness* property: program will reach a desirable state.
- *partial correctness*: *If* the program terminates, it is in a desired final state (safety property).
- *termination*: all histories are finite.[8]
- *total correctness*: The program terminates and is partially correct.

[7] the program "has" that property, the program satisfies the property ...

[8] that's also called *strong* termination. Remember: non-determinism.

Properties: Invariants

- *invariant* (adj): constant, unchanging
- cf. also "loop invariant"

Definition (Invariant)

an invariant = state property, which holds for holds for all reachable states.

- safety property
- appropriate for also non-terminating systems (does not talk about a final state)
- *global* invariant talks about the state of many processes at once, preferably the entire system
- *local* invariant talks about the state of one process

proof principle: induction

one can show that an invariant is correct by

1. showing that it holds initially,
2. and that each atomic statement maintains it.

How to check properties of programs?

- *Testing* or *debugging* increases confidence in a program, but gives no guarantee of correctness.
- *Operational reasoning* considers *all* histories of a program.
- *Formal analysis*: Method for reasoning about the properties of a program without considering the histories one by one.

Dijkstra's diktum:

A test can only show errors, but "never" prove correctness!

Mutual exclusion: combines sequences of operations in a *critical section* which then behave like atomic operations.

- When the non-interference requirement parallel processes does not hold, we use *synchronization* to restrict the possible histories.
- Synchronization gives coarse-grained atomic operations.
- The notation $\langle S \rangle$ means that S is performed atomically.[9]

Atomic operations:

- Internal states are *not visible* to other processes.
- Variables *cannot* be changed underway by other processes.

Example The example from before can now be written as:

$$\texttt{int}\ x = 0; \texttt{co}\langle x := x + 1\rangle \parallel \langle x := x - 1\rangle\ \texttt{oc}\{\ x = 0\ \}$$

[9] In programming languages, one could find it as $\texttt{atomic}\{S\}$ or similar.

Conditional critical sections

Await statement

$$\langle \texttt{await}(b)\ S \rangle$$

- boolean condition b: *await condition*
- body S: executed atomically (conditionally on b) (indicated by)

  Example

  $$\langle \texttt{await}(y > 0)\ y := y - 1 \rangle$$

- *synchronization*: decrement *delayed* until (if ever) $y > 0$ holds

Conditional critical sections (2)

- two "special cases"
  - mutex/unconditional critical section

$$\langle x := 1; y := y + 1 \rangle$$

  - Condition synchronization:[10]

$$\langle \texttt{await}(counter > 0)\ \rangle$$

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

- "critical statements" *not* enclosed in ⟨angle brackets⟩. Why?
- invariant: $0 \leq counter \leq 1$ (= counter acts as "*binary lock*")
- very bad style would be: touch counter inside "crit. statements" or elsewhere (e.g. access it *not* following the "await-inc-CR-dec" pattern)
- in practice: beware(!) of exceptions in the critical statements

[10] one may also see sometimes just `await`(b): however, eval. of b better be

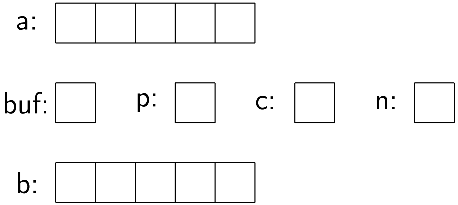
Example: (silly version of) producer/consumer synchronization

- strong *coupling*
- buf as shared variable ("one element buffer")
- synchronization
  - coordinating the "speed" of the two procs (rather stricly here)
  - to avoid, reading data which is not yet produced
  - (related:) avoid w/r conflict on shared memory

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

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

Example (continued)



- An invariant holds in *all states* in *all* histories (traces/executions) of the program.
- *Global Invariant*: $\texttt{c} \leq \texttt{p} \leq \texttt{c+1}$
- *Local Invariant (Producer)*: $\texttt{0} \leq \texttt{p} \leq \texttt{n}$

[1] G. R. Andrews.
Foundations of Multithreaded, Parallel, and Distributed Programming.
Addison-Wesley, 2000.

[2] E. W. Dijkstra.
Solution of a problem in concurrent programming control.
Communications of the ACM, 8(9):569, 1965.