Concurrency Appreciation

Johannes Åman Pohjola
UNSW
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Definitions

Definition

Concurrency is an abstraction for the programmer, allowing programs to be structured as multiple threads of control, called *processes*. These processes may communicate in various ways.

Example Applications: Servers, OS Kernels, GUI applications.

Anti-definition

Concurrency is **not** *parallelism*, which is a means to exploit multiprocessing hardware in order to improve performance.

Sequential vs Concurrent

We could consider a *sequential* program as a sequence (or *total order*) of *actions*:

$$\bullet \longrightarrow \bullet \longrightarrow \bullet \longrightarrow \bullet \longrightarrow \bullet \longrightarrow \bullet \longrightarrow \cdots$$

The ordering here is "happens before". For example, processor instructions:

$$\texttt{LD R0,X} \longrightarrow \texttt{LDI R1,5} \longrightarrow \texttt{ADD R0,R1} \longrightarrow \texttt{ST X,R0}$$

A concurrent program is not a total order but a partial order.

$$\begin{tikzcd}
\circ \arrow[r] \arrow[dr] & \circ \arrow[r] & \circ \arrow[r] & \circ \arrow[r] & \circ \arrow[r] & \circ \arrow[r] & \cdots \\
\bullet \arrow[r] & \bullet \arrow[r] & \bullet \arrow[r] \arrow[urr] & \bullet \arrow[r] & \bullet \arrow[r] & \bullet \arrow[r] & \cdots
\end{tikzcd}$$

This means that there are now multiple possible *interleavings* of these actions — our program is non-deterministic where the interleaving is selected by the scheduler.

Concurrent Programs

Consider the following concurrent processes, sharing a variable n.

var $n := 0$		
p_1: **var** $x := n$;	q_1: **var** $y := n$;	r_1: **var** $z := n$;
p_2: $n := x + 1$;	q_2: $n := y - 1$;	r_2: $n := z + 1$;

Question

What are the possible returned values?

A Sobering Realisation

How many scenarios are there for a program with n processes consisting of m steps each?

	$n = 2$	3	4	5	6
$m = 2$	6	90	2520	113400	$2^{22.8}$
3	20	1680	$2^{18.4}$	$2^{27.3}$	$2^{36.9}$
4	70	34650	$2^{25.9}$	$2^{38.1}$	$2^{51.5}$
5	252	$2^{19.5}$	$2^{33.4}$	$2^{49.1}$	$2^{66.2}$
6	924	$2^{24.0}$	$2^{41.0}$	$2^{60.2}$	$2^{81.1}$

$$\frac{(nm)!}{m!^n}$$

Volatile Variables

var $y, z := 0, 0$	
p_1: **var** x;	q_1: $y := 1$;
p_2: $x := y + z$;	q_2: $z := 2$;

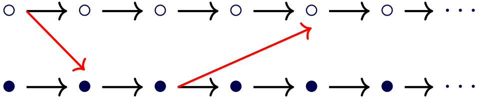
Question

What are the possible final values of x?
What about $x = 2$? Is that possible?
It is possible, as we cannot guarantee that the statement p_2 is executed atomically — that is, as one step.

Typically, we require that each statement only accesses (reads from or writes to) at most one shared variable at a time. Otherwise, we cannot guarantee that each statement is one atomic step. This is called the *limited critical reference* restriction.

Synchronisation

In order to reduce the number of possible interleavings, we must allow processes to synchronise their behaviour, ensuring more orderings (and thus fewer interleavings).



The red arrows are synchronisations.

Atomicity

The basic unit of synchronisation we would like to implement is to group multiple steps into one atomic step, called a *critical section*. A sketch of the problem can be outlined as follows:

forever do	**forever do**
non-critical section	*non-critical section*
pre-protocol	*pre-protocol*
critical section	**critical section**
post-protocol	*post-protocol*

The non-critical section models the possibility that a process may do something else. It can take any amount of time (even infinite). Our task is to find a pre- and post-protocol such that certain atomicity properties are satisfied.

Desiderata

We want to ensure two main properties:

- **Mutual Exclusion** No two processes are in their critical section at the same time.
- **Eventual Entry** (or *starvation-freedom*) Once it enters its pre-protocol, a process will eventually be able to execute its critical section.

Question

Which is safety and which is liveness?
Mutex is safety, Eventual Entry is liveness.

First Attempt

We can implement **await** using primitive machine instructions or OS syscalls, or even using a busy-waiting loop.

var *turn* := 1	
forever do	**forever do**
p_1 *non-critical section*	q_1 *non-critical section*
p_2 **await** $turn = 1$;	q_2 **await** $turn = 2$;
p_3 **critical section**	q_3 **critical section**
p_4 $turn := 2$	q_4 $turn := 1$

Question

Mutual Exclusion? Yup!
Eventual Entry? Nope! What if q_1 never finishes?

Second Attempt

var *wantp*, *wantq* := False, False	
forever do	**forever do**
p_1 *non-critical section*	q_1 *non-critical section*
p_2 **await** $wantq = \text{False}$;	q_2 **await** $wantp = \text{False}$;
p_3 $wantp := \text{True}$;	q_3 $wantq := \text{True}$;
p_4 **critical section**	q_4 **critical section**
p_7 $wantp := \text{False}$	q_7 $wantq := \text{False}$

Mutual exclusion is violated if they execute in lock-step (i.e. $p_1 q_1 p_2 q_2 p_3 q_3$ etc.)

Third Attempt

var *wantp*, *wantq* := False, False	
forever do	**forever do**
p_1 *non-critical section*	q_1 *non-critical section*
p_2 *wantp* := True;	q_2 *wantq* := True;
p_3 **await** *wantq* = False;	q_3 **await** *wantp* = False;
p_4 **critical section**	q_4 **critical section**
p_7 *wantp* := False	q_7 *wantq* := False

Now we have a stuck state (or *deadlock*) if they proceed in lock step, so this violates eventual entry also.

Fourth Attempt

var *wantp*, *wantq* := False, False			
forever do		**forever do**	
p_1	*non-critical section*	q_1	*non-critical section*
p_2	*wantp* := True;	q_2	*wantq* := True;
p_3	**while** *wantq* **do**	q_3	**while** *wantp* **do**
p_4	*wantp* := False;	q_4	*wantq* := False;
p_5	*wantp* := True	q_5	*wantq* := True
	od		**od**
p_6	**critical section**	q_6	**critical section**
p_7	*wantp* := False	q_7	*wantq* := False

We have replaced the deadlock with live lock (looping) if they continuously proceed in lock-step. Still potentially violates eventual entry.

Fifth Attempt

var *wantp*, *wantq* := False, False **var** *turn* := 1	
forever do	**forever do**
p_1 *non-critical section*	q_1 *non-critical section*
p_2 *wantp* = True;	q_2 *wantq* = True;
p_3 **while** *wantq* **do**	q_3 **while** *wantp* **do**
p_4 **if** *turn* = 2 **then**	q_4 **if** *turn* = 1 **then**
p_5 *wantp* := False;	q_5 *wantq* := False;
p_6 **await** *turn* = 1;	q_6 **await** *turn* = 2;
p_7 *wantp* := True	q_7 *wantq* := True
fi	**fi**
od	**od**
p_8 **critical section**	q_8 **critical section**
p_9 *turn* := 2	q_9 *turn* := 1
p_{10} *wantp* := False	q_{10} *wantq* := False

Reviewing this attempt

The fifth attempt (Dekker's algorithm) works well except if the scheduler pathologically tries to run the loop at $q_3 \cdots q_7$ when $turn = 2$ over and over rather than run the process p (or vice versa).

What would we need to assume to prevent this?

Fairness

The *fairness assumption* means that if a process can always make a move, it will eventually be scheduled to make that move.

With this assumption, Dekker's algorithm is correct.

Machine Instructions

There exists algorithms to generalise this to any number of processes (Peterson's algorithm), but they're outside the scope of this course.

What about if we had a single machine instruction to swap two values atomically, `XC`?

var *common* := 1	
var *tp* := 0	**var** *tq* := 0
forever do	**forever do**
p_1 *non-critical section*	q_1 *non-critical section*
repeat	**repeat**
p_2 `XC`(*tp*, *common*)	q_2 `XC`(*tq*, *common*);
p_3 **until** $tp = 1$	q_3 **until** $tq = 1$
p_4 **critical section**	q_4 **critical section**
p_5 `XC`(*tp*, *common*)	q_7 `XC`(*tq*, *common*)

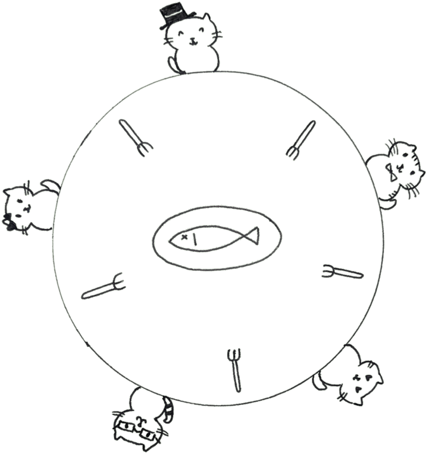
Locks

The variable *common* is called a *lock*. A lock is the most common means of concurrency control in a programming language implementation. Typically it is abstracted into an abstract data type, with two operations:

- *Taking* the lock — the first exchange (step p_2/q_2)
- *Releasing* the lock — the second exchange (step p_5/q_5)

var *lock*			
forever do		**forever do**	
p_1	*non-critical section*	q_1	*non-critical section*
p_2	**take** (*lock*)	q_2	**take** (*lock*);
p_3	**critical section**	q_3	**critical section**
p_4	**release** (*lock*)	q_4	**release** (*lock*);

Dining Philosophers



Five philosophers sit around a dining table with a huge bowl of spaghetti in the centre, five plates, and five forks, all laid out evenly. For whatever reason, philosophers can eat spaghetti only with two forks[a]. The philosophers would like to alternate between eating and thinking.

[a] More convincing with chopsticks.

Looks like Critical Sections

forever do
  think
  pre-protocol
  eat
  post-protocol

For philosopher $i \in 0 \dots 4$:

f_0, f_1, f_2, f_3, f_4

forever do
  think
  take(f_i)
  take$(f_{(i+1) \bmod 5})$
  eat
  release(f_i)
  release$(f_{(i+1) \bmod 5})$

Deadlock is possible (consider lockstep).

Fixing the Issue

f_0, f_1, f_2, f_3, f_4	
Philosophers $0 \ldots 3$	Philosopher 4
forever do	**forever do**
think	*think*
take(f_i)	**take**(f_0)
take$(f_{(i+1) \bmod 5})$	**take**(f_4)
eat	*eat*
release(f_i)	**release**(f_0)
release$(f_{(i+1) \bmod 5})$	**release**(f_4)

We have to enforce a global ordering of locks.