Systems, Networks & Concurrency 2020

4

Non-determinism

Uwe R. Zimmer - The Australian National University

Non-determinism

References for this chapter

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Non-determinism

Definitions

Non-determinism *by design*:

A property of a computation which may have more than one result.

Non-determinism *by interaction*:

A property of the operation environment which may lead to different sequences of (concurrent) stimuli.

Non-determinism

Non-determinism by design

Dijkstra's **guarded commands** (non-deterministic case statements):

```
if  x <= y -> m := x
❑   x >= y -> m := y
fi
```

Selection is non-deterministic for x=y

☞ The programmer needs to design the alternatives as 'parallel' options:
all cases need to be covered and overlapping conditions need to lead to the same result

All true case statements in any language are potentially concurrent and non-deterministic.

Non-determinism

Non-determinism by design

Dijkstra's **guarded commands** (non-deterministic case statements):

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Selection is non-deterministic for x=y

☞ The programmer needs to design the alternatives as 'parallel' options:
all cases need to be covered and overlapping conditions need to lead to the same result

All true case statements in any language are potentially concurrent and non-deterministic.

Numerical non-determinism in **concurrent statements** (Chapel):

```
writeln (+ reduce [i in 1..10] exp (i));
writeln (+ reduce [i in 1..1000000] i ** 2.0);
```

Results may be non-deterministic depending on numeric type

☞ The programmer needs to understand the numerical implications of out-of-order expressions.

Non-determinism

Non-determinism by design

Motivation for non-deterministic design

By explicitly leaving the sequence of evaluation or execution undetermined:

☞ The compiler / runtime environment can directly (i.e. without any analysis) translate the source code into a concurrent implementation.

☞ The implementation gains potentially significantly in performance

☞ The programmer does not need to handle any of the details of a concurrent implementation (access locks, messages, synchronizations, ...)

A programming language which allows for those formulations is required!

☞ current language support: Ada, X10, Chapel, Fortress, Haskell, OCaml, ...

Non-determinism

Non-determinism by interaction

Selective waiting in Occam2

```
ALT
   Guard1
      Process1
   Guard2
      Process2
...
```

- Guards are referring to boolean expressions and/or channel input operations.
- The boolean expressions are local expressions, i.e. if none of them evaluates to true at the time of the evaluation of the ALT-statement, then the process is stopped.
- If all triggered channel input operations evaluate to false, the process is suspended until further activity on one of the named channels.
- Any Occam2 process can be employed in the ALT-statement
- The ALT-statement is non-deterministic (there is also a deterministic version: PRI ALT).

Non-determinism

Non-determinism by interaction

Selective waiting in Occam2

```
ALT
   NumberInBuffer < Size & Append ? Buffer [Top]
      SEQ
         NumberInBuffer := NumberInBuffer + 1
         Top := (Top + 1) REM Size
   NumberInBuffer > 0 & Request ? ANY
      SEQ
         Take ! Buffer [Base]
         NumberInBuffer := NumberInBuffer - 1
         Base := (Base + 1) REM Size
```

- Synchronization on input-channels only (channels are directed in Occam2):
  ☞ to initiate the sending of data (`Take ! Buffer [Base]`), a request need to be made first which triggers the condition: (`Request ? ANY`)

CSP (Communicating Sequential Processes, Hoare 1978) also supports non-deterministic selective waiting

Non-determinism

Non-determinism by interaction

Select function in POSIX

```
int pselect(int n, fd_set *readfds, fd_set *writefds, fd_set *exceptfds,
            const struct timespec *ntimeout, sigset_t *sigmask);
```

with:

- n being one more than the maximum of any file descriptor in any of the sets.
- after return the sets will have been reduced to the channels which have been triggered.
- the return value is used as success / failure indicator.

The POSIX select function implements parts of general selective waiting:

- pselect returns if one or multiple I/O channels have been triggered or an error occured.
- ¬ Branching into individual code sections is not provided.
- ¬ Guards are not provided.

After return it is required that the following code implements a *sequential* testing of *all* channels in the sets.

Non-determinism

Selective Synchronization

Message-based selective synchronization in Ada

Forms of selective waiting:

```
select_statement ::= selective_accept       |
                     conditional_entry_call |
                     timed_entry_call       |
                     asynchronous_select
```

... underlying concept: Dijkstra's guarded commands

`selective_accept` implements ...

- ... wait for more than a single rendezvous at any one time
- ... time-out if no rendezvous is forthcoming within a specified time
- ... withdraw its offer to communicate if no rendezvous is available immediately
- ... terminate if no clients can possibly call its entries

Non-determinism

Selective Synchronization

Message-based selective synchronization in Ada

```
selective_accept ::= select
                       [guard] selective_accept_alternative
                   { or   [guard] selective_accept_alternative }
                   [ else sequence_of_statements ]
                     end select;

guard ::= when <condition> => selective_accept_alternative ::= accept_alternative |
                                                               delay_alternative   |
                                                               terminate_alternative

accept_alternative    ::= accept_statement [ sequence_of_statements ]
delay_alternative     ::= delay_statement  [ sequence_of_statements ]
terminate_alternative ::= terminate;
accept_statement ::= accept entry_direct_name [(entry_index)] parameter_profile [do
                       handled_sequence_of_statements
                     end [entry_identifier]];
delay_statement  ::= delay until delay_expression; | delay delay_expression;
```


Non-determinism

Selective Synchronization

Basic forms of selective synchronization

(select-accept)

```
select
   accept ...
or
   accept ...
or
   accept ...
...
end select;
```

- *If none of the entries have waiting calls*
  ☞ **the process is suspended** until a call arrives.
- *If exactly one of the entries has waiting calls*
  ☞ **this entry is selected.**
- *If multiple entries have waiting calls*
  ☞ **one of those is selected** (non-deterministically). The selection can be prioritized by means of the real-time-systems annex.

The code following the selected entry (if any) is executed and the `select` statement completes.

Non-determinism

Selective Synchronization

Basic forms of selective synchronization

(select-guarded-accept)

```
select
   when <condition> => accept ...
or
   when <condition> => accept ...
or
   when <condition> => accept ...
...
end select;
```

- *If all conditions are 'true'*
  ☞ **identical to the previous form.**
- *If some condition evaluate to 'true'*
  ☞ **the accept statement after those conditions are treated like in the previous form.**
- *If all conditions evaluate to 'false'*
  ☞ `Program_Error` **is raised.**
  Hence it is important that the set of conditions covers all possible states.

This form is identical to Dijkstra's guarded commands.

Non-determinism

Selective Synchronization

Basic forms of selective synchronization

(select-guarded-accept-else)

```
select
   when <condition> => accept ...
or
   when <condition> => accept ...
or
   when <condition> => accept ...
...
else
   <statements>
end select;
```

- *If all currently open entries have no waiting calls or all entries are closed*
  ☞ **The else alternative is chosen**, the associated statements executed and the select statement completes.
- Otherwise ☞ **one of the open entries with waiting calls is chosen as above.**

This form never suspends the task.

This enables a task to *withdraw* its offer to accept a set of calls if no tasks are currently waiting.

Non-determinism

Selective Synchronization

Basic forms of selective synchronization

(select-guarded-accept-delay)

```
select
   when <condition> => accept ...
or
   when <condition> => accept ...
or
   when <condition> => accept ...
...
or
   when <condition> => delay [until] ...
      <statements>
or
   when <condition> => delay [until] ...
      <statements>
...
end select;
```

- *If none of the open entries have waiting calls before the deadline specified by the earliest open* **delay** *alternative*
  ☞ **This earliest delay alternative is chosen** and the statements associated with it executed.
- *Otherwise* ☞ **one of the open entries with waiting calls is chosen as above.**

This enables a task to *withdraw* its offer to accept a set of calls if no other task is calling after some time.

Non-determinism

Selective Synchronization

Basic forms of selective synchronization

(select-guarded-accept-terminate)

```
select
   when <condition> => accept ...
or
   when <condition> => accept ...
or
   when <condition> => accept ...
...
or
   when <condition> => terminate;
...
end select;
```

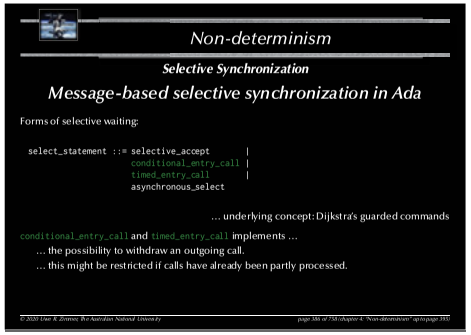
`terminate` cannot be mixed with `else` or `delay`

- *If none of the open entries have waiting calls and none of them can ever be called again*
  ☞ **The `terminate` alternative is chosen, i.e. the task is terminated.**

This situation occurs if:

☞ ... all tasks which can possibly call on any of the open entries are terminated.

☞ or ... all remaining tasks which can possibly call on any of the open entries are waiting on select-terminate statements themselves and none of their open entries can be called either. In this case all those waiting-for-termination tasks are terminated as well.


Non-determinism
Selective Synchronization
Message-based selective synchronization in Ada
Forms of selective waiting:
select_statement ::= selective_accept |
conditional_entry_call |
timed_entry_call |
asynchronous_select
… underlying concept: Dijkstra's guarded commands
conditional_entry_call and timed_entry_call implements …
… the possibility to withdraw an outgoing call.
… this might be restricted if calls have already been partly processed.
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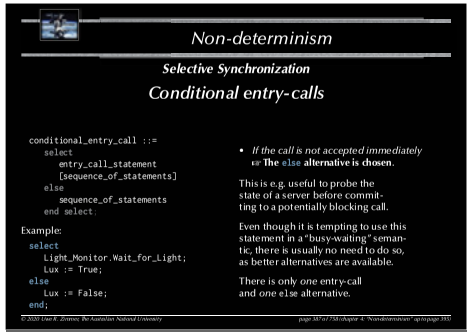
Non-determinism
Selective Synchronization
Conditional entry-calls
conditional_entry_call ::=
select
entry_call_statement
[sequence_of_statements]
else
sequence_of_statements
end select;
Example:
select
Light_Monitor.Wait_for_Light;
Lux := True;
else
Lux := False;
end;
• If the call is not accepted immediately
☞ The else alternative is chosen.
This is e.g. useful to probe the state of a server before committing to a potentially blocking call.
Even though it is tempting to use this statement in a "busy-waiting" semantic, there is usually no need to do so, as better alternatives are available.
There is only one entry-call and one else alternative.
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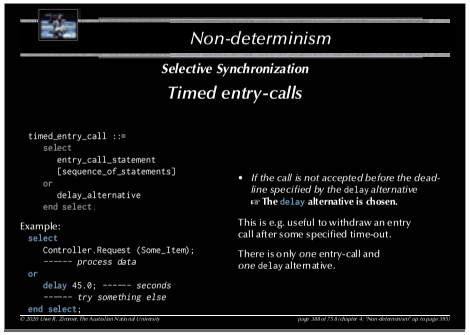
Non-determinism
Selective Synchronization
Timed entry-calls
timed_entry_call ::=
select
entry_call_statement
[sequence_of_statements]
or
delay_alternative
end select;
Example:
select
Controller.Request (Some_Item);
------ process data
or
delay 45.0; ------ seconds
------ try something else
end select;
• If the call is not accepted before the deadline specified by the delay alternative
☞ The delay alternative is chosen.
This is e.g. useful to withdraw an entry call after some specified time-out.
There is only one entry-call and one delay alternative.
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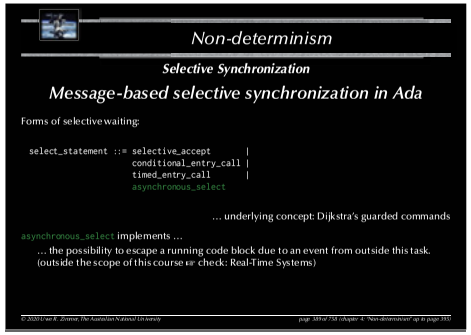
Non-determinism
Selective Synchronization
Message-based selective synchronization in Ada
Forms of selective waiting:
select_statement ::= selective_accept |
conditional_entry_call |
timed_entry_call |
asynchronous_select
… underlying concept: Dijkstra's guarded commands
asynchronous_select implements …
… the possibility to escape a running code block due to an event from outside this task.
(outside the scope of this course ☞ check: Real-Time Systems)
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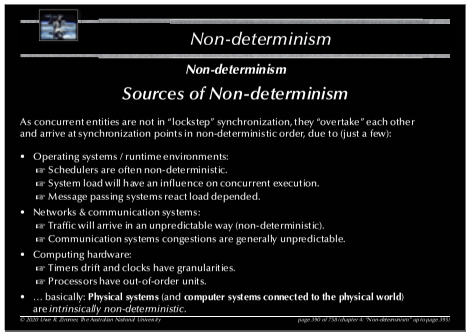
Non-determinism
Non-determinism
Sources of Non-determinism
As concurrent entities are not in "lockstep" synchronization, they "overtake" each other and arrive at synchronization points in non-deterministic order, due to (just a few):
• Operating systems / runtime environments:
☞ Schedulers are often non-deterministic.
☞ System load will have an influence on concurrent execution.
☞ Message passing systems react load depended.
• Networks & communication systems:
☞ Traffic will arrive in an unpredictable way (non-deterministic).
☞ Communication systems congestions are generally unpredictable.
• Computing hardware:
☞ Timers drift and clocks have granularities.
☞ Processors have out-of-order units.
• … basically: Physical systems (and computer systems connected to the physical world) are intrinsically non-deterministic.
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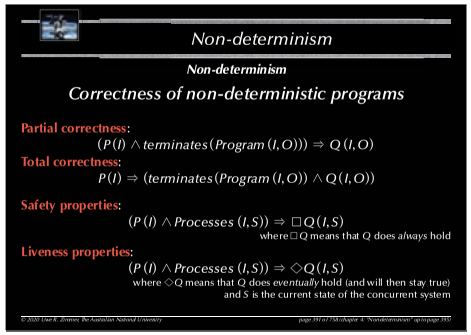
Non-determinism
Non-determinism
Correctness of non-deterministic programs
Partial correctness:
$(P(I) \wedge terminates(Program(I,O))) \Rightarrow Q(I,O)$
Total correctness:
$P(I) \Rightarrow (terminates(Program(I,O)) \wedge Q(I,O))$
Safety properties:
$(P(I) \wedge Processes(I,S)) \Rightarrow \Box Q(I,S)$
where $\Box Q$ means that Q does always hold
Liveness properties:
$(P(I) \wedge Processes(I,S)) \Rightarrow \Diamond Q(I,S)$
where $\Diamond Q$ means that Q does eventually hold (and will then stay true)
and S is the current state of the concurrent system
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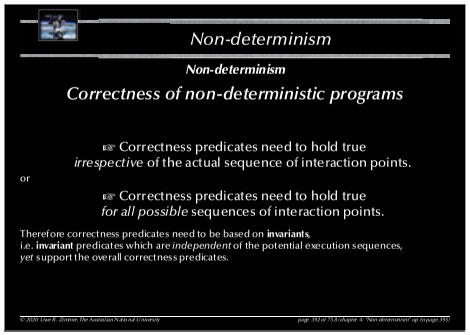
Non-determinism
Non-determinism
Correctness of non-deterministic programs
☞ Correctness predicates need to hold true
irrespective of the actual sequence of interaction points.
or
☞ Correctness predicates need to hold true
for all possible sequences of interaction points.
Therefore correctness predicates need to be based on invariants,
i.e. invariant predicates which are independent of the potential execution sequences,
yet support the overall correctness predicates.
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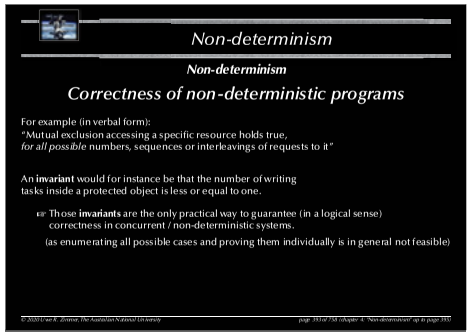
Non-determinism
Non-determinism
Correctness of non-deterministic programs
For example (in verbal form):
"Mutual exclusion accessing a specific resource holds true,
for all possible numbers, sequences or interleavings of requests to it"
An invariant would for instance be that the number of writing tasks inside a protected object is less or equal to one.
☞ Those invariants are the only practical way to guarantee (in a logical sense) correctness in concurrent / non-deterministic systems.
(as enumerating all possible cases and proving them individually is in general not feasible)
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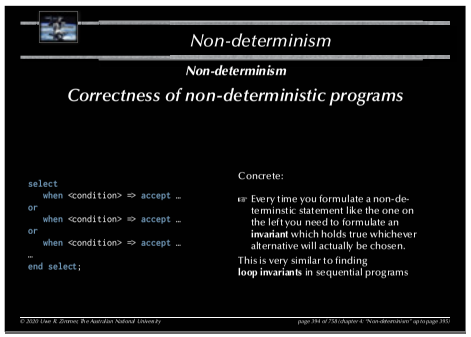
Non-determinism
Non-determinism
Correctness of non-deterministic programs
select
when <condition> => accept …
or
when <condition> => accept …
or
when <condition> => accept …
…
end select;
Concrete:
☞ Every time you formulate a non-determinstic statement like the one on the left you need to formulate an invariant which holds true whichever alternative will actually be chosen.
This is very similar to finding loop invariants in sequential programs
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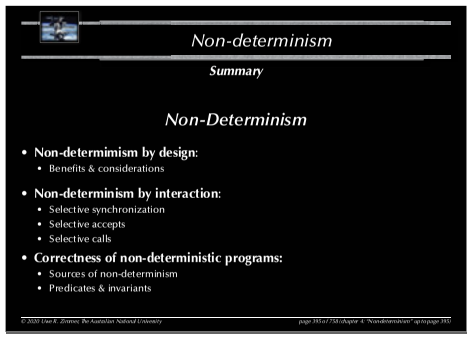
Non-determinism
Summary
Non-Determinism
• Non-determimism by design:
• Benefits & considerations
• Non-determinism by interaction:
• Selective synchronization
• Selective accepts
• Selective calls
• Correctness of non-deterministic programs:
• Sources of non-determinism
• Predicates & invariants
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