RE-EXAM
Software Engineering using Formal Methods
TDA293/DIT270

Day: **21/12/2016** Time: **08.30 – 12:30**

Responsible:	Wolfgang Ahrendt Tel.: 031-772-1011
Extra aid:	Only dictionaries may be used. Other aids are *not* allowed!
Grade intervals:	**U**: 0 – 23p, **3**: 24 – 35p, **4**: 36 – 47p, **5**: 48 – 60p, **G**: 24 – 47p, **VG**: 48 – 60p, **Max.** 60p.

Please observe the following:

- This exam has 13 numbered pages, plus two pages of the Spin Reference Card. **Please check immediately that your copy is complete**
- Answers must be given in English
- Use page numbering on your pages
- Start every assignment on a fresh page
- Write clearly; unreadable = wrong!
- Fewer points are given for unnecessarily complicated solutions
- Indicate clearly when you make assumptions that are not given in the assignment

Good luck!

Assignment 1 Linear Temporal Logic(LTL) (10p)

Consider the following PROMELA model:

```
byte mode  = 1;
byte count = 0;

active proctype m() {

endLoop:
  if
    :: mode = 1
    :: mode = 2
  fi;
  do
    :: mode == 1 && count < 30 -> count++
    :: mode == 2 -> count = 0; goto endLoop
    :: mode == 3 -> break
    :: else -> goto endLoop;
  od;
  count = 0
}

active proctype n() {
  do
   :: mode = 3
  od
}
```

(a) *(8p)* Formalise the following properties in LTL and indicate for each whether it is valid or not valid with respect to the above PROMELA model. (You do not need to provide explanation.) Assume the scheduler guarantees weak-fairness.

1. `count` is never greater-or-equal than 30.
2. If in some state `count` becomes greater than 0, it remains strictly positive until, eventually, `mode` becomes greater than 1.
   (Hint: With "until, eventually," we mean the strong until.)
3. If `count` is greater-than 0 in some state it will eventually be reset to 0 at some later point.
4. `mode` will eventually become 3.

Solution

(a)

1. $\neg\Diamond(count >= 30)$ *(or also accepted:* $\Box(count < 30)$*); invalid*

2. $\Box(count > 0 \rightarrow ((count > 0) U (mode > 1)))$*; valid*
3. $\Box(count > 0 \rightarrow \Diamond(count == 0))$*; valid*
4. $\Diamond(mode == 3)$*; valid*

(b) *(2p)* We now alter the scenario from (a), in so far as weak fairness is no longer assumed. For which of the four properties from (a) does this change the validity/invalidity status of the property?

Solution

(b)

2., 3., and 4. become invalid.

Assignment 2 (First-Order Sequent Calculus) (12p)

We work here in untyped first-order logic with the trivial type $\top$, which is omitted in the formulas below.

Let p denote a predicate of arity 2 and c, d be constant symbols. Prove that the following sequent is valid, using the *first-order sequent calculus*. For each step, name the rule you apply. If you invent a *new* constant, state that clearly.

You are only allowed to use the calculus rules presented in the lectures.

Your task is to build a proof for the following sequent:

$$\begin{array}{l} \forall x; \forall y; (p(x,y) \rightarrow p(y,x)), \\ \forall x; \forall y; \forall z; ((p(x,y) \wedge p(y,z)) \rightarrow p(x,z)), \\ \exists z; (p(d,z) \wedge p(z,c)) \\ \Rightarrow \\ p(c,d) \end{array}$$

Hint: You may abbreviate formulas, but only if you clearly describe your abbreviations. The proof gets easier if you start with eliminating the existential quantifier, and then instantiate the formula $\forall x; \forall y; \forall z; \ldots$

Solution

exLeft introduce new constant e,
andLeft
allLeft on transitivity formula instantiate with d,
allLeft on resulting formula and instantiate with e,
allLeft on resulting formula and instantiate with c,
allLeft on symmetry formula and instantiate with d,
allLeft on result and instantiate with c,
impLeft on resulting formula from previous step
Two goals (1) and (2):

Goal (1) with $p(d,e) \wedge p(e,c) \rightarrow p(d,c)$ on left side:
Apply impLeft (two goals (3) and (4)

Goal (3) with $p(d,e) \wedge p(e,c)$ on right side:
Apply rule andRight (two new goals (3a) and (3b)): (3a) close (3b) close

Goal (4) with $p(d,c)$ on right and left side: close

Goal (2) with $p(c,d)$ on left side:
close with p(c,d)

Assignment 3 (PROMELA and SPIN) (10p)

```
mtype = {vegetarian, meat, fish};

chan order = [5] of {mtype, int};
chan out = [5] of {mtype, int};


active [2] proctype cook() {
  // implement
}

active [3] proctype guest() {
  // implement
}
```

In a restaurant the cooks receive orders from their guests. An order includes the requested meal (vegetarian, meat or fish) and the guests `_pid`. The cooks put the prepared meal in the `out` channel from where the guest can pick them up.

The procedure for guests and cooks in slightly more detail is as follows:

Guests:

1. Each guest chooses arbitrarily among the possible meals, composes and sends out her/his order.
2. The guest waits then for her/his order to arrive and takes it if it is addressed to her/him.
3. Afterwards, the guest orders either a further meal or leaves the restaurant.

Cooks:

1. A cook takes an order and prepares the meal.
2. The finished meal is then put in the `out` channel awaiting for client to pick it up.

Tasks:

(a) *(8p)* Implement the proctypes `cook` and `guest` according to the specified protocol.
Hint: Pattern matching on the content of variables can be achieved by using `eval`(*var*). For instance, `channel ? eval(i)` is only executable if the message in `channel` has the value of variable `i`.
Solution

```
mtype = {vegetarian, meat, fish}

chan order = [5] of {mtype, int};
chan out = [5] of {mtype, int};


active [2] proctype cook() {

  mtype orderedMeal;
  int client;

endOrderLoop:
  do
    :: order ? orderedMeal, client; out ! orderedMeal, client
  od
}

active [3] proctype guest() {

  mtype meal, receivedMeal;

endStartOrder:
  if
    :: meal = vegetarian
    :: meal = meat
    :: meal = fish
  fi;
  order ! meal, _pid;
  out ? receivedMeal, eval(_pid);
served:  assert receivedMeal == meal;
  if /* leave the restaurant or continue ordering */
    :: goto exitRestaurant;
    :: goto endStartOrder;
  fi;
exitRestaurant:
  printf("Bye")
}
```

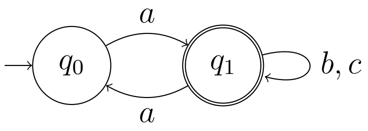
(b) *(2p)* Explain how you ensure that a guest takes only her/his meal and not the one of someone else. Put an assertion into the code ensuring that the received meal is the ordered one.

Solution

pattern matching on _pid; assertion see above

Assignment 4 (Büchi Automata, ω-expressions, and LTL) (9p)

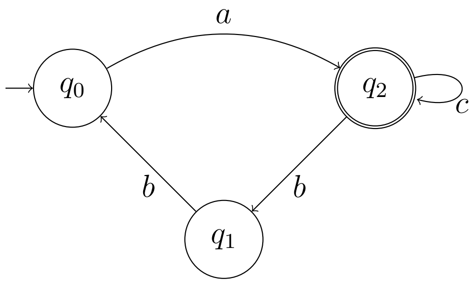
(a) *(2p)* Give the ω-expression representing exactly the language recognised by the Büchi automaton below.



(b) *(2p)* Give the Büchi automaton recognising exactly the language represented by the following ω-expression:

$$a((aa)^*bb)^\omega$$

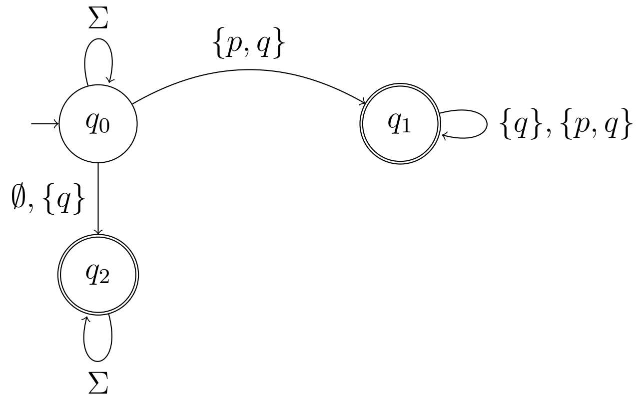
(c) *(2p)* Give the ω-expression representing exactly the language recognised by the Büchi automaton below.



(d) *(3p)* Consider the LTL formula $\Diamond(p \to \Box q)$

Does the following Büchi automaton accept exactly those runs satisfying the the above formula? Explain your answer. (We suggest a few sentences.)

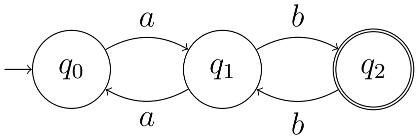
$\Sigma := \{\emptyset, \{p\}, \{q\}, \{p, q\}\}$



Solution

(a) $a(aa + b + c)^\omega$

(b)



(c) $a(bba + c)^\omega$

(d) The answer to the question is yes. The reason is that both, the runs that satisfy the formula, and the runs (ω-words of states) that are accepted by the Büchi automaton, can be characterised in the same way. It is exactly the set of runs which reach a state where either p is false, or where p is true and q remains true from thereon.

Assignment 5 (Java Modeling Language) (13p)

(The description of this assignment has two pages.)
A flight route is divided into a sequence of legs, each of which is a straight line between a startpoint $(startX, startY)$ and an endpoint $(endX, endY)$.

Consider the following Java classes:

```
public class Leg {

   private /*@ spec_public @*/ int startX;
   private /*@ spec_public @*/ int startY;
   private /*@ spec_public @*/ int endX;
   private /*@ spec_public @*/ int endY;

  // some methods

}


public class FlightRoute {

 private /*@ spec_public @*/ int size;
 private /*@ spec_public nullable @*/ Leg[] route;

 public void append(Leg leg) { ... }

 public int replace(Leg oldLeg, Leg[] newLegs) { ... }

 // some more methods
}
```

In the following, observe the usual restrictions under which Java elements can be used in JML specifications. You are not allowed to introduce any other methods, neither for implementation, nor for specification purposes.

1. Augment the class `Leg` with a JML specification stating that start and end point are not the same.
2. The class `FlightRoute` manages its legs using the array `route` of a fixed size. The integer typed attribute `size` points to the next free element of the array not yet occupied by a leg, i.e., all array components up-to but excluding `size` are non-null.

   Augment the class `FlightRoute` by JML specifications stating that

   (a) the attribute `route` is never `null`.

   (b) the attribute `size` is never negative and less-or-equal than the length of the array `route`.

(c) the array *route* does not contain duplicates (the same object does not occur twice)

(d) a route is a consecutive sequence of legs, i.e., a route does not have holes.

(e) if method `append` is called in a state where

- `size` is strictly smaller than the length of array `route`
- the given parameter `leg` appended to the route does not violate the property stated in items 2c and 2d

then the method terminates normally and in its final state

- the handed over leg has been appended to (added to the end of) the route and
- the field `size` has been updated correctly.

(f) if method `replace` is called in a state where

- the route contains the object `oldLeg`,
- the array `route` has enough space to store the route resulting from replacing leg `oldLeg` by a *non-empty* sequence of new legs `newLegs`, and,
- the replacement does not violate properties 2c and 2d

then the method terminates normally and in its final state

- leg `oldLeg` is no longer part of the route,
- the returned value is the index of the array component containing `oldLeg`
- the given sequence `newLegs` has been inserted at the index of the old leg and all to its right have been shifted according to the length of the inserted sequence. All preceding legs of the route remain unchanged.
- the attribute `size` has been updated correctly to reflect the new route

For the method contracts, please do not forget to provide the `assignable` clause.

Solution

[1; 1+1+1+2+2+5]

```
public class Leg {

  private /*@ spec_public @*/ int startX;
  private /*@ spec_public @*/ int startY;
  private /*@ spec_public @*/ int endX;
  private /*@ spec_public @*/ int endY;

 /*@ public invariant startX != endX || startY != endY; @*/

  // some methods
}

public class FlightRoute {
```

```
  //@ public instance invariant size >= 0 && size <= route.length;
  private /*@ spec_public @*/ int size;

  // route not null; attention removing the nullable is too strong
  // as non_null requires the array elements to be non_null too
  /*@ public instance invariant route != null; @*/

  /*@ public instance invariant // no duplicates
    @ (\forall int i;\forall int j;
    @          i>=0 && i<j && j<size;route[i]!=route[j]);
    @ public instance invariant // consecutive
    @   (\forall int i; i>=0 && i<size-1;
    @                       route[i].endX == route[i+1].startX
    @                    && route[i].endY == route[i+1].startY );
    @*/
  private /*@ spec_public nullable @*/ Leg[] route;

  /*@ public normal_behavior
    @ requires size < route.length;
    @ requires (\forall int i; i>=0 && i<size; route[i] != leg);
    @ requires size > 0 ==> (leg.startX == route[size - 1].endX &&
    @                                 leg.startY == route[size - 1].endY
);
    @ ensures route[\old(size)] == leg;
    @ ensures size == \old(size) + 1;
    @ assignable size, route[size];
    @*/
  public void append(Leg leg) { ... }

  /*@ public normal_behavior
    @ requires (\exists int i; i>=0 && i<size; route[i] == oldLeg);
    @ requires newLegs.length >= 1;
    @ requires size <= route.length - newLegs.length + 1;
    @ requires (\forall int i; i>=0 && i<size;
    @                    (\forall int j; j>=0 && j<newLegs.length;
    @                             route[i] != newLegs[j]));
    @ // The following requires clause was accepted as sufficient,
    @ // even if it does not check whether newLegs has holes already.
    @ requires size > 0 ==>
    @   (   newLegs[0].startX == oldLeg.startX
    @    && newLegs[0].startY == oldLeg.startY
    @    && newLegs[newLegs.length - 1].endX == oldLeg.endX
    @    && newLegs[newLegs.length - 1].endY == oldLeg.endY);
    @ // The next requires clause was not asked for; any other
    @ // solution or ignoring the issue was accepted, too.
```

```
    @ requires
    @  (\forall int i; i>=0 && i<newLegs.length; newLegs[i] != oldLeg);
    @ ensures (\forall int i; i>=0 && i<size; route[i] != oldLeg);
    @ ensures \old(route[\result])==oldLeg;
    @ ensures (\forall int i; i>=0&&i<\result;
    @                         route[i]==\old(route[i]));
    @ ensures (\forall int i; i>=\result && i<\result+newLegs.length;
    @                         route[i]==newLegs[i - \result]);
    @ ensures (\forall int i;
    @                  i>=\result+newLegs.length && i<size;
    @                  route[i]==\old(route[i-newLegs.length+1]);
    @ ensures size == \old(size) + newLegs.length - 1;
    @ assignable size, route[*];
    @*/
  public int replace(Leg oldLeg, Leg[] newLegs) { ... }
  // some more methods
}
```

Assignment 6 (Loop-Invariant) (6p)

Consider the following JML annotated method:

```
/*@ public normal_behavior
  @ requires true;
  @ ensures
  @  (\forall int i; i>=0 && i< values.length;
  @      \result[i] == values[values.length - 1 - i] );
  @*/
public int[] reverse(int[] values) {
  int[] out = new int[values.length];
  int i = 0;
  while (i<values.length) {
    out[i] = values[values.length-1-i];
    i++;
  }
  return out;
}
```

Provide a strong enough loop invariant for method `reverse` such that the method's post-condition can be verified. Provide also a variant (decreasing term) and the loop's assignable clause as precise as possible.

Solution

```
/*@ loop_invariant    i>=0
  @               && i <= values.length
  @               && (\forall int j;
  @                           j>=0 && j<i;
  @                           out[j]==values[values.length-j-1]);
  @ decreasing values.length - i;
  @ assignable i, out[*];
  @*/
```

(total 60p)

Liveness:

```
spin -a file
gcc -o pan pan.c
pan -a -f or ./pan -a -f
spin -t -p -l -g -r -s file
```

Spin arguments

`-a`	generate verifier and syntax check
`-i`	interactive simulation
`-I`	display Promela program after preprocessing
`-nN`	seed for random simulation
`-t`	guided simulation with trail
`-tN`	guided simulation with Nth trail
`-uN`	maximum number of steps is N
`-f`	translate an LTL formula into a never claim
`-F`	translate an LTL formula in a file into a never claim
`-N`	include never claim from a file
`-l`	display local variables
`-g`	display global variables
`-p`	display statements
`-r`	display receive events
`-s`	display send events

Compile arguments

`-DBFS`	breadth-first search
`-DNP`	enable detection of non-progress cycles
`-DSAFETY`	optimize for safety
`-DBITSTATE`	bitstate hashing
`-DCOLLAPSE`	collapse compression
`-DHC`	hash-compact compression
`-DMA=n`	minimized DFA with maximum n bytes
`-DMEMLIM=N`	use up to N megabytes of memory

Pan arguments

`-a`	find acceptance cycles
`-f`	weak fairness
`-l`	find non-progress cycles
`-cN`	stop after Nth error
`-c0`	report all errors
`-e`	create trails for all errors
`-i`	search for shortest path to error
`-I`	approximate search for shortest path to error
`-mN`	maximum search depth is N
`-wN`	2^N hash table entries
`-A`	suppress reporting of assertion violations
`-E`	suppress reporting of invalid end states

Caveats

- Expessions must be side-effect free.
- Local variable declarations always take effect at the beginning of a process.
- A `true` guard can always be selected; an `else` guard is selected only if all others are false.
- Macros and `inline` do *not* create a new scope.
- Place labels before an `if` or `do`, *not* before a guard.
- In an `if` or `do` statement, interleaving can occur between a guard and the following statement.
- Processes are activated and die in LIFO order.
- Atomic propositions in LTL formulas must be identifiers starting with lowerase letters and must be boolean variables or symbols for boolean-valued expressions.
- Arrays of `bit` or `bool` are stored in bytes.
- The type of a message field of a channel cannot be an array; it can be a `typedef` that contains an array.
- The functions `empty` and `full` cannot be negated.

References

- G. J. Holzmann. *The Spin Model Checker: Primer and Reference Manual*, Addison-Wesley, 2004. `http://spinroot.com`.
- M. Ben-Ari. *Principles of the Spin Model Checker*, Springer, 2008. `http://www.springer.com/978-1-84628-769-5`.

Spin Reference Card

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October 1, 2007

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Datatypes

`bit` (1 bit)
`bool` (1 bit)
`byte` (8 bits unsigned)
`short` (16^* bits signed)
`int` (32^* bits signed)
`unsigned` ($\leq 32^*$ bits unsigned)
* - for a 32-bit machine.
`pid`
`chan`
`mtype` = { name, name, ... } (8 bits)
`typedef` typename { sequence of declarations }

Declaration - type var [= initial value]
Default initial values are zero.
Array declaration - type var[N] [= initial value]
Array initial value assigned to all elements.

Operators (descending precedence)

```
()   []   .
!    ~    ++   --
*    /    %
+    -
<<   >>
<    <=   >    >=
==   !=
&
^
```

`|`
`&&`
`||`
`( ... -> ... : ... )` conditional expression
`=`

Predefined
Constants - `true`, `false`
Variables (read-only except `_`):
  `_` - write-only hidden scratch variable
  `_nr_pr` - number of processes
  `_pid` - instantiation number of executing process
  `timeout` - no executable statements in the system?

Preprocessor
`#define` name (arguments) string
`#undef`, `#if`, `#ifdef`, `#ifndef`, `#else`, `#endif`
`#include` ”file name”
`inline` name (arguments) { ... }

Statements
Assignment - var = expression, var++, var--
`assert`(expression)

`printf`, `printm` - print to standard output
  `%c` (character), `%d` (decimal), `%e` (`mtype`),
  `%o` (octal), `%u` (unsigned), `%x` (hex)
`scanf` - read from standard input in simulation mode

`skip` - no operation
`break` - exit from innermost `do` loop
`goto` - jump to label
Label prefixes with a special meaning:
  `accept` - accept cycle
  `end` - valid end state
  `progress` - non-progress cycle

`atomic` { ... } - execute without interleaving
`d_step` { ... } - execute deterministically (no jumping in or out; deterministic choice among true guards; only the first statement can block).

{ ... } `unless` { ... } - exception handling.

Guarded commands
`if` :: guard `->` statements :: ... `fi`
`do` :: guard `->` statements :: ... `od`
`else` guard - executed if all others are false.

Processes
Declaration - `proctype` procname (parameters) { ... }
Activate with prefixes - `active` or `active`[N]
Explicit process activation - `run` procname (arguments)
Initial process - `init` { ... }
Declaration suffixes:
  `priority` - set simulation priority
  `provided` (e) - executable only if expression `e` is true

Channels
`chan` ch = [capacity] `of` { type, type, ... }

ch ! args	send
ch !! args	sorted send

ch ? args	receive and remove if *first* message matches
ch ?? args	receive and remove if *any* message matches
ch ? <args>	receive if *first* message matches
ch ?? <args>	receive if *any* message matches
ch ? [args]	poll *first* message (side-effect free)
ch ?? [args]	poll *any* message (side-effect free)

Matching in a receive statement: constants and `mtype` symbols must match; variables are assigned the values in the message; `eval`(expression) forces a match with the current value of the expression.

`len`(ch) - number of messages in a channel
`empty`(ch) / `nempty`(ch) - is channel empty / not empty?
`full`(ch) / `nfull`(ch) - is channel full / not full?

Channel use assertions:
  `xr` ch - channel ch is receive-only in this process
  `xs` ch - channel ch is send-only in this process

Temporal logic

`!`	not
`&&`	and
`||`	or
`->`	implies
`<->`	equivalent to
`[]`	always
`<>`	eventually
`X`	next
`U`	strong until
`V`	dual of U defined as `pVq <-> !(!pU!q)`

Remote references
Test the control state or the value of a variable:
  process-name `@` label-name
  proctype-name [expression] `@` label-name
  process-name : label-name
  proctype-name [expression] : label-name

Never claim
`never` { ... }.
Predefined constructs that can only appear in a never claim:
  `_last` - last process to execute
  `enabled`(p) - is process enabled?
  `np_` - true if no process is at a progress label
  `pc_value`(p) - current control state of process
  remote references
See also `trace` and `notrace`.

Variable declaration prefixes
`hidden` - hide this variable from the system state
`local` - a global variable is accessed only by one process
`show` - track variable in Xspin message sequence charts

Verification
Safety:
  `spin -a file`
  `gcc -DSAFETY -o pan pan.c`
  `pan` or `./pan`
  `spin -t -p -l -g -r -s file`