Program Verification: Lecture 22

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Fairness is a property ensuring that in certain kinds of conflict situations a given transition will not be preempted almost forever. That is, if it is infinitely enabled to be applied, it will actually be applied, not a finite, but an infinite number of times.

Weak and Strong Fairness

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3. **Object/Process/Thread Fairness** is even more detailed: we need to specify to which object/process/thread has transition l been applied by encoding this in the resulting state $[v]$ as, say, $[v].l(o)$, where o is the object/process/thread identifier.

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The difference between (2) and (3) is that between applying a rule l, and applying an instance of rule l to a given object o.

I will illustrate modes (1) and (3) by examples.

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```
mod TRAFFIC-LIGHTS is
  sorts Conf LightState Intersection Direction Light Car .
  subsorts LightState Intersection Car < Conf .
  op mt : -> Conf [ctor] .
  op _ _ : Conf Conf -> Conf [ctor assoc comm id: mt] .
  op [_] : Conf -> Intersection [ctor] .
  ops h v : -> Direction [ctor] .
  op car : Direction -> Car [ctor] .
  ops green red yellow  : Direction -> Light [ctor] .
  op {_,_} : Light Light -> LightState [comm] .

   op init : -> Conf .

  vars d d1 d2 : Direction . var L : Light .  var C : Conf .

  eq init = {green(h),red(v)} [mt] .
```

A Traffic Lights Example (II)

```
  rl [g2y] : {green(d1),red(d2)} [C] => {yellow(d1),red(d2)} [C] .
  rl [y2r] : {yellow(d1),red(d2)} [mt]  => {red(d1),green(d2)} [mt] .

  rl [car.in] : {green(d),L} [mt] => {green(d),L} [car(d)] .
  rl [car.in] : {green(d),L} [mt] => {green(d),L} [car(d) car(d)] .
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A Traffic Lights Example (III)

```
in model-checker.maude

mod TRAFFIC-LIGHTS-PREDS is
  protecting TRAFFIC-LIGHTS .  protecting SATISFACTION .

  subsort Conf < State .

  vars L L' : Light .  vars C C' : Conf .  vars d d1 d2 : Direction .

  op enabled : -> Prop [ctor] .

  eq {green(d1),red(d2)} [C] C' |= enabled = true .
  eq {yellow(d1),red(d2)} [mt] C |= enabled = true .
  eq {green(d),L} [mt] C |= enabled = true .
  eq  {green(d),L} [car(d) car(d)]  C |= enabled = true .
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  eq  {yellow(d),L} [car(d)]  C |= enabled = true .

  op on : Light -> Prop [ctor] .

   eq {L,L'} C |= on(L) = true .
```

A Traffic Lights Example (IV)

```
   op side-collision-dngr : -> Prop [ctor] .

   eq [car(h) car(v) C'] C |= side-collision-dngr = true .

   op yellow-enabled : Direction -> Prop [ctor] .

   eq {green(d1),red(d2)} [C] C' |= yellow-enabled(d1) = true .
endm

mod TRAFFIC-LIGHTS-CHECK is
  protecting TRAFFIC-LIGHTS-PREDS .
  including MODEL-CHECKER .

  op yellow-fair : -> Formula .

  eq yellow-fair = (([] <> yellow-enabled(h)) ->  ([] <> on(yellow(h)))) /\
                   (([] <> yellow-enabled(v)) ->  ([] <> on(yellow(v)))) .
endm
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```

Let's verify some properties. The main safety invariant is absence of side collisions:

A Traffic Lights Example (V)

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red modelCheck(init,[] ~ side-collision-dngr) .

result Bool: true
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A key property is that in any direction red always follows yellow:

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A key property is that in any direction red always follows yellow:

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red modelCheck(init,[] (on(yellow(h)) -> (on(yellow(h)) U on(red(h))))) .

result Bool: true

red modelCheck(init,[] (on(yellow(v)) -> (on(yellow(v)) U on(red(v))))) .

result Bool: true
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result Bool: true

red modelCheck(init,[] (on(yellow(v)) -> (on(yellow(v)) U on(red(v))))) .

result Bool: true
```

However, yellow doesn't always follow green:

A Traffic Lights Example (VI)

```
red modelCheck(init,[] (on(green(h)) -> (on(green(h)) U on(yellow(h))))) .

result ModelCheckResult:  counterexample(nil,
                            {[mt] {green(h),red(v)},'car.in}
                            {[car(h)] {green(h),red(v)},'car.out})
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A Traffic Lights Example (VI)

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red modelCheck(init,[] (on(green(h)) -> (on(green(h)) U on(yellow(h))))) .

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As the counterexample shows this is due to a conflict between the g2y rule and the `car.in` rules, and g2y gets forever preempted.

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We can take two steps: **Step 1**. Consider TRAFFIC-LIGHTS a high-level design missing some details and, assuming yellow-fair, show that TRAFFIC-LIGHTS works as expected:

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We can take two steps: **Step 1**. Consider `TRAFFIC-LIGHTS` a high-level design missing some details and, assuming `yellow-fair`, show that `TRAFFIC-LIGHTS` works as expected:

```
red modelCheck(init,yellow-fair ->
            ([] (on(green(h)) -> (on(green(h)) U on(yellow(h)))))) .

result Bool: true

red modelCheck(init,yellow-fair ->
            ([] (on(green(v)) -> (on(green(v)) U on(yellow(v)))))) .

result Bool: true
```

A Traffic Lights Example (VII)

Step 2. Develop a more detailed design where the traffic lights system works as expected because its design ensures fairness by construction. This second step is taken in the Appendix to this lecture.

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Next we consider the **Object/Process/Thread Fairness** mode by revisiting the `PARALLEL` programming language from Lecture 20.

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This example has illustrated the **State-Based** mode: we didn't need to explicitly encode the taking of a conflict transition like g2y in the state because its effect could be detected by the yellow light for the relevant direction being on after it was taken.

Next we consider the **Object/Process/Thread Fairness** mode by revisiting the `PARALLEL` programming language from Lecture 20. This will also allow us to illustrate the LTL formal verification of concurrent imperative programs.

PARALLEL Revisited

In PARALLEL, to verify some LTL program properties we need to be able to express **Process Fairness**. We can do so by: (1) slightly modifying the main state costructor:

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and (2) slightly modify the rewrite rules of PARALLEL so that they record the pid of the last executing process.

The only changes needed in the specification of PARALLEL in Lecture 20 are the slight modifications (1) and (2) explained above. Here is the modified specification of PARALLEL:

PARALLEL Revisited (II)

```
mod PARALLEL is
  inc SEQUENTIAL .
  inc TESTS .

  sorts Pid Process Soup MachineState .
  subsort Process < Soup .
  subsort Int < Pid .
  op [_,_] : Pid Program -> Process .
  op empty : -> Soup .
  op _|_ : Soup Soup -> Soup [prec 61 assoc comm id: empty] .
  op {_,_,_} : Soup Memory Pid -> MachineState .

  vars P R : Program .  var S : Soup .  var U : UserStatement .
  var L : LoopingUserStatement .  vars I J : Pid . var M : Memory .
  var Q : Qid .  vars N X : Int . var T : Test . var E : Expression .
```

PARALLEL Revisited (III)

```
  rl {[I, U ; R] | S, M, J} => {[I, R] | S, M, I} .

  rl {[I, L ; R] | S, M, J} => {[I, L ; R] | S, M, I} .

  rl {[I, (Q := E) ; R] | S, [Q, X] M, J} =>
        {[I, R] | S, [Q,eval(E,[Q, X] M)] M, I} .

  crl {[I, (Q := E) ; R] | S, M, J} =>
        {[I, R] | S, [Q,eval(E,M)] M, I} if Q in M =/= true .

  rl {[I, if T then P fi ; R] | S, M, J} =>
        {[I, if eval(T, M) then P else skip fi ; R] | S, M, I} .

  rl {[I, while T do P od ; R] | S, M, J} =>
     {[I, if eval(T, M) then (P ; while T do P od) else skip fi ; R]
         | S, M, I} .

  rl {[I, repeat P forever ; R] | S, M, J} =>
        {[I, P ; repeat P forever ; R] | S, M, I} .
endm
```

Dekker's Mutex Algorithm

Dekker's algorithm is specified extending the modified PARALLEL:

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```
mod DEKKER is inc PARALLEL . subsort Int < Pid .
  op crit : -> UserStatement .
  op rem : -> LoopingUserStatement .
  ops p1 p2 : -> Program .
  op initialMem : -> Memory .
  op initial : -> MachineState .
  eq p1 =
        repeat
          'c1 := 1 ;
          while 'c2 = 1 do
            if 'turn = 2 then
              'c1 := 0 ;
              while 'turn = 2 do skip od ;
              'c1 := 1
            fi
          od ;
          crit ;
          'turn := 2 ;
          'c1 := 0 ;
          rem
        forever .
```

Dekker's Mutex Algorithm (II)

```
  eq p2 =
      repeat
        'c2 := 1 ;
        while 'c1 = 1 do
          if 'turn = 1 then
            'c2 := 0 ;
            while 'turn = 1 do skip od ;
            'c2 := 1
          fi
        od ;
        crit ;
        'turn := 1 ;
        'c2 := 0 ;
        rem
      forever .

  eq initialMem = ['c1, 0] ['c2, 0] ['turn, 1] .
  eq initial = { [1, p1] | [2, p2], initialMem, 0 } .
endm
```

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LTL Model Checking of Dekker's Algorithm

We need to define an `enabled` predicate and three predicates parameterized by the process id: `in-crit` and `in-rem`, when the process is resp. in its critical section, resp. in its remaining code fragment, and `exec`, when the process has just executed.

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We need to define an `enabled` predicate and three predicates parameterized by the process id: `in-crit` and `in-rem`, when the process is resp. in its critical section, resp. in its remaining code fragment, and `exec`, when the process has just executed.

```
mod DEKKER-PREDS is inc DEKKER .  inc SATISFACTION .
  inc LTL-SIMPLIFIER .
  subsort MachineState < State .

  vars P R : Program .  var S : Soup .  var U : UserStatement .
  var L : LoopingUserStatement .  vars I J : Pid . var M : Memory .
  var Q : Qid .  vars N X : Int . var T : Test . var E : Expression .

  op enabled : -> Prop .

  eq {[I, U ; R] | S, M, J} |= enabled = true .
  eq {[I, L ; R] | S, M, J} |= enabled = true .
  eq {[I, (Q := E) ; R] | S, [Q, X] M, J} |= enabled = true .
  eq {[I, (Q := E) ; R] | S, M, J} |= enabled = true .
  eq {[I, if T then P fi ; R] | S, M, J} |= enabled = true .
  eq {[I, while T do P od ; R] | S, M, J} |= enabled = true .
  eq {[I, repeat P forever ; R] | S, M, J} |= enabled = true .
```

LTL Model Checking of Dekker's Algorithm (II)

```
ops in-crit in-rem exec : Pid -> Prop .

  eq {[I, crit ; R] | S, M, J} |= in-crit(I) = true .
  eq {[I, rem ; R] | S, M, J} |= in-rem(I) = true .
  eq {S, M, J} |= exec(J) = true .
endm

mod DEKKER-CHECK is inc DEKKER-PREDS .  inc MODEL-CHECKER .
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We can now verify mutual exclusion and deadlock freedom:

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We can now verify mutual exclusion and deadlock freedom:

```
red modelCheck(initial,[]~ (in-crit(1) /\ in-crit(2))) .

result Bool: true

red modelCheck(initial,[] enabled) .

result Bool: true
```

LTL Model Checking of Dekker's Algorithm (III)

The strong fairness property that executing infinitely often implies entering one's critical section infinitely often does fail:

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result ModelCheckResult:
counterexample({{[1,repeat 'c1 := 1 ; while 'c2 = 1 do if 'turn = 2 then ...
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If p1 and p2 both get to execute infinitely often, the property that if p1 is infinitely often out of its `rem` section it enters its critical section infinitely often does hold. And the same holds for p2.

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```
red  modelCheck(initial,[]<> exec(1) /\ []<> exec(2)
                                 -> []<> ~ in-rem(1) -> []<> in-crit(1)) .

result Bool: true

red  modelCheck(initial,[]<> exec(2) /\ []<> exec(1)
                                 -> []<> ~ in-rem(2) -> []<> in-crit(2)) .

result Bool: true
```

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For `PARALLEL` we only needed to record in the machine state the `pid` of the process that had last executed. But in other **Object/Process/Thread Fairness** mode examples we often need to record more information. For example, information of the form $l(o)$, recording that rule l was the last rule executed and that it was applied to object/process/thread o.