Universität Bremen

Design of Information Systems

Railway Planner

AG Datenbanksysteme
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by

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Contents

1. Introduction

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This paper is the result of our efforts to model a rudimentary railway planning system, as part of the course "Design of Information Systems" in the summer semester of 2017. Our model was developed and evaluated using USE (UML Based Specification Environment), a tool to model information systems based on UML (Unified Modeling Language) and OCL (Object Constraint Language) developed at the University of Bremen by the Database Systems Group.

First we will describe our system on a high level basis, followed by presenting the system's UML class diagram. Afterwards, we will discuss invariants represented as OCL expressions. What will be following is a description of the operations with their corresponding SOIL (Simple OCL-based Imperative Language) implementations. Finally, we will present a few example scenarios to test our invariants and operations and show a few exemplary OCL expressions used to query useful information.

1.1 System description

The system being modelled in this paper is a planning system for a ficticious railway company. Its purpose is to enable the planning of regular scheduled railway traffic. The finer details of the system are described below.

The system's centerpiece are routes. In general, a route describes a train ride from one train station to another, more specifically it describes a complete journey of a train from its starting station to its final destination. Usually there are several train stations along the way. Each stage along the journey is defined in a separate object. A route contains all stages making up the complete route, an assigned train as well as a train driver and a conductor. The start and end stations as well as departure and arrival times are all contained within the individual stages.

A stage describes a direct train ride from one train station to another. It consists of a source platform as well as a destination platform, both having associated train stations. Also, each stage has a departure and arrival time. Additionally, every stage is assigned a track section that has to connect the source and destination. The time is specified by hours and minutes.

A train station has a unique name specifying its exact location. Moreover, a train station has multiple platforms that all have an ID that is unique for its assigned train station. A track section is defined by the two connected train stations. Since there can be multiple track sections between two train stations and we want to assign specific tracks to specific stages, a track section also has a unique id.

Every train has a type and a number, the combination of which is unique for every train. Finally, there are two types of employees: Train drivers and conductors, both having unique employee ids.

There are several things that have to be considered when planning routes. For example, when a track sections is used for multiple stages at the same time, the destination of all stages needs to be the same (so that the trains don't collide head-on) and there has to be a certain difference in both the departure times and arrival times so that all trains remain at a certain distance over the section. Other limitations include employees and trains not being able to service multiple routes with overlapping timeframes or platforms not being able to host multiple trains at the same time.

There are multiple ways in which the system can assist while planning railway traffic, for instance by asking the system to display all connections between two train stations. Moreover, giving a specific time, one could ask for the next connection between two stations. One could also ask for all visited stations on a route.

When looking for employees to assign to routes, one could also retrieve all employees that are available during a specified time period. The same can be done for trains. Also, one could specify a train station and a point in time and ask for all available platforms.

2. Model

Author: Marlon Flügge

Figure 2.1 shows the class diagram for our railway planner. This basically shows the specifications given in the system overview implemented in actual OCL. In the following we will briefly discuss the classes and their attributes included in your model. Operations will be discussed in a more in-depth manner in chapter 4.

2.1 Classes

First of all, all defined classes will be presented.

2.1.1 Train

This class represents a simple train. Its only attribute is `type`, which is used to model different classes of trains, like 'ICE' or 'RE'. The class has two operations: One is a simple initialization operation that sets the type parameter, the other one lets us assign the train to given route.

2.1.2 Route

As described in the system overwiew a route represents a train ride from an origin station to a destination, which can span across multiple train stations modeled using `Stage` objects. Origin and destination can be derived by looking at the first and last stage respectively. `Route` has 7 methods in total: An initialization function, operations to add or remove stages, the operation "overlaps", which takes another `Route` object and checks if they temporally overlap and 3 utility methods to get an available train, conductor or driver for this route.

2.1.3 Employee, Conductor & Driver

`Employee` is an abstract class that models any kind of employee involved in the process. It is supposed to store all of the attributes and operations that are universal to employees regardless of their specific position. For now it only stores the attribute `name`, but is easily expandable. Since it is an abstract class, it does not have an initialization operation. We included two subclasses of `Employee` in our model, namely `Driver` and `Conductor`.

A driver only symbolically represents the train's driver without actually having any explicit functionality inside our system. `Conductor`, however, does have a purpose, additional to

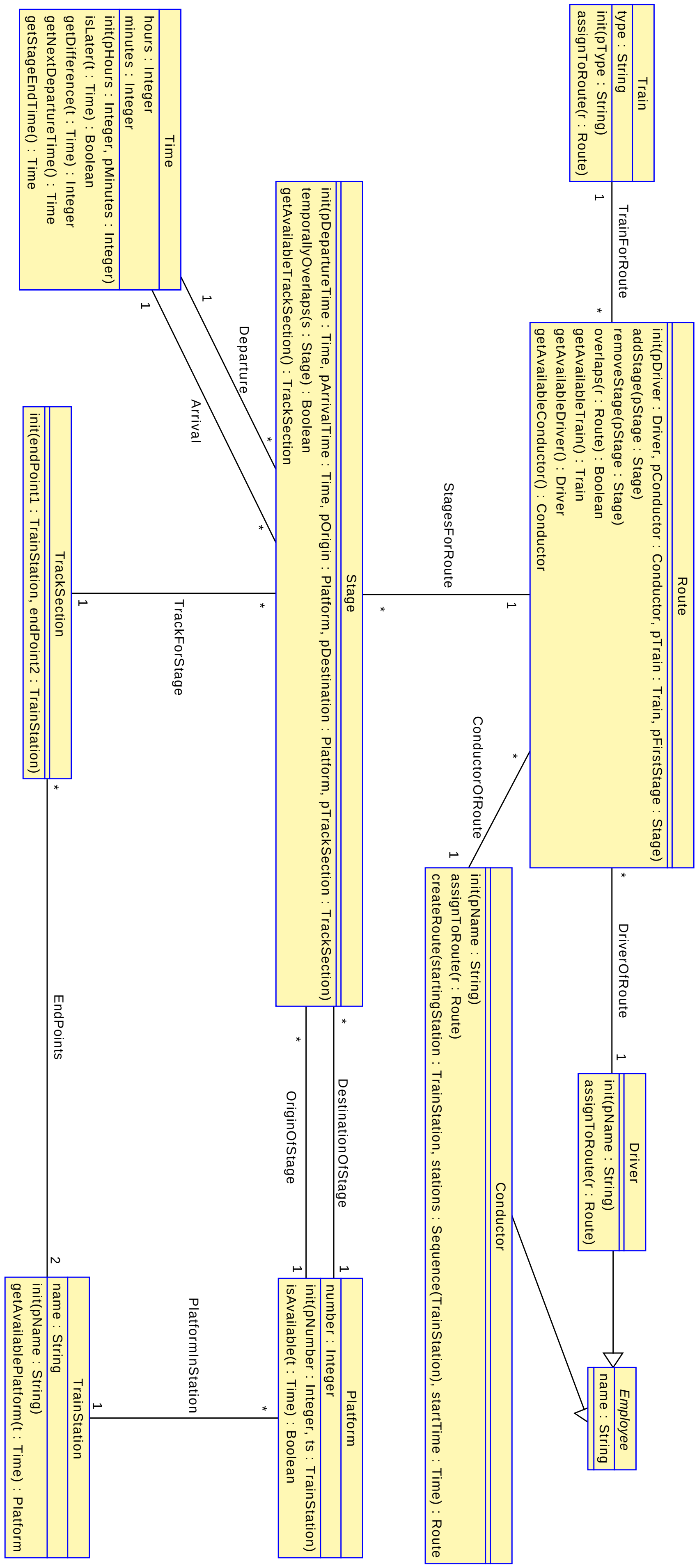


Figure 2.1: Railway Planner Class Diagram

functioning as a symbolical conductor for a given route. The conductor is responsible for creating new routes in our system, using the `createRoute` operation.

Both `Driver` and `Conductor` have basic initialization operations as well as operations to assign them to a given route.

2.1.4 Stage

`Stage` models an elementary part of a route. We call a train ride "elementary" if it is leading from one train station to another without crossing any other train station on the way. Stages form the central aspect of a route, determining where the route starts, end and what train stations are passed on the way. Apart from the ubiquitous `init`-operation, stages also have an operation that checks if they temporally overlap with another, given stage as well as an operation to query a track section that could be used for this stage.

2.1.5 TrainStation, TrainSection & Platform

`TrackSection` models a track section connecting two train stations. `TrainStation` models a train station inside our system. Every train station needs a name so the user can differentiate between them more easily. A TrainStation can be queried for an available platform. `Platform` represents a platform on a train station. There can't be more trains in a train stations at the same time than there are platforms on a station. A Platform can be queried to check if it is available at a given time.

2.1.6 Time

When scheduling railway traffic time is obviously a central aspect. In order to properly model this we created the class `Time`, which represents different points in time that can be associated with destinations and arrivals at train stations. This class offers operations that can be used to enforce a lot of constraints and invariants. While a time object has `hours` and `minutes` attributes, seconds or dates are not modeled within our system, since we only try to model a daily schedule and railway traffic cannot be accurately scheduled to within seconds since there are several outside factors that can influence the length of a train ride.

The `Time`-class also offers several utility operations, e.g. comparing two times to check which one is later.

2.2 Associations

Using the multiplicities next to the associations we can see what is needed for an object of a given class to be valid. We also mention a few of the invariants that are thoroughly explained in chapter 3.

2.2.1 TrainForRoute

This association connects the `Train` and `Route` classes. It models the prerequisite that every planned route in our system needs exactly one assiocated train that is doing the actual ride. Additionally it allows a train to be associated to multiple routes at once. Via the **TrainNotUsedSimultaneously** invariant we make sure that these associated routes do not overlap in time.

2.2.2 DriverOf & ConductorOf

These associations exist between the `Route` class and the `Employee` subclasses. Every route needs exactly one of each as formalized in the associations' multiplicities. Similar to the train in the **TrainForRoute** association drivers and conductors can be associated with multiple routes, as long as these routes do not temporally overlap.

2.2.3 StagesForRoute

At heart a route is just a collection of stages which is modeled using this association. As previously explained a stage is just an elementary connection between two train stations without any intermediate stops. If a route is planned to span across multiple train stations every elementary connection from train station to train station will be modeled using a seperate stage. Thus, the **StagesForRoute** association makes sure every route consists of at least one stage but doesn't specify an upper bound for the number of stages that can make up a route. A stage, however, can only ever be part of a single route. Having the same stage associated to multiple routes would not make sense, since that would mean that multiple trains would be using the same track section at the same time.

2.2.4 TrackForStage

This association links a track section to a stage. Every stage needs a track section that the train can use to go the from one train station to another. A track section can be associated to multiple stages as long as these dont temporally overlap, which enforced using the invariants **TimeDifferenceSameDirection** and **NoOverlapsOppositeDirections**.

2.2.5 DestinationOfStage & OriginOfStage

A stage always has to lead from one train station to another, which is modeled using this association. The origin and destinations points are instances of the class **Platform** which are linked to certain train stations via the **PlatformInStation** association. Using these links it is possible to set or later one determine the start and end points of a stage. Again, platforms can be used by multiple stages as long as these do not overlap in time.

2.2.6 PlatformInStation

As described this association links platforms to certain train stations. While a platform can only belong to one train station, a train station can obviously have multiple platforms in order to hold multiple trains at the same time.

2.2.7 EndPoints

This association represents the fact that track sections have to begin an end somewhere. In our model these points can only be train station, which is why **EndPoints** is connecting track sections to train stations. Since beginning and end have to be specified, a track section needs two associated train stations while the latter may be connected to variable number of track sections.

2.2.8 Departure & Arrival

As previously mentioned the concept of time is obviously essential for any problem that contains some form of scheduling as it is for our system. Using the **Departure** and **Arrival** associations we can model departure and arrival times of different stages, which later on can be used for planning and invariant checks. Consequently, these associations connect a stage with a departure and arrival time, respectively. Since points in time are not unique a given `Time` object might be used by multiple stages.

3. Invariants

Author: Merlin Burri

In the following chapter, the invariants, i. e. formal constraints, for the model will be discussed. This includes verbal descriptions as well as the OCL representations for our constraints for all classes in the model. If there are no invariants for a specific class, the class is not mentioned in this chapter. The tests for all invariants can be found in chapter 5.1, which follows the same structure as this chapter. For every invariant, the constraint is first described and what follows is the OCL representation. Since our model almost exclusively contains attributes defined by associations, for the most part, we do not need invariants that guarantee attributes being defined. This is implicitly covered by the multiplicities of our associations.

3.1 Train

The only invariant for the `Train` class is **TrainNotUsedSimultaneously**. The constraint makes sure that `Train` objects are not assigned to multiple `Route` objects that contain some form of temporal overlap, ensuring that trains are not used simultaniously in multplie routes. For the OCL representation, a utility operation called *overlaps* of the `Route` class is used. The operation is further described in 4.16.

```
--Train is not assigned to multiple Routes at the same time
context Train inv TrainNotUsedSimultaneously:
  self.route->forAll(r1: Route, r2: Route |
    r1.overlaps(r2) implies r1 = r2
  )
```

3.2 Driver

In accordance with the `Train` invariant, the only `Driver` class invariant is called **DriverNotUsedSimultaneously** and ensures that no `Driver` objects are assigned to multiple `Route` objects, providing that the `Route` objects overlap in time. Here, we again make use of the *overlaps* operation of the `Route` class.

```
--Driver is not assigned to multiple Routes at the same time
context Driver inv DriverNotUsedSimultaneously:
  self.route->forAll(r1: Route, r2: Route |
```

```
    r1.overlaps(r2) implies r1 = r2
  )
```

3.3 Conductor

In accordance with the two previously described invariants, for the second `Employee` subclass `Conductor` we have defined only one invariant: **ConductorNotUsedSimultaneously**. By again using the *overlaps* utility operation, the constraint ensures that a `Conductor` object is only assigned to multiple `Route` objects if there is is no temporal overlap between the routes.

```
--Conductor is not assigned to multiple Routes at the same time
context Conductor inv ConductorNotUsedSimultaneously:
  self.route->forAll(r1: Route, r2: Route |
    r1.overlaps(r2) implies r1 = r2
  )
```

It should be noted that it is not sufficient to define one invariant for the `Employee` class because...

3.4 Route

The first invariant of the `Route` class is called **DepartureAfterArrivalPreviousStage**. It makes sure that for the ordered set of `Stage` objects that the Route is associated with, the departure time of the next stage is later than the arrival time of the previous stage. To determine the next (and previous) stage(s), we take advantage of the used data structure for the `StagesForRoute` association, which – as mentioned – is implemented as an ordered set. To check whether or not a specific time is later than another time, we use the utility operation *isLater* of the `Time` class which is further explained in chapter 4.6.

```
--For every Stage in the Route, the Departure Time has to be after
--the Arrival Time of the previous Stage
context Route inv DepartureAfterArrivalPreviousStage:
  self.stage->forAll(s : Stage |
    let currentStageNumber : Integer = stage->indexOf(s)
    in if (currentStageNumber < stage->size()) then
      stage->at(currentStageNumber + 1).departureTime
        .isLater(s.arrivalTime)
    else
      true
    endif
  )
```

Secondly, we have defined an invariant that similarly ensures that the destination (i. e. the arrival `Platform` object) of the previous stage equals the origin (the departure `Platform` object) of the next stage in the route: **DeparturePlatformPreviousPlatform**. This guarantees that a train arriving to a platform will always depart from that same platform. Since `Platform` objects are uniquely associated with `TrainStation` objects, the constraint also makes sure that the train station the train is departing from always equals the train station that it has previously arrived to. We again make use of the `StagesForRoute` association's implementation to determine next and previous stage(s).

```
--For every Stage in the Route, the Platform that the Train is departing
--from has to be the platform that the Train arrived on in the previous
--Stage. This also makes sure that the TrainStation the Train is departing
--from equals the TrainStation that it arrived on in the previous Stage.
context Route inv DeparturePlatformPreviousPlatform:
  self.stage->forAll(s : Stage |
    let currentStageNumber : Integer = stage->indexOf(s)
    in if (currentStageNumber < stage->size()) then
      s.destination = stage->at(currentStageNumber + 1).origin
    else
      true
    endif
  )
```

The last invariant **NoCircles** for the `Route` class forbids circles within routes. For this purpose, we check every stage in the route and ensure that two different stages in one route never arrive to or depart from the same `TrainStation`. Routes starting and ending in the same train station are allowed.

```
--Routes do not contain circles, which equates to every Stage in the Route
--having differing source and destination TrainStations
context Route inv NoCircles:
  self.stage->forAll(s1, s2 : Stage |
    (s1.origin.trainStation = s2.origin.trainStation
    or
    s1.destination.trainStation = s2.destination.trainStation)
    implies
    s1 = s2
  )
```

3.5 Stage

The first invariant for the class *Stage* that we defined is called **ArrivalAfterDeparture** and regulates the arrival and departure time of a stage. By using the *isLater* utility operation of the `Time` class, we make sure that the arrival time of a stage is later than the departure time, so a train always arrives after it has departed.

```
--Departure time has to be before arrival time
context Stage inv ArrivalAfterDeparture:
  self.arrivalTime.isLater(self.departureTime)
```

The second invariant **TrackSectionConnectOriginDestination** concerns itself with the `TrackSection` objects associated with stages, i. e. with the `TrackForStage` association. The constraint ensures that the assigned track section does in fact connect the two train stations that the stage is departing from/arriving to, with the departing and arriving station being defined by the departing and arriving platform of the stage.

```
--the used TrackSection has to connect the origin and the
--destination of the stage
context Stage inv TrackSectionConnectOriginDestination:
  self.trackSection.trainStation->exists(s : TrainStation |
    s = self.destination.trainStation
  )
```

```
  and self.trackSection.trainStation->exists(s : TrainStation |
    s = self.origin.trainStation
  )
```

The **NoOverlapsOppositeDirections** invariant asserts that there are no trains using the same track section at the same time while going in opposite directions. To be more specific, the constraint checks for all possible `Stage` pairs if they have the same assigned `TrackSection` object and, via another utility operation called *temporallyOverlaps* provided by the `Stage` class, whether the stages overlap in time. If that is the case, we make sure that both stages have the same destination by using the `DestinationOfStage` association, which of course amounts to them going in the same direction. The *temporallyOverlaps* operation is further elaborated on in chapter 4.21.

```
--No stages using the same sections at overlapping time frames
--going in opposite directions.
--Same used TrackSection and temporal overlap imply same direction
context s1, s2: Stage inv NoOverlapsOppositeDirections:
  not (s1 = s2) and s1.trackSection = s2.trackSection
  and s1.temporallyOverlaps(s2) implies
  s1.destination.trainStation = s2.destination.trainStation
```

Lastly, we defined an invariant called **TimeDifferenceSameDirection**, which ensures that trains using the same track section at the same time going in the same direction have a certain difference (we arbitrarily chose 10 minutes) in their arrival and departures times. We again check all possible `Stage` pairs for usage of the same `TrackSection` object and temporal overlap. If there is overlap, we have to differentiate between two cases: In the first case, the first stage's departure time is before the second stage's. We then have to make sure that both the departure and the arrival time of the first stage are 10 minutes earlier than the respective times of the second. Accordingly, if the second stage's departure time is before the first's, the departure and arrival time of the second stage have to be before the respective times of the first. To extract the temporal difference between two `Time` objects, we use a utility operation called *getDifference* provided by the `Time` class, which is further explained in chapter 4.7.

Here, we can not just check the difference between arrival and departure times because of the implementation of the *getDifference* operation. Doing so without checking which train departs first would cause a system state in which a train overlaps another train while using the same track section to be valid. All in all, in combination with our **NoOverlapsOppositeDirections** invariant, we make sure that trains using the same track section while overlapping in time have to go into the same direction and that there has to be a difference of more than 10 minutes in their arrival and departure times, while forbidding overtakings.

```
--Same used TrackSection and temporal overlap imply a certain
--difference in arrival and departure times
context s1, s2: Stage inv TimeDifferenceSameDirection:
  not (s1 = s2) and s1.trackSection = s2.trackSection
  and s1.temporallyOverlaps(s2) implies
  if s2.departureTime.isLater(s1.departureTime) then
    s1.departureTime.getDifference(s2.departureTime) > 10 and
    s1.arrivalTime.getDifference(s2.arrivalTime) > 10
  else
```

```
    s2.departureTime.getDifference(s1.departureTime) > 10 and
    s2.arrivalTime.getDifference(s1.arrivalTime) > 10
  endif
```

3.6 Platform

For our `Platform` class, we have defined one invariant: **MaxOneTrainPerPlatform**. The constraint asserts that at the same time, no platform is occupied by multiple trains. To be more precise, all `Stage` objects associated with a `Platform` object via the `DestinationOfStage` association are inspected. First of all, the constraint ensures that multiple trains do not arrive at a single platform at the same time. Secondly, it is made sure that if two trains do arrive on the same platform, one of the trains has to depart again before the second arrives by inspecting the `Stage` set of the `Route` object associated to the current `Stage` object.

```
--The next train may only arrive after the previous train has departed
--Thus, each platform may host at most one train at a time
context Platform inv MaxOneTrainPerPlatform:
  self.arrivingStage->forAll(a1, a2 |
    a1 = a2 or
    --trains not arriving at same time
    (a2.arrivalTime.isLater(a1.arrivalTime) or a1.arrivalTime
      .isLater(a2.arrivalTime))
    and
    --every stopping train needs to depart before the next one arrives
    (a2.arrivalTime.isLater(a1.arrivalTime) implies
    a2.arrivalTime.isLater(a1.route.stage
      ->at((a1.route.stage->indexOf(a1))+1).departureTime))
)
```

3.7 Time

The first invariant is called **MinutesInInterval**. Since we want to model a common clock with minute values in the interval from 0 to 59 and hour values from 0 to 23, the constraint ensures that the value for the `minutes` attribute is in exactly that interval.

```
-- The value for the minutes attribute has to be in the interval [0,59]
context Time inv MinutesInInterval:
  Time.allInstances->forAll( t: Time |
    t.minutes >= 0 and t.minutes < 60
  )
```

Accordingly, the **HoursInInterval** invariant makes sure that the value for the `hours` attribute is in the interval from 0 to 23.

```
-- The value for the hours attribute has to be in the interval [0,23]
context Time inv HoursInInterval:
  Time.allInstances->forAll( t: Time |
    t.hours >= 0 and t.hours < 24
  )
```

4. Operations

Author: Tilman Ihrig

In this chapter the operations for each class in our model are introduced. This includes both the specification using pre- and post-conditions and the SOIL-implementations adhering to these specifications. Throughout this chapter, `self` is used to refer to the object on which the respective operation is called.

4.1 Train::init()

Initializes a `Train` object by assigning its `type`.

Parameters:

pType (`String`)	Gives the `type` of a `Train`, e.g. *RE* or *ICE*.

Return value:

The operation has no return value.

Preconditions:

freshInstance	`self` must be a fresh instance, i.e. its `type` must be undefined.
typeNotEmpty	The given `pType` must contain at least one character.

A case could be made to also check whether the given type adheres to a specific naming scheme (e.g. 'RE', 'ICE' etc.). We have decided against specifying such a scheme. As such, nonsensical types are possible. On the other hand, there is complete freedom in expanding the number of train-types, as the precondition does not need to be changed every time a new train-type is introduced.

Postconditions:

typeAssigned	The given type must be assigned correctly.

Implementation:

Assigns the given `pType` to `type`.

Code:

```
init(pType: String)
  begin
    self.type := pType
  end
  pre freshInstance: self.type.isUndefined()
  pre typeNotEmpty: pType.size > 0
  post typeAssigned: self.type = pType
```

4.2 Train::assignToRoute()

Assigns a `Train`-object to a given `Route` by creating a corresponding `TrainForRoute`-association. If the `Route` already has an assigned `Train`, that association is deleted.

Parameters:

r (`Route`) The route to which `self` shall be assigned.

Return value:

The operation has no return value.

Preconditions:

trainRouteDefined The given `Route` must be defined.

Postconditions:

isAssigned `self` must be the train of the given `Route`.

A postcondition to check whether the association to a previously assigned `Train` has been deleted is not necessary, since the number of assignable `Trains` is limited to 1 in `TrainForRoute`.

Implementation:

Deletes the association between `r` and its currently assigned `Train`, if it already has an assigned `Train`, then creates an association between `self` and the given `Route` in `TrainForRoute`.

Code:

```
-- assigns the train to the given route
assignToRoute(r: Route)
  begin
    if r.train.isDefined()
    then
      delete (r.train, r) from TrainForRoute;
    end;
    insert(self, r) into TrainForRoute;
  end
  pre trainRouteDefined: r.isDefined()
  post isAssigned: r.train = self
```

4.3 TrainStation::init()

Initializes a `TrainStation` by assigning its `name`.

Parameters:

pName (`String`) Gives the `name` of a `TrainStation`, e.g. *Bremen Hbf.*

Return value:

The operation has no return value.

Preconditions:

freshInstance	`self` must be a fresh instance, i.e. its `name` must be undefined.
nameNotEmpty	The given `pName` must contain at least one character.

Postconditions:

nameAssigned The given name must be assigned correctly.

Implementation:

Assigns the given `pName` to `name`.

Code:

```
init(pName: String)
  begin
    self.name := pName
  end
  pre freshInstance: self.name.isUndefined()
  pre nameNotEmpty: pName.size > 0
  post nameAssigned: self.name = pName
```

4.4 TrainStation::getAvailablePlatform()

Returns a `Platform` that is not used by any trains at a given `Time`.

Parameters:

t (`Time`) The `Time` at which the `Platform` needs to be available.

Return value:

The operation returns a `Platform` that is available at the given `Time`. If no `Platform` is available, `null` is returned.

Preconditions:

hasPlatforms	`self` needs to have at least one `Platform`.
timeDefined	The time for which to check the availability needs to be defined.

Postconditions:

The operation has no postconditions.

Implementation:

Selects a `Platform` from all those that are available. For the availability check, *Platform::isAvailable()* is used.

Code:

```
 --returns a platform that is available at the given time
 getAvailablePlatform(t : Time) : Platform =
   self.platform -> any(p : Platform | p.isAvailable(t))
 pre hasPlatforms: self.platform -> size > 0
 pre timeDefined: t.isDefined()
```

4.5 Time::init()

Initializes a `Time`-object by assigning it a point in time, given as hours and minutes.

Parameters:

pHours (`Integer`)	Specifies the hours of a point in time.
pMinutes (`Integer`)	Specifies the minutes of a point in time.

Return value:

The operation has no return value.

Preconditions:

freshInstance	`self` must be a fresh instance, i.e. the `hours` and `minutes` must be undefined.
hoursInCorrectInterval	The given `pHours` must be valid hours in the 24-hour-system, i.e. between inclusively 0 and 23.
minutesInCorrectInterval	The given `pMinutes` must be valid, i.e. between inclusively 0 and 59.

Postconditions:

timeAssigned	The given `pHours` and `pMinutes` must be assigned correctly.

Implementation:

Assigns the given `pHours` to `hours` and `pMinutes` to `minutes`.

Code:

```
 init(pHours: Integer, pMinutes: Integer)
   begin
     self.hours := pHours;
     self.minutes := pMinutes;
   end
   pre freshInstance: self.hours.isUndefined() and
                      self.minutes.isUndefined()
   pre hoursInCorrectInterval: pHours >= 0 and pHours < 24
   pre minutesInCorrectInterval: pMinutes >= 0 and pMinutes < 60
   post timeAssigned: self.hours = pHours and
                      self.minutes = pMinutes
```

4.6 Time::isLater()

Checks whether a `Time`-object is later than a given `Time`.

Parameters:

t (`Time`) The `Time`-object to which `self` shall be 'compared'.

Return value:

The operation returns a `Boolean` value: `True` if `self` is later than `t` and `False` otherwise.

Preconditions:

The operation does not have any preconditions.

Postconditions:

The operation does not have any postconditions

Implementation:

In addition to the two cases where `self` is intuitively later than `t` (hours are later or hours are equal and minutes are later), there is also a third case that needs to be considered, since dates are not modeled, but only 24-hour schedules. If a train departs shortly before midnight but arrives after midnight, then the arrival would not be considered later than the departure in the context of the two intuitive cases. For this reason, there is another case in which `self` is considered later, which is when the `hours` of `self` are 0 and the `hours` of the given `Time`-object are 23.
For `Stage`s which span more than 1 hour between departure and arrival, this would not be enough, but expanding this to more hours before/after midnight would probably lead to more incorrect results than keeping it like this.
All three cases are disjuncted so that only one of them needs to be true to return `True`.

Code:

```
-- checks if the Time the method is called on is
-- after the given Time
isLater( t: Time ) : Boolean =
  (self.hours > t.hours) or
  ((self.hours = t.hours) and (self.minutes > t.minutes)) or
  (self.hours = 0 and t.hours = 23);
```

4.7 Time::getDifference()

Calculates the difference in minutes between a `Time`-object and a given `Time`.

Parameters:

t (`Time`) The `Time` to compute the difference to.

Return value:

The operation returns an `Integer` which is positive if `t` is later than `self` and negative if `self` is later than `t`.

Preconditions:

The operation does not have any preconditions.

Postconditions:

The operation does not have any postconditions.

Implementation:

Calculates the difference by subtracting the hours and minutes of `self` from those of `t`, multiplying the difference in hours by 60 to get the difference in minutes.

Code:

```
-- returns the difference between the given Time and self
-- in minutes. Only positive if the given Time is later
getDifference( t: Time) : Integer =
    ((t.hours - self.hours) * 60 + (t.minutes - self.minutes))
```

4.8 Time::getNextDepartureTime()

Creates a new `Time`-object that is a default staying length later than `self`. The default length is set to 2 minutes. Used to automatically create a route without knowing all the times.

Note: This operation does not account for the hours change to 00 when crossing midnight. This was noticed too late to change it.

Parameters:

The operation does not have any parameters.

Return value:

The operation returns a `Time`-object.

Preconditions:

timeDefined `self` must have a defined time, i.e. its `hours` and `minutes` must be defined.

Postconditions:

The operation does not have any postconditions.

Implementation:

Creates a new `Time`-object that is 2 minutes later than `self`. If `minutes` are 58 or higher, this means that the `hours` are increased by 1 and the `minutes` decreased by 58.

Code:

```
-- returns a default new departure time from a station with self
-- as the arrival time at that station. Default staying time in
-- a station is set at 2 minutes.
getNextDepartureTime() : Time
  begin
    declare newTime : Time;
    newTime := new Time();
    if (self.minutes < 58) then
      newTime.init(self.hours, self.minutes + 2)
    else
      newTime.init(self.hours + 1, self.minutes - 58)
    end;
    result := newTime
  end
  pre timeDefined: hours.isDefined() and minutes.isDefined()
```

4.9 Time::getStageEndTime()

Creates a new `Time`-object that is a default driving length later than `self`. The default length is set to 30 minutes. Used to automatically create a route without knowing all the times.

Note: This operation does not account for the hours change to 00 when crossing midnight. This was noticed too late to change it.

Parameters:

The operation does not have any parameters.

Return value:

The operation returns a `Time`-object.

Preconditions:

timeDefined `self` must have a defined time, i.e. its `hours` and `minutes` must be defined.

Postconditions:

The operation does not have any postconditions.

Implementation:

Creates a new `Time`-object that is 30 minutes later than `self`. If `minutes` are 30 or higher, this means that the `hours` are increased by 1 and the `minutes` decreased by 30.

Code:

```
-- returns a default ending time for a stage with self as the
-- starting time. Default stage length is 30 minutes.
getStageEndTime() : Time
  begin
    declare newTime : Time;
    newTime := new Time();
    if (self.minutes < 30) then
      newTime.init(self.hours, self.minutes + 30)
    else
      newTime.init(self.hours + 1, self.minutes - 30)
    end;
    result := newTime
  end
  pre timeDefined: hours.isDefined() and minutes.isDefined()
```

4.10 Platform::init()

Initializes a `Platform` by assigning it a `number` and a `TrainStation`.

Parameters:

pNumber (`Integer`)	Gives the `number` of the `Platform`.
ts (`TrainStation`)	Gives the `TrainStation` in which the `Platform` is located.

Return value:

The operation has no return value.

Preconditions:

freshInstance	`self` must be a fresh instance, i.e. its number must be undefined and it must not be associated with a `TrainStation`.
numberPositive	The given `pNumber` must be positive.
stationDefined	The given `TrainStation` must be defined.
platformNumberNotTaken	The given `TrainStation` must not have a `Platform` with the same number as `self`.

Postconditions:

numberAssigned	The given number must be assigned correctly.
platformAssigned	`self` must be assigned to the given `TrainStation`.

Implementation:

Assigns the given `pNumber` to `number` and inserts an association between `self` and `ts` into `PlatformInStation`.

Code:

```
-- A platform needs an existing trainstation and can't change
-- to a different TrainStation.
init(pNumber: Integer, ts: TrainStation)
  begin
    self.number := pNumber;
    insert(self, ts) into PlatformInStation
  end
  pre freshInstance: self.number.isUndefined() and
                     self.trainStation.isUndefined()
  pre numberPositive: pNumber > 0
  pre stationDefined: ts.isDefined()
  pre platformNumberNotTaken: not(ts.platform->exists(p |
                                       p.number = pNumber))
  post numberAssigned: self.number = pNumber
  post platformAssigned: ts.platform->exists(p | p = self)
```

4.11 Platform::isAvailable()

Checks whether a `Platform` is available at a given `Time`.

Parameters:

t (`Time`) The `Time` at which the `Platform` needs to be available.

Return value:

The operation returns a `Boolean`: `True` if `self` is free at the given `Time` and `False` otherwise.

Preconditions:

timeDefined The time for which to check the availability needs to be defined.

Postconditions:

The operation has no postconditions.

Implementation:

A `Platform` is available at a `Time` if there is no `Train` currently on it (arrived with a previous `Stage` and didn't depart) and no `Train` was on it 5 minutes prior or arrives on it until at least 5 minutes later.
All arriving trains must therefore arrive at least 5 minutes after `t`, which can be checked using *Time::getDifference* which only returns a positive value if the given `Time` is later then the one on which the operation is called, or depart again at least 5 minutes before `t`, which can be checked using *Time::getDifference* again. A corresponding departing stage for an arriving stage is defined as a stage that uses the same train and departs after the arriving stage has arrived.

Code:

```
-- checks whether a platform is available at a given time
-- (no trains currently on that platform or arriving/departing
-- within 5 minutes)
isAvailable(t: Time) : Boolean =
self.arrivingStage -> forAll
            (aS: Stage |
             t.getDifference(aS.arrivalTime) > 5 or
             self.departingStage -> exists
                 (dS: Stage |
                  dS.route.train = aS.route.train and
                  dS.departureTime.isLater(aS.arrivalTime) and
                  (t.getDifference(dS.departureTime) < -5)
                  )
             )
pre timeDefined: t.isDefined()
```

4.12 TrackSection::init()

Initializes a `TrackSection` by assigning it two `TrainStation`s as the two train stations this section connects.

Parameters:

endPoint1 (`TrainStation`)	One end point of the `TrackSection`.
endPoint2 (`TrainStation`)	The other end point of the `TrackSection`.

Return value:

The operation has no return value.

Preconditions:

freshInstance	`self` must be a fresh instance, i.e. it must not have any end points assigned to it yet.
endPointsDefined	The given `endPoint1` and `endPoint2` must be defined.

Postconditions:

typeAssigned	The given type must be assigned correctly.

Implementation:

Assigns the given `pType` to `type`.

Code:

```
init(endPoint1: TrainStation, endPoint2: TrainStation)
  begin
    insert(self, endPoint1) into EndPoints;
    insert(self, endPoint2) into EndPoints;
  end
  pre freshInstance: self.trainStation -> size() = 0
  pre endPointsDefined: endPoint1.isDefined() and
                        endPoint2.isDefined()
  post sectionConnectedToStations: self.trainStation->exists
                                          (s1,s2 |
                                           s1=endPoint1 and
                                           s2=endPoint2)
```

4.13 Route::init()

Initializes a `Route` by assigning it a `Driver`, a `Conductor`, a `Train` and a first `Stage`.

Parameters:

pDriver (`Driver`)	The driver of the train for this `Route`.
pConductor (`Conductor`)	The conductor of the train for this `Route`.
pTrain (`Train`)	The train to be assigned to this `Route`.
pFirstStage (`Stage`)	The first Stage of this `Route`.

Return value:

The operation has no return value.

Preconditions:

freshInstance	`self` must be a fresh instance, i.e. it must not have any driver, conductor, train or stage.
driverDefined	The given `pDriver` must be defined.
conductorDefined	The given `pConductor` must be defined.
trainDefined	The given `pTrain` must be defined.
stageDefined	The given `pFirstStage` must be defined.

Postconditions:

driverAssigned	The given `Driver` must be assigned correctly.
conductorAssigned	The given `Conductor` must be assigned correctly.
trainAssigned	The given `Train` must be assigned correctly.
firstStageAssigned	The given first `Stage` must be assigned correctly.

Implementation:

The *assignToRoute()*-operations of `Driver`, `Conductor` and `Train` are used to assign the driver, conductor and train to `self`. Then `pFirstStage` is added to `self` by inserting the corresponding association into `StagesForRoute`. This is enough since `self` has no previous `Stages`, so it can only be the first `Stage` in the `Route`. *Route::addStage()* cannot be used since it requires the `Route` to have at least one `Stage` already.

Code:

```
init(pDriver: Driver, pConductor: Conductor,
     pTrain: Train, pFirstStage: Stage)
  begin
    pDriver.assignToRoute(self);
    pConductor.assignToRoute(self);
    pTrain.assignToRoute(self);
    insert (pFirstStage, self) into StagesForRoute;
  end
  pre driverDefined: pDriver.isDefined()
  pre conductorDefined: pConductor.isDefined()
  pre trainDefined: pTrain.isDefined()
  pre stageDefined: pFirstStage.isDefined()
  pre freshInstance: self.driver.isUndefined() and
                     self.conductor.isUndefined() and
```

```
                      self.train.isUndefined() and
                      self.stage -> size() = 0
    post driverAssigned: self.driver = pDriver
    post conductorAssigned: self.conductor = pConductor
    post trainAssigned: self.train = pTrain
    post firstStageAssigned: self.stage->at(1) = pFirstStage
```

4.14 Route::addStage()

Adds a given `Stage` to the end of a `Route`.

Parameters:

pStage (`Stage`) A `Stage` to be added to `self`.

Return value:

The operation has no return value.

Preconditions:

stageDefined	The given pStage must be defined.
stageComplete	The given pStage must be complete, i.e. all its components must be defined.
stageStartEqualsPreviousEnd	The given `pStage` must depart at the same `Platform` the currently last `Stage` arrives at. This also requires the `Route` to have at least one `Stage` already.
stageNotUsed	The given pStage must not be used in a different `Route` because that would imply two trains sharing the same `Platform` at the same time.

Postconditions:

stageAdded The given `pStage` must now be the last `Stage` in `self`

Implementation:

An association between the given `pStage` and `self` is inserted into `StagesForRoute`. Since `StagesForRoute` is ordered, the added `pStage` is automatically the last `Stage` in `self`.

Code:

```
  addStage(pStage: Stage)
    begin
      insert(pStage, self) into StagesForRoute
    end
    pre stageDefined: pStage.isDefined()
    pre stageComplete: pStage.departureTime.isDefined() and
                       pStage.arrivalTime.isDefined() and
                       pStage.origin.isDefined() and
                       pStage.destination.isDefined() and
                       pStage.trackSection.isDefined()
    pre stageStartEqualsPreviousEnd:
      self.stage->last.destination = pStage.origin
```

```
    -- stage should not be part of another route
    pre stageNotUsed: Route.allInstances -> forAll
                                  (r: Route |
                                    not (r.stage -> includes(pStage))
                                  )
    post stageAdded: self.stage-> last = pStage
```

4.15 Route::removeStage()

Removes a given `Stage` from a `Route`.

Parameters:

pStage (`Stage`) The `Stage` to be removed from `self`.

Return value:

The operation has no return value.

Preconditions:

stageDefined	The given `pStage` must be defined.
stageRemovable	The given `pStage` must be the first or last stage of `self`. Removing any other stage would result in the train arriving at a different platform than the one the next stage departs from.

Postconditions:

stageRemoved The given `pStage` must not be in `self`'s list of stages anymore.

Implementation:

Deletes the association between `pStage` and `self` from `StagesForRoute`.

Code:

```
  removeStage(pStage: Stage)
    begin
      delete(pStage, self) from StagesForRoute;
    end
    pre stageDefined: pStage.isDefined()
    -- stages may only be removed if they are the first or last
    -- stage of the route so that the route will still be
    -- completeable
    pre stageRemovable: self.stage -> last = pStage or
                        self.stage -> first = pStage
    post stageRemoved: not(self.stage -> includes(pStage))
```

4.16 Route::overlaps()

Checks if a `Route` and a given `Route` have overlapping time frames.

Parameters:

r (`Route`) A `Route` for which to check if its time frame between departure and arrival overlaps with that of `self`.

Return value:

The operation returns a `Boolean`: `True` if `self` and `r` overlap, `False` otherwise.

Preconditions:

The operation has no preconditions.

Postconditions:

The operation has no postconditions.

Implementation:

A temporal overlap exists if the interval between departure time of the first `Stage` and arrival time of the last `Stage` in each `Route` is *not* completely disjunct. Those intervals *are* completely disjunct only if one `Route`'s departure time is after the other `Route`'s arrival time. Thus, this is checked for both possible orders and negated afterwards.

Code:

```
-- checks if the time frames of the two given Route objects
-- overlap
overlaps( r: Route ) : Boolean =
  not(
      (self.stage->first.departureTime.isLater
          (r.stage->last.arrivalTime)) or
      (r.stage->first.departureTime.isLater
          (self.stage->last.arrivalTime))
      )
```

4.17 Route::getAvailableTrain()

Select a `Train` that could be used for this `Route`, i.e. a `Train` that is not assigned to a different `Route` in the time frame needed for `self`. Should only be used once all `Stages` needed for `self` are already added to it.

Parameters:

The operation does not have any parameters.

Return value:

The operation returns a `Train` that is available for this `Route`.

Preconditions:

hasStages `self` must have at least 1 `Stage`, so that a time frame for the `Route` can be discerned.

Postconditions:

foundAvailableTrain An available `Train` must be found, because this operation is used within *Conductor::createRoute* and no found `Train` would lead to errors later on.

Implementation:

Selects a `Train` from all `Train` instances that is not assigned to any `Route` which overlaps in time to `self`.

Code:

```
-- returns a Train that is available for this Route
getAvailableTrain() : Train =
  Train.allInstances -> any
      (t: Train | t.route->forAll
            (r: Route | not r.overlaps(self))
       )
pre hasStages: self.stage -> size > 0
post foundAvailableTrain: result.isDefined()
```

4.18 Route::getAvailableDriver()

Select a `Driver` that could be used for this `Route`, i.e. a `Driver` that is not assigned to a different `Route` in the time frame needed for `self`. Should only be used once all `Stage`s needed for `self` are already added to it.

Parameters:

The operation does not have any parameters.

Return value:

The operation returns a `Driver` that is available for this `Route`.

Preconditions:

hasStages `self` must have at least 1 `Stage`, so that a time frame for the `Route` can be discerned.

Postconditions:

foundAvailableDriver An available `Driver` must be found, because this operation is used within *Conductor::createRoute* and no found `Driver` would lead to errors later on.

Implementation:

Selects a `Driver` from all `Driver` instances that is not assigned to any `Route` which overlaps in time to `self`.

Code:

```
--returns a Driver that is available for this Route
getAvailableDriver() : Driver =
  Driver.allInstances -> any
      (d: Driver | d.route->forAll
            (r: Route | not r.overlaps(self))
       )
pre hasStages: self.stage -> size > 0
post foundAvailableDriver: result.isDefined()
```

4.19 Route::getAvailableConductor()

Select a `Conductor` that could be used for this `Route`, i.e. a `Conductor` that is not assigned to a different `Route` in the time frame needed for `self`. Should only be used once all `Stages` needed for `self` are already added to it.

Parameters:

The operation does not have any parameters.

Return value:

The operation returns a `Conductor` that is available for this `Route`.

Preconditions:

hasStages	`self` must have at least 1 `Stage`, so that a time frame for the `Route` can be discerned.

Postconditions:

foundAvailableConductor	An available `Conductor` must be found, because this operation is used within *Conductor::createRoute* and no found `Conductor` would lead to errors later on.

Implementation:

Selects a `Conductor` from all `Conductor` instances that is not assigned to any `Route` which overlaps in time to `self`.

Code:

```
--returns a Conductor that is available for this Route
getAvailableConductor() : Conductor =
  Conductor.allInstances -> any
      (c: Conductor | c.route->forAll
            (r: Route | not r.overlaps(self))
       )
pre hasStages: self.stage -> size > 0
post foundAvailableConductor: result.isDefined()
```

4.20 Stage::init()

Initializes a `Stage` by assigning it a departure and arrival `Time`, a departure and destination `Platform` and a `TrackSection` to use between the departure and arrival platform.

Parameters:

pDepartureTime (`Time`)	The `Time` at which this stage departs from its origin.
pArrivalTime (`Time`)	The `Time` at which this stage arrives at its destination.
pOrigin (`Platform`)	The `Platform` from which this stage departs.
pDestination (`Platform`)	The `Platform` at which this stage arrives.
pTrackSection (`TrackSection`)	The `TrackSection` this stage uses.

Return value:

The operation has no return value.

Preconditions:

freshInstance	`self` must be a fresh instance, i.e. its `departureTime`, `arrivalTime`, `origin`, `destination` and `trackSection` must be undefined.
timesDefined	The given `pDepartureTime` and `pArrivalTime` must be defined.
platformsDefined	The given `pOrigin` and `pDestination` must be defined.
trackDefined	The given `pTrackSection` must be defined.
trackConnectsOriginAndDestination	The given `pTrackSection` must connect the `TrainStations` in which `pOrigin` and `pDestination` are located.

The preconditions for the times and platforms being defined are not split up further because the parameters for an operation being defined is a very trivial condition.

Postconditions:

departureTimeAssigned	The given `pDepartureTime` must be assigned correctly.
arrivalTimeAssigned	The given `pArrivalTime` must be assigned correctly.
originAssigned	The given `pOrigin` must be assigned correctly.
destinationAssigned	The given `pDestination` must be assigned correctly.
trackSectionAssigned	The given `pTrackSection` must be assigned correctly.

Implementation:

Inserts associations between `self` and the given parameters into `Departure`, `Arrival`, `OriginOfStage`, `DestinationOfStage` and `TrackForStage`.

Code:

```
-- A stage needs an existing arrival- and departure-time
-- as well as an existing origin- and destination-platform
-- and an existing TrackSection
 init(pDepartureTime: Time, pArrivalTime: Time,
      pOrigin:Platform, pDestination: Platform,
      pTrackSection: TrackSection)
   begin
     insert(pDepartureTime, self) into Departure;
     insert(pArrivalTime, self) into Arrival;
     insert(pOrigin, self) into OriginOfStage;
     insert(pDestination, self) into DestinationOfStage;
     insert(pTrackSection, self) into TrackForStage
   end
   pre freshInstance: departureTime.isUndefined() and
                      arrivalTime.isUndefined() and
                      origin.isUndefined() and
                      destination.isUndefined() and
                      trackSection.isUndefined()
   pre timesDefined: pDepartureTime.isDefined() and
                     pArrivalTime.isDefined()
   pre platformsDefined: pOrigin.isDefined() and
                         pDestination.isDefined()
```

```
    pre trackDefined: pTrackSection.isDefined()
    pre trackConnectsOriginAndDestination:
      pTrackSection.trainStation->exists
          (s : TrainStation | s = pDestination.trainStation) and
      pTrackSection.trainStation->exists
          (s : TrainStation | s = pOrigin.trainStation)
    post departureTimeAssigned: self.departureTime =
                                  pDepartureTime
    post arrivalTimeAssigned: self.arrivalTime = pArrivalTime
    post originAssigned: self.origin = pOrigin
    post destinationAssigned: self.destination = pDestination
    post trackSectionAssigned: self.trackSection = pTrackSection
```

4.21 Stage::temporallyOverlaps()

Checks if a `Stage` and a given `Stage` have overlapping time frames.

Parameters:

s (`Stage`)	A `Stage` for which to check if its time frame between departure and arrival overlaps with that of `self`.

Return value:

The operation returns a `Boolean`: `True` if `self` and `s` overlap, `False` otherwise.

Preconditions:

The operation has no preconditions.

Postconditions:

The operation has no postconditions.

Implementation:

The implementation checks for a temporal overlap in the same way as *Route::overlaps()*.

Code:

```
 -- checks if two given Stage objects overlap temporally
 temporallyOverlaps( s: Stage) : Boolean =
   not(
       (self.departureTime.isLater(s.arrivalTime)) or
       (s.departureTime.isLater(self.arrivalTime))
       )
```

4.22 Stage::getAvailableTrackSection()

Returns a `TrackSection` that can be used for a `Stage`.

Parameters:

The operation has no parameters.

Return value:

The operation returns a `TrackSection` that connects `origin` and `destination` and is not yet used in the time frame of `self`.

Preconditions:

timesDefined	The departure and arrival times of `self` must be defined to check for the availability in that time frame.
stationsDefined	`origin` and `destination` of `self` must be defined to filter for matching `TrackSections`.

Postconditions:

foundAvailableTrack	An available `TrackSection` must be found, because this operation is used within *Conductor::createRoute* and no found `TrackSection` would lead to errors later on.

Implementation:

Selects any `TrackSection` from all `TrackSection`-instances that connects `origin` and `destination` and is not yet used in the time frame needed for `self`.

Code:

```
-- returns a TrackSection that can be used for this stage,
-- if there is any, i. e. a TrackSection that is not yet
-- used in the time frame of this stage and connects origin
-- and destination
getAvailableTrackSection() : TrackSection
begin
  declare track : TrackSection;
  track := TrackSection.allInstances -> any
      (ts: TrackSection |
          (ts.stage -> forAll
              (s: Stage |
                  not(s.temporallyOverlaps(self))
              )
          ) and
          ts.trainStation ->
              includes(self.origin.trainStation) and
          ts.trainStation ->
              includes(self.destination.trainStation)
      );
  result := track;
end
pre timesDefined: self.departureTime.isDefined() and
                  self.arrivalTime.isDefined()
pre stationsDefined: self.origin.isDefined() and
                     self.destination.isDefined()
post foundAvailableTrack: result.isDefined()
```

4.23 Driver::init()

Initializes a `Driver` by assigning it a name.

Parameters:

pName (`String`)	The name for the driver.

Return value:

The operation has no return value.

Preconditions:

freshInstance	`self` must be a fresh instance, i.e. it must not have a name yet.
nameNotEmpty	The given `pName` must contains at least one character.

Postconditions:

nameIsInitialized	The given `pName` must be assigned correctly.

Implementation:

Assigns the given `pName` to `name`.

Code:

```
init(pName: String)
  begin
      self.name := pName
  end
  pre freshInstance: name.isUndefined()
  pre nameNotEmpty: pName.size > 0
  post nameIsInitialized: self.name = pName
```

4.24 Driver::assignToRoute()

Assigns a `Driver` to a given `Route` by creating a corresponding `DriverOfRoute`-association. If the `Route` already has an assigned `Driver`, that association is deleted.

Parameters:

r (`Route`)	The route to which `self` shall be assigned.

Return value:

The operation has no return value.

Preconditions:

routeDefined	The given `Route` must be defined.

Postconditions:

isAssigned	`self` must be the driver for the given `Route`.

A postcondition to check whether the association to a previously assigned `Driver` has been deleted is not necessary, since the number of assignable `Drivers` is limited to 1 in `DriverOfRoute`.

Implementation:

Deletes the association between `r` and its currently assigned `Driver`, if it already has an assigned `Driver`, then creates an association between `self` and the given `Route` in `DriverOfRoute`.

Code:

```
--assigns this driver to the given route
 assignToRoute (r: Route)
   begin
     if(r.driver.isDefined()) then
       delete (r.driver, r) from DriverOfRoute;
     end;
     insert(self, r) into DriverOfRoute
   end
   pre routeDefined: r.isDefined()
   post isAssigned: r.driver = self
```

4.25 Conductor::init()

Initializes a `Conductor` by assigning it a name.

Parameters:

pName (`String`) The name for the conductor.

Return value:

The operation has no return value.

Preconditions:

freshInstance `self` must be a fresh instance, i.e. it must not have a name yet.
nameNotEmpty The given `pName` must contains at least one character.

Postconditions:

nameIsInitialized The given `pName` must be assigned correctly.

Implementation:

Assigns the given `pName` to `name`.

Code:

```
 init(pName: String)
   begin
       self.name := pName
   end
   pre freshInstance: name.isUndefined()
   pre nameNotEmpty: pName.size > 0
   post nameIsInitialized: self.name = pName
```

4.26 Conductor::assignToRoute()

Assigns a `Conductor` to a given `Route` by creating a corresponding `ConductorOfRoute`-association. If the `Route` already has an assigned `Conductor`, that association is deleted.

Parameters:

r (`Route`) The route to which `self` shall be assigned.

Return value:

The operation has no return value.

Preconditions:

routeDefined The given `Route` must be defined.

Postconditions:

isAssigned `self` must be the conductor for the given `Route`.

A postcondition to check whether the association to a previously assigned `Conductor` has been deleted is not necessary, since the number of assignable `Conductors` is limited to 1 in `ConductorOfRoute`.

Implementation:

Deletes the association between `r` and its currently assigned `Conductor`, if it already has an assigned `Conductor`, then creates an association between `self` and the given `Route` in `ConductorOfRoute`.

Code:

```
--assigns this conductor to the given route
assignToRoute (r: Route)
  begin
    if(r.conductor.isDefined()) then
      delete (r.conductor, r) from ConductorOfRoute;
    end;
    insert(self, r) into ConductorOfRoute
  end
  pre routeDefined: r.isDefined()
  post isAssigned: r.conductor = self
```

4.27 Conductor::createRoute()

Creates a `Route` with a given starting `TrainStation`, a given starting `Time` and a sequence of following `TrainStations`. The `Platforms` for each `Stage` are chosen depending on which `Platforms` are available, the `Time` interval for each `Stage` is set to 30 minutes. The staying time in each `TrainStation` is set to 2 minutes. The `Train`, `Driver` and `Conductor` are assigned based on which ones are available for the created `Route`.

Parameters:

startingStation (`TrainStation`)	The `TrainStation` from which the `Route` departs.
stations (`Sequence(TrainStation)`)	The `TrainStations` that are serviced with this `Route` (in order).
startTime (`Time`)	The starting `Time` for this `Route`.

Return value:

The operation returns a newly created `Route`.

Preconditions:

startingStationDefined	The first `TrainStation` needs to be defined.
startTimeDefined	The given `startTime` must be defined.
enoughStations	There must be at least one more `TrainStation` in addition to the `startingStation` so that the created `Route` can have at least one `Stage`.

Postconditions:

driverAssigned	The created `Route` must have an assigned `Driver`.
conductorAssigned	The created `Route` must have an assigned `Conductor`.
trainAssigned	The created `Route` must have an assigned `Train`.
allStagesAdded	For every `TrainStation` in `stations` there must be a `Stage` in the newly created `Route`.
correctDepartingTime	The created `Route` must depart at the specified `startTime`

Note that to correctly define the operation, the stages in the created route would have to be checked for connecting the correct cities. This was noticed too late and thus could not be added as a postcondition anymore.

Implementation:

A new `Route` (`newRoute`) is created first, as well as a new `Stage` (`currentStage`) that departs from the `startingStation`. The `startingStation` and `startTime` are associated to the newly created `Stage`. Then, for each `TrainStation` in `stations`, an available `Platform` is searched using *TrainStation::getAvailablePlatform()*, the arrival `Time` is generated using *Time::getStageEndTime()* and a `TrackSection` is searched using *Stage::getAvailableTrackSection()*. The resulting arrival time, destination platform and used track section are associated to the `currentStage`.
After that, the departure time of the next `Stage` is generated using *Time::getNextDepartureTime()*. The next `origin` platform is the same as the previous `destination`. The next `Stage` becomes the new `currentStage` and the previous steps are repeated until the last `TrainStation` is reached. The last created `currentStage` is destroyed (along with its created associations) because it does not have a destination and should not be part of the `Route`.
Once all `Stage`s are added, a `Driver`, `Conductor` and `Train` are searched using *Route::getAvailableDriver()*, *Route::getAvailableConductor()* and *Route::getAvailableTrain()* and then assigned to `newRoute` using *Driver::assignToRoute()*, *Conductor::assignToRoute()* and *Train::assignToRoute()*, respectively. The resulting `Route` is returned.

Note that if there are not enough resources (drivers, conductors, trains, available platforms etc.), the operation will fail midway due to violating postconditions of utility operations or operating on returned `null`. This is not a nice solution but it works and is intended to work like this for simplicity's sake.

Code:

```
-- create a route using a list of train stations and a
-- start time. The time for each stage is set to 30 minutes.
-- To keep the code relatively simple, the departure time
-- is the same as the previous arrival time.
```

```
createRoute(startingStation: TrainStation,
            stations: Sequence(TrainStation),
            startTime: Time) : Route
  begin
    declare newRoute: Route,
            currentStage: Stage,
            currentTime: Time;
    newRoute := new Route();
    currentStage := new Stage();
    insert(startTime, currentStage) into Departure;
    insert(startingStation.getAvailablePlatform(startTime),
           currentStage) into OriginOfStage;

    for station in stations do
      currentTime :=
          currentStage.departureTime.getStageEndTime();
      insert(station.getAvailablePlatform(currentTime),
             currentStage) into DestinationOfStage;
      insert(currentTime, currentStage) into Arrival;
      insert(currentStage.getAvailableTrackSection(),
             currentStage) into TrackForStage;
      if(newRoute.stage -> size() = 0) then
        insert(currentStage, newRoute) into StagesForRoute;
      else newRoute.addStage(currentStage);
      end;
      currentStage := new Stage();
      insert(newRoute.stage -> last.destination,
             currentStage) into OriginOfStage;
      currentTime := currentTime.getNextDepartureTime();
      insert(currentTime, currentStage) into Departure;
    end;
    -- remove last 'currentStage' and its associations
    -- as well as last 'currentTime'
    destroy currentStage;
    destroy currentTime;

    newRoute.getAvailableDriver().assignToRoute(newRoute);
    newRoute.getAvailableConductor().assignToRoute(newRoute);
    newRoute.getAvailableTrain().assignToRoute(newRoute);
    result := newRoute;
  end
  --there need to be at least 2 stations in a route
  pre startingStationDefined: startingStation.isDefined()
  pre startTimeDefined: startTime.isDefined()
  pre enoughStations: stations -> size() > 0
  post driverAssigned: result.driver.isDefined()
  post conductorAssigned: result.conductor.isDefined()
  post trainAssigned: result.train.isDefined()
  post allStagesAdded: result.stage -> size() =
                       stations -> size()
  post correctDepartingTime: result.stage ->
                             first.departureTime = startTime
```

5. Scenarios

In this chapter, various test cases checking the correctness and completness of our operations and invariants will be presented. For each test case, we will start by giving a verbal explanation of the test case and its purpose. What will be following are the command sequences and the corresponding object diagrams as well as screenshots, for example showing violated constraints. In the first part of the chapter, our inviariants are evaluated. Both negative (invariants violated) and positive scenerios are discussed. Generally, we refrain from providing screenshots of the constraint evaluation for positive test cases.

5.1 Invariants

Author: Merlin Burri

The command sequence for every test case can be found in the `code/tests` folder. For many invariants, the initial test case is a simple state that does not violate any constraints. This configuration is used multiple times and is constructed as follows: There is one `Route` object consisting of one stage, i. e. it is associated with a single `Stage` object. Associated with the route there is one `Train`, one `Driver` and one `Conductor` object. The stage is associated with two `Platform` objects, with each of them being associated with a `TrainStation` (*bremen* being the origin and *rotenburg* being the destination). The stage's departure and arrival times are defined by a `Time` object, with the attribute values equating to 12:15 and 13:15 respectively. The command sequence (`initial_state.cmd`) used to create the initial state can be found next.

```
-- Bremen
!create bremen : TrainStation
!set bremen.name := 'Bremen Hauptbahnhof'

!create b1 : Platform
!set b1.number := 1

-- Rotenburg (Wuemme)
!create rotenburg : TrainStation
!set rotenburg.name := 'Rotenburg (Wuemme)'

!create r1 : Platform
!set r1.number := 2
```

```

-- Route 1 Bremen-Rotenburg
!create br1 : Route

-- Bremen to Rotenburg (Wuemme)
!create brStage : Stage
!create brRail1 : TrackSection

-- Train
!create train1 : Train
!set train1.type := 'ICE'

-- Employees
!create driver1 : Driver
!set driver1.name := 'John Lok'

!create conductor1 : Conductor
!set conductor1.name := 'Thomas'

-- Times
!create departure : Time
!set departure.hours := 12
!set departure.minutes := 15

!create arrival : Time
!set arrival.hours := 13
!set arrival.minutes := 15

--
-- Associations
--

-- PlatformInStation
!insert (b1,bremen) into PlatformInStation
!insert (r1,rotenburg) into PlatformInStation

-- Employee Associations
!insert (driver1,br1) into DriverOfRoute
!insert (conductor1,br1) into ConductorOfRoute

-- TrainForRoute
!insert (train1,br1) into TrainForRoute

-- Stages StagesForRoute
!insert (brStage,br1) into StagesForRoute

-- TrackForStage
!insert (brRail1,brStage) into TrackForStage

-- OriginOfStage
!insert (b1, brStage) into OriginOfStage

```

```
-- DestinationOfStage
!insert (r1, brStage) into DestinationOfStage

-- Departure
!insert (departure, brStage) into Departure

-- Arrival
!insert (arrival, brStage) into Arrival

-- EndPoints
!insert (brRail1, bremen) into EndPoints
!insert (brRail1, rotenburg) into EndPoints
```

5.1.1 Train, Driver and Conductor

Since all our invariants for the classes `Train`, `Driver` and `Conductor` simply forbid the simultaneous use of ressources, we construct test cases to check these three invariants at once.

Test case 01 – TC_01_ressources_NotUsedSimultaneously_0

This test case is the first positive scenario for all **NotUsedSimultaneously** invariants. Starting from the initial state, we add a second route *br_route2* and assign the existing driver *driver1*, conductor *conductor1* and train *train1* to that second route. All three ressources are now assigned to multiple routes. By setting the departure and arrival time of the new route (or more precisely, the new stage associated with the new route) to 14:35 and 15:35 respectively, we do not create temporal overlap between the two routes. Therefore, no **NotUsedSimultaneously** invariant is violated. Figure 5.1 shows the object diagram for this test case.

```
open initial_state.cmd

-- create new platforms for new route/stage and associate them with
-- train stations
!create r2 : Platform
!set r2.number := 2
!insert (r2,rotenburg) into PlatformInStation

!create b2 : Platform
!set b2.number := 2
!insert (b2,bremen) into PlatformInStation

-- create route 2 Rotenburg - Bremen
!create br_route2 : Route

-- create stage from Rotenburg to Bremen
!create rbStage : Stage
!insert (rbStage,br_route2) into StagesForRoute

-- create arrival and departure time
-- no temporal overlap with the first route
!create departure2 : Time
!set departure2.hours := 14
!set departure2.minutes := 35
```

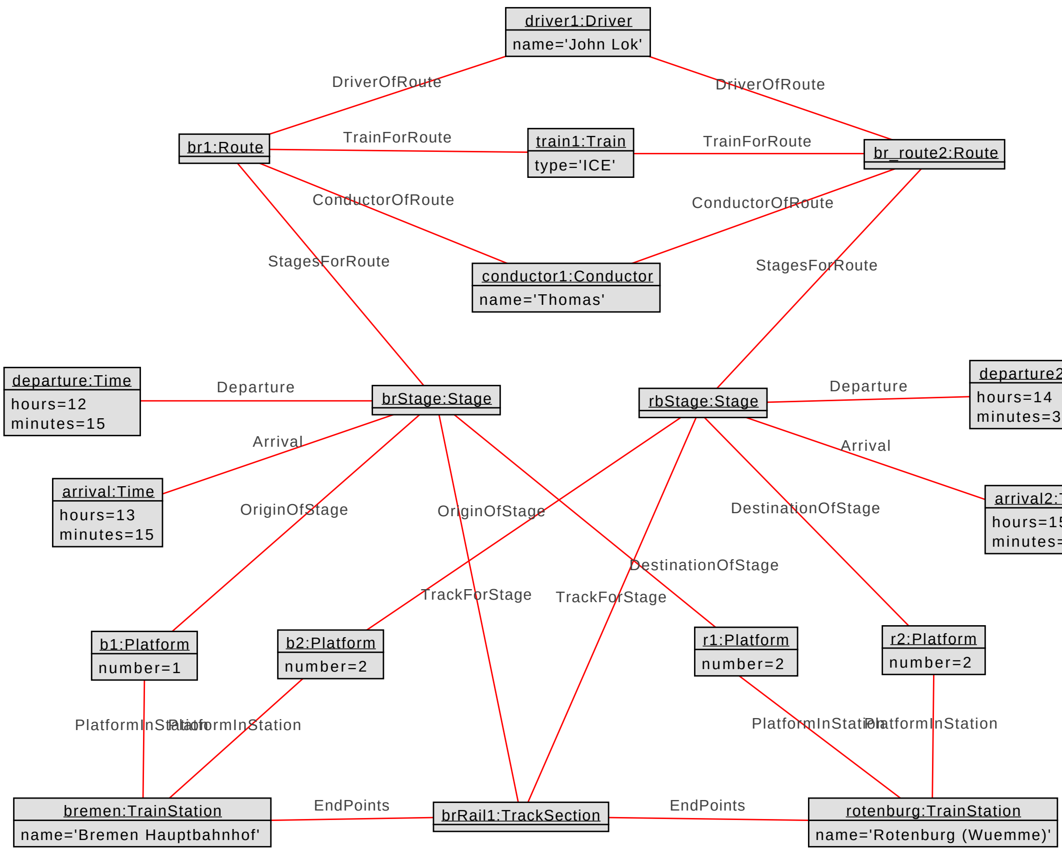


Figure 5.1: Object diagram for test case 01 - no violations

```

!create arrival2 : Time
!set arrival2.hours := 15
!set arrival2.minutes := 35

-- associate new stage with track section, platforms and times
!insert (brRail1,rbStage) into TrackForStage
!insert (b2, rbStage) into OriginOfStage
!insert (r2, rbStage) into DestinationOfStage
!insert (departure2, rbStage) into Departure
!insert (arrival2, rbStage) into Arrival

-- no violation of "train_NotUsedSimultaneously"
!insert (train1,br_route2) into TrainForRoute

-- no violation of "conductor_NotUsedSimultaneously"
-- and "driver_NotUsedSimultaneously"
!insert (driver1,br_route2) into DriverOfRoute
!insert (conductor1,br_route2) into ConductorOfRoute
```

Test case 02 – TC_02_ressources_NotUsedSimultaneously_0

For our second positive test case for the **NotUsedSimultaneously** invariants, we again start from the initial state. Like in test case 02, a second route from Bremen to Rotenburg is added. This time however, we set the departure and arrival time to 12:35 and 13:35

respectively, causing temporal overlap between the two routes. We introduce new `Driver`, `Conductor` and `Train` objects and assign them to that second route. Since no single ressource is assigned to multiple routes with temporal overlap, no **NotUsedSimultaneously** is violated. Figure 5.2 shows the object diagram for this test case.

```
open initial_state.cmd

-- create new platforms for new stage and associate them with
-- train stations
!create r2 : Platform
!set r2.number := 2
!insert (r2,rotenburg) into PlatformInStation

!create b2 : Platform
!set b2.number := 2
!insert (b2,bremen) into PlatformInStation

-- create route 2 Rotenburg - Bremen
!create br_route2_tempOverlap : Route

-- create stage from Rotenburg to Bremen
!create rbStage : Stage
!insert (rbStage,br_route2_tempOverlap) into StagesForRoute

-- create arrival and departure time
-- temporal overlap with the first route
!create departure2 : Time
!set departure2.hours := 12
!set departure2.minutes := 35

!create arrival2 : Time
!set arrival2.hours := 13
!set arrival2.minutes := 35

-- associate new stage with track section, platforms and times
!insert (brRail1,rbStage) into TrackForStage
!insert (b2, rbStage) into OriginOfStage
!insert (r2, rbStage) into DestinationOfStage
!insert (departure2, rbStage) into Departure
!insert (arrival2, rbStage) into Arrival

-- different train, conductor and driver for the new, overlapping route
!create driver2 : Driver
!set driver2.name := 'John Lok II'
!create conductor2 : Conductor
!set conductor2.name := 'Thomas II'
!create train2 : Train
!set train2.type := 'RE'

!insert (driver2,br_route2_tempOverlap) into DriverOfRoute
!insert (conductor2,br_route2_tempOverlap) into ConductorOfRoute
!insert (train2,br_route2_tempOverlap) into TrainForRoute
```

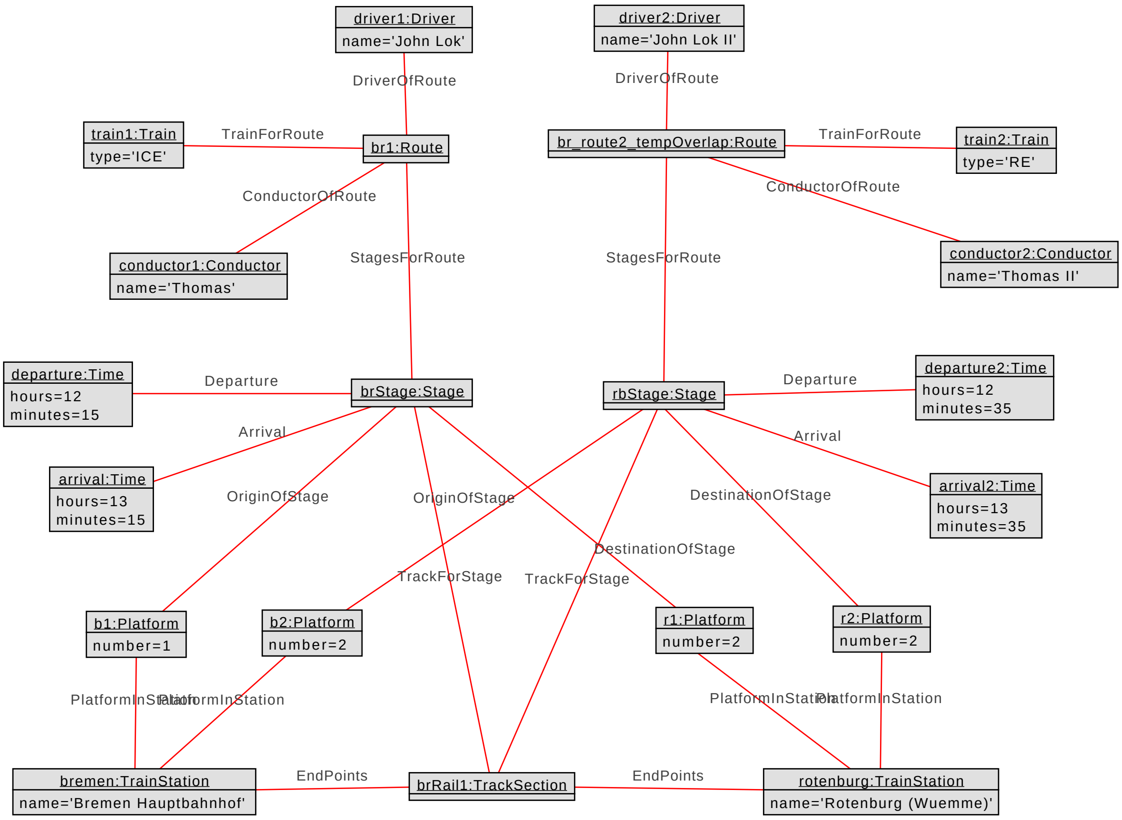


Figure 5.2: Object diagram for test case 02 - no violations

Test case 03 – TC_03_ressources_NotUsedSimultaneously_1

We now introduce a negative test case for the **NotUsedSimultaneously** invariants. In accordance to test case 02, we start with the initial state and add a route that overlaps in time with the first route included in the initial state. In contrast to test case 02, we do not add new objects but assign the existing `Driver`, `Conductor` and `Train` objects to this new overlapping route. All three **NotUsedSimultaneously** are therefore violated, which is shown in figure 5.4. The object diagram is shown in figure 5.3.

```
open initial_state.cmd

-- create new platforms for new stage and associate them with
-- train stations
!create r2 : Platform
!set r2.number := 2
!insert (r2,rotenburg) into PlatformInStation

!create b2 : Platform
!set b2.number := 2
!insert (b2,bremen) into PlatformInStation

-- create route 2 Rotenburg - Bremen
!create br_route2_tempOverlap : Route

-- create stage from Rotenburg to Bremen
!create rbStage : Stage
!insert (rbStage,br_route2_tempOverlap) into StagesForRoute
```

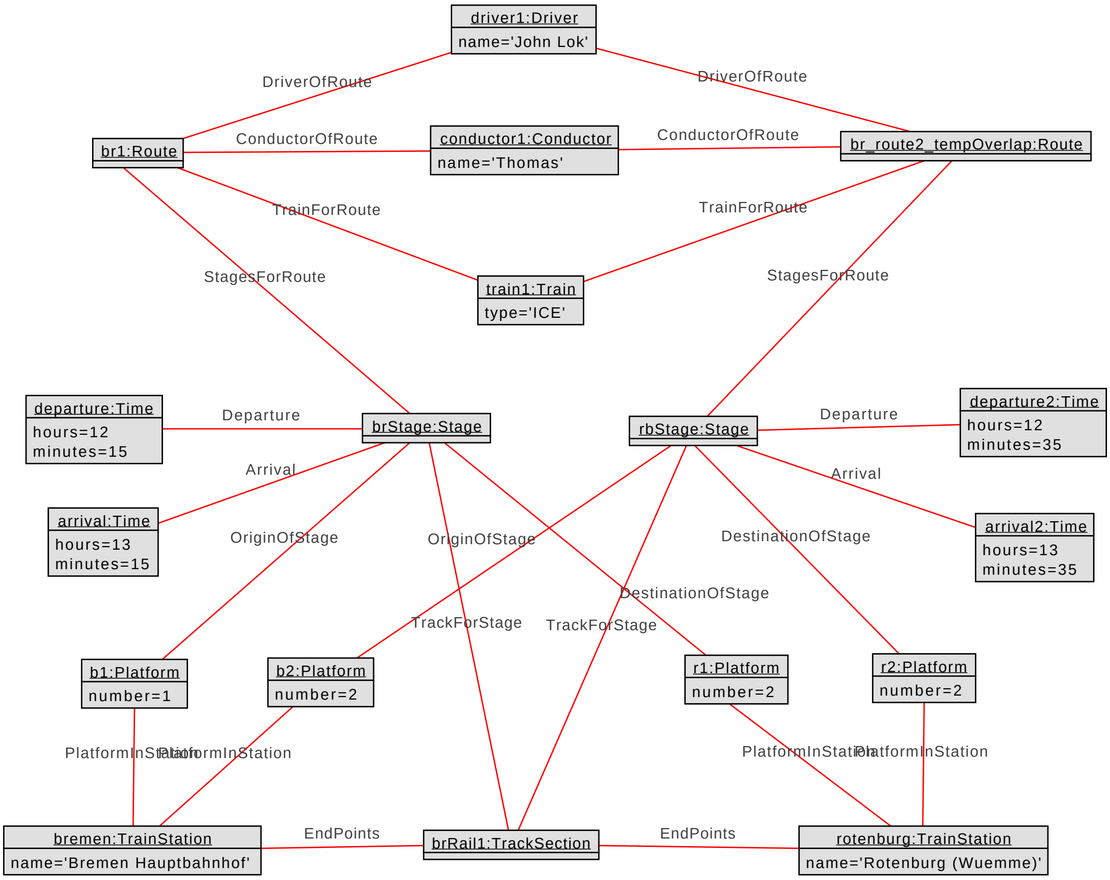


Figure 5.3: Object diagram for test case 03 – **NotUsedSimultaneously** constraints violated

```

-- create arrival and departure time
-- temporal overlap with the first route
!create departure2 : Time
!set departure2.hours := 12
!set departure2.minutes := 35

!create arrival2 : Time
!set arrival2.hours := 13
!set arrival2.minutes := 35

-- associate new stage with track section, platforms and times
!insert (brRail1,rbStage) into TrackForStage
!insert (b2, rbStage) into OriginOfStage
!insert (r2, rbStage) into DestinationOfStage
!insert (departure2, rbStage) into Departure
!insert (arrival2, rbStage) into Arrival

-- violate all "NotUsedSimultaneously" constraints
!insert (driver1,br_route2_tempOverlap) into DriverOfRoute
!insert (conductor1,br_route2_tempOverlap) into ConductorOfRoute
!insert (train1,br_route2_tempOverlap) into TrainForRoute
```

Class invariants

Invariant	Loaded	Active	Negate	Satisfied
Conductor::ConductorNotUsedSimultaneously	☐	☑	☐	false
Driver::DriverNotUsedSimultaneously	☐	☑	☐	false
Platform::MaxOneTrainPerPlatform	☐	☑	☐	true
Route::DepartureAfterArrivalPreviousStage	☐	☑	☐	true
Route::DeparturePlatformPreviousPlatform	☐	☑	☐	true
Route::NoCircles	☐	☑	☐	true
Stage::ArrivalAfterDeparture	☐	☑	☐	true
Stage::NoOverlapsOppositeDirections	☐	☑	☐	true
Stage::TimeDifferenceSameDirection	☐	☑	☐	true
Stage::TrackSectionConnectOriginDestination	☐	☑	☐	true
Time::HoursInInterval	☐	☑	☐	true
Time::MinutesInInterval	☐	☑	☐	true
Train::TrainNotUsedSimultaneously	☐	☑	☐	false

3 constraints failed. (11ms) 100%

Figure 5.4: Violated constraints for test case 03

5.1.2 Route

To show the correctness of our `Route` class constraints, we introduce an extension of our initial state. It is very similar to the previously presented initial state, with one major addition: The route is associated with two stages, so Rotenburg is now an intermediate stop and the last stop is Hamburg.

Test case 04 – TC_04_route_0

This initial state also serves as the positive scenario for all three `Route` class constraints. As mentioned, we use two stages for the route, *brStage* being the first and *rhStage* the second. Platform *r1* of Rotenburg is both the destination of the first stage and and the second stage's origin. Therefore, **DeparturePlatformPreviousPlatform** is not violated. Also, the first stage's arrival time is 13:15 and the second stage's departure time is 13:16, so the train departs after it has arrived and not before. Thus, **DepartureAfterArrival-PreviousStage** is also satisfied. As the route also contains no circles, **NoCircles** is not violated either. Figure 5.5 illustrates the described valid system state.

```
open initial_state.cmd

-- Hamburg
!create hamburg : TrainStation
!set hamburg.name := 'Hamburg Hauptbahnhof'

!create h1 : Platform
!set h1.number := 1

-- Rotenburg (Wuemme) to Hamburg
!create rhStage : Stage
!create rhRail1 : TrackSection

--
-- Associations
--

-- PlatformInStation
!insert (h1,hamburg) into PlatformInStation

-- Stages StagesForRoute
!insert (rhStage,br1) into StagesForRoute
```

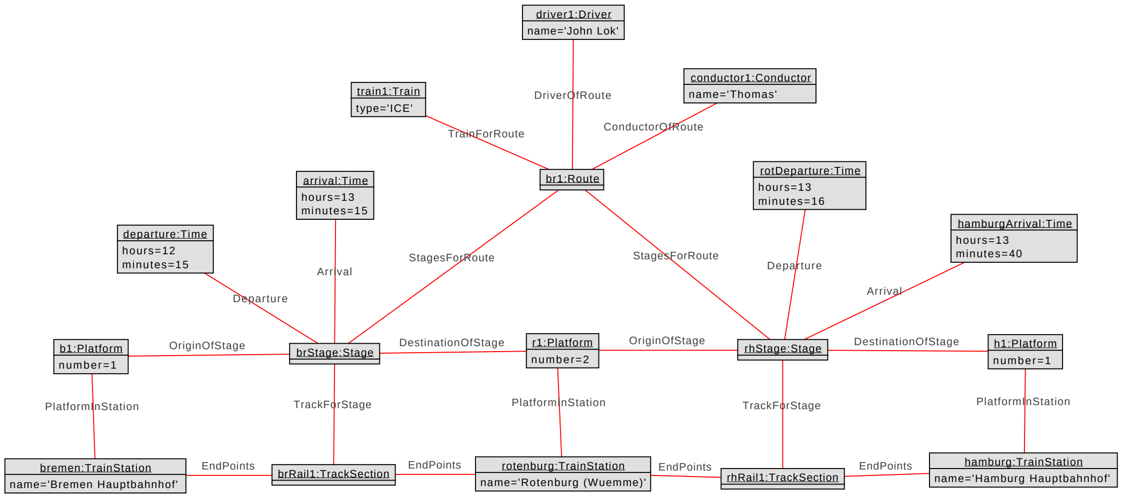


Figure 5.5: Object diagram for test case 04 – no violations

```

-- TrackForStage
!insert (rhRail1,rhStage) into TrackForStage

-- DestinationOfStage
!insert (h1, rhStage) into DestinationOfStage

-- EndPoints
!insert (rhRail1, rotenburg) into EndPoints
!insert (rhRail1, hamburg) into EndPoints

-- Arrival time in hamburg (not relevant for this test case)
!create hamburgArrival : Time
!set hamburgArrival.hours := 13
!set hamburgArrival.minutes := 40
!insert (hamburgArrival, rhStage) into Arrival

-- not violating "DeparturePlatformPreviousPlatform"
!insert (r1, rhStage) into OriginOfStage

--
-- not violating "DepartureAfterArrivalPreviousStage"
-- Departure time after arrival time of previous Stage
--

!create rotDeparture : Time
!set rotDeparture.hours := 13
!set rotDeparture.minutes := 16
!insert (rotDeparture, rhStage) into Departure
```

Test case 05 – TC_05_route_DepartureAfterArrivalPreviousStage_1

In our negative scenario for the **DepartureAfterArrivalPreviousStage** invariant, we simply set the arrival time of the first stage to 13:16. If we consider the departure time of the next stage, which is 13:16 as well, the constraint has been violated. The resulting object diagram can be seen in figure 5.6 and the resulting constraint evaluation window in

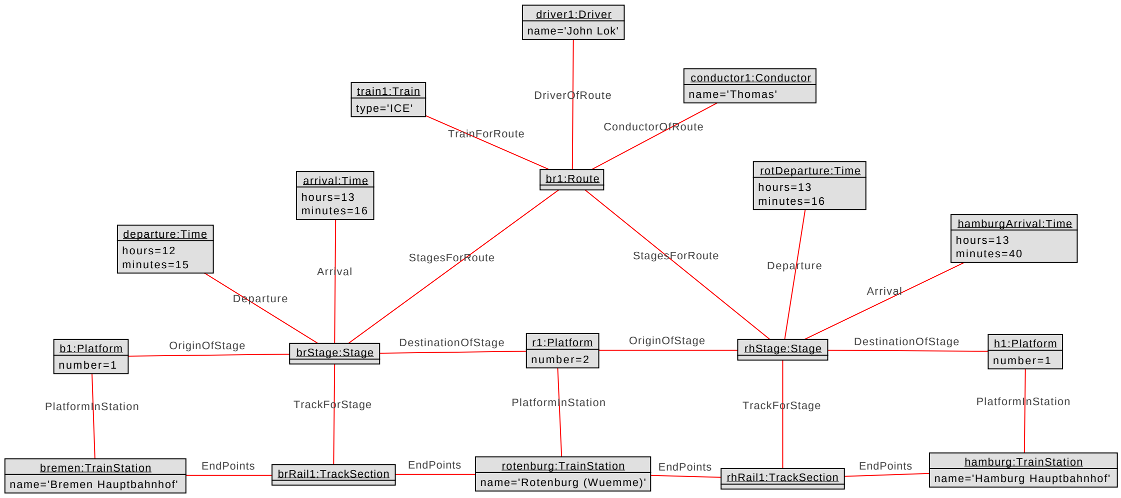
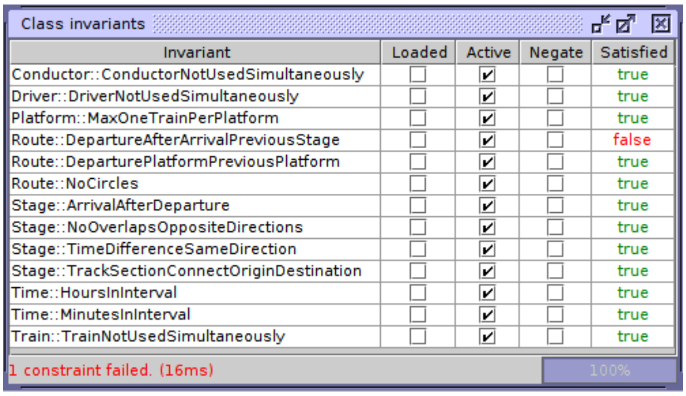


Figure 5.6: Object diagram for test case 05 – **DepartureAfterArrivalPreviousStage** violated



Invariant	Loaded	Active	Negate	Satisfied
Conductor::ConductorNotUsedSimultaneously	☐	☑	☐	true
Driver::DriverNotUsedSimultaneously	☐	☑	☐	true
Platform::MaxOneTrainPerPlatform	☐	☑	☐	true
Route::DepartureAfterArrivalPreviousStage	☐	☑	☐	false
Route::DeparturePlatformPreviousPlatform	☐	☑	☐	true
Route::NoCircles	☐	☑	☐	true
Stage::ArrivalAfterDeparture	☐	☑	☐	true
Stage::NoOverlapsOppositeDirections	☐	☑	☐	true
Stage::TimeDifferenceSameDirection	☐	☑	☐	true
Stage::TrackSectionConnectOriginDestination	☐	☑	☐	true
Time::HoursInInterval	☐	☑	☐	true
Time::MinutesInInterval	☐	☑	☐	true
Train::TrainNotUsedSimultaneously	☐	☑	☐	true

Figure 5.7: Violated constraints for test case 05

figure 5.7.

```
open TC_04_route_0.cmd

-- violate DepartureAfterArrivalPreviousStage
!set arrival.hours := 13
!set arrival.minutes := 16
```

Test case 06 – TC_06_route_DeparturePlatformPreviousPlatform_1

The negative scenario for the **DeparturePlatformPreviousPlatform** works similarly. Instead of changing the arrival time of the first stage like in test case 05, we instead change the arriving platform. To archieve that, we introduce a new platform *r2* associated with Rotenburg and associate the destination platform of the stage connecting Bremen and Rotenburg with that same platform. Since the next stage in the route, Rotenburg to Hamburg, departs from *r1* and not *r2*, the constraint is violated. The resulting object diagram is displayed in figure 5.8 and the violated constraints in figure 5.9.

```
open TC_04_route_0.cmd

-- create new platform for Rotenburg station
!create r2 : Platform
!set r2.number := 2
```

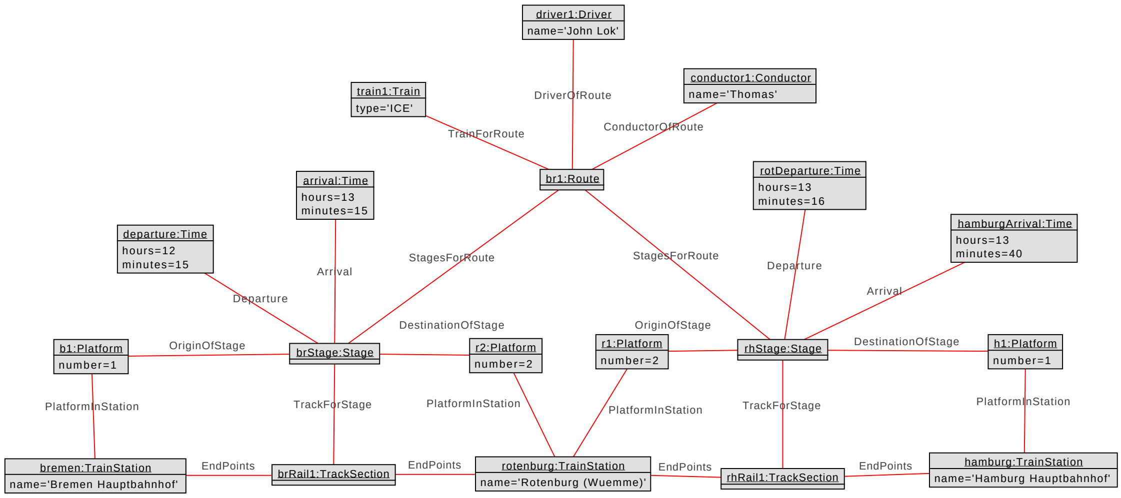
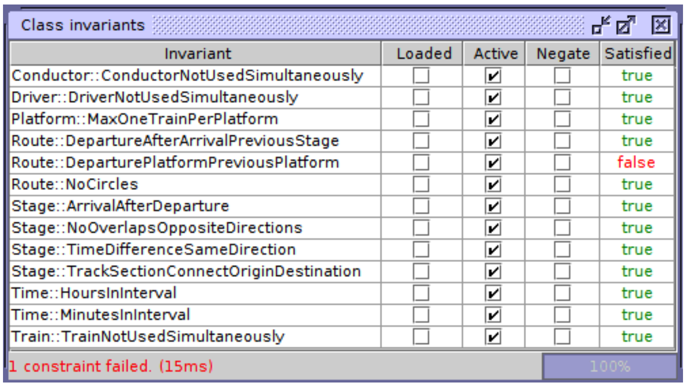


Figure 5.8: Object diagram for test case 06 – **DeparturePlatformPrevious-Platform** violated



Class invariants

Invariant	Loaded	Active	Negate	Satisfied
Conductor::ConductorNotUsedSimultaneously	☐	☑	☐	true
Driver::DriverNotUsedSimultaneously	☐	☑	☐	true
Platform::MaxOneTrainPerPlatform	☐	☑	☐	true
Route::DepartureAfterArrivalPreviousStage	☐	☑	☐	true
Route::DeparturePlatformPreviousPlatform	☐	☑	☐	false
Route::NoCircles	☐	☑	☐	true
Stage::ArrivalAfterDeparture	☐	☑	☐	true
Stage::NoOverlapsOppositeDirections	☐	☑	☐	true
Stage::TimeDifferenceSameDirection	☐	☑	☐	true
Stage::TrackSectionConnectOriginDestination	☐	☑	☐	true
Time::HoursInInterval	☐	☑	☐	true
Time::MinutesInInterval	☐	☑	☐	true
Train::TrainNotUsedSimultaneously	☐	☑	☐	true

1 constraint failed. (15ms) 100%

Figure 5.9: Violated constraints for test case 06

```

!insert (r2,rotenburg) into PlatformInStation

-- change destination platform of Bremen-Rotenburg
-- to r2 to violate constraint, as
-- Rotenburg-Hamburg departs from r1
!delete (r1, brStage) from DestinationOfStage
!insert (r2, brStage) into DestinationOfStage
```

Test case 07 – TC_07_route_NoCircles_1

There is no need to explicitly provide a positive scenario for the **NoCircles** invariant, since basically every previous test case is just that. Test case 17 provides a positive example that is a bit more advanced, because there are multiple stages assigned to one route. To now provide a negative test case, we take the system state introduced by test case 04 and remove `TrainStation` *hamburg*, `Platform` *h1* and `TrackSection` *rhRail1*. We then assign *rhStage* to *brRail1* and *b1* as destination. We then add a stage equal the *brStage* with different arrival and departure times. Now, *br1* first goes from *bremen* to *rotenburg*, then back and afterwards again to*rotenburg*. We have a circle and the constraint is thus violated, which is shown in figure 5.11. Figure 5.10 shows the object diagram.

```
open TC_04_route_0.cmd

```

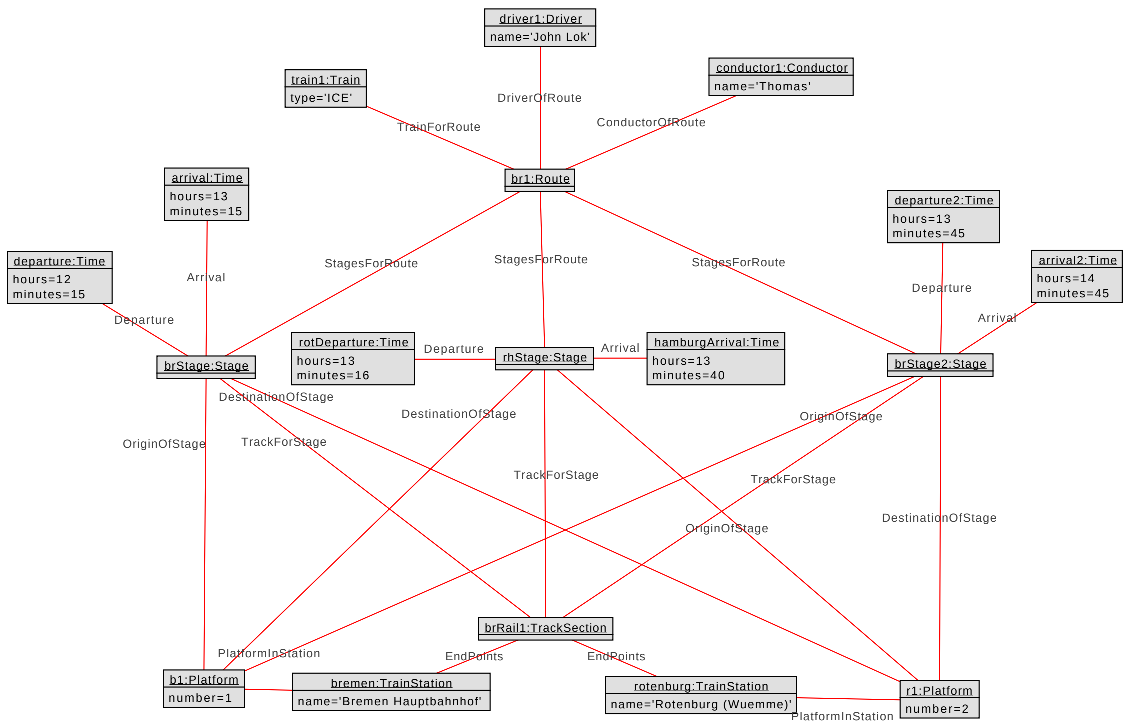
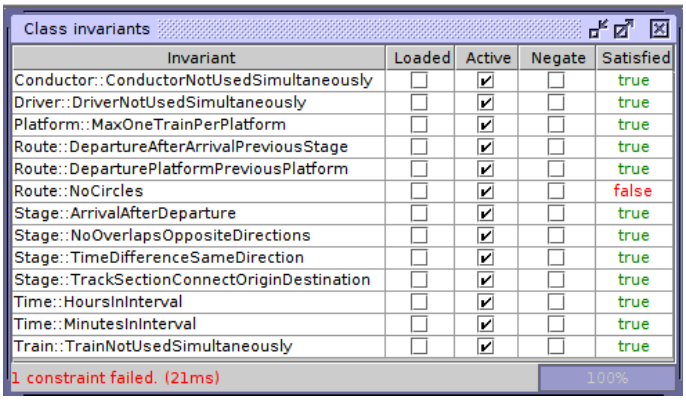


Figure 5.10: Object diagram for test case 07 – **NoCircles** violated

```
-- destroy Hamburg and track section
!destroy hamburg
!destroy h1
!destroy rhRail1

-- make rhStage go from Rotenburg to Bremen
!insert (brRail1, rhStage) into TrackForStage
!insert (b1, rhStage) into DestinationOfStage

-- add new stage equal to brStage with different times
!create brStage2 : Stage

!create departure2 : Time
!set departure2.hours := 13
!set departure2.minutes := 45

!create arrival2 : Time
!set arrival2.hours := 14
!set arrival2.minutes := 45

!insert (brStage2,br1) into StagesForRoute
!insert (brRail1,brStage2) into TrackForStage
!insert (b1, brStage2) into OriginOfStage
!insert (r1, brStage2) into DestinationOfStage
!insert (departure2, brStage2) into Departure
!insert (arrival2, brStage2) into Arrival
```


Class invariants

Invariant	Loaded	Active	Negate	Satisfied
Conductor::ConductorNotUsedSimultaneously	☐	☑	☐	true
Driver::DriverNotUsedSimultaneously	☐	☑	☐	true
Platform::MaxOneTrainPerPlatform	☐	☑	☐	true
Route::DepartureAfterArrivalPreviousStage	☐	☑	☐	true
Route::DeparturePlatformPreviousPlatform	☐	☑	☐	true
Route::NoCircles	☐	☑	☐	false
Stage::ArrivalAfterDeparture	☐	☑	☐	true
Stage::NoOverlapsOppositeDirections	☐	☑	☐	true
Stage::TimeDifferenceSameDirection	☐	☑	☐	true
Stage::TrackSectionConnectOriginDestination	☐	☑	☐	true
Time::HoursInInterval	☐	☑	☐	true
Time::MinutesInInterval	☐	☑	☐	true
Train::TrainNotUsedSimultaneously	☐	☑	☐	true

1 constraint failed. (21ms) 100%

Figure 5.11: Violated constraints for test case 07

5.1.3 Stage

Positive test cases for the **ArrivalAfterDeparture** invariant of the `Stage` class are implicitly given by all previous test cases, which contain (multiple) `Stage` objects with assigned arrival times being after the departure time and **ArrivalAfterDeparture** not being violated.

Test case 08 – TC_08_stage_ArrivalAfterDeparture_1

To create a negative test case for the **ArrivalAfterDeparture** invariant, we simply take the initial state introduced in the introduction of section 5.1 and change the arrival time of the only existing stage to 12:14. Since the stage's departure time is set to 12:15, **ArrivalAfterDeparture** is violated. Figure 5.12 shows the resulting object diagram and figure 5.13 the violated constraints. We prefer to present an otherwise valid system state as oppposed to a minimal system state that for example only contains a stage and time objects, so only the constraint, which we want to present a negative scenario for, is actually violated.

```
open initial_state.cmd

-- change arrival time of Stage to 12:14
-- since departure time is 12:15
-- ArrivalAfterDeparture is violated
!set arrival.hours := 12
!set arrival.minutes := 14
```

Test case 09 – TC_09_stage_TrackSectionConnectOriginDestination_1

Again, we do not provide a specific positive test case for the **TrackSectionConnectOriginDestination** invariant. All previous test cases show examples of system states rightfully and evidently not violating the constraint. For instance, in the initial state, we can see that the `TrackSection` *brRail1* assigned to the single stage *brStage* is associated with the two train stations that the origin and destination platform of *brStage* are associated with, resulting in no violation of **TrackSectionConnectOriginDestination**.

To provide a negative example, we take the initial state specified in the introduction of the section 5.1 and add a new `TrainStation` *hamburg* and associate *brRail1* to that train station instead of *bremen*. Thus, the track section assigned to *brStage* is no longer connecting the two train stations assigned to the origin and destination platform. In figure 5.14, the resulting system state is illustrated and figure 5.15 shows the violated constraints.

```
open initial_state.cmd
```

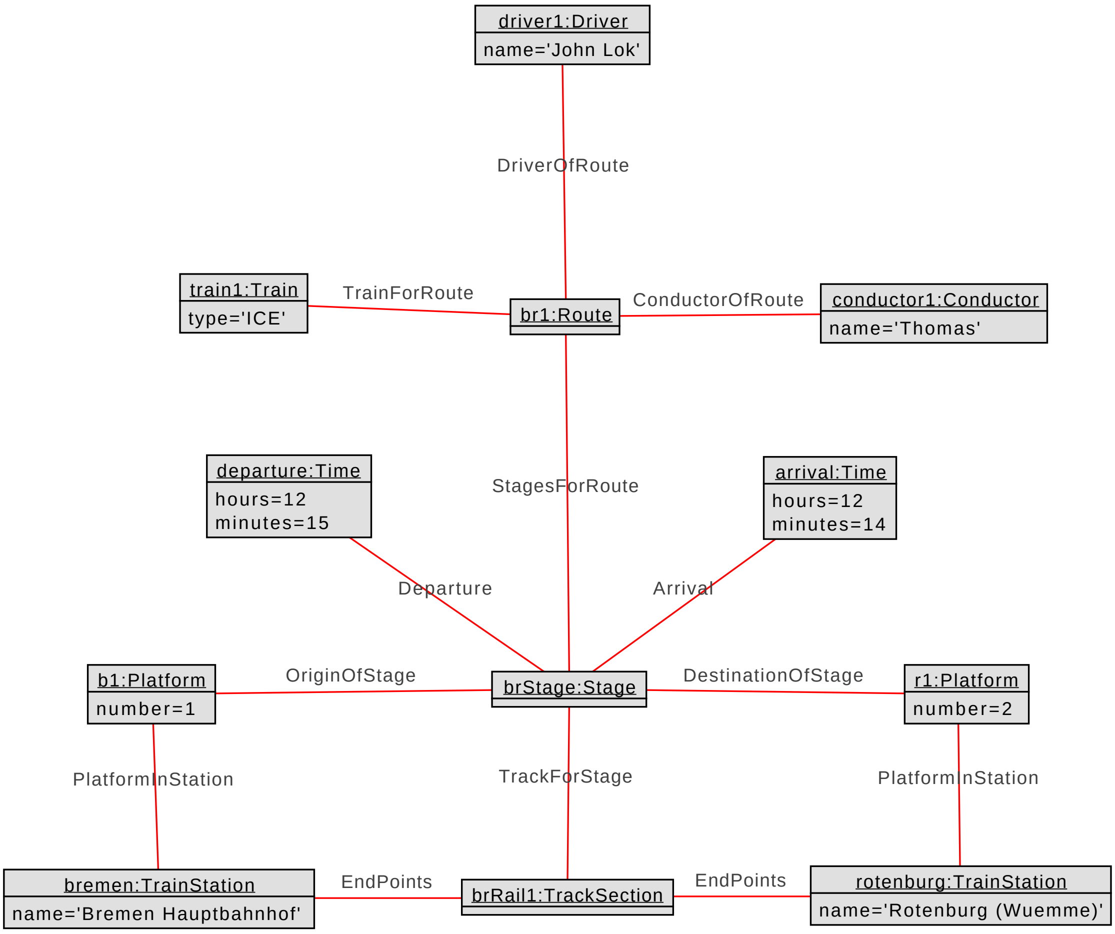
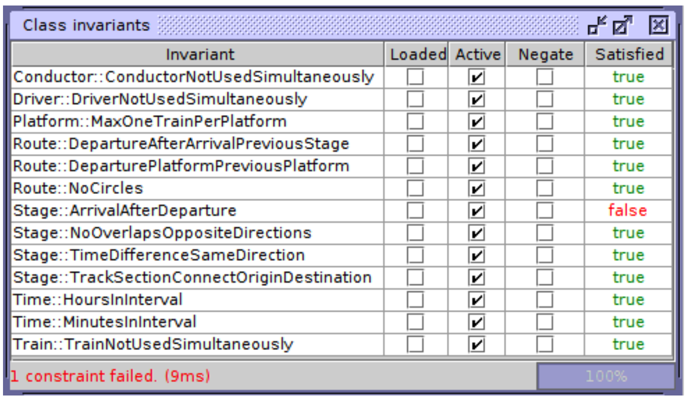


Figure 5.12: Object diagram for test case 08 – **ArrivalAfterDeparture** violated


Class invariants

Invariant	Loaded	Active	Negate	Satisfied
Conductor::ConductorNotUsedSimultaneously	☐	☑	☐	true
Driver::DriverNotUsedSimultaneously	☐	☑	☐	true
Platform::MaxOneTrainPerPlatform	☐	☑	☐	true
Route::DepartureAfterArrivalPreviousStage	☐	☑	☐	true
Route::DeparturePlatformPreviousPlatform	☐	☑	☐	true
Route::NoCircles	☐	☑	☐	true
Stage::ArrivalAfterDeparture	☐	☑	☐	false
Stage::NoOverlapsOppositeDirections	☐	☑	☐	true
Stage::TimeDifferenceSameDirection	☐	☑	☐	true
Stage::TrackSectionConnectOriginDestination	☐	☑	☐	true
Time::HoursInInterval	☐	☑	☐	true
Time::MinutesInInterval	☐	☑	☐	true
Train::TrainNotUsedSimultaneously	☐	☑	☐	true

1 constraint failed. (9ms) 100%

Figure 5.13: Violated constraints for test case 08

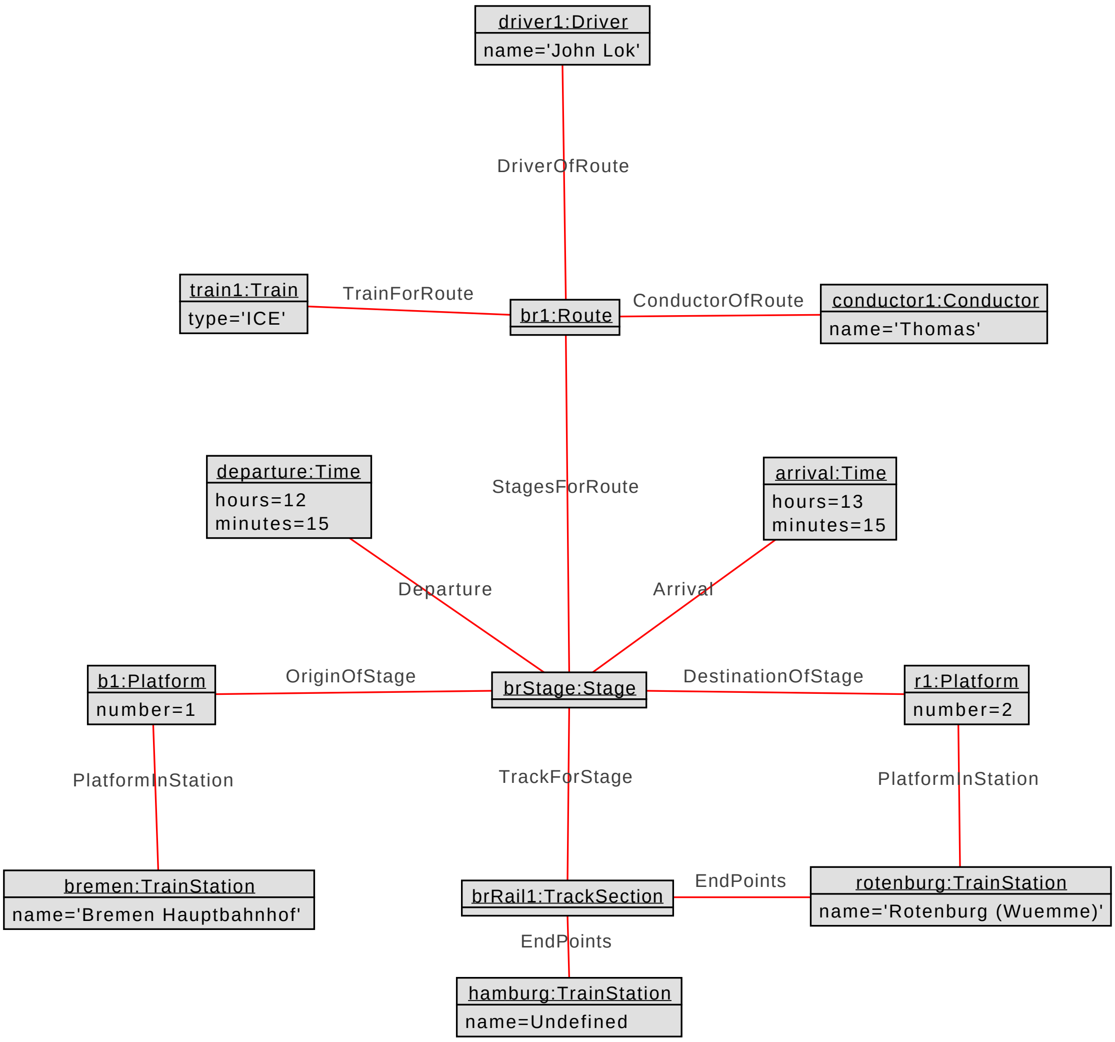
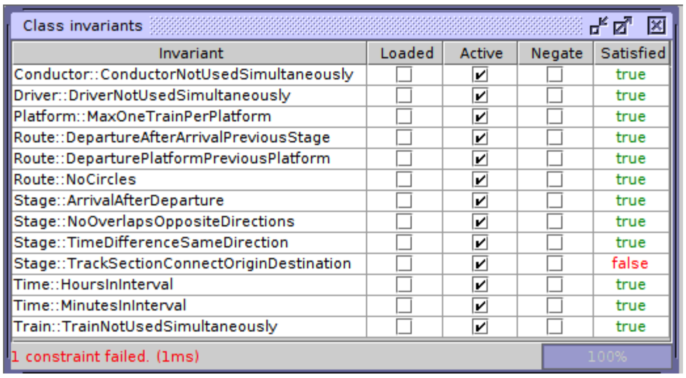


Figure 5.14: Object diagram for test case 09 – **TrackSectionConnectOrigin-Destination** violated

```

-- add new train station hamburg and change
-- assignment of track section brRail1 to hamburg
-- thus violating the constraint
!create hamburg : TrainStation
!delete (brRail1, bremen) from EndPoints
!insert (brRail1, hamburg) into EndPoints
```

Test case 10 – TC_10_stage_NoOverlapsOppositeDirections_0

In the first positive test case for **NoOverlapsOppositeDirections**, we want to show that two stages using the same track section without any temporal overlap does not violate our constraint, even if the trains go in opposite directions. We therefore take the system state introduced for test case 02 and change the departure and arrival time of the our `Stage` *rbStage* to 13:35 and 14:35 respectively, since we do not want temporal overlap. To then make the two trains go in opposite directions, we switch `Platform` objects assigned to our *Stage rbStage*, causing *r2* to be the origin and *b2* the destination platform. Since there is no temporal overlap, **NoOverlapsOppositeDirections** is not violated. The resulting object diagram is shown in figure 5.16.



Class invariants

Invariant	Loaded	Active	Negate	Satisfied
Conductor::ConductorNotUsedSimultaneously	☐	☑	☐	true
Driver::DriverNotUsedSimultaneously	☐	☑	☐	true
Platform::MaxOneTrainPerPlatform	☐	☑	☐	true
Route::DepartureAfterArrivalPreviousStage	☐	☑	☐	true
Route::DeparturePlatformPreviousPlatform	☐	☑	☐	true
Route::NoCircles	☐	☑	☐	true
Stage::ArrivalAfterDeparture	☐	☑	☐	true
Stage::NoOverlapsOppositeDirections	☐	☑	☐	true
Stage::TimeDifferenceSameDirection	☐	☑	☐	true
Stage::TrackSectionConnectOriginDestination	☐	☑	☐	false
Time::HoursInInterval	☐	☑	☐	true
Time::MinutesInInterval	☐	☑	☐	true
Train::TrainNotUsedSimultaneously	☐	☑	☐	true

1 constraint failed. (1ms) 100%

Figure 5.15: Violated constraints for test case 09

```
open TC_02_ressources_NotUsedSimultaneously_0.cmd

-- change times so there is no temporal overlap
!set departure2.hours := 13
!set departure2.minutes := 35

!set arrival2.hours := 14
!set arrival2.minutes := 35

-- switch destination and platform assignments
-- of rbStage
!delete (b2, rbStage) from OriginOfStage
!delete (r2, rbStage) from DestinationOfStage

!insert (r2, rbStage) into OriginOfStage
!insert (b2, rbStage) into DestinationOfStage
```

Test case 11 – TC_11_stage_NoOverlapsOppositeDirections_0

For the second positive test case, we want to show that the constraint is not violated if two trains use differing track sections at the same time, while driving in opposite directions. We start with the system state introduced for test case 02 and again swap the origin and destination platform for `Stage` *rbStage*. We create a new `TrackSection` *brRail2* and, after associating it with the two existing train stations, assign it to *rbStage*. Now, there is temporal overlap between our two stages and the trains go in opposite directions. Since different track sections are used, **NoOverlapsOppositeDirections** is not violated. Figure 5.17 shows the resulting object diagram.

```
open TC_02_ressources_NotUsedSimultaneously_0.cmd

-- switch destination and platform assignments
-- of rbStage
!delete (b2, rbStage) from OriginOfStage
!delete (r2, rbStage) from DestinationOfStage

!insert (r2, rbStage) into OriginOfStage
!insert (b2, rbStage) into DestinationOfStage

-- introduce new track section between
-- Bremen and Rotenburg
```

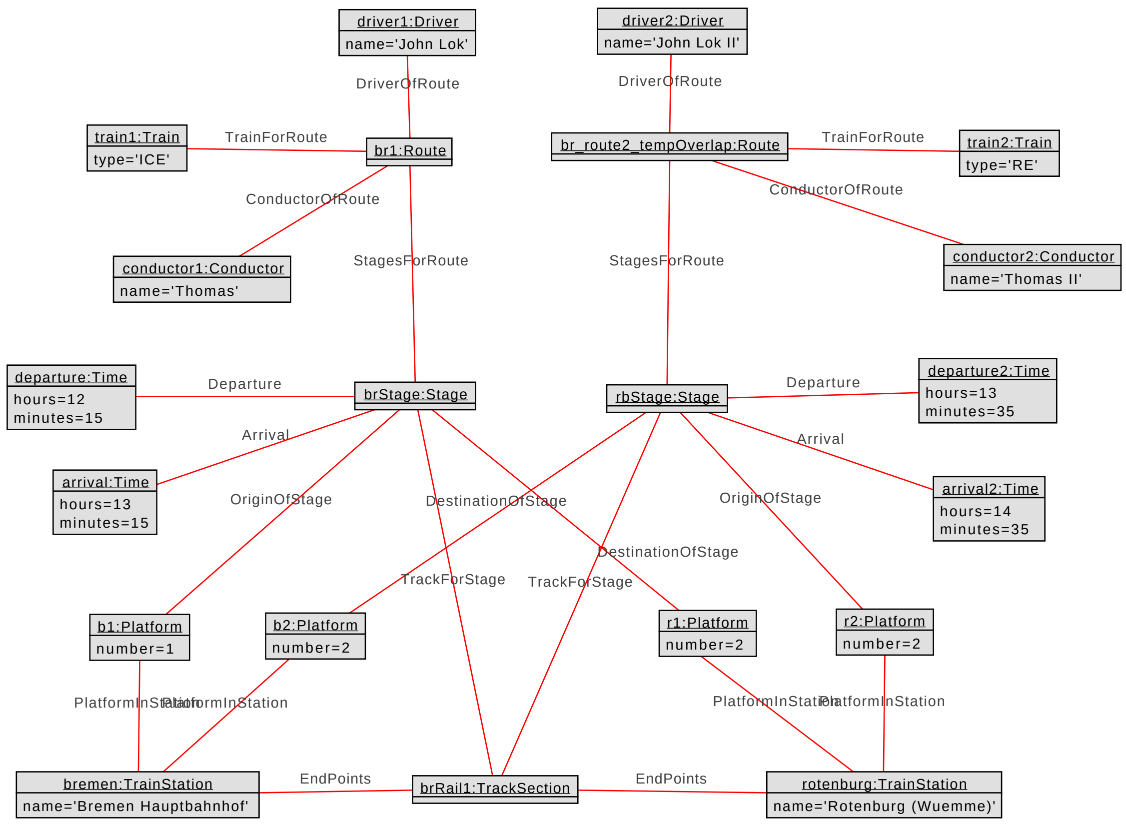


Figure 5.16: Object diagram for test case 10 – no violations

```
!create brRail2 : TrackSection
!insert (brRail2, bremen) into EndPoints
!insert (brRail2, rotenburg) into EndPoints

-- assign new track section to rbStage
!delete (brRail1,rbStage) from TrackForStage
!insert (brRail2,rbStage) into TrackForStage
```

Test case 12 – TC_12_stage_NoOverlapsOppositeDirections_1

To provide a negative test case for **NoOverlapsOppositeDirections**, we construct a system state similar to the one introduced for test case 11. This time, we do not create a new track section. Thus, we have two trains using the same track section going in opposite directions while overlapping in time and **NoOverlapsOppositeDirections** is violated, which is shown in figure 5.19. The resulting object diagram is shown in figure 5.18.

```
open TC_02_ressources_NotUsedSimultaneously_0.cmd

-- switch destination and platform assignments
-- of rbStage causing trains going in opposite directions
-- violating NoOverlapsSameDirection due to temporal overlap
!delete (b2, rbStage) from OriginOfStage
!delete (r2, rbStage) from DestinationOfStage

!insert (r2, rbStage) into OriginOfStage
!insert (b2, rbStage) into DestinationOfStage
```

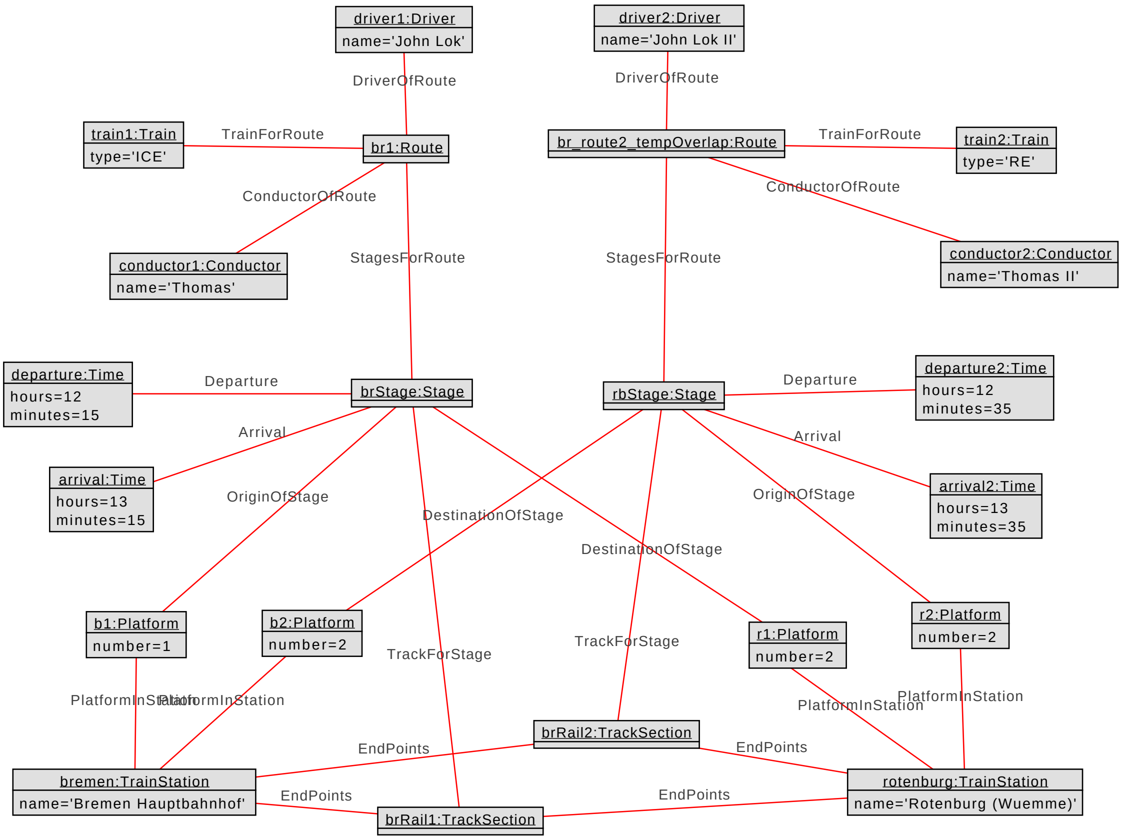


Figure 5.17: Object diagram for test case 11 – no violations

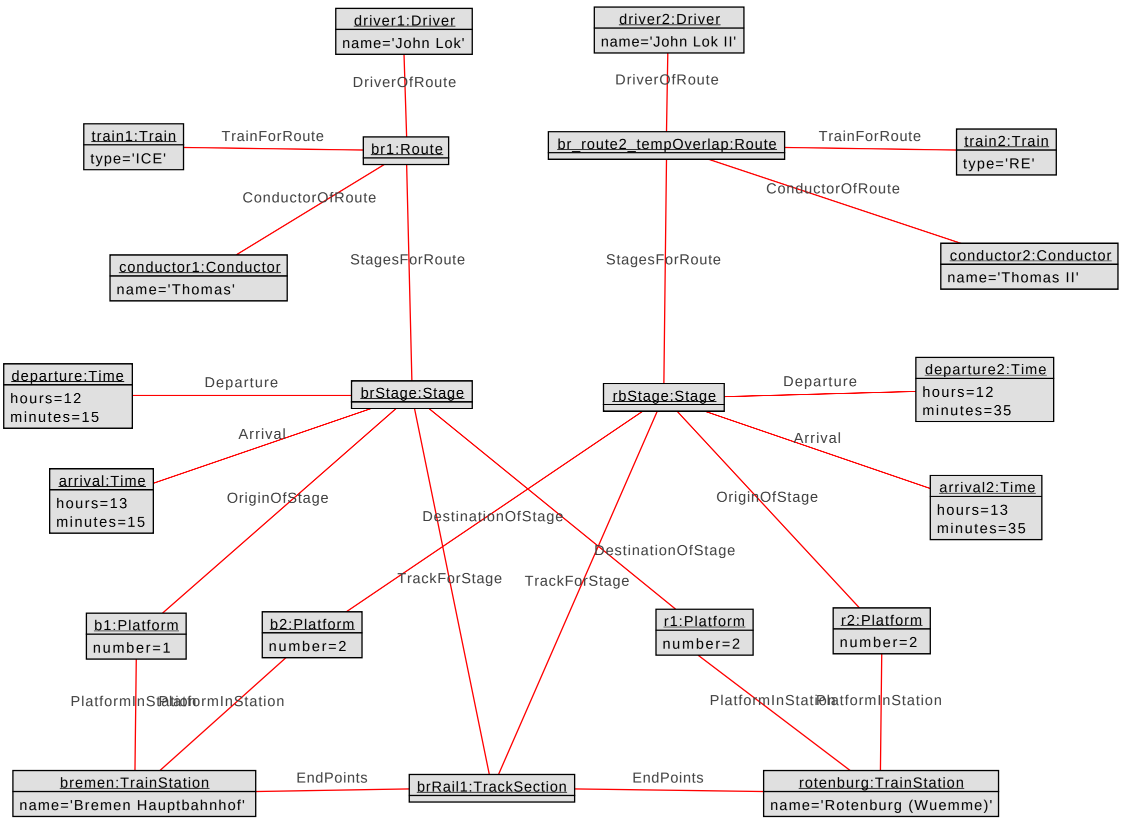
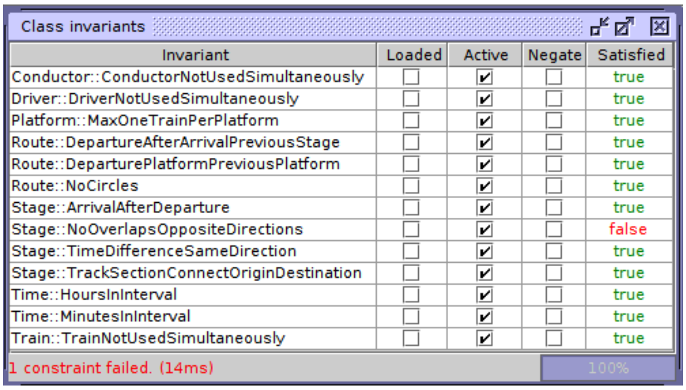


Figure 5.18: Object diagram for test case 12 – **NoOverlapsOppositeDirections** violated


Class invariants

Invariant	Loaded	Active	Negate	Satisfied
Conductor::ConductorNotUsedSimultaneously	☐	☑	☐	true
Driver::DriverNotUsedSimultaneously	☐	☑	☐	true
Platform::MaxOneTrainPerPlatform	☐	☑	☐	true
Route::DepartureAfterArrivalPreviousStage	☐	☑	☐	true
Route::DeparturePlatformPreviousPlatform	☐	☑	☐	true
Route::NoCircles	☐	☑	☐	true
Stage::ArrivalAfterDeparture	☐	☑	☐	true
Stage::NoOverlapsOppositeDirections	☐	☑	☐	false
Stage::TimeDifferenceSameDirection	☐	☑	☐	true
Stage::TrackSectionConnectOriginDestination	☐	☑	☐	true
Time::HoursInInterval	☐	☑	☐	true
Time::MinutesInInterval	☐	☑	☐	true
Train::TrainNotUsedSimultaneously	☐	☑	☐	true

1 constraint failed. (14ms) 100%

Figure 5.19: Violated constraints for test case 12

A positive test case for the **TimeDifferenceSameDirection** invariant is given by test case 02. It shows that when two trains do in fact use the same track section while going in the same direction and overlapping in time, the constraint is not violated if the difference in departure and arrival time does exceed 10 minutes respectively. The first train is set to depart at 12:15 and arrive at 13:15, while the second train departs at 12:35 and arrives at 13:35. For both stages, the `TrackSection` *brRail1* is used. The difference is of course 20 minutes for both the arrival and departure times so the constraint is not violated.

Test case 13 – TC_13_stage_TimeDifferenceSameDirection_1

With our first negative test case for **TimeDifferenceSameDirection**, we want to make sure that the constraint is violated if one train overtakes the other while using the same track section, i. e. if one train arrives before the other, even though it departs later. The initial state is given by the system state used in test case 02. The departure time of the `Stage` *brStage* is then set to 12:50. Now, both the respective arrival and the departure times are still more than 10 minutes apart, but since the departure of *brStage* is earlier than the departure of *rbStage*, the same has to hold true for the arrival times. As that is not the case, the constraint is violated. Figure 5.20 shows the violated constraints. We refrain from providing an object diagram for this test case, since it basically equals the one shown in figure 5.2 with one small difference in the `minutes` attribute in the `Time` object *departure*.

```
open TC_02_ressources_NotUsedSimultaneously_0.cmd

-- setting departure of first stage to 12:50
-- thus violating the constraint, as the train
-- arrives before the other one which is departing earlier
!set departure.minutes := 50
```

Test case 14 – TC_14_stage_TimeDifferenceSameDirection_1

The second negative test case for **TimeDifferenceSameDirection** ensures that the constraint is violated, if the differences in arrival and departure times do not exceed 10 minutes. We again use the system state presented in test case 2 and manipulate the departure and arrival time for `Stage` *brStage*. The departure time is set to 12:30 and the arrival time to 13:30. Since the difference is now 5 minutes each, the constraint is violated, which is shown in figure 5.21. As in the previous test case, the resulting object diagram is not provided due to the differences being only marginal.

```
open TC_02_ressources_NotUsedSimultaneously_0.cmd

```

Class invariants

Invariant	Loaded	Active	Negate	Satisfied
Conductor::ConductorNotUsedSimultaneously	☐	☑	☐	true
Driver::DriverNotUsedSimultaneously	☐	☑	☐	true
Platform::MaxOneTrainPerPlatform	☐	☑	☐	true
Route::DepartureAfterArrivalPreviousStage	☐	☑	☐	true
Route::DeparturePlatformPreviousPlatform	☐	☑	☐	true
Route::NoCircles	☐	☑	☐	true
Stage::ArrivalAfterDeparture	☐	☑	☐	true
Stage::NoOverlapsOppositeDirections	☐	☑	☐	true
Stage::TimeDifferenceSameDirection	☐	☑	☐	false
Stage::TrackSectionConnectOriginDestination	☐	☑	☐	true
Time::HoursInInterval	☐	☑	☐	true
Time::MinutesInInterval	☐	☑	☐	true
Train::TrainNotUsedSimultaneously	☐	☑	☐	true

1 constraint failed. (10ms) 100%

Figure 5.20: Violated constraints for test case 13

Class invariants

Invariant	Loaded	Active	Negate	Satisfied
Conductor::ConductorNotUsedSimultaneously	☐	☑	☐	true
Driver::DriverNotUsedSimultaneously	☐	☑	☐	true
Platform::MaxOneTrainPerPlatform	☐	☑	☐	true
Route::DepartureAfterArrivalPreviousStage	☐	☑	☐	true
Route::DeparturePlatformPreviousPlatform	☐	☑	☐	true
Stage::ArrivalAfterDeparture	☐	☑	☐	true
Stage::NoOverlapsOppositeDirections	☐	☑	☐	true
Stage::TimeDifferenceSameDirection	☐	☑	☐	false
Stage::TrackSectionConnectOriginDestination	☐	☑	☐	true
Time::HoursInInterval	☐	☑	☐	true
Time::MinutesInInterval	☐	☑	☐	true
Train::TrainNotUsedSimultaneously	☐	☑	☐	true

1 constraint failed. (6ms) 100%

Figure 5.21: Violated constraints for test case 14

```
-- setting departure of first stage to 12:30
-- and arrival to 13:30 thus violating the constraint,
-- as the train departs already 5 minutes after the
-- other has departed and arrives
!set departure.minutes := 30
!set arrival.minutes := 30
```

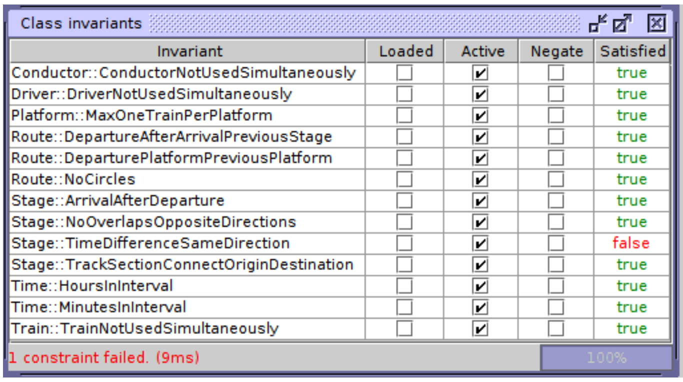
Test case 15 – TC_15_stage_TimeDifferenceSameDirection_1

For our next negative test case for the **TimeDifferenceSameDirection** invariant, we want to show that the constraint is also violated if only the difference in the departure times of trains using the same track section while going in the same direction does not exceed 10 minutes. Corresponding to test case 14, we set the departure time of `Stage` *brStage* to 12:30 without manipulating the arrival time. The constraint is violated. We again refrain from providing the resulting object diagram. The violated constraints are shown in figure 5.22.

```
open TC_02_ressources_NotUsedSimultaneously_0.cmd

-- setting departure of first stage to 12:30 thus violating
-- the constraint, as the train departs only 5 minutes earlier
-- than the other one
!set departure.minutes := 30
```

Test case 16 – TC_16_stage_TimeDifferenceSameDirection_1

Corresponding to test case 15, with our last negative test case for **TimeDifference-SameDirection** we want to show that the constraint is violated if only the difference in the arrival time of trains using the same track section does not exceed 10 minutes. This

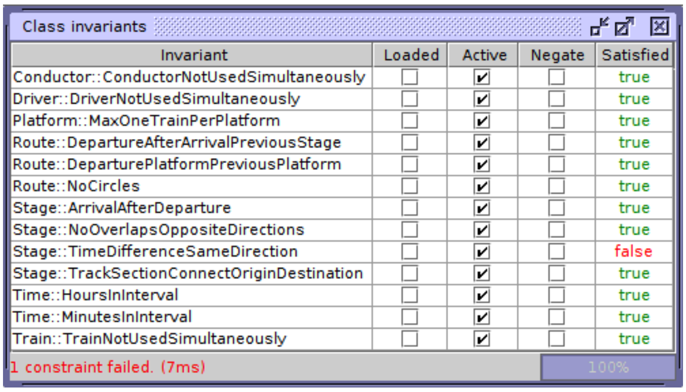


Class invariants

Invariant	Loaded	Active	Negate	Satisfied
Conductor::ConductorNotUsedSimultaneously	☐	☑	☐	true
Driver::DriverNotUsedSimultaneously	☐	☑	☐	true
Platform::MaxOneTrainPerPlatform	☐	☑	☐	true
Route::DepartureAfterArrivalPreviousStage	☐	☑	☐	true
Route::DeparturePlatformPreviousPlatform	☐	☑	☐	true
Route::NoCircles	☐	☑	☐	true
Stage::ArrivalAfterDeparture	☐	☑	☐	true
Stage::NoOverlapsOppositeDirections	☐	☑	☐	true
Stage::TimeDifferenceSameDirection	☐	☑	☐	false
Stage::TrackSectionConnectOriginDestination	☐	☑	☐	true
Time::HoursInInterval	☐	☑	☐	true
Time::MinutesInInterval	☐	☑	☐	true
Train::TrainNotUsedSimultaneously	☐	☑	☐	true

1 constraint failed. (9ms) 100%

Figure 5.22: Violated constraints for test case 15



Class invariants

Invariant	Loaded	Active	Negate	Satisfied
Conductor::ConductorNotUsedSimultaneously	☐	☑	☐	true
Driver::DriverNotUsedSimultaneously	☐	☑	☐	true
Platform::MaxOneTrainPerPlatform	☐	☑	☐	true
Route::DepartureAfterArrivalPreviousStage	☐	☑	☐	true
Route::DeparturePlatformPreviousPlatform	☐	☑	☐	true
Route::NoCircles	☐	☑	☐	true
Stage::ArrivalAfterDeparture	☐	☑	☐	true
Stage::NoOverlapsOppositeDirections	☐	☑	☐	true
Stage::TimeDifferenceSameDirection	☐	☑	☐	false
Stage::TrackSectionConnectOriginDestination	☐	☑	☐	true
Time::HoursInInterval	☐	☑	☐	true
Time::MinutesInInterval	☐	☑	☐	true
Train::TrainNotUsedSimultaneously	☐	☑	☐	true

1 constraint failed. (7ms) 100%

Figure 5.23: Violated constraints for test case 16

time, we manipulate the arrival time of *brStage* to 13:30, thus violating the constraint which is shown in figure 5.23.

```
open TC_02_ressources_NotUsedSimultaneously_0.cmd

-- setting arrival of first stage to 13:30 thus violating
-- the constraint, as the train arrives only 5 minutes earlier
-- than the other one
!set arrival.minutes := 30
```

5.1.4 Platform

To check the correctness of the **MaxOneTrainPerPlatform** invariant, we need to construct a system state that contains multiple stages arriving at the same platform. We therefore take the system state introduced for test case 2 and set the destination of `Stage` *rbStage* to `Platform` *r1*.

Test case 17 – TC_17_platform_MaxOneTrainPerPlatform_0

To create a positive scenario for our invariant, we also add a new `TrainStaiton` object *hamburg* with one associated platform *h1*. We then create a new `Stage` *rhStage* for our route *br1* going from *rotenburg* to *hamburg*. By setting the departure time of *rhStage* to 13:30, we make sure that the train departs from platform *r1* before the train assigned to route *br_route2_tempOverlap* arrives. Thus, no constraint is violated. The object diagram can be seen in figure 5.24.

```
open TC_02_ressources_NotUsedSimultaneously_0.cmd

```

```
-- set destination platform of rbStage to
-- r1 and remove r2
!destroy r2
!insert (r1, rbStage) into DestinationOfStage

-- add Hamburg train station and platform/track section
!create hamburg : TrainStation
!set hamburg.name := 'Hamburg Hauptbahnhof'

!create h1 : Platform
!set h1.number := 1
!insert (h1,hamburg) into PlatformInStation

-- add stage between Rotenburg and Hamburg
!create rhStage : Stage
!insert (rhStage,br1) into StagesForRoute
!create rhRail1 : TrackSection
!insert (rhRail1, rotenburg) into EndPoints
!insert (rhRail1, hamburg) into EndPoints
!insert (rhRail1,rhStage) into TrackForStage
!insert (h1, rhStage) into DestinationOfStage
!insert (r1, rhStage) into OriginOfStage

-- setting departure from platform r1 to 13:30
!create rotDeparture : Time
!set rotDeparture.hours := 13
!set rotDeparture.minutes := 30
!insert (rotDeparture, rhStage) into Departure

!create hamburgArrival : Time
!set hamburgArrival.hours := 13
!set hamburgArrival.minutes := 50
!insert (hamburgArrival, rhStage) into Arrival
```

Test case 18 – TC_18_platform_MaxOneTrainPerPlatform_1

For our first negative test case, we want to show that if one train does not depart from a platform at all and another one arrives, the constraint is violated. We take the previous system state and simply refrain from adding a second stage to our route *br1*. As a result we have two trains arriving at platform *r1* without one of them departing at all. The first train is blocking the platform and consequently, the constraint is violated, which is shown in figure 5.26. The resulting object diagram can be found in figure 5.25.

```
open TC_02_ressources_NotUsedSimultaneously_0.cmd

-- set destination platform of rbStage to
-- r1 and remove r2
-- since the first train does not depart at all
-- the arrival of the second train at the same
-- platform causes a violation of the constraint
!destroy r2
!insert (r1, rbStage) into DestinationOfStage
```

Test case 19 – TC_19_platform_MaxOneTrainPerPlatform_1

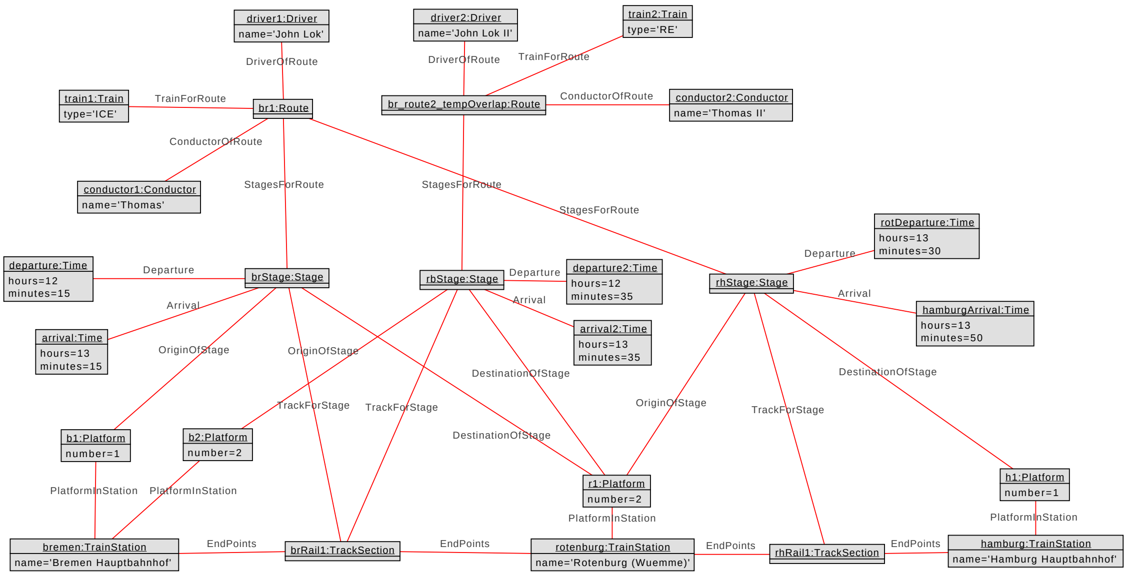


Figure 5.24: Object diagram for test case 17 – no violations

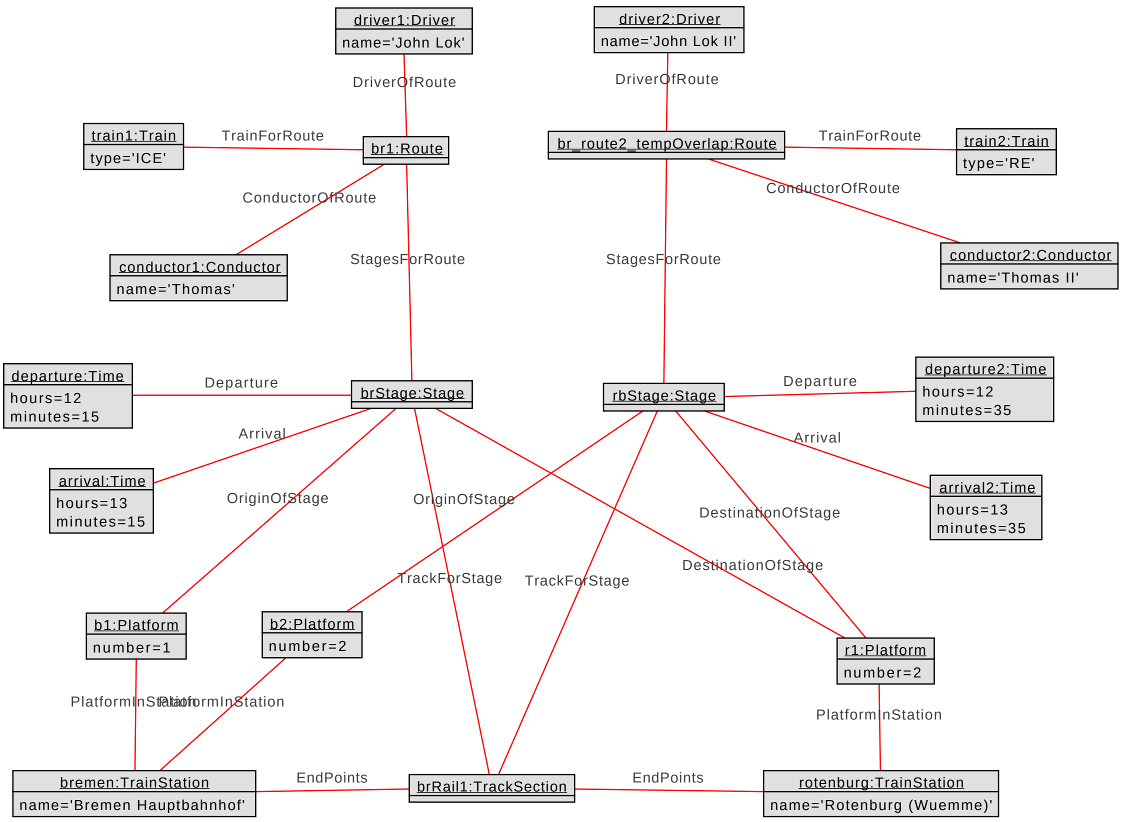


Figure 5.25: Object diagram for test case 18 – **MaxOneTrainPerPlatform** violated

Class invariants

Invariant	Loaded	Active	Negate	Satisfied
Conductor::ConductorNotUsedSimultaneously	☐	☑	☐	true
Driver::DriverNotUsedSimultaneously	☐	☑	☐	true
Platform::MaxOneTrainPerPlatform	☐	☑	☐	false
Route::DepartureAfterArrivalPreviousStage	☐	☑	☐	true
Route::DeparturePlatformPreviousPlatform	☐	☑	☐	true
Route::NoCircles	☐	☑	☐	true
Stage::ArrivalAfterDeparture	☐	☑	☐	true
Stage::NoOverlapsOppositeDirections	☐	☑	☐	true
Stage::TimeDifferenceSameDirection	☐	☑	☐	true
Stage::TrackSectionConnectOriginDestination	☐	☑	☐	true
Time::HoursInInterval	☐	☑	☐	true
Time::MinutesInInterval	☐	☑	☐	true
Train::TrainNotUsedSimultaneously	☐	☑	☐	true

1 constraint failed. (12ms) 100%

Figure 5.26: Violated constraints for test case 18

Class invariants

Invariant	Loaded	Active	Negate	Satisfied
Conductor::ConductorNotUsedSimultaneously	☐	☑	☐	true
Driver::DriverNotUsedSimultaneously	☐	☑	☐	true
Platform::MaxOneTrainPerPlatform	☐	☑	☐	false
Route::DepartureAfterArrivalPreviousStage	☐	☑	☐	true
Route::DeparturePlatformPreviousPlatform	☐	☑	☐	true
Route::NoCircles	☐	☑	☐	true
Stage::ArrivalAfterDeparture	☐	☑	☐	true
Stage::NoOverlapsOppositeDirections	☐	☑	☐	true
Stage::TimeDifferenceSameDirection	☐	☑	☐	true
Stage::TrackSectionConnectOriginDestination	☐	☑	☐	true
Time::HoursInInterval	☐	☑	☐	true
Time::MinutesInInterval	☐	☑	☐	true
Train::TrainNotUsedSimultaneously	☐	☑	☐	true

1 constraint failed. (7ms) 100%

Figure 5.27: Violated constraints for test case 19

To provide another negative test case, we use the system state introduced for test case 17. This time around, we set the departure time of *rhStage* to 13:36, which causes the train of the first route to block the platform *r1* when the train of the second route is set to arrive at 13:35. The constraint is thus violated. We again refrain from providing the resulting object diagram since it equals the one shown in figure 5.24, with one difference in the value for the `minutes` attribute in the `Time` object *rotDeparture*. The violated constraints are shown in figure 5.27.

```
open TC_17_platform_MaxOneTrainPerPlatform_0.cmd

-- setting departure from platform r1 to 13:36
-- thus violating the constraint
!set rotDeparture.minutes := 36
```

5.1.5 Time

Most of the previous test cases can serve as positive test cases that show that our **InInterval** invariants are not violated when the `minutes` and `hours` values are within the correct interval. In the following, we therefore only explicitly present negative test cases.

Test case 20 – TC_20_time_HoursInInterval_1

The used system state for our negative scenario for the **HoursInInterval** invariant consists one single `Time` object. The value for the `hours` attribute is set to 24. The value being not in the interval from 0 to 23, **HoursInInterval** is violated, which is shown in figure 5.29. The object diagram is shown in figure 5.28.

```
!create hoursTooHigh : Time
!set hoursTooHigh.hours := 24
!set hoursTooHigh.minutes := 59
```

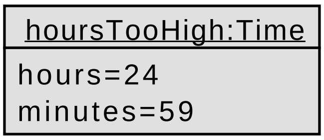
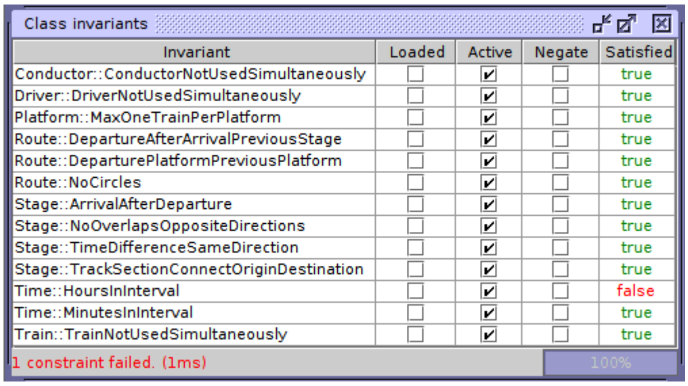


Figure 5.28: Object diagram for test case 20 – **HoursInInterval** violated



Invariant	Loaded	Active	Negate	Satisfied
Conductor::ConductorNotUsedSimultaneously	☐	☑	☐	true
Driver::DriverNotUsedSimultaneously	☐	☑	☐	true
Platform::MaxOneTrainPerPlatform	☐	☑	☐	true
Route::DepartureAfterArrivalPreviousStage	☐	☑	☐	true
Route::DeparturePlatformPreviousPlatform	☐	☑	☐	true
Route::NoCircles	☐	☑	☐	true
Stage::ArrivalAfterDeparture	☐	☑	☐	true
Stage::NoOverlapsOppositeDirections	☐	☑	☐	true
Stage::TimeDifferenceSameDirection	☐	☑	☐	true
Stage::TrackSectionConnectOriginDestination	☐	☑	☐	true
Time::HoursInInterval	☐	☑	☐	false
Time::MinutesInInterval	☐	☑	☐	true
Train::TrainNotUsedSimultaneously	☐	☑	☐	true

Figure 5.29: Violated constraints for test case 20

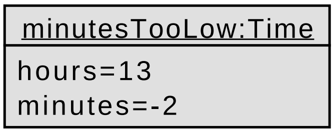
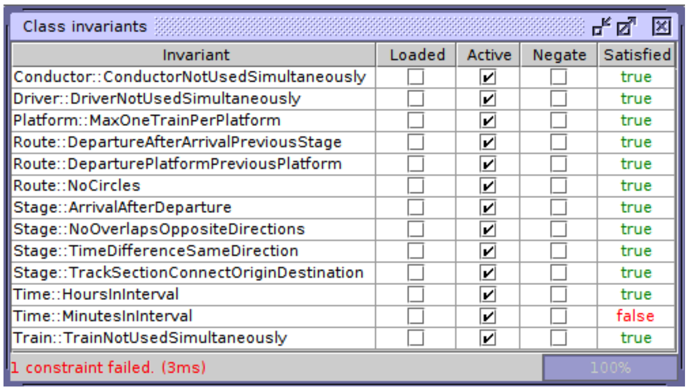


Figure 5.30: Object diagram for test case 21 – **MinutesInInterval** violated



Invariant	Loaded	Active	Negate	Satisfied
Conductor::ConductorNotUsedSimultaneously	☐	☑	☐	true
Driver::DriverNotUsedSimultaneously	☐	☑	☐	true
Platform::MaxOneTrainPerPlatform	☐	☑	☐	true
Route::DepartureAfterArrivalPreviousStage	☐	☑	☐	true
Route::DeparturePlatformPreviousPlatform	☐	☑	☐	true
Route::NoCircles	☐	☑	☐	true
Stage::ArrivalAfterDeparture	☐	☑	☐	true
Stage::NoOverlapsOppositeDirections	☐	☑	☐	true
Stage::TimeDifferenceSameDirection	☐	☑	☐	true
Stage::TrackSectionConnectOriginDestination	☐	☑	☐	true
Time::HoursInInterval	☐	☑	☐	true
Time::MinutesInInterval	☐	☑	☐	false
Train::TrainNotUsedSimultaneously	☐	☑	☐	true

Figure 5.31: Violated constraints for test case 21

Test case 21 – TC_21_time_MinutesInInterval_1

For the **MinutesInInterval** invariant, we provide a negative scenario by constructing a system state consisting of one `Time` object and setting the value for the `minutes` attribute to -2. Since the value is not in the interval from 0 to 59, the constraint is violated. The violated constraints are shown in 5.31 and the object diagram can be found in figure 5.30.

```
!create minutesTooLow : Time
!set minutesTooLow.hours := 13
!set minutesTooLow.minutes := -2
```

5.2 Operations

Author: Tilman Ihrig

In this section, the implemented operations will be testet. The initial state will again be used for these scenarios. For every scenario an object diagram and a sequence diagram will be given. The object diagram can be used to verify the success or failure of the test while the sequence diagram shows which operations were used in which order.

Because the commands cannot be split into multiple lines, some lines will not be completely visible. The code for all test cases will be provided in the *tests*-folder.

Test case 22 – TC_22_init_0

Since all classes have an *init()*-operation that can be used to easily assign attributes or associations, the first test checks whether all those operations work properly with valid inputs. For this, new objects of each class are created and initialized using their respective

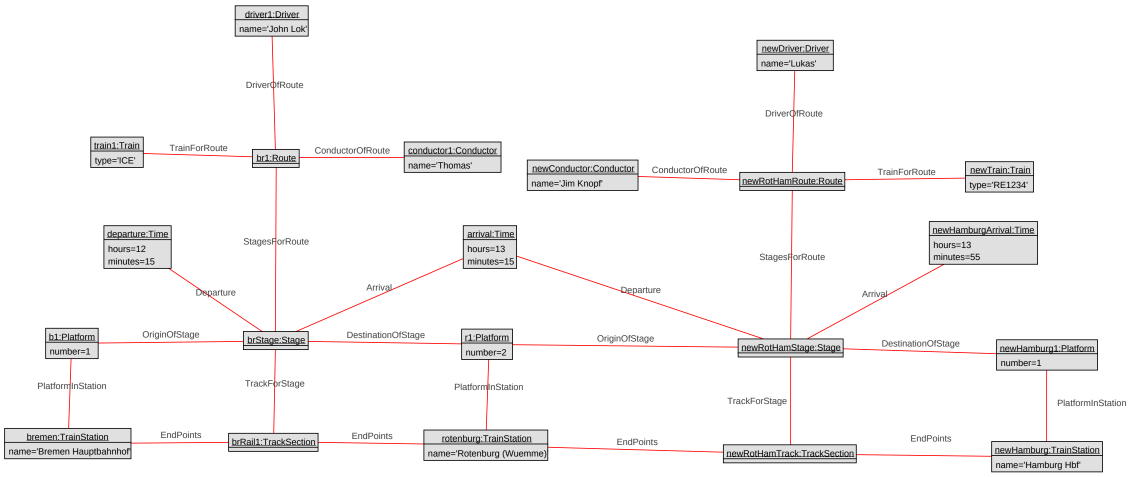


Figure 5.32: Object diagram for test case 22

init()-operations. The object diagram 5.32 shows that all attributes are set correctly and all associations have been created correctly.

```
open initial_state.cmd

-- tests init()-operations for all classes

-- create objects to be initialized
-- names contain 'new' so that they can be easily
-- found in object diagram
!create newHamburgArrival: Time
!create newHamburg: TrainStation
!create newHamburg1: Platform
!create newRotHamTrack: TrackSection
!create newDriver : Driver
!create newConductor: Conductor
!create newTrain: Train
!create newRotHamStage: Stage
!create newRotHamRoute: Route

!newHamburgArrival.init(13, 55)
!newHamburg.init('Hamburg Hbf')
!newHamburg1.init(1, newHamburg)
!newRotHamTrack.init(rotenburg, newHamburg)
!newDriver.init('Lukas')
!newConductor.init('Jim Knopf')
!newTrain.init('RE1234')
-- use previous arrival in rotenburg as departure time
!newRotHamStage.init(arrival, newHamburgArrival, r1, newHamburg1, newRotHamTra
!newRotHamRoute.init(newDriver, newConductor, newTrain, newRotHamStage)
```

Test case 23 – TC_23_addStage_0

Next, we want to test whether `addStage` works as expected if it receives a valid stage. As can be seen in the object diagram 5.34, the created valid stage `newRotHamStage` has been successfully added to `br1`.

```
open initial_state.cmd
```

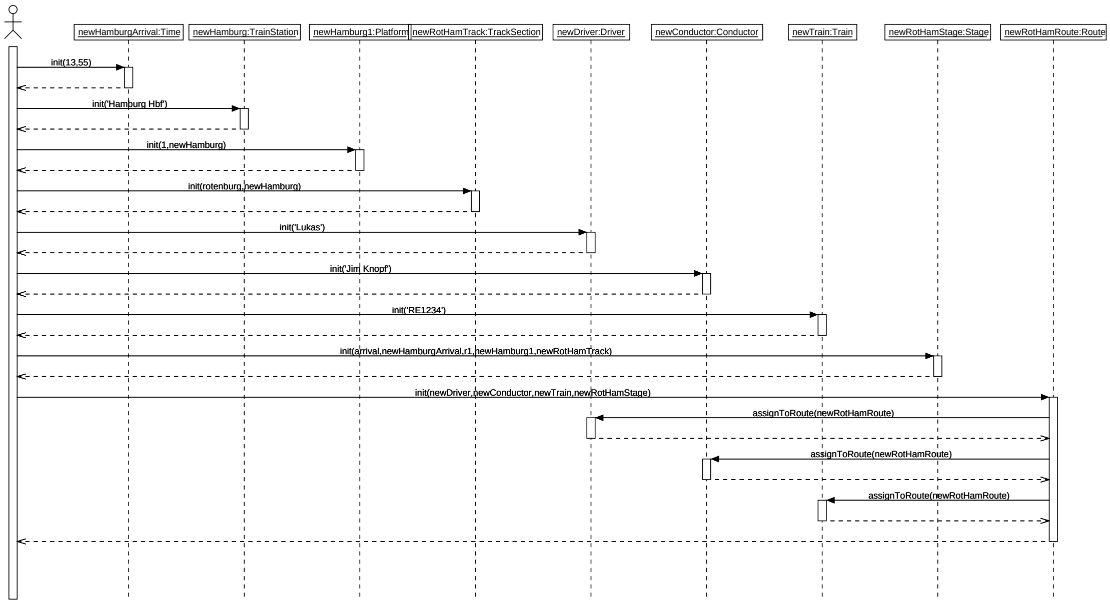


Figure 5.33: Sequence diagram for test case 22

```

!create newRotenburgDeparture: Time
!create newHamburgArrival: Time
!create newHamburg: TrainStation
!create newHamburg1: Platform
!create newRotHamTrack: TrackSection
!create newRotHamStage: Stage

!newRotenburgDeparture.init(13, 16)
!newHamburgArrival.init(13, 55)
!newHamburg.init('Hamburg Hbf')
!newHamburg1.init(1, newHamburg)
!newRotHamTrack.init(rotenburg, newHamburg)
!newRotHamStage.init(newRotenburgDeparture, newHamburgArrival, r1, newHamburg1

--add new Stage to br1-Route
!br1.addStage(newRotHamStage)
```

Test case 24 – TC_24_addStage_1

To check that `addStage` can also fail to work we create a test case that violates a precondition, specifically *stageStartEqualsPreviousEnd*. For this, we let the next `Stage` start on a different platform in Rotenburg than the one it arrived in. In the object diagram 5.36 you can see that the created `newRotHamStage` is not linked to the route `br1`, because `addStage` failed. Consequently, `addStage` does not show up in the sequence diagram 5.37.

```
open initial_state.cmd

!create newRotenburgDeparture: Time
!create newHamburgArrival: Time
!create newHamburg: TrainStation
!create newHamburg1: Platform
!create newRot2: Platform
```

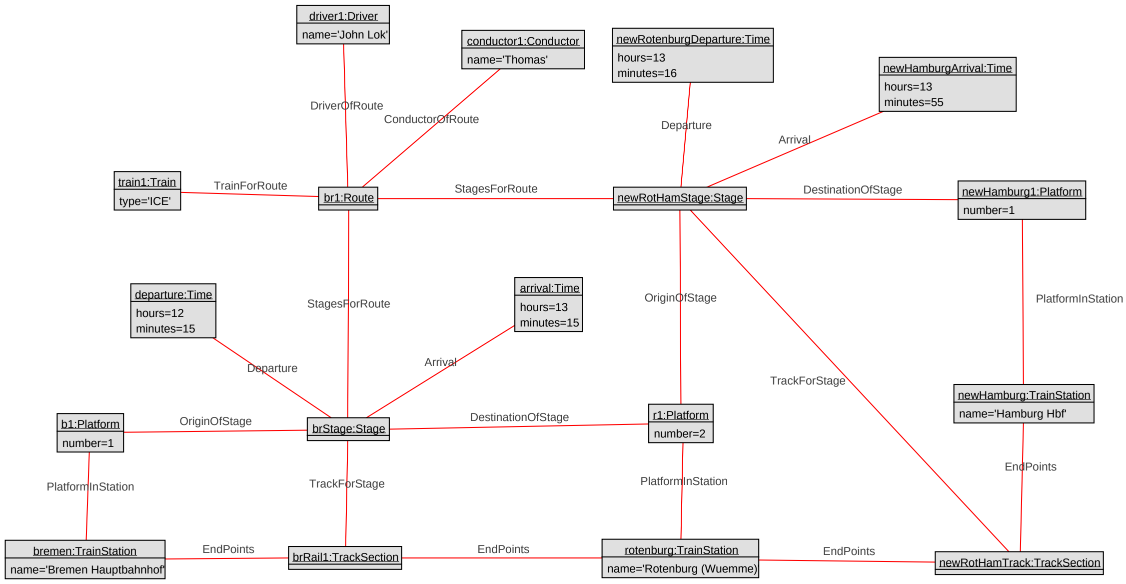


Figure 5.34: Object diagram for test case 23

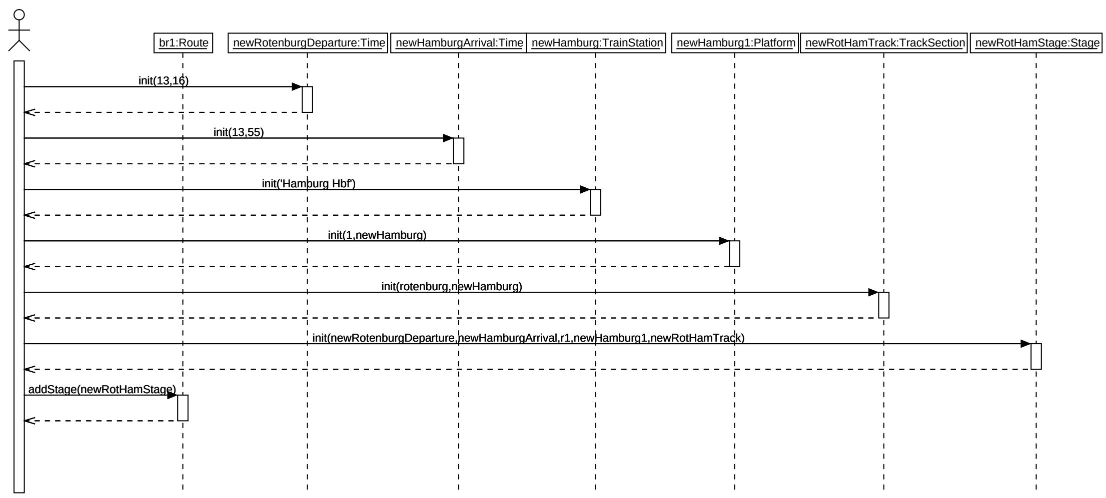


Figure 5.35: Sequence diagram for test case 23

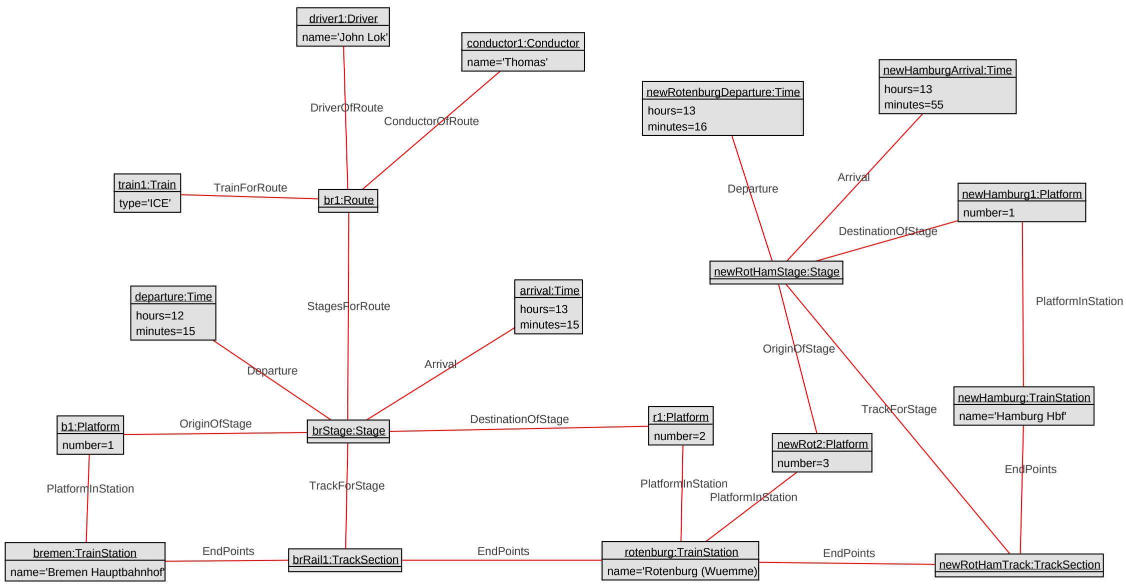


Figure 5.36: Object diagram for test case 24

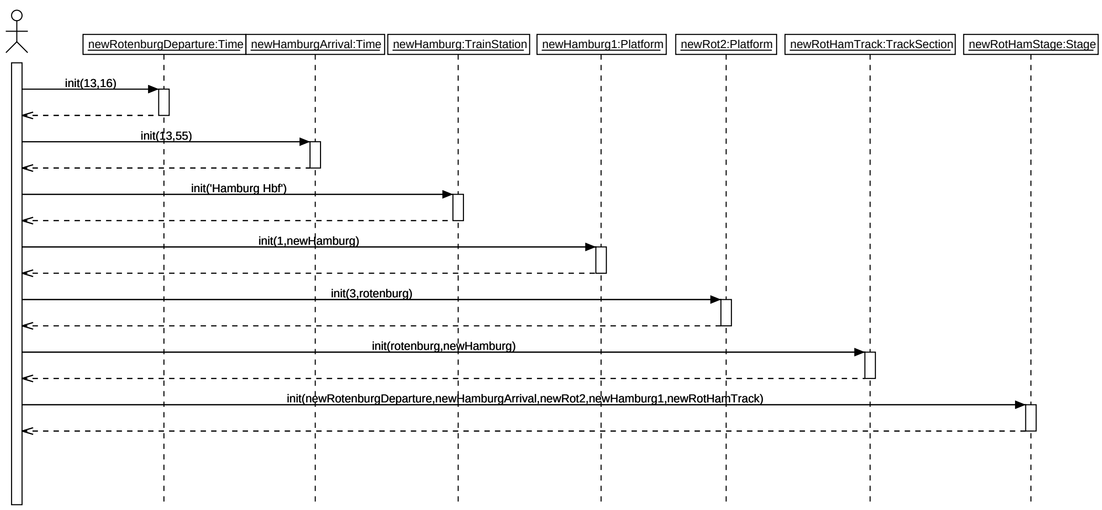


Figure 5.37: Sequence diagram for test case 24

```
!create newRotHamTrack: TrackSection
!create newRotHamStage: Stage

!newRotenburgDeparture.init(13, 16)
!newHamburgArrival.init(13, 55)
!newHamburg.init('Hamburg Hbf')
!newHamburg1.init(1, newHamburg)
!newRot2.init(3, rotenburg)
!newRotHamTrack.init(rotenburg, newHamburg)
--let stage start in bremen instead of rotenburg
!newRotHamStage.init(newRotenburgDeparture, newHamburgArrival, newRot2, newHan

--add new Stage to br1-Route
!br1.addStage(newRotHamStage)
```

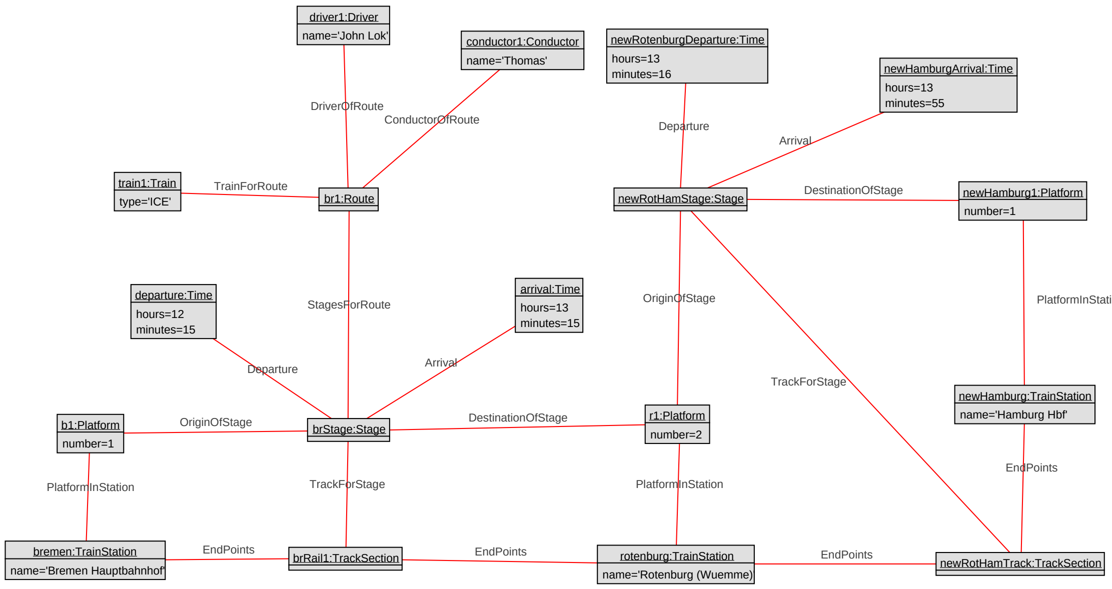


Figure 5.38: Object diagram for test case 25

Test case 25 – TC_25_removeStage_0

We also want to test if a Stage can be removed using `removeStage` if its conditions are fulfilled. For this, we use Test case 23 and remove `newRotHamStage` from `br1` again. As can be seen in the object diagram 5.38, `newRotHamStage` is no longer associated with `br1`, so the operation works as expected.

```
open TC_23_addStage_0.cmd

!br1.removeStage(newRotHamStage)
```

Test case 26 – TC_26_removeStage_1

To assert that you can't just remove any stage from a route, we will now try to remove a stage that is in the middle of a route. For that, we add another stage back from Hamburg to Bremen to the state created in test case 23. Then we try to remove the middle stage from Rotenburg to Hamburg. In the object diagram 5.40 you can see that `newRotHamStage`, the stage from Rotenburg to Hamburg, is still associated with `br1`, because the precondition `stageRemovable` does not hold. Consequently, *removeStage()* does not show up in the sequence diagram 5.41.

```
open TC_23_addStage_0.cmd

-- create additional stage back from hamburg to bremenArrival
!create hamburgDeparture: Time
!create bremenArrival: Time
!create bremHamTrack: TrackSection
!create bremHamStage: Stage

!hamburgDeparture.init(13, 56)
!bremenArrival.init(14, 55)
!bremHamTrack.init(newHamburg, bremen)
!bremHamStage.init(hamburgDeparture, bremenArrival, newHamburg1, b1, bremHamTr

--add new Stage to br1-Route
```

Figure 5.39: Sequence diagram for test case 25

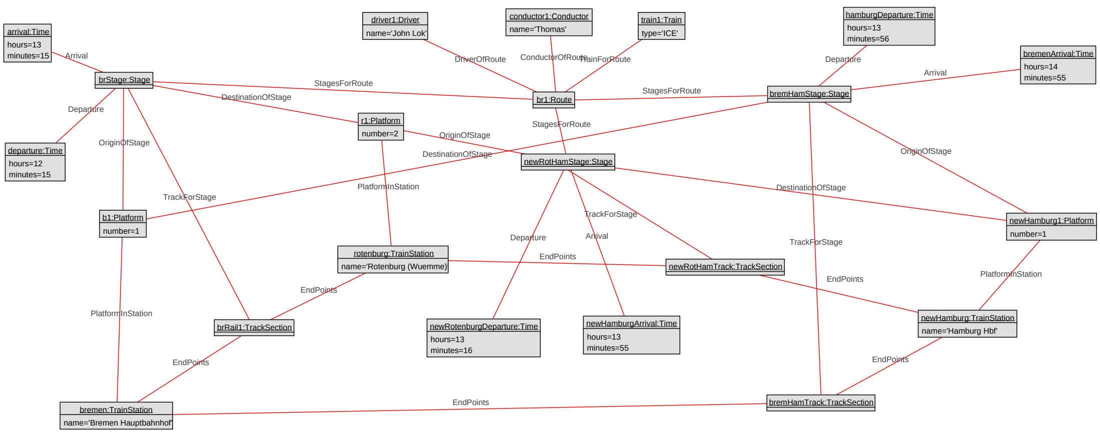


Figure 5.40: Object diagram for test case 26

```
!br1.addStage(bremHamStage)

--try to remove middle stage: should not be possible
!br1.removeStage(newRotHamStage)
```

Test case 27 – TC_27_assignToRoute_0

In Test case 22, *assignToRoute()* was already tested for a newly created `Route`, because it is used in *Route::init()* for assigning the driver, conductor and train. Now we want to check whether assigning a driver, conductor and train also works as expected if the route already has those assigned. For this, a new driver, conductor and train are created and assigned to `br1`. As can be seen in the object diagram 5.42, the old driver, conductor and train are no longer associated with `br1`, while the new ones are. The operation has worked as expected.

```
open initial_state.cmd

-- tests assigning driver, conductor and train to a route
-- which already has a driver, conductor and train

!create newDriver : Driver
```

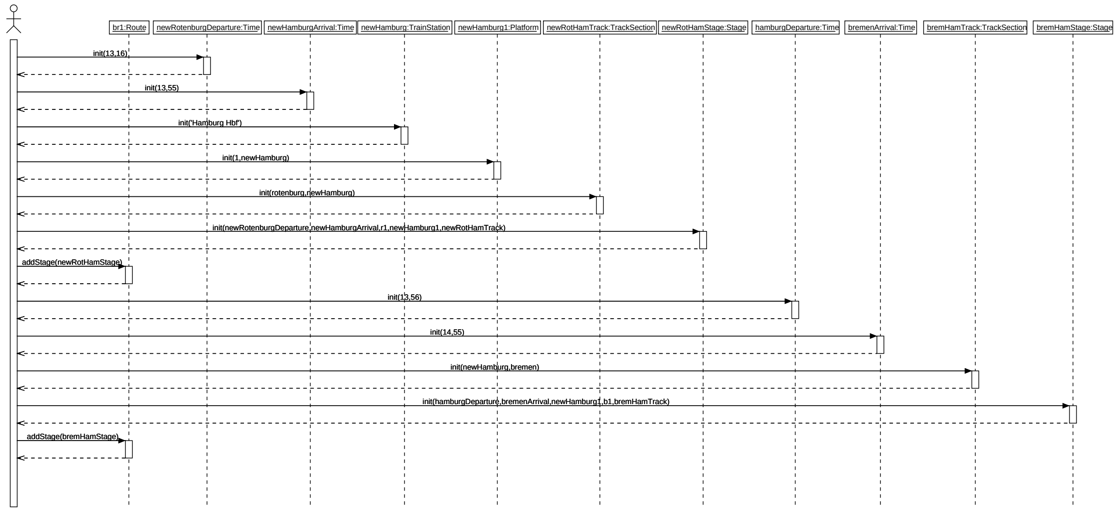


Figure 5.41: Sequence diagram for test case 26

```
!create newConductor: Conductor
!create newTrain: Train

!newDriver.init('Lukas')
!newConductor.init('Jim Knopf')
!newTrain.init('RE1234')

!newDriver.assignToRoute(br1)
!newConductor.assignToRoute(br1)
!newTrain.assignToRoute(br1)
```

Test case 28 – TC_28_createRoute_0

Lastly we want to check if creating a route using *Conductor::createRoute()* works as intended. Because this operation uses so many utility operations this test case also tests *TrainStation::getAvailablePlatform()*, *Time::getStageEndTime()*, *Stage::getAvailableTrackSection()*, *Time::getNextDepartureTime()* on valid system states.
To create a system state where a new `Route` can be created automatically, a new TrainStation `hamburg` along with a `Platform` and a `Tracksection` connecting it to `rotenburg` are created. The new `Route` shall start in Bremen and end in Hamburg via Rotenburg. Since the only platform in Rotenburg is taken by `train1`, a new platform is created there as well. Lastly, a new driver, conductor and train for the new route are created. The departure time is set to 18:18, so that it will not collide temporally with the existing route `br1`.
The object diagram 5.44 shows that a new Route has been created successfully with Stages from Bremen to Rotenburg and Rotenburg to Hamburg. No invariants are violated and no unnecessary objects have been created.
The sequence diagram 5.45 in this case is limited to just the *Conductor::createRoute()*-operation and its operation calls. It shows the non-query operations used in *createRoute()* in the process of creating the new `Route`.

```
open initial_state.cmd

-- tests automatically creating a Route
-- if all necessary resources are available

!create newRouteDeparture: Time
```

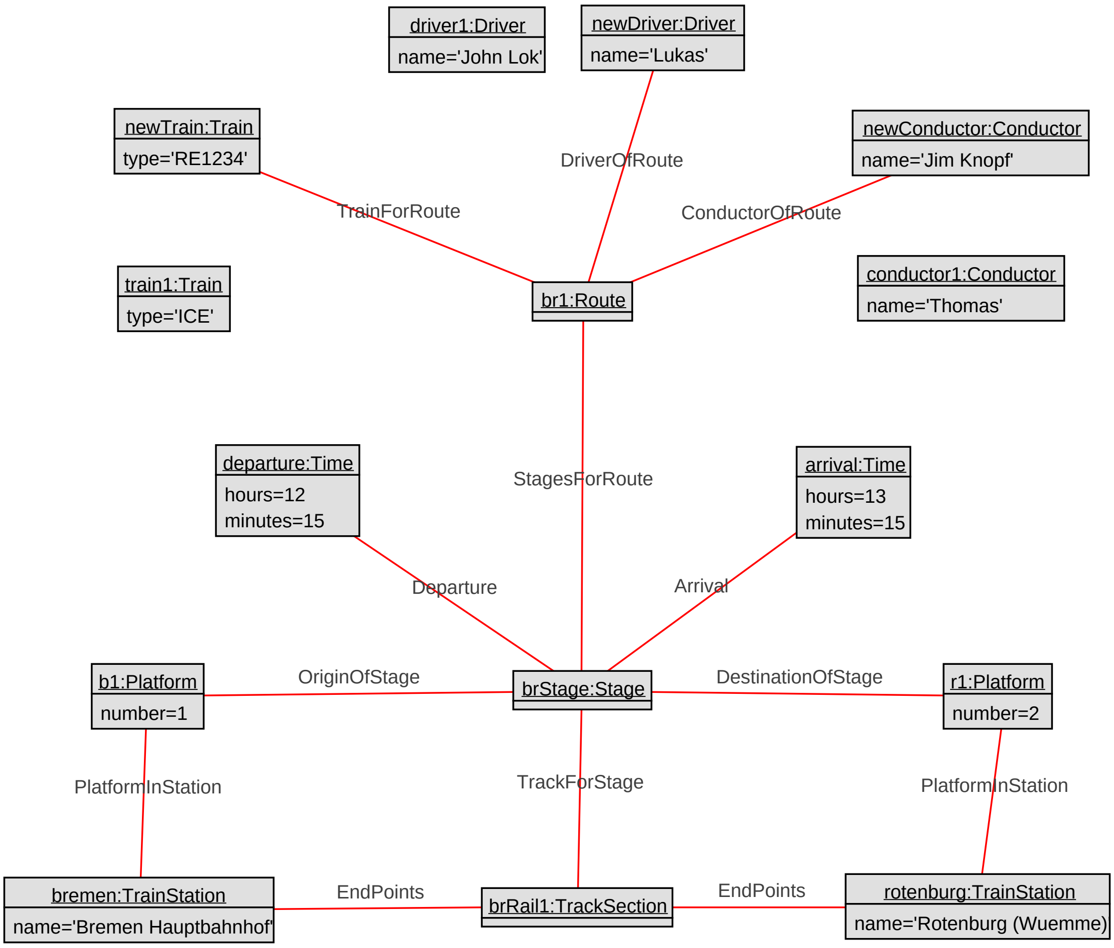


Figure 5.42: Object diagram for test case 27

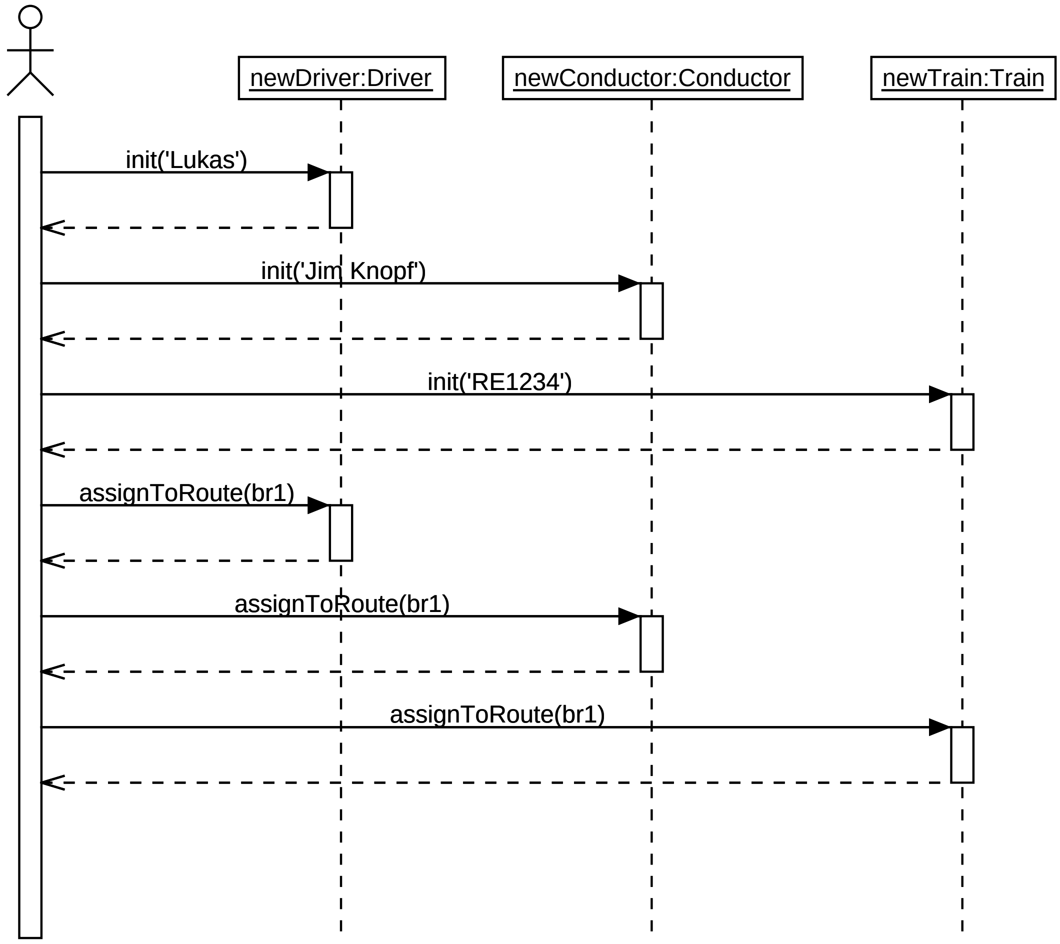


Figure 5.43: Sequence diagram for test case 27

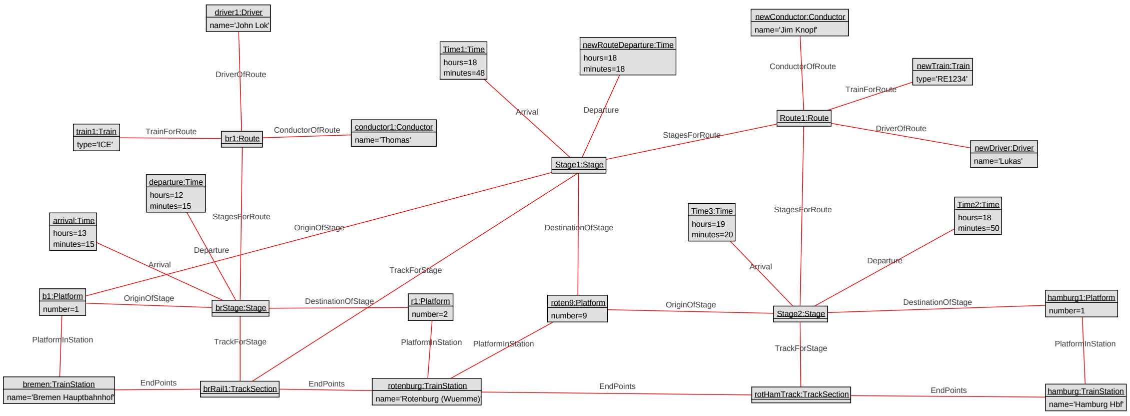


Figure 5.44: Object diagram for test case 28

```
!create hamburg: TrainStation
!create hamburg1: Platform
-- create new Rotenburg platform because r1 is
-- blocked by train1
!create roten9: Platform
!create rotHamTrack: TrackSection
!create newDriver : Driver
!create newConductor: Conductor
!create newTrain: Train

!newRouteDeparture.init(18, 18)
!hamburg.init('Hamburg Hbf')
!hamburg1.init(1, hamburg)
!roten9.init(9, rotenburg)
!rotHamTrack.init(rotenburg, hamburg)
!newDriver.init('Lukas')
!newConductor.init('Jim Knopf')
!newTrain.init('RE1234')

!newConductor.createRoute(bremen, Sequence{rotenburg, hamburg}, newRouteDepart
```

Test case 29 – TC_29_createRoute_1

We also want to check at least one case where creating a route with *Conductor::createRoute()* does not work. For this, we take test case 28, but don't create an additional platform in Rotenburg, so that there is no available platform there. As expected, the operation fails because *TrainStation::getAvailablePlatform()* returns `null`. In the sequence diagram 5.47 you can see that the *createRoute()*-operation does not finish successfully. The object diagram 5.46 only contains the objects created before calling the *Conductor::createRoute()*-operation, so the system behaves as expected.

```
open initial_state.cmd

-- tests automatically creating a Route
-- with no available platform in Rotenburg

!create newRouteDeparture: Time
!create hamburg: TrainStation
!create hamburg1: Platform
```

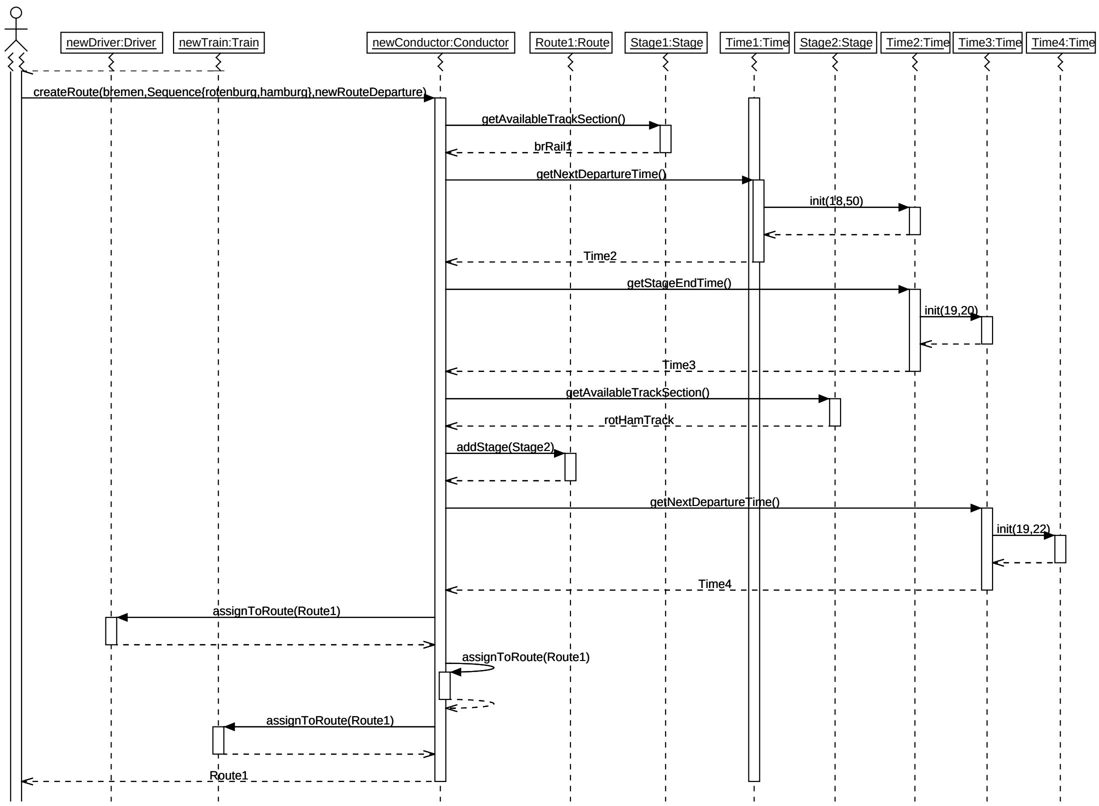


Figure 5.45: Sequence diagram for test case 28

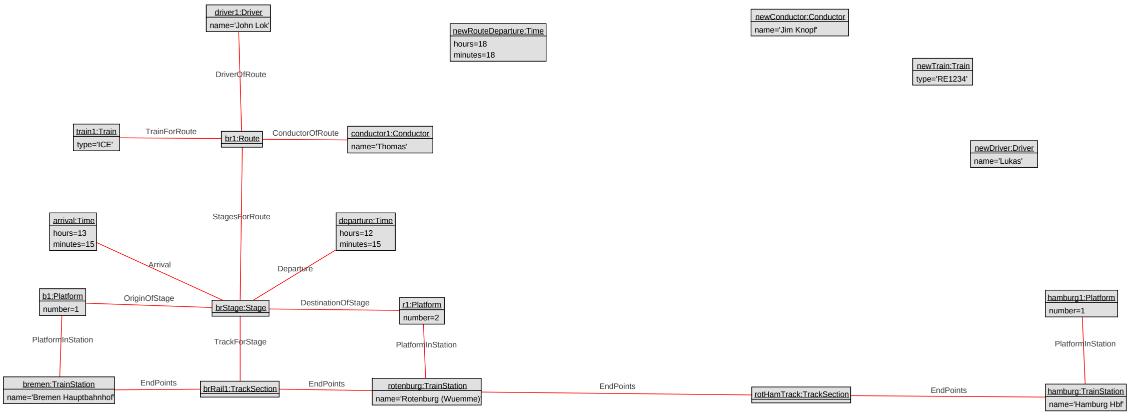


Figure 5.46: Object diagram for test case 29

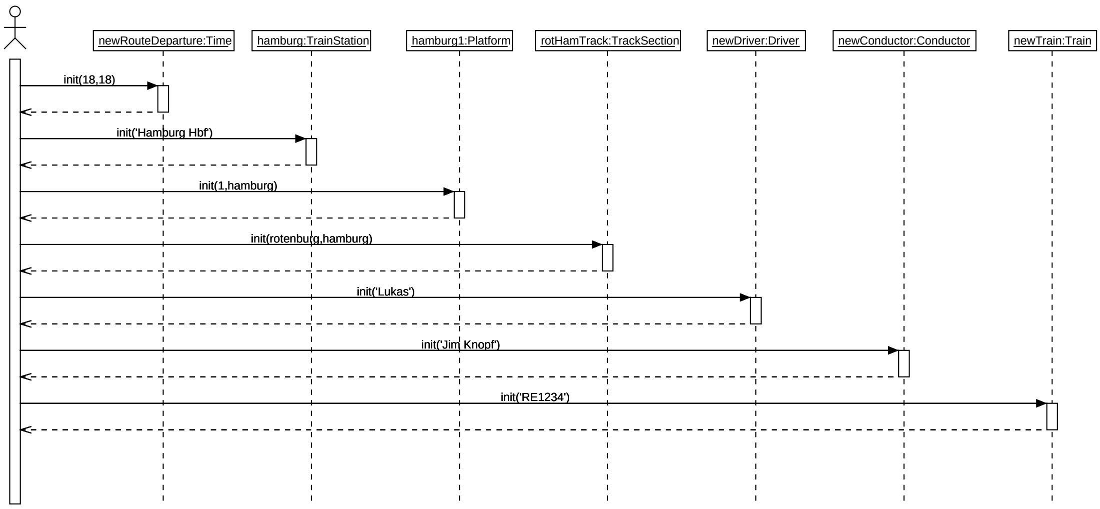


Figure 5.47: Sequence diagram for test case 29

```
!create rotHamTrack: TrackSection
!create newDriver : Driver
!create newConductor: Conductor
!create newTrain: Train

!newRouteDeparture.init(18, 18)
!hamburg.init('Hamburg Hbf')
!hamburg1.init(1, hamburg)
!rotHamTrack.init(rotenburg, hamburg)
!newDriver.init('Lukas')
!newConductor.init('Jim Knopf')
!newTrain.init('RE1234')

!newConductor.createRoute(bremen, Sequence{rotenburg, hamburg}, newRouteDepart
```

6. Queries

Author: Merlin Burri

In the following chapter, possible queries, i. e. OCL expressions that can query useful information contained in our model, will be discussed. For each query, we will start by giving a verbal explanation. Afterwards, the query itself will be presented and, if necessary, further explained. Lastly, the query will be evaluated, which mostly equates to stating the result of the query. The code for every query can also be found in the `query_code.txt` file. In order for the queries to return the expected results, the `query_initial.cmd` state has to be loaded and, if the corresponding query section demands it, the listed additional commands have to be executed.

To illustrate the queries, we will be using calls with exemplary parameters. Our initial state will be the same for all queries, unless otherwise stated, and is constructed as follows. We will start with the state presented in section 5.1 for test case 16. Another `TrainStation` object *munich* with no associations is created. We also introduce another track section between *bremen* and *rotenburg*. Futhermore, we set the arrival time of the `Stage` object *rbStage* to 13:40. The corresponding command sequence can be found in the following, the resulting object diagram in figure 6.1.

```
open tests/TC_16_platform_MaxOneTrainPerPlatform_0.cmd

-- add new train station not connected to any other train station
!create munich : TrainStation
!set munich.name := 'Muenchen'

-- add new track section between bremen and rotenburg
!create brRail2 : TrackSection
!insert (brRail2, bremen) into EndPoints
!insert (brRail2, rotenburg) into EndPoints

-- set arrival time of second stage to 13:40
!set arrival2.minutes := 40
```

6.1 Ressources

In this section, queries regarding our normal resources, i. e. `Train`, `Driver` and `Conductor` will be discussed.

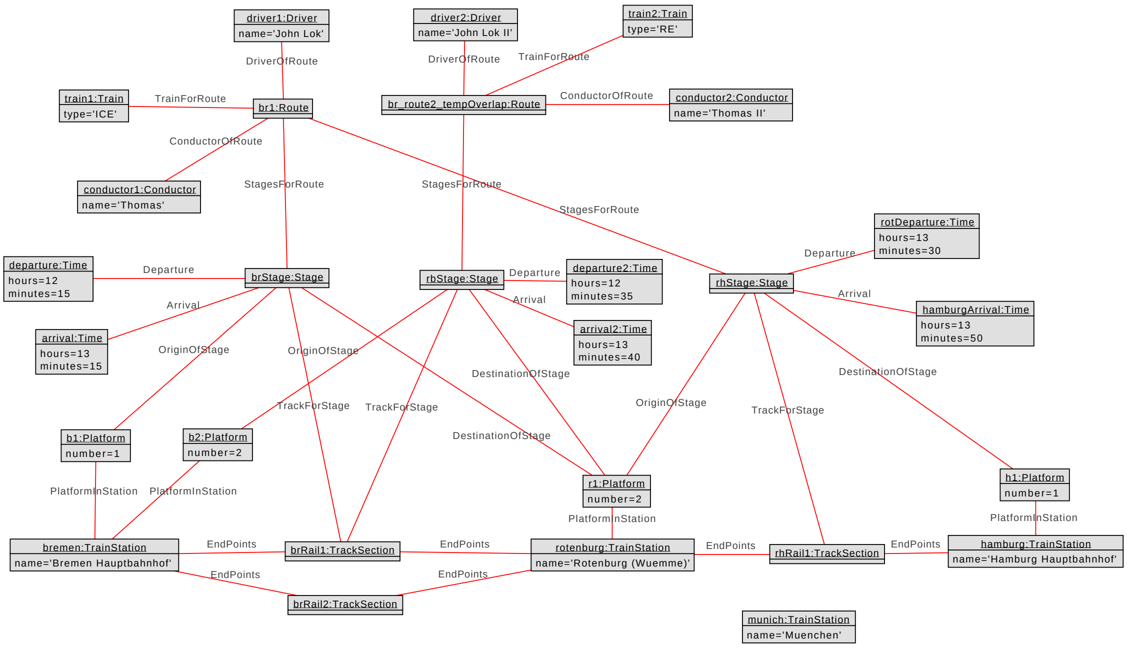


Figure 6.1: Object diagram for the state used for the demonstration of our queries

6.1.1 Workload

The next query allows us to determine the total working time for a resource, for example the total time a driver is assigned to a route. Pauses in between stages are included in that total working time, so long the stages are associated to the same route. To make the evaluation of this query (for `Driver`) a bit more interesting, starting from the initial query state, we set the departure and arrival time of `Stage` *rbStage* to 15:35 and 16:40, respectively, and assign *driver1* to the second route *br_route2_tempOverlap* so he is assigned to multiple routes, while removing *driver2* from the same route. The corresponding command sequence is listed next, the resulting object diagram is shown in figure 6.2.

```
!set departure2.hours := 15
!set arrival2.hours := 16
!delete (driver2, br_route2_tempOverlap) from DriverOfRoute
!insert (driver1, br_route2_tempOverlap) into DriverOfRoute
```

The only parameter is the `Driver` object that the information is to be retrieved for. For our example query, we use *driver1*.

```
let
  theDriver : Driver = @driver1
in
  theDriver.route->collect( r : Route |
    r.stage->first().departureTime
      .getDifference(r.stage->last().arrivalTime)
  )->sum()
```

As a result, we obtain the total workload in minutes. For *driver1*, this amounts to 160 minutes, as the first route *br1* starts at 12:15 and ends at 13:50 (95 minutes), while the second route *br_route2_tempOverlap* does so at 15:35 and 16:40 (65 minutes), respectively.

```
160 : Integer
```

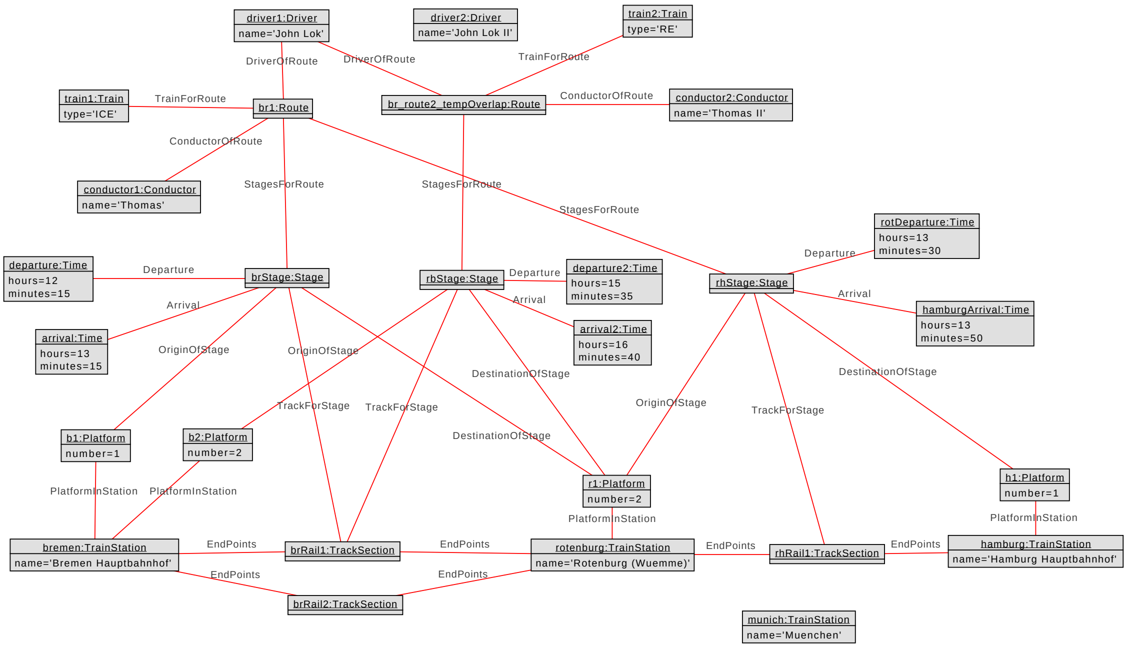


Figure 6.2: Object diagram for the state used for the demonstration of the workload for driver query

If we query the same information for *driver2*, 0 is returned, since *driver2* is not associated to any route.

```
0 : Integer
```

Similarly, the same query can of course be constructed for `Constructor` and `Train` objects by simply replacing all occurences of 'Driver' in the query with 'Conductor' or 'Train', respectively, and passing objects with the corresponding types as the argument.

6.1.2 Available resources for route

This type of query allows the extraction of resources that are available for a given route. For all objects of the respective resource type, all assigned routes are checked for temporal overlap with the new given route. If there is no temporal overlap for all assigned routes, the resource is added to the given list. If the given route is already associated to an object of the respective type, that object is also returned.

To check for the availability of `Driver` objects, the query trying to determine available drivers for `Route` *br1* would look as follows:

```
let
  theRoute : Route = @br1
in
  Driver.allInstances()->select( d : Driver |
    d.route->forAll( r : Route |
      not r.overlaps(theRoute)
    )
    or
    theRoute.driver.isDefined() and theRoute.driver = d
  )
```

Since *driver1* is already assigned to *br1*, it is returned. Driver *driver2* is assigned to route *br_route2_tempOverlap*, which overlaps in time with *br1*. Therefore, *driver2* is not returned:

```
Set{driver1} : Set(Driver)
```

If we change the departure and arrival time for the stage associated with route *br_route2_tempOverlap* so there is no temporal overlap, the query will also return *driver2*. The corresponding command sequence can be found in the following, the result of the same query used previously after that.

```
!set departure2.hours := 15
!set arrival2.hours := 16
```

```
Set{driver1,driver2} : Set(Driver)
```

Similarly to the query in section 6.1.1, we can easily adapt this query to extract `Conductor` or `Train` instead of `Driver` objects by replacing all occurrences of 'Driver' and 'driver' with 'Conductor' and 'conductor' or 'Train' and 'train', respectively.

If we wanted to sort the returned ressource objects by their total working time (lowest to highest), for example to determine the available ressource with the lowest current workload, we can sort the output of this query by using the query presented in section 6.1.1:

```
let
  newRoute : Route = @br1
in
  Driver.allInstances()->select( d : Driver |
    d.route->forAll( r : Route |
      not r.overlaps(newRoute)
    )
    or
    newRoute.driver.isDefined() and newRoute.driver = d
  )->sortedBy(d | d.route->collect( r : Route |
    r.stage->first().departureTime
    .getDifference(r.stage->last().arrivalTime)
    )->sum()
  )
```

Querying the state previously created, one would get the following result, which makes sense, since *driver1* is assigned to one route for a total of 95 minutes and *driver2* to one for a total workload of 65 minutes:

```
Sequence{driver2,driver1} : Sequence(Driver)
```

6.2 Route

In the following section, we will discuss several queries concerning routes, not in the sense of the object `Route`, but in a more general one. Most of these queries could for example be used for a railway traffic application where users can look up specific routes.

6.2.1 Stops for route

The first query can be used to extract all stops for a route. All stages assigned to the route are considered and all destination stations are extracted, together with the respective arrival times. The start station of the route is not included. As the single parameter, a route is required. We choose *br1* for our examplary query.

```
let
  theRoute : Route = @br1
in
  theRoute.stage->collect(s : Stage |
    Tuple{
      stop : s.destination.trainStation,
      hours : s.arrivalTime.hours,
      minutes : s.arrivalTime.minutes
    }
  )
```

The result of the query is as follows:

```
Sequence{Tuple{stop=rotenburg,hours=13,minutes=15},
Tuple{stop=hamburg,hours=13,minutes=50}}
: Sequence(Tuple(stop:TrainStation,hours:Integer,minutes:Integer))
```

6.2.2 Routes for origin and destination

With our second route specific query, one can determine all routes that go from one given train station to another. To also account for routes that contain the origin and destination as intermediate stations, we not only check the first and the last stage of every route, but every stage. Since we assume that within a route trains never go in circles, we simply check every route for stages that contain the given origin train station as source and the given destination as the target train station. If there is one stage that fulfills that criteria, the assigned route is considered. The same holds true if there are two stages, where one contains the origin as source and one the destination as target. The input parameters are two `TrainStation` objects, the origin and the destination. In our example query, we want to look up all routes going from *bremen* and *rotenburg*.

```
let
  origin : TrainStation = @bremen,
  destination : TrainStation = @rotenburg
in
  Route.allInstances()->select( r : Route |
    r.stage->exists( s : Stage |
      s.origin.trainStation = origin
    )
    and r.stage->exists( s : Stage |
      s.destination.trainStation = destination
    )
  )
```

The result of the query would be the following:

```
Set{br1,br_route2_tempOverlap} : Set(Route)
```

6.2.3 Routes for origin and destination with departure and arrival times

Our next query is an extension of the previous one. We now want to retrieve the departure time at the given origin station (which is not necessarily the first station in the route) and the arrival time at the given destination station (which is not necessarily the last station in the route). From the selected routes, next to the route itself we collect the departure and the arrival time of the stages assigned to the origin and destination, respectively. The parameters are equal to the one described in section 6.2.2, the same goes for the example parameters. Since we assume circle free routes, when creating the tuple, we can safely select the first element of the selected collection of stages, since it can only contain one single object. If there were multiple stages in one route going to a single train station (or departing from one), there would be a circle.

```
let
  origin : TrainStation = @bremen,
  destination : TrainStation = @rotenburg
in
  Route.allInstances()->select( r : Route |
    r.stage->exists( s : Stage |
      s.origin.trainStation = origin
    )
    and
    r.stage->exists( s : Stage |
      s.destination.trainStation = destination
    )
  )->collect( r : Route |
    let
      departureStage : Stage = r.stage->select( s : Stage |
                                  s.origin.trainStation = origin
                                )->first(),
      arrivalStage : Stage = r.stage->select( s : Stage |
                                s.destination.trainStation = destination
                              )->first()
    in
      Tuple{
        route : r,
        dHours: departureStage.departureTime.hours,
        dMinutes: departureStage.departureTime.minutes,
        aHours: arrivalStage.arrivalTime.hours,
        aMinutes: arrivalStage.arrivalTime.minutes
      }
  )
```

As a result, we obtain the following bag, where *dHours* and *dMinutes* determine the departure time and *aHours* and *aMinutes* the arrival time at the specified stations:

```
Bag{Tuple{route=br1,dHours=12,dMinutes=15,aHours=13,aMinutes=15},
Tuple{route=br_route2_tempOverlap,dHours=12,dMinutes=35,aHours=13,
aMinutes=40}}
: Bag(Tuple(route:Route,dHours:Integer,dMinutes:Integer,
aHours:Integer,aMinutes:Integer))
```

6.2.4 Routes for origin, destination, current time

We now introduce a query that additionally takes the current time as a parameter and returns all routes departing later than specified by the given time from the given origin and later arriving at the given destination. We adapt the query presented in section 6.2.3 and finally, sort the returned tuple by the difference of current time and departure time.

As additional parameters, we have the current time specified by two `Integer`s *hours* and *minutes*, which we initially set to 12:00. We again use *bremen* as the given origin and *rotenburg* as the destination. In addition to the routes themselves, we again return the departure and arrival times.

```
let
  origin : TrainStation = @bremen,
  destination : TrainStation = @rotenburg,
  hours : Integer = 12,
  minutes : Integer = 00
in
  Route.allInstances()->select( r : Route |
    r.stage->exists( s : Stage |
      s.origin.trainStation = origin
      and
      (s.departureTime.hours > hours) or
      ((s.departureTime.hours = hours)
      and (s.departureTime.minutes > minutes)) or
      (s.departureTime.hours = 0 and hours = 23)
    )
    and
    r.stage->exists( s : Stage |
      s.destination.trainStation = destination
    )
  )->collect( r : Route |
    let
      departureStage : Stage = r.stage->select( s : Stage |
                                  s.origin.trainStation = origin
                                )->first(),
      arrivalStage : Stage = r.stage->select( s : Stage |
                                s.destination.trainStation = destination
                              )->first()
    in
      Tuple{
        route : r,
        dHours: departureStage.departureTime.hours,
        dMinutes: departureStage.departureTime.minutes,
        aHours: arrivalStage.arrivalTime.hours,
        aMinutes: arrivalStage.arrivalTime.minutes
      }
  )->sortedBy(t | ((t.dHours - hours) * 60
    + (t.dMinutes - minutes))
  )
```

The result is the following sequence. As expected, route *br1* is in front of the second route, since the departure times are 12:15 and 12:35, respectively.

```
Sequence{Tuple{route=br1,dHours=12,dMinutes=15,aHours=13,aMinutes=15},
Tuple{route=br_route2_tempOverlap,dHours=12,dMinutes=35,aHours=13,
aMinutes=40}}
: Sequence(Tuple(route:Route,dHours:Integer,dMinutes:Integer,
aHours:Integer,aMinutes:Integer))
```

If we now set the current time parameter to 12 (hours) and 30 (minutes), we obtain the following sequence solely containing the values for the second route, since the train of the first route has already departed:

```
Sequence{Tuple{route=br_route2_tempOverlap,dHours=12,dMinutes=35,
aHours=13,aMinutes=40}}
: Sequence(Tuple(route:Route,dHours:Integer,dMinutes:Integer,
aHours:Integer,aMinutes:Integer))
```

6.2.5 Routes for origin, destination, arrival time

Instead of looking for routes that depart after a certain point in time, one might look for trains arriving before a specific time. To create a query that can extract exactly that, we take the query of the previos section 6.2.4 and, as opposed to checking the departure time of the stage in the route that departs from the given origin, now check the arrival time of the stage arriving to the given destination. We sort the extracted routes by the difference between the arrival time and the desired arrival time. Like previously, we also return departure and arrival times for the routes in question.

For the origin and destination, we use *bremen* and *rotenburg*, respectively. We set the desired arrival time to 13:45.

```
let
  origin : TrainStation = @bremen,
  destination : TrainStation = @rotenburg,
  arrivalHours : Integer = 13,
  arrivalMinutes : Integer = 45
in
  Route.allInstances()->select( r : Route |
    r.stage->exists( s : Stage |
      s.origin.trainStation = origin
    )
    and
    r.stage->exists( s : Stage |
      s.destination.trainStation = destination
      and
      (arrivalHours > s.arrivalTime.hours) or
      ((arrivalHours = s.arrivalTime.hours)
      and (arrivalMinutes > s.arrivalTime.minutes)) or
      (arrivalHours = 0 and s.arrivalTime.hours = 23)
    )
  )->collect( r : Route |
    let
      departureStage : Stage = r.stage->select( s : Stage |
                                 s.origin.trainStation = origin
                               )->first(),
      arrivalStage : Stage = r.stage->select( s : Stage |
                               s.destination.trainStation = destination
                             )->first()
    in
      Tuple{
        route : r,
        dHours: departureStage.departureTime.hours,
        dMinutes: departureStage.departureTime.minutes,
        aHours: arrivalStage.arrivalTime.hours,
        aMinutes: arrivalStage.arrivalTime.minutes
      }
```

```
  )->sortedBy(t | ((arrivalHours - t.aHours) * 60
    + (arrivalMinutes - t.aMinutes))
  )
```

Corresponding to our expectations, the following sequence is returned:

```
Sequence{Tuple{route=br_route2_tempOverlap,dHours=12,dMinutes=35,
aHours=13,aMinutes=40},
Tuple{route=br1,dHours=12,dMinutes=15,aHours=13,aMinutes=15}}
: Sequence(Tuple(route:Route,dHours:Integer,dMinutes:Integer,
aHours:Integer,aMinutes:Integer))
```

If we now set the desired arrival time to 13:35, the second route *br_route2_tempOverlap* will no longer be included in the returned sequence, since the assigned train arrives at 13:40:

```
Sequence{Tuple{route=br1,dHours=12,dMinutes=15,aHours=13,aMinutes=15}}
: Sequence(Tuple(route:Route,dHours:Integer,dMinutes:Integer,
aHours:Integer,aMinutes:Integer))
```

6.2.6 Routes for origin, destination, current time and train type

Again extending the query presented in section 6.2.4, we add another parameter, the train type. In a possible scenario, one might only want to retrieve routes with a certain train type because of the restrictions of his ticket. To filter the train type, we modify the select-expression used to extract viable routes. As parameters, we therefore have the origin, the destination, the current time and the train type as a `String`.

For our example query, we choose *bremen* as origin, *rotenburg* as destination, 12:00 as the current time and 'RE' as the desired train type.

```
let
  origin : TrainStation = @bremen,
  destination : TrainStation = @rotenburg,
  hours : Integer = 12,
  minutes : Integer = 00,
  trainType : String = 'RE'
in
  Route.allInstances()->select( r : Route |
    r.train.type = trainType
    and
    r.stage->exists( s : Stage |
      s.origin.trainStation = origin
      and
      (s.departureTime.hours > hours) or
      ((s.departureTime.hours = hours)
      and (s.departureTime.minutes > minutes)) or
      (s.departureTime.hours = 0 and hours = 23)
    )
    and
    r.stage->exists( s : Stage |
      s.destination.trainStation = destination
        )
  )->collect( r : Route |
    let
```

```
      departureStage : Stage = r.stage->select( s : Stage |
                                  s.origin.trainStation = origin
                               )->first(),
      arrivalStage : Stage = r.stage->select( s : Stage |
                               s.destination.trainStation = destination
                            )->first()
    in
      Tuple{
        route : r,
        dHours: departureStage.departureTime.hours,
        dMinutes: departureStage.departureTime.minutes,
        aHours: arrivalStage.arrivalTime.hours,
        aMinutes: arrivalStage.arrivalTime.minutes
      }
  )->sortedBy(t | ((t.dHours - hours) * 60
    + (t.dMinutes - minutes))
  )
```

In contrast to the first result of the query presented in section 6.2.4, our result sequence does not include *br1*, because the assigned train is of the type 'ICE':

```
Sequence{Tuple{route=br_route2_tempOverlap,dHours=12,dMinutes=35,
aHours=13,aMinutes=40}}
: Sequence(Tuple(route:Route,dHours:Integer,dMinutes:Integer,
aHours:Integer,aMinutes:Integer))
```

6.3 Miscellaneous

Author: Marlon Flügge

In the following section we will be presenting a few more miscellaneous queries.

6.3.1 Conductor's timetable

This query returns the routes and corresponding time intervals a conductor is currently assigned to. It could be used by conductors themselves to check when and where they have to work but also by people planning the routes in order to quickly visualize availability for certain timeslots.

The query takes a parameter `conductorSearch`, which is a search term that is subsequently used to only generate timetables for people of interest. Timetables are created separately for any conductor whose name contains the search term, each timetable represented inside its own `Tuple`. After identifying relevant conductors all the routes for each conductor are collected. For each route an identifier is generated using the names of the origin and destination stations. Additionally a textual representation of the time interval reserved for the specific route is created using the departure and arrival times of the first and last stage respectively. These two strings are bundled inside a `Tuple` and symbolically represent a timeslot inside the conductor's timetable.

In this example we chose `'Thomas'` as search term, which returns timeslots for both `Thomas` and `Thomas II`.

```
let
 conductorSearch : String = 'Thomas'
in
```

```
  Conductor.allInstances()->select(con : Conductor |
    con.name.indexOf(conductorSearch) > 0
      )->collect( c : Conductor |
        let
          condRoutes = Route.allInstances()->select( r : Route |
            r.conductor = c
          )
        in
          Tuple{
            conductor : c.name,
            routes : condRoutes.collect(r : Route |
              let
                origName = r.stage->first().origin.trainStation.name,
                destName = r.stage->last().destination.trainStation.name,
                departure = r.stage->first().departureTime,
                arrival = r.stage->last().arrivalTime
              in
                Tuple{
                  routeName : origName.concat(' to ').concat(destName),
                  interval : 'From '.concat(departure.hours.toString())
                              .concat(':')
                                .concat(departure.minutes.toString())
                                  .concat(' until ')
                                    .concat(arrival.hours.toString())
                                      .concat(':')
                                        .concat(arrival.minutes.toString())
                }
            )
          }
      )
```

The result of the query is the following:

```
Bag{Tuple{conductor='Thomas',routes=Bag{Tuple{routeName=
'Bremen Hauptbahnhof to Hamburg Hauptbahnhof',
interval='From 12:15 until 13:50'}}}, Tuple{conductor='Thomas II',
routes=Bag{Tuple{routeName='Bremen Hauptbahnhof to Rotenburg (Wuemme)',
 interval='From 12:35 until 13:40'}}}} : Bag(Tuple(conductor:String,
routes:Bag(Tuple(routeName:String,interval:String))))
```

6.3.2 Reachable train stations from train station

For our last query, we want to determine all train stations that are reachable from a given train station. To archieve that, we first go through all train stations directly connected via track sections. We do the same for all these train stations, and so forth, by using the *closure* operation. All these train stations are added to a list and transformed into a set to remove duplicate entries. The input parameter is a `TrainStation` object and in our example, we want to get all connected train stations for *bremen*.

```
let
  theStation : TrainStation = @bremen
in
  theStation.trackSection.trainStation->closure(t : TrainStation |
```

```
      t.trackSection.trainStation
  )->asSet()
```

The result of the query is the following:

```
Set{bremen,hamburg,rotenburg} : Set(TrainStation)
```

`TrainStation` *munich* is not included, since it is not connected to any train station. If we were to call the query on *munich*, the returned set would be empty. We now add a track section in between *munich* and hamburg:

```
!create muRail : TrackSection
!insert (muRail, munich) into EndPoints
!insert (muRail, hamburg) into EndPoints
```

The query will now return *munich* as well:

```
Set{bremen,hamburg,munich,rotenburg} : Set(TrainStation)
```

7. Outlook

Author: Marlon Flügge

In this paper we presented a system to model the scheduling of daily railroad traffic. The system does not model actual railway traffic completely, however. There are a number of ways in which the system overly simplifies the problem because of a limitation in man-hours.

General simplifications include:

- 7-day week: Only daily railway traffic is scheduled. In real life, the railway schedule may differ on different days, e.g. on weekends. Going even further, holidays may also impact the schedule, so that even a 7-day week would not be enough.
- TrackSections usable from whole TrainStations: In the model, TrackSections only connect TrainStations, implying that every track laid between two stations can be reached from every platform in each of those stations. In real life, this is usually not the case, limiting the connections to a number of platforms per TrainStation.

More specific simplifications and resulting problems include:

- Stages overlapping: *Stage::temporallyOverlaps()* assumes two Stages to be overlapping when their time intervals are not completely disjunct. This is then used to determine whether a TrackSection is available for a Stage at a given time. If two stages both head in the same direction, a small temporal overlap is not a problem, though, making the system in its current state inefficient in the utilization of available track sections. This could be remedied by introducing additional cases where there is no temporal overlap if two Stages go in the same direction with a minimum difference in departure and arrival times (e.g. 5 minutes).
- Teleporting resources: *Route::getAvailableTrain()* and its driver- and conductor-counterparts do not check for the current location of those resources. A train is considered available in Bremen if it just arrived in Hamburg, as long as it finished its Route and has no other Route planned in the near future. The transportation to the new station as well as the needed time are not considered, leading to potentially practically impossible schedules.
  This could be fixed by only making those resources available if their last serviced Stage ended in the same station as the one the querying Route departs from. Also, a corresponding invariant should be added.

- Midnight troubles: A train departing at 23:30 and arriving at 00:15 obviously arrives later than it departs, yet its time is lower. This is partially considered in *Time::isLater()*, but not every possible case can be covered. We also forgot to incorporate the midnight changing into *Time::getNextDepartureTime()* and *Time::getStageEndTime()*. Because of a limited amount of operations test cases, there could be more instances where we forgot to account for this that we haven't noticed yet.
  The only 'real' fix for this would be to create a full schedule with a complete calendar, i.e. also including day, month and year, which was not the intended goal of this system.

A. Code

```
model RailwayPlanner

-- classes

class Train
attributes
  type : String;

operations
  init(pType: String)
    begin
      self.type := pType
    end
    pre freshInstance: self.type.isUndefined()
    pre typeNotEmpty: pType.size > 0
    post typeAssigned: self.type = pType

  -- assigns the train to the given route
  assignToRoute(r: Route)
    begin
      if r.train.isDefined()
      then
        delete (r.train, r) from TrainForRoute;
      end;
      insert(self, r) into TrainForRoute;
    end
    pre trainRouteDefined: r.isDefined()
    post isAssigned: r.train = self
end

class TrainStation
attributes
  name : String;

operations
```

```
  init(pName: String)
    begin
      self.name := pName
    end
    pre freshInstance: self.name.isUndefined()
    pre nameNotEmpty: pName.size > 0
    post nameAssigned: self.name = pName

  --returns a platform that is available at the given time
  getAvailablePlatform(t : Time) : Platform =
    self.platform -> any(p : Platform | p.isAvailable(t))
  pre hasPlatforms: self.platform -> size > 0
  pre timeDefined: t.isDefined()
end

-- only models hours and minutes because this is for scheduled daily traffic
class Time
attributes
  hours : Integer;
  minutes : Integer;

operations
  init(pHours: Integer, pMinutes: Integer)
    begin
      self.hours := pHours;
      self.minutes := pMinutes;
    end
    pre freshInstance: self.hours.isUndefined() and
                       self.minutes.isUndefined()
    pre hoursInCorrectInterval: pHours >= 0 and pHours < 24
    pre minutesInCorrectInterval: pMinutes >= 0 and pMinutes < 60
    post timeAssigned: self.hours = pHours and
                       self.minutes = pMinutes

  -- checks if the Time the method is called on is
  -- after the given Time
  isLater( t: Time ) : Boolean =
    (self.hours > t.hours) or
    ((self.hours = t.hours) and (self.minutes > t.minutes)) or
    (self.hours = 0 and t.hours = 23);

  -- returns the difference between the given Time and self
  -- in minutes. Only positive if the given Time is later
  getDifference( t: Time) : Integer =
      ((t.hours - self.hours) * 60 + (t.minutes - self.minutes))

  -- returns a default new departure time from a station with self
  -- as the arrival time at that station. Default staying time in
  -- a station is set at 2 minutes.
  getNextDepartureTime() : Time
    begin
      declare newTime : Time;
```

```
      newTime := new Time();
      if (self.minutes < 58) then
        newTime.init(self.hours, self.minutes + 2)
      else
        newTime.init(self.hours + 1, self.minutes - 58)
      end;
      result := newTime
    end
    pre timeDefined: hours.isDefined() and minutes.isDefined()

  -- returns a default ending time for a stage with self as the
  -- starting time. Default stage length is 30 minutes.
  getStageEndTime() : Time
    begin
      declare newTime : Time;
      newTime := new Time();
      if (self.minutes < 30) then
        newTime.init(self.hours, self.minutes + 30)
      else
        newTime.init(self.hours + 1, self.minutes - 30)
      end;
      result := newTime
    end
    pre timeDefined: hours.isDefined() and minutes.isDefined()
end

class Platform
attributes
  number : Integer;
operations
  -- A platform needs an existing trainstation and can't change
  -- to a different TrainStation.
  init(pNumber: Integer, ts: TrainStation)
    begin
      self.number := pNumber;
      insert(self, ts) into PlatformInStation
    end
    pre freshInstance: self.number.isUndefined() and
                       self.trainStation.isUndefined()
    pre numberPositive: pNumber > 0
    pre stationDefined: ts.isDefined()
    pre platformNumberNotTaken: not(ts.platform->exists(p |
                                        p.number = pNumber))
    post numberAssigned: self.number = pNumber
    post platformAssigned: ts.platform->exists(p | p = self)

  -- checks whether a platform is available at a given time
  -- (no trains currently on that platform or arriving/departing
  -- within 5 minutes)
  isAvailable(t: Time) : Boolean =
  self.arrivingStage -> forAll
           (aS: Stage |
```

```
            t.getDifference(aS.arrivalTime) > 5 or
            self.departingStage -> exists
               (dS: Stage |
                dS.route.train = aS.route.train and
                dS.departureTime.isLater(aS.arrivalTime) and
                (t.getDifference(dS.departureTime) < -5)
                )
            )
  pre timeDefined: t.isDefined()
end

class TrackSection
attributes
operations
  init(endPoint1: TrainStation, endPoint2: TrainStation)
    begin
      insert(self, endPoint1) into EndPoints;
      insert(self, endPoint2) into EndPoints;
    end
    pre freshInstance: self.trainStation -> size() = 0
    pre endPointsDefined: endPoint1.isDefined() and
                          endPoint2.isDefined()
    post sectionConnectedToStations: self.trainStation->exists
                                       (s1,s2 |
                                        s1=endPoint1 and
                                        s2=endPoint2)
end

class Route
operations
  init(pDriver: Driver, pConductor: Conductor,
       pTrain: Train, pFirstStage: Stage)
    begin
      pDriver.assignToRoute(self);
      pConductor.assignToRoute(self);
      pTrain.assignToRoute(self);
      insert (pFirstStage, self) into StagesForRoute;
    end
    pre driverDefined: pDriver.isDefined()
    pre conductorDefined: pConductor.isDefined()
    pre trainDefined: pTrain.isDefined()
    pre stageDefined: pFirstStage.isDefined()
    pre freshInstance: self.driver.isUndefined() and
                       self.conductor.isUndefined() and
                       self.train.isUndefined() and
                       self.stage -> size() = 0
    post driverAssigned: self.driver = pDriver
    post conductorAssigned: self.conductor = pConductor
    post trainAssigned: self.train = pTrain
    post firstStageAssigned: self.stage->at(1) = pFirstStage

  addStage(pStage: Stage)
```

```
    begin
      insert(pStage, self) into StagesForRoute
    end
    pre stageDefined: pStage.isDefined()
    pre stageComplete: pStage.departureTime.isDefined() and
                       pStage.arrivalTime.isDefined() and
                       pStage.origin.isDefined() and
                       pStage.destination.isDefined() and
                       pStage.trackSection.isDefined()
    pre stageStartEqualsPreviousEnd:
      self.stage->last.destination = pStage.origin
    -- stage should not be part of another route
    pre stageNotUsed: Route.allInstances -> forAll
                             (r: Route |
                               not (r.stage -> includes(pStage))
                              )
    post stageAdded: self.stage-> last = pStage

  removeStage(pStage: Stage)
    begin
      delete(pStage, self) from StagesForRoute;
    end
    pre stageDefined: pStage.isDefined()
    -- stages may only be removed if they are the first or last
    -- stage of the route so that the route will still be
    -- completeable
    pre stageRemovable: self.stage -> last = pStage or
                        self.stage -> first = pStage
    post stageRemoved: not(self.stage -> includes(pStage))

  -- checks if the time frames of the two given Route objects
  -- overlap
  overlaps( r: Route ) : Boolean =
    not(
        (self.stage->first.departureTime.isLater
            (r.stage->last.arrivalTime)) or
        (r.stage->first.departureTime.isLater
            (self.stage->last.arrivalTime))
        )

  -- returns a Train that is available for this Route
  getAvailableTrain() : Train =
    Train.allInstances -> any
        (t: Train | t.route->forAll
             (r: Route | not r.overlaps(self))
         )
  pre hasStages: self.stage -> size > 0
  post foundAvailableTrain: result.isDefined()

  --returns a Driver that is available for this Route
  getAvailableDriver() : Driver =
    Driver.allInstances -> any
```

```
        (d: Driver | d.route->forAll
             (r: Route | not r.overlaps(self))
         )
  pre hasStages: self.stage -> size > 0
  post foundAvailableDriver: result.isDefined()

  --returns a Conductor that is available for this Route
  getAvailableConductor() : Conductor =
    Conductor.allInstances -> any
        (c: Conductor | c.route->forAll
             (r: Route | not r.overlaps(self))
         )
  pre hasStages: self.stage -> size > 0
  post foundAvailableConductor: result.isDefined()
end

class Stage
operations
  -- A stage needs an existing arrival- and departure-time
  -- as well as an existing origin- and destination-platform
  -- and an existing TrackSection
  init(pDepartureTime: Time, pArrivalTime: Time,
       pOrigin:Platform, pDestination: Platform,
       pTrackSection: TrackSection)
    begin
      insert(pDepartureTime, self) into Departure;
      insert(pArrivalTime, self) into Arrival;
      insert(pOrigin, self) into OriginOfStage;
      insert(pDestination, self) into DestinationOfStage;
      insert(pTrackSection, self) into TrackForStage
    end
    pre freshInstance: departureTime.isUndefined() and
                       arrivalTime.isUndefined() and
                       origin.isUndefined() and
                       destination.isUndefined() and
                       trackSection.isUndefined()
    pre timesDefined: pDepartureTime.isDefined() and
                      pArrivalTime.isDefined()
    pre platformsDefined: pOrigin.isDefined() and
                          pDestination.isDefined()
    pre trackDefined: pTrackSection.isDefined()
    pre trackConnectsOriginAndDestination:
      pTrackSection.trainStation->exists
          (s : TrainStation | s = pDestination.trainStation) and
      pTrackSection.trainStation->exists
          (s : TrainStation | s = pOrigin.trainStation)
    post departureTimeAssigned: self.departureTime =
                                  pDepartureTime
    post arrivalTimeAssigned: self.arrivalTime = pArrivalTime
    post originAssigned: self.origin = pOrigin
    post destinationAssigned: self.destination = pDestination
    post trackSectionAssigned: self.trackSection = pTrackSection
```

```

  -- checks if two given Stage objects overlap temporally
  temporallyOverlaps(s: Stage) : Boolean =
    not(
        (self.departureTime.isLater(s.arrivalTime)) or
        (s.departureTime.isLater(self.arrivalTime))
        )

  -- returns a TrackSection that can be used for this stage,
  -- if there is any, i.e. a TrackSection that is not yet
  -- used in the time frame of this stage and connects origin
  -- and destination
  getAvailableTrackSection() : TrackSection
  begin
    declare track : TrackSection;
    track := TrackSection.allInstances -> any
        (ts: TrackSection |
            (ts.stage -> forAll
                (s: Stage |
                    not(s.temporallyOverlaps(self))
                 )
             ) and
            ts.trainStation ->
                includes(self.origin.trainStation) and
            ts.trainStation ->
                includes(self.destination.trainStation)
          );
    result := track;
  end
  pre timesDefined: self.departureTime.isDefined() and
                    self.arrivalTime.isDefined()
  pre stationsDefined: self.origin.isDefined() and
                       self.destination.isDefined()
  post foundAvailableTrack: result.isDefined()
end

abstract class Employee
attributes
  name : String;
end

class Driver < Employee
operations
  init(pName: String)
    begin
        self.name := pName
    end
    pre freshInstance: name.isUndefined()
    pre nameNotEmpty: pName.size > 0
    post nameIsInitialized: self.name = pName

  --assigns this driver to the given route
```

```
  assignToRoute (r: Route)
    begin
      if(r.driver.isDefined()) then
        delete (r.driver, r) from DriverOfRoute;
      end;
      insert(self, r) into DriverOfRoute
    end
    pre routeDefined: r.isDefined()
    post isAssigned: r.driver = self
end

class Conductor < Employee
operations
  init(pName: String)
    begin
        self.name := pName
    end
    pre freshInstance: name.isUndefined()
    pre nameNotEmpty: pName.size > 0
    post nameIsInitialized: self.name = pName

  --assigns this conductor to the given route
  assignToRoute (r: Route)
    begin
      if(r.conductor.isDefined()) then
        delete (r.conductor, r) from ConductorOfRoute;
      end;
      insert(self, r) into ConductorOfRoute
    end
    pre routeDefined: r.isDefined()
    post isAssigned: r.conductor = self

  -- create a route using a list of train stations and a
  -- start time. The time for each stage is set to 30 minutes.
  -- To keep the code relatively simple, the departure time
  -- is the same as the previous arrival time.
  createRoute(startingStation: TrainStation,
              stations: Sequence(TrainStation),
              startTime: Time) : Route
    begin
      declare newRoute: Route,
              currentStage: Stage,
              currentTime: Time;
      newRoute := new Route();
      currentStage := new Stage();
      insert(startTime, currentStage) into Departure;
      insert(startingStation.getAvailablePlatform(startTime),
             currentStage) into OriginOfStage;

      for station in stations do
        currentTime :=
            currentStage.departureTime.getStageEndTime();
```

```
          insert(station.getAvailablePlatform(currentTime),
                 currentStage) into DestinationOfStage;
          insert(currentTime, currentStage) into Arrival;
          insert(currentStage.getAvailableTrackSection(),
                 currentStage) into TrackForStage;
          if(newRoute.stage -> size() = 0) then
            insert(currentStage, newRoute) into StagesForRoute;
          else newRoute.addStage(currentStage);
          end;
          currentStage := new Stage();
          insert(newRoute.stage -> last.destination,
                 currentStage) into OriginOfStage;
          currentTime := currentTime.getNextDepartureTime();
          insert(currentTime, currentStage) into Departure;
        end;
        -- remove last 'currentStage' and its associations
        -- as well as last 'currentTime'
        destroy currentStage;
        destroy currentTime;

        newRoute.getAvailableDriver().assignToRoute(newRoute);
        newRoute.getAvailableConductor().assignToRoute(newRoute);
        newRoute.getAvailableTrain().assignToRoute(newRoute);
        result := newRoute;
      end
      --there need to be at least 2 stations in a route
      pre startingStationDefined: startingStation.isDefined()
      pre startTimeDefined: startTime.isDefined()
      pre enoughStations: stations -> size() > 0
      post driverAssigned: result.driver.isDefined()
      post conductorAssigned: result.conductor.isDefined()
      post trainAssigned: result.train.isDefined()
      post allStagesAdded: result.stage -> size() =
                           stations -> size()
      post correctDepartingTime: result.stage ->
                                first.departureTime = startTime
end


-- associations

association PlatformInStation between
  Platform[*];
  TrainStation[1];
end

association DriverOfRoute between
  Driver[1];
  Route[*];
end

association ConductorOfRoute between
```

```
  Conductor[1];
  Route[*];
end

association TrainForRoute between
  Train[1];
  Route[*];
end

association StagesForRoute between
  Stage[*] ordered;
  Route[1];
end

association TrackForStage between
  TrackSection[1];
  Stage[*];
end

association OriginOfStage between
  Platform[1] role origin;
  Stage[*] role departingStage;
end

association DestinationOfStage between
  Platform[1] role destination;
  Stage[*] role arrivingStage;
end

association Departure between
  Time[1] role departureTime;
  Stage[*];
end

association Arrival between
  Time[1] role arrivalTime;
  Stage[*] role routePart;
end


association EndPoints between
  TrackSection[*];
  TrainStation[2];
end



--++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

constraints

--invariants for definedness of attributes
```

```

-- -----------------------------------------------------------------------
-- Section: The following Constraints apply to the class Train
-- -----------------------------------------------------------------------

--Train is not assigned to multiple Routes at the same time
context Train inv TrainNotUsedSimultaneously:
  self.route->forAll(r1: Route, r2: Route |
    r1.overlaps(r2) implies r1 = r2
  )

-- -----------------------------------------------------------------------
-- Section: The following Constraints apply to the class Employee and
-- its subclasses (Conductor and Driver)
-- -----------------------------------------------------------------------

--Driver is not assigned to multiple Routes at the same time
context Driver inv DriverNotUsedSimultaneously:
  self.route->forAll(r1: Route, r2: Route |
    r1.overlaps(r2) implies r1 = r2
  )

--Conductor is not assigned to multiple Routes at the same time
context Conductor inv ConductorNotUsedSimultaneously:
  self.route->forAll(r1: Route, r2: Route |
    r1.overlaps(r2) implies r1 = r2
  )

-- -----------------------------------------------------------------------
-- Section: The following Constraints apply to the class Route
-- -----------------------------------------------------------------------

--For every Stage in the Route, the Departure Time has to be after
--the Arrival Time of the previous Stage
context Route inv DepartureAfterArrivalPreviousStage:
  self.stage->forAll(s : Stage |
    let currentStageNumber : Integer = stage->indexOf(s)
    in if (currentStageNumber < stage->size()) then
      stage->at(currentStageNumber + 1).departureTime
        .isLater(s.arrivalTime)
    else
      true
    endif
  )

--For every Stage in the Route, the Platform that the Train is departing
--from has to be the platform that the Train arrived on in the previous
--Stage. This also makes sure that the TrainStation the Train is departing
--from equals the TrainStation that it arrived on in the previous Stage.
context Route inv DeparturePlatformPreviousPlatform:
  self.stage->forAll(s : Stage |
    let currentStageNumber : Integer = stage->indexOf(s)
```

```
    in if (currentStageNumber < stage->size()) then
      s.destination = stage->at(currentStageNumber + 1).origin
    else
      true
    endif
  )

--Routes do not contain circles, which equates to every Stage in the Route
--having differing source and destination TrainStations
context Route inv NoCircles:
  self.stage->forAll(s1, s2 : Stage |
    (s1.origin.trainStation = s2.origin.trainStation
    or
    s1.destination.trainStation = s2.destination.trainStation)
    implies
    s1 = s2
  )

-- -----------------------------------------------------------------------------
-- Section: The following Constraints apply to the class Stage
-- -----------------------------------------------------------------------------

--Departure time has to be before arrival time
context Stage inv ArrivalAfterDeparture:
  self.arrivalTime.isLater(self.departureTime)

--the used TrackSection has to connect the origin and the
--destination of the stage
context Stage inv TrackSectionConnectOriginDestination:
  self.trackSection.trainStation->exists(s : TrainStation |
     s = self.destination.trainStation
  )
  and self.trackSection.trainStation->exists(s : TrainStation |
     s = self.origin.trainStation
  )

--No stages using the same sections at overlapping time frames
--going in opposite directions.
--Same used TrackSection and temporal overlap imply same direction
context s1, s2: Stage inv NoOverlapsOppositeDirections:
    not (s1 = s2) and s1.trackSection = s2.trackSection
    and s1.temporallyOverlaps(s2) implies
    s1.destination.trainStation = s2.destination.trainStation

--Same used TrackSection and temporal overlap imply a certain
--difference in arrival and departure times
context s1, s2: Stage inv TimeDifferenceSameDirection:
    not (s1 = s2) and s1.trackSection = s2.trackSection
    and s1.temporallyOverlaps(s2) implies
    if s2.departureTime.isLater(s1.departureTime) then
      s1.departureTime.getDifference(s2.departureTime) > 10 and
      s1.arrivalTime.getDifference(s2.arrivalTime) > 10
```

```
    else
      s2.departureTime.getDifference(s1.departureTime) > 10 and
      s2.arrivalTime.getDifference(s1.arrivalTime) > 10
    endif

-- -----------------------------------------------------------------------
-- Section: The following Constraints apply to the class TrackSection
-- -----------------------------------------------------------------------

-- -----------------------------------------------------------------------
-- Section: The following Constraints apply to the class TrainStation
-- -----------------------------------------------------------------------


-- -----------------------------------------------------------------------
-- Section: The following Constraints apply to the class Platform
-- -----------------------------------------------------------------------

--The next train may only arrive after the previous train has departed
--Thus, each platform may host at most one train at a time
context Platform inv MaxOneTrainPerPlatform:
  self.arrivingStage->forAll(a1, a2 |
    a1 = a2 or
    --trains not arriving at same time
    (a2.arrivalTime.isLater(a1.arrivalTime) or a1.arrivalTime
      .isLater(a2.arrivalTime))
    and
    --every stopping train needs to depart before the next one arrives
    (a2.arrivalTime.isLater(a1.arrivalTime) implies
    a2.arrivalTime.isLater(a1.route.stage
      ->at((a1.route.stage->indexOf(a1))+1).departureTime))
    )

-- -----------------------------------------------------------------------
-- Section: The following Constraints apply to the class Time
-- -----------------------------------------------------------------------

-- The value for the minutes attribute has to be in the interval [0,59]
context Time inv MinutesInInterval:
  Time.allInstances->forAll( t: Time |
    t.minutes >= 0 and t.minutes < 60
  )

-- The value for the hours attribute has to be in the interval [0,23]
context Time inv HoursInInterval:
  Time.allInstances->forAll( t: Time |
    t.hours >= 0 and t.hours < 24
  )
```