Domain engineering of railroad systems

source material:
Dines Bjørner et al

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source material

- Bjørner et al: Towards a TRain book (2004)
  - particularly Chapter 2
- Bjørner et al: “UML”-ising Formal Techniques (2004)

Dines Bjørner

- famous in the formal methods community
- current focus areas: (1) domain engineering, (2) requirements engineering, and (3) software design methods
- behind RAISE (Rigorous Approach to Industrial Software Engineering)
  - RAISE Specification Language (RSL) and tools
- www2.imm.dtu.dk/~db/

a *domain*

A (somewhat cyclic) definition:

Definition

An application (or business) domain: a universe of discourse, an area of human and societal activity, ...

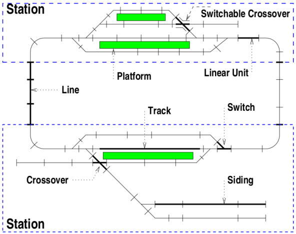
TRain (The Railway Domain)

- www.railwaydomain.org

  "Because we need a grand challenge project in order to gather enough momentum to make progress along the road to industrially scalable and useful, integrated formal techniques."

“basic railway domain model”

- the physical structure of railways
  - an *intrinsic facet* of the railway domain(?) ♠
- as collections and compositions of “railway nets, lines, stations, tracks (rail) units, and connectors”
  - components which “can be physically demonstrated”
    - but abstracting away a number of physical attributes
  - “top-down” description—decreasingly composite



examples of attributes abstracted away

- of rail units
  - length
  - topology, i.e. the three-dimensional layout of a unit, including “tilting” of rails in curves, etc.
  - context: on a bridge, in a tunnel, along a platform, along a quay, etc.

a domain description

- An *informal narrative* describing a domain, **and** a *mathematical text* formalising the description.
- Problem: Our use of natural language is very flexible. We hardly notice as we slip from one mode of description to another.
  - might encounter serious problems in formalising an informal description
  - no single specification language can cater for all modes: functional, imperative, logical, temporal, concurrency (with events and behaviors)

a natural language description of railway nets

1. A railway net consists of one or more lines and two or more stations.
2. A railway net consists of rail units.
3. A line is a linear sequence of one or more linear rail units.
4. The rail units of a line must be rail units of the railway net of the line.
5. A station is a set of one or more rail units.
6. The rail units of a station must be rail units of the railway net of the station.
7. No two distinct lines and/or stations of a railway net share rail units.
8. ...

RAISE specification language (RSL)

- supports different specification styles
  - algebraic or model-oriented
  - applicative or imperative
  - sequential or concurrent
- supports modular specifications
- does not cater for “true” concurrency or time

a mathematical description of railway nets

- sorts
  - abstract types—no specified structure
  - respectively: network, line, station, track, rail unit, connector

type N, L, S, Tr, U, C

example: railway net representation and constraints

1. A railway net consists of one or more lines and two or more stations.
2. A railway net consists of rail units.

value

1. obs_Ls : N $\rightarrow$ L-**set**
1. obs_Ss : N $\rightarrow$ S-**set**
2. obs_Us : N $\rightarrow$ U-**set**

axiom

1. $\forall$ n:N • **card** obs_Ls(n) ≥ 1
1. $\forall$ n:N • **card** obs_Ss(n) ≥ 2

example: linear sequence predicate

17. A linear sequence of (linear) rail units is a non-cyclic sequence of linear units such that neighbouring units share connectors.

value

lin_seq: U-**set** $\rightarrow$ **Bool**

lin_seq(us) $\equiv$

$\forall$ u:U $\bullet$ u $\in$ us $\Rightarrow$ is_Linear(u) $\wedge$

$\exists$ q:U* $\bullet$ **len** q $=$ **card** us $\wedge$ **elems** q $=$ us $\wedge$

$\forall$ i:**Nat** $\bullet$ $\{$i, i$+$i$\}$ $\subseteq$ **inds** q $\Rightarrow$ $\exists$ c:C $\bullet$

obs_Cs(q(i)) $\cap$ obs_Cs(q(i$+$1)) $=$ $\{$c$\}$ $\wedge$

len q $> 1 \Rightarrow$

obs_Cs(q(i)) $\cap$ obs_Cs(q(**len** q)) $=$ $\{\}$

example: well-formed route subtype

(A route is a sequence of pairs of units and paths...)
23. ...such that the path of a unit/path pair is a possible path of some state of the unit, and such that "neighbouring" connectors are identical.

type

$R = \{|\ r : R' \bullet \text{wf\_R}(r)\ |\}$

axiom

$\text{wf\_R} : R' \rightarrow \textbf{Bool}$

$\text{wf\_R}(r) \equiv \textbf{len}\ r > 0 \wedge$

$\quad \forall\ i : \textbf{Nat} \bullet i \in \textbf{inds}\ r \wedge \textbf{let}\ (u, (c, c')) = r(i)\ \textbf{in}$

$\quad\quad (c, c') \in \bigcup \text{obs\_}\Omega(u) \wedge i + 1 \in \textbf{inds}\ r \Rightarrow$

$\quad\quad \textbf{let}\ (\_, (c'', \_)) = r(i + 1)\ \textbf{in}\ c' = c''\ \textbf{end}\ \textbf{end}$

example: "does a line connect to a station" query

- LS_Connection is a partial function, with guards
- N for railway net, L for line, S for station
- U for rail unit, C for connector
- a station is a set of units; cf. **5.** obs_Us : $S \rightarrow$ U-**set**
- note overload of obs_Us

$$
\begin{array}{l}
\textbf{value} \\
\text{LS\_Connection} : N \times L \times S \stackrel{\sim}{\rightarrow} \textbf{Bool} \\
\text{LS\_Connection}(n, l, s) \equiv \\
\quad \exists\ u, u' : U \bullet u \in \text{obs\_Us}(l) \wedge u' \in \text{obs\_Us}(s) \wedge \\
\quad\quad \exists\ c : C \bullet \text{obs\_Cs}(u) \cap \text{obs\_Cs}(u') = \{c\} \\
\quad \textbf{pre}\ l \in \text{obs\_Ls}(n) \wedge s \in \text{obs\_Ss}(n)
\end{array}
$$

modular RSL

- RSL supports `scheme` and `class` syntax
  - for structuring, i.e. breaking up a model into smaller parts
    - this opens up reuse possibilities
  - like *concepts*, with types, signatures, and axioms
  - a `scheme` declaration is parameterizable
  - a `scheme` may combine and extend others by adding types, signatures, and axioms
  - Examples: [extend] and [generics]

modular RSL versus UML

- suitable structuring of an RSL specification may make it amenable to “UML-ising”
  - not everything is expressible in UML, but makes for a more visual representation
  - may provide a useful “view” into certain aspects of the model

UML example

- Example [uml]
- **1.** A railway net consists of one or more lines and two or more stations.
  - can be modeled with UML *composition*
- **12.** A rail unit is either a linear unit, a switch, a simple crossover, or a switchable crossover.
  - can be modeled with UML *generalization*; unit is an *abstract class*
- **14.** A linear rail unit has two distinct connectors, a switch rail unit has three distinct connectors, crossover rail units have four distinct connectors, etc.
  - can be modeled with UML *associations*

dynamism

- a railway net would ideally be a *programmed, dynamic active system*
- less ideally (in the real world) it is a *dynamic reactive system*
- Bjørner et al primarily regard a railway net as "programmed", assuming its managers are in control of its time-wise behavior
- a *managed rail net* has state
  - e.g. switches and signals have state
- "small" parts of a rail net may be undergoing change
  - e.g. new lines and stations being added, old ones removed or put under repair
  - $T \to N$

states of a rail unit

- either in *stable*, *transition*, or *reconfiguration* state
- it is assumed that durations can be observed
- stable state: determines how a train can move across a unit
- transition state: between stable states; a transition takes time
- reconfiguration state: change of (stable) state space
  - enable additional paths, or disable previously valid paths
  - units may have "dangling" connectors

formalisms for modeling time

- plain RSL
- Timed RSL (TRSL)
- Duration Calculus (DC)

plain RSL

- no built-in way to model time
- time can be modeled, but “not in general very satisfactorily”
  - e.g. impossible to specify *timeout*
  - Example [time]

Timed RSL (TRSL)

- an extension to RSL; only
  - type `Time`, an alias for the non-negative subtype of `Real`
  - a `wait` construct; takes an expression of type `Time`

$$\text{sensor\_state} := \text{high} \; ; \; \textbf{wait}\ \delta \; ; \; \text{sensor\_state} := \text{low}$$

- implementing a timeout with `wait` and the external choice operator

$$\begin{array}{l} \text{normal?} \; ; \; \ldots \\ \square \\ \textbf{wait}\ \text{t} \; ; \; \text{abnormal!()} \end{array}$$

Duration Calculus (DC)

- well suited for (timed) requirements specifications
- example: any complete period with a `high` state must have a duration ℓ of at least δ

$$
\begin{aligned}
\Box((&\lceil \mathsf{sensor\_state} = \mathsf{low} \rceil \bullet \\
&\lceil \mathsf{sensor\_state} = \mathsf{high} \rceil \bullet \\
&\lceil \mathsf{sensor\_state} = \mathsf{low} \rceil) \Rightarrow \ell \geq \delta)
\end{aligned}
$$

RSL, TRSL, and DC used together

1. specify un-timed properties in RSL
2. specify requirements for real-time properties in DC
3. add timing information to RSL, with TRSL extensions
4. verify that the TRSL specification satisfies the DC specification

- satisfaction verification typically through *abstract interpretation*
    - by defining *operational semantics* for TRSL wrt DC

“all things railways”

- timetables (Chapter 3 of Towards a TRain book)
- rolling stock maintenance (Chapter 4)
- rostering (Chapter 5)
- station interlocking (Chapter 6)
- signalling on lines (Chapter 7)
- line direction agreement (Chapter 8)

timetables

- route and timetable information might be published in some machine accessible/readable manner ♠
  - to allow for implementation of services
- suggested: use OWL (Web Ontology Language), a semantic markup language for specifying ontologies
  - "An *ontology* formally represents knowledge as a set of concepts within a domain, and the relationships between those concepts." (Wikipedia)
  - the *Semantic Web* idea/movement: publish information on the web in a structured form
    - to enable complex queries, especially in combination with other information providers
    - application-independence matches Bjørner's thinking ♠
- popular choice: scraping and web service APIs ♠

rolling stock maintenance

- “Rolling stock comprises all the vehicles that move on a railway. It usually includes both powered and unpowered vehicles, for example locomotives, railroad cars, coaches and wagons.” (Wikipedia)
- maintenance: regular checks, cleaning of carriages, refuelling, refilling supplies, etc.
- *maintenance routing*: for types of maintenance not planned in advance for given rolling stock, modify plans to route rolling stock to maintenance stations in a timely manner, according to operating hours elapsed and kilometers travelled and associated limits
    - output: set of changes in rolling stock roster for the next few days (or all possible sets)

rostering

- *staff rostering*: ordering of *duties* (short-term working schedules) into *base rosters* (long-term working schedules), and assignment of specific staff members to rosters
  - hiring decisions can be made based on such staff planning
- based on a suitable formal model, from a given schedule, staff type, depot, and rules, can produce a set of rosters

$$\text{gen\_sross: SCH} \times \text{StfTp} \times \text{Dep} \times \text{eRS} \rightarrow \text{Ros}$$

station interlocking: recall definition for a route

22. A route is a sequence of pairs of units and paths...
23. ...such that the path of a unit/path pair is a possible path of some state of the unit, and such that "neighbouring" connectors are identical.

station interlocking

- routes may (also) be described in terms of units, switches, signals, and interlocking tables
  - "A *signal* is a mechanical or electrical device erected beside a railway line to pass information relating to the state of the line ahead to train/engine drivers." (Wikipedia)
  - "An *interlocking* is an arrangement of signal apparatus that prevents conflicting movements through an arrangement of tracks such as junctions or crossings." (Wikipedia)
  - an *interlocking table*: for all routes of a station, can present valid interlockings (required setting—if any—for each switch and signal) as a table
    - Example [table]

station interlocking: modeling formalism

- capture interlocking requirements as *Petri nets*
  - consist of *places*, *transitions*, and *arcs*; places may contain *tokens*
  - are suitable for modeling and simulating concurrent behavior of distributed systems
  - have nondeterministic execution semantics
- e.g. ensure that a switch can only change state when no route requiring its current state is active
  - by having transitions require a certain number of tokens to fire, and by having open routes keep tokens away from switches

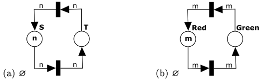


Fig. 6.2. (a) Petri Net for a Switch, (b) Petri Net for a Signal

interlude: Statecharts and Live Sequence Charts

- entities in the charts may be physical phenomena, processes, objects, etc.
- *Statecharts* (SC) are used to describe the sequences of states an entity may pass through in response to external stimuli (internal behavior)
- *Live Sequence Charts* (LSC) are used to specify sequences of communication—i.e. the protocol—between two or more entities (external behavior)
- in combination specify both internal and external behavior

signalling on lines

- high-speed trains cannot stop within a sighting distance of a signal—hence automatic signalling
- might model automatic line signalling as Statecharts (as opposed to Petri nets)
    - states for a line (agreed line direction): `OpenAB`, `OpenBA`, `Close`
    - states for a line *segment*: `segFree`, `segOccupied` (i.e., occupied by a train)
    - signal states: `sigOnRed`, `sigOnGreen`, `sigOnYellow`, `sigOff`

signalling on lines: example Statechart

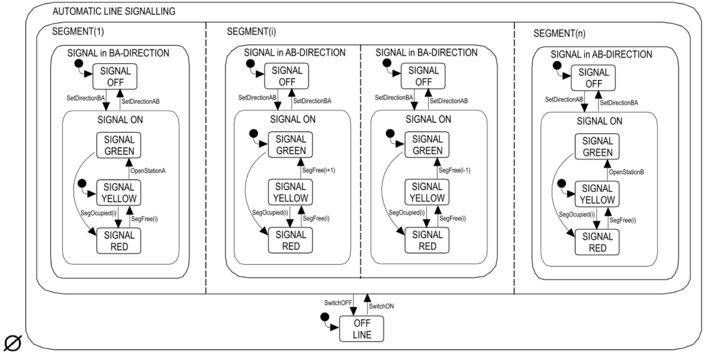


Fig. 7.3. General State Charts for Automatic Line Signalling

line direction agreement

- safety property: two trains are not allowed to move in opposite directions on any railway line
- Line Direction Agreement System (LDAS) for two stations to agree on the direction of trains between them
- the externally visible behavior of an LDAS may be specified using Live Sequence Charts
  - entities: Station A (SA), LDAS, and Station B (SB)

line direction agreement: protocol

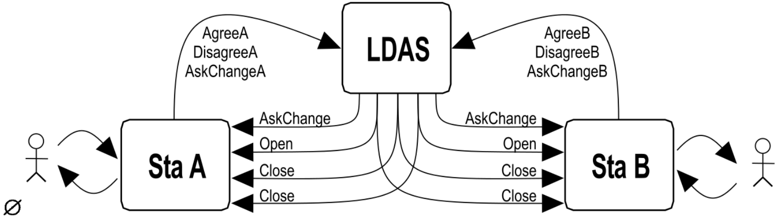
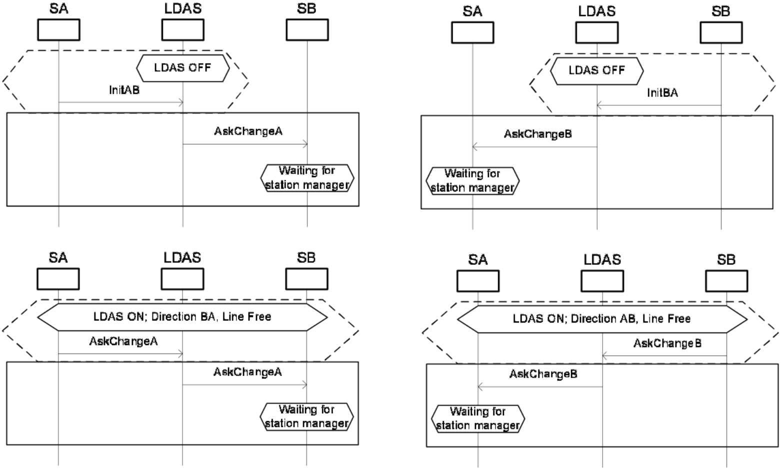


Fig. 8.1. Comunication with LDAS

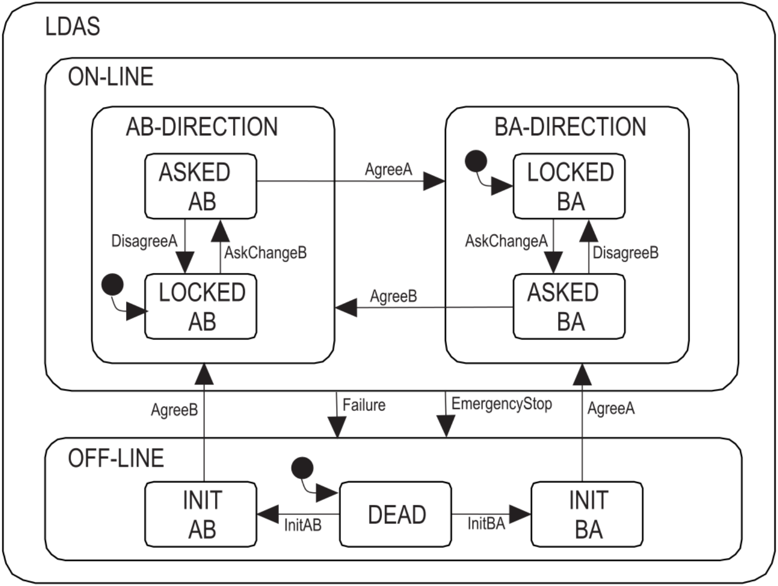
line direction agreement: external behavior

Live Sequence Chart



line direction agreement: internal behavior

Statechart



what can be done with a formal model

- queries
  - e.g., recall the `LS_Connection` function to compute whether a line connects to a station
  - e.g., compute possible changes to the rolling stock roster to meet maintenance requirements
- verification
  - e.g., check interlocking and the LDAS logic for correctness, for safety reasons
- documentation
  - particularly diagrammatic constructs might appeal to readers (Petri Nets, SCs, LSCs, UML diagrams, ...)

further reading

- Univan Ahn and Chris George. C++ Translator for RAISE Specification Language. Technical Report 220, UNU-IIST, P.O. Box 3058, Macau, November 2000.
- George and Haxthausen: The Logic of the RAISE Specification Language.
  - doesn't cover `scheme` syntax or Timed RSL (TRSL)
- He Hua. A Prettyprinter for the RAISE Specification Language. Technical Report 150, UNU-IIST, P.O.Box 3058, Macau, December 1998.