RailCons Railway Infrastructure Verification

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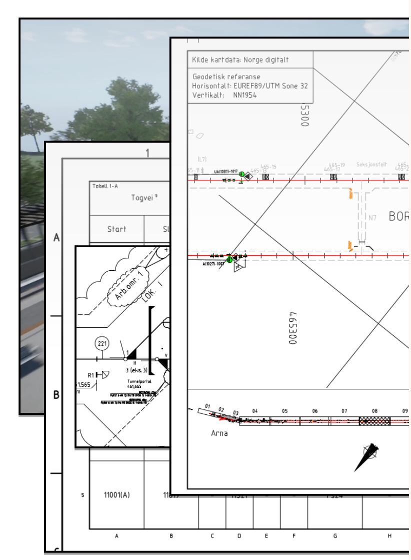
UiO : University of Oslo

RailCOMPLETE

Background: railway engineering

- Costly projects with high quality requirements, complicated regulations.
- Produce a lot of tables, drawings, 3D models, specifications, documentation, etc.
- Evaluation relies on a lot of manual checking of regulations compliance.
- Coordination between disciplines require constant re-evaluation of designs.



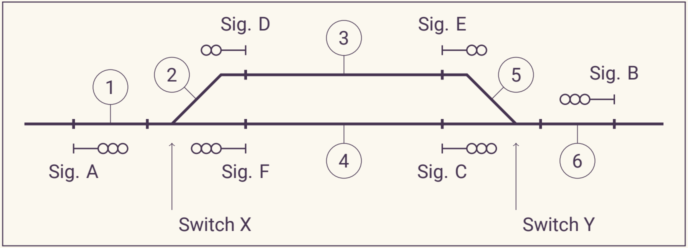
RailCons project: automated verification

Project objectives:

- Verify that railway signalling and interlocking designs comply with regulations.
- Provide tools which allow railway engineers to perform such verification as part of their daily routine ("lightweight verification").
  - Earlier detection of errors avoid costly re-evaluations later.

> "Formal methods will never have a significant impact until they can be used by people that don't understand them."
>
> — (attributed to) Tom Melham

Models: railway signalling and interlocking designs



(a) Track and signalling component layout

Route	Start	End	Sw. pos	Detection sections	Conflicts
AC	A	C	X right	1, 2, 4	AE, BF
AE	A	E	X left	1, 2, 3	AC, BD
BF	B	F	Y left	4, 5, 6	AC, BD
BD	B	D	Y right	3, 5, 6	AE, BF

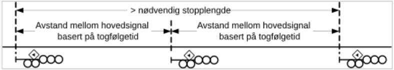
(b) Tabular interlocking specification

Properties: technical regulations

- In our case study: Norwegian regulations from national railways (Bane NOR)
- Static kind of properties, often related to object properties, topology and geometry (example on next slide)

https://trv.jbv.no/wiki/Signal/Prosjektering/Lyssignal

e) Dersom nødvendig stopplengde er lengre enn avstanden mellom to etterfølgende hovedsignal, skal det benyttes gjennomsignalering ved hjelp av ATC (Signal/Prosjektering/ATC), se Figur 7.



Figur 7: Forsignalplassering og gjennomsignalering

f) Et forsignal skal plasseres på foregående hovedsignals mast dersom avstanden mellom det tilhørende hovedsignalet og det foregående hovedsignalet er ≤ 2200 meter.

g) Mellom et forsignal og det tilhørende hovedsignalet skal det ikke plasseres andre hoved- eller forsignal.

h) Et forsignal skal plasseres slik at siktavstanden oppfyller kravene til enten "brutt sikt" eller til "ubrutt sikt" i Tabell 4:

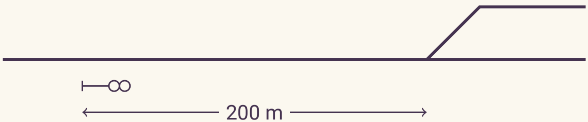
Tabell 4: Siktkrav til forsignal

Sikt	Strekningens høyeste tillatte kjørehastighet [km/h]																		
	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120	125	≥130
	Siktavstand [m]																		
Ubrutt	78	88	97	107	117	126	136	146	156	165	175	185	194	204	214	224	233	243	250

Properties: technical regulations

Example from regulations:

- A *home main signal* shall be placed at least 200 m in front of the first controlled, facing switch in the entry train path.



Datalog

- Basic Datalog: conjunctive queries with fixed-point operators ("SQL with recursion")
  - Guaranteed termination
  - Polynomial running time (in the number of facts)
- Expressed as logic programs in a Prolog-like syntax:

$$a(X, Y) \mathrel{:\!-} b(X, Z), c(Z, Y)$$

$$\Updownarrow$$

$$\forall x, y : ((\exists z : (b(x, z) \wedge c(z, y))) \rightarrow a(x, y))$$

- We also use:
  - Stratified negation (negation-as-failure semantics)
  - Arithmetic (which is "unsafe")

Encoding facts and rules in Datalog

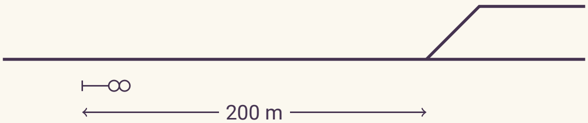
- The process of formalizing the railway data and rules to Datalog format is divided into three stages:
  1. Railway designs (station data) – facts
  2. Derived concepts (used in several rules) – rules
  3. Technical regulations to be verified – rules

Technical regulations as Datalog rules

- Detecting errors in the design corresponds to finding objects involved in a regulation violation
- To *validate* the rules in a given design, we show that there are no satisfiable instances of the *negation* of the rule
- Some examples:
  - Example 1, home signal placement: topological and geometrical layout property for placement of a home signal
  - Example 2, train detector conditions: relates interlocking to topology
- These are Norwegian regulations which are relevant for automatic verification

Rule: example 1

- A *home main signal* shall be placed at least 200 m in front of the first controlled, facing switch in the entry train path.
- Uses arithmetic and negation



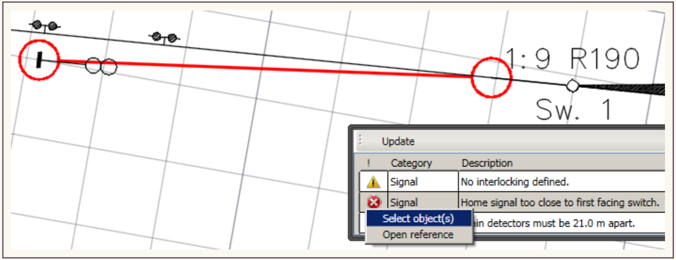
$$\textit{isFirstFacingSwitch}(b, s) \leftarrow \textit{stationBoundary}(b) \wedge \textit{facingSwitch}(s) \wedge$$
$$\neg(\exists x : \textit{facingSwitch}(x) \wedge \textit{between}(b, x, s)),$$

$$\textit{ruleViolation}(b, s) \leftarrow \textit{isFirstFacingSwitch}(b, s) \wedge$$
$$(\neg(\exists x : \textit{signalFunction}(x, \text{home}) \wedge \textit{between}(b, x, s)) \vee$$
$$(\exists x, d, l : \textit{signalFunction}(x, \text{home}) \wedge$$
$$\wedge\, \textit{distance}(x, s, d, l) \wedge l < 200).$$

Datalog verification tool

- Prototype using XSB Prolog tabled predicates, front-end is the RailCOMPLETE tool based on Autodesk AutoCAD
- Rule base in Prolog syntax with structured comments giving information about rules

```
%| rule: Home signal too close to first facing switch.
%| type: technical
%| severity: error
homeSignalBeforeFacingSwitchError(S,SW) :-
    firstFacingSwitch(B,SW,DIR),
    homeSignalBetween(S,B,SW),
    distance(S,SW,DIR,L), L < 200.
```



Challenge: participatory verification

Challenge: Users (railway engineers) are not experts in verification techniques, so how can they

- build models of the systems to be verified?
- write properties in the verifier's input language?
- interpret the output of the verifier when violated properties are found?

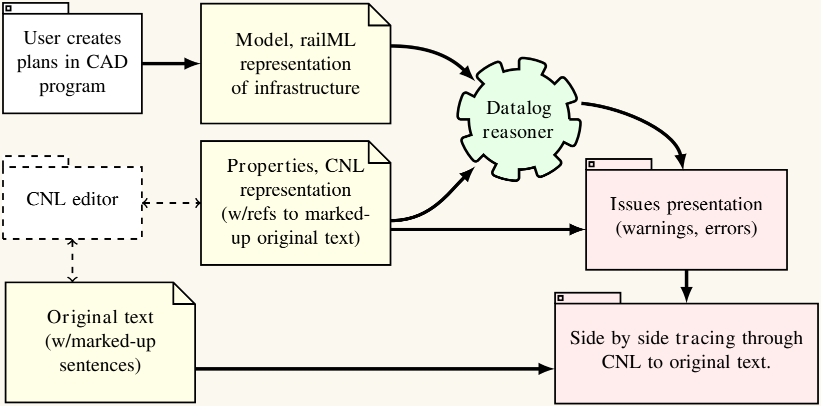
Input to verification:

- Models: CAD extended with structured railway data (familiar to engineers, user-friendly)
- Properties: Datalog (unfamiliar to engineers, not user-friendly enough)

... consider another verification property input language?

CNL: Overview of approach

- Define a Controlled Natural Language as a high-level domain-specific language to write properties.
- Represent properties as rephrasing of natural language specifications (adds tracability of requirements)



RailCNL language design: graph module

For writing statements about the topology and geometry of objects' placement wrt. to railway tracks.

Example 2 (Parse tree for a railway layout statement.)

CNL: *Distance from an entry signal to first facing switch must be greater than 200.0 m.*

AST:
```
DistanceRestriction Obligation
    (SubjectClass (StringClassAdjective "entry"
      (StringClass "signal")))
    (FirstFound FacingSwitch)
    (Gt (MkValue (StringTerm "200.0m")))
```

Tooling

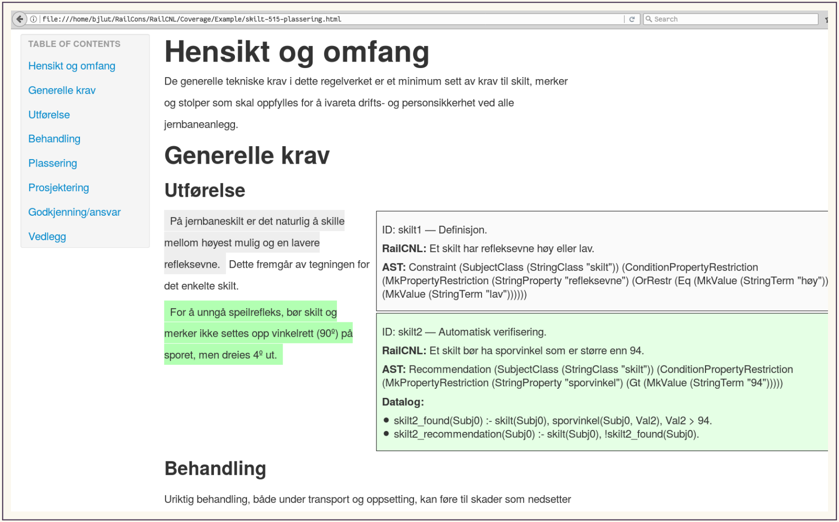
- The quality of the tool support influences the success of a domain-specific language for non-IT-experts. Textual input is a part of the overall user interface design.

Tool support for RailCNL:

- Paraphrasing view – present originals and CNL paraphrases side-by-side.
- Issues view – present verification errors in the CAD tool with links to the paraphrasing view.
- Editor – Text editor with support for writing (correct) CNL phrases.

Side-by-side CNL/original (paraphrasing view)

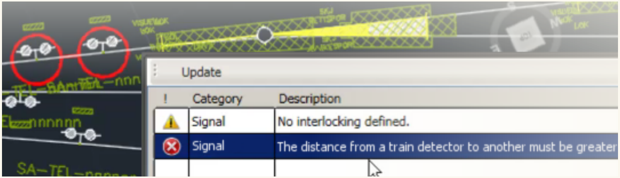
- Requirements tracing



Issues view

- Backwards tracing – explanation of non-compliance

CAD program showing issues in layout plan



↕

CNL debug view paraphrased text and translations

ID: detector_1

RailCNL: The distance from an axle counter to another must be larger than 21.0m.

AST: DistanceRestriction Obligation (SubjectClass (StringClassNoAdjective (String "axle_counter"))) (AnyFound (AnyDirectionObject SubjectOtherImplied)) (Gt (MkVal

Datalog: detector_1_start(Subj0, End, Dist) :- trainDetector(Subj0), next(Subj0, End

↕

Original text highlighting source of paraphrased text

Placement and length

This section gives generalized rules for placement and length for train detection systems and its relationship to other infrastructure components. Detailed requirements are given in appendices.

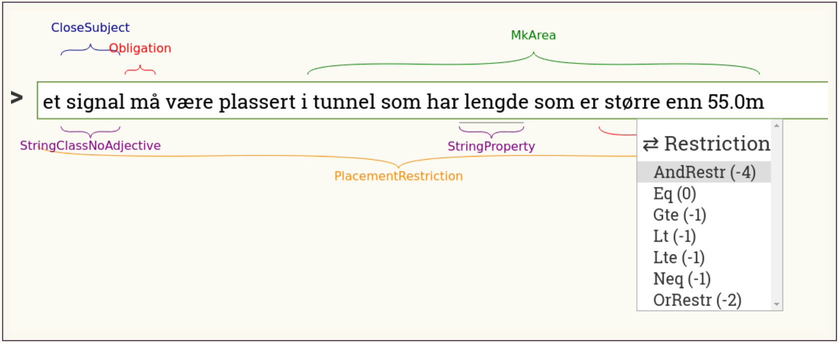
General

a) No detection sections shall be shorter than 21 meters.

b) No dead zone shall be longer than 3 meters.

Text editor CNL support

- Rule authoring tool – syntax checks, predictive parsing, chunked parsing, language exploration



Advantages

RailCNL as a front-end for property input for verification:

- RailCNL is domain-specific: tailored to Datalog logic and regulations terminology. Gives readability and maintainability.
- Resembles natural language – improves readability and engineer participation.
- Separate textual explanation (such as comments used in programming) are typically not needed.
- RailCNL statements are linked the original text. so that reading them side by side reveals to domain experts whether the CNL paraphrasing of the natural text is valid. If not, they can edit the CNL text.

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Some common general interests:

- railways,
- regulations compliance,
- design tradeoffs,
- techniques similar to (static/dynamic) program analysis.

Specific goal: documented compliance

Further challenges and future work

Participatory verification:

- RailCNL is a common language shared between programmers and railway engineers for verification work.
- CNLs are not a magical solution to end-user programming.
- DSLs evolve along-side the application.

Language:

- Structures in regulations that span several phrases/rules (scopes, exceptions) – represent on textual or GUI level?
- Macros – can users extend the language within the scope of their texts?

Tool support:

- Can railway engineers from other disciplines create their properties themselves, from scratch, with editor support?
- Is example-based and editor-supported language learning good enough?

Coverage

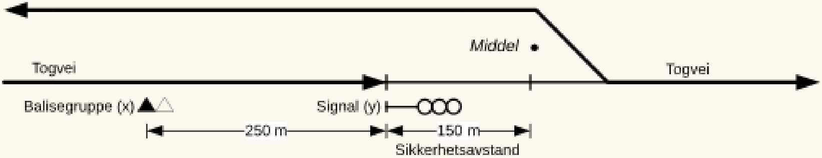
Classification for coverage analysis:

- Not relevant for verification, examples:
  Non-normative: *the technical qualities of the track construction ensure safe and efficient traffic, with the least possible environmental impact.*
  Non-checkable: *the tracks' construction must take into account the topography, soil, hydrology, climate, etc. of the location.*

- Out of scope for static analysis, examples:
  Construction: *Signs must have their original wrapping during transportation.*
  Operation: *A signal which cannot signal "stop" because of fault must be unlit.*

Coverage

- Not covered:
  - exceptions (awkward to write out all premises)
  - linguistically complex: *The safety zone (overlap) can be reduced to 200 m if the speed control system is designed such that the velocity at balise group (x) is not higher than 40 km/h when the signal (y) shows a "stop" aspect, and rolling stock will stop before the fouling point even when speed control communcation has failed in both the balise group and in the main signal.*



- Covered:
  - ontology, graph, areas, interlocking (targets), ...

Coverage statistics

Eng. discipline	**Chapter title**	Phrases	Normative	Relevant	Covered	**Coverage**
Track	Planning: general technical	140	74	74	70	95%
Track	Planning: geometry	278	157	152	119	78%
Signalling	Planning: detectors	144	106	35	21	60%
Signalling	Planning: interlocking	376	265	130	81	62%
Total		938	602	391	291	**74%**

Table 1: Coverage evaluation for a subset of Norwegian regulations. *Phrases* of the original text which could be classified as *normative* (i.e. applying some restriction on design) were evaluated for *relevance* to static infrastructure verification. The *coverage* is the percentage of relevant phrases expressible in RailCNL.

Participatory verification: experience from meetings between programmers and railway engineers

Positive:

- invites engineers to splitting hairs
  - discuss semantics of natural language
  - leads to discussion of interpretation of regulations
- example-based learning
  - explain and explore language with the editor
  - change names and values / copy-paste coding

Negative:

- total understanding of language is infeasible
  - extend language: ask for examples, not grammar

Datalog verification

- Datalog with negation (n.-as-failure) and arithmetic, implemented in e.g. XSB Prolog, RDFox, Soufflé.
- Prefer very fast (< 100 msec) re-evaluation integrated into CAD tool.
- Incremental Datalog approaches can exploit locality.

Railway construction process

1. Politicians allocate funds for new railways, upgrades or maintenance.

2. National railway administration define high level requirements, such as passenger/freight capacities, travel times, maintainability, etc.

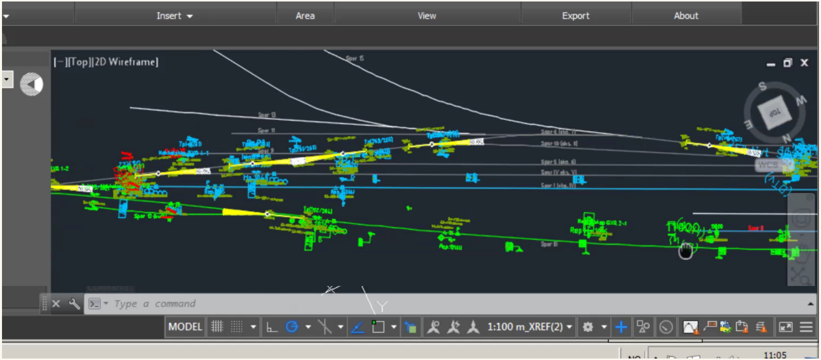
3. **Engineering companies work out the detailed plans and specifications of the upcoming construction project.**

4. Construction/implementation companies build the railway and implement control systems.

5. Finally, train companies can transport passengers and goods.

CAD programs in railway signalling

- Overview of a station, typically showing tracks and signalling system components (signals, signs, balises)



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- We also use:
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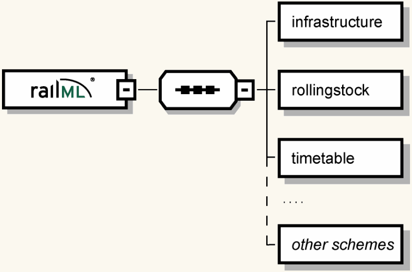
The railML XML standard data exchange format

- Thoroughly modelled infrastructure schema
- XML schema development by international standard committee



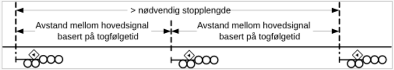

```
<tracks>
  <track id="tr0" name="01">
    <trackTopology>
      <trackBegin id="x399" pos="0.000000" absPos="34
        <connection id="co399" ref="co397"/>
      </trackBegin>
      <trackEnd id="y151" pos="80.000000" absPos="346
        <connection id="co151_2" ref="co151_1"/>
      </trackEnd>
    </trackTopology>
    <trackElements>
      <speedChanges>
        <speedChange id="spu399" pos="0.000000" absPo
        <speedChange id="spd403" pos="30.000000" absP
        <speedChange id="spu405" pos="30.000000" absP
        <speedChange id="spd151" pos="80.000000" absP
      </speedChanges>
      <gradientChanges>
        <gradientChange id="gr399" pos="0.000000" abs
      </gradientChanges>
      <radiusChanges>
        <radiusChange id="ra399" pos="0.000000" absPo
      </radiusChanges>
      <platformEdges>
        <platformEdge id="pe399" pos="0.000000" absPo
      </platformEdges>
    </trackElements>
    <ocsElements>
      <signals>
        <signal id="si399" pos="0.000000" absPos="346
" code="6"/>
```

Technical regulations

- In our case study: Norwegian regulations from infrastructure manager Jernbaneverket
- Static kind of properties, often related to object properties, topology and geometry (examples later)

https://trv.jbv.no/wiki/Signal/Prosjektering/Lyssignal

e) Dersom nødvendig stopplengde er lengre enn avstanden mellom to etterfølgende hovedsignal, skal det benyttes gjennomsignalering ved hjelp av ATC (Signal/Prosjektering/ATC), se Figur 7.



Figur 7: Forsignalplassering og gjennomsignalering

f) Et forsignal skal plasseres på foregående hovedsignals mast dersom avstanden mellom det tilhørende hovedsignalet og det foregående hovedsignalet er ≤ 2200 meter.

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Tabell 4: Siktkrav til forsignal

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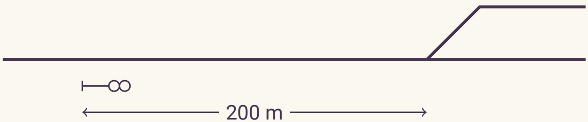
Technical regulations

Example from regulations:

- A *home main signal* shall be placed at least 200 m in front of the first controlled, facing switch in the entry train path.



- Can be classified as follows:
  - Object properties
  - Topological layout properties
  - Geometrical layout properties
  - Interlocking properties

Formalization of rule checking

- Formalize the following information
  - The CAD design (extensional information, or facts)
  - The regulations (intensional information, or rules)
- Use a solver which:
  - Is capable of verifying the rules
  - Runs fast enough for on-the-fly verification

Input documents representation

- Translate the railML XML format into Datalog facts using the ID attribute as key:

$$
\begin{aligned}
\textit{track}(a) &\leftarrow \text{element}_a \text{ is of type } \texttt{track},\\
\textit{signal}(a) &\leftarrow \text{element}_a \text{ is of type } \texttt{signal},\\
&\vdots\\
\textit{pos}(a,p) &\leftarrow (\text{element}_a.\texttt{pos} = p), \quad a \in \text{Atoms}, p \in \mathbb{R},\\
&\vdots\\
\textit{signalType}(a,t) &\leftarrow (\text{element}_a.\texttt{type} = t),\\
& t \in \{\text{main, distant, shunting, combined}\}\,.
\end{aligned}
$$

Derived concepts

- Derived concepts are defined through intermediate rules
- Railway concepts defined independently of the design
- Example:

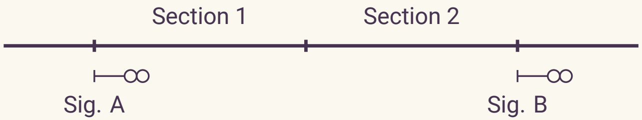
$$\mathit{directlyConnected}(a,b) \leftarrow \exists t : \mathit{track}(t) \wedge \mathit{belongsTo}(a,t) \wedge \mathit{belongsTo}(b,t),$$

$$\begin{aligned}\mathit{connected}(a,b) \leftarrow {} & \mathit{directlyConnected}(a,b) \vee (\exists c_1, c_2 : \mathit{connection}(c_1,c_2) \wedge \\ & \mathit{directlyConnected}(a,c_1) \wedge \mathit{connected}(c_2,b)).\end{aligned}$$

- A library of concepts allows concise expression of technical regulations

Rule: example 2

- Each pair of adjacent train detectors defines a track detection section. For any track detection sections overlapping the route path, there shall exist a corresponding condition on the activation of the route.



Tabular interlocking:

Route	Start	End	Sections must be clear
AB	A	B	1, 2

Rule: example 2

$$\textit{adjacentDetectors}(a, b) \leftarrow \textit{trainDetector}(a) \wedge \textit{trainDetector}(b) \wedge \neg \textit{existsPathWithDetector}(a, b),$$

$$\textit{detectionSectionOverlapsRoute}(r, d_a, d_b) \leftarrow \textit{trainRoute}(r) \wedge \textit{start}(r, s_a) \wedge \textit{end}(r, s_b) \wedge \textit{adjacentDetectors}(d_a, d_b) \wedge \textit{overlap}(s_a, s_b, d_a, d_b),$$

$$\textit{detectionSectionCondition}(r, d_a, d_b) \leftarrow \textit{detectionSectionCondition}(c) \wedge \textit{belongsTo}(c, r) \wedge \textit{belongsTo}(d_a, c) \wedge \textit{belongsTo}(d_b, c).$$

$$\textit{ruleViolation}(r, d_a, d_b) \leftarrow \textit{detectionSectionOverlapsRoute}(r, d_a, d_b) \wedge \neg \textit{detectionSectionCondition}(r, d_a, d_b).$$

Prototype tool implementation

- Prototype using XSB Prolog tabled predicates, front-end is the RailCOMPLETE tool based on Autodesk AutoCAD
- Rule base in Prolog syntax with structured comments giving information about rules

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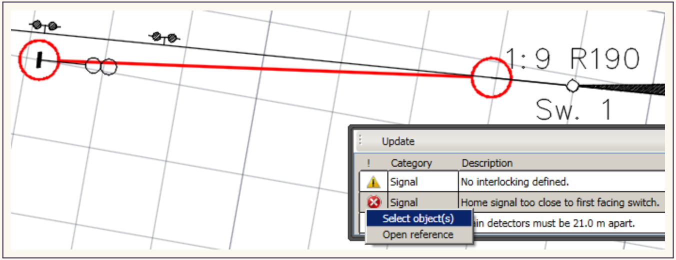


REMU project – Chalmers/GU Gothenburg

REMU project: Reliable Multilingual Digital Communication –

- Goals (among others): grammar development, testing, analysis.
- Tools: Grammatical Framework – Programming language for multilingual grammar applications.

- Controlled natural language
  Controlled natural languages (CNLs) are subsets of natural languages that are obtained by restricting the grammar and vocabulary in order to reduce or eliminate ambiguity and complexity.

Grammatical Framework

Define domain model in an abstract syntax, define one or more mappings to text in a concrete syntax.

Abstract syntax:

- Domain-specific tree data structure for representing the desired content.

```
abstract ToyRailway = {
  cat Subject; Length; Restriction; Statement;
  fun Signal, Switch, Detector : Subject;
      LengthMeters : Int -> Length;
      GreaterThan, LessThan : Length -> Restriction;
      ObjectSpacing : Subject -> Subject -> Restriction
                    -> Statement; }
```

- Example phrase in abstract syntax:

```
ObjectSpacing Signal Switch (GreaterThan (LengthMeters 20))
```

Grammatical Framework

Concrete syntax:

- A mapping from the abstract syntax to text.
- Invertible, so a GF concrete syntax gives you a parser and a linearization (generator).

```
concrete ToyRailwayEng of ToyRailway = {
  lincat Subject = Str; Length = Str; (...)
  lin Signal = "signal"; (...)
      LengthMeters i = i ++ "m"
      GreaterThan l = "more than" ++ l
      ObjectSpacing o1 o2 r =
          "a" ++ o1 ++ "must be" ++ r
          ++ "from a" ++ o2; }
```

- Parse: “`a signal must be more than 20 m from a switch`”

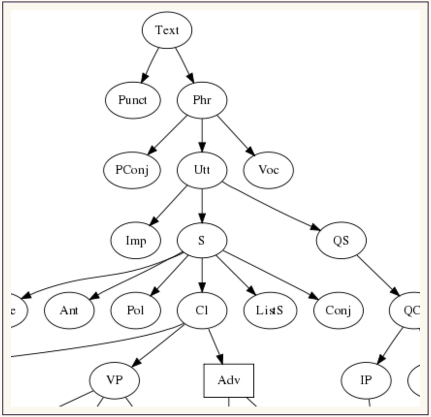
```
ObjectSpacing Signal Switch (GreaterThan (LengthMeters 20))
```

- Complexity and constraints of natural language quickly becomes infeasible to handle when the language grows...

Grammatical Framework's Resource Grammars

Comprehensive linguistic model of natural languages with a unified API for forming sentences.

- Parse/generate in 31 languages using a unified API.
- Ensures grammatical correctness of phrases using the type system.



API usage example:

```
OrientationAngleTo vec =
        mkCN (mkCN angle_N)
             (mkAdv to_Prep (mkNP the_Det vec));
```

Related work

Domain-specific languages for railway verification:

- Verification of implementation of railway control systems (Vu, Haxthausen, Peleska, 2014). Concise verification properties.
- Verification of railway layouts (James, Roggenbach, 2014). Focus on integrating domain modeling (UML) with verification, focus on control systems and fixed designs.

Controlled natural languages – formally defined restricted subsets of natural language – used for:

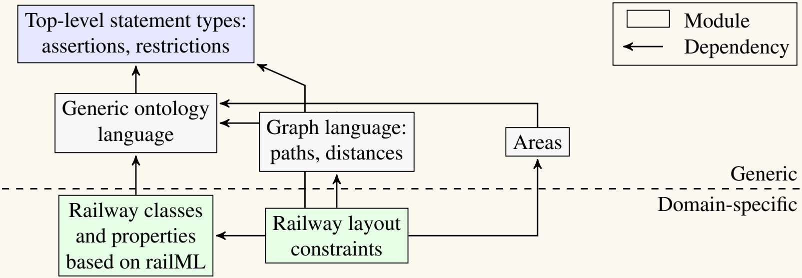
- Object Constraint Langauge, KeY reasoning about Java programs (Johannisson, 2007).
- Contract language $\mathcal{CL}$ (Prisacariu, Schneider, 2012) mapped into natural language and also diagrams (Camilleri, Paganelli, Schneider, 2014).
- Database queries for tax fraud detection (Calafato, Colombo, Pace, 2016).

RailCNL: Language design

Top-level statements:

- Constraint: logical constraints, typically used by a Datalog reasoner to infer new facts.
- Obligation: design requirement, CAD model is checked for compliance.
- Recommendation: design heuristics, CAD model checked, but violations are shown as warnings, can be dismissed.

Modules:



RailCNL language design: ontology module

Statements about classes of objects and their properties and relations form a basis for for knowledge representation.

- Class names: "*signal*", "*switch*", ...
- Properties and values: "*color*", "*red*", "*200.0m*", ...
- Restrictions: Equality: "*A signal must have height 4.5m*".
- Relations name and multiplicity. "*A distant signal should have one or more associated signals.*"

Example 1 (Parse tree for an obligation statement.)

CNL: *A vertical segment must have length greater than 20.0m.*

AST:

```
OntologyRestriction Obligation
   (SubjectClass (StringClassAdjective "vertical"
       (StringClass "segment")))
   (ConditionPropertyRestriction (MkPropertyRestriction
       (StringProperty "length")
       (Gt (MkValue (StringTerm "20.0m")))))
```