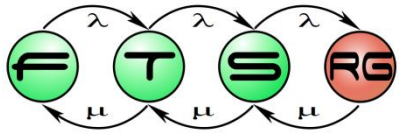
Model Queries

General Concepts
Graph Patterns
Incrementality
VIATRA QUERY

Model Driven Systems Development
Lecture 04

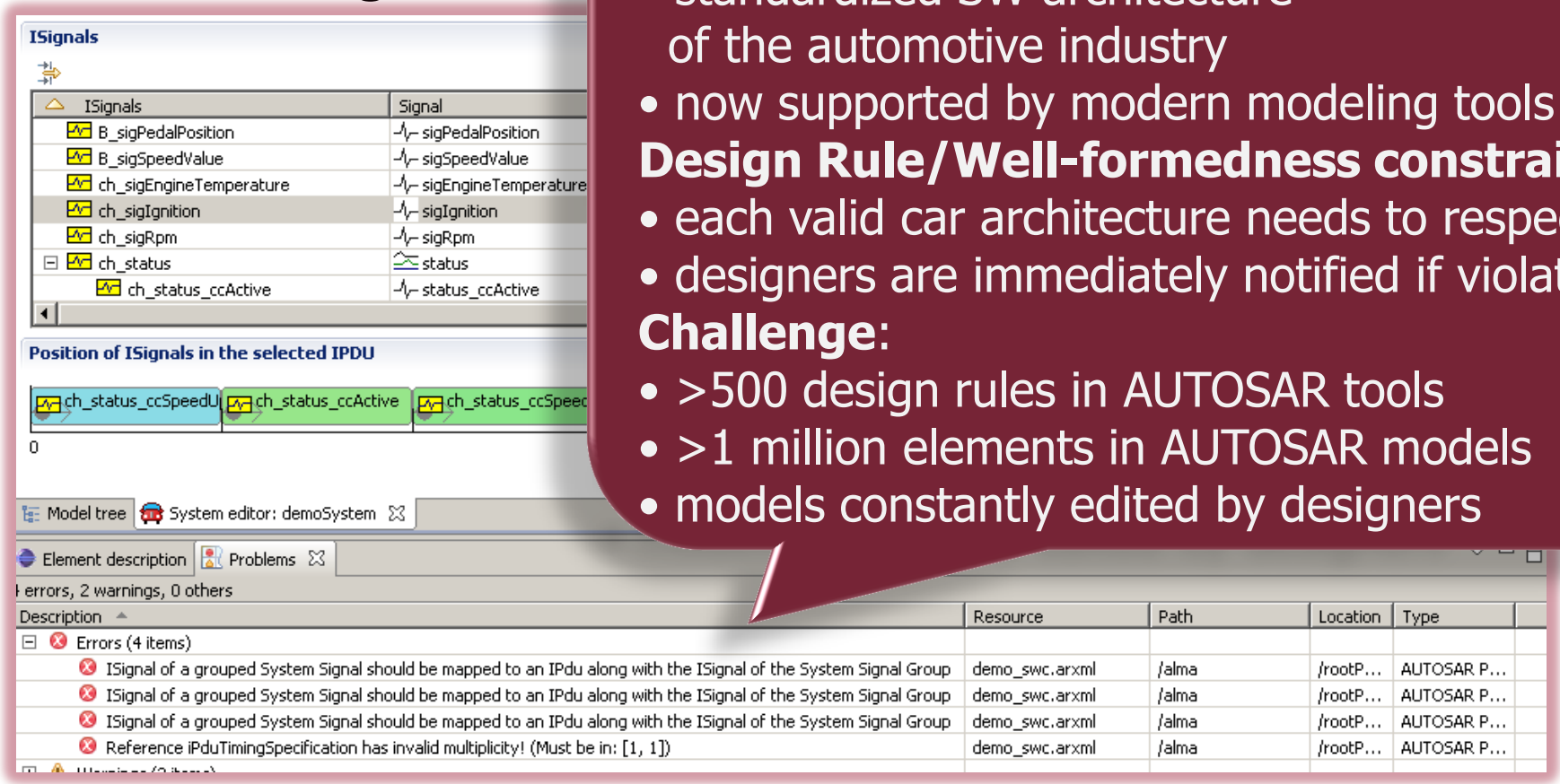


MOTIVATION

Motivation: early validation of design rules

SystemSignalGroup design rule (from AUTOSAR)

- A *SystemSignal* an
- Challenge: find v



AUTOSAR:

- standardized SW architecture of the automotive industry
- now supported by modern modeling tools

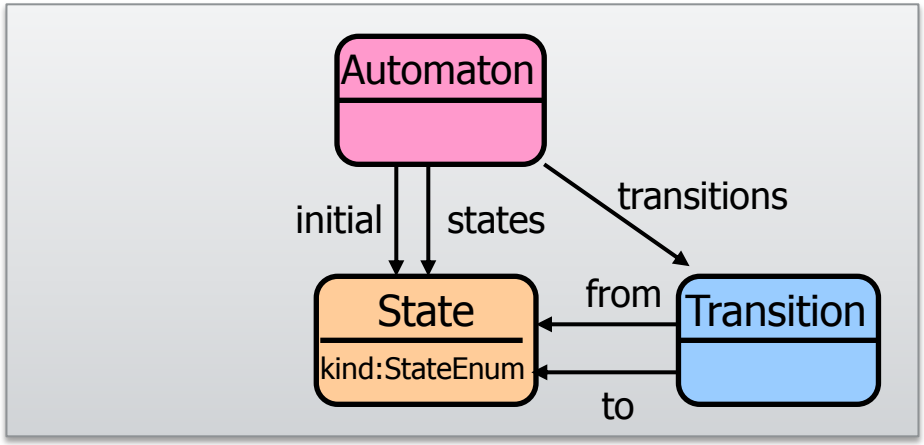
Design Rule/Well-formedness constraint:

- each valid car architecture needs to respect
- designers are immediately notified if violated

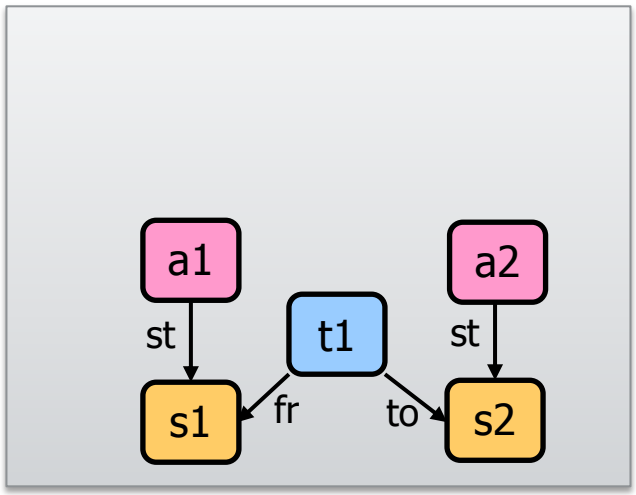
Challenge:

- >500 design rules in AUTOSAR tools
- >1 million elements in AUTOSAR models
- models constantly edited by designers

A simple example



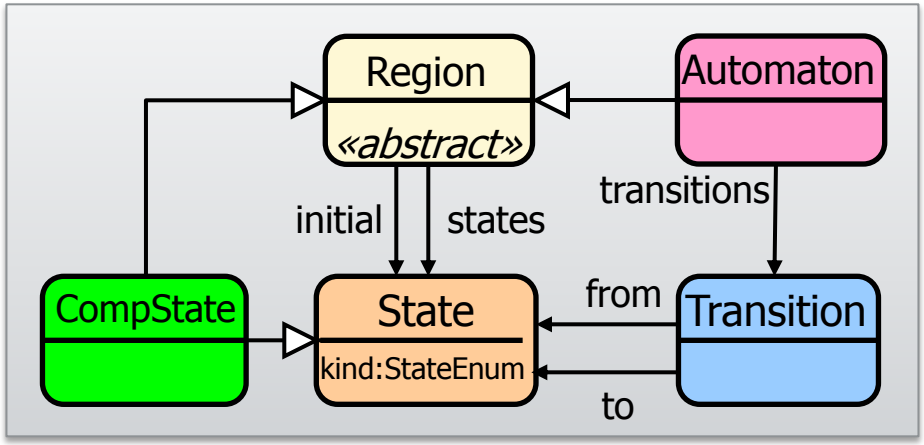
Metamodel



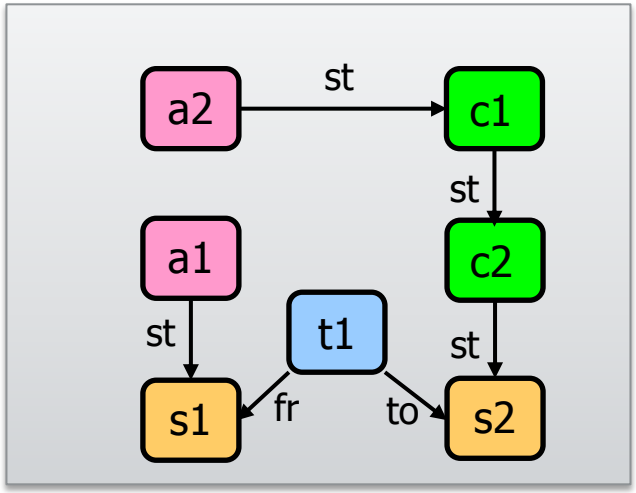
Violation example

- Well-formedness constraint:
  - Transition source & target states must be owned by same automaton
- Goal: to find violations...
  - A violation is a *Transition*, whose „*from*” link points to a *State x*, and „*to*” link points to a *State y*, where the automaton of *x* is not the automaton of *y*
  - How to check this?

A more complex example



Metamodel

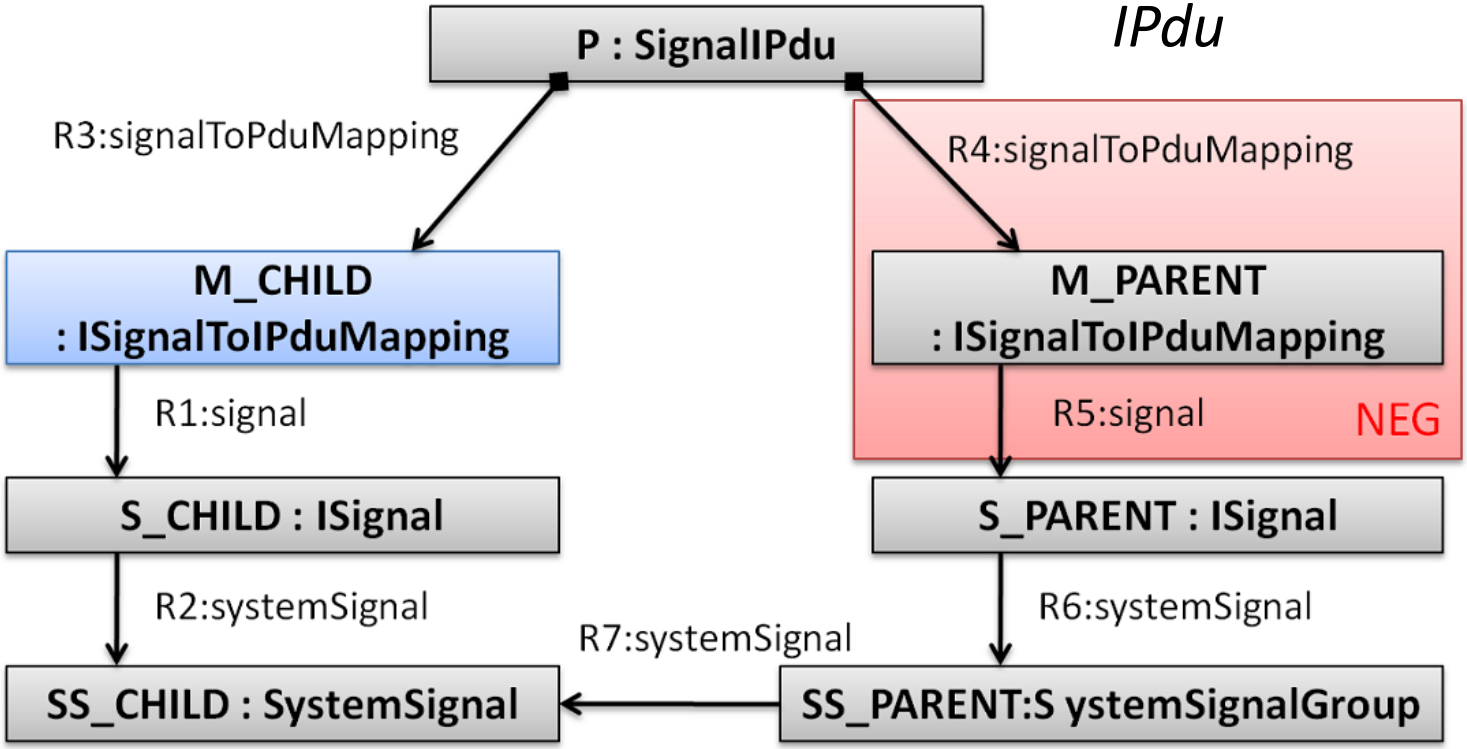


Violation example

- Well-formedness constraint:
  - Transition source & target states must be owned by regions belonging to same automaton
- Goal: to find violations...
  - A violation is a *Transition*, whose „*from*” link points to a *State x*, and „*to*” link points to a *State y,* where...
  - How to check this?

Another complex example

- Well-formedness constraint:
  - A *SystemSignal* and its group must be in the same *IPdu*



Programmatic traversal vs. queries

- Goal: find constraint violations in model
  - Traverse model in general-purpose language

```
for (Automaton automaton : automatons) {
  for (Transition transition : automaton.getTransitions()) {
    State sourceState = transition.from;
    // which automaton defines this state?
    Automaton sourceAutomaton = null;
    for (Automaton candidate : automatons) {
      if (candidate.getStates().contains(sourceState)) {
        sourceAutomaton = candidate;
        break;
      }
    }
    // ... do the same for targetState, then
    if (sourceAutomaton != targetAutomaton)
      // report violation
  }
}
```

„simple example”

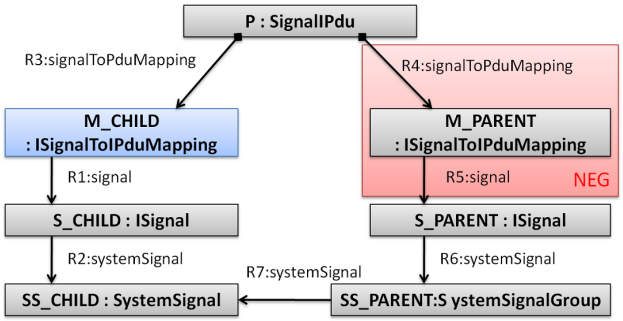
(though much simpler when bidirectional navigation is available)

Programmatic traversal vs. queries

- Goal: find constraint violations in model
  - Traverse model in general-purpose language
  - Use a **Query DSL**
    - More concise
    - **Declarative** functional specification of the query
    - Freely interpreted by **query engine** (e.g. optimization)
    - Can be platform-independent
- Validation is just one use cases for **model queries**
  - Derived features
  - M2M/M2T Transformation, Simulation
  - …

Query Language Styles

- SQL-like (relational algebra)
  - Example: EMF Query
  - ☺ Good for attribute restrictions
  - ☹ Not very concise for relationships (many joins)

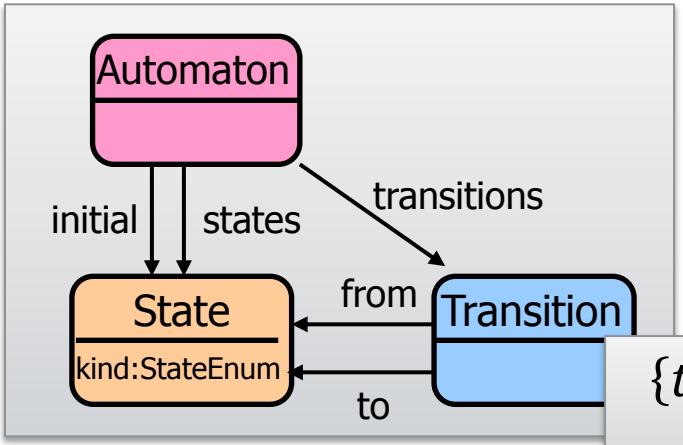


- Functional style
  - Example: OCL
  - Not very declarative

```
context Transition inv:
  Automaton.allInstances()->forAll(a |
    a.states->includes(self.from) =
    a.states->includes(self.to)
  );
```

- Logic style
  - Domain relational calculus / graph patterns / Datalog
  - Even more declarative

Model Query as Logic



Metamodel

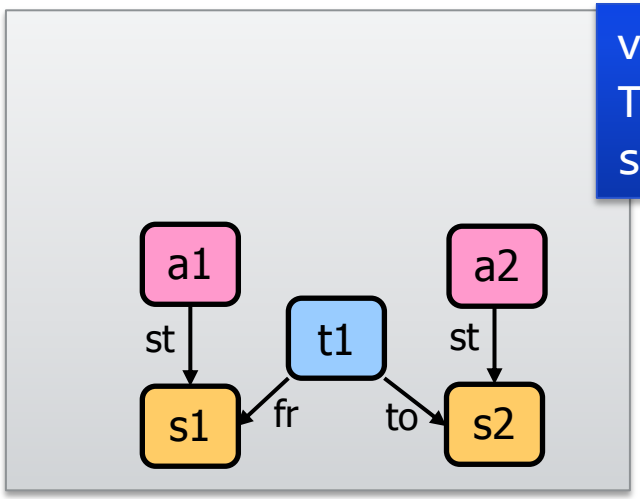
A violation is a *Transition*,
whose „*from*” link points to a *State x*
and „*to*” link points to a *State y*,
where the automaton of *x*
is not the automaton of *y*

in formal logic (Domain Relational Calculus)

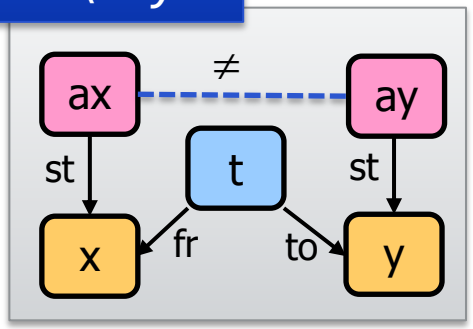
$$\{t \mid Transition(t) \wedge \exists x, y, ax, ay: from(t,x) \wedge to(t,y) \wedge states(ax,x) \wedge states(ay,y) \wedge ax \neq ay\}$$

Datalog-like query languages

```
violates(t):-
Transition(t),from(t,x),to(t,y),
states(ax,x),states(ay,y),ax=\=ay
```



Violation example



Graph pattern

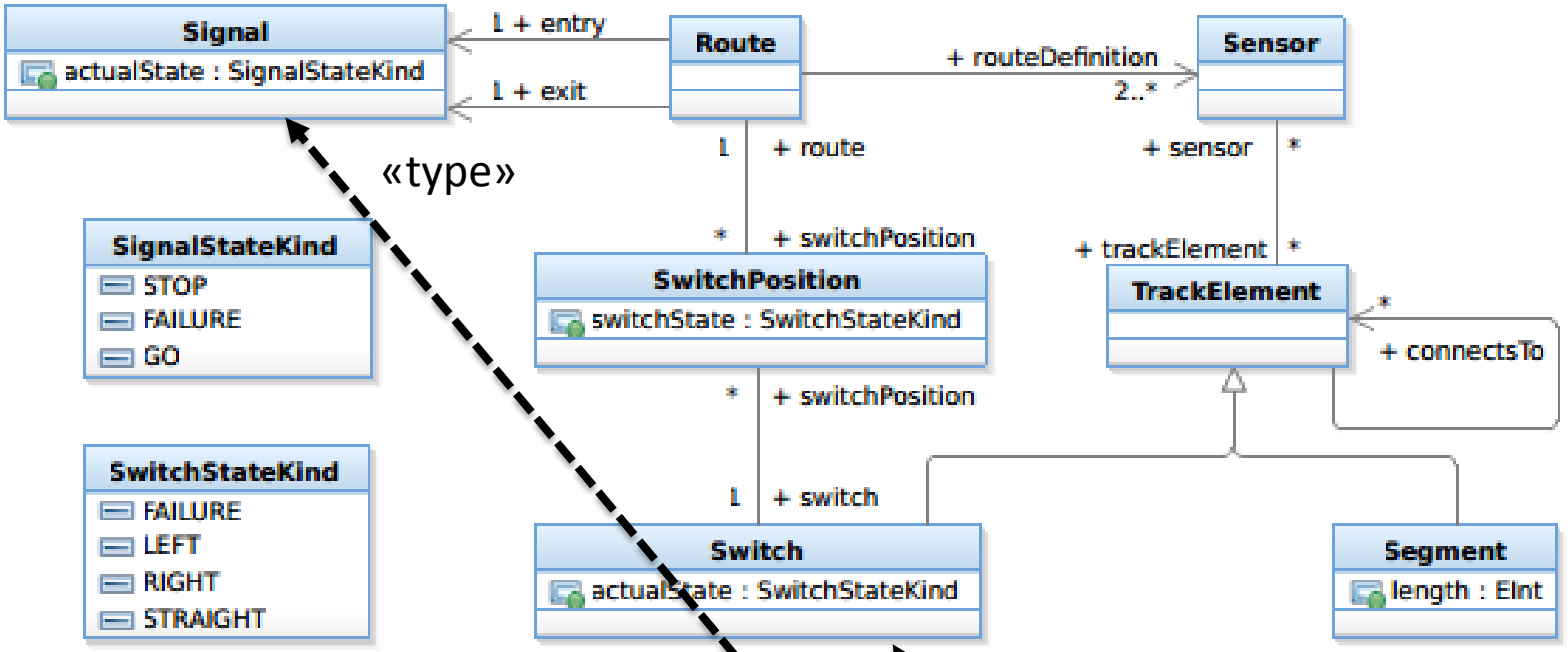
MODEL QUERIES AND GRAPH PATTERN MATCHING

What is a model query?

- For a programmer:
  - A piece of code that searches for parts of the model
- For the scientist:
  - **Query** = set of constraints that have to be satisfied by (parts of) the (graph) model
  - **Result** = set of model element tuples that satisfy the constraints of the query
  - **Match** = bind constraint variables to model elements
- A query engine: Support
  - the definition&execution of model queries

Query(A,B) ← $\wedge \text{cond}_i(A_i,B_i)$
- all tuples of model elements *a,b*
- satisfying the query condition
- along the match *A=a* and *B=b*
- parameters A,B can be input/ output

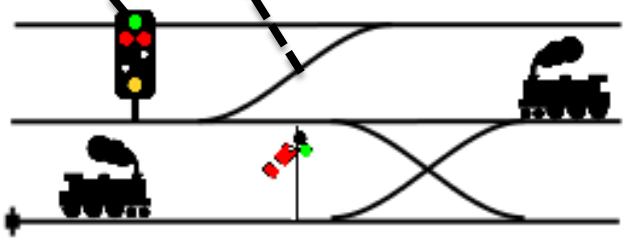
Motivating example



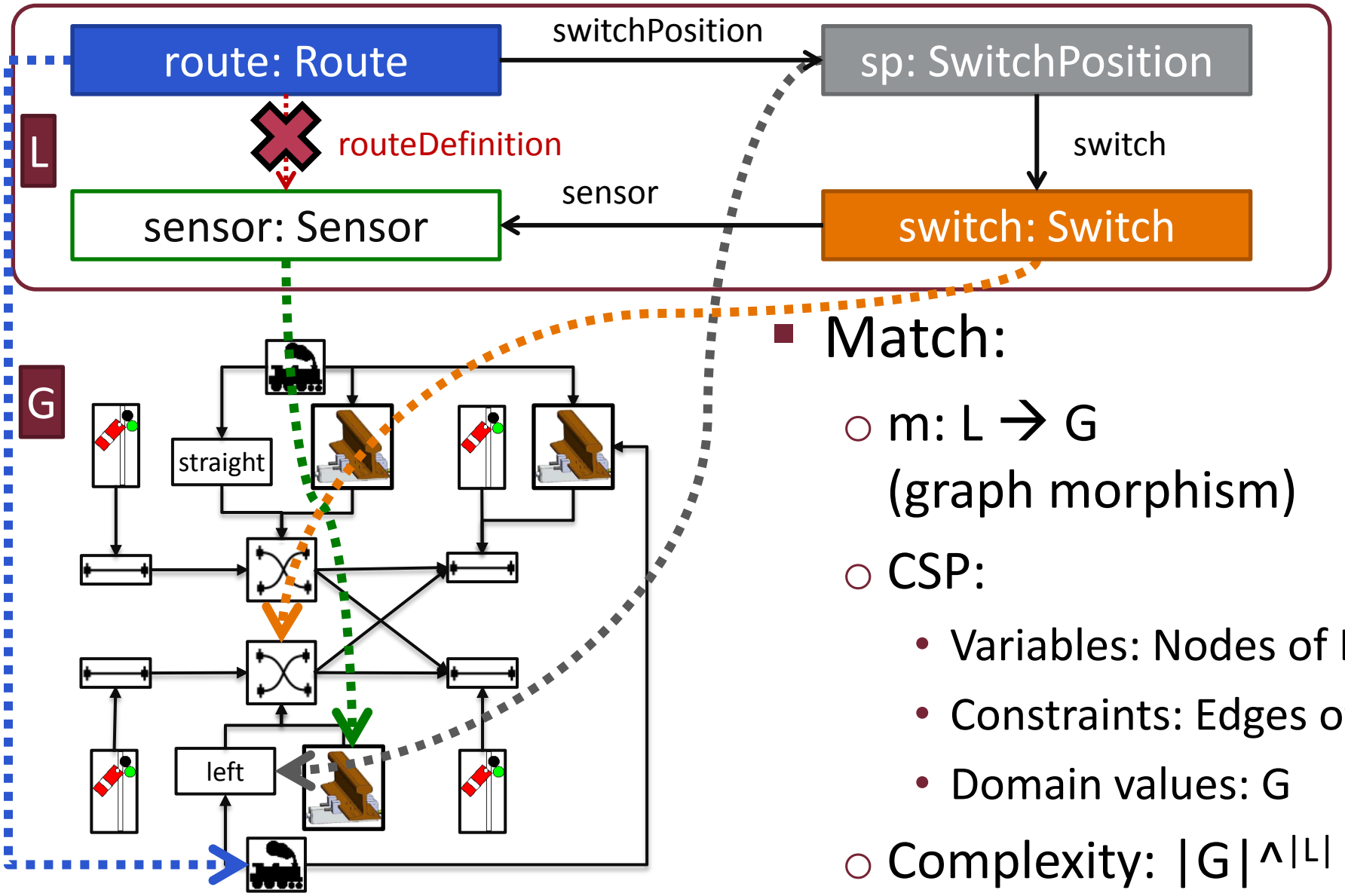
Meta-model

Model

Abstract



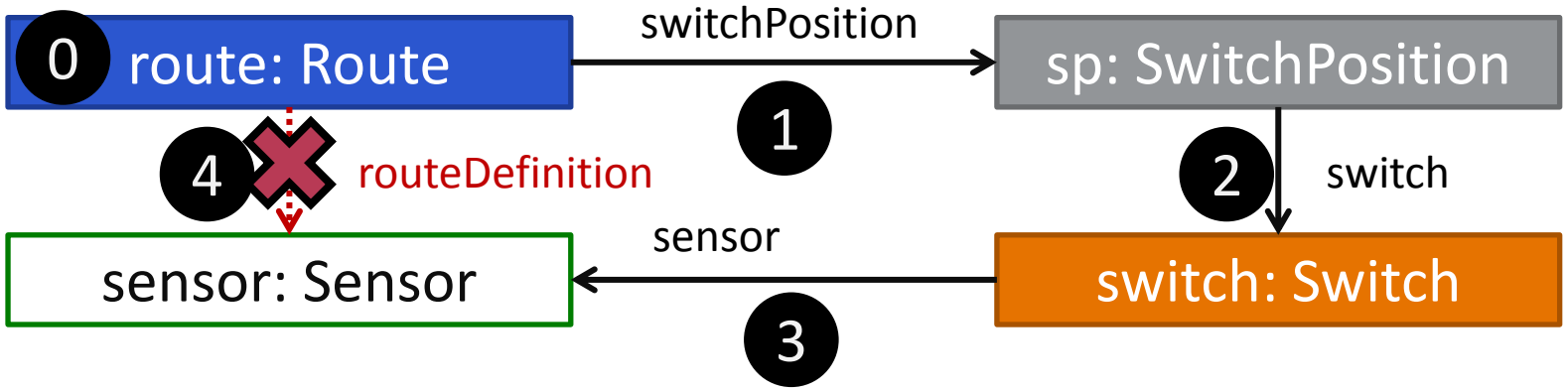
Graph Pattern Matching for Queries

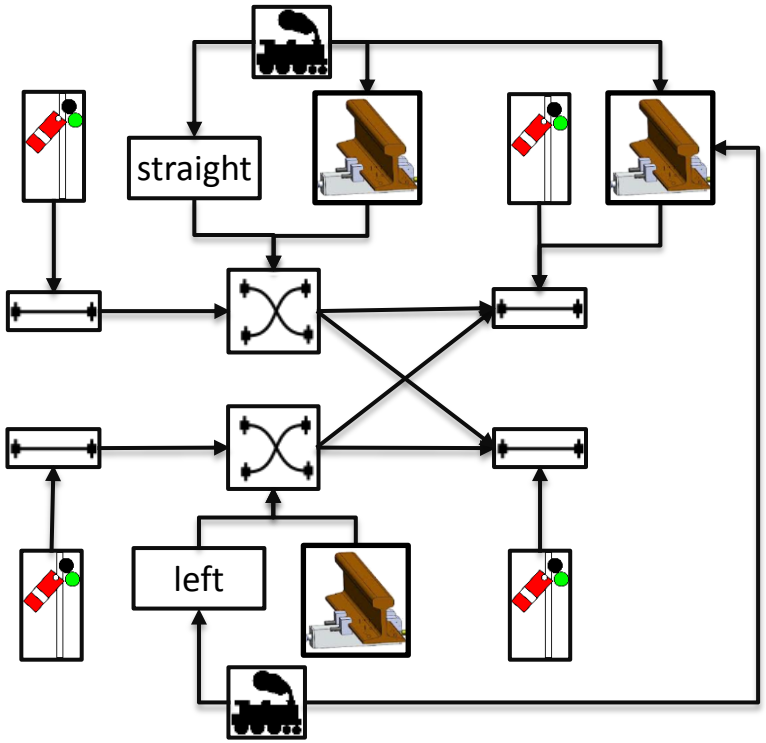


- Match:
  - m: L → G (graph morphism)
  - CSP:
    - Variables: Nodes of L
    - Constraints: Edges of L
    - Domain values: G
  - Complexity: $|G|^{|L|}$

All sensors with a switch that belongs to a route must directly be linked to the same route.

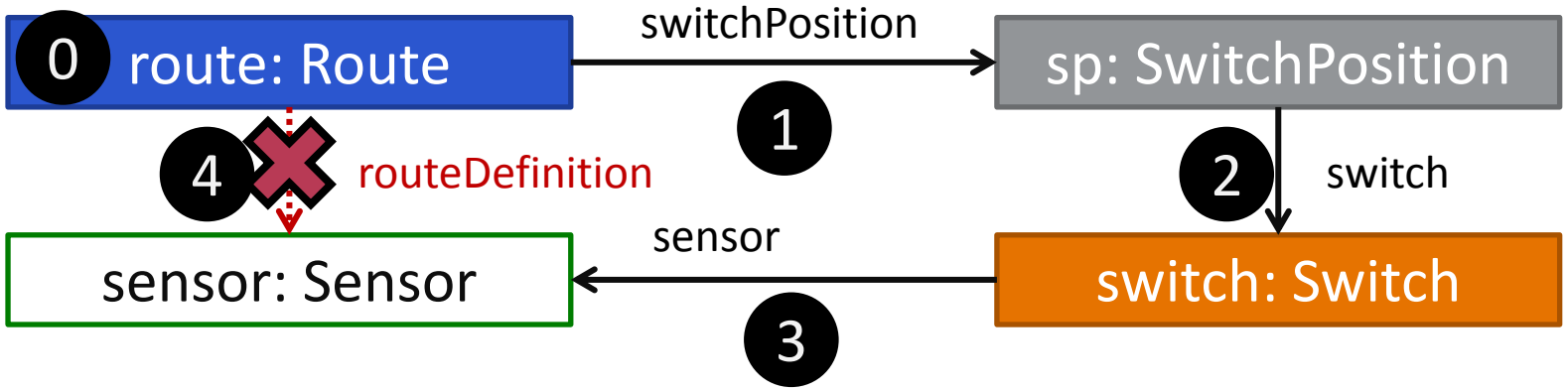
Graph Pattern Matching (Local Search)

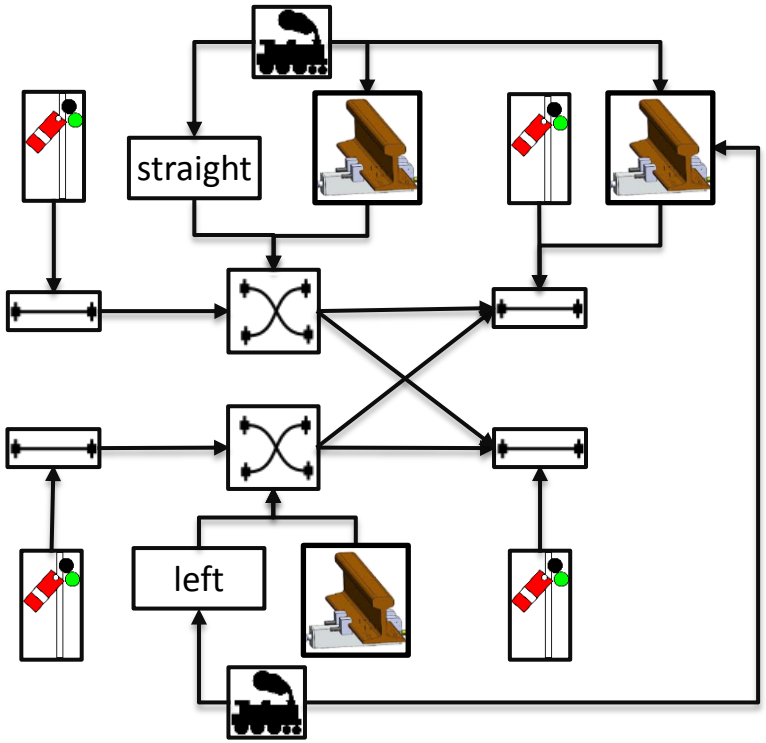




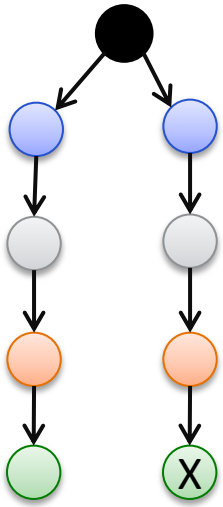
- Search Plan:
  - Select the first node to be matched
  - Define an ordering on graph pattern edges
- Search is restarted from scratch each time

Graph Pattern Matching (Local Search)

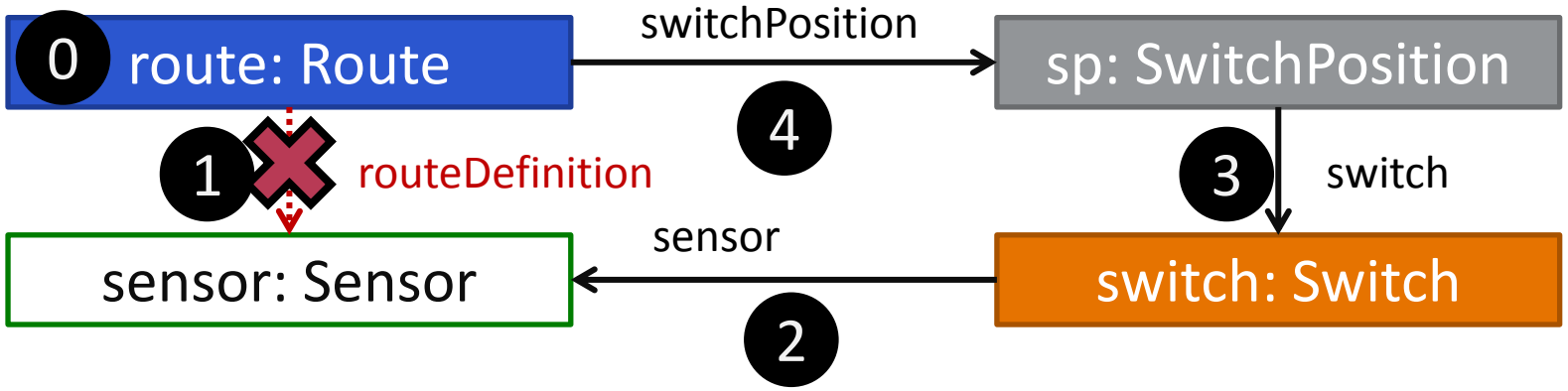


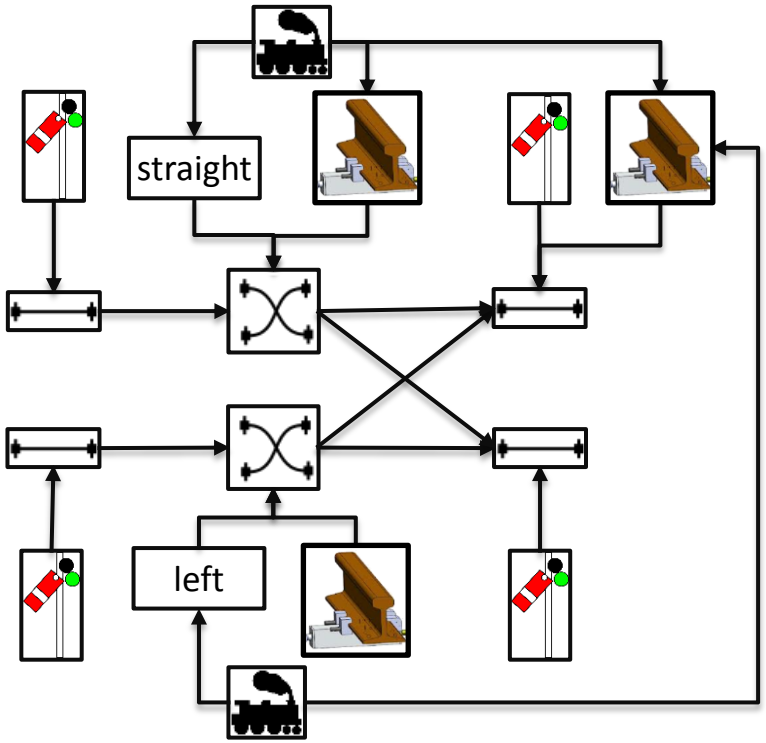


- Search Tree:

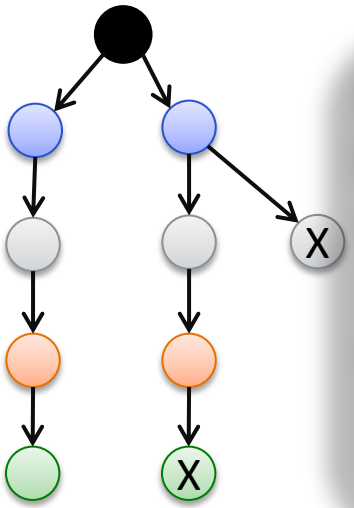


Graph Pattern Matching (Local Search)





- Alternate Search Tree:



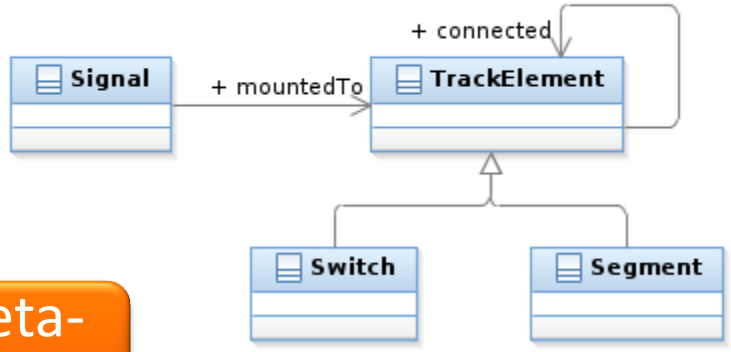
Local Search based PM

- Runtime depends on search plan
- Good search plan: narrow at root wide at leaves

INCREMENTALITY IN QUERIES AND TRANSFORMATIONS

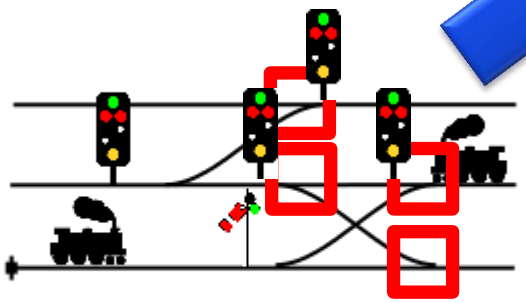
Validation of Well-formedness Constraints

Domain-specific modeling language



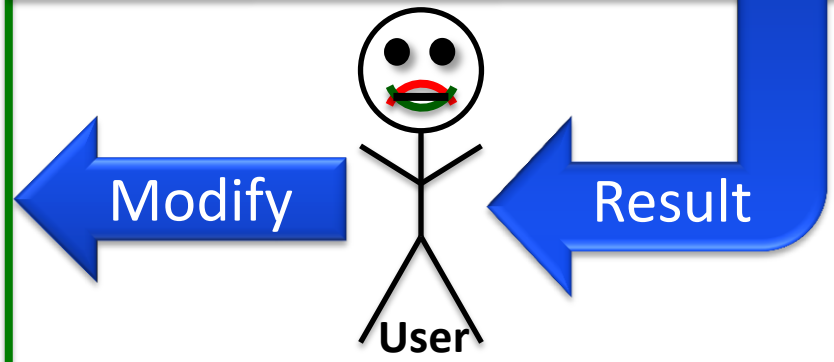
Meta-model

Model



Query

```
pattern switchWOSignal(sw) {
  Switch(sw);
  neg find switchHasSignal(sw);
}

pattern switchHasSignal(sw) {
  Switch(sw);
  Signal(sig);
  Signal.mountedTo(sig, sw);
}
```



Model sizes in practice

- Models with 10M+ elements are common:
  - Car industry
  - Avionics
  - Source code analysis
- Models evolve and change continuously

Application	Model size
System design models	10^8
Sensor data	10^9
Geospatial models	10^{12}

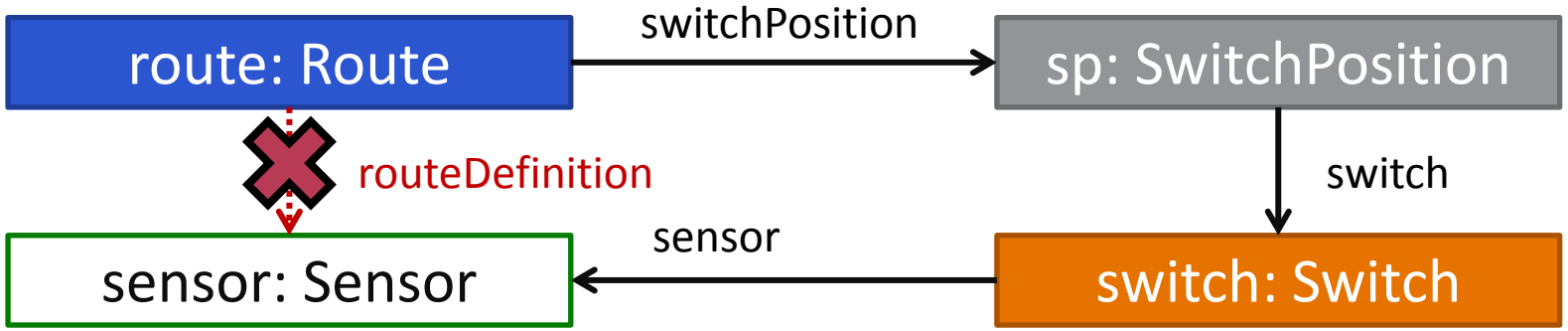
Validation can take hours

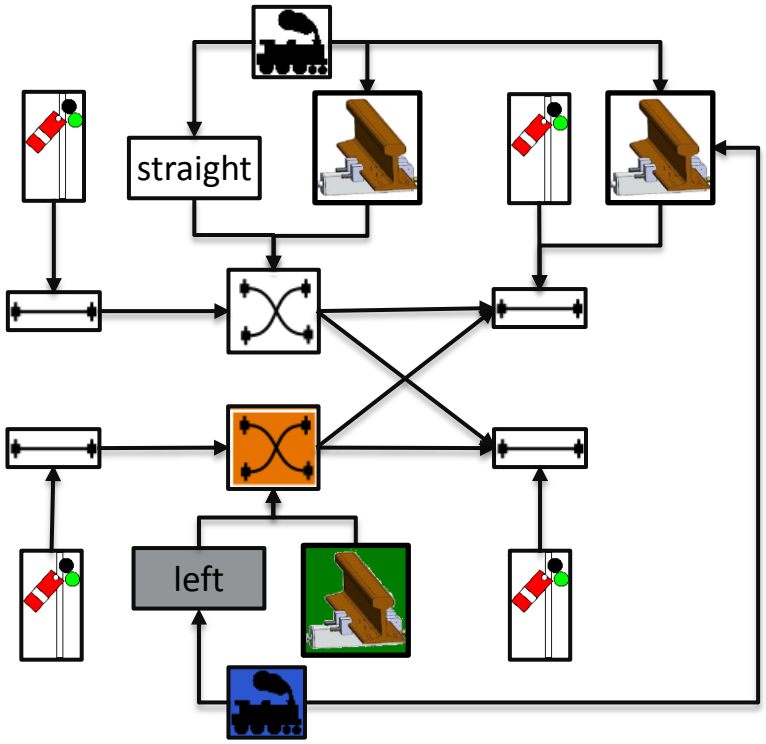
Source: Markus Scheidgen, *How Big are Models – An Estimation*, 2012.

Performance of query evaluation

- Query performance = Execution time as a function of
  - Query complexity
  - Model size
  - Result set size
- Motivation for incrementality
  - Don’t forget previously computed results!
  - Models changes are usually small, yet up-to-date query results are needed all the time.
  - Incremental evaluation is an essential, but not a well supported feature.

Incremental Graph Pattern Matching





route	sp	switch	sensor
r1	sp1	sw1	

- Main idea: More space, less time
  - Cache matches of patterns
  - Instantly retrieve match (if valid)
  - Update caches upon model changes
  - Notify about relevant changes
- Approaches:
  - TREAT, LEAPS, RETE, …
  - Tools: VIATRA, GROOVE, MoTE, TCore

Batch vs. Live Query Scenarios

- **Batch query** (pull / request-driven):
  1. Designer selects a query
  2. One/All matches are calculated
  3. Action is applied on one/all matches
  4. All Steps 1-3 are redone if model changes
- Query results obtained upon designer demand

- **Live query** (push / event-driven):
  1. Model is loaded
  2. Queries loaded
  3. Calculate full match set
  4. Model is changed
  5. Iterate Steps 3 and 4 until system is stopped
- Query results are always available for designer

VIATRA Query: An Open Source Eclipse Project

Definition

- **Declarative graph query language**
  - Transitive closure, Negative cond., etc.
  - Compositional, reusable

Execution

- **Incremental evaluation**
  - Cache result set
  - Maintain incrementally upon model change

Features

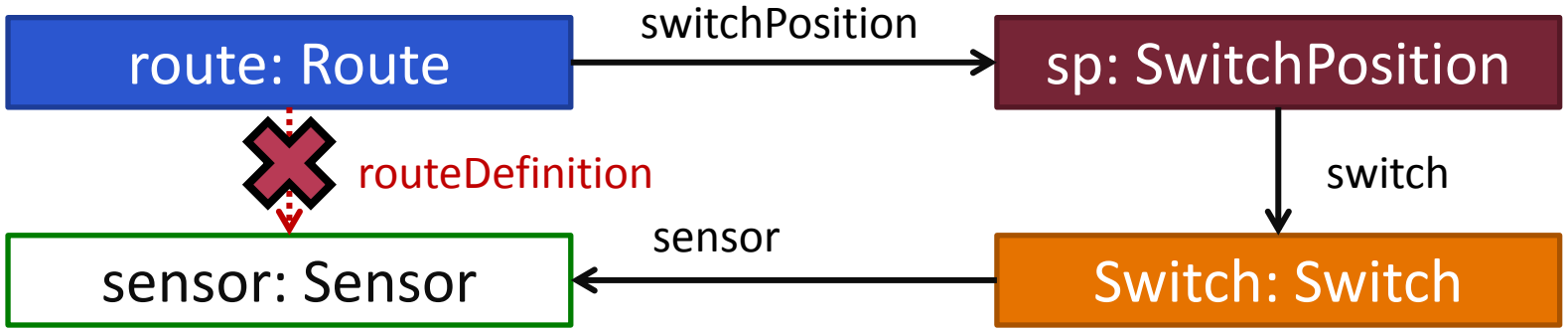
- Derived features,
- On-the-fly validation
- View generation,
- Works out-of-the-box with EMF applications

http://eclipse.org/viatra

Formerly known as EMF-IncQuery

GRAPH MODEL QUERIES: THE LANGUAGE

The VIATRA QUERY Language (VQL)

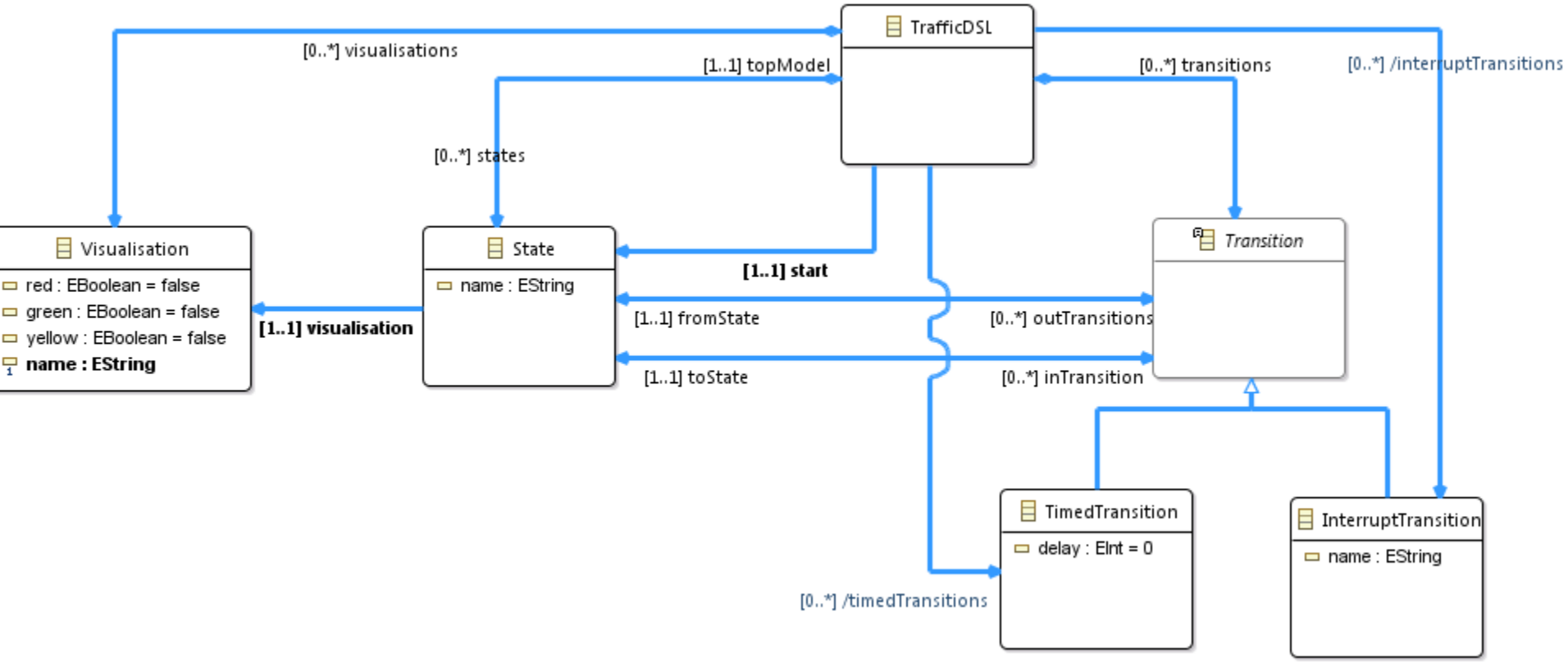



```
pattern routeSensor(sensor: Sensor) = {
        TrackElement.sensor(switch,sensor);
        Switch(switch);
        SwitchPosition. switch(sp, switch);
        SwitchPosition(sp);
        Route.switchPosition(route, sp);
        Route(route);
        neg find head(route, sensor);
}
pattern head(R, Sen) = {
        Route.routeDefinition(R, Sen);
}
```

- VQL: declarative query language
  - Attribute constraints
  - Local + global queries
  - Compositionality+Reusabilility
  - Negation, Aggregations
  - Recursion, Transitive Closure over Regular Path Queries
  - Syntax: DATALOG style

Example Statecharts metamodel

- Other detailed examples



VQL Simple queries

```
// s is a state of a statemachine with name n
pattern state(s: State, n: java String) {
    State.name(s,n);
}
// Old VIATRA style
pattern state(s,n) {
    State(s);
    NamedElement.name(s,n);
}
// Smart type inference
pattern state(s,n) {
    State.name(s,n);
}
// Checks if a state is red
pattern redState(s: State) {
    State.visualisation.red(s, true);
    State.visualisation.green(s, false);
    State.visualisation.yellow(s, false);
}
```

Simple queries

```
// s is a state of a statemachine with name n
pattern state(s: State, n: java String) {
    State.name(s,n);
}
// Old VIATRA style
pattern state(s,n) {
    State(s);
    NamedElement.name(s,n);
}
// Smart type inference
pattern state(s,n) {
    State.name(s,n);
}
// Checks if a state is red
pattern redState(s: State) {
    State.visualisation.red(s, true);
    State.visualisation.green(s, false);
    State.visualisation.yellow(s, false);
}
```

Query definition

Optional parameter type

Type constraint

Support for EMF types and Java datatypes

Query parameters

Attribute navigation

Conjunction of constraints

Path expression

VQL Pattern composition and negation

```
// t is an interrupt transition between a
// from state and a to state with event e
pattern interruptTransition(t,from,to,e) {
    Transition.fromState(t,from);
    Transition.toState(t,to);
    InterruptTransition.name(t,e);
}
```

```
// The result of event is non-deterministic in state
pattern nondeterministicState(state, event) {
    find interruptTransition(_,state,to1,event);
    find interruptTransition(_,state,to2,event);
    to1 != to2;
}
// No events handled by state
pattern noInterruptTransition(state) {
    State(state);
    neg find interruptTransition(_,state,_,_);
}
```

Pattern composition / call

Negation „no such”

Anonymous variables „any” (see Prolog/Datalog)

VQL Transitive closure and disjunction

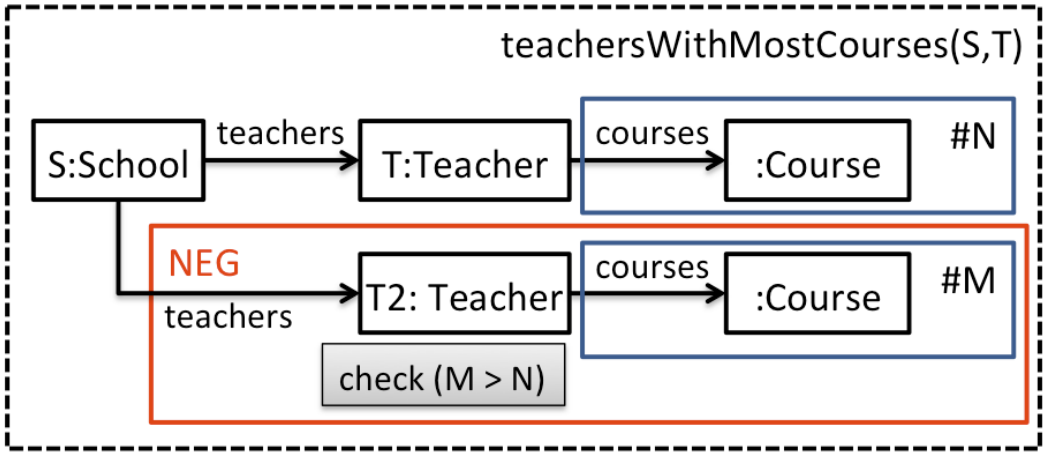
```
pattern transition(from,to) {
    Transition.fromState(t,from);
    Transition.toState(t,to);
}

pattern reachable(from:State,to:State) {
    from == to;
} or {
    find transition+(from,to);
}

pattern unreachableState(s:State) {
    TrafficDSL.states(dsl,s);
    TrafficDSL.start(dsl,start);
    neg find reachable(start,s);
}
```

Disjunction
(on pattern level)

Transitive closure
over binary (2-param) patterns

Note that:
- negative calls do not bind variables of header parameters
- patterns should be connected by edges (avoid Cartesian product)

VQL Check expression & Aggregation



Exercise: this would be even more efficient with **max find**… how and why?

```
pattern teachersWithMostCourses(
 school : School, teacher : Teacher) = {
   School.teachers(school,teacher);
   neg find moreCourses(teacher);
}

pattern moreCourses(teacher : Teacher) = {
    n == count find coursesOfTeacher(teacher,_course);
    m == count find coursesOfTeacher(teacher2,_course2);
    Teacher(teacher2);
    teacher != teacher2;
    check(n < m);
}
```

Match counting

Check expression for attribute values (pure!)

VQL Clarifying semantics

```
pattern reachableRec(from:State,to:State) {
    from == to;
} or {
    find transition(from, intermediate);
    find reachableRec(intermediate, to);
}
```

Query

Results

from	to
s1	s1
s1	s2
s2	s2
…	…

- **Set** semantics → query results form a **relation** (sets of tuples)
  - Order of tuples returned is undetermined
  - No tuples are duplicated (super important for aggregation!)
    - Not even if they differ in a hidden internal variable (e.g. **`intermediate`**)
    - Not even if they come from different **`or`**-connected pattern bodies (e.g. <s1,s1> via loop)
- (Partial) parameter binding/substitution
  - Find all states reachable from s1 ⇔ substitute s1 into **`from`**, filter relation
- Recursion semantics: least fixed point
  - (Runtime option switch required)

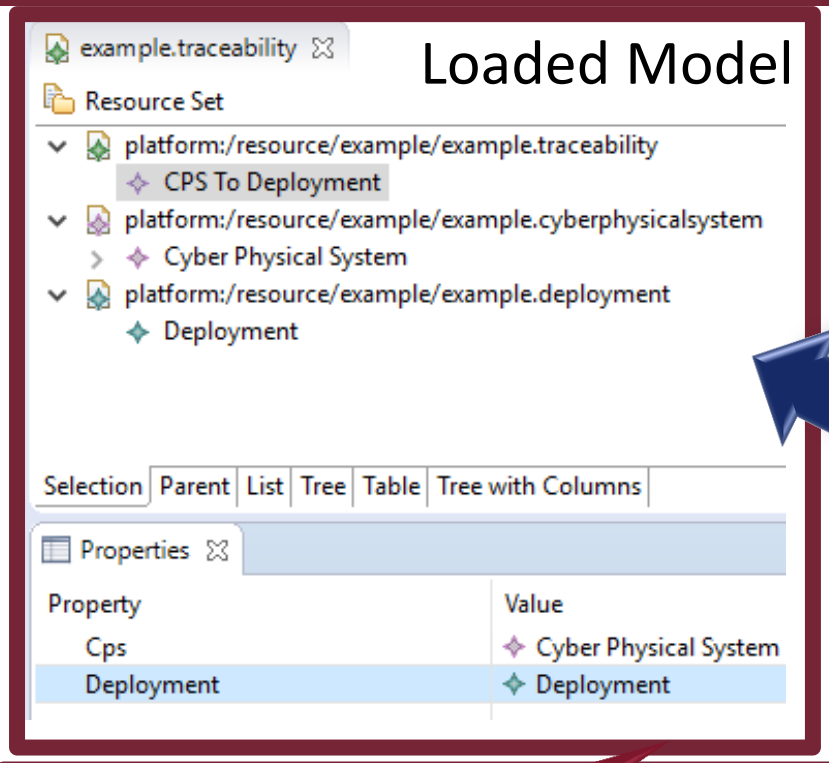
No need to pre-declare which parameter is input/output

Recursion is difficult, hence transitive closure support

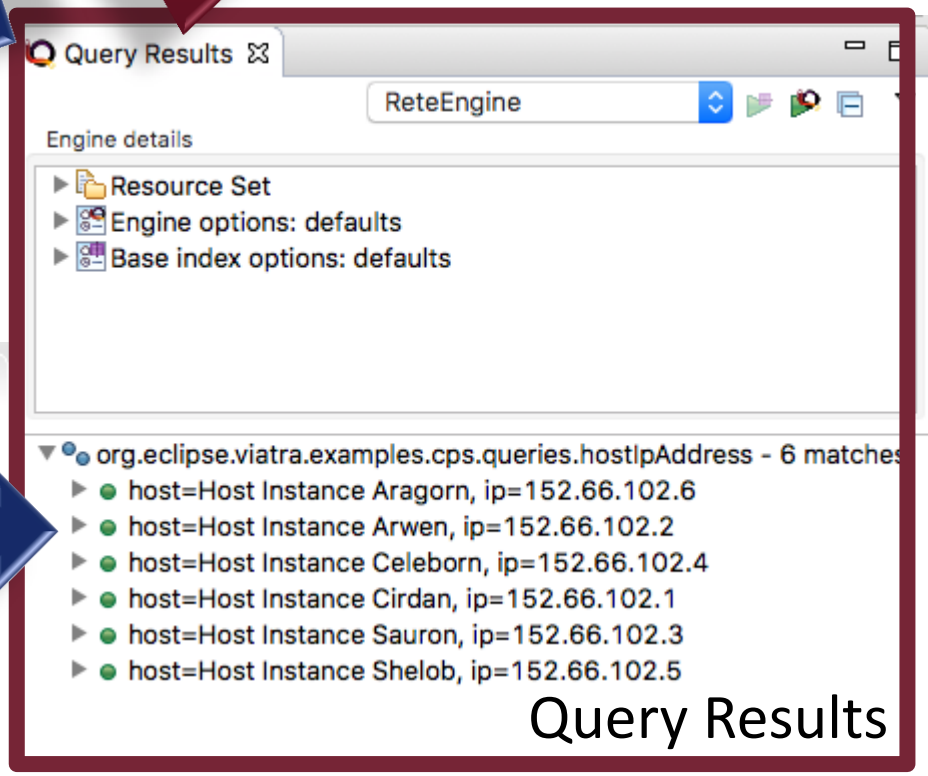
Overview of VIATRA QUERY Language

- Features of the pattern language
  - Works with any *(pure)* EMF based DSL and application
  - Reusability by pattern composition
  - Recursion, negation
  - Generic and parameterized model queries
  - Bidirectional navigability of edges / references
  - Immediate access to all instances of a type
  - Complex change detection
- Benefits
  - Fully declarative + Scalable performance

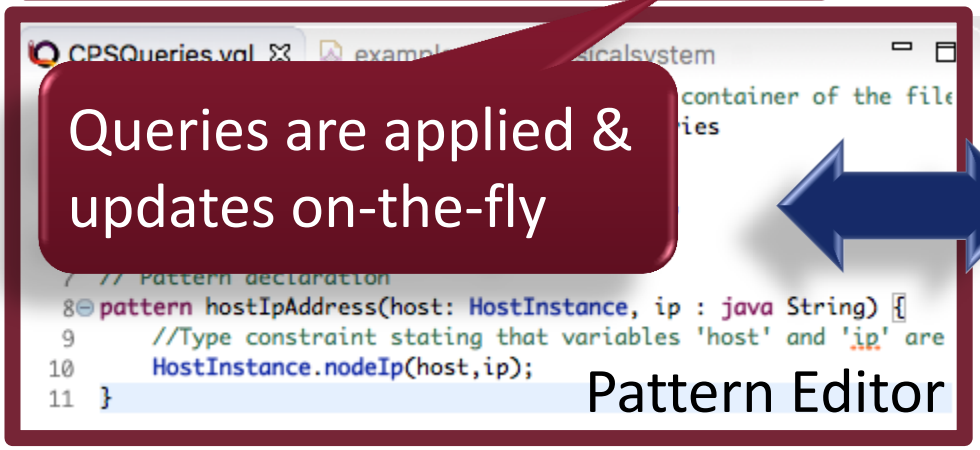
VIATRA QUERY Development Tools



- Works with most EMF-based editors out-of-the-box
- Reveals matches as selection



Queries are applied & updates on-the-fly



VIATRA QUERY
VALIDATION FRAMEWORK

VIATRA QUERY Validation Framework

- Simple validation engine
  - Supports on-the-fly validation through incremental pattern matching and problem marker management
  - Uses VIATRA QUERY graph patterns to specify constraints
- Simulates EMF Validation markers
  - To ensure compatibility and easy integration with existing editors
  - Doesn't use EMF Validation directly
    - Execution model is different

Well-formedness rule specification by graph patterns

- WFRs: *Invariants* which must hold at all times
- Specification = set of elementary constraints + context
  - Elementary constraints: Query (pattern)
  - Location/context/key: a model element on which the problem marker will be placed
- Constraints by graph patterns
  - Define a pattern for the “bad case”
    - Either directly
    - Or by negating the definition of the “good case”
  - Assign one of the variables as the location/context

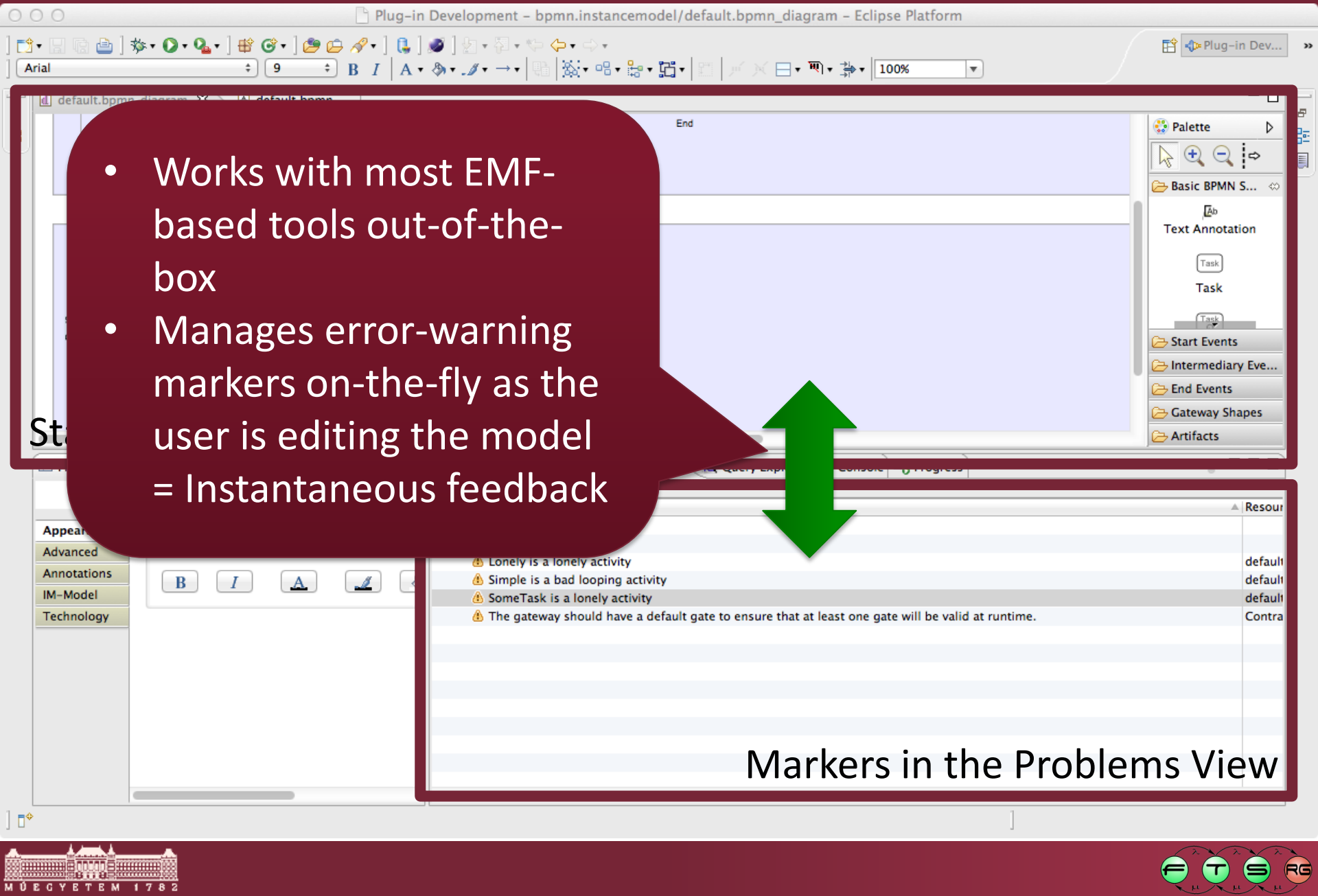
Match:
A violation of the invariant

EXAMPLE Statechart validation constraint

- "All interrupt names on transitions going out of a single state must be distinct."
- Capture the bad case as a query
  - There are two outgoing interrupt transitions triggered by the same event
- Add a @constraint annotation to derive an error/warning message

```
@Constraint(key = {a, event}, message = „State $a.name$ handles event
$e.name$ ambiguously", severity = "warning" )
pattern nondeterministicState(a, event) {
    find interruptTransition(_,a,to1,event);
    find interruptTransition(_,a,to2,event);
    to1 != to2;
}
@Constraint(key = {state}, message = "There should be at least one timed
transition going from a state", severity = "error")
pattern noTimedTransition(state) {
    State(state);
    neg find timedTransition(_,state,_,_);
}
```

Example GUI – Viatra Model Validation



- Works with most EMF-based tools out-of-the-box
- Manages error-warning markers on-the-fly as the user is editing the model
  = Instantaneous feedback

Validation lifecycle

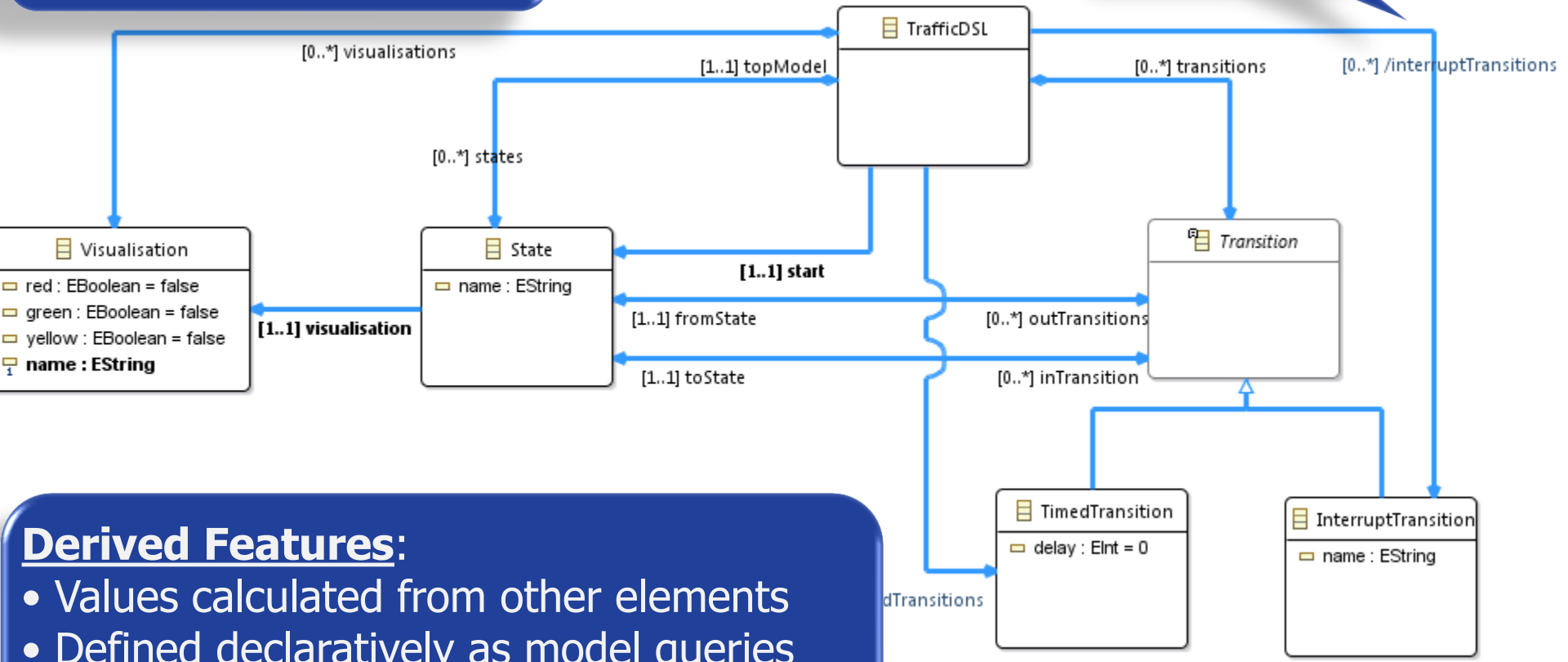
- Constraint violations
  - Represented by Problem Markers (Problems view)
  - Marker text is updated if affected elements are changed in the model
  - Marker removed if violation is no longer present
- Lifecycle
  - Editor bound validation (markers removed when editor is closed)
  - Incremental maintenance not practical outside of a running editor

CALCULATING DERIVED FEATURES BY INCREMENTAL QUERIES

Metamodels with Derived Features

/interruptTransitions(A,B):
- B is an InterruptTransition
- B is a transition in A

Derived Reference



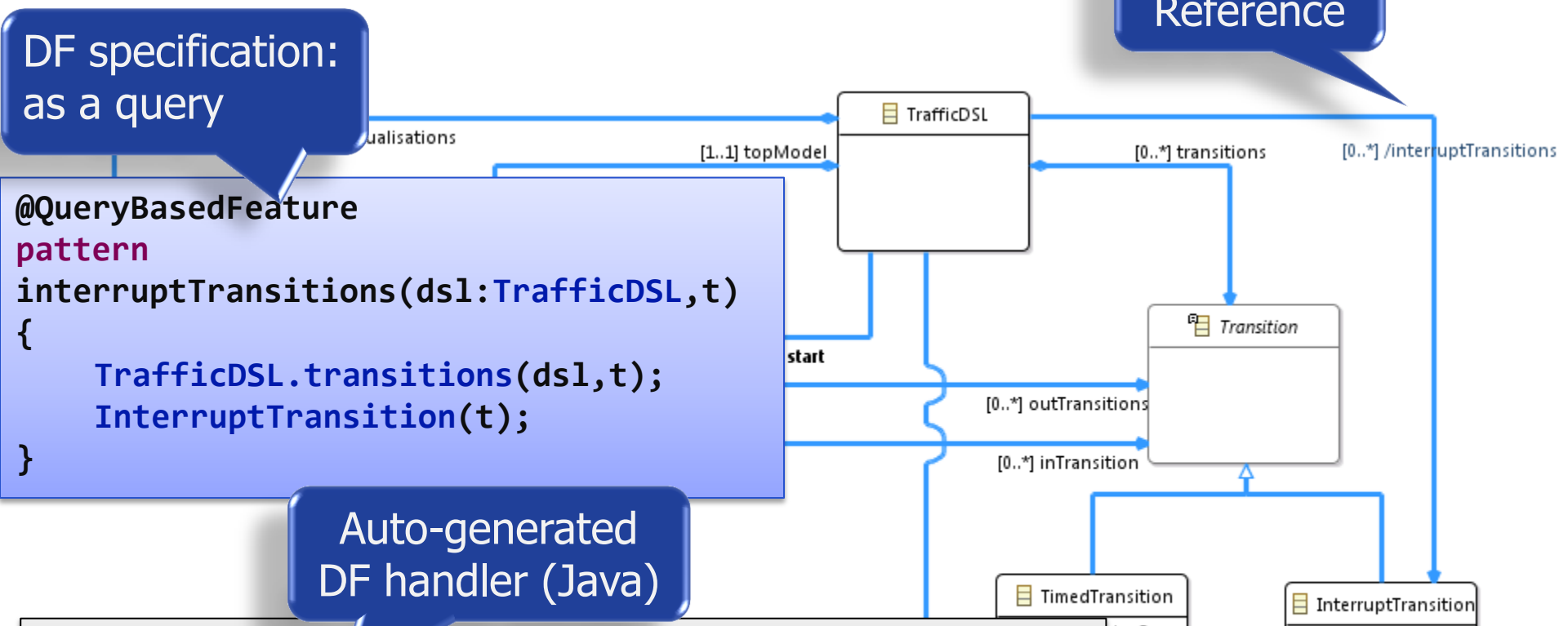
Derived Features:
- Values calculated from other elements
- Defined declaratively as model queries (e.g. OCL, graph queries)
- Tooling: handle as regular EMF elements

Example Handling Derived Features as Queries

Derived Reference

DF specification: as a query

```
@QueryBasedFeature
pattern
interruptTransitions(dsl:TrafficDSL,t)
{
    TrafficDSL.transitions(dsl,t);
    InterruptTransition(t);
}
```



Auto-generated DF handler (Java)

```
private IncqueryDerivedF      e interruptTransitionsHandler;
public EList<InterruptTr      nsition> getInterruptTransitions() {
 if (interruptTransitionsHandler == null) {
  interruptTransitionsHandler = IncqueryFeatureHelper.getIncqueryDerivedFeature(
     this, SystemPackageImpl.Literals.DATA__READING_TASK,
     "system.queries.InterruptTransitions", "TrafficDSL", "InterruptTransition",
     FeatureKind.MANY_REFERENCE, true, false);}
 return interruptTransitionsHandler.getManyReferenceValueAsEList(this);}
```

Query-based Derived Features: Why?

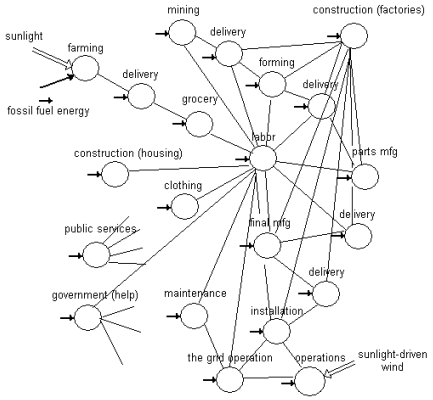
- Benefits of declarative derived specification
  - Guaranteed consistency of change notifications
    - Required e.g. for correct UI display (e.g. derived node label)
    - Provided by VIATRA QUERY incremental engine
  - Conciseness
    - As with implementing any model query
    - Especially if change notifications are relevant
- Exercise: how would you manually implement:

„A *Component X* **strongly depends** on another *Component Y* if it or any of its direct or indirect *child components Z* has a *feature F* typed with Y, but only mandatory (non-0 lower bound multiplicity) features and child components count”

How to manually react to:
- Changing a multiplicity
- Moving a component

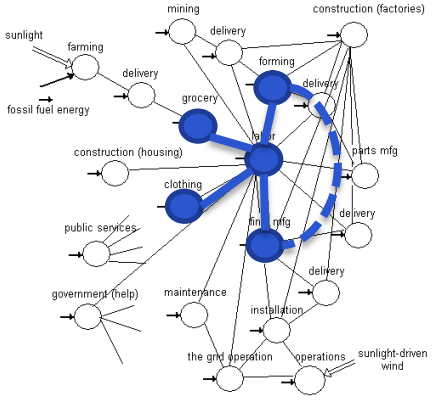
VIATRA VIEWERS

Live abstractions



Complex model

abstract



Computed overlay
aka. “View”

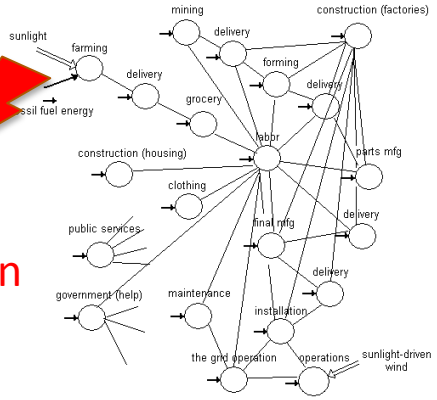
Defined by a **query**

Items = SELECT …

Id	Label	Prop0	Prop1
0	N1	a	B
1	N2	c	D

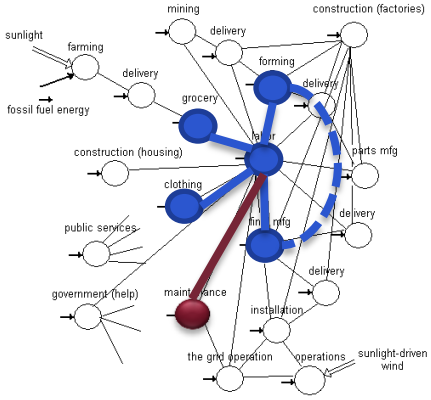
Live abstractions

Model Modification



Complex model

abstract



Computed overlay
aka. “View”

UI update

Change notification

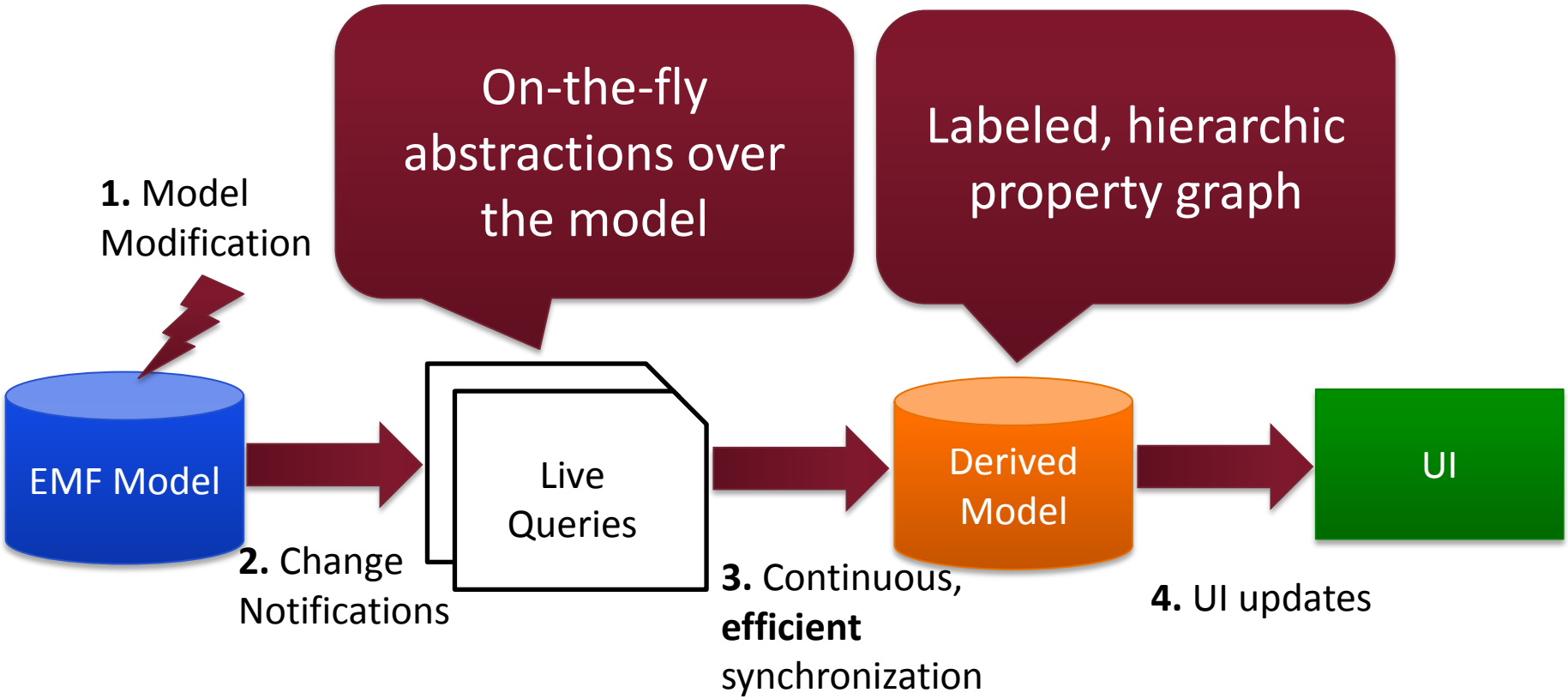
Defined by a **query**

Items = SELECT …

Id	Label	Prop0	Prop1
0	N1	a	B
1	N2	c	D
2	N3	e	F

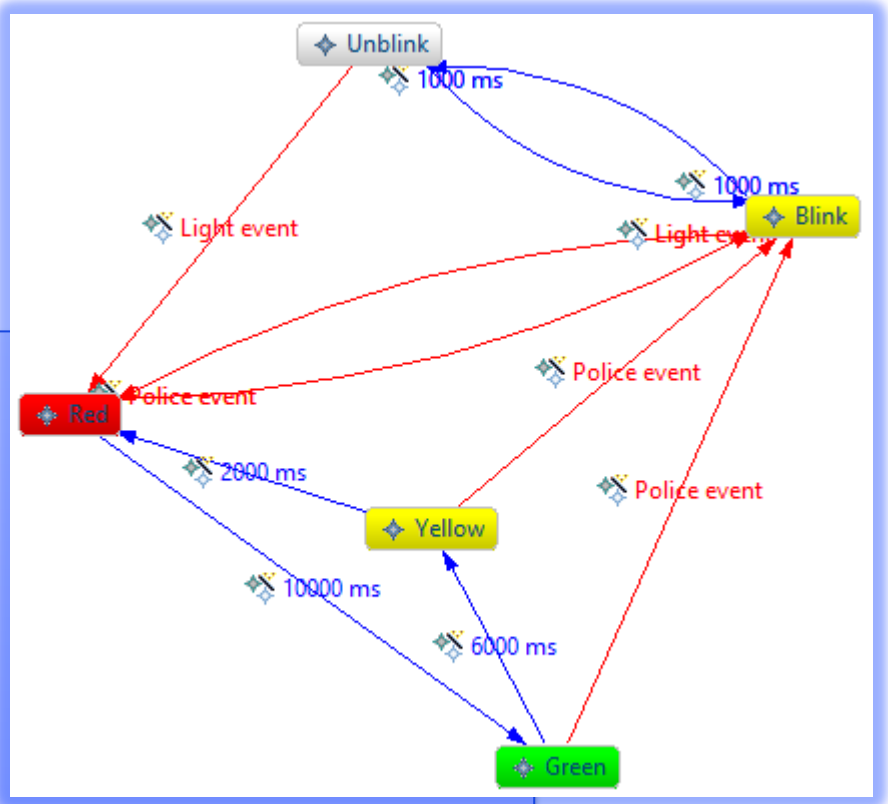
Query result update

VIATRA Viewers



- Visualize things that are not (directly) present in your model
- Provides an easy-to-use API for integration into your presentation layer
  - Eclipse Data Binding
  - Simple callbacks

Example Query based view annotations




```
@Format(color = "#ff0000")
@Item(item = s, label = "$n$")
pattern redState(s: State,n) { … }

@Item(item = s, label = "$n$")
pattern state(s,n) = { … }

@Format(lineColor = "#0000ff")
@Edge(source = from, target = to, label = "$d$ ms")
pattern timedTransition(t,from,to,d) = { … }

@Format(lineColor = "#ff0000")
@Edge(source = from, target = to, label = "$e$ event")
pattern interruptTransition(t,from,to,e) = { … }
}
```

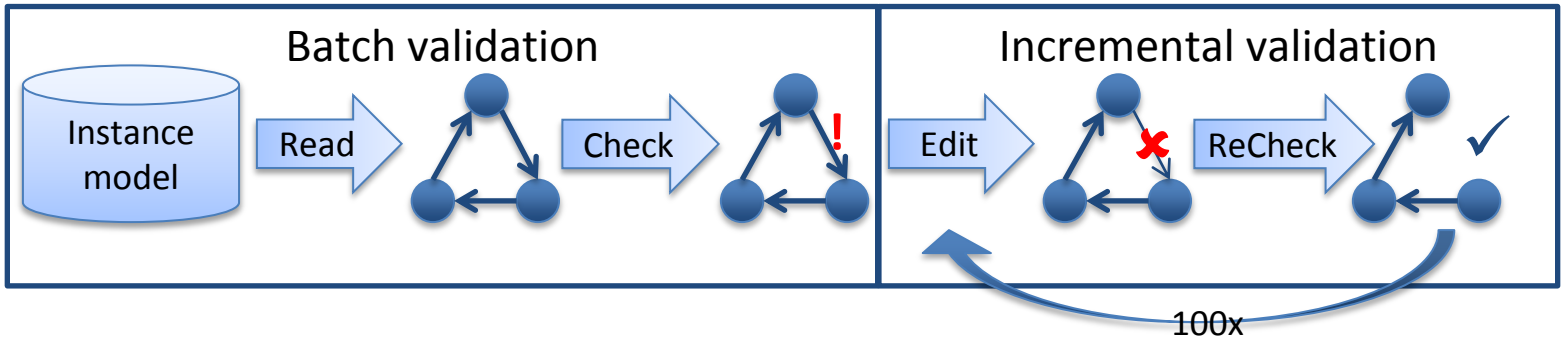
What can I do with all this? – query-based live abstractions

Syntax	Eclipse technology	Pros
Trees, tables, Properties (JFace viewers)	EMF.Edit	The real deal: doesn't hide abstract syntax
Diagrams	GEF, GMF, Graphiti	Easy to read and write for non-programmers
Textual DSLs	Xtext	Easy to read and write for programmers
JFace, Zest, yFiles Your tool!	**VIATRA Viewers**	**Makes understanding and working with complex models a lot easier**

PERFORMANCE BENCHMARKS

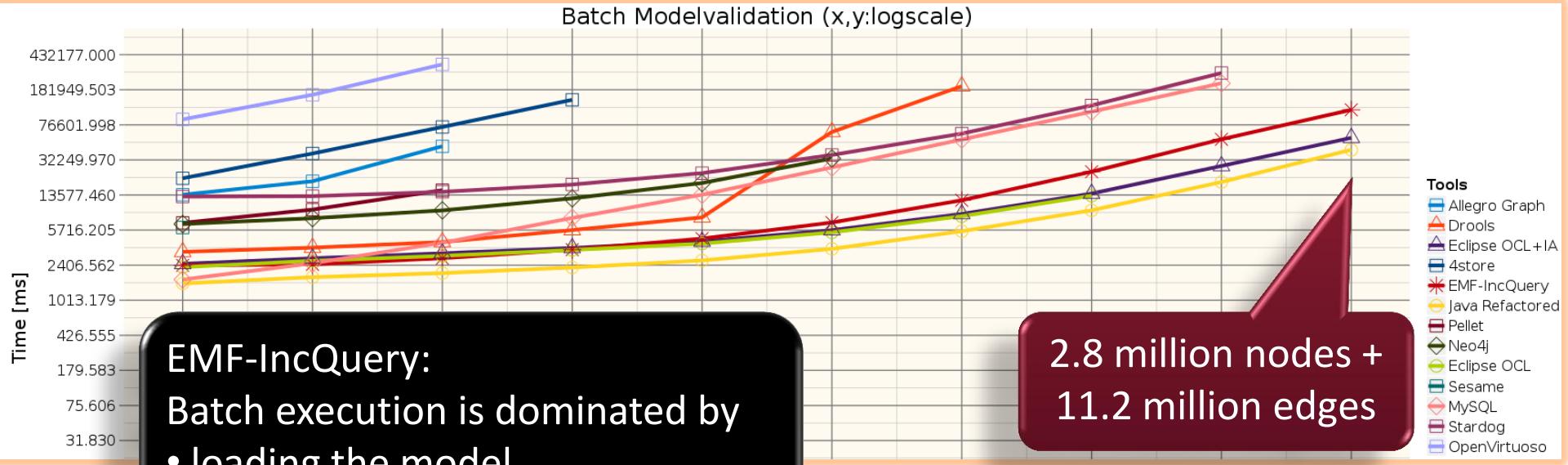
The Train Benchmark

- Model validation workload:
  - User edits the model
  - Instant validation of well-formedness constraints
  - Model is repaired accordingly
- Scenario:
  - Load
  - Check
  - Edit
  - Re-Check
- Models:
  - Randomly generated
  - Close to real world instances
  - Following different metrics
  - Customized distributions
  - Low number of violations
- Queries:
  - Two simple queries (<2 objects, attributes)
  - Two complex queries (4-7 joins, negation, etc.)
  - Validated match sets



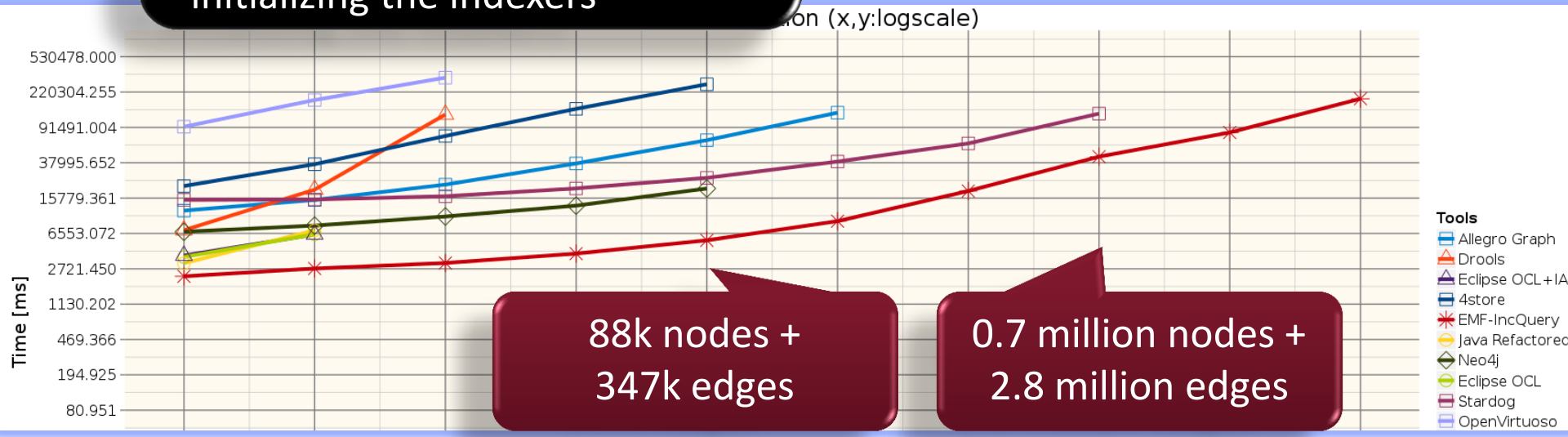
What Tools are Compared?

Batch validation runtime (complex queries)



EMF-IncQuery:
Batch execution is dominated by
- loading the model
- initializing the indexers

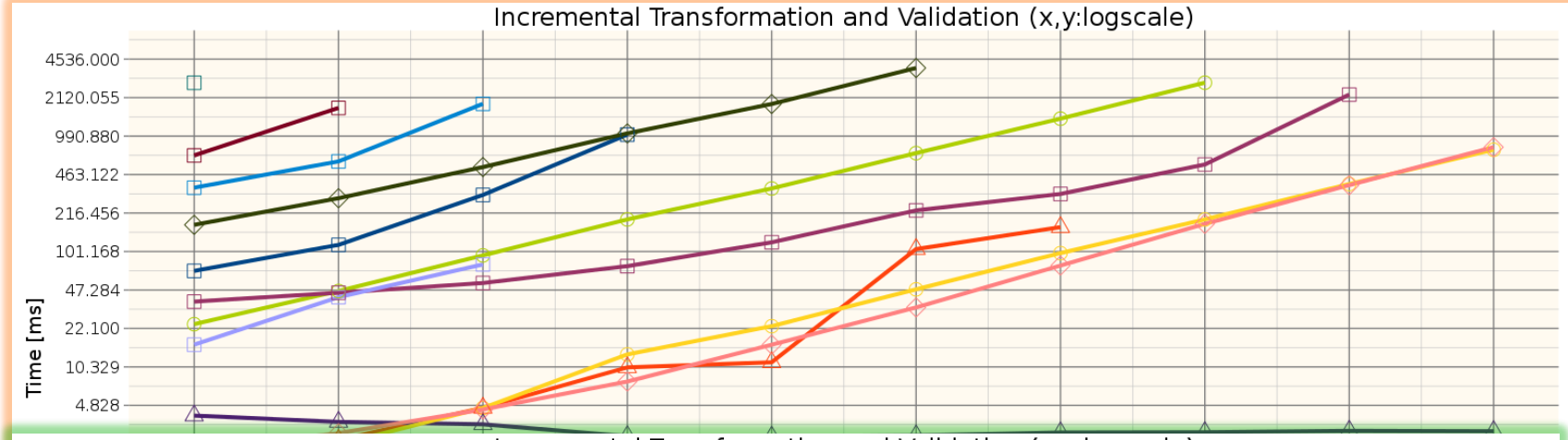
2.8 million nodes +
11.2 million edges

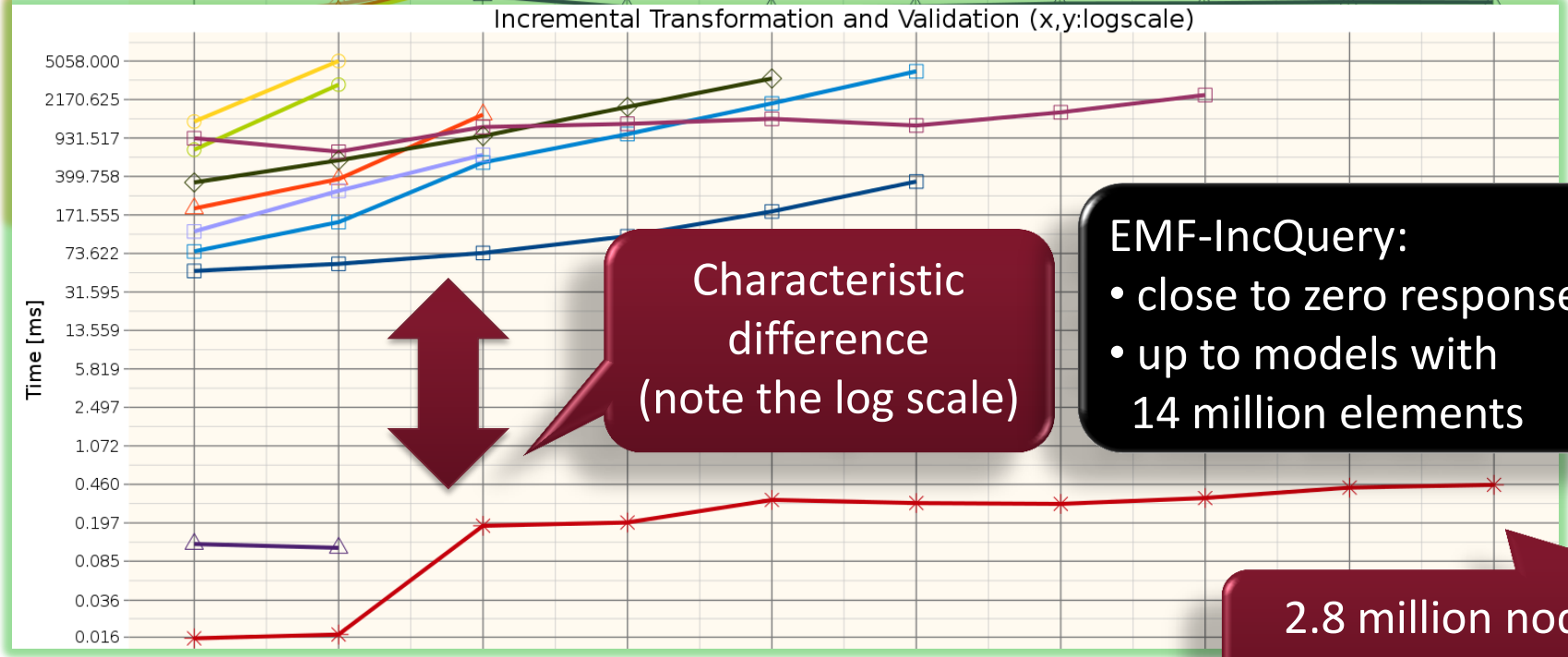


88k nodes +
347k edges

0.7 million nodes +
2.8 million edges

Re-validation time (complex queries)





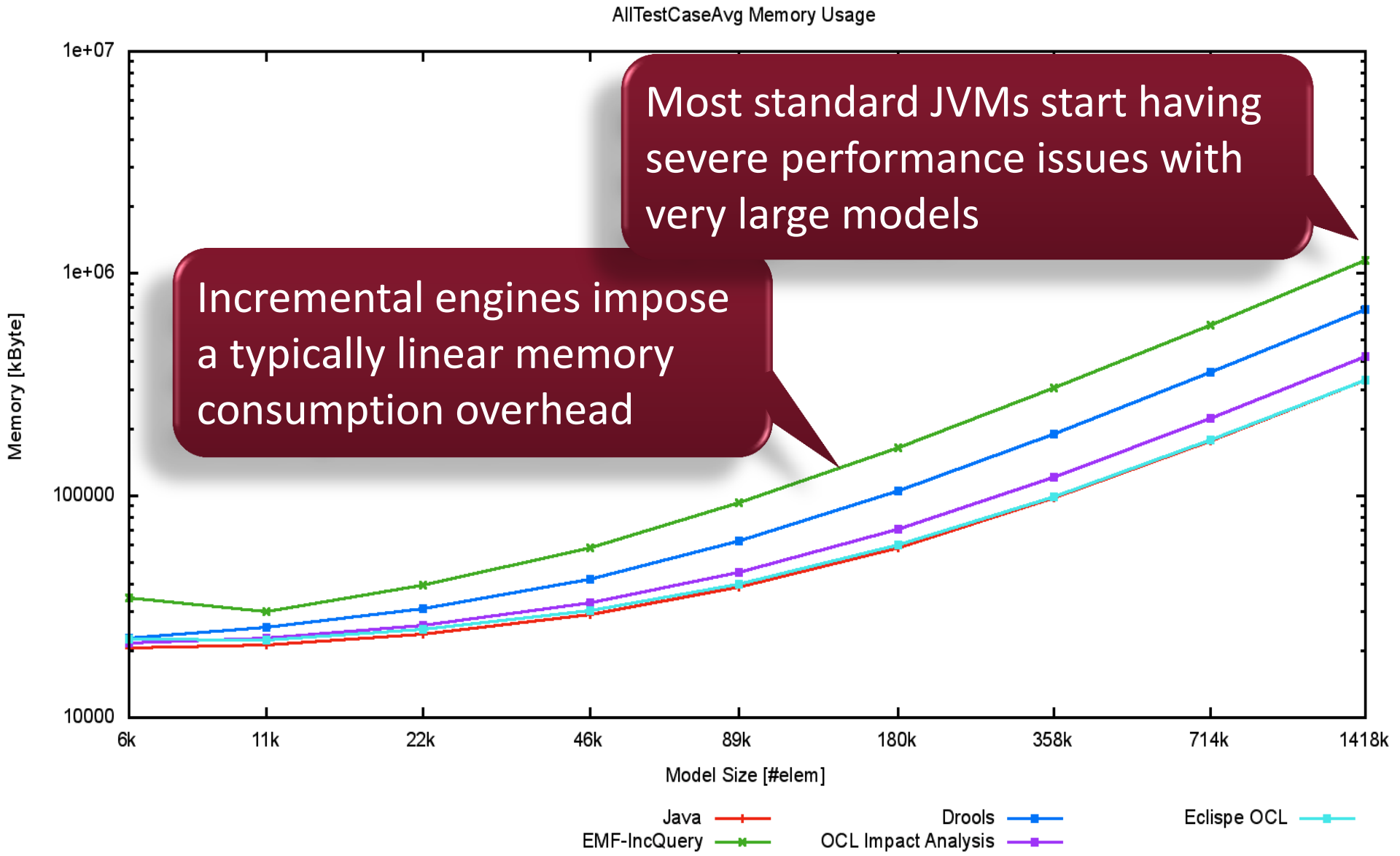
Characteristic difference (note the log scale)

EMF-IncQuery:
- close to zero response time
- up to models with 14 million elements

2.8 million nodes + 11.2 million edges

http://incquery.net/publications/trainbenchmark for more details

Memory usage



Most standard JVMs start having severe performance issues with very large models

Incremental engines impose a typically linear memory consumption overhead

CONCLUSIONS

Selected Applications of VIATRA QUERY

- Complex traceability
- Query driven views
- Abstract models by derived objects

Toolchain for IMA configs

- Connect to Matlab Simulink model
- Export: Matlab2EMF
- Change model in EMF
- Re-import: EMF2Matlab

MATLAB-EMF Bridge

- Live models (refreshed 25 frame/s)
- Complex event processing

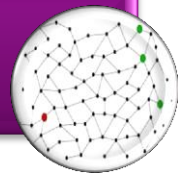
Gesture recognition

- Experiments on open source Java projects
- Local search vs. Incremental vs. Native Java code

Detection of bad code smells

- Rules for operations
- Complex structural constraints (as GP)
- Hints and guidance
- Potentially infinite state space

Design Space Exploration



- Itemis (developer)
- Embraer
- Thales
- ThyssenKrupp
- CERN

Known Users