DSM TP 2017

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# Model Transformation


## Eugene Syriani

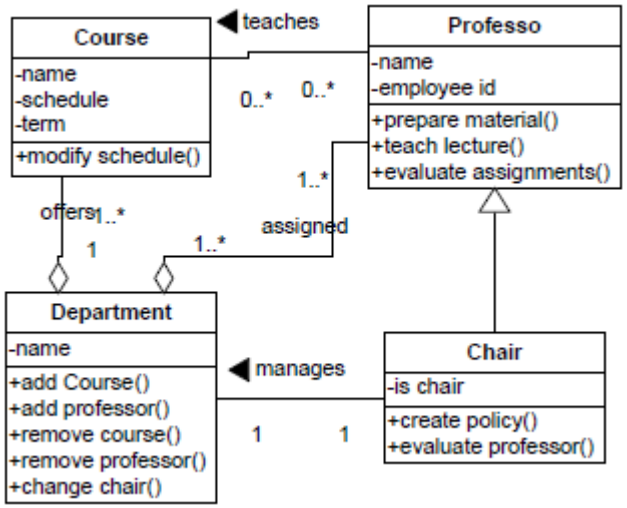
with a little help from Hans Vangheluwe
and later, some modifications

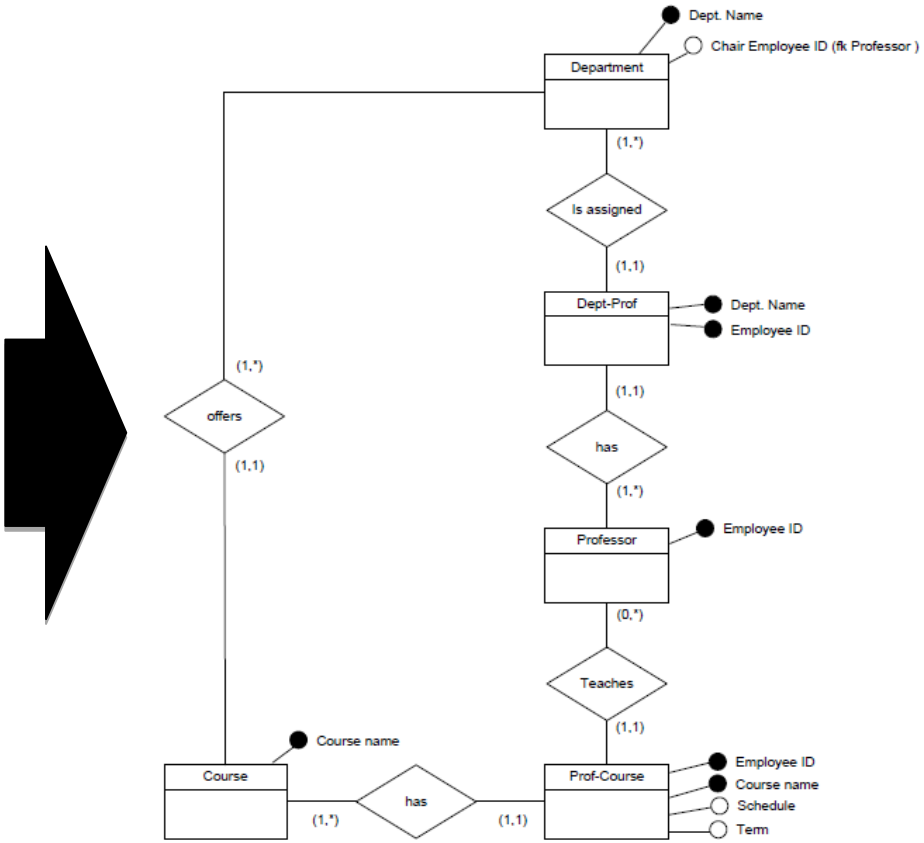

Universiteit Antwerpen · Ansymo Antwerp Systems & Software Modelling University of Antwerp · Nexor Cyber-Physical Systems University of Antwerp · Flanders Make Manufacturing Innovation Network · McGill · MPM4CPS · cost

Software Modeling & Simulation · geodes Département d'informatique et de recherche opérationnelle · Université de Montréal

# Motivation

How would you convert
any UML Class Diagram into an E-R diagram
(e.g., for model storage in a relational database)?



# The “programming” solution

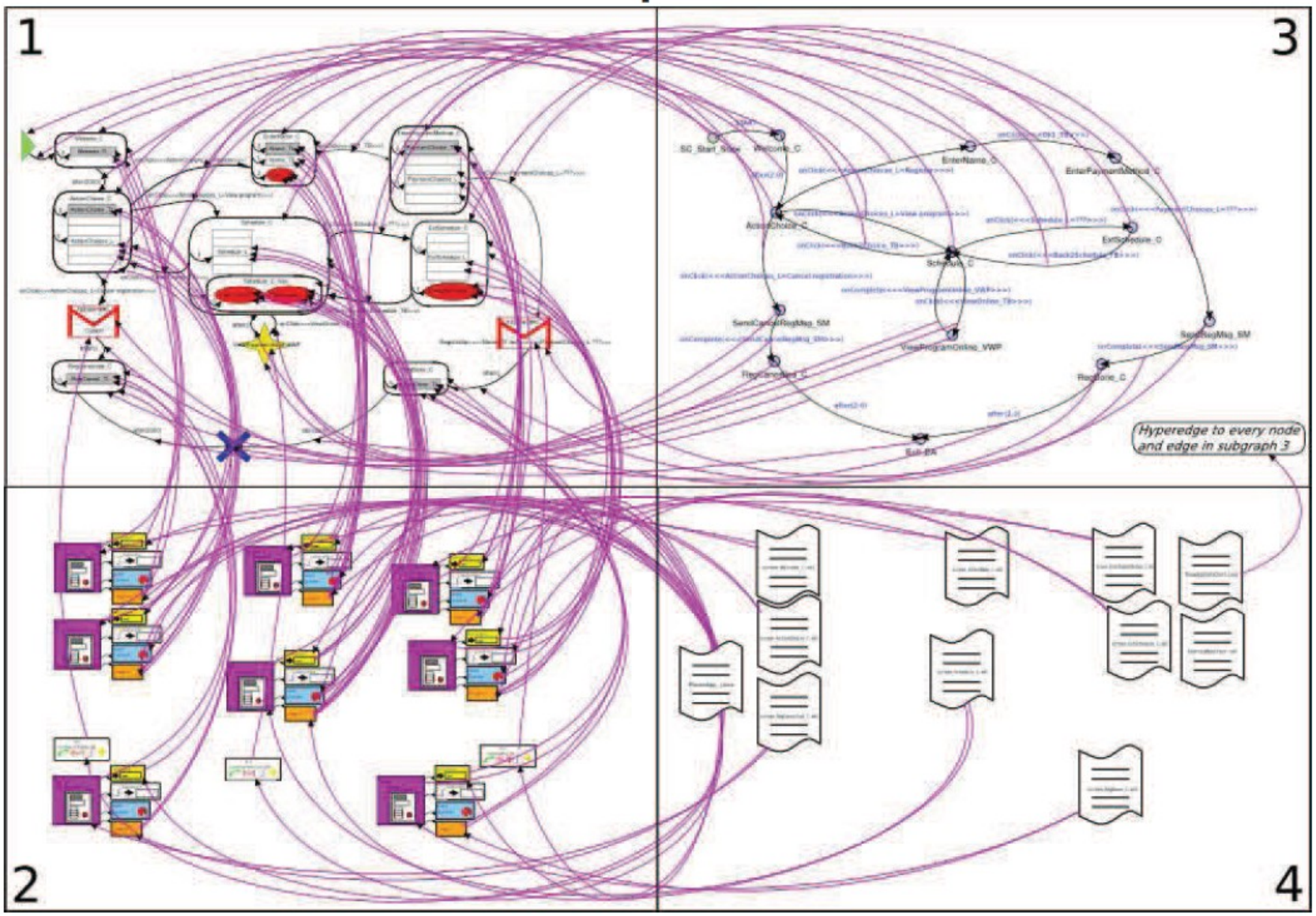
- Write a program that takes as input a .UML file and outputs a .ER file
- What are the issues?
  - What if the UML CD file is a diagram? in XML or XMI format? Probably end up limiting input from a specific tool only
  - Similarly in ER, should I output a diagram (in Dia or Visio)? In code (Java, C#)?
  - How do I organize my program?
    - Requires knowledge from both domains
    - Need a loader (from input file)
    - Need some kind of visitor to traverse the model, probably graph-like data structure
    - Need to encode a “transformer”
    - Need to develop an ER exporter
- Not an easy task …

# The “modeling” way

1. Describe a meta-model of UML CD
   - Define concepts and concrete visual syntax
   - Generate an editor
2. Describe a meta-model of ER
3. Define a transformation T: $MM_{UML\ CD} \rightarrow MM_{ER}$
   - This is done in the form of rules with pre/post-conditions
     - describes “what” instead of “how”

- Transformation model is executed (compiled or interpreted) to produce the result
- Some model transformation languages give you a bi-directional solution (or at least trace-ability) for free!

# Can be Multi-Step/Multi-Formalism




trace-ability links

# What's the difference?

- Typically encounter the **same problems** (need for documentation, testing, debugging, ...) in modeling as in programming

- The difference is that you can **find** the problems more easily, **fix** them very quickly and **re-deploy** the solution automatically

- Changed the level of **abstraction** to reduce **accidental complexity**

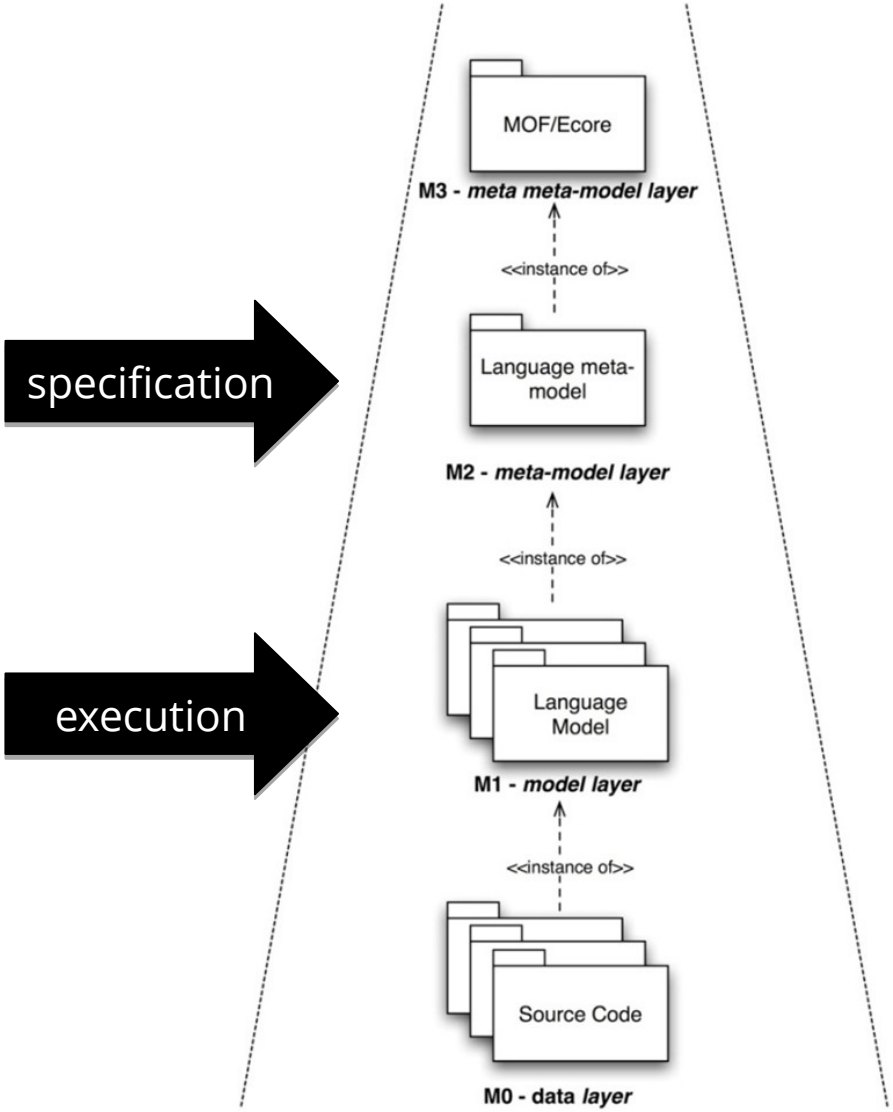
# What is a model transformation?

# Definition

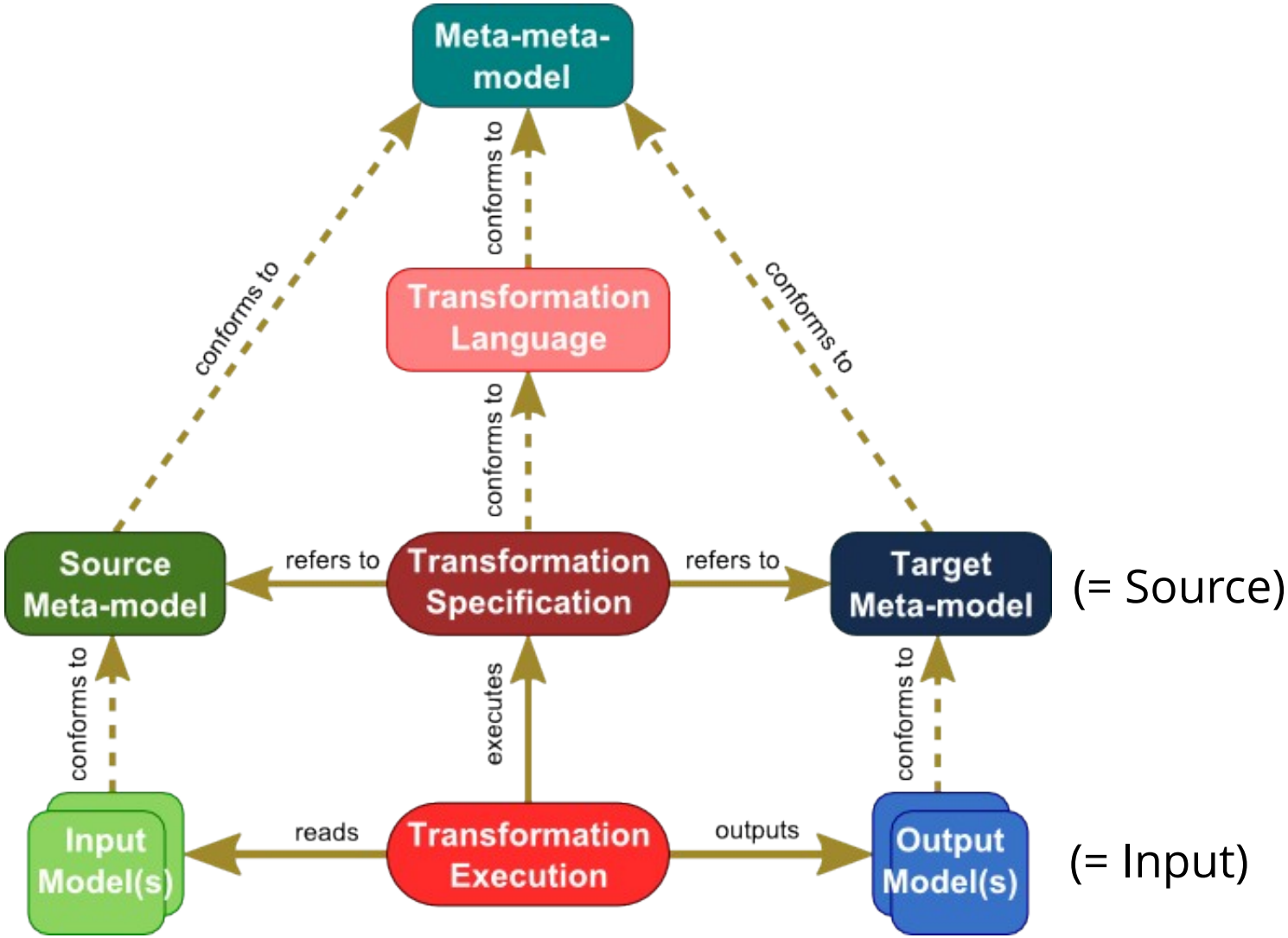
A **model** transformation is the
**automatic** manipulation of **input models**
to produce **output models**,
that conforms to a **specification**
and has a specific **intent**.

L. Lúcio, M. Amrani, J. Dingel, L. Lambers, R. Salay, G. Selim, E. Syriani & M. Wimmer. Model transformation intents and their properties. *Software & Systems Modeling*: 15(3), pp. 647-684 (2016).

# Where should MT be specified and executed?



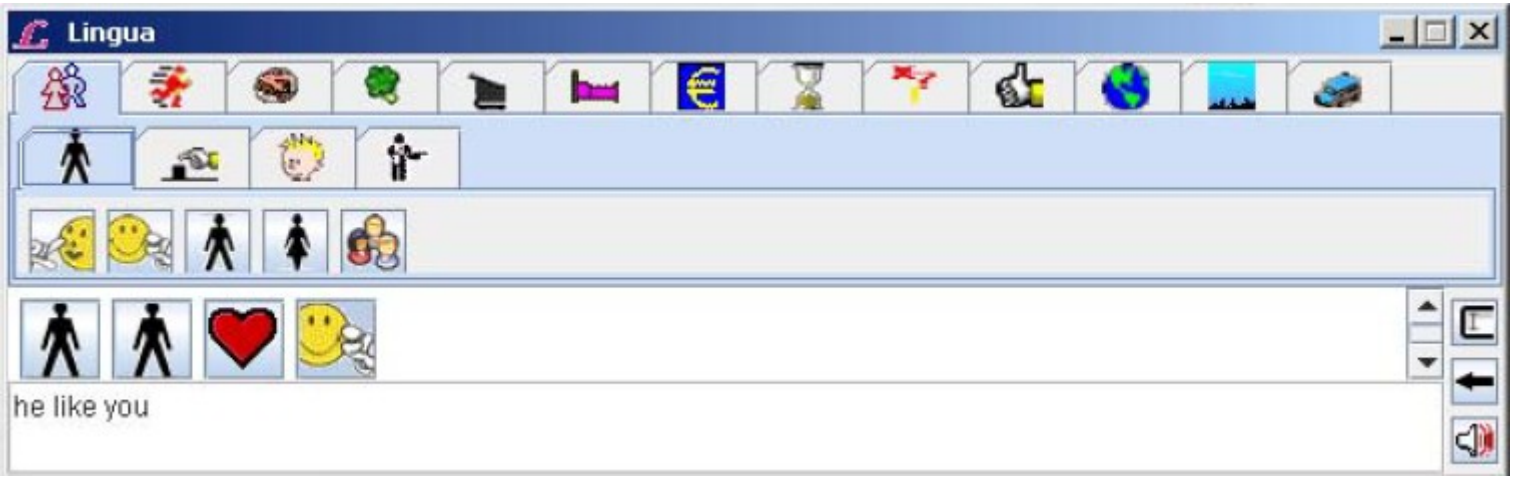
# Terminology



# Data structures to transform

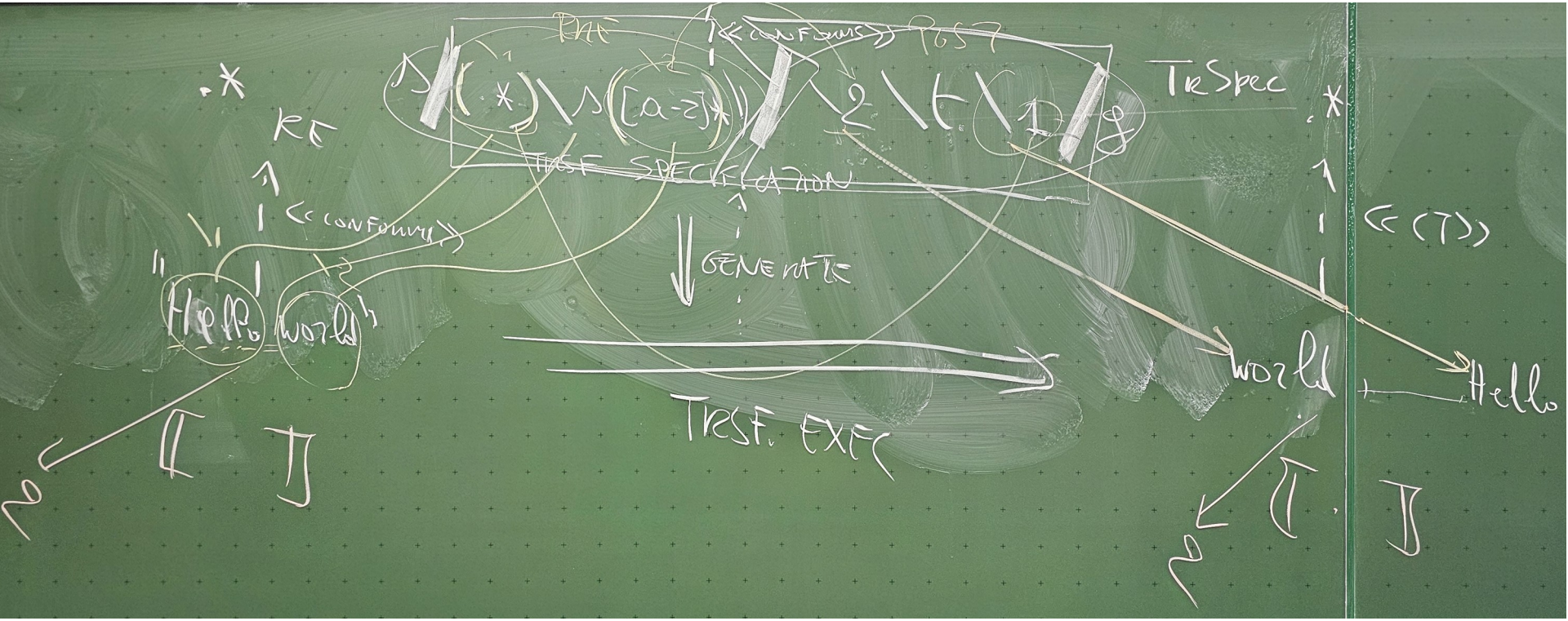
## Sequence

- Linear sequence of symbols
  - Data: symbol
  - Connector: successor
- Example: string, iconic sentence
- Manipulation through **string rewriting**



# String rewriting

- Model transformation paradigm: **regular expression**
  - Stream Editor (sed)
- Model "`Hello world`"
- Metamodel `.*`
- Model transformation `s/(.*)\s([a-z]*)/\2\t\1/g`
- Transformation language is rule-based, regular expression
  - s/ LHS to be matched /
  - / RHS /g to rewrite, with "labels"
    referring to matched sub-strings from LHS



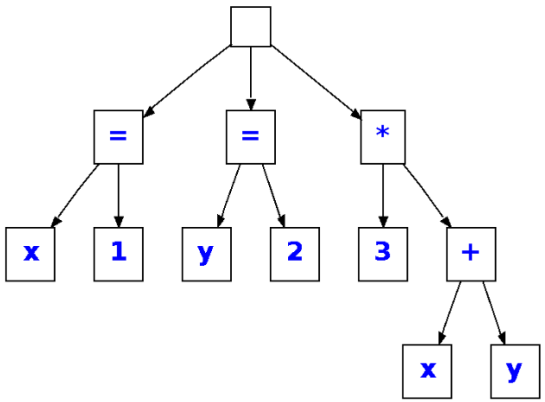

$$[\![ \text{TrSpec} ]\!]_{\text{TRSPECLANG}} = \{ (\text{"Hello world"}, \text{"world\_Hello"}), (\ldots) \ldots \}$$

$(\mathcal{E}, ?)$

# Data structures to transform

## Tree

- Acyclic connected simple graph
  - Data: nodes $N$
  - Connector: edges $E \subseteq N \times N : |E| = |N| - 1$
- Example: Abstract syntax tree of a program, XML
- Manipulation through **tree rewriting**




```
<bookstore>
  <book category="cooking">
    <title lang="en">Everyday Italian</title>
    <author>Giada De Laurentiis</author>
    <year>2005</year>
    <price>30.00</price>
  </book>
  <book category="children">
    <title lang="en">Harry Potter</title>
    <author>J K. Rowling</author>
    <year>2005</year>
    <price>29.99</price>
  </book>
</bookstore>
```

# Tree rewriting

- Model transformation paradigm: **parser**
  - Gentle compiler construction system
- Model
- Metamodel
- Model transformation
  - Transformation language is **term rewriting** with production rules

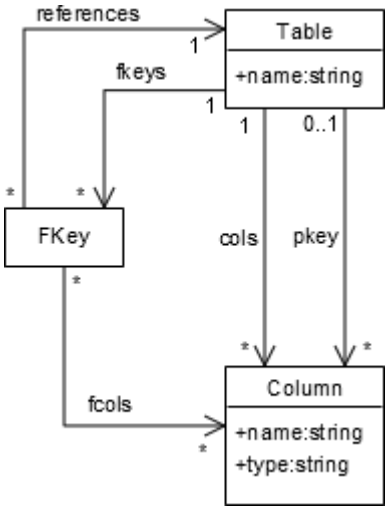
```
expression ::= expression "+" expr2 |
expr2
expr2 ::= expr2 "*" expr2 | Number
```

```
root expr(->X)
nonterm expr(->Expr)
  rule expr(->X): expr2(->X)
  rule expr(->add(X,Y)): expr(->X) "+" expr2(->Y)
nonterm expr2(->Expr)
  rule expr2(->mult(X,Y)): expr2(->X) "*" expr2(->Y)
  rule expr2(->num(X)): Number(->X)
token Number(->INT)
```

# Data structures to transform

## Graph

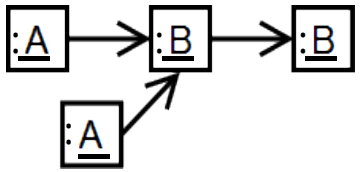
- Typed attributed graphs, hypergraphs, multigraphs
  - Data: nodes $N$
  - Connector: edges $E \subseteq N \times N$
- Example: Class diagrams, Statecharts
- Manipulation through **graph transformation**



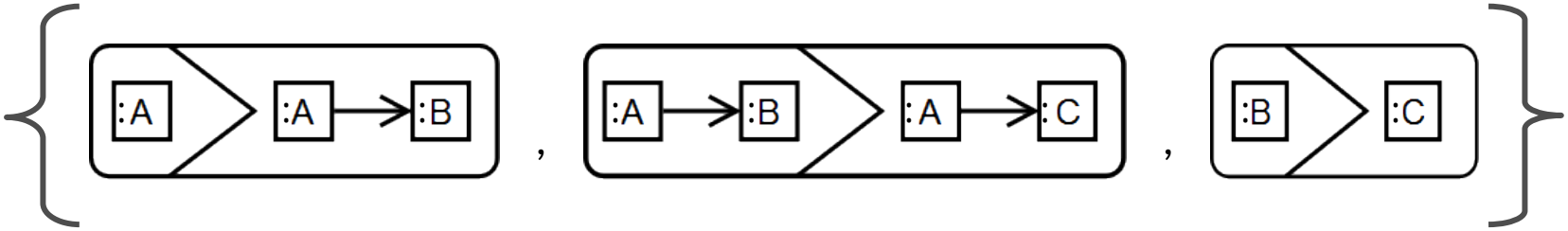
# Graph transformation

- Model transformation paradigm:
  **algebraic graph transformation**

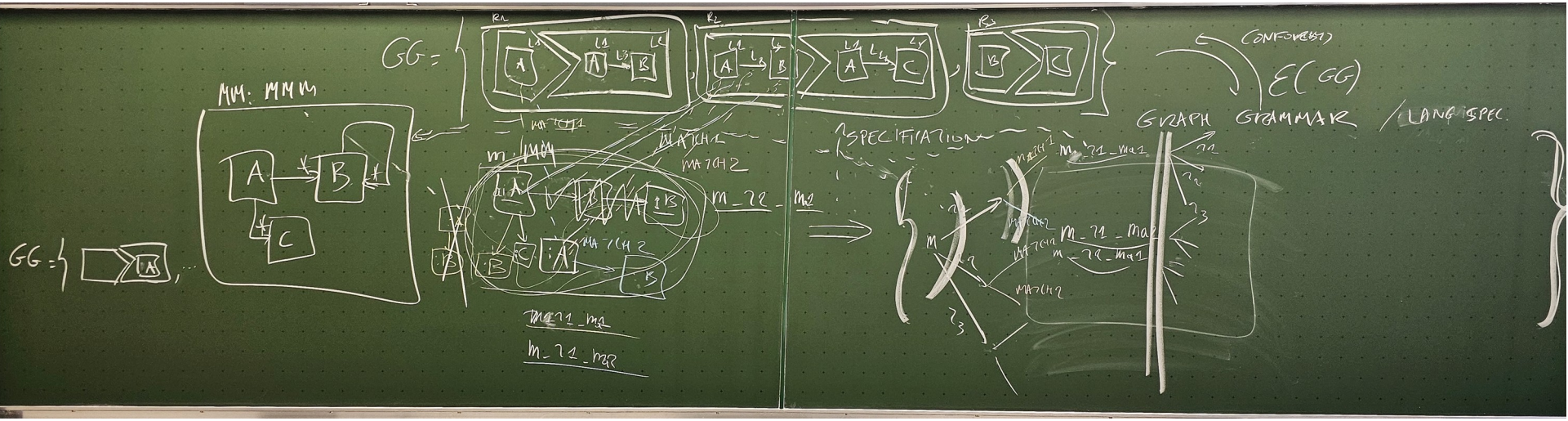
- Model




- Model transformation
  - Rule-based Graph Transformation vs. Graph Grammar



# Graph transformation



# Transformations for language engineering

- Abstract syntax to abstract syntax
  - Tree rewriting
  - Graph transformation (Model-to-model and simulation)
- Abstract syntax to concrete syntax (textual)
  - Model-to-text transformation
- Concrete syntax to concrete syntax (textual)
  - String rewriting
- Concrete syntax to abstract syntax
  - Tree rewriting (Parsing)

# Two main transformation types in MDE

- Model-to-text
  - **Visitor-based**: traverse the model in an object-oriented framework
  - **Template-based**: target syntax with meta-code to access source model
- Model-to-Model
  - **Direct manipulation**: access to the API of M3 and modify the models directly
  - **Operational**: similar to direct manipulation but at the model-level (OCL)
  - **Rule-based**
    - **Graph transformation**: implements directly the theory of graph transformation, where models are represented as typed, attributed, labelled, graphs in category theory. It is a declarative way of describing operations on models.
    - **Relational**: declarative, describing mathematical relations. It define constraints relating source and target elements that need to be solved. They are naturally multi-directional, but in-place transformation is harder to achieve

K. Czarnecki and S. Helsen. Feature-based survey of model transformation approaches. *IBM Systems Journal:* 45(3), 621-645 (2006).

# Typical use cases of model transformation

# Model transformation intent classification

### *Refinement*
- Refinement
- Synthesis
  - Serialization

### *Abstraction*
- Abstraction
- Reverse Engineering
- Restrictive Query
- Approximation

### *Semantic Definition*
- Translational Semantics
- Simulation

### *Language Translation*
- Translation
- Migration

### *Constraint Satisfaction*
- Model Finding
- Model Generation

### *Analysis*

### *Editing*
- Model Editing
- Optimization
- Model Refactoring
- Normalization
  - Canonicalization

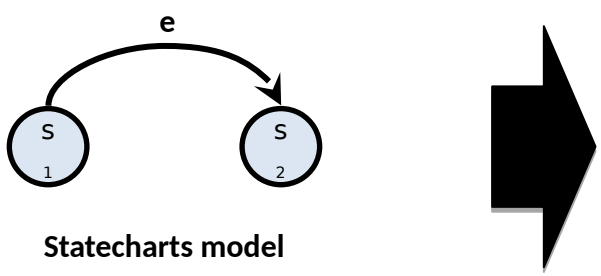
### *Model Visualization*
- Animation
- Rendering
- Parsing

### *Model Composition*
- Model Merging
- Model Matching
- Model Synchronization

L. Lúcio, M. Amrani, J. Dingel, L. Lambers, R. Salay, G. Selim, E. Syriani & M. Wimmer. Model transformation intents and their properties. *Software & Systems Modeling*: 15(3), pp. 647-684 (2016).

# Synthesis

- Refinement where the output is an **executable artifact** expressed in a well-defined language format
  - Typically textual
- **Model-to-code generation**: transformation that produces source code in a target programming language
- Refinement often precedes synthesis




Statecharts model

**Statecharts to Python Compiler**

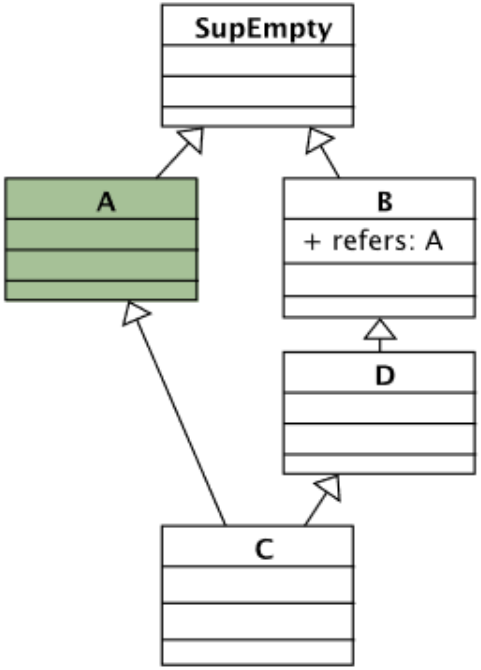
```
if e == 0:                # event "e"
        if table[1] and self.isInState(1) and self.testCondition(3):
        if (scheduler == self or scheduler == None) and table[1]:
                self.runActionCode(4)     # output action(s1)
                self.runExitActionsForStates(-1)
                self.clearEnteredStates()
                self.changeState(1, 0)
                self.runEnterActionsForStates(self.StatesEntered, 1)

self.applyMask(DigitalWatchStatechart.OrthogonalTable[1], table)
                handled = 1
        if table[0] and self.isInState(0) and self.testCondition(4):
                if (scheduler == self or scheduler == None) and
table[0]:
                        self.runActionCode(5)     # output action(s2)
                        self.runExitActionsForStates(-1)
                        self.clearEnteredStates()
                        self.changeState(0, 0)

self.runEnterActionsForStates(self.StatesEntered, 1)
self.applyMask(DigitalWatchStatechart.OrthogonalTable[0], table)
                        handled = 1
```

**Generated Python code**

M. Raphael & H. Vangheluwe. Modular artifact synthesis from domain-specific models. *Innovations in Systems and Software Engineering*: 8(1) pp. 65-77 (2012).

# Querying models with IncQuery

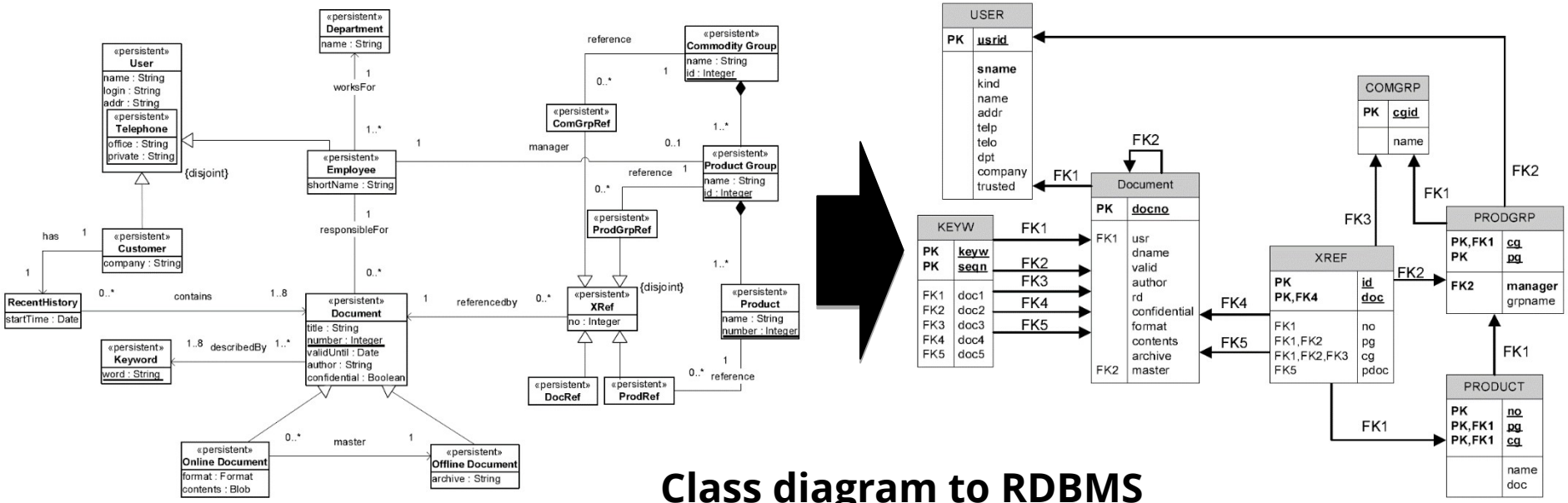
```
pattern superClass(sub : Class, sup : Class) {
  Generalization.specific(gen, sub);
  Generalization(gen);
  Generalization.general(gen, sup);
}

pattern hasOperation(cl : Class, op : Operation) {
  Class.ownedOperation(cl, op);
} or {
  find superClass+(cl, owner);
  Class.ownedOperation(owner, op);
}

pattern emptyClass(cl : Class) {
  neg find hasOperation(cl, _op);
  neg find hasProperty(cl, _pr);
  Class.name(cl, n);
  check(!(n.endsWith("Empty")));
}
```




Z. Ujhelyi, et al. EMF-IncQuery: An integrated development environment for live model queries. *Science of Computer Programming:* 98, 80-99 (2015).

# Translation

- **Maps** concepts of a model in a source language to concepts of another target language, while translating the **semantics** of the former in terms of the latter
- Similar to translational semantics, but the source language already has a semantics

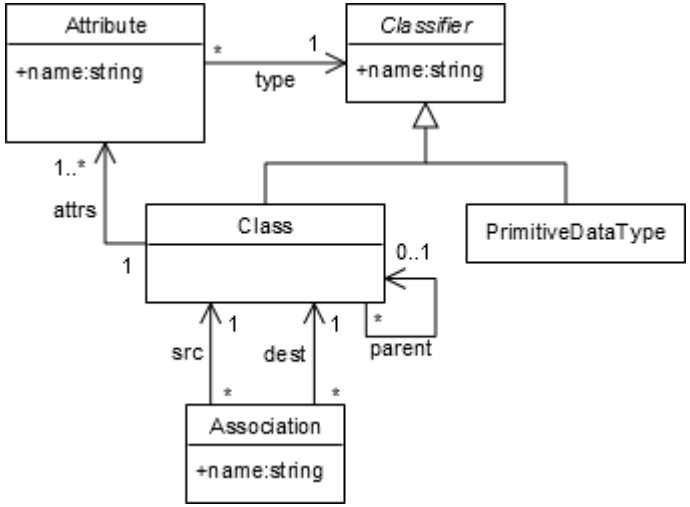



**Class diagram to RDBMS**

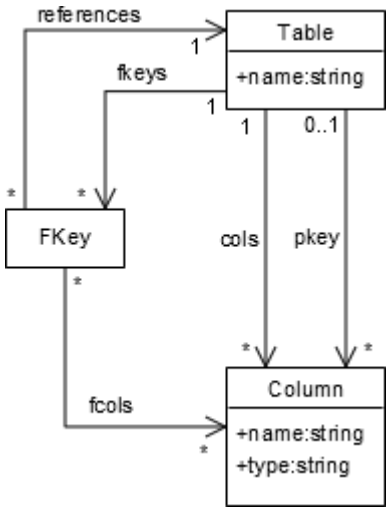
J. Bézivin et al. Model Transformation in Practice Workshop Announcement. *MODELS*, 2005

# CD to RDBMS transformation

source language
CD metamodel

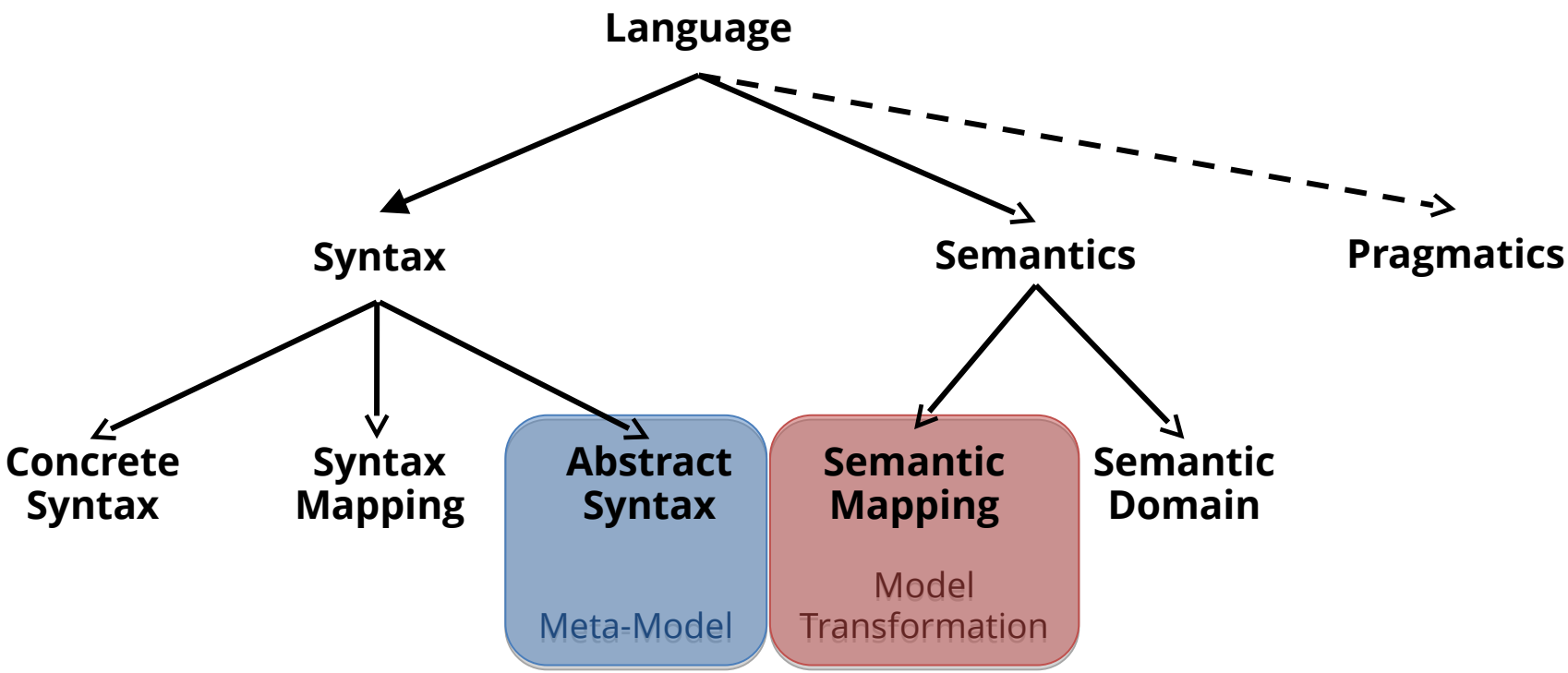



target language
RDBMS metamodel



# Translational Semantics

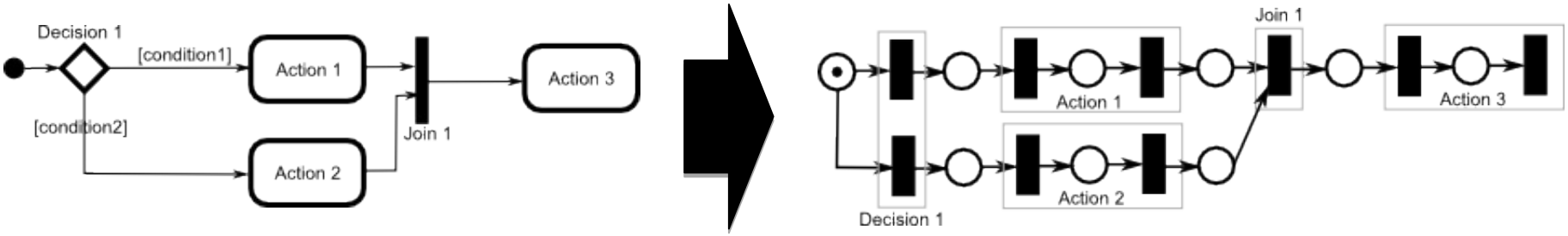
- Gives the **meaning** of a model in a source language in terms of the concepts of another target language
- Typically used to capture the semantics of **new DSLs**



# Translational Semantics

- Simulink Block Diagram's semantics expressed as Ordinary Differential Equations

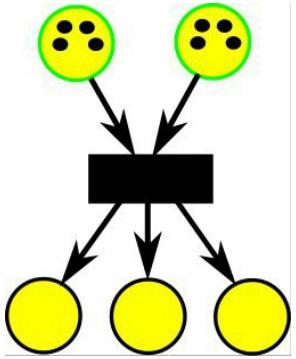
- UML activity diagrams semantics expressed as Petri nets




E. Syriani and H. Ergin. Operational Semantics of UML Activity Diagram: An Application in Project Management. *RE 2012 Workshops*: pp. 1-8, IEEE (2012)

# Simulation

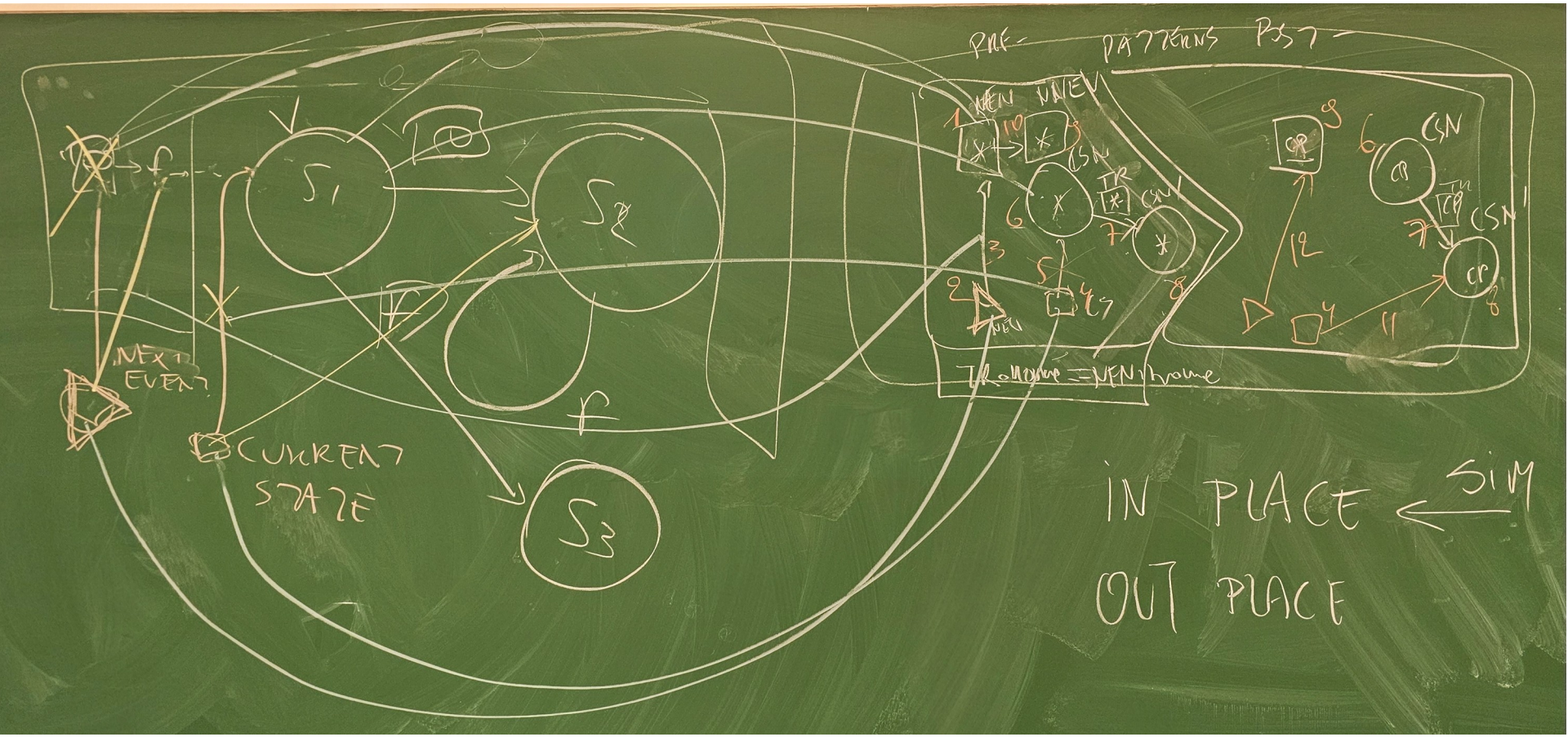
- Defines the **operational semantics** of a modeling language that updates the state of the system modeled
- The source and target meta-models are **identical**
- The target model is an **"updated"** version of the source model: no new model is created
- Simulation updates the abstract syntax, which may trigger modifications in the concrete syntax



**Petri nets simulator**

T. Kühne, G. Mezei, E. Syriani, H. Vangheluwe and M. Wimmer. Explicit Transformation Modeling. *MODELS 2009 Workshops*, LNCS: 6002, pp. 240-255, Springer (2010).

# FSA Operational Semantics



# Vocabulary

- Relationship between source & target meta-models
  - **Endogenous**: Source meta-model = Target meta-model
  - **Exogenous**: Source meta-model ≠ Target meta-model
- Relationship between source & target models
  - **In-place**: Transformation executed within the same model
  - **Out-place**: Transformation produces a different model

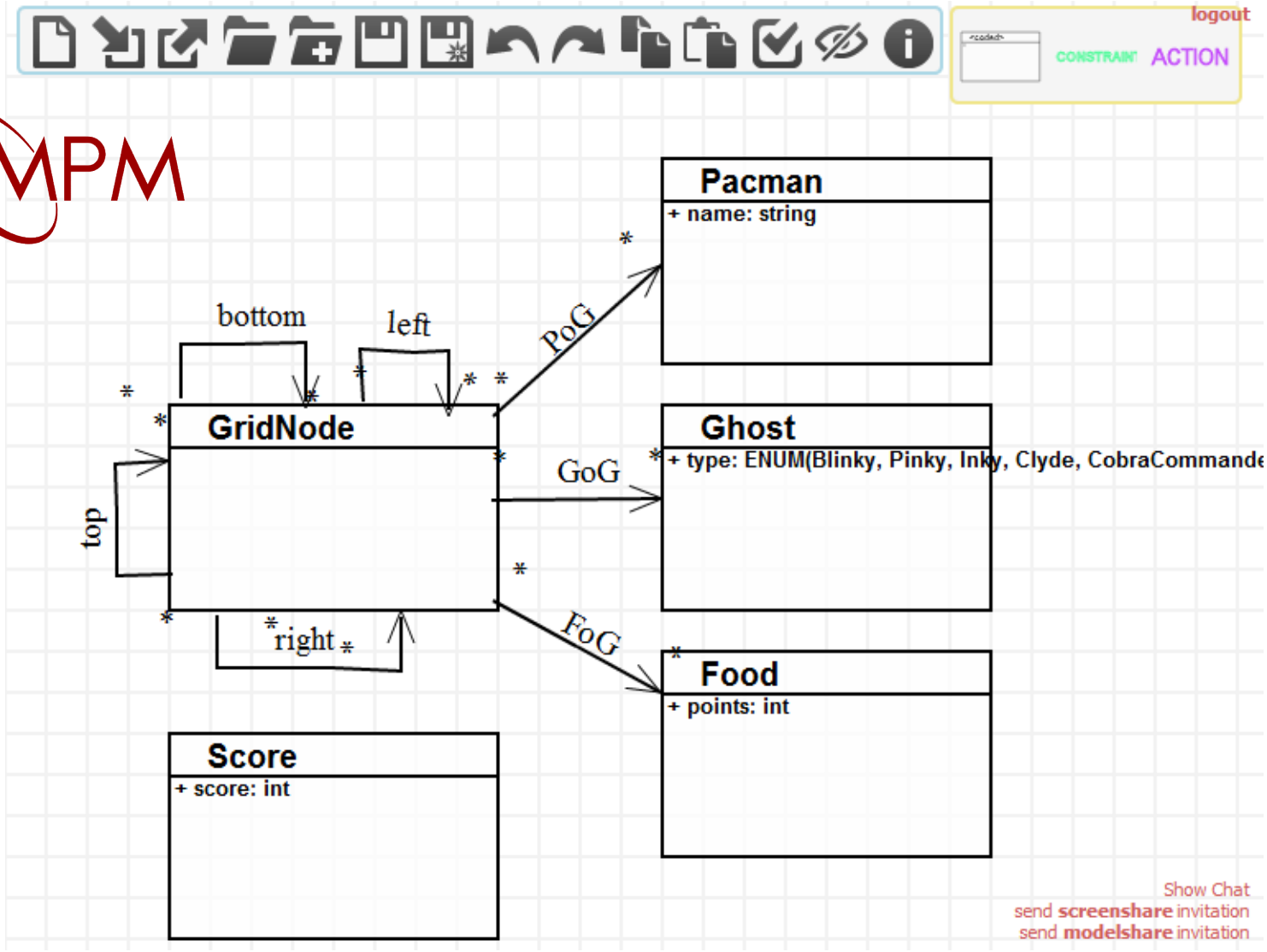
| | **Outplace** | **Inplace** |
|---|---|---|
| **Endogenous** | Refinement, Query | Simulation |
| **Exogenous** | Refinement, Synthesis,<br>Translational semantics | |

# Rule-based model transformation

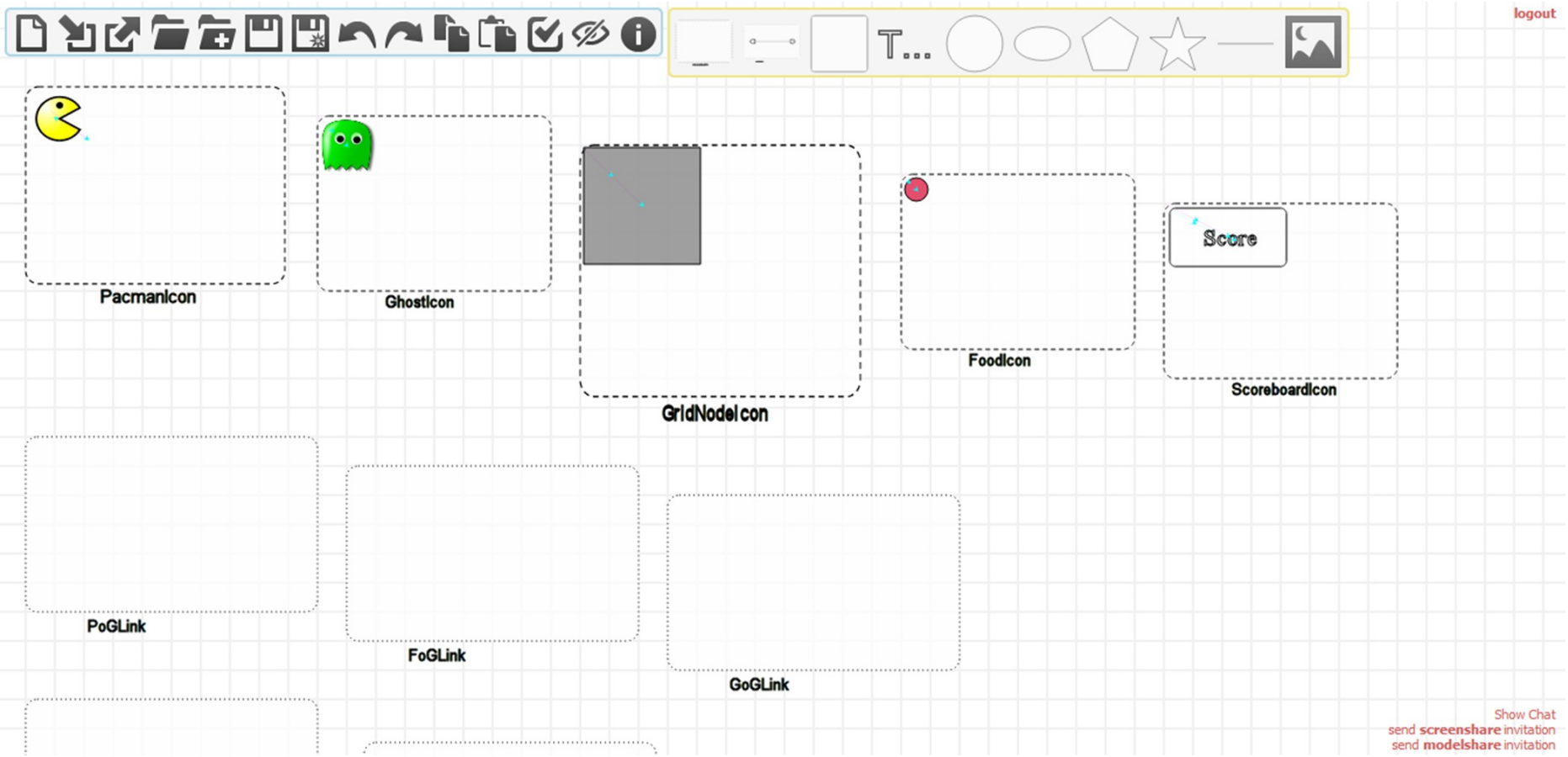
# Graph transformation for simulation

- Models are considered as directed, typed, attributed graphs
- Transformations on such graphs are considered as graph rewritings
- Features:
  - Declarative paradigm
  - Rules defined as pre- and post-conditions
- Tools: **MoTif**, Henshin, GReAT

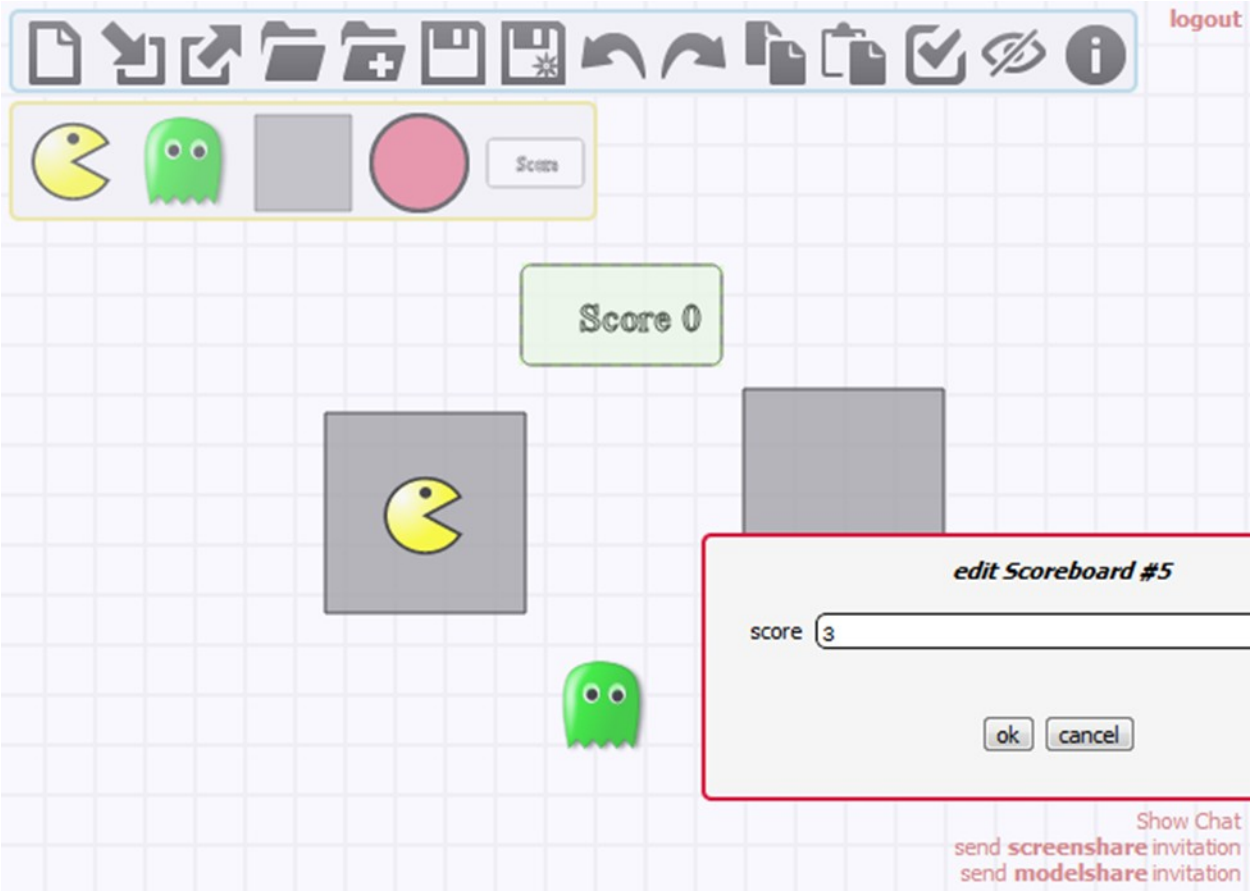
# Metamodel of Pacman



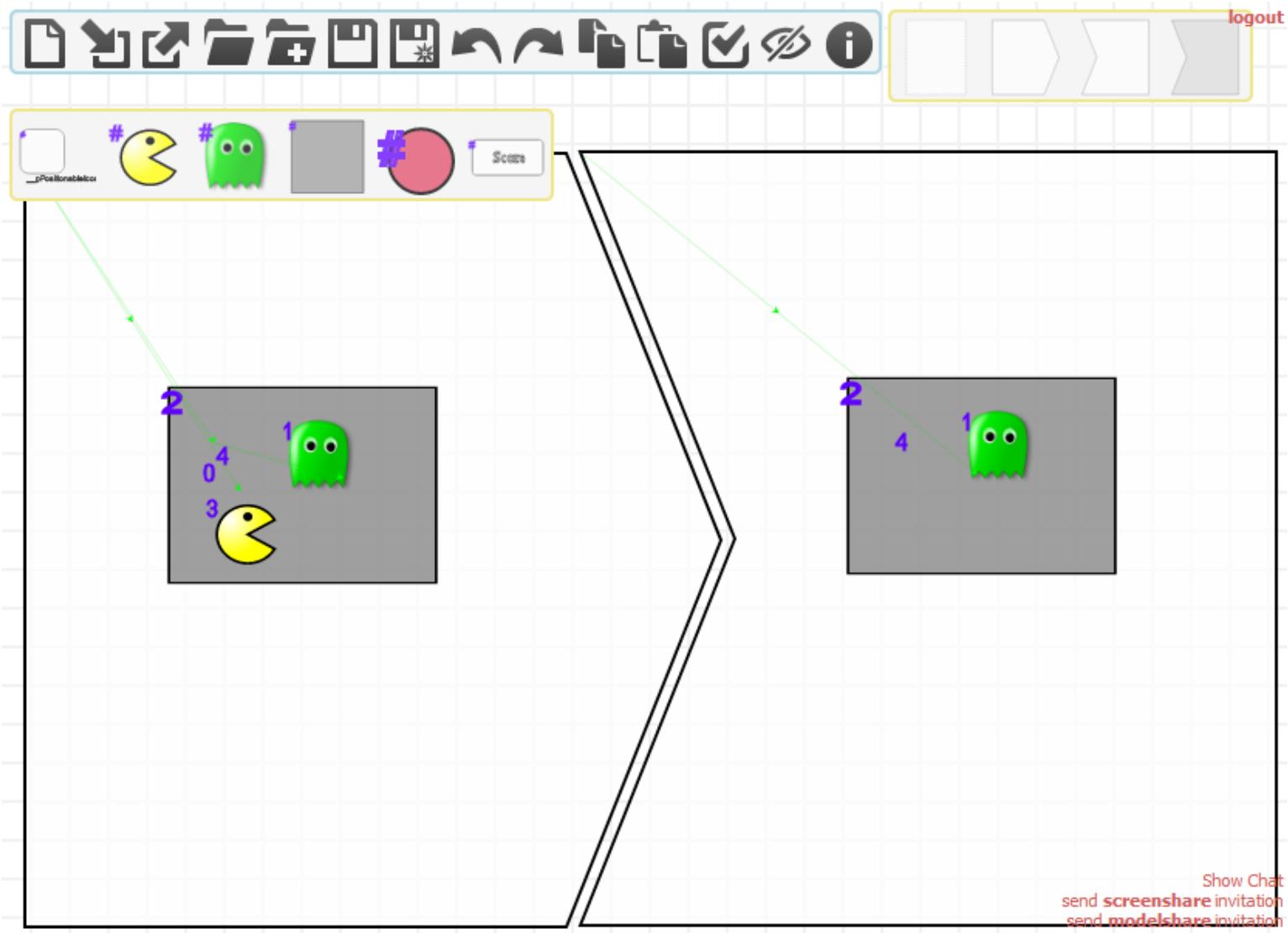
# Concrete syntax



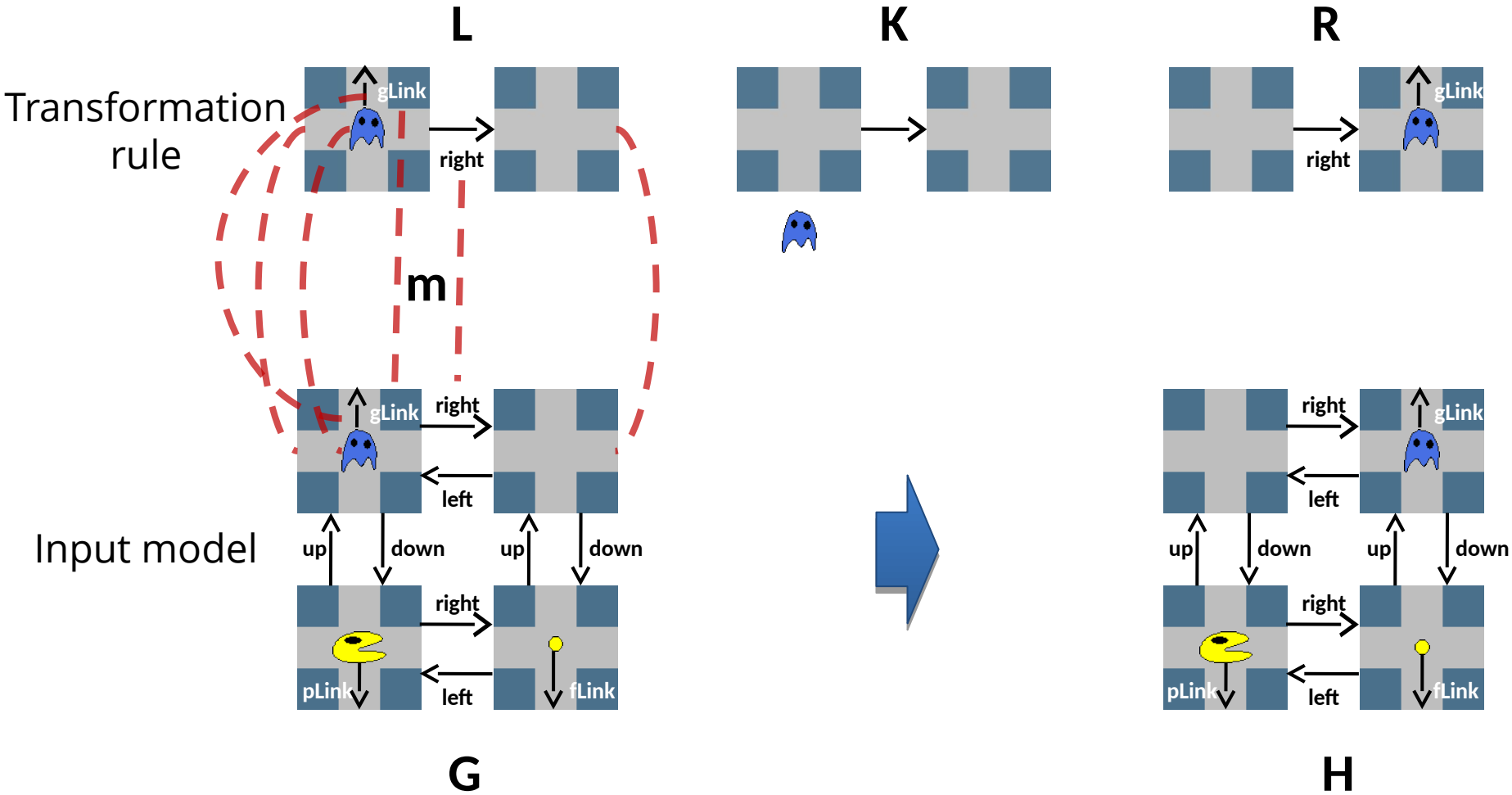
# Generate modeling environment



# Graph transformation rule



# Rule-based graph transformation



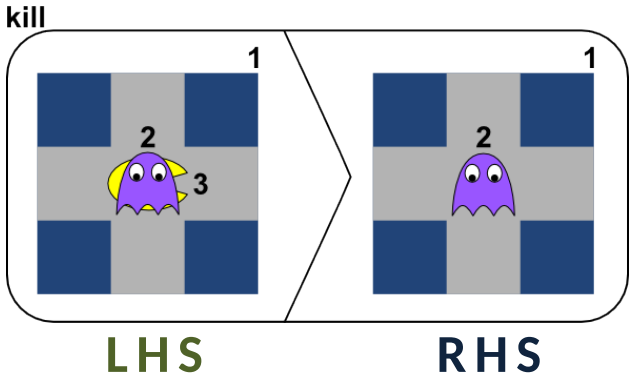

If there exists an occurrence of **L** in **G** then replace it with **R**

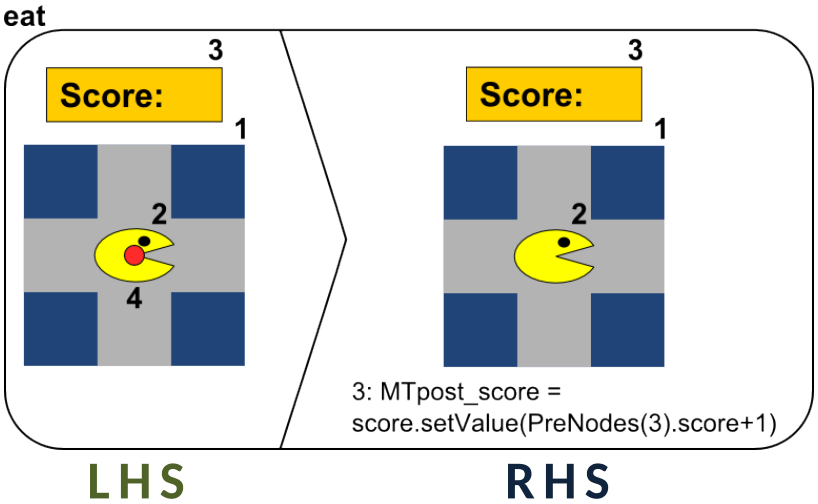
# Mechanics of rule application

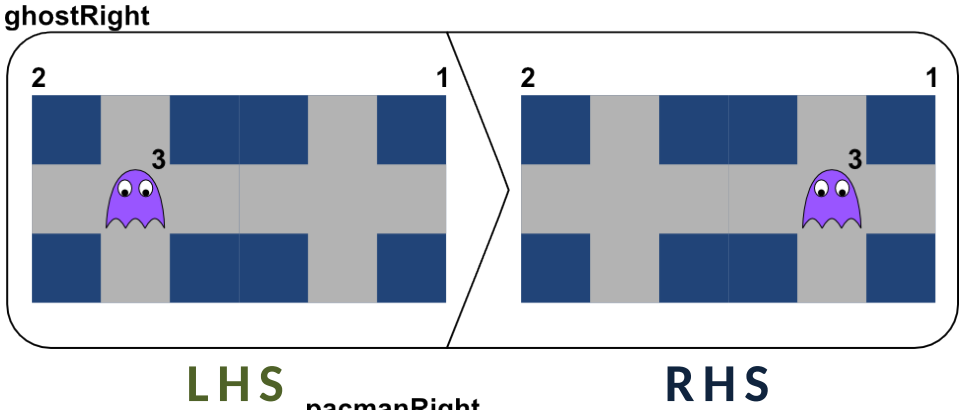
1. <u>Matching Phase</u>
   - Find an embedding $m$ of the LHS pattern $L$ in the host graph $G$
   - An occurrence of $L$ is called a **match**: $m(L)$
   - Thus, $m(L)$ is a sub-graph of $G$
2. <u>Rewriting Phase</u>
   Transform $G$ so that it satisfies the RHS pattern:
   - **Remove** all elements from $m(L - K)$ from $G$
   - **Create** the new elements of $R - K$ in $G$
   - **Update** the properties of the elements in $m(L \cap K)$

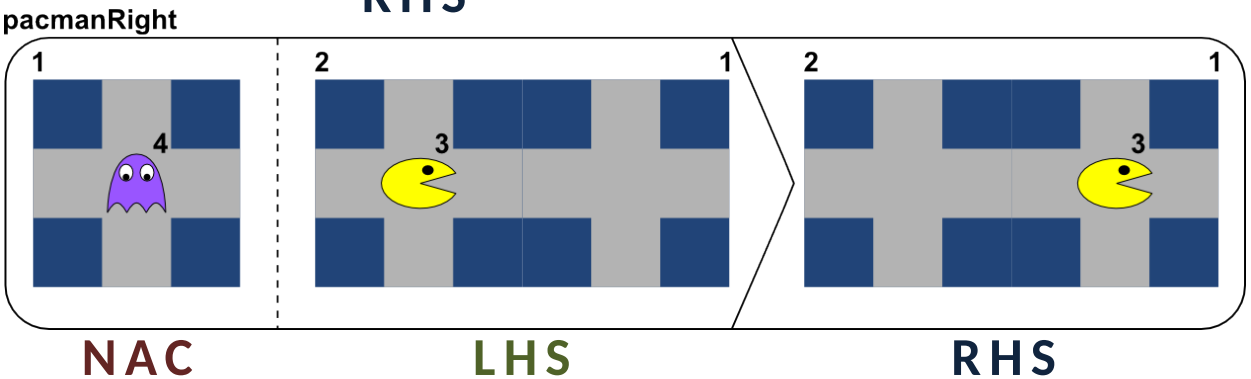
- When a match of the LHS can be found in $G$, the rule is **applicable**
- When the rewriting phase has been performed, the rule was **successfully applied**

# Operational semantics



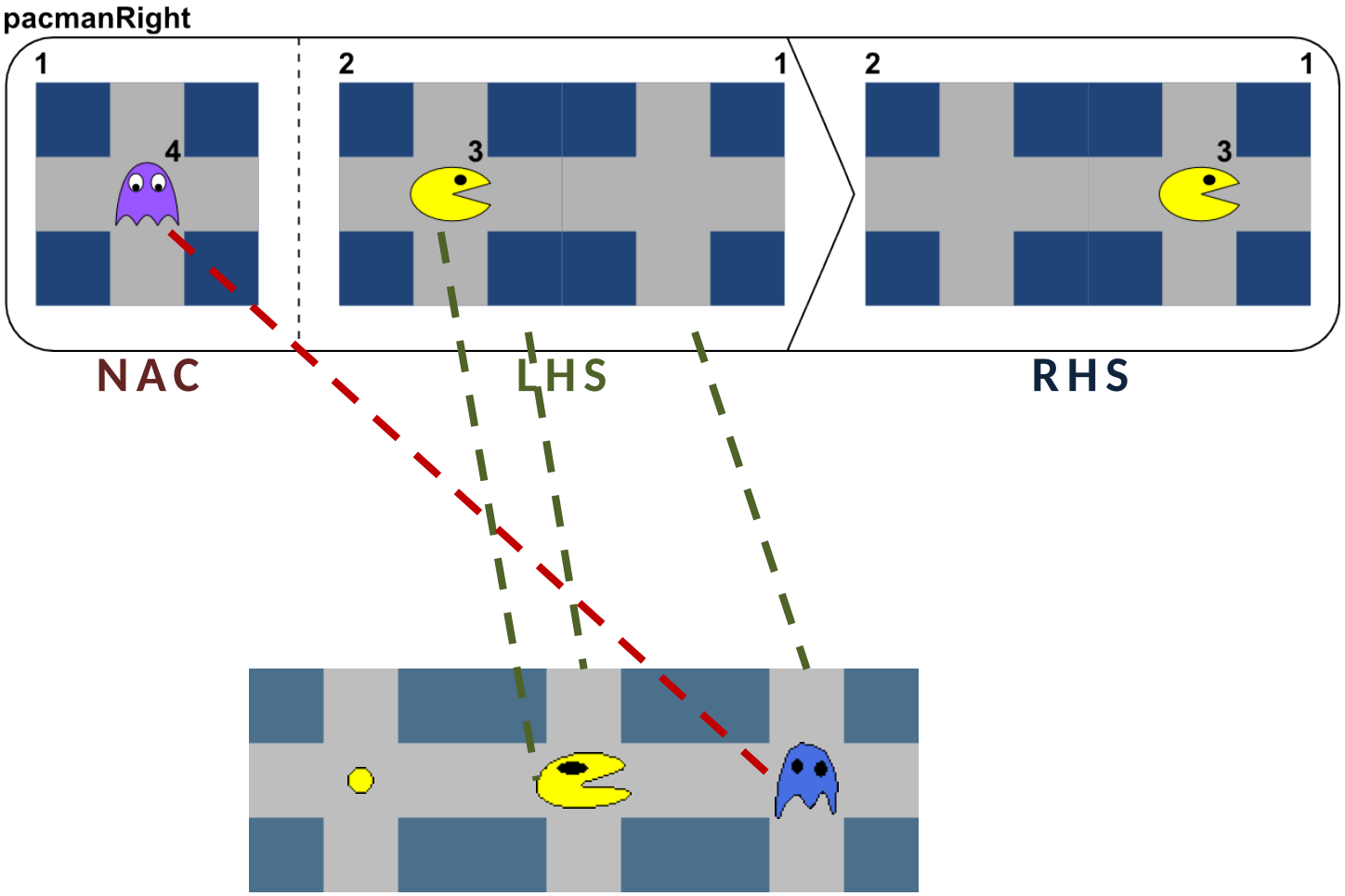



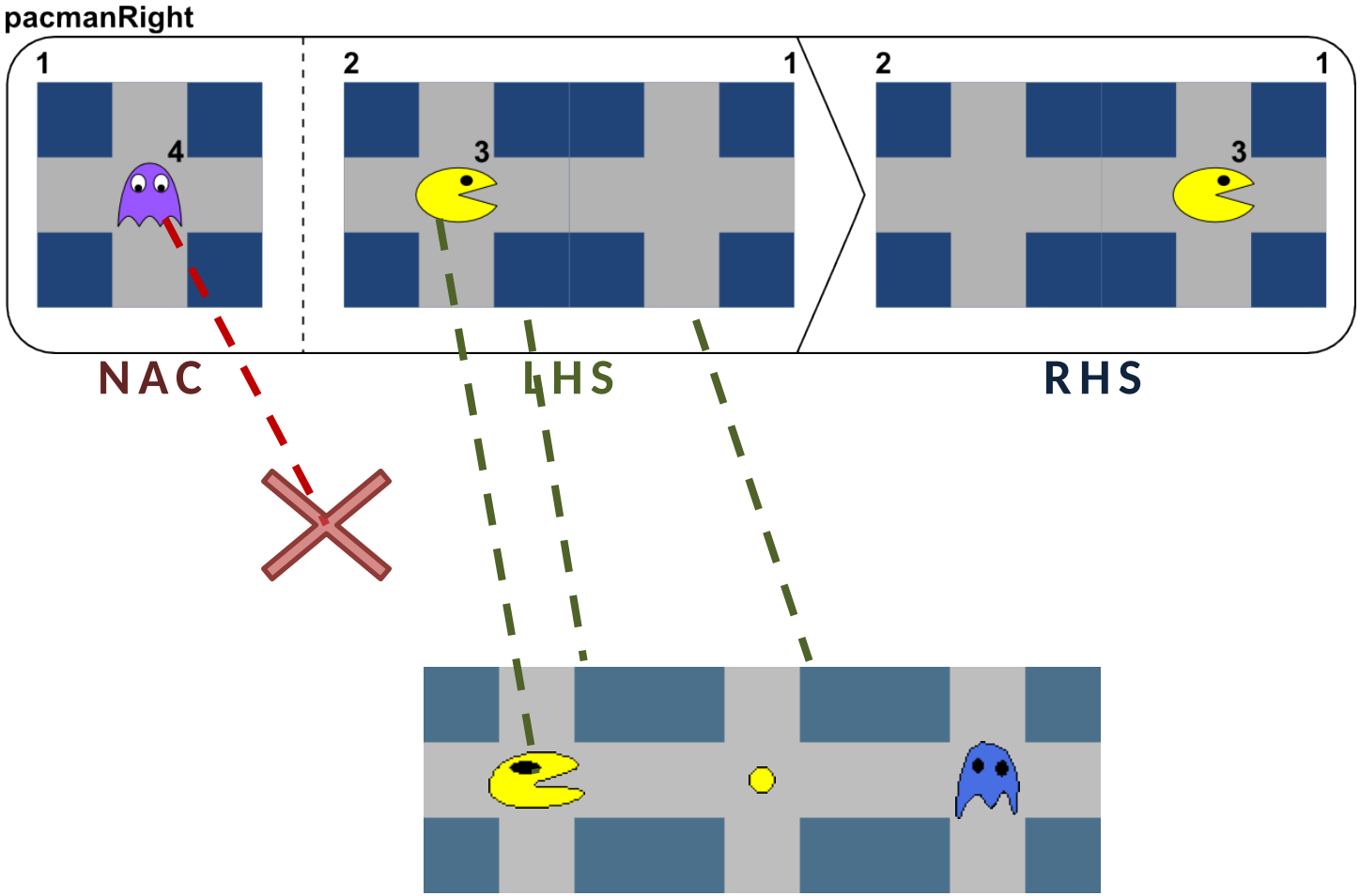
# Negative application conditions

## Non-applicable rule



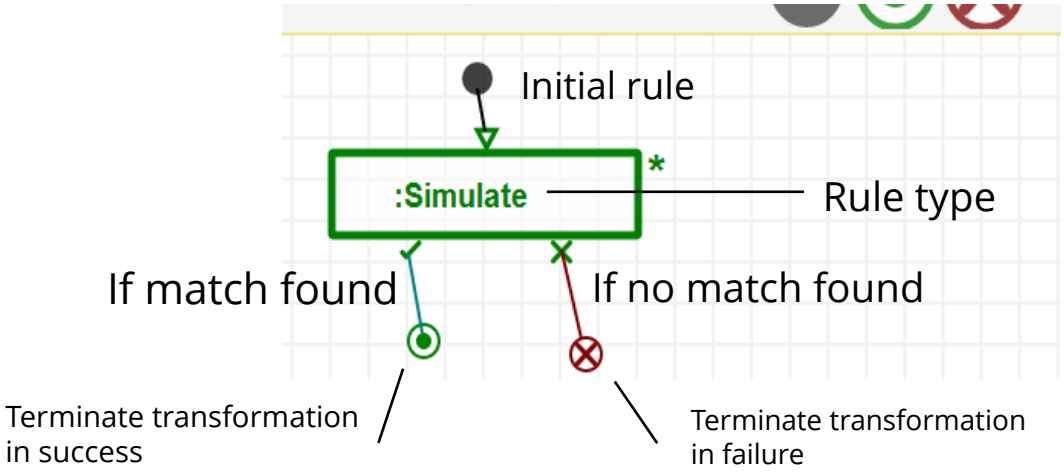
# Negative application conditions

## Applicable rule

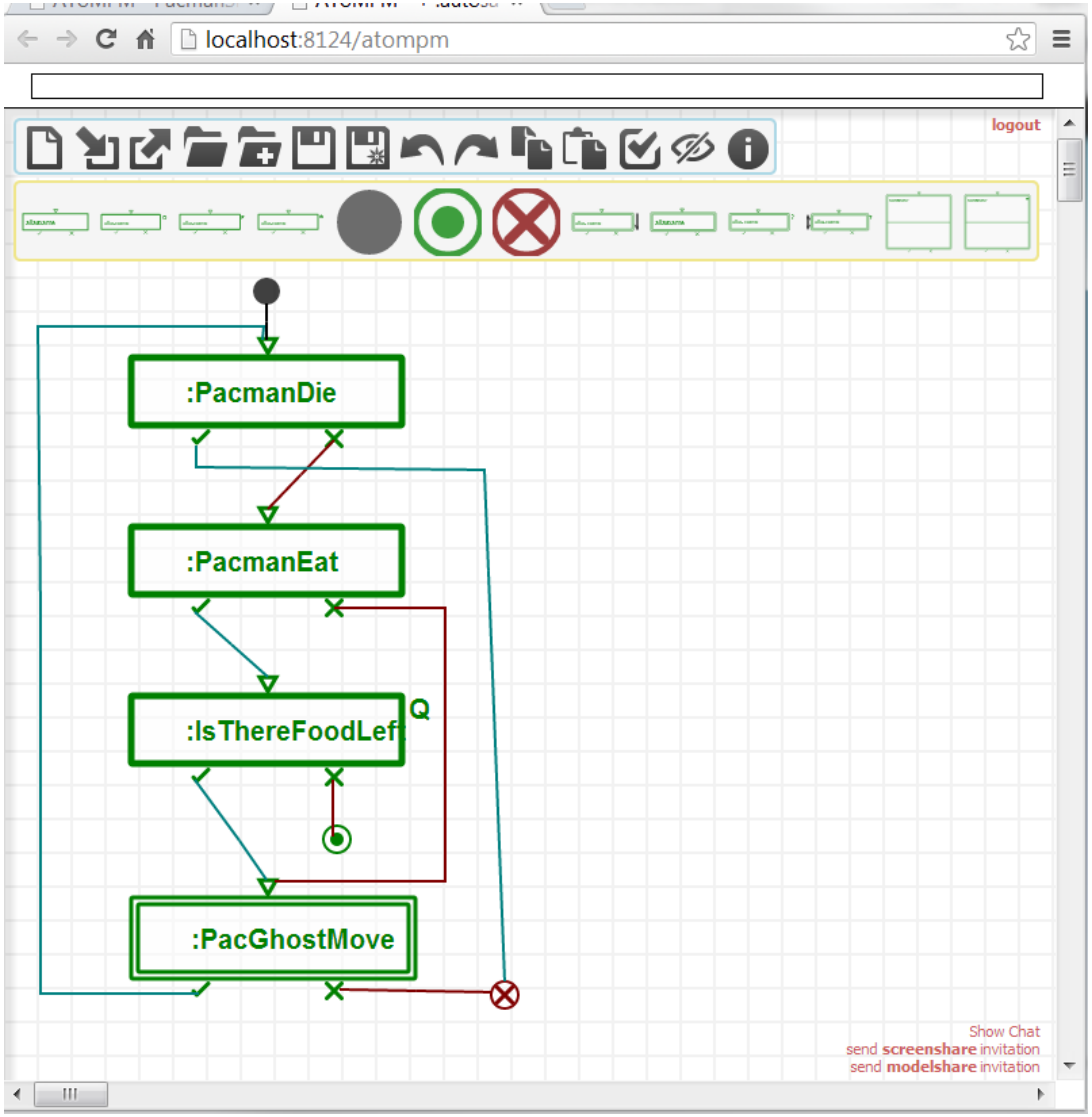


# Rule scheduling

- In what order should the rules be executed?
  - Don't care: randomly, non-deterministically
  - Partial order
  - Explicit ordering
- **MoTif** is the transformation language of AToMPM

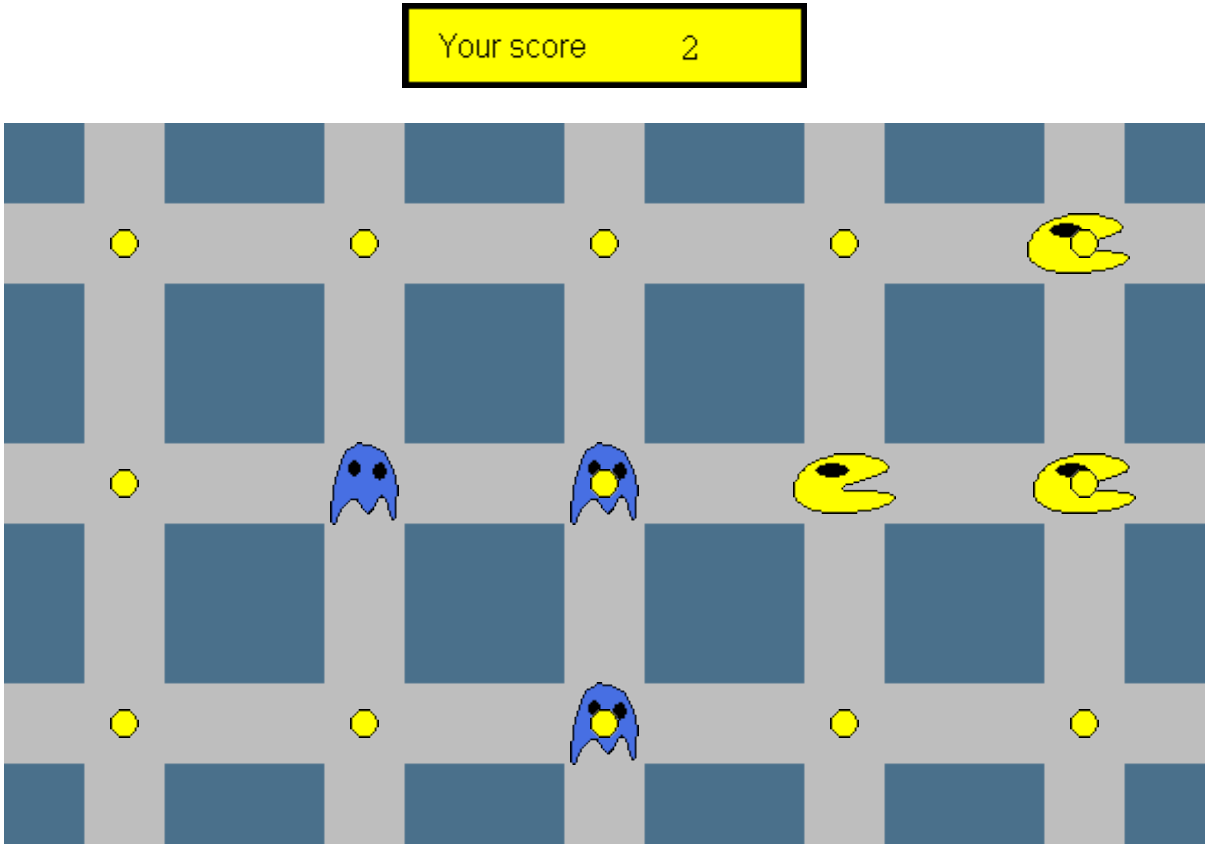


# Scheduling of the rules

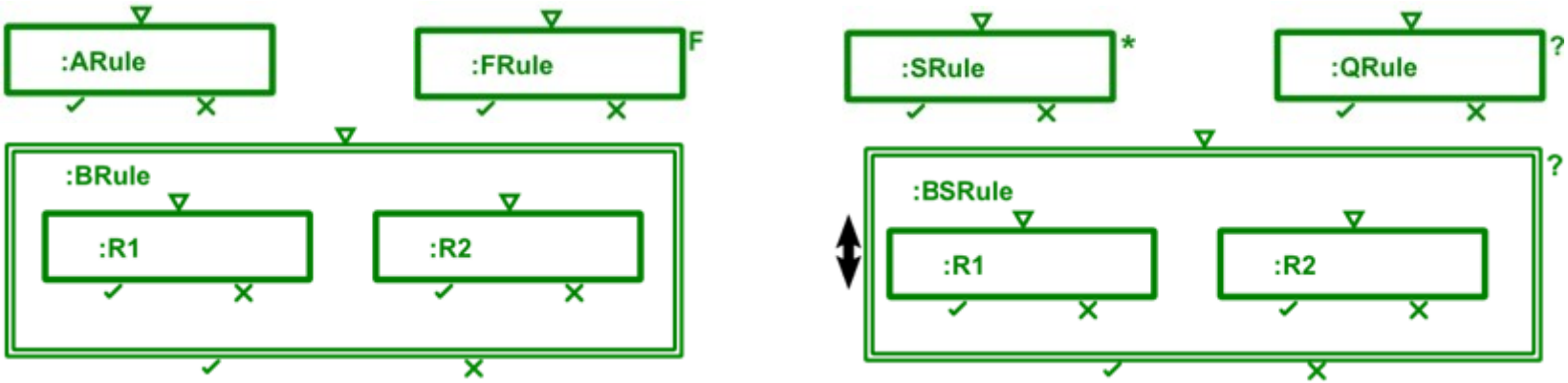


# Simulation of a model

1. pacmanDie
2. pacmanEat
3. isThereFoodLeft
4. ghostMoveLeft
5. ghostMoveRight
6. ghostMoveUp
7. ghostMoveDown
8. pacmanMoveLeft
9. pacmanMoveRight
10. pacmanMoveUp
11. pacmanMoveDown



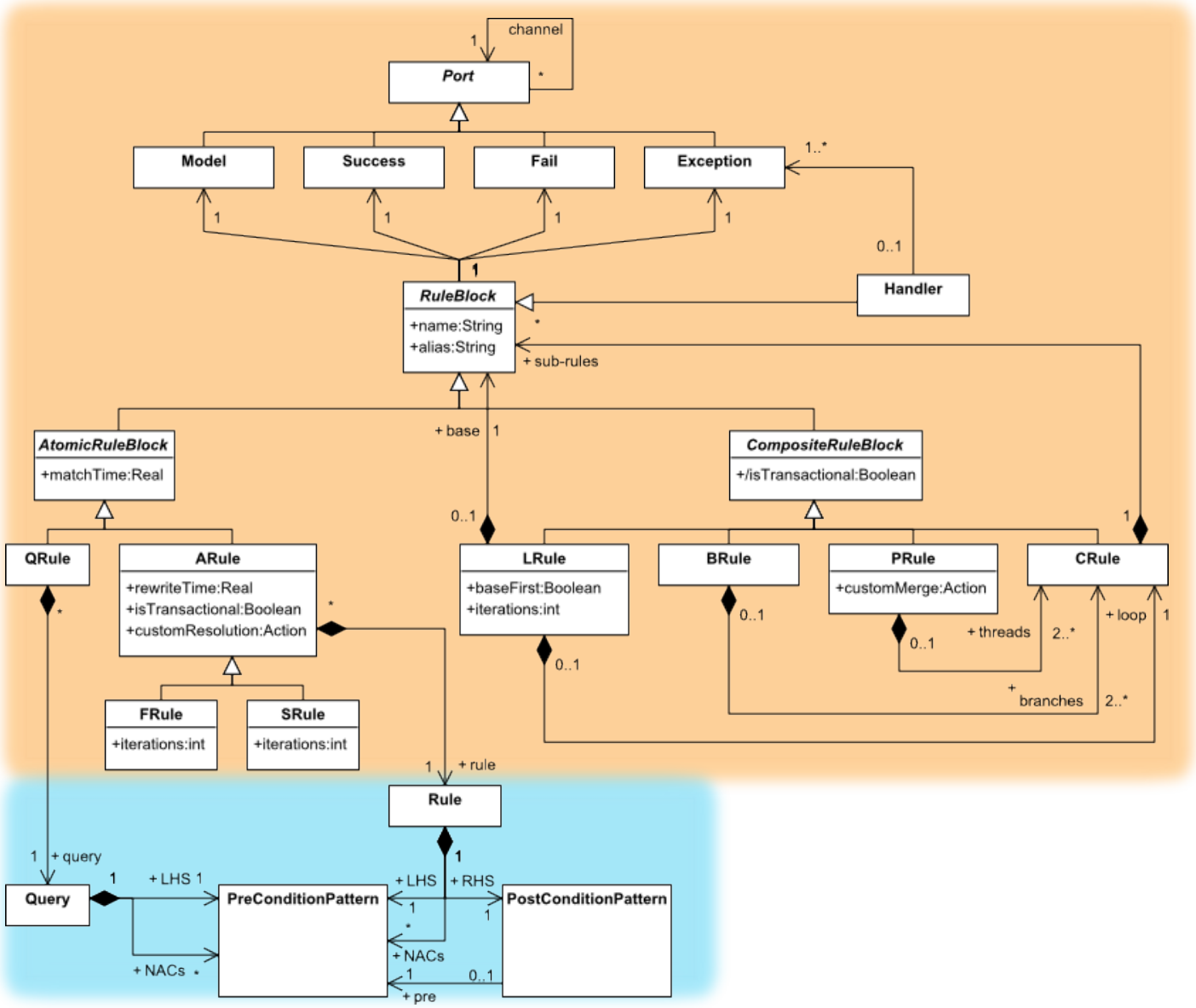
# MoTif main rule types



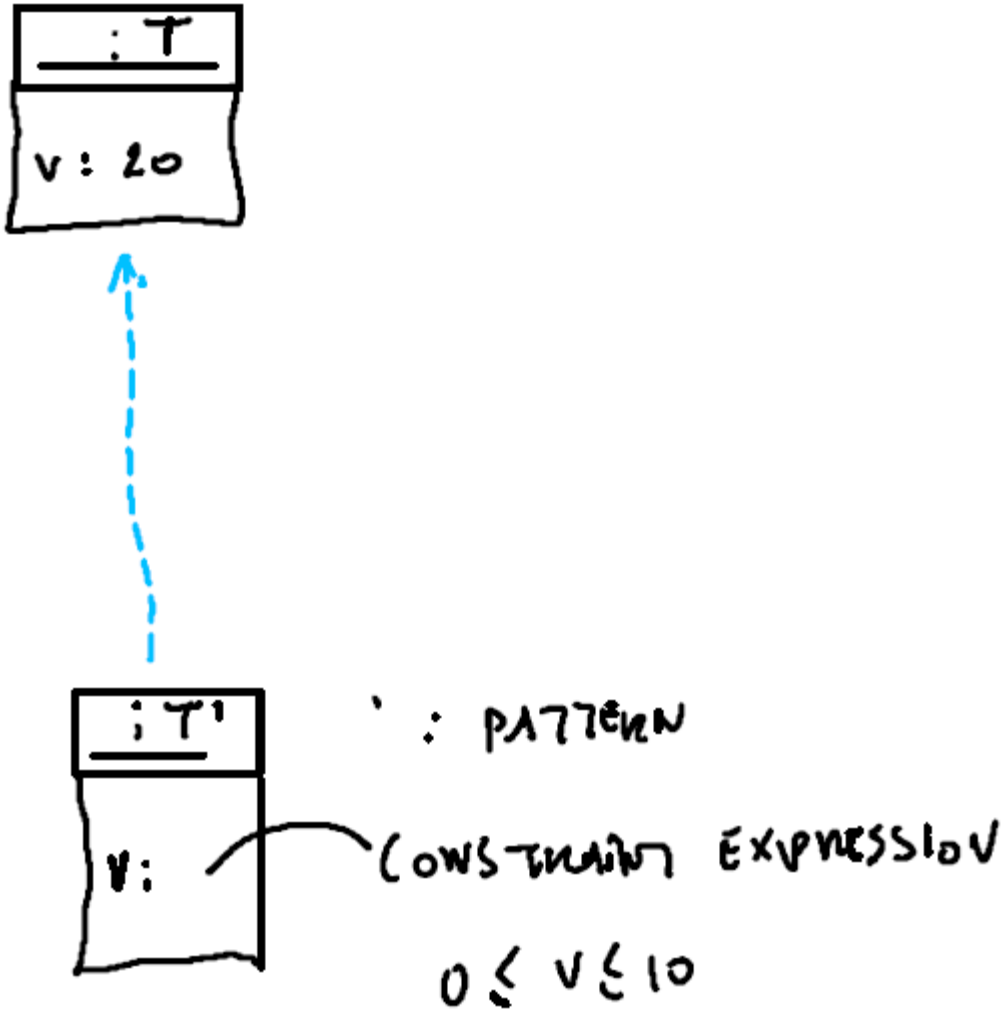

- **ARule:** (atomic) Applies rule on one match
- **FRule:** (for all) Applies rule on all matches found in parallel
- **SRule:** (star) Applies rule recursively as long as a match is found
- **QRule:** (query) Finds a match, only LHS no RHS
- **BRule:** (branch) Randomly (uniformly!) selects one matching rule
- **BSRule:** (branch star) Applies BRule as long as one rule matches

# Model Transformation





# Pattern model <> Instance model

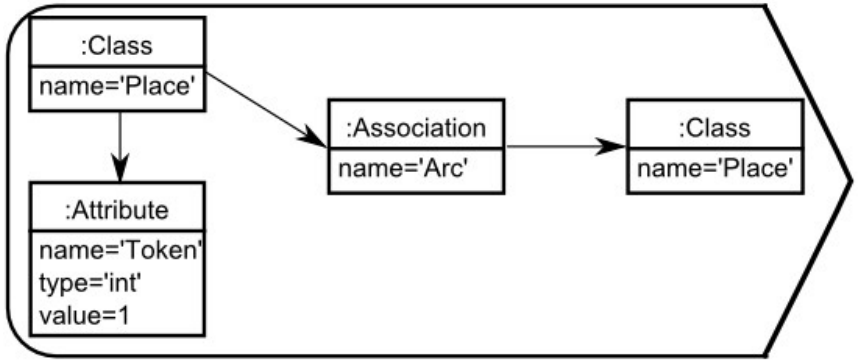



Instance model

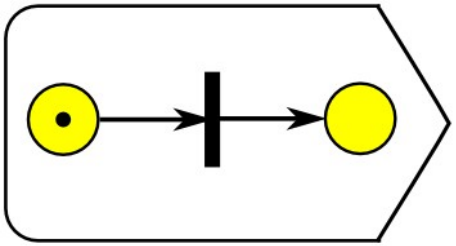
Pattern model

# Pattern language

1. Generic pattern language
   + Most economic solution
   - Generic concrete syntax (MOF-like)
   - Allow to specify patterns that will never occur

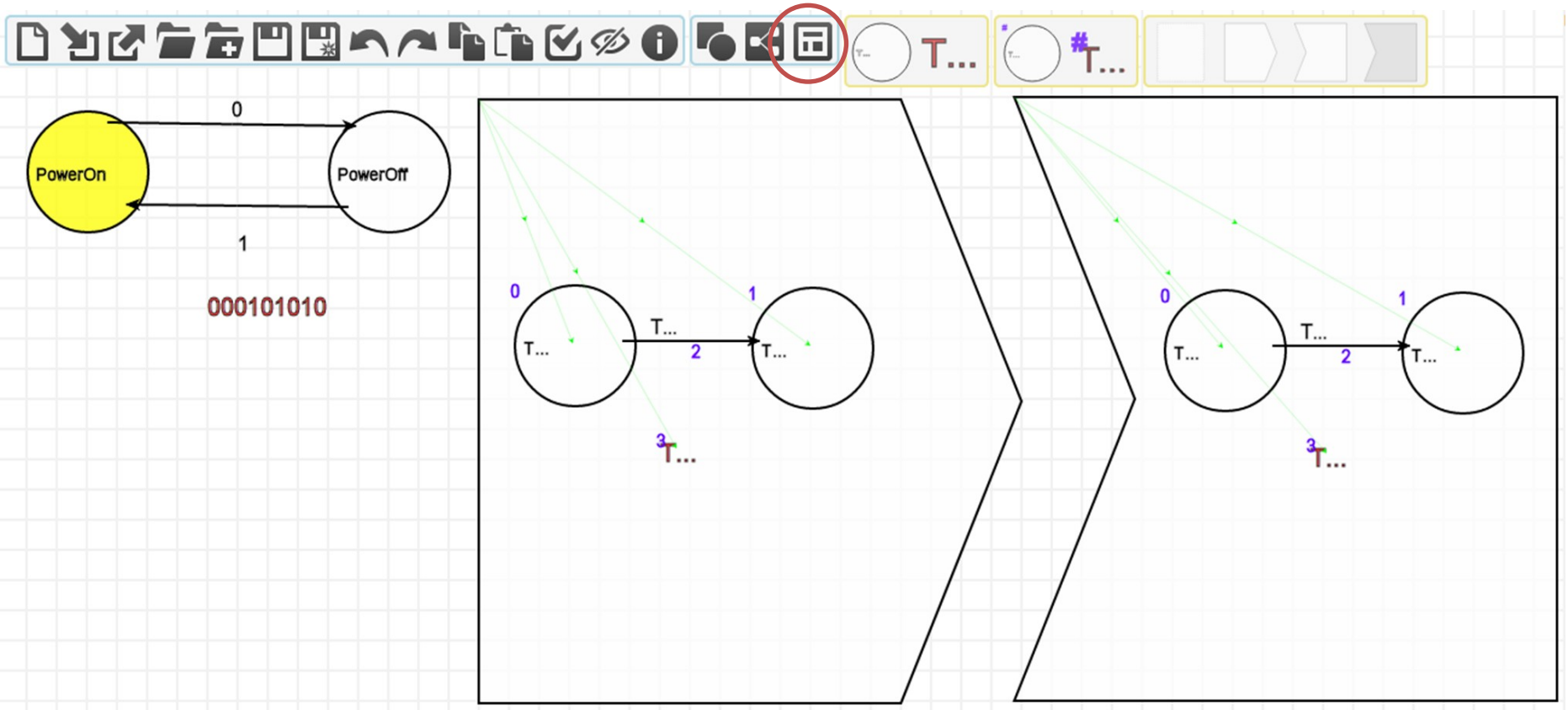



2. Customized pattern language
   + Concrete syntax adapted to the source/target languages (DSL)
   + Exclude patterns that do not have a chance to match
   - More work for the tool builder



[E.b1]

# RAMification process



# Domain-specific pattern languages

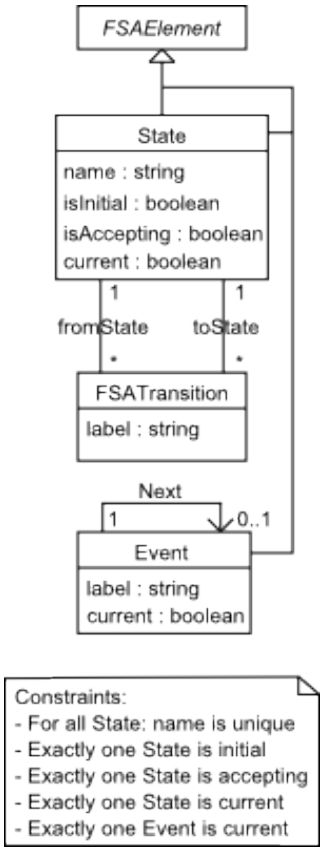
**Ramification Process:** automatically generated environment for pattern language

**Input Meta-Model** **Output Meta-Model**

**Relax Augment Modify**

**Customized Pattern Meta-Model**

# RAMification process: starting point meta-model(s)

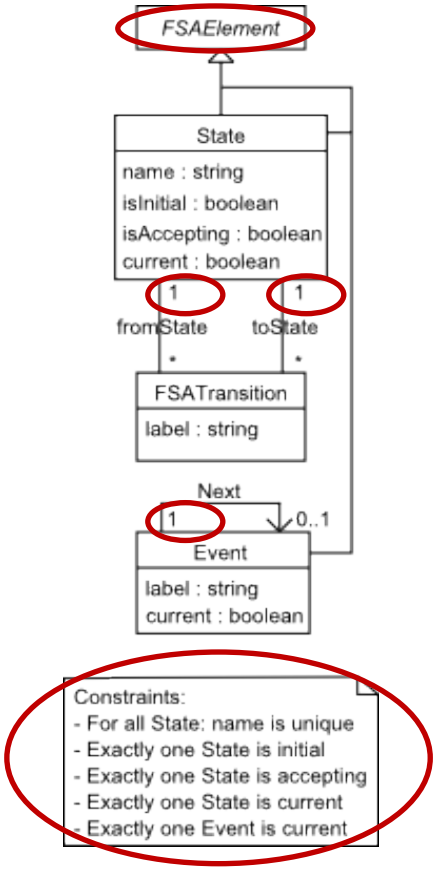


# RAMification process

## Relaxation

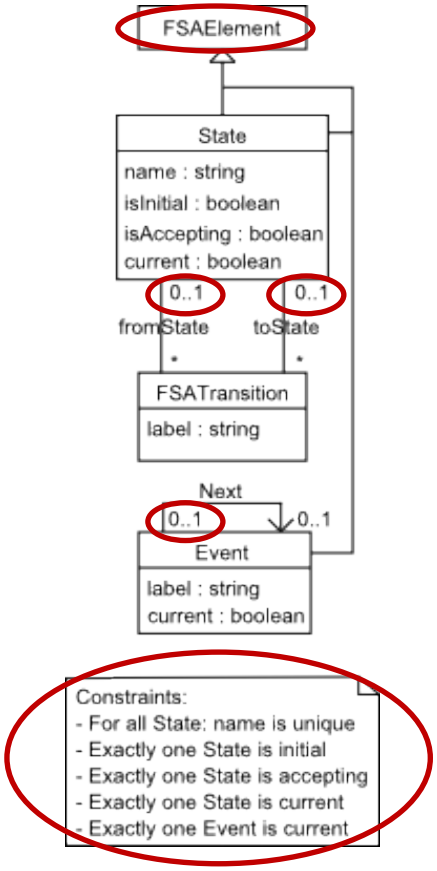
- Relaxes the constraints imposed by the meta-model(s) of the domain (source and target when exogenous)
- Make abstract classes concrete (to allow instantiation)
- Reduction of minimal multiplicity of every association end
- Constraints relaxation (manual)
  - Removed
  - Preserved
  - Depends on static semantics of the language(s)

# RAMification process




Relax

# RAMification process

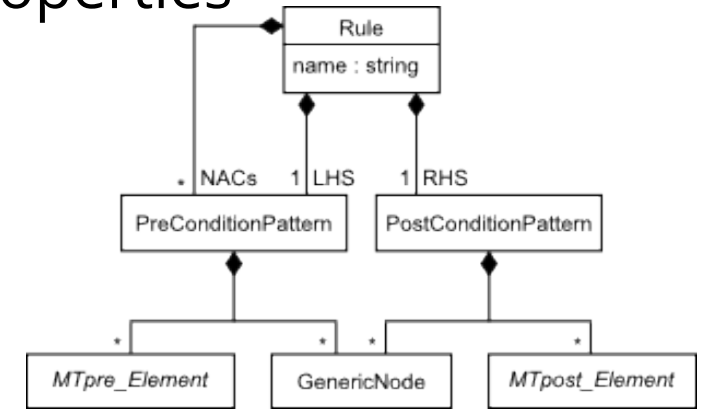



Relax

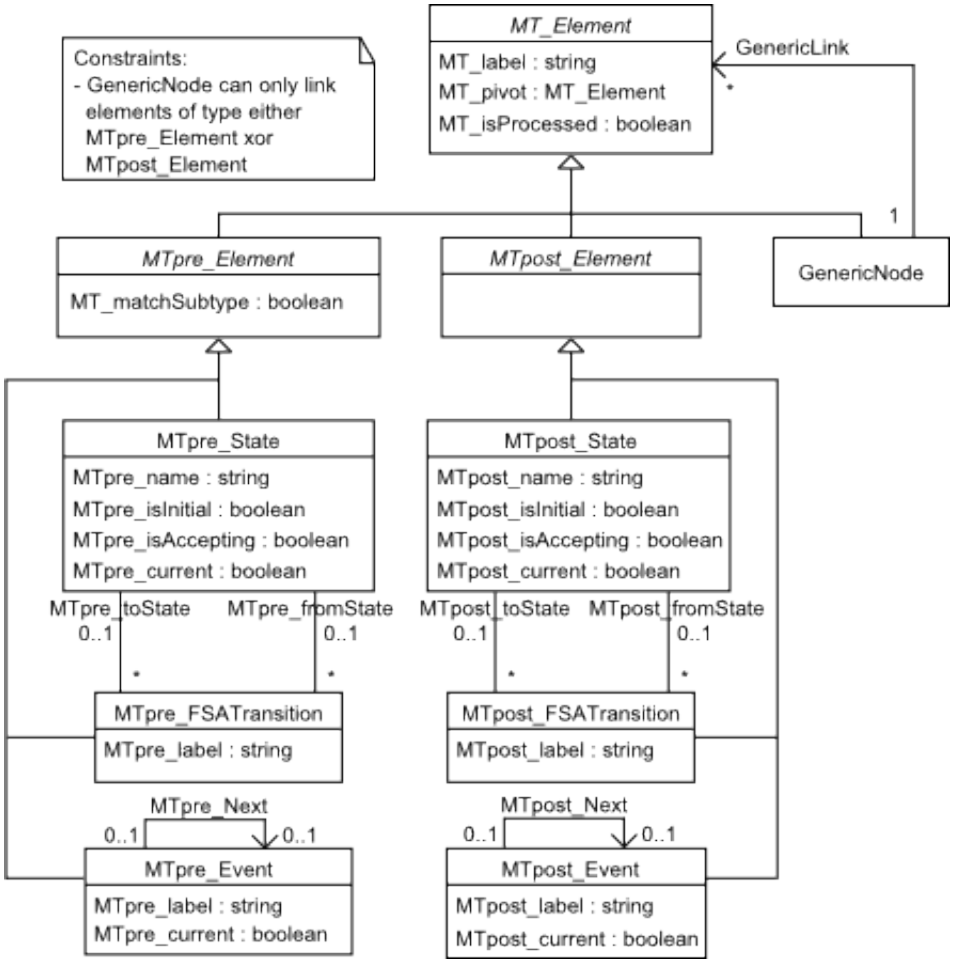
# RAMification process

## Augmentation

- Augments the resulting meta-model with additional information
- Classes and associations integrated in a rule meta-model
- Re-typing of all meta-model entities to pre/post
- Add model transformation-specific properties
  - Labels
  - Parameter passing (pivots)
- Allow abstract rules
- Augmented constraints
- Connection with generic/trace elements



# RAMification process



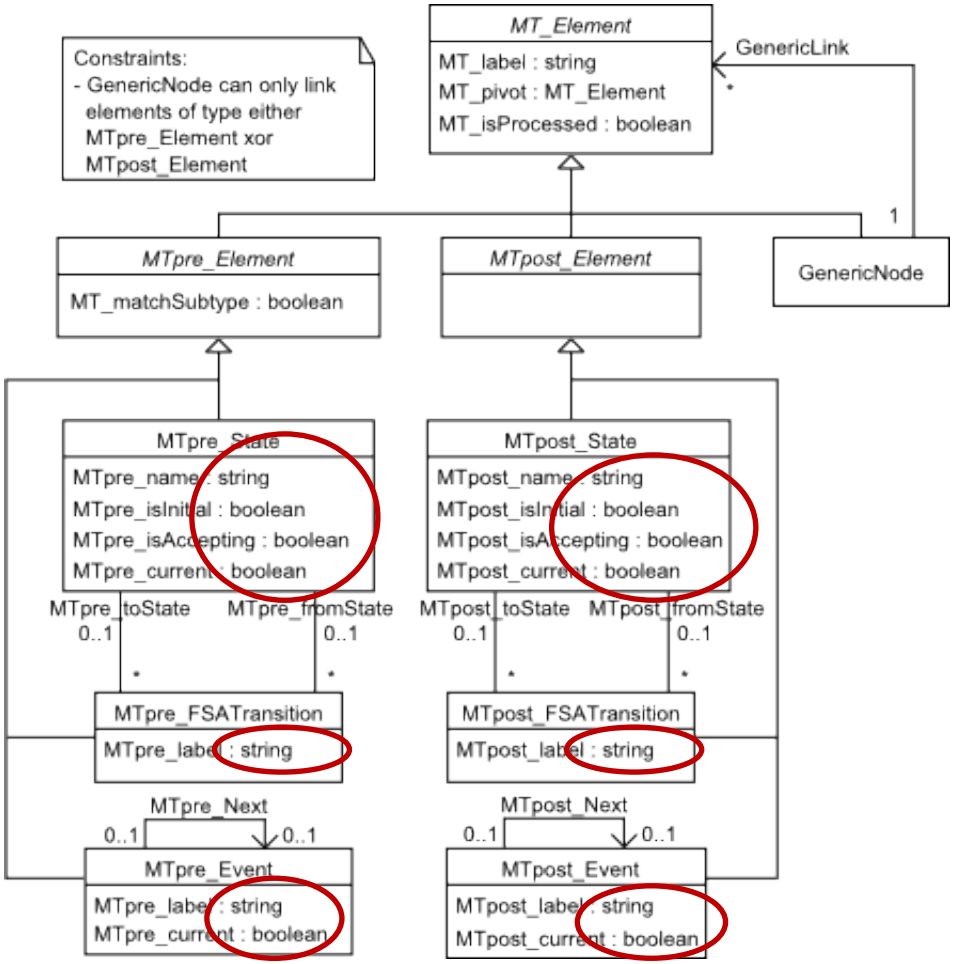

Augment

# RAMification process

## Modification

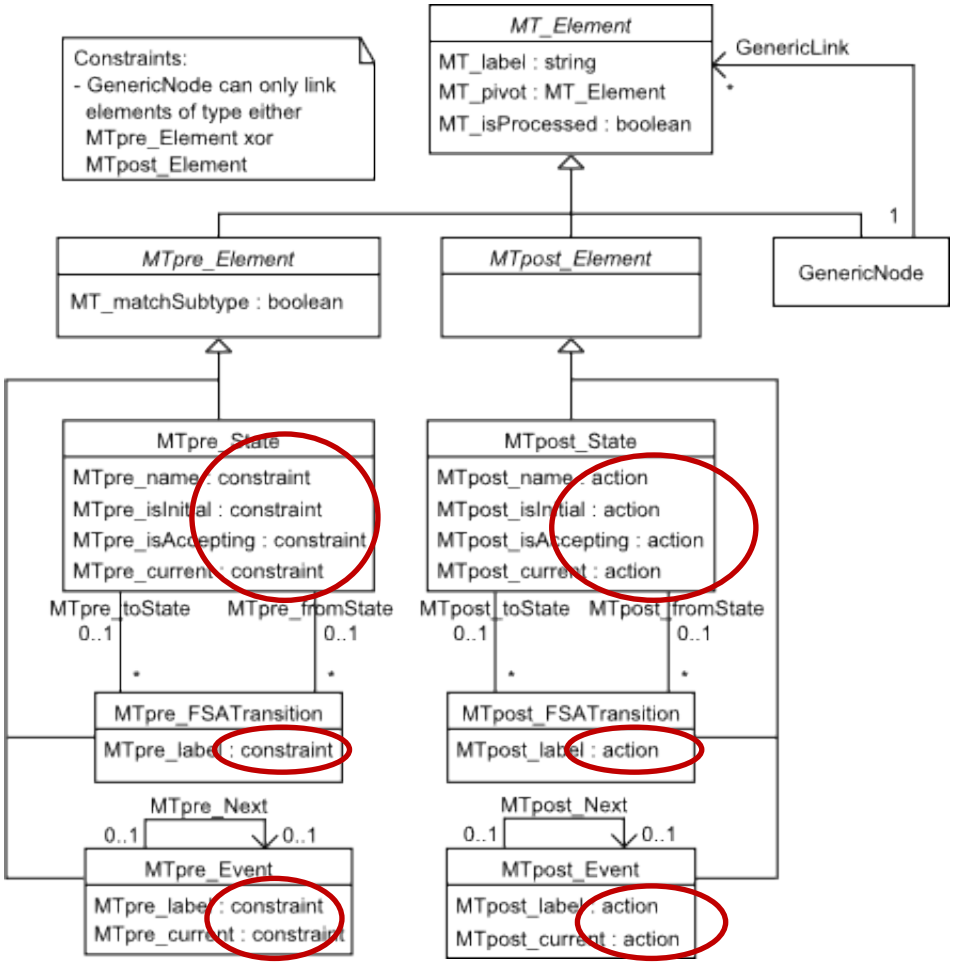
- Performs further modifications on the resulting meta-model
- Update namespaces
- Change type of attributes
  - Pre-condition classes: constraint type
  - Post-condition classes: action type
  - But preserve knowledge of original type for well-formedness
- Adaptation of concrete syntax (semi-automatic)
  - Abstract classes get a concrete syntax
  - Association ends
  - Other (e.g., replace topological visual syntax constraints)

# RAMification process




Modify

# RAMification process




Modify

$$[\![ \text{"}A+B\text{"} ]\!]_{\text{REG EXP}} = \{ \text{"}AB\text{"}, \text{"}AAB\text{"}, \ldots \}$$

GRAMMAR

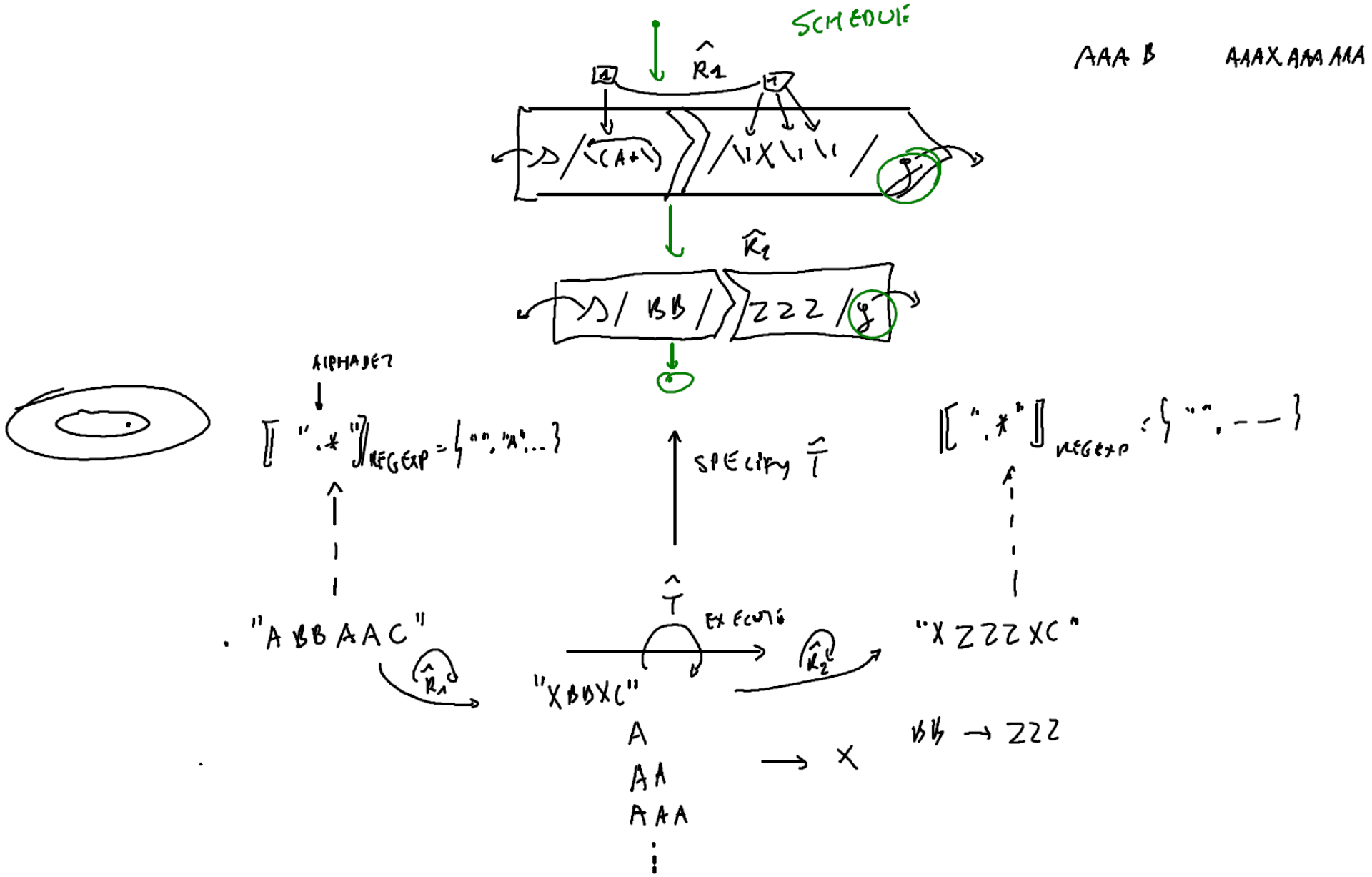
GME

&

$MM_{CD}$

GRAPH GRAMMAR

" TRANSFORMATION


SCHEDULE
AAA B
AAAX AAA AAA
ALPHABET
"ABBAAC"
"XBBXC"
"XZZZXC"
SPECIFY
EXECUTE
BB → ZZZ
A → X
AA
AAA

# Transforming Strings, Trees, or Graphs?

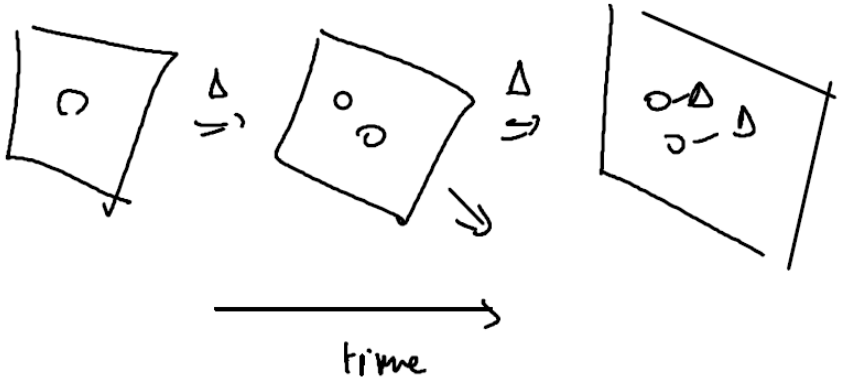
STRINGS / SEQUENCE ⊆ TREES ⊆ GRAPHS

JAVA / Python ... ⟷ TRSF ⊆ TRSF ⊆ TRSF

COGNITIVE ↑ WHAT? ↑ ↑ DECLARATIVE

HOW

DYNAMIC STRUCTURE




WHY NOT ALWAYS USE GRAPHS / GRAPH TRSF. ?

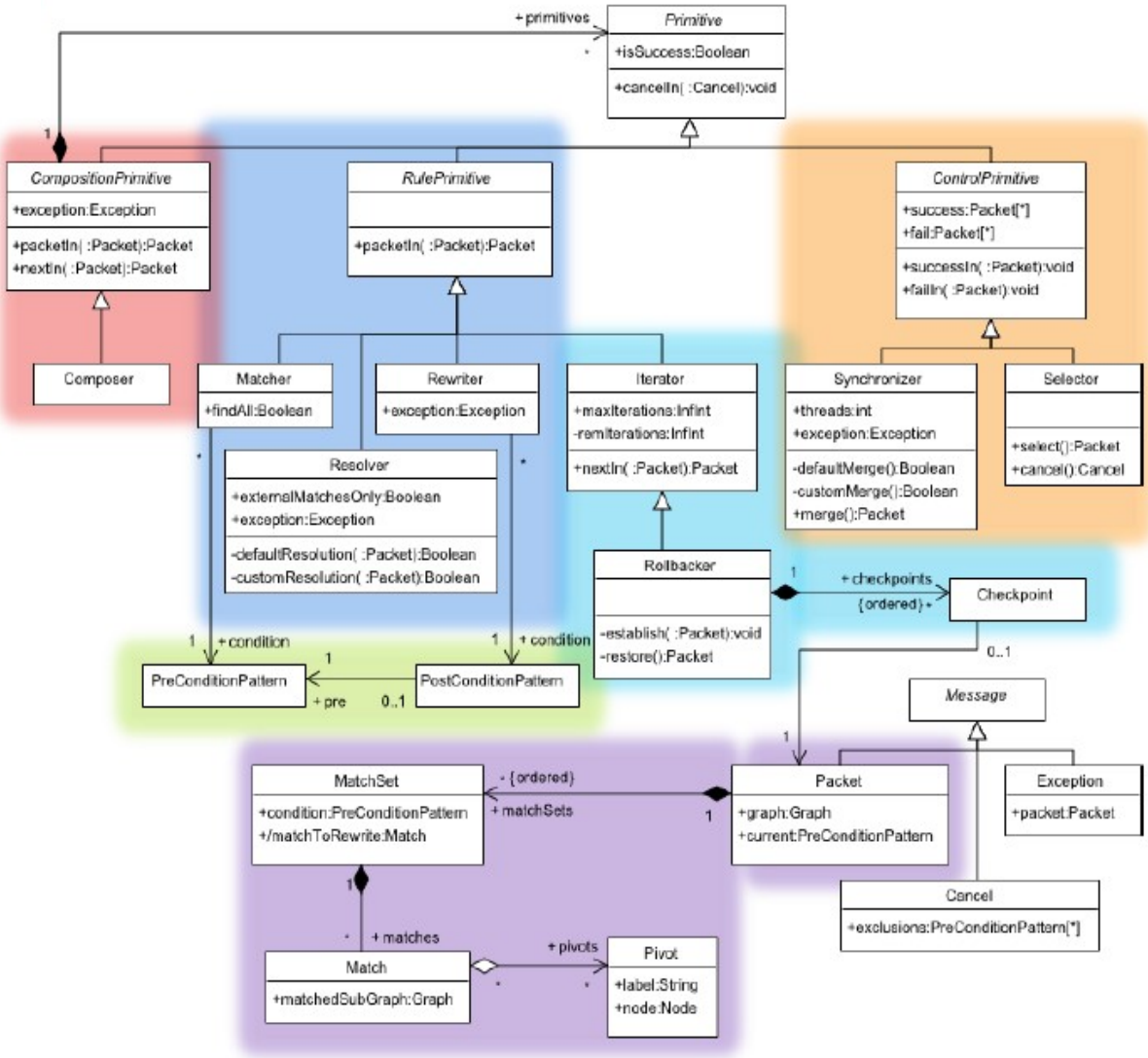
① COMPLEXITY → PERFORMANCE / EFFICIENCY

② COGNITIVE / UNDERSTANDING

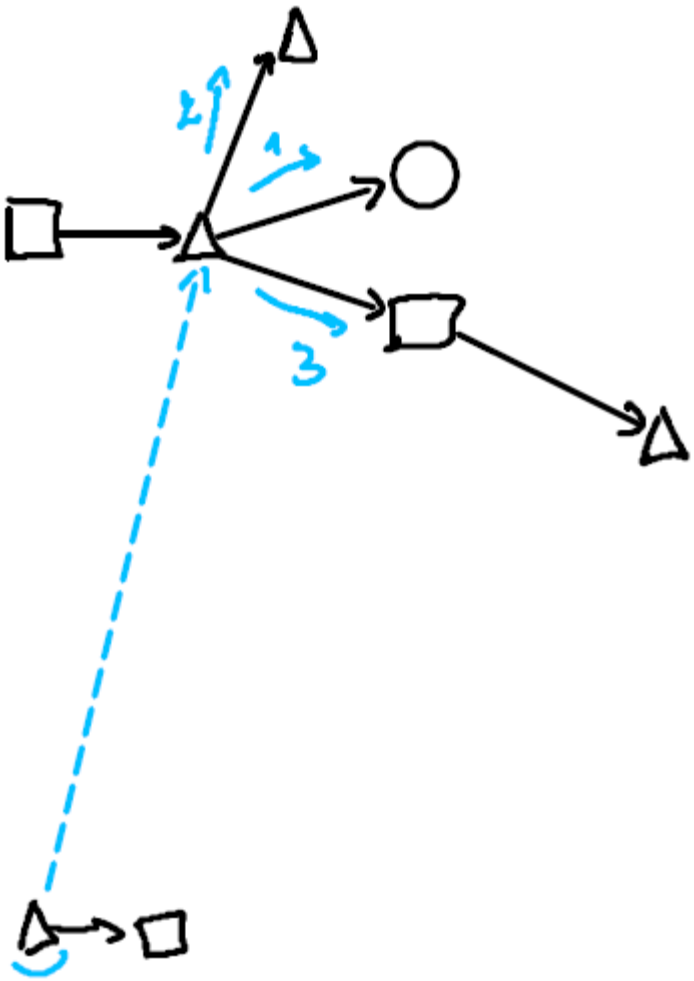
MOST APPROPRIATE - ABSTRACTION - FORMALISM

( DATA / COMPUTATION ... ENERGY / COST / ... )

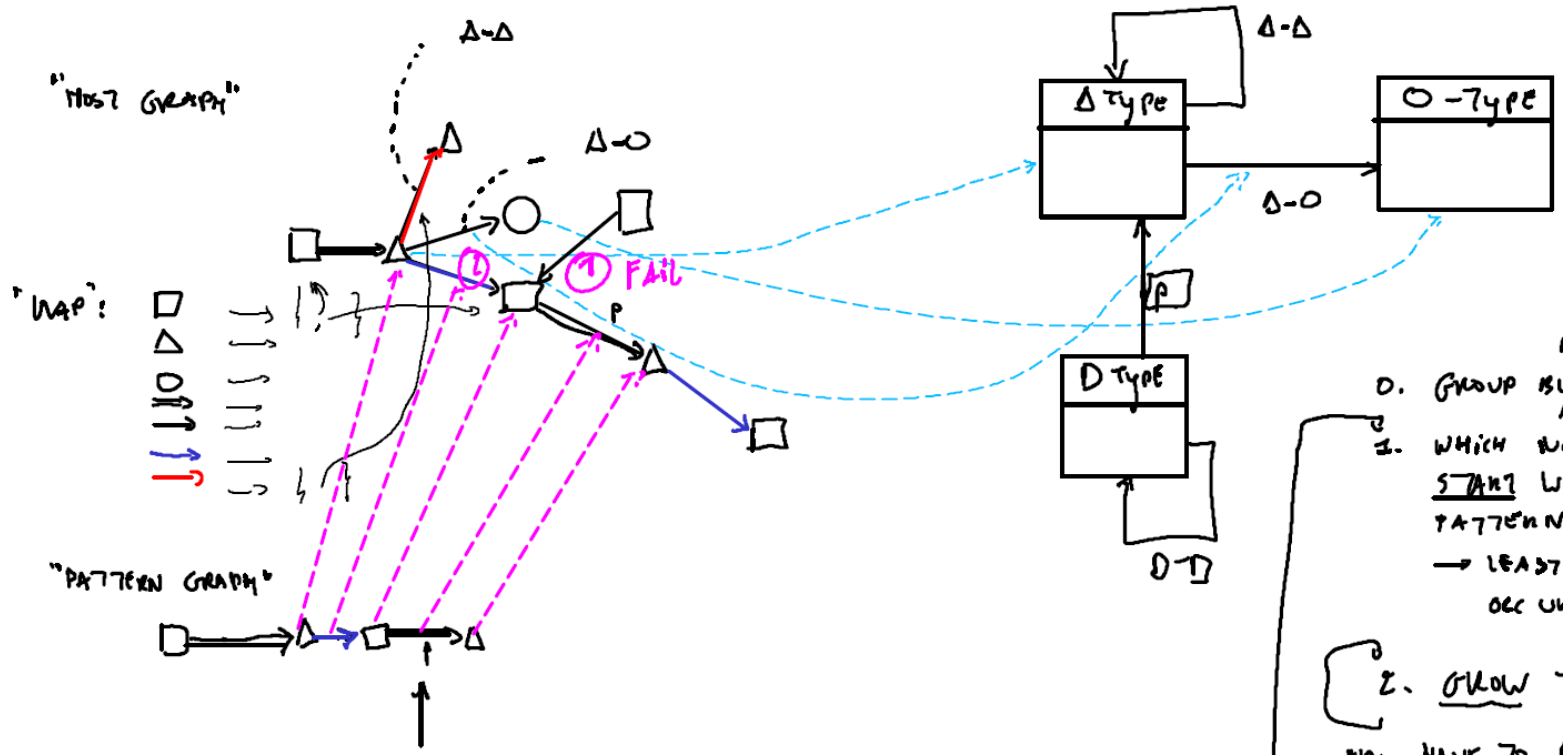
# matching, pivot, scope



# Matching Algorithms (1): Search Plans



# Matching Algorithms (2): Constraint Satisfaction




BUILD / UPDATE "MAP"

0. GROUP BY TYPE (HOST)
1. WHICH NODE/EDGE TO START WITH IN PATTERN?
   → LEAST FREQUENTLY OCCURRING TYPE
2. GROW THE MATCH
   MAY HAVE TO BACTRACK
3. COLLECT IN MATCH SET
4. REWRITE $\mathcal{D}(D+A)$

$L \quad K \quad R$

$L \setminus K$ DELETE

$R \setminus K$ ADD

$D = \text{SIZE}(L \setminus K)$

$A = \text{SIZE}(R \setminus K)$

# Matching Algorithms (2): improving performance through (user) "hints"

PIVOT PARTIAL MATCH

SUB-GRAPH OF HOST GRAPH

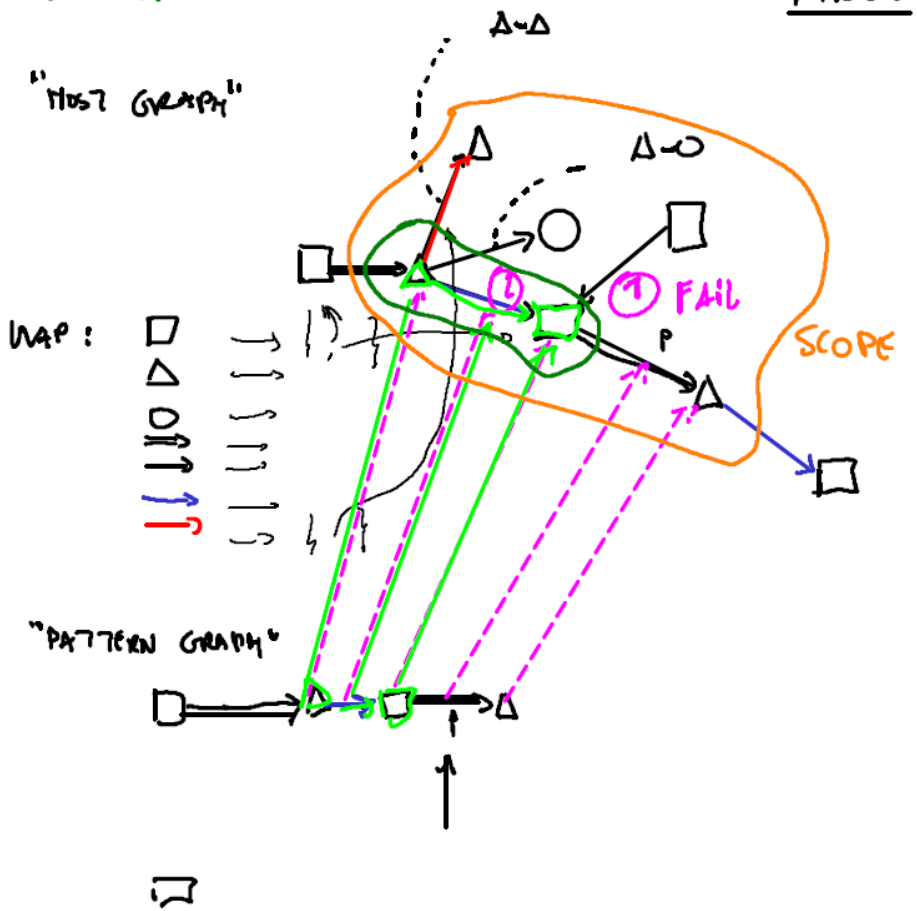
WHERE TO START

FIRST MATCH

$\Theta$( SIZE (PATTERN GRAPH))

LINEAR!

SIZE (HOST GRAPH) $> 10^6$




"COMPLEX PATTERN"

→ FAIL EARLIER

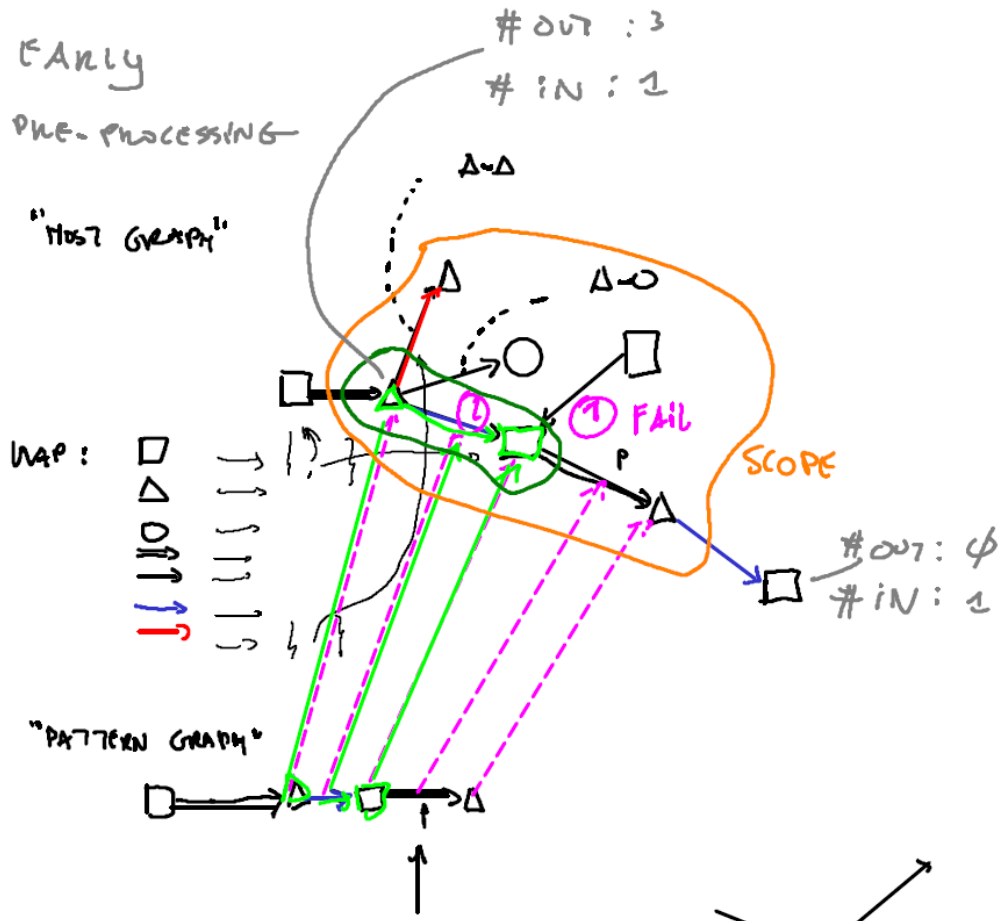
(FEWER MATCHES)

SCOPE WHAT TO EXCLUDE FROM HOST GRAPH ~ SIZEOF (SCOPE GRAPH)

# Matching Algorithms (2): improving performance through heuristics

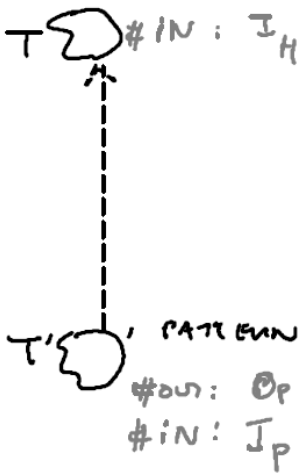
HEURISTIC FAIL EARLY

EXTRA PRE-PROCESSING




UPDATE WHEN HOST CHANGES

IN RHS OF RULE "REWRITE" PHASE

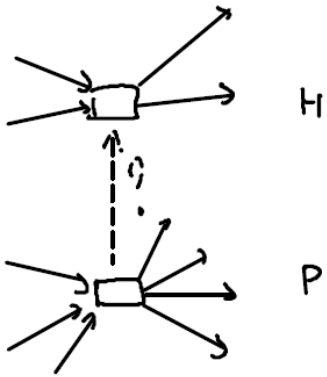



NO UPDATE NEEDED

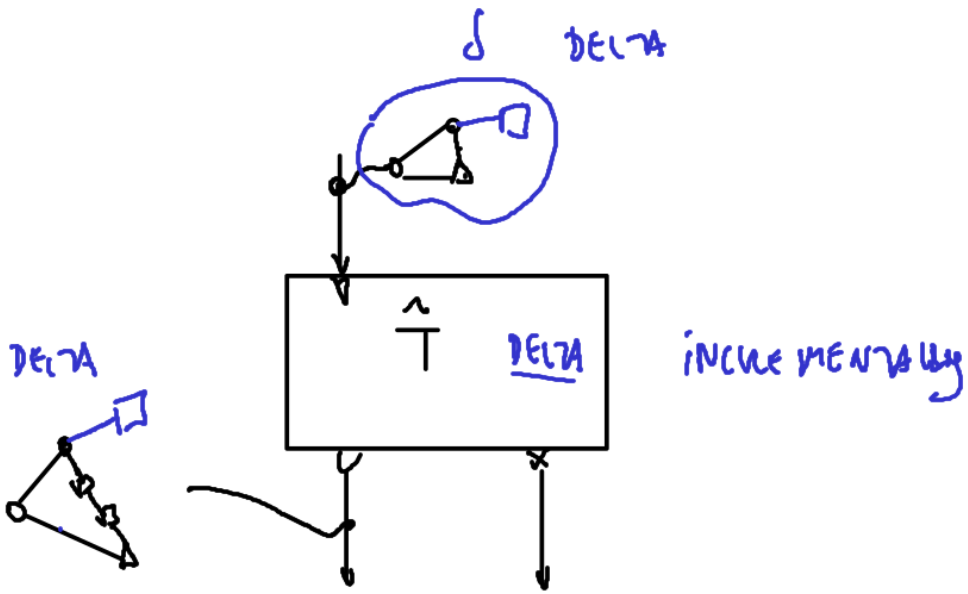
$I_P <= I_H$

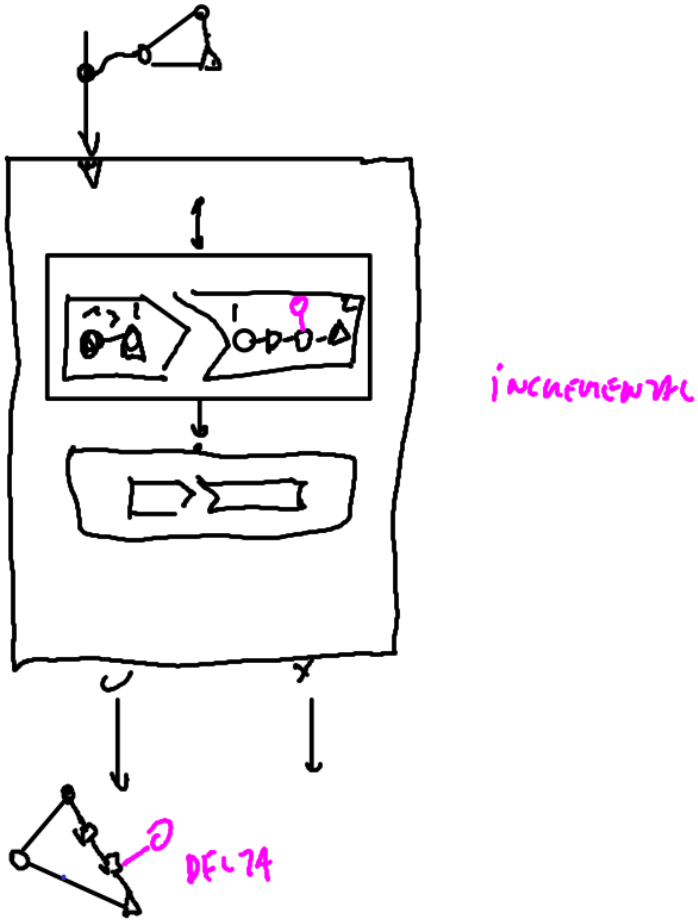
$O_P <= O_H$

VF2 "Very Fast 2"



# Matching Algorithms: improving performance of "incremental" model transformation: the Rete algorithm

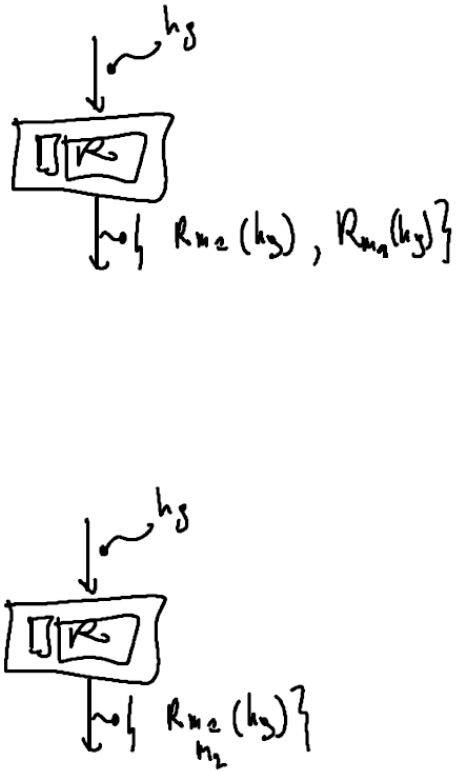


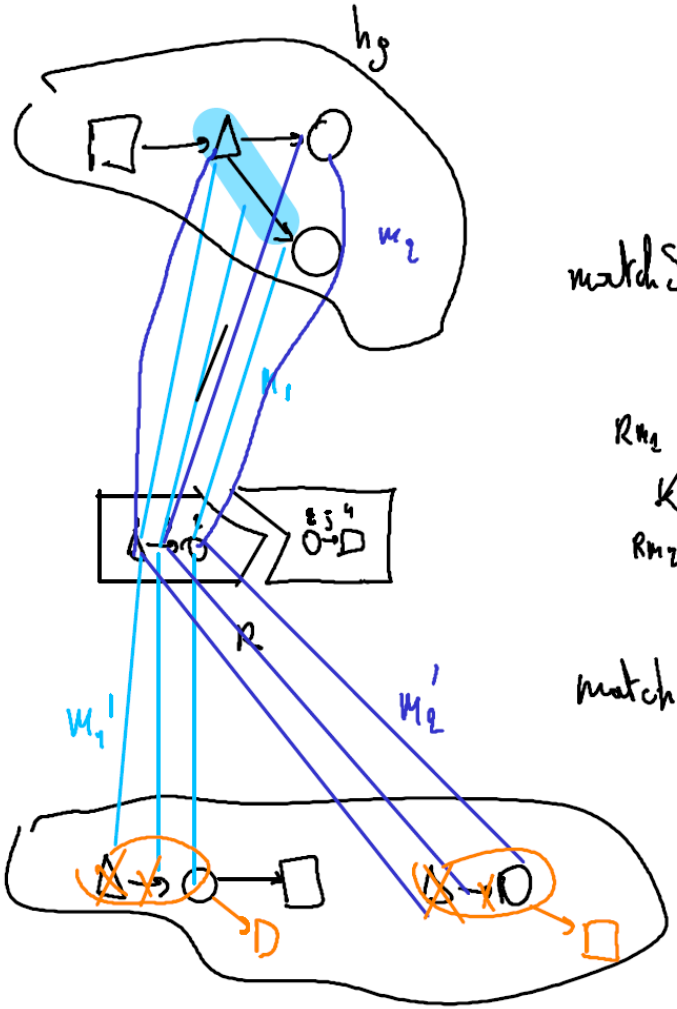




RETE

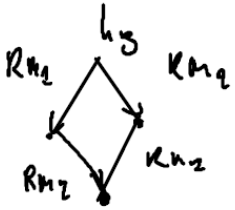
Prolog

# Choice → parallel independence, critical pairs




matchSet = $\{m_1, m_2\}$




$\bigcap \mathrm{IMG}_{h_g}(m_i) = \emptyset$

NO

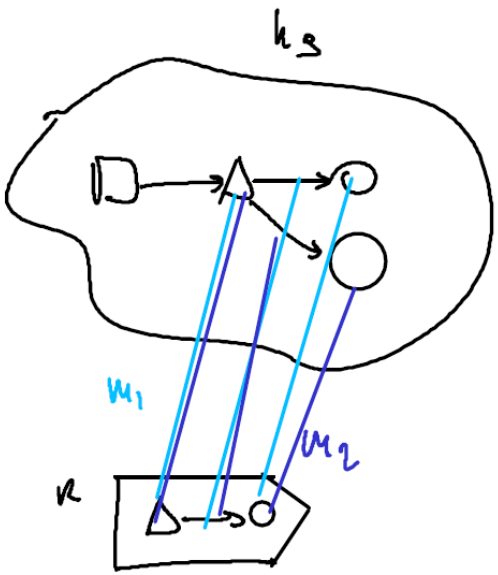
YES

matchSet' = $\{m_1', m_2'\}$

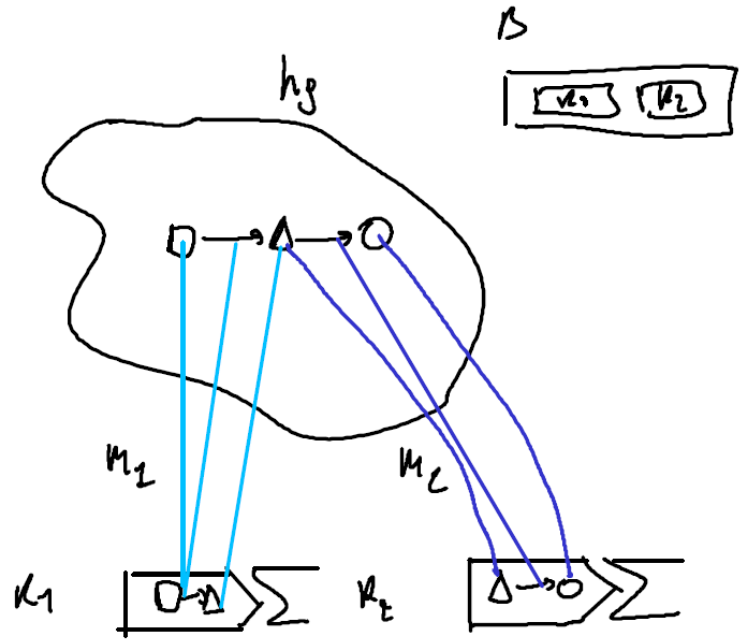
Apply in //

# Choice (vs. enumerate all, see Petri Nets reachability graph)

**single** rule, multiple matches




**multiple** rules, multiple matches



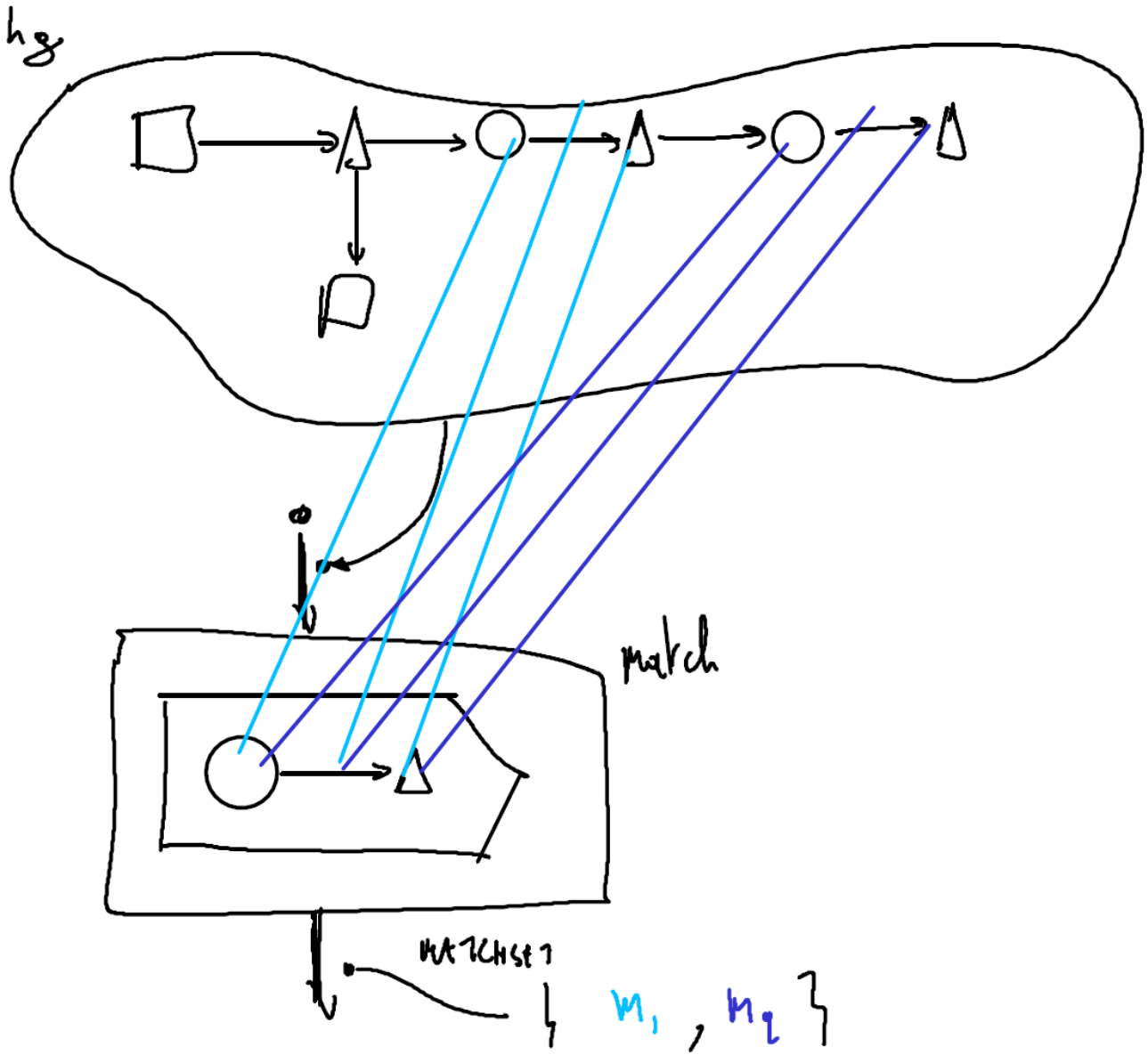

RANDOM CHOICE (REPEATABLE)

FROM ALL MATCHES

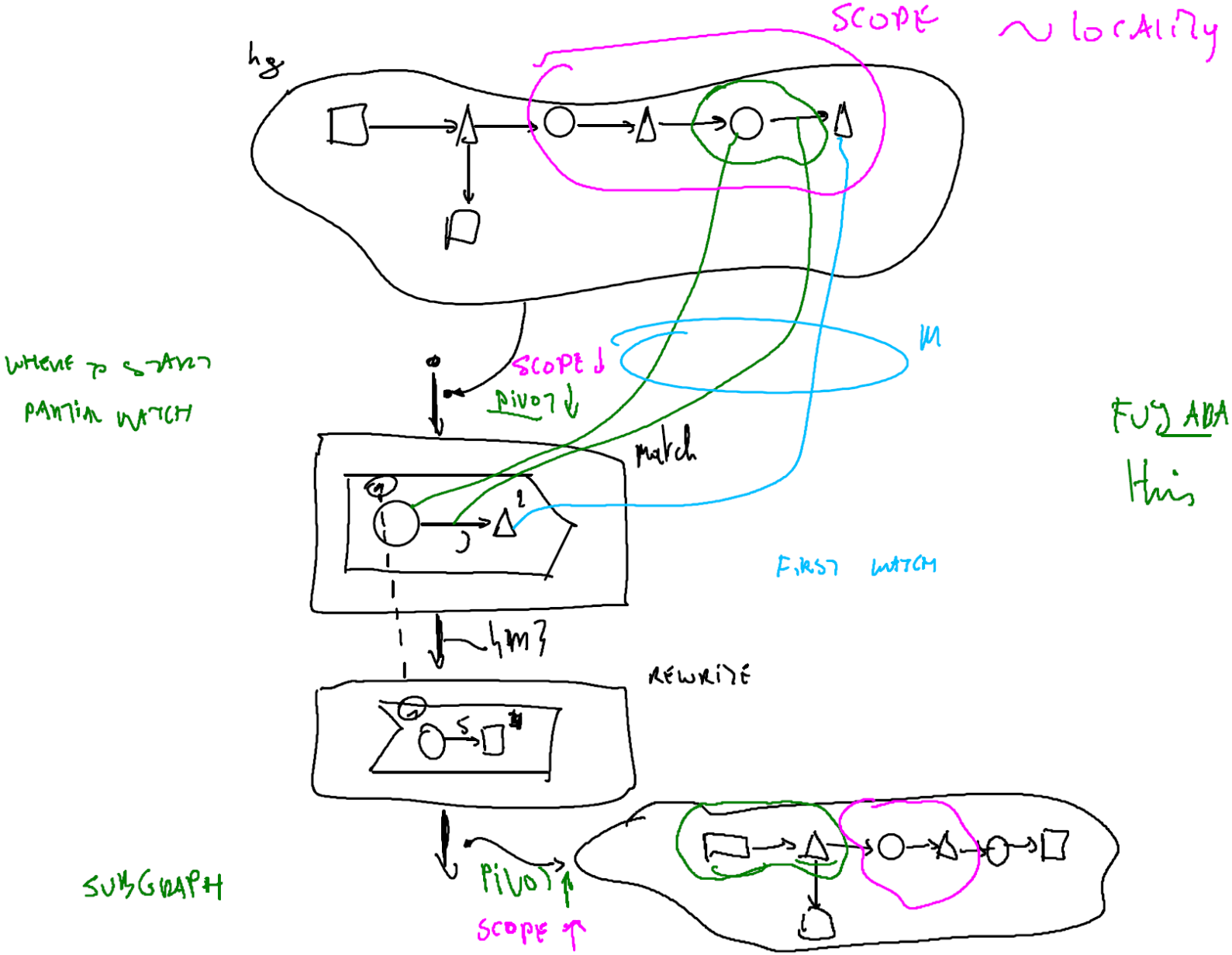
SELECT ( $\{\overset{\phi}{m_1}, \overset{1}{m_2}\}$ )

$U_I([0,1])$ PSEUDO-RANDOM NR. GENERATOR (SEED)

# MatchSet = the set of all the matches (morphisms)



# De-constructing a rule into Matching and Re-Writing



# Model-to-model transformation for translation

- Declarative paradigm
- Rules defined as non-destructing pre- and post-conditions
  - Source pattern to be matched in the source model
  - Target pattern to be created/updated in the target model for each match during rule application
- Typically models are represented in Ecore
- Input model is read-only
- Output model is write-only
- Tools: **ATL**, ETL, QVT-R

# ATL transformation

## Classes–Tables + Attributes–Columns

Create new model

Standard rule

LHS: 1 element type

RHS: elements to create in new model

Call implicitly another rule

Call temporary queries

Helper in OCL

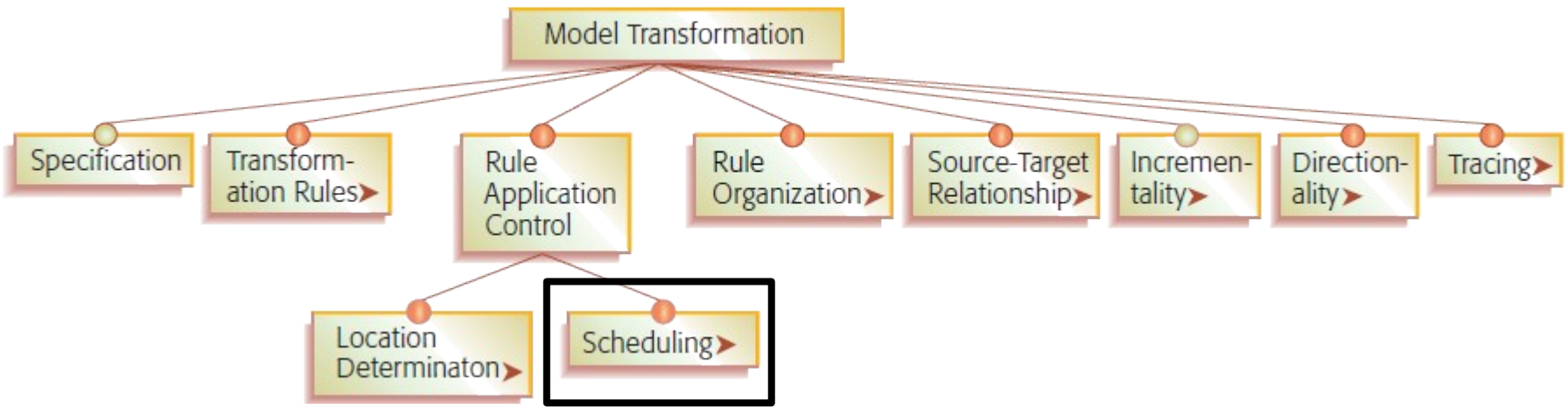
```
module CD2RDB;
create DB: RDBMS from CD: CD;

rule Class2Table {
    from
       c : CD!Class
    to
       t : DB!Table (
          name <- c.name
          cols <- c.attrs
          pkey <- pcol )
       pcol : DB!Columun (
          name <- 'id'
          type <- 'int32' )
}

rule Attr2Col {
    from
       a : CD!Attribute
    to
       t : DB!Column (
         name <- a.name
         type <- a.convertedType() )
}

helper context CD!Attribute def: convertedType(): String =
    if a.type.name = 'String' then 'string'
    else if a.type.name = 'Int' then 'int32'
        else a.type.name
        endif
    endif;
```

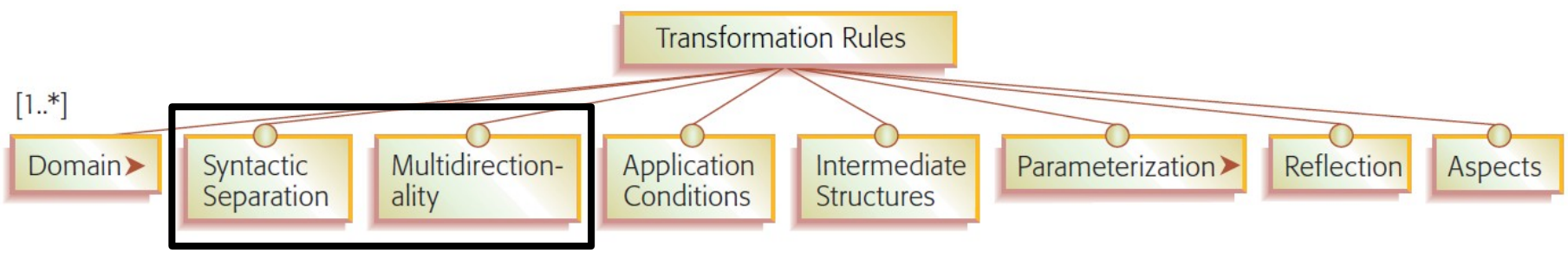
# Execution of a declarative rule in ATL

1. Find all possible matches in the source model
2. Create elements specified in the target pattern on a target model
3. Initialize attributes and links of the newly created elements
4. Create **traceability** links from the elements in the source model matched by the source pattern to the created elements in the target model

- **Standard ATL rule** applied once for each match
  - Like FRule

# Feature-Based Survey of Model Transformation Approaches



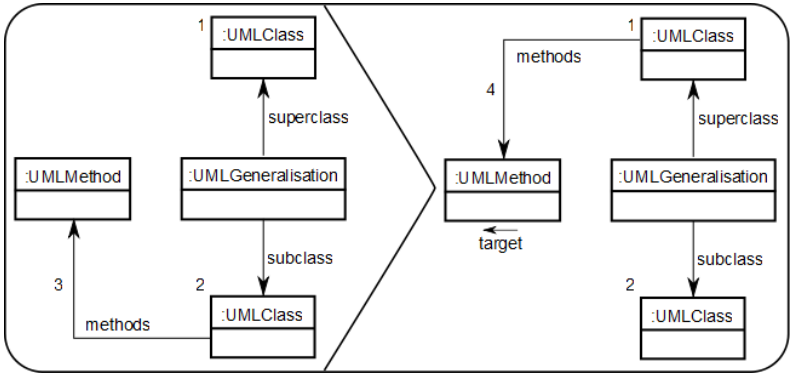




K. Czarnecki and S. Helsen. Feature-based survey of model transformation approaches. *IBM Systems Journal:* 45(3), 621-645 (2006).

# Rule patterns

- Model fragments
- Using abstract or concrete syntax
- Syntactic separation

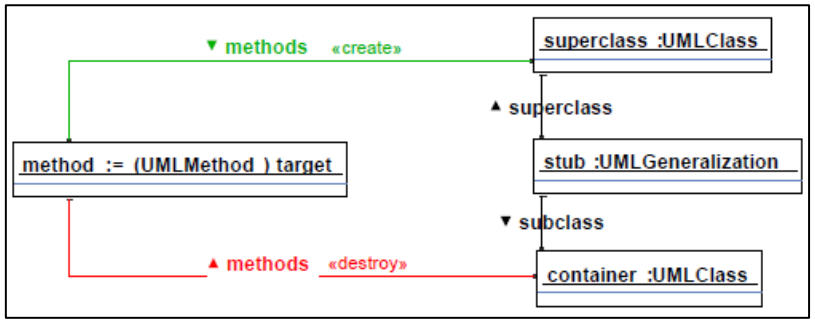
MoTif rule



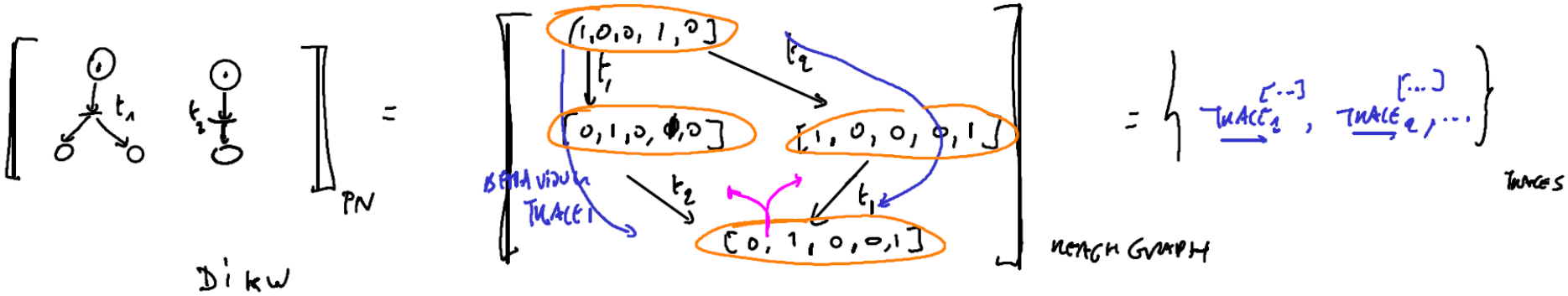

ATL rule

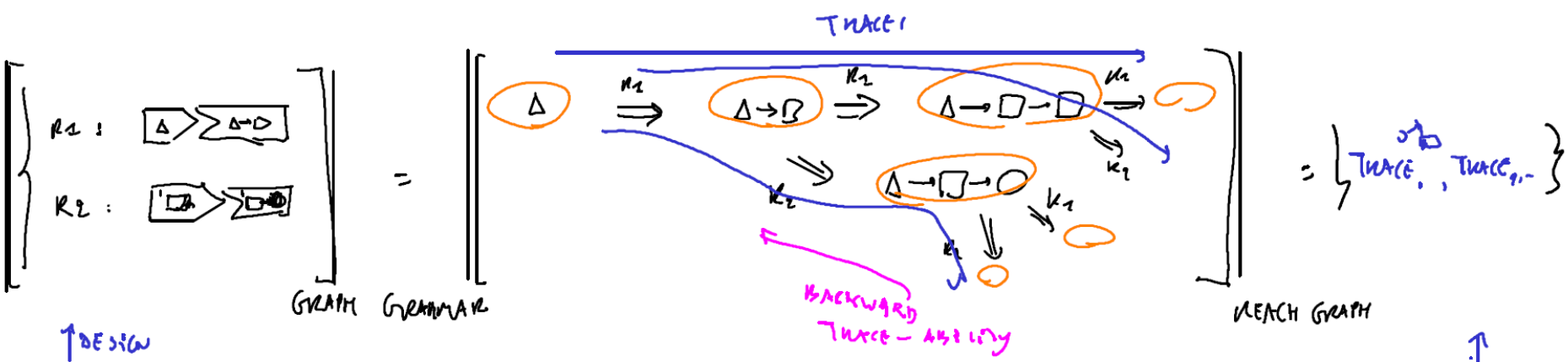
```
module Person2Contact;
create OUT: MMb from IN: MMa {

rule Start {
   form p: MMa!Person(
      p.function = 'Boss'
   )
   to c: MMb!Contact(
      name <- p.first_name + p.last_name)
}
```

FUJABA/Henshin compact notation



# Choice → explore all possibilities → analysis over all traces




↑ DESIGN

↓ REQ

PROPERTIES

CTL*/LTL

→ GROOVE MODEL CHECKER FOR (GT//GG ⟷ ATMPM

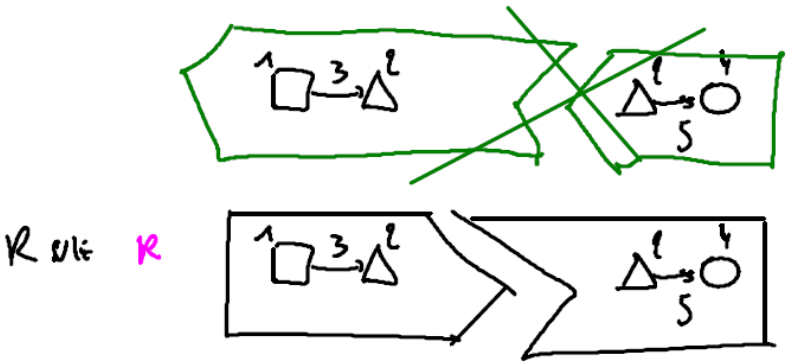
→ MAUDE " " " ( " ) "

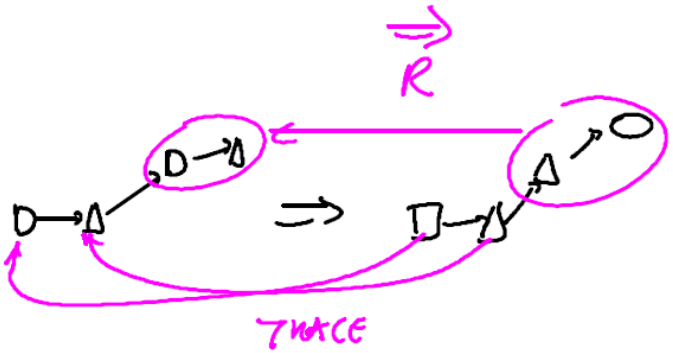
ANALYSIS

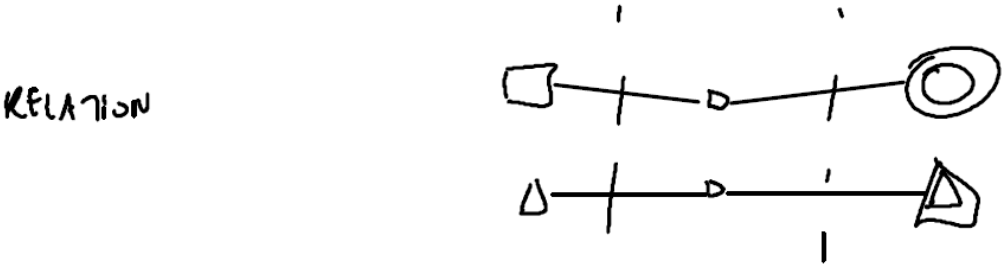
GT

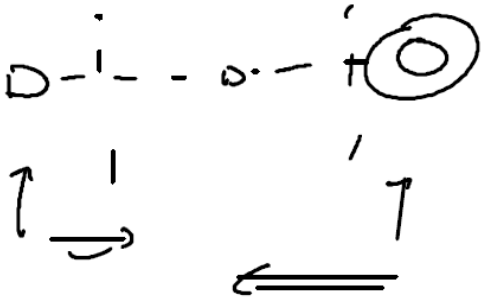
EXECUTION

# Trace of Transformation **Execution** vs. **Bi-Directional** Transformations



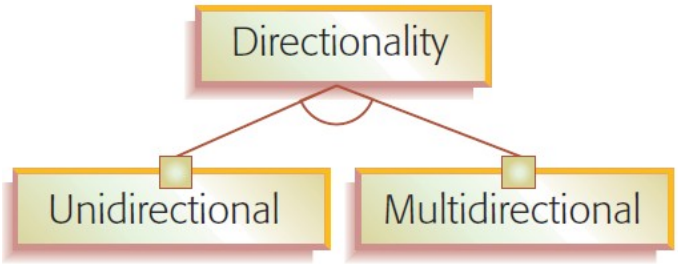



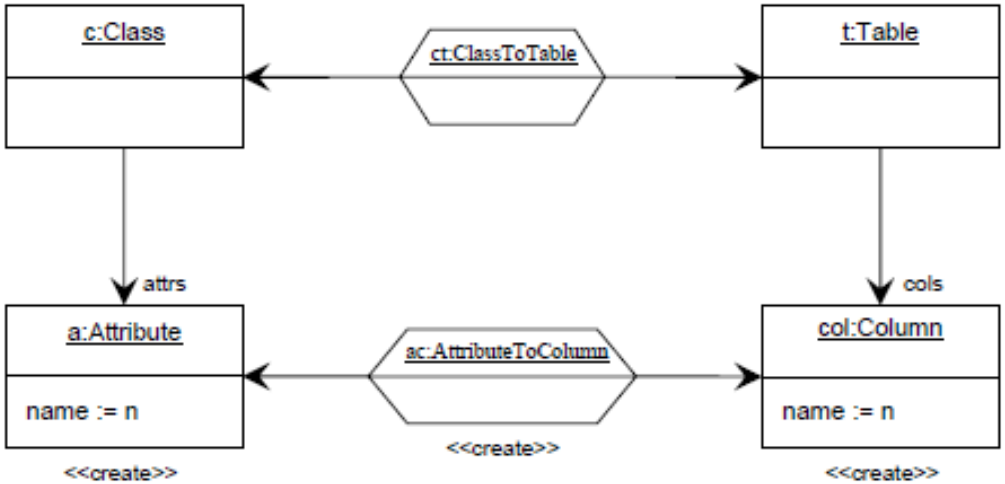



BI-DIRECTIONAL TRSF.

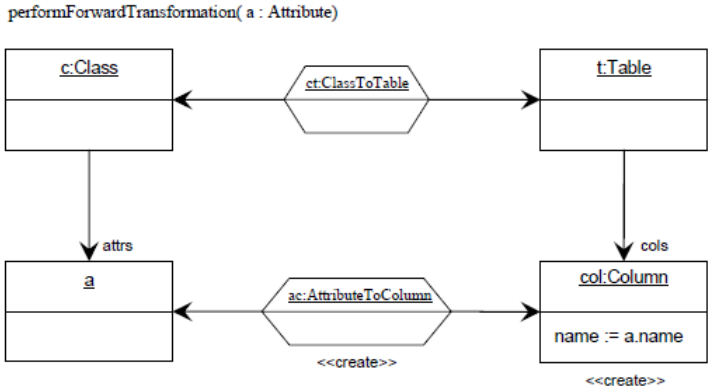
# Multi-directional rules

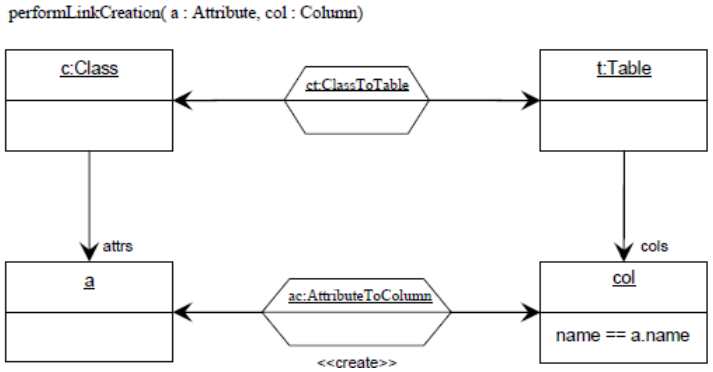


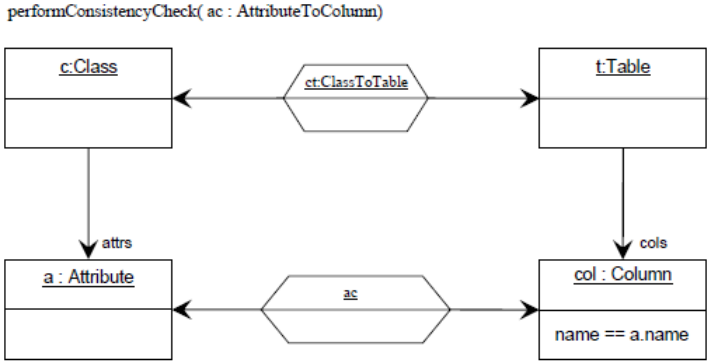

TGG rule




TGG operational rules

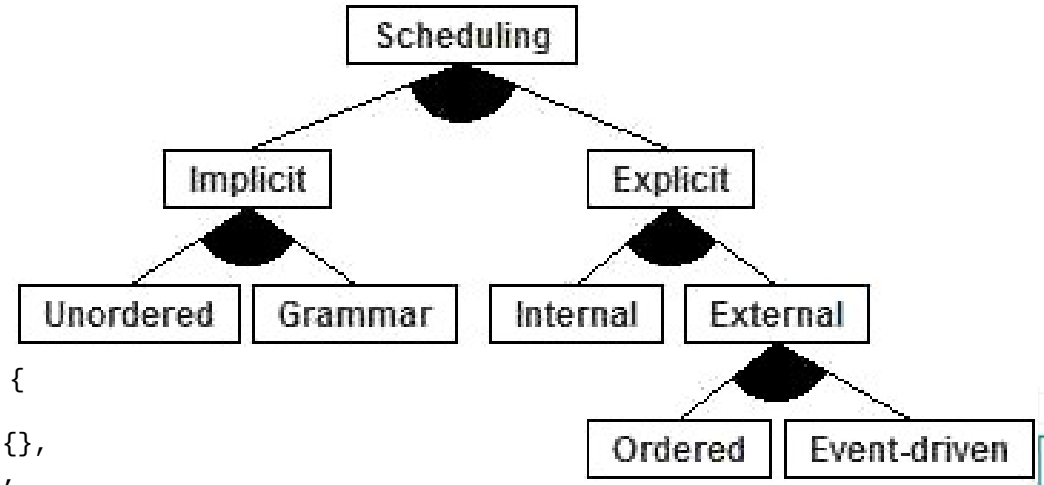


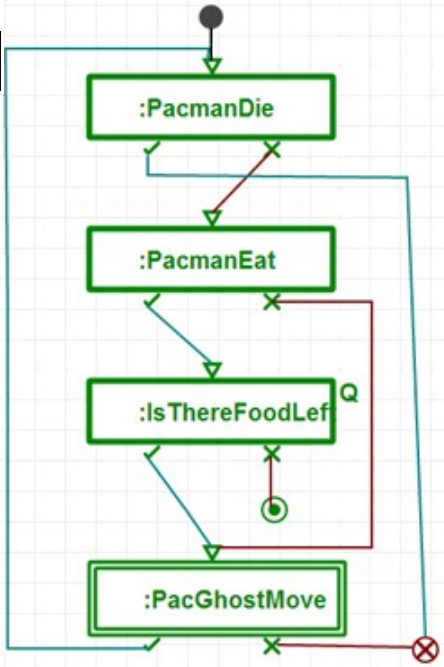



# Rule scheduling strategies

## Explicit




```
top relation ClassToTable {
    domain uml c:Class {
        package = p:Package{},
        isPersistent = true,
        name = cn
    }
    domain rdbms t:Table {
     schema = s:Schema{},
     name = cn,
     cols = cl:Column {
     name = cn + '_tid',
     type = 'NUMBER'},
     pkey = cl
    }
    when {
     PackageToSchema (p, s);
    }
    where {
     AttributeToColumn (c, t);
    }
}
```



# Rule Scheduling (aka Control)

SCHEDULING LANGUAGES

(+)

RULE LANGUAGE

STRING / TREE / GRAPH

GRAPH

CBD / DATA FLOW

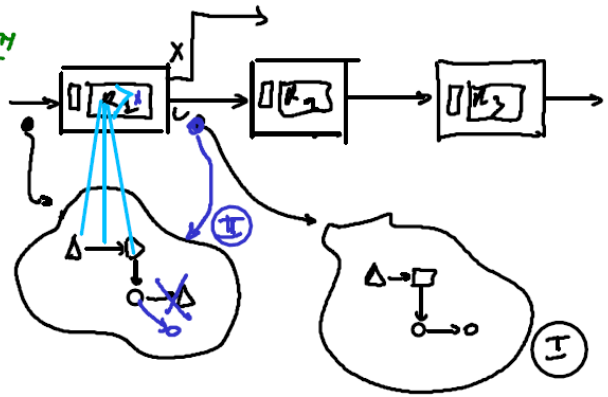
OPERATIONS : GRAPH TRSF.

SPECIFIED BY RULE

⊥ HIERARCHY

(+)

1.



GREAT (GME)

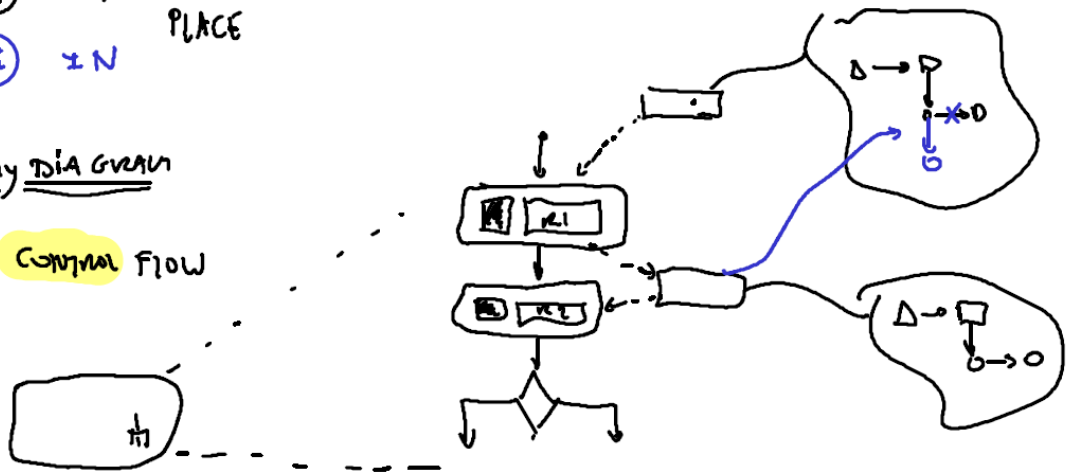
(I) OUT

(II) IN

PLACE

2. ACTIVITY DIAGRAM

CONTROL FLOW



FUJABA

"this"

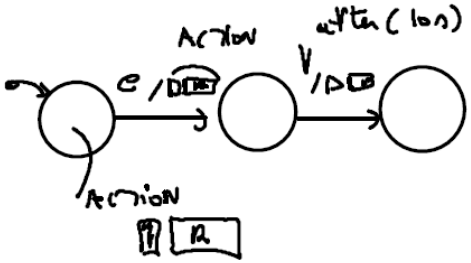
PIVOT

FIRST MATCH

# Rule Scheduling (aka Control)

3. TIMED STATE AUTOMATA

STATECHARTS

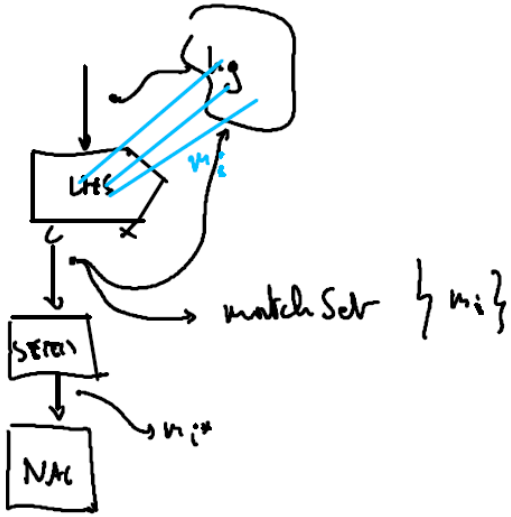



TIMED HT

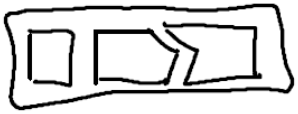
CONCURRENCE

4. DEVS

- TIME
- HIERARCHY
- DEV
- CONCURRENCY




MoTif



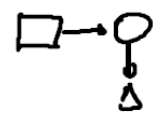
A RULE

# Rule Scheduling (aka Control)

GREAT FUJAKA MOTIF

COMPILER

5. PROGRAMMING LANGUAGE



NAC LHS RHS

hg = GRAPH()

LHS rule = LHS RULE()

matcher = MATCHER()

match set = matcher.match(LHS rule, hg)

match = select(match set)

...

REWRITER()

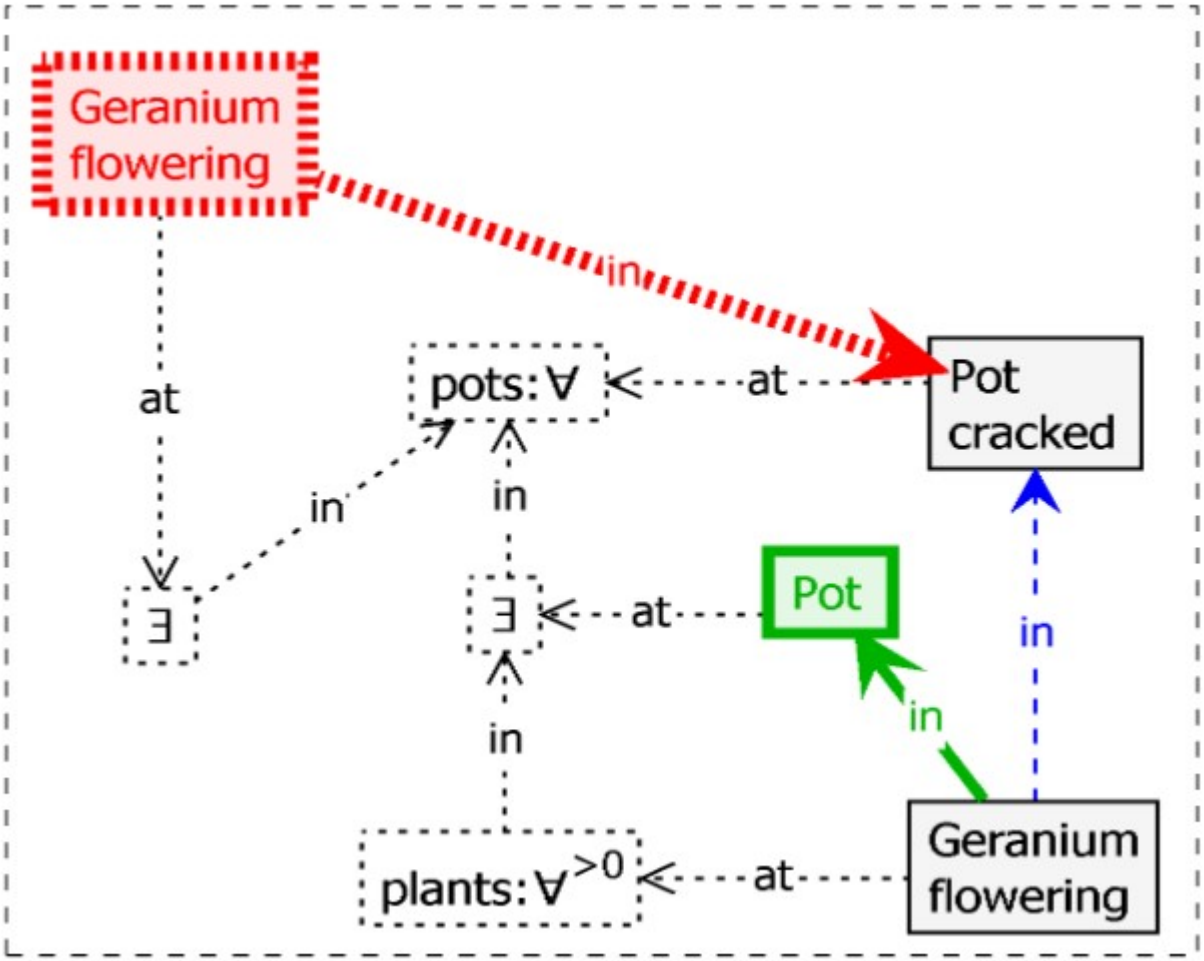
T-Core

# Increased Expressiveness: rule amalgamation

Arend Rensink and Jan-Hendrik Kuperus. *Repotting the Geraniums: On Nested Graph Transformation Rules.* Graph Transformation and Visual Modeling Techniques (GT-VMT). In ECEASST Volume 18. 2009.

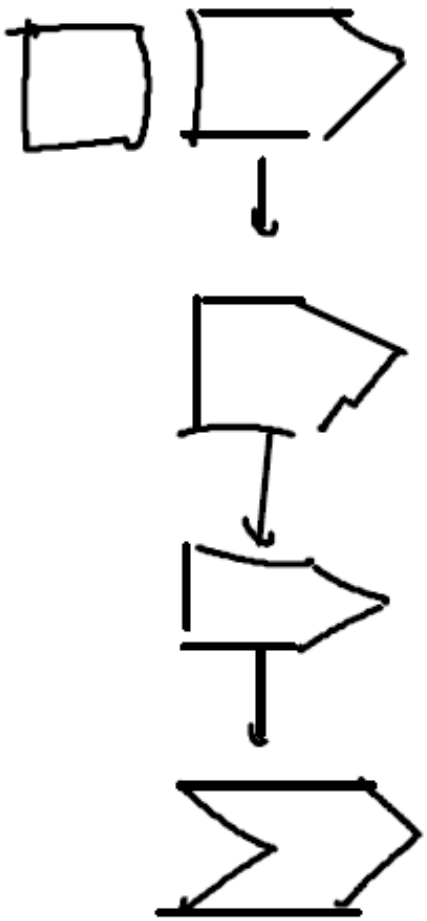
https://journal.ub.tu-berlin.de/eceasst/article/view/260

We have a number of flower pots, each of which contains a number of geranium plants. These tend to fill all available space with their roots, and so some of the pots have cracked. For each of the cracked pots that contains a geranium that is currently in flower, we want to create a new one, and moreover,to move all flowering plants from the old to the new pot. Create a single parallel rule that achieves this in a single application, without the use of control expressions.



# Increased Expressiveness: rule amalgamation

Operationally (in terms of T-Core building blocks):
Match – Match - … - Re-Write



# Plethora of model transformation languages

ATL

medini Q

QvT SmarT

A Tool for Multi-formalism and Meta-Modeling

Even our logos are modeled!

Visit MSDL at http://msdl.cs.mcgill.ca

FUJABA Tool Suite

MoTif

GrGen.NET

AGG

epsilon

VIATRA

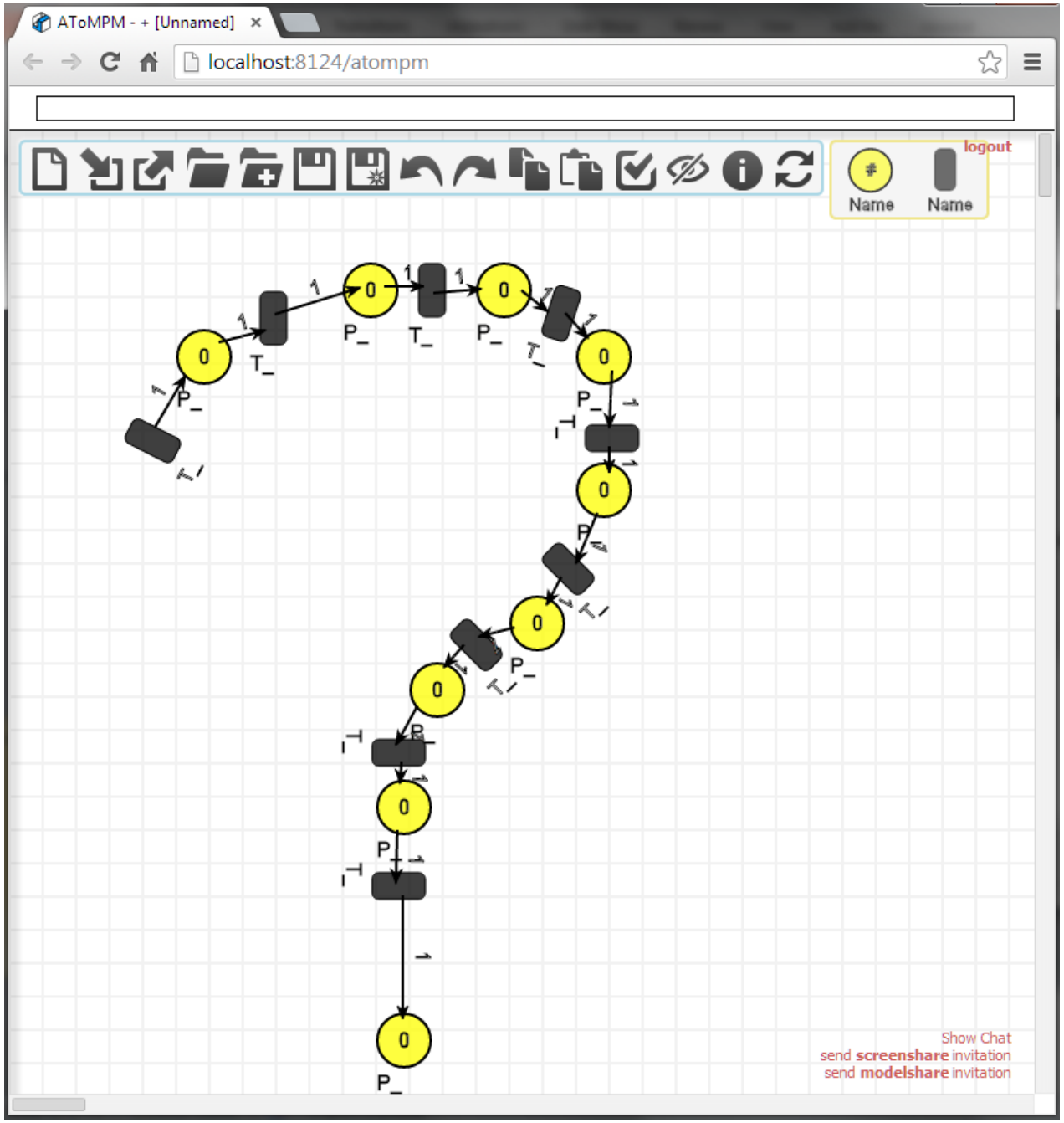
EMF-IncQuery

Henshin emf

MOFLON

VMTS

GReAT DSLTrans ProGReS MOLA


AToMPM - + [Unnamed]
localhost:8124/atompm
logout
Name
Name
Show Chat
send screenshare invitation
send modelshare invitation