(Domain-Specific) Modelling Language Engineering

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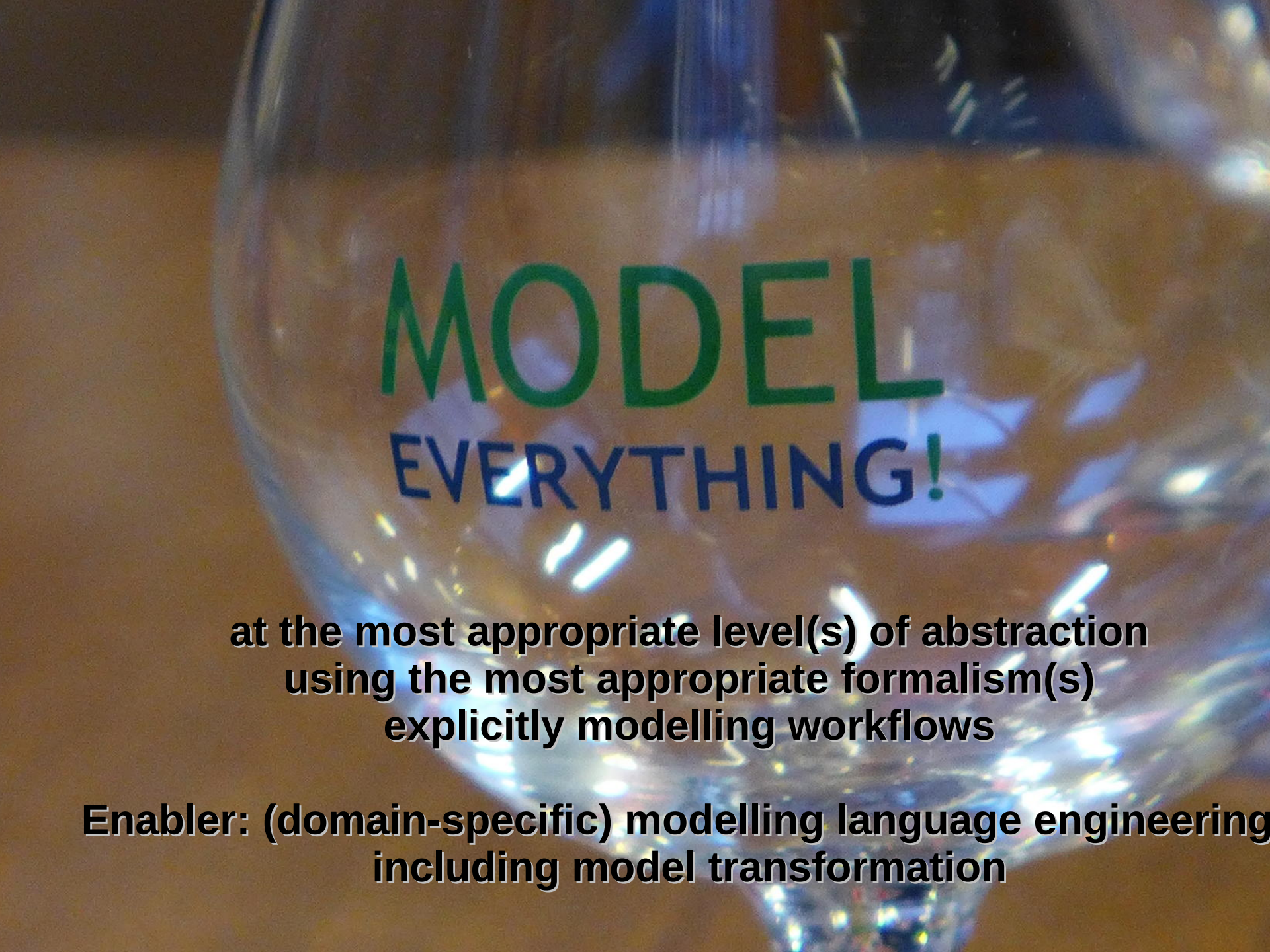
FLANDERS MAKE
MANUFACTURING INNOVATION NETWORK

McGill



at the most appropriate level(s) of abstraction
using the most appropriate formalism(s)
explicitly modelling workflows

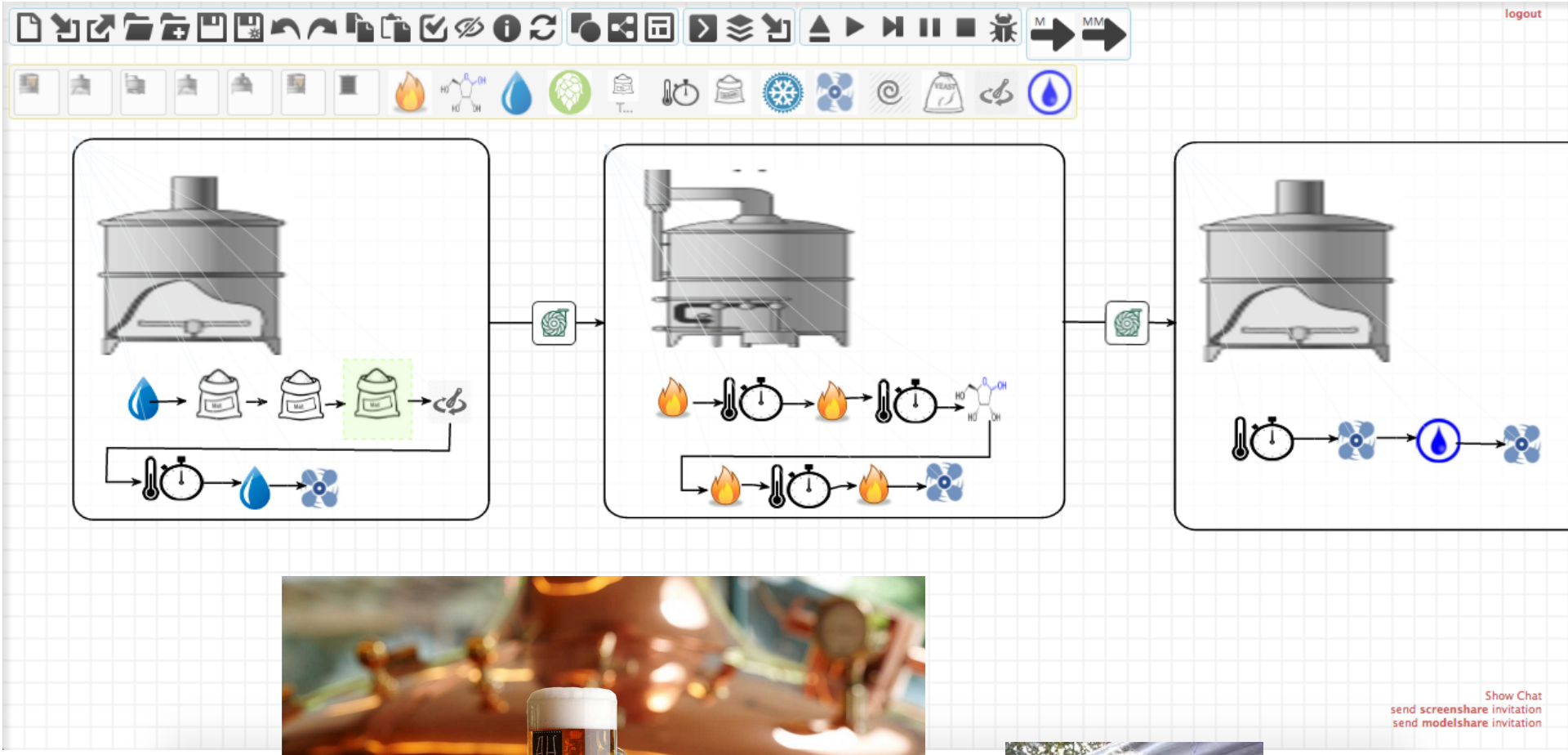
Enabler: (domain-specific) modelling language engineering
including model transformation

DSM TP 2014
Theory and Practice

5th International Summer School
on Domain Specific Modeling

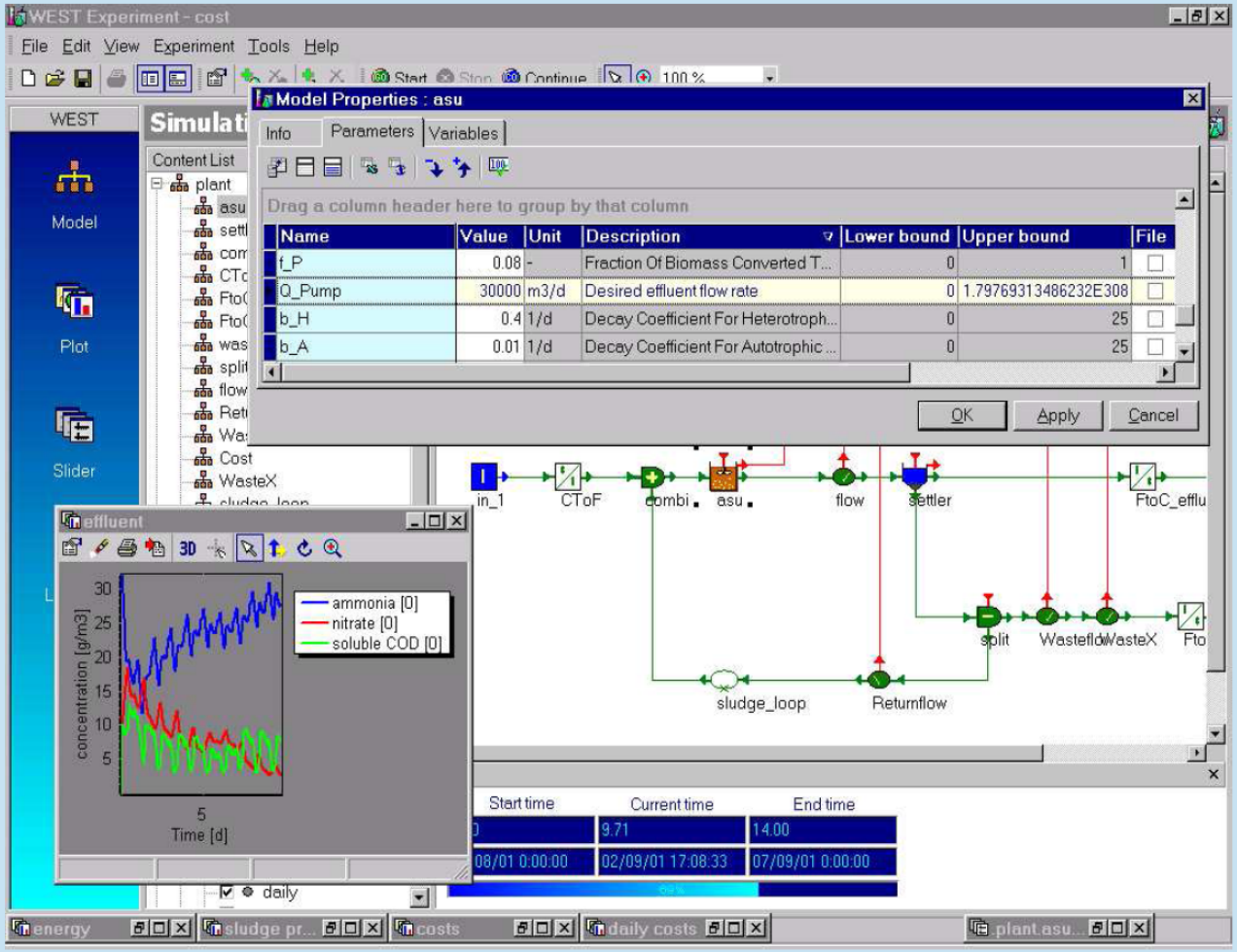
Antwerp, Belgium
25 - 29 August

Thomas Kühne

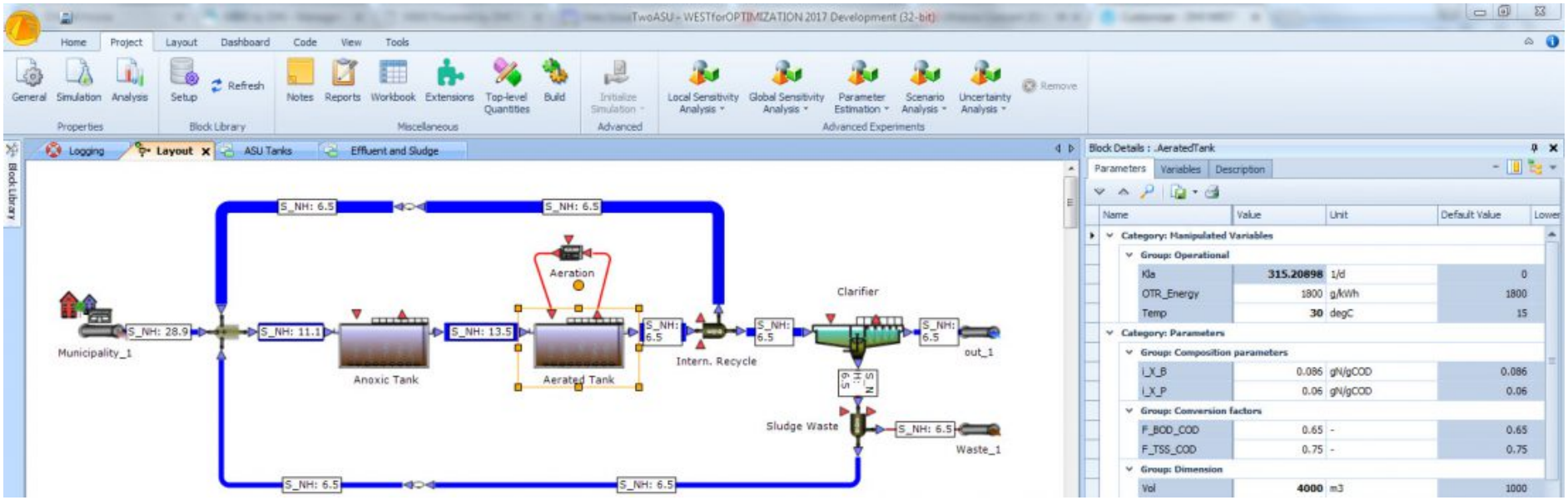


Joachim Denil

DS(V)M Environment



WEST: modelling biological wastewater treatment.
Henk Vanhooren, Jurgen Meirlaen, Youri Amerlinck, Filip Claeys, Hans Vangheluwe and Peter A.Vanrolleghem.
Journal of Hydroinformatics 5 (2003) 27-50



http://www.mikebydhi.com/products/west

Why DS(V)M ?
(as opposed to General Purpose modelling)

- **match the user's mental model** of the problem domain
- **maximally constrain** the user (to the problem at hand)
  $\Rightarrow$ easier to learn
  $\Rightarrow$ avoid errors
- **separate** domain-expert's work
  from analysis/transformation expert's work

Anecdotal evidence of 5 to 10 times speedup

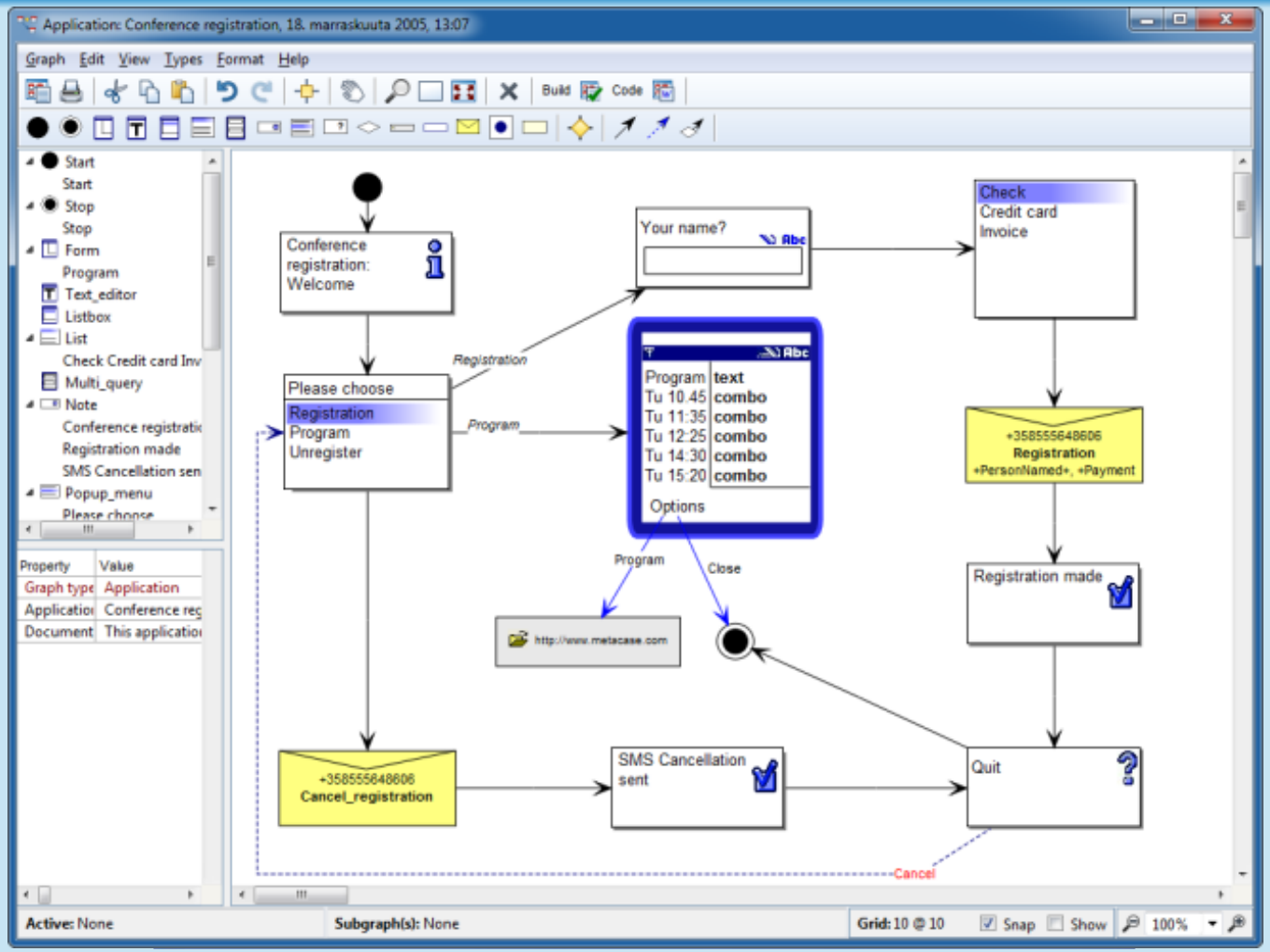
Steven Kelly and Juha-Pekka Tolvanen. Domain-Specific Modeling: Enabling Full Code Generation. Wiley, 2008.

Laurent Safa. The practice of deploying DSM, report from a Japanese appliance maker trenches. In Proceedings of the 6th OOPSLA Workshop on Domain-Specific Modeling (DSM'06), pp. 185-196, 2006.

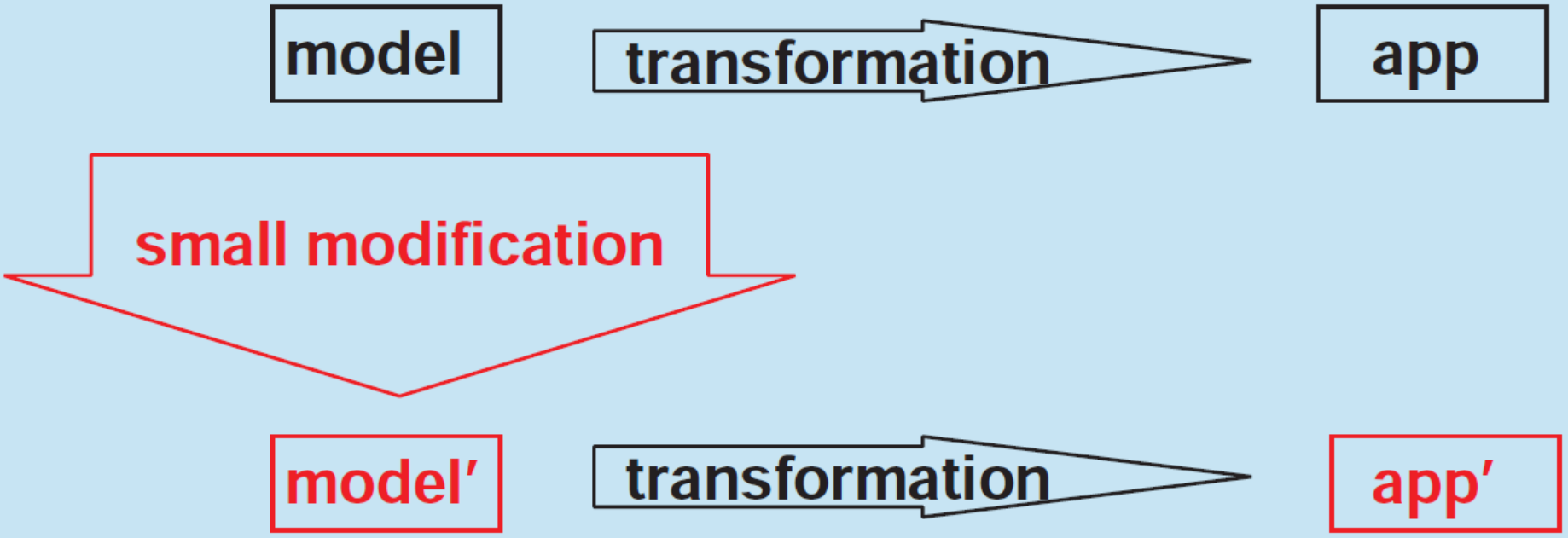
DS(V)M Example in Software Domain
smart phones, the application

MetaEdit+ (www.metacase.com)

DS(V)M Example: smart phones, the Domain-Specific model



Model-Based Development:
Modify the Model
(e.g., based on feature model of product family)



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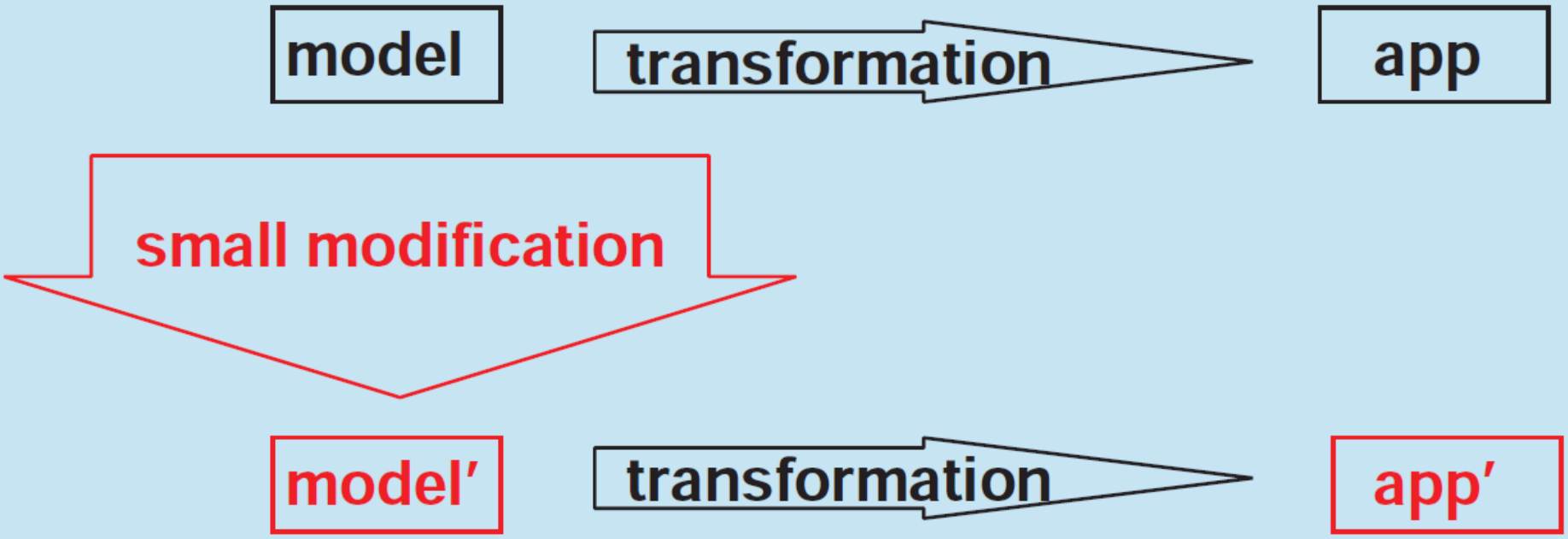
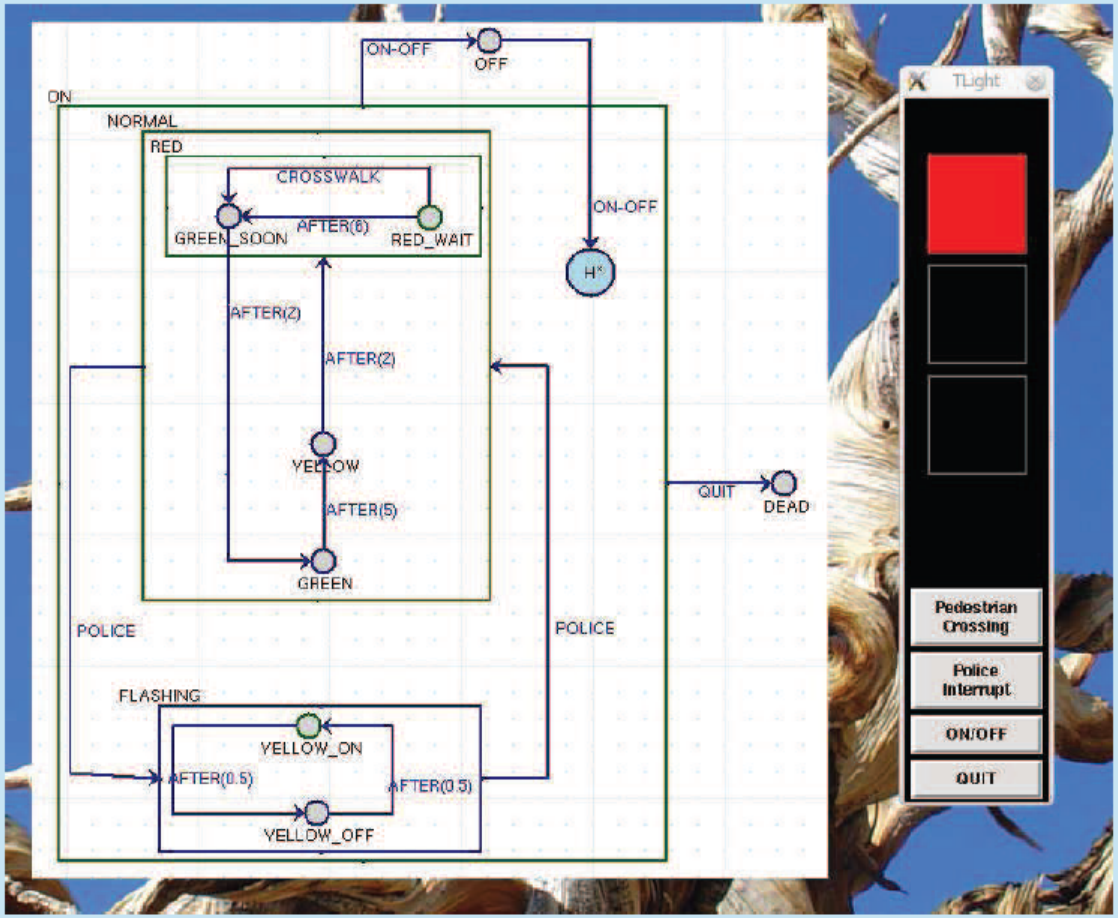


small **modification** in model may lead to large change in **app**
$\sim$ choice of formalism (e.g., Statecharts)

Statecharts



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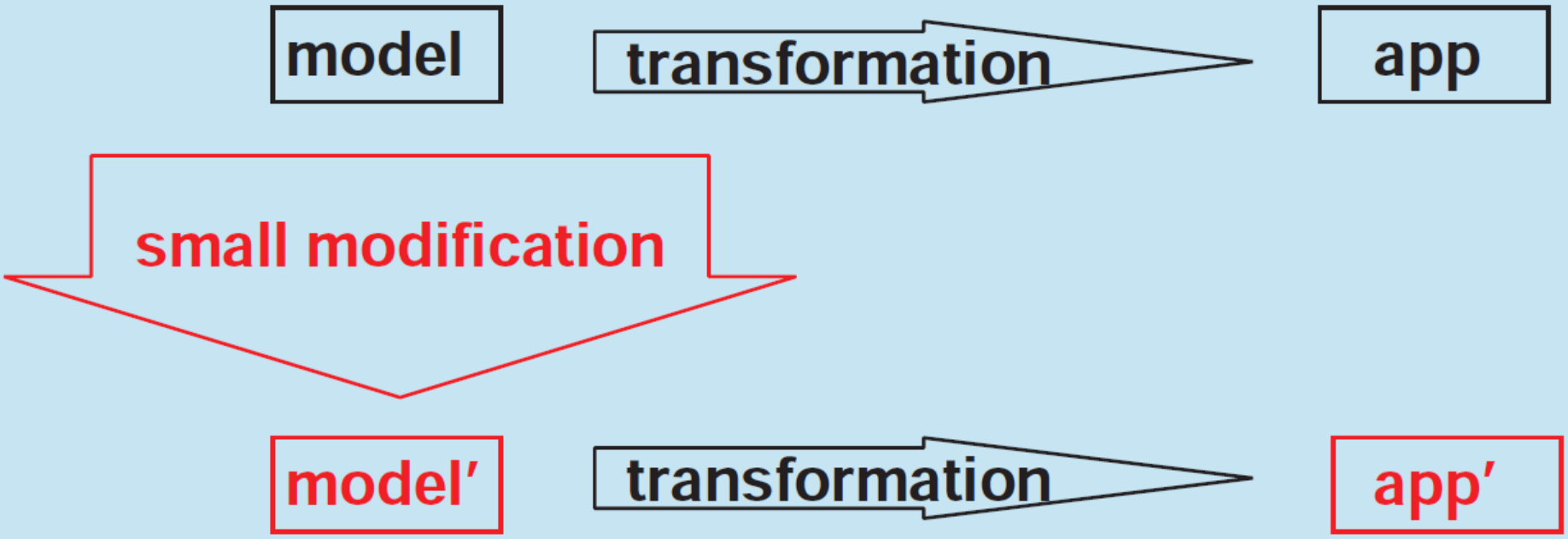
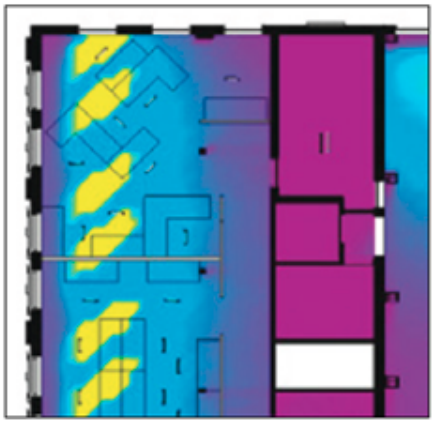


small **modification** in model may lead to large change in **app**
$\sim$ choice of formalism (e.g., Statecharts)


AUTODESK.
AUTODESK.

Nagy, Danil, Damon Lau, John Locke, Jim Stoddart, Lorenzo Villaggi, Ray Wang, Dale Zhao and David Benjamin.
“Project Discover : An Application of Generative Design for Architectural Space Planning.” (2017).

“fitness”

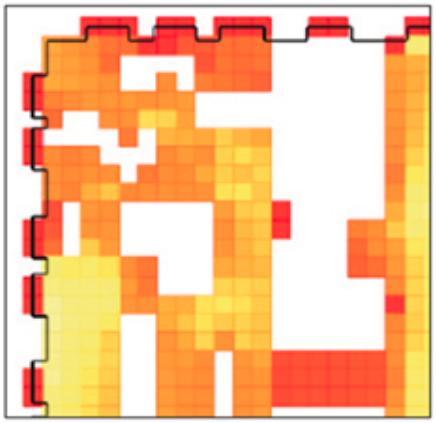


1. Daylight

2. Low Visual Distraction

3. Views to Outside

4. Adjacency Preference



5. Circulation

6. Work Styles

7. Low Acoustic Distraction

8. Low Density

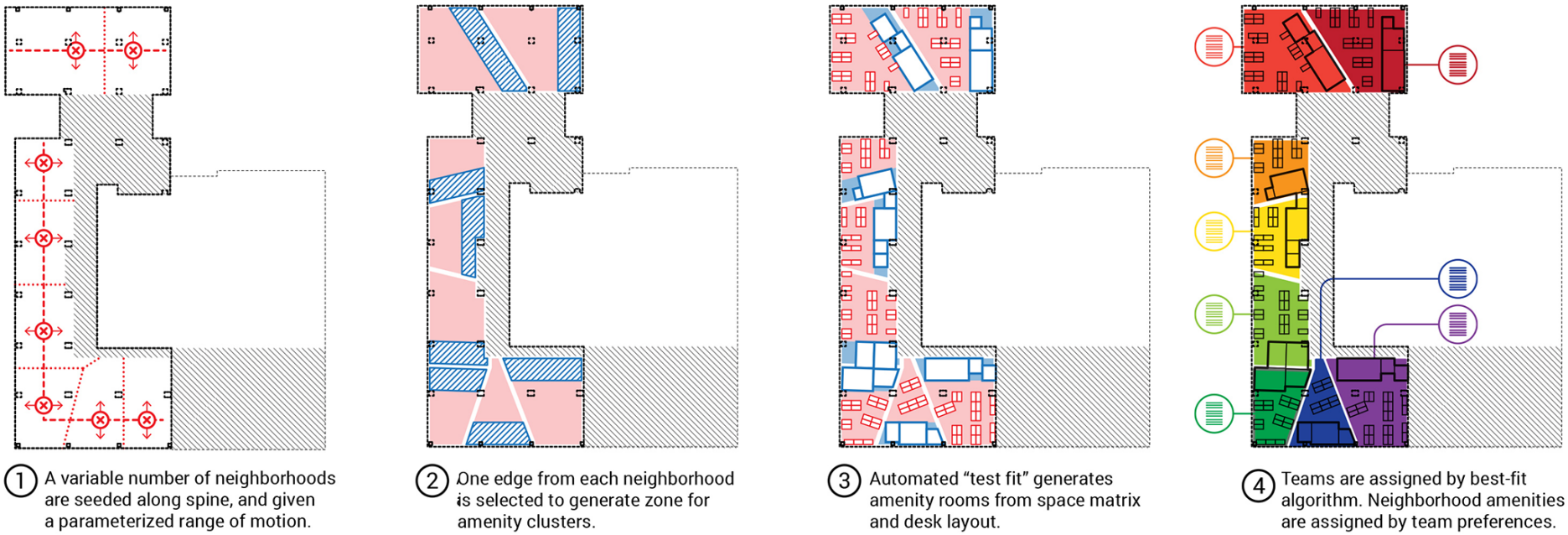
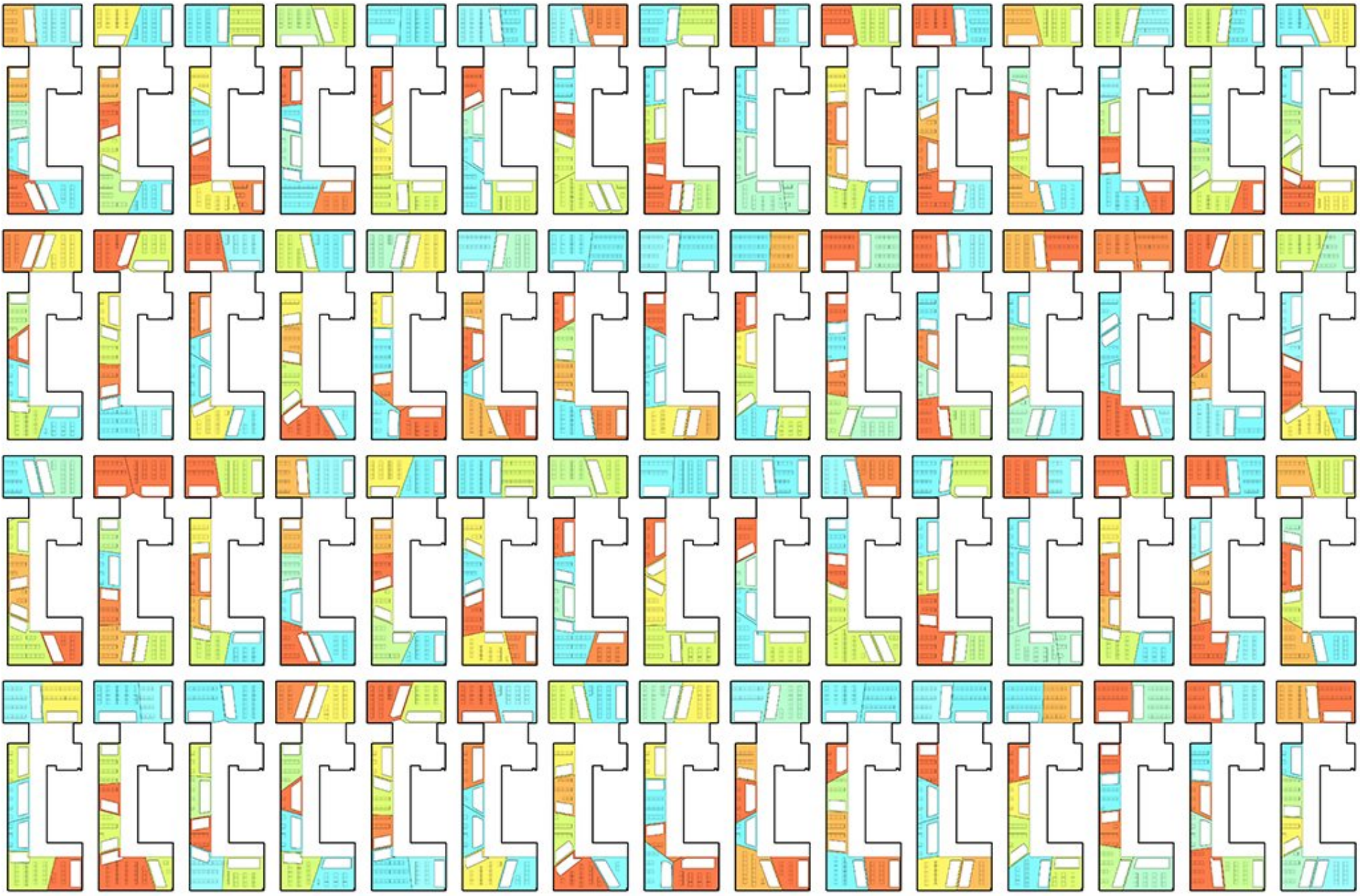


Figure 1. Description of specification of geometric model

generated (evolutionary – e.g., Genetic Algorithms)



“fitness” evaluation
for each of the generated designs

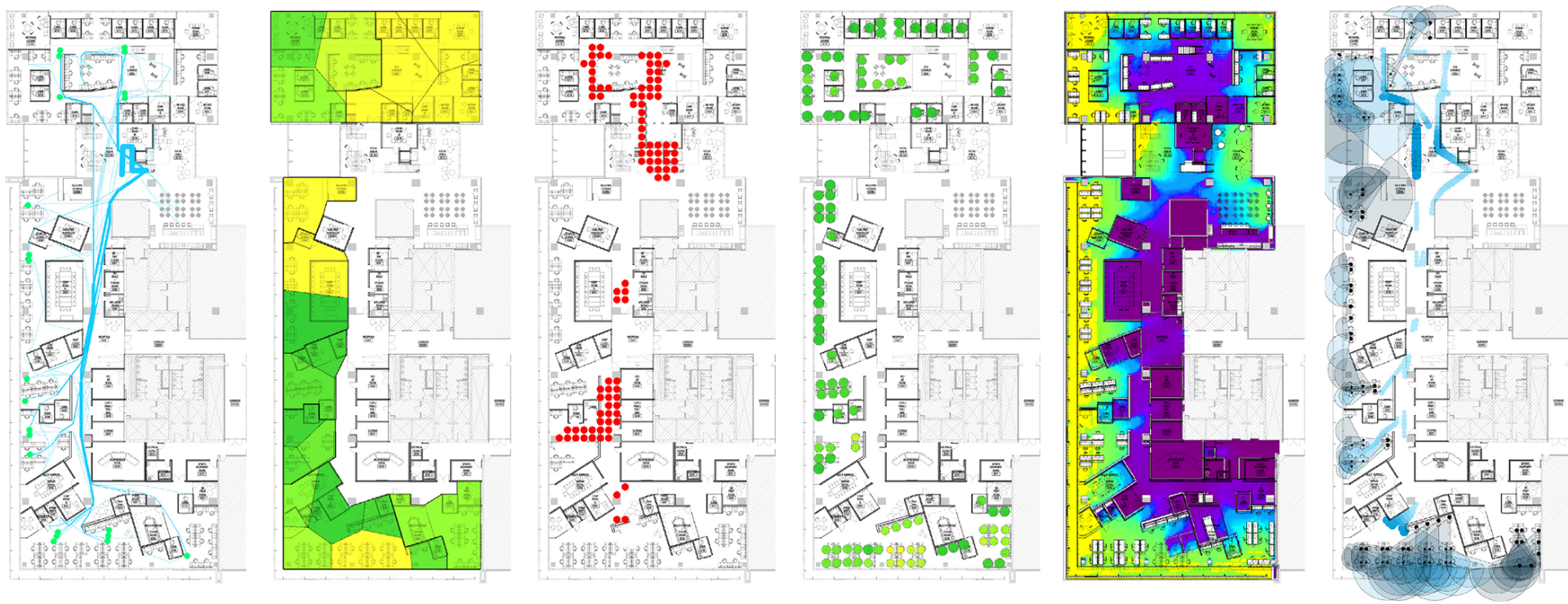
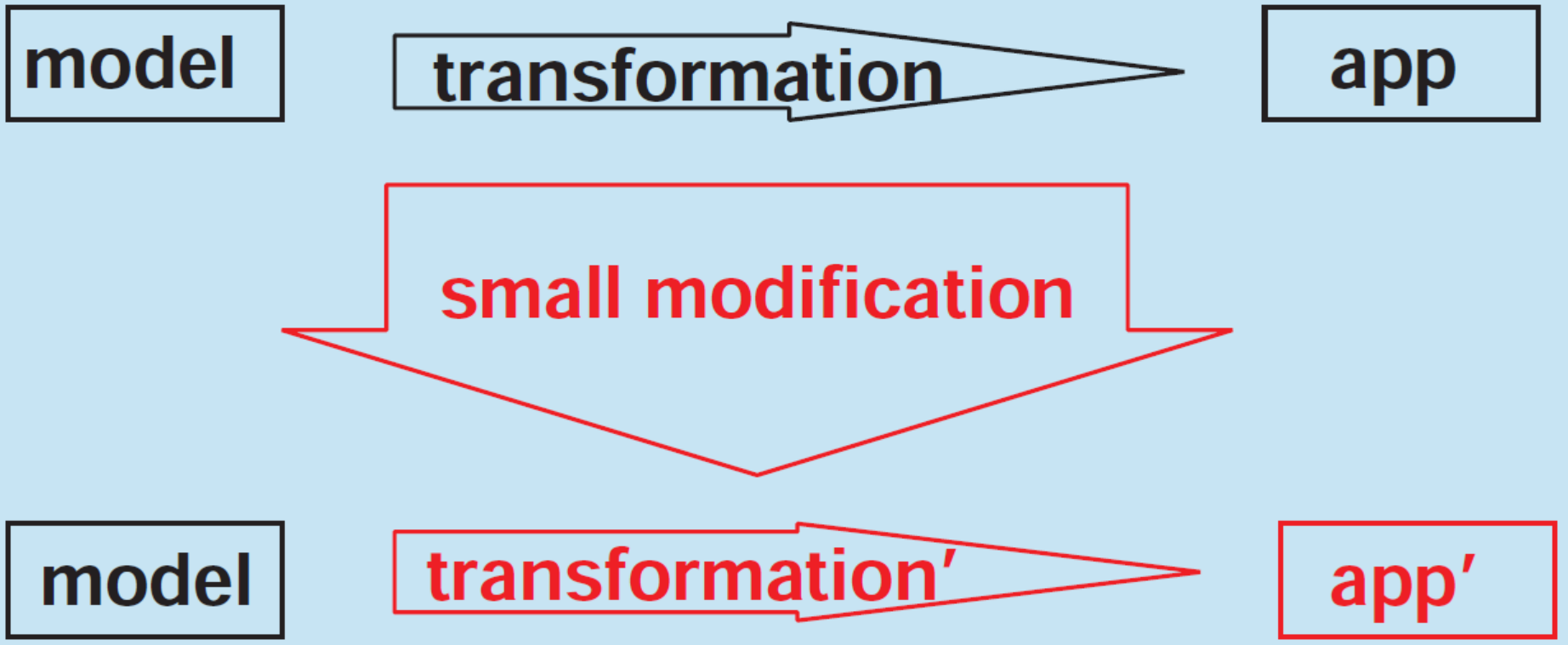
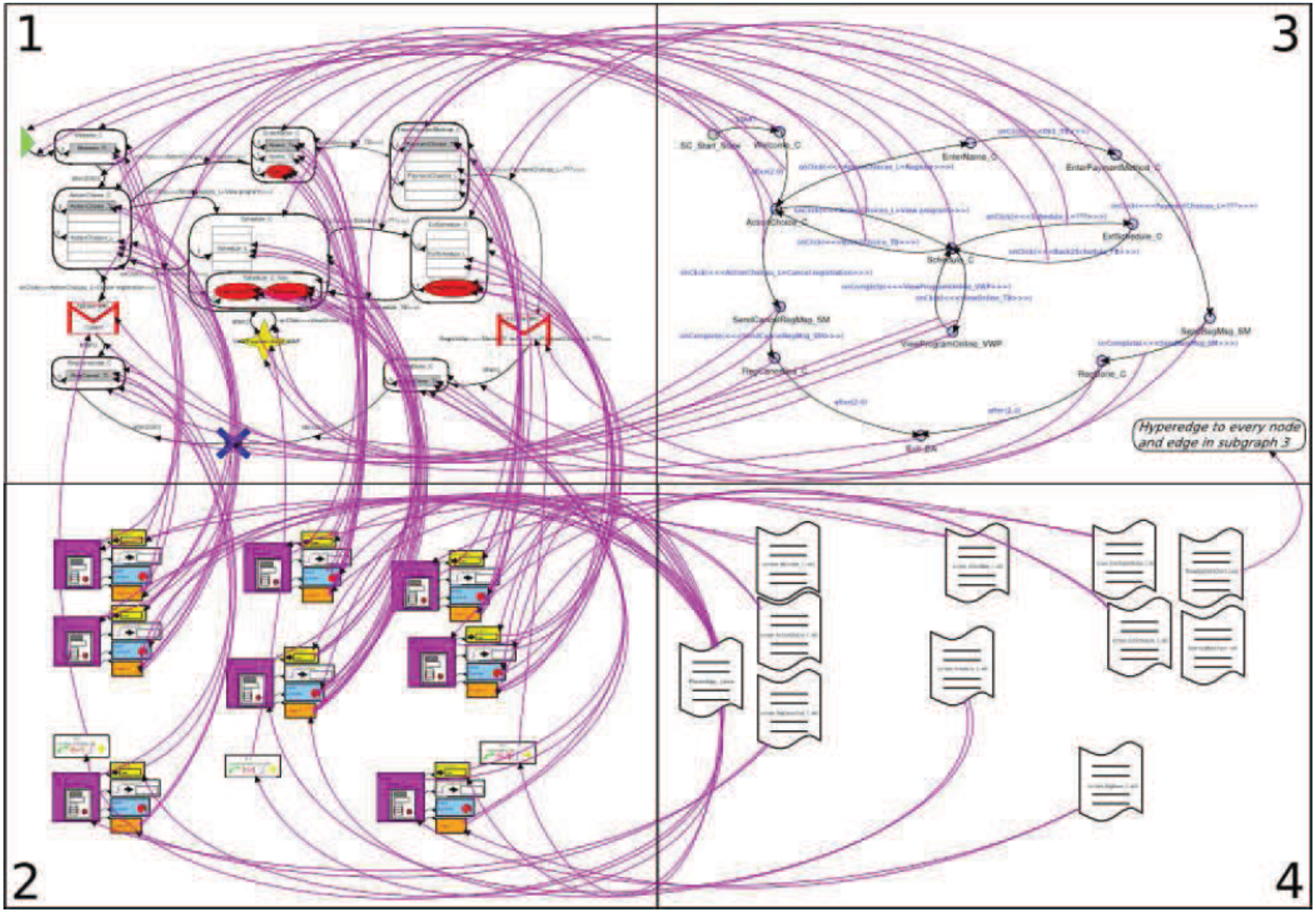


Figure 2. Design metrics (from left to right: adjacency preference, work style preference, buzz, productivity, daylight, and views to outside)

Model-Based Development:
Modify the Transformation
(e.g., target platform changes, or optimization)



Can be Multi-Step/Multi-Formalism

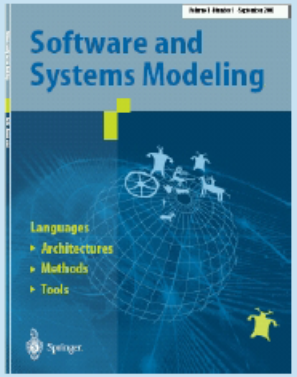


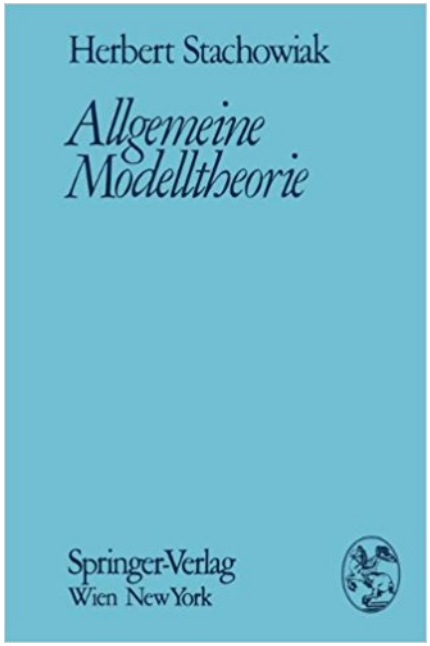
Building DS(V)M Tools Effectively . . .

- **development cost** of DS(V)M Tools may be prohibitive!
- $\Rightarrow$ need **Modelling Language Engineering**

Dissecting Modelling

Thomas Kühne. *Matters of (Meta-)Modeling*.
Software and System Modeling 5(4): 369-385 (2006)

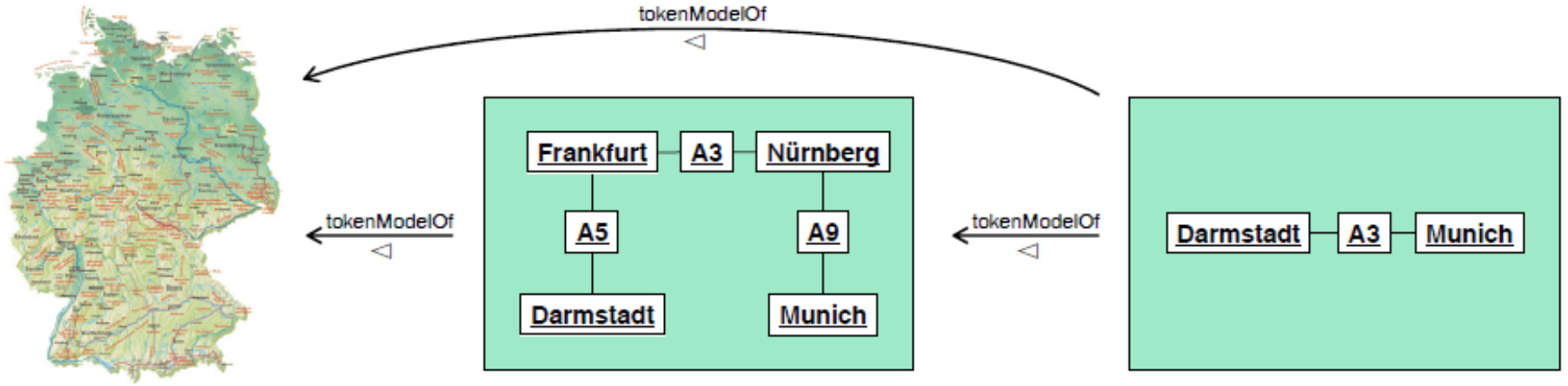




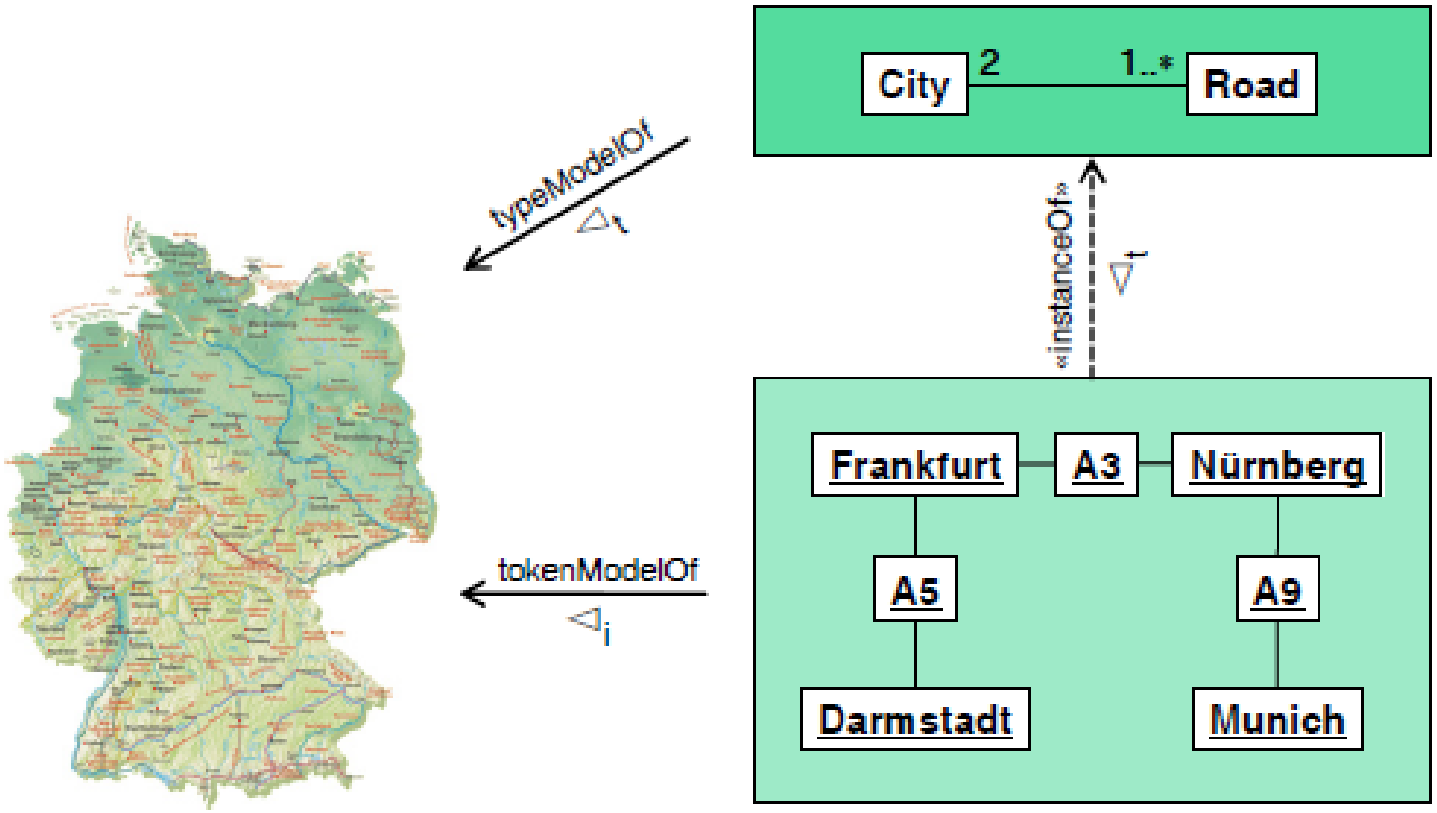
Model Features

mapping feature	A model is based on an original.[4]
reduction feature	A model only reflects a (relevant) selection of an original's properties.
pragmatic feature	A model needs to be usable in place of an original with respect to some purpose.

Token Models



Rôles a Model may Play



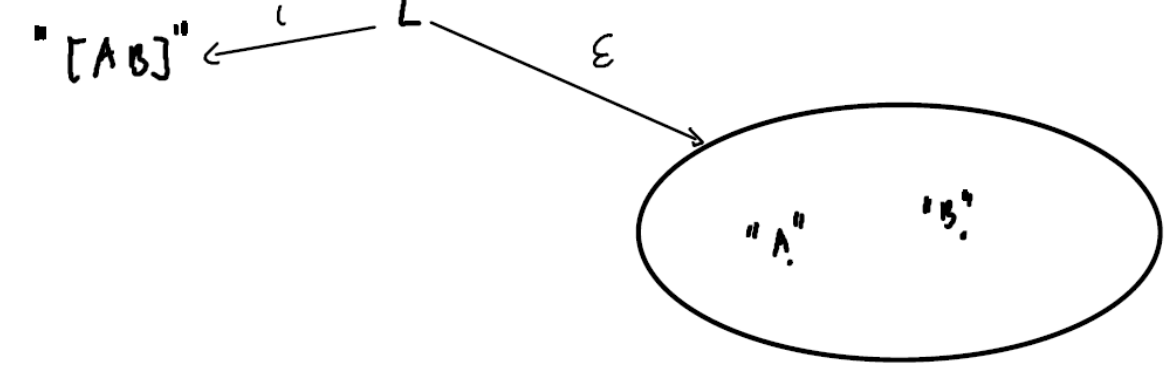
$[\![\text{"A+B*"}]\!]_{RE} = \{ \text{"A"}, \text{"AA"}, \ldots, \text{"AB"}, \text{"AAB"}, \ldots \}$

$[\![\text{"[AB]"}]\!]_{RE} = \{ \text{"A"}, \text{"B"} \}$

"INTENSION"

"EXTENSION"

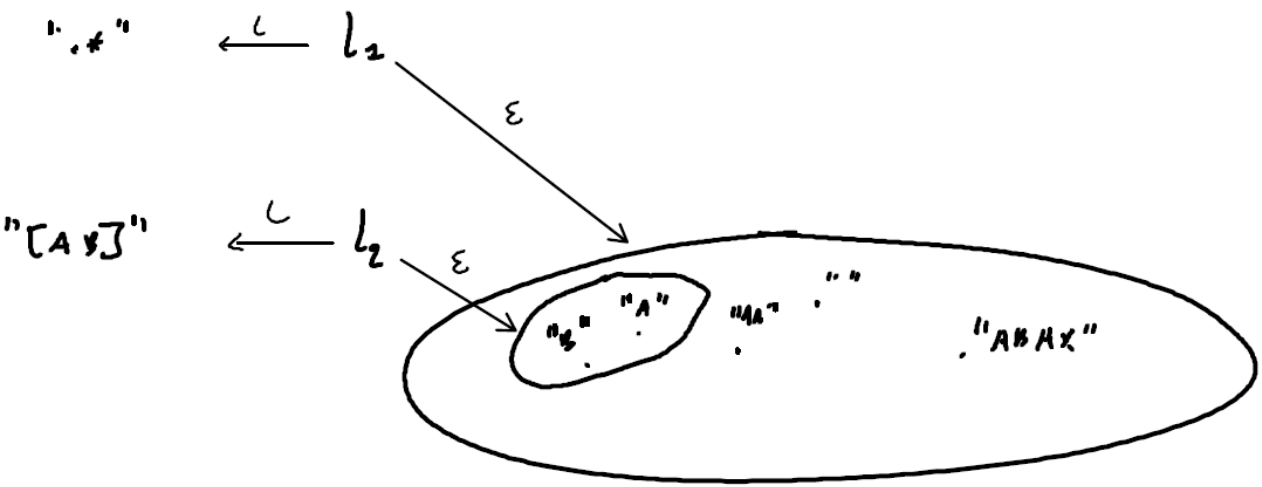
LANGUAGE L



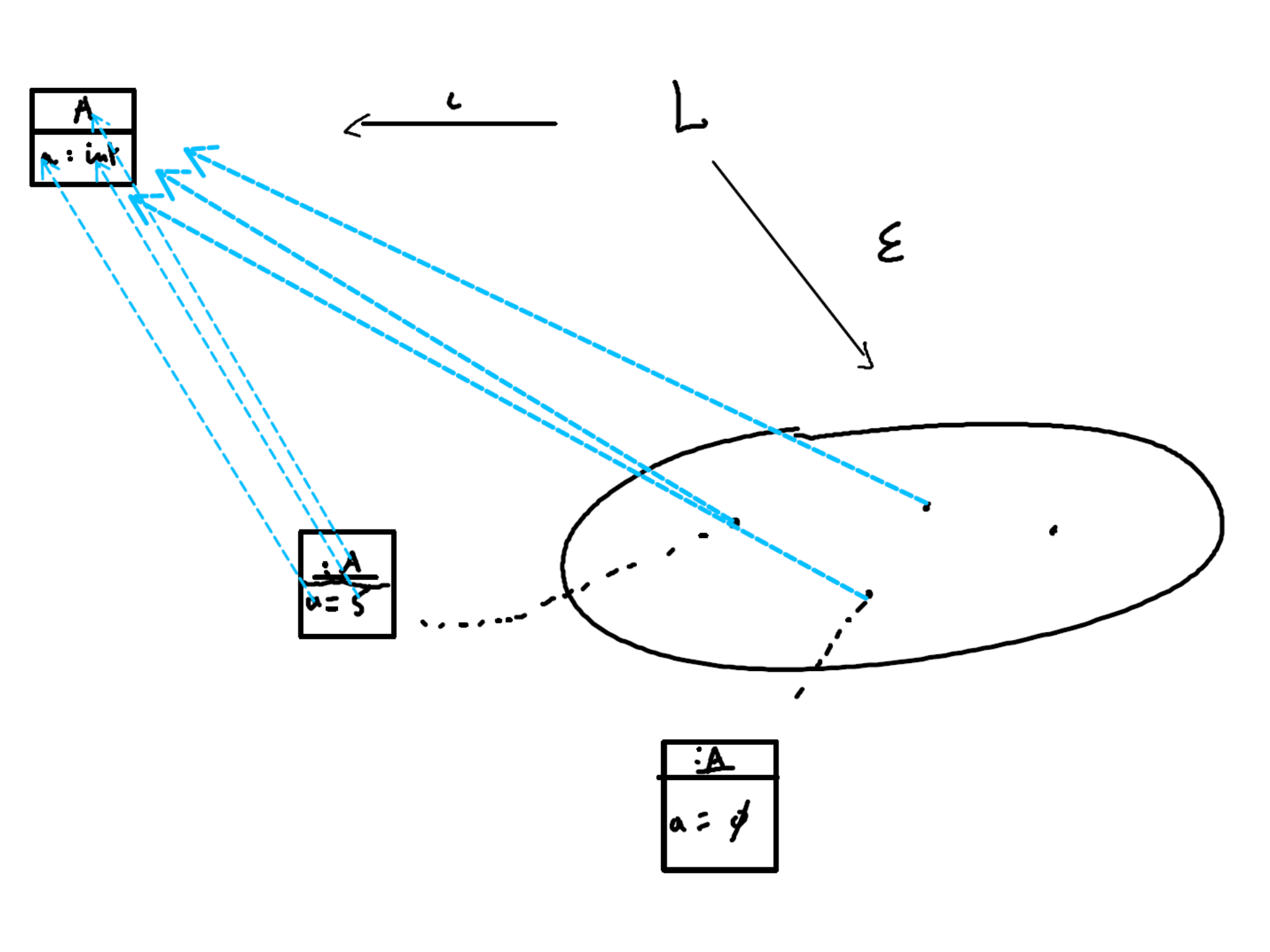
. ≡ ANY CHAR FROM ALPHABET

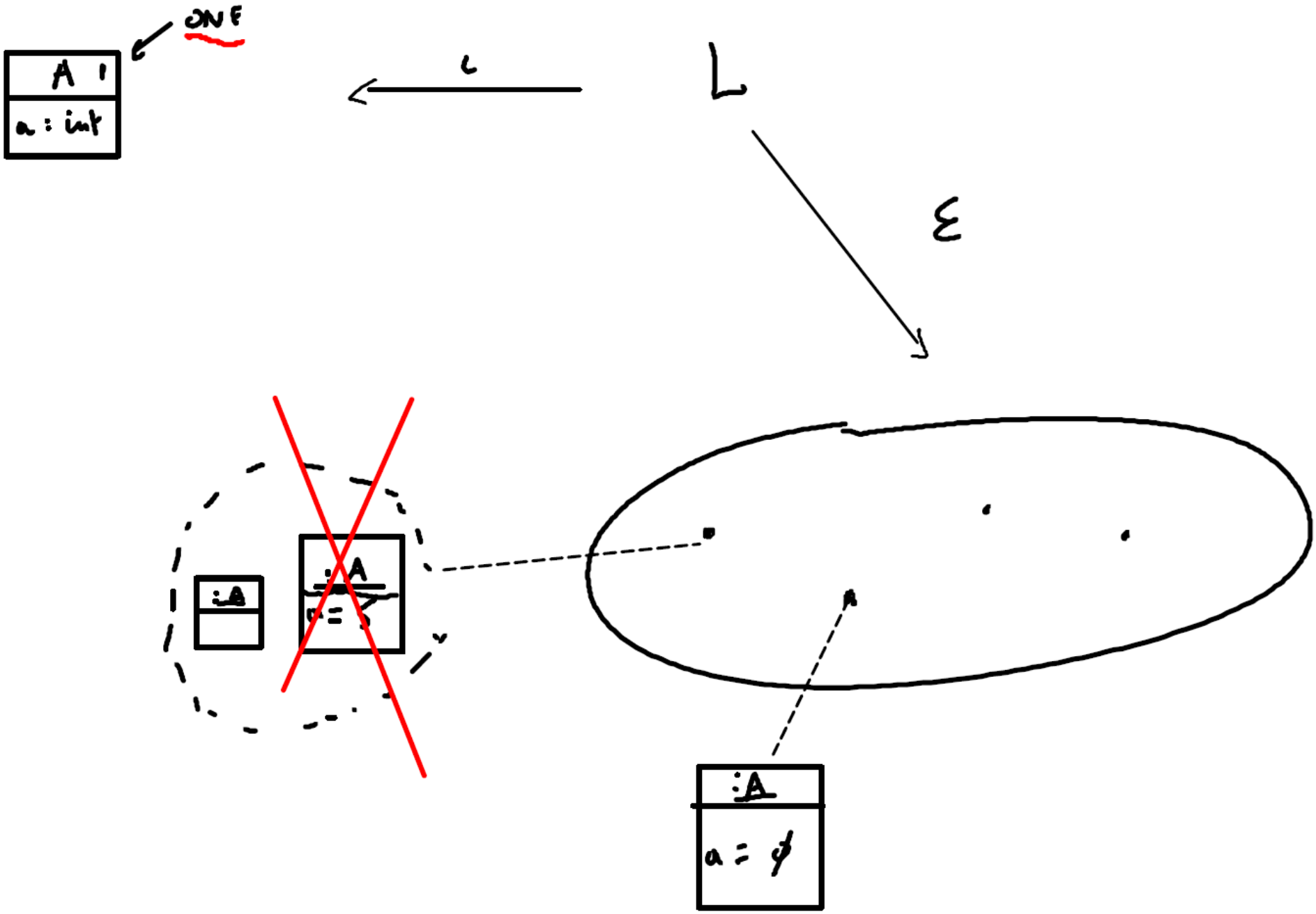
$\iota(L_1)$ = ".*" $\quad \mathcal{E}(L_1) = \{$"", "A", "AA", ... $\}$

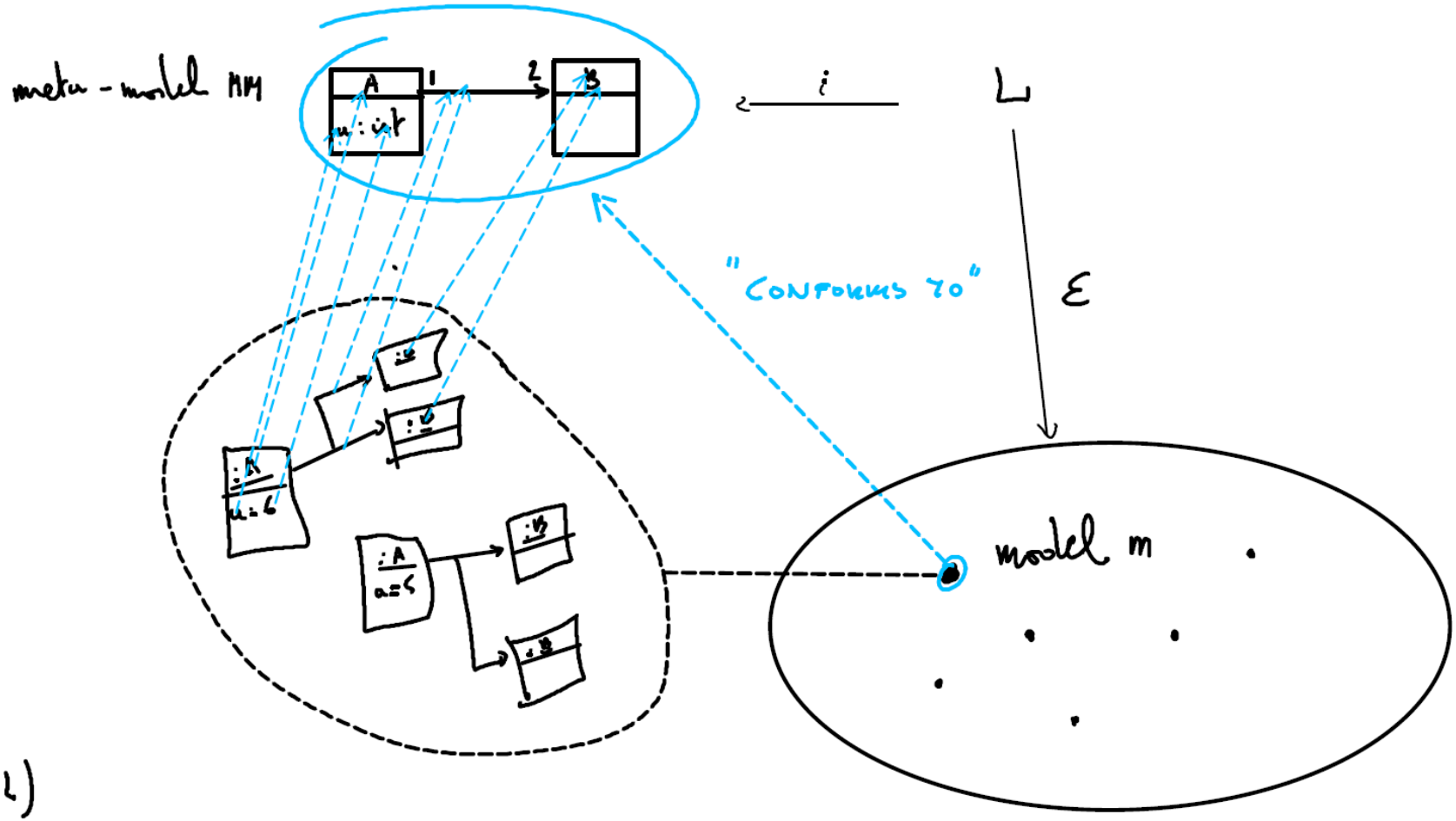
$\iota(L_2)$ = "[AB]" $\quad \mathcal{E}(L_2) = \{$"A", "B"$\}$



$\iota(L_2) <: \iota(L_1) \Leftrightarrow \mathcal{E}(L_2) \subseteq \mathcal{E}(L_1)$


A
a : int
:A
a = 5
:A
a = 6


ONF
A
a : int
L
ε
:A
:A
a = 5
:A
a = ∅



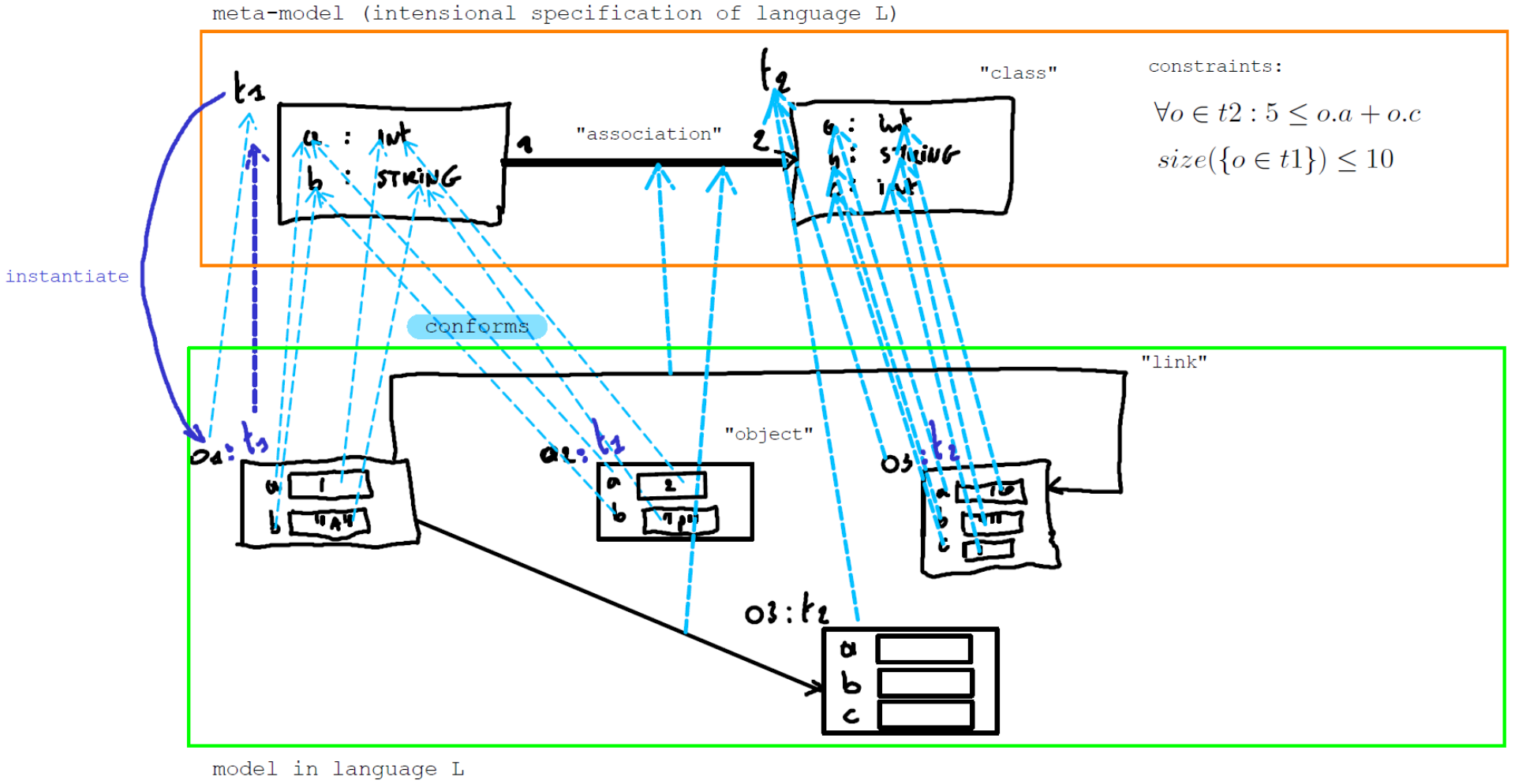
$MM = \iota(L)$

M CONFORMS TO MM $\equiv$ $m \in \mathcal{E}(L)$

verify (m, MM) = True (WITH PARTICULAR BINDING / MORPHISM ...)

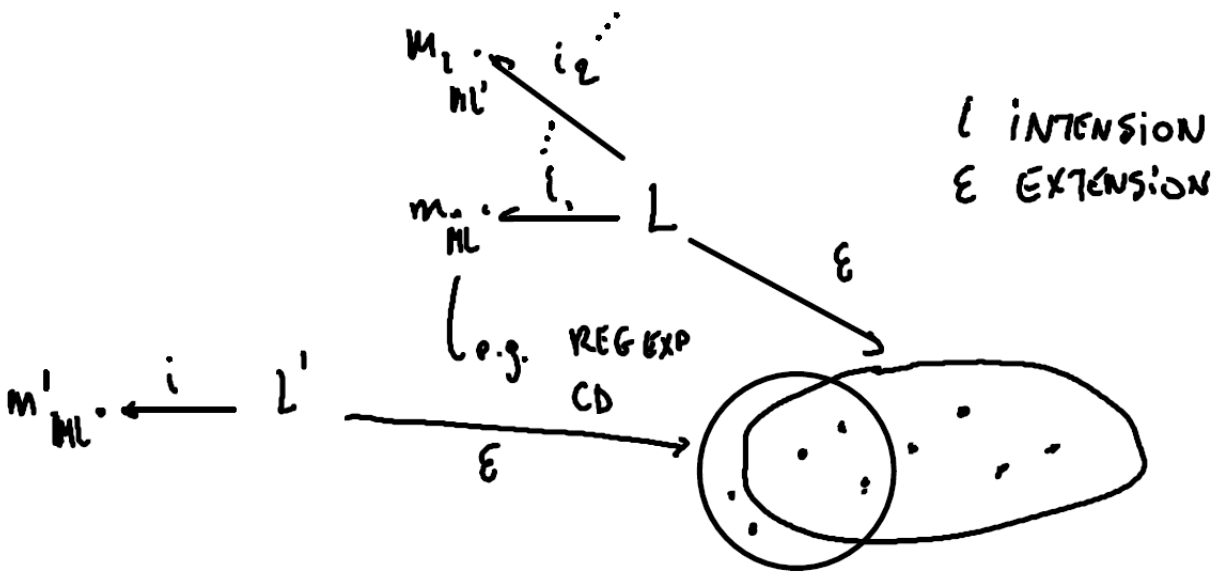
$\mu(MM) = L$

$[\![MM]\!]_{CD\_MM} = \mathcal{E}(L)$

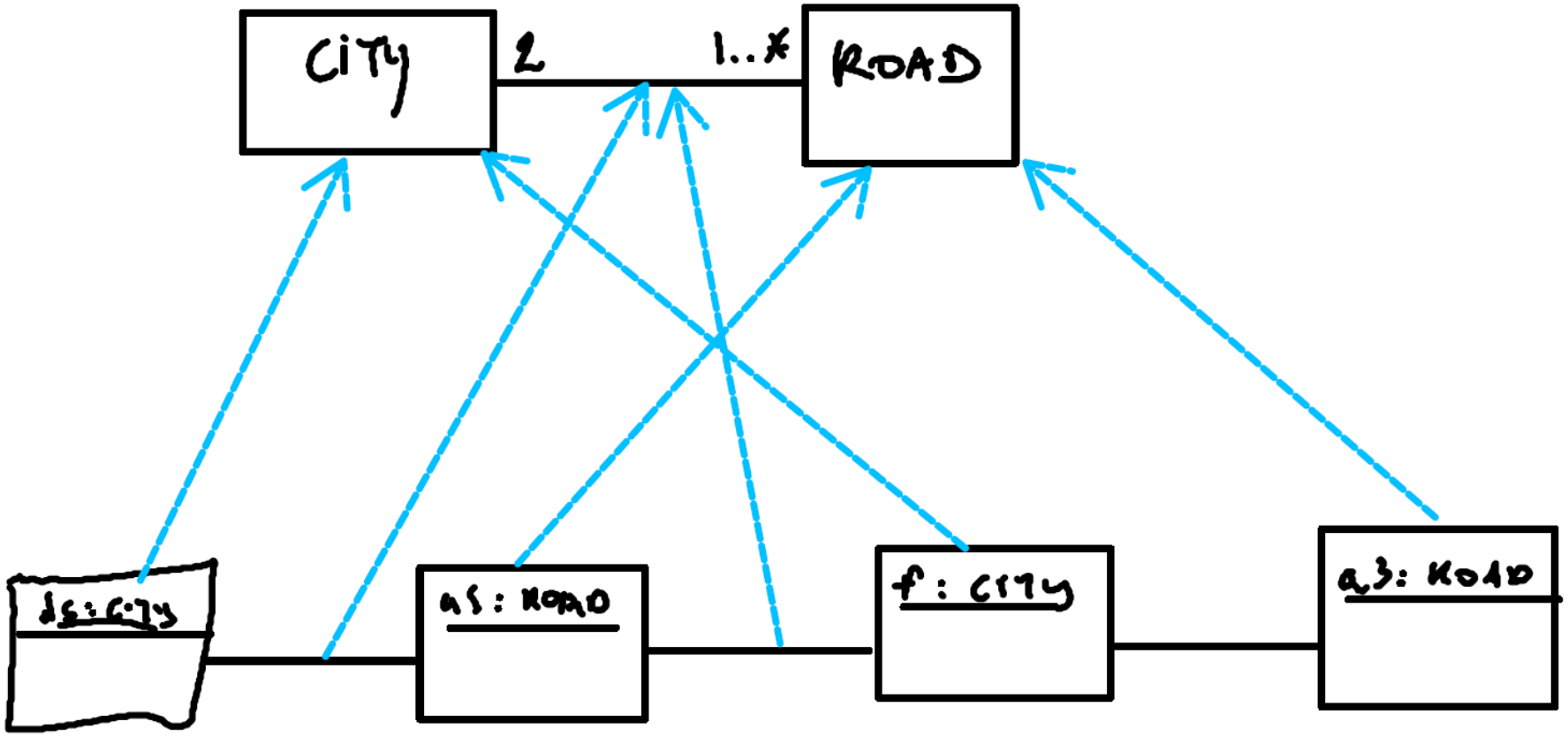

meta-model (intensional specification of language L)
"class"
constraints:
$\forall o \in t2 : 5 \leq o.a + o.c$
$size(\{o \in t1\}) \leq 10$
"association"
instantiate
conforms
"link"
"object"
model in language L

note that there may be different (types of)
conforms_to relationships:
name-based (also known as nominal), structure based, ...

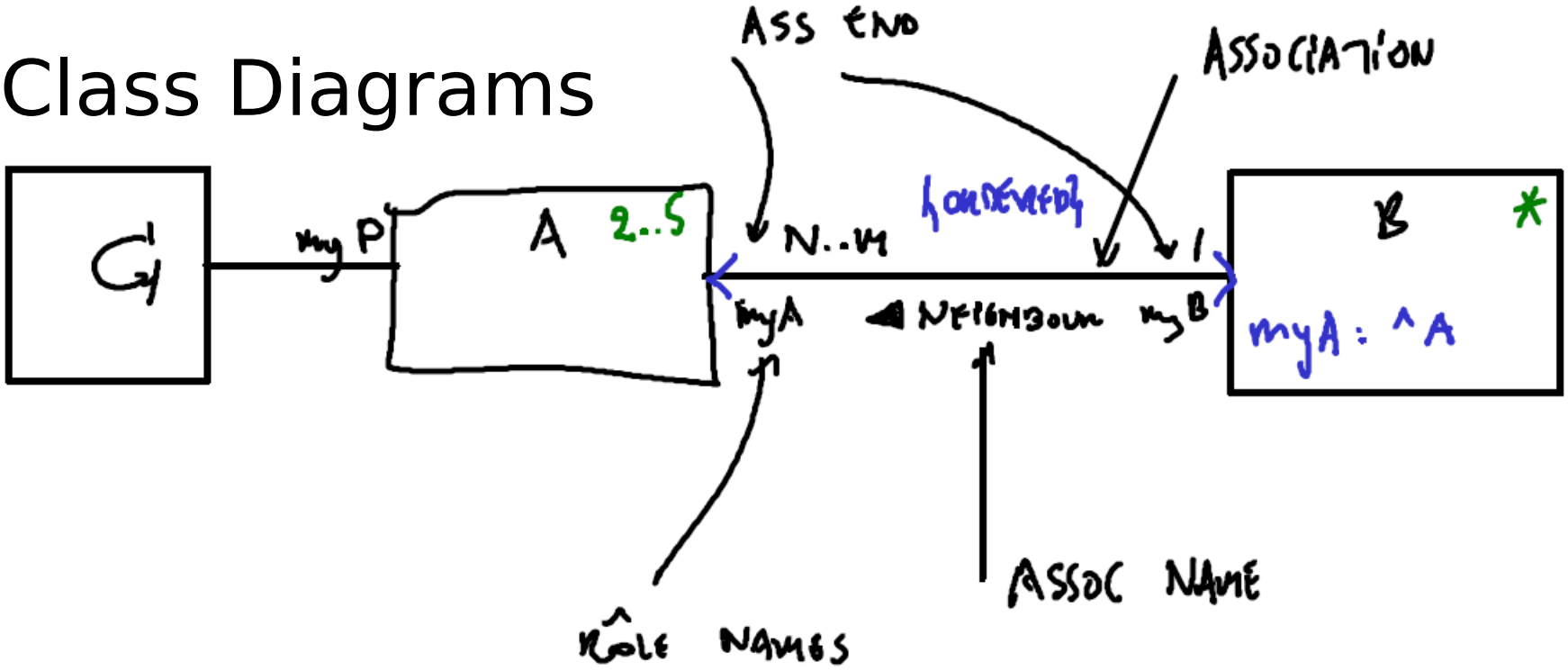
a single language may have multiple intensional descriptions

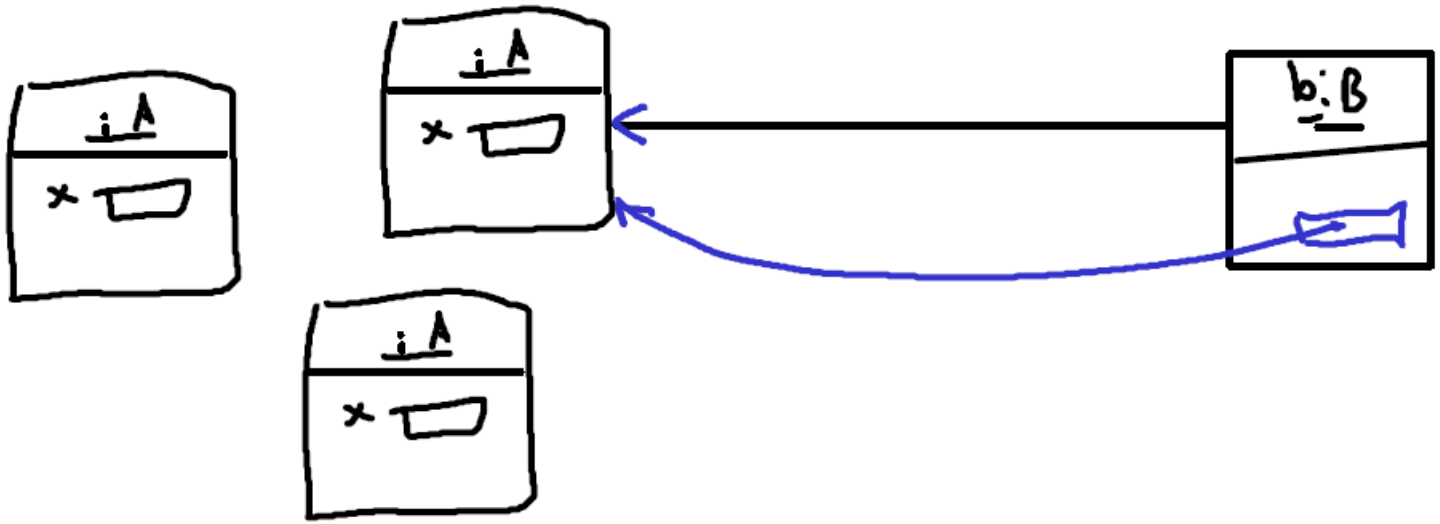


languages may (partially) overlap

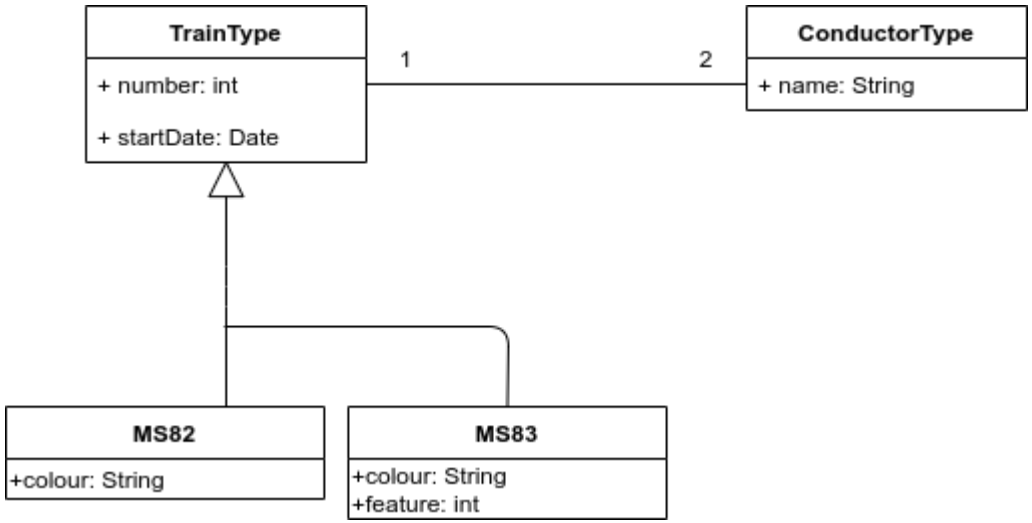

City
2
1..*
ROAD
a5: ROAD
f: City
a3: ROAD

Class Diagrams

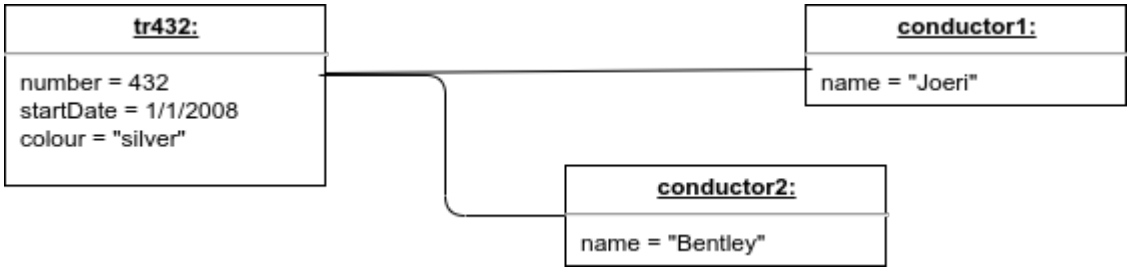




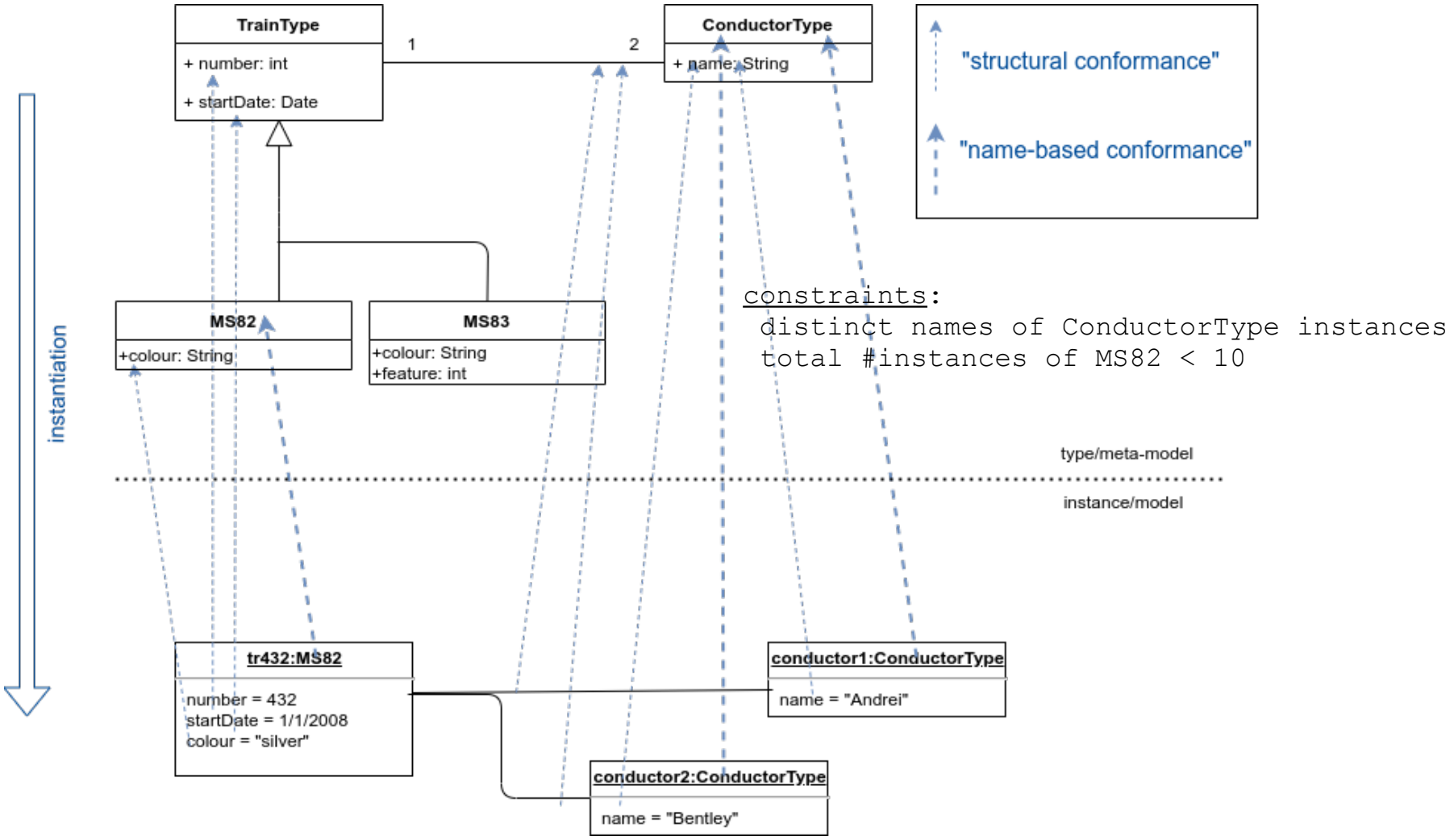
Class Diagram



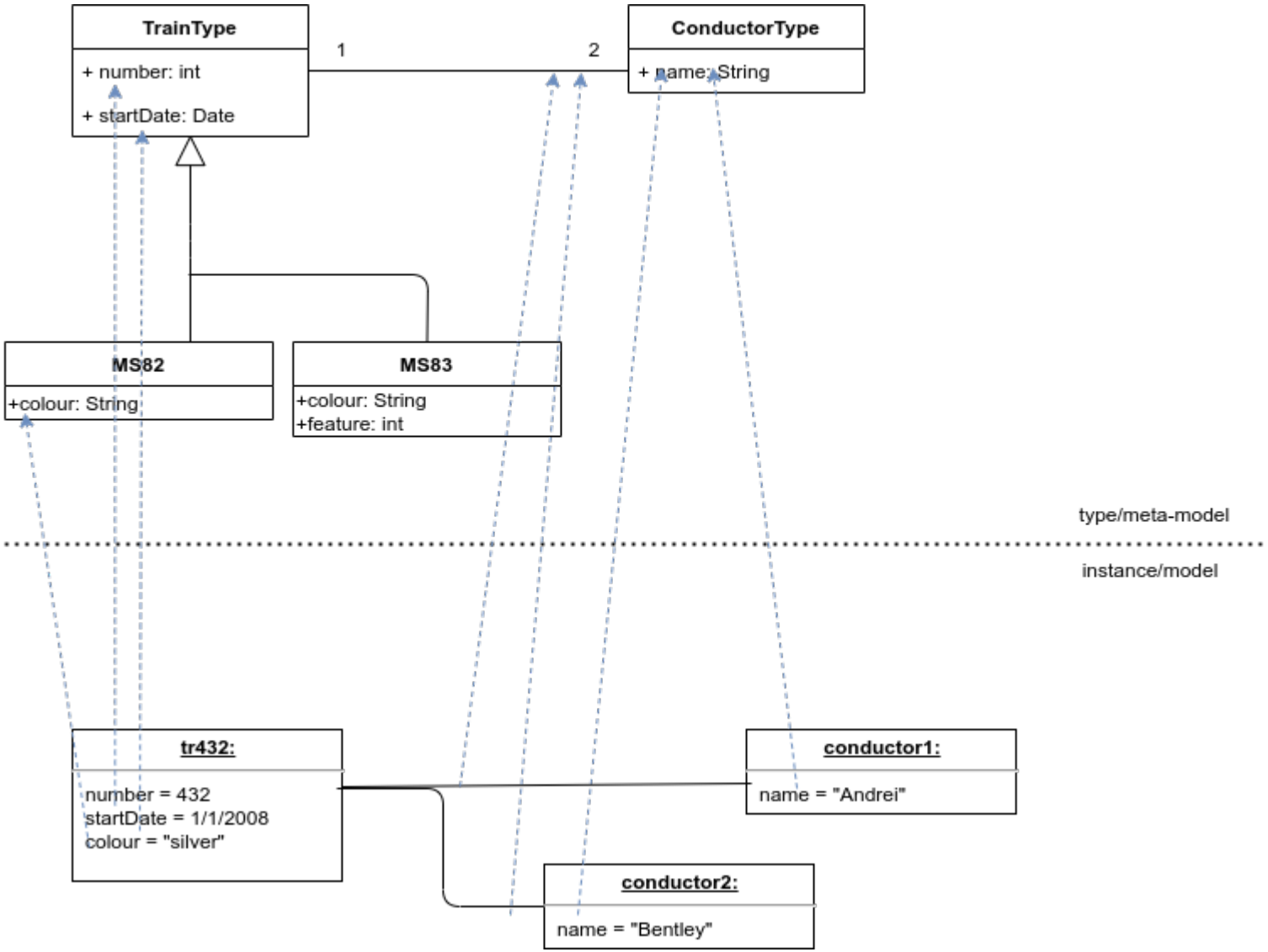
Object Diagram



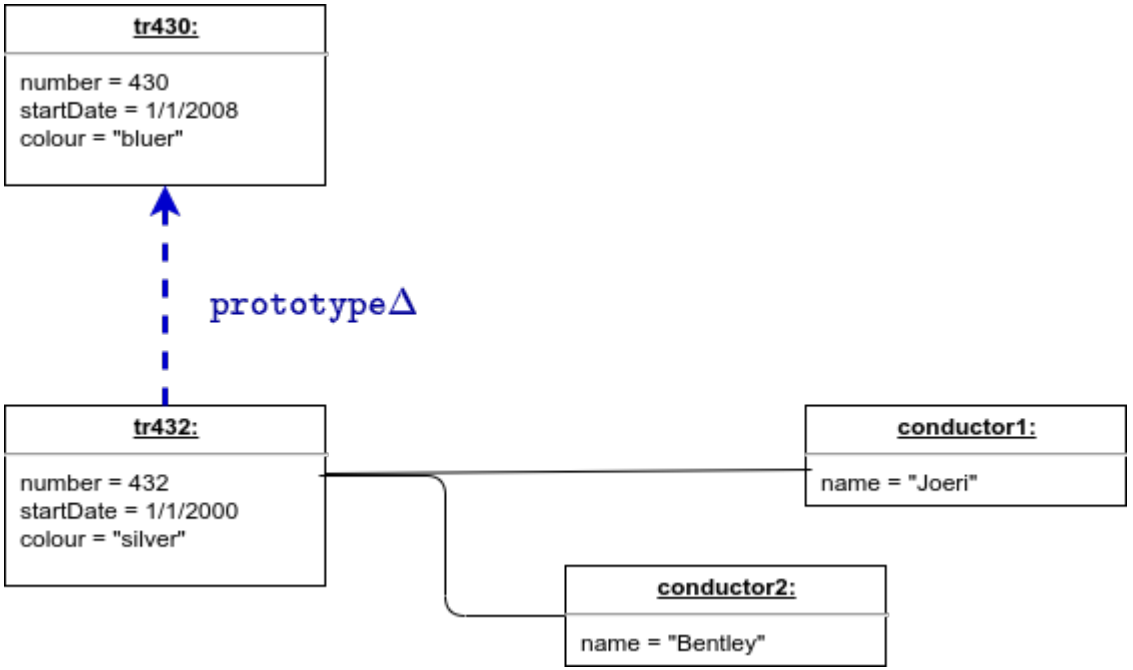
Class vs. Instance

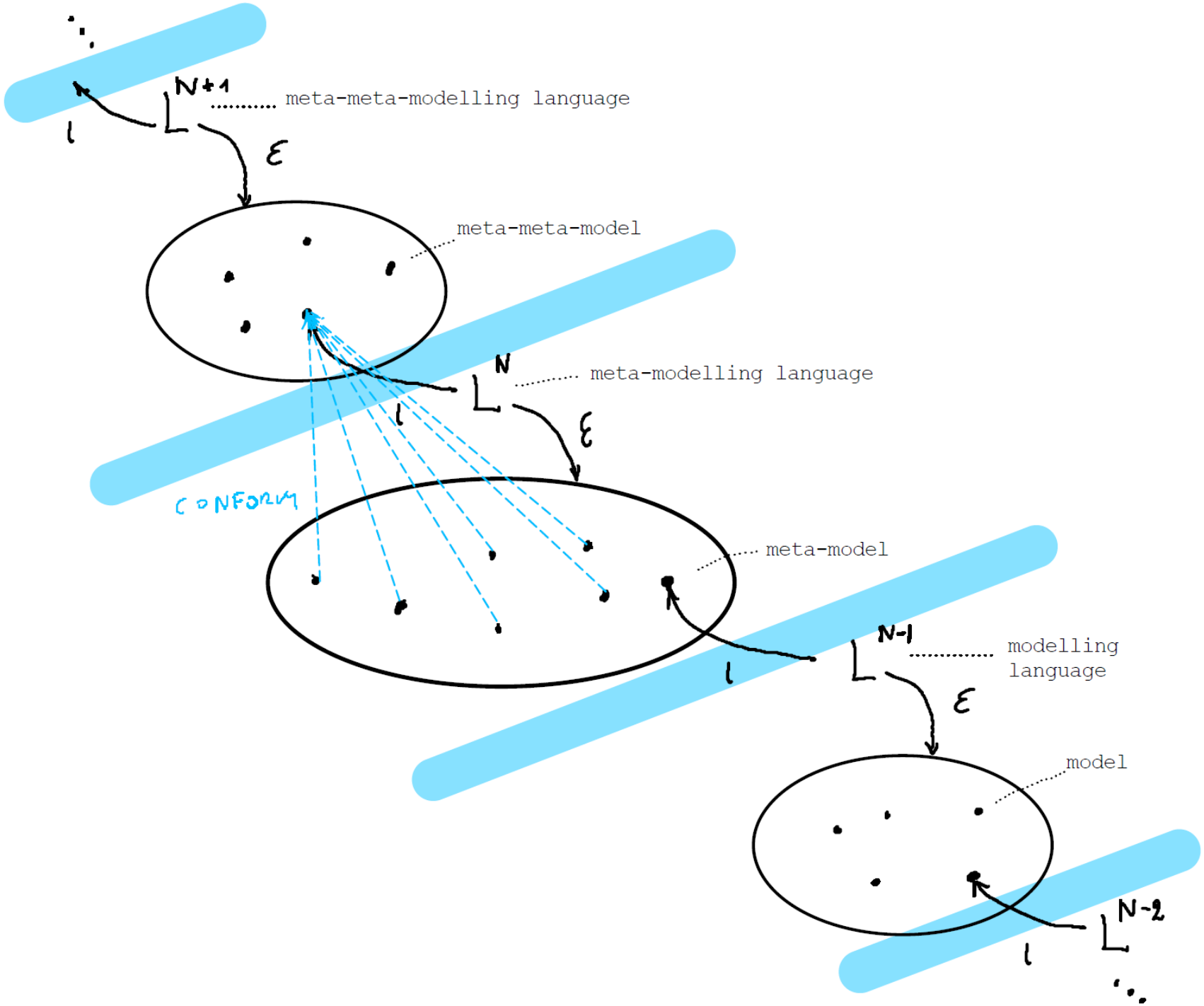


“duck typing”


TrainType
+ number: int
+ startDate: Date
1
2
ConductorType
+ name: String
MS82
+colour: String
MS83
+colour: String
+feature: int
type/meta-model
instance/model
tr432:
number = 432
startDate = 1/1/2008
colour = "silver"
conductor1:
name = "Andrei"
conductor2:
name = "Bentley"

delegation, object-based




N+1
meta-meta-modelling language
meta-meta-model
N
meta-modelling language
CONFORM
meta-model
N-1
modelling language
model
N-2

meta-ness

$$e_1 R^n e_2 = \begin{cases} \exists e : e_1 R^{n-1} e \wedge\ e R\, e_2 & , n > 1 \\ e_1 R\, e_2 & , n = 1 \end{cases}$$

acyclic $\forall\, e_1, e_2, n : e_1 R^n\, e_2 \rightarrow \neg\, e_2 R\, e_1$, and

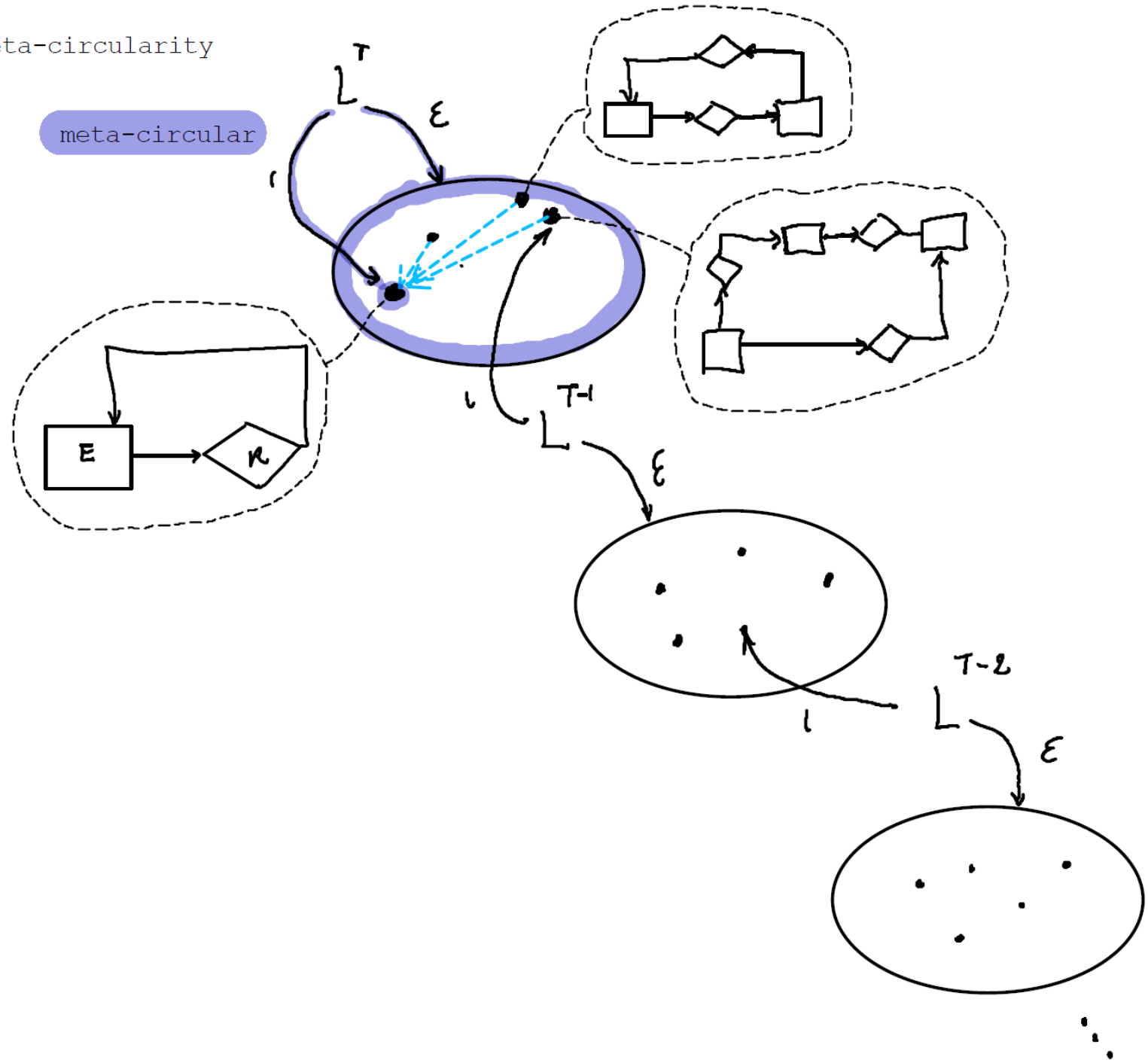
anti-transitive $\forall\, n \geq 2 : R^n \cap R = \emptyset.$

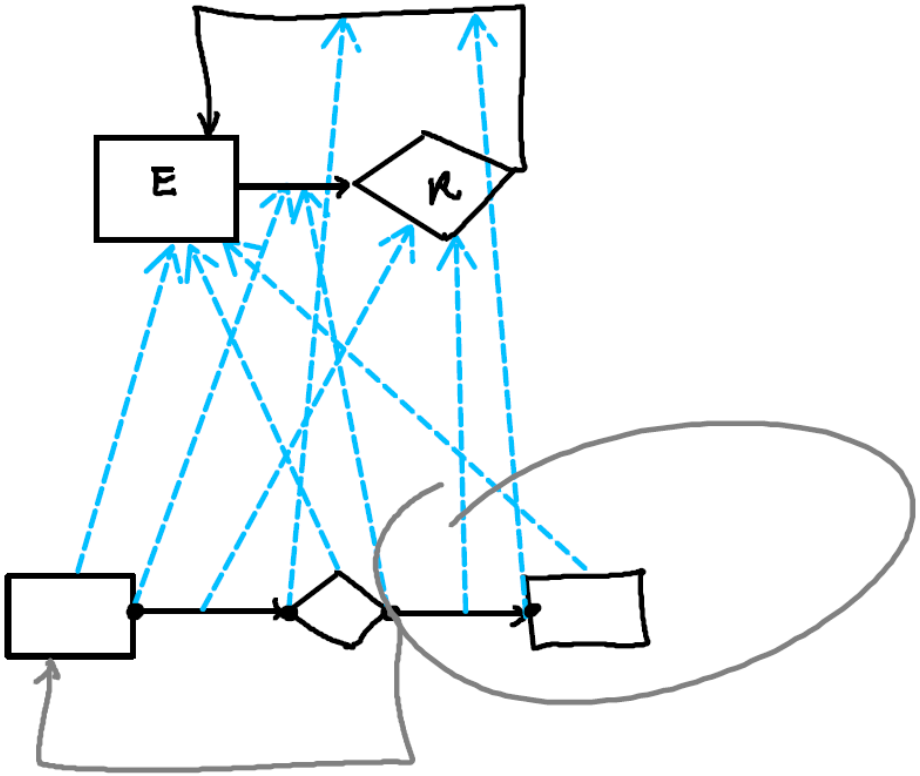
level respecting $\forall\, n, m :$

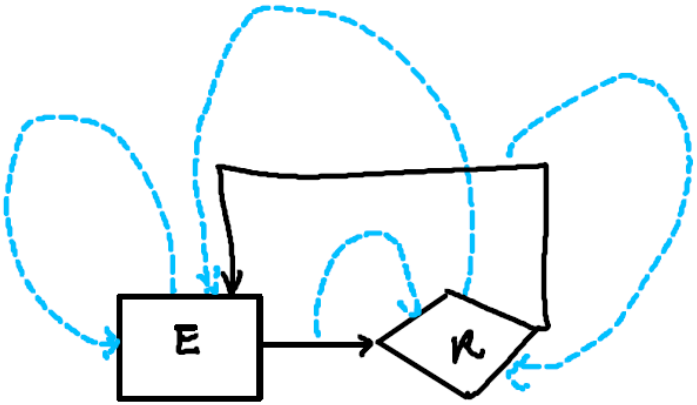
$$(\exists\, e_1, e_2 : e_1 R^n e_2 \wedge\ e_1 R^m e_2) \rightarrow$$

$$n = m$$

meta-circularity







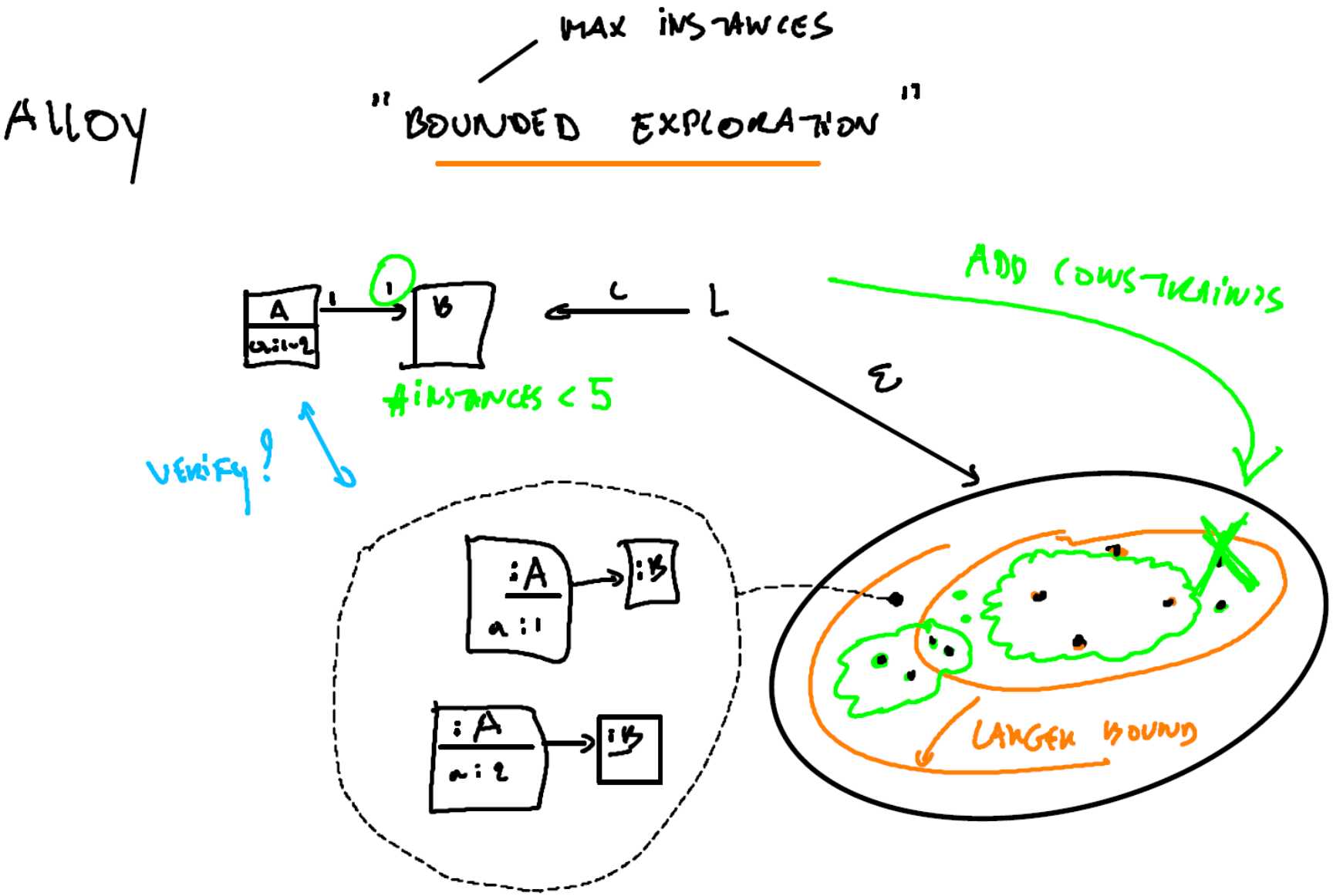
Entity Relationship Diagram (ERD)

can be used as the MMMCL
Meta-Model at the Meta-Circular Level

MMMCL can be used to "bootstrap"
a meta-modelling infrastructure.
e.g., Node and Edge in metaDepth

Bounded Exploration (of a language defined through a meta-model)

http://alloytools.org/ Daniel Jackson @ MIT



$$\mathcal{S} \lhd \mathcal{M}$$

System vs. Model

$$\rho(\mathcal{S}, \mathcal{M}) \longrightarrow \mathcal{S} \lhd \mathcal{M}$$

representation relationship
(representative, placeholder for)

$$\mathcal{S} \lhd \mathcal{M}_1 \wedge \rho(\mathcal{S}, \mathcal{M}_1)$$
$$\mathcal{M}_1 \lhd \mathcal{M}_2 \wedge \rho(\mathcal{S}, \mathcal{M}_2)$$
as opposed to $\rho(\mathcal{M}_1, \mathcal{M}_2)$.

$$\mathcal{M} = \alpha(\mathcal{S}).$$

Model is abstraction of System

$$\alpha = \tau \circ \alpha' \circ \pi$$

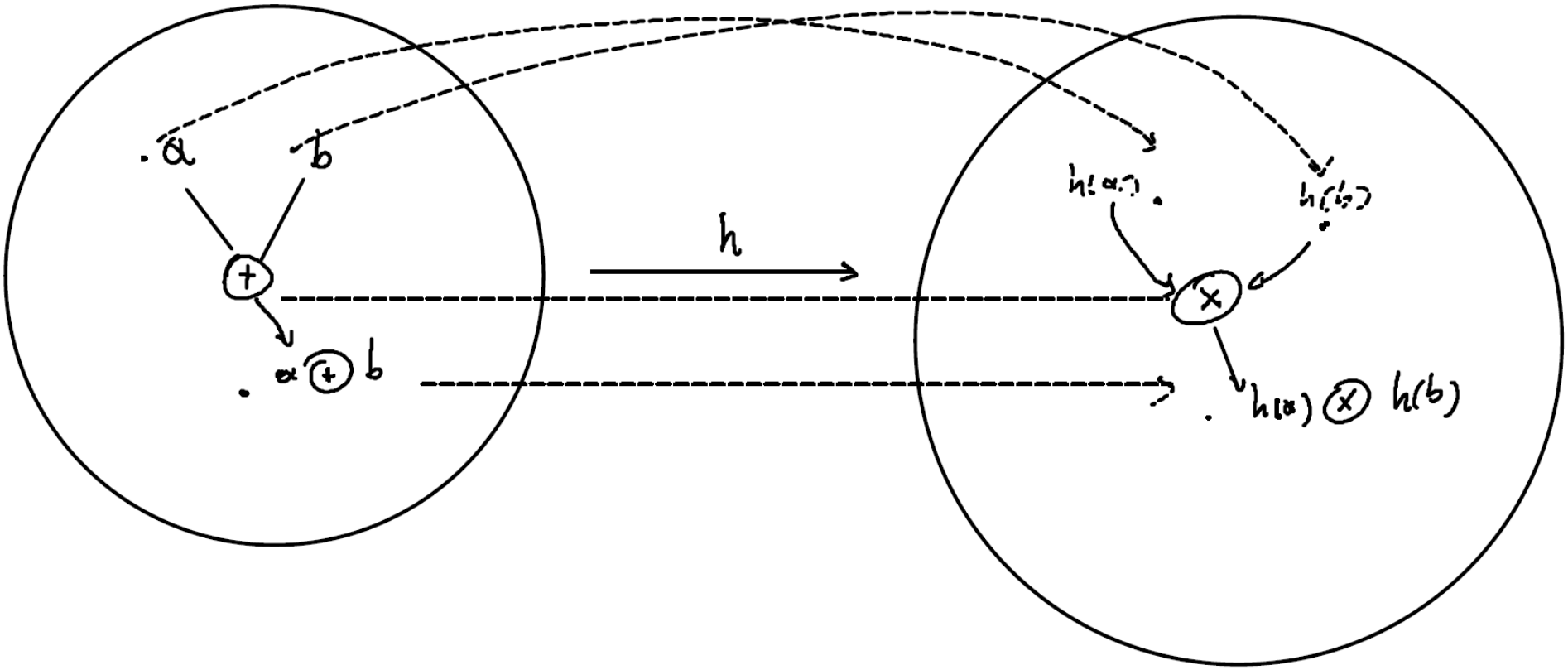
translation o abstraction o projection

mapping feature	A model is based on an original.[4]
reduction feature	A model only reflects a (relevant) selection of an original's properties.
pragmatic feature	A model needs to be usable in place of an original with respect to some purpose.

$$h(a \oplus b) = h(a) \otimes h(b)$$

projection is an injective homomorphism

maps distinct elements of its domain to distinct elements of its codomain


a
b
+
a + b
h
h(a)
h(b)
×
h(a) × h(b)

token (aka “snapshot”) model: projection and translation $\alpha' = id$

$$\pi(e_1) = \pi(e_2) \nrightarrow e_1 = e_2$$

$$e_1 \sim_\pi e_2 \rightarrow \pi(e_1) = \pi(e_2)$$

equivalence (wrt. property)

for concept C pertaining to property satisfaction P:
extension vs. intension

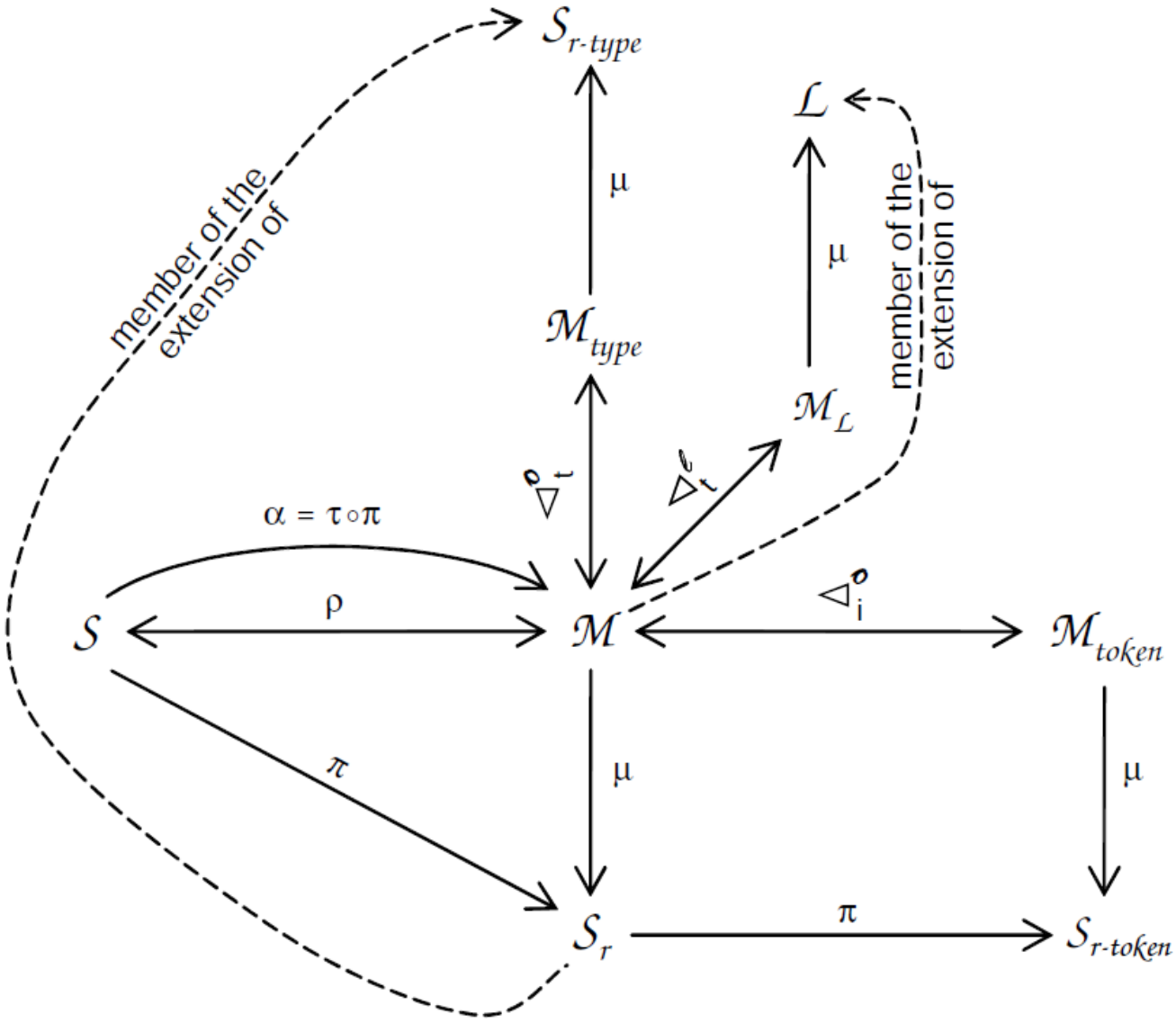
$$\varepsilon(C) = \{x \mid P(x)\}, \text{ where } P = \iota(C)$$

generalization vs. specialization

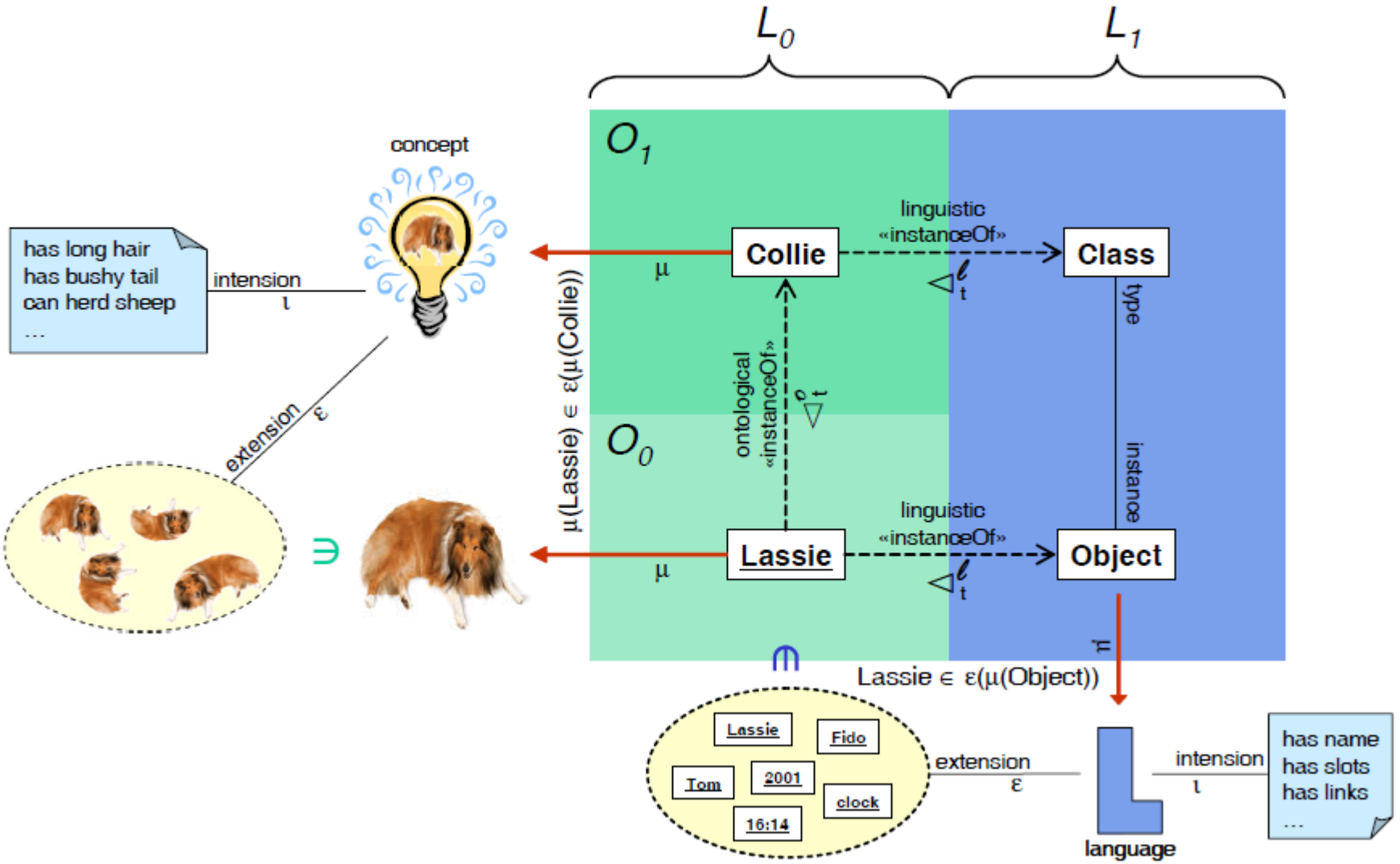
$$\forall x : \iota(C_{special})(x) \rightarrow \iota(C_{general_1})(x)$$

$$\varepsilon(C_{special}) \subseteq \varepsilon(C_{general})$$

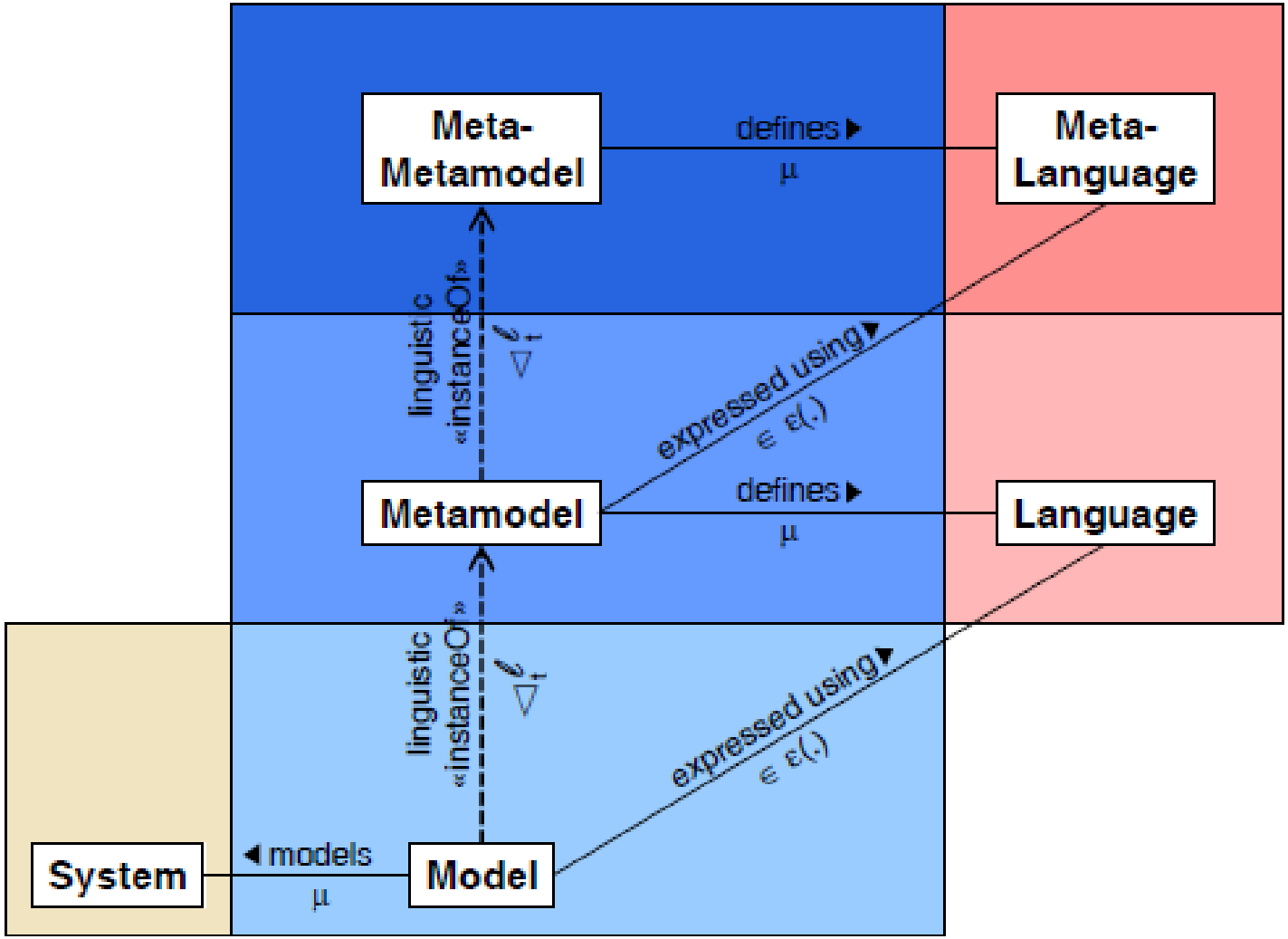
notation	*name*	*description*
α	abstraction	creates a model from a system using projection (π) and possibly classification (Λ) and generalization (Γ), hence $\mathbb{S} \lhd \alpha(\mathbb{S})$.
Λ	classification	creates a type model, hence $\mathcal{M} \lhd_t \Lambda(\mathcal{M})$
Γ	generalization	creates a supermodel, hence $\mathbb{S} \lhd_t \mathcal{M} \rightarrow \mathbb{S} \lhd_t \Gamma(\mathcal{M})$
π	projection	a homomorphic mapping creating a reduced system from a given system, using selection and reduction of information.
ρ	represents	records the intention of a model to represent a system.
μ	meaning	assigns meaning to a model (element). If $\rho(\mathbb{S}, \mathcal{M})$ then one may define $\mu(\mathcal{M}) = \pi(\mathbb{S})$.
$\lhd$	model-of	holds between a system and a model describing the former.
$\lhd_i$	token model-of	holds between a system and a model representing the former in a one-to-one fashion. Model elements may be regarded as designators for system elements.
$\lhd_t$	type model-of	holds between a system and a model classifying the former in a many-to-one fashion. Model elements are regarded as classifiers for system elements.
$\lhd^o$	ontological model-of	indicates that the model controls the *content* of its elements, hence $\mathbb{S} \lhd_t^o \mathcal{M} \rightleftharpoons \mu(\mathbb{S}) \in \varepsilon(\mu(\mathcal{M}))$ and $\mathbb{S} \lhd_i^o \mathcal{M} \rightleftharpoons \mu(\mathcal{M}) = \pi(\mu(\mathbb{S}))$. Assuming $\mu(\mathbb{S}) = \mathbb{S}$, for systems which do not model anything, we have $\mathbb{S} \lhd_i^o \mathcal{M} \rightleftharpoons \mu(\mathcal{M}) = \pi(\mathbb{S})$ and thus $\rho(\mathbb{S}, \mathcal{M}) \rightarrow \mathbb{S} \lhd_i^o \mathcal{M}$ (see definition of μ above).
$\lhd^l$	linguistic model-of	indicates that the model controls the *form* of its elements. This automatically implies $\lhd_t^l$ and, hence $\mathbb{S} \lhd_t^l \mathcal{M} \rightleftharpoons \mathbb{S} \in \varepsilon(\mu(\mathcal{M}))$


$\mathcal{S}_{r\text{-}type}$
$\mathcal{L}$
μ
μ
member of the extension of
member of the extension of
$\mathcal{M}_{type}$
$\mathcal{M}_{\mathcal{L}}$
$\triangle_t^{\circ}$
$\triangle_l^{\circ}$
$\alpha = \tau \circ \pi$
ρ
$\mathcal{S}$
$\mathcal{M}$
$\triangle_i^{\circ}$
$\mathcal{M}_{token}$
π
μ
μ
$\mathcal{S}_r$
π
$\mathcal{S}_{r\text{-}token}$

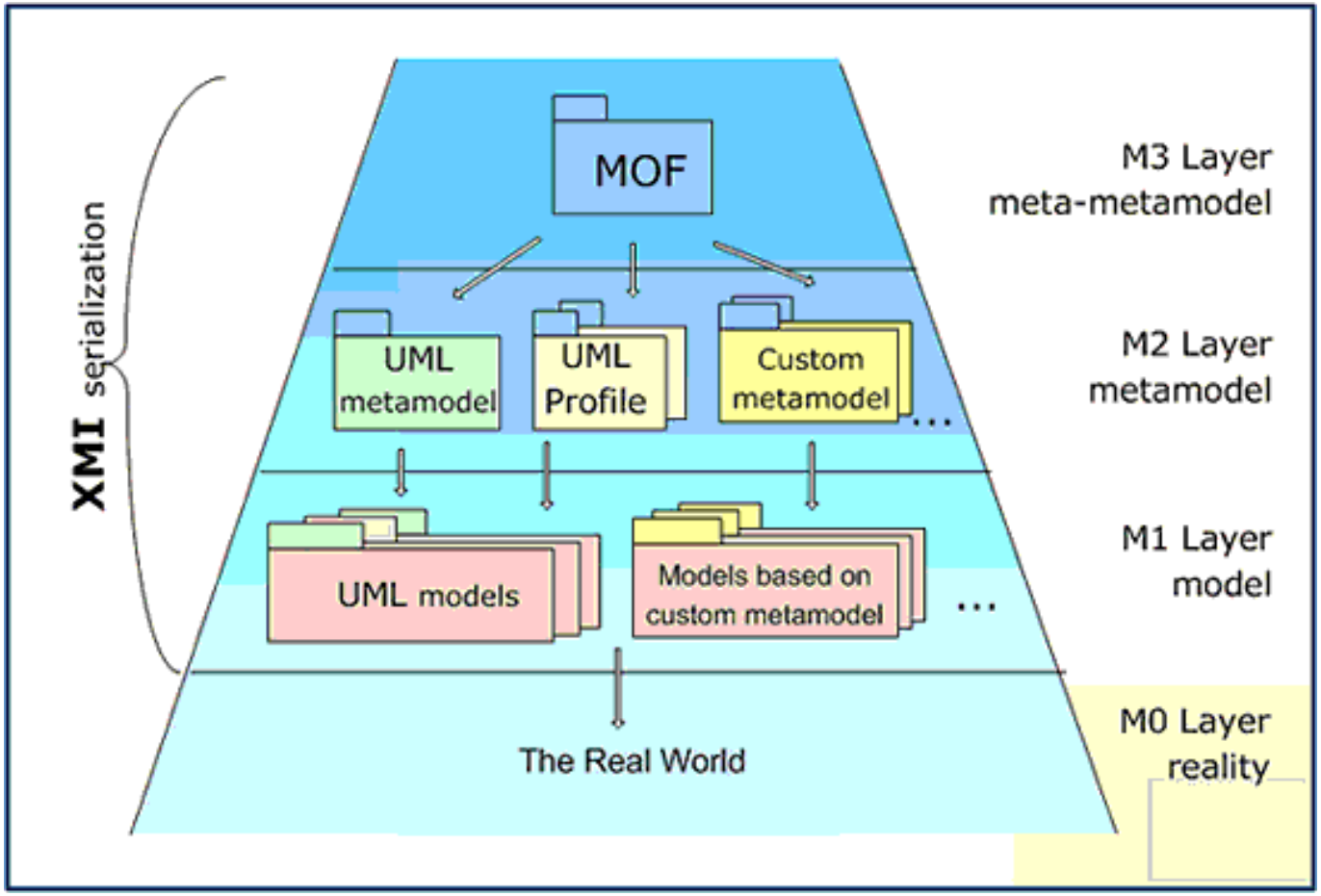
Ontological vs. Linguistic Conformance/Instantiation

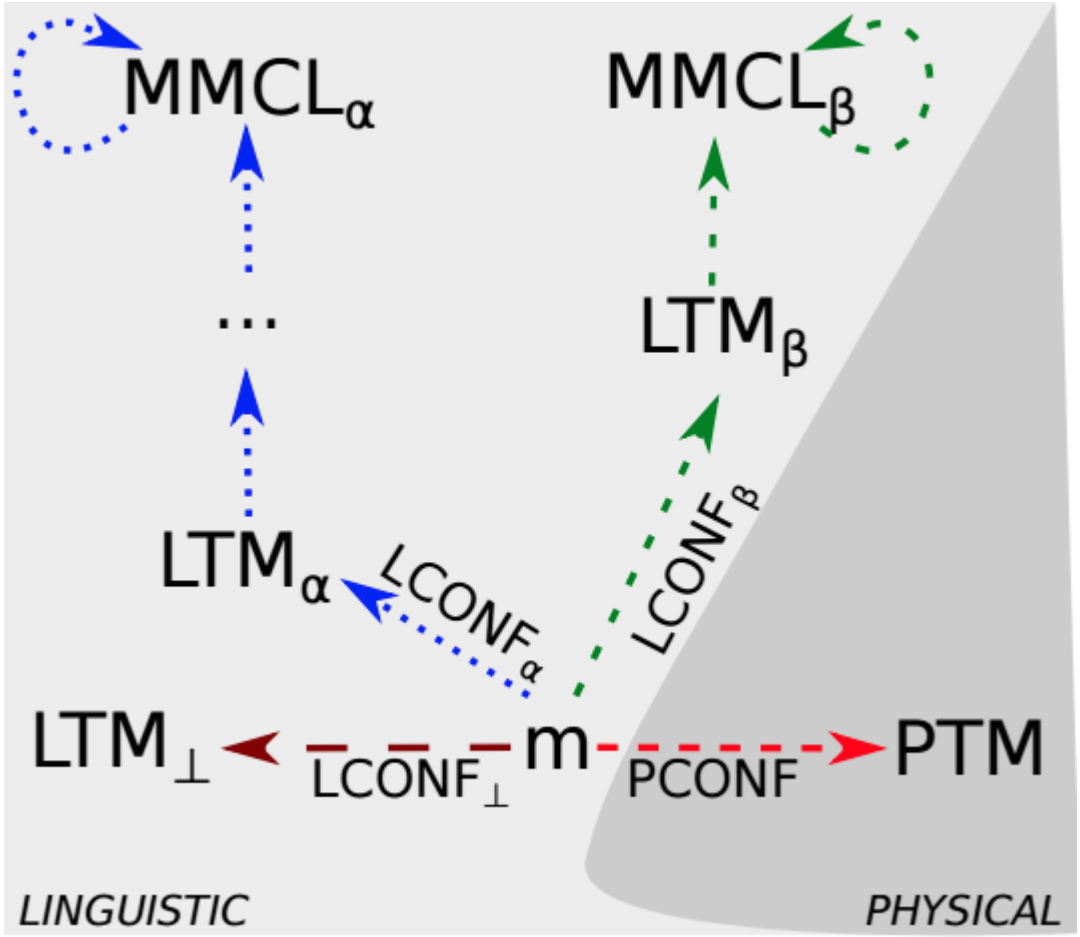


Language Definition Stack



Meta-hierarchy – OMG's 4 Layer Architecture





Simon Van Mierlo, Bruno Barroca, Hans Vangheluwe, Eugene Syriani, and Thomas Kuehne. Multi-level modelling in the Modelverse. In The first Workshop on Multi-Level Modelling (MULTI), co-located with the 17th International Conference on Model Driven Engineering Languages and Systems (MoDELS), Valencia, Spain, volume 1286 of CEUR Workshop Proceedings , pages 83 - 92, 2014.

Yentl Van Tendeloo, Bruno Barroca, Simon Van Mierlo, Hans Vangheluwe. Modelverse specification. 2016. http://msdl.cs.mcgill.ca/people/yentl/files/Modelverse.pdf

metaDepth http://metadepth.org/

Textual language for (multi-level) (meta-)modelling

Constraint and operations in the Epsilon Object Language (EOL)
`https://www.eclipse.org/epsilon/`

EOL is similar the UML's Object Constraint Language (OCL)

EOL can be used in metaDepth for:

- Queries within the model (limited to navigation)
- Computation/assignment, for example to give operational semantics

metaDepth: meta-model

```
Model TrainNet {

     Node Train{
          train_name : String {id};
          maxVelocity : int;
          maxVConstraint: $self.maxVelocity > 0 and self.maxVelocity <= 300$
          currSegment : Segment[1];
     }

     Node Segment{
               currTrain : Train[0..1];
               nextSegment : Segment[0..1];
     }


     Node FastTrain : Train {}
     Node IntercityExpress: Train {}
}
```

metaDepth: model

```
TrainNet tn {
    Train train1 {train_name = "T3456"; maxVelocity = 300; currSegment = seg1;}

    IntercityExpress train2 {train_name = "ICE1234"; maxVelocity = 250;}

    Segment seg1 {currTrain = train1;}
    Segment seg2 {}
}`      `
```

Verifying conformance between `tn` and `TrainNet`:

Constraint fails: `cardinality 0 nota allowed for currSegment in train2`

Reason: `train2` is not on a `Segment`

metaDepth - Epsilon Object Language (EOL)

Example query: What are the trains in each segment?

```
operation main(){
    for (s in Segment.allInstances()){
        if (Train.allInstances.excludes(s.currTrain)){
          ('Segment ' + s + "has no train.").println();
        }
        else{
          ("Segment " + s + " has train: '" + s.currTrain.toString + "'").println();
        }
}
```

Result:

```
Segment seg2 has no train.
Segment seg1 has train 'train1'
```

Caveat: explicit navigation (via . . .), need to know types
(or be able to query: Types.allInstances())

MetaDepth http://metadepth.org/

Meta-model ↔ model

```
strict Model PetriNets@1 {
  abstract Node NamedElement{
    name  : String {id};
  }
  Node Place : NamedElement {
    tokens   : int = 0;
    outTrans : Transition[*] {ordered,unique};
    inTrans  : Transition[*] {ordered,unique};
    minTokens: $self.tokens>=0$
  }
  Node Transition : NamedElement {
    inPlaces : Place[*] {ordered,unique};
    outPlaces: Place[*] {ordered,unique};
  }
  Edge ArcPT (Place.outTrans, Transition.inPlaces) {
    weight: int = 1;
  }
  Edge ArcTP (Transition.outPlaces, Place.inTrans) {
    weight: int = 1;
  }
  minWeight(ArcTP, ArcPT): $self.weight>0$
  minPlaces:$Place.allInstances().size()>0$
}
```

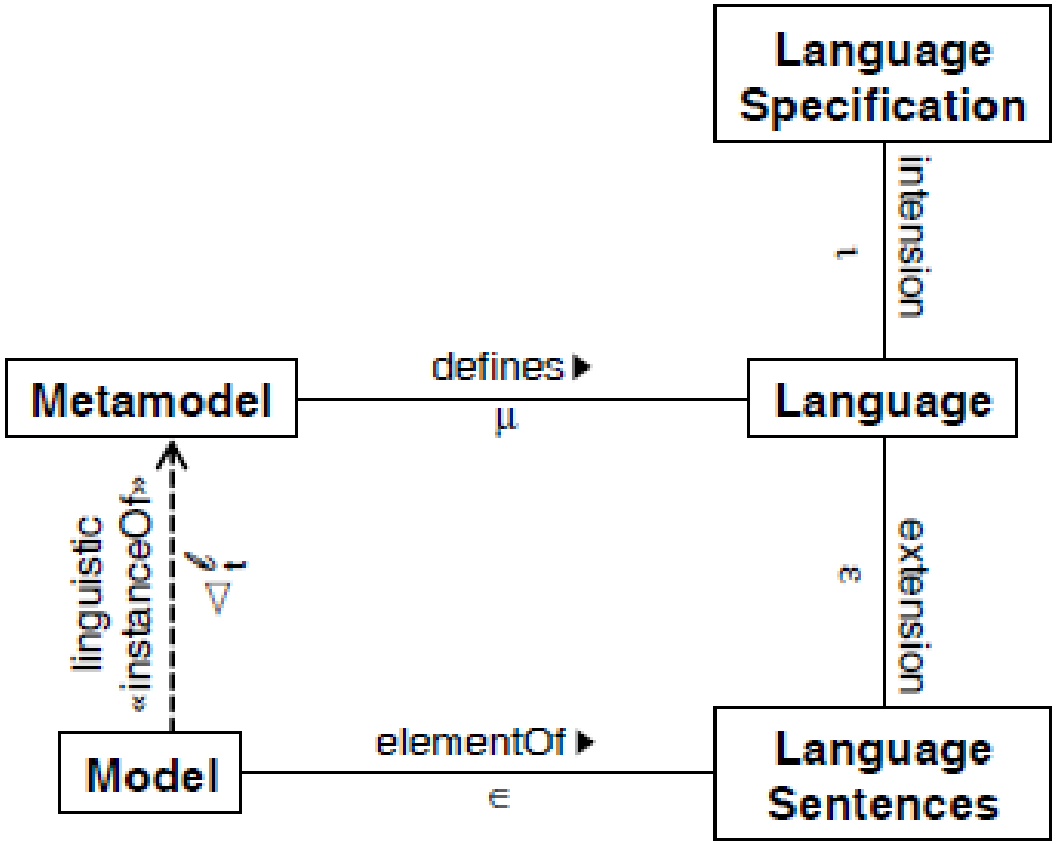
```
load "PetriNets"
PetriNets Test{
  Place p0{name="p0"; tokens=2;}
  Place p1{name="p1"; tokens=0;}
  Place p2{name="p2"; tokens=2;}
  Transition t1{name="t1";}
  ArcPT pt0(p0,t1){weight=1;}
  ArcPT pt1(p2,t1){weight=1;}
  ArcTP tp(t1,p1){weight=2;}
}
```

MetaDepth

operational semantics

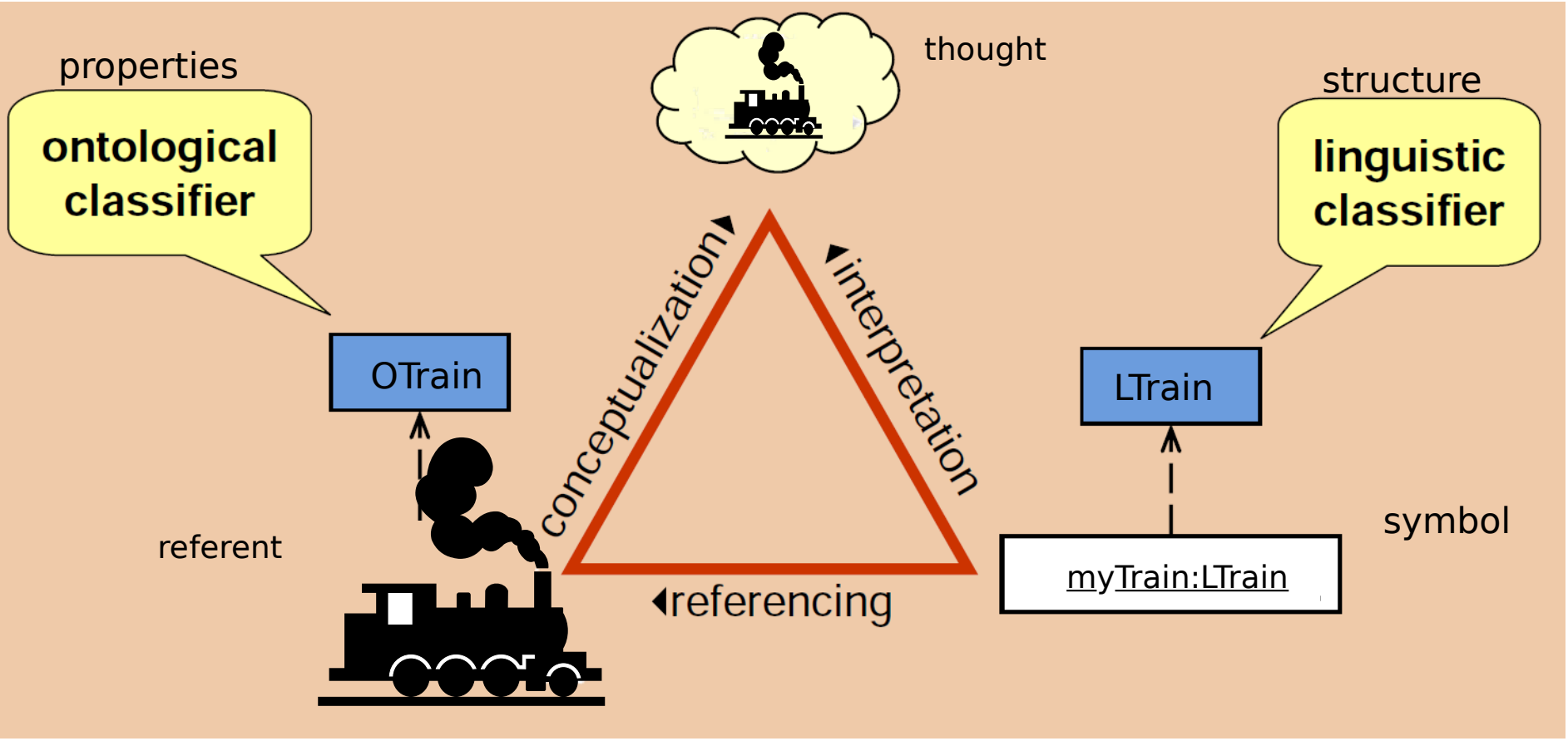
```
operation main() {
  'Simulating the Petri Net'.println();
  while (Transition.allInstances()->exists(t|t.enabled() and t.fire()) ) {}
}
operation Transition enabled() : Boolean {
  ('checking enabledness of '+self.name).println();
  return self.ArcPT->forAll(arc| arc.inPlaces.tokens>=arc.weight);
}
operation Transition fire() : Boolean {
  ('Firing '+self.name).println();
  for (arc in self.ArcPT)
    arc.inPlaces.tokens := arc.inPlaces.tokens-arc.weight;
  for (arc in self.ArcTP)
    arc.outPlaces.tokens := arc.outPlaces.tokens+arc.weight;
  return true;
}
```

Meta-models as Language Definitions



Triangle of Meaning
aka triangle of reference or semiotic triangle
Ogden and Richards in “the meaning of meaning” (1923)

caveat: collaborative modelling only works if collaborators have a shared interpretation



Syntax, **Semantics**, and all that Stuff

David Harel, Bernhard Rumpe.
Meaningful Modeling: What's the Semantics of "Semantics"?
IEEE Computer, vol. 37, no. 10, pp. 64-72, October, 2004.

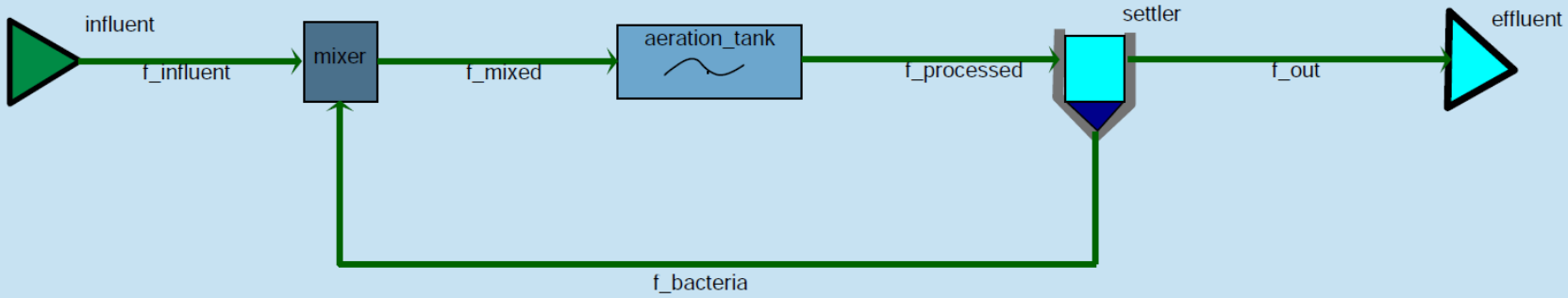
- "operational" semantics
- "denotational" (transformational) semantics

Operational vs. Denotational (Translational) semantics

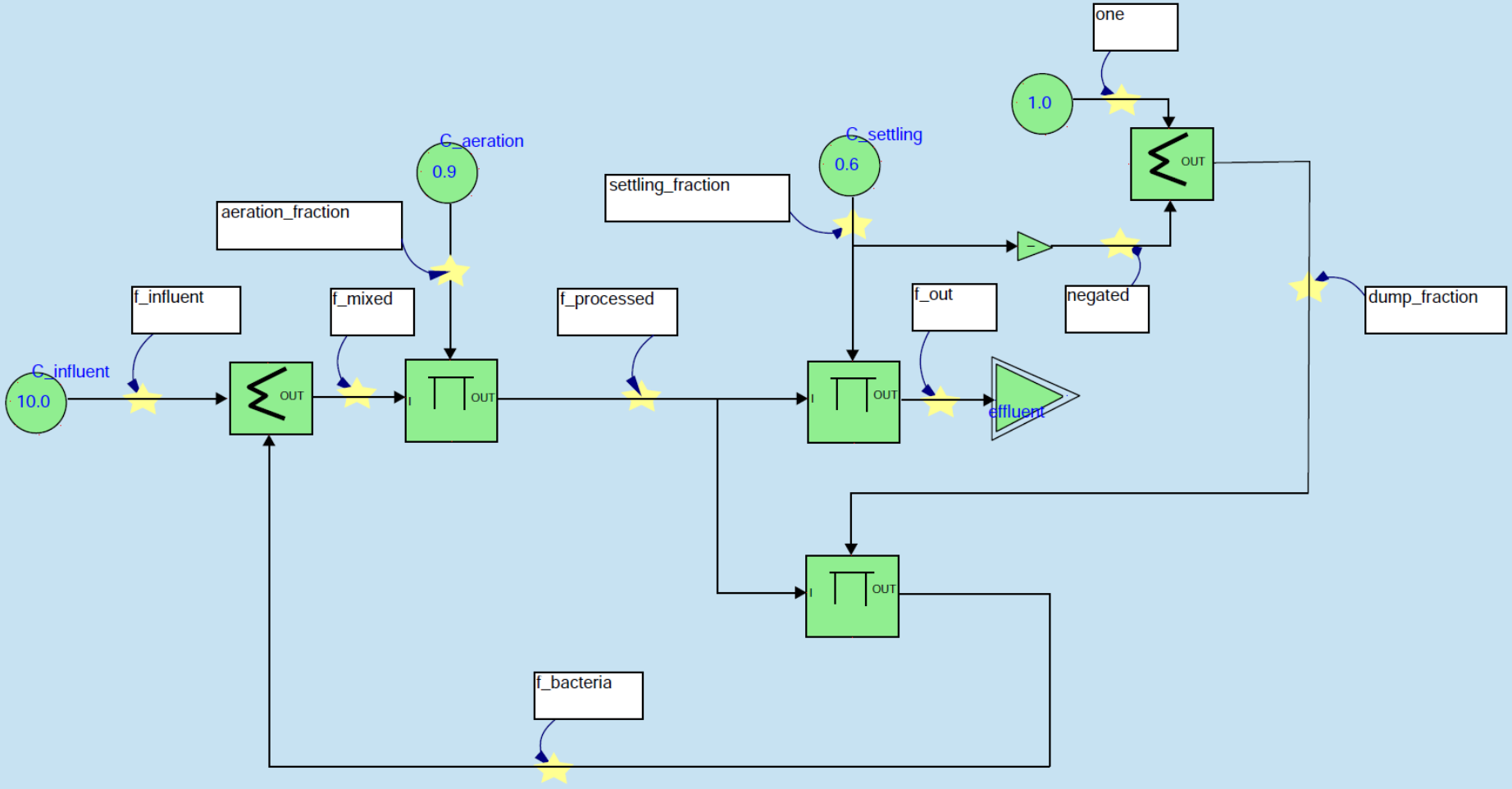
NATO's Sarajevo Waste Water Treatment Plant

www.nato.int/sfor/cimic/env-pro/waterpla.htm

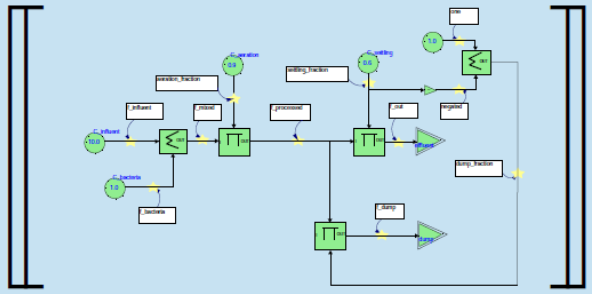
What does this WWTP model mean?



. . . its meaning (steady-state abstraction): Causal Block Diagram (CBD)

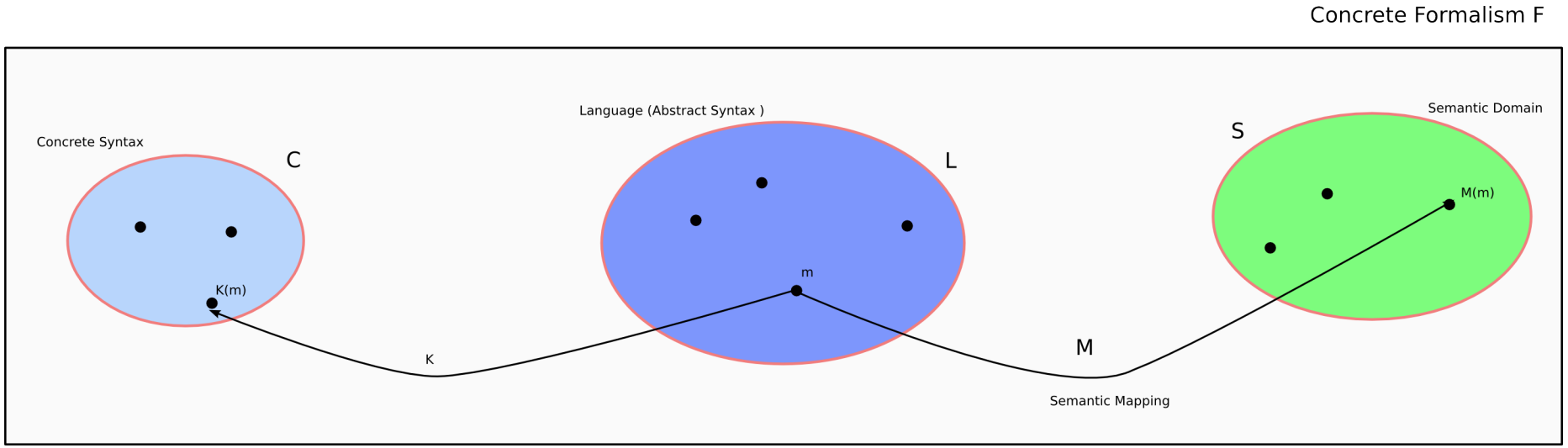


Meaning of the CBD . . . semantic mapping onto algEqns

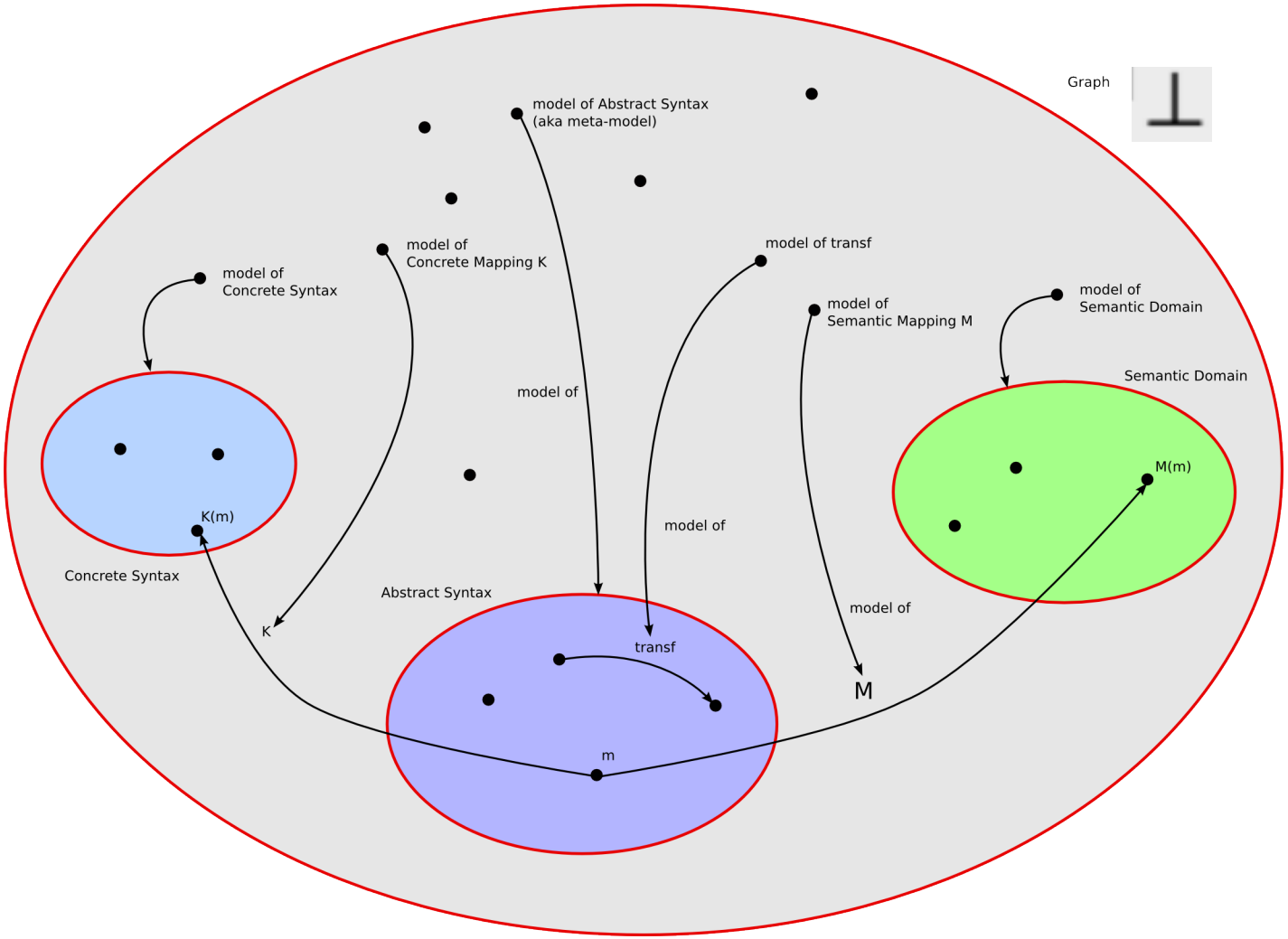


$$
\left\{
\begin{array}{rcl}
f\_influent & = & C\_influent \\
f\_bacteria & = & C\_bacteria \\
f\_mixed & = & f\_influent + f\_bacteria \\
aeration\_fraction & = & C\_aeration \\
f\_processed & = & aeration\_fraction * f\_mixed \\
settling\_fraction & = & C\_settling \\
negated & = & -settling\_fraction \\
one & = & 1 \\
dump\_fraction & = & one + negated \\
f\_dump & = & f\_processed * dump\_fraction \\
f\_out & = & settling\_fraction * f\_processed
\end{array}
\right.
$$

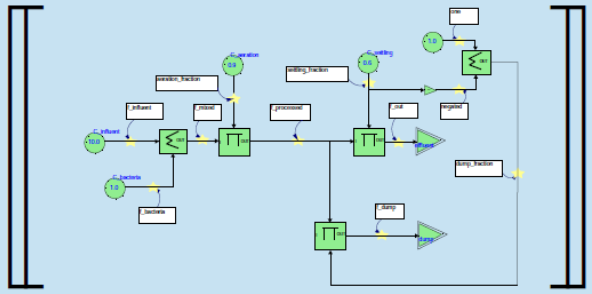
“linguistic” view on Modelling Languages/ Formalisms: Syntax and Semantics



Explicit “linguistic” Modelling of Modelling Languages/ Formalisms



Meaning of the CBD . . . semantic mapping onto algEqns



$$
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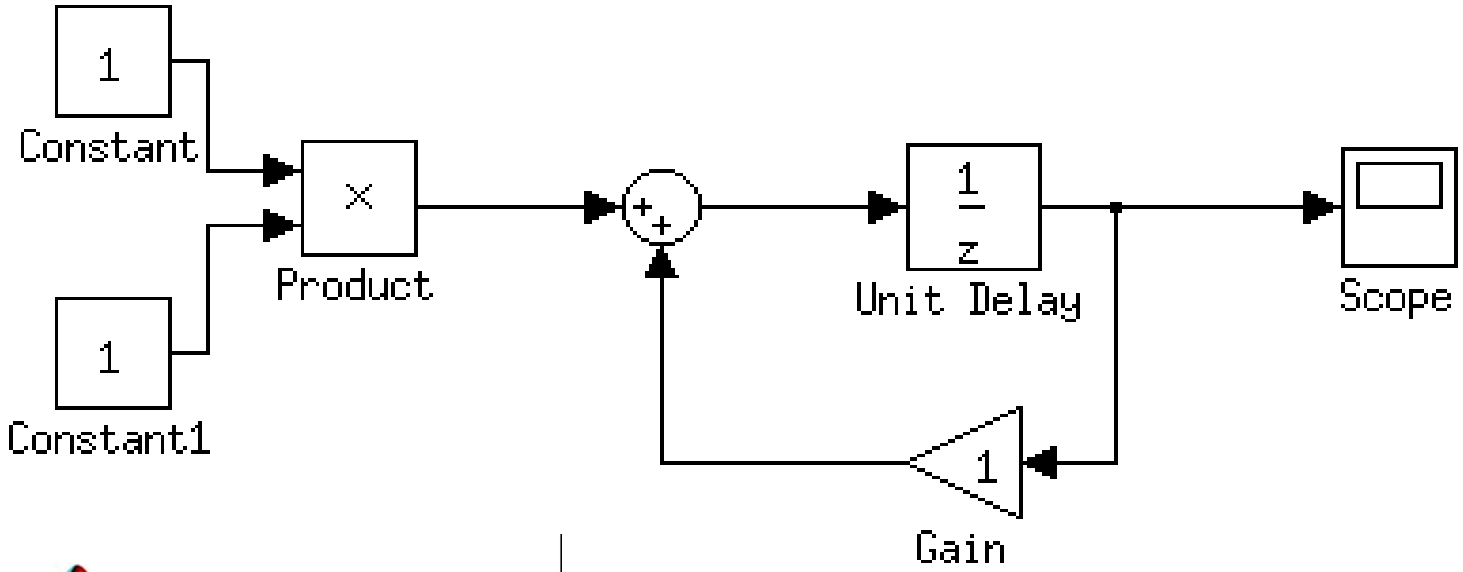
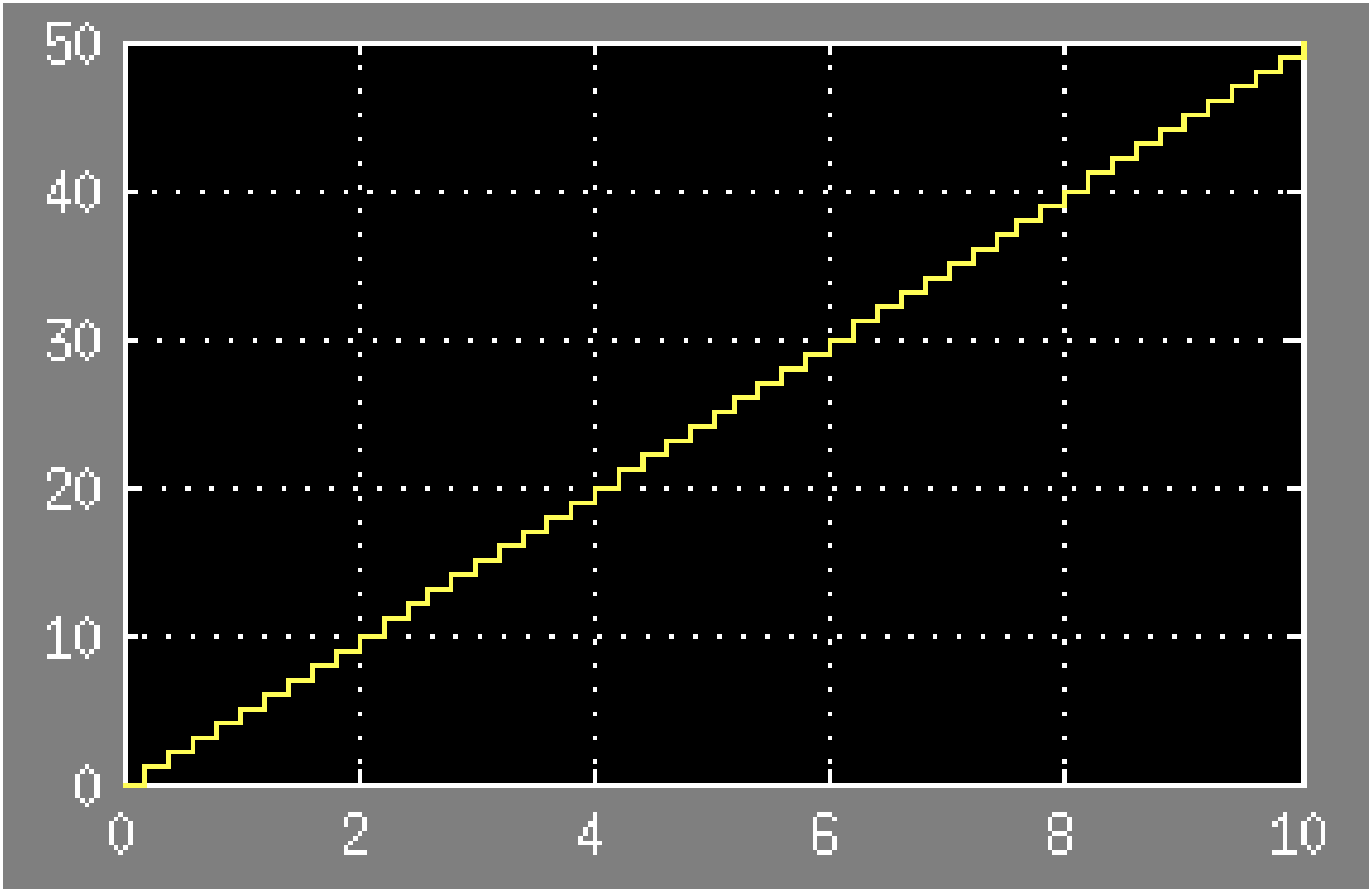
settling\_fraction & = & C\_settling \\
negated & = & -settling\_fraction \\
one & = & 1 \\
dump\_fraction & = & one + negated \\
f\_dump & = & f\_processed * dump\_fraction \\
f\_out & = & settling\_fraction * f\_processed
\end{array}
\right.
$$

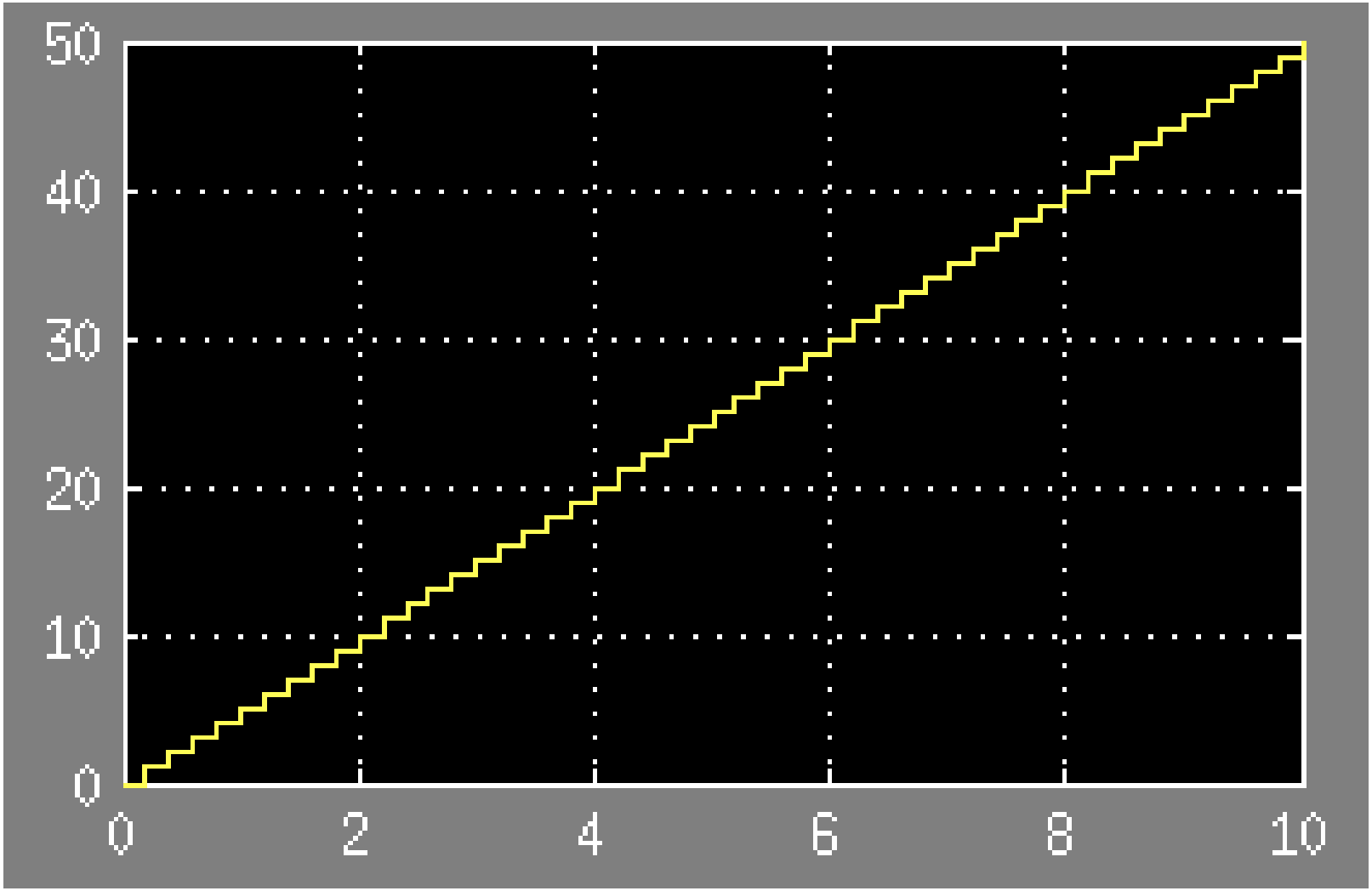
Causal Block Diagrams (syntax)



MATLAB®
SIMULINK®


50
40
30
20
10
0
0
2
4
6
8
10

$logicalTime \leftarrow 0$
while not end_condition **do**
    $schedule \leftarrow LOOPDETECT(DEPGRAPH(cbd))$
    for gblock **in** schedule **do**
        $COMPUTE(gblock)$
    end for
    $logicalTime \leftarrow logicalTime + \Delta t$
end while


50
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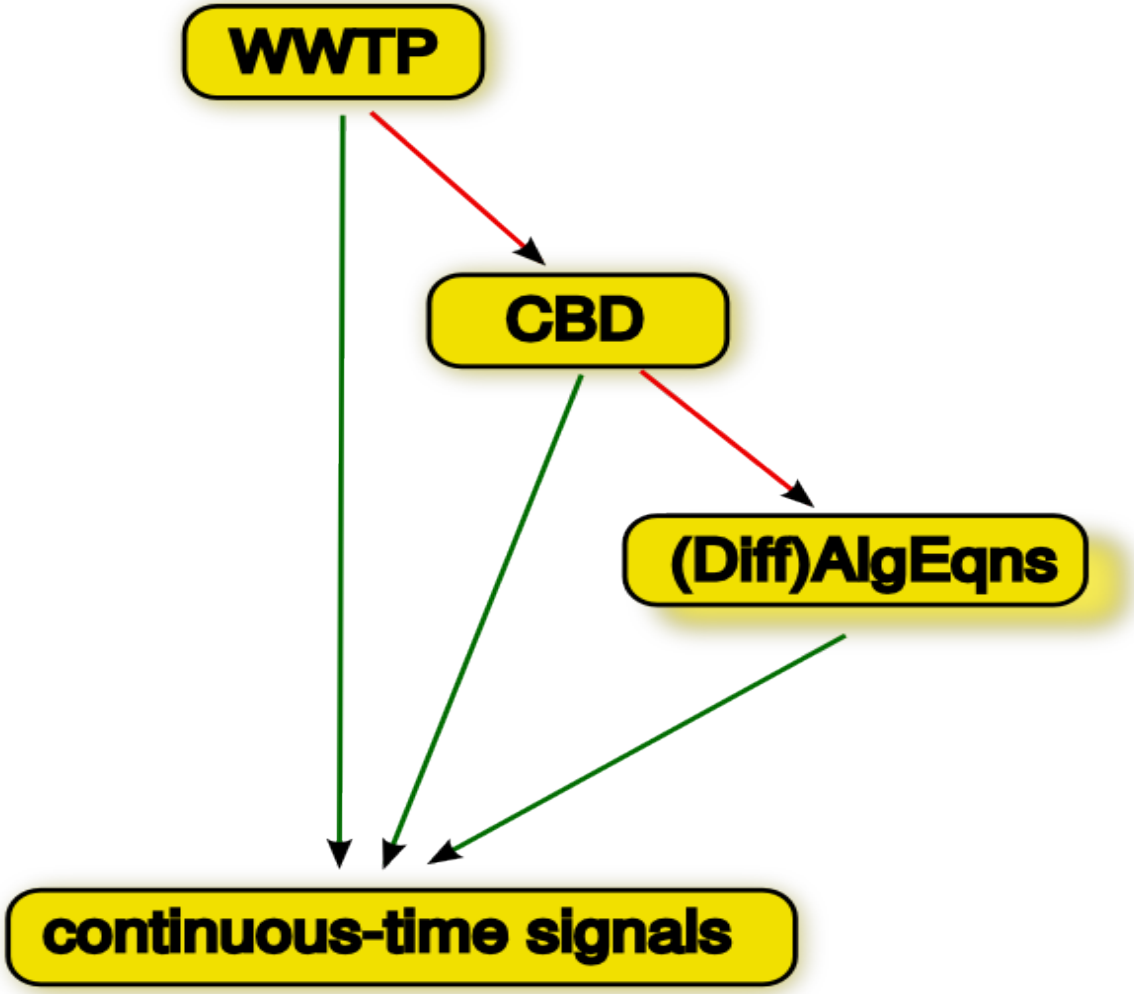
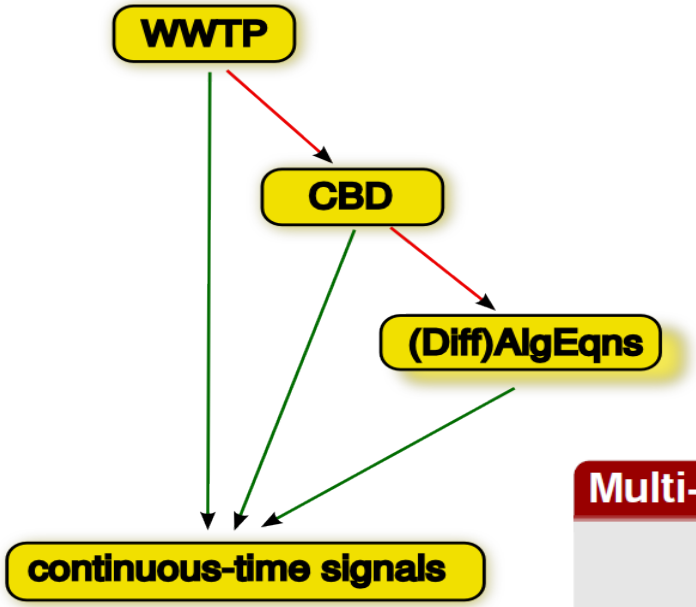
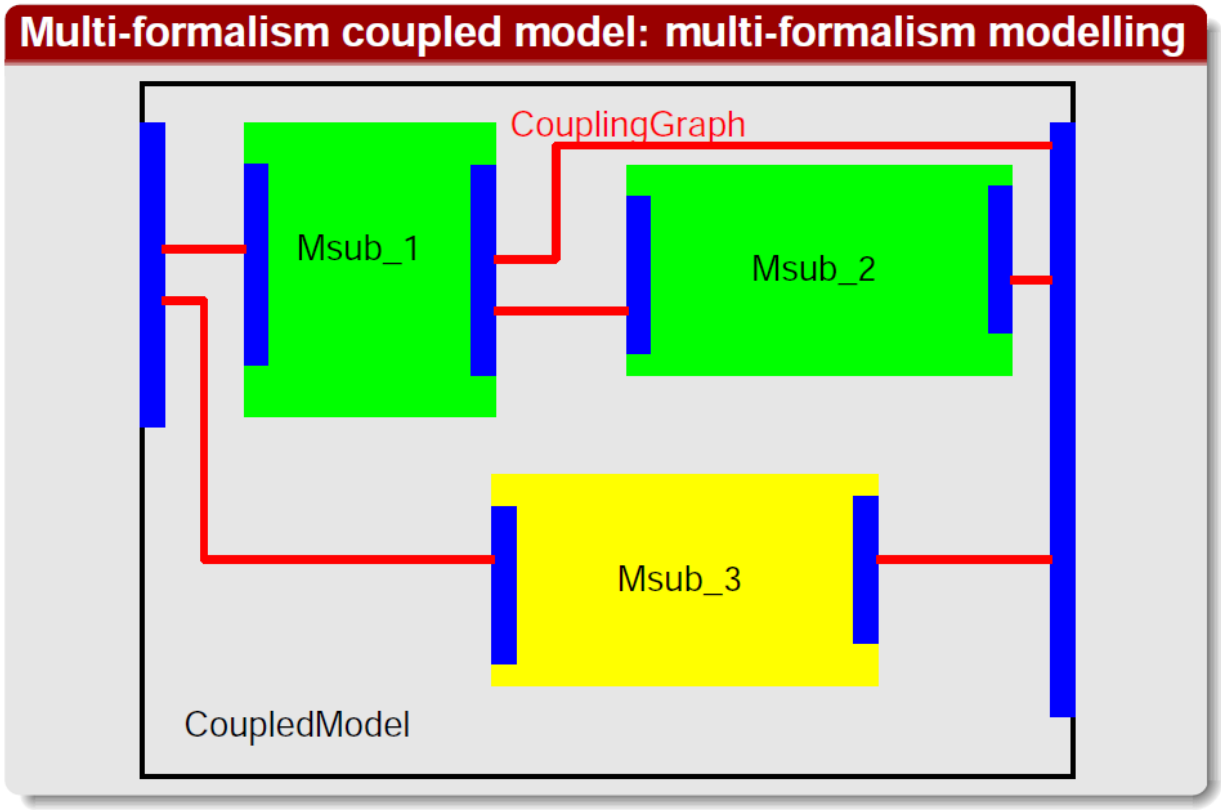
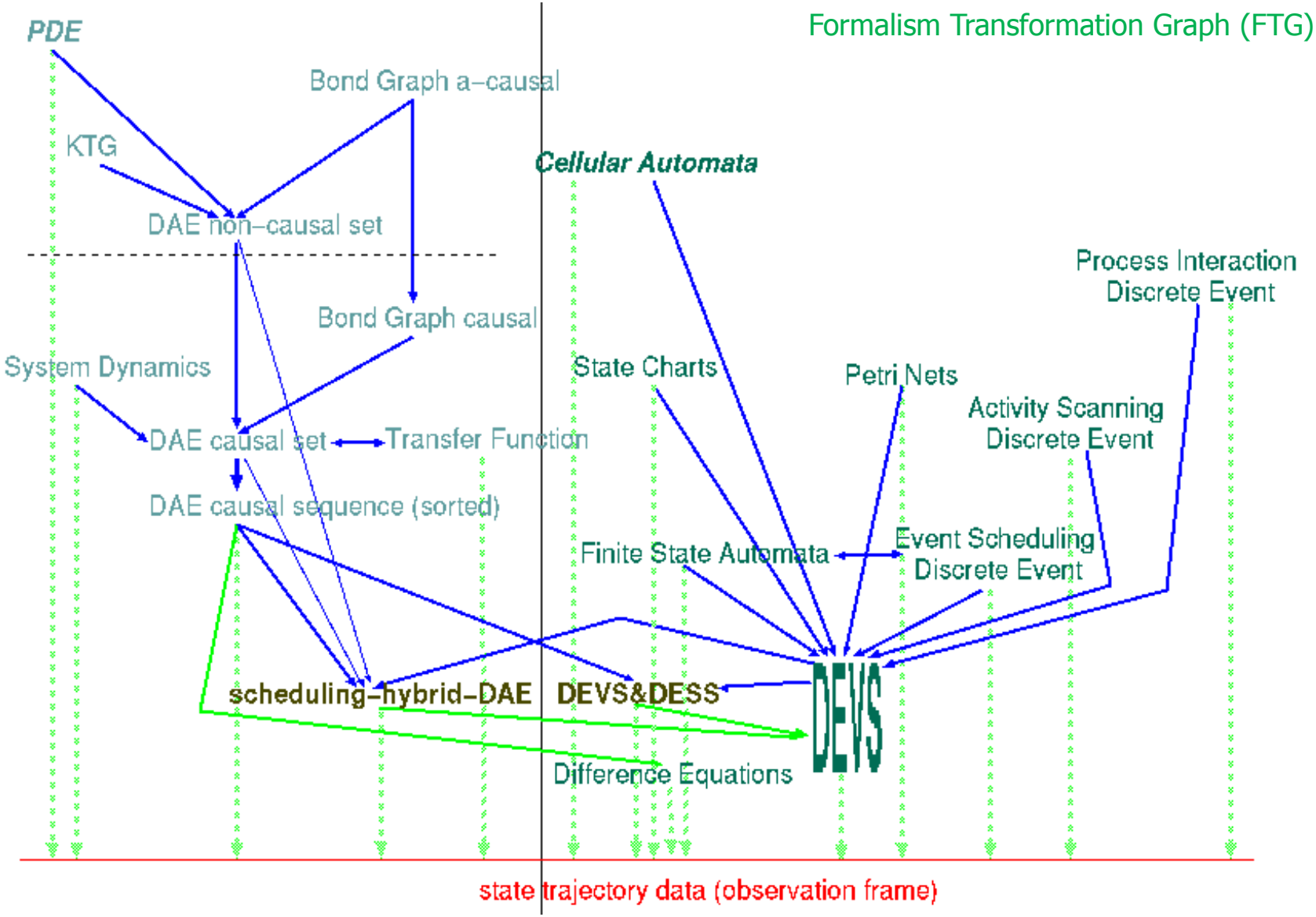

WWTP
CBD
(Diff)AlgEqns
continuous-time signals



Bran Selic: “fragmentation problem”

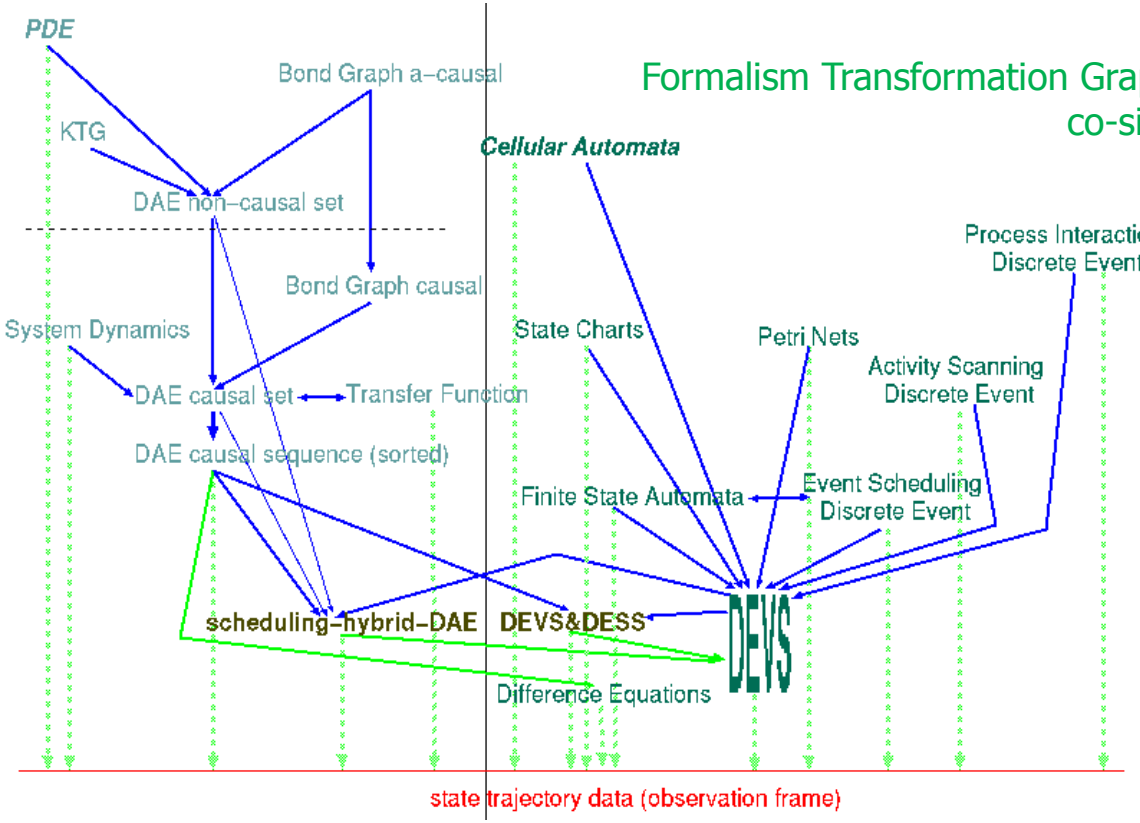


Formalism Transformation Graph (FTG)

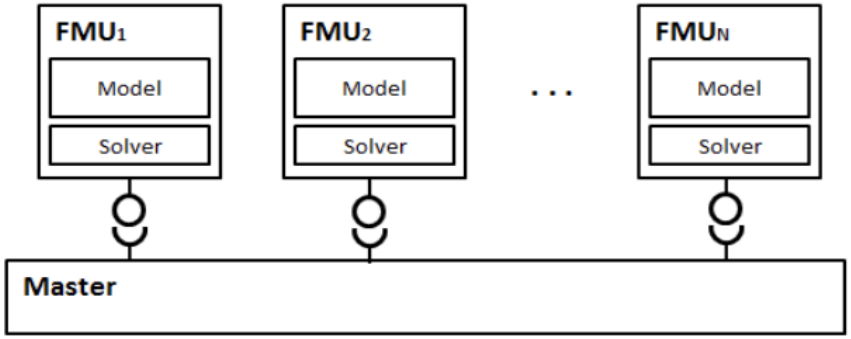


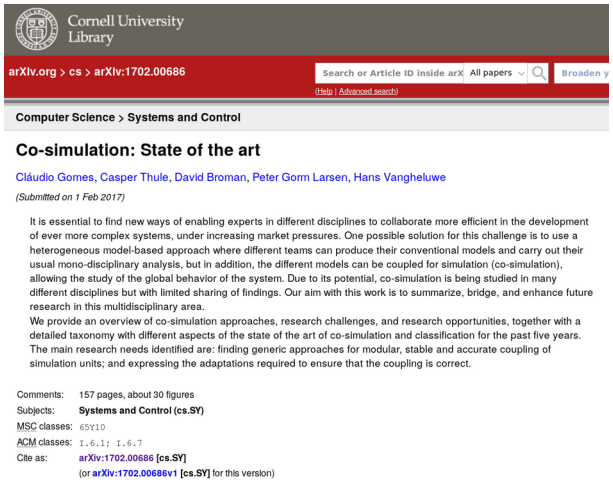
Hans Vangheluwe and Ghislain C. Vansteenkiste. A multi-paradigm modeling and simulation methodology: Formalisms and languages. In European Simulation Symposium (ESS) , pages 168 – 172. Society for Computer Simulation International (SCS), October 1996. Genoa, Italy.

Formalism Transformation Graph (FTG) co-simulation



FUNCTIONAL MOCK-UP INTERFACE

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Computer Science > Systems and Control

Co-simulation: State of the art

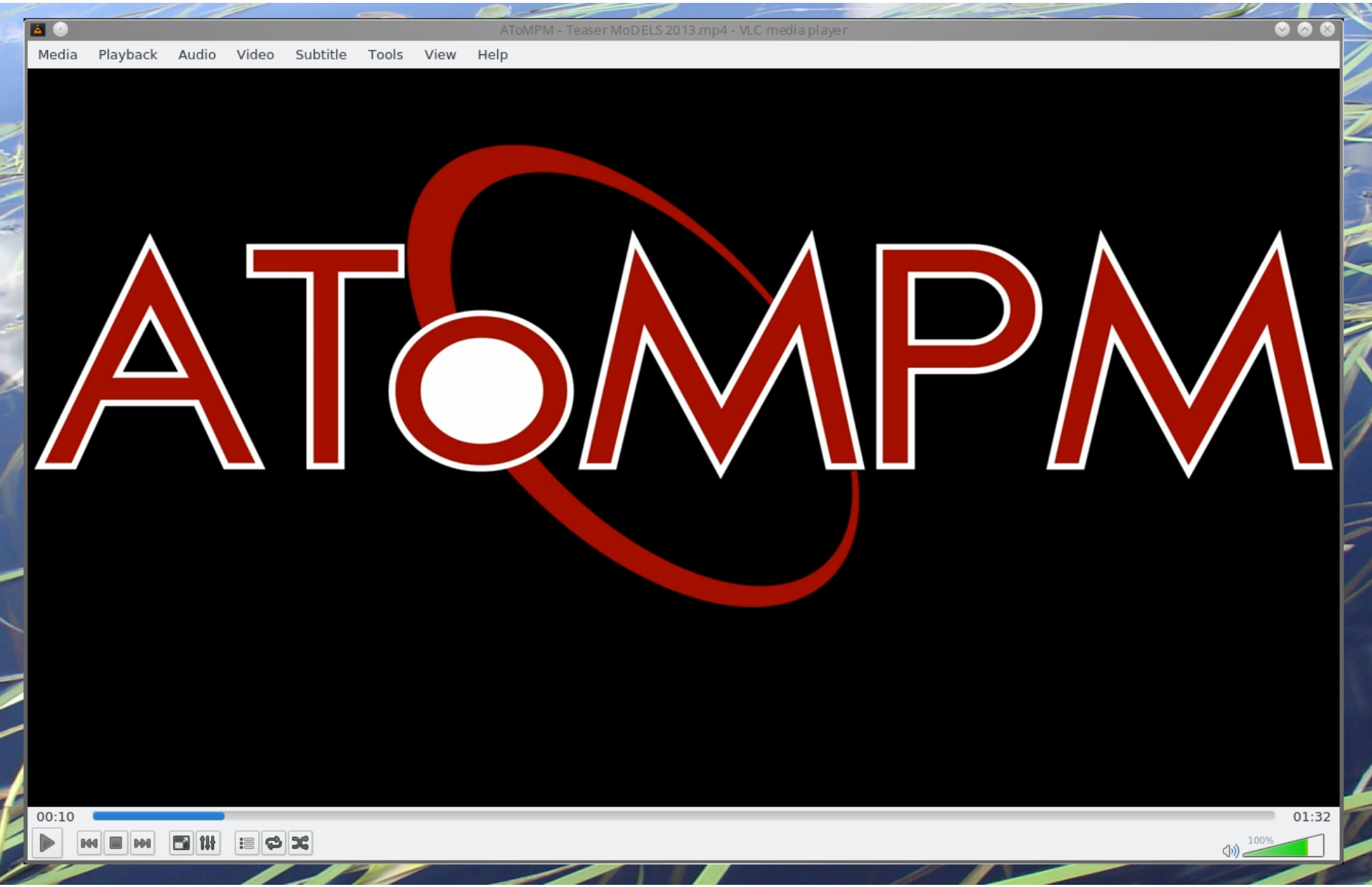
Cláudio Gomes, Casper Thule, David Broman, Peter Gorm Larsen, Hans Vangheluwe

(Submitted on 1 Feb 2017)

It is essential to find new ways of enabling experts in different disciplines to collaborate more efficient in the development of ever more complex systems, under increasing market pressures. One possible solution for this challenge is to use a heterogeneous model-based approach where different teams can produce their conventional models and carry out their usual mono-disciplinary analysis, but in addition, the different models can be coupled for simulation (co-simulation), allowing the study of the global behavior of the system. Due to its potential, co-simulation is being studied in many different disciplines but with limited sharing of findings. Our aim with this work is to summarize, bridge, and enhance future research in this multidisciplinary area.
We provide an overview of co-simulation approaches, research challenges, and research opportunities, together with a detailed taxonomy with different aspects of the state of the art of co-simulation and classification for the past five years. The main research needs identified are: finding generic approaches for modular, stable and accurate coupling of simulation units; and expressing the adaptations required to ensure that the coupling is correct.

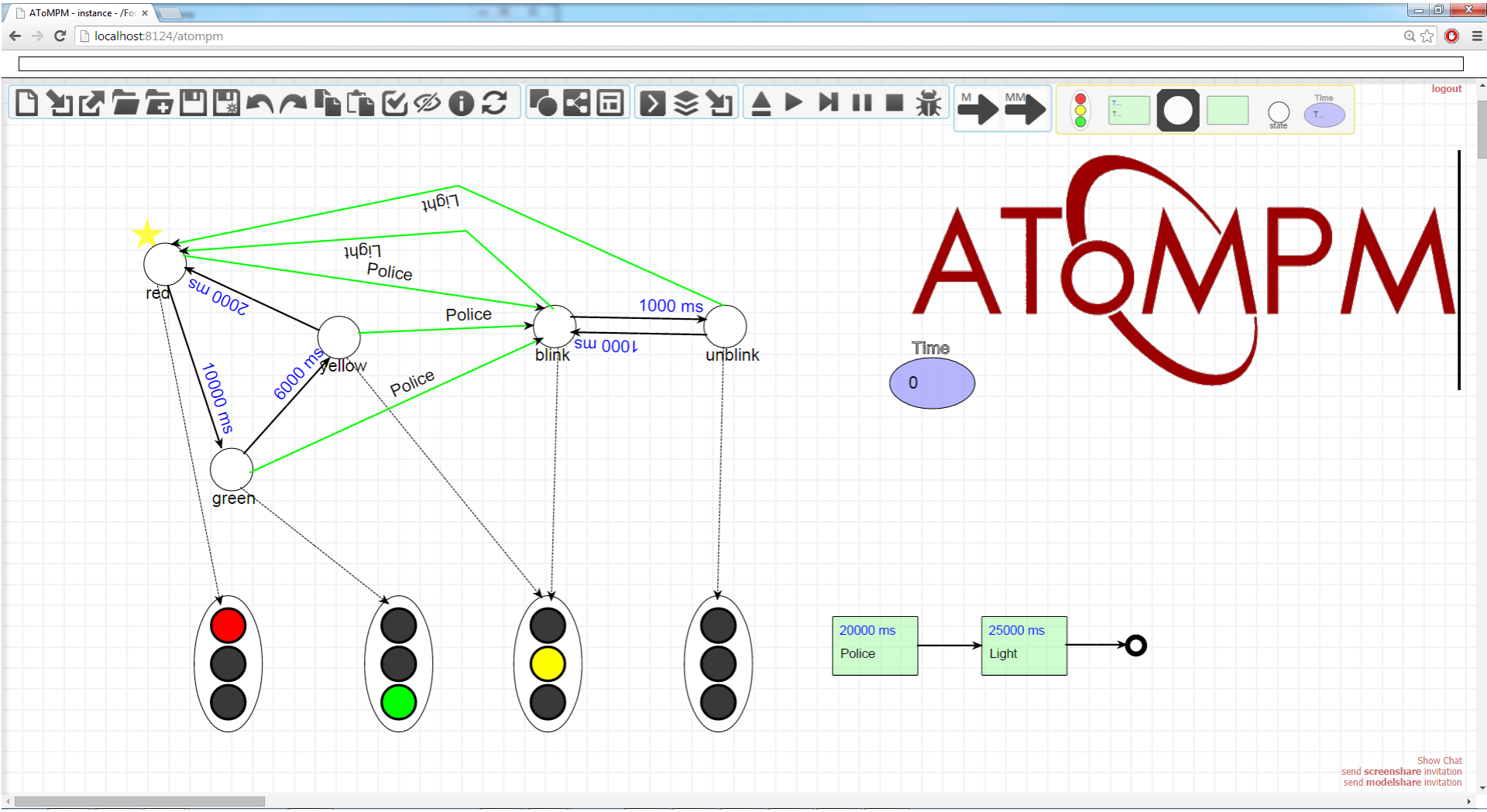
Comments: 157 pages, about 30 figures
Subjects: **Systems and Control (cs.SY)**
MSC classes: 65Y10
ACM classes: I.6.1; I.6.7
Cite as: **arXiv:1702.00686 [cs.SY]**
(or **arXiv:1702.00686v1 [cs.SY]** for this version)

Cláudio Gomes, Casper Thule, David Broman, Peter Gorm Larsen, Hans Vangheluwe. Co-simulation: State of the art. ArXiv 1702.00686. 2017.



https://www.youtube.com/watch?v=RYtea2BiQ98

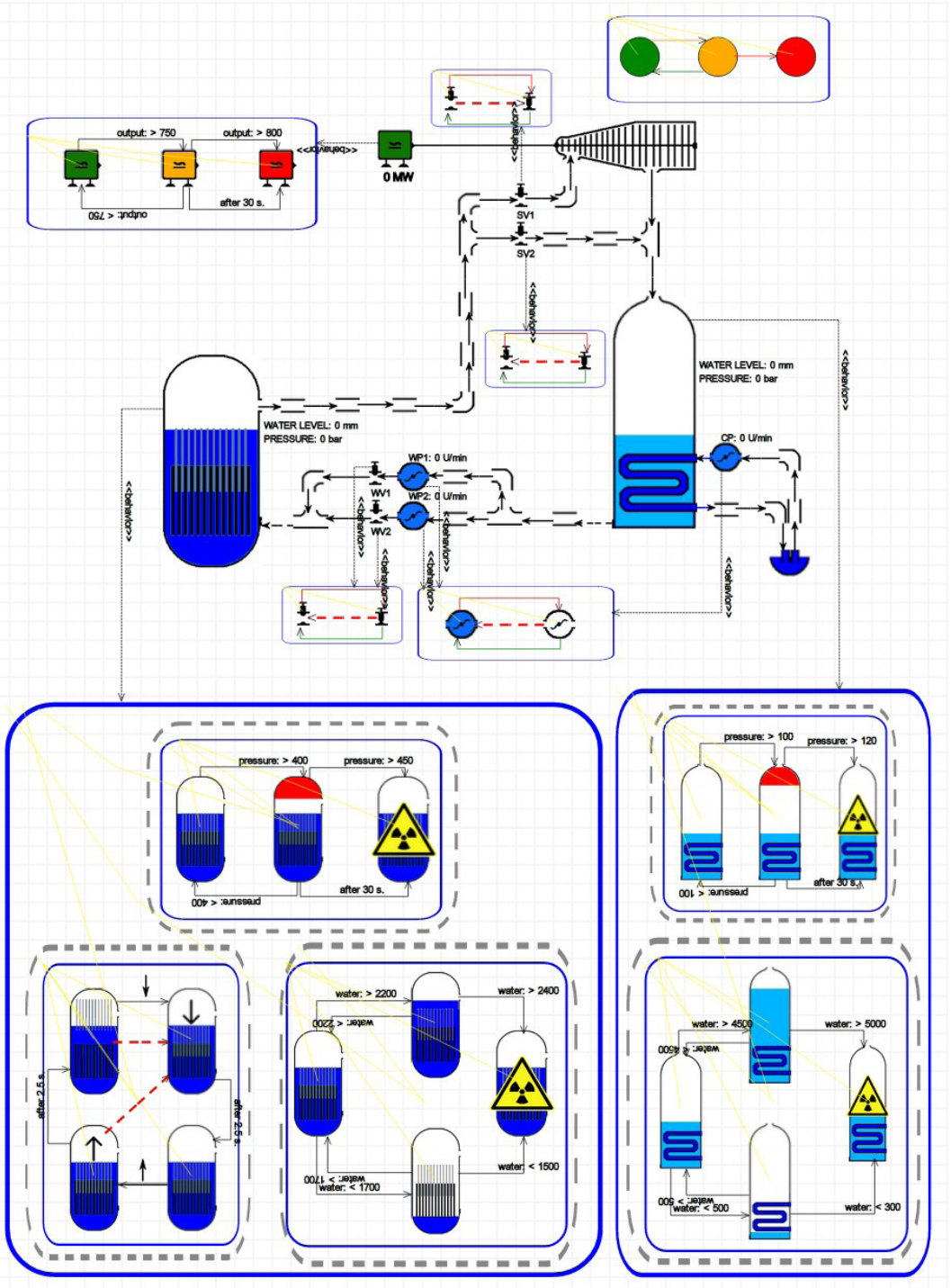
(domain-specific) “linguistic” Modelling Language Engineering



Raphael Mannadiar. A Multi-Paradigm Modelling Approach to the Foundations of Domain-Specific Modelling. PhD thesis, McGill Univ., 2012.

Eugene Syriani, Hans Vangheluwe, Raphael Mannadiar, Conner Hansen, Simon Van Mierlo, and Huseyin Ergin. AToMPM: A web-based modeling environment. In Proceedings of MODELS'13 Demonstration Session co-located with the 16th International Conference on Model Driven Engineering Languages and Systems (MODELS 2013), Miami, USA, pages 21- 25, 2013.

https://www.youtube.com/watch?feature=player_detailpage&v=RYtea2BiQ98


output: > 750
output: > 800
output: < 750
after 30 s.
<<behavior>>
0 MW
SV1
SV2
WATER LEVEL: 0 mm
PRESSURE: 0 bar
WP1: 0 l/min
WP2: 0 l/min
WV1
WV2
CP: 0 l/min
pressure: > 400
pressure: > 450
pressure: < 400
after 30 s.
pressure: > 100
pressure: > 120
pressure: < 100
after 30 s.
after 2.5 s.
after 2.5 s.
water: > 2200
water: > 2400
water: < 2200
water: < 1700
water: < 1500
water: > 4500
water: > 5000
water: < 4500
water: < 500
water: < 300
water: < 500

at the most appropriate level(s) of abstraction
using the most appropriate formalism(s)
explicitly modelling workflows

Enabler: (domain-specific) modelling language engineering, including model transformation

Pieter J. Mosterman and Hans Vangheluwe. Computer Automated Multi-Paradigm Modeling: An Introduction. Simulation: Transactions of the Society for Modeling and Simulation International , 80(9):433- 450, September 2004. Special Issue: Grand Challenges for Modeling and Simulation.