

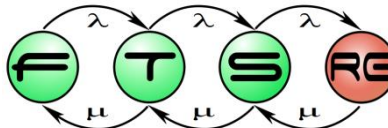
# Foundations of Model Transformation

**Gábor Bergmann**

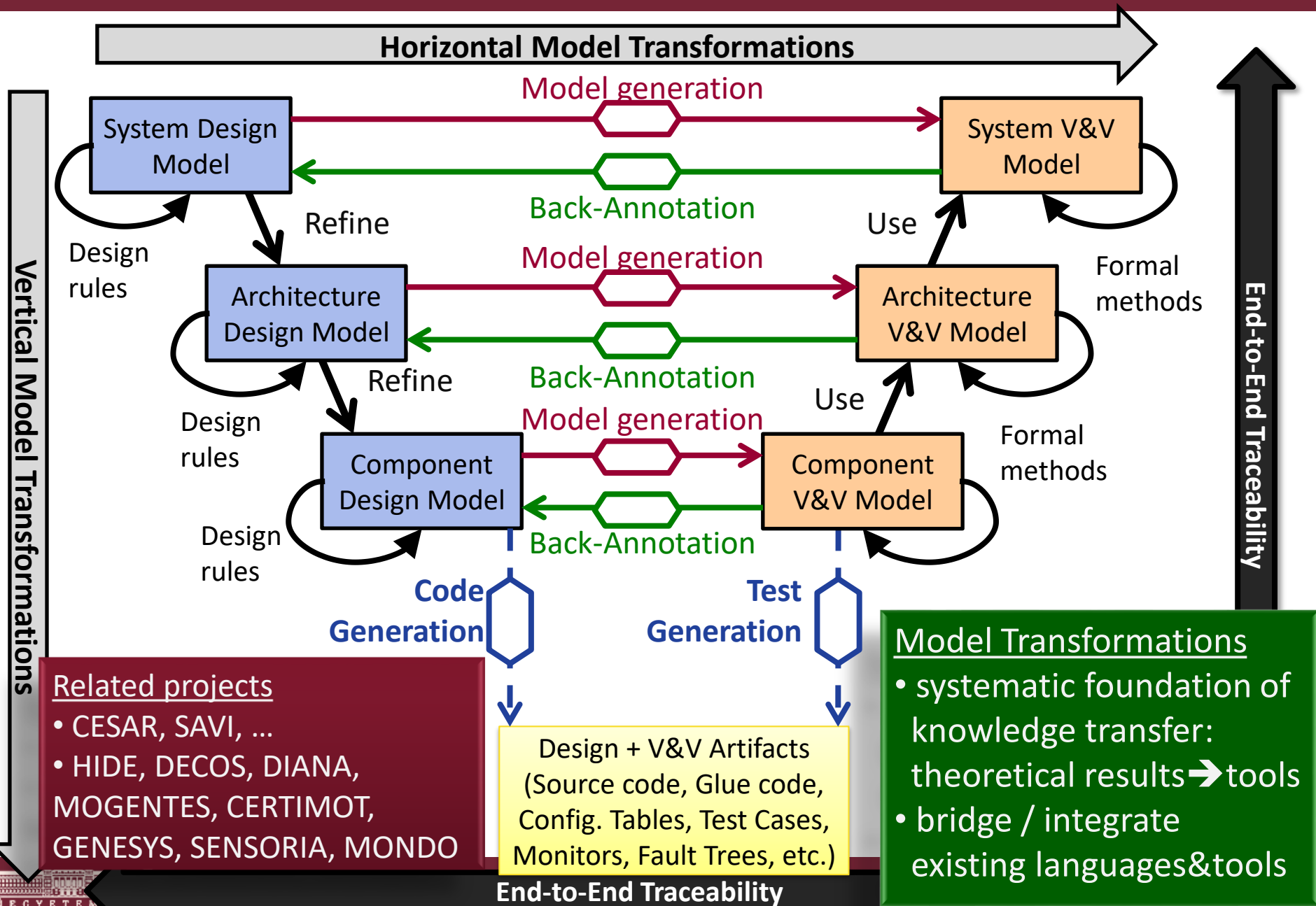
Dániel Varró, István Ráth,  
Ákos Horváth, Oszkár Semeráth

Model Driven Systems Development

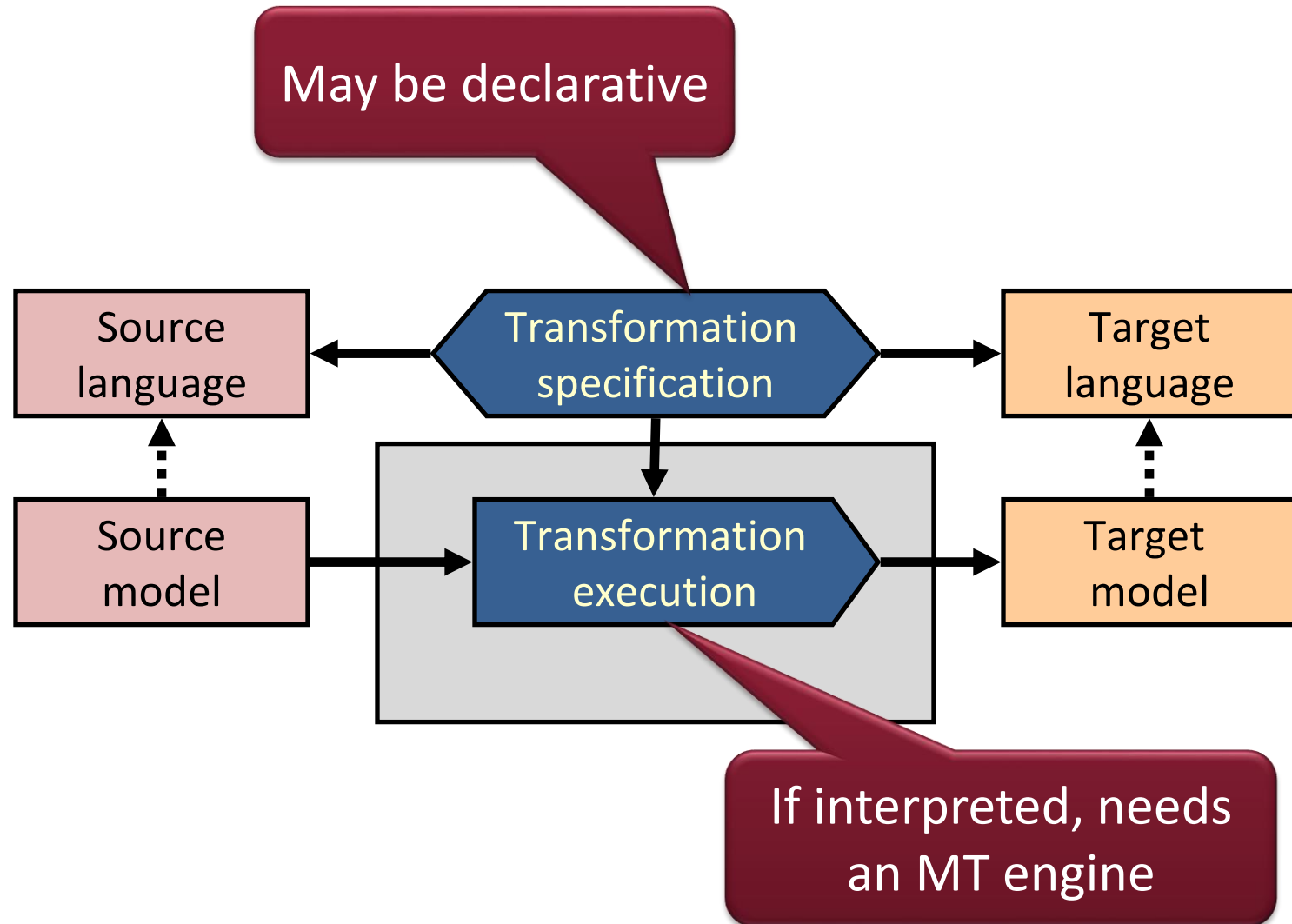
Lectures 8-9



# Models and Transformations in Critical Systems



# Definition of Model Transformation

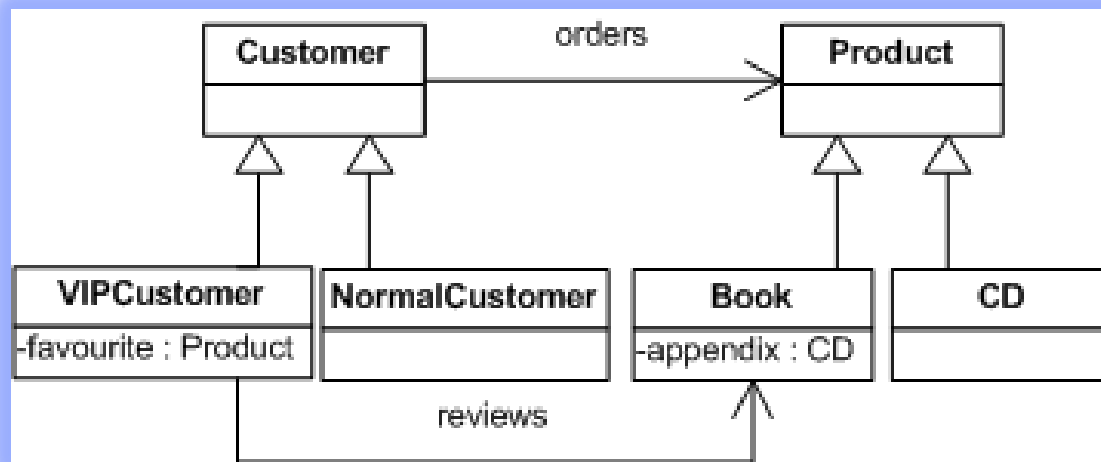


# Motivating Example

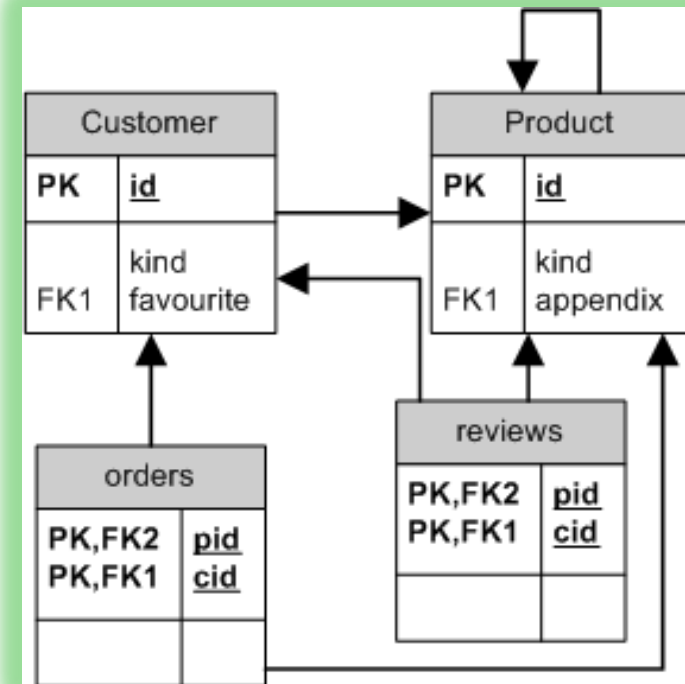
Object Relational Schema mapping

# Example: Object-relational mapping

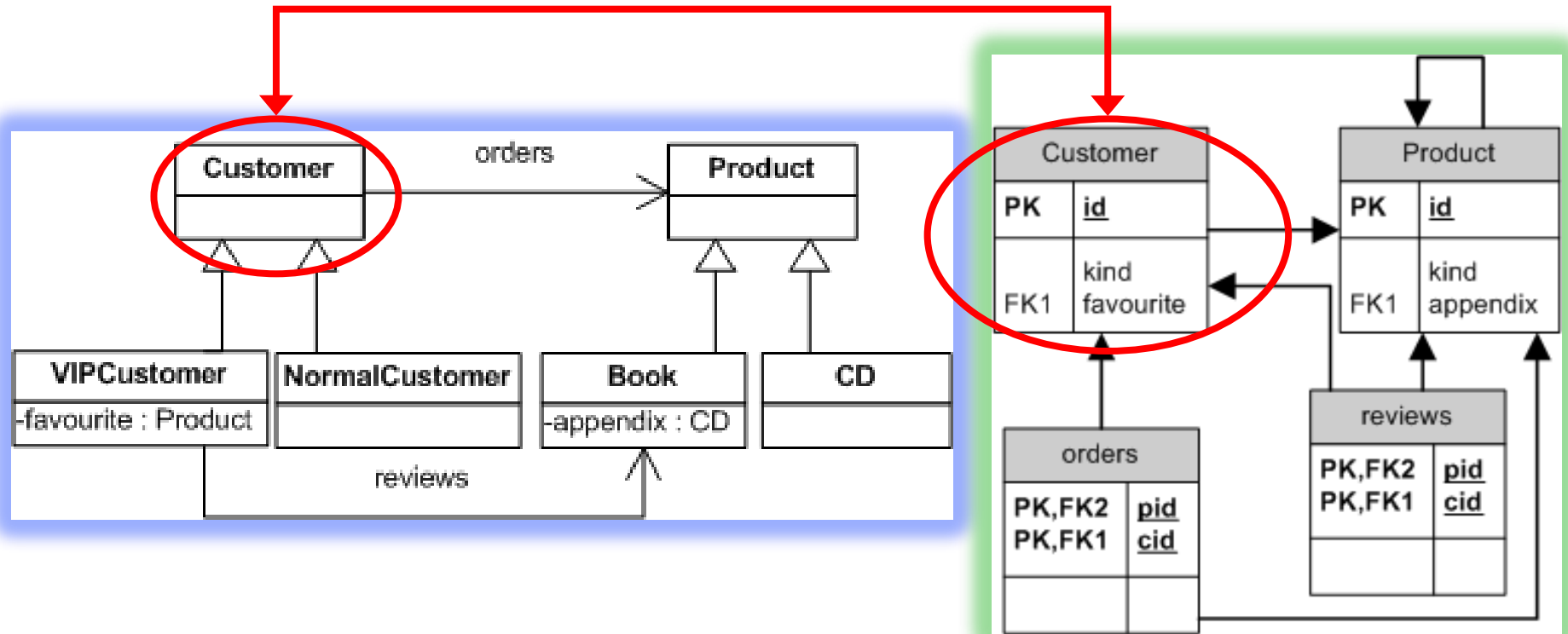
- Important as:
  - Model transformation benchmark
  - Most widely used industrial model transformation (pl. Hibernate, EJB, CDO)
- Objective:
  - **Input:**  
UML class diagram
  - **Output**  
Relational database schema



Several alternative ORM strategies, we'll use one



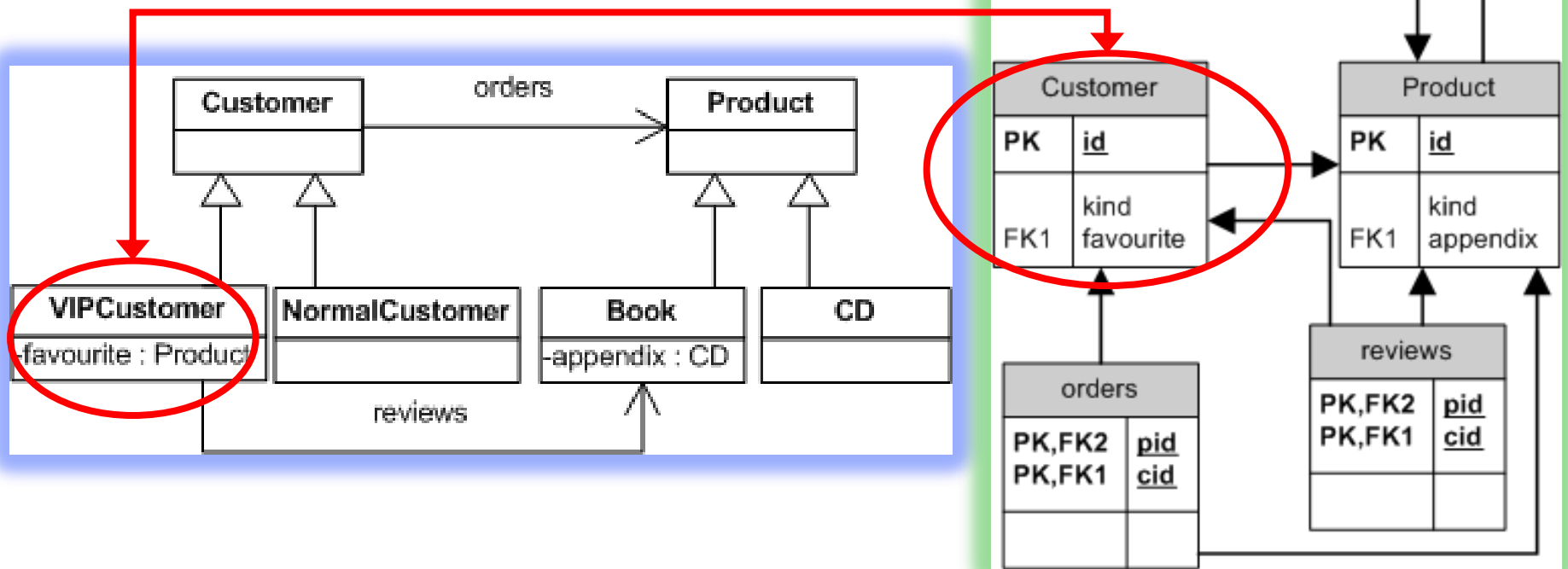
# Informal definition of the MT



Topmost (generalization) classes → Database table + 2 column:

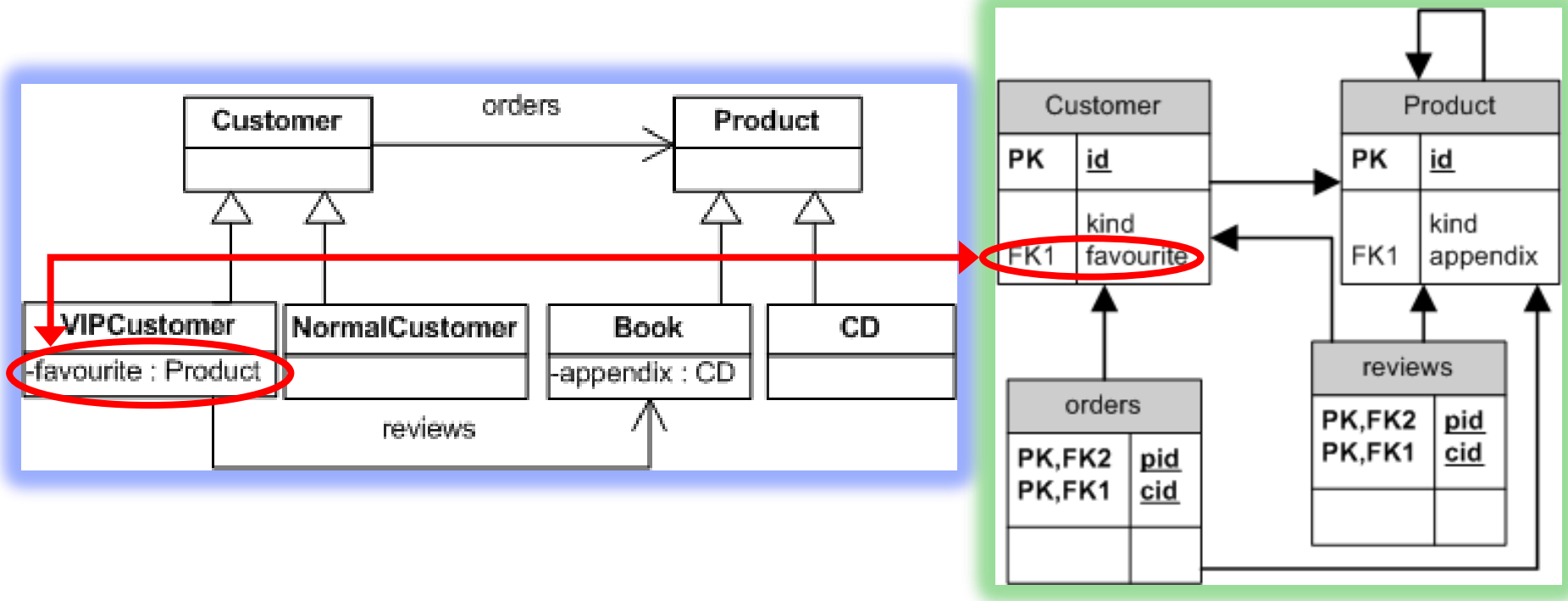
- Unique identifier (primary key),
- type definition

# Informal definition of the MT



Subclasses → Store instances in the same table as the root class

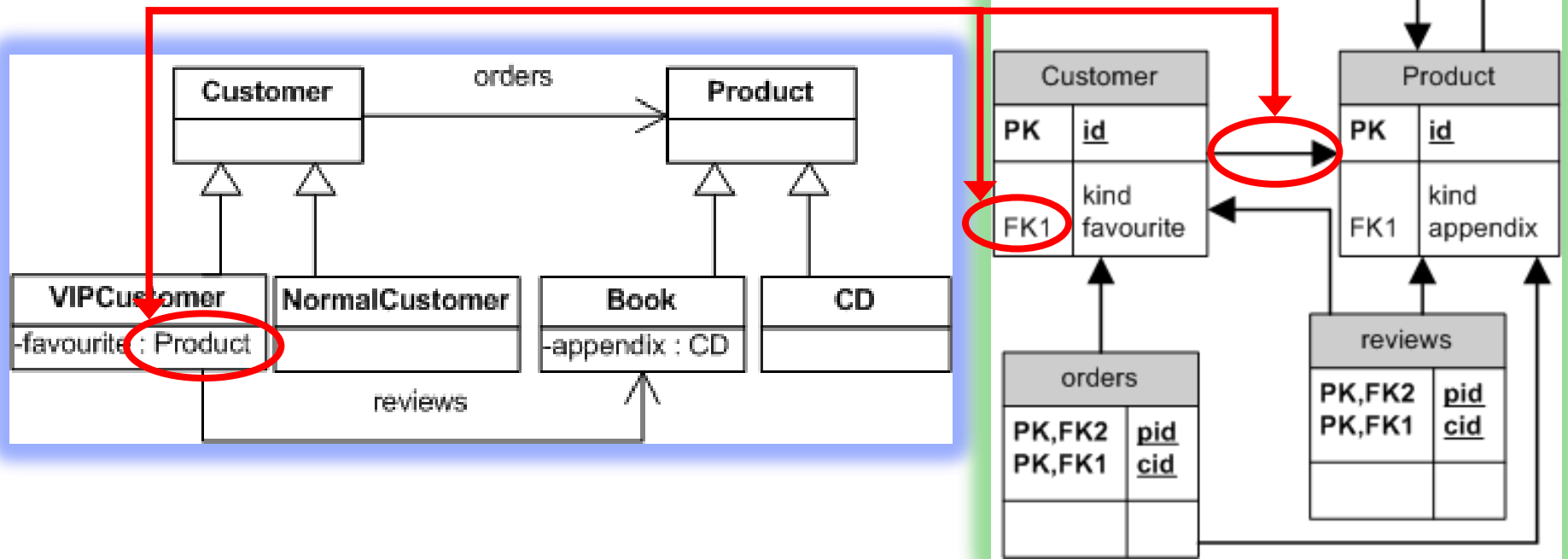
# Informal definition of the MT



Class attributes → Column of the table

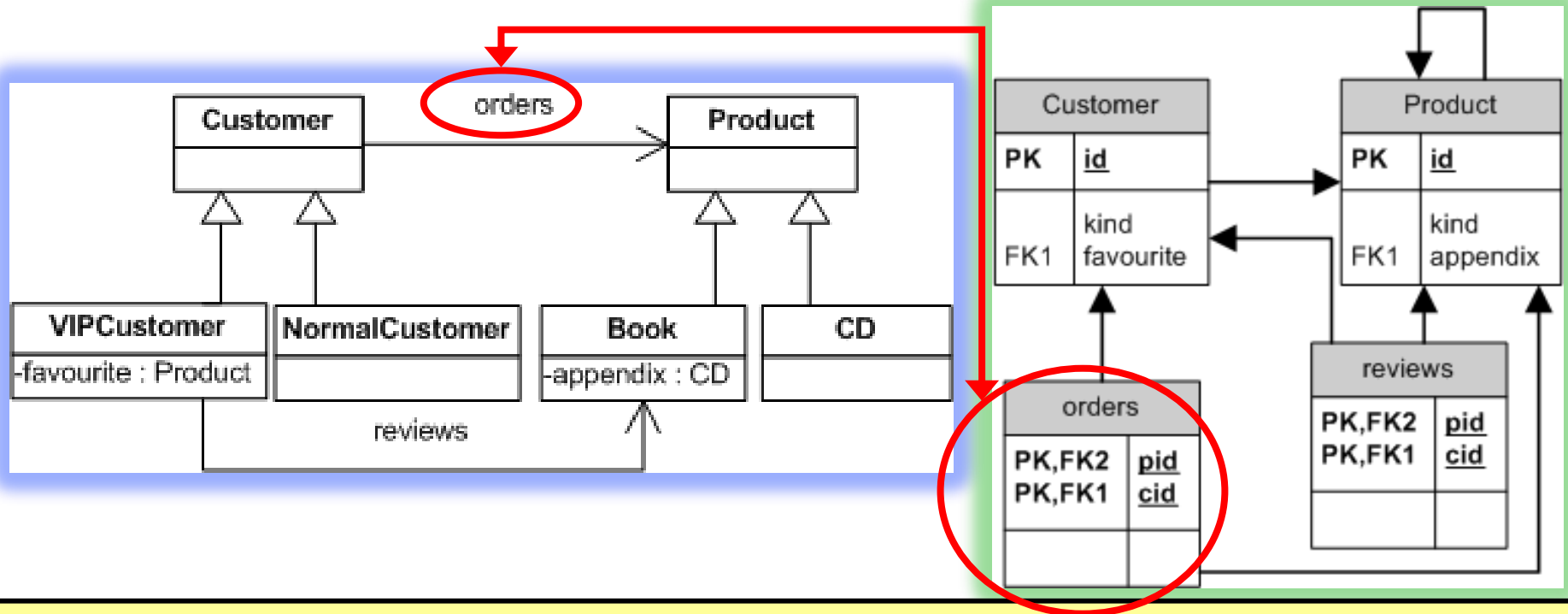


# Informal definition of the MT



Type of the attributes → foreign key

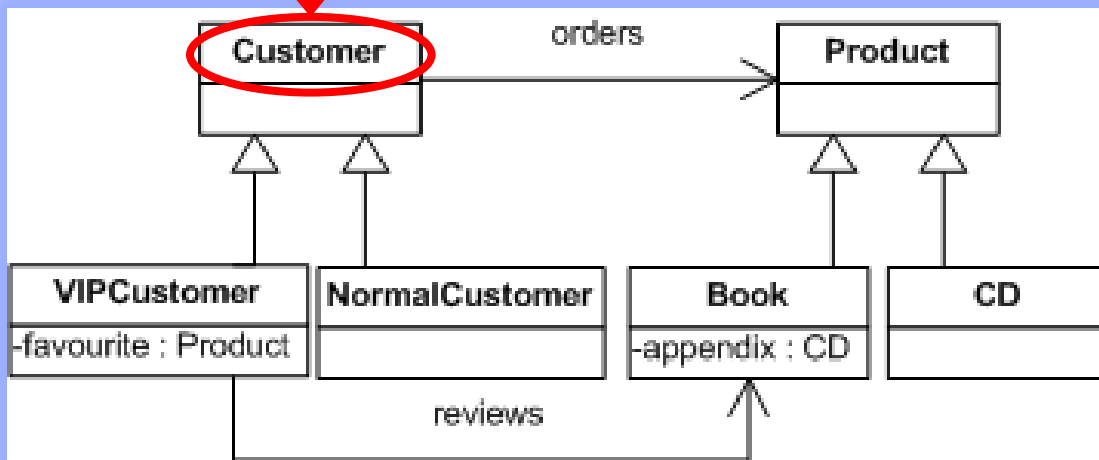
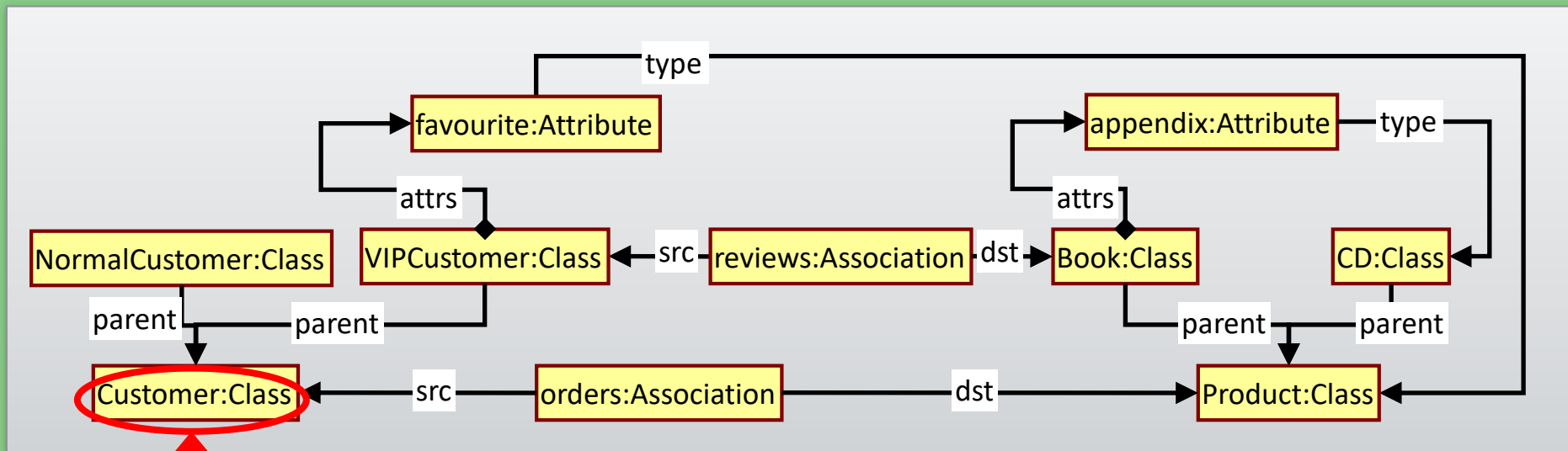
# Informal definition of the MT



Association ➔ A table with two columns

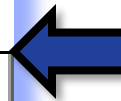
- source and target identifiers
- foreign keys (for consistency)

# Language structure (UML)



## Abstract syntax

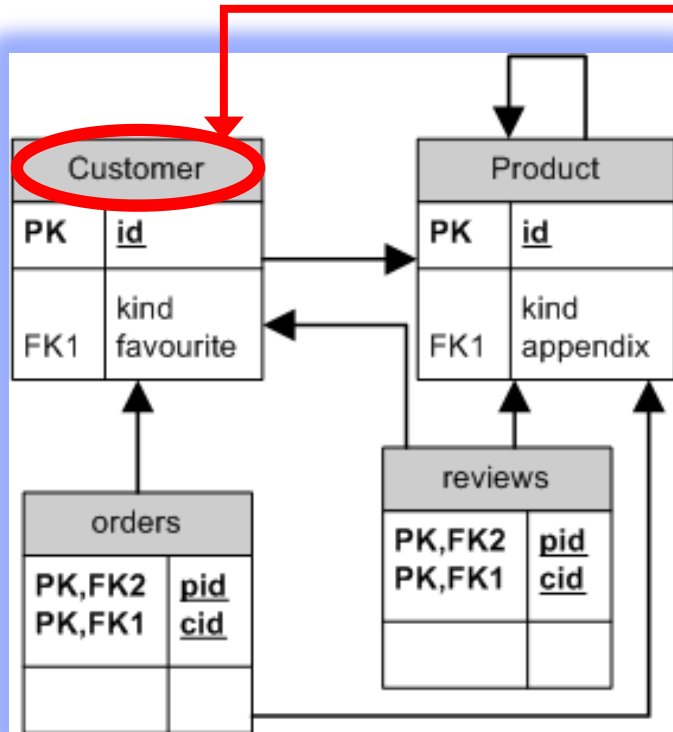
- Graph based model representation
- Machine readable



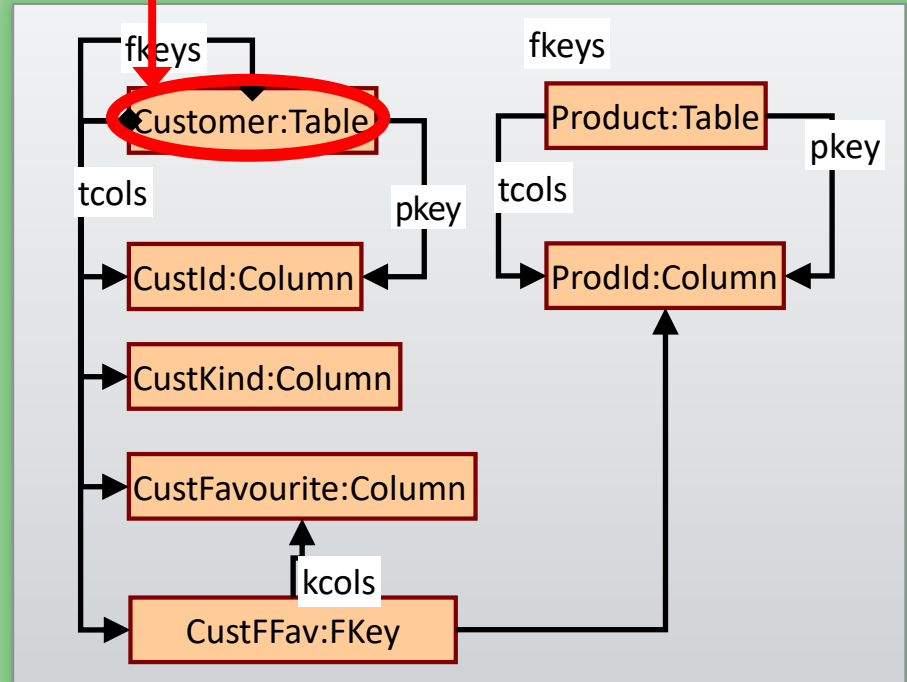
## Concrete syntax

- Visual/textual representation
- Human readable

# Language structure (RDB Schema)

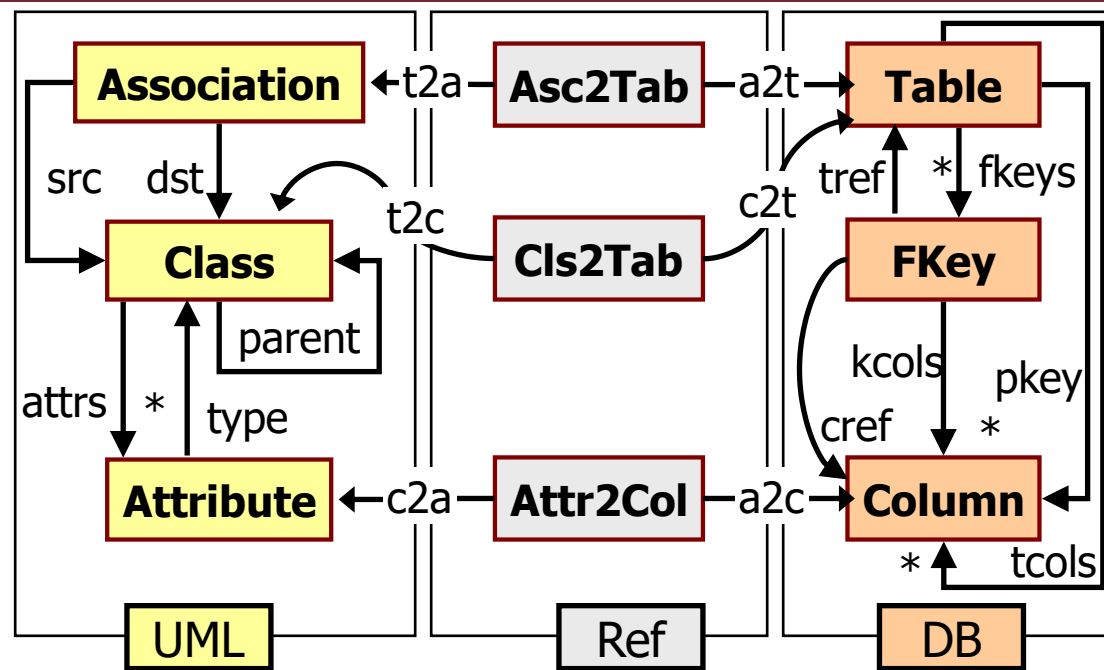


Concrete syntax

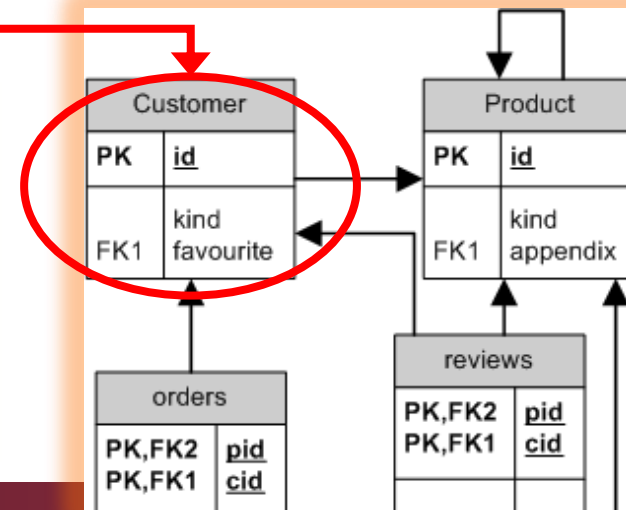
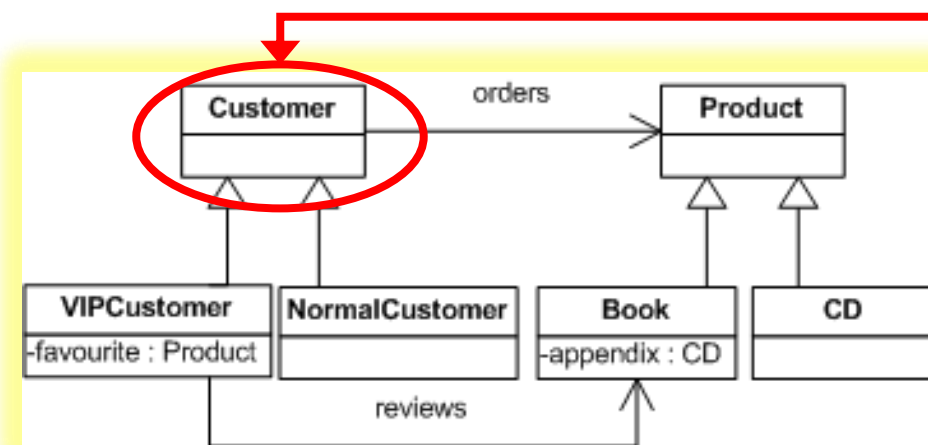


Abstract syntax

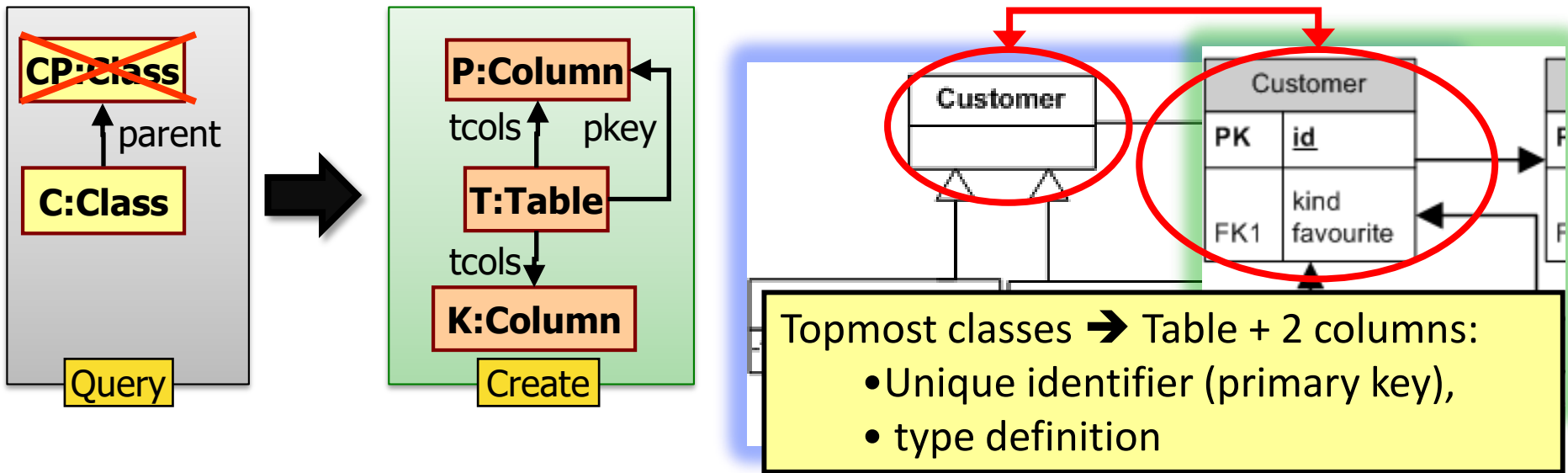
# Metamodel of the O-R mapping



- Source, Target metamodels
- Correspondence / traceability metamodel:**
  - For saving correspondence between source and target
  - Many use cases, see later



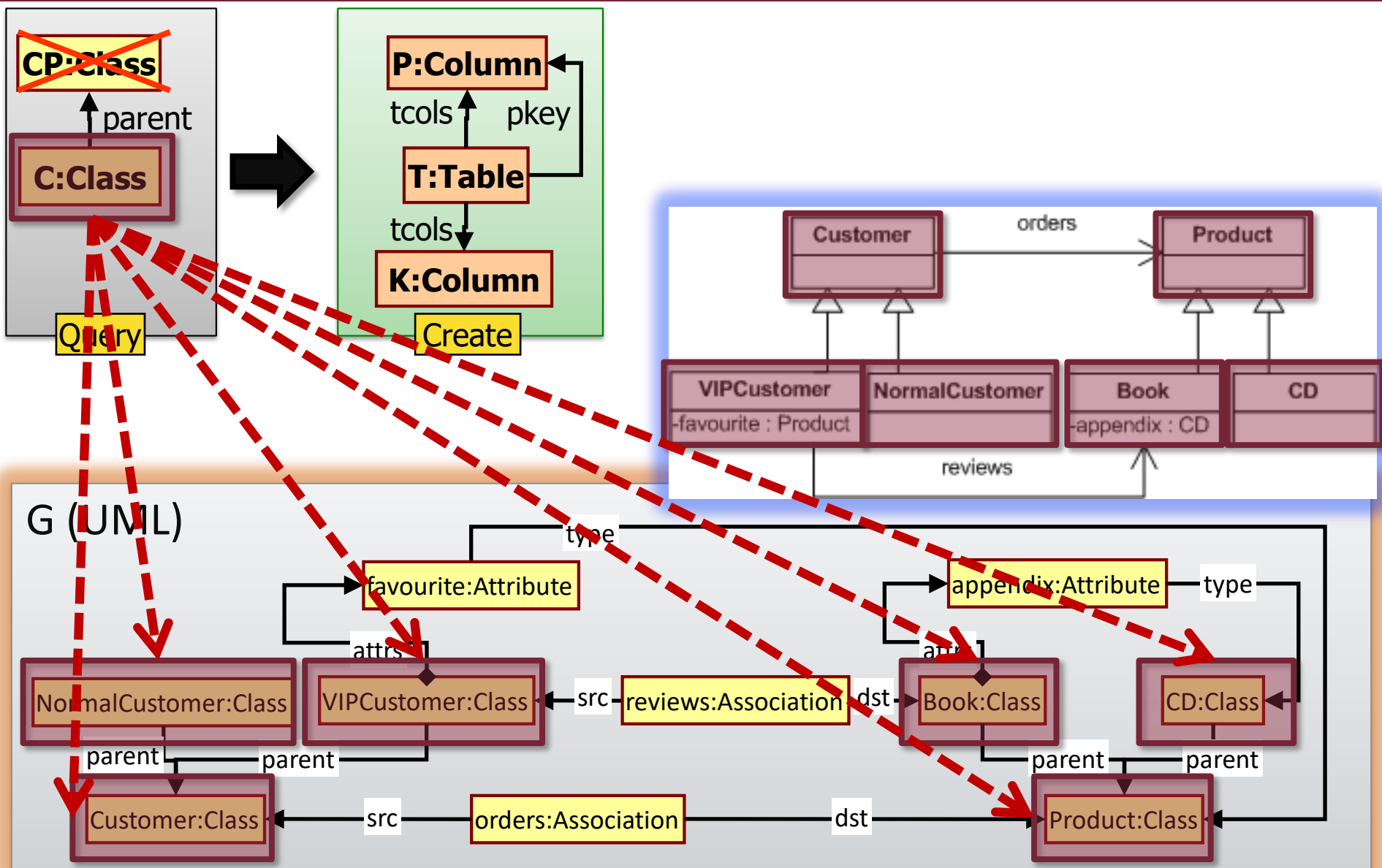
# Elaborating the Solution



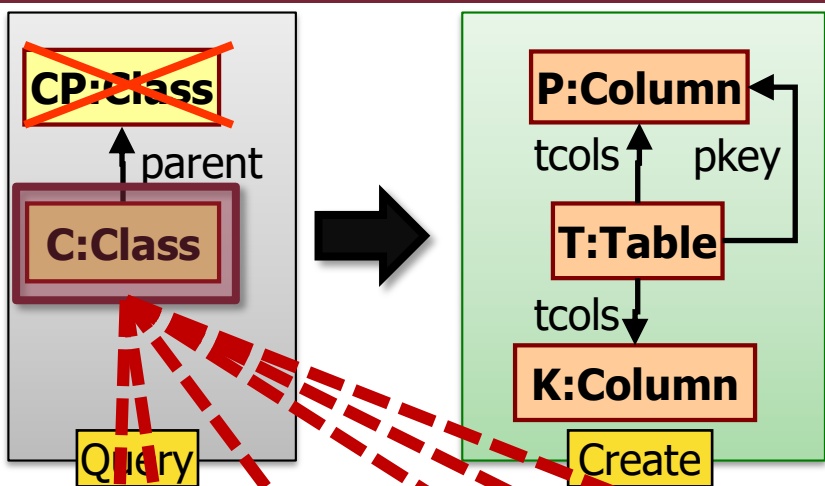
## ■ How to execute?

- 1) Evaluate **model query** on source model, find **matches**
  - Classes without superclass

# Revision: graph pattern matching

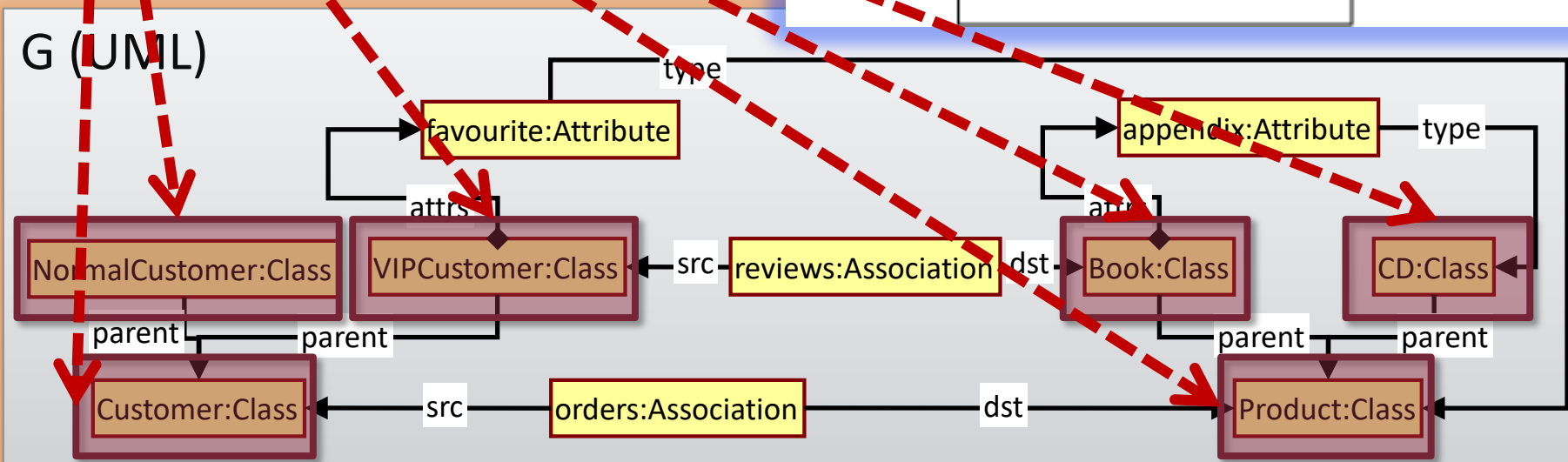
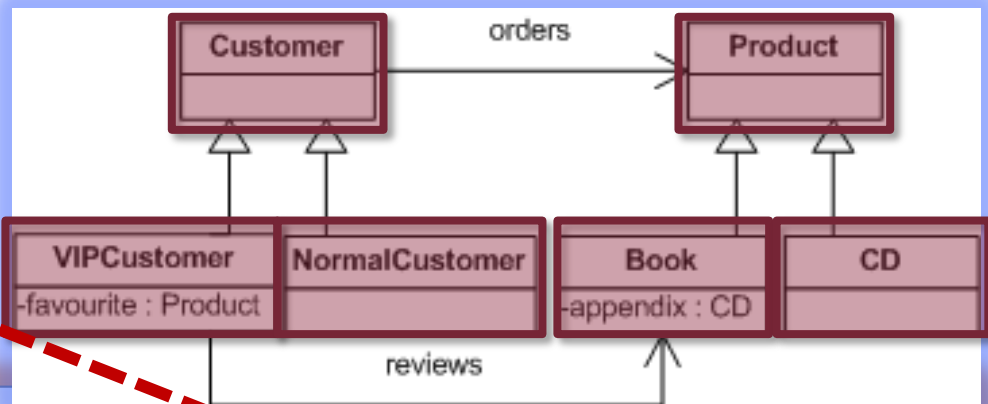


# Revision: graph pattern matching



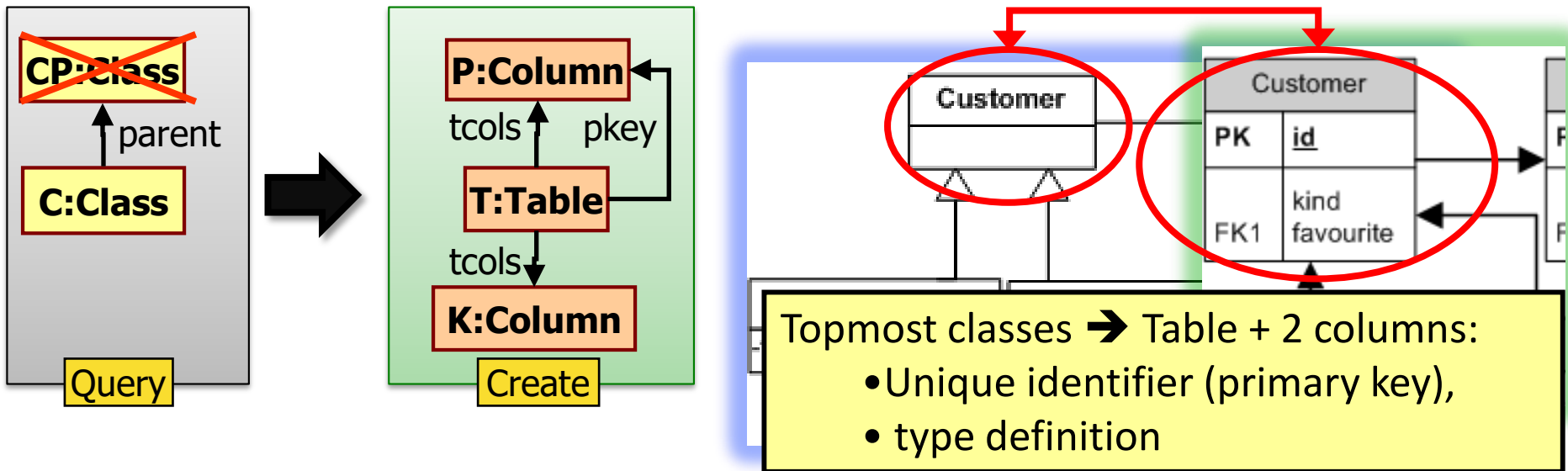
## Negated constraint

- Successful match of negative condition → pattern does not match





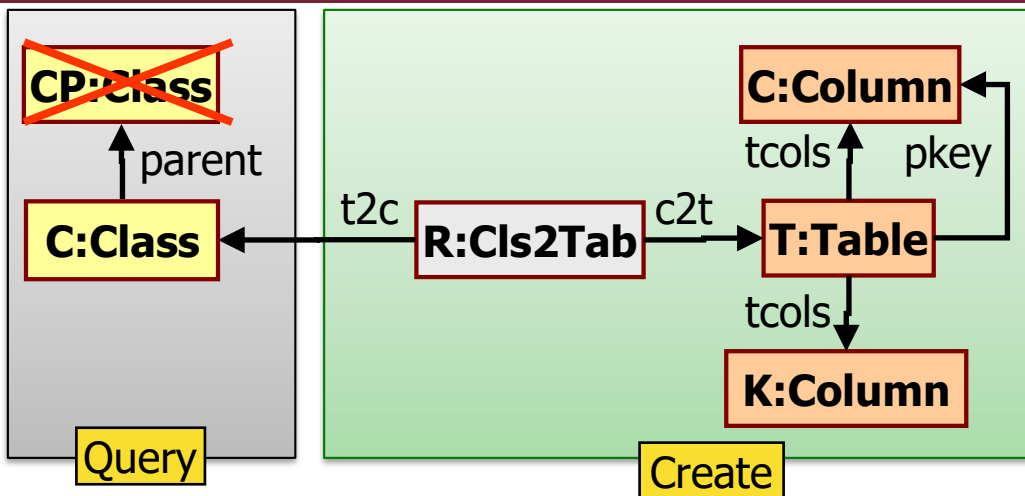
# Elaborating the Solution



## ■ How to execute?

- 1) Evaluate **model query** on source model, find **matches**
  - Classes without superclass
- 2) For each match, create new model elements
  - Table with primary key and type columns
  - Something is missing...

# Elaborating the Solution

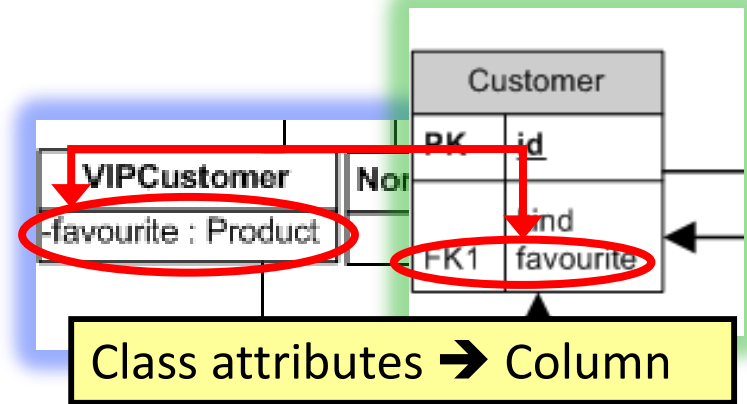
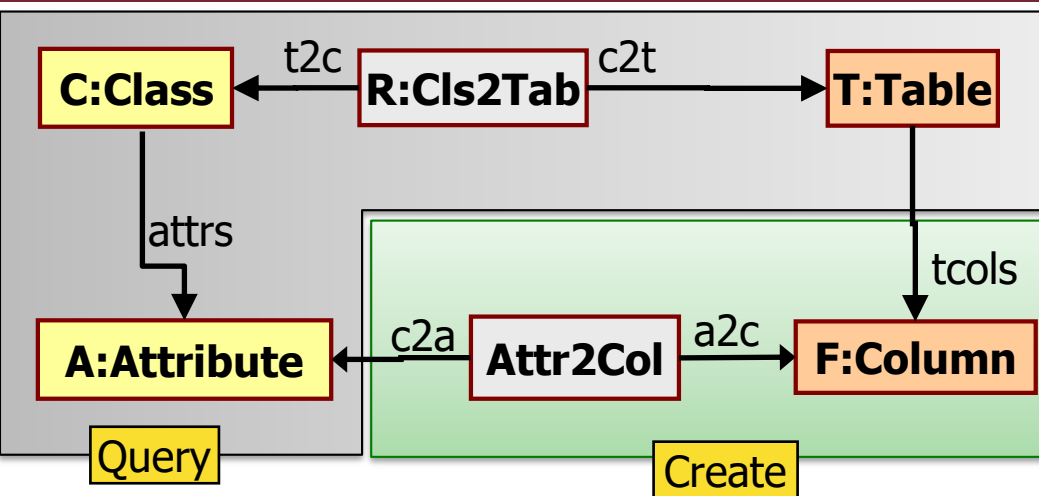


What will we use it for?

## ■ How to execute?

- 1) Evaluate **model query** on source model, find **matches**
  - Classes without superclass
- 2) For each match, create new model elements
  - Table with primary key and type columns
  - **Correspondence** (traceability) between table and class

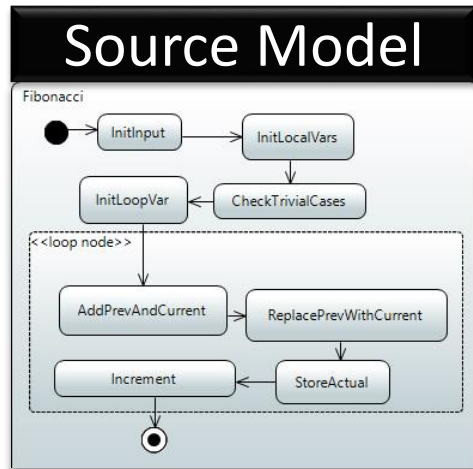
# Elaborating the Solution



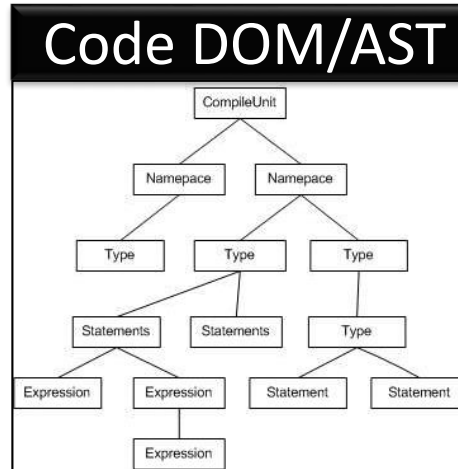
- Which table should the column belong to?
  - Build on previous steps, using correspondence
- Apply the same idea for the rest:
  - Associate subclass to table of parent class
  - Map associations, map types of attributes, etc.

# Chaining and Traceability of Model Transformations

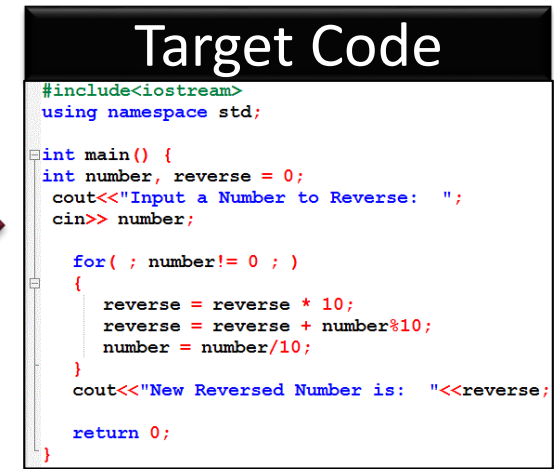
# Code Generation by Model Transformations



M2M



M2T



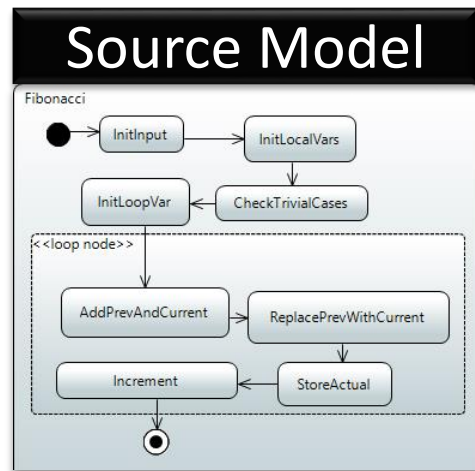
## Model-to-Model (M2M) Transformation

- SRC: In-memory model (objects)
- TRG: In-memory model (objects)

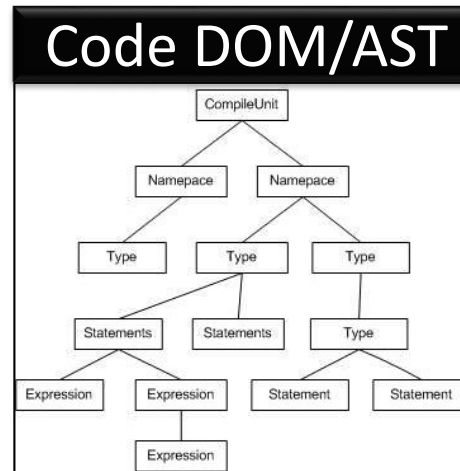
## Model-to-Text (M2T) Transformation

- SRC: In-memory model (objects)
- TRG: Textual code (string)

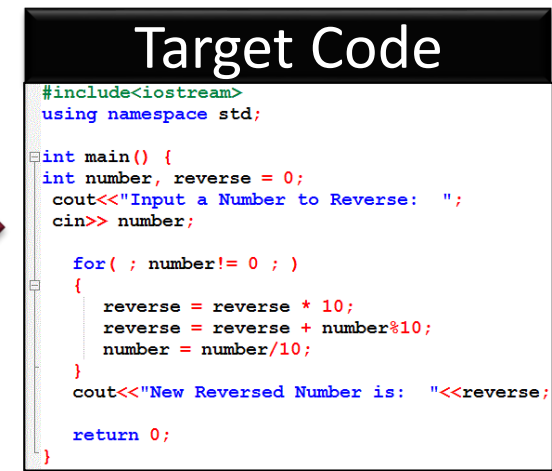
# Chaining of Model Transformations



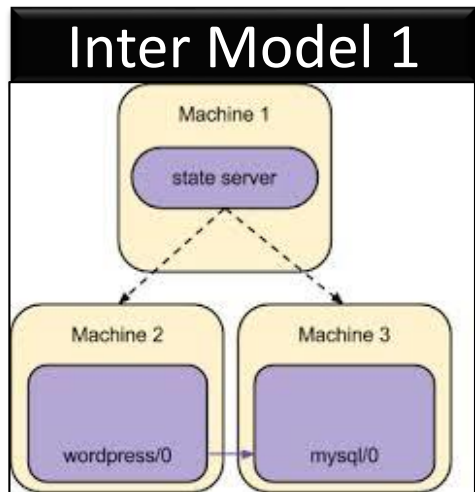
M2M



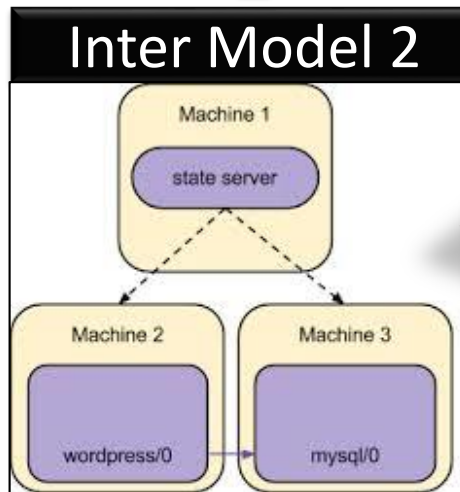
M2T



M2M



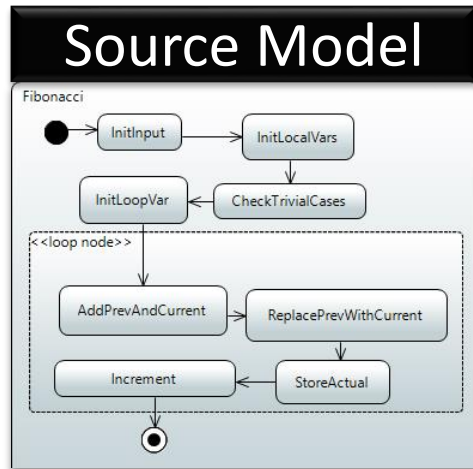
M2M



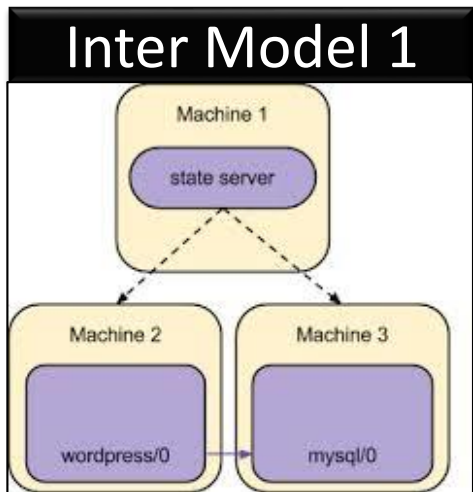
Goal:

- Reduce abstraction gap by „divide and conquer“
- Intermediate models
- Chain of model transformations

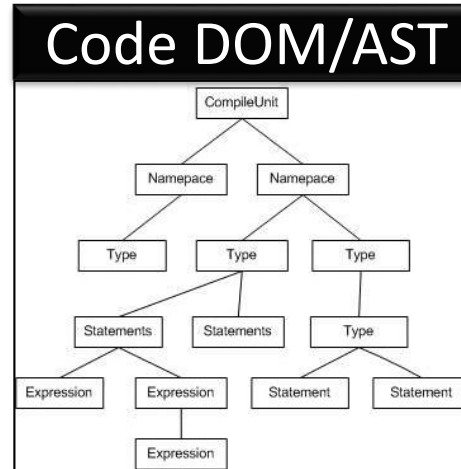
# Model Transformation Flows / Chains



M2M



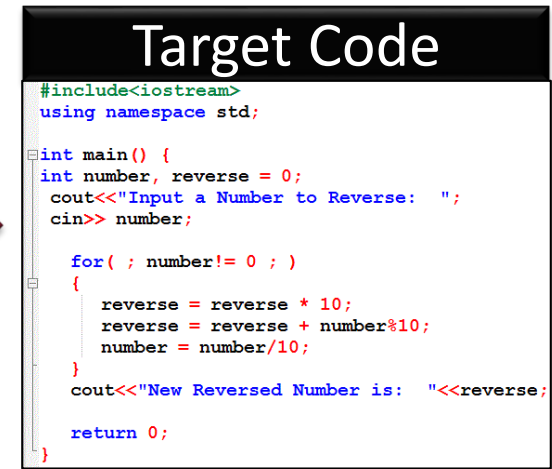
M2M



M2M

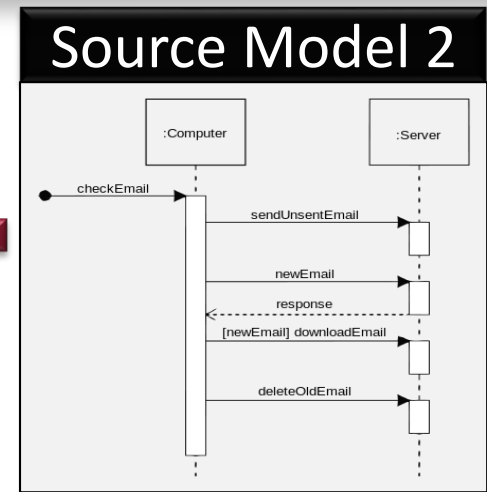


M2T

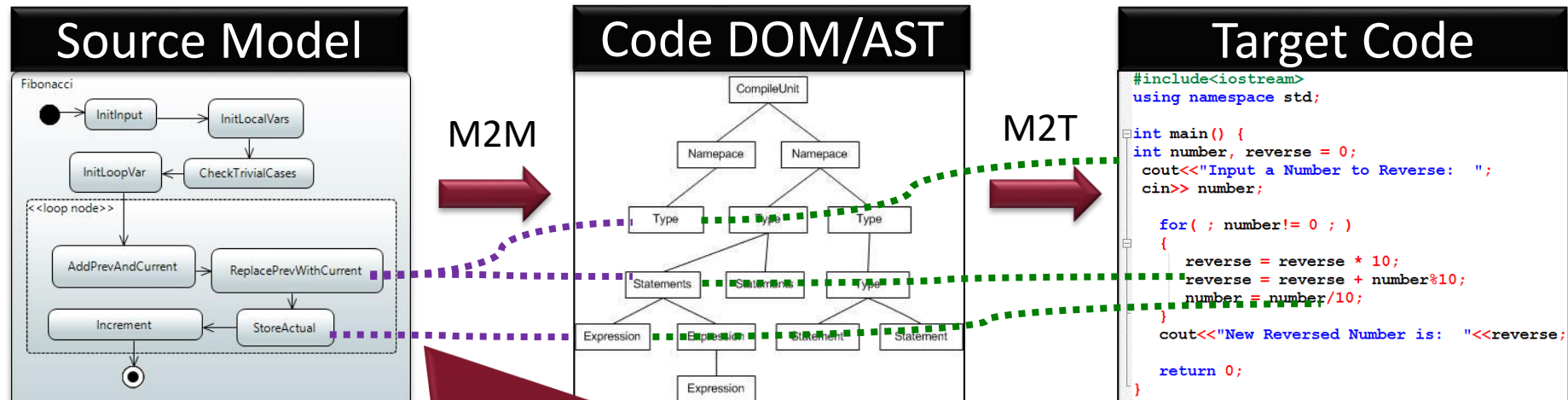


Joint optimization steps

M2M



# Traceability in Model Transformations



Traceability / correspondence links:

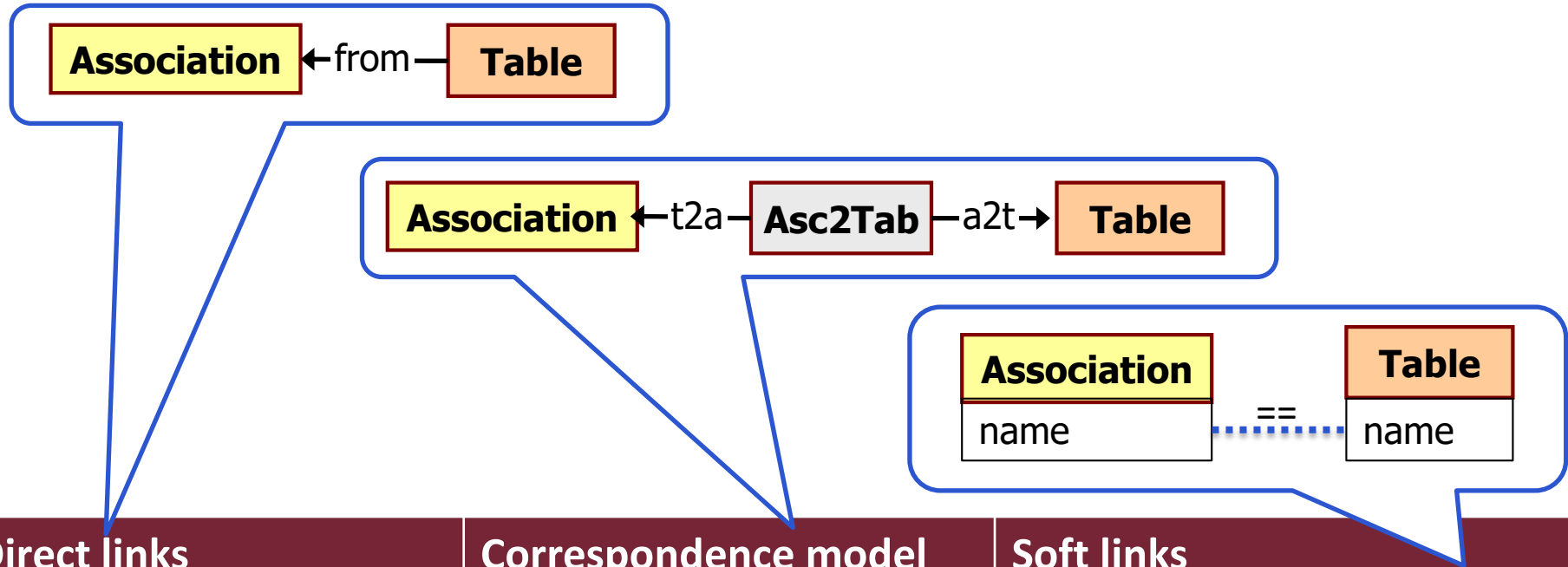
- Connect SRC and TRG models

Objectives:

- Make transformation specification easier
- Support end-to-end traceability
- Improve incrementality (see later)



# Forms of Traceability



## Direct links

Cross-reference between  
SRC↔TRG

Intrusive: must extend  
meta & instance models

## Correspondence model

Stored in separate  
metamodel & model

Complex, large overhead

## Soft links

Match by id / qualified name  
using model query / index

Requires unique identifier;  
limited expressiveness  
(tells which one, not why)

# Rule-based Transformations

# Model Transformation Specification

- Imperative with direct model manipulation
  - Quick&easy for simple batch transformations
  - But what if we need...
    - Incrementality?
    - Bidirectionality?
- **Rule-based declarative**
  - *Graph Transformation* based
  - Hybrid: query + imperative action (VIATRA etc.)
  - „Relational” (QVT-R, TGG, ATL, etc.)
  - „Explicit”

# Rule-based MT core idea

## ■ Unit: **MT rule**

| For each occurrence of...                      | ...transform it like this                |
|--|--|
| Root class in inheritance hierarchy            | Create entity table with default columns |
| Attribute of class                             | Add columns to table of class            |
| Association between classes                    | Create switch with foreign key columns   |
| <b>PRECONDITION</b><br>Declarative Model Query | <b>ACTION</b><br>May be imperative       |

- This is just the core idea, many variants
  - We'll discuss two formalisms later (VIATRA, GT)

# Inversion of Control (IoC)

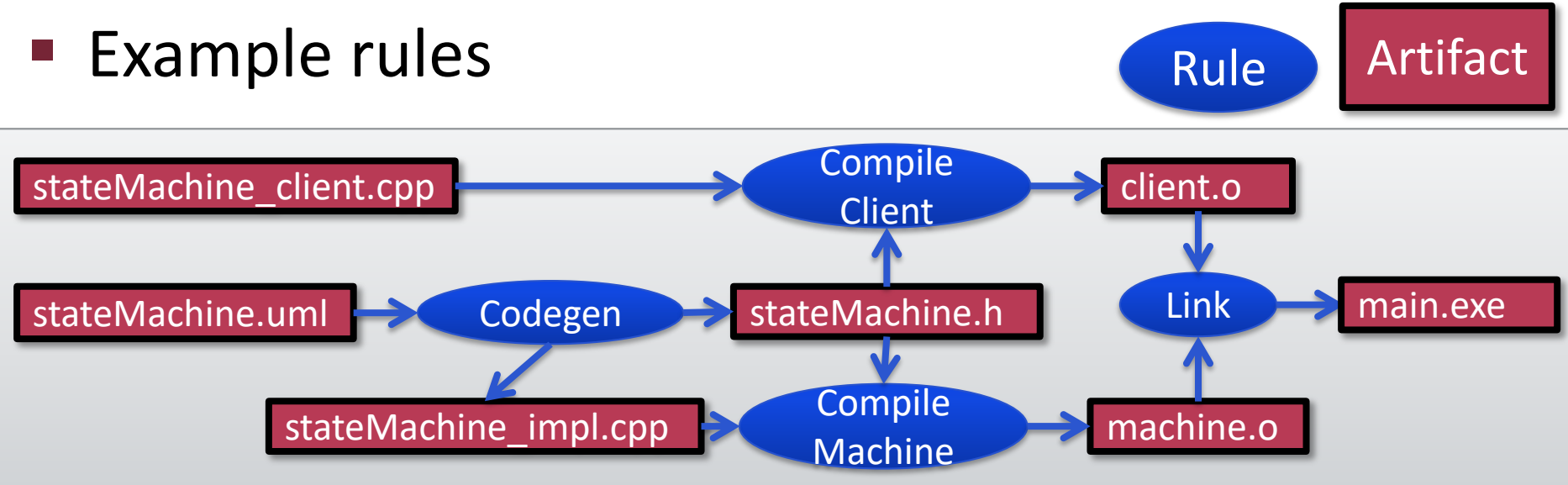
- Declarative rule execution
  - **Transformation engine** interprets preconditions
  - Rules are **fired** by engine when&where enabled
- Several variants
  - „As long as possible” / „fire why possible” semantics
    - Iterate while there are **rule activations**
    - Select one activation (**conflict resolution**), fire it
  - „Fire all current” semantics
    - Select all *current* activations, fire them all, stop
  - Arbitrary control flow

# Rule-based Systems

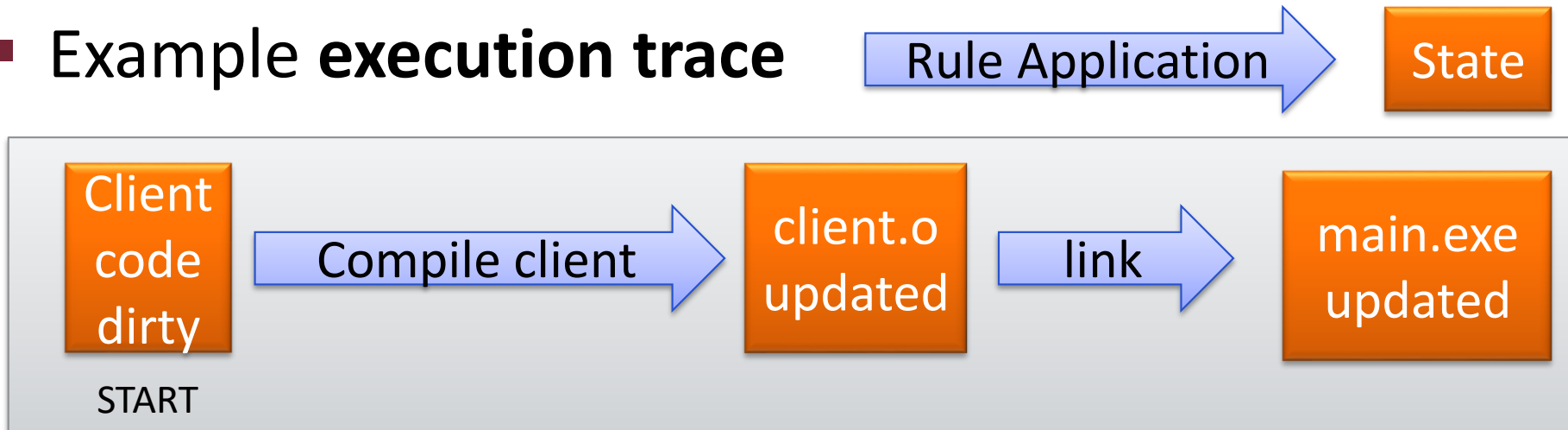
- Where have I seen rule-based systems?
  - **Model transformations** We are interested in this
  - Build scripts (MAKEFILE, Maven, etc.) Easy example
    - Rule: build this artifact *like this* (action) when those others are ready and dirty (precondition)
  - Business rule & expert systems (Jboss Drools, etc.)
  - Context-free grammars (see Textual Syntax Lecture)
  - CSS
  - ...
- There are some vague commonalities

# Build Script Example

## Example rules

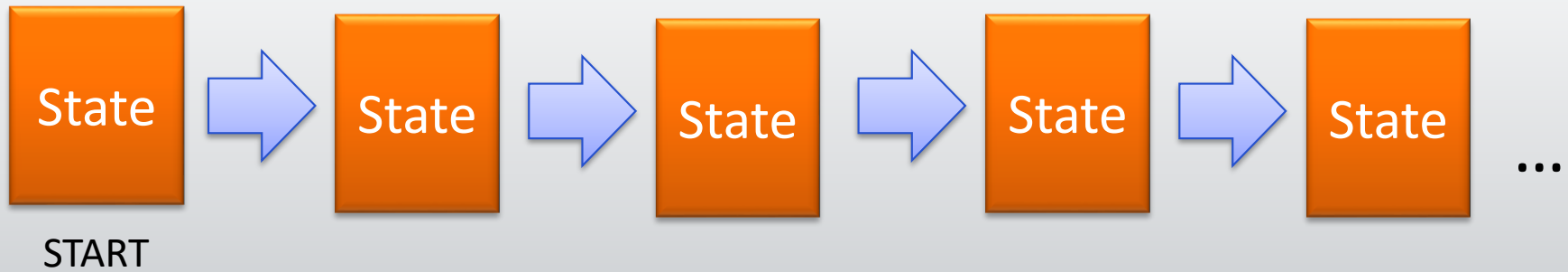


## Example execution trace



# Common Rule-based Problems

## ■ Problem 1: **Termination**

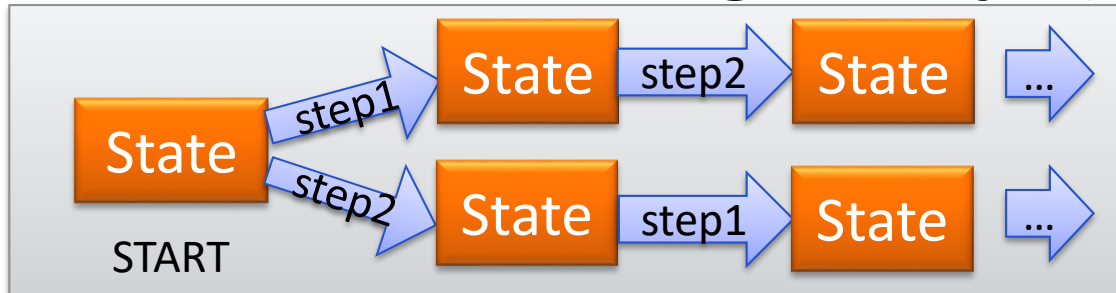


- Vital to ensure!
- Non-terminating examples
  - Makefile: a build step overwrites (re-dirties) one of its inputs
  - MT rule creates new object, has to be xformed by same rule
  - MT Rule1 creates element, Rule2 deletes it, Rule 1 again, ...
- No systematic way to guarantee, requires thought



# Common Rule-based Problems

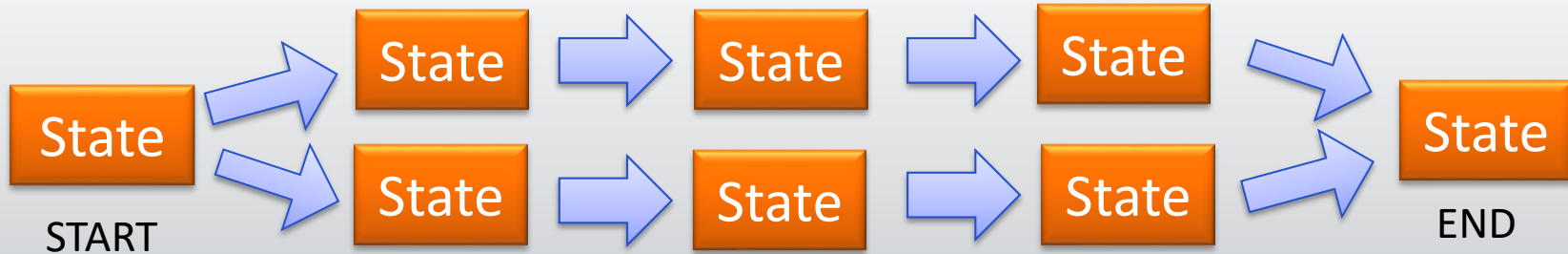
## ■ Problem 2: **Ordering of steps** (rule applications)



- May be required for correctness
  - MT example: transform attribute only after relevant class
- In other cases, only performance is impacted
  - Makefile: if client is built before dirty .uml, must rebuild
- How to manage?
  - Smart engine (limited applicability, works for Makefile)
  - Express in precondition (attribute rule requires class)
  - **Rule priorities** (execute class rules before attribute rules)

# Common Rule-based Problems

## ■ Problem 3: **Confluence**



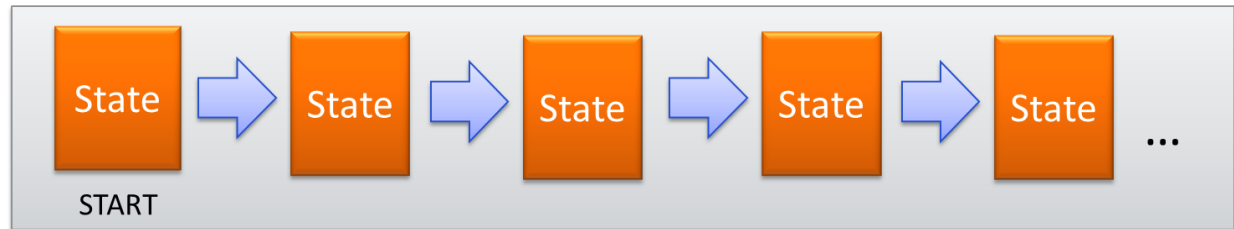
- Final state must be determined by start state
  - No matter the internal choices (which rule to apply now?)
  - Confluence is important; full determinism is optional
- Examples
  - ORM: Which root class to transform first? Doesn't matter.
  - Makefile: Which dirty file to recompile first? Doesn't matter.
- No systematic way to guarantee, requires thought

# Graph Transformation (GT) Rules

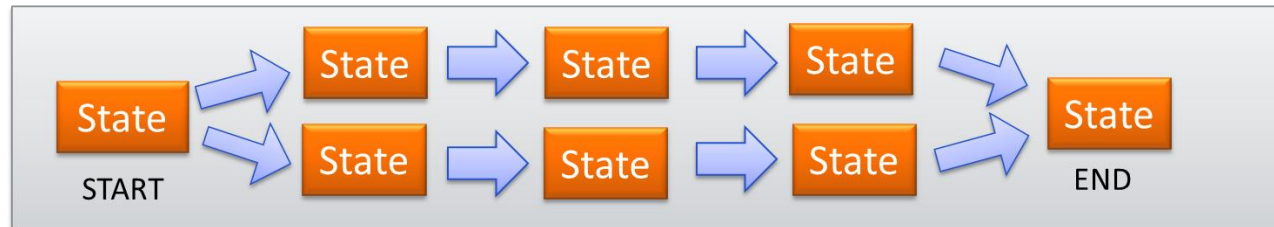
# The Motivation for GT

- Writing correct rule-based MTs may be hard

- Termination



- Confluence



- ...

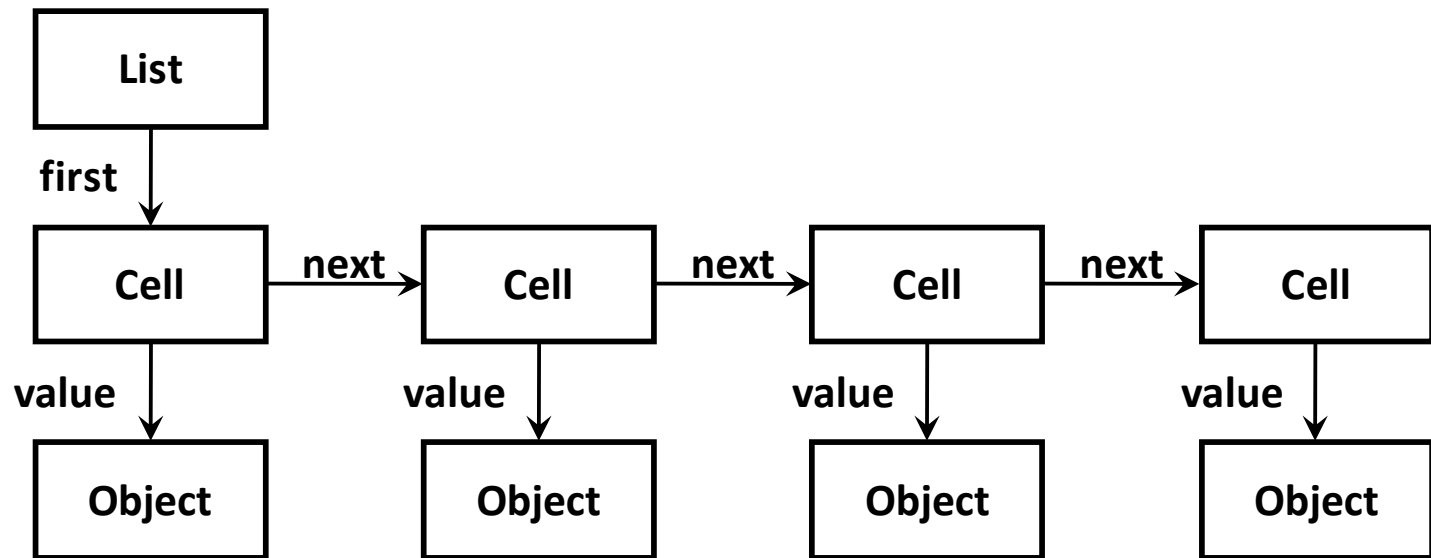
- Graph Transformation (GT)

- Formal mathematical model...

- ...to represent MT rules...

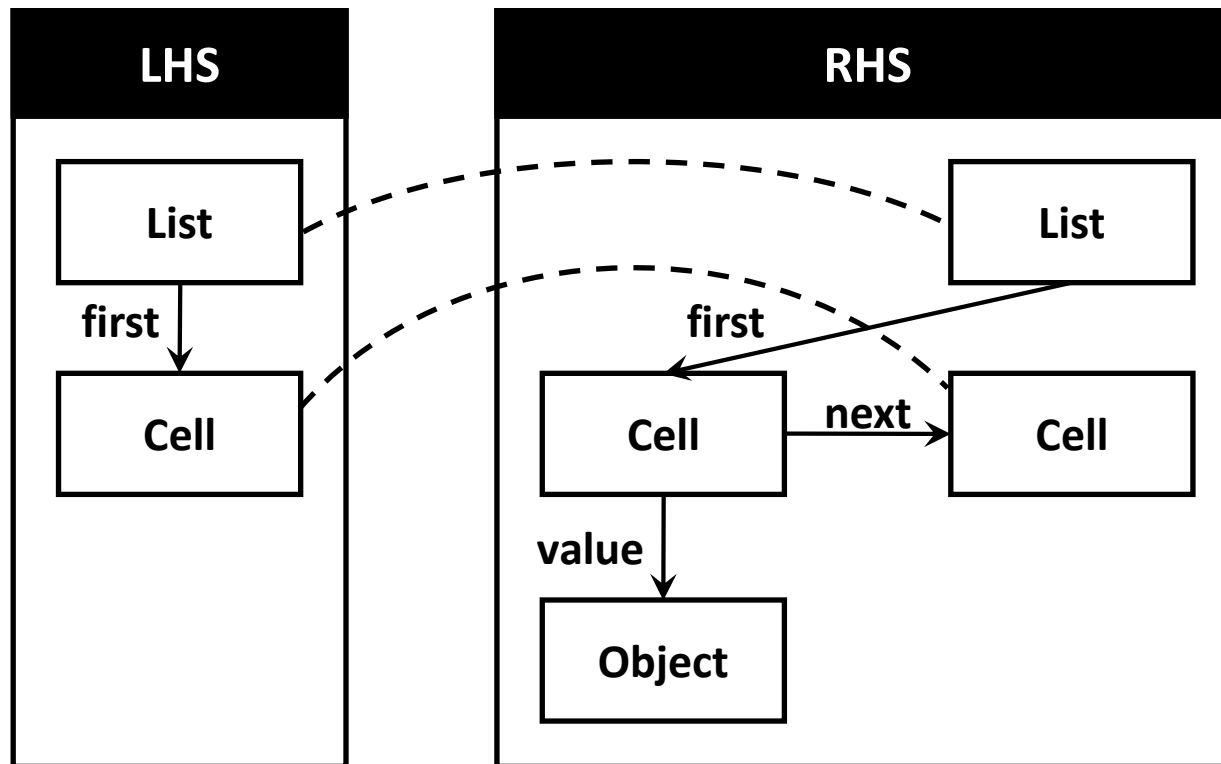
- ...and reason about them

# Model = Labelled Graph



# Operation = Graph Transformation

- Graph transformation as graph rewriting rules
- Left Hand Side: Precondition
- Right Hand Side: Postcondition



# Execution of Graph Transformation Rules

Matching Precondition

LHS

List

first

Cell

List

first

Cell

next

Cell

next

Cell

next

Cell

value

Object

value

Object

value

Object

value

Object

# Execution of Graph Transformation Rules

Matching precondition

LHS

List

first

Cell

List

first

Cell

next

Cell

next

Cell

next

Cell

value

Object

value

Object

value

Object

value

Object



# Execution of Graph Transformation Rules

Rewriting the graph by the match

RHS

List

Present in LHS, but not in RHS →  
DELETE

first

first

Cell

next

Cell

next

Cell

next

Cell

next

Cell

value

Object

value

Object

value

Object

value

Object

value

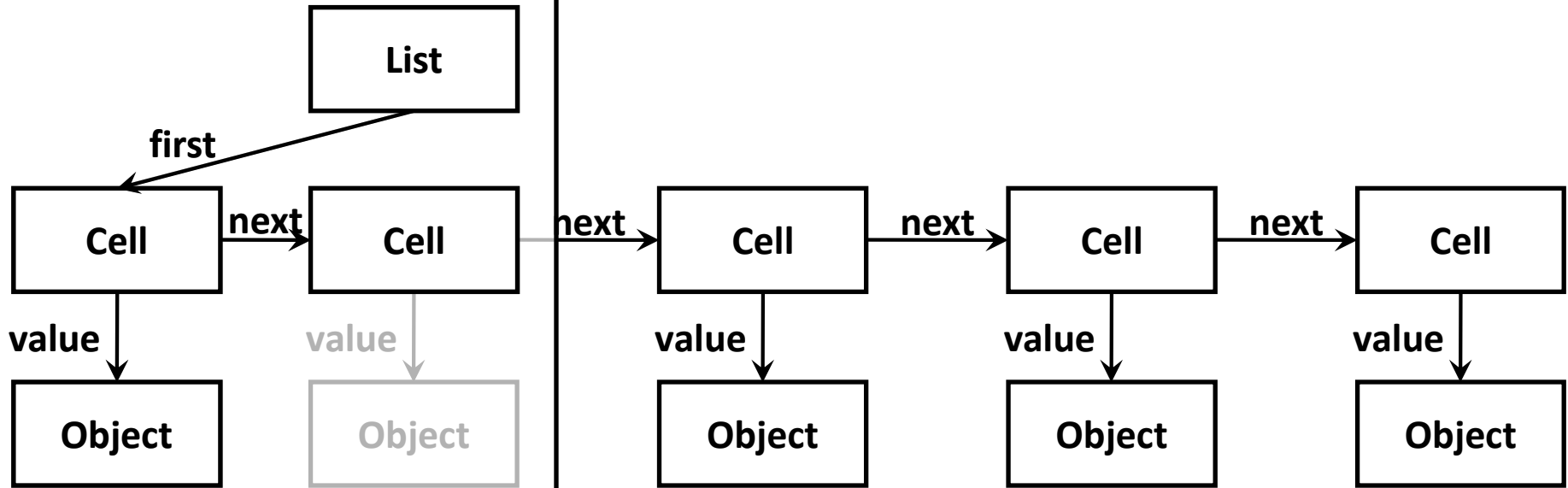
Object

Present in RHS, but not in LHS →  
CREATE

# Execution of Graph Transformation Rules

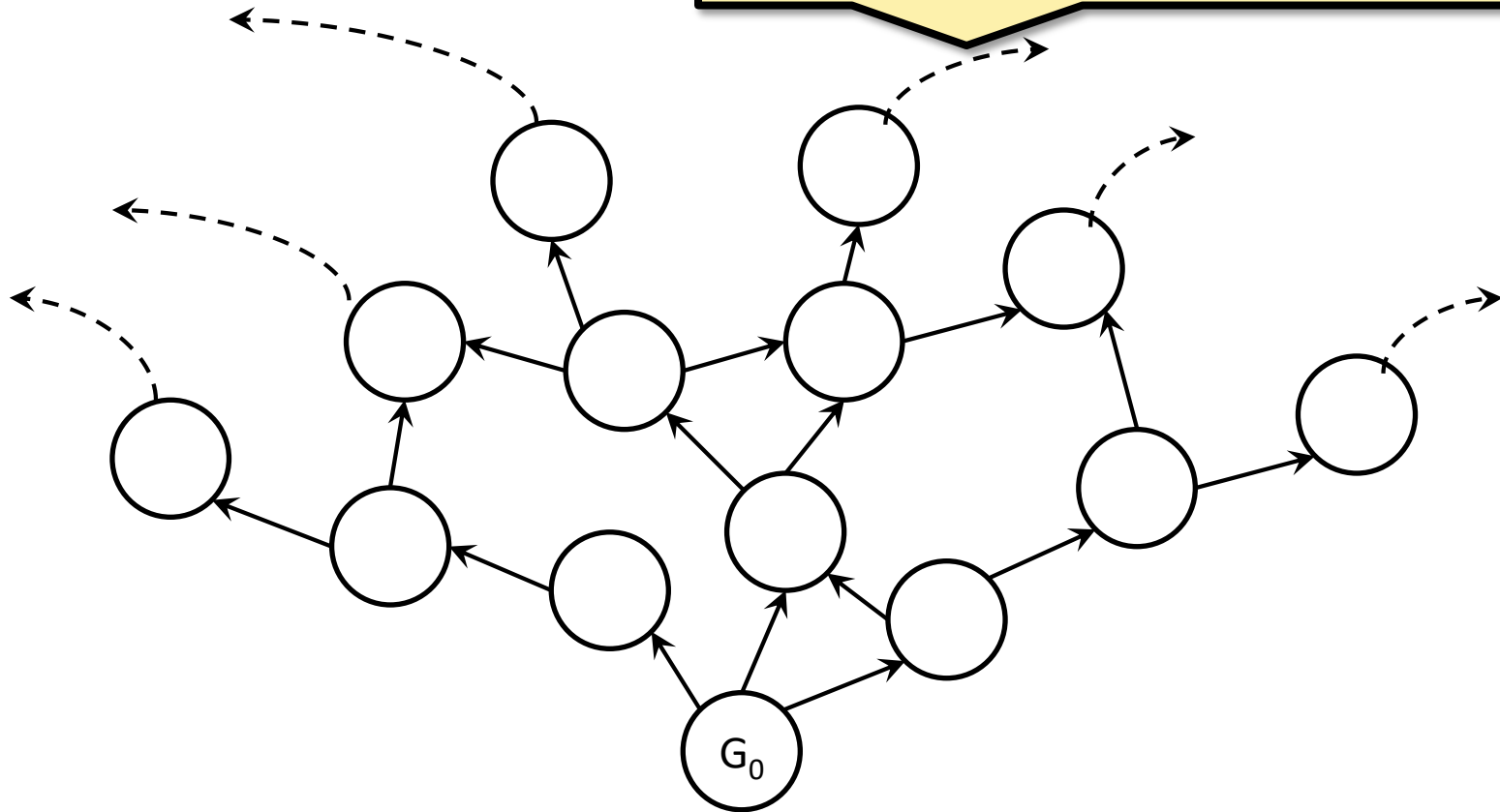
We get a new graph

RHS



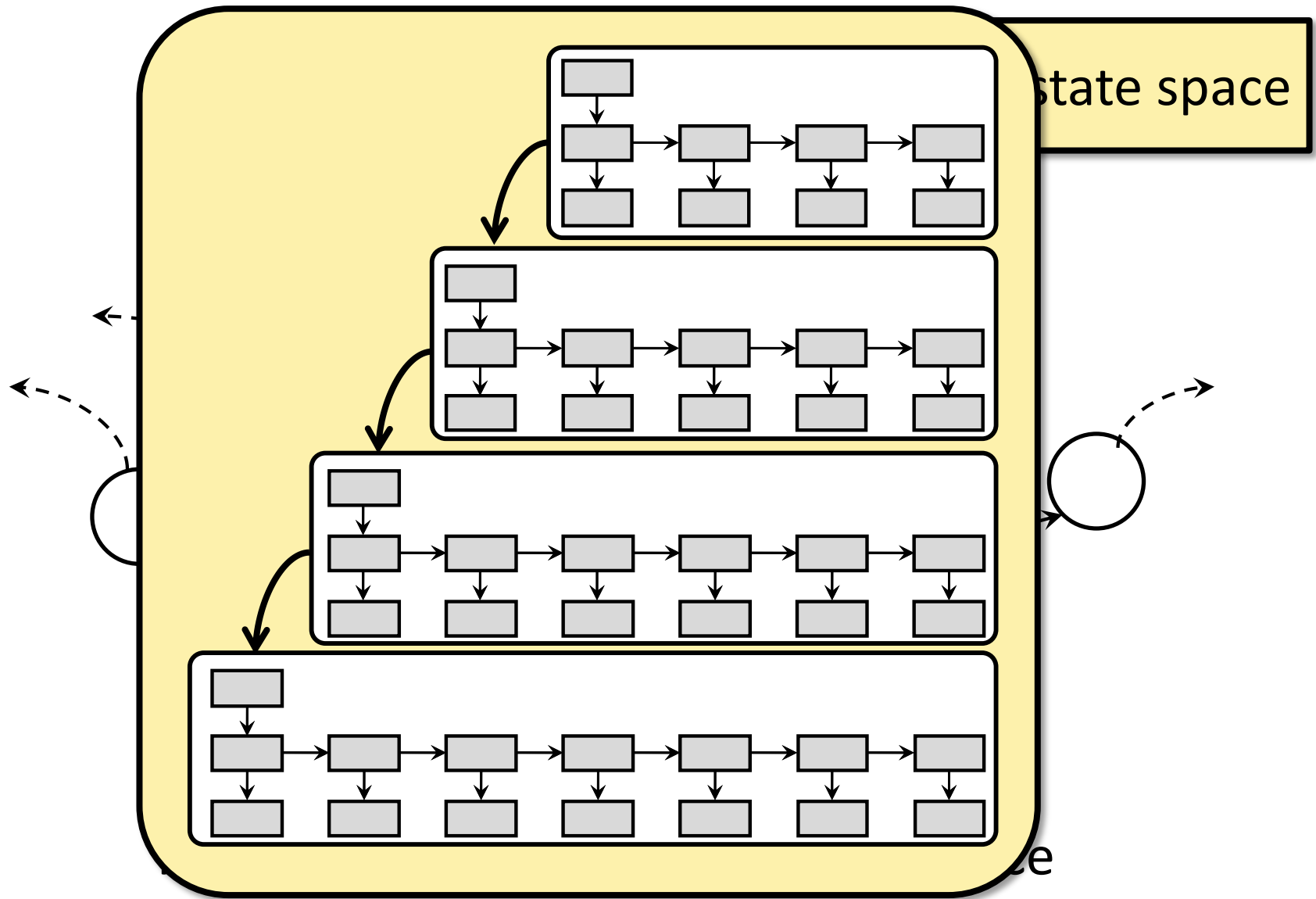
# State Space

Potentially infinite state space

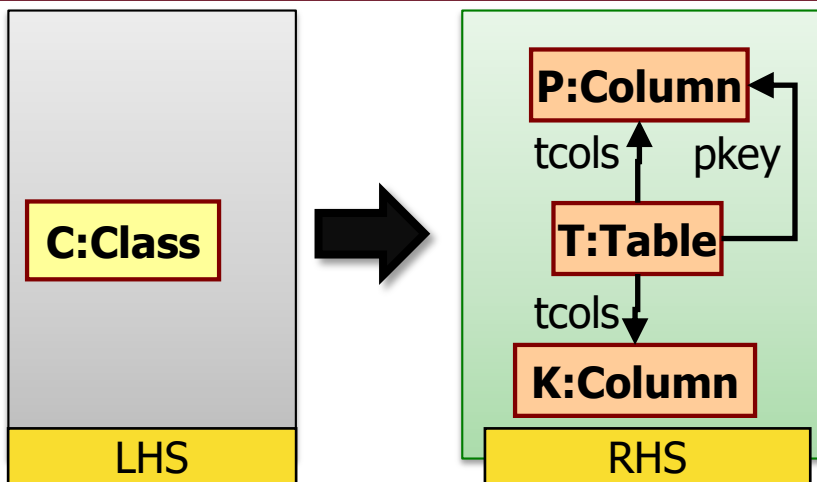


Initial Graph + GT rules  $\rightarrow$  State Space

# State Space



# Structure of a GT rule



## ■ Graph Transformation Rules

### ○ Left hand side - LHS

- Graph pattern
- Precondition for the rule application

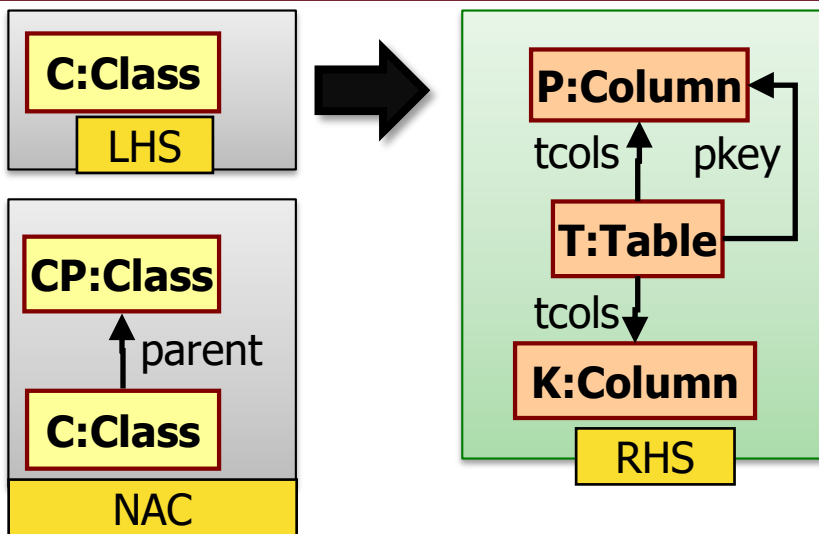
### ○ Right hand side - RHS:

- Graph pattern + LHS mapping
- Declarative definition of the rule application
  - What we get (and not how we get it)

## ■ Graph Transformation (GT):

- Declarative and formal paradigm
- Rule base transformation
- Match of the LHS → Image of the RHS
- Generalization of Chomsky grammars (hierarchy) (text → graph)

# Structure of a GT rule



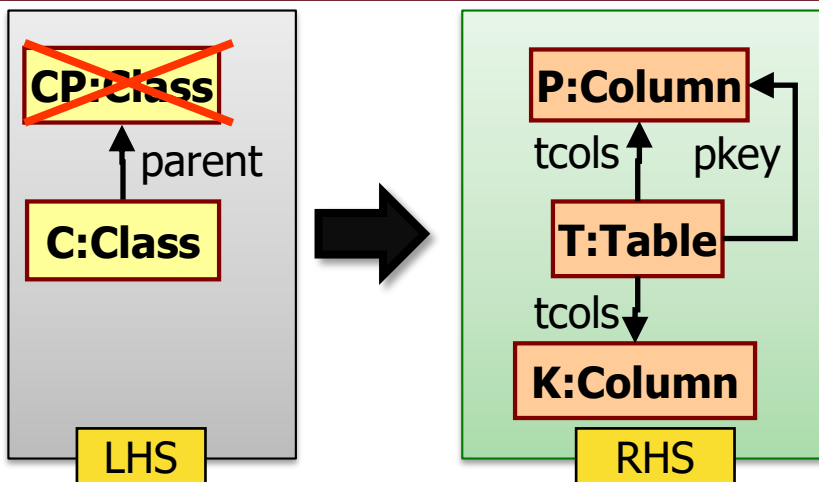
## ■ Graph Transformation Rules

- **Left hand side - LHS**
  - Graph pattern
  - Precondition for the rule application
- **Right hand side - RHS:**
  - Graph pattern + LHS mapping
  - Declarative definition of the rule application
    - What we get (and not how we get it)
- **Negative Application Condition(NAC):**
  - Graph pattern + LHS mapping
  - Negative precondition of the rule application
  - If it can be made true → the rule cannot be applied
  - Multiple NACs → only one is true → rule cannot be applied

## ■ Graph Transformation (GT):

- Declarative and formal paradigm
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# Structure of a GT rule



## ■ Graph Transformation (GT):

- Declarative and formal paradigm
- Rule base transformation
- Match of the LHS → Image of the RHS
- Generalization of Chomsky grammars (hierarchy) (text → graph)

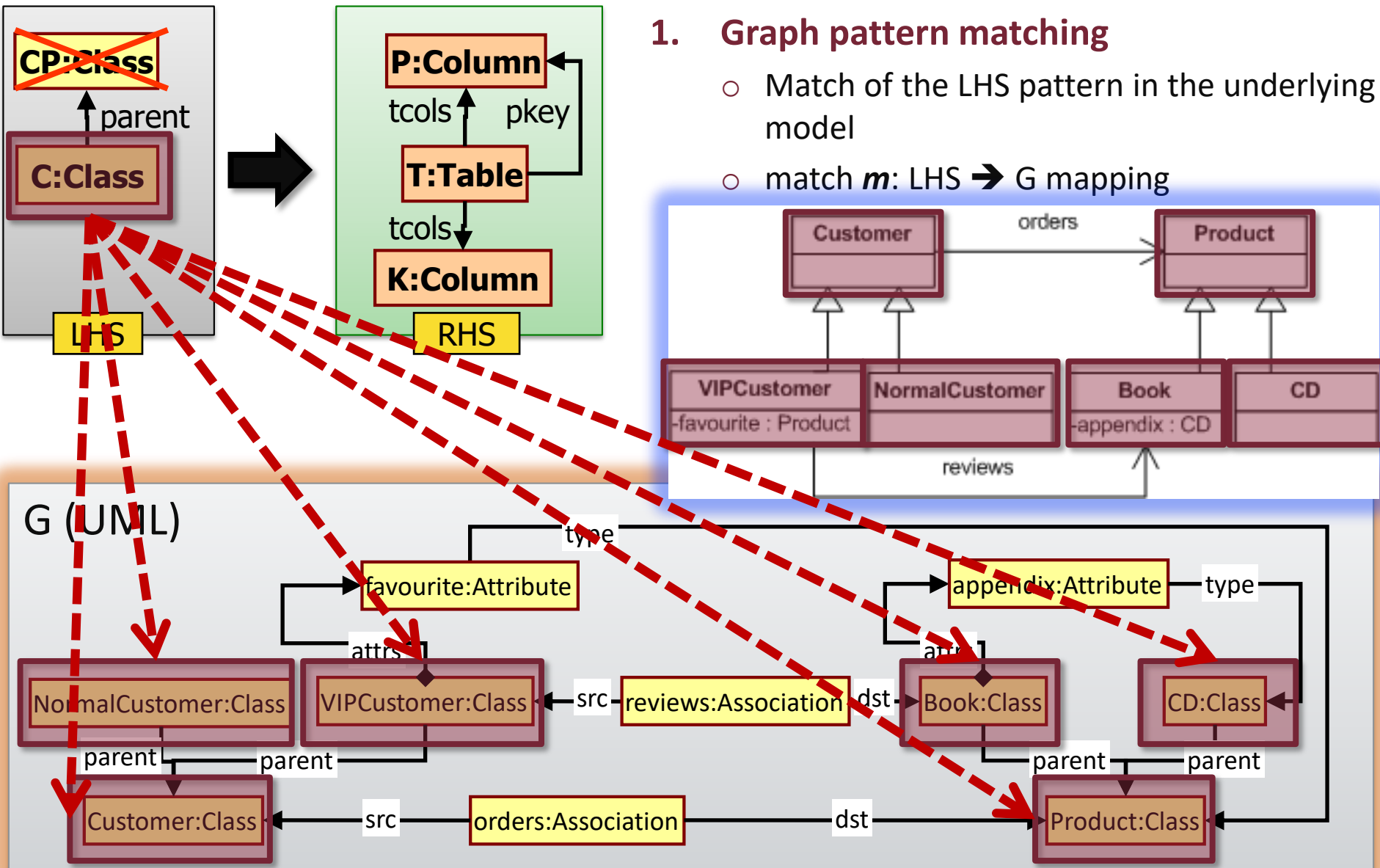
## ■ Graph Transformation Rules

- **Left hand side - LHS**
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  - Negative precondition of the rule application
  - If it can be made true → the rule cannot be applied
  - Multiple NACs → only one is true → rule cannot be applied

# Application of GT rules

## 1. Graph pattern matching

- Match of the LHS pattern in the underlying model
- match *m*: LHS  $\rightarrow$  G mapping



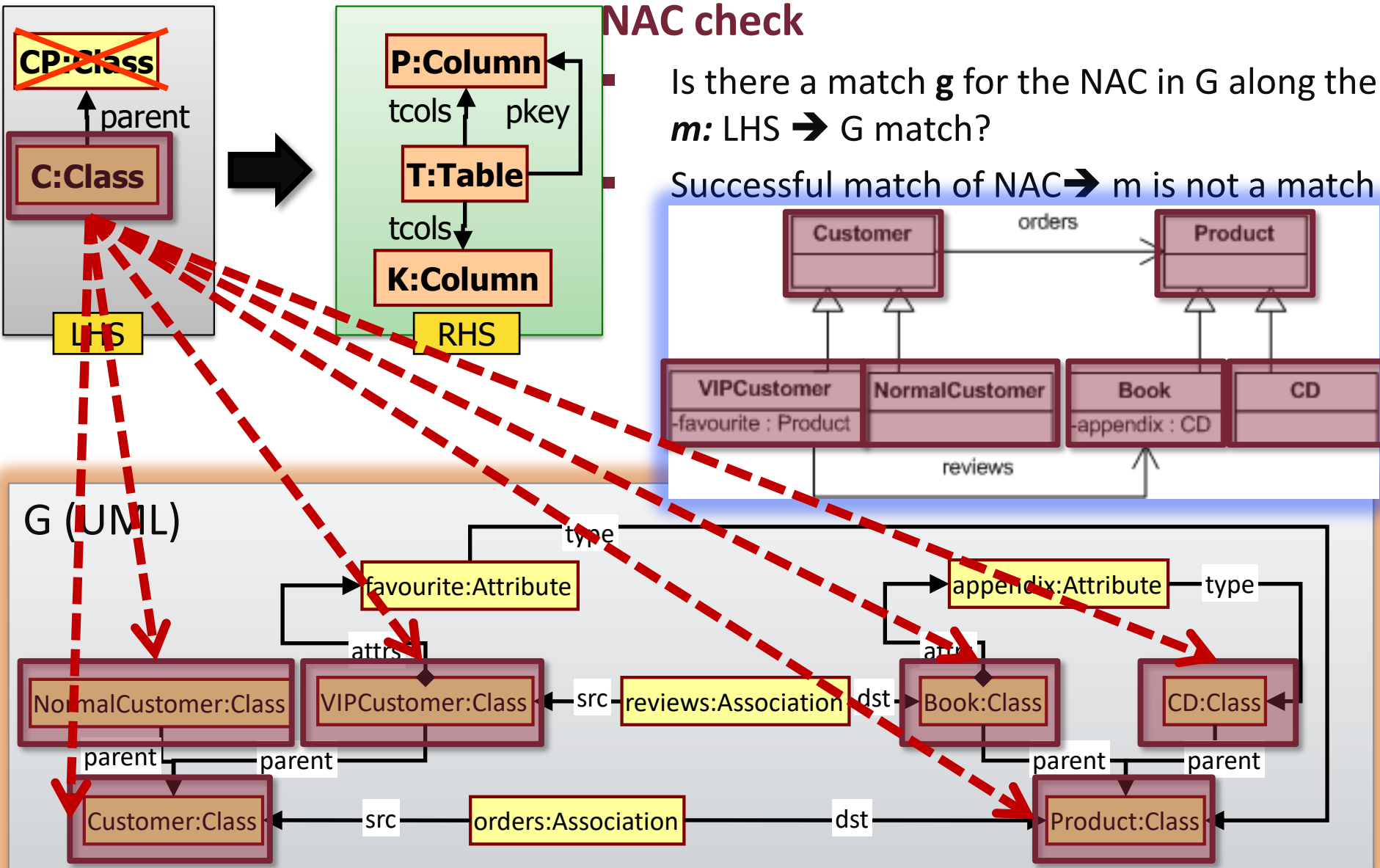


# Application of GT rules

## NAC check

Is there a match  $g$  for the NAC in  $G$  along the  $m$ : LHS  $\rightarrow$  G match?

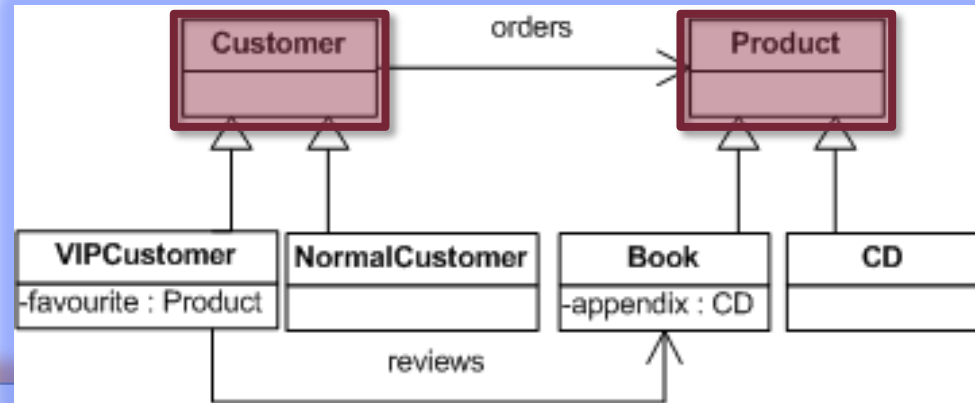
Successful match of NAC  $\rightarrow$   $m$  is not a match



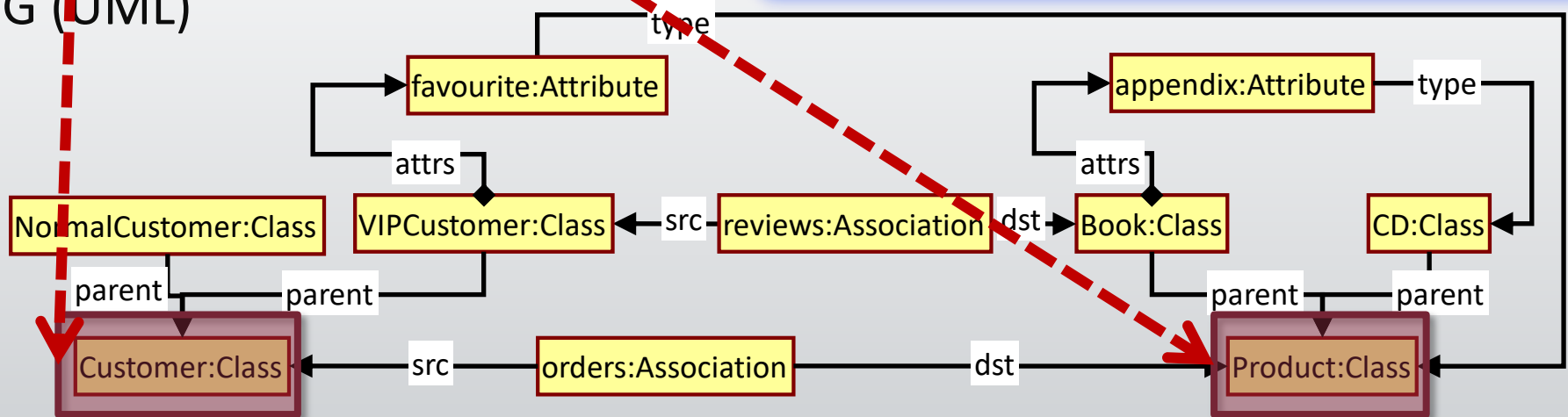
# Application of GT rules

## 3. Non-deterministic selection

- Random selection of a match (if more than one)
- No match → rule fails



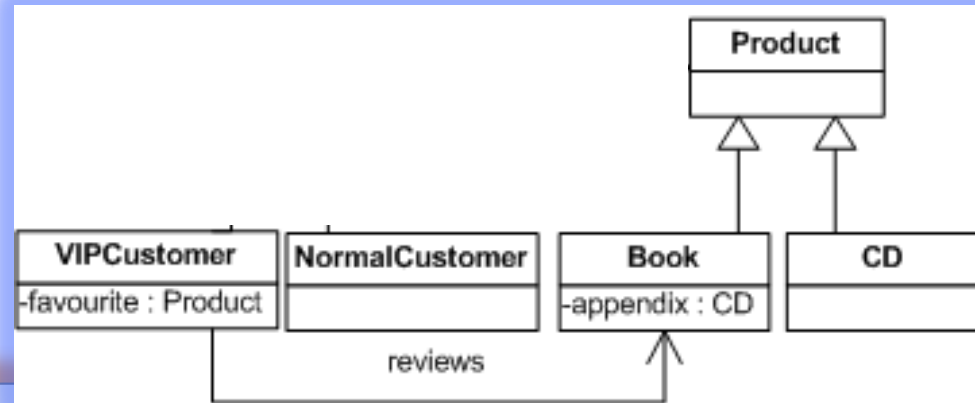
G (UML)



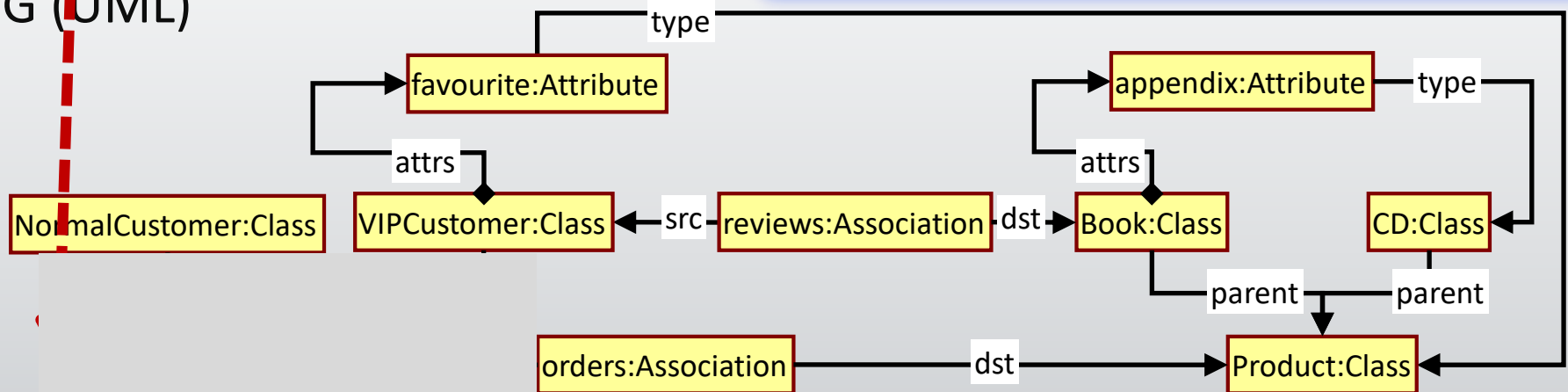
# Application of GT rules

## 4. Deletion

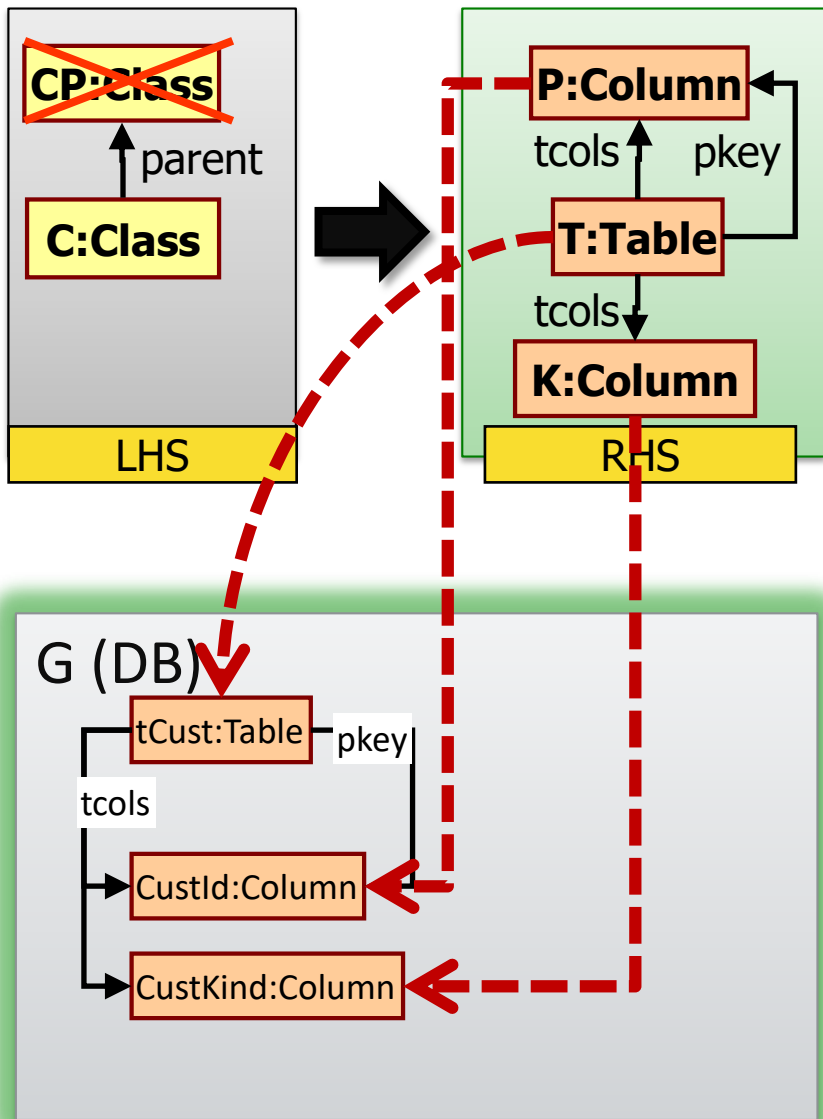
- Deletion of LHS \ RHS from G
- In LHS yes, in RHS no



G (UML)



# Application of GT rules



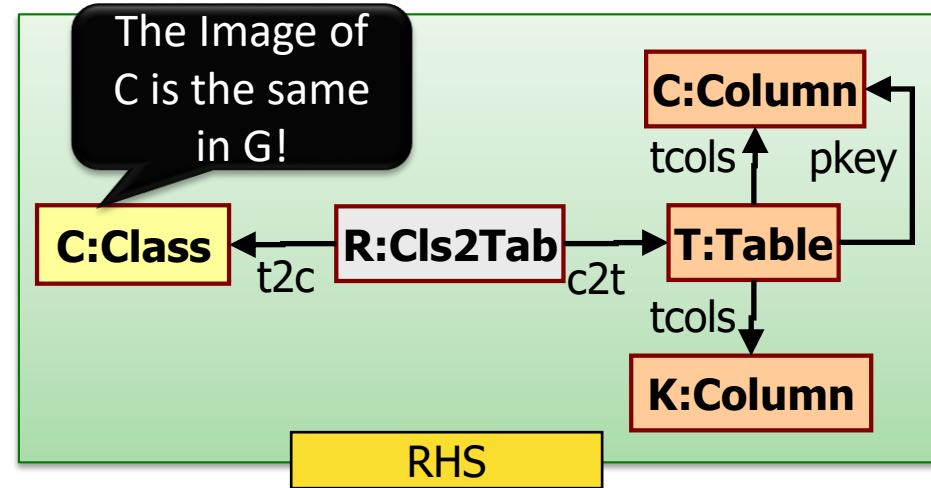
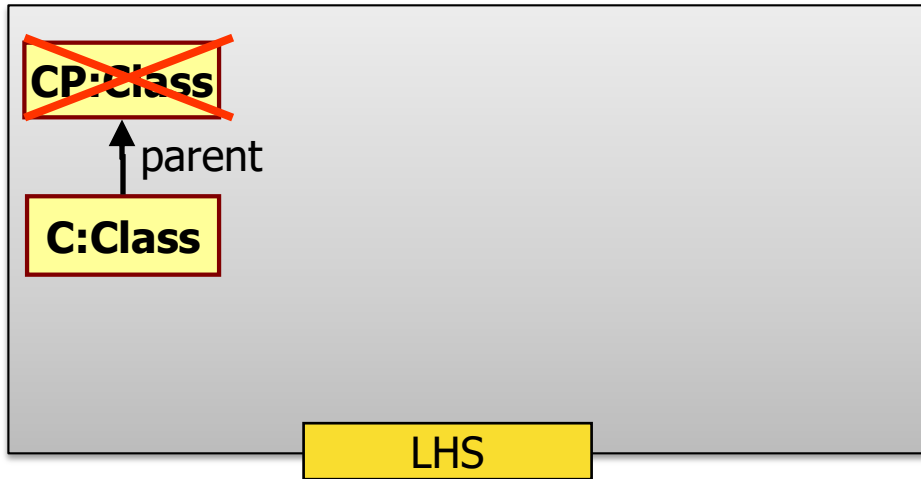
## 5. Creation (and binding)

- Creation of RHS \ LHS in G with their corresponding relations
- Output: a „match” (image) of RHS in G

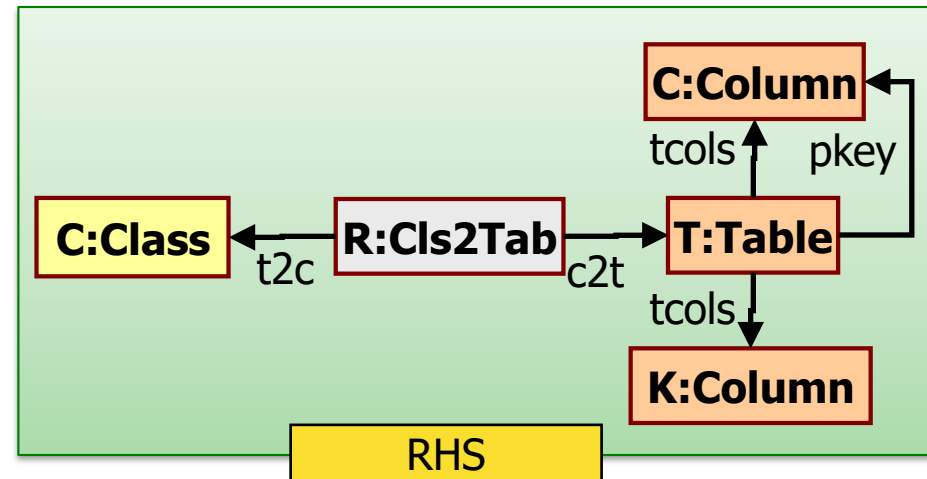
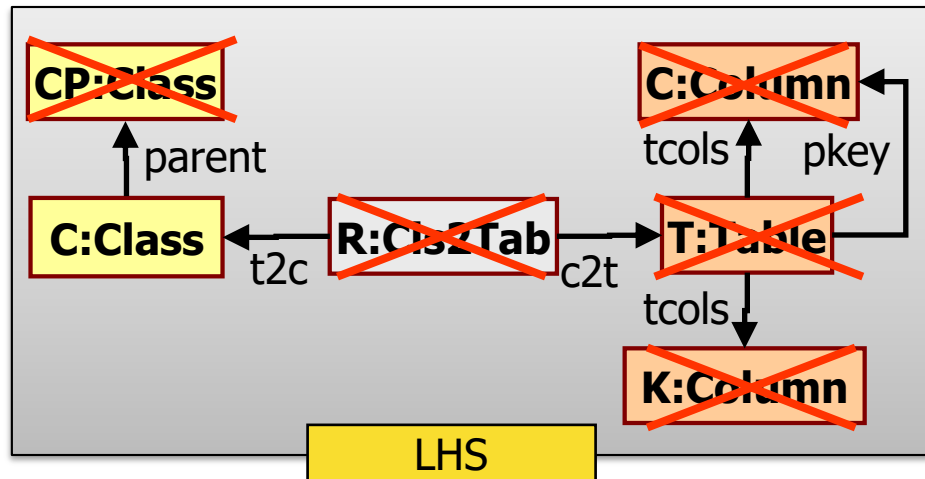
| Customer |           |
|----------|-----------|
| PK       | <u>id</u> |
|          | kind      |

# Typical problems...

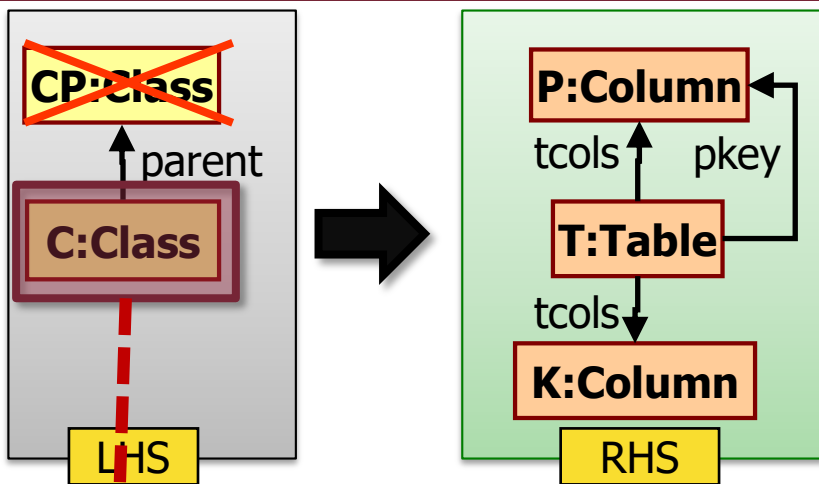
## 1) Saving the source model, traceability



## 2) Application of the same rule along the same match



# Semantics : Handling of Dangling edges

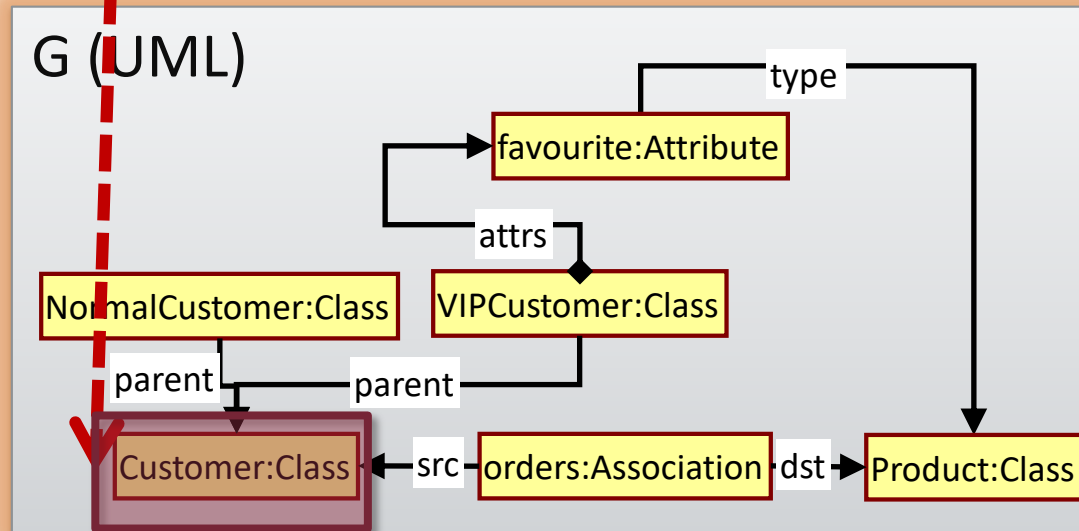


## ■ Dangling edges:

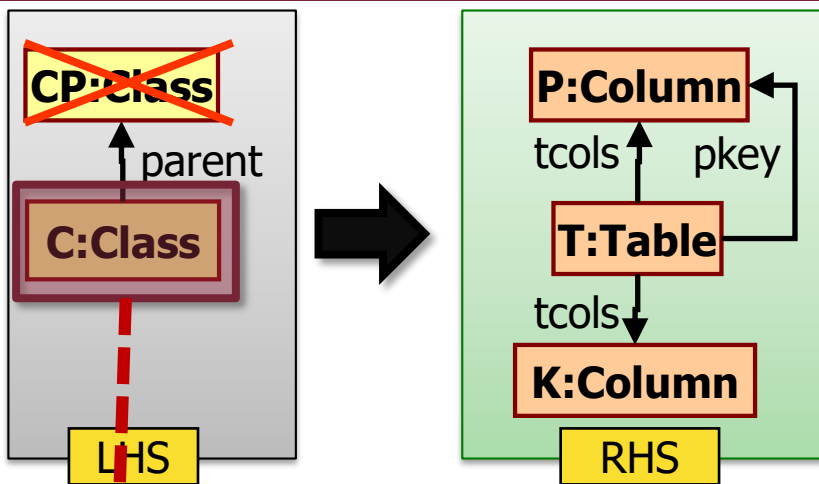
- Delete a node
  - What to do with the dangling edges?

## ■ Greedy approach

- Delete all dangling edges
- **Pro:**
  - Intuitive for engineers
  - Easy to implement
- **Con:**
  - Verification is hard (side effect of rules)



# Semantics : Handling of Dangling edges

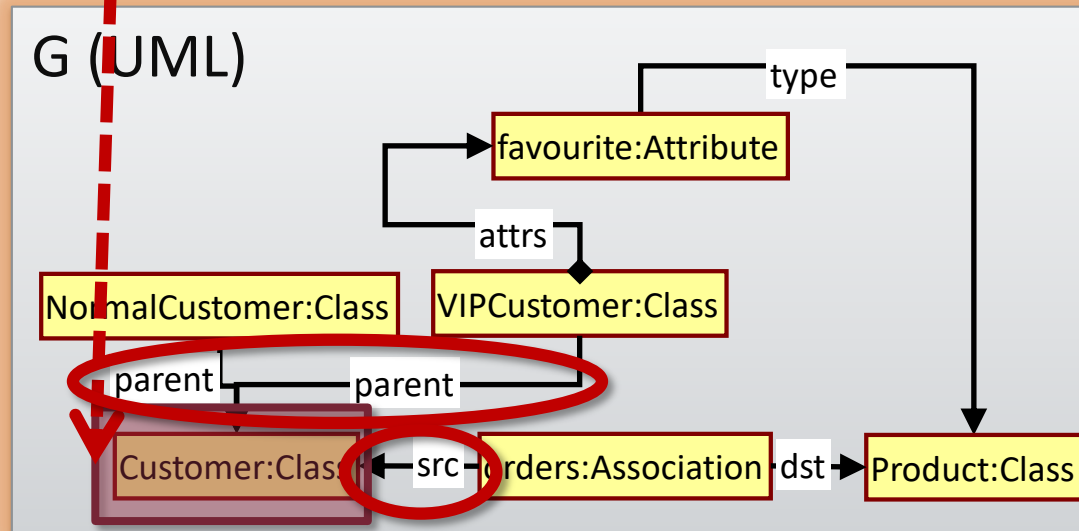


## ■ Dangling edges:

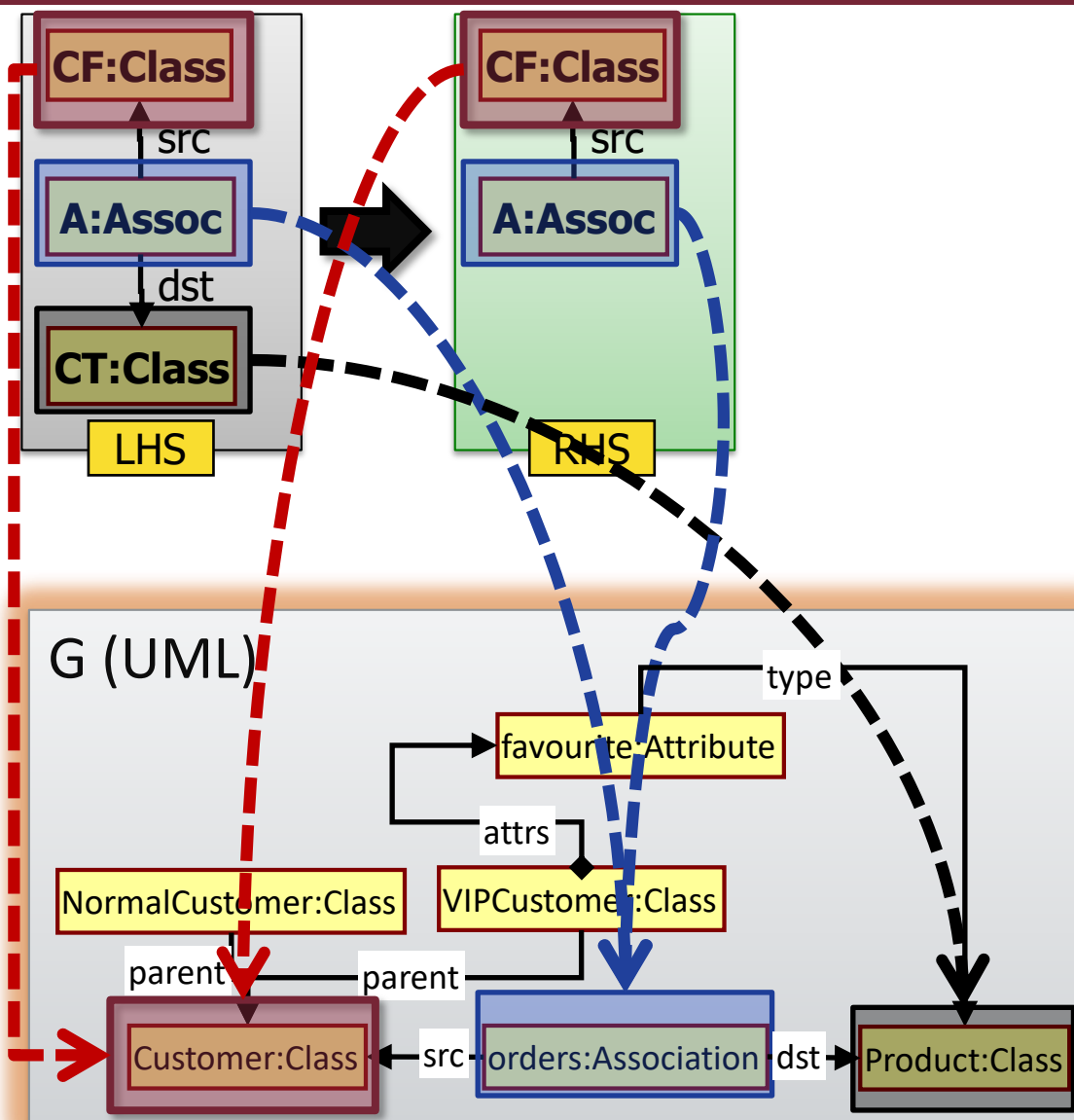
- Delete a node
  - What to do with the dangling edges?

## ■ Conservative approach

- Rule cannot be applied if it would yield dangling edge
- **Pro:**
  - Side effect free rules
  - Helps verification
- **Con:**
  - Harder to implement
  - Meaningful for engineers? (not mathematicians)



# Semantics: Injective matching



## ■ Injective matching („kisajátító”)

- For all nodes in the LHS → separate nodes are matched in G

## ■ Pro:

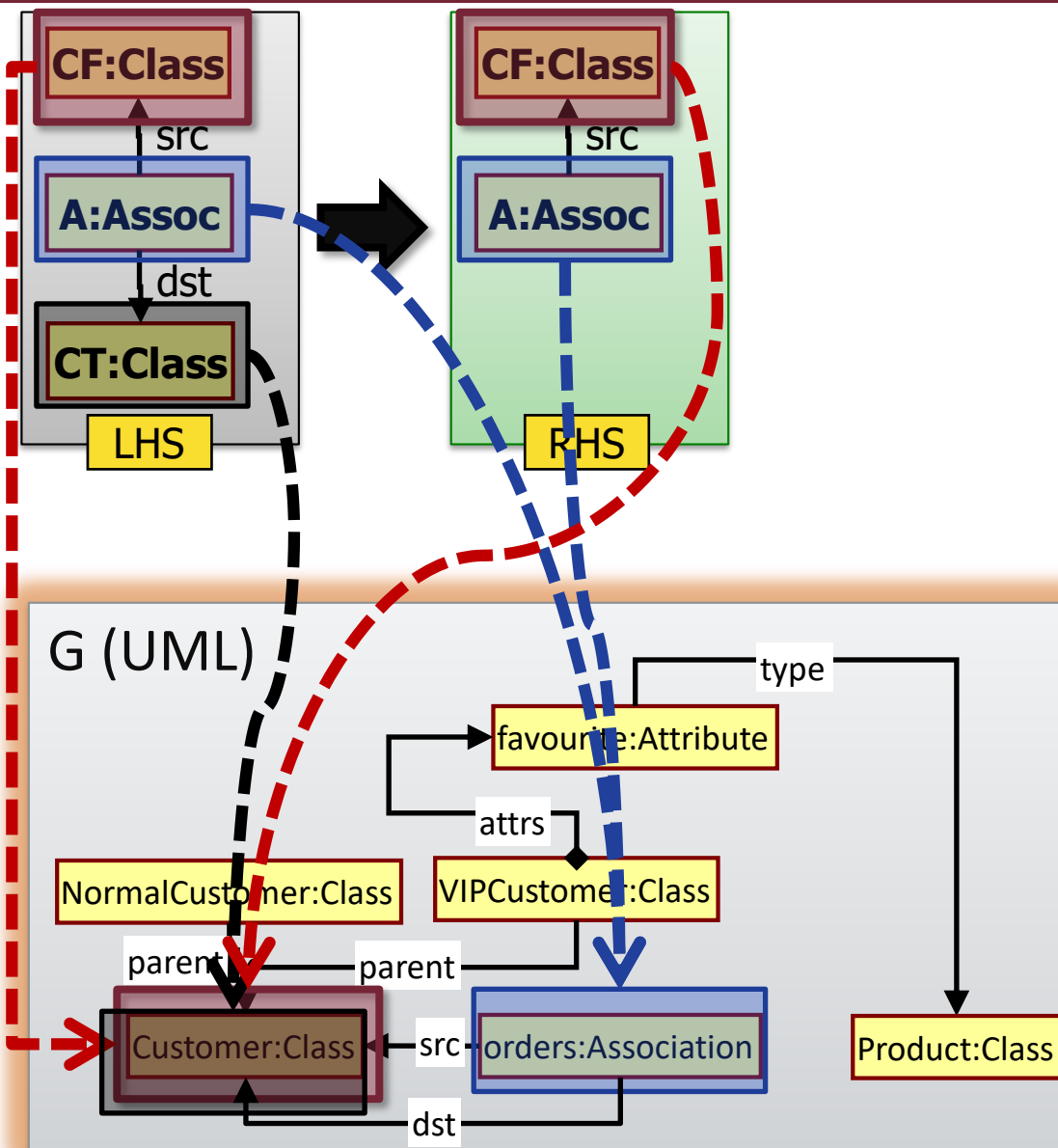
- Intuitive for engineers

## ■ Con:

- Verbose specification of rules (many alternate subrules)



# Semantics: Non-injective matching



## ■ Non-Injective matching („közösködő“)

- Multiple nodes in LHS → the same node can be matched in G

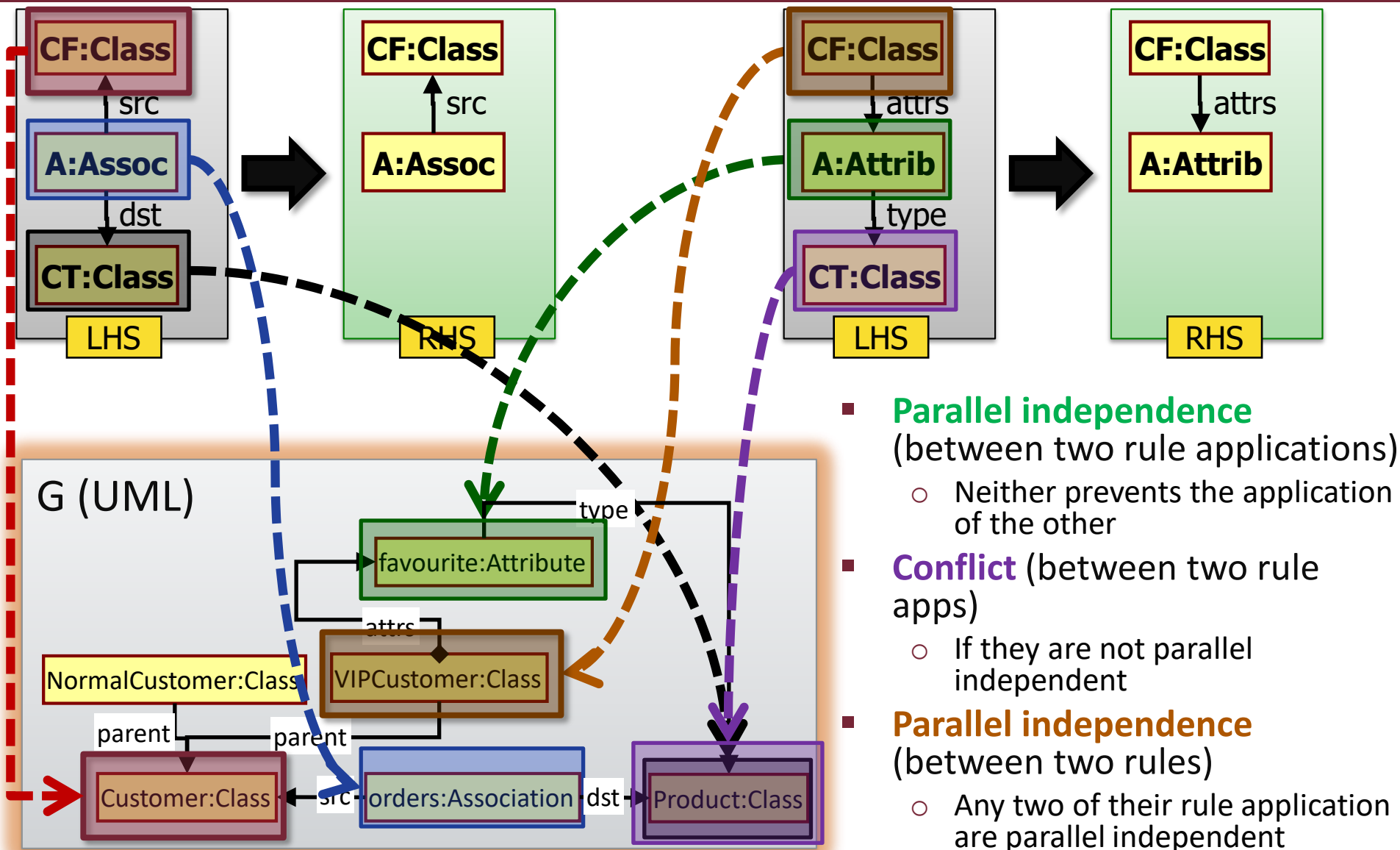
## ■ Con:

- Contradictory specification for a node
  - For **CF** : keep it
  - For **CT** : delete

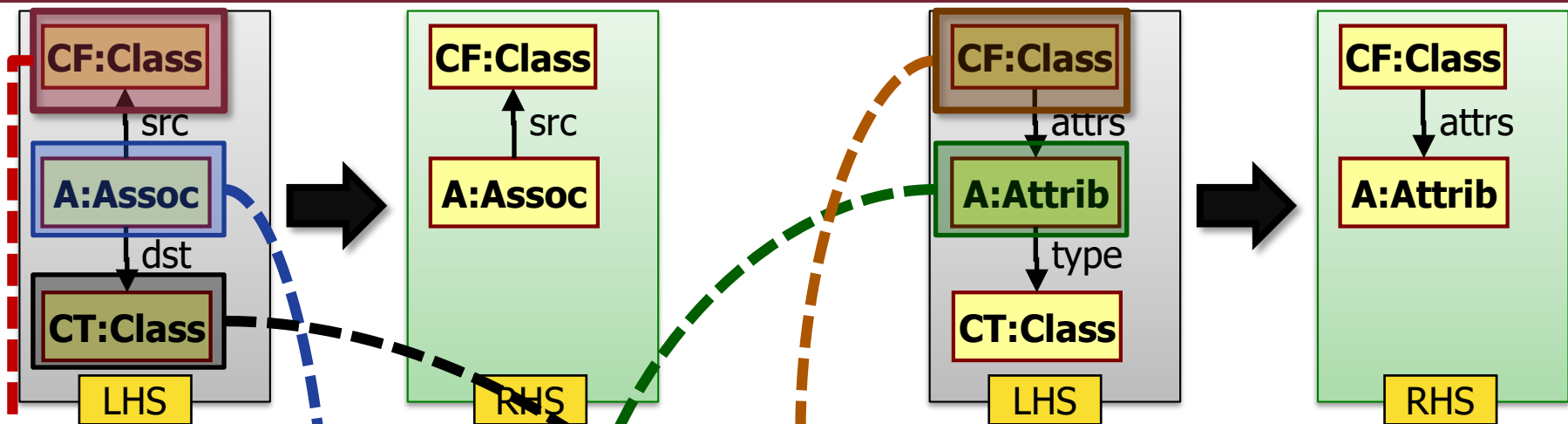
## ■ Solution:

- Nodes to be deleted in LHS are matched with injective semantics

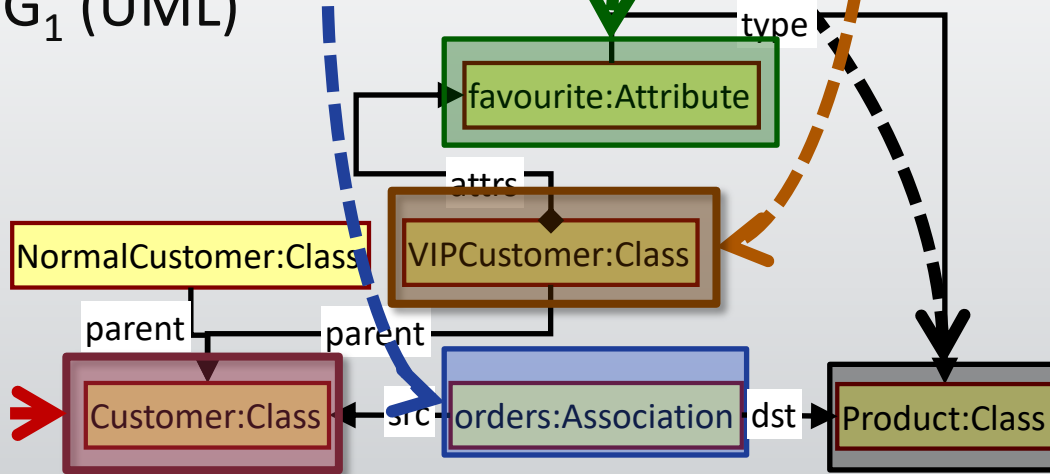
# Conflict / Parallel independence



# Sequential independence



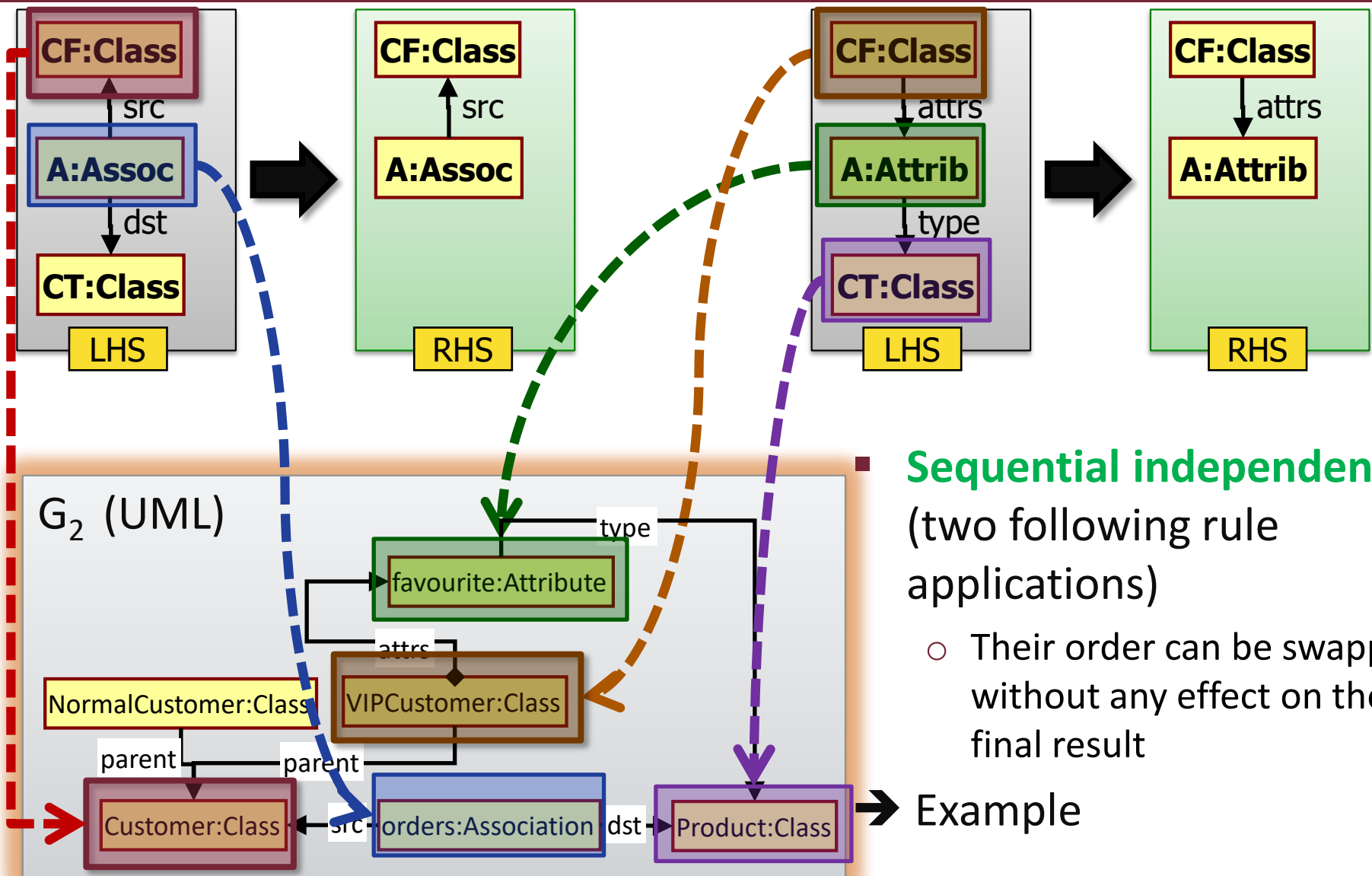
$G_1$  (UML)



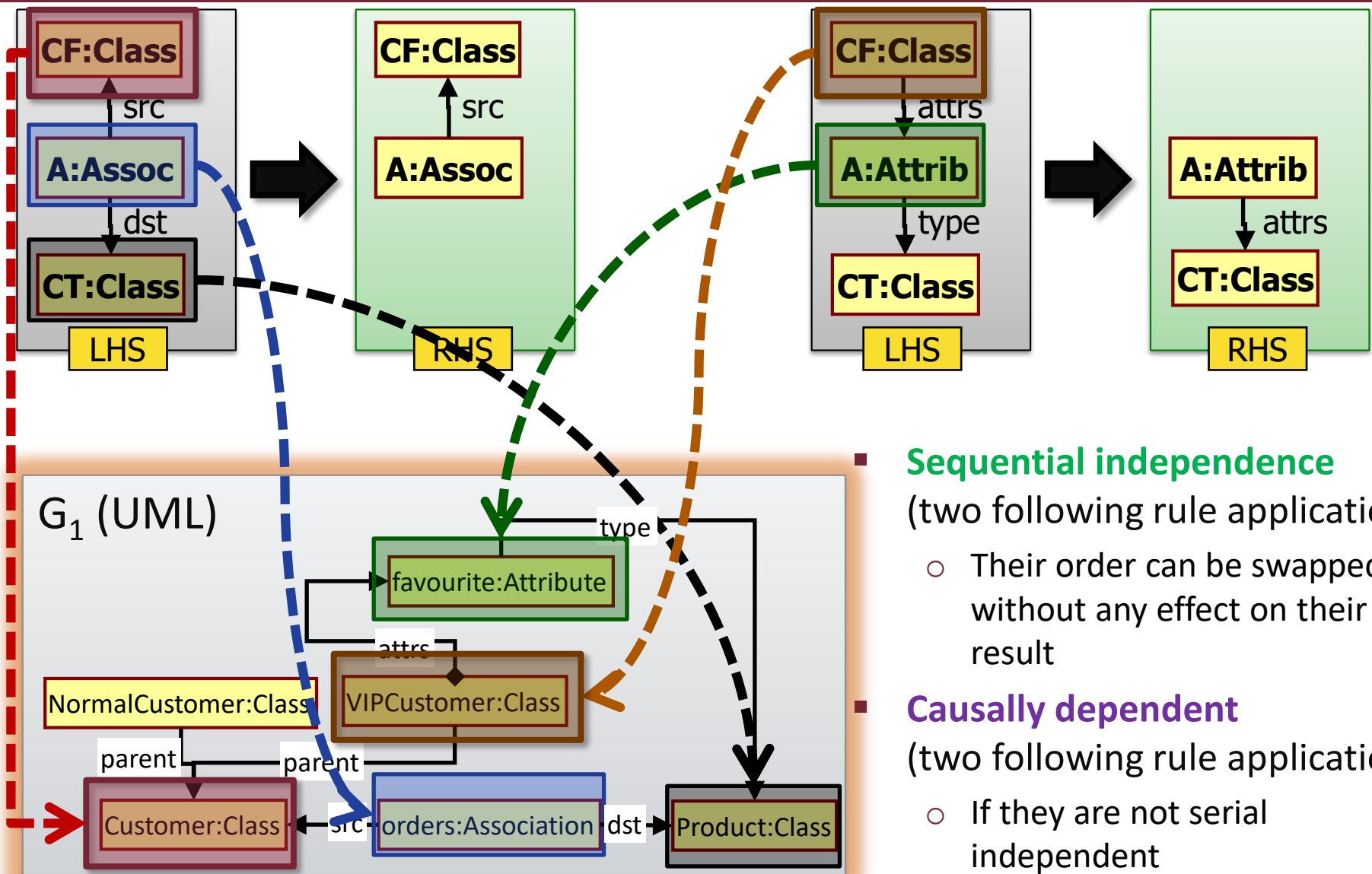
**Sequential independence**  
(two following rule applications)

- Their order can be swapped without any effect on their final result

# Sequential independence



# Causal dependence I.



## Sequential independence

(two following rule applications)

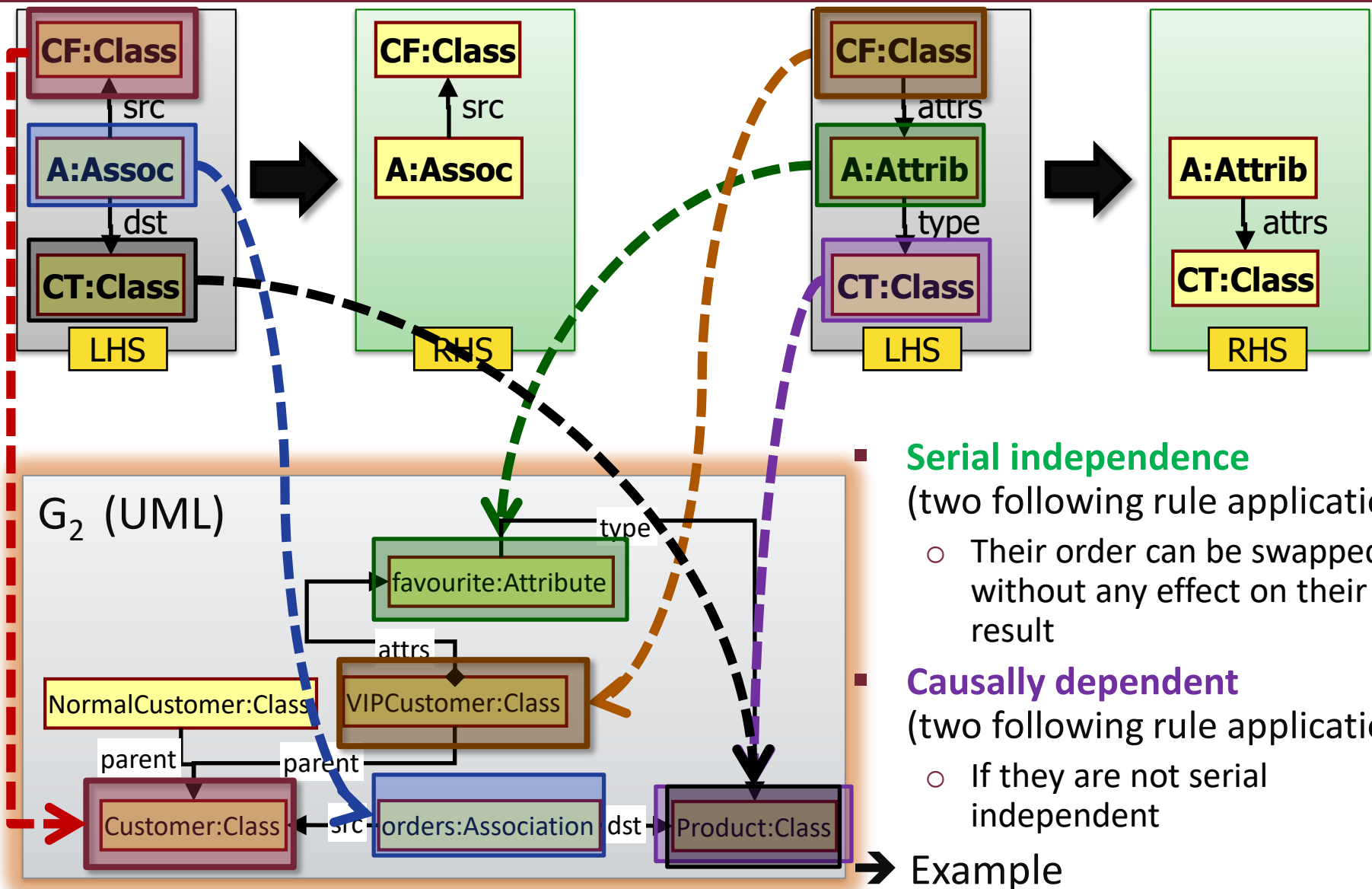
- Their order can be swapped without any effect on their final result

## Causally dependent

(two following rule applications)

- If they are not serial independent

# Causally dependence II.



# Summary

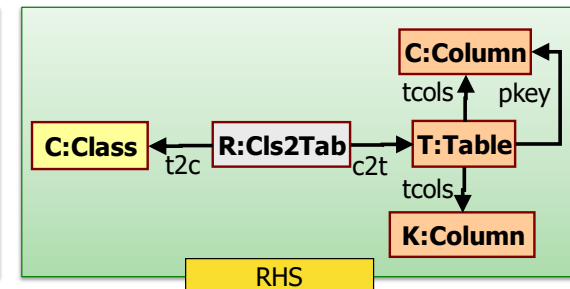
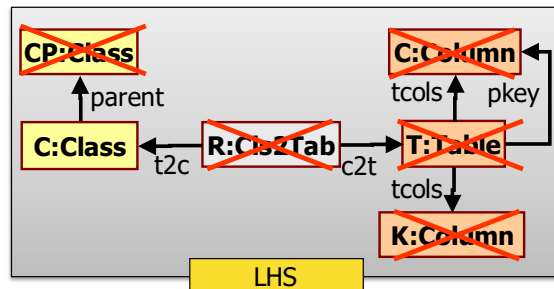
- **Graph transformation,**  
as a model transformation paradigm
  - Rule and pattern based formal specification
  - Querying and manipulating graph based models
  - Intuitive graph based specification

- **Structure**

- LHS graph pattern: precondition
  - RHS graph pattern: postcondition
  - NAC: negative condition

- **Rule application**

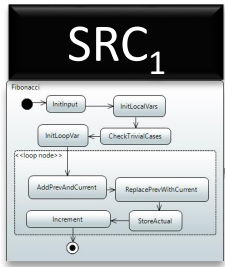
- Graph pattern matching
  - Deletion + Creation
  - Dangling edges and injectivity
  - Affect of multiple rule application (conflicts and causality)



# Incrementality in model transformations

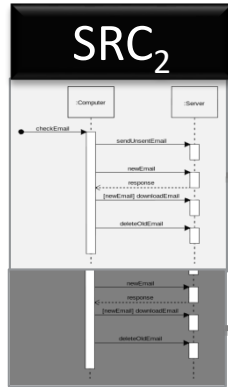
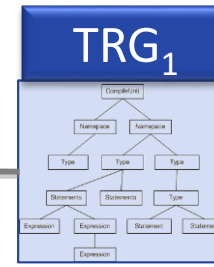


# No Incrementality: Batch Transformations

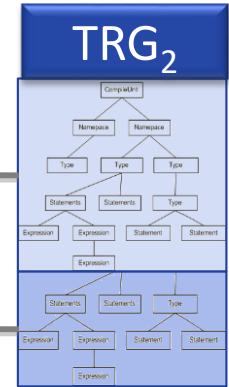


# TRACE<sub>1</sub>

| New Technology |                 | Verification Method |        |        |       |       | Verification Property | Verification Task/Complexity |
|----------------|-----------------|---------------------|--------|--------|-------|-------|-----------------------|------------------------------|
| Prop. Language | State           | Test                | Abstr. | Simul. | Form. | Model |                       |                              |
| 1.1            | BF Conjunctions |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.2            | BF Disjunctions |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.3            | BF Implications |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.4            | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.5            | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.6            | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.7            | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.8            | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.9            | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.10           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.11           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.12           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.13           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.14           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.15           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.16           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.17           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.18           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.19           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.20           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.21           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.22           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.23           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.24           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.25           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.26           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.27           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.28           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.29           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.30           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.31           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.32           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.33           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.34           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.35           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.36           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.37           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.38           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.39           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.40           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.41           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.42           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.43           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.44           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.45           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.46           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.47           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.48           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.49           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.50           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.51           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.52           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.53           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.54           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.55           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.56           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.57           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.58           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.59           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.60           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.61           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.62           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.63           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.64           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.65           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.66           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.67           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.68           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.69           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.70           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.71           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.72           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.73           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.74           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.75           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.76           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.77           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.78           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.79           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.80           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.81           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.82           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.83           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.84           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.85           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.86           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.87           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.88           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.89           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.90           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.91           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.92           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.93           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.94           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.95           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.96           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.97           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.98           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.99           | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |
| 1.100          | BF Formulas     |                     |        |        |       |       | $\mathcal{N}^{1,1}$   | 1                            |



# TRACE<sub>2</sub>



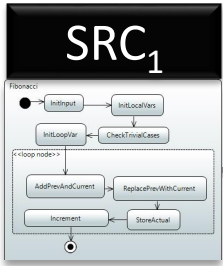
## 1. First transformation

## 2. Source model changes

### 3. Re-execute from scratch for all source models

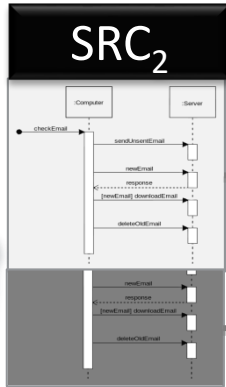
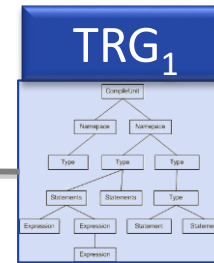


# Dirty Incrementality

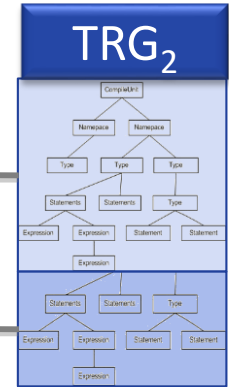


# TRACE<sub>1</sub>

| Verification Method |                |      |          |       |                       |                      |
|---------------------|----------------|------|----------|-------|-----------------------|----------------------|
| Run Parameters      | File           | Test | Analysis | Class | Verification Progress | Effective Test Cases |
| 1.1                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 1.2                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 1.3                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 1.4                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 1.5                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 1.6                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 1.7                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 1.8                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 1.9                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 2.0                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 2.1                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 2.2                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 2.3                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 2.4                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 2.5                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 2.6                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 2.7                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 2.8                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 2.9                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 3.0                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 3.1                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 3.2                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 3.3                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 3.4                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 3.5                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 3.6                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 3.7                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 3.8                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 3.9                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 4.0                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 4.1                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 4.2                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 4.3                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 4.4                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 4.5                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 4.6                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 4.7                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 4.8                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 4.9                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 5.0                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 5.1                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 5.2                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 5.3                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 5.4                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 5.5                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 5.6                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 5.7                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 5.8                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 5.9                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 6.0                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 6.1                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 6.2                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 6.3                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 6.4                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 6.5                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 6.6                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 6.7                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 6.8                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 6.9                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 7.0                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 7.1                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 7.2                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 7.3                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 7.4                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 7.5                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 7.6                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 7.7                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 7.8                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 7.9                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 8.0                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 8.1                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 8.2                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 8.3                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 8.4                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 8.5                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 8.6                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
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| 9.3                 | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
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| 10.0                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 10.1                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 10.2                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 10.3                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 10.4                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 10.5                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 10.6                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 10.7                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 10.8                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 10.9                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 11.0                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 11.1                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 11.2                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 11.3                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 11.4                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 11.5                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 11.6                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 11.7                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 11.8                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 11.9                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 12.0                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 12.1                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 12.2                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 12.3                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 12.4                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 12.5                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 12.6                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 12.7                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 12.8                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 12.9                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 13.0                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 13.1                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 13.2                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
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| 13.5                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 13.6                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
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| 13.8                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 13.9                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 14.0                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 14.1                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 14.2                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 14.3                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 14.4                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 14.5                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 14.6                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 14.7                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 14.8                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 14.9                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 15.0                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 15.1                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 15.2                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 15.3                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 15.4                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 15.5                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 15.6                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 15.7                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 15.8                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 15.9                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
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| 16.3                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 16.4                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 16.5                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 16.6                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 16.7                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 16.8                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 16.9                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 17.0                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 17.1                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 17.2                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 17.3                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 17.4                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 17.5                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 17.6                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 17.7                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 17.8                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 17.9                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 18.0                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 18.1                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 18.2                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 18.3                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 18.4                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 18.5                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 18.6                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
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| 18.8                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 18.9                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 19.0                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 19.1                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 19.2                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 19.3                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 19.4                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 19.5                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 19.6                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 19.7                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 19.8                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 19.9                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 20.0                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 20.1                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 20.2                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 20.3                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 20.4                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 20.5                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 20.6                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 20.7                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 20.8                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 20.9                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 21.0                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 21.1                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 21.2                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 21.3                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 21.4                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 21.5                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 21.6                | RF2 Test Cases | •    | •        | •     | 9.2/1                 | 9.2/1                |
| 21.7                | RF2 Test Cases | •    | •        |       |                       |                      |



# TRACE<sub>2</sub>



## Pros:

- Large-step incrementality
- Avoids continuous exec.

## Cons:

- Complex MT can be slow
- Cleanup (after an error)?
- Chaining?

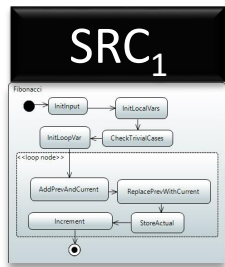
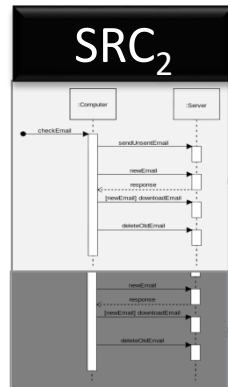
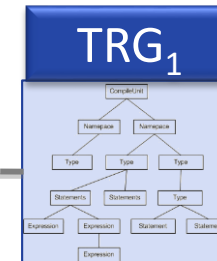
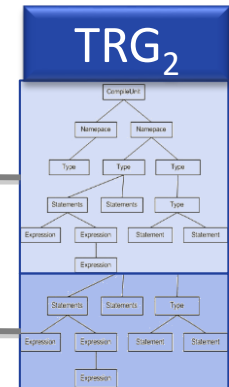
## 1. First transformation

## 2. Source model changes

### 3. Re-execute from scratch only for changed models



# Incrementality by Traceability

## Pros:

- Small-step incrementality
- Better performance

## Cons:

- Highly depends on traceability links
- Smart matcher needed

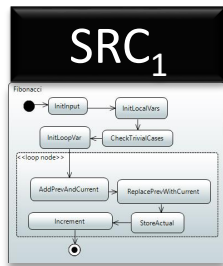
1. First transformation

2. Source model changes

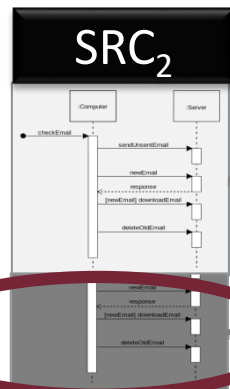
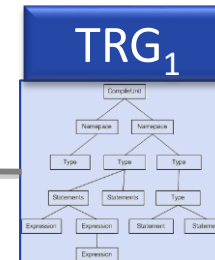
3. Detect missing trace links

4. Re-execute MT only for untraceable elements

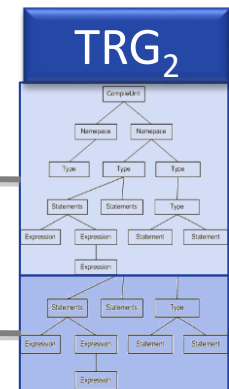
# Event Driven Transformations



| Step | Event              | Type  | Value | Time | Location | Priority | Trace |
|------|--------------------|-------|-------|------|----------|----------|-------|
| 1    | Start              | Event |       | 0.00 |          | 1        |       |
| 2    | Input              | Event |       | 0.01 |          | 1        |       |
| 3    | InitLocalVars      | Event |       | 0.02 |          | 1        |       |
| 4    | InitLoopVar        | Event |       | 0.03 |          | 1        |       |
| 5    | CheckTermination   | Event |       | 0.04 |          | 1        |       |
| 6    | AddPrevAndCurrent  | Event |       | 0.05 |          | 1        |       |
| 7    | ReplaceWithCurrent | Event |       | 0.06 |          | 1        |       |
| 8    | Increment          | Event |       | 0.07 |          | 1        |       |
| 9    | StoreActual        | Event |       | 0.08 |          | 1        |       |
| 10   | CheckTermination   | Event |       | 0.09 |          | 1        |       |
| 11   | End                | Event |       | 0.10 |          | 1        |       |



| Step | Event         | Type  | Value | Time | Location | Priority | Trace |
|------|---------------|-------|-------|------|----------|----------|-------|
| 1    | Start         | Event |       | 0.00 |          | 1        |       |
| 2    | checkEmail    | Event |       | 0.01 |          | 1        |       |
| 3    | sendEmail     | Event |       | 0.02 |          | 1        |       |
| 4    | readEmail     | Event |       | 0.03 |          | 1        |       |
| 5    | downloadEmail | Event |       | 0.04 |          | 1        |       |
| 6    | deleteEmail   | Event |       | 0.05 |          | 1        |       |
| 7    | readEmail     | Event |       | 0.06 |          | 1        |       |
| 8    | downloadEmail | Event |       | 0.07 |          | 1        |       |
| 9    | deleteEmail   | Event |       | 0.08 |          | 1        |       |
| 10   | End           | Event |       | 0.09 |          | 1        |       |



## Pros:

- Refined context: driven by changes of query result set
- Chaining
- Avoids continuous comp.

## Cons:

- Language-level restrictions
- Must "listen" live

1. First transformation

2. Source model changes

3. Process change notification

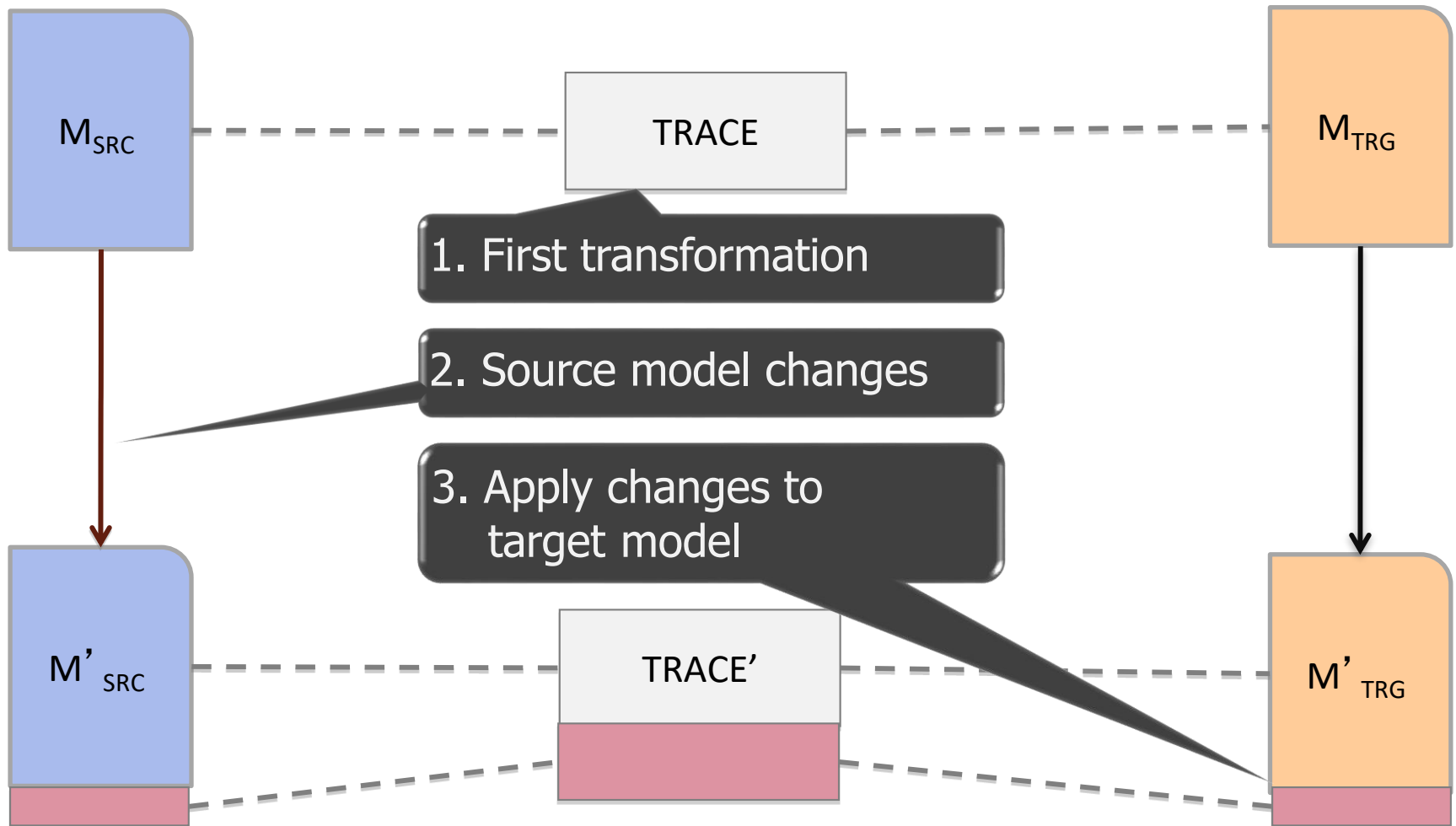
4. Propagate change



# Aspects of Incrementality

- Goals: to save work by...
  - **Target Incrementality**
    - ...reusing unchanged parts of the target
    - Further benefits
      - Existing links to unchanged parts preserved
      - Existing analysis on unchanged parts preserved
      - Does not propagate along transformation chains
  - **Source Incrementality**
    - ...ignoring unchanged parts of the source
    - Use incremental model query!

# Incremental Forward Transformation

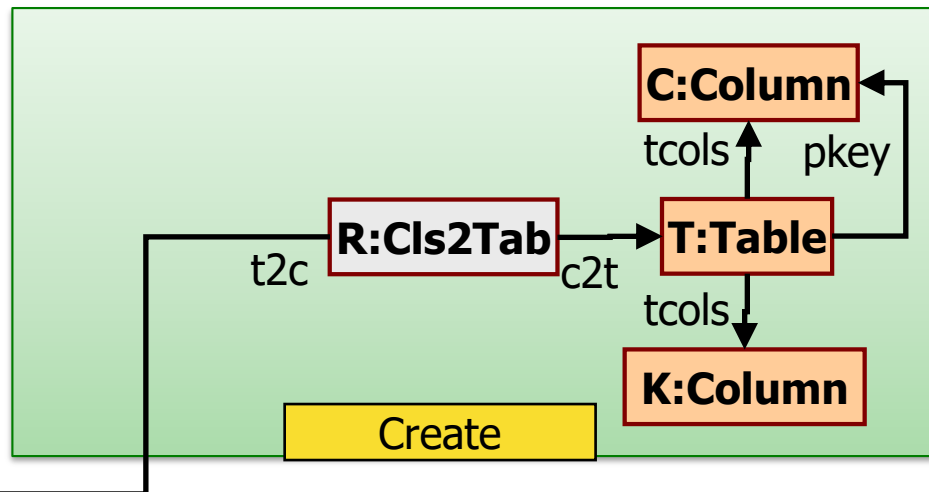
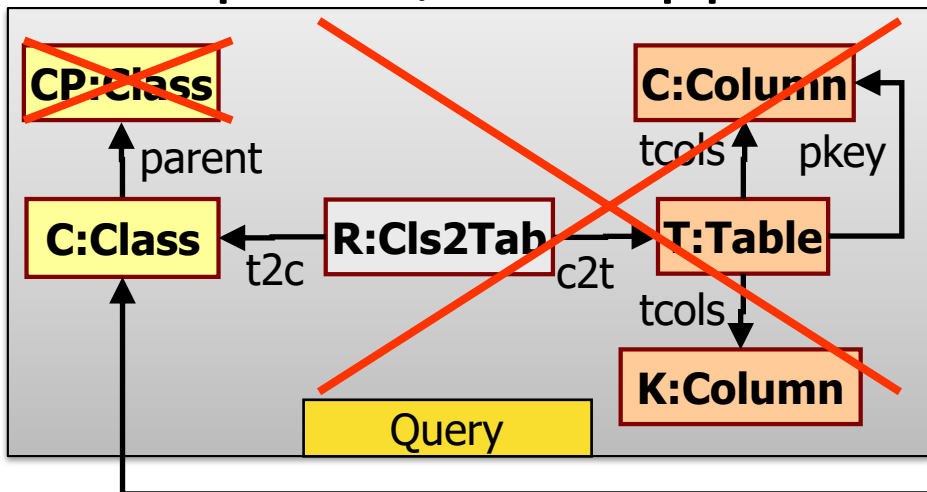


Practical application scenarios:

- Incremental model synchronization
- Tool integration

# Revisit Motivating Example

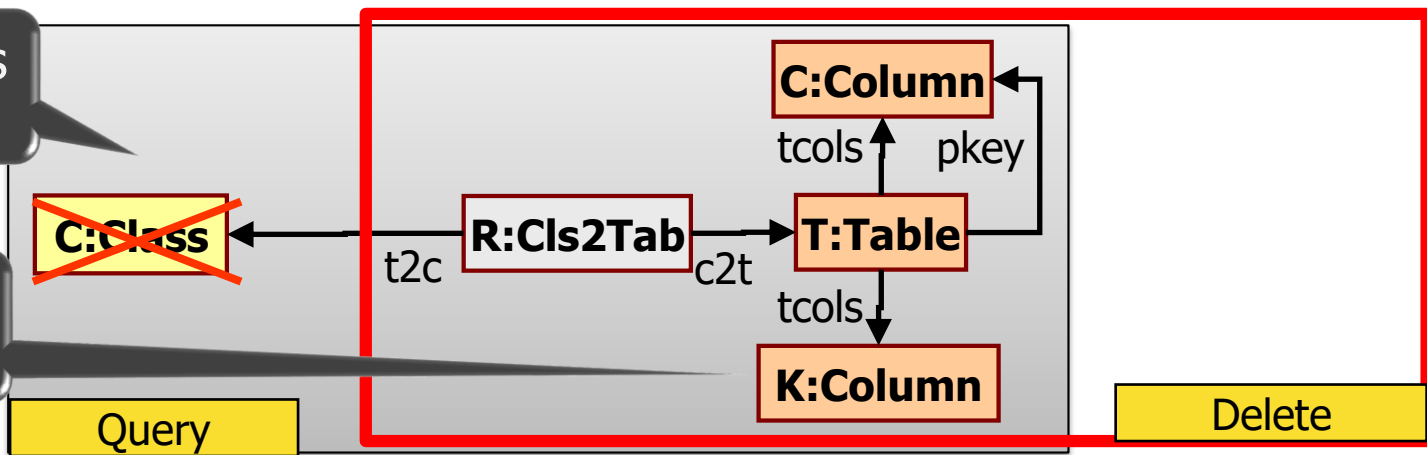
- Map new, unmapped root classes to tables



- Remove old tables no longer having a source class

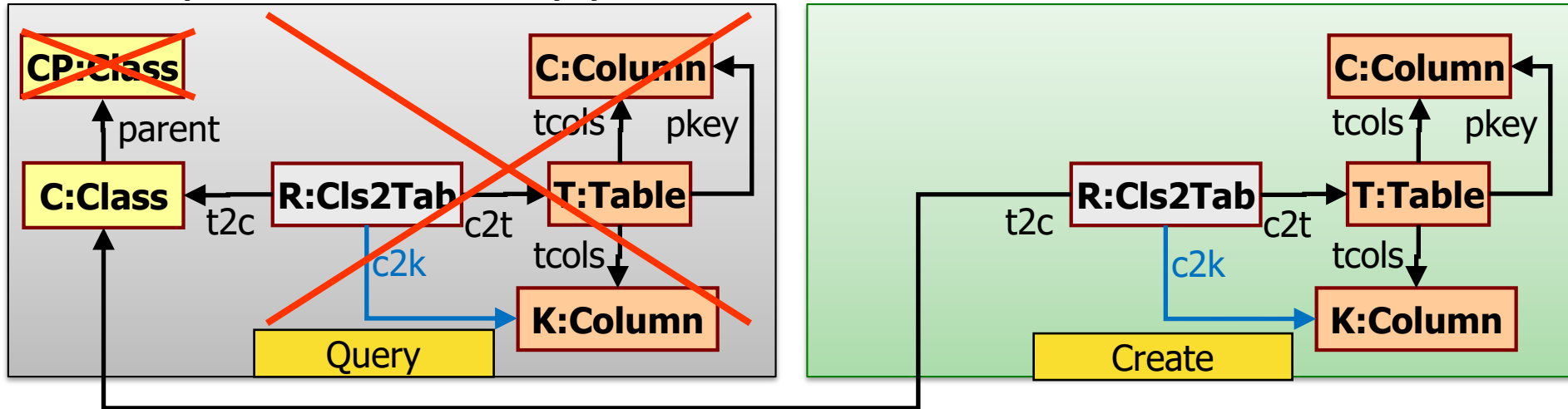
Exercise: what is missing here?

Wait... which was the type column?



# Revisit Motivating Example

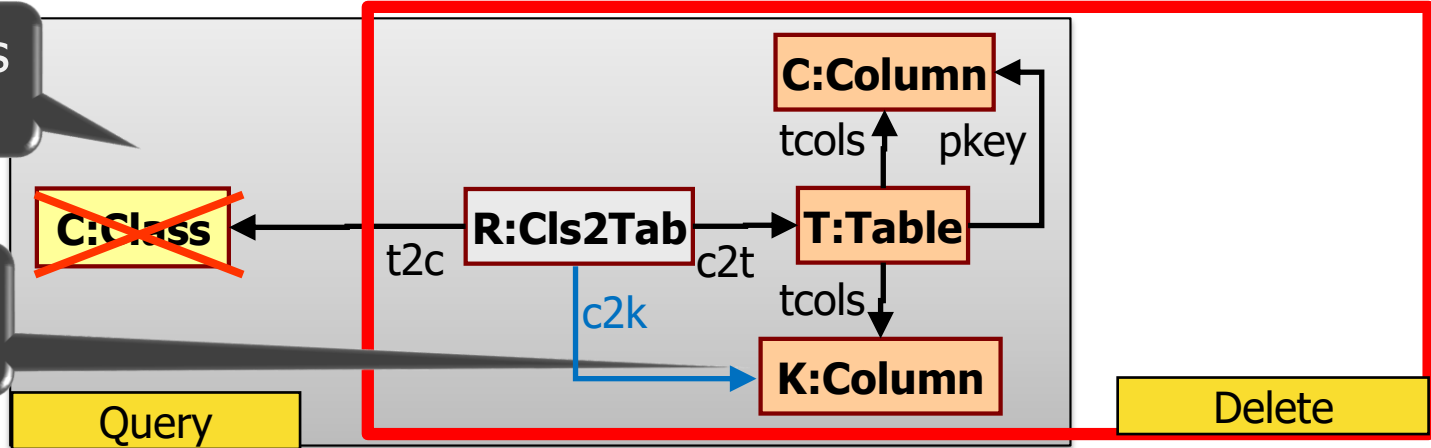
- Map new, unmapped root classes to tables



- Remove old tables no longer having a source class

Exercise: what is missing here?

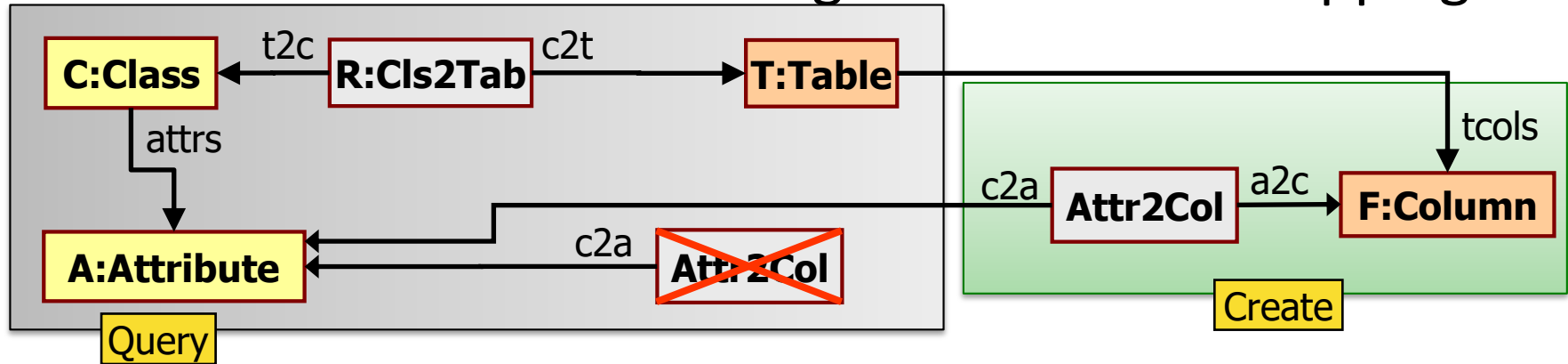
Identify using traceability info



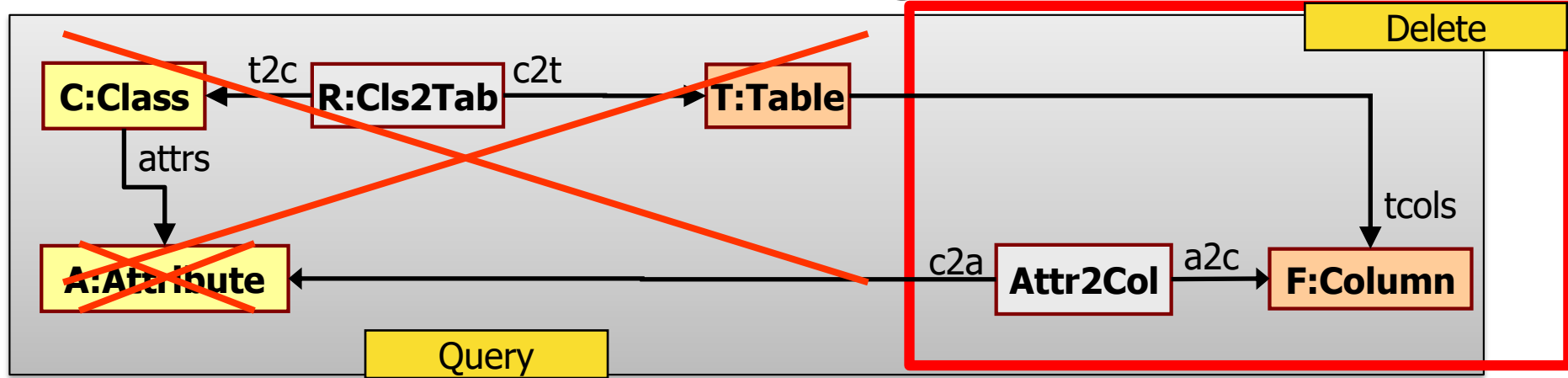


# Revisit Motivating Example 2

- Map new, unmapped attributes to columns...
  - ...in context of an existing class-to-table mapping



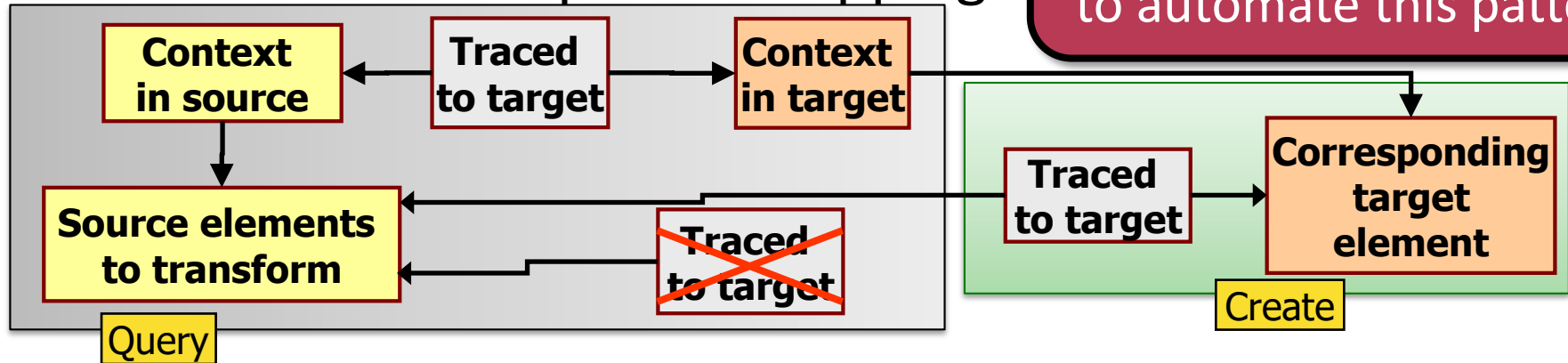
- Remove old columns no longer needed



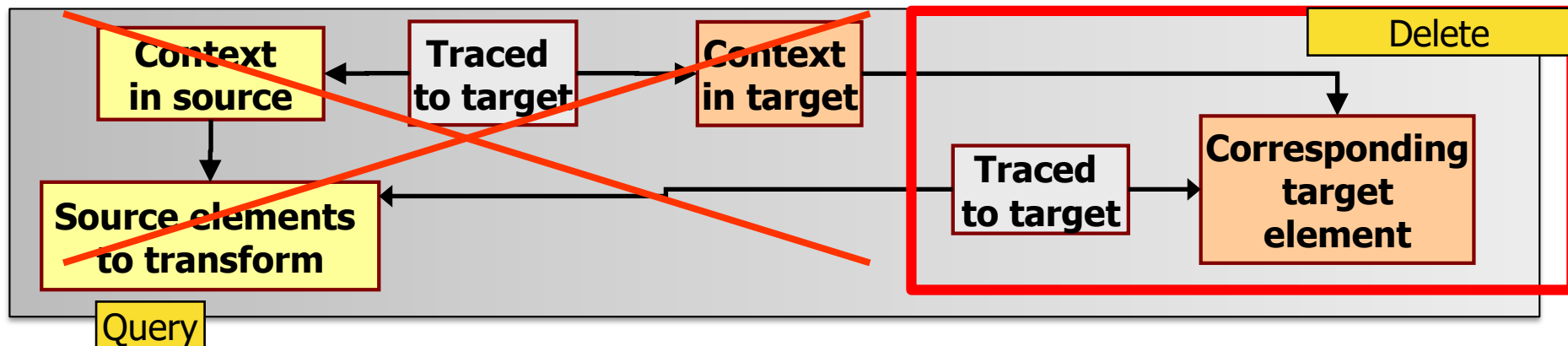
# Common pattern for incremental rules

- Map new source elements to target
  - ...in context of parent mappings

TGG, QVT, etc.:  
very high-level languages  
to automate this pattern



- Remove target elements no longer needed

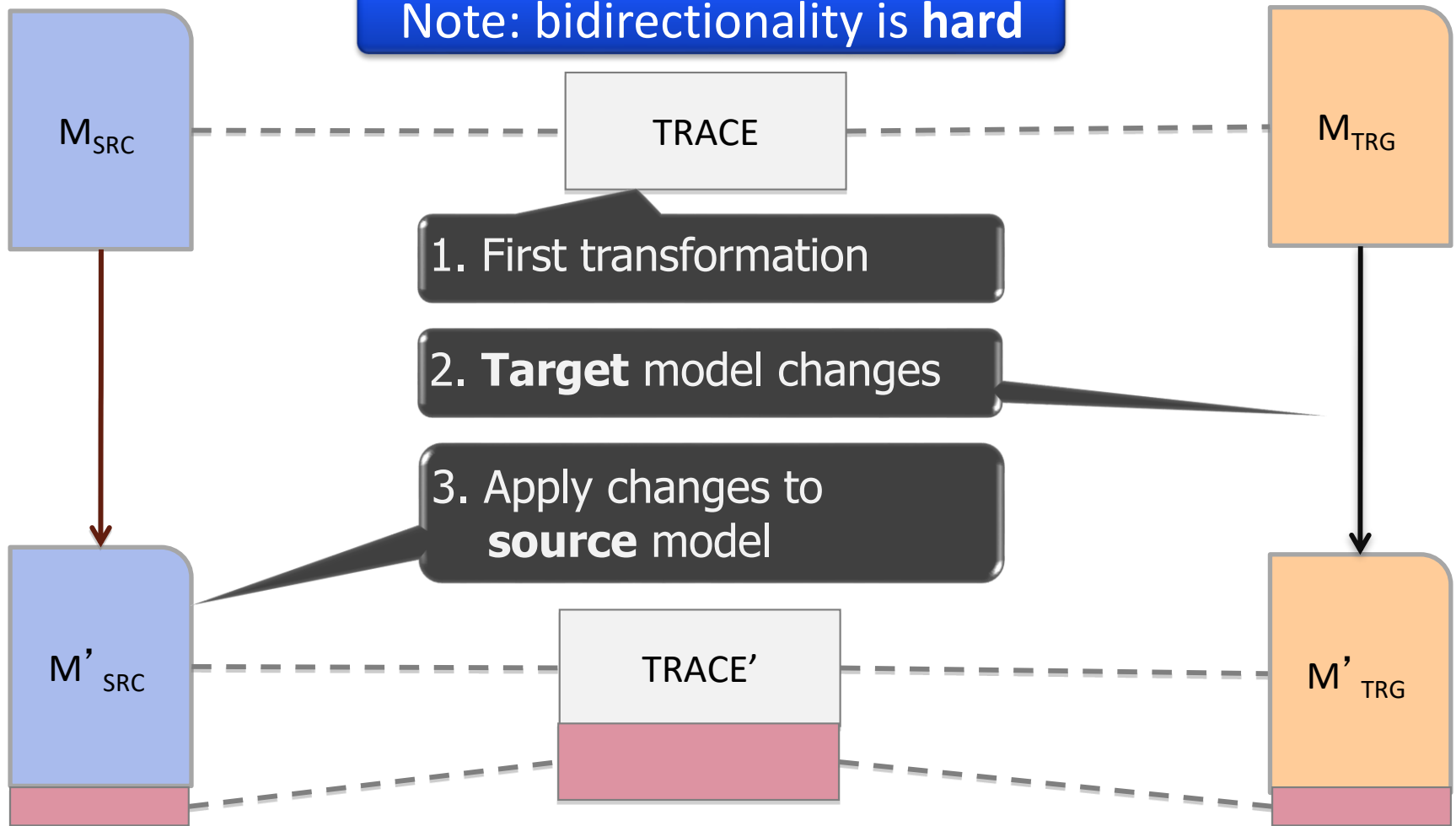


# Common pattern for incremental rules

- Challenge in incrementality:
  - What if context is removed before?
  - E.g. Table deleted before its columns
- Solutions
  - Rule ordering
    - Priorities
    - Extra application conditions
  - Deletion rule graceful / tolerant of missing context
  - Context deletion rule removes dependent elements

# Incremental Backward Transformation

Note: bidirectionality is hard



**Extra challenge if not hard enough:**

SRC  $\rightarrow$  TRG specified

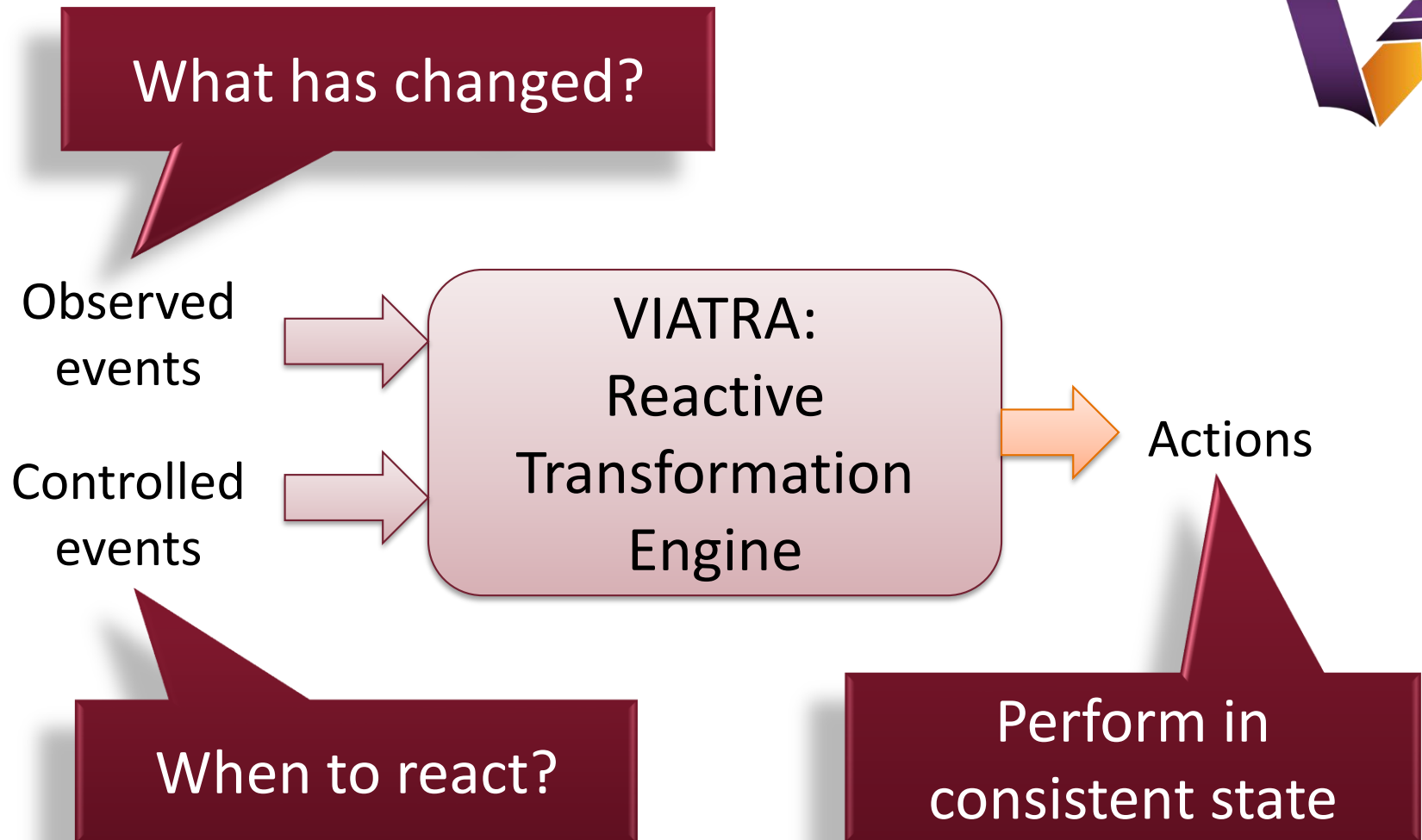
TRG  $\rightarrow$  SRC inferred

**Recent Approaches:**

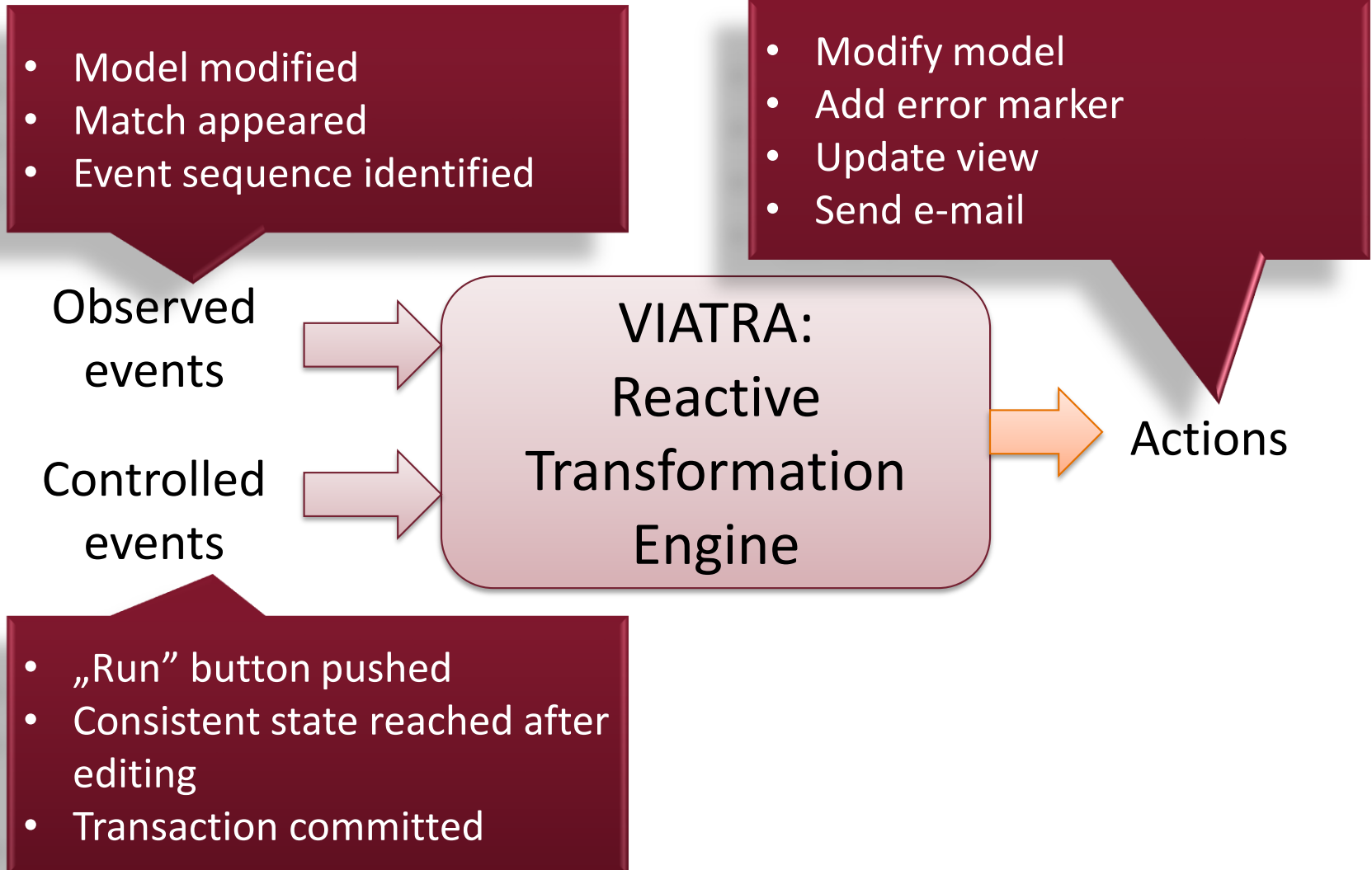
A. Schürr, P. Stevens, N. Foster, T. Hettel,  
Cicchetti&Pierantonio, Czarnecki&Diskin

# VIATRA: A Reactive Incremental Transformation Platform

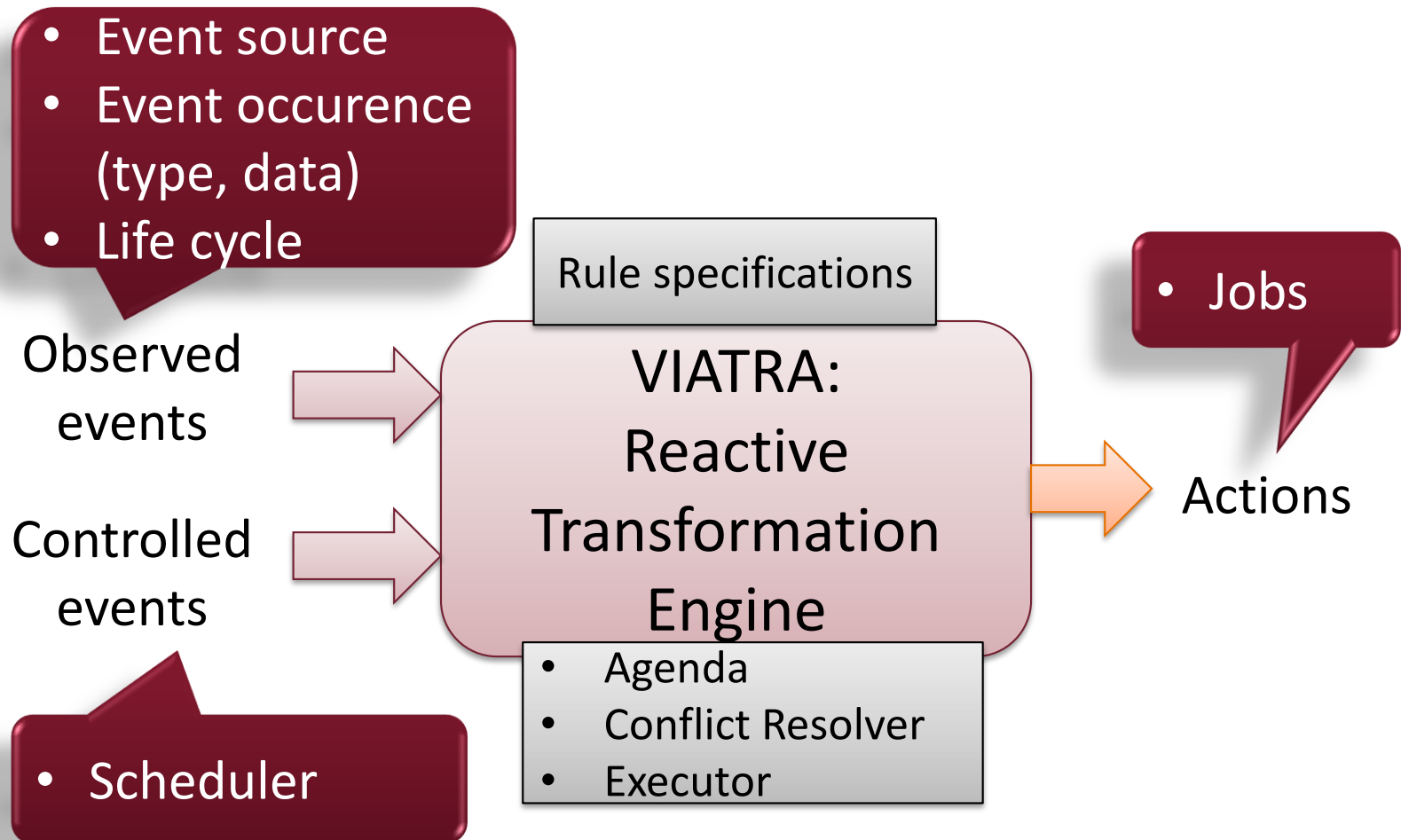
# Reactive Event Driven Transformations



# Reactive Event Driven Transformations



# Reactive Event Driven Transformations





# Language Example

**pattern** someCondition(**param1, param2**) {...} Query language

Xtend (Java)

**val** rule = createRule().precondition(**on**).

action[ **match** | // perform action ].build

**val** incrRule = createRule().precondition(**someCondition**).

lifecycle(**ActivationLifecycles.incremental**).

action(**::Appeared**)[

**match** | // perform action].

action(**::Disappeared**)[

**match** | // perform action].

build

Event data

- Event source
- Event occurrence (type, data)
- Life cycle

Observed events

Controlled events

• Scheduler

Rule specifications

Reactive Transformation Framework

- Agenda
- Executor

• Conflict resolver

• Jobs

Actions

# Language Example

**pattern** `someCondition( param1, param`

Rule specification

Xtend (Java)

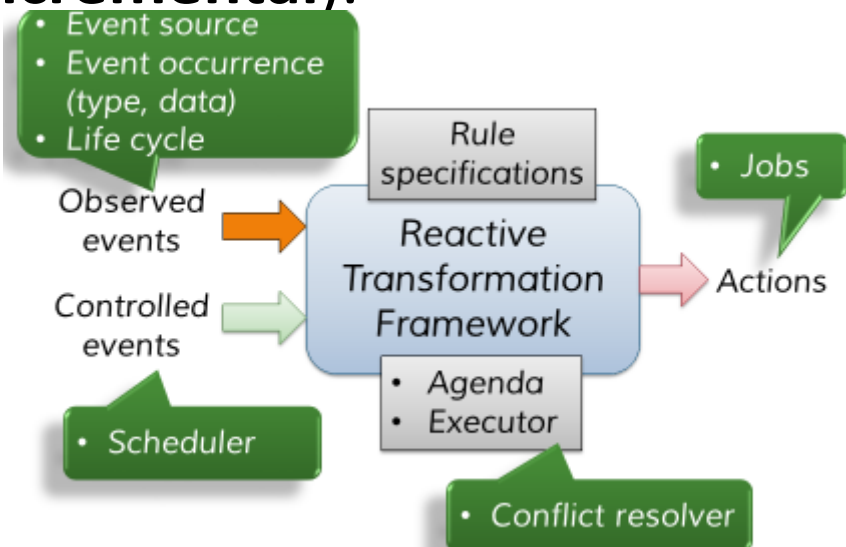
```
val rule = createRule().precondition(someCondition).  
  action[ match | // perform action ].build
```

```
val incrRule = createRule().precondition(someCondition).  
  lifecycle(ActivationLifecycles.incremental).
```

```
  action(::Appeared)[  
    match | // perform action].
```

```
  action(::Disappeared)[  
    match | // perform action].
```

```
  build
```



# Language Example

**pattern** **someCondition**( **param1**, **param2** ) {...} Query language

Xtend (Java)

**val** rule = createRule().precondition(**someCondition**).

action[ **match** | // perform action ].build

**val** incrRule = createRule().precondition

Observed events

lifecycle(**ActivationLifecycles.incremental**).

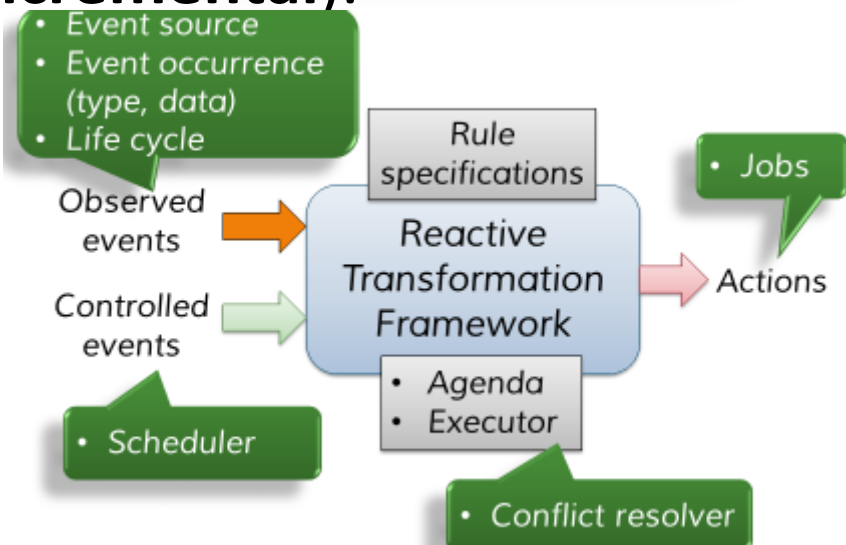
action(**::Appeared**)[

**match** | // perform action].

action(**::Disappeared**)[

**match** | // perform action].

build



# Language Example

**pattern** someCondition( param1, param2 ) {...} Query language

---

Xtend (Java)

**val** rule = createRule().precondition(someCondition).

action[ match | // perform action ].build

**val** incrRule = createRule().precondition(someCondition).

lifecycle( // actionLifecycle.incremental ).

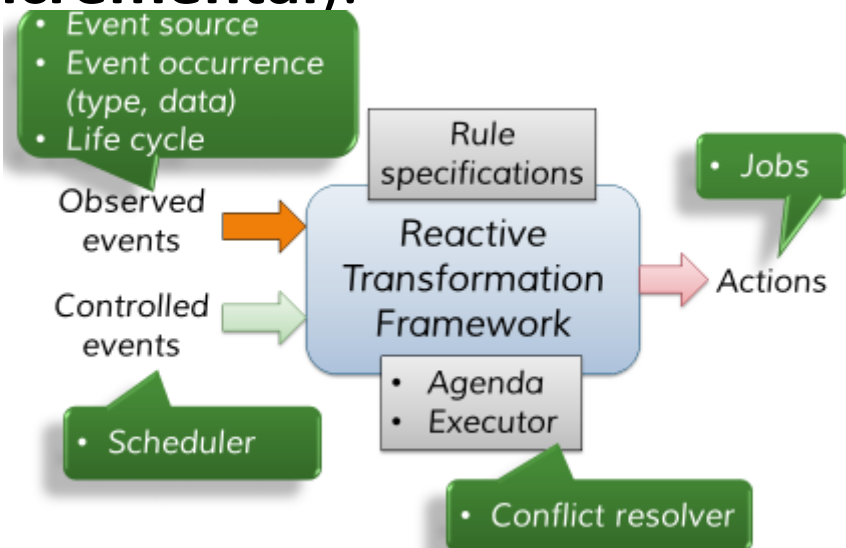
action Job specification

match | // perform action].

action(::Disappeared)[

match | // perform action].

build

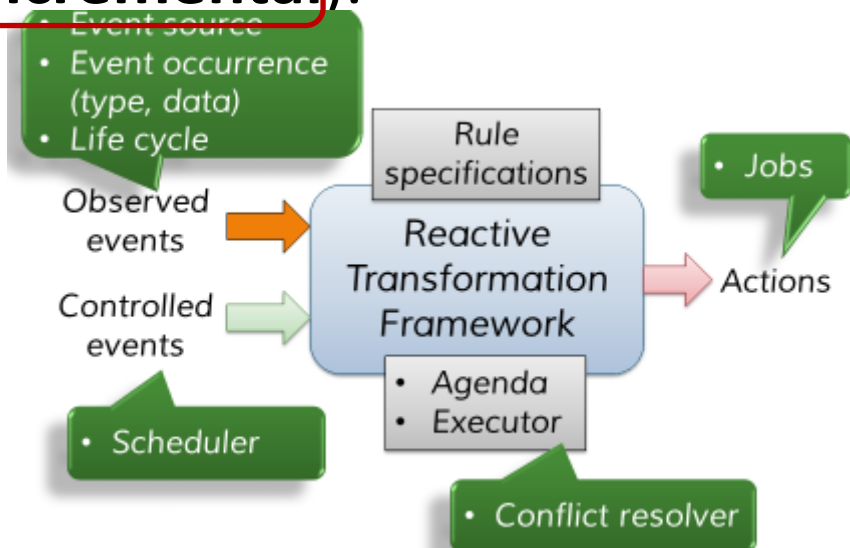


# Language Example

```
pattern someCondition( param1, param2 ) { ... }
```

```
val rule = createRule().precondition(someCondition).  
    action[ match | // perform action ].build  
val incrRule = createRule().precondition(someCondition).  
    lifecycle(ActivationLifecycles.incremental).  
    action(::Appeared)[  
        match | // perform action].  
    action(::Disappeared)[  
        match | // perform action].  
    build
```

Activation  
state-event  
transitions



# Language Example

**pattern** **someCondition**( **param1**, **param2** ) {...} Query language

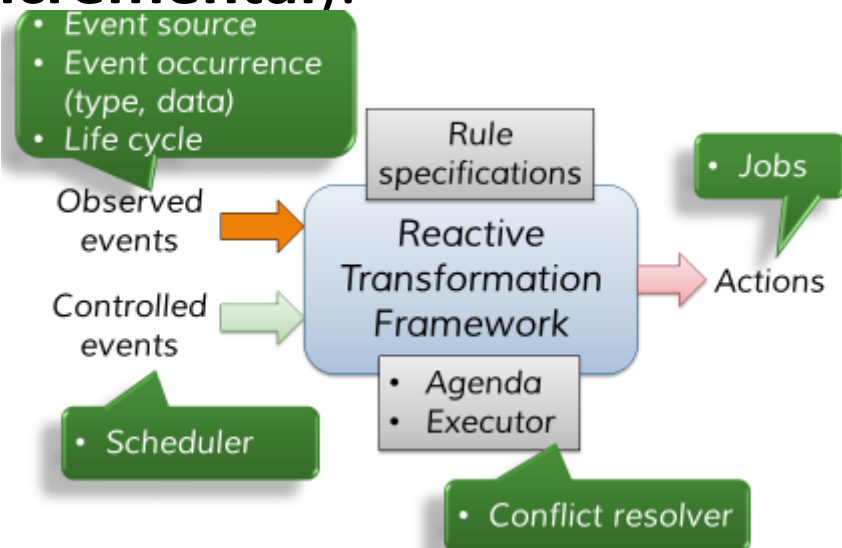
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Xtend (Java)

Jobs associated with event types  
`Rule().precondition(someCondition).  
// perform action ].build`

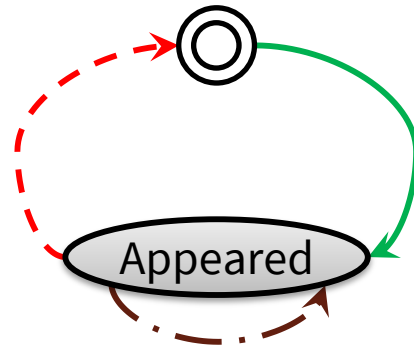
`var Rule = createRule().precondition(someCondition).  
lifecycle(ActivationLifecycles.incremental).`

`action::Appeared[  
    match | // perform action].  
action::Disappeared[  
    match | // perform action].  
build`

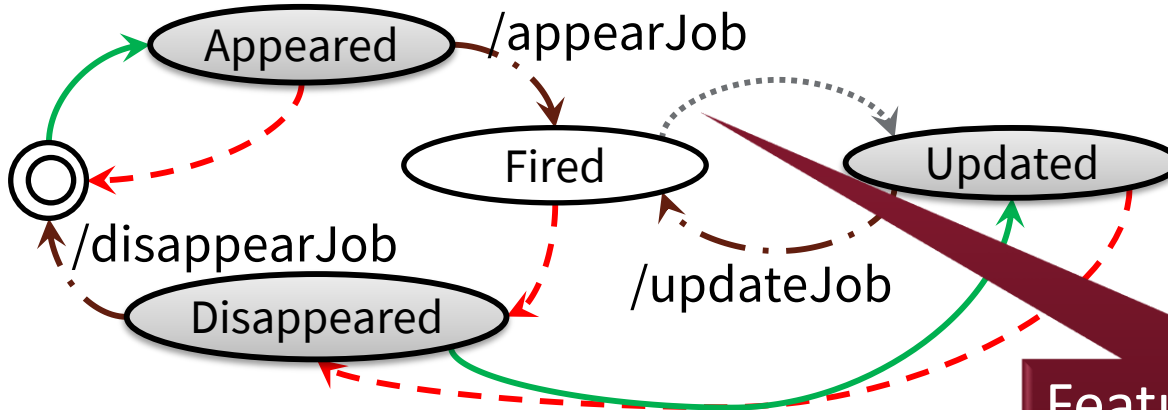


# Activation Lifecycles

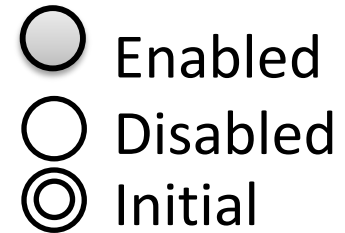
## ■ Batch transformation



## ■ Event-driven transformation



### Phases

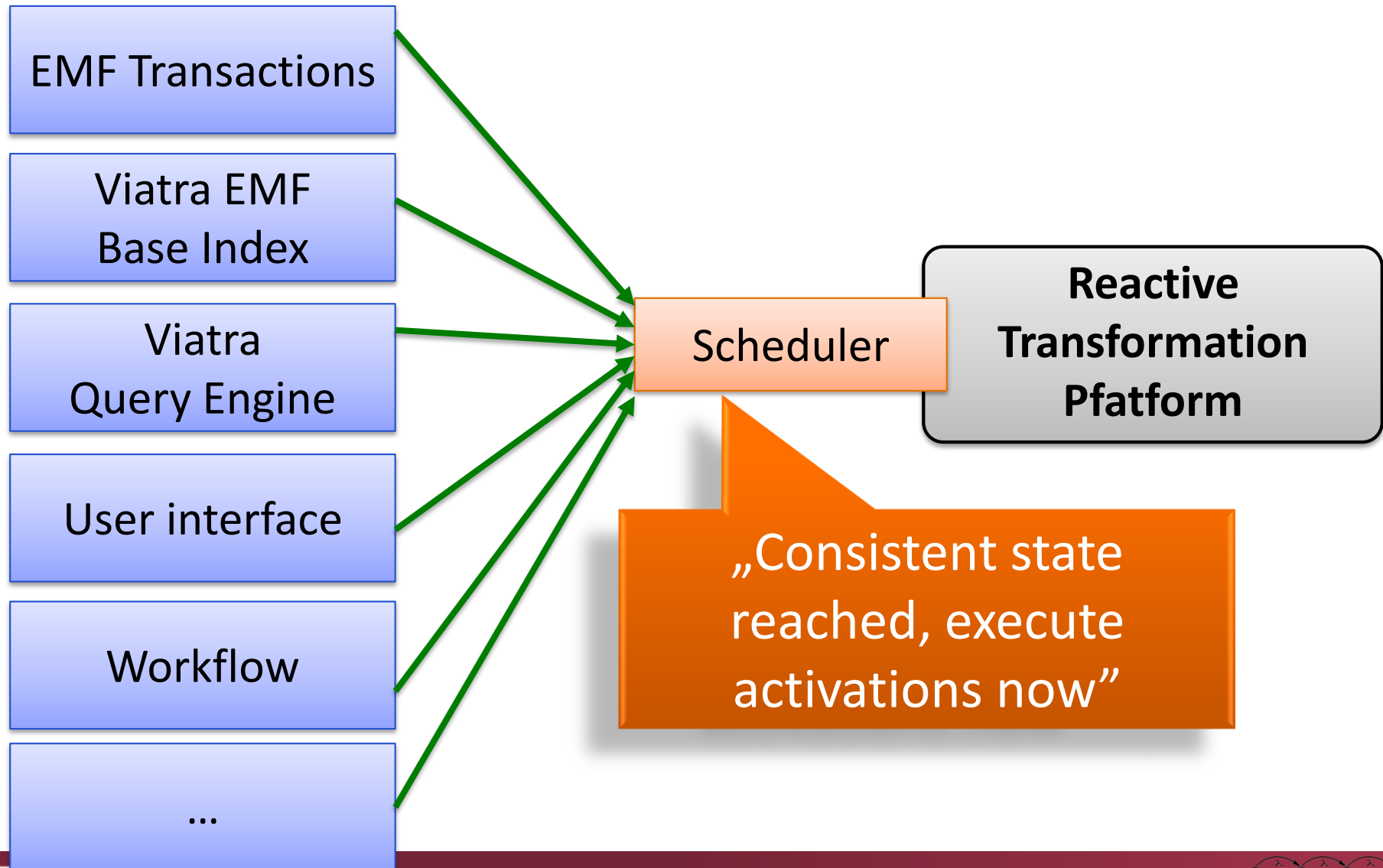


### Transitions



Feature of event data  
object has changed

# Scheduling





# Conflict Resolution

- Multiple actions available
  - Activations of different rules
  - Different activations in the same rule
    - Different matches of the precondition pattern
- Which activation to execute next?
- Conflict resolver can be selected
  - Global conflict set: deals with all rules
  - Scoped conflict set: selected rules
  - Customizable resolution strategy: e.g. priority-based

# VIATRA: Overview of Features

## ■ Reactive MT Platform

### ○ MT Language:

- Internal DSL over Xtend
- Transformation API

### ○ MT Engine:

- Event-driven virtual machine
- Batch + Incremental MTs
- Control flow library
- Compiles to Java
- Debugger
- High performance

### ○ Integrations:

- EMF, Viatra Query, Xtend, EMF-UML, ...

### Design Space Exploration

- Explore design model candidates
- Satisfying multiple criteria
- Rule based exploration
- Optimization

### Complex Event Processing

- Detect complex event sequences
- Rule based reaction
- Xtext based language

### Model Obfuscator

- Remove sensitive information from confidential models
- Original model → Obfuscated model

# Performance benchmarks

<https://github.com/viatra/viatra-cps-benchmark>

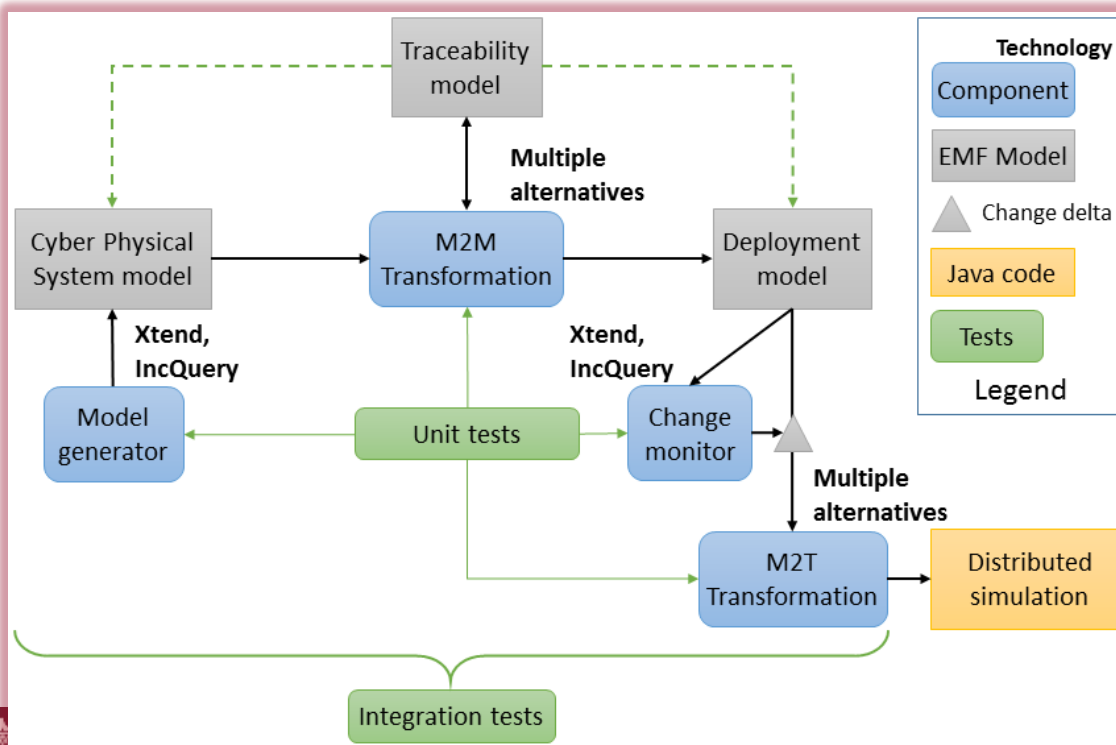
# CPS Reallocation Benchmark

## ■ Benchmark setup

- Rule-based redeployment for cloud-based CPS
  - Model generator + Unit tests
  - M2M + M2T transformations

## ■ Different target architecture / platform

- Industrial (Low-Synch)
- Client-Server
- Publish-Subscribe



# Test Scenario

## ■ Different transformation variants

- Batch
  - Xtend (2 versions)
  - IncQuery+Xtend
- Incremental
  - Dirty (2 approaches)
  - Explicit traceability
  - Query-driven
  - Change-driven (VIATRA-EVM)

## ■ Executions

- First transformation execution
- Small modification + (re)execution

## ■ Environment

- New machine with 16 GB RAM

## ■ Parameters

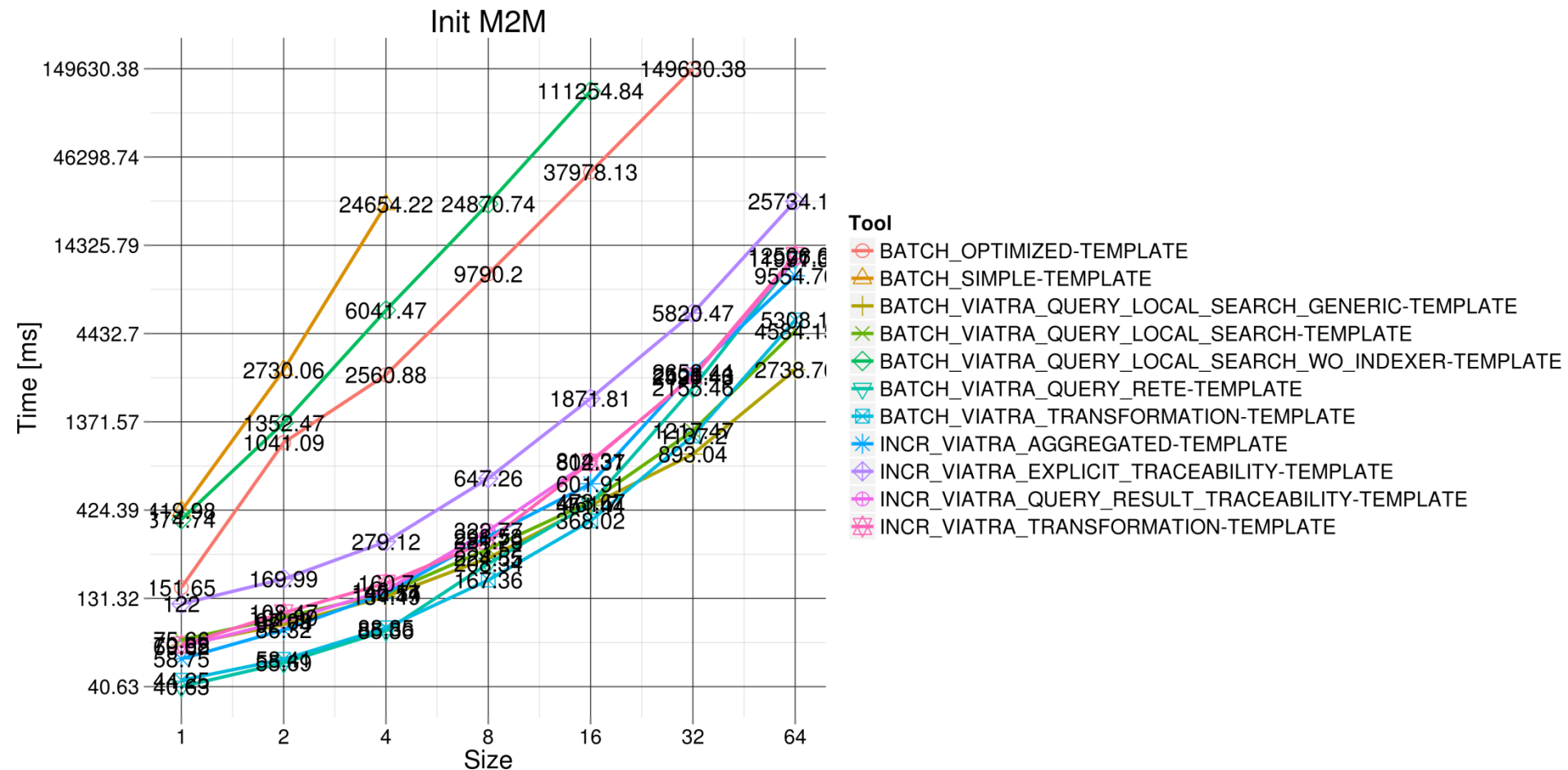
- 10 GB Heap
- Maximum 10 minutes execution times for complete chain

| Scale | SRC Objects | SRC References | TRG Objects | TRG References | Trace Objects | Trace References | SUM Objects    | SUM References   |
|-------|-------------|----------------|-------------|----------------|---------------|------------------|----------------|------------------|
| 1     | 395         | 772            | 366         | 736            | 354           | 720              | <b>1 115</b>   | <b>2 228</b>     |
| 2     | 790         | 1544           | 732         | 1472           | 708           | 1440             | <b>2 384</b>   | <b>4 891</b>     |
| 4     | 1580        | 3088           | 1464        | 2944           | 1416          | 2880             | <b>4 750</b>   | <b>10 725</b>    |
| 8     | 3160        | 6176           | 2928        | 5888           | 2832          | 5760             | <b>10 124</b>  | <b>29 739</b>    |
| 16    | 6320        | 12352          | 5856        | 11776          | 5664          | 11520            | <b>22 056</b>  | <b>115 824</b>   |
| 32    | 12640       | 24704          | 11712       | 23552          | 11328         | 23040            | <b>50 319</b>  | <b>651 623</b>   |
| 64    | 25280       | 49408          | 23424       | 47104          | 22656         | 46080            | <b>125 703</b> | <b>4 556 465</b> |

Trace model's size  
similar to target model

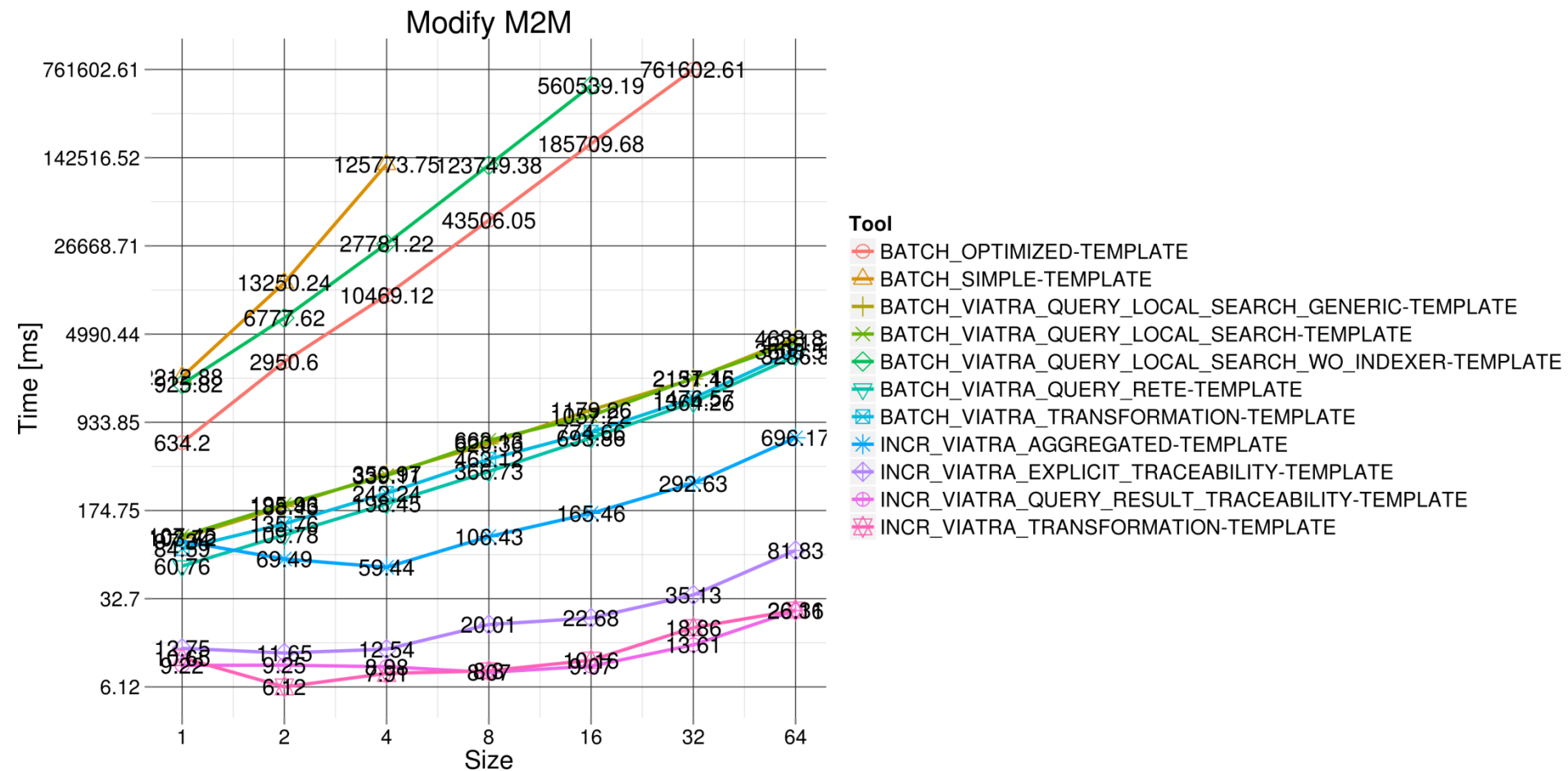
# Benchmark results

## ■ Runtime of initialization and first M2M phase



# Benchmark results

## ■ Runtime of model modification and M2M phase



# Design Space Exploration

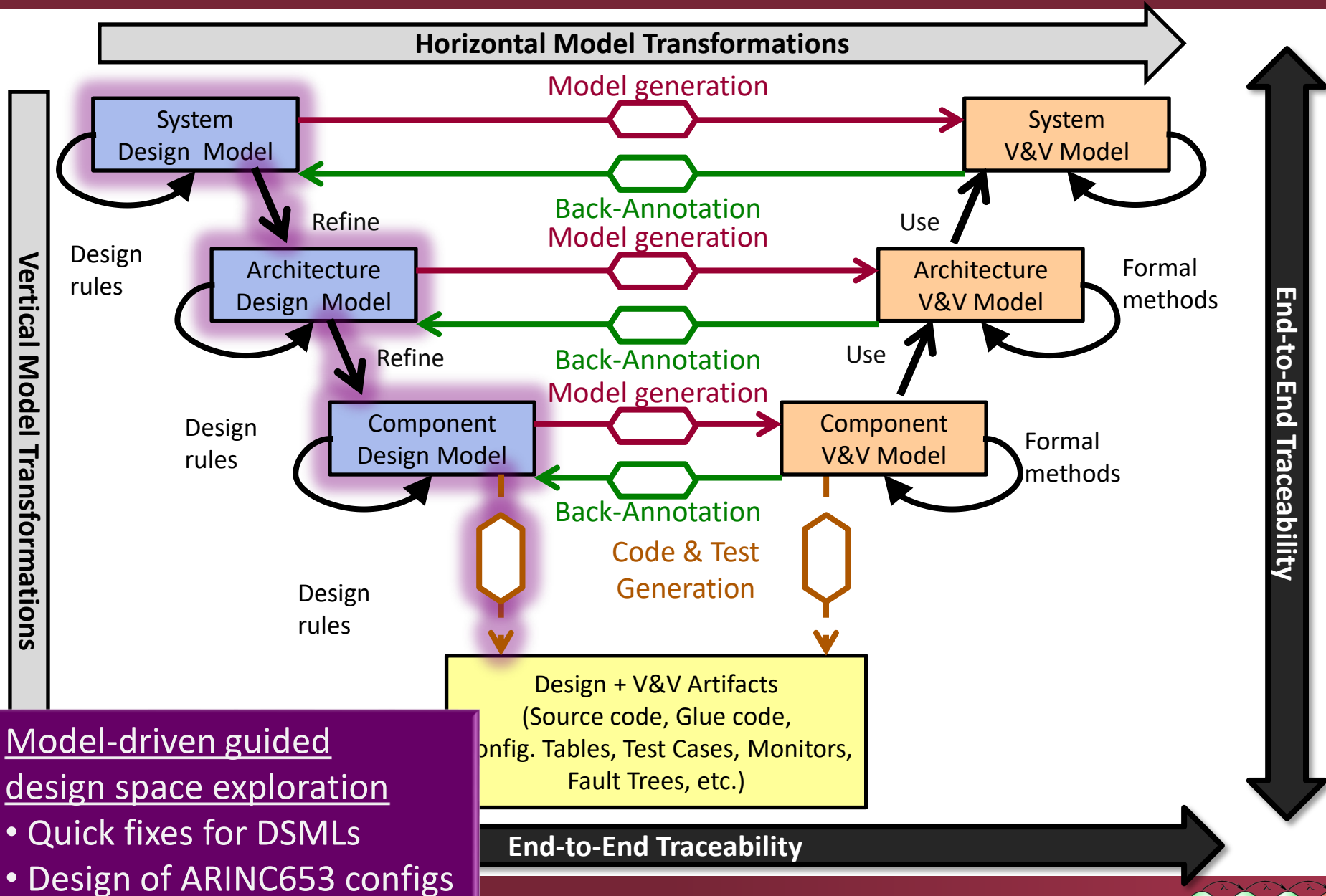
Á. Hegedüs, Á. Horváth, D. Varró:

A model-driven framework for guided design space exploration.  
Automated Software Engineering (August 2014)

DOI: 10.1007/s10515-014-0163-1



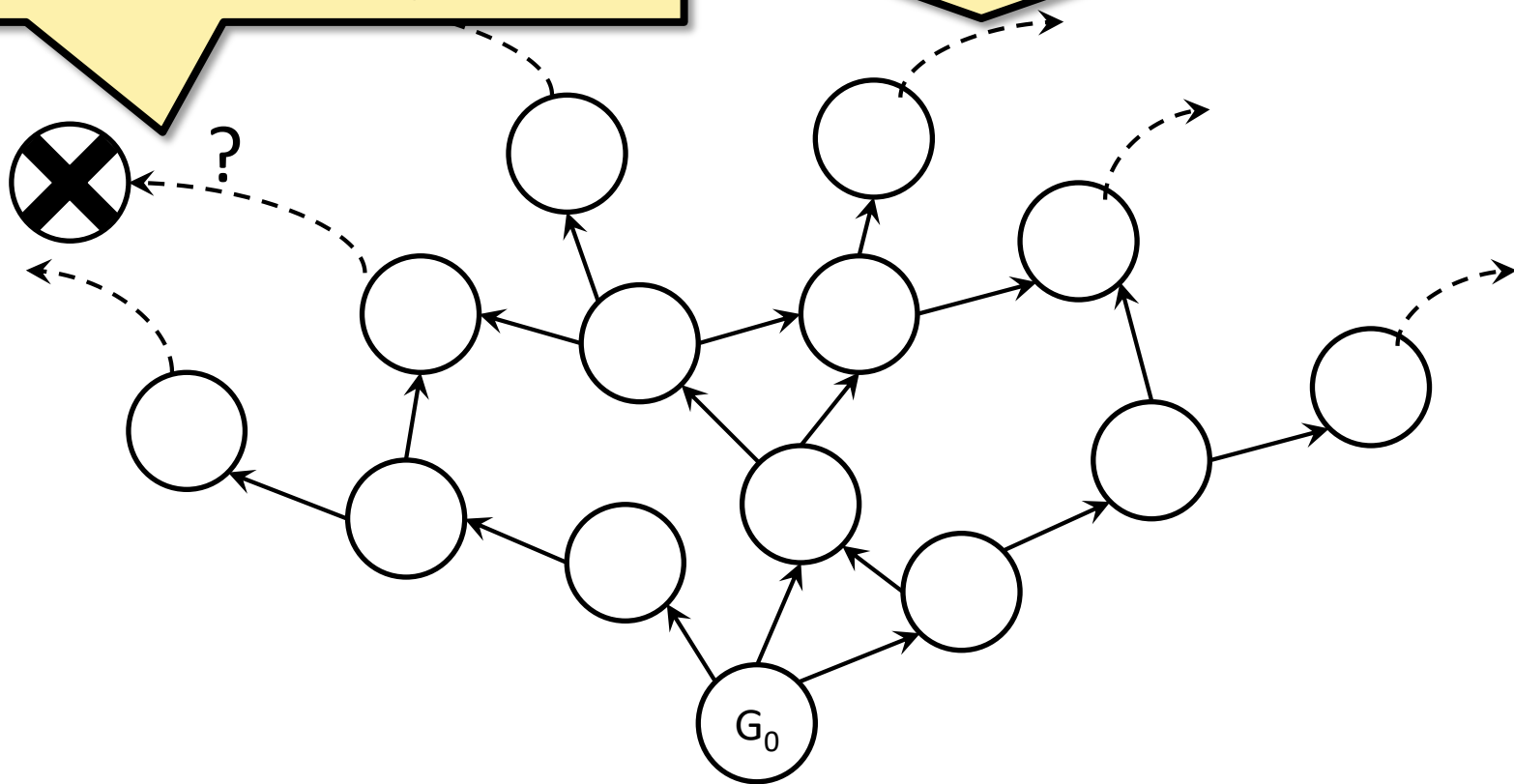
# Model-Driven Guided Design Space Exploration



# Revisit: state space of GT system

Solutions are  
in the state space

Potentially infinite state space



Initial Graph + GT rules  $\rightarrow$  State Space

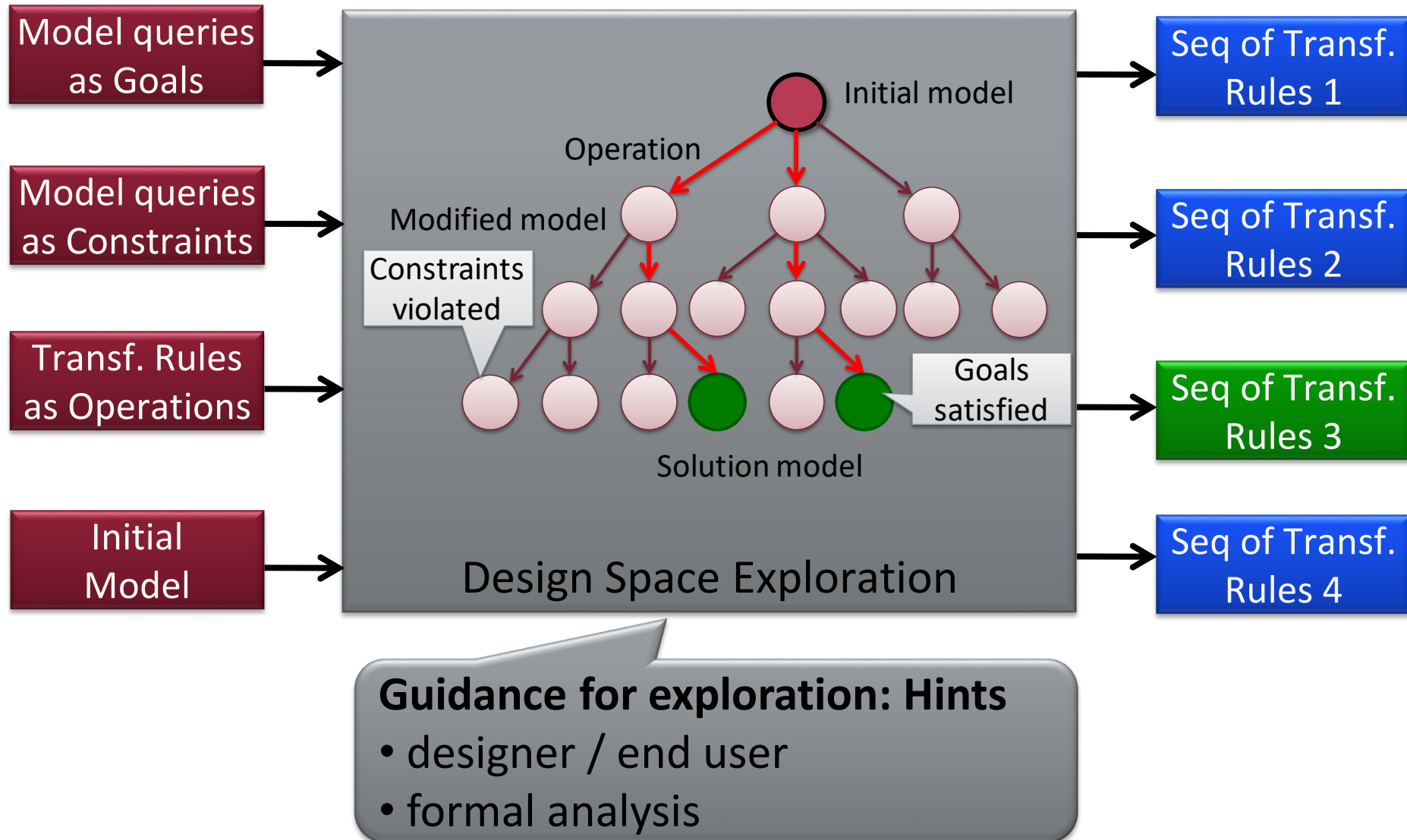
# Design Space Exploration



## Special state space exploration

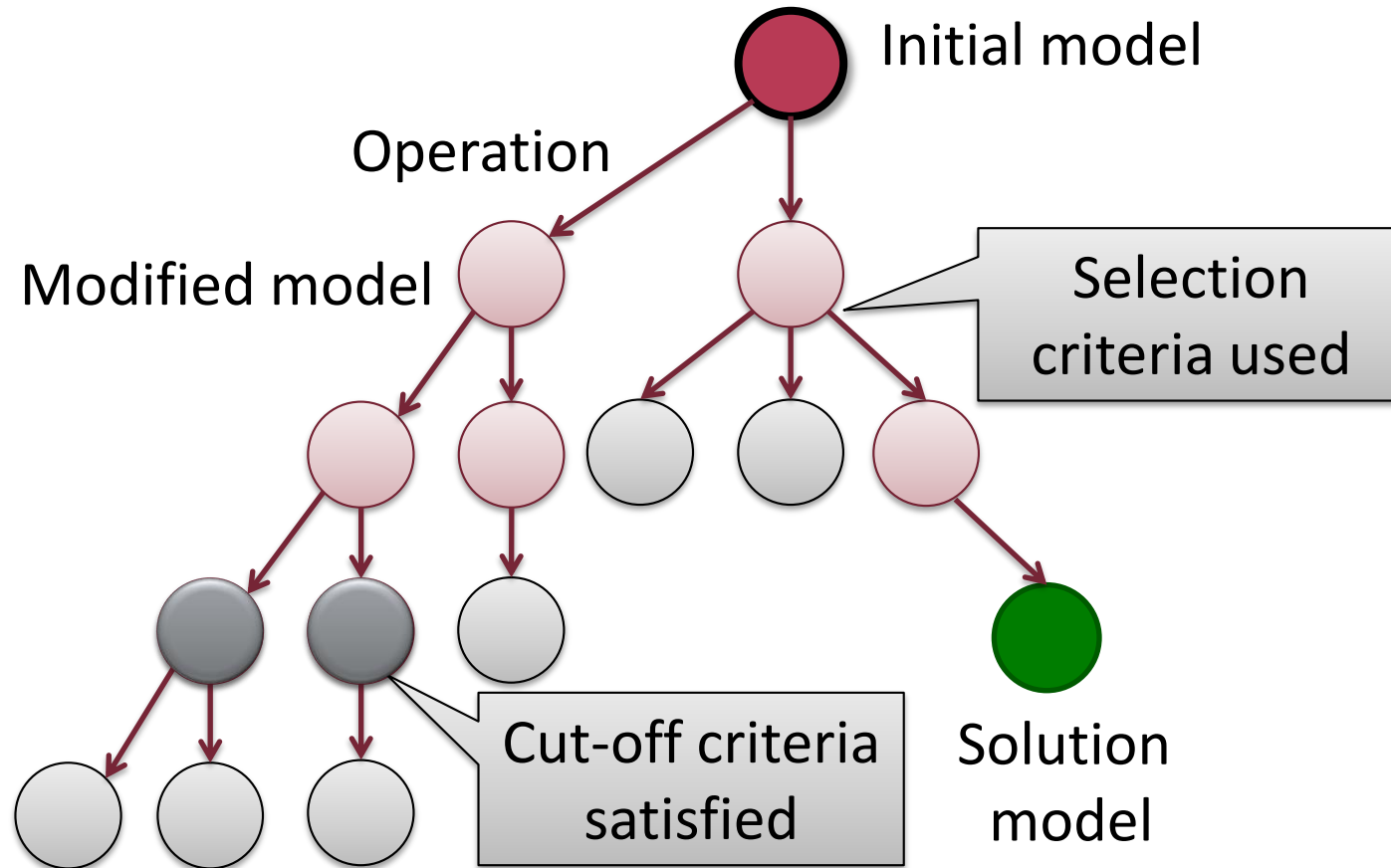
- potentially infinite state space
- „dense” solution space

# Model Driven Guided Design Space Exploration



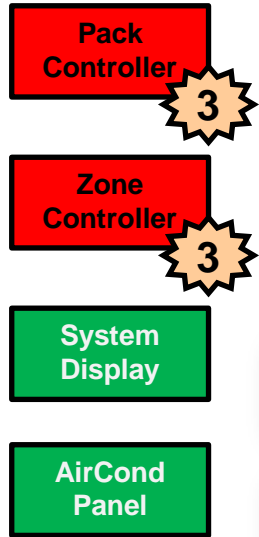
# Guided Design Space Exploration

- High-level overview

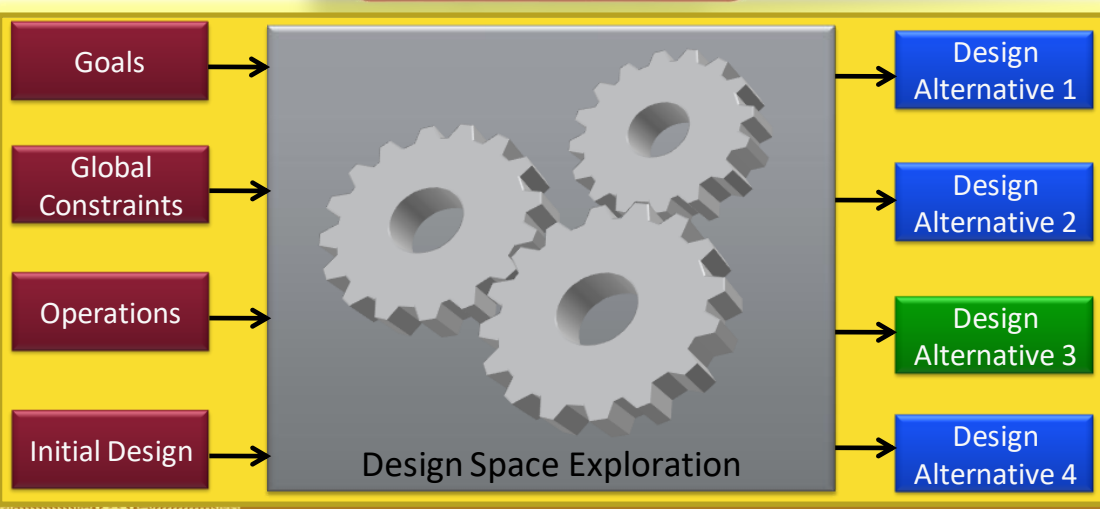
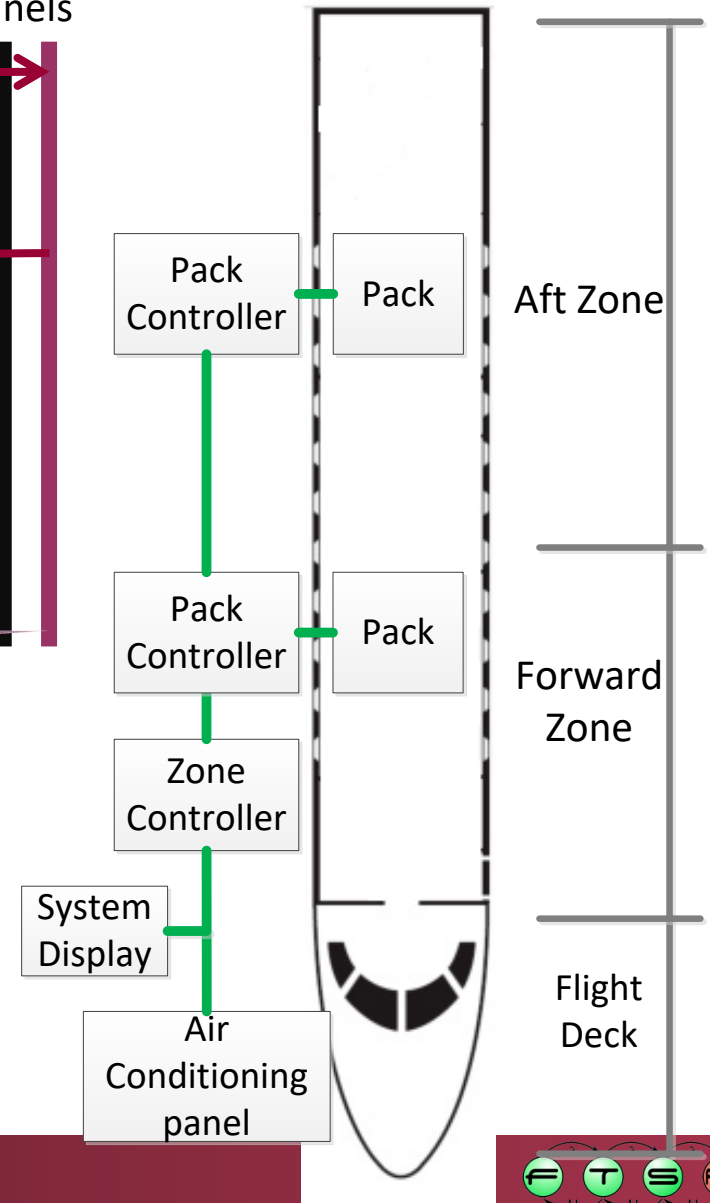
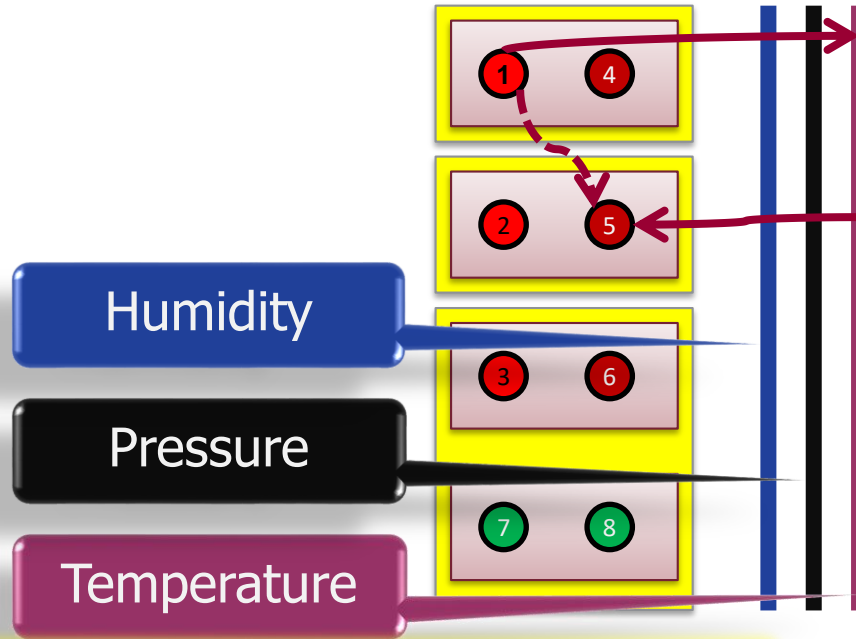


# Design Space Exploration for IMA Config. Design

SW functionality

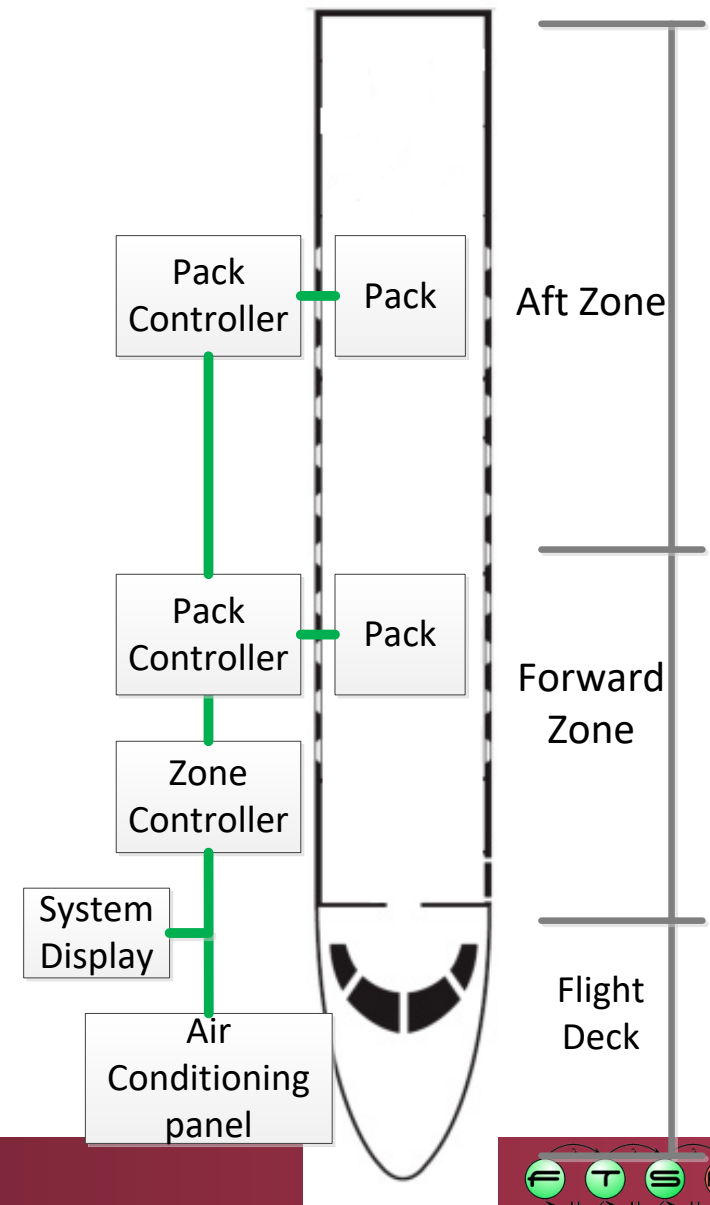
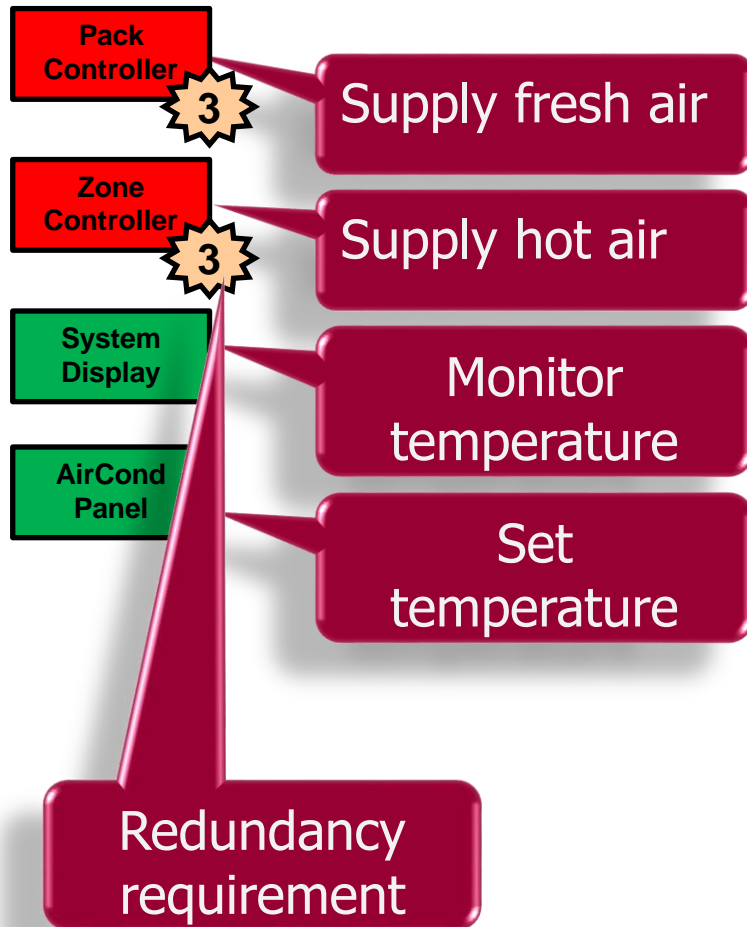


Communication channels



# Designing ARINC653 configurations

SW functionality  
(critical + non-critical)

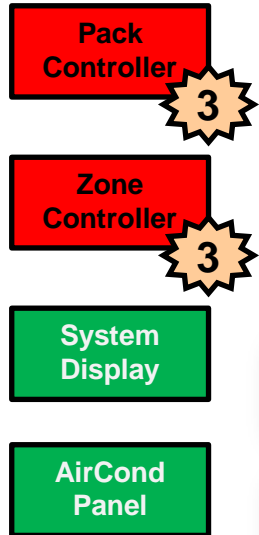




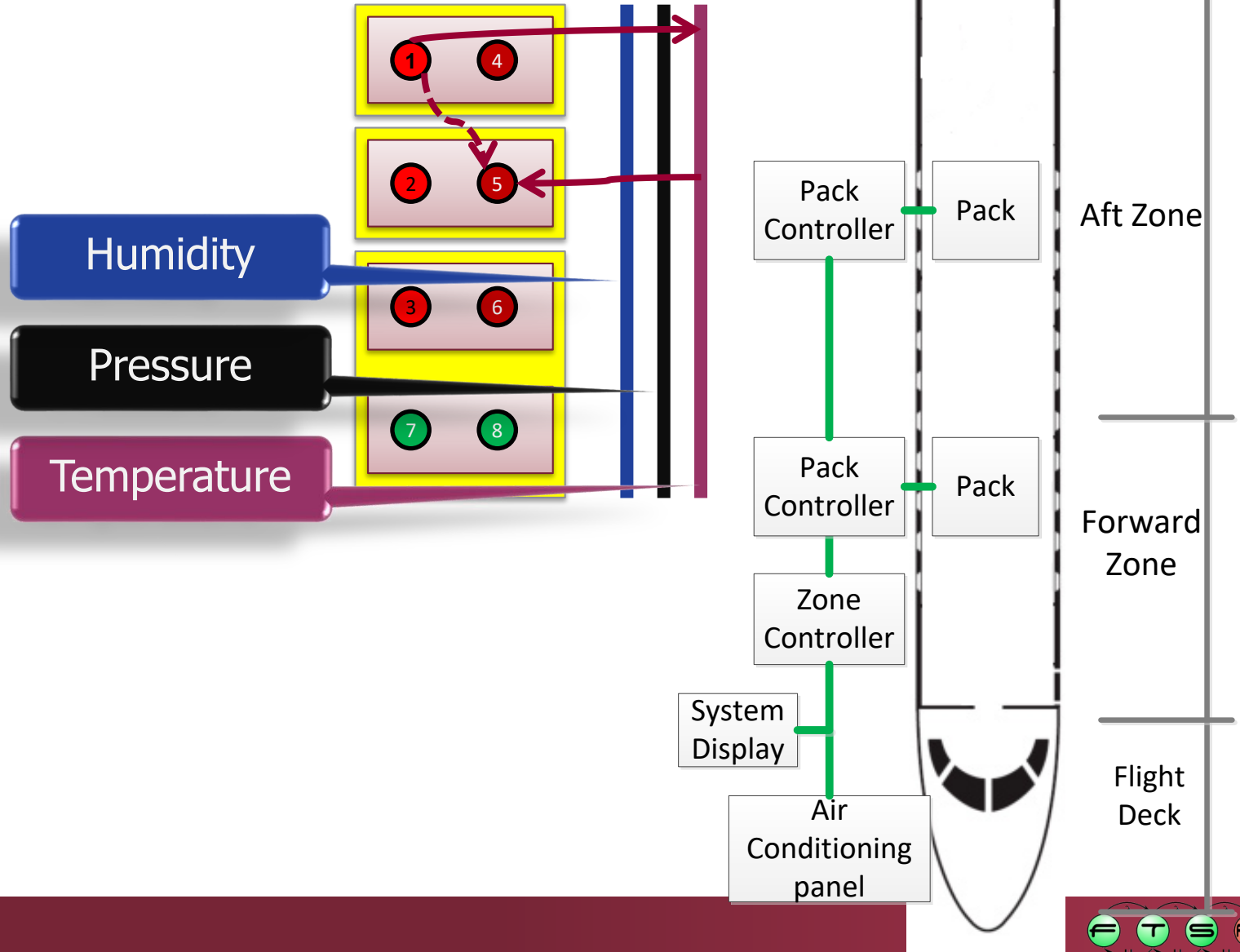


# Allocating communication channels

SW functionality



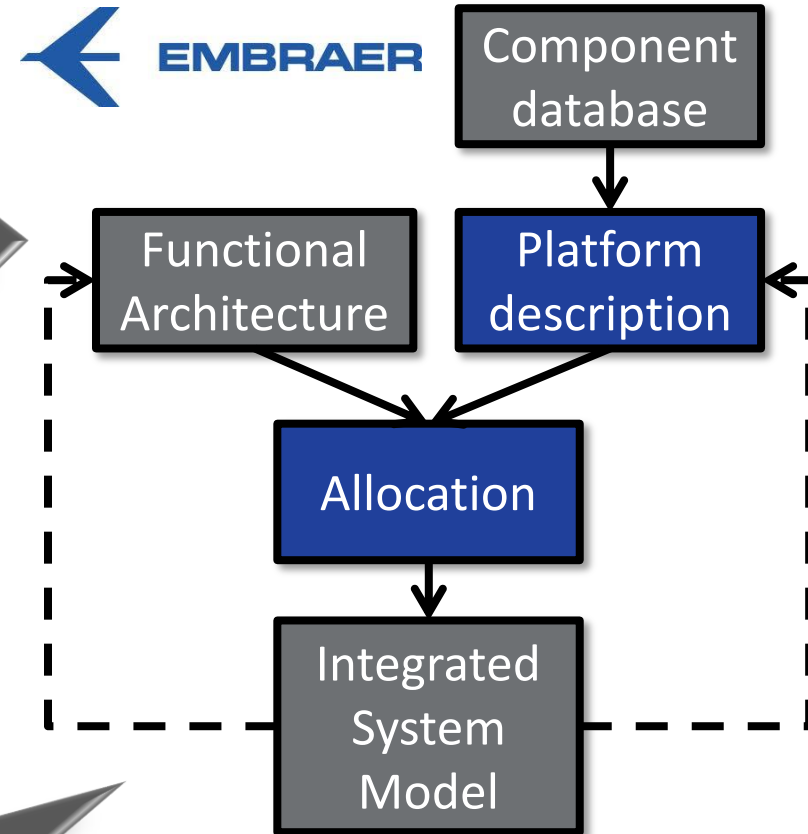
Communication channels



# Model Driven Development of IMA Configs

## Inputs:

- Platform Independent Model (PIM) (functional + nonfunc. reqs; Simulink)
- Platform Description Model (PDM) for ARINC 653 (DSML)



## Output:

- Integrated system model
- Ready for simulation
- End-to-end traceability



# Model Driven Development of IMA Configs

Model transformation chains:

- Designer-guided manual steps
- Automated steps
  - design space exploration
  - optimization
  - code generators
- Continuous validation of design rules

