51. Model and Program Analysis with Graph Reachability

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Version 12-0.6, 17.01.13

1) Model Mapping
2) EARS for Reachability
3) Regular graph reachability
    1) Graph slicing
4) Context-free graph reachability
5) More on the Graph-Logic Isomorphism
6) Implementation in Tools

Literature

- Hannes Schwarz, Jürgen Ebert, and Andreas Winter. Graph-based traceability: a comprehensive approach. Software and System Modeling, 9 (4):473-492, 2010.
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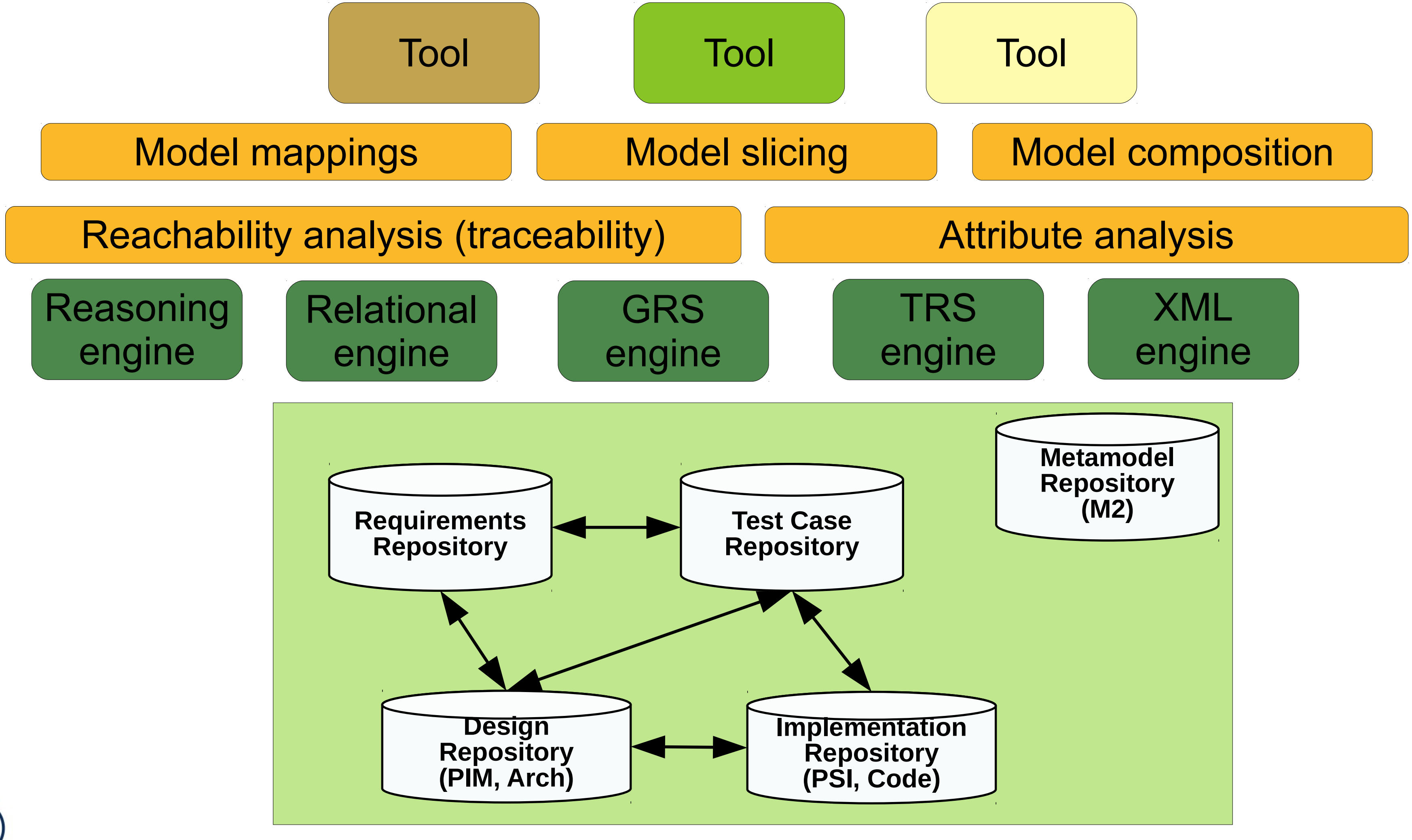
Tools in an Integrated Development Environment (IDE)

- **Model mappings** relate different artefacts to enable **traceability (reachability)** and **impact analysis**



Literature

- Frédéric Jouault and Ivan Kurtev. On the Architectural Alignment of ATL and QVT. In: Proceedings of the 2006 ACM Symposium on Applied Computing (SAC 06). ACM Press, Dijon, France, chapter Model transformation (MT 2006), pages 1188—1195.
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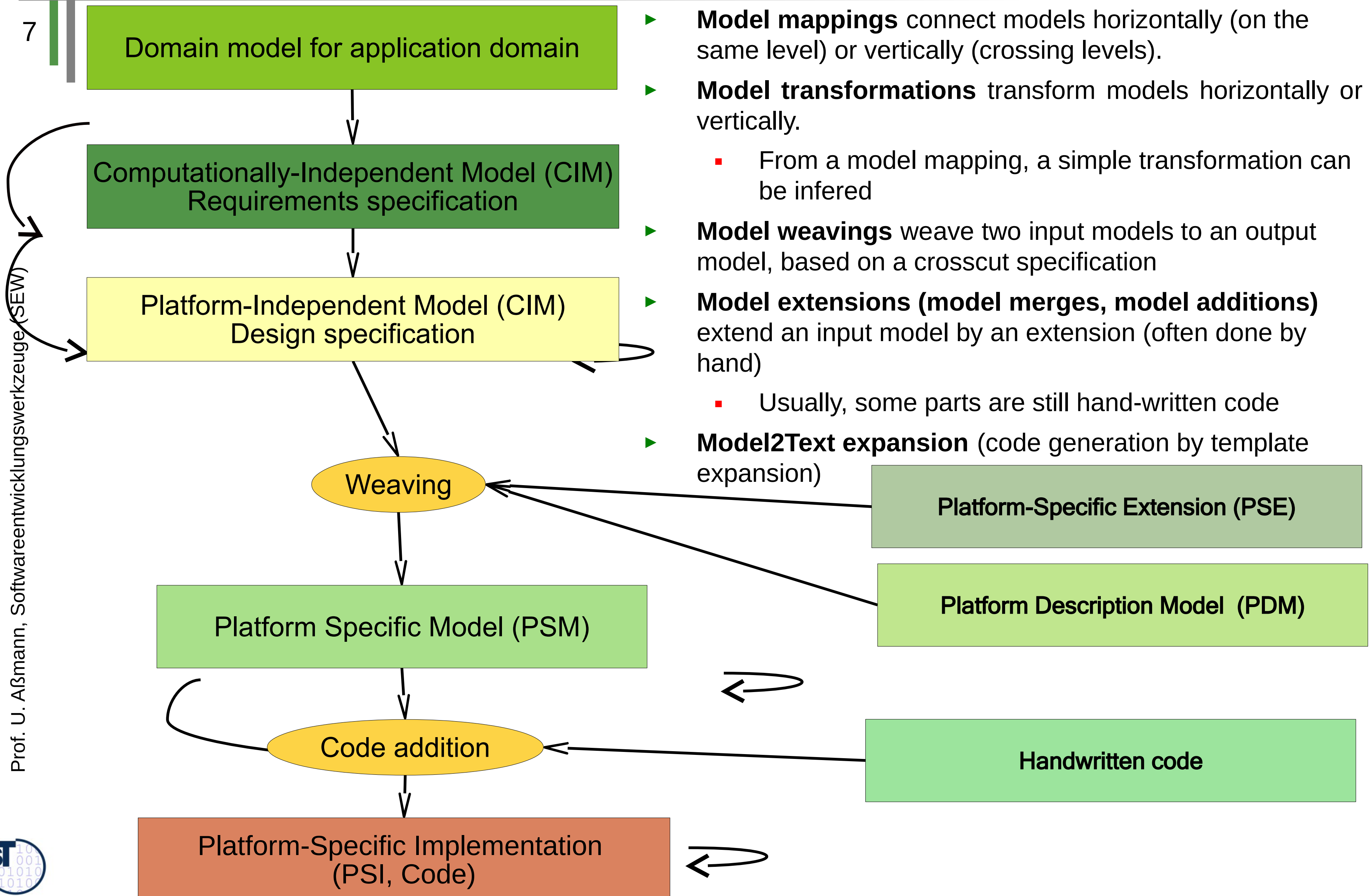
- K. Lano. Catalogue of Model Transformations
  - http://www.dcs.kcl.ac.uk/staff/kcl/tcat.pdf
- Implementation in ATL
  - http://www.eclipse.org/m2m/atl/atlTransformations/EquivalenceAttributesAssociations/EquivalenceAttributesAssociations.pdf

51.1 Model Mapping (Modellverknüpfung)

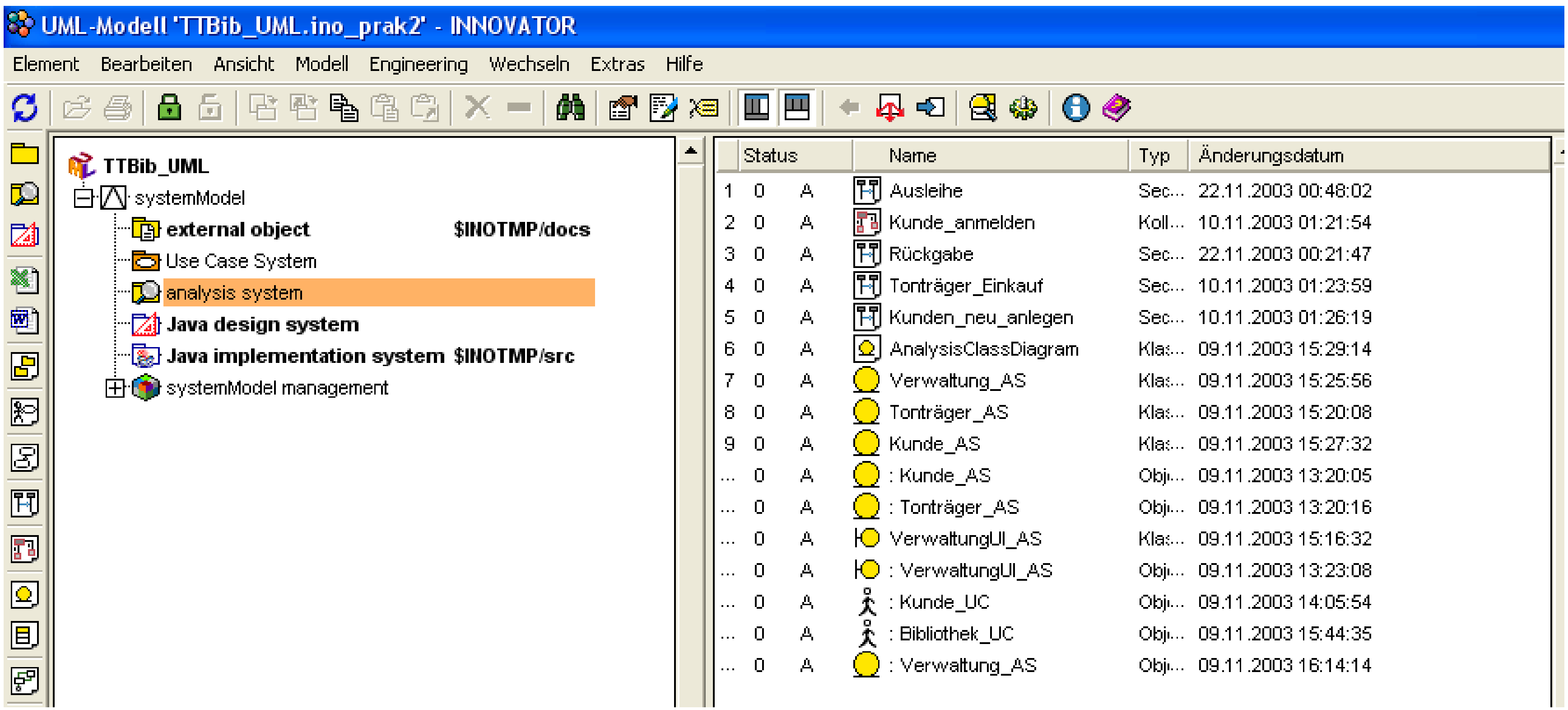
Model Mappings and Model Weavings

- **Model mappings** connect models horizontally (on the same level) or vertically (crossing levels).
- **Model transformations** transform models horizontally or vertically.
  - From a model mapping, a simple transformation can be infered
- **Model weavings** weave two input models to an output model, based on a crosscut specification
- **Model extensions (model merges, model additions)** extend an input model by an extension (often done by hand)
  - Usually, some parts are still hand-written code
- **Model2Text expansion** (code generation by template expansion)



Model Mapping (Modell-Verknüpfung) with MID INNOVATOR

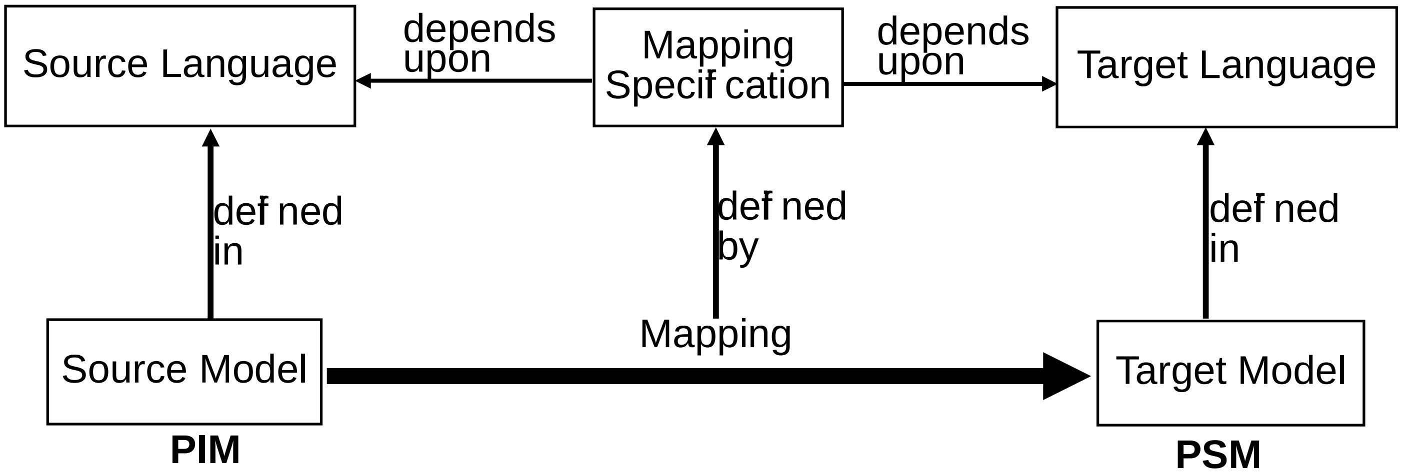
- Innovator can be used for requirements models, design models, implementation models, as well as for transformations in between
- How to relate these models systematically?



Rpt. from ST-II: Model Mapping, Transformation and Synchronization in the MDA

The MDA architecture derives from a *platform-independent model* (**PIM) by hand, by rules, by transformations, by metaprograms** *platform-specif c* models (**PSM)**

- Model mapping connects systematically all elements of a **source model** to the elements of a **target model.**
- From the mappings, a translation, transformation, or synchronization can be automatically infered.



Quelle: Kleppe, A., Warmer, J., Bast, W.: MDA Explained - Practice and Promise of the Model Driven Architecture; Addison Wesley 2003 (Draft 25.10.02)

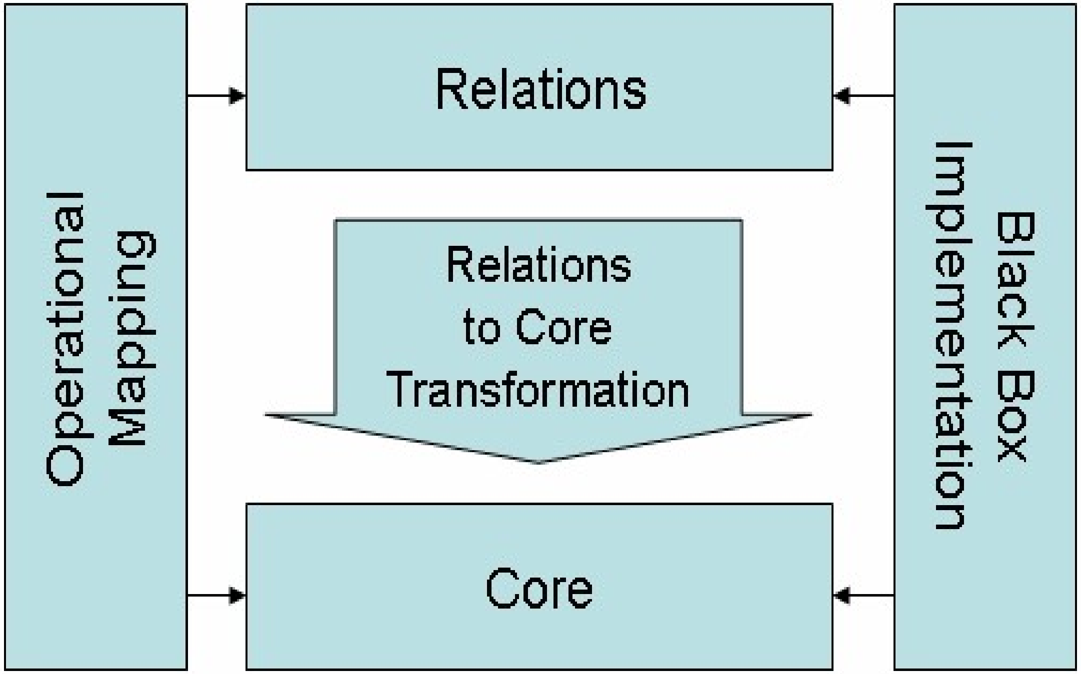
Problem: Analysis and Reachability

- We need graph reachability analyzers
  - to create trace graphs for reachability and traceability
  - to create model mappings, model slicings
  - to prepare refactorings, transformers, and optimizers
    - For models: For model refactoring, adaptation and specialization, weaving and composition
    - For code: Portability to new processor types and memory hierarchies
    - For optimization (time, memory, energy consumption)
- However, reachability analyzers are big beasts
  - Current implementation techniques are hard to understand and to a large extent unsystematic
- Idea: Use graph-logic isomorphism

51.1.1 Query-View-Transformations (QVT)

The language of the OMG for model transformations within MDA

QVT Dialects



Transitive Closure with QVT Relations

- QVT relations uses logic expressions on base and derived relations (graph-logic isomorphism)

```
// Transitive Closure in QVT relations,
// Modeled with recursiven relation "transitiverelation"
relation transitiverelation {
  domain node:Node {
    // matching attributes
    name = sameName;
  }
  domain node2:Node {
    // node2 must have the
    // same name as node
    name = sameName;
  }
  domain node3:Node {
    // node3 must also
    // have the same name
    name = sameName;
  }
  when {
    // conditions: base relation must exist
    baserelation(node,node2) or
    // or a transitive relation to a base relation
    (transitiverelation(node,neighbor)
    and baserelation(neighbor,node2));
  }
  where { // Aufruf einer Transformation
    makeNodeSound(node);
  }
}
```

QVT Tools

Tool			
Eclipse M2M Project	Operational	http://www.eclipse.org/m2m/	
Magic Draw	Operational		
MediniQVT	Relational	http://projects.ikv.de/qvt/wiki	

OCL for Model Search, Query, and Mapping

- OCL is a graph-query language, similar to EARS and .QL
- OCL can be called within QVT scripts
  - Two different DQL are combined within a single language

```
// this is QVT
rule checkNoDoubleFeatureInSuperClasses(name:String) {
  from node: Class (
    node->TransitiveClosure()->collect.().exists(s |
s.name() = name);
  )
  to
    System.out.println("Error: super class has doubly
defined feature: "+s.name());
}
```

51.2 Using EARS for Analysis and Mappings of Models and Code

- Graph reachability engines are A-tools answering questions about structure of models and programs
- EARS can be employed for regular graph reachability, context-free graph reachability, slicing, data-flow analysis

EARS for Model Mapping

- QVT Relational is a language for **Edge addition rewrite systems (EARS)**
- EARS can be used for model mapping:
  - Transitive closure
  - Regular path reachability
  - Context-free path reachability

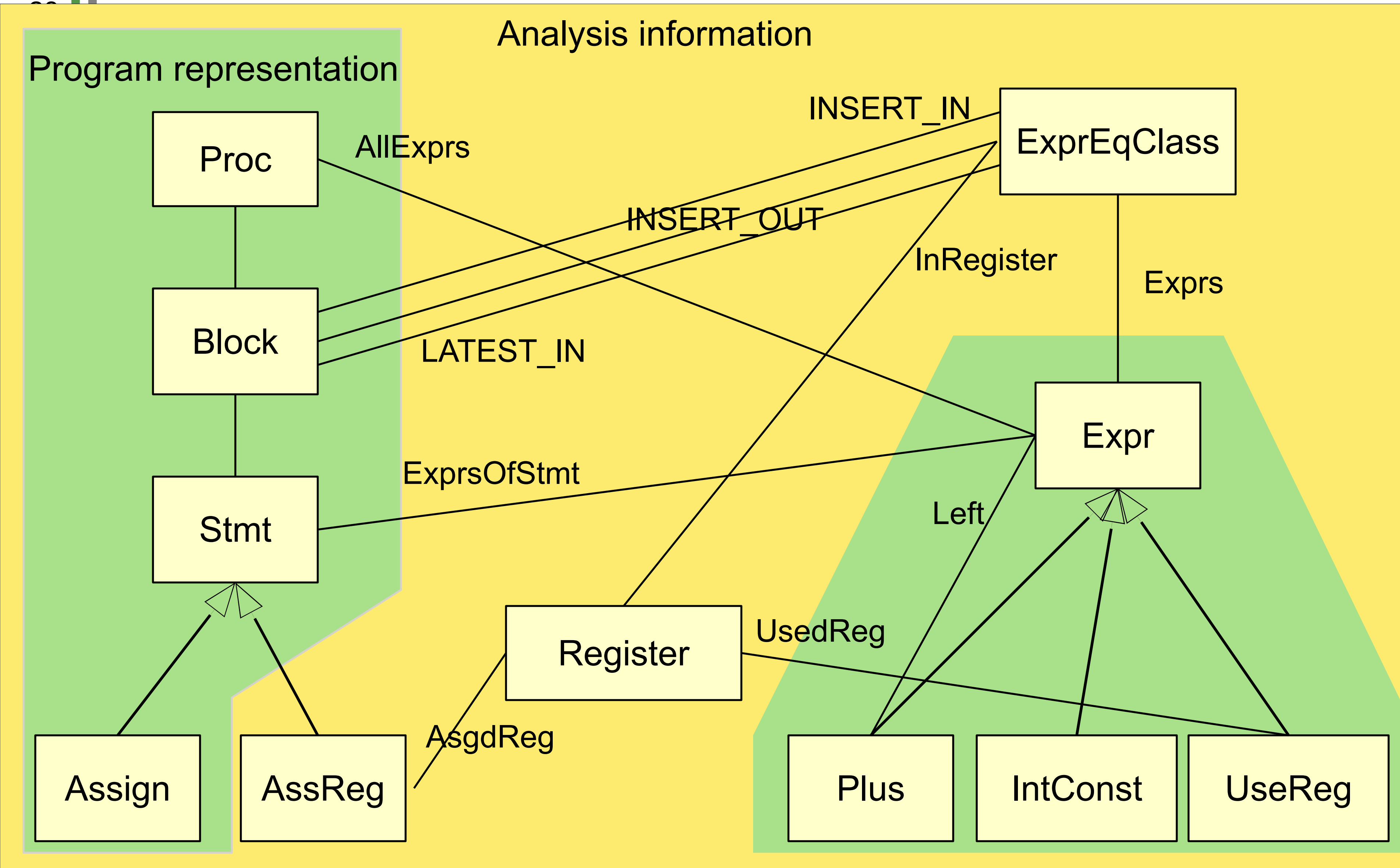
Model Analysis with Graph Reachability

- Use the graph-logic-isomorphism: Represent everything in a program or a model as directed graphs
  - Program code (control flow, statements, procedures, classes)
  - Model elements (states, transitions, ...)
  - Analysis information (abstract domains, flow info ...)
  - Directed graphs with node and edge types, node attributes, one-edge condition (no multi-graphs)
- Use edge addition rewrite systems (EARS) and other graph reachability specification languages to
  - Query the graphs (on values and patterns)
  - Analyze the graphs (on reachability of nodes)
  - Map the graphs to each other (model mapping)
- Later: Use graph rewrite systems (GRS) to construct and augment the graphs, transform the graphs
- Use the graph-logic isomorphism to encode
  - Facts in graphs
  - Logic queries in graph rewrite systems

Specification Process

1) Specification of the data model (graph schema)
   - Specification of the graph schema with a graph-like DDL (ERD, MOF, GXL, UML or similar):
     - **Schema of the program representation**: program code as objects and basic relationships. This data, i.e., the start graph, is provided as result of the parser
     - **Schema of analysis information** (the infered predicates over the program objects) as objects or relationships
2) Program analysis (preparing the abstract interpretation)
   - Querying graphs, enlarging graphs
   - Materializing implicit knowledge to explicit knowledge
   - Materializing *model mappings*
3) Abstract Interpretation (program analysis as interpretation)
   - Specifying the transfer functions of an abstract interpretation of the program with graph rewrite rules on the analysis information
4) Model and Program transformation (optimization)
   - Transforming the program representation

A Simple Program (Code) Model (Schema) in MOF/UML



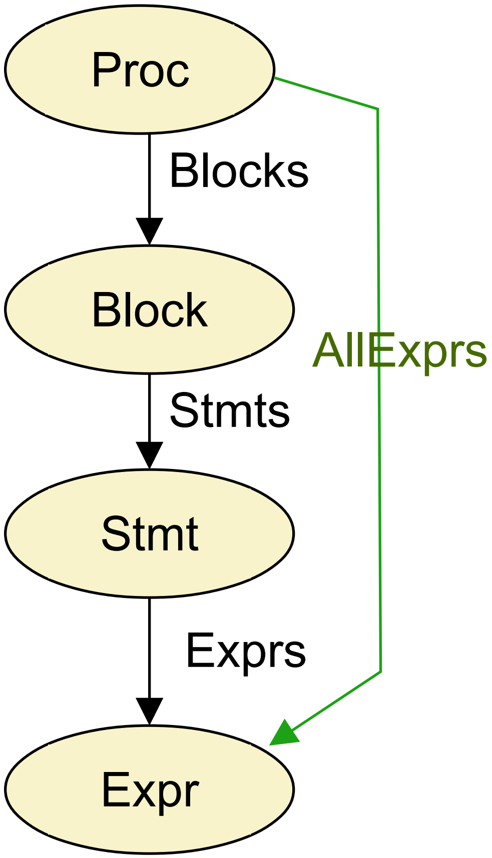
51.2. Simple Reachability: Path Abbreviations in Graph Analysis

- With edge addition rewrite systems

Path Abbreviations

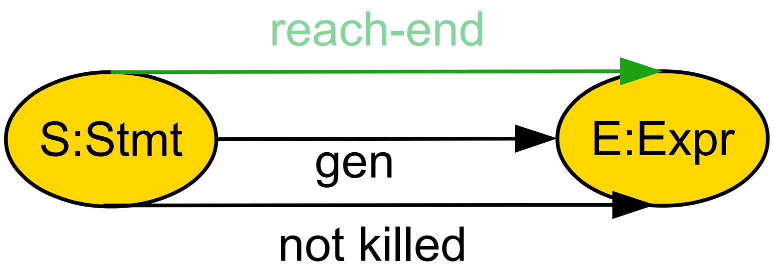
- Path abbreviations shorten paths in the manipulated graph.
- They may collect nodes into the neighborhood of other nodes.
- Ex.: Collection of Expressions for a procedure: edge addition

```
-- Datalog notation:
AllExprs(Proc,Expr) :-
    Blocks(Proc,Block),
    Stmts(Block,Stmt),
    Exprs(Stmt,Expr).
-- if-then rules:
if  Blocks(Proc,Block),
    Stmts(Block,Stmt),
    Exprs(Stmt,Expr)
then
   AllExprs(Proc,Expr);
– regular expression notation (TGreQL):
AllExprs := Proc Blocks.Stmts.Exprs Expr
```

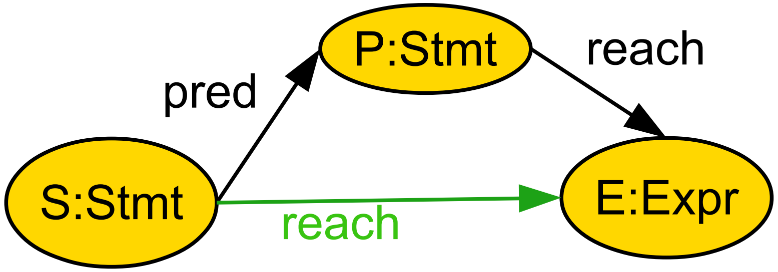


Transitive Closure

- Reachability most often can be reduced to transitive closure
- “Does an Stmt S reach a expression E?”
- Left or right recursion in F-Datalog
- Kleene * in TgreQL
- Thick arrow in Fujaba




```
// TGreQL
reach*(S:Stmt,E:Expr)
```

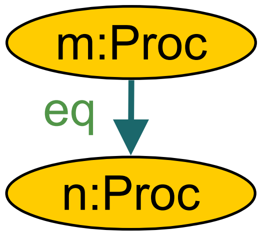



```
// F-Datalog
reach(S:Stmt,E:Expr) :- gen(S:Stmt,E:Expr), not killed(S:Stmt,E:Expr).
reach(S:Stmt,E:Expr) :- pred(S:Stmt,P), reach(P,E:Expr).
```

Relating Nodes into Equivalence Classes

- Ex.: Computing equivalent nodes
- Context-sensitive problem, because m is not in the context of n

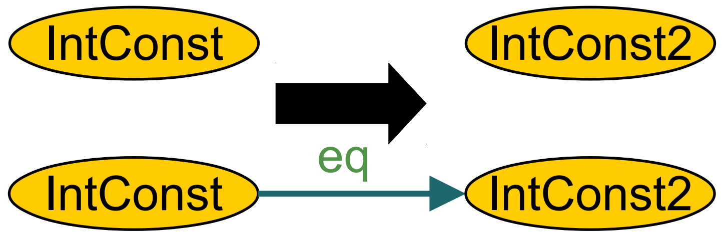
```
baserule:
eq(m:Proc,n:Proc) :-
   m.name != n.name.


–
If (m:Proc, n:Proc) and m.name !=
   n.name)
   eq(m,n)
}
– TgreQL regular expression:
m:Proc eq n.Proc if
m.name != n.name
```



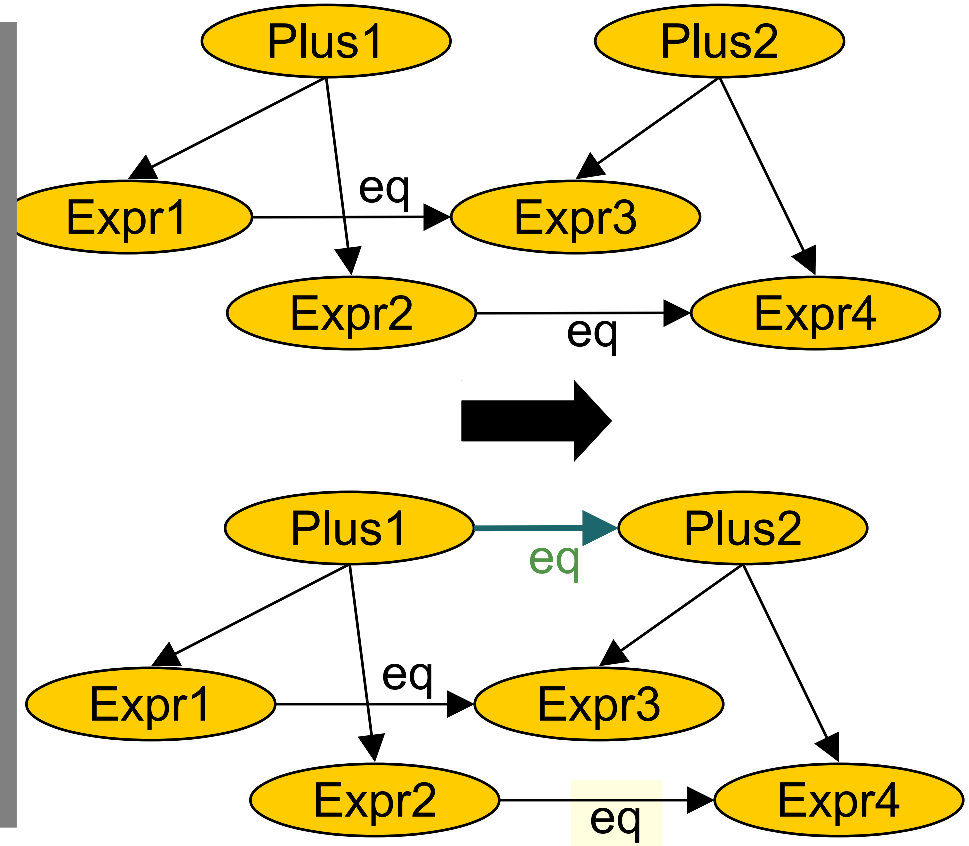
m.name != n.name

Relating Nodes into Equivalence Classes (Here: Value Numbering, Synt. Expression Equivalence)

- Ex.: Computing structurally equivalent expressions




```
baserule:
eq(IntConst1,IntConst2) :-
   IntConst1 ~ IntConst(Value),
   IntConst2 ~ IntConst(Value).
recursive_rule:
eq(Plus1,Plus2) :-
   Plus1 ~ Plus(Type),
   Plus2 ~ Plus(Type),
   Left(Plus1,Expr1),
   Right(Plus1,Expr2),
   Left(Plus2,Expr3),
   Right(Plus2,Expr4).
   eq(Expr1,Expr3),
   eq(Expr2,Expr4).
```



51.3. Data-Flow Analysis as Graph Reachability

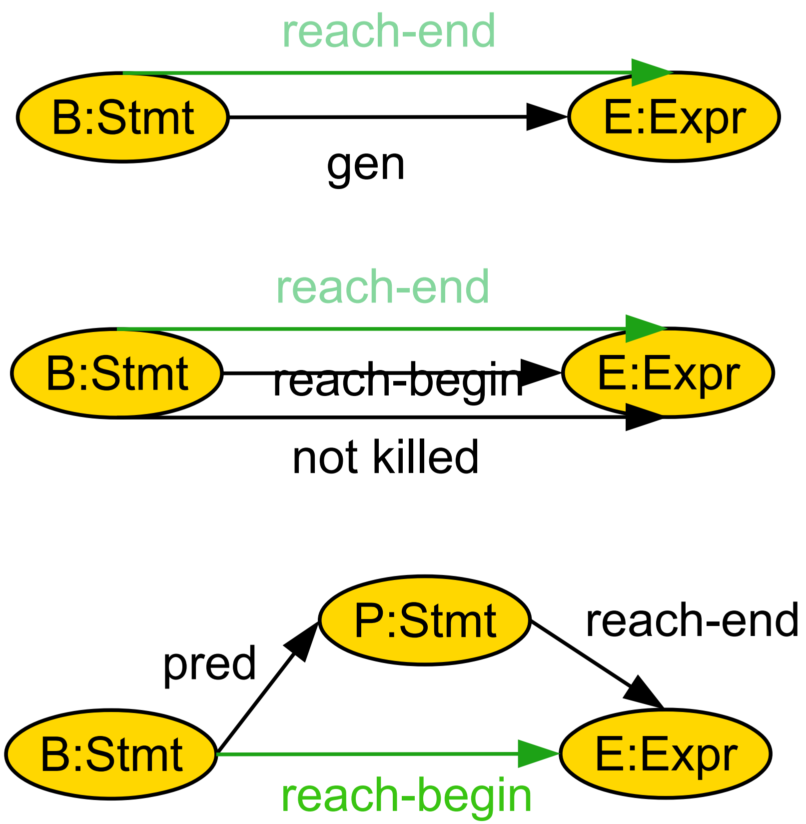
- with edge additions

Data-flow Analysis for Reachability and Traceability

- **Data-flow analysis** is a specific form of abstract interpretation asking **reachability questions**, i.e., computing the flow of data through the program, from variable assignments to variable uses
  - Result: the **value-flow graph (data-flow graph)**
- **Examples of reachability problems:**
- **AllSuperClasses:** find out for a class transitively all superclasses
- **AllEnclosingScopes:** find out for a scope all enclosing scopes
- **Reaching Definitions Analysis:** Which Definitions (Assigments) of a variable can reach which statement?
- **Live Variable Analysis:** At which statement is a variable live, i.e., will further be used?
- **Busy Expression Analysis:** Which expression will be used on all outgoing paths?
  - Central part: 1 recursive system

Reaching Definition Analysis

- **Reaching Definitions Analysis:**
  - Which Assigments of a variable can reach which using statement?
  - Which variable definitions reach which expression?
- Graph rewrite rules implement an abstract interpreter
  - On instructions or on blocks of instructions
  - Flow information is expressed with edges of relations “reach-*”
- Recursive system (via edge reach-begin)
  - B reach-end E == E reaches end of block B



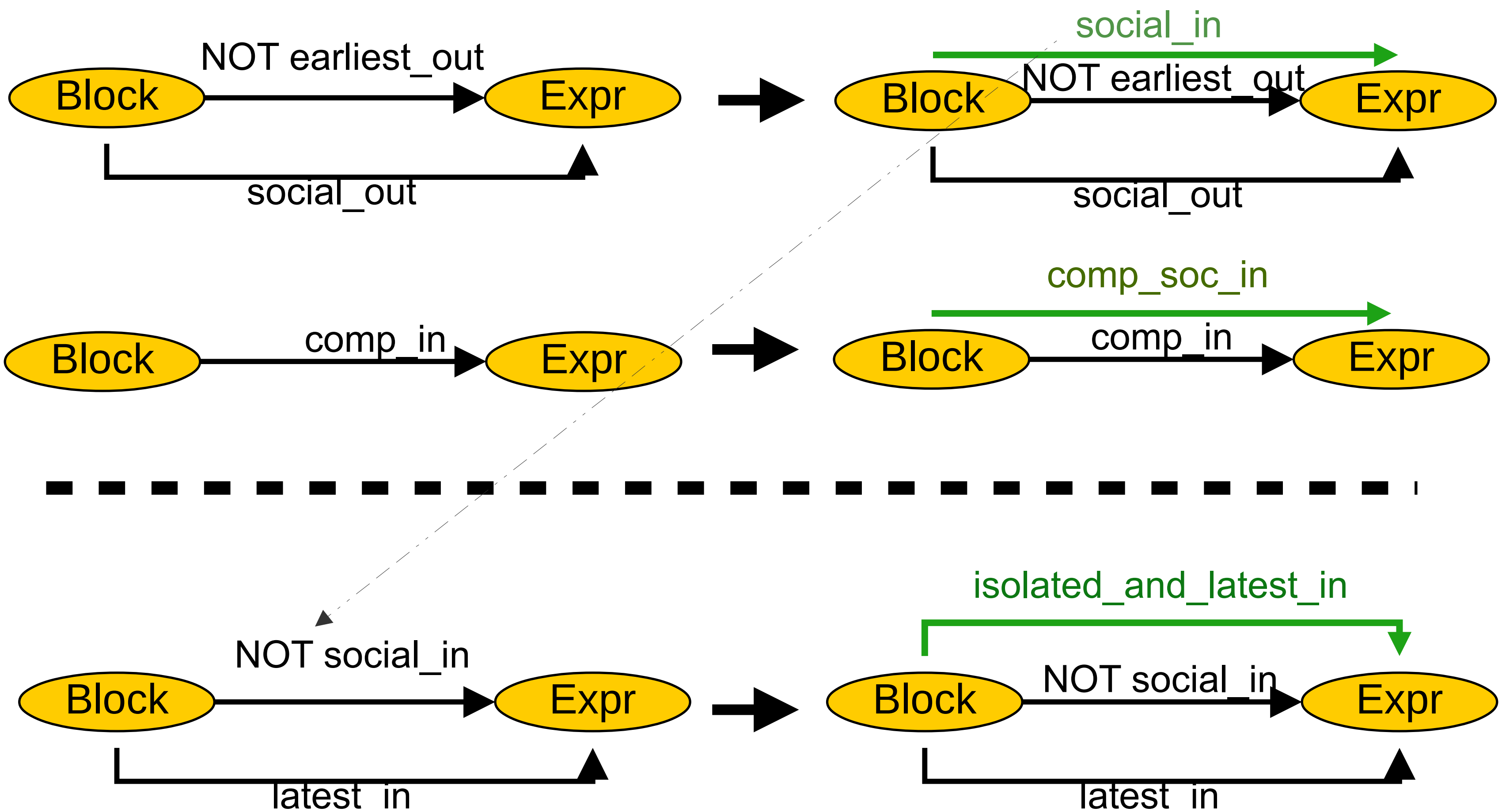

```
reach-end(B,E) :- gen(B,E).
reach-end(B,E) :- reach-begin(B,E), not killed(B,E).
reach-begin(B,E) :-pred(B,P), reach-end(P,E).
```

Code Motion Analysis

- **Code motion** is an essential transformation to speed up the generated code. However, it is a complex transformation:
  - Discovering loop-invariant expressions by data-flow analysis
  - Moving loop-invariant expressions out of loops upward
  - Code motion needs complex data-flow analysis
- **Busy Code Motion (BCM)** moves expressions as upward (early) as possible
- **Lazy Code Motion (LCM)**
  - Moving expressions out of loops to the front of the loop, upward, but carefully:
  - Moving expressions to an optimal place so that register lifetimes are shorter and not too long (optimally early)
  - LCM analysis computes this optimal early place of an expression [Knoop/Steffen]
    - Analyze an optimally early place for the placement of an expression
    - About 6 equation systems similar to reaching-definitions
  - Every equation system is an EARS

Excerpt from LCM Analysis with Overlaps

- Compute an optimally early block for an expression (out of a loop)

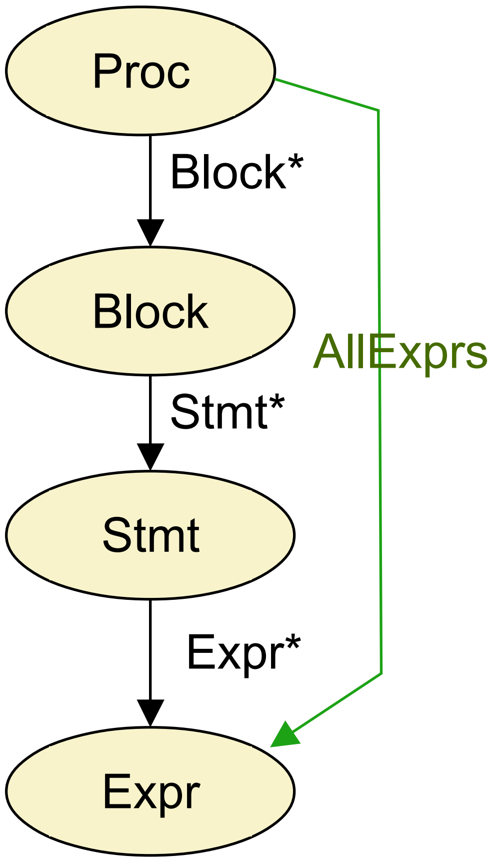


51.3 Regular Graph Reachability

Regular Graph Reachability

- If the query can be expressed as a regular expression, the query is a **regular graph reachability problem**
- Kleene star is used as transitive closure operator
- TqreQL and Fujaba are languages offering Kleene *

```
-- F-Datalog notation:
AllExprs(Proc,Expr) :-
    Block*(Proc,Block),
    Stmt*(Block,Stmt),
    Expr*(Stmt,Expr).
-- if-then rules:
if  Block*(Proc,Block),
    Stmt*(Block,Stmt),
    Expr*(Stmt,Expr)
then
   AllExprs(Proc,Expr);
– regular expression notation (TGreQL):
AllExprs := Proc Block*.Stmt*.Expr* Expr
```



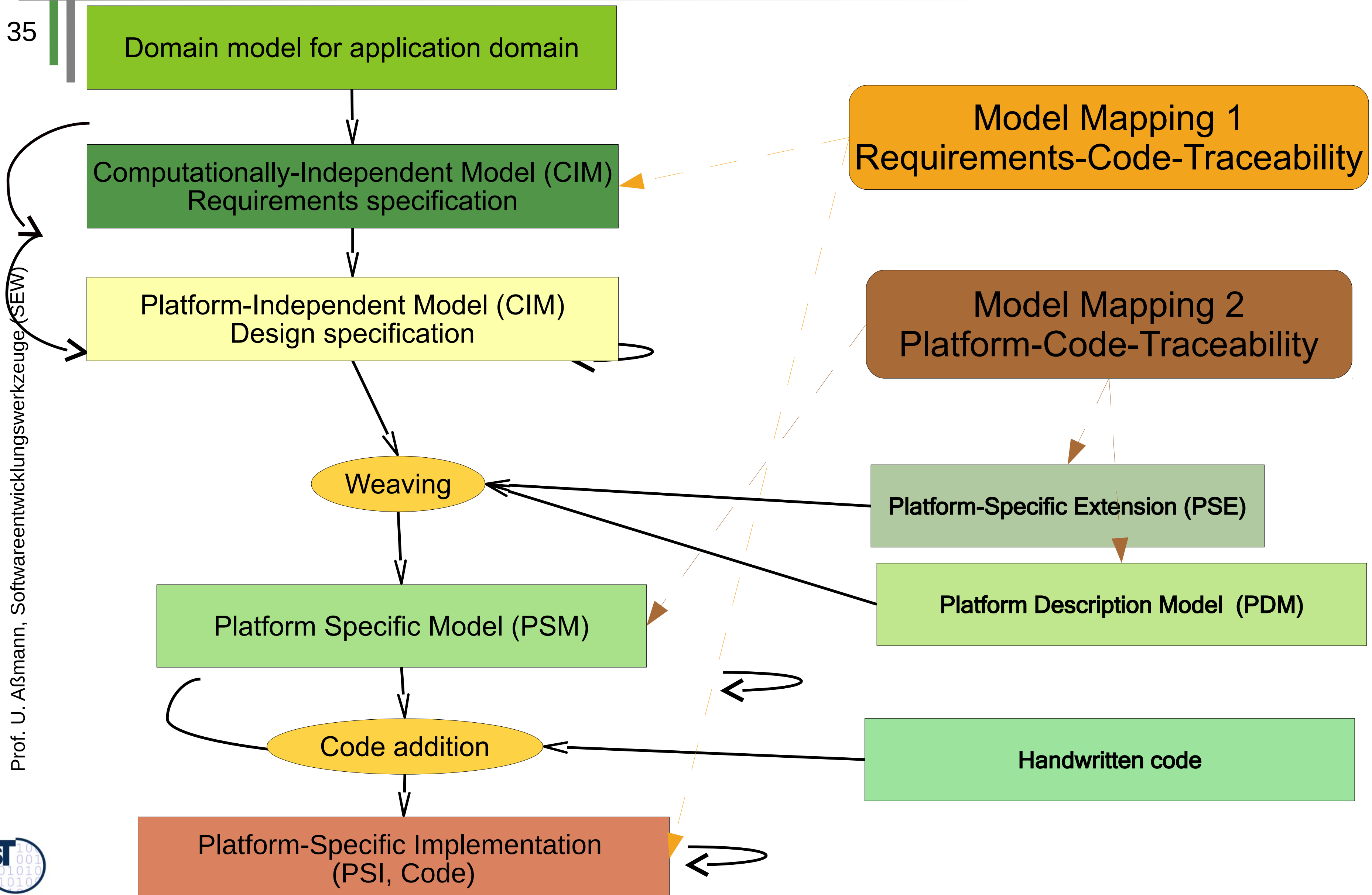
51.3.1 Static Slicing: Single-Source-Multiple-Target Regular Reachability

- [Weiser] [Tip]
- A **static slice** is the region of a program or model reached from *one source* node by a regular reachability query
- A **forward slice** is a region in forward direction of the program
  - The uses of a variable
  - The callees of a call
  - The uses of a type
- A **backward slice** is a region in backward direction of the program
  - The assignments which can influence the value of a variable
  - The callers of a method
  - The type of a variable
- A static slice introduces path abbreviations from one entity to a region
- Slicing can map arbitrary entities in programs and models to other entities, based on a regular graph expression

Traceability between Models

- Data-flow analysis (graph reachability, slicing) can be done
  - intraprocedurally
  - Interprocedurally (program-wide)
  - intermodel: then it creates trace relations
  - interspecification: between requirements models, design models, and code models
  - Inter-MDA
- **Traceability** is intermodel slicing and graph reachability
- A **model mapping** is an intermodel trace graph

Application of Traceability: Model Mappings and Model Weavings



51.3.2 Context-Free Graph Reachability

- F-Datalog and EARS can describe other recursions than regular ones (linear recursions)
  - Context-free recursions
  - Cross-recursions
- Then, we speak of **context-free graph reachability**
  - A context-free language describes graph reachability
- Application: interprocedural, whole-program analysis (see separate optional chapter)
  - Interprocedural IDFS framework (Reps)

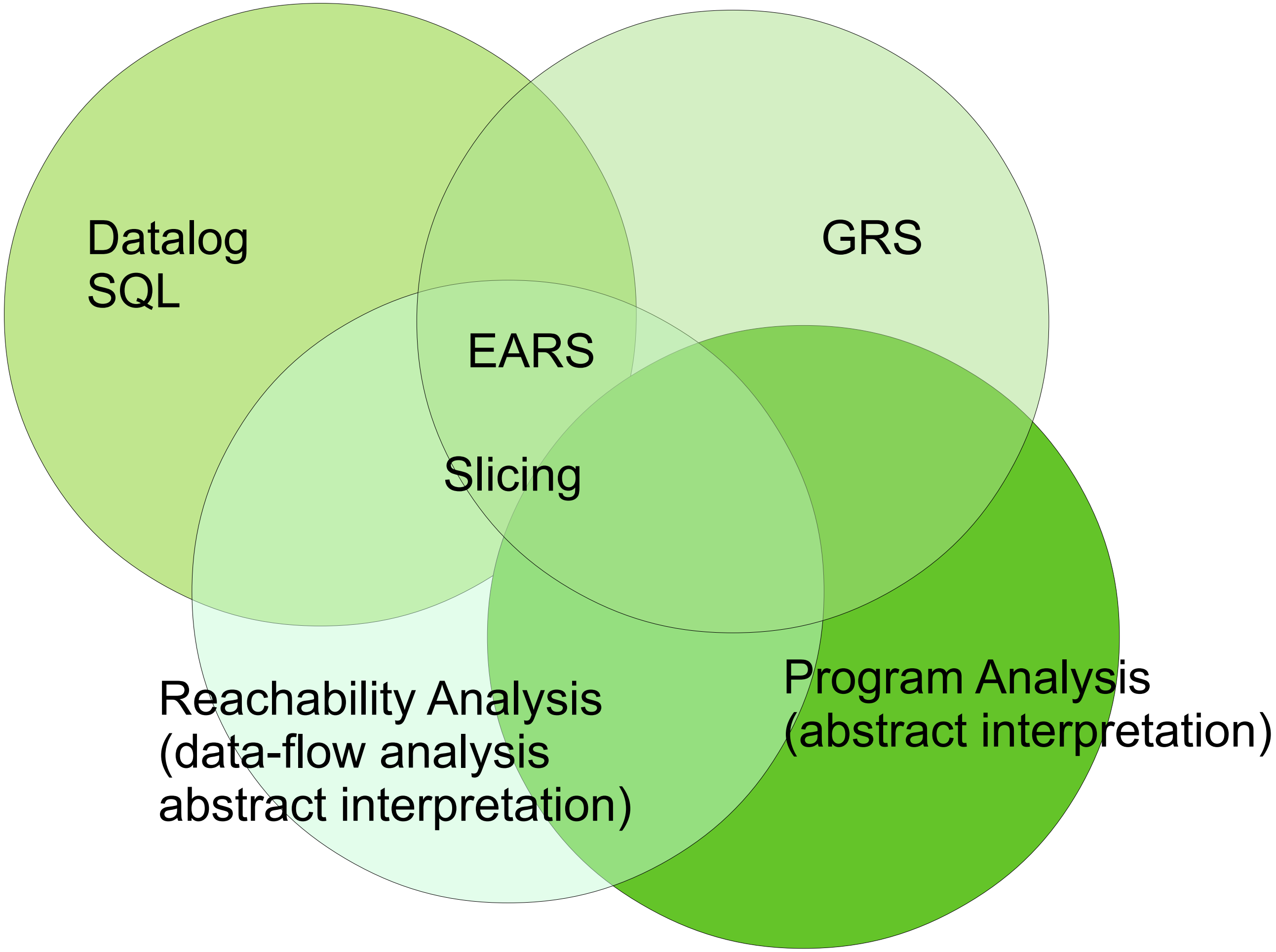
51.4 More on the Logic-Graph Isomorphism

Program and Model Analyses Covered by Graph Reachability

- Reachability Analysis is a simple form of abstract interpretation
  - Slicing is a Single-Source-Multiple-Target reachability analysis
- Every abstract interpretation where a mapping of the abstract domains to graphs can be found.
  - monotone and distributive data-flow analysis
    - control flow analysis
    - SSA construction
    - Interprocedural IDFS framework (Reps)

The Common Core of Logic, Graph Rewriting and Program Analysis

- Graph rewriting, DATALOG and data-flow analysis have a common core: EARS



Relation DFA/DATALOG/GRS

- Abstract interpretation (Data-flow analysis), DATALOG and graph rewrite systems have a common kernel: EARS
  - As DATALOG, graph rewrite systems can be used to query the graph.
- Contrary to DATALOG graph rewrite systems materialize their results instantly.
  - Graph rewriting is restricted to binary predicates and always yields all solutions.
- Graph rewriting can do transformation, i.e. is much more powerful than DATALOG.
  - Graph rewriting enables a uniform view of the entire optimization process
  - There is no methodology on how to specify general abstract interpretations with graph rewrite systems
  - In interprocedural analysis, instead of chaotic iteration special evaluation strategies must be used [Reps95] [Knoop92].
  - Currently strategies have to be modeled in the rewrite specifications explicitly.

Relation DFA/DATALOG/GRS

- Uniform Specification of Analysis and Transformation
  - If the program analysis (including abstract interpretation) is specified with GRS
  - It can be unified with program transformation

51.5 Implementation in Tools

Efficient Evaluation Algorithms from Logic Programming

- Tool OPTIMIX uses the „Order algorithm“ scheme [Aßmann00]
  - Variant of nested loop join
  - Easy to generate into code of a programming language
  - Works effectively on very sparse directed graphs
  - Sometimes fixpoint evaluations can be avoided
  - Use of index structures possible
  - Linear bitvector union operations can be used
- F-DATALOG optimization techniques can be employed
  - Bottom-up evaluation is normal, as in F-Datalog
  - Top-down evaluation as in Prolog possible, with resolution
  - semi-naive evaluation
  - index structures
  - magic set transformation
  - transitive closure optimizations

Related Tools

- Fujaba and MOFLON graph rewrite systems
  - TGG for Model Mapping
  - QVT Relational is very similar to TGG
  - See chapter MOFLON and course ST-II
- AGG graph rewrite system (From Berlin)
- VIATRA2 graph rewrite system
- Program Analysis Generators
  - PAG (Alt, Martin)
  - Sharlit (Tijang)
  - MetaFrame with modal logic (Knoop, Steffen)
  - Slicing-Tools (Reps, Field/Tip, Kamkar)

The End - Appendix Comprehension Questions

- Explain program slicing
- Why is regular graph reachability “regular”?
- How do you create a model mapping with regular graph reachability?
- Explain a typical data-flow analysis

Terminology for Automated Graph Rewriting and Graph Reachability

- **Graph rewrite rule:** rule (left, right hand side) to match left-hand side in the graph and to transform it to the right-hand side
- **Graph rewrite system:** set of graph rewrite rules
- **Start graph (axiom):** input graph to rewriting
- **Graph rewrite problem:** a graph rewrite system applied to a start graph
- **Manipulated graph (host graph):** graph which is rewritten in graph rewrite problem
- **Redex**: (reducible expression) application place of a rule in the manipulated graph
- **Derivation:** a sequence of rewrite steps on the manipulated graph, starting from the start graph and ending in the normal form
- **Normal form:** result graph of rewriting; manipulated graphs without further redex
- **Unique normal form:** unique result of a rewrite system, applied to one start graph
- **Terminating GRS:** rewrite system that stops after finite number of rewrites
- **Confluent GRS:** two derivations always can be commuted, resp. joined together to one result
- **Convergent GRS:** rewrite system that always yields unique results (terminating and confluent)