TECHNISCHE UNIVERSITÄT DRESDEN

Fakultät Informatik, Institut für Software- und Multimediatechnik, Lehrstuhl für Softwaretechnologie

13) Validation of Graph-Based Models and Programs (Analysis and Consistency of Models)

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- Gruppe Softwaretechnologie
- http://st.inf.tu-dresden.de/teaching/swt2
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Contents

- Different kinds of relations: Lists, Trees, DAGs, Graphs
- The **graph-logic isomorphism**
- Analysis, querying, searching graph-based models
  - The “Same Generation” Problem
  - Datalog and Edge Addition Rewrite Systems (EARS)
  - Transitive Closure
- Consistency checking of graph-based specifications (aka model validation)
  - Projections of graphs
  - Transformation of graphs

- Understand that software models can become very large
  - the need for appropriate techniques to handle large models
  - the need for automatic analysis of the models

- Learn how to use graph-based techniques to analyze and check models for consistency, well-formedness and integrity
  - Datalog,
  - Graph Query Languages,
  - Description Logic,
  - Edge Addition Rewrite Systems and
  - Graph Transformations.

- Understand some basic concepts of simplicity in software models

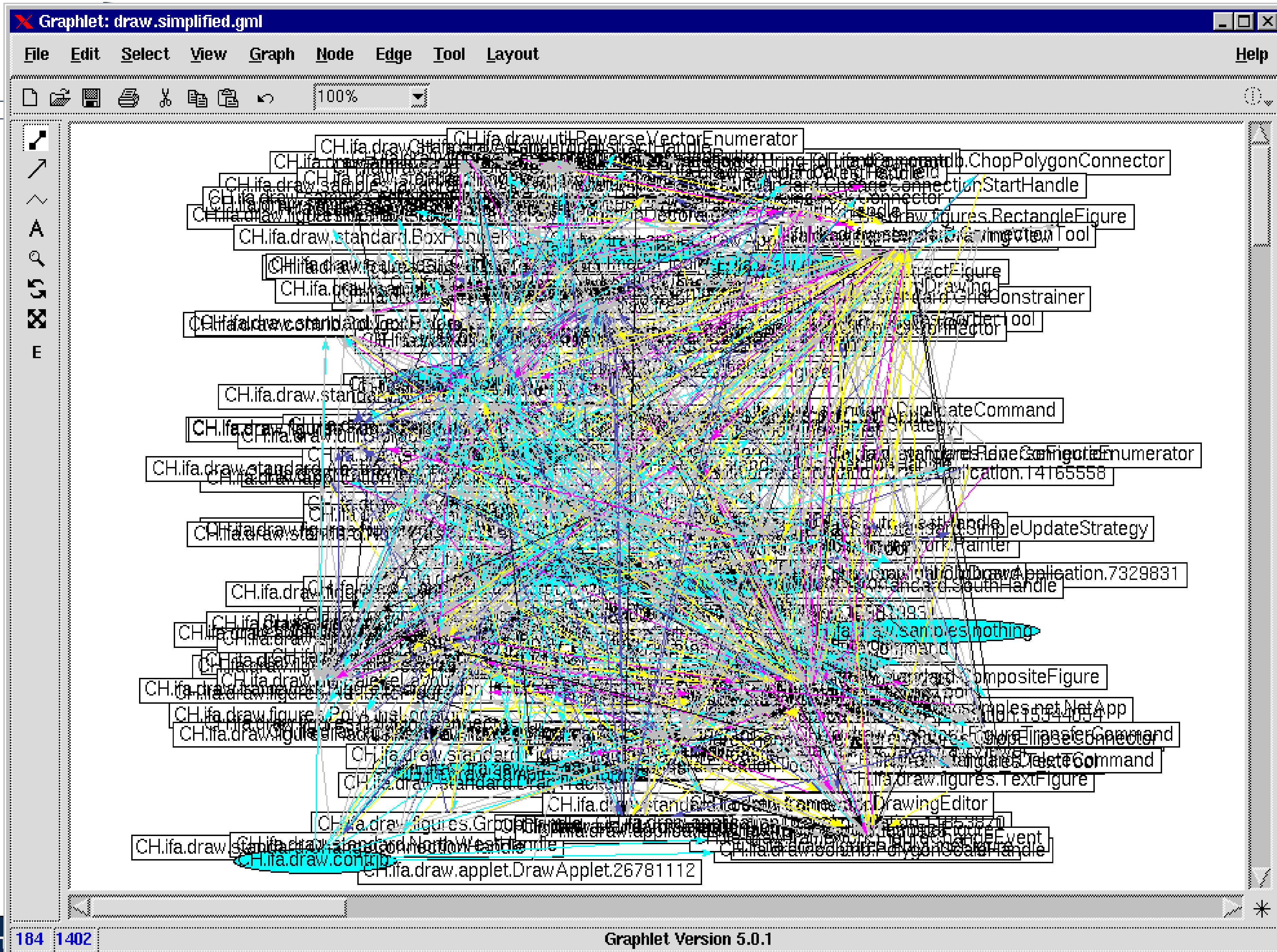
- Software engineers must be able to
  - handle ***big*** design specifications (design models) during development
  - work with ***consistent*** models
  - ***measure*** models and implementations
  - ***validate*** models and implementations

- Real models and systems become very complex
- Most specifications are graph-based
  - We have to deal with basic graph theory to be able to measure well

- Large models have large graphs
- They can be hard to understand

Figures taken from Goose Reengineering Tool, analysing a Java class system [Goose, FZI Karlsruhe]

13.1 THE PROBLEM: HOW TO MASTER LARGE MODELS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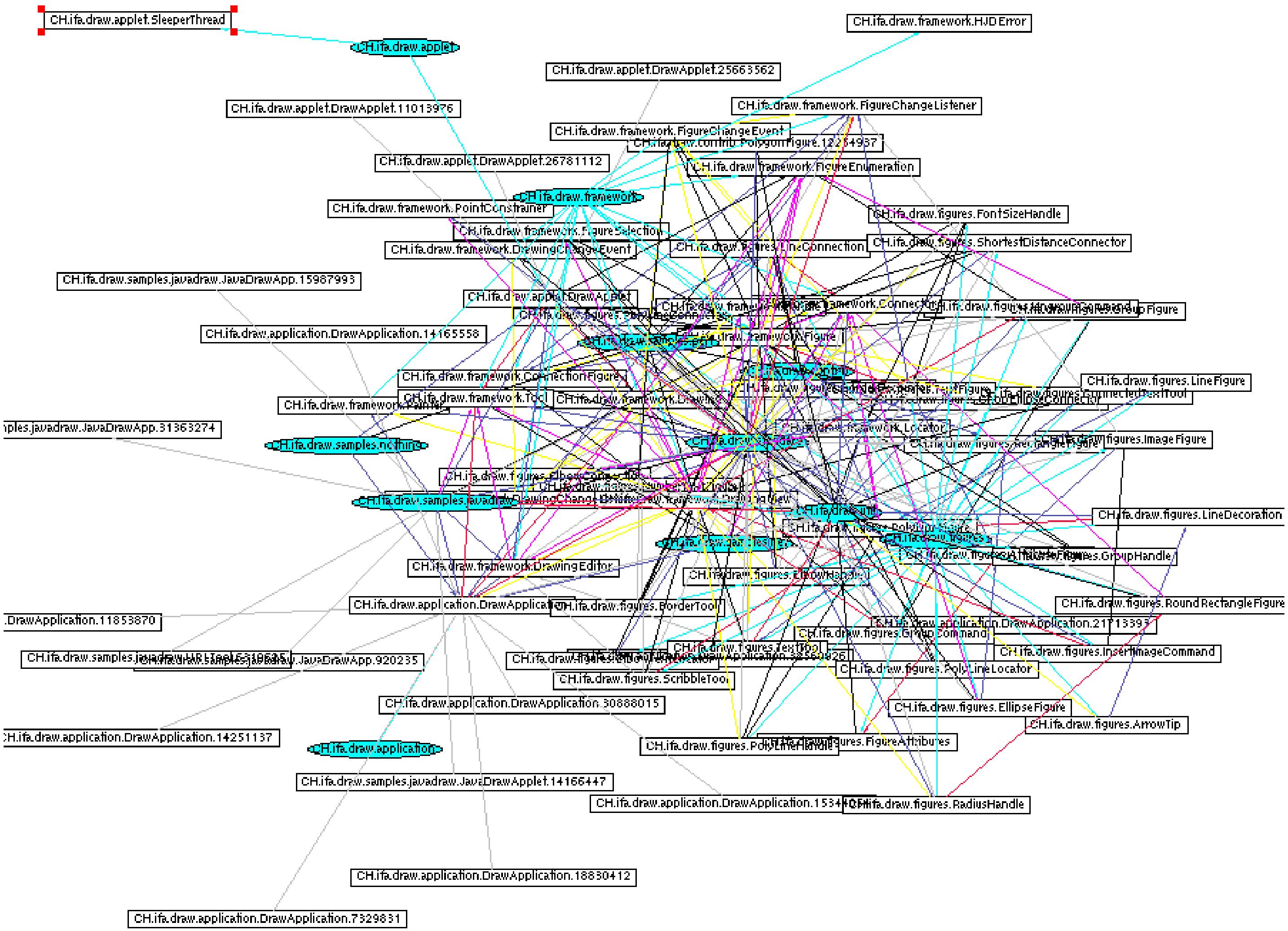

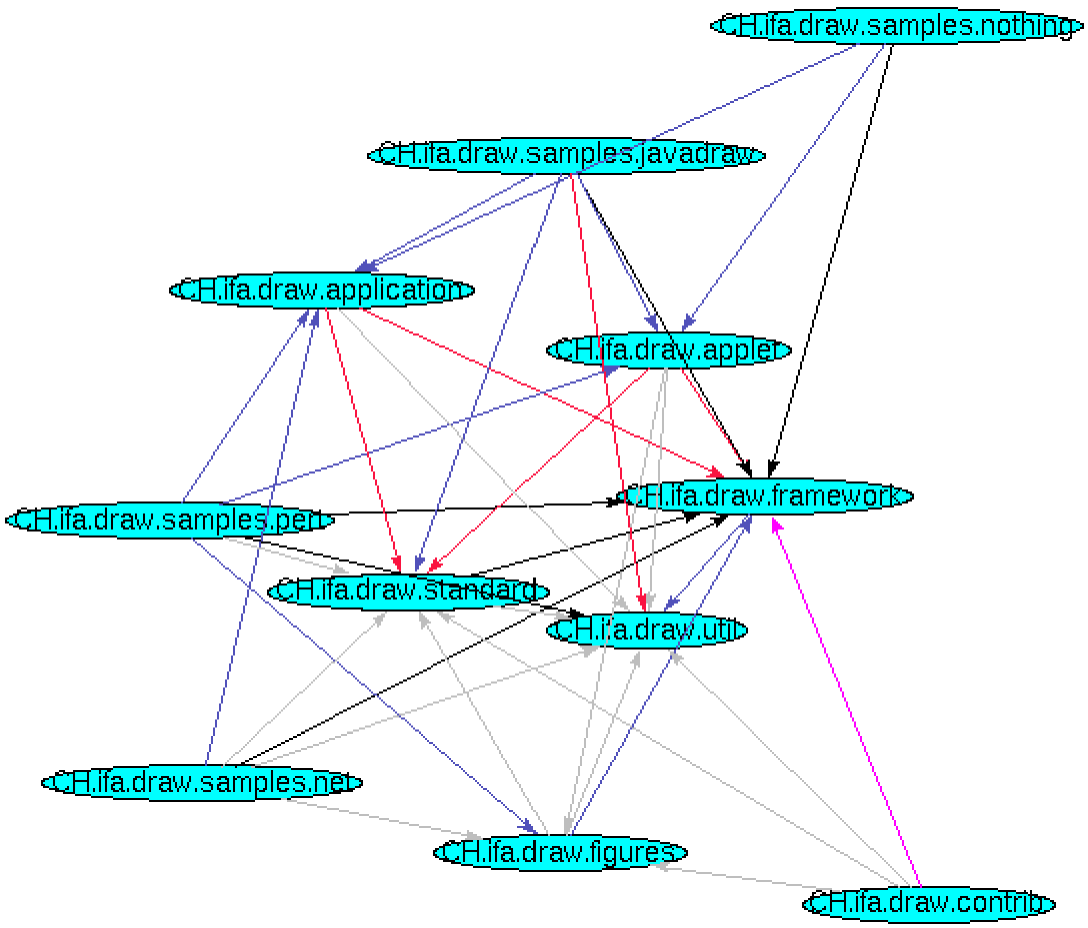
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Requirements for Modeling in Requirements and Design

- We need guidelines how to develop simple models
- We need analysis techniques to
  - Analyze models
    - Find out about their complexity
    - Find out about simplifications
  - Search in models
  - Check the consistency of the models

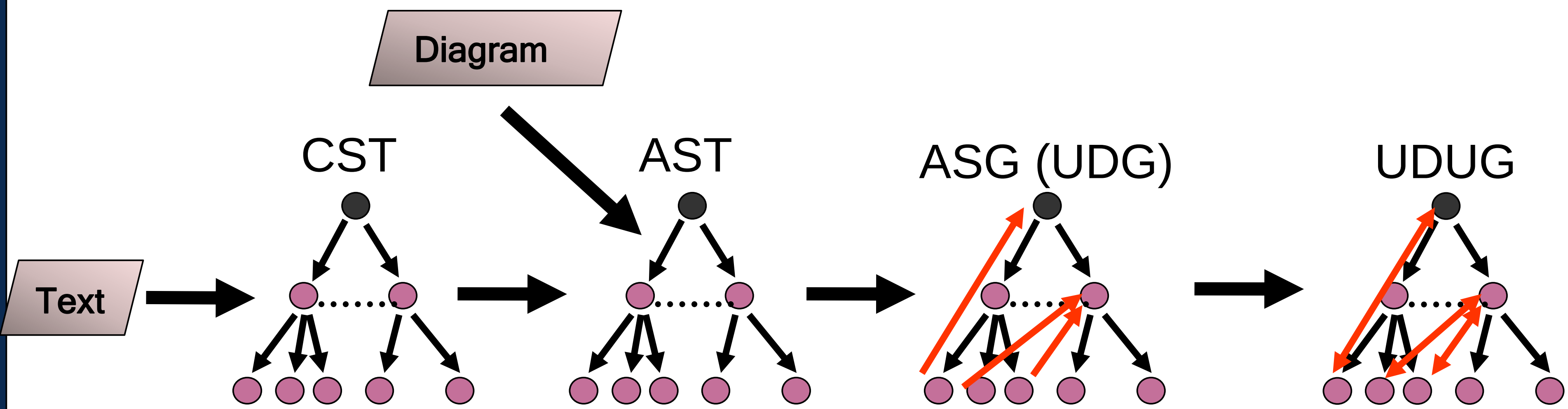
How are models and programs represented in a Software Tool?

Some Relationships (Graphs) in Software Systems

13.2 GENERATING GRAPHS FROM DIAGRAMS AND PROGRAMS

All Specifications and All Programs have an Internal Graph-Based Representation

- Texts are parsed to abstract syntax trees (AST)
  - Two-step procedure
    - Concrete Syntax Tree (CST)
    - Abstract Syntax Tree (AST)
- Through name analysis, they become abstract syntax graphs (ASG) or Use-Def-Graphs (UDG)
- Through def-use-analysis, they become Use-def-Use Graphs (UDUG)

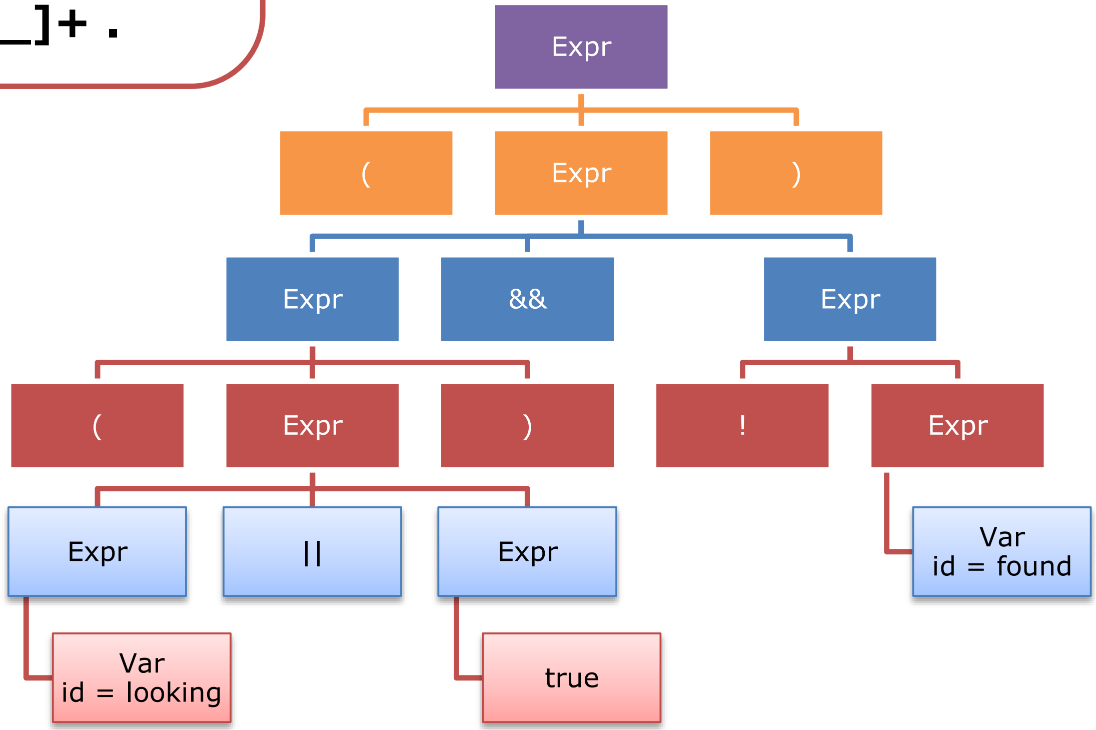


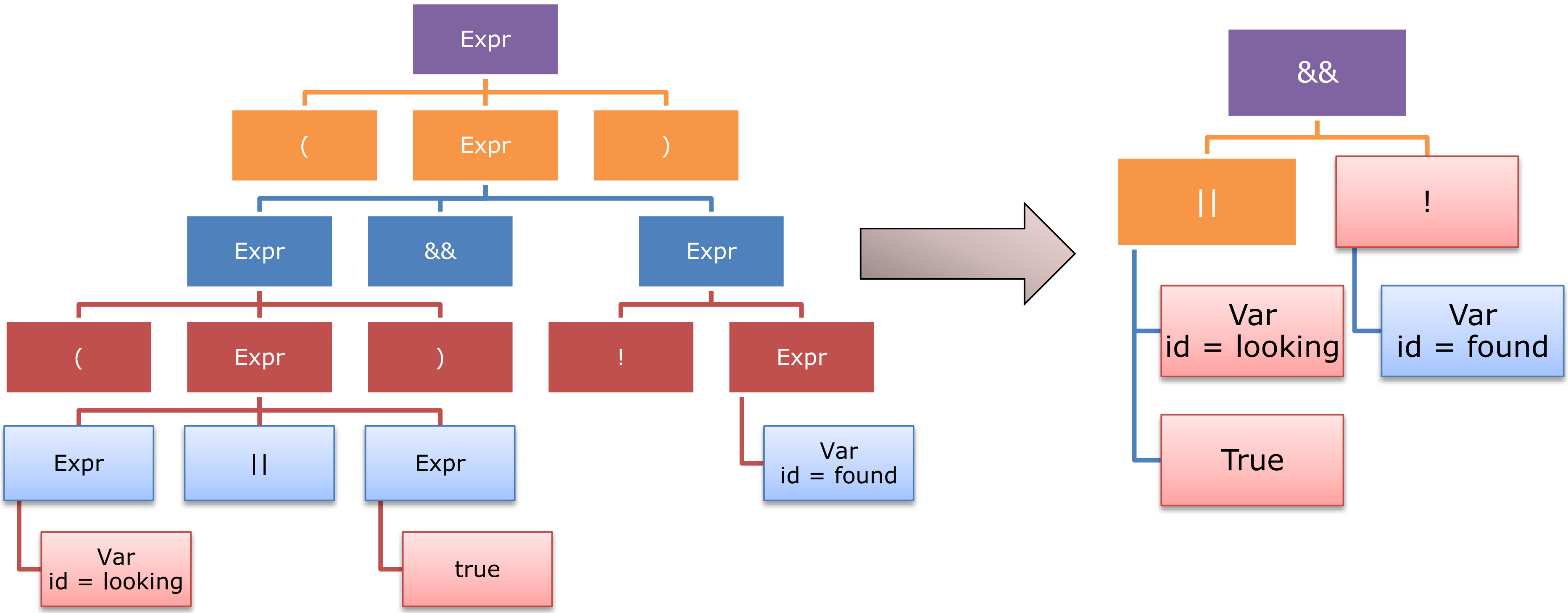
Expr ::= ***'(' Expr ')'***
| Expr ***'&&' Expr***
| Expr '||' expr
| ***'!' Expr***
| Lit .
Lit ::= Var | ***'true'*** **|** ***'false'.***
Var ::= [a-z][a-z 0-9_]+ .

Parsing this string:
((looking || true) && !found)

Expr ::= ‘(’ ***Expr*** ‘)’
| **Expr ‘&&’ *Expr***
| **Expr ‘||’ expr**
| ‘!’ ***Expr***
| **Lit .**
Lit ::= **Var | ‘*true*’ | ‘*false*’.**
Var ::= **[a-z][a-z 0-9_]+ .**

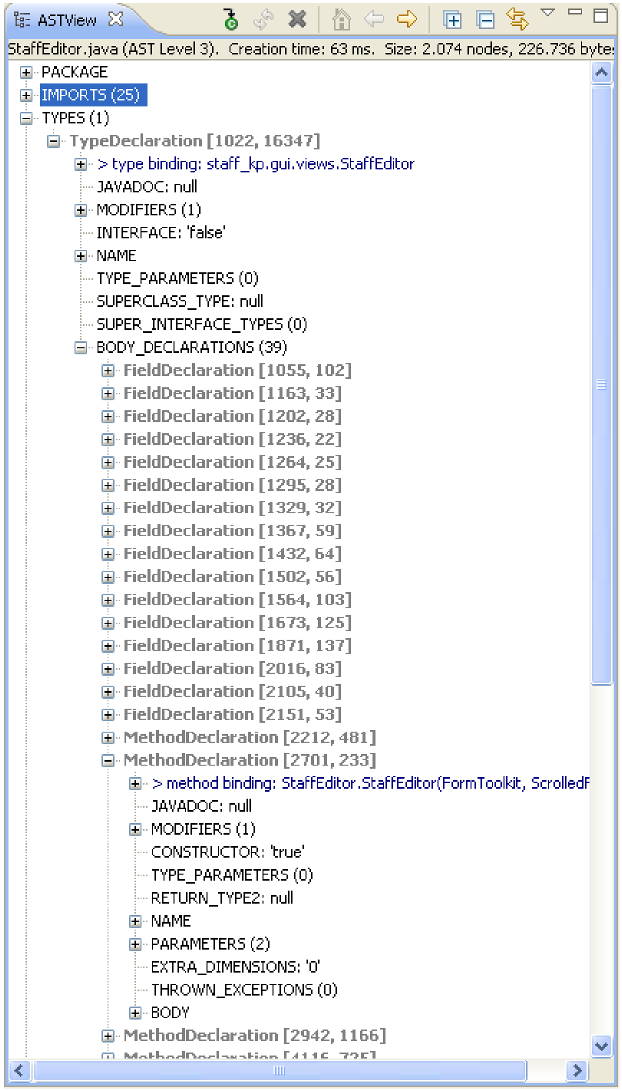
Parsing this string:
((looking || true) && !found)




Expr
(
Expr
)
Expr
&&
Expr
(
Expr
)
!
Expr
Expr
||
Expr
Var
id = found
Var
id = looking
true
&&
||
!
Var
id = looking
Var
id = found
True

Abstract Syntax Trees (AST)

- Parse trees (CST) waste a fair amount of space for representation of terminal symbols and productions
- Compilers post-process parse trees into ASTs
- ASTs are the fundamental data structure of IDEs (ASTView in Eclipse JDT)



- Problem with ASTs: They do not support static semantic checks, re-factoring and browsing operations, e.g.:
  - Name semantics:
    - Have all used variables been declared? Are they declared once?
    - Have all classes used been imported?
  - Are the types used in expressions / assignments compatible? (type checking)
  - Referencing:
    - Navigate to the declaration of method call / variable reference / type
  - How can I pretty-print the AST to a CST again, so that the CST looks like the original CST

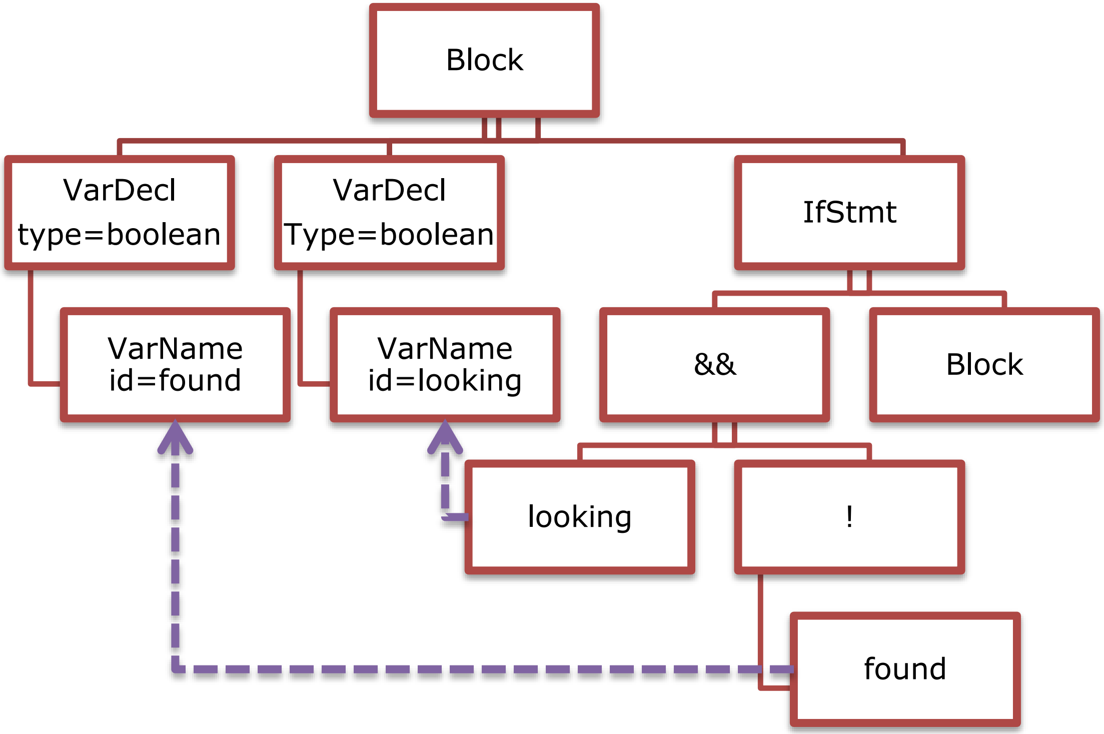
Def-Use Graphs (DUG) and Use-Definition-Use Graphs (UDUG)

- Many languages and notations have
  - ***Definitions*** of items (definition of the variable `Foo`), which specify the type or other metadata
  - ***Uses*** of items (references to `Foo`)
- We talk in specifications or programs about *names of objects* and their use
  - Definitions are done in a data definition language (DDL)
  - Uses are part of a data query language (DQL) or data manipulation language (DML)
- Starting from the abstract syntax tree, *name analysis* finds out about the definitions of uses of names
  - Building the *Use-Def graph*
  - This revolves the meaning of used names to definitions
  - Inverting the Use-Def graph to a Use-Def-Use graph (UDUG)
  - This links all definitions to their uses

Abstract Syntax Graphs (ASG) are UDGs

- Abstract Syntax Graphs have *use-def edges* that reflect semantic relationships
  - from uses of names to definitions of names
- These edges are used for static semantic checks
  - Type checking
  - Type inference

```
boolean looking, found;
...
if (looking && !found ) {...}
```



Refactoring on Complete Name-Resolved Graphs (Use-Def-Use Graphs)

- UDUGs are used in refactoring operations (e.g., renaming a class or a method consistently over the entire program).

- For renaming of a definition, all uses have to be changed, too
  - We need to trace all uses of a definition in the Use-Def-graph, resulting in its inverse, the *Def-Use-graph*
  - Refactoring works always on Def-Use-graphs *and* Use-Def-graphs, the *complete name-resolved graph* (the *Use-Def-Use graphs*)

Refactor the name Person to Human, using bidirectional use-def-use links:

```
class Person { .. }
class Course {
Person teacher = new Person("Jim");
Person student = new Person("John");
}
```

Definition

Reference (Use)

```
class Human { .. }
class Course {
    Human teacher = new Human("Jim");
    Human student = new Human("John");
}
```

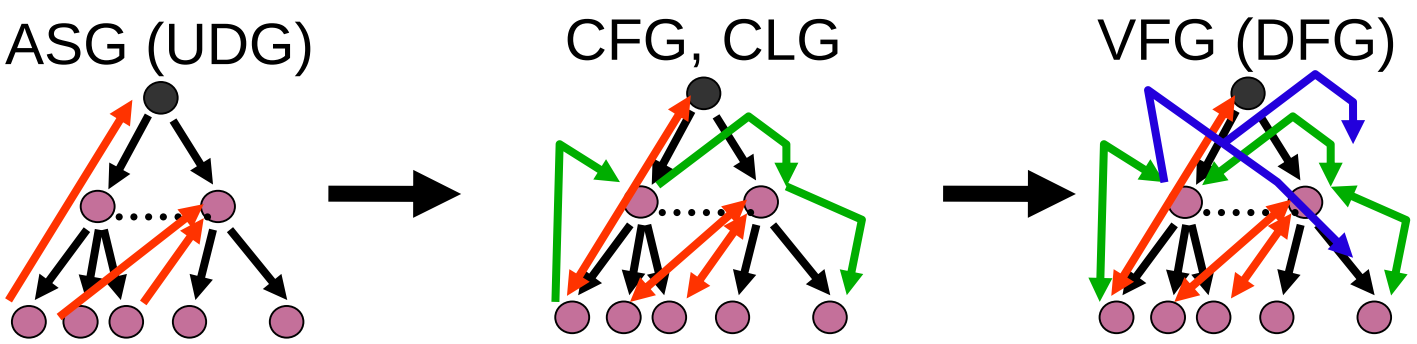
- Refactoring works always in the same way:
  - Change a definition
  - Find all dependent references
  - Change them
  - Recursively handle other dependent definitions
- Refactoring can be supported by tools
  - The Use-Def-Use-graph forms the basis of refactoring tools
- However, building the Use-Def-Use-Graph for a complete program costs a lot of space and is a difficult program analysis task
  - Every method that structures this graph provides a benefit for the refactoring by
    - either simplifying or accelerating it
- UDUGs are large
  - Efficient representation important

From the ASG or an UDUG, more graph-based program representations can be derived

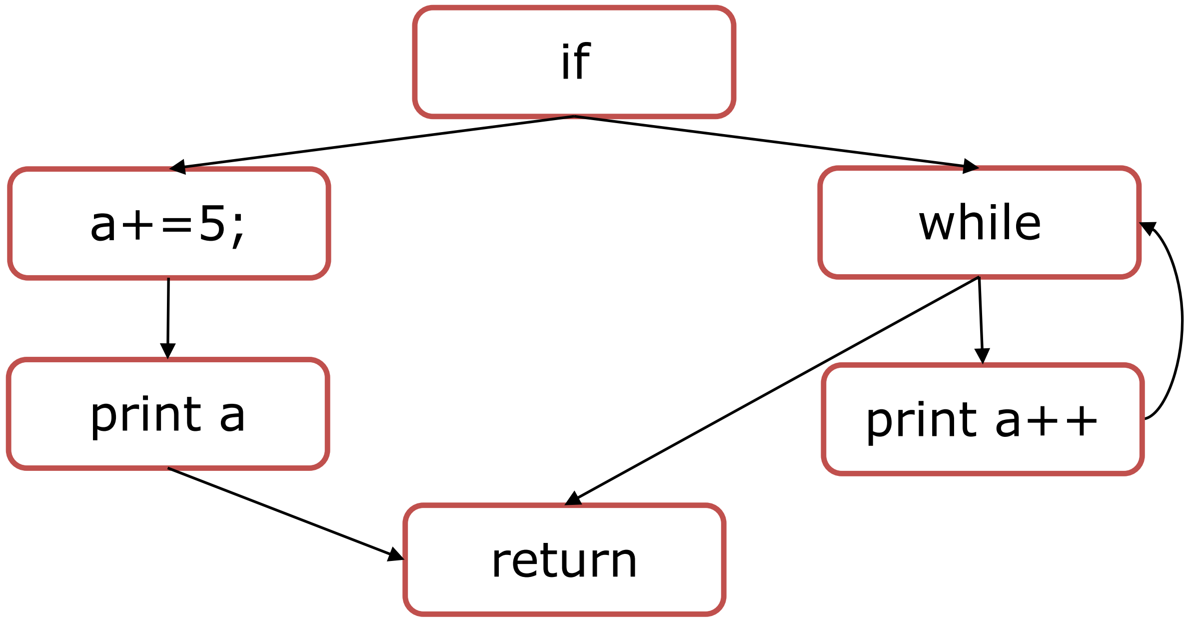
- Control-flow Analysis -> Control-Flow Graph (CFG), Call graph (CLG)
  - Records control-flow relationships
- Data-Flow Analysis -> Data-Flow Graph (DFG) or Value-Flow Graph (VFG)
  - Records flow relationships for data values

The same remarks holds for graphic specifications

- Hence, all specifications are graph-based!



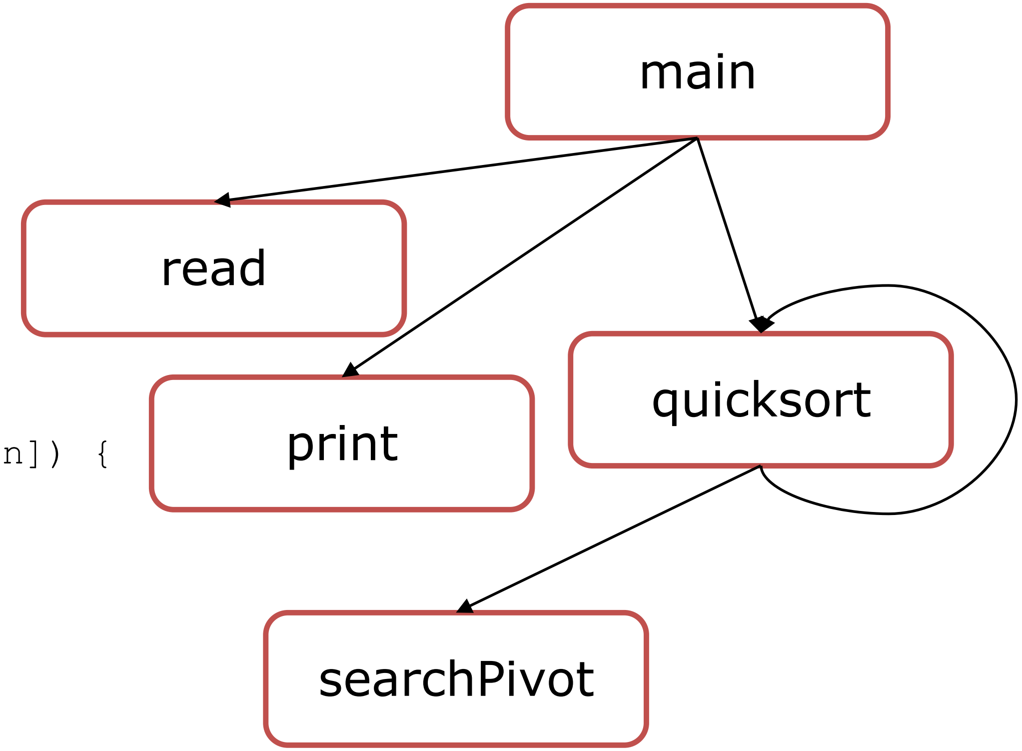
- Describe the control flow in a program
- Typically, if statements and switch statements split control flow
  - Their ends join control flow
- Control-Flow Graphs *resolve* symbolic labels
  - Perform name analysis on labels
- Nested loops are described by nested control flow graphs



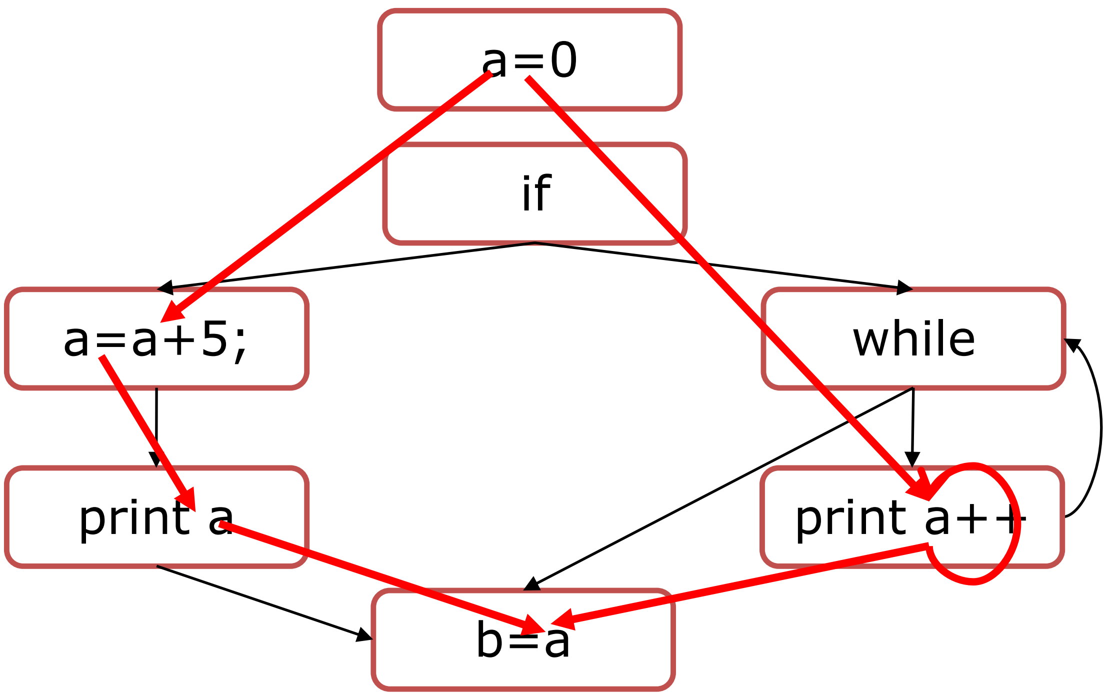
Simple (Flow-Insensitive) Call Graph (CLG)

- Describe the call relationship between the procedures
  - Interprocedural control-flow analysis performs name analysis on called procedure names

```
main = procedure () {
  array int[] a = read();
  print(a);
  quicksort(a);
  print(a);
}
quicksort = procedure(a: array[0..n]) {
  int pivot = searchPivot(a);
  quicksort(a[0], a[pivot-1]);
  quicksort(a[pivot+1,n]);
}
```

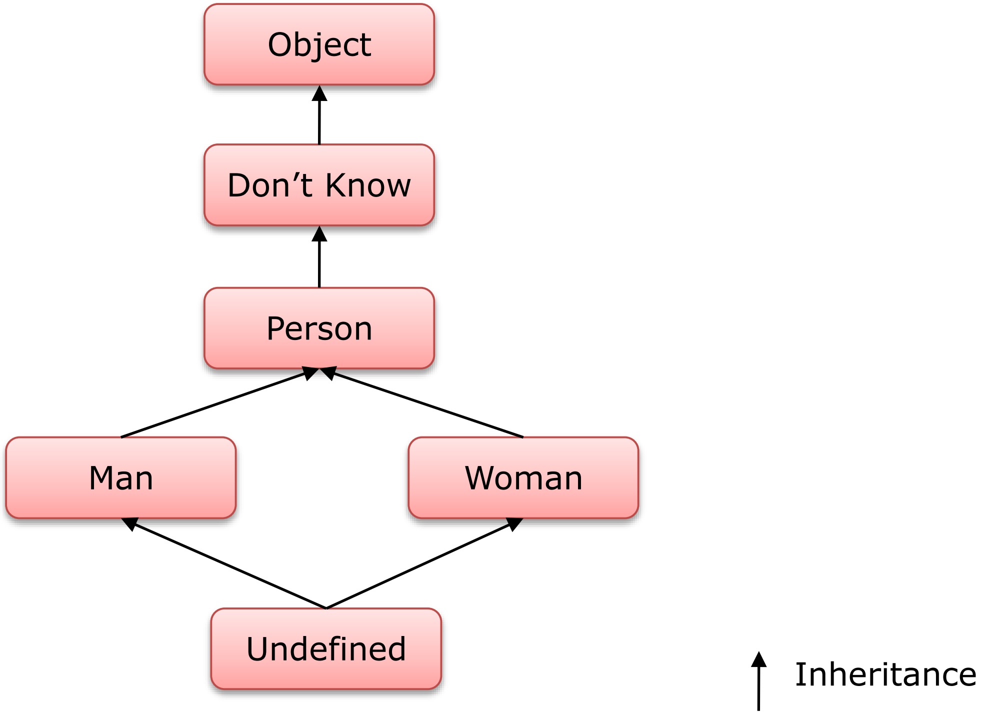


- A *data-flow graph (DFG)* aka *value-flow graph (VFG)* describes the flow of data through the variables
  - DFG are based on control-flow graphs
- Building the data-flow graph is called *data-flow analysis*
  - Data-flow analysis is often done by *abstract interpretation,* the symbolic execution of a program at compile time



Building an Inheritance Tree or Inheritance Lattice

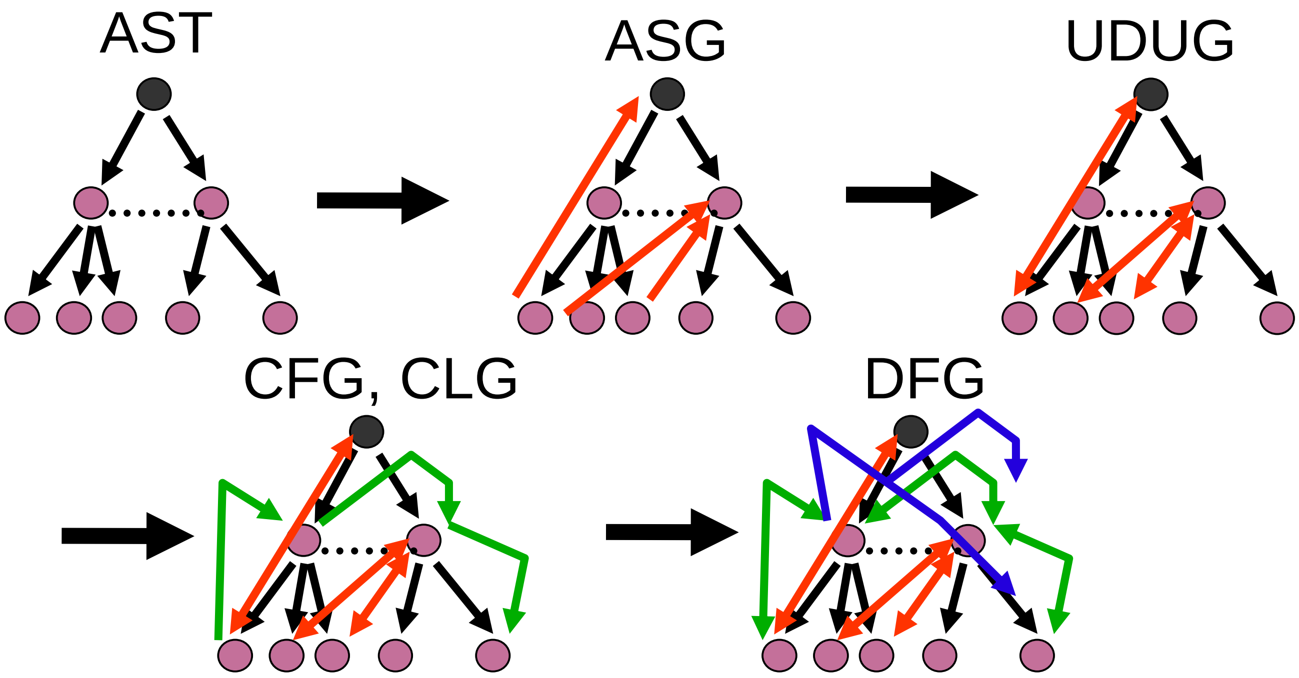
- A *lattice* is a partial order with largest and smallest element
- Inheritance hierarchies can be generalized to inheritance lattices
- An *inheritance analysis* builds the transitive closure of the inheritance lattice



- All diagram sublanguages of UML generate internal graph representations
  - They can be analyzed and checked with graph techniques
  - Graphic languages, such as UML, need a graph parser to be recognized, or a specific GUI who knows about graphic elements

- Hence, graph techniques are an essential tool of the software engineer

- Texts are parsed to abstract syntax trees (AST)
- Graphics are parsed by GUI or graph parser to AS, too.
- Through name analysis, they become abstract syntax graphs (ASG)
- Through def-use-analysis, they become Use-def-Use Graphs (UDUG)
- Control-flow Analysis -> CFG, CLG
- Data-Flow Analysis -> DFG



Lists, Trees, DAGs, Graphs

Structural constraints on graphs

(background information)

13.3 TYPES OF GRAPHS IN SPECIFICATIONS

Modeling Graphs on Two Abstraction Levels

- In modeling, we deal mostly with *directed graphs (digraphs)* representing unidirectional relations
  - lists, trees, DAGs, overlay graphs, reducible (di-)graphs, graphs
- There are two different abstraction levels; we are interested in the logical level:
  - **Logical level** (conceptual, abstract, often declarative, problem oriented)
    - Methods to specify algorithms on graphs:
      - Relational algebra
      - Datalog, description logic
      - Graph rewrite systems, graph grammars
      - Recursion schemas
  - **Physical level** (implementation level, concrete, often imperative, machine oriented)
    - Representations: Data type adjacency list, boolean (bit)matrix, binary decision diagrams (BDDs)
    - Imperative algorithms
    - Pointer based representations and algorithms

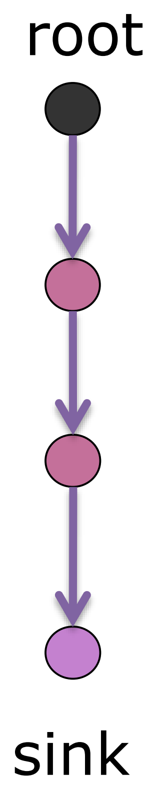
Essential Graph Definitions

- Fan-in
  - In-degree of a node under a certain relation
  - Fan-in(n) = 0: n is *root* node (*source*)
  - Fan-in(n) > 0: n is *reachable* from other nodes
- Fan-out
  - Out-degree of node under a certain relation
  - Fan-out(n) = 0: n is *leaf* node (*sink*)
  - An *inner node* is neither a root nor a leaf
- Path
  - A path $p = (n_1, n_2,\dots,n_k)$ is a sequence of nodes of length k

- One source (root)
- One sink
- Every other node has fan-in 1, fan-out 1

- Represents a *total order* (sequentialization)

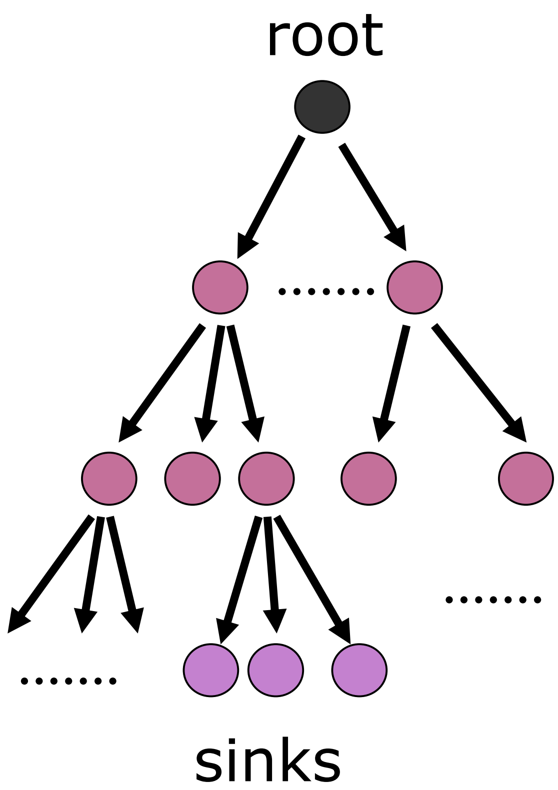
- Gives
  - Prioritization
  - Execution order



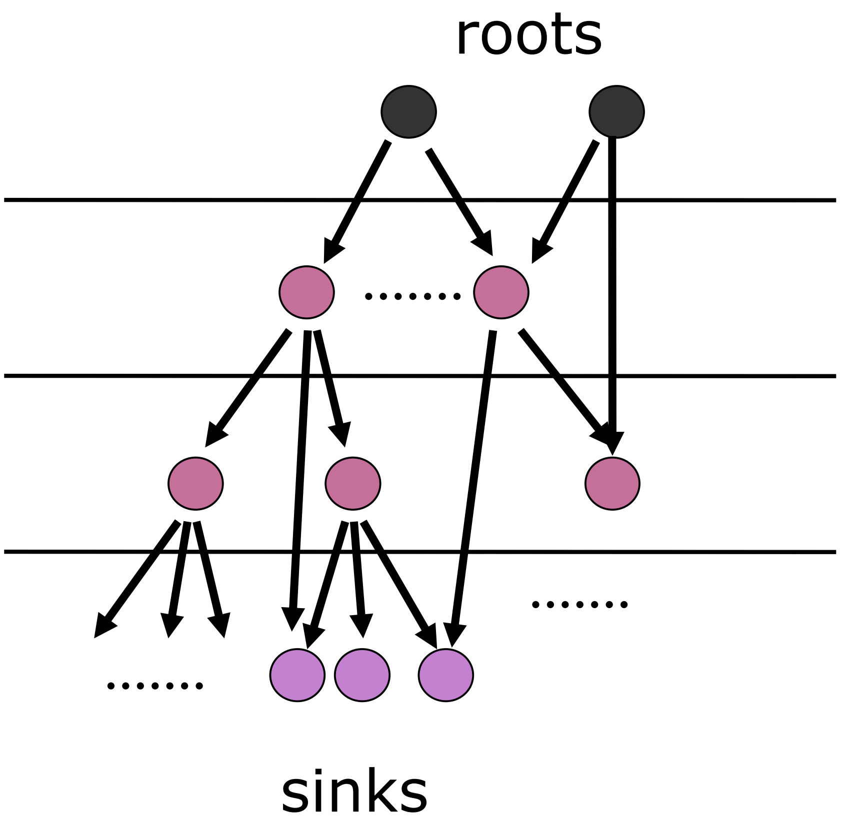
- One source (root)
- Many sinks (leaves)
- Every node has fan-in <= 1

- *Hierarchical abstraction*:
  - A node *represents* or *abstracts* all nodes of a sub tree

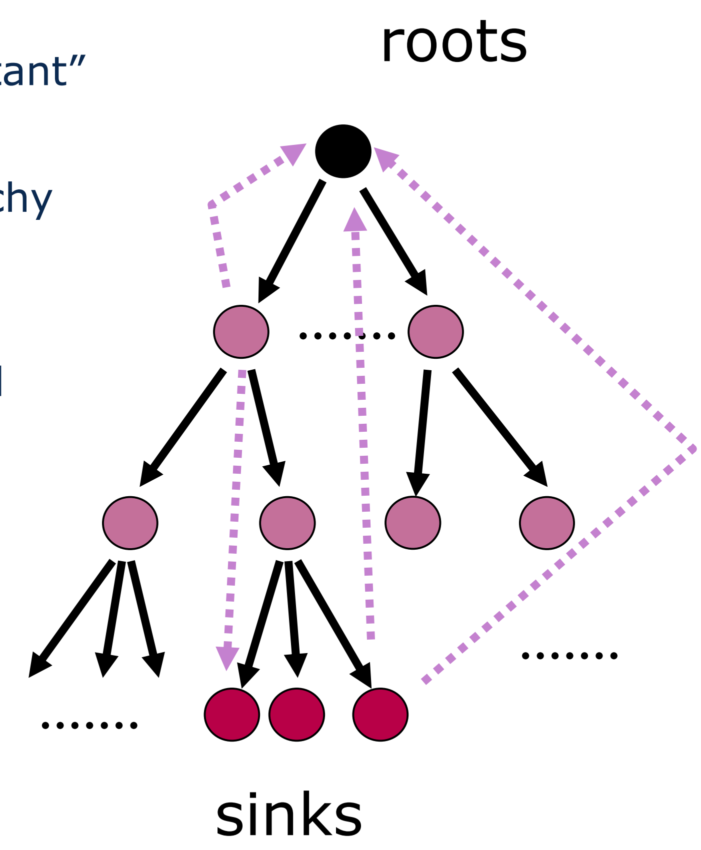
- Example
  - Structured Analysis (SA) function trees
  - Organization trees (line organization)



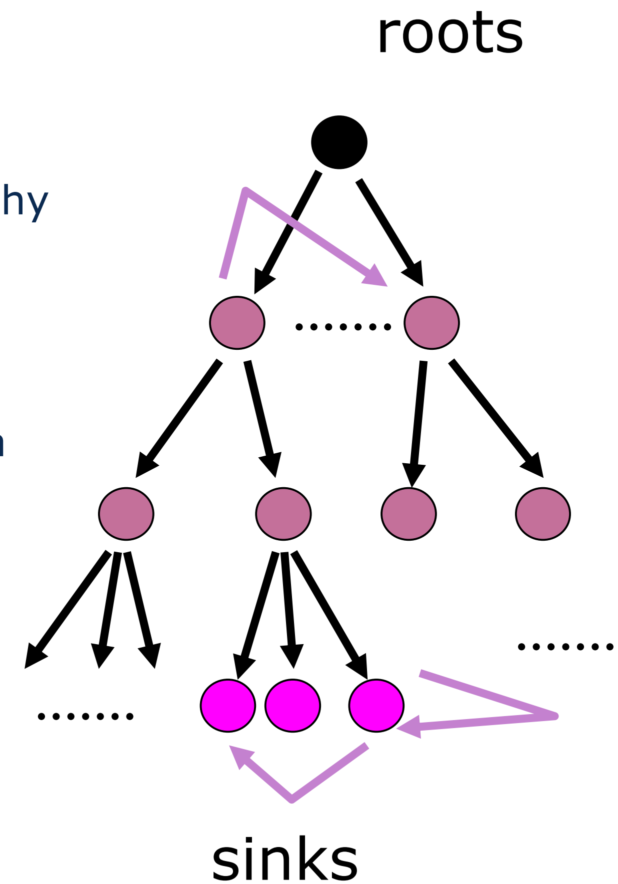
- Many sources
  - A jungle (term graph) is a dag with one root
- Many sinks
- Fan-in, fan-out arbitrary
- Represents a partial order
  - Less constraints than in a total order
- Weaker hierarchical abstraction feature
  - Can be layered
- Example
  - UML inheritance DAGs
  - Inheritance lattices



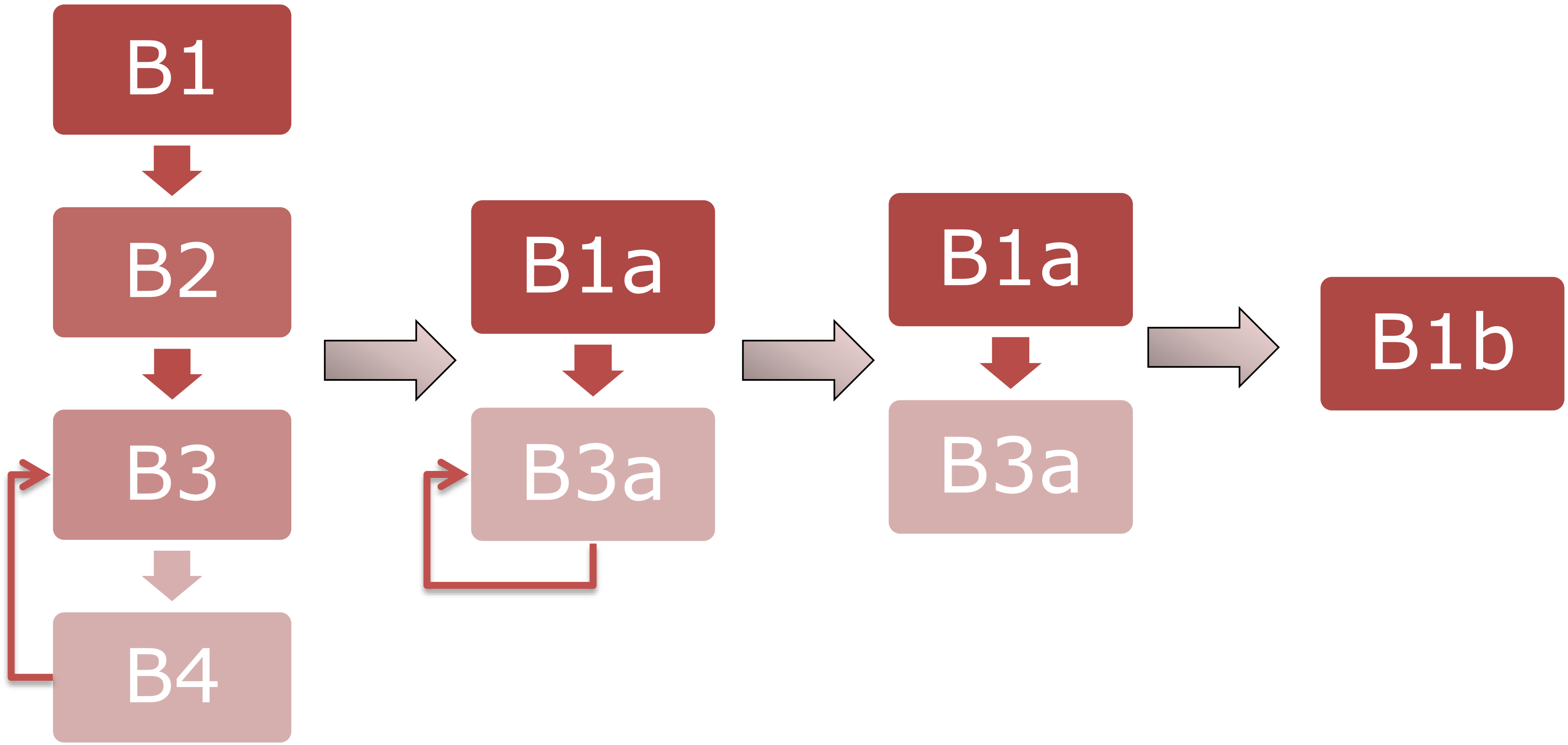
- Skeleton tree with **overlay graph** (secondary links)
  - Skeleton tree is primary
  - Overlay graph is secondary: "less important"
- Advantage of an Overlay Graph
  - Tree can be used as a conceptual hierarchy
  - References to other parts are possible
- Example
  - XML, e.g., XHTML. Structure is described by Xschema/DTD, links form the secondary relations
  - AST with name relationships after name analysis (name-resolved trees, abstract syntax graphs)



- A **reducible graph** is a graph with cycles, however, only between siblings
  - No cycles between hierarchy levels
- Graph can be "reduced" to one node
- Advantage
  - Tree can be used as a conceptual hierarchy
- Example
  - UML statecharts
  - UML and SysML component diagrams
  - Control-flow graphs of Modula, Ada, Java (not C, C++)
  - SA data flow diagrams
  - Refined Petri Nets

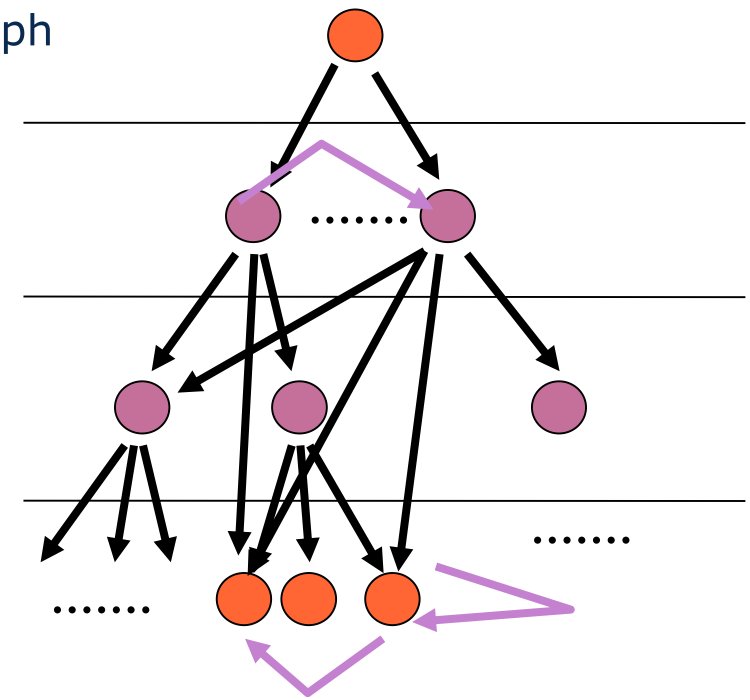


Reduction of a Reducible Graph

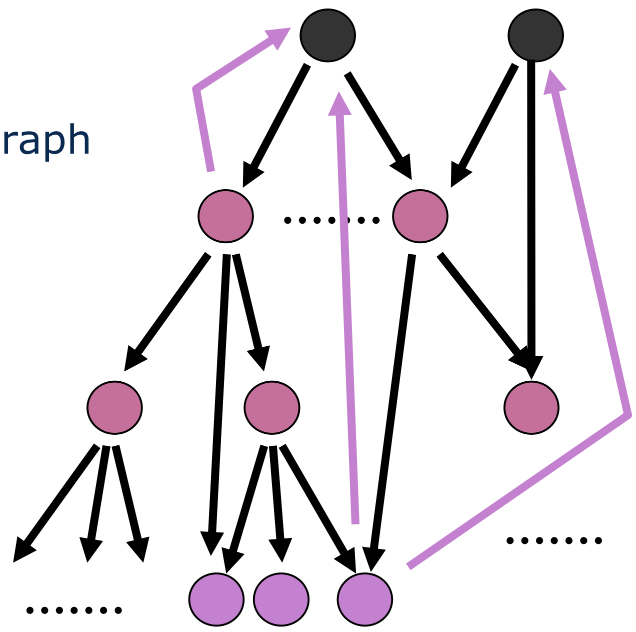


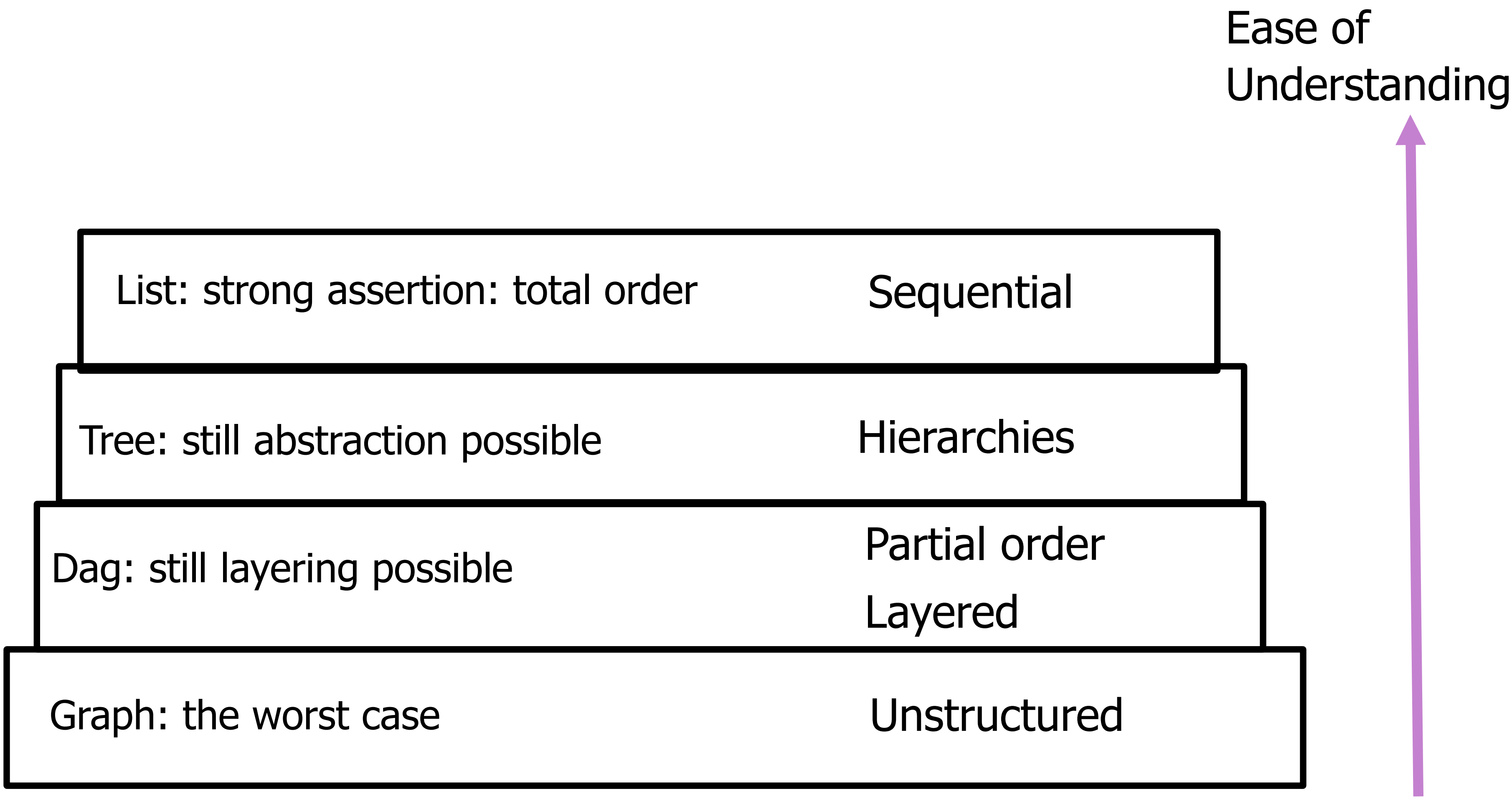
Layerable Graphs with Skeleton DAGs

- Like reducible graphs, however, sharing between different parts of the skeleton trees
  - Graph cannot be “reduced” to one node
- Advantage
  - Skeleton can be used to layer the graph
  - Cycles only within one layer
- Example
  - Layered system architectures



- Wild, unstructured graphs are the worst structure we can get
  - Wild, unstructured, irreducible cycles
  - Unlayerable, no abstraction possible
  - No overview possible
- Many roots
  - A digraph with one source is called flow graph
- Many sinks
- Example
  - Many diagrammatic methods in Software Engineering
  - UML class diagrams




Ease of Understanding
List: strong assertion: total order
Sequential
Tree: still abstraction possible
Hierarchies
Dag: still layering possible
Partial order
Layered
Graph: the worst case
Unstructured

Strength of Assertions in Models

- Saying that a relation is
  - A list: very strong assertion, total order!
  - A tree: still a strong assertion: hierarchies possible, easy to think
  - A dag: still layering possible, still a partial order
  - A layerable graph: still layering possible, but no partial order
  - A reducible graph: graph with a skeleton tree
  - A graph: hopefully, some structuring or analysis is possible. Otherwise, it's the worst case
- And those propositions hold for every kind of diagram in Software Engineering!
- Try to model reducible graphs, dags, trees, or lists in your specifications, models, and designs
  - Systems will be easier, more efficient

Structuring Improves Worst Case

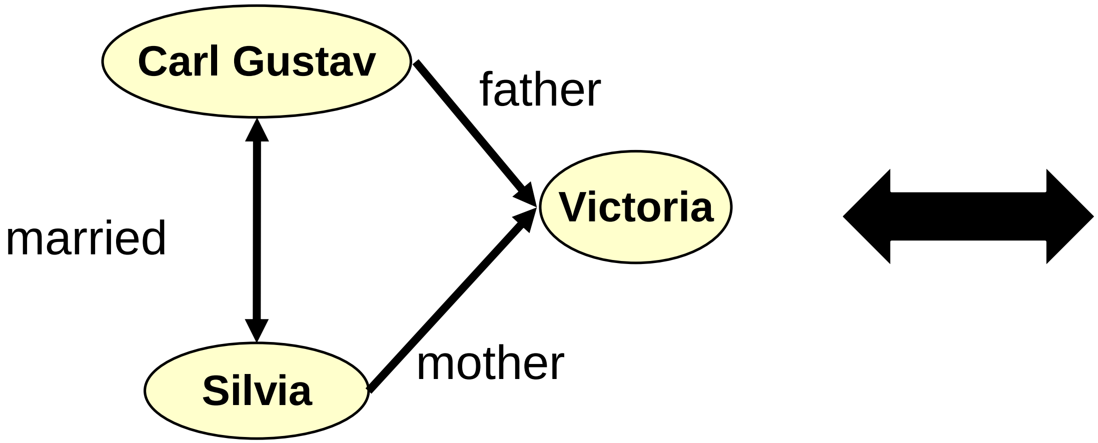
Ease of Understanding ↑

List: strong assertion: total order	Sequential
Tree: still abstraction possible	Hierarchies
Dag: still layering possible	Partial order Layered
Structured graph (reducible, skeleton dag)	Structured
Graph with analyzed features	Unstructured
Graph: the worst case	Unstructured

13.4 METHODS AND TOOLS FOR ANALYSIS OF GRAPH-BASED MODELS

The Graph-Logic Isomorphism

- In the following, we will make use of the graph-logic isomorphism:
- Graphs can be used to represent logic
  - Nodes correspond to constants
  - (Directed) edges correspond to binary predicates over nodes (*triple statements)*
  - Hyperedges (n-edges) correspond to n-ary predicates
- Consequence:
  - Graph algorithms can be used to test logic queries on graph-based specifications
  - Graph rewrite systems can be used for deduction

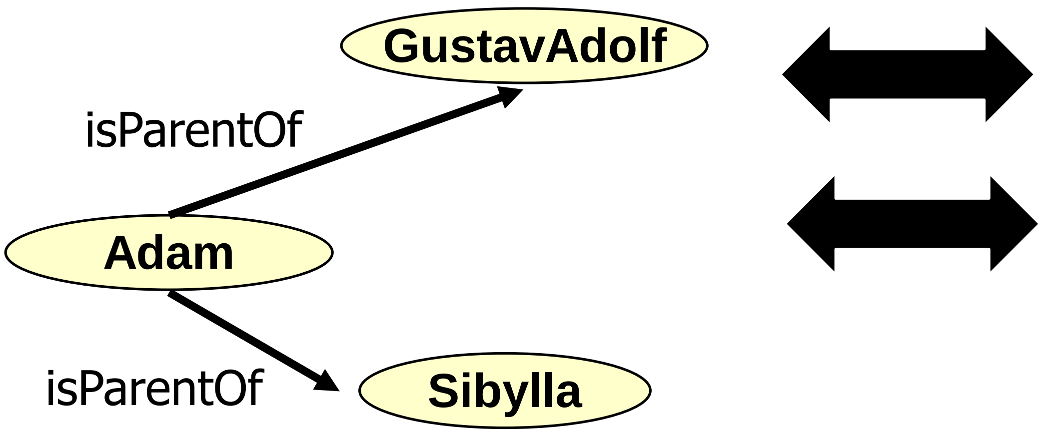


// fact base
married(CarlGustav,Silvia).
married(Silvia, CarlGustav).
father(CarlGustav,Victoria).
mother(Silvia,Victoria).

// Normalized English
CarlGustav is married to Silvia.
Silvia is married to CarlGustav.
CarlGustav is father to Victoria.
Silvia is mother to Victoria.

- Graphs can also be noted textually
- Graphs consist of nodes, relations
- Relations link nodes

- Fact data bases consist of constants (data) and predicates
- Nodes of graphs can be regarded as constants, edges as predicates between constants (*facts*):




```
// OWL Triples
Adam isParentOf GustavAdolf.
Adam isParentOf Sibylla.

// Facts
isParentOf(Adam,GustavAdolf).
isParentOf(Adam,Sibylla).
```

- Since graph-based models are a mess, we try to analyze them
- Knowledge is either
  - **Explicit**, i.e., represented in the model as edges and nodes
  - **Implicit**, i.e., hidden, not directly represented, and must be analyzed
- Query and analysis problems try to *make implicit knowledge explicit*
  - E.g., does the graph have one root? How many leaves do we have? Is this subgraph a tree? Can I reach that node from this node?
- Determining features of nodes and edges
  - Finding certain nodes, or patterns
- Determining global features of the model
  - Finding paths between two nodes (e.g., connected, reachable)
  - Finding paths that satisfy additional constraints
  - Finding subgraphs that satisfy additional constraints

Queries for Checking Consistency (Model Validation)

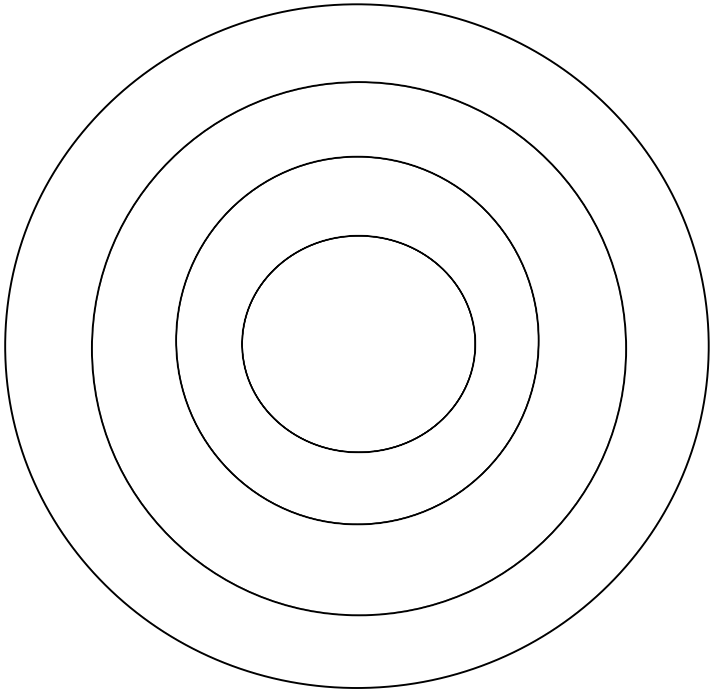
- Queries can be used to find out whether a graph is *consistent (i.e., valid, well-formed)*
  - Due to the graph-logic isomorphism, constraint specifications can be phrased in logic and applied to graphs
- Example:
  - if a car is exported to England, steering wheel and pedals should be on the right side; otherwise on the left

12.4.1 Layering Graphs: How to Analyze a System for Layers

- With the "Same Generation" Problem
- How to query and search in a DAG
- How to layer a DAG – a simple structuring problem

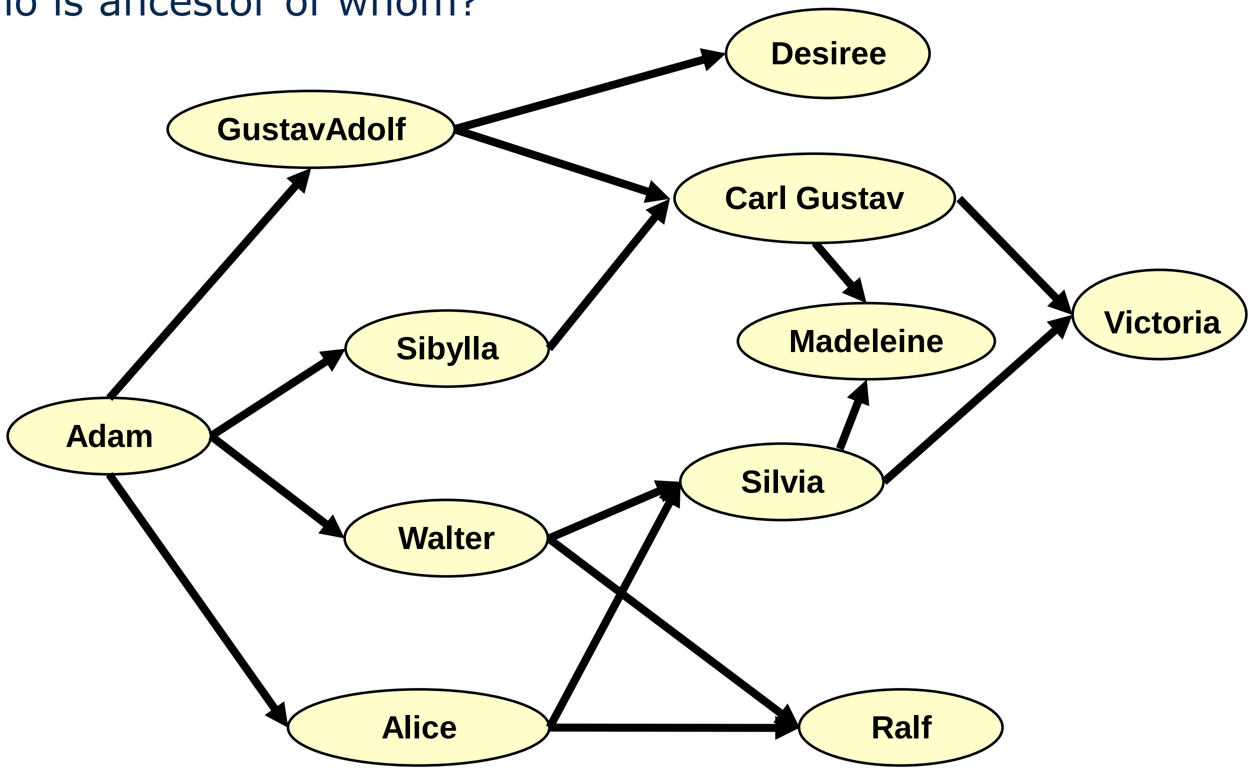
Layering of Systems

- To be comprehensible, a system should be structured in layers
  - Several relations in a system can be used to structure it, e.g., the
    - Call graph: layered call graph
    - Layered definition-use graph



- A *layered architecture* is the dominating style for large systems
- Outer, upper layers use inner, lower layers (layered USES relationship)
- Legacy systems can be analyzed for layering, and if they do not have a layered architecture, their structure can be improved towards this principle

- Given any acyclic relation, it can be made layered
  - Same Generation analysis creates layers for trees or DAGs
- Example: layering a family tree:
  - Who is whose contemporary?
  - Who is ancestor of whom?

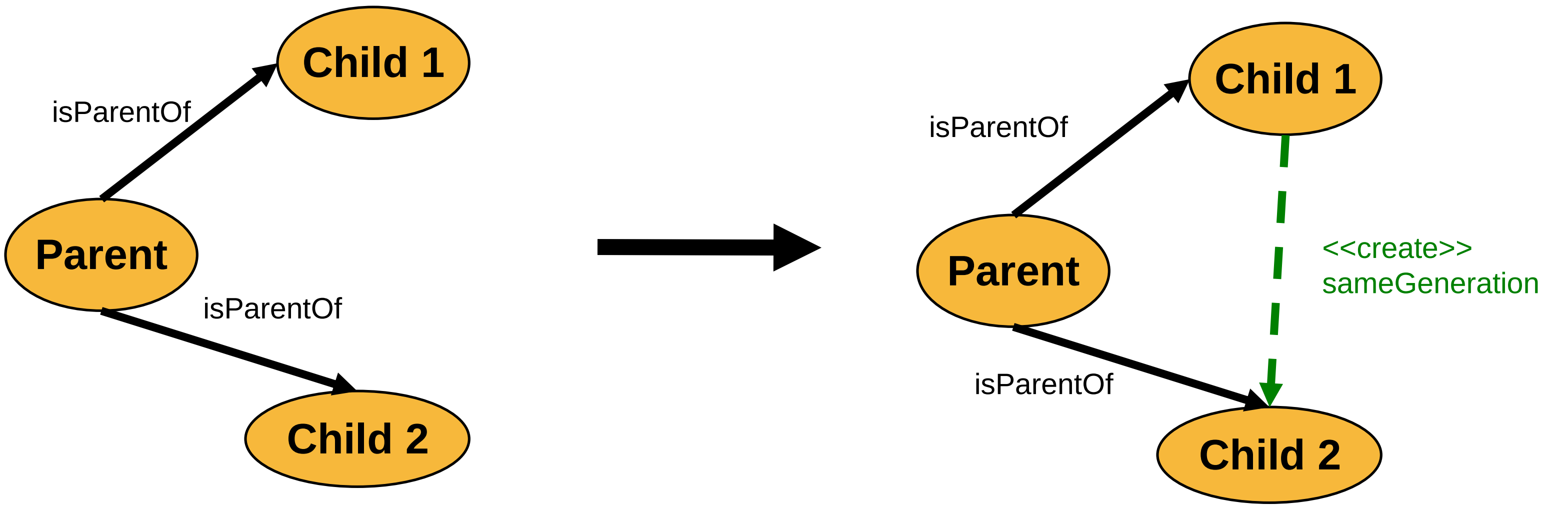


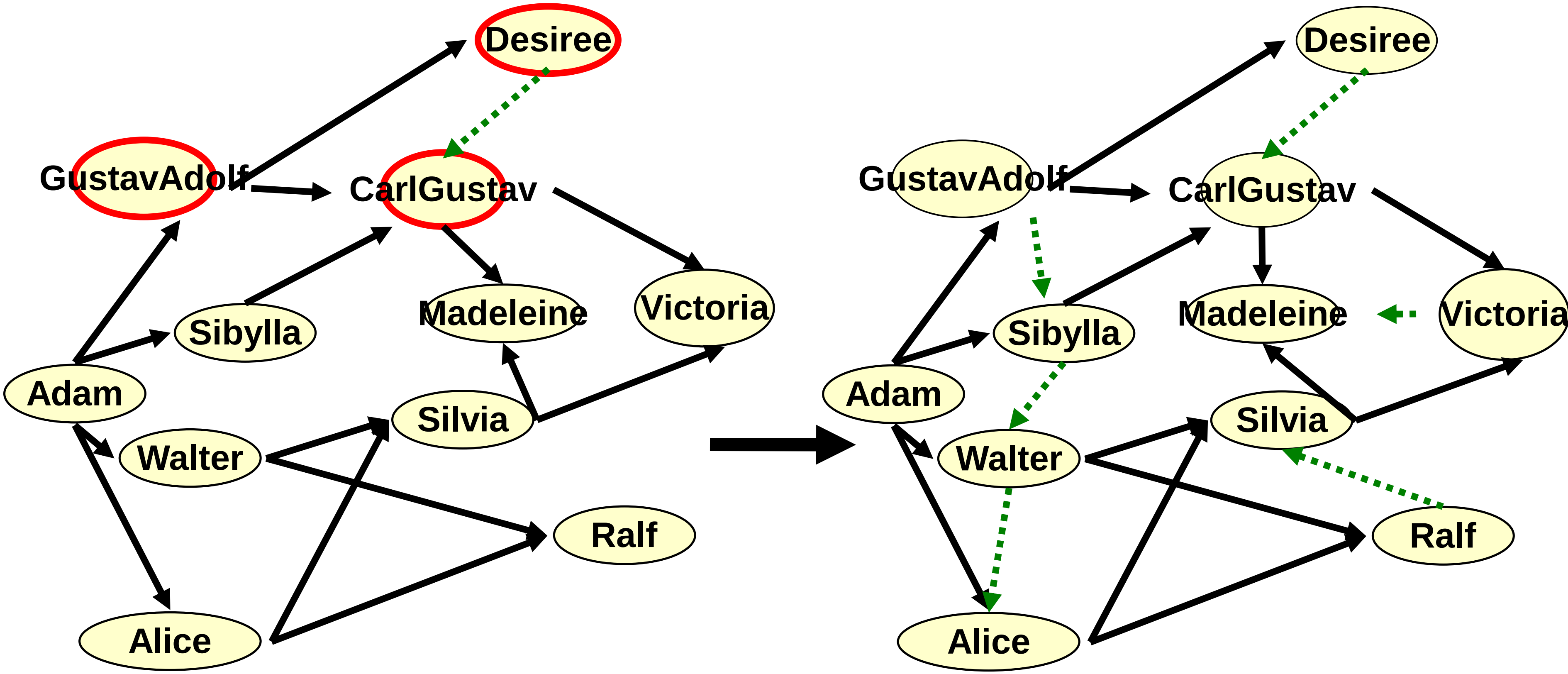
- Parenthood can be described by a *graph pattern*
- We can write the graph pattern also in logic:

```
isParentOf(Parent,Child1) && isParentOf(Parent,Child2)
```

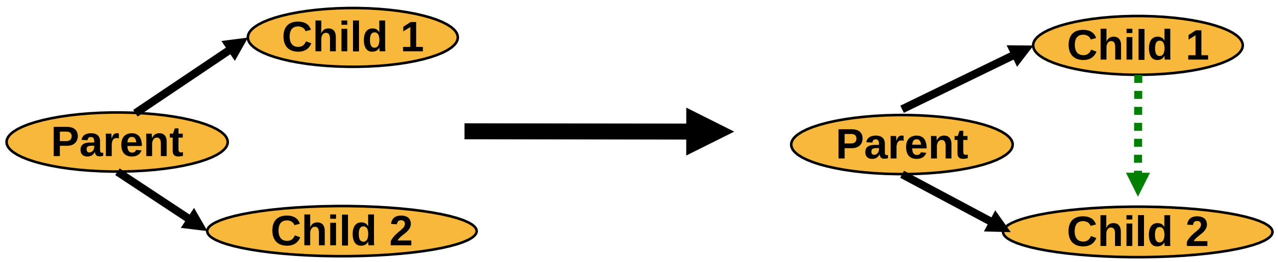
- And define the rule

```
if isParentOf(Parent,Child1) && isParentOf(Parent,Child2)
then sameGeneration(Child1,Child2)
```

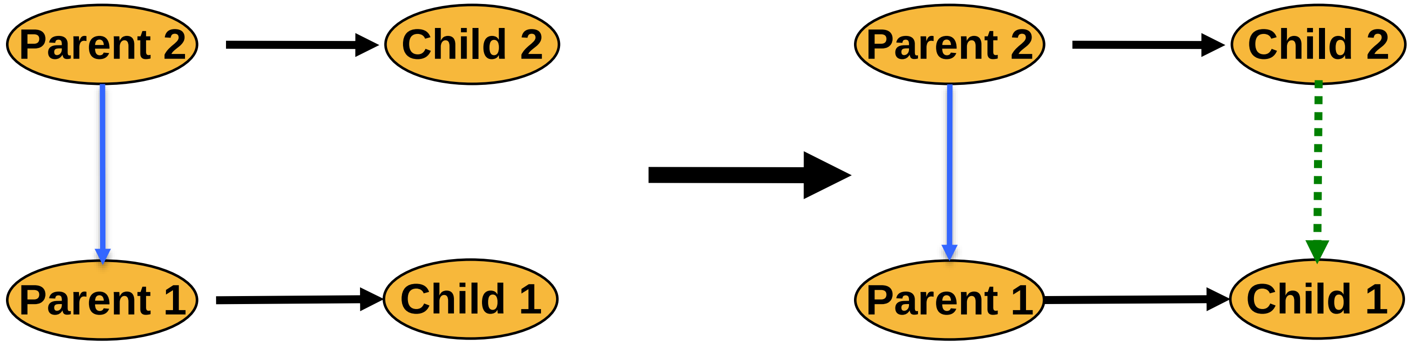



Desiree
GustavAdolf
CarlGustav
Madeleine
Victoria
Sibylla
Adam
Silvia
Walter
Ralf
Alice
Desiree
GustavAdolf
CarlGustav
Madeleine
Victoria
Sibylla
Adam
Silvia
Walter
Ralf
Alice

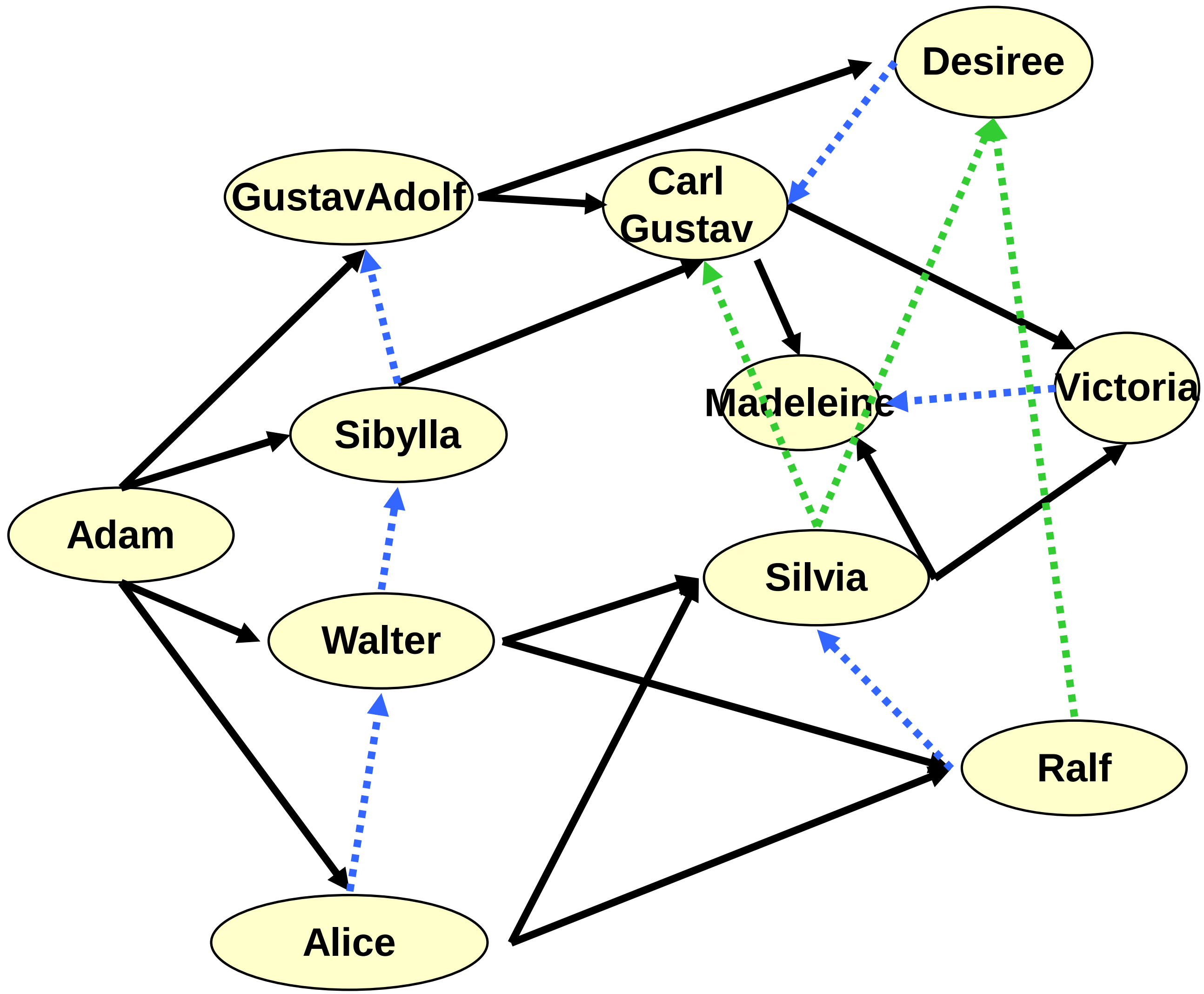
- Base rule: Beyond sisters and brothers we can link all people of same generation



- Additional rule (transitive): Enters new levels into the graph



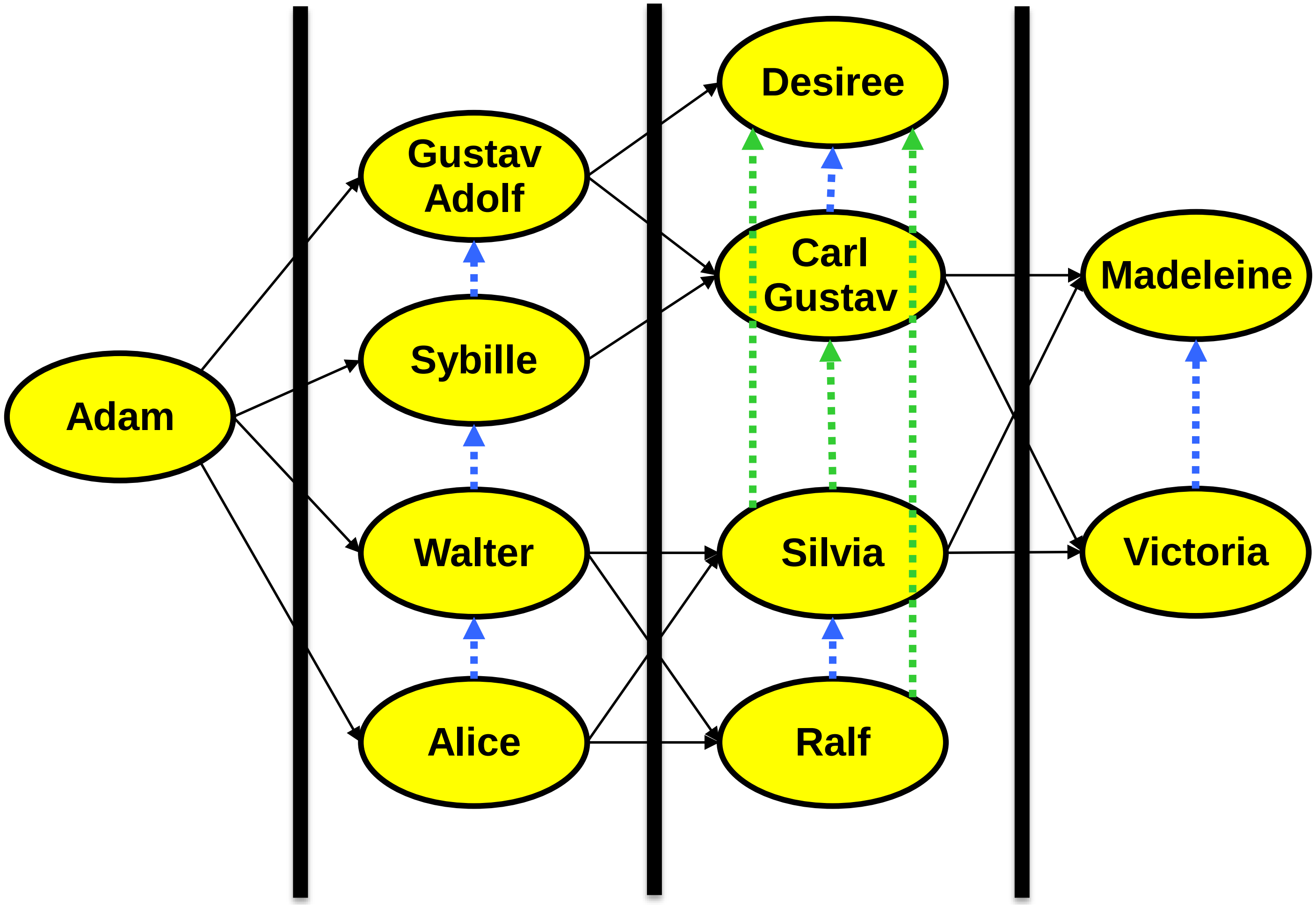
Impact of Transitive Rule



"Same Generation" Introduces Layers

- Computes all nodes that belong to one layer of a dag
  - If backedges are neglected, also for an arbitrary graph
- Algorithm:
  - Compute Same Generation
  - Go through all layers and number them
- Applications:
  - Compute layers in a call graph
    - Find out the call depth of a procedure from the main procedure
  - Restructuring of legacy software (refactoring)
    - Compute layers of systems by analyzing the USES relationships (ST-I)
    - Insert facade classes for each layer (Facade design pattern)
      - Every call into the layer must go through the facade
    - As a result, the application is much more structured

The Generations as Layers



13.4.2 SEARCHING GRAPHS – SEARCHING IN SPECIFICATIONS WITH DATALOG AND EARS

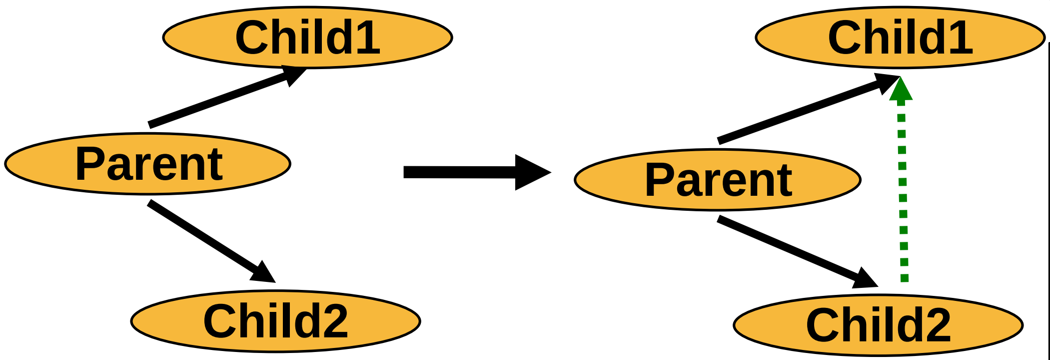
SameGeneration as a Graph Rewrite System

- The rule system SameGeneration only adds edges.
- An *edge addition rewrite system (EARS)* adds edges to graphs
  - It enlarges the graph, but the new edges can be marked such that they are not put permanently into the graph
  - **EARS** are declarative
    - No specification of control flow and an abstract representation
    - **Confluence**: The result is independent of the order in which rules are applied / all orders of applying rules lead to the same result
    - **Recursion**: The system is recursive, since relation "Same Generation" is used and defined
    - **Termination**: terminates, if all possible edges are added, latest, when graph is complete
- EARS compute
  - Reachability of nodes
  - Paths in graphs

- "Same Generation" can be used for graph analysis

- Rule systems can be noted textually or graphically (DATALOG vs. EARS)
- Datalog contains
  - textual if-then rules, which test predicates about the constants
  - rules contain variables

```
// conclusion
sameGeneration(Child1, Child2)
:-   // say: "if"
// premise
isParentOf(Parent,Child1),
isParentOf(Parent,Child2).
```




```
// premise
if isParentOf(Parent,Child1) &&
   isParentOf(Parent,Child2)
then
// conclusion
sameGeneration(Child1,Child2)
```

Same Generation Datalog Program

```
isParentOf(Adam,GustavAdolf).
isParentOf(Adam,Sibylla).
.....
if isParentOf(Parent,Child1), isParentOf(Parent,Child2)
then sameGeneration(Child1, Child2).
if sameGeneration(Parent1,Parent2),
  isParentOf(Parent1,Child1), isParentOf(Parent2,Child2)
then
  sameGeneration(Child1, Child2).
```

Solving Path Problems With Datalog

- **S**ingle Source **M**ultiple Target **P**ath **P**roblem – SMPP
- **M**ultiple Source **S**ingle Target **P**ath **P**roblem – MSPP
- **M**ultiple Source **M**ultiple Target **P**ath **P**roblem – MMPP

```
# A SMPP problem (searching for Single source a set of Multiple targets)
descendant(Adam,X)?
X={ Silvia, Carl-Gustav, Victoria, ....}

# An MSPP problem (multiple source, single target)
descendant(X,Silvia)?
X={Walter, Adam, Alice}

# An MMPP problem (multiple source, multiple target)
ancestor(X,Y)?
{X=Walter, Y={Adam}
 X=Victoria, Y={CarlGustav, Silvia, Sibylla, ...}
```

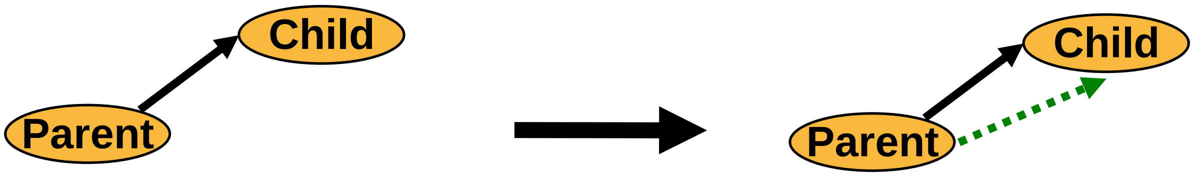
- The Swiss-Knife of Graph Analysis

13.5 REACHABILITY QUERIES WITH TRANSITIVE CLOSURE IN DATALOG AND EARS

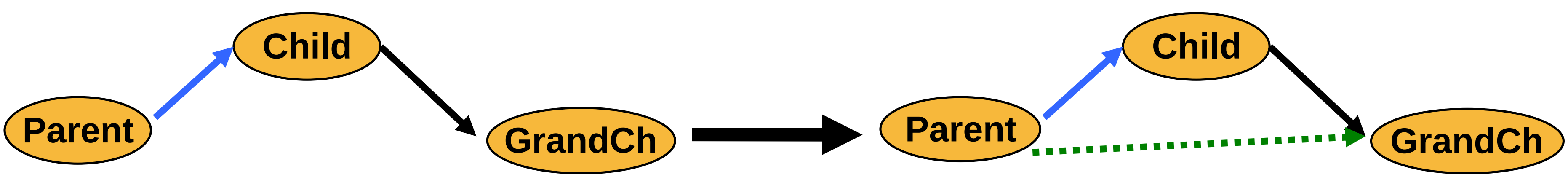
Who is Descendant of Whom?

- Sometimes we need to know *transitive* edges, i.e., edges after edges of the same color
  - Question: what is *reachable* from a node?
  - Which descendants has Adam?
- Answer: Transitive closure calculates *reachability* over nodes
  - It contracts a graph, inserting masses of edges to all reachable nodes
  - It contracts all paths to single edges
  - It makes reachability information explicit
- After transitive closure, it can easily be decided whether a node is reachable or not
  - Basic premise: base relation is *not changed* (offline problem)

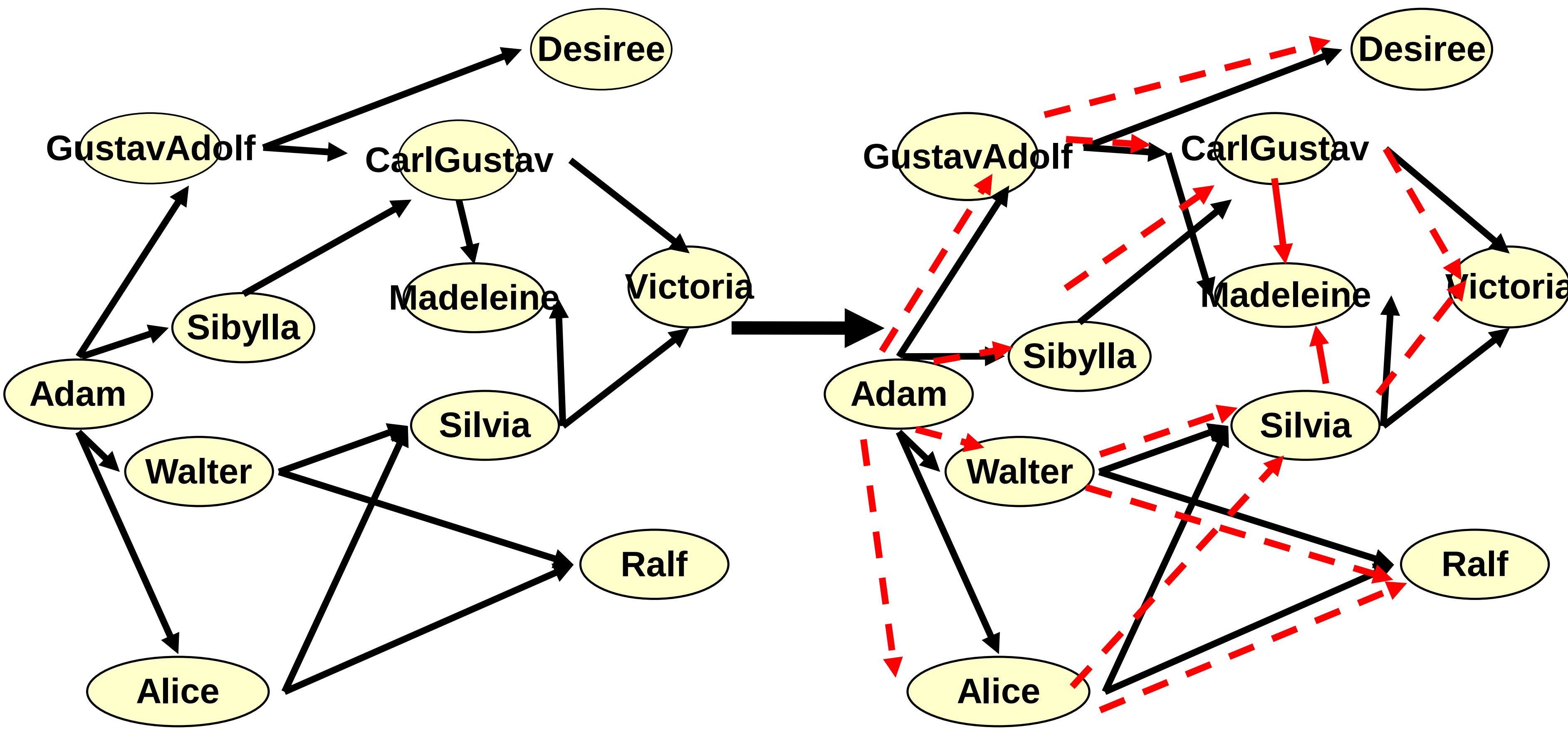
- Basic rule `descendant(Parent,Child) :- isChildOf(Parent,Child).`

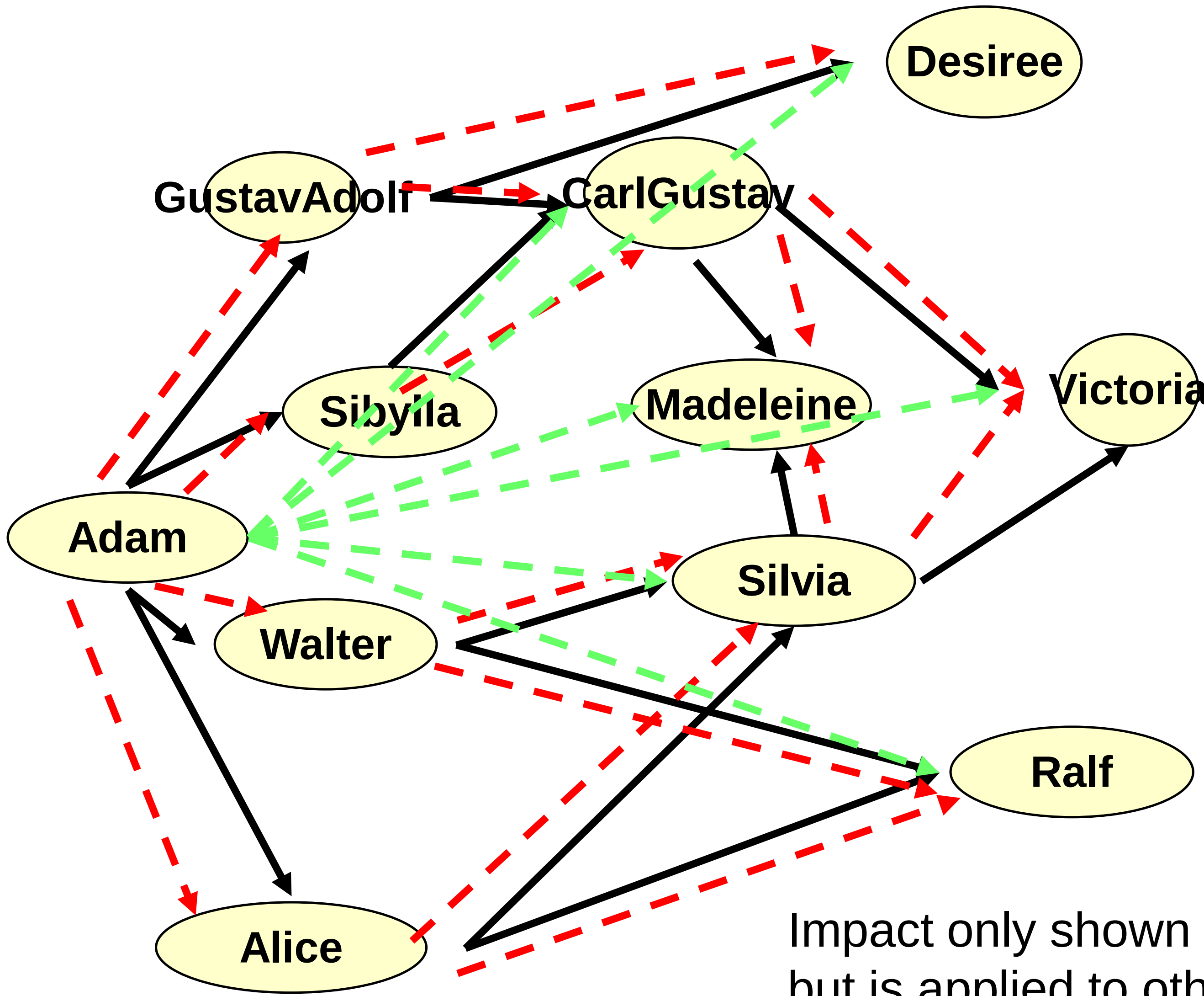


- Transitive rule (recursion rule)
- left recursive: `descendant(Parent,GrandCh) :- descendant(Parent,X),isChildOf(X,GrandCh).`
- right recursive: `descendant(Parent,GrandCh) :- isChildOf(Parent,X), descendant(X,GrandCh).`



Impact of Basic Rule





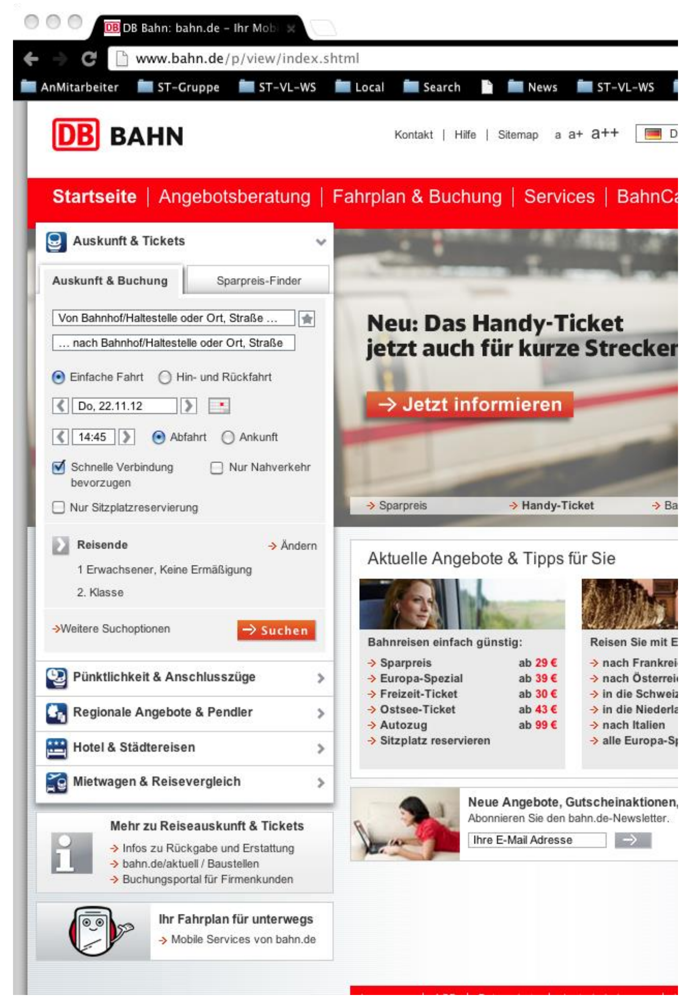
Impact only shown for Adam, but is applied to other nodes too

[S|M][S|M]PP Path Problems are Special Cases of Transitive Closure

- Single Source Single Target Path Problem, SSPP:
  - Test, whether there is a path from a source to a target
- Single Source Multiple Target SMPP:
  - Test, whether there is a path from a source to several targets
  - Or: find n targets, reachable from one source
- Multiple Source Single Target MSPP:
  - Test, whether a path from n sources to one target
- Multiple Source Multiple Target MMPP:
  - Test, whether a path of n sources to n targets exists
- All can be computed with transitive closure:
  - Compute transitive closure
  - Test sources and targets on direct neighboarship

Example: Railway Routes as Reachability Queries

- The info system of DB could be based on a graph of German railway stations.
- Base (Facts):
  - **`directlyLinked(Berlin, Potsdam).`**
  - **`directlyLinked(Potsdam,Braunschweig).`**
  - **`directlyLinked(Braunschweig, Hannover).`**
- Define the predicates
  - **`linked(A,B)`**
  - **`alsoLinked(A,B)`**
  - **`unreachable(A,B)`**
- Answer the queries
  - **`linked(Berlin,X)`**
  - **`unreachable(Berlin, Hannover)`**



Application: Inheritance Analysis as Reachability Queries

- Base (Facts):
  - `class(Person). class(Human). class(Man). class(Woman).`
  - `extends(Person, Human).`
  - `extends(Man,Person).`
  - `extends(Woman,Person).`

- Define the predicates
  - `superScope(A,B) :- class(A), class(B), isA(A,B).`
  - `transitiveSuperScope(A,B) :- superScope(A,C), transitiveSuperScope(C,B).`

- Answer the queries
  - `? transitiveSuperScope(Man,X)`
  - `>> {X=Person,X=Human}`
  - `? transitiveSuperScope(Woman,Y)`
  - `>> {Y=Person,Y=Human}`

The End: What Have We Learned

- Graphs and Logic are isomorphic to each other
- Using logic or graph rewrite systems, models can be validated
  - Analyzed
  - Queried
  - Checked for consistency
  - Structured
- Applications are many-fold, using all kinds of system relationships
  - Consistency of UML class models (domain, requirement, design models)
  - Structuring (layering) of USES relationships
- Logic and graph rewriting technology involves reachability questions

> Logic and edge addition rewrite systems are the Swiss army knifes of the validating modeler

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