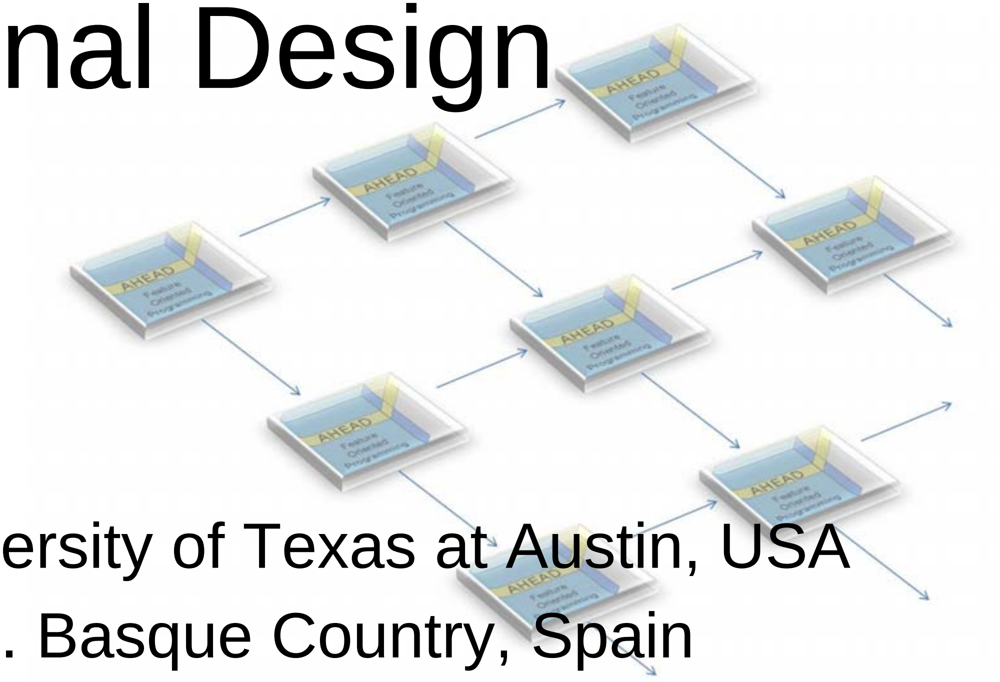
The Objects And Arrows Of Computational Design



Don Batory – University of Texas at Austin, USA
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João Saraiva – Univ. Minho, Portugal

Introduction

- Future of software design and development is automation
  - mechanize repetitive tasks
  - free programmers for more creative activities

- Entering the age of **Computational Design**
  - program design and synthesis is a computation

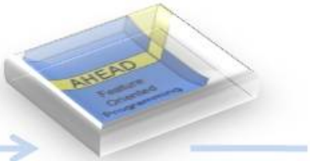
- **Design**: steps to take to create an artifact
  - metaprogram

- **Synthesis**: evaluate steps to produce the artifact
  - metaprogram execution

Forefront of Automated Development

- **Model Driven Engineering (MDE)**
  - high-level models define applications
  - transformed into lower-level models
  - general-purpose approach
- **Software Product Lines (SPL)**
  - domain-specific approach
  - we know the problems, solutions of a domain
  - we want to automate the construction of these programs
- Both complement each other
  - strength of MDE is weakness of SPLs, and vice versa
  - not disjoint, but I will present their strengths as such

My Background



- In prior lifetime, I was a database researcher
  - program generation was **relational query optimization (RQO)**
  - query evaluation programs were relational algebra expressions
  - designs of such programs could be optimized

- Took me years to recognize the significance of RQO
  - compositional paradigm, computational design

- Fundamentally shaped my view of automated software development
  - you'll see impact…

My Work

- SPLs with emphasis on language and tool support

- I needed a simple language to express program design and synthesis as a computation
    - **modern algebra fits the bill**

- Programs are **structures**
    - tools transform, manipulate, analyze

    - OO structures are methods, classes, packages
    - compilers transform source structures
    - refactoring tools transform source structures
    - meta-models of MDE define allowable structures of instances; transformations map instances for analysis or synthesis

So What??

- Well … mathematics is the science of structure and the manipulation of structure

- Once I recognized that transformations are fundamental to software development

    - I was on the road to mathematical thinking

    - basic ideas are relevant

    - once I understood the connection...

My Work

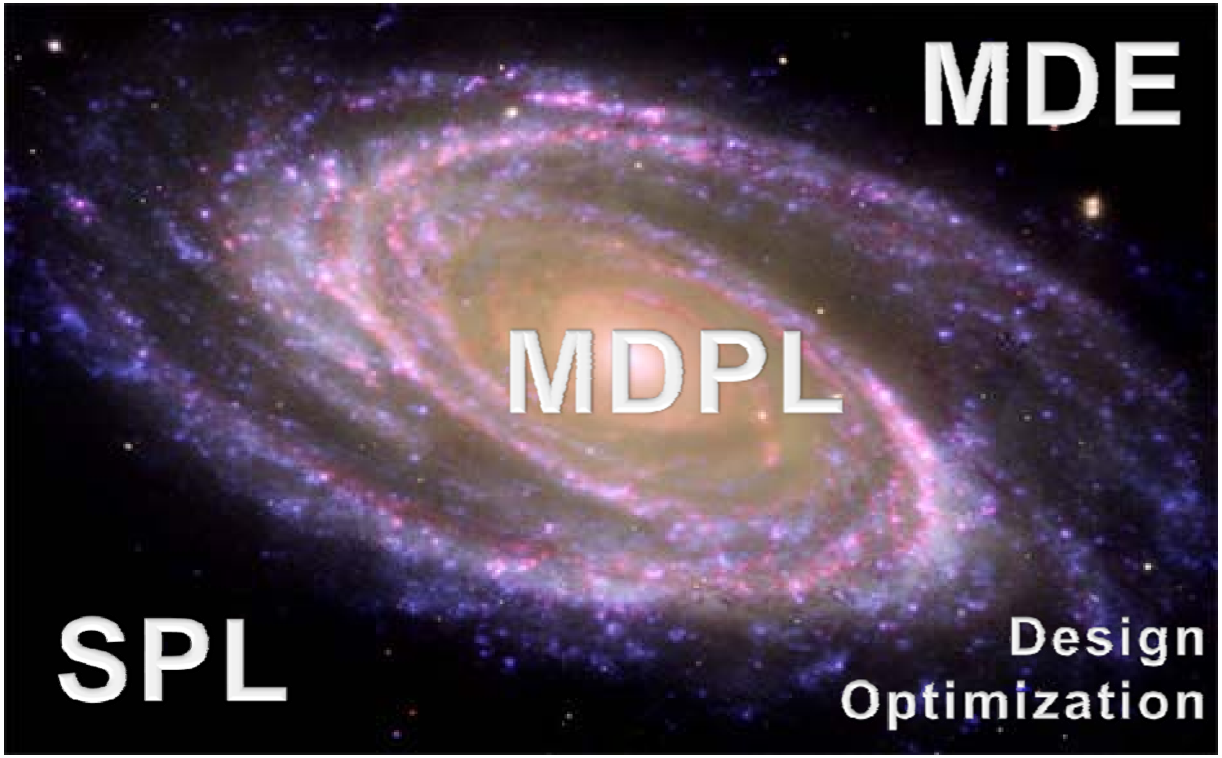
- I use mathematics as an informal design methodology and language to explain computational designs
  - **not a formalism!**

- This is a modeling talk aimed at practitioners
  - no special mathematical background

- Core ideas inspired from category theory
  - theory of mathematical structures
  - result of a domain analysis of geometry, topology, algebra…
  - basic concepts in CT are core ideas in MDE, SPL

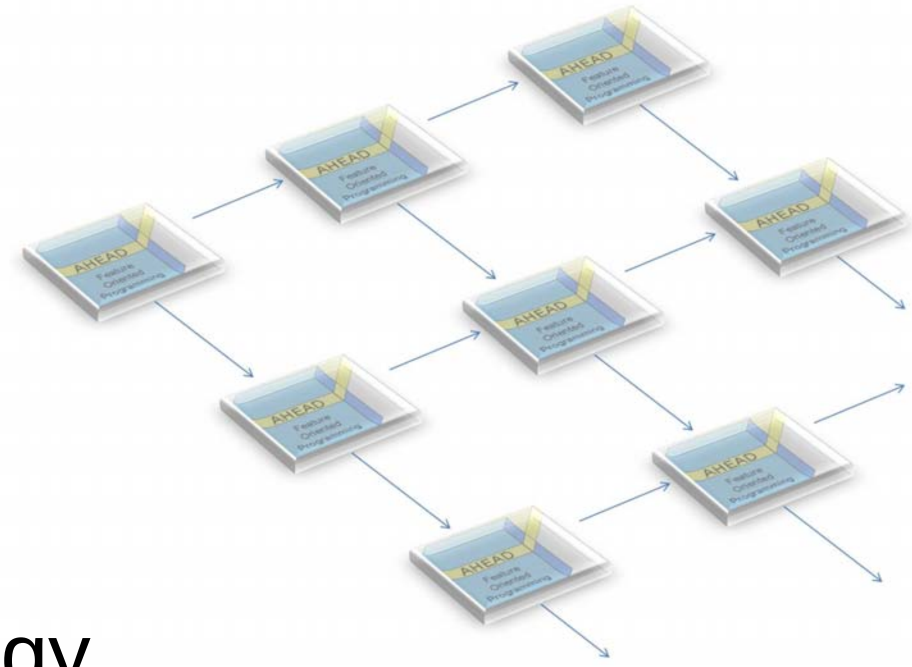
This Talk

- Expose underlying principles of MDE and SPL
  - not category theory – functors, pushouts, products of categories, …
- Series of mini-tutorials (10 minutes apiece)



categories
on an
industrial
scale

Part 1: Categories in MDE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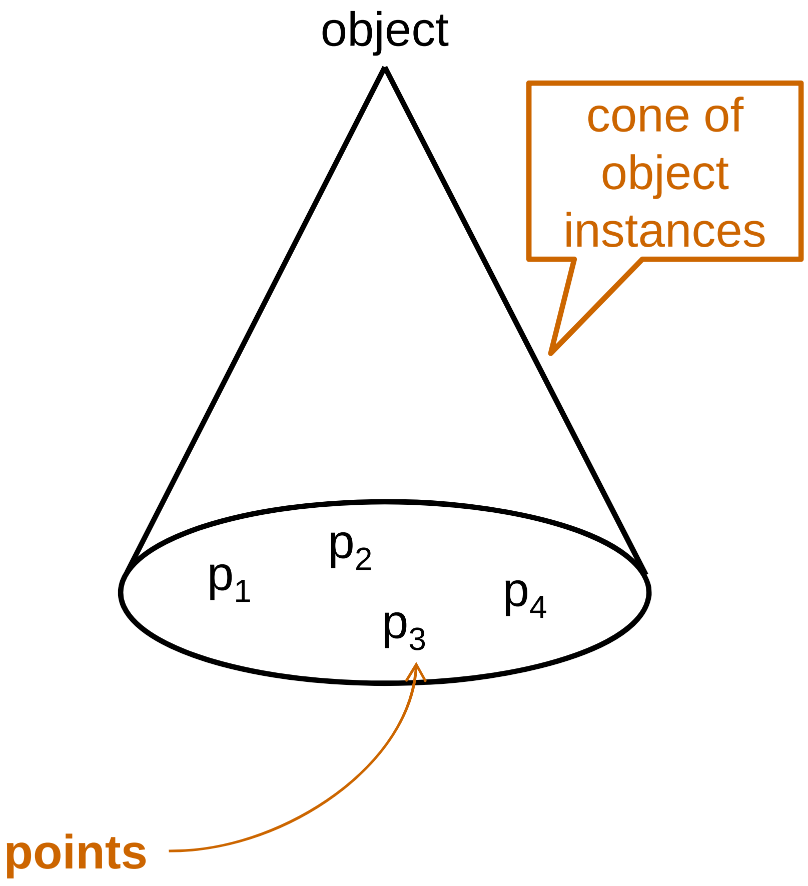
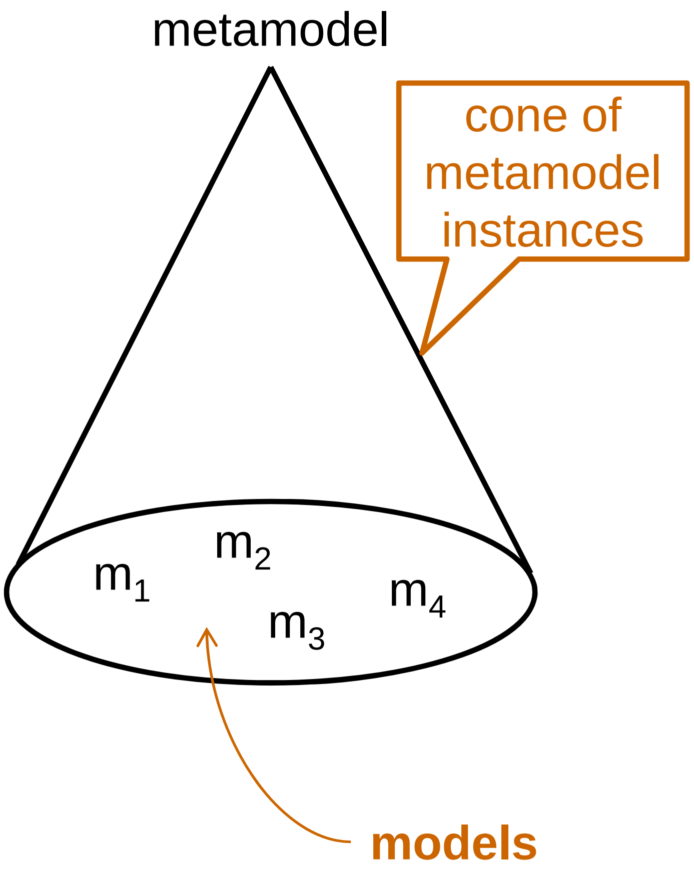
let’s start with some unfortunate terminology…

Objects

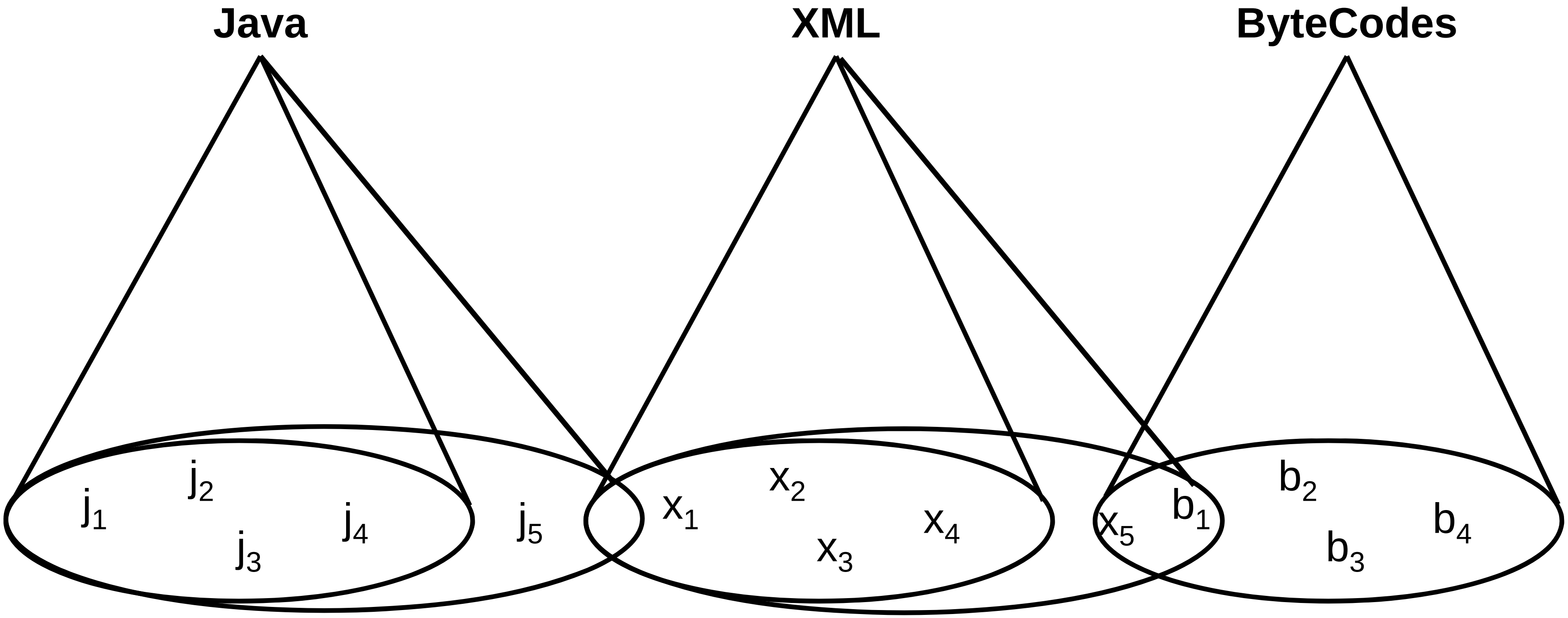
- An **object** is a domain of **points** (no standard term)
- **Metamodel** defines a domain of **models**





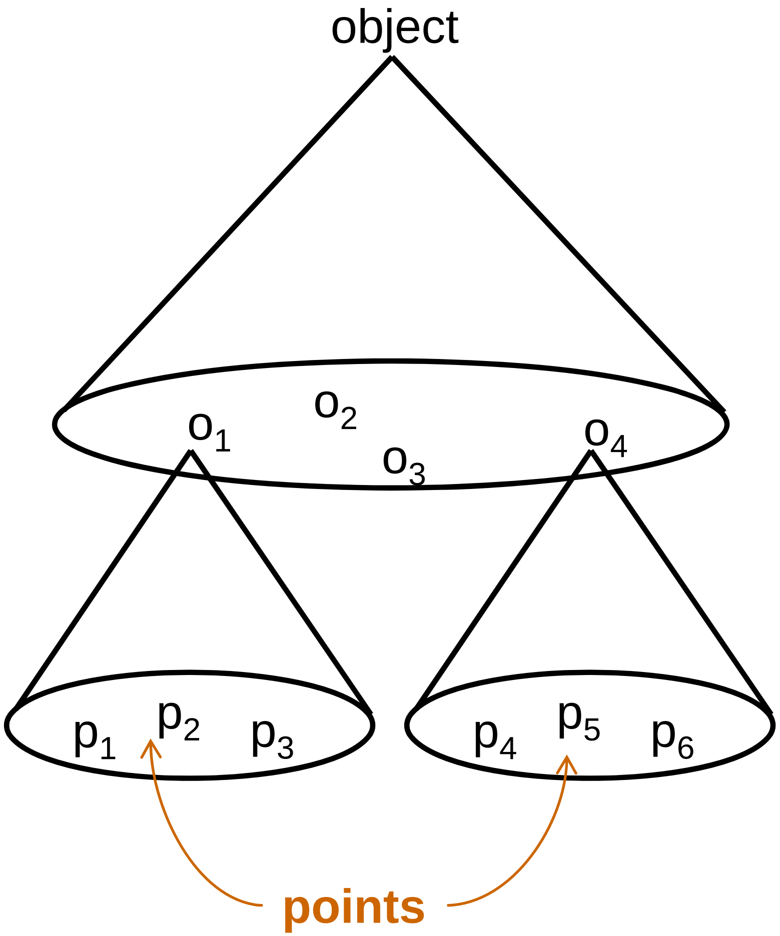
Examples

- MDE focuses on UML metamodels and their instances
- Ideas of objects & instances also apply to non-MDE artifacts
  - **technical spaces** of Bezivin, et al.

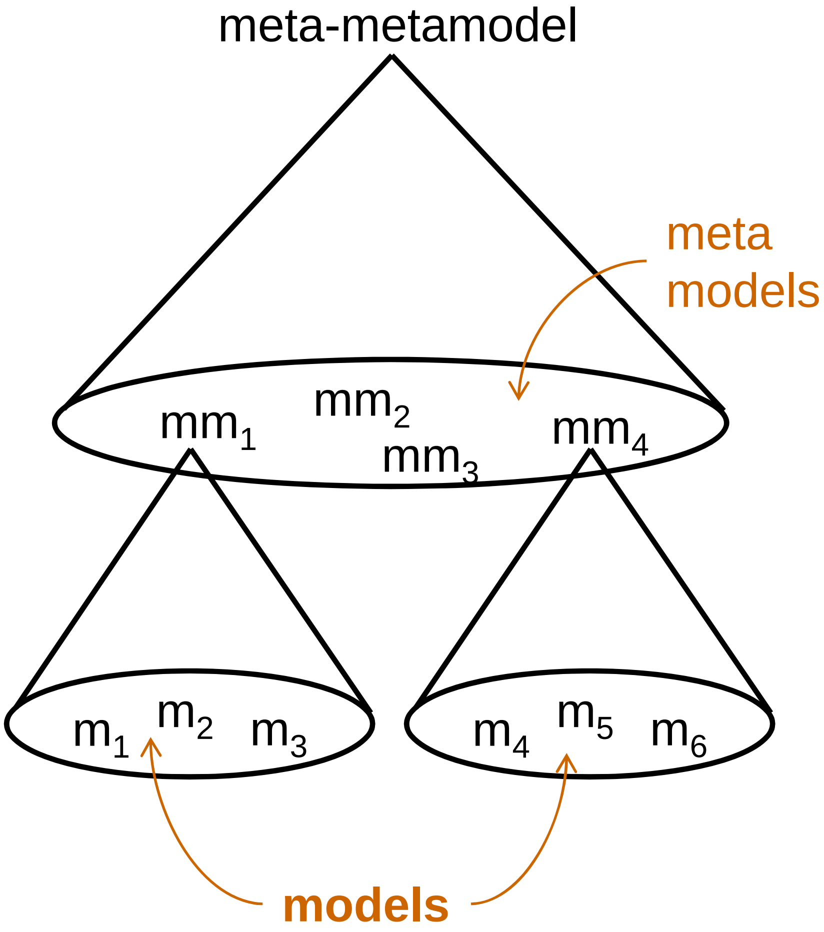


Recursion

- A point can be an object

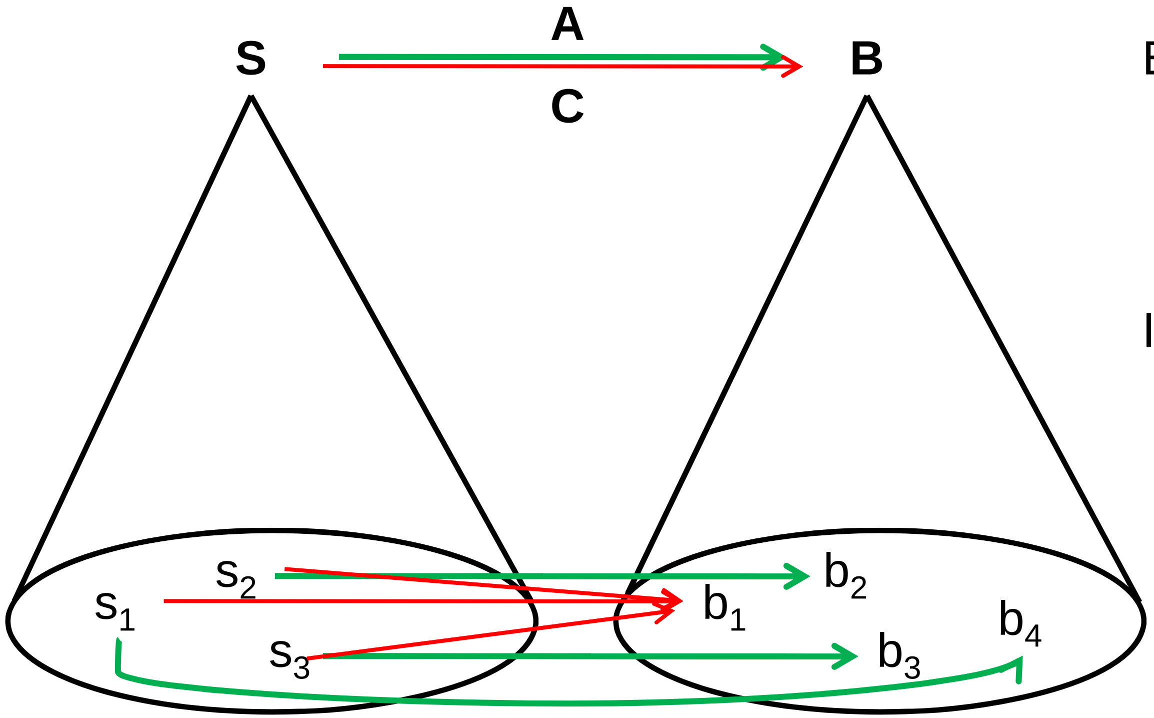


- Standard MOF architecture



Arrow

- Is **map** or **function** or **transformation** or **morphism** between objects (all names are used)
    - implementation is unspecified



External Diagram

Internal Diagram

My Terminology (for this talk)

- **Arrow** – denotes a map
- **Transformation** – an MDE implementation of an arrow
  - ATL, RubyTL, GReAT, QVT …
- **Tool** – is a non-MDE implementation of an arrow
  - standard tools of software engineers

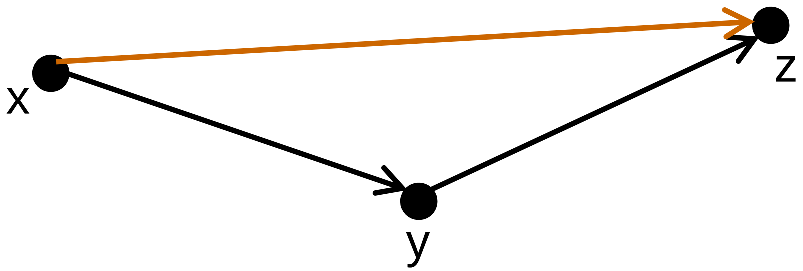
External Diagrams

$$\begin{tikzcd}
\text{MSC} \arrow[loop above] \arrow[r, "\text{M2MX}"] & \text{SC} \arrow[loop above] \arrow[r, "\text{M2TX}"] & \text{Java} \arrow[loop above] \arrow[r, "\text{javac}"] & \text{ByteCode} \arrow[loop above]
\end{tikzcd}$$

- **Category** – a collection of objects and arrows
  - above is a category of 4 objects, 3 non-identity arrows
  - categories satisfy 3 simple properties…

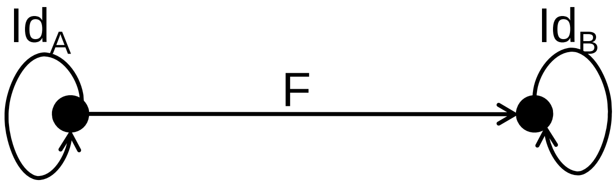
Properties of Categories

- Arrows are composable



- Composition is associative: $A \bullet (B \bullet C) = (A \bullet B) \bullet C$

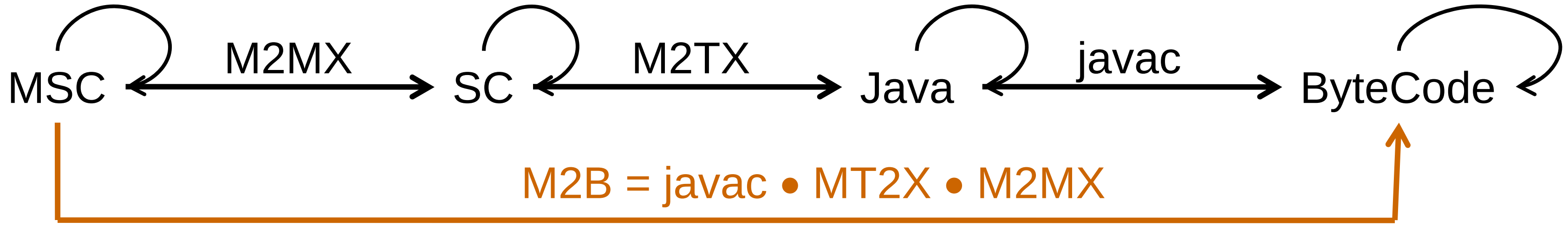
- Identities



$F \bullet Id_B = F$

$Id_A \bullet F = F$

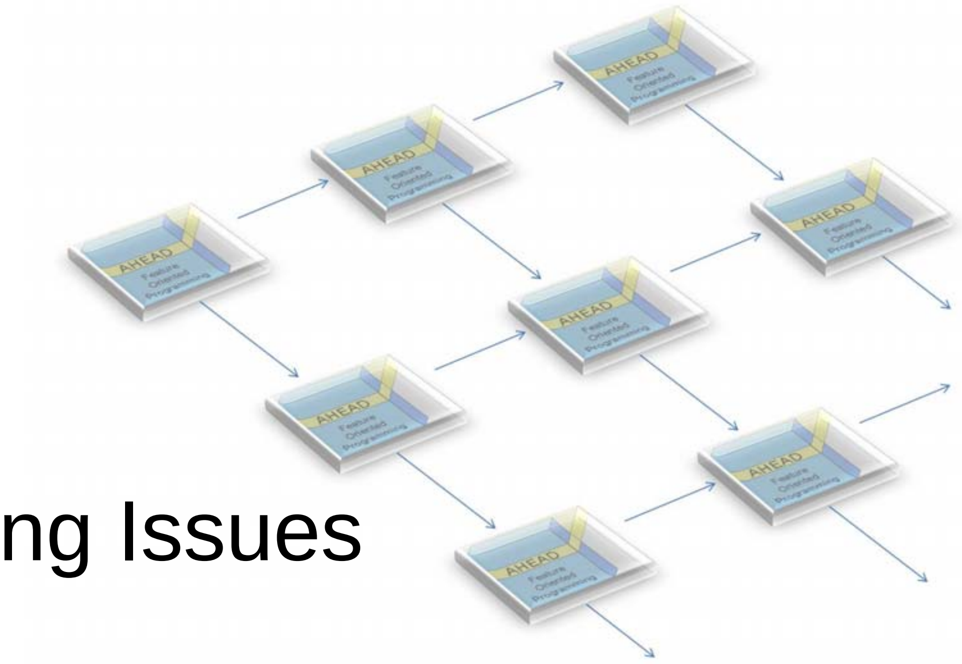
Support for These Abstractions



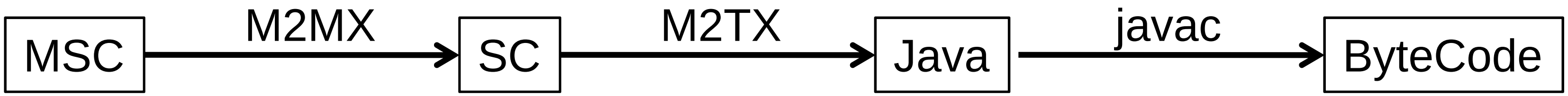
**tool chains,
makefiles,
metaprogram**

- Treat arrows and objects uniformly
  - hide their implementation technologies
  - GROVE, UniTI, etc.
  - lack of support obscures fundamental relationships
  - remove artificial complexity, expose essential complexity

Notation and Modeling Issues



External Diagrams in MDE



MSC

M2MX

SC

M2TX

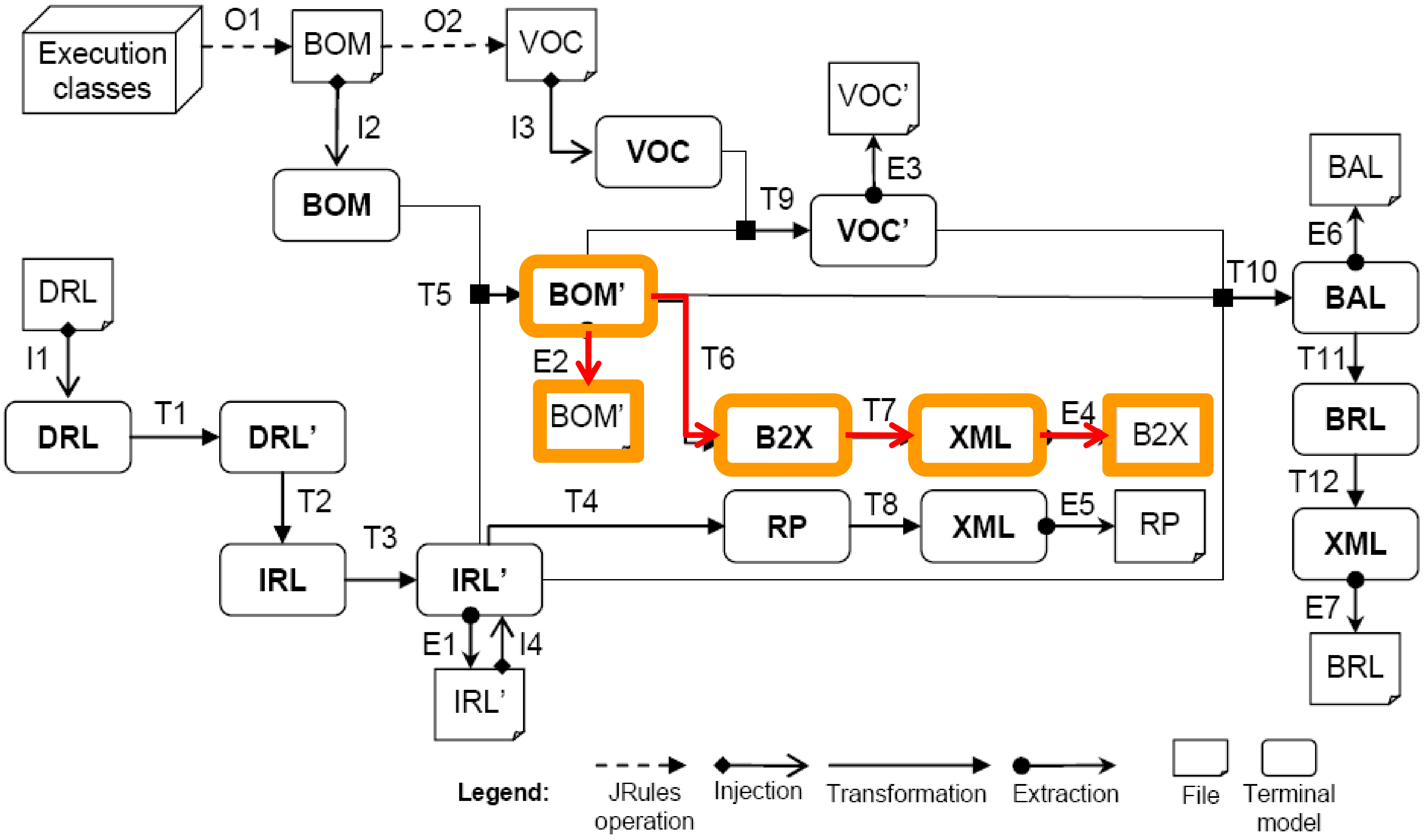
Java

javac

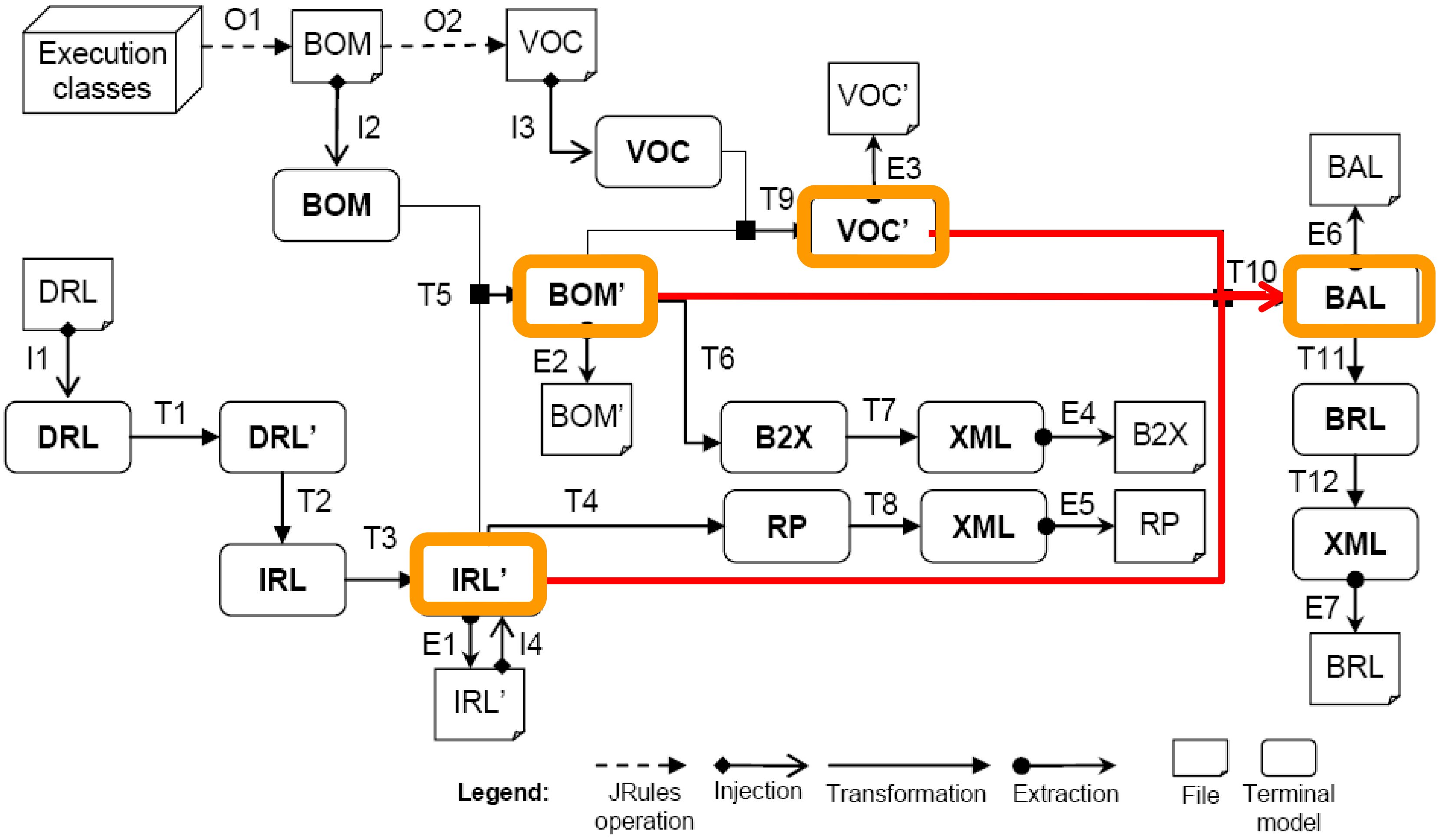
ByteCode

- No standard names for such diagrams in MDE
  - drawn differently (sans identity arrows)
  - **Toolchain diagrams** (MIC)
  - **MegaModels** (ATL)

External Diagrams in MDE



External Diagrams in MDE



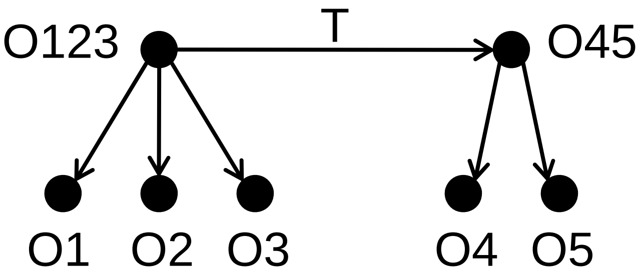
Arrows with Multiple Inputs, Outputs

- Arrows 1 input object to 1 output object

  what about T: O1, O2, O3 → O4, O5 ?
  occurs in model weaving …

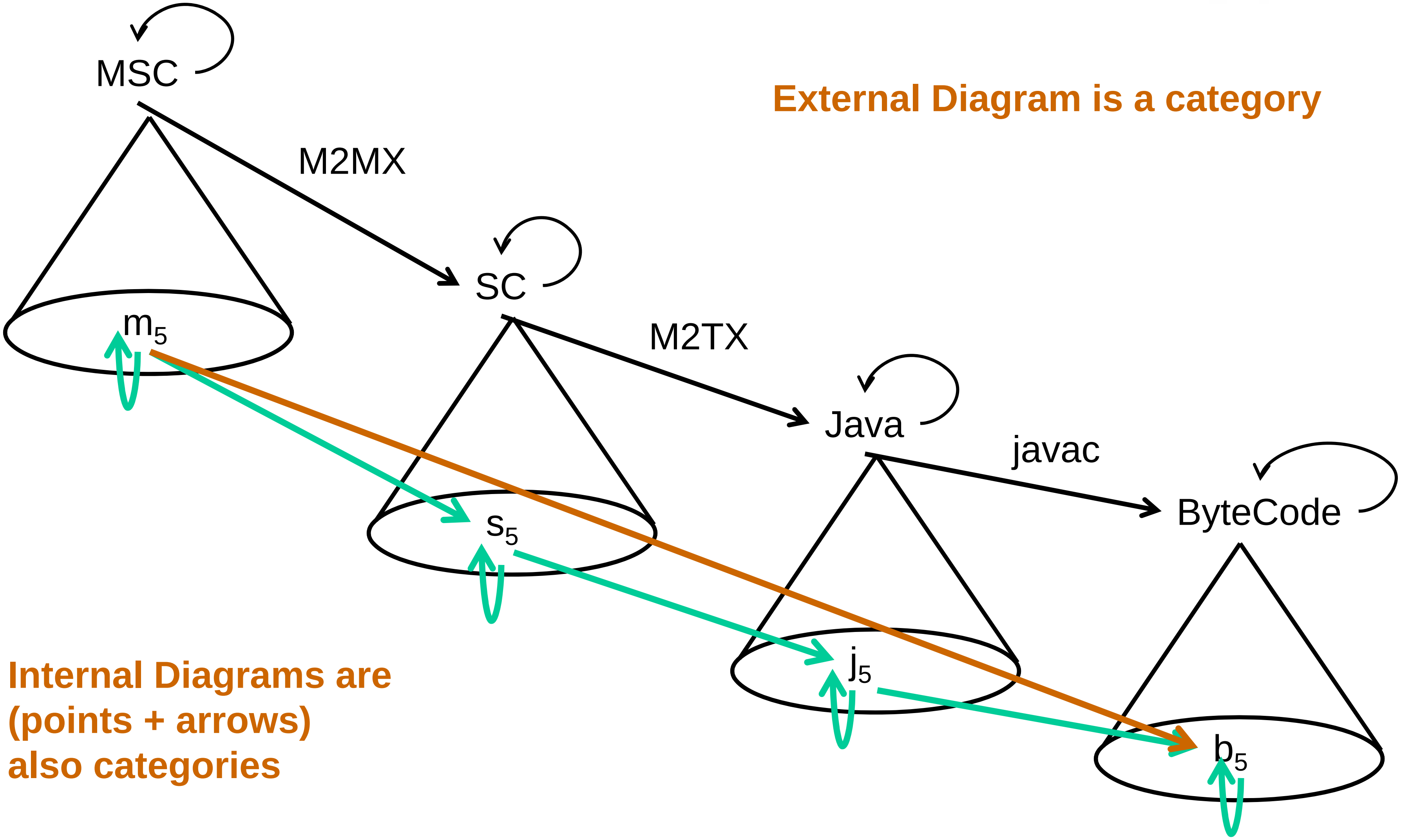
- Ans: create tuple of objects, which is itself an object

  O123 = [O1, O2, O3]
  O45 = [O4, O5]



projection arrows

Internal Diagrams



External Diagram is a category

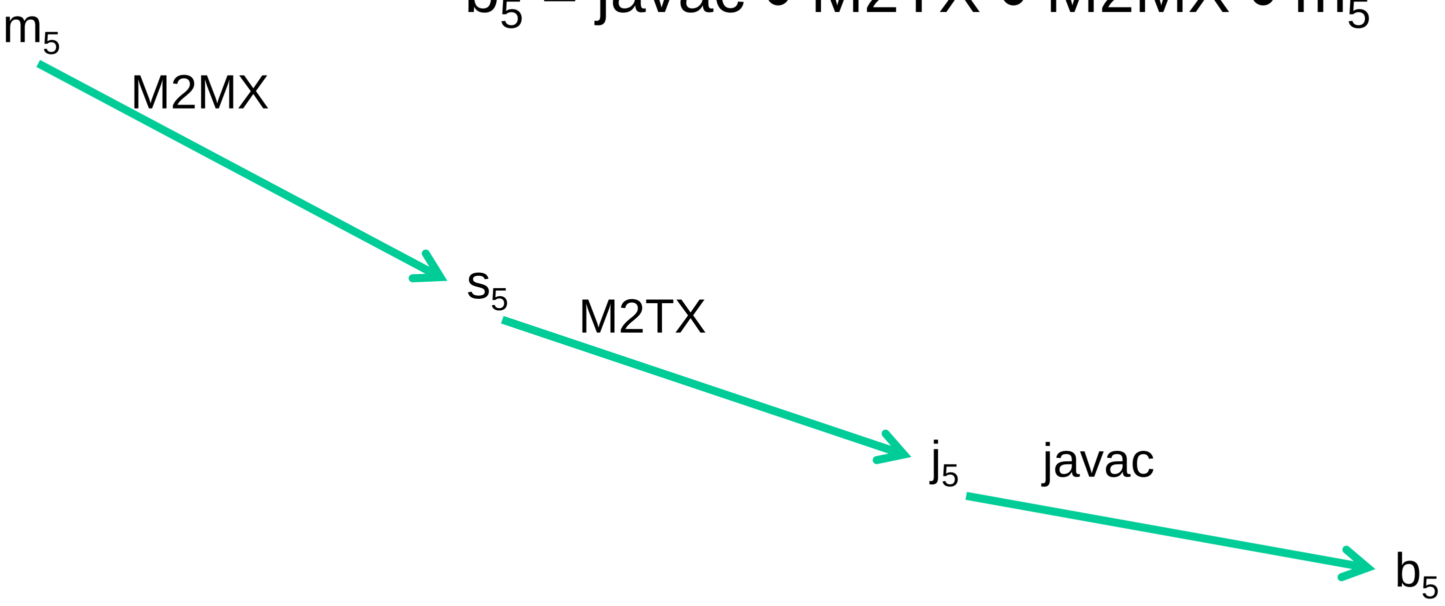
Internal Diagrams are (points + arrows) also categories

degenerate or trivial category: point is a domain with a single program

Computational Design

- Design of an artifact is an expression
  - synthesis is expression evaluation
  - RQO paradigm

$$b_5 = javac \bullet M2TX \bullet M2MX \bullet m_5$$



m_5

M2MX

s_5

M2TX

j_5

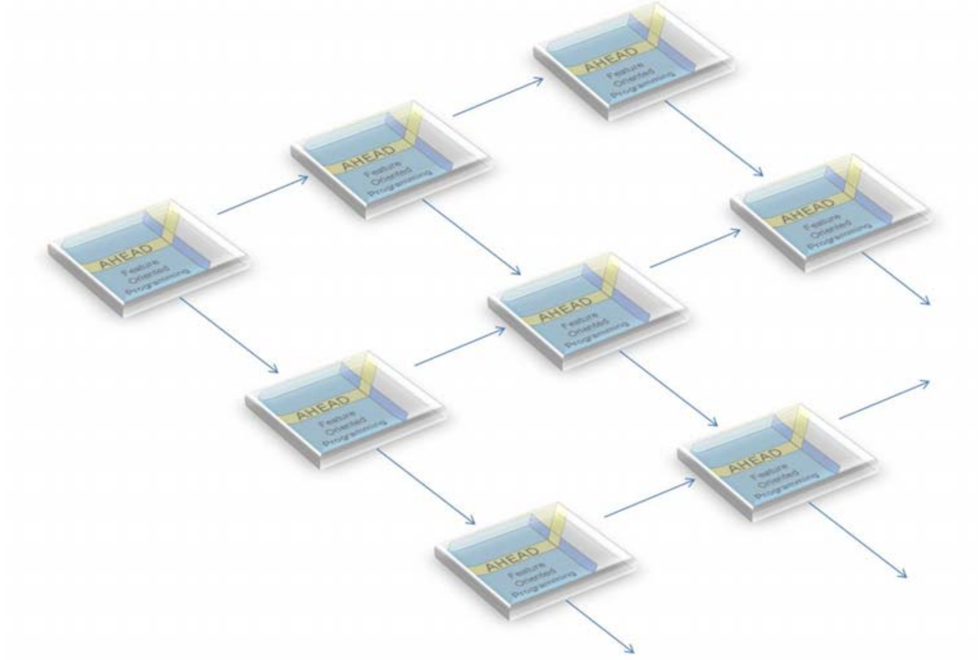
javac

b_5

Recap

- Categories lie at the heart of MDE
    - found at all levels in an MDE architecture
    - categories on an industrial scale
- Informally, categories provide a compact set of ideas to express relationships that arise among objects in MDE
    - language and terminology for MDE computational designs
    - can use CT more formally (e.g., Meseguer, Ehrig, Täntzer, Diskin) …
- Now let’s look for categories in Product Lines

Part 2: Categories in SPLs



SPL Overview

- SPL is a set of similar programs

- Programs are defined by **features**
  - increment in program functionality that customers use to distinguish one program from another

- Programs are related by features
  - program P is derived from program G by adding feature F
  - feature is a function:

$$P = F(G)$$

4-Program Product Line

```
class calculator {
    float result;
    void add( float x ) { result=+x; }
    void sub( float x ) { result=-x; }
}

class gui {
   JButton format = new JButton(“format”);
   JButton add    = new JButton(“+”);
   JButton sub    = new JButton(“-”);

   void initGui() {
     ContentPane.add( format );
     ContentPane.add( add );
     ContentPane.add( sub );
   }

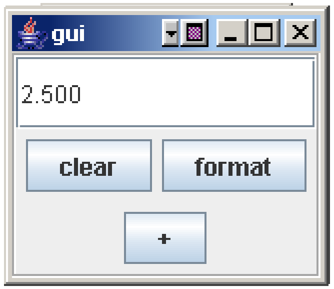
   void initListeners() {

     add.addActionListener(...);
     sub.addActionListener(...);
   }

   void formatResultString() {...}
}
```

new methods

new fields



2.500

new fields

extend existing methods

extend existing methods

$\text{format} \bullet \text{sub} \bullet \text{base} = p_4$

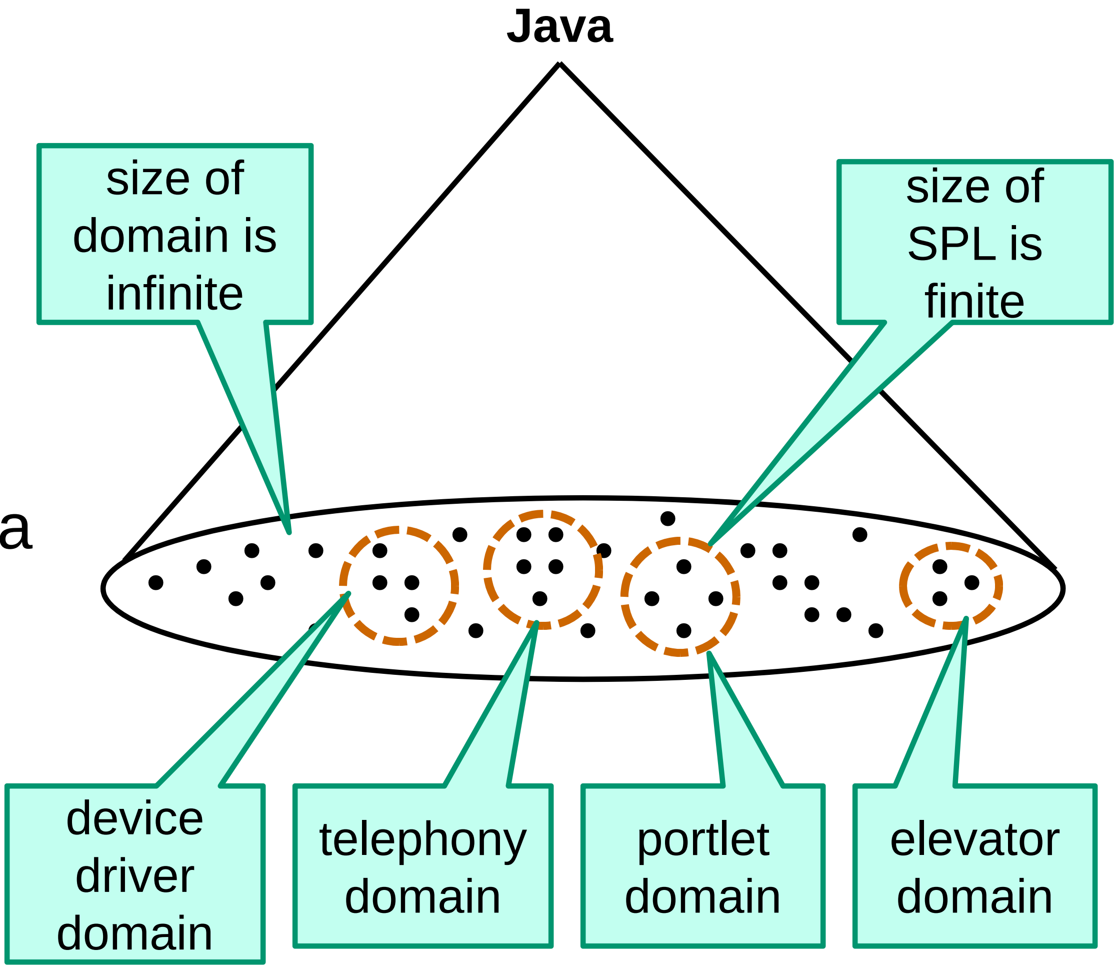
new methods

Ideas Scale...

- 1986 database systems 80K LOC
- 1989 network protocols
- 1993 data structures
- 1994 avionics
- 1997 extensible Java preprocessors 40K LOC
- 1998 radio ergonomics
- 2000 program verification tools
- 2002 fire support simulators
- 2003 AHEAD tool suite 250K LOC
- 2004 robotics controllers
- 2006 web portlets

Perspective on Product Lines

- SPL is a set of similar programs
- Is a ***miniscule*** subset of a domain
- Infinite set of SPLs in a domain



Java

size of domain is infinite

size of SPL is finite

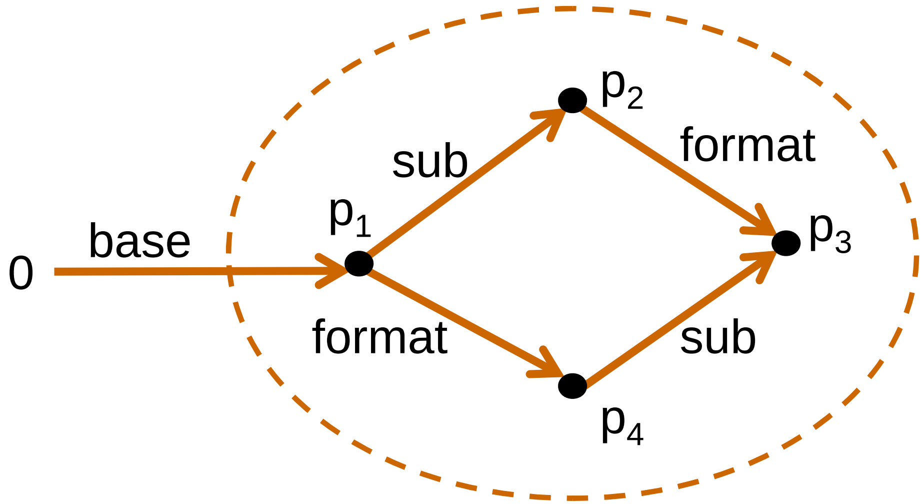
device driver domain

telephony domain

portlet domain

elevator domain

Perspective on Product Lines

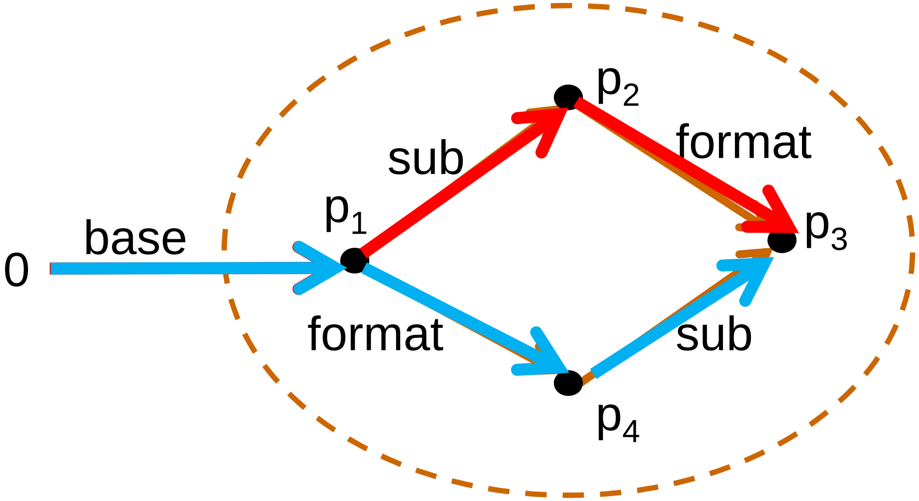


- SPL defines relationships between its programs
  - how are programs related?
  - by arrows, of course!

- Empty program (0) may (or may not) be part of SPL

- Each arrow is a **feature**

Computational Design



p_3 = format • sub • base

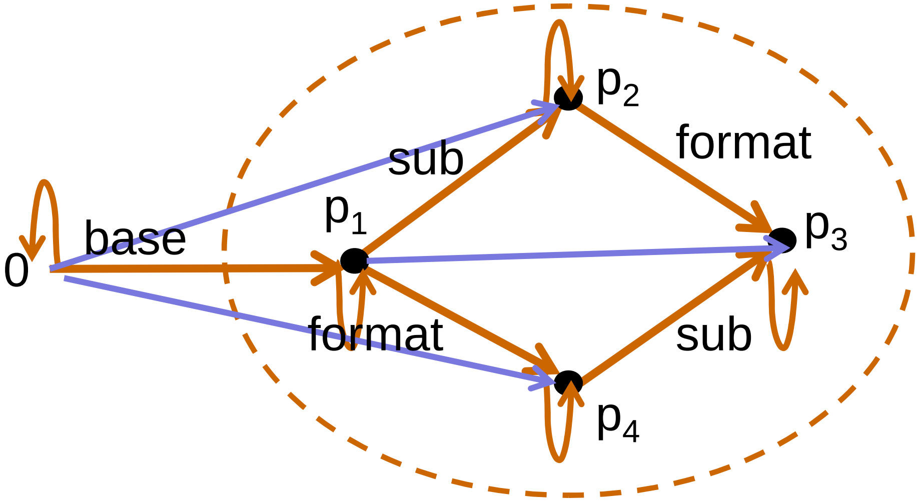
p_3 = sub • format • base

- Program design is an expression
  - RQO paradigm
  - programs can have multiple designs

evaluating both expressions yields the same program

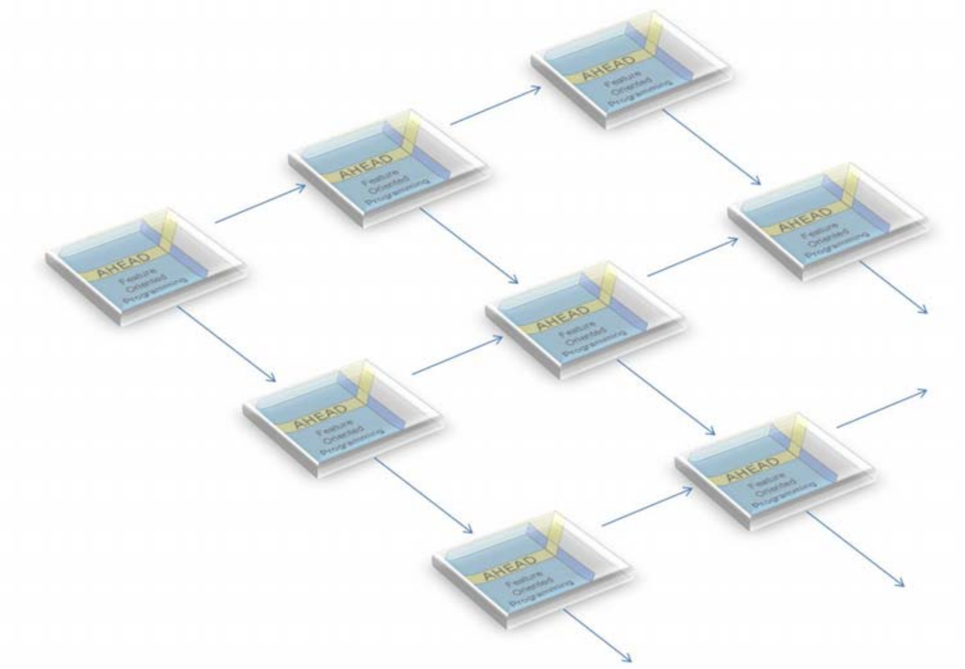
format, sub are **commutative**

A Product Line is a Category



- Degenerate or trivial category
  - point is a domain with a single program in it
- Has implied identity arrows
- Has implied composed arrows, as required

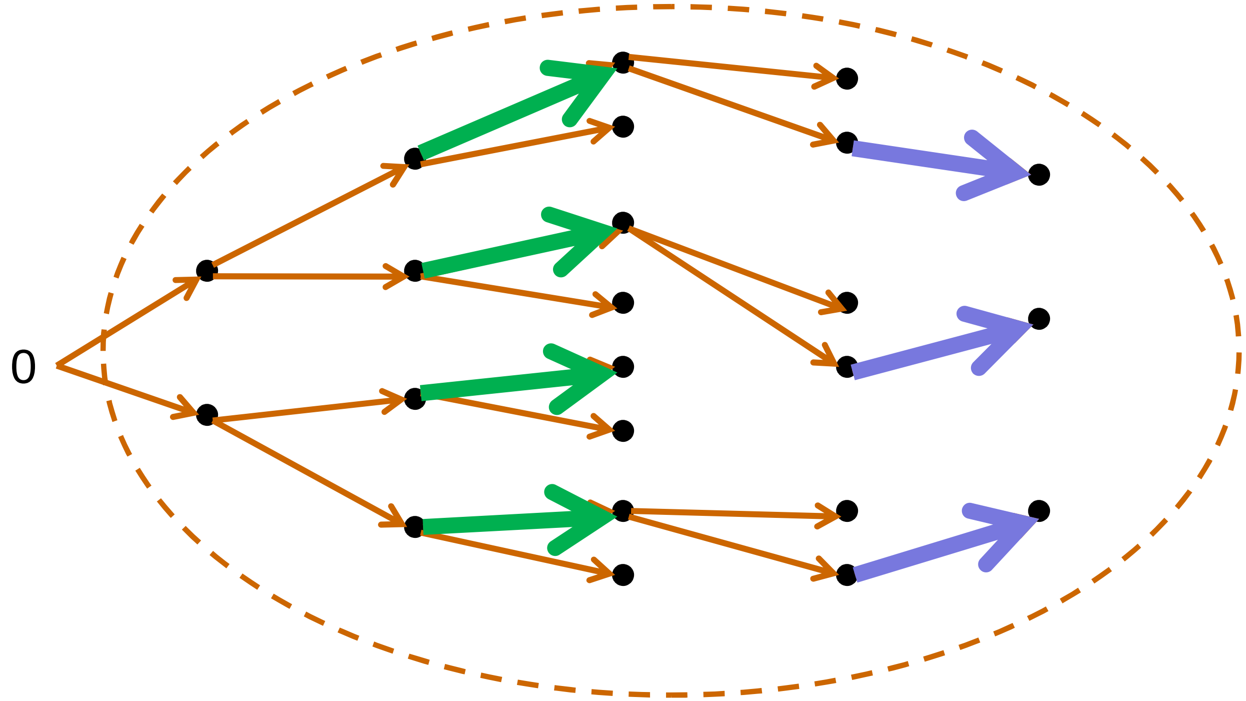
Implementing SPLs



Implementing SPLs

want this:

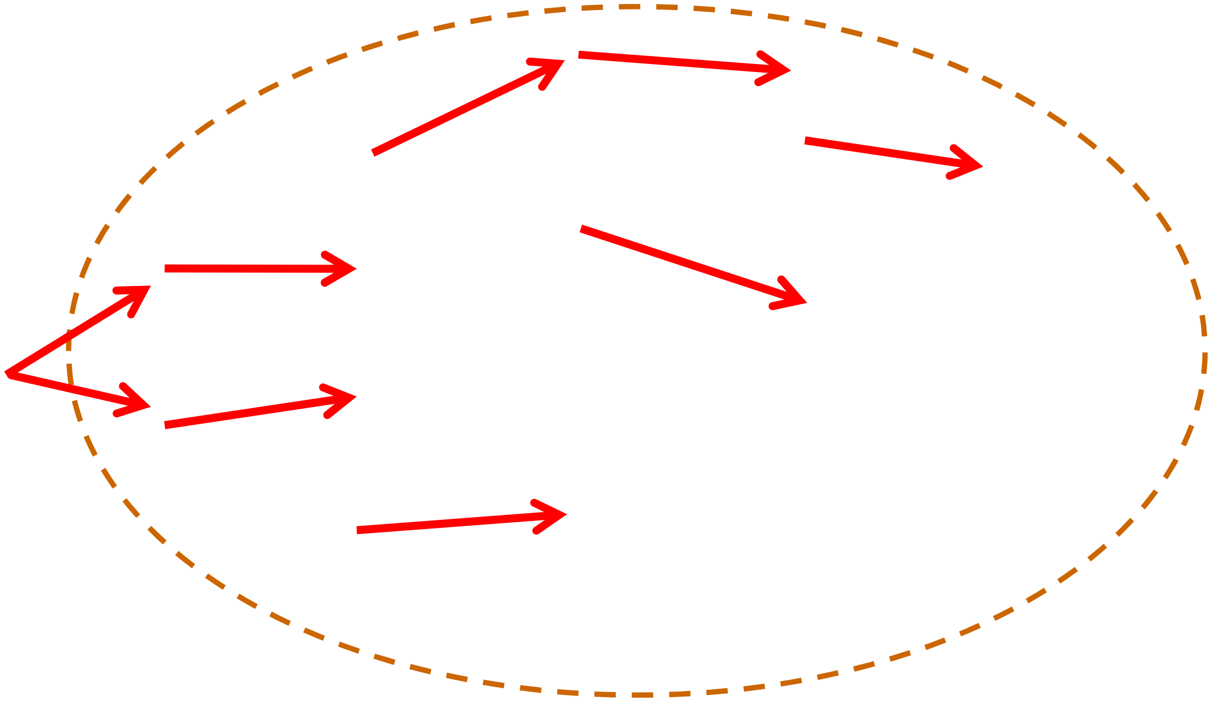
know this:



- Same function being applied to different inputs

Implementing SPLs

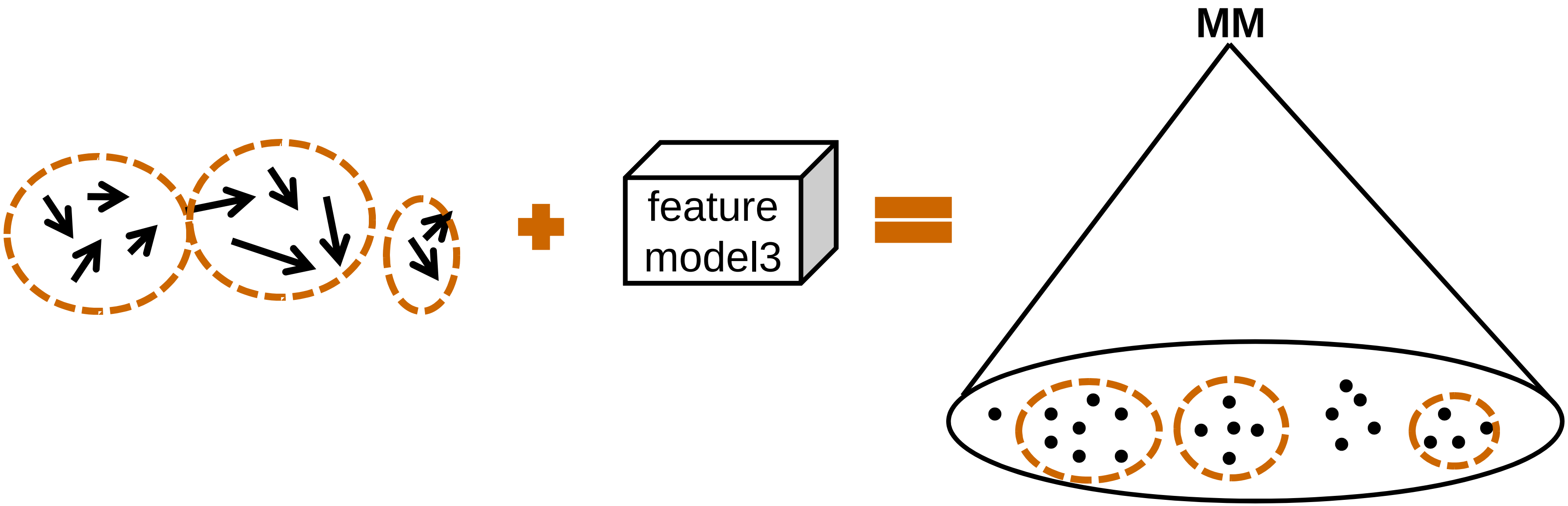
store this:



- Just store arrows regardless of how they are implemented
  - n optional features, 2^n possible programs
  - compact representation of an SPL

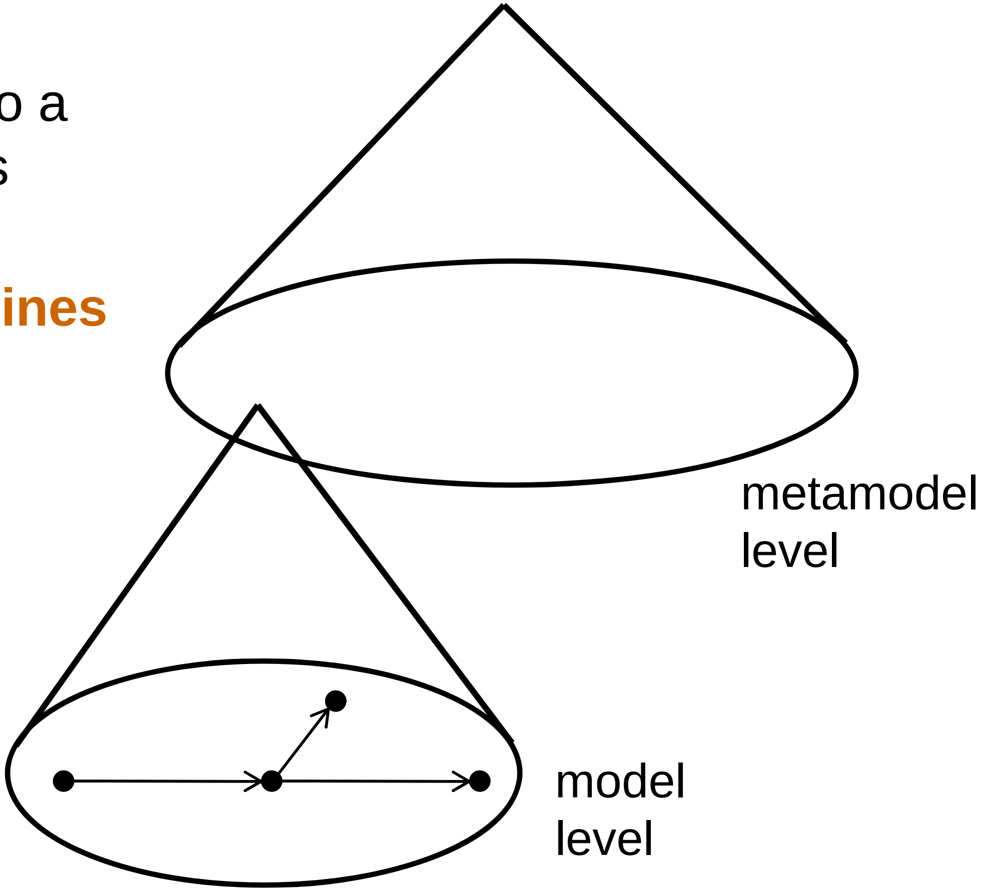
Models of SPLs

- Implement a set of arrows
- Define a feature model to define legal compositions of arrows
- Yields a product line
- See paper for more details



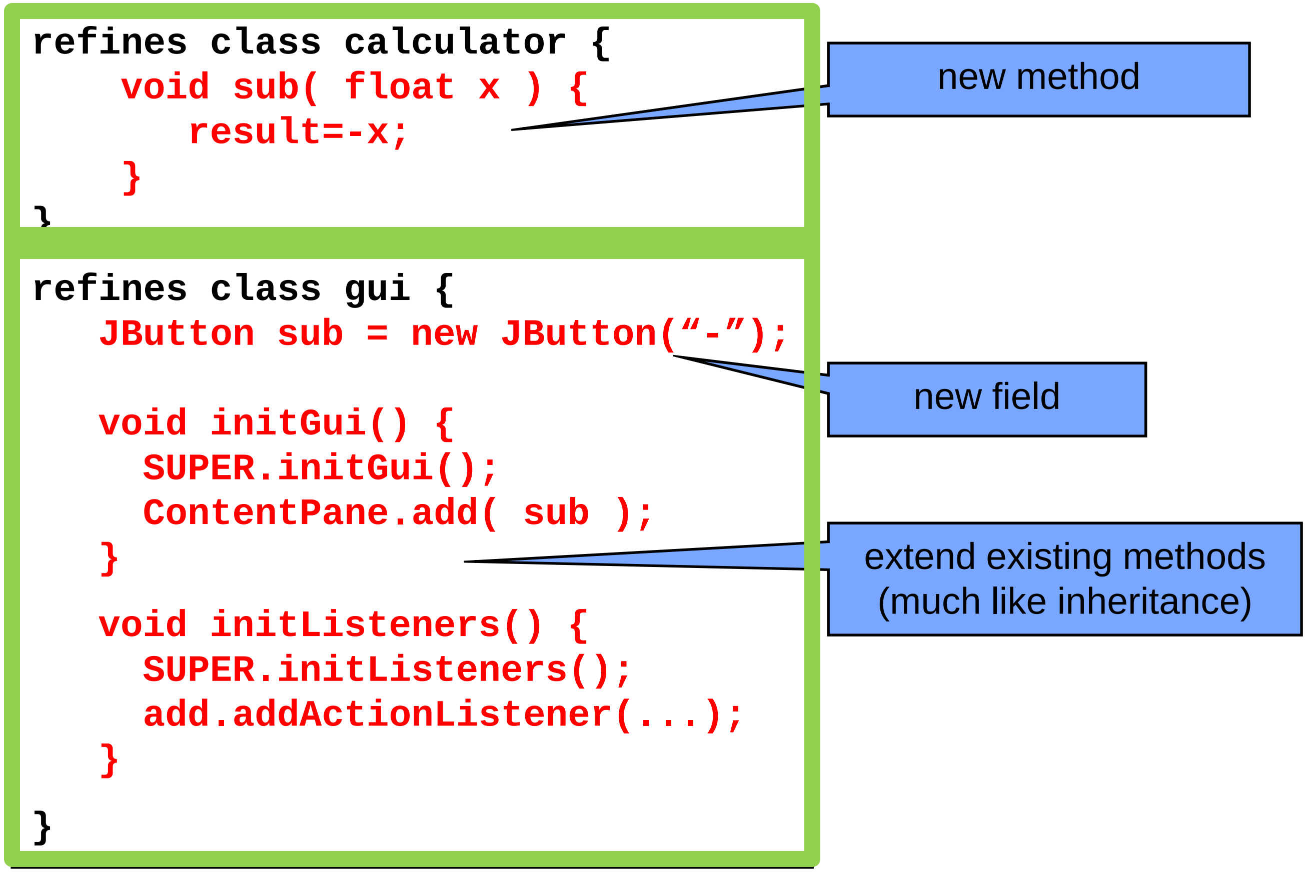
Recursion

- SPLs can appear at any level of an MDE architecture
  - arrow add same feature to a large domain of programs
  - **Model Driven Product Lines** to be discussed shortly
- **Superposition** is standard technique



Code Arrows in AHEAD

- AHEAD refines (Scala, ClassBox/J, …)
  - “sub” feature adds (superimposes) new fields, members, wrappers…



```
refines class calculator {
    void sub( float x ) {
       result=-x;
    }
}
```

```
refines class gui {
   JButton sub = new JButton(“-”);

   void initGui() {
     SUPER.initGui();
     ContentPane.add( sub );
   }

   void initListeners() {
     SUPER.initListeners();
     add.addActionListener(...);
   }
}
```

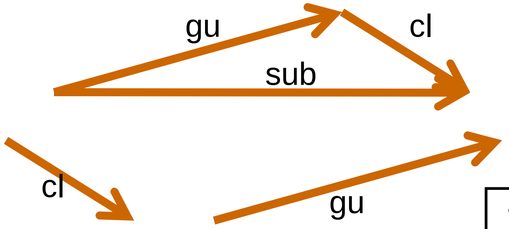
new method

new field

extend existing methods
(much like inheritance)

Code Arrows in AHEAD

- “sub” arrow is composed from 2 simpler arrows



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   void initGui() {
     SUPER.initGui();
     ContentPane.add( sub );
   }

   void initListeners() {
     SUPER.initListeners();
     add.addActionListener(...);
   }
}
```

sub

=

```
refines class calculator {
    void sub( float x ) {
       result=-x;
    }
}
```

cl

●

```
refines class gui {
   JButton sub   = new JButton(“-”);

   void initGui() {
     SUPER.initGui();
     ContentPane.add( sub );
   }

   void initListeners() {
     SUPER.initListeners();
     add.addActionListener(...);
   }
}
```

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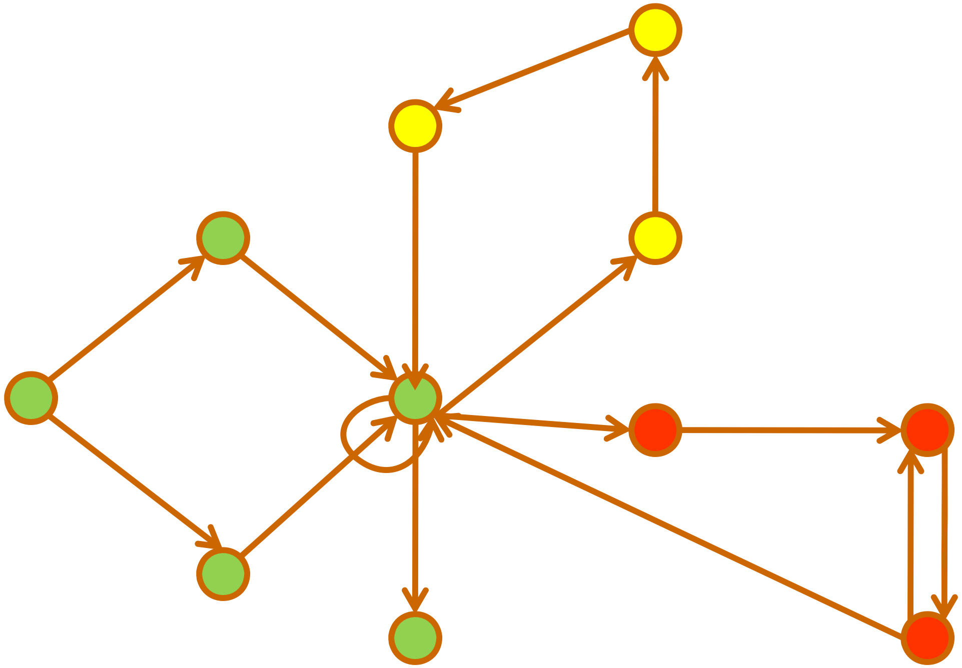
Model Arrows in AHEAD

- Example: Product Lines of State Machines
  - ICSR 2000: fire support simulators
  - ICSE 2007: web portlet product line



Synthesizing customized state charts by composing features

Feature arrows are implemented by model deltas – additional elements and relationships are superimposed onto a base model

Makes SPL designs easier to understand and analyze

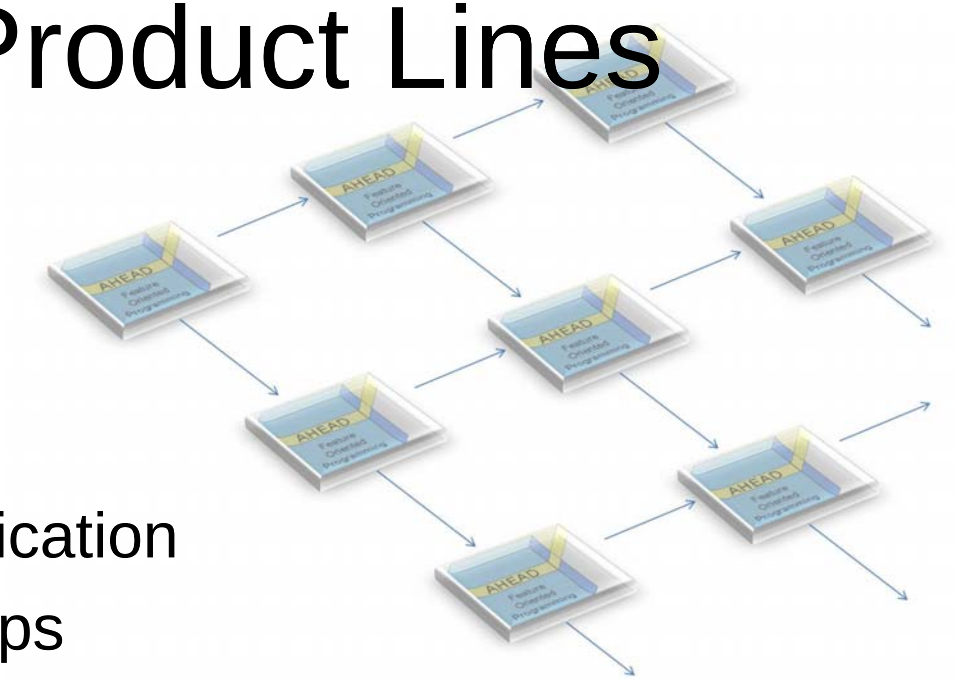
Don't use power of full transformation language to implement arrows

orange • yellow • base

Recap

- Categories lie at the heart of Software Product Lines
  - SPLs appear at all levels of an MDE architecture
- Informally, categories provides a clean set of ideas to express relationships that arise among objects in SPL
  - enabled me to place in perspective what MDE and SPL communities have been doing
- Next topic: **model-driven product lines (MDPLs)**

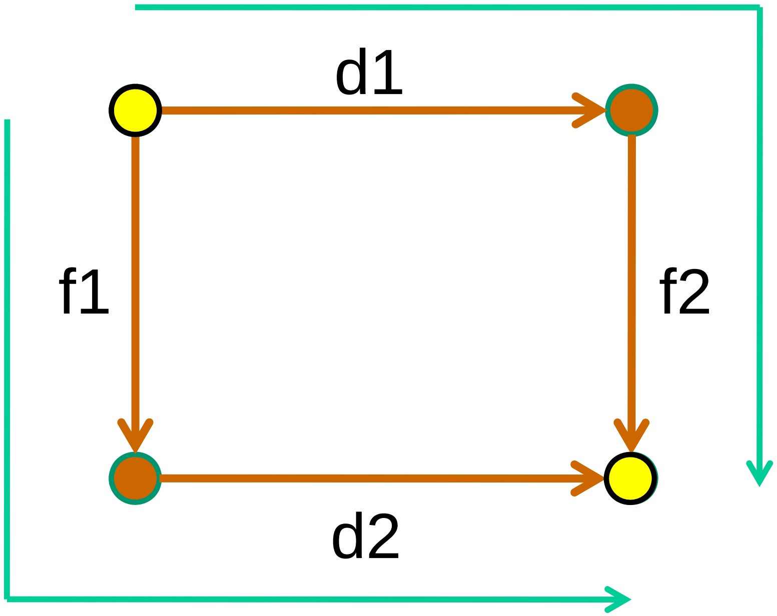
Part 3: Categories in Model Driven Product Lines



Exposing fundamental verification and optimization relationships

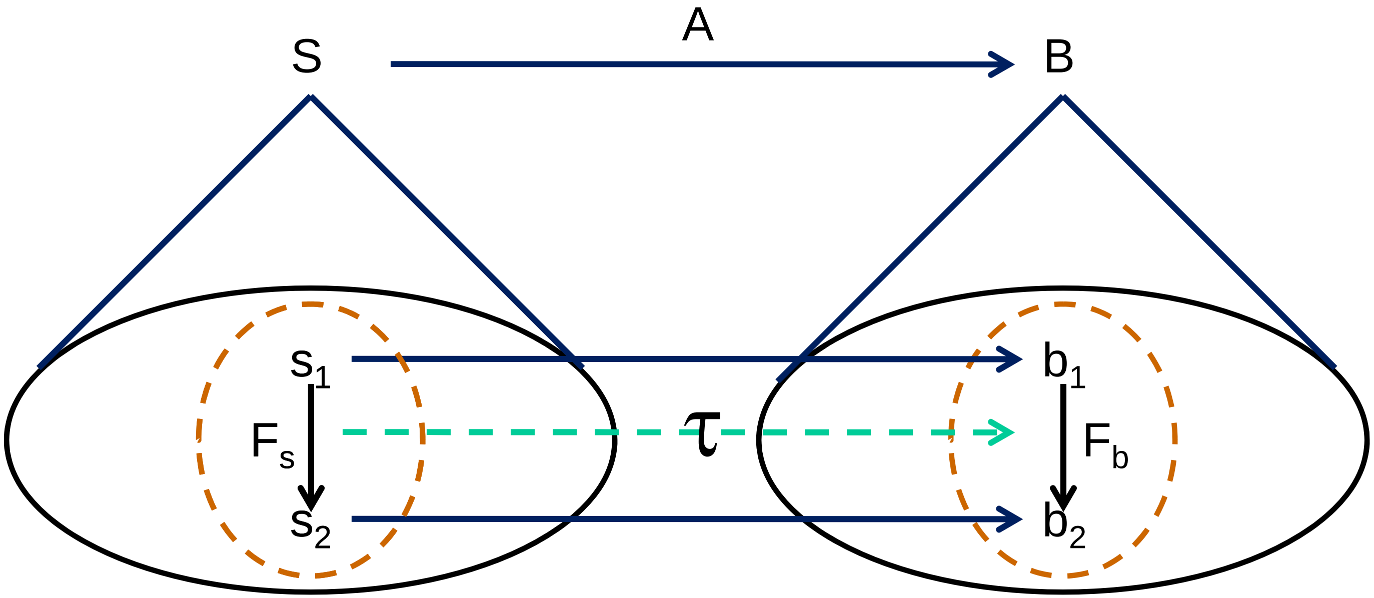
Commuting Diagram

- Fundamental concept in category theory
  - all paths between two objects yield same result
  - theorems of CT



$$f1 \bullet d2 = d1 \bullet f2$$

Diagrams in MDPLs

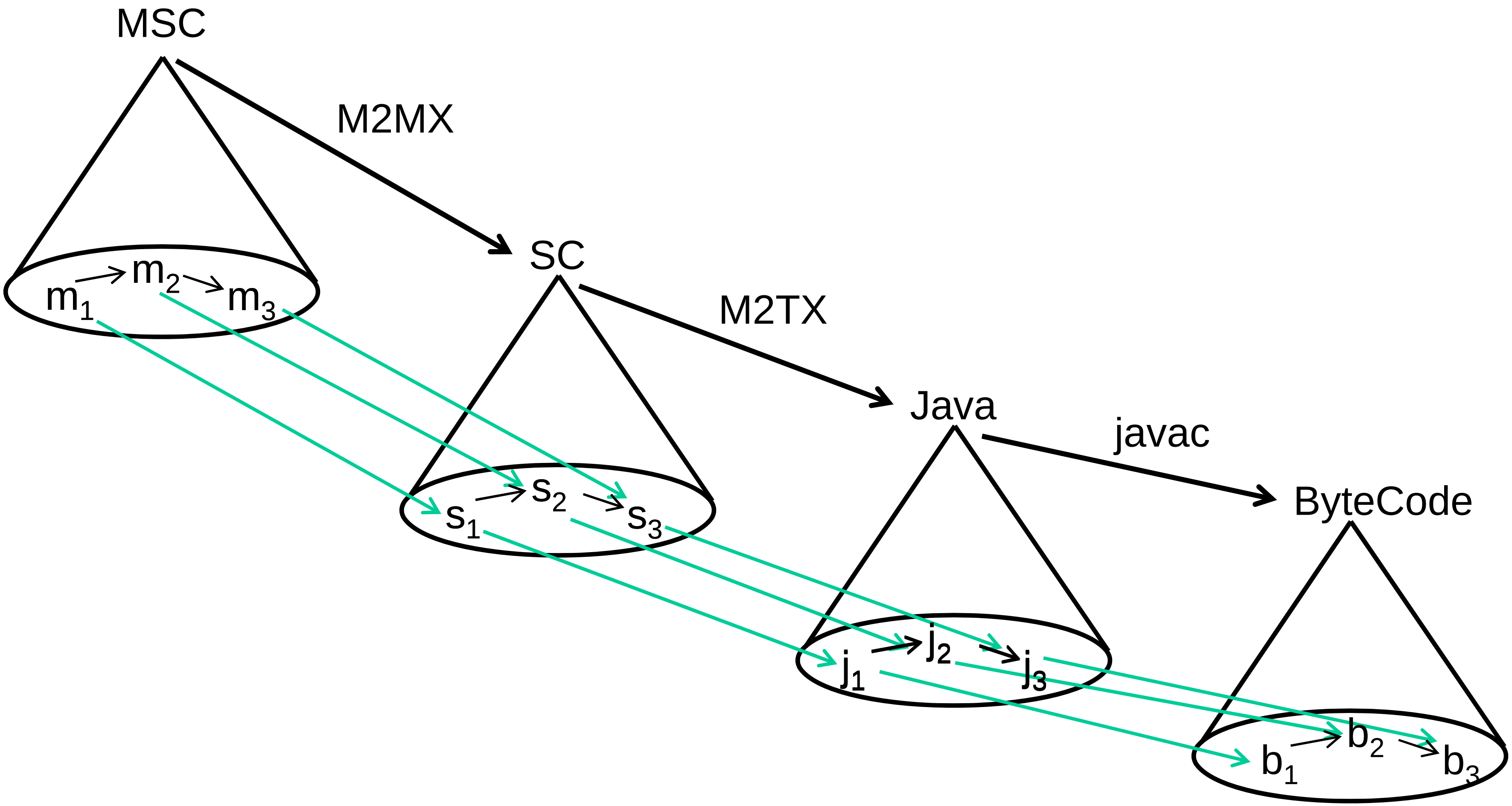


- Want to map a product line of S models into its corresponding product line of B models

- Transformations of MDE map objects

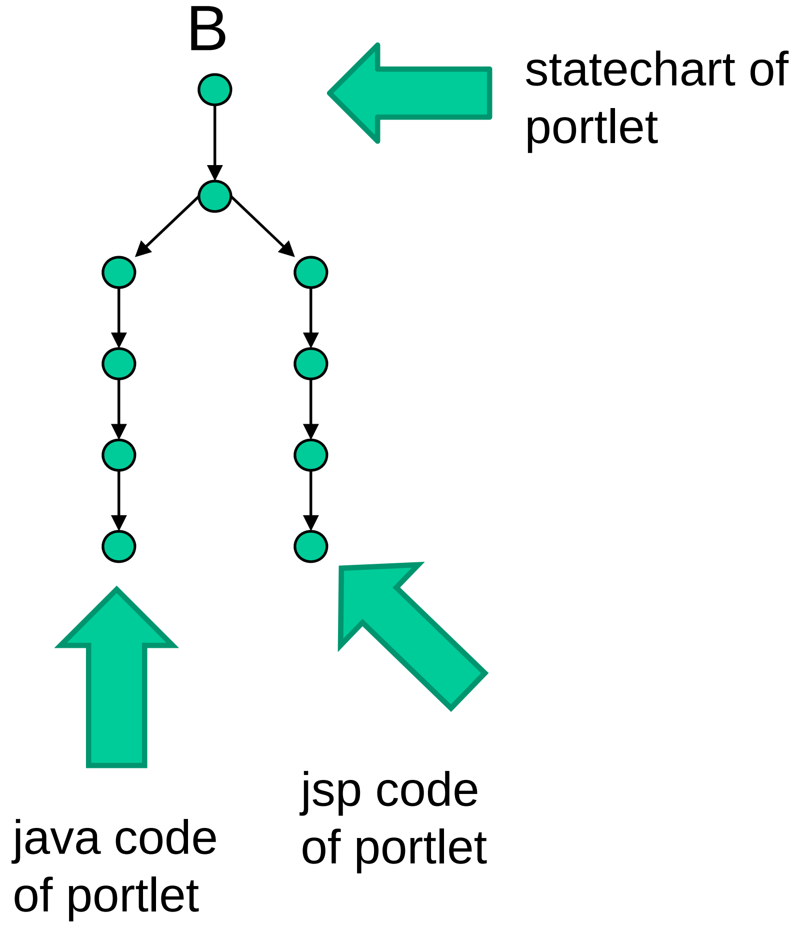
- Operator τ to map arrow F_s to arrow F_b: $\tau(F_s) = F_b$

How Commuting Diagrams Arise



Commuting Diagrams in PinkCreek

- Trujillo, et al. ICSE 2007
- Portlet synthesis
- Transform state chart into a series of lower level representations until Java and JSP code reached



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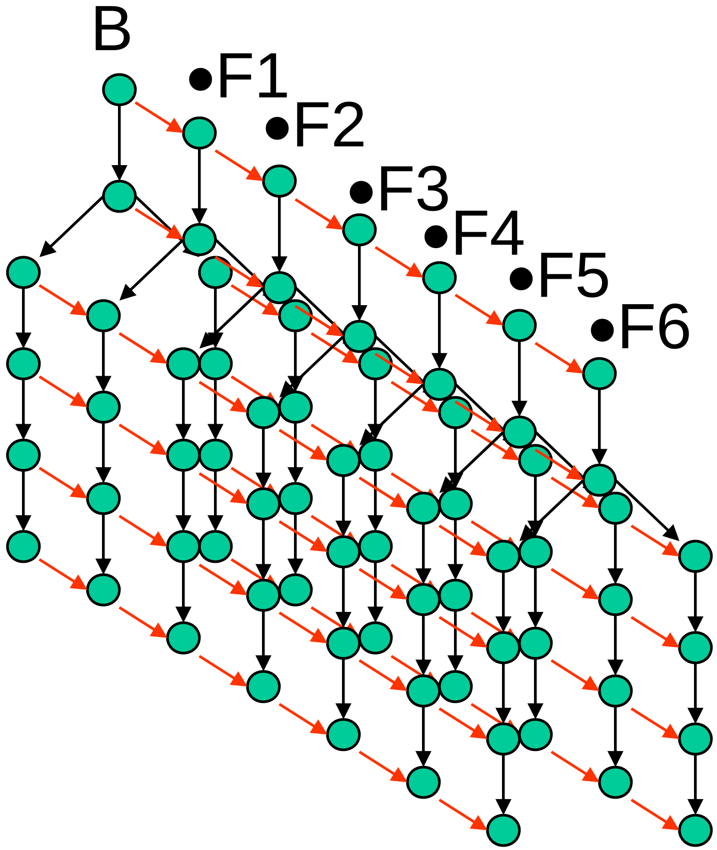
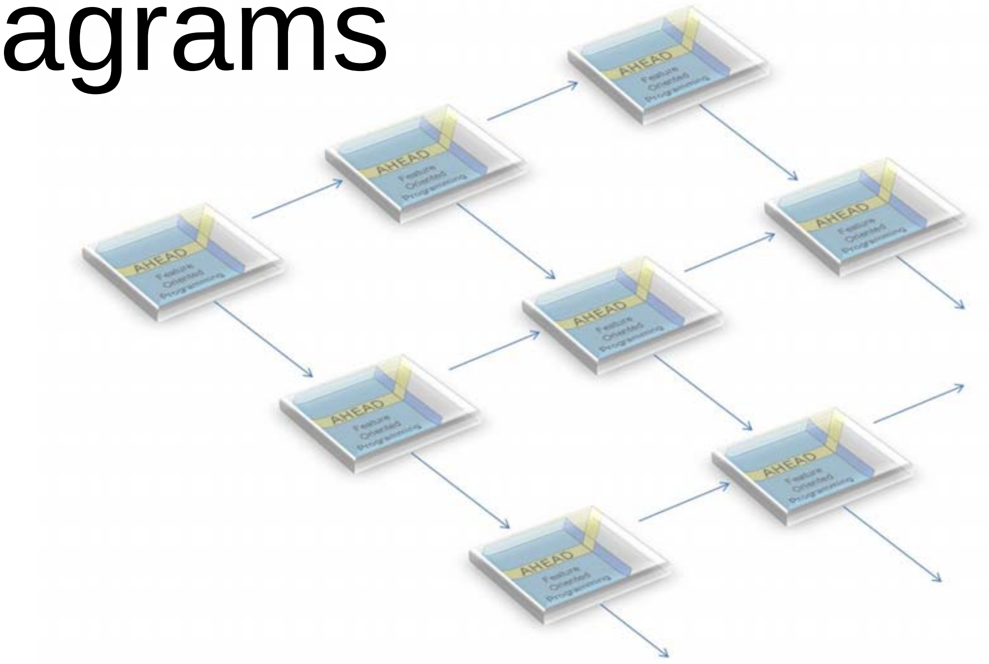


Warning!

- Operators easy to draw…
  - may (or may not) be easy to implement
  - may (or may not) be practical to implement
  - CT is not constructive – it doesn’t say how to implement arrow
  - no more than UML class diagrams tell you how to implement a method
- Tells you certain relationships exist, and if you can implement arrows, you can exploit commuting diagrams

Examples that Exploit Commuting Diagrams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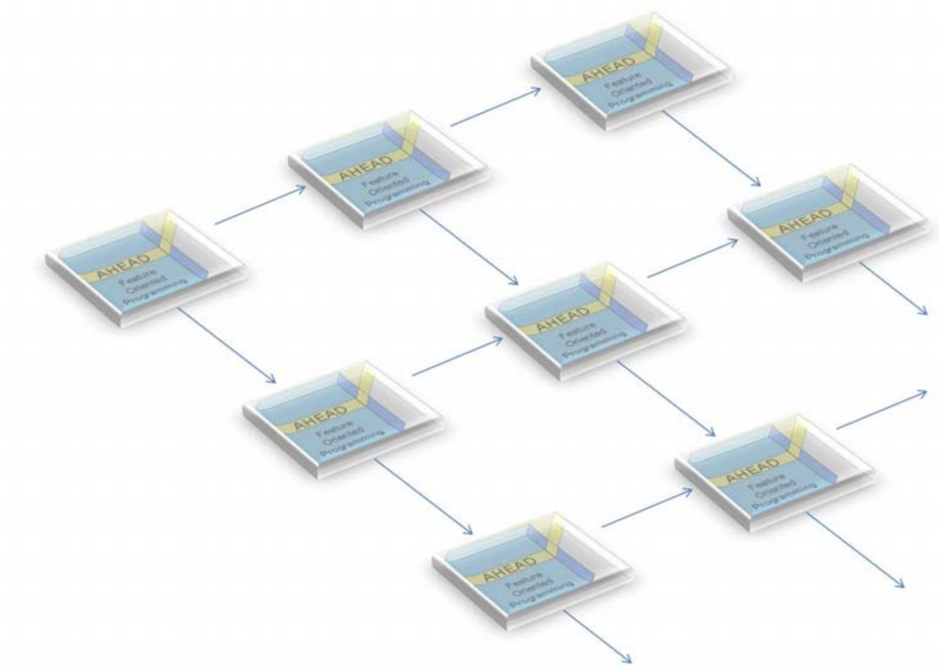
Feature Oriented Programming

Writing Operators

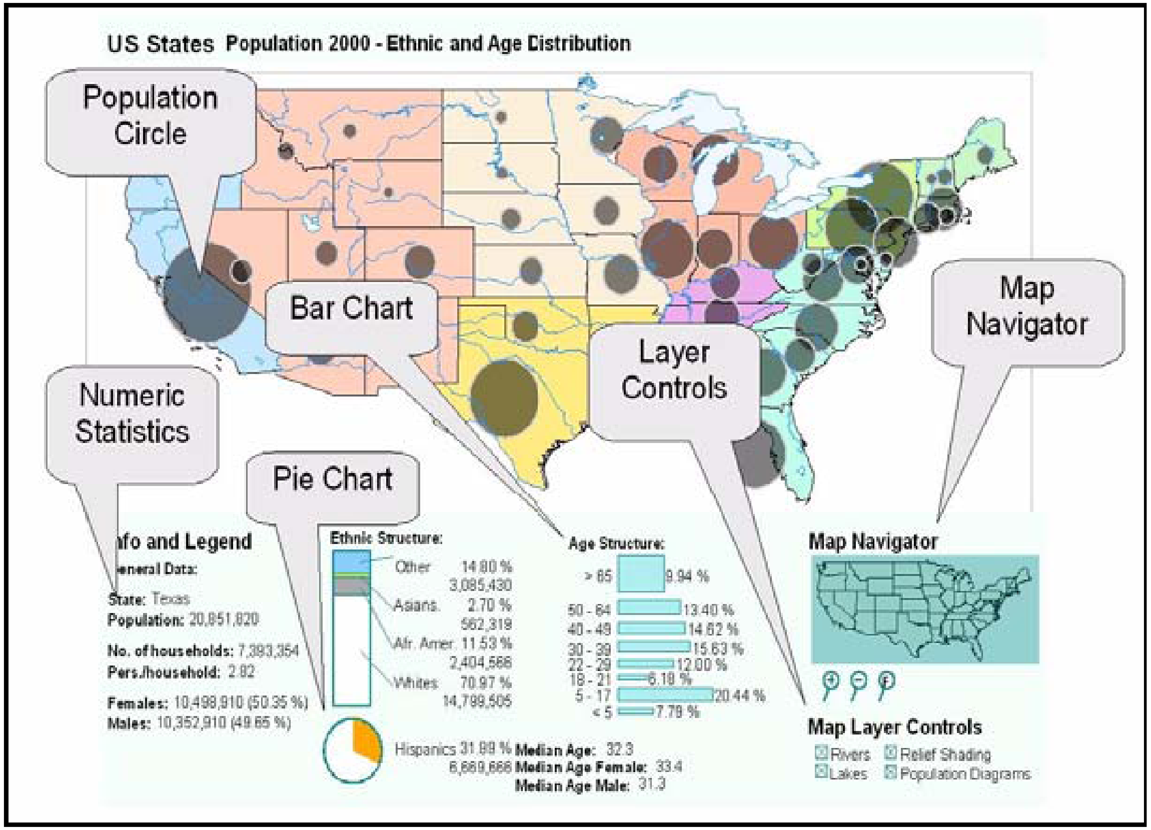
- In last 2 years, we found uses for commuting diagrams and arrow operators in MDPLs:
  - **simplifying implementation (ICMT 2008)**
  - **improving test generation (SIGSOFT 2007)**
  - understanding feature interactions (GPCE 2008)
  - understanding AHEAD (GPCE 2008)
  - improving synthesis performance (ICSE 2007)
- Briefly review the first two of these…

General Technique for Implementing MDPLs



Example 1: ICMT 2008 Paper

- Work with G. Freeman and G. Lavender
- MDPL of applications written in SVG and JavaScript
  - selectively customize application (removing, adding charts, controls)



US States Population 2000 - Ethnic and Age Distribution

nfo and Legend

eneral Data:

State: Texas
Population: 20,851,820

No. of households: 7,393,354
Pers./household: 2.82

Females: 10,498,910 (50.35 %)
Males: 10,352,910 (49.65 %)

Ethnic Structure:

Other	14.80 %	3,085,430
Asians.	2.70 %	562,319
Afr. Amer.	11.53 %	2,404,566
Whites	70.97 %	14,799,505
Hispanics	31.99 %	6,669,666

Age Structure:

> 65	9.94 %
50 - 64	13.40 %
40 - 49	14.62 %
30 - 39	15.63 %
22 - 29	12.00 %
18 - 21	6.18 %
5 - 17	20.44 %
< 5	7.79 %

Median Age: 32.3
Median Age Female: 33.4
Median Age Male: 31.3

Map Navigator

Map Layer Controls

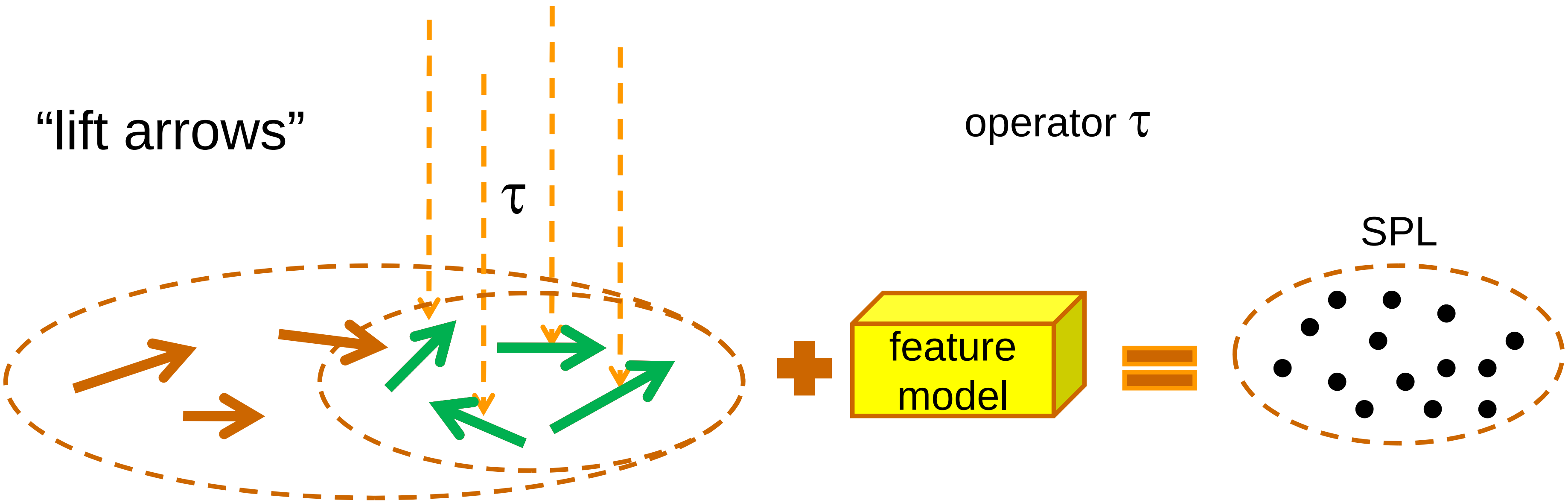
☒ Rivers ☒ Relief Shading
☒ Lakes ☒ Population Diagrams

Example 1: ICMT 2008 Paper

- Created a set of arrows and a feature model for our MDPL
    - red arrows (defining a product line of charts) were tedious to write
    - created DSL for charts, where arrows were easy to write, compose
    - defined an operator τ to map 1:1 from green arrows to red arrows

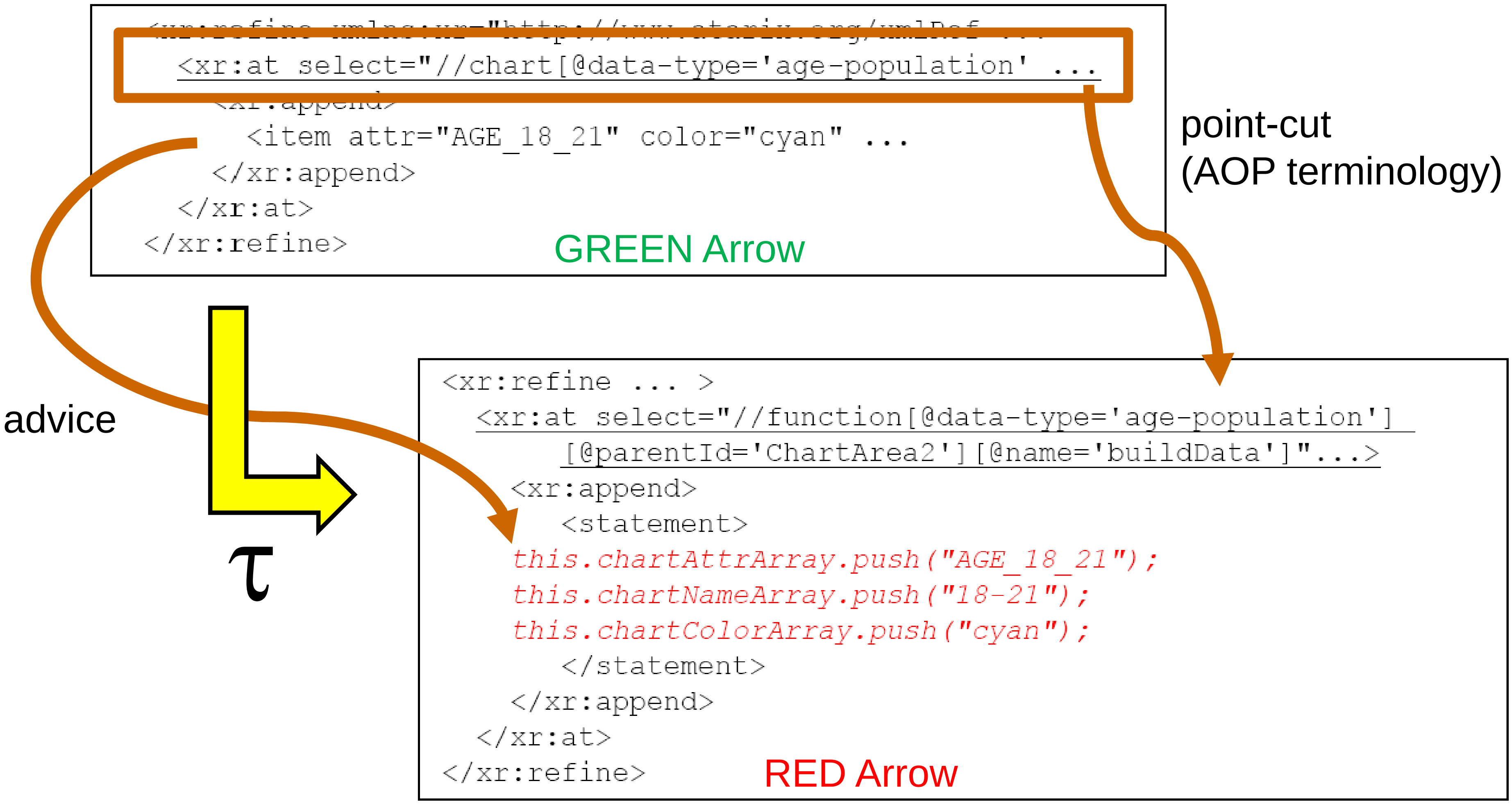
DSL for chart arrows

operator τ



“lift arrows”

τ Translation Example



```
<xr:refine xmlns:xr="http://www.atarix.org/xmlRef ...
  <xr:at select="//chart[@data-type='age-population' ...
    <xr:append>
      <item attr="AGE_18_21" color="cyan" ...
    </xr:append>
  </xr:at>
</xr:refine>
```

GREEN Arrow

point-cut
(AOP terminology)

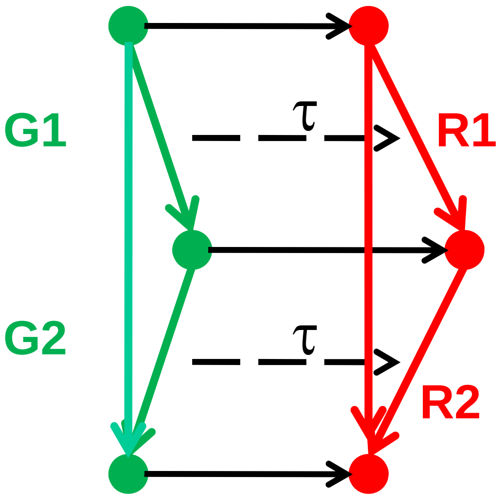
advice

τ

```
<xr:refine ... >
  <xr:at select="//function[@data-type='age-population']
       [@parentId='ChartArea2'][@name='buildData']"...>
    <xr:append>
       <statement>
    this.chartAttrArray.push("AGE_18_21");
    this.chartNameArray.push("18-21");
    this.chartColorArray.push("cyan");
       </statement>
    </xr:append>
  </xr:at>
</xr:refine>
```

RED Arrow

Diagram Constraints



$$\tau(G1 \bullet G2) = \tau(G1) \bullet \tau(G2)$$

$$= R1 \bullet R2$$

- Same ranslate OR we tr rows

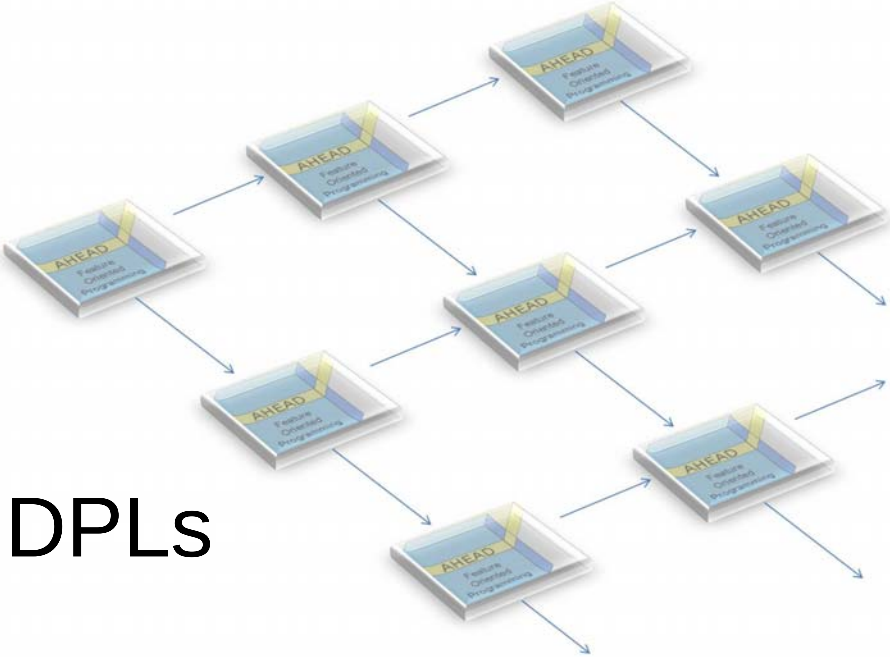
- **Hom** ne algebra (**GRE** ther (**RED**)

Verification condition: Implementation is correct if this equality holds!

Guess What?

- Initially our tools did not satisfy diagram constraints
  - equalities of homomorphisms didn’t hold
  - our tools had bugs – we had to fix our tools
  - now we have greater confidence in tools because they implement explicit relationships of domain models
  - win from engineering perspective
    - » we have an insight into domains that we didn’t have before
    - » by imposing categorical structure on our domain, we have better understanding, better models, and better tools
- Lifting is not specific to our application,
  it is a general technique for building MDPLs

Test Generation for MDPLs


AHEAD
Feature Oriented Programming
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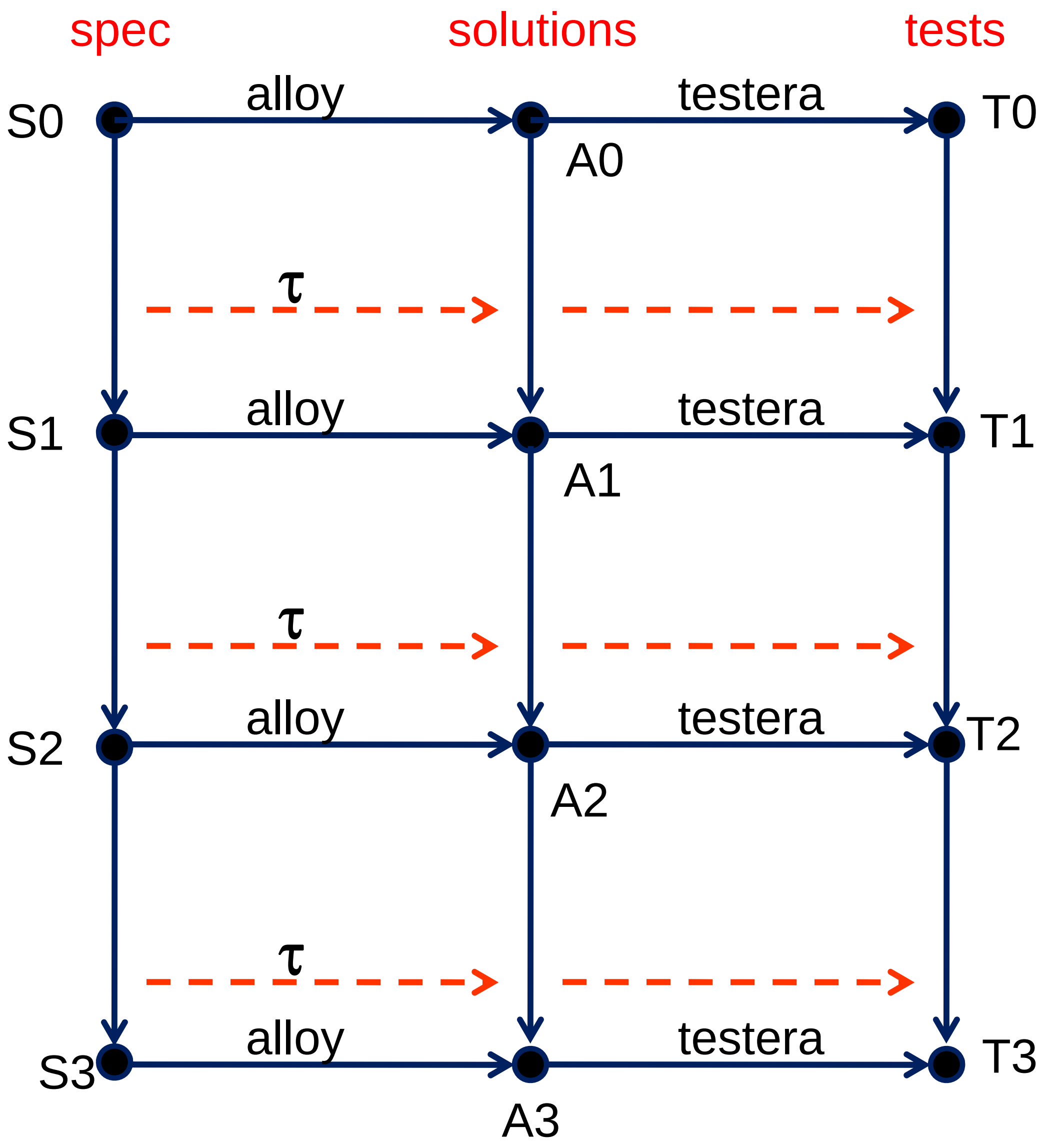
Example 2: ISSRE 2008 Paper

- Work with E. Uzuncaova and S. Khurshid (ECE@UTexas)

- Testing SPLs is a basic problem
  - we can generate different programs, but how do we know that the programs are correct?

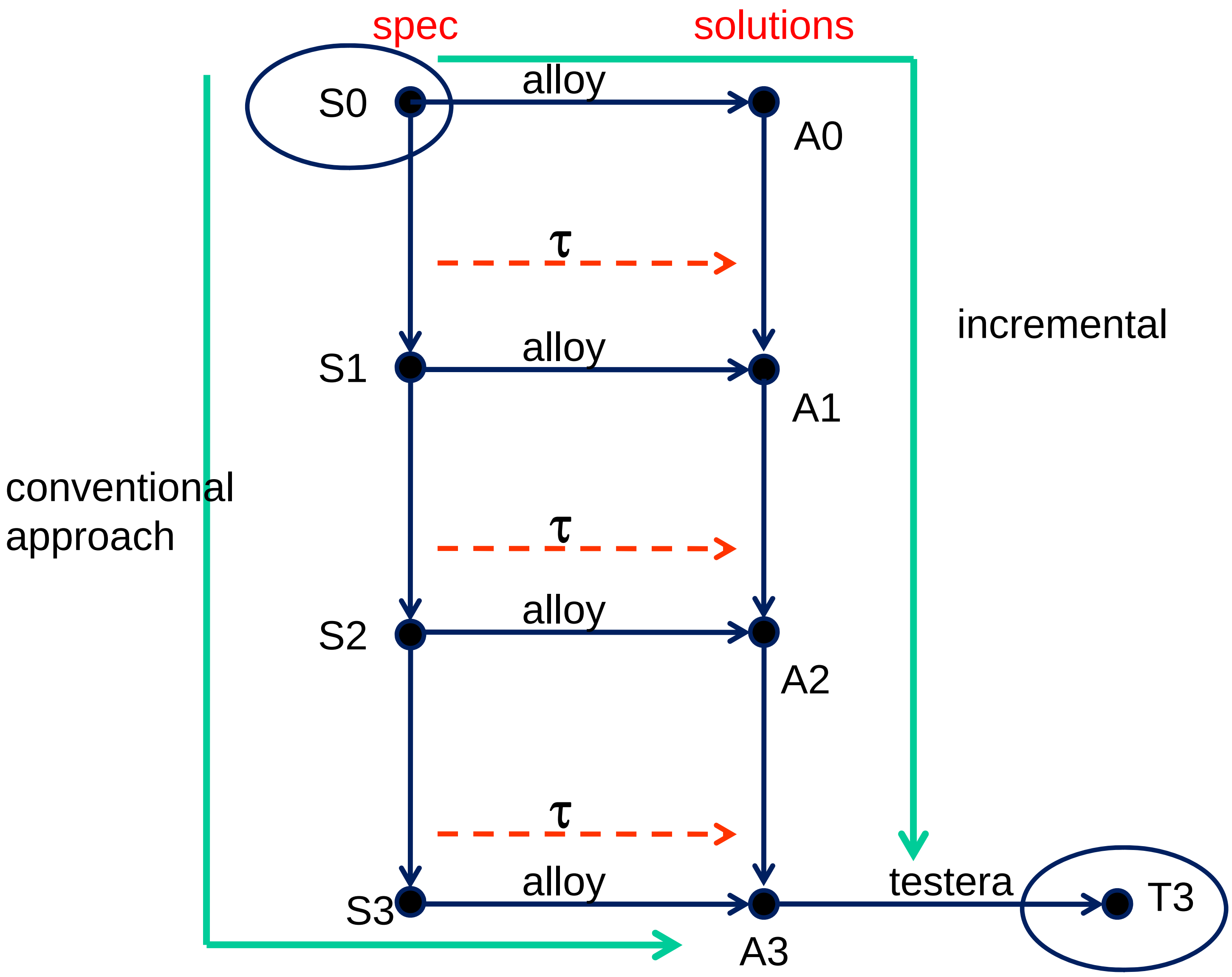
- Specification-based testing can be effective
  - start with a spec (model) of program
  - automatically derive tests
  - Alloy is example

Conventional Test Generation



Challenge:
is there
a τ
operator?

Incremental Test Generation



Implementing τ

- Spec S1 = $(A \vee B) \wedge (\neg A \vee C)$ // 20K clauses

  a solution: [A,B,C] = [$\underline{1, 0, 1}$]

- Spec S2 = $(A \vee B) \wedge (\neg A \vee C) \wedge (D \vee \neg A)$

  a solution: [A,B,C,D] = [$\underline{1, 0, 1}$, 1]

- Solution for S1 “bounds” solution for S2
  - sound, complete

- Reason for efficiency…

Preliminary Results

- In product lines that we examined (typical of Alloy research), majority of cases incremental approach is faster
  - 30-50× faster
  - can now solve larger problems with Alloy

- Although preliminary, results are encouraging

- See paper(s) for details

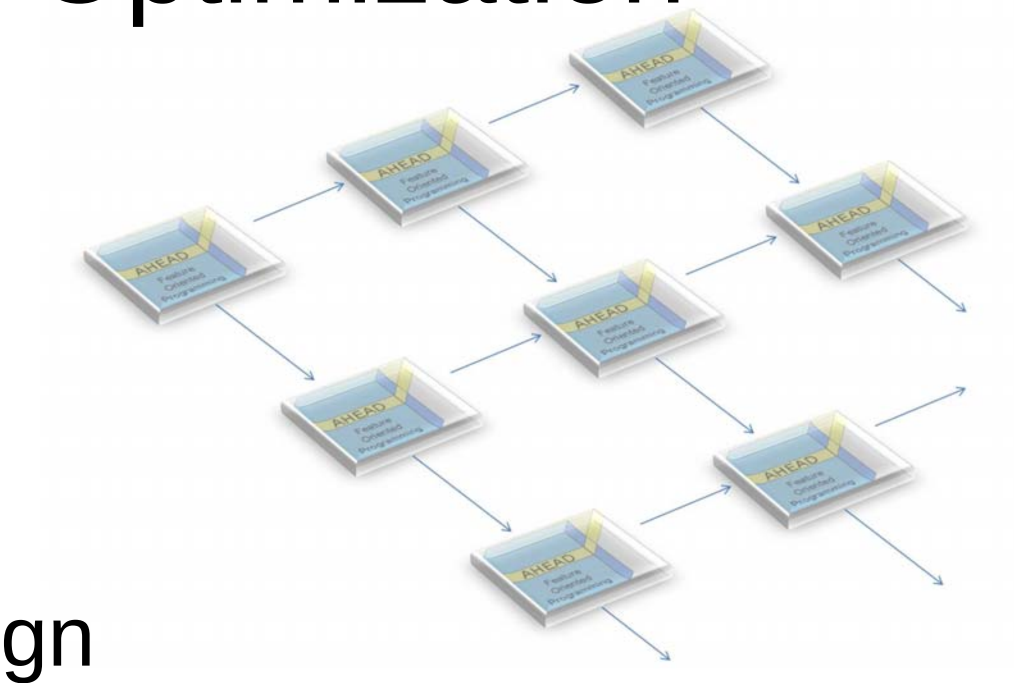
Recap

- Creating a SPL or MDE application creates industrial–sized categories

- Putting them together reveals a foundational idea of categories – commuting diagrams
  - involves mapping both objects of a category AND arrows
  - need operators (transformation – to – transformation maps)

- Can exploit exposed relationships as
  - verification conditions
  - optimization possibilities

Part 4: Design Optimization

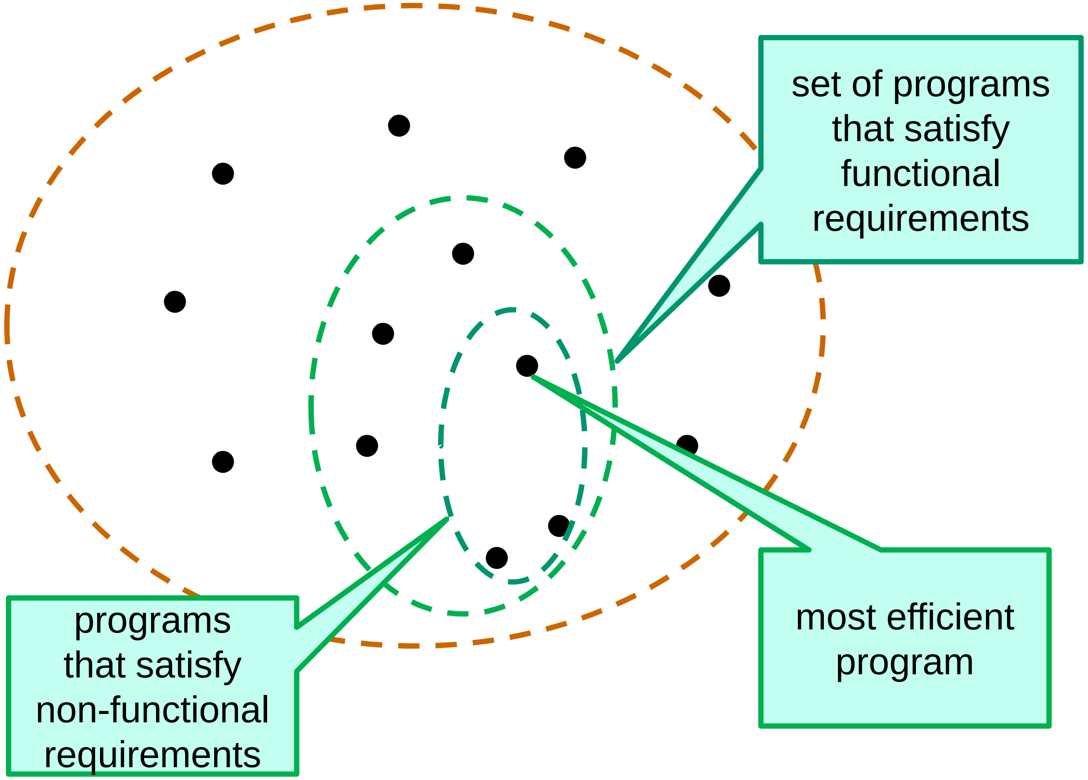


Frontier of
Computational Design

Principles of Computational Design

- Design = expression
- Synthesis = expression evaluation
- Design Optimization = expression optimization
  - find program that satisfies functional requirements and optimizes some non-functional properties (performance, energy consumption)

paradigm of relational query optimization



set of programs that satisfy functional requirements

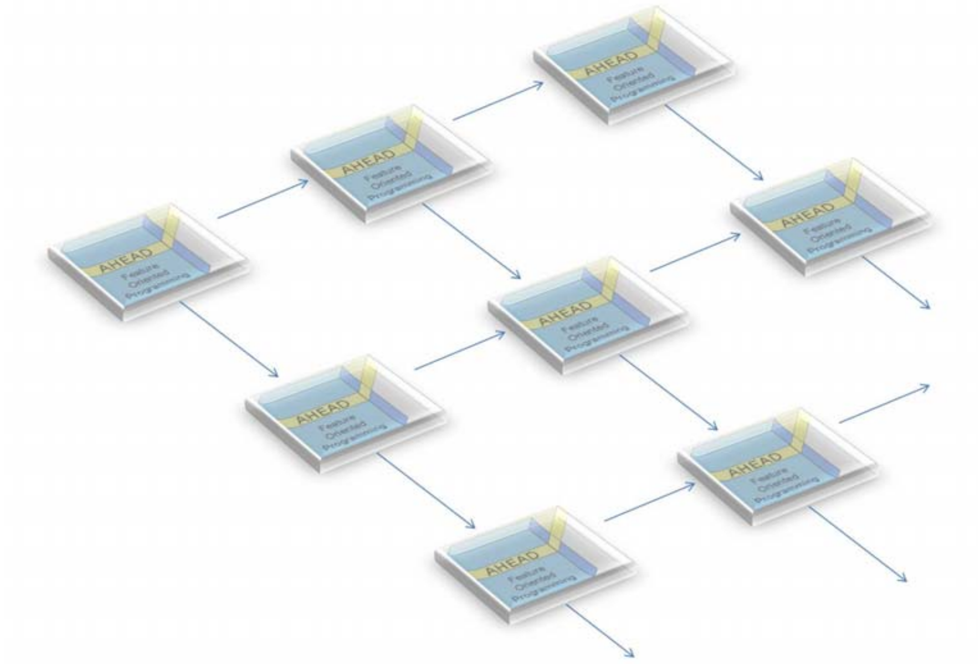
programs that satisfy non-functional requirements

most efficient program

At Present…

- I know of few examples of design optimization …
    - relational query optimization (1980s)
    - data structure optimizations (1990s)
    - Neema’s work on synthesizing adaptive computing (2001)
    - Püschel’s work on numerical library synthesis (2006)
    - Benavides work on configurators (2005)
    - …
- Main challenge: finding domains where there are different ways to implement the same functionality
    - commuting diagrams
    - this is where design optimization occurs
- If you think in terms of arrows, you have a conceptual framework and tools to explain and address design optimization in a principled, non-ad hoc way

Conclusions



Role of Mathematics in Design

- RQO helped bring database systems out of stone age

- Relational Model was based on set theory
  - this was the key to understanding a modern view of databases
  - set theory used was shallow
  - fortunate for programmers and database users
  - set select, union, join, intersect
  - disappointment for mathematicians

- Computational Design uses category theory
  - basic ideas useful – allows us to place research results in context
  - new insight on verification, optimization issues
  - whether theorems from CT are applicable, I don’t know

Key To Success

- Educational benefit of the connection
  - common terminology, concepts
  - new perspectives

- How often in MDE, SPL, MDPL do commuting diagrams arise?
  - don’t know; too early
  - but if you look, you’ll find them
  - theory says they exist
  - whether creation of operators practical decided on a per domain basis

Look for Them!

Final Comments

- Future of software design and synthesis is in automation
    - seeking principles that have a mathematical basis
- Made great strides understanding structure (UML)
- Need to take few more strides in understanding arrows
    - tools, transformations used in design and synthesis
- Software design & synthesis seems to rest on simple ideas
    - programs (models) are values
    - transformations map programs to programs
    - operators map transformations to transformations

Final Comments

- Clear that ideas are being reinvented in different contexts
  - not accidental – evidence we are working toward general paradigm
  - modern mathematics provides a simple language to express computational designs, expose useful relationships in SPL and MDE architectures
  - maybe others may be able to find deeper connections