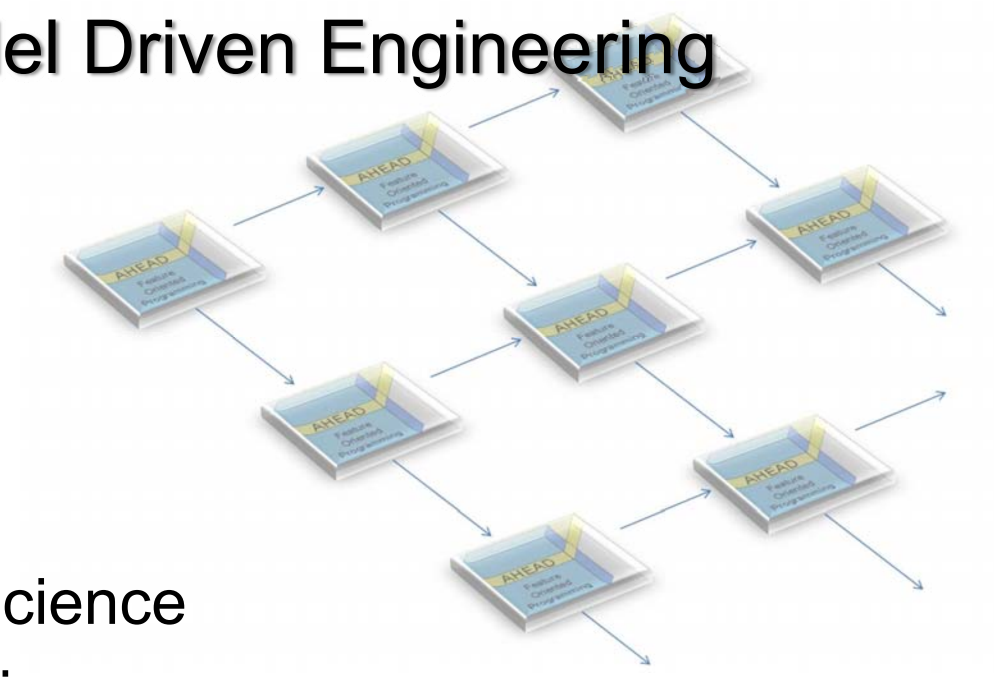
Design by Transformation (D×T)

Principles of Model Driven Engineering



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Introduction

- My research is at intersection of
  - software product-lines (SPLs)
  - program refactoring
  - model driven engineering (MDE)
  - database systems

- I come from world of
  - informal software engineering and design
  - *not* compilers, formal software development, mathematics

- What distinguishes my work
  - start with practice, find a theory that fits practice
  - I use algebra to explain my ideas
  - foundation for more formal theories of automated development

Keys to the Future

- New paradigms will embrace:
  - **Generative Programming (GP)**
    - want software development to be automated
  - **Domain-Specific Languages (DSLs)**
    - not Java & C#, but high-level notations
  - **Automatic Programming (AP)**
    - declarative specs → efficient programs
- Need simultaneous advance in all three fronts to make a significant change

Not Wishful Thinking...

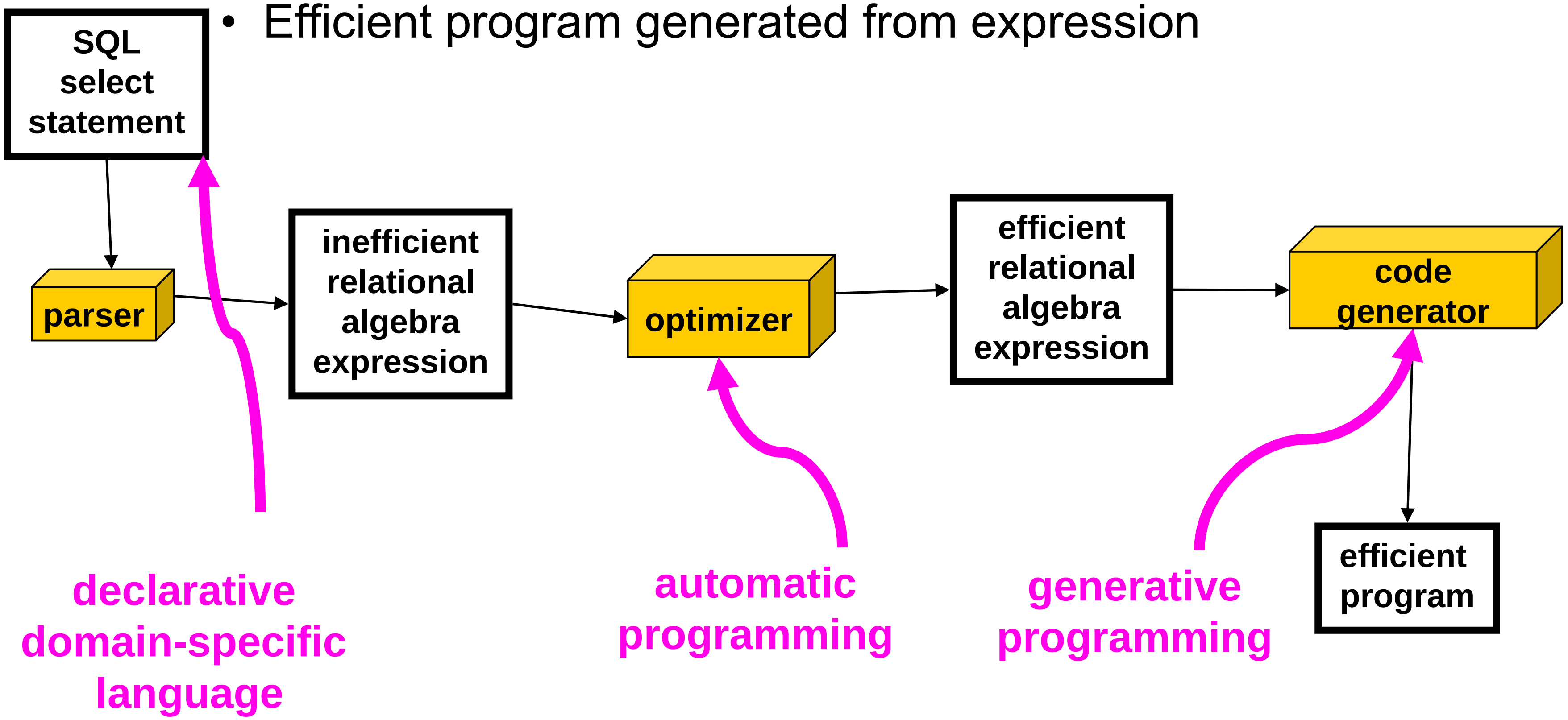
- Example of this futuristic paradigm realized 30 years ago
  - around time when many AI researchers gave up on automatic programming

Relational Query Optimization

- The most significant result in automated program design and development, period
- Not mentioned in typical SE texts …

Relational Query Optimization (RQO)

- Declarative query is mapped to an relational algebra expression
- Each expression represents a unique program
- Expression is optimized using algebraic identities
- Efficient program generated from expression



SQL select statement

parser

inefficient relational algebra expression

optimizer

efficient relational algebra expression

code generator

efficient program

declarative domain-specific language

automatic programming

generative programming

Keys to Success

- Automated development of query evaluation programs
    - hard-to-write, hard-to-optimize, hard-to-maintain
    - revolutionized and simplified database usage
- Represented program designs as algebraic **expressions**
    - different expressions represented different programs
    - compositions of relational operations
- Compositionality is hallmark of great engineering
- Use algebraic identities to optimize expressions
    - equates the semantics of different programs

This Tutorial

- Sketch the future:
  - automated software design & maintenance from an algebraic perspective
  - extrapolating 25+ years of experience
  - characteristics of new languages, compilers, tools

- Essential complexity of software structure
  - is exposed when program construction and design is viewed as a computation
  - hides accidental complexity

- **Design by Transformation (D×T)** – generalization of RQO paradigm
  - programs are values
  - transformations map programs to programs
  - operators map transformations to transformations
  - **meta-expressions**

Tutorial Overview

1. Program Refactoring, Program Synthesis, and Model Driven Engineering

   algebra underlies program construction

2. Objects and Arrows of **D×T**

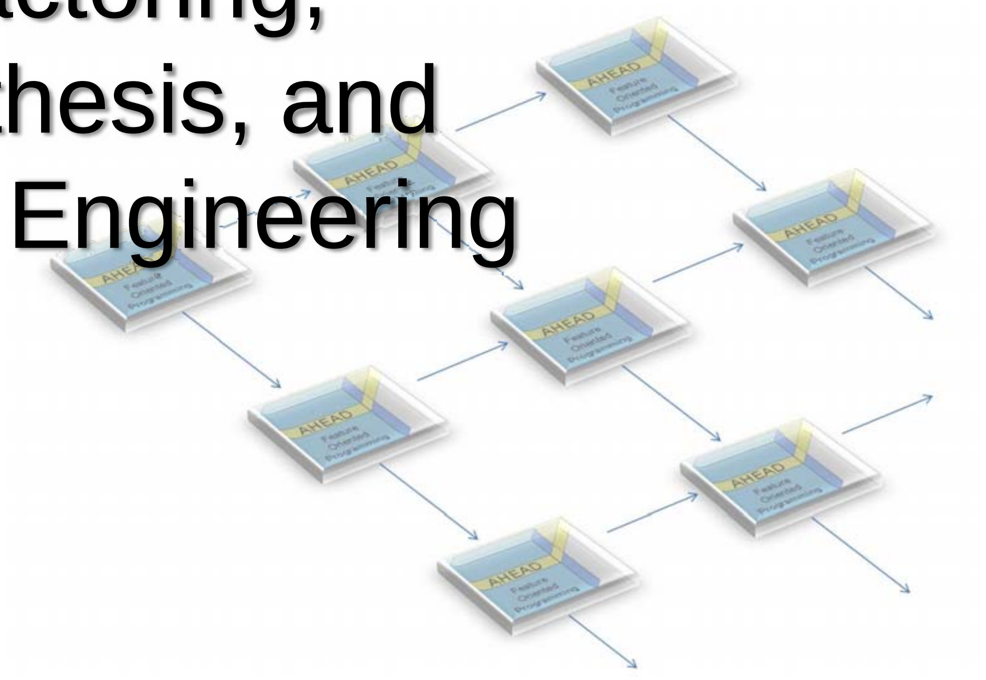
   the relevance of categories and category theory

3. Extraction of MDE Architectures from Parallel Streaming Applications

   stepwise development of software architectures by applying domain-specific identities

Buckle Up!

Lecture 1:
Program Refactoring,
Program Synthesis, and
Model Driven Engineering



Upcoming Topics – Four Mini Talks

1. **Basics of D×T**

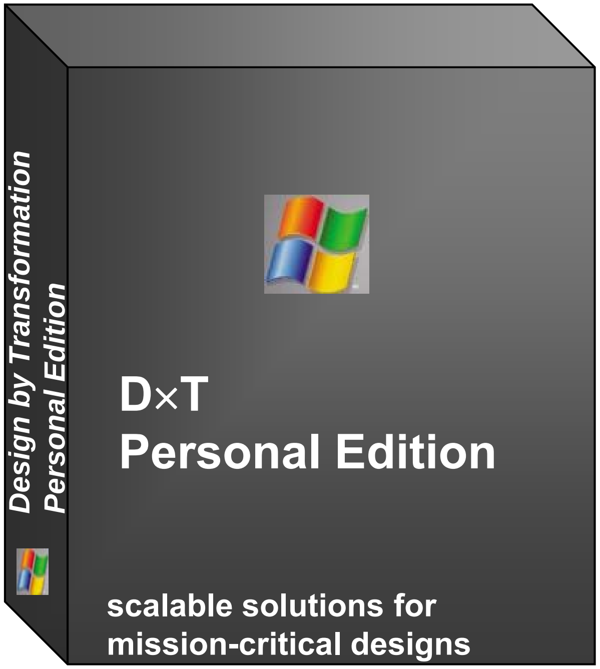
2. **Program Refactoring**
   - Dig & Johnson (Illinois)

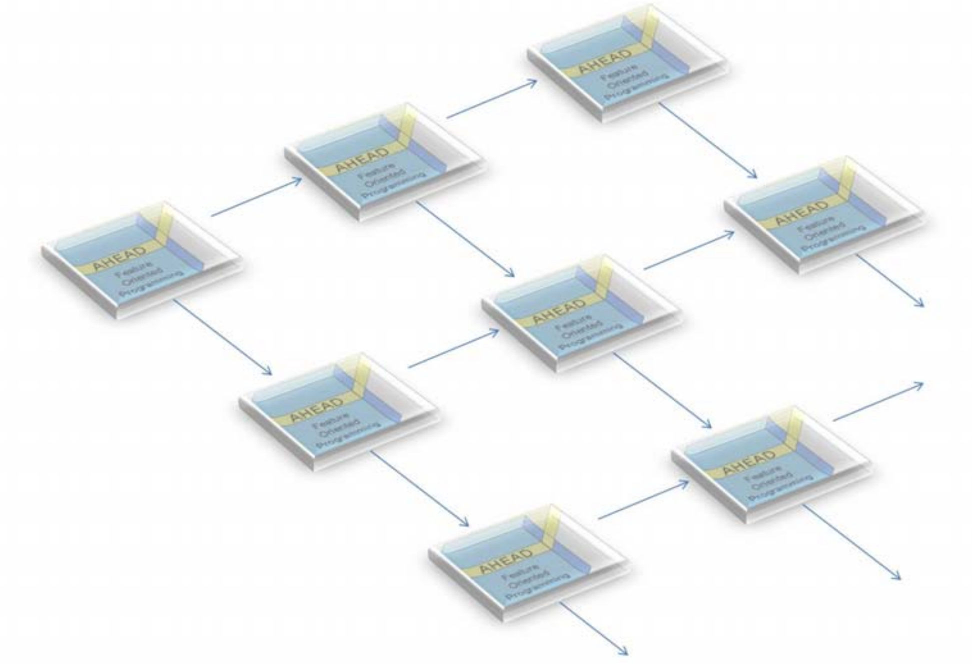
3. **Program Synthesis**
   - Lopez-Herrejon (Texas) & Lengauer (Passau)

4. **Model Driven Engineering**
   - Trujillo & Diaz (Basque Country)

- All describe systems that have been built
  - step back and give a simple D×T explanation of their results
  - pave way for following lectures

#1: Basics of D×T





D×T

- Programs are **values**

- Here is a value (Java definition of class C):

```
class C {
   int x;
   void inc() {…}
   …
}
```

- Here is another value:

```
class D {
   void compute()
   {..}
   ..
}
```

1st Operation: + (Sum)

- Let D =

```
class D {
   void compute()
   {..}
}
```

and C =

```
class C {
   int x;
   void inc() {...}
```

- D + C =

```
class D {
   void compute()
   {..}
}
```

```
class C {
   int x;
   void inc() {...}
```

Another Example

- Let C1 =

```
class C {
   void comp () {..}



}
```

and C2 =

```
class C {

   int x;
   void inc() {...}
}
```

- C1 + C2 =

```
class C {
   void comp () {..}
   int x;
   void inc() {...}
}
```

+ (Sum) is Disjoint Union

- Has expected properties:
  - 0 is identity (null program)

    P = 0 + P = P + 0

  - commutative (because disjoint set union is commutative)

    A + P = P + A

  - associative (because disjoint set union is associative)

    (A + B) + C = A + (B + C)

- So what? Why are these properties important?

2nd Operation: – (Subtraction)

- Subtraction is set difference

$$(D + C) - C = D$$

- Has expected properties:
  - left associative $P - C - D = ((P - C) - D)$
  - not commutative $P - C \neq C - P$
  - identity $P - 0 = P$
- Again, we need these rules why?

3rd Operation: Distributive Transformations

- **Transformation** is a function that maps a program to another program

- **Rename(p, q, r)** – in program "p" replace name "q" with "r"

Rename(

```
class C {
   int x;
   void inc() {..x..}
   ...
}
```

, C.x, C.z) =

```
class C {
   int z;
   void inc() {.. z ..}
   ...
}
```

Another Example

Rename(

```
class D {
   void compute()
   {..}
   ..
}
```

, C.x, C.z) =

```
class D {
   void compute()
   {..}
   ..
}
```

nothing changed!

- Called a **fixed point**:

a value x such that f(x) = x

- Distributive transformations have lots of fixed points

Key Property (where they get their name)

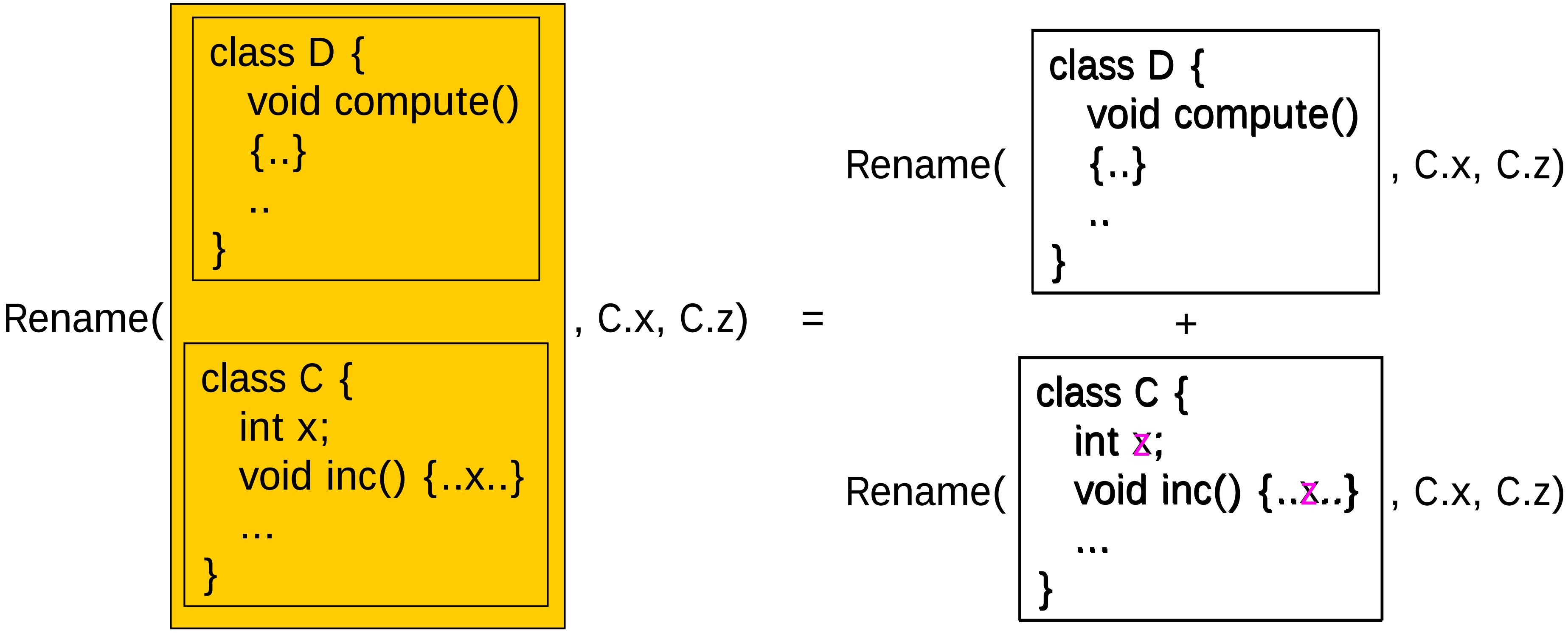
- Transformations **distribute** over + and –

$$f(A + B) = f(A) + f(B)$$

$$f(C - D) = f(C) - f(D)$$

- Here’s an example...

Example of Distributivity



Rename(

```
class D {
   void compute()
   {..}
   ..
}

class C {
   int x;
   void inc() {..x..}
   ...
}
```

, C.x, C.z) =

Rename(

```
class D {
   void compute()
   {..}
   ..
}
```

, C.x, C.z)

+

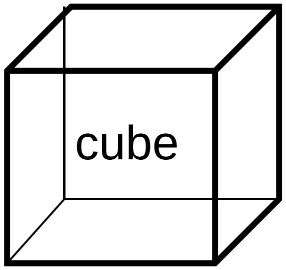
Rename(

```
class C {
   int xz;
   void inc() {..xz..}
   ...
}
```

, C.x, C.z)

Structures & Properties

- **Structure** – *what are the parts and how are they connected?*



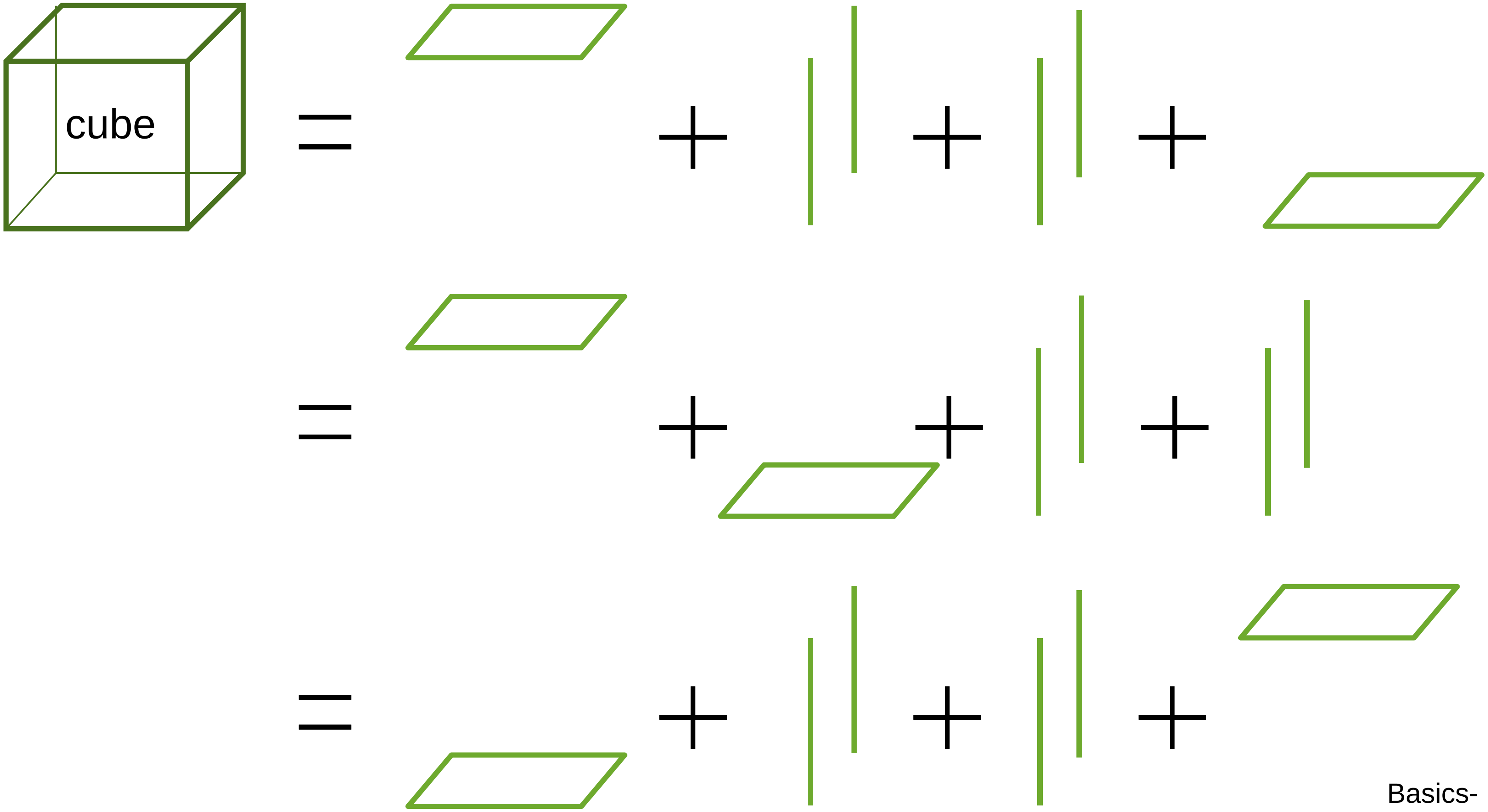
a solid bounded by six equal squares, the angle between any two adjacent faces is a right angle.

- **Properties** of structure = *attributes derivable from structure*

  - surface area = $6*E^2$ // E is edge length
  - volume = E^3

Design

- **Design** is a meta-expression (or more generally a meta-program) that says how to construct a program (structure)



Note!

- Many meta-expressions produce the same program
- This means there are many ways in which a program can be designed and built
- Makes intuitive sense

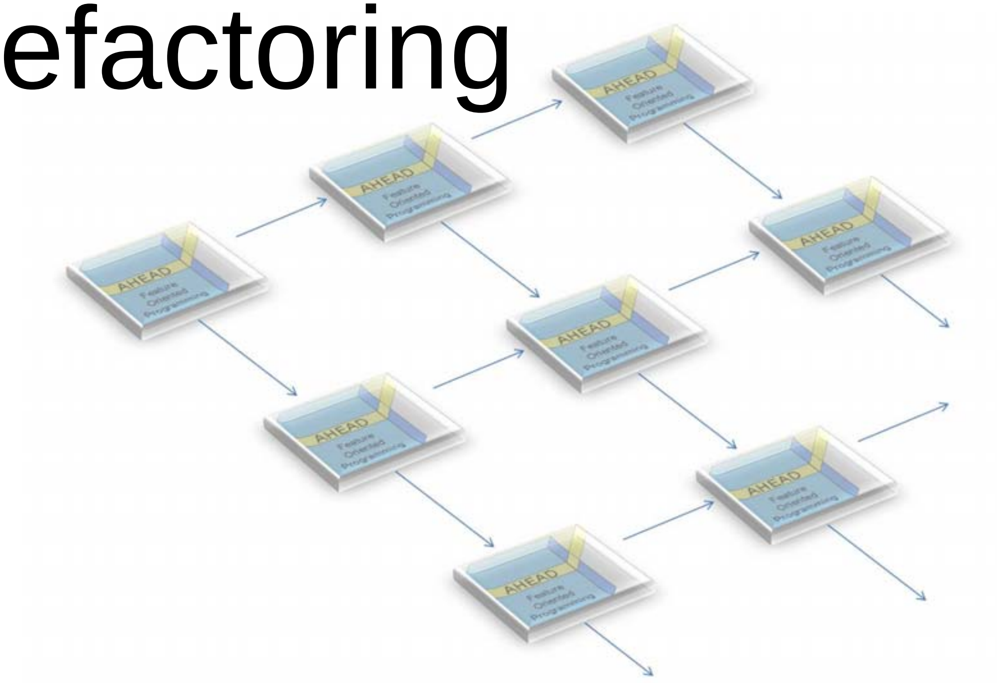
Properties

- **Property** of a program – is derived from its structure
  - compilers verify type correctness of programs
    (in addition to translating program to bytecodes)
  - other research guarantees other properties (ex. security) of programs – also enforced by special compilers
  - but it is possible to write programs that do not have the properties we want – why we write tests

In this lecture,
I focus on program structure.

The above list gives you an idea
of common properties to check.

#2: Advances in Program Refactoring



Refactoring

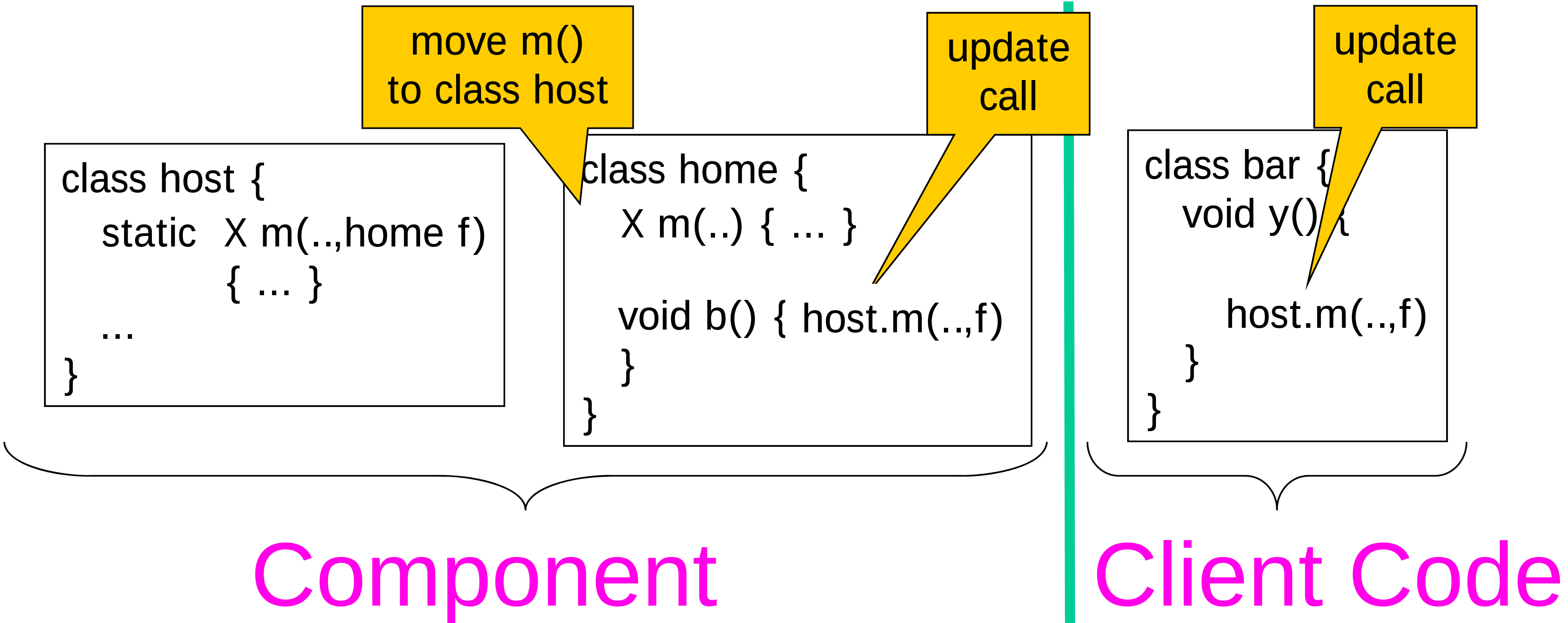
- Is a transformation that changes the structure of a program, but not the property of its behavior
  - rename methods
  - move method from subclass to superclass ...
- Most design patterns are end-products of refactorings
  - see Kerievsky, "Refactoring to Patterns“ text
- Common IDEs (Eclipse, Visual Studio, IntelliJ) have refactoring tools or plug-ins
- Here’s an interesting refactoring problem noticed by Dig and Johnson ~2005
  - resulted in an addition to Eclipse in 2007

Evolution of APIs

- Use of components (e.g. frameworks, libraries) are common in software development
  - build systems faster and cheaper
- **Application Program Interface (API)** of a component – set of (Java) interfaces and classes that are exported to application developers
  - ideally, APIs don't change, but of course they do!
  - **when APIs change, client code must also change**
  - **very disruptive event in program development**
- Need an easy and safe way to update applications when component's API changes

A Common API Change

- Move Method
  - instance method becomes static method of host class
  - moved method takes instance of home class as extra argument
  - references to old method replaced with calls to moved method



move m()
to class host

update
call

update
call

```
class host {
    static  X m(..,home f)
            { … }
    …
}
```

```
class home {
    X m(..) { … }

    void b() { host.m(..,f)
    }
}
```

```
class bar {
    void y() {

        host.m(..,f)
    }
}
```

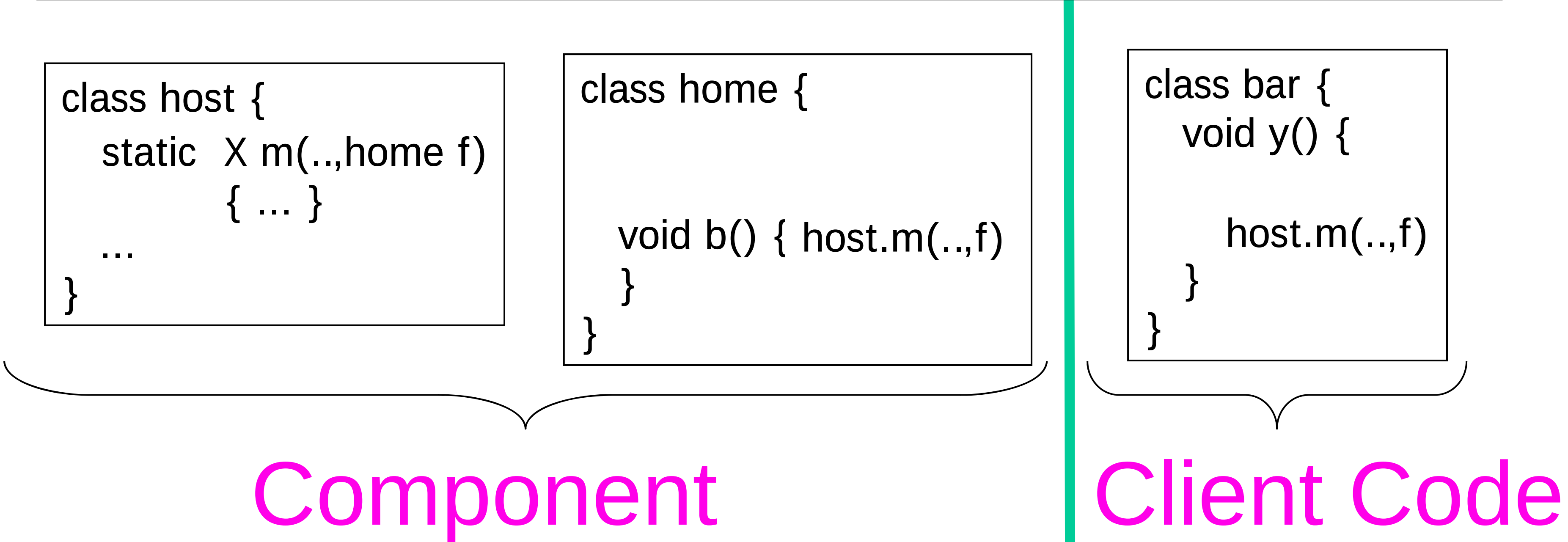
Component

Client Code

A Common API Change

Note: although component code changes,
client code must also change.

But a component developer doesn't have the client code!!
User must make changes manually!



```
class host {
   static  X m(..,home f)
           { … }
   …
}
```

```
class home {


   void b() { host.m(..,f)
   }
}
```

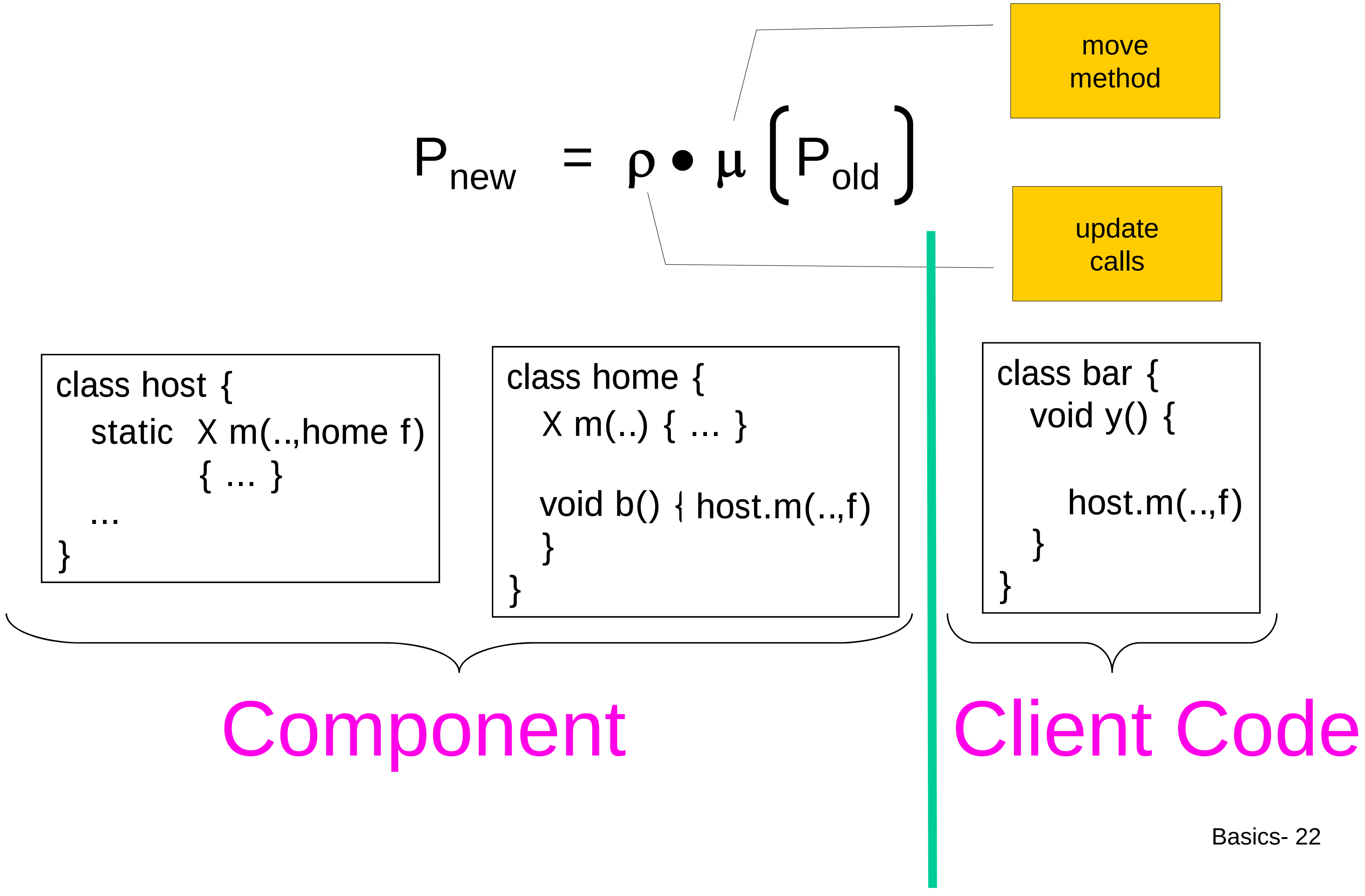
```
class bar {
   void y() {

      host.m(..,f)
   }
}
```

Component

Client Code

Express Change as a Meta-Expression



$$P_{new} = \rho \bullet \mu \left(P_{old} \right)$$

move method

update calls

```
class host {
   static  X m(..,home f)
           { ... }
   ...
}
```

```
class home {
   X m(..) { ... }

   void b() { host.m(..,f)
   }
}
```

```
class bar {
   void y() {

      host.m(..,f)
   }
}
```

Component

Client Code

Other Common API Changes

- Move Field
- Delete Method
  - usually done after method is renamed or moved
- Change Argument Type
  - ex: replace argument type with its supertype
- Factory Method
  - add a factory method to a class
- Lots of others...
  - preliminary work suggests all can be written as meta-expressions

Dig and Johnson Paper

“How do APIs Evolve: A Story of Refactoring”
Jour. Software Maintenance & Evolution:
Research & Practice 2006

- Manually analyzed change logs and documentation of different versions of 5 medium to large systems (50K to 2M LOC)
  - Eclipse, Struts, JHotDraw...
- Found over 80% of API changes are refactorings
  - means LOTS of tedious & error-prone updates can be **automated**
  - explain elegance of their solution using meta-expressions

In the Future

- Programmers will use advanced IDEs that “mark” API classes, methods, fields
  - only way marked elements can change is by refactorings (β)
  - “private” component edits modeled by transformations (**e**)

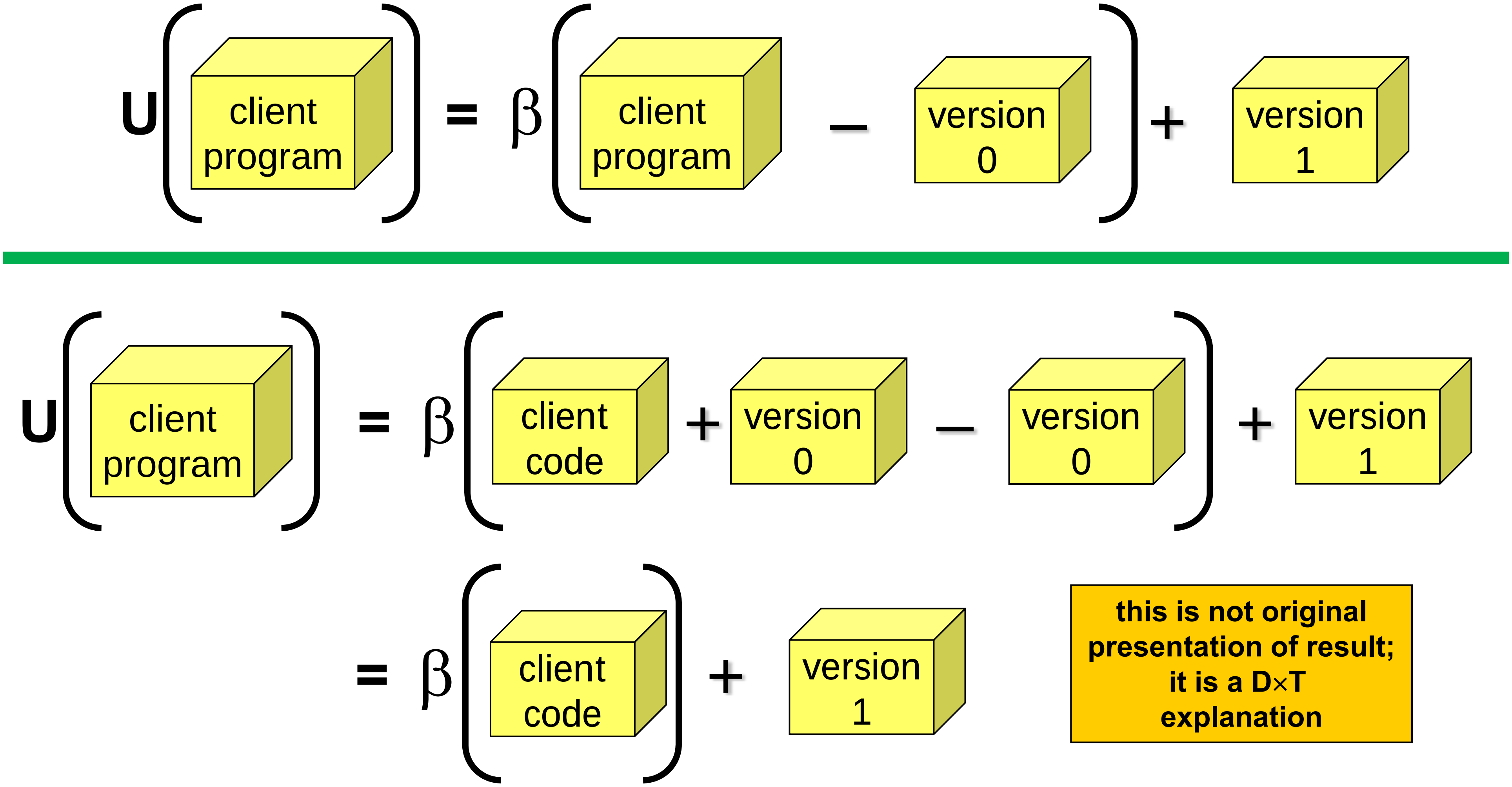
$$\beta3\bullet e3\bullet e2\bullet\boldsymbol{\beta2}\bullet\boldsymbol{\beta1}\bullet e1\left(\boxed{\begin{array}{c}\text{version}\\0\end{array}}\right) = \boxed{\begin{array}{c}\text{version}\\1\end{array}}$$

$$\beta = \beta3\bullet\beta2\bullet\beta1$$

transformations to be applied to update client code w.r.t. changes in API

- API updates are expressed by β, a projection of changes where “private” edits are removed and only API changes remain

Client Update is a Meta-Function U



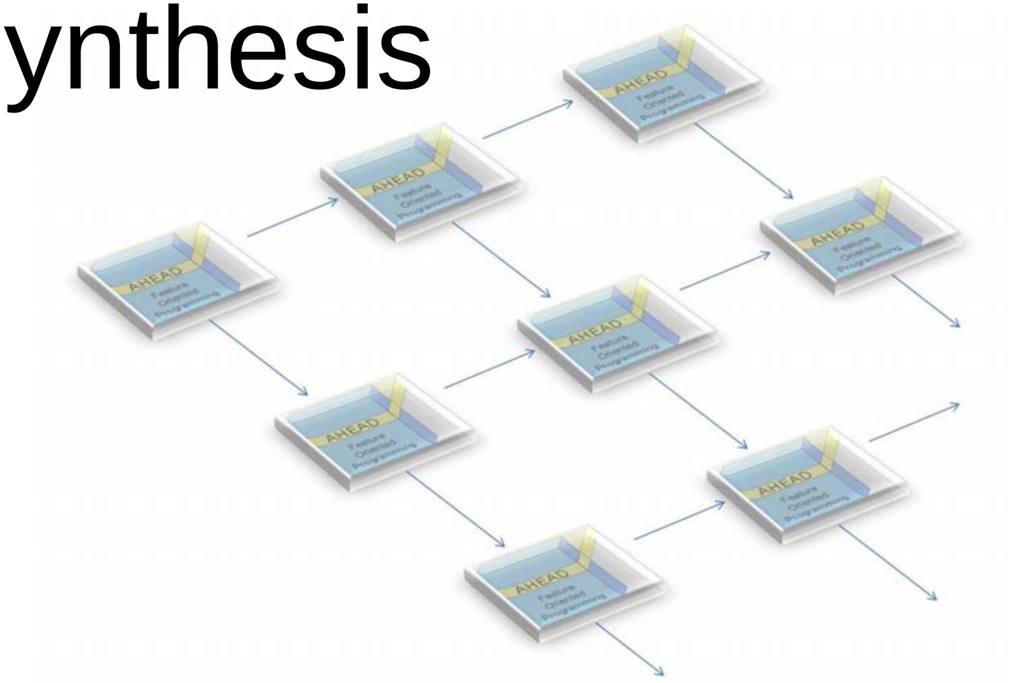
this is not original presentation of result; it is a D×T explanation

In Eclipse Since 2007

- IDEs create update meta-functions like U to distribute
    - transformations are distributed, not components

- IDEs transform code bases to automatically update them
- D×T expresses the core idea elegantly

#3: Advances in Program Synthesis



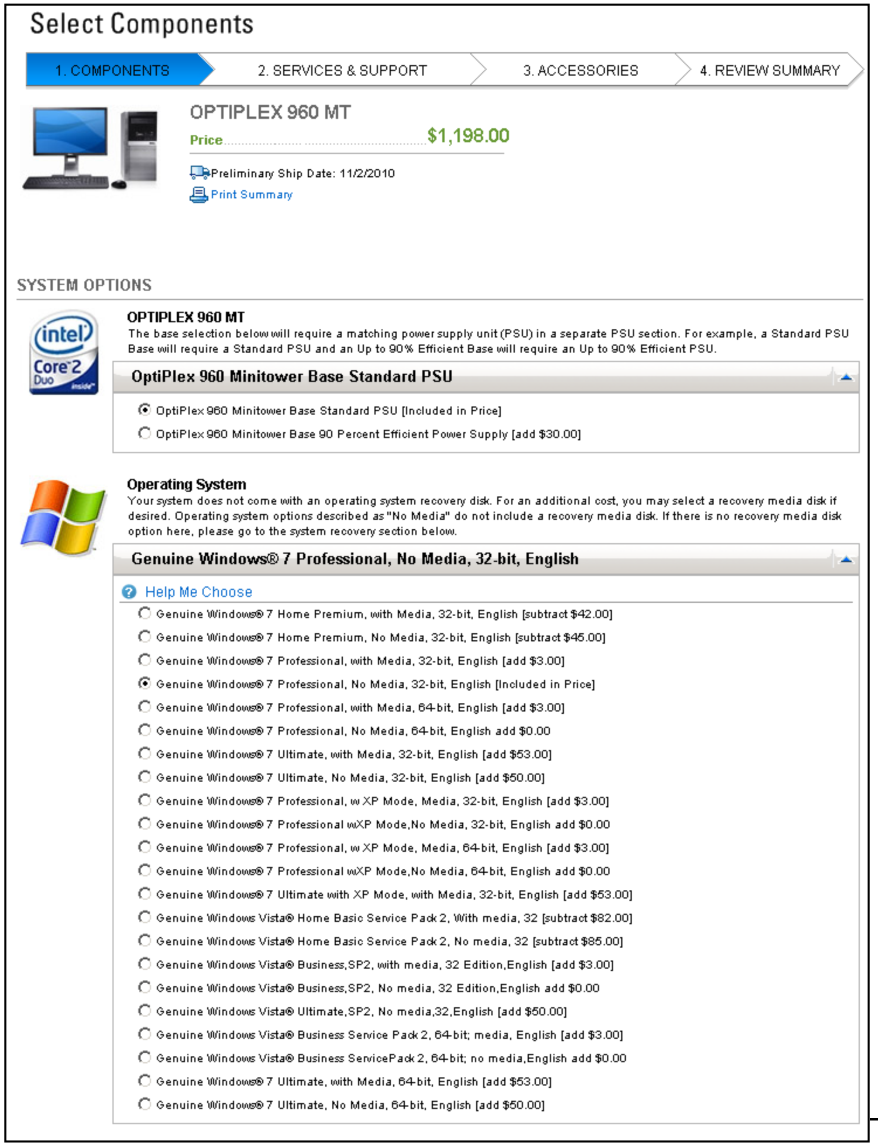
Background

- Maintaining programs automatically via refactorings is useful
- But we also want to build programs automatically too
- We want simple declarative languages to specify programs
  - that any one could use
  - *not* starting with formal logic specifications
- Ans: **Software Product Lines**
  - **feature** is an increment in product functionality
  - features are a declarative way to specify customized programs

Features used in Engineering

- Dell web pages
  - declarative DSL
  - specify target product by features

- Other examples
  - design your own BMW
  - faucets, sinks



Select Components

OPTIPLEX 960 MT

Price $1,198.00

Preliminary Ship Date: 11/2/2010

SYSTEM OPTIONS

OPTIPLEX 960 MT

The base selection below will require a matching power supply unit (PSU) in a separate PSU section. For example, a Standard PSU Base will require a Standard PSU and an Up to 90% Efficient Base will require an Up to 90% Efficient PSU.

OptiPlex 960 Minitower Base Standard PSU

- ● OptiPlex 960 Minitower Base Standard PSU [Included in Price]
- ○ OptiPlex 960 Minitower Base 90 Percent Efficient Power Supply [add $30.00]

Operating System

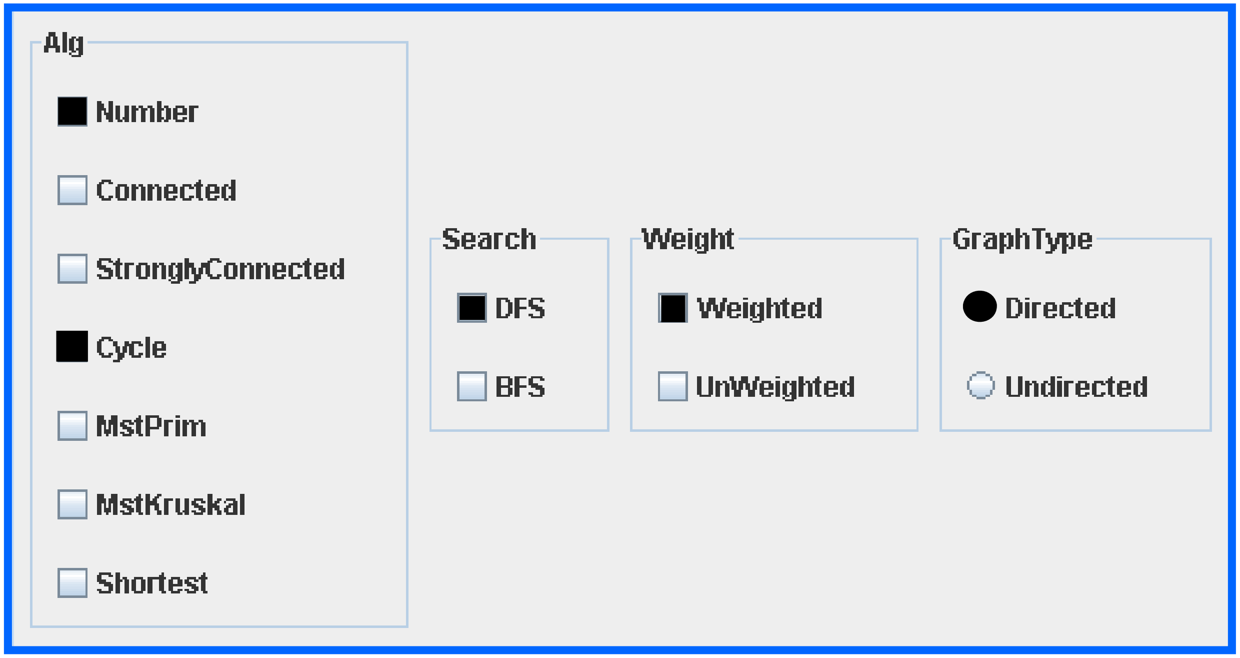
Your system does not come with an operating system recovery disk. For an additional cost, you may select a recovery media disk if desired. Operating system options described as "No Media" do not include a recovery media disk. If there is no recovery media disk option here, please go to the system recovery section below.

Genuine Windows® 7 Professional, No Media, 32-bit, English

- ○ Genuine Windows® 7 Home Premium, with Media, 32-bit, English [subtract $42.00]
- ○ Genuine Windows® 7 Home Premium, No Media, 32-bit, English [subtract $45.00]
- ○ Genuine Windows® 7 Professional, with Media, 32-bit, English [add $3.00]
- ● Genuine Windows® 7 Professional, No Media, 32-bit, English [Included in Price]
- ○ Genuine Windows® 7 Professional, with Media, 64-bit, English [add $3.00]
- ○ Genuine Windows® 7 Professional, No Media, 64-bit, English add $0.00
- ○ Genuine Windows® 7 Ultimate, with Media, 32-bit, English [add $53.00]
- ○ Genuine Windows® 7 Ultimate, No Media, 32-bit, English [add $50.00]
- ○ Genuine Windows® 7 Professional, w XP Mode, Media, 32-bit, English [add $3.00]
- ○ Genuine Windows® 7 Professional wXP Mode,No Media, 32-bit, English add $0.00
- ○ Genuine Windows® 7 Professional, w XP Mode, Media, 64-bit, English [add $3.00]
- ○ Genuine Windows® 7 Professional wXP Mode,No Media, 64-bit, English add $0.00
- ○ Genuine Windows® 7 Ultimate with XP Mode, with Media, 32-bit, English [add $53.00]
- ○ Genuine Windows Vista® Home Basic Service Pack 2, With media, 32 [subtract $82.00]
- ○ Genuine Windows Vista® Home Basic Service Pack 2, No media, 32 [subtract $85.00]
- ○ Genuine Windows Vista® Business,SP2, with media, 32 Edition,English [add $3.00]
- ○ Genuine Windows Vista® Business,SP2, No media, 32 Edition,English add $0.00
- ○ Genuine Windows Vista® Ultimate,SP2, No media,32,English [add $50.00]
- ○ Genuine Windows Vista® Business Service Pack 2, 64-bit; media, English [add $3.00]
- ○ Genuine Windows Vista® Business ServicePack 2, 64-bit; no media,English add $0.00
- ○ Genuine Windows® 7 Ultimate, with Media, 64-bit, English [add $53.00]
- ○ Genuine Windows® 7 Ultimate, No Media, 64-bit, English [add $50.00]

Declarative Program Specifications

- Graph Product Line



Alg

■ Number

□ Connected

□ StronglyConnected

■ Cycle

□ MstPrim

□ MstKruskal

□ Shortest

Search

■ DFS

□ BFS

Weight

■ Weighted

□ UnWeighted

GraphType

● Directed

○ Undirected

Program = Cycle • Number • DFS • Weighted • Directed

Scalability: Long History of Applications

• 1986 database systems	75K LOC
• 1989 network protocols	
• 1993 data structures	
• 1994 avionics	
• 1997 extensible Java precompilers	35K LOC
• 1998 radio ergonomics	
• 2000 program verification tools	
• 2001 verified compiler for Java1.0	
• 2002 fire support simulators	
• 2003 AHEAD tool suite	250K LOC
• 2004 robotics controllers	
• 2006 web portlets	
• 2008 SGI+JavaScript application	
• 2009 ZipMe compression library	

Feature Oriented Programming (FOP)

- FOP is an example of D×T: features are transformations

- Constants *(constant functions or values)*

  f – base program with feature f

  h – base program with feature h

- Unary Functions *(optional features)*

  $i \bullet x$ – adds feature i to program x

  $j \bullet x$ – adds feature j to program x

- An FOP "model" of a domain is an algebra

  $M = \{ f, h, \ldots\ i, j, \ldots \}$

- Different meta-expressions represent different programs of a product line

  $P_1 = i \bullet f$ // P_1 has i, f

  $P_2 = j \bullet i \bullet h$ // P_2 has j, i, h

FOP Implementations

- Use superposition
  - simpler (and more practical) than AOP
  - explore it in more detail in Lecture 2
  - basis for Bracha’s most recent language, Newspeak

- If we peer inside FOP features we see familiar ideas popularized by Aspect Oriented Programming (AOP)
  - here I use terminology of AOP, not AOP definitions

    google “functional aspects”

  - ideas I use appeared long before AOP

Two Ideas

- **Introduction** – adds new members to existing classes
    - metaprogramming addition

- **Advice** – modifies methods at particular points, called **join points**
    - distributive transformation
    - advice is generally behavior-extending, *not* behavior-preserving

- No “subtraction” in AOP or in FOP

Introductions

- Incrementally add new members, classes

Program P

```
class C {
   void foo(){..}
   int i;
   String b;
}

class D {
  String bar;
  int cnt(){..}
}
```

Meta-Expression

P = C.b + C.foo + C.i + D.bar + D.cnt

Program P

```
class C {
   void foo(){..}
   int i;
   String b;
}

class D {
  String bar;
  int cnt(){..}
}
```

Advice

- Defined in terms of events called **join points**
  - when method is called
  - when method is executed
  - when a field is updated, …

- **Advice**: when particular join point event occurs, execute a given piece of code

- Although advice has a “dynamic” interpretation, we can give it a “static” metaprogramming interpretation
  - **join point shadows**
  - how aspect compilers work

- View advice as a distributive transformation
  - when you advise a program, you advise all of its parts

Advice

Program P

```
class C {
   int i,j;
   void setI (int x){ i=x;              }
   void setJ (int x){ j=x;              }
}

 after(): execution (void C.set*(..))
   { print(“hi”); }
```

Meta-Expression

Program P

```
class C {
   int i,j;
   void setI’(int x){ i=x;              }
   void setJ’(int x){ j=x;              }
}

after(): execution (void C.set*(..))
   { print(“hi”); }
```

```
P  =  hi(C.i  +   C.j   +     C.setI  +    C.setJ )
   =  hi(C.i) + hi(C.j) +  hi(C.setI) + hi(C.setJ)
   =     C.i  +    C.j  + hi(C.setI) + hi(C.setJ)
   =     C.i  +    C.j  +    C.setI’  +   C.setJ’
```

Features

- Features are transformations that:
  - introduce new terms (i)
  - advise or alter (α) existing program (x)

adds new terms

alters existing terms to integrate new functionality

$$F(x) \;=\; i_f \;+\; \alpha_f(x)$$

- Composition:

$$G(\,F(\,B\,)\,) \;=\; i_g + \alpha_g\,(\,i_f \;+\; \alpha_f\,(\,b\,)\,)$$

In the Future

- Program designs will be calculations

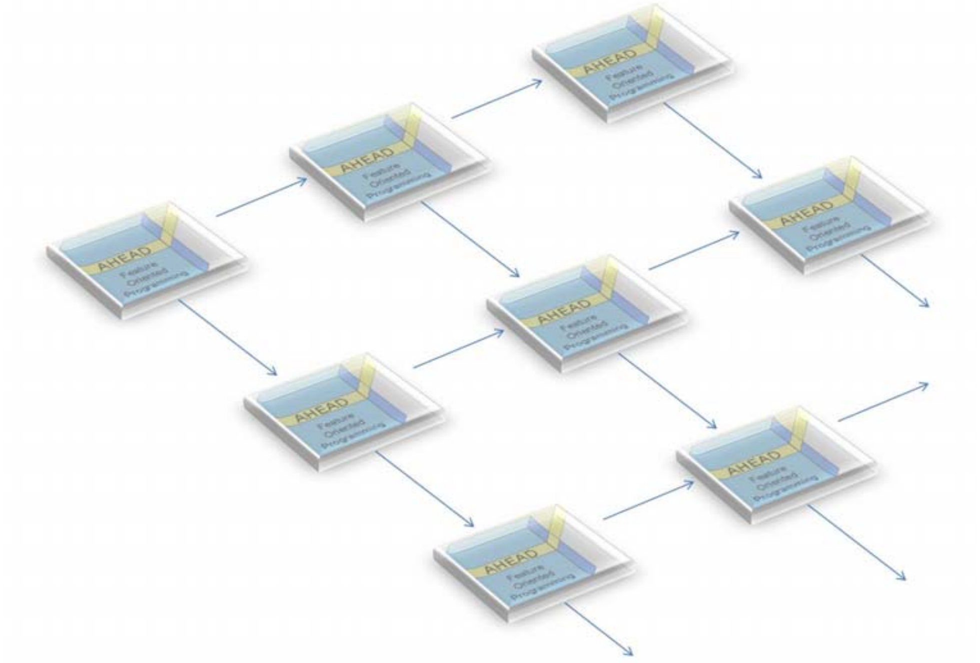
- Compilers will be **program calculators**
  - inhale source code
  - generate meta-expression, maybe optimize expression
  - evaluate to synthesize program

- D×T expresses the core idea elegantly
  - google “AHEAD”, “FeatureHouse”

- 3rd Lecture…

An Interesting Question:

What is the Relationship Between Advice and Refactorings?



Big Picture

- Refactorings and advice are both transformations

- Suppose we have a refactoring and advice to apply to a program. What does it mean to compose them?

- Note: Advice *does not* modify a refactoring

  a refactoring is not a language construct;
  there are no join points in a refactoring

- Note: But a refactoring *can* modify programs with advice

Example

change method names

Program P

Rename(

```
class C {
   int i,j;
   void SETI (int x){ i=x;         }
   void SETJ (int x){ j=x;         }
}

after(): execution (void C.SET* (..))
   { print(“hi”); }
```

, C.set*, C.SET*)

change advice declaration

D×T

- Remember differential operators in calculus?

  transform expressions

$$\frac{\partial(\mathbf{a+b+c})}{\partial \mathbf{y}} = \frac{\partial \mathbf{a}}{\partial \mathbf{y}} + \frac{\partial \mathbf{b}}{\partial \mathbf{y}} + \frac{\partial \mathbf{c}}{\partial \mathbf{y}}$$

  each term is transformed

- Rename refactoring is similar – it transforms each term of a meta expression

$$\beta(\ \mathbf{i} + \mathbf{a}(\mathbf{x})\ ) = \beta(\mathbf{i}) + \beta(\mathbf{a})(\ \beta(\mathbf{x})\ )$$

Homomorphisms

- Operators (expr to expr maps) is an example of:

Homomorphism

  - mapping of expressions of one algebra to expressions of another

- Grounded in **Category Theory**
  - theory of mathematical structures and their relationships
  - more later...

How Meta-Calculation Proceeds

Rename(

```
                 Program P
class C {
   int i,j;
   void SETI (int x){ i=x;        }
   void SETJ (int x){ j=x;        }
}

after(): execution (void C.SET* (..))
   { print("hi"); }
```

, C.set*, C.SET*)

```
  β( hi  (   C.i   +   C.j   +   C.setI   +   C.setJ   ) )
= β( hi )( β(C.i) + β(C.j) + β(C.setI) + β(C.setJ) )
= β( hi )(   C.i   +   C.j   + β(C.setI) + β(C.setJ) )
= β( hi )(   C.i   +   C.j   +   C.SETI   +   C.SETJ   )
=    HI  (   C.i   +   C.j   +   C.SETI   +   C.SETJ   )
```

Recap

- Refactorings are *operators* on expressions that have higher-precedence than advice in D×T
    - **operator** maps a transformation to another transformation

- Note:
    - refactorings
    - advice
    - introductions

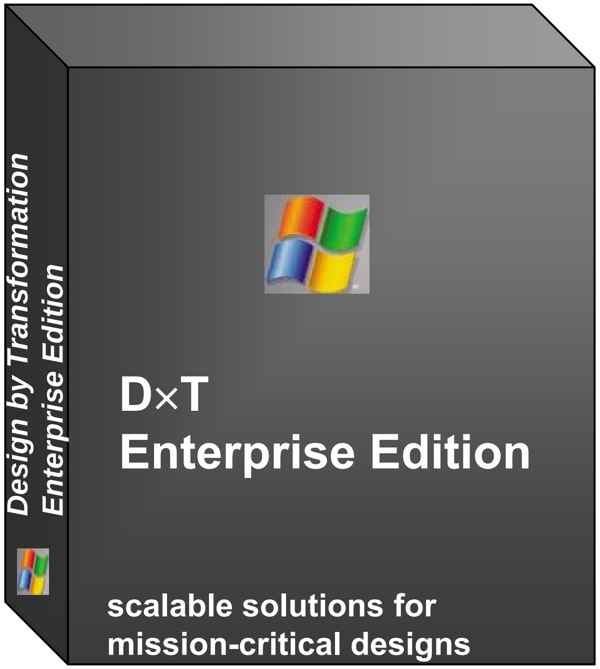
    - modify **structure** of code

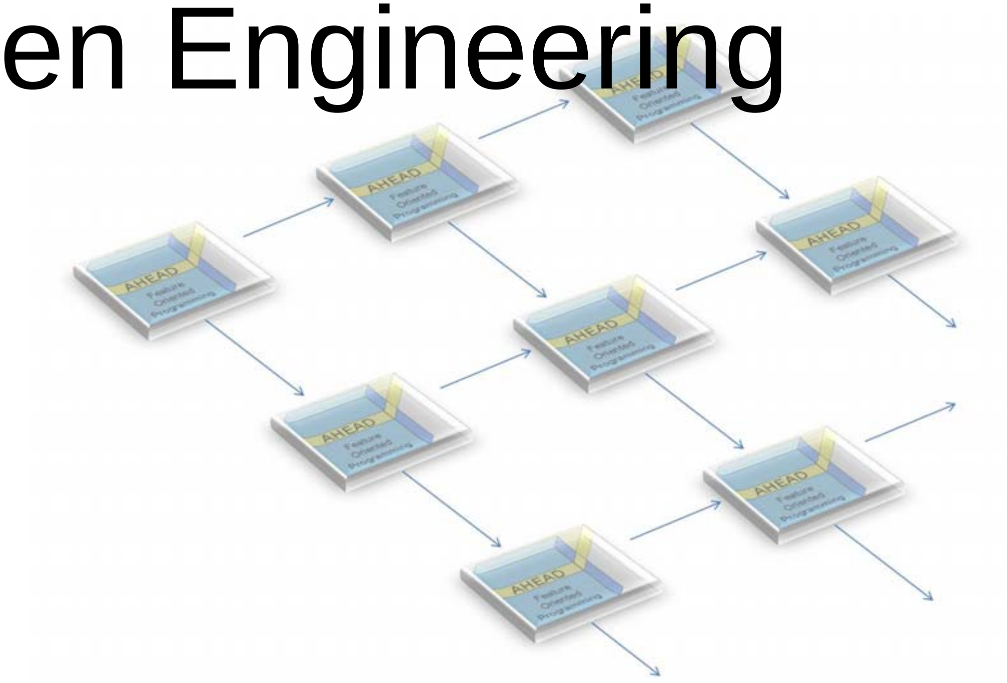
    - but could also modify **structure** of grammars, makefiles, xml documents... as well

- Algebraic viewpoint is universal – it applies to non-code representations as well

leads to our next topic…

#4: Advances in Model Driven Engineering





Introduction

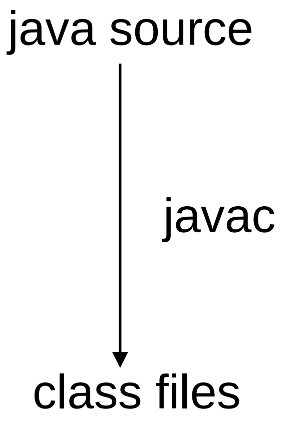
- **Model Driven Engineering (MDE)** is a paradigm for software creation
  - uses **domain-specific languages (DSL)**
  - encourages automation
  - exploits data exchange standards

- Model is written in a DSL
  - captures particular details of program's design
  - several models are needed to specify a program
  - **models can be derived from other models by transformations**
  - program synthesis is transforming high-level models into executables (which are also models)

Metaprogramming Connection

- MDE embraces concept that program development is a **computation**
  - **claim**: MDE is a metaprogramming & D×T paradigm
  - models are values
  - transformations map models to models

- Common example



java source

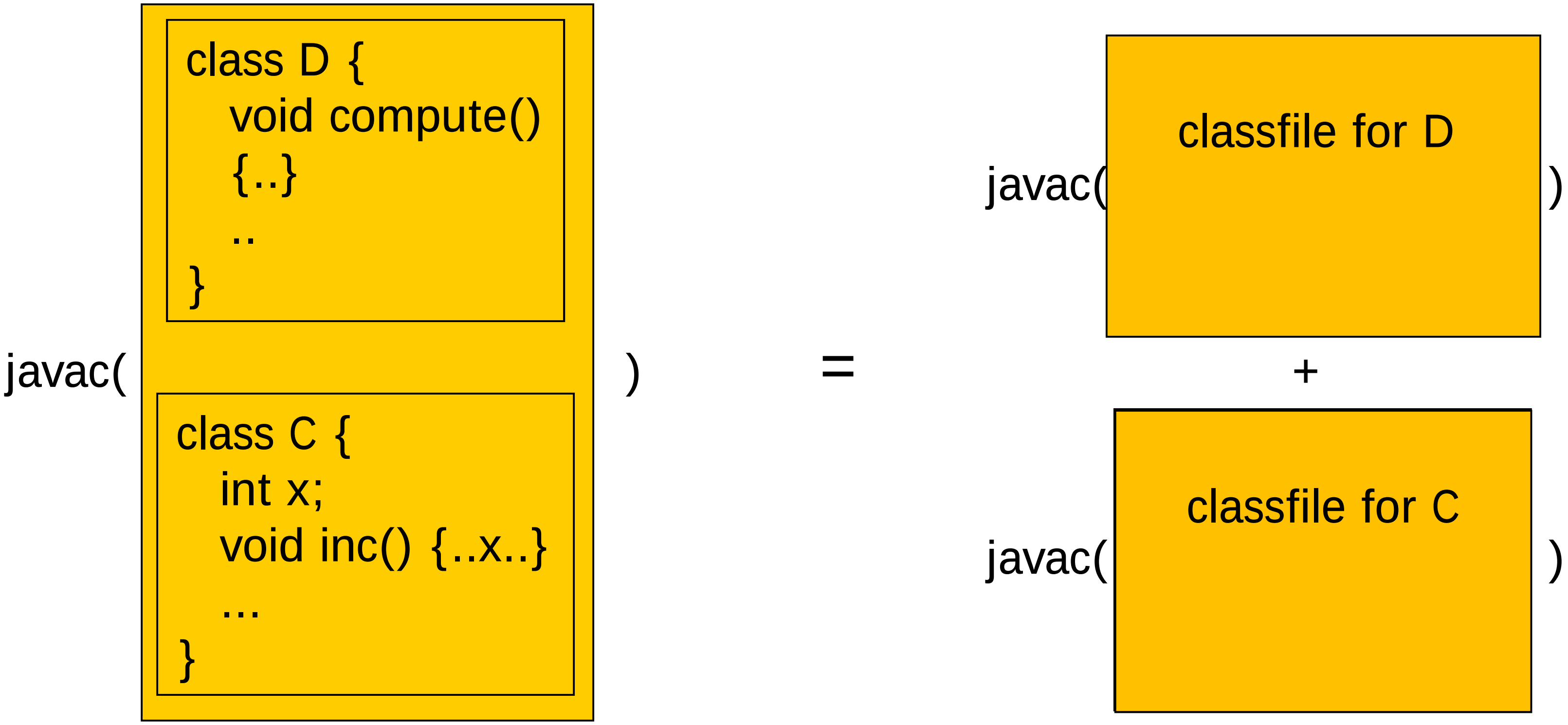
javac

class files

javac transforms java source to class files

Interesting Question

- If javac is a transformation, is it distributive?



javac(

```
class D {
   void compute()
   {..}
   ..
}
```

```
class C {
   int x;
   void inc() {..x..}
   ...
}
```

)

=

javac(classfile for D)

+

javac(classfile for C)

Interesting Question

javac is not distributive!

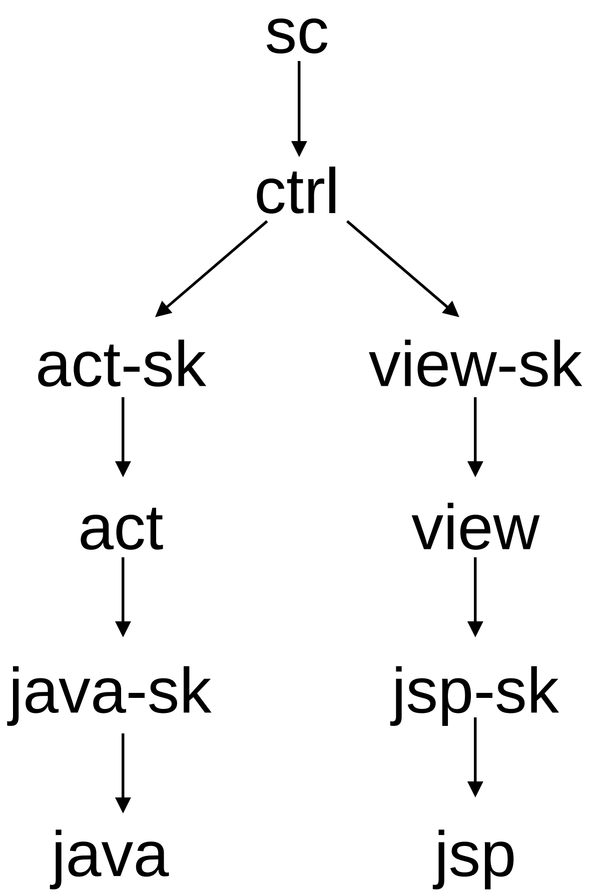
Although there is research by Ancona et. al. on

Separate Class Compilation

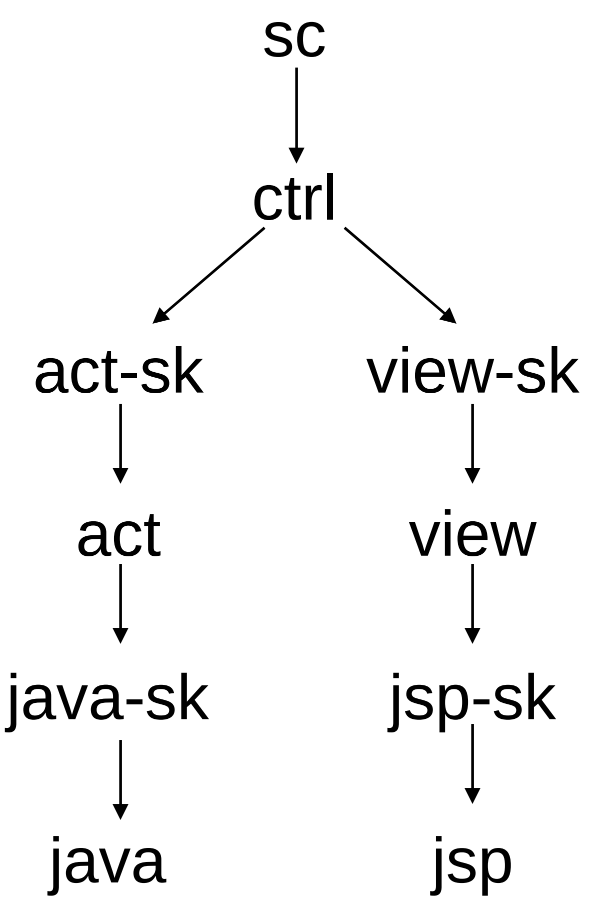
that makes it so…

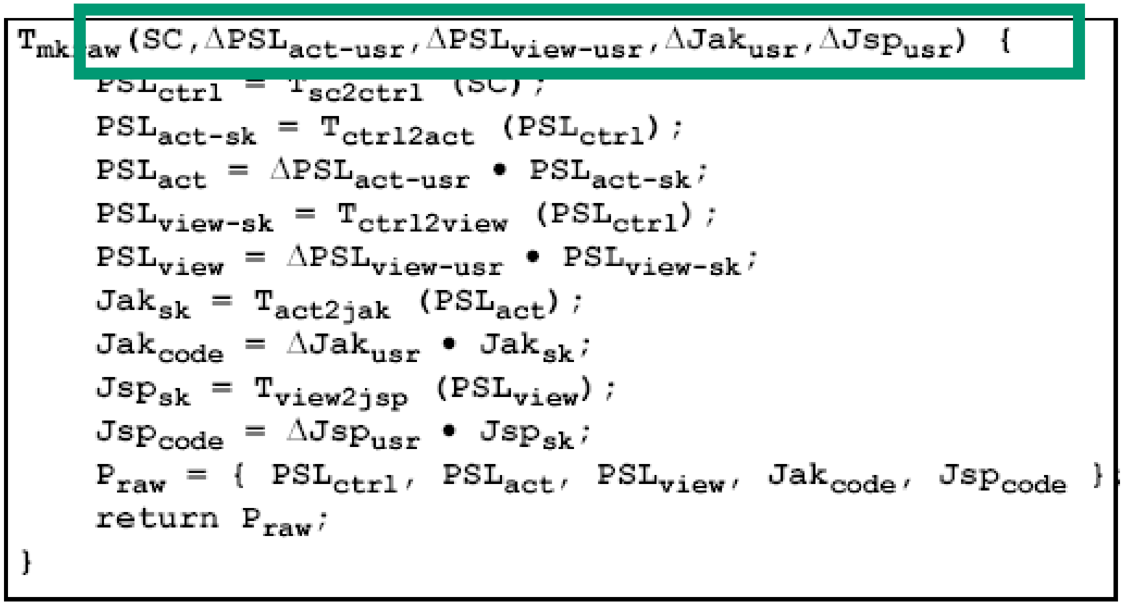
More Typical MDE Example: PinkCreek

- Work with S. Trujillo and O. Diaz
- Portlet is a web component
- PinkCreek is an MDE case study for synthesizing portlets
- Uses transformations to map an annotated state chart (sc) to different representations (Java code, JSP code)



Portlet Synthesis Metaprogram

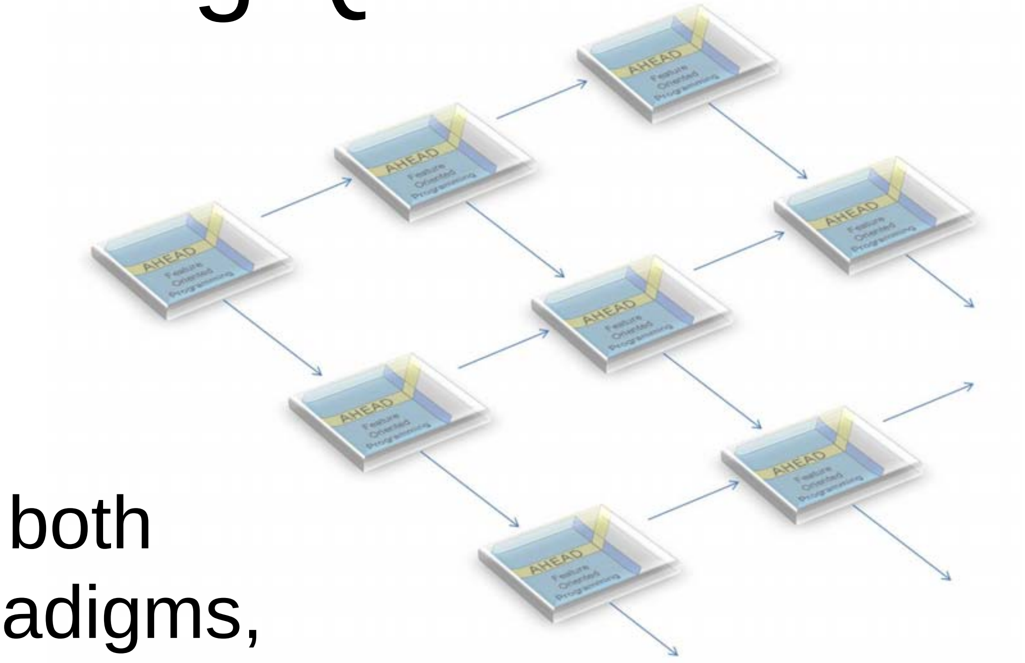




```
$T_{mk-raw}$($SC$,$\Delta PSL_{act-usr}$,$\Delta PSL_{view-usr}$,$\Delta Jak_{usr}$,$\Delta Jsp_{usr}$)  {
    $PSL_{ctrl}$ = $T_{sc2ctrl}$ (SC);
    $PSL_{act-sk}$ = $T_{ctrl2act}$ ($PSL_{ctrl}$);
    $PSL_{act}$ = $\Delta PSL_{act-usr}$ • $PSL_{act-sk}$;
    $PSL_{view-sk}$ = $T_{ctrl2view}$ ($PSL_{ctrl}$);
    $PSL_{view}$ = $\Delta PSL_{view-usr}$ • $PSL_{view-sk}$;
    $Jak_{sk}$ = $T_{act2jak}$ ($PSL_{act}$);
    $Jak_{code}$ = $\Delta Jak_{usr}$ • $Jak_{sk}$;
    $Jsp_{sk}$ = $T_{view2jsp}$ ($PSL_{view}$);
    $Jsp_{code}$ = $\Delta Jsp_{usr}$ • $Jsp_{sk}$;
    $P_{raw}$ = { $PSL_{ctrl}$, $PSL_{act}$, $PSL_{view}$, $Jak_{code}$, $Jsp_{code}$ };
    return $P_{raw}$;
}
```

Example of using transformations
to derive different models
or representations of a program

Another Interesting Question...


AHEAD
Feature Oriented Programming
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Feature Oriented Programming
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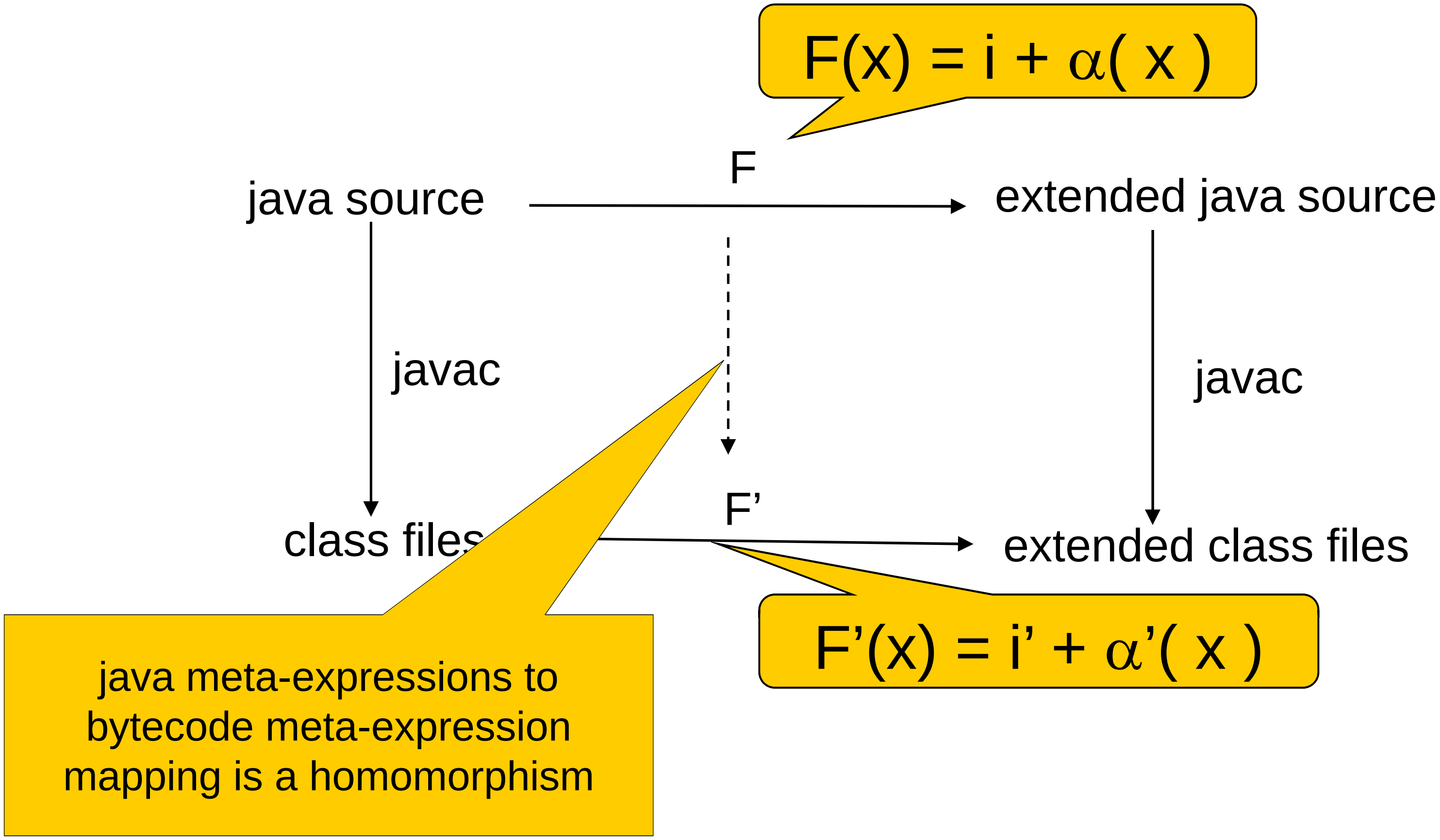
Feature Oriented Programming

As FOP and MDE are both metaprogramming paradigms, how do they combine?

Now and in the Future

- Features “extend” models
- An example:



$F(x) = i + \alpha(\, x\,)$

$F'(x) = i' + \alpha'(\, x\,)$

java meta-expressions to bytecode meta-expression mapping is a homomorphism

Fundamental Relationship

- Relationship between transformations that derive models from those that extend models

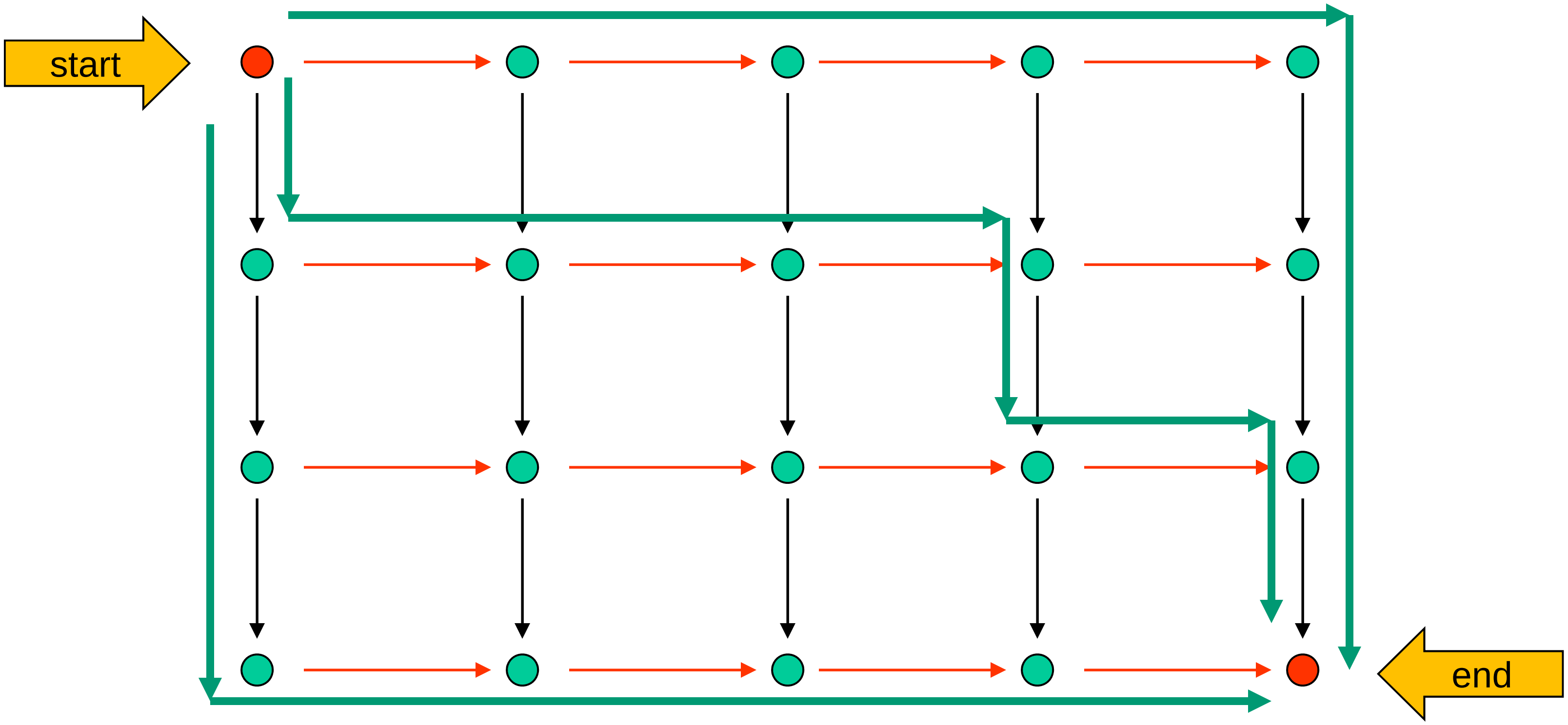
Pushout

$$\begin{tikzcd}
M0 \arrow[r, "F"] \arrow[d, "D"'] & M1 \arrow[d, "D"'] \\
C0 \arrow[r, "F'"] & C1
\end{tikzcd}$$

$$D \bullet F = F' \bullet D$$

Commuting Diagram

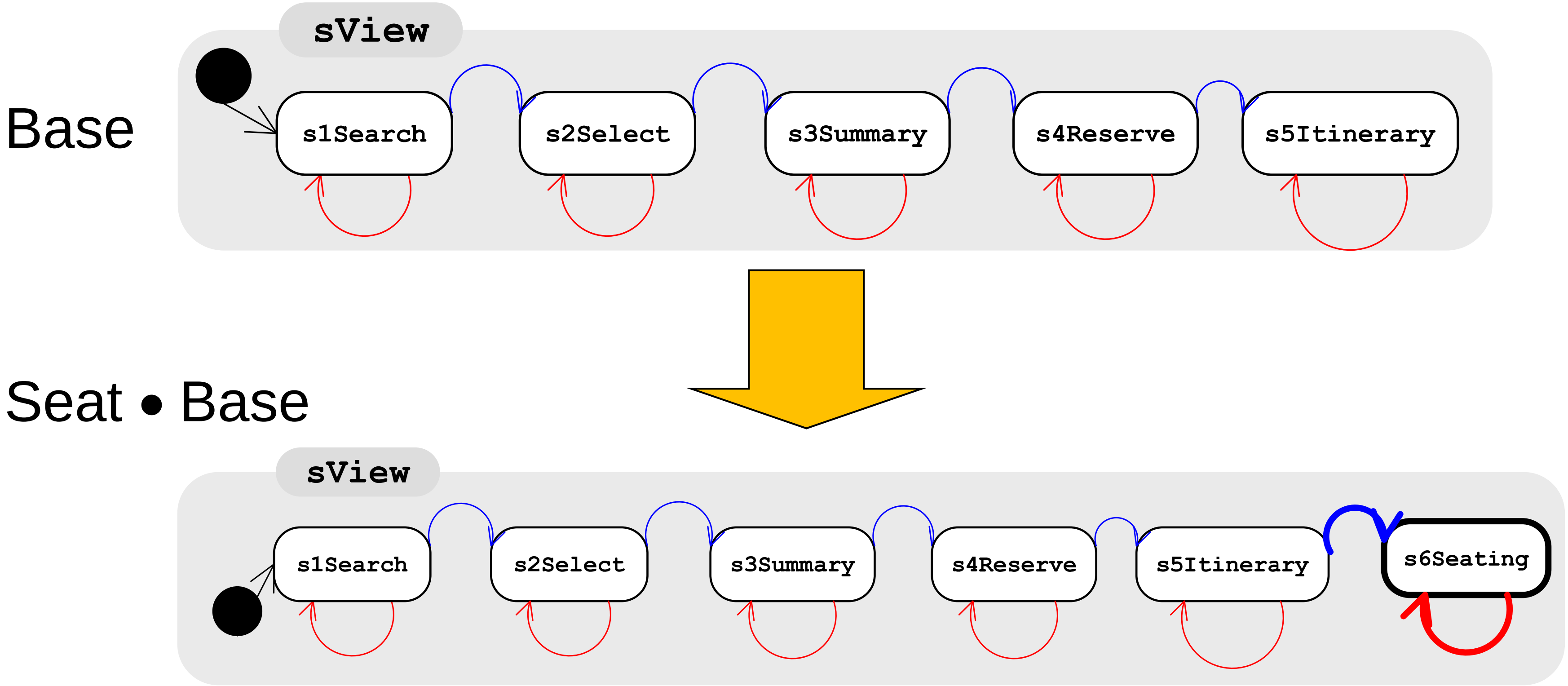
Property of Commuting Diagrams



- Diagrams can be “pasted” together
- Given model in upper left, want to compute model in lower right
- Each path represents a different metaprogram
- Every path from upper left to lower right produces same result

Extending State Charts in PinkCreek

- Features extend state charts by adding new states, transitions, annotations, etc.



Base

sView

s1Search

s2Select

s3Summary

s4Reserve

s5Itinerary

Seat • Base

sView

s1Search

s2Select

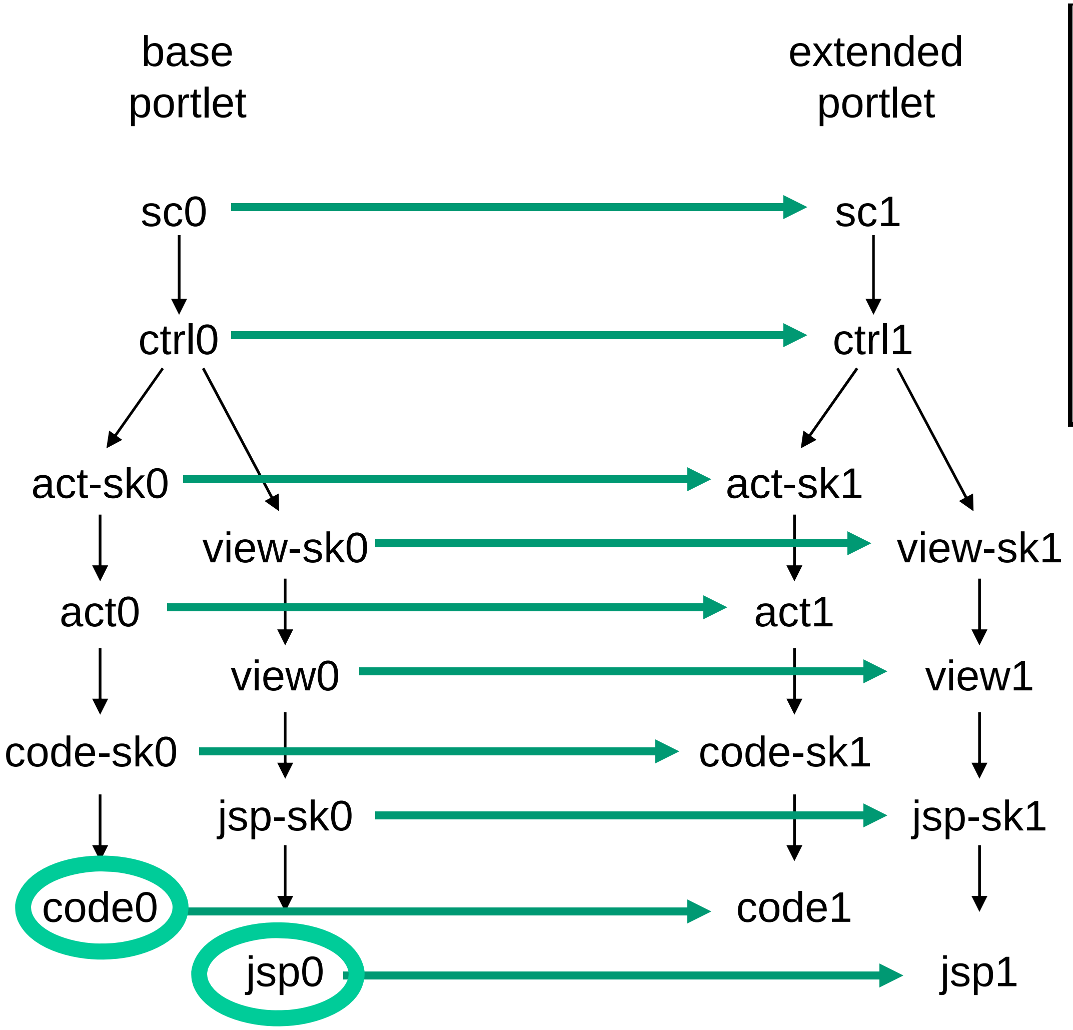
s3Summary

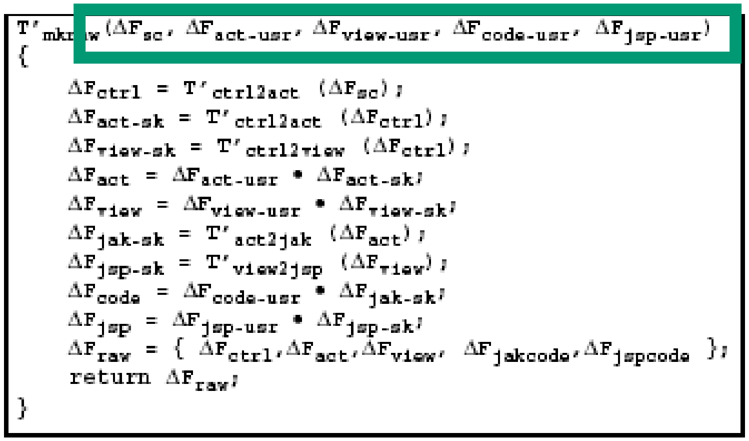
s4Reserve

s5Itinerary

s6Seating

Extending State Charts in PinkCreek



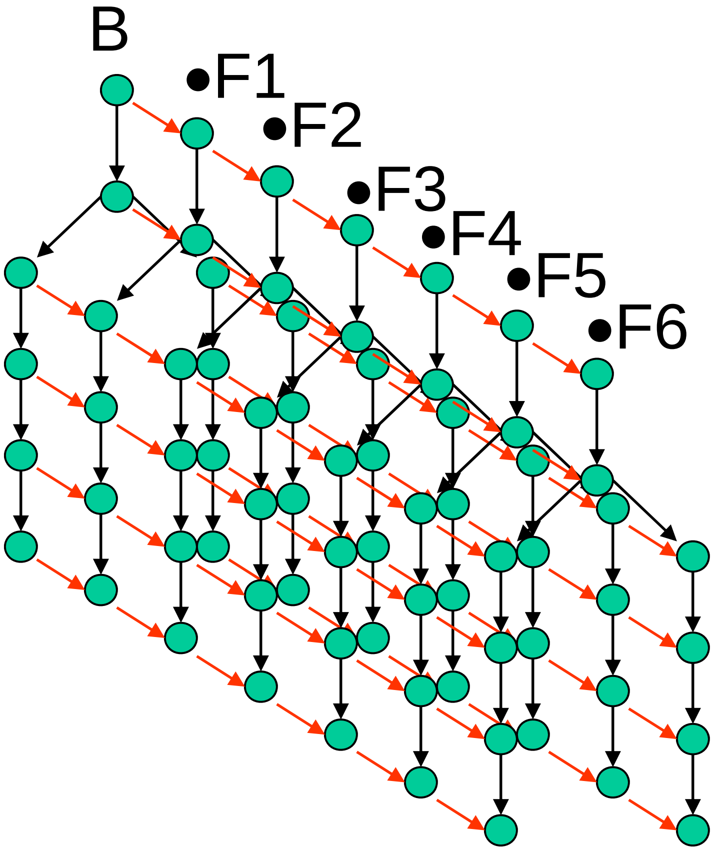


$$
\begin{array}{l}
T'_{mkraw}(\Delta F_{sc},\ \Delta F_{act\text{-}usr},\ \Delta F_{view\text{-}usr},\ \Delta F_{code\text{-}usr},\ \Delta F_{jsp\text{-}usr}) \\
\{ \\
\quad \Delta F_{ctrl} = T'_{ctrl2act}\ (\Delta F_{sc}); \\
\quad \Delta F_{act\text{-}sk} = T'_{ctrl2act}\ (\Delta F_{ctrl}); \\
\quad \Delta F_{view\text{-}sk} = T'_{ctrl2view}\ (\Delta F_{ctrl}); \\
\quad \Delta F_{act} = \Delta F_{act\text{-}usr} \bullet \Delta F_{act\text{-}sk}; \\
\quad \Delta F_{view} = \Delta F_{view\text{-}usr} \bullet \Delta F_{view\text{-}sk}; \\
\quad \Delta F_{jak\text{-}sk} = T'_{act2jak}\ (\Delta F_{act}); \\
\quad \Delta F_{jsp\text{-}sk} = T'_{view2jsp}\ (\Delta F_{view}); \\
\quad \Delta F_{code} = \Delta F_{code\text{-}usr} \bullet \Delta F_{jak\text{-}sk}; \\
\quad \Delta F_{jsp} = \Delta F_{jsp\text{-}usr} \bullet \Delta F_{jsp\text{-}sk}; \\
\quad \Delta F_{raw} = \{\ \Delta F_{ctrl}, \Delta F_{act}, \Delta F_{view},\ \Delta F_{jakcode}, \Delta F_{jspcode}\ \}; \\
\quad \text{return } \Delta F_{raw}; \\
\}
\end{array}
$$

Commuting Diagrams in PinkCreek

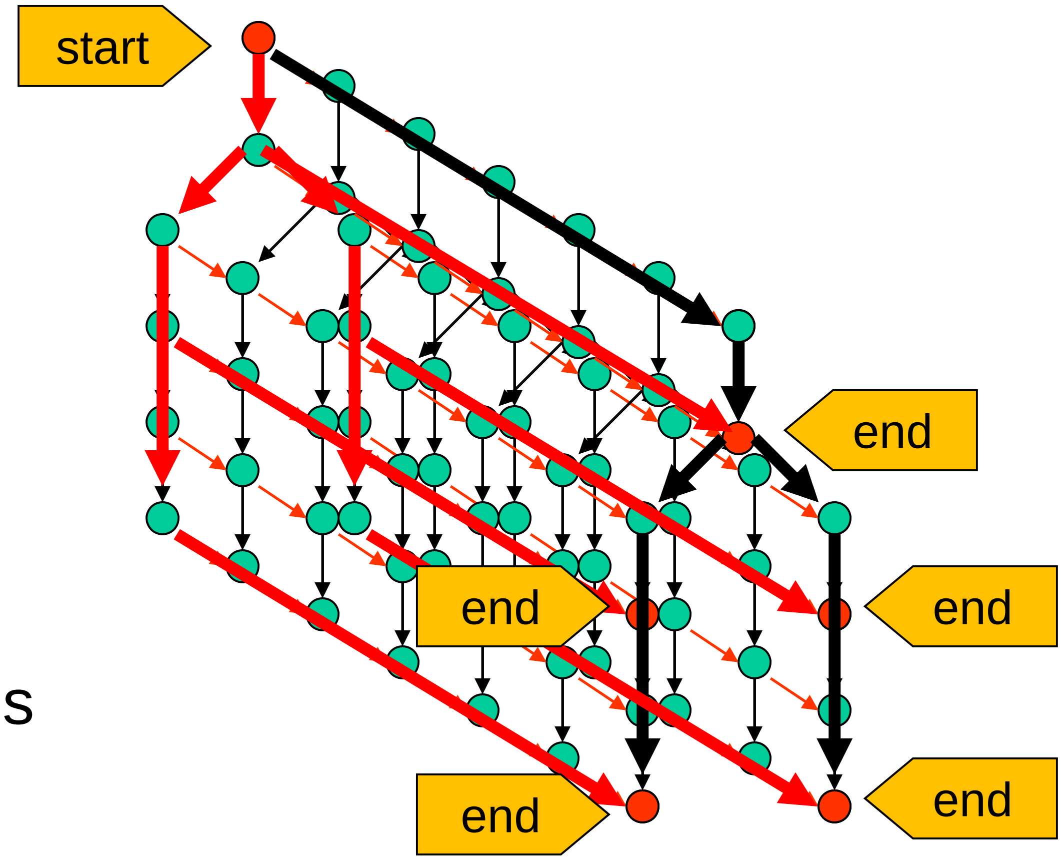
- Features map space of artifacts by extending them

- Composing features sweeps out the commuting diagram to traverse to synthesize portlet representations



Portlet Synthesis

- Shortest path is a **geodesic**
- Start at upper left compute nodes on lower right
- #1: extend models and then derive
- #2: derive representations and then extend
- #2 is faster than #1 by factor of 2-3 times



see ICSE 2007 paper by Trujillo et al.

Experience

- Our tools initially did not satisfy properties commuting diagrams
  - synthesizing via different paths yields different results
  - exposed errors in our tools & specifications
- Significance of commuting diagrams
  - validity checks provides assurances on the correctness of our model abstractions, portlet specifications, and our tools
  - applies also to individual transformations
    (as they too have commuting diagrams)
  - win – better understanding, better model, better tools
  - reduce problem to its essence

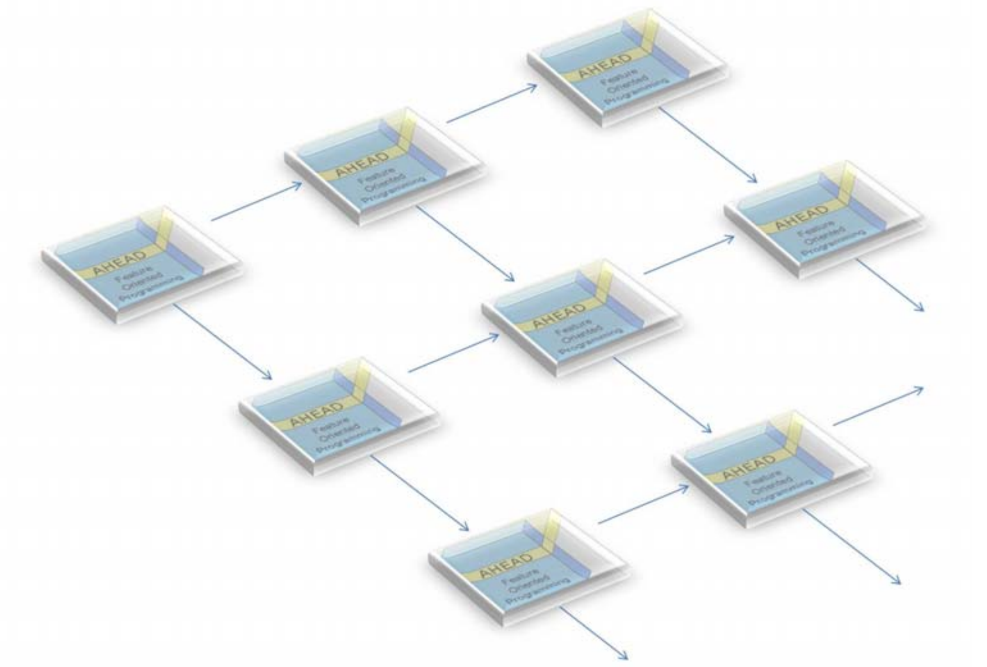
In the Future

- Better understanding of these ideas & their practicality
- Theory, methodology, tools of architectural metaprogramming use elementary ideas from

Category Theory

  - where homomorphisms, pushouts, and commuting diagrams arise...
  - topic of Lecture #2

Conclusions



We are…

- Extraordinarily good at:
  - languages
  - compilers
  - optimizations
  - analyses

- Programming in the **small**:
  - understand abstractions
  - their models
  - their relationships
  - their integration

- Not good at:
  - languages
  - compilers
  - optimizations
  - analyses

- Programming in the **large**:
  - ¬ understand abstractions
  - ¬ their models
  - ¬ their relationships
  - ¬ their integration

My Message: Getting Closer

- Program design and synthesis has a simple algebraic underpinning

design is all about
structure definition and manipulation

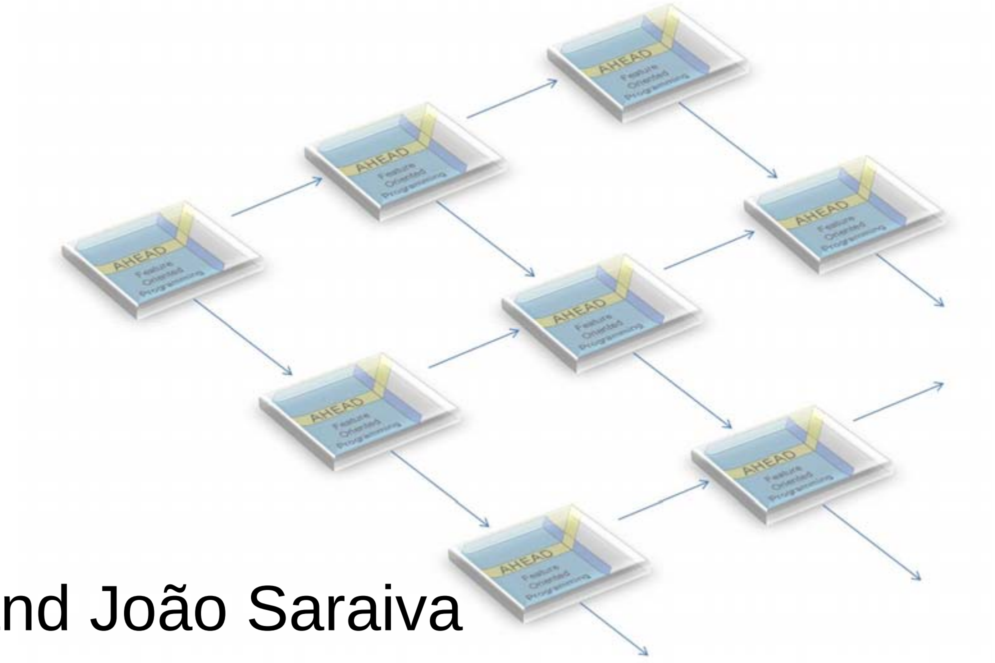
which is what mathematics is about

- This lecture sets the stage for our next lectures

category theory

designs by algebra

Lecture 2:
The Objects and Arrows of D×T



work with Maider Azanza and João Saraiva

Recap from Lecture 1

- Future of software design and development is automation
  - mechanize repetitive tasks
  - free programmers for more creative activities
- **Design by Transformation** is a paradigm where program design and synthesis is a computation
- **Design**: steps to take to create an artifact
  - meta-expression
- **Synthesis**: evaluate steps to produce the artifact
  - meta-expression evaluation
- **Design Optimization**: meta-expression optimization

Forefront of Automated Development

- **Model Driven Engineering (MDE)**
  - general-purpose approach
  - high-level models define applications
  - transformed into lower-level models

- **Software Product Lines (SPL)**
  - domain-specific approach
  - we know the problems, solutions of a domain
  - we want to automate the construction of these programs

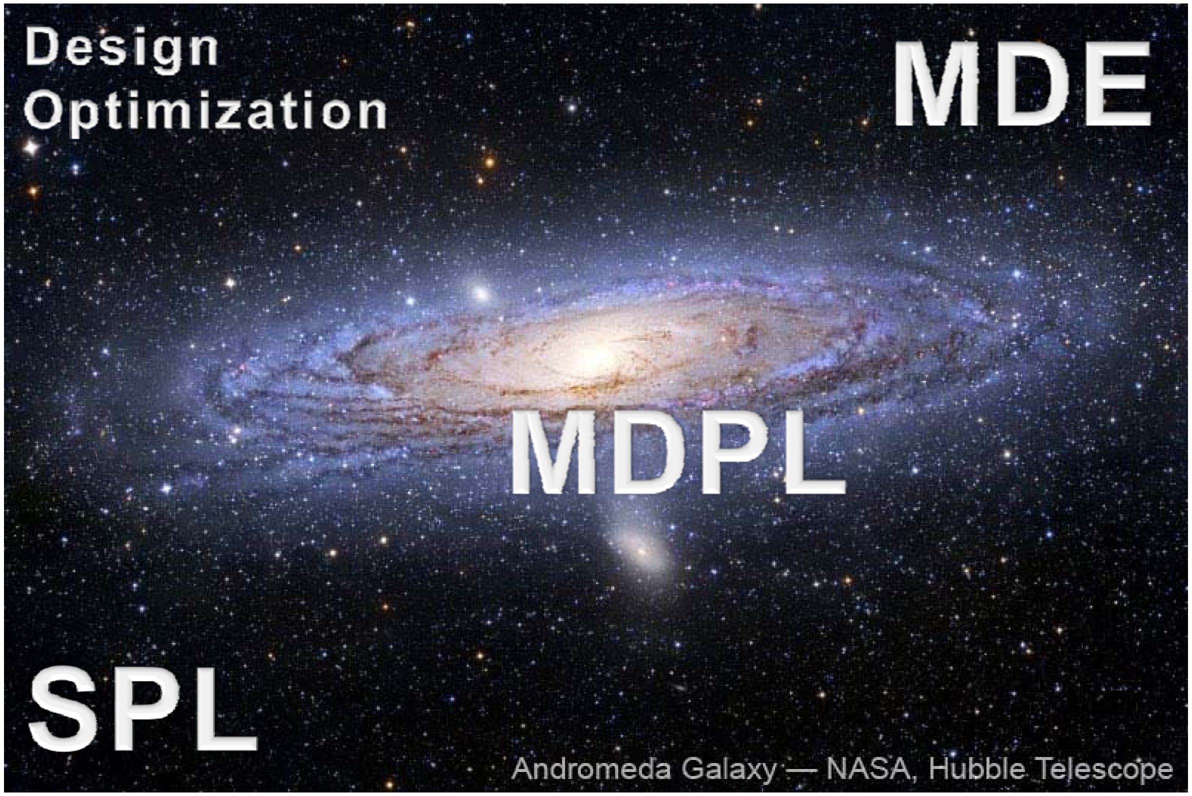
- Both complement each other
  - strength of MDE is weakness of SPLs, and vice versa
  - not disjoint, but I will present their strengths as such here

This Lecture

- This is a modeling talk aimed at practitioners
  - no special mathematical background
- Review core ideas in **Category Theory**
  - theory of mathematical structures
  - result of a domain analysis of geometry, topology, algebra…
  - these concepts are fundamental to MDE, SPL

This Lecture

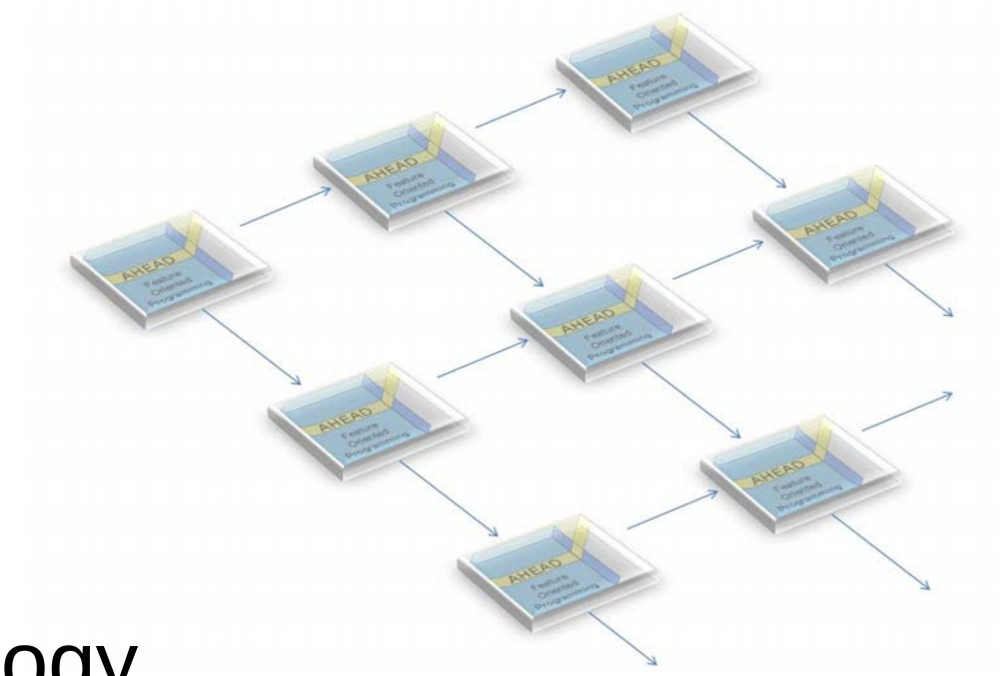
- Show categories provide unifying foundation for MDE & SPLs
- Series of mini-tutorials (10 minutes apiece)



Andromeda Galaxy — NASA, Hubble Telescope

categories
on an
industrial
scale

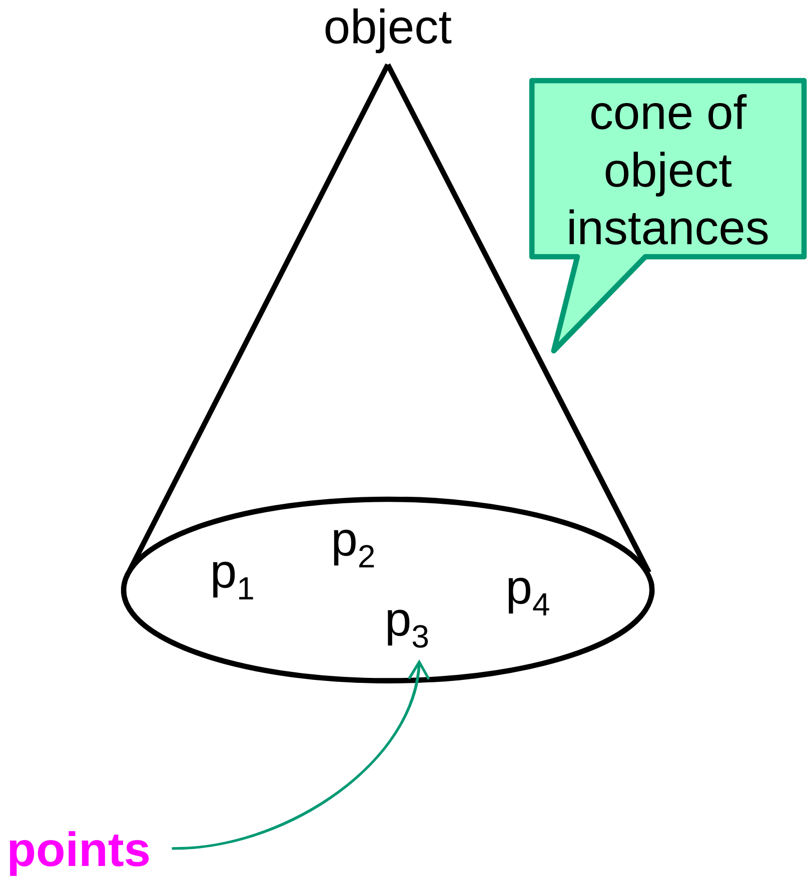
#1: Categories in MDE

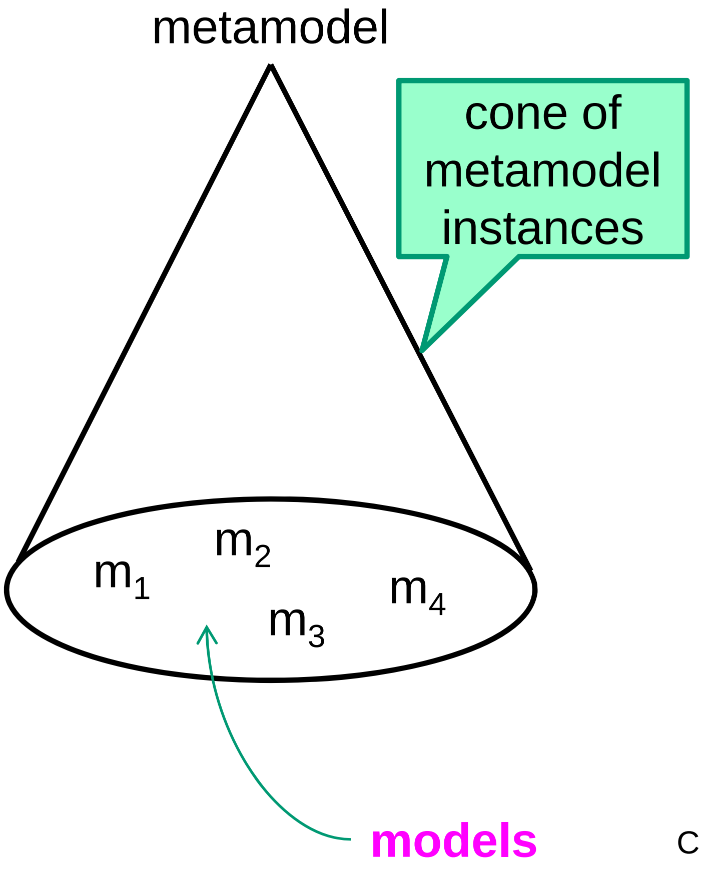


let’s start with some
unfortunate terminology…

Objects in Categories

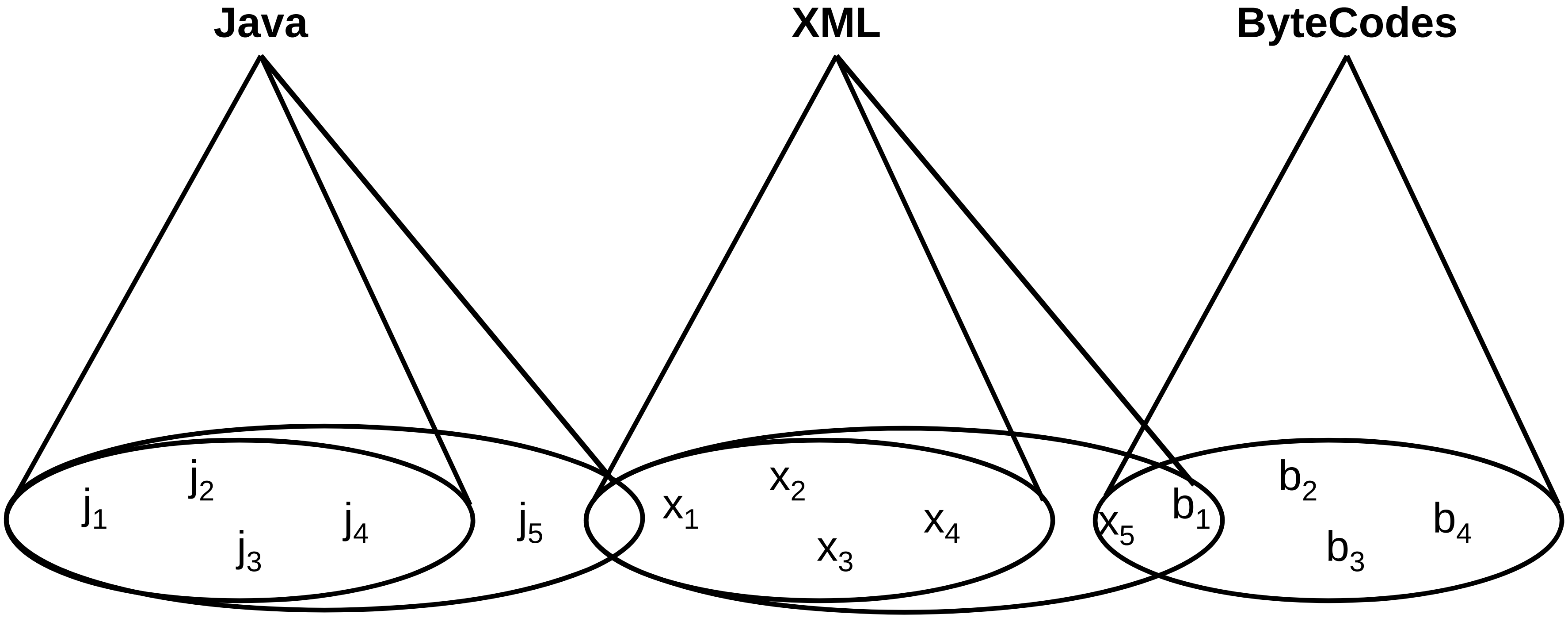
- An **object** is a domain of **points** (no standard term)
- **Metamodel** defines a domain of **models**





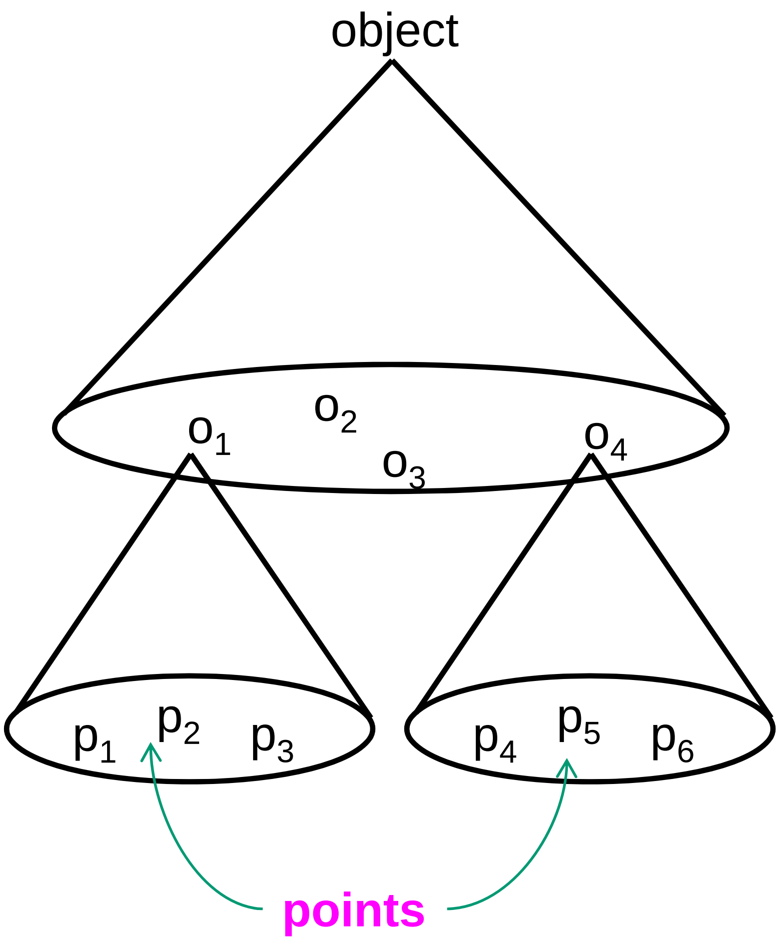
Examples

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

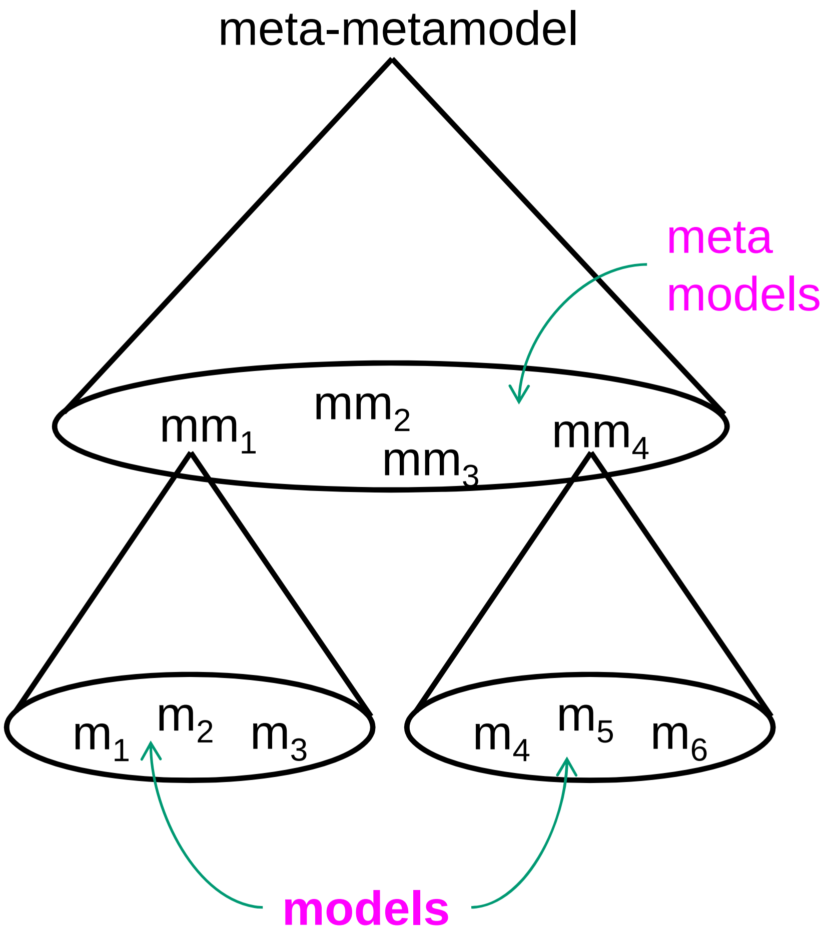


Recursion

- A point can be an object

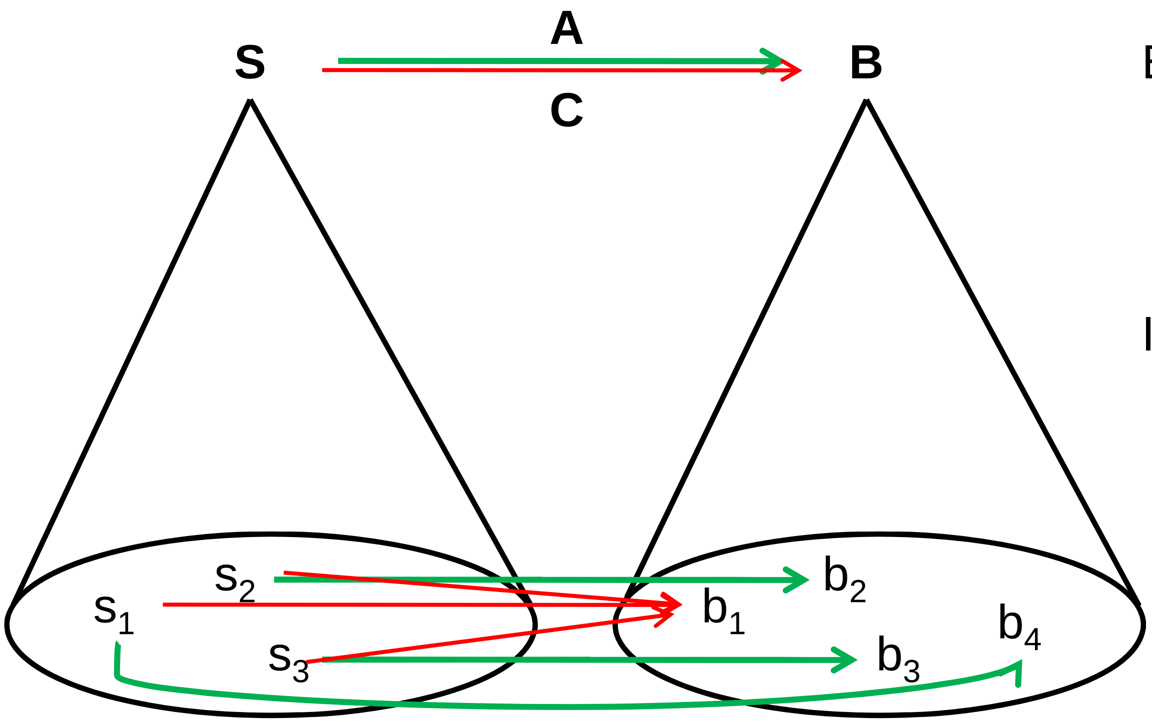


- Standard MOF architecture



Arrow

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



External Diagram

Internal Diagram

My Terminology (for this lecture)

- **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

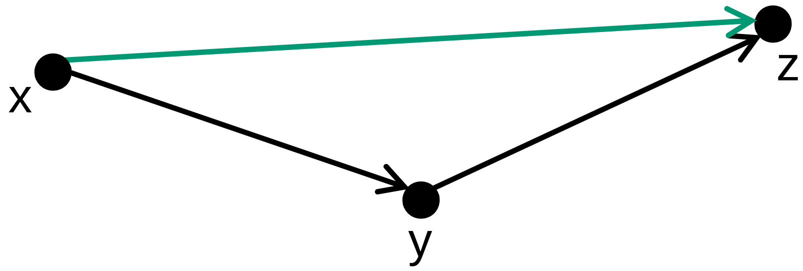
External Diagrams

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

- **Category** – a collection of objects and arrows
  - above is a category of 4 objects, 3 non-identity arrows
  - 4 identity arrows (not always shown)
  - categories satisfy 3 simple properties…

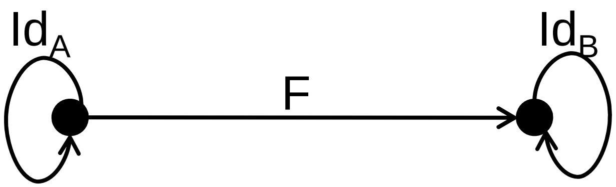
Properties of Categories

- Arrows are composable:



- Composition is associative: A•(B•C) = (A•B)•C

- Identities



$F \bullet Id_B = F$

$Id_A \bullet F = F$

External Diagrams in MDE

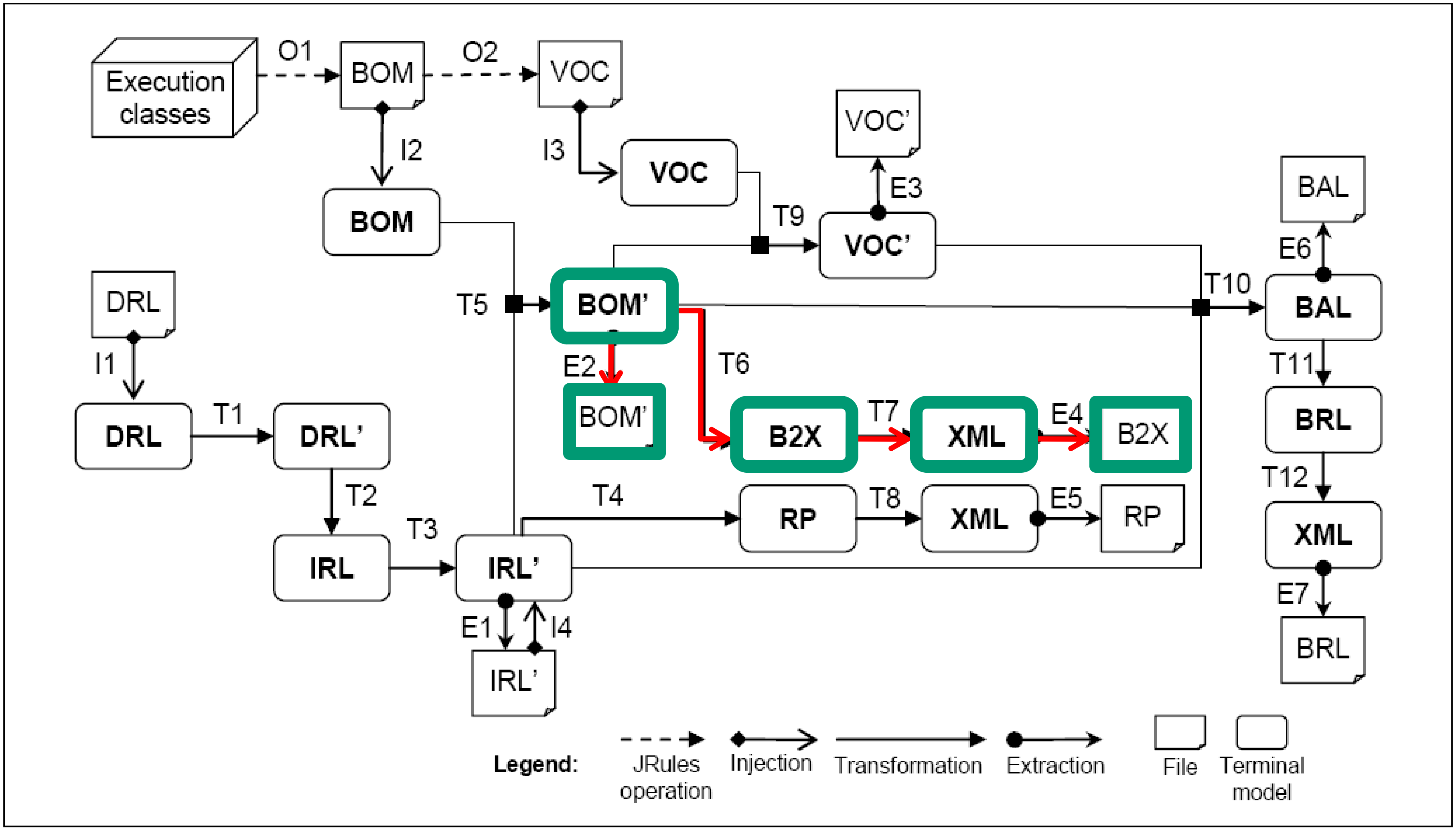
$$\begin{tikzcd}
\boxed{\text{MSC}} \arrow[r, "\text{M2MX}"] & \boxed{\text{SC}} \arrow[r, "\text{M2TX}"] & \boxed{\text{Java}} \arrow[r, "\text{javac}"] & \boxed{\text{ByteCode}}
\end{tikzcd}$$

- No standard names for such diagrams in MDE
  - drawn differently (without identity arrows)
  - **Toolchain diagrams** (MIC)
  - **MegaModels** (ATL)

- MDE “designs” are categories on an industrial scale
  - not the microscopic and often obscure examples in texts

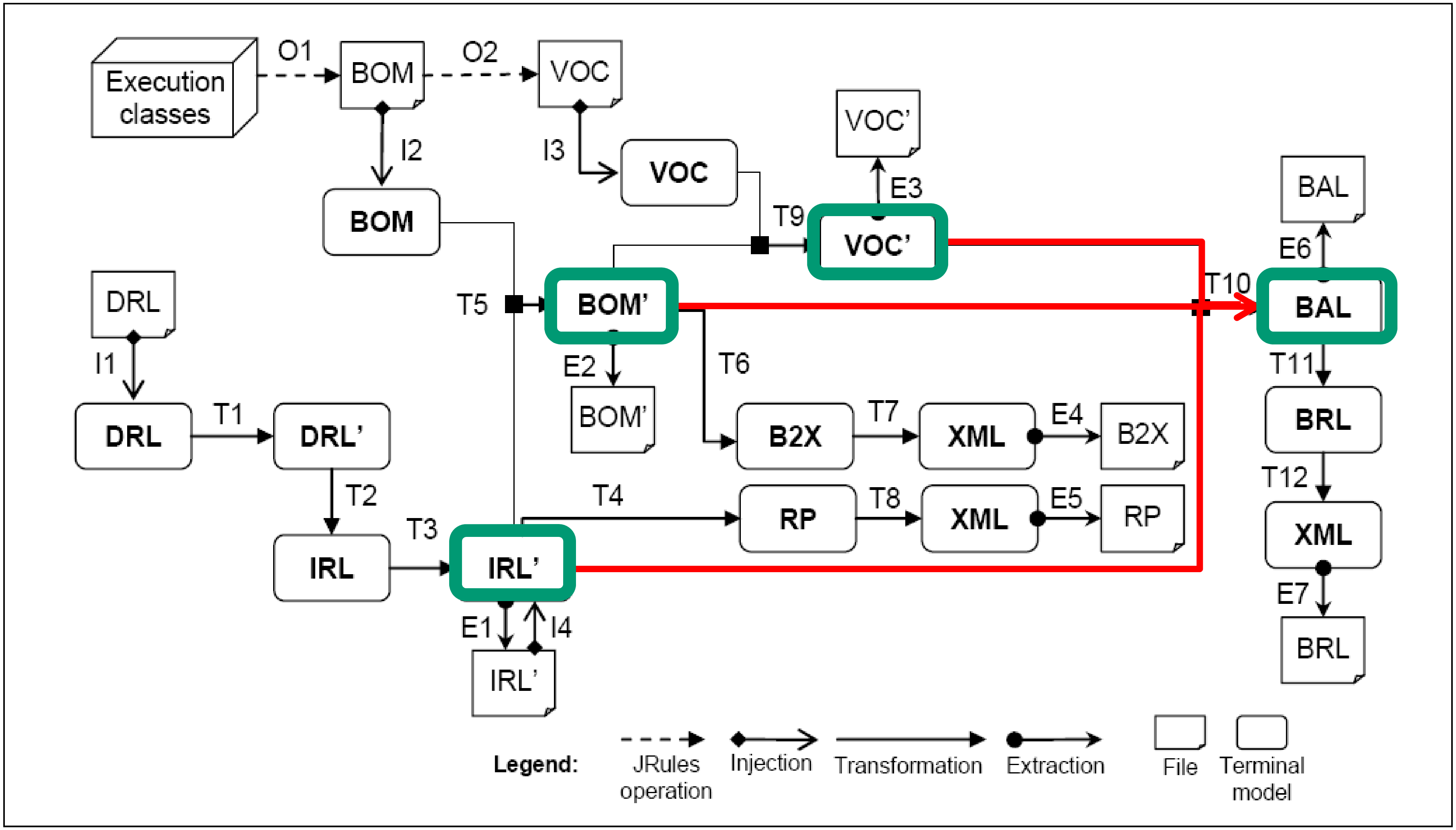
External Diagrams in MDE

provided by J. Bezivin



External Diagrams in MDE

provided by J. Bezivin



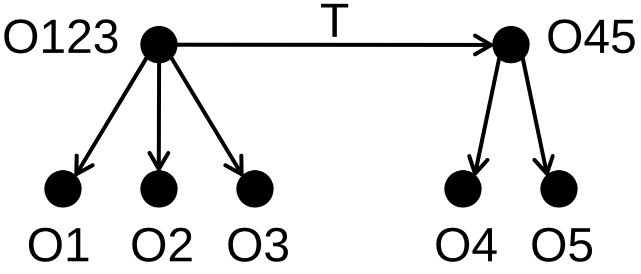
Arrows with Multiple Inputs, Outputs

- Arrow maps 1 input object to 1 output object
- But transformation T occurs in model synthesis:

T: O1, O2, O3 → O4, O5 ?

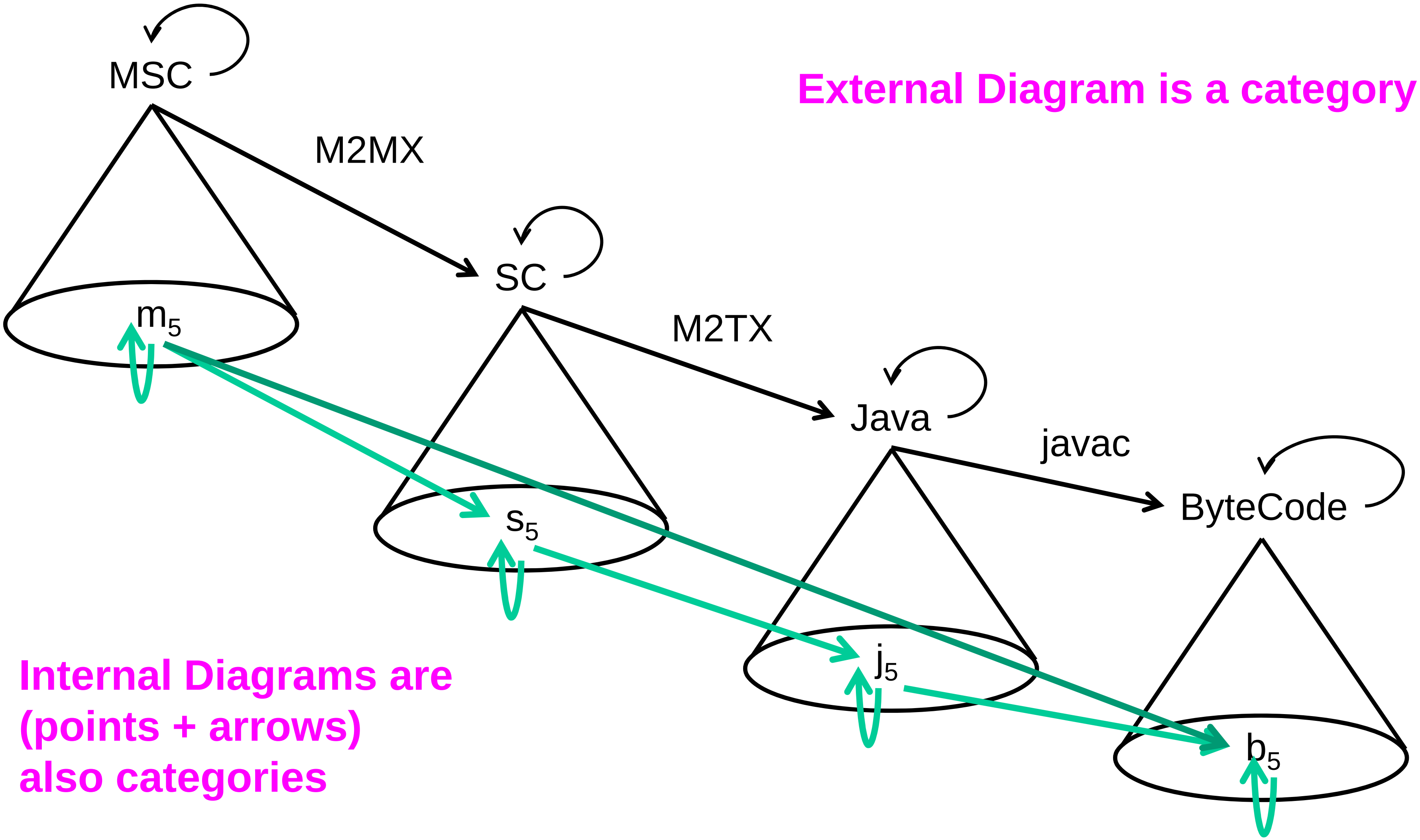
- Ans: create tuple of objects, which is itself an object

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



projection arrows

Internal Diagrams



External Diagram is a category

Internal Diagrams are
(points + arrows)
also categories

point is a domain with a single program

D×T

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

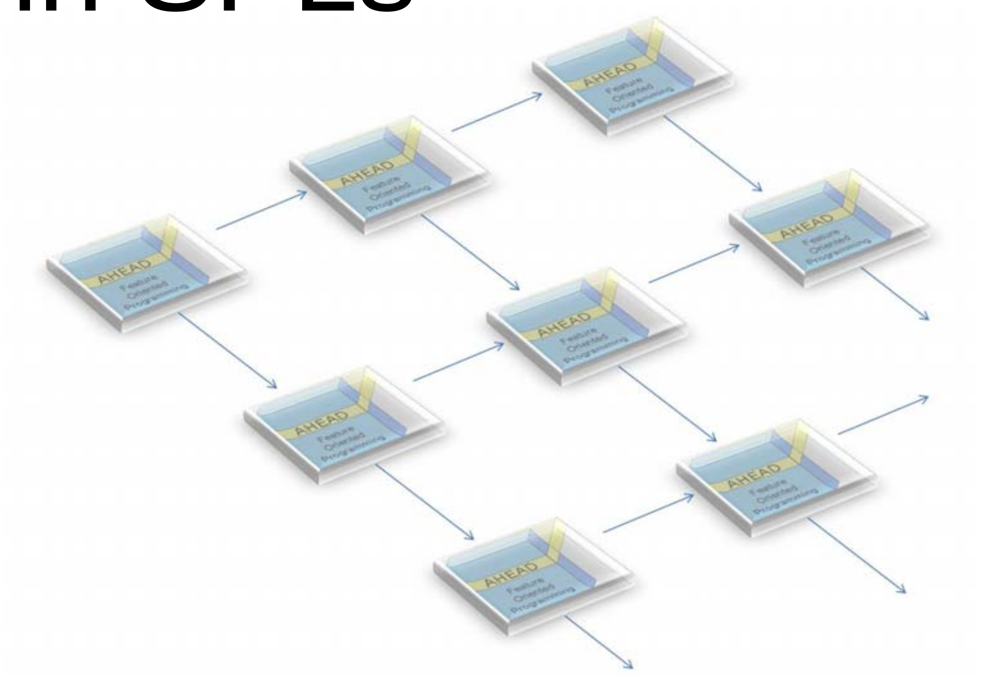
$$b_5 = \text{javac} \bullet \text{M2TX} \bullet \text{M2MX} \bullet m_5$$

$$\begin{tikzcd}
m_5 \arrow[dr, "\text{M2MX}"] & & & \\
& s_5 \arrow[dr, "\text{M2TX}"] & & \\
& & j_5 \arrow[dr, "\text{javac}"] & \\
& & & b_5
\end{tikzcd}$$

Recap

- Categories lie at the heart of MDE
  - found at all levels in an MDE architecture
  - MDE is 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 D×T
  - can use CT more formally
    (e.g., Meseguer, Ehrig, Täntzer, Diskin, Czarnecki, …)
- Now let’s look for categories in Software Product Lines

#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
  - from our 1st lecture, a feature is a function:

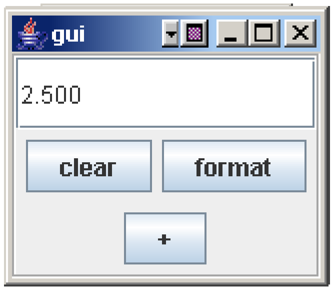
$$P = F(G)$$

4-Program Product Line with Superposition

```
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

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

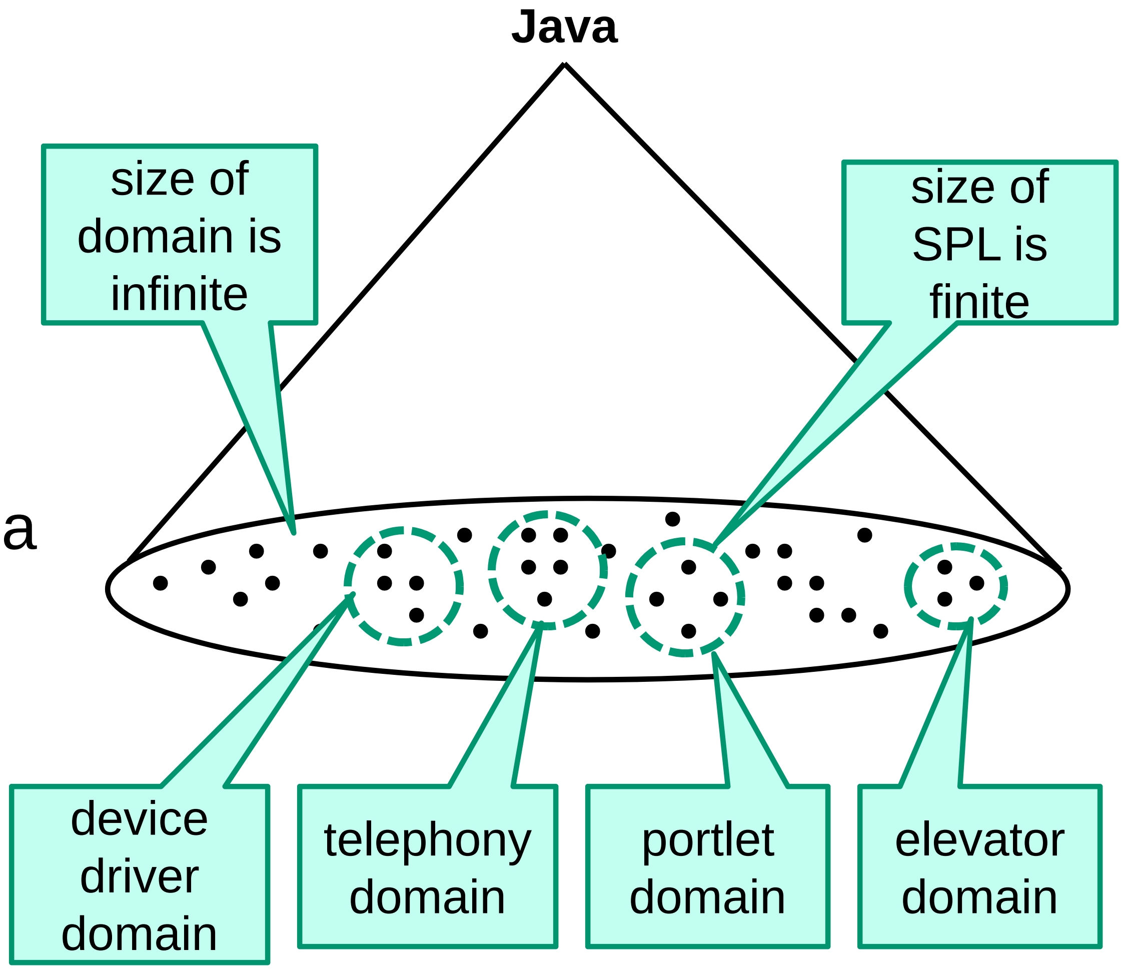
new methods

Scale Reminder (From Lecture #1)

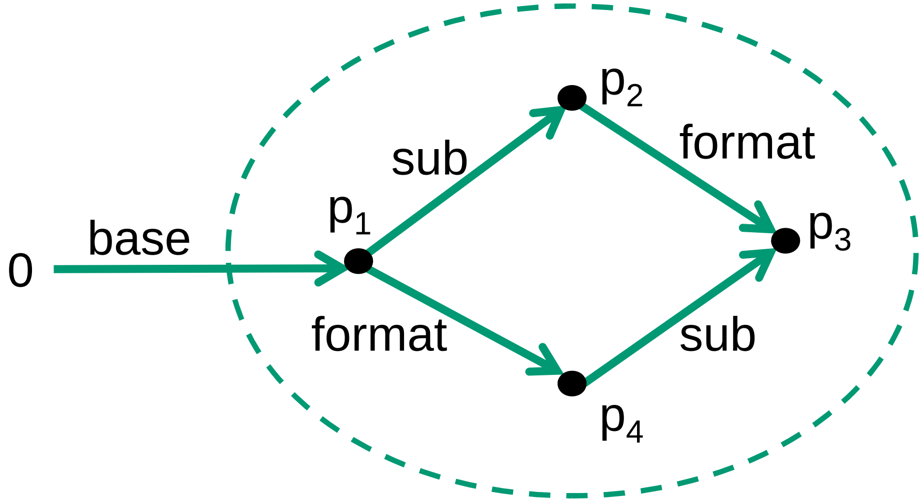
- 1986 database systems 75K LOC
- 1989 network protocols
- 1993 data structures
- 1994 avionics
- 1997 extensible Java precompilers 35K LOC
- 1998 radio ergonomics
- 2000 program verification tools
- 2001 verified compiler for Java1.0
- 2002 fire support simulators
- 2003 AHEAD tool suite 250K LOC
- 2004 robotics controllers
- 2006 web portlets
- 2008 SGI+JavaScript application
- 2009 ZipMe compression library

Perspective on Product Lines

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

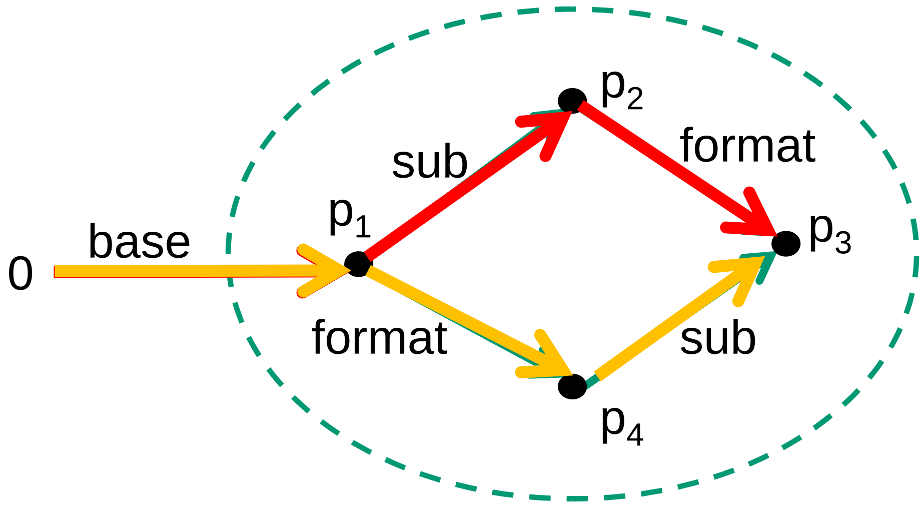


Perspective on Product Lines



- SPL defines relationships between its programs
  - how are programs related?
  - by arrows, of course!
  - each arrow is a **feature**
- Empty program (0) may or may not be part of SPL

D×T



p_3 = format • sub • base

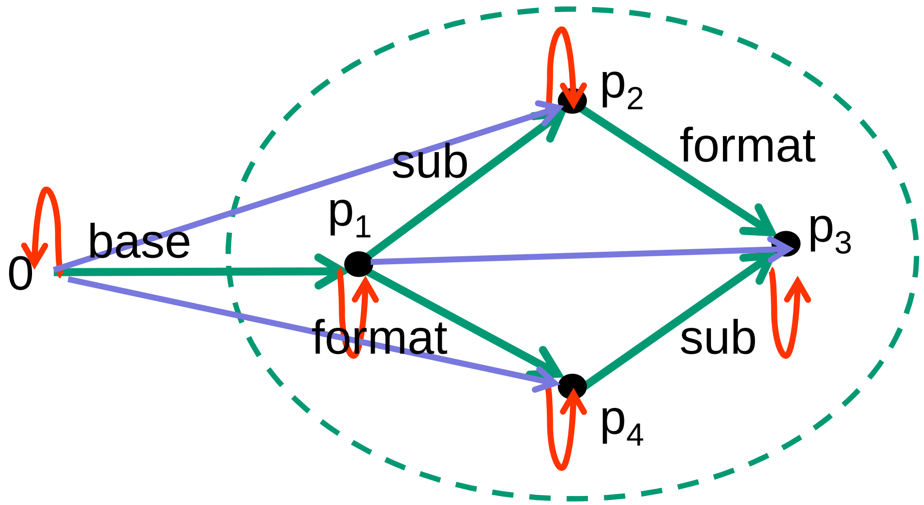
p_3 = sub • format • base

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

evaluating both meta-expressions yields the same program

format, sub are **commutative**

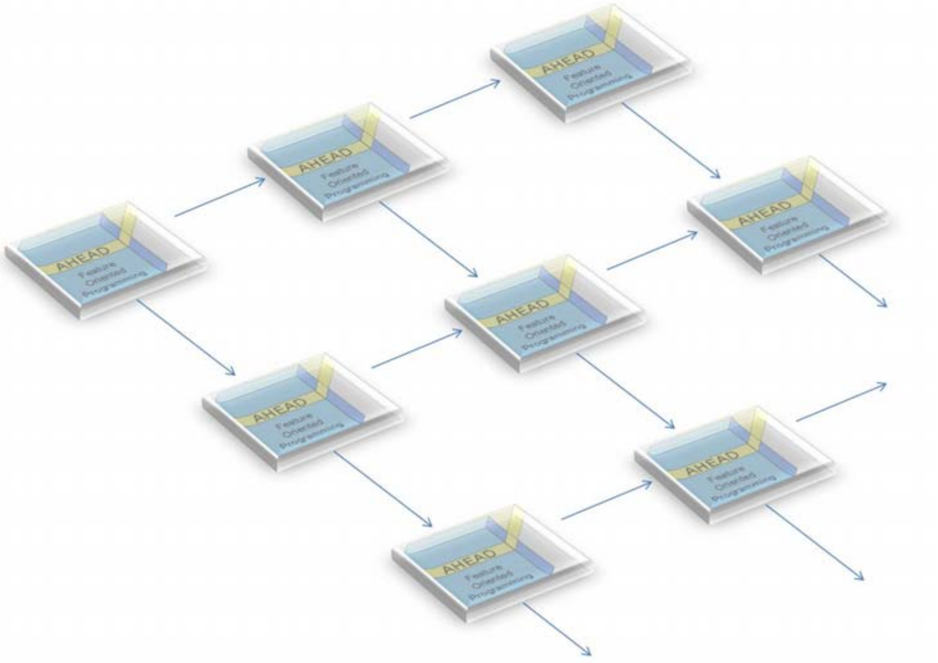
A Product Line is also a Category



- Category
    - point is a domain with a single program in it

- Has implied identity arrows

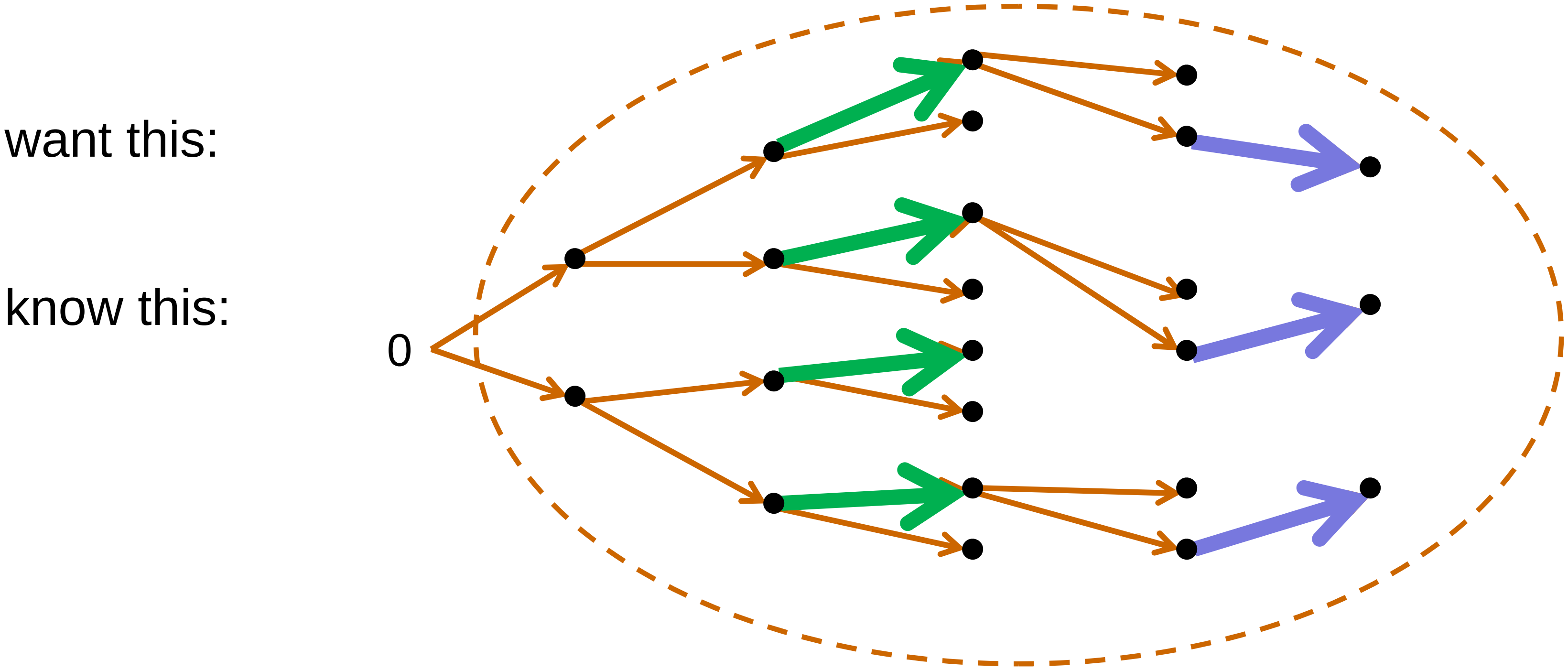
- Has implied composed arrows, as required



Fundamental Ideas in SPL Implementations

(devoid of implementation details)

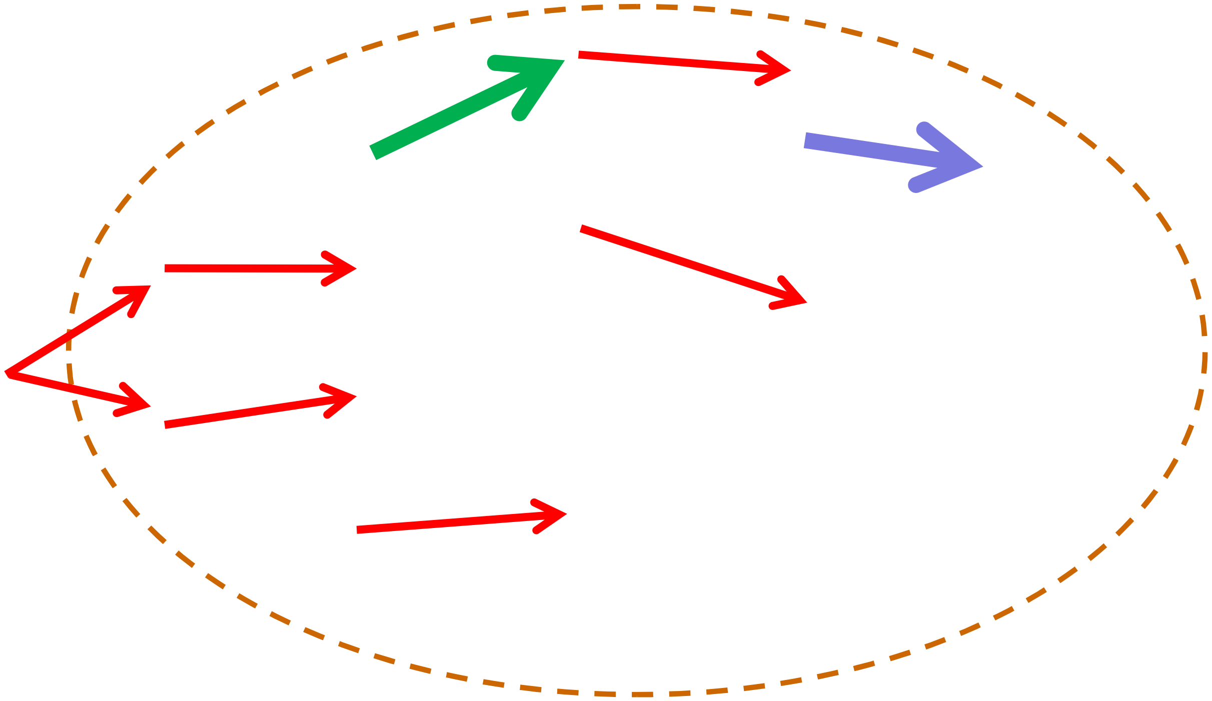
Implementing SPLs



- Same function being applied to different inputs

Implementing SPLs

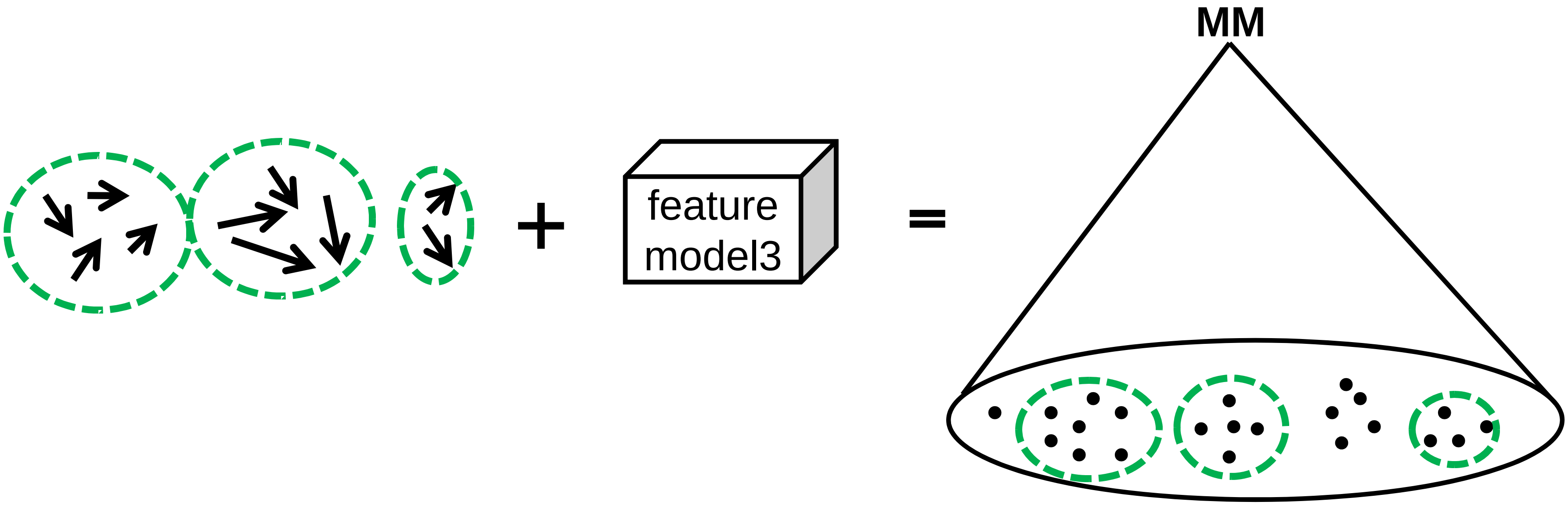
store this:



- Just store arrows once and reuse!
  - *n* optional features, 2^n possible programs
  - compact representation of an SPL

Models of SPLs

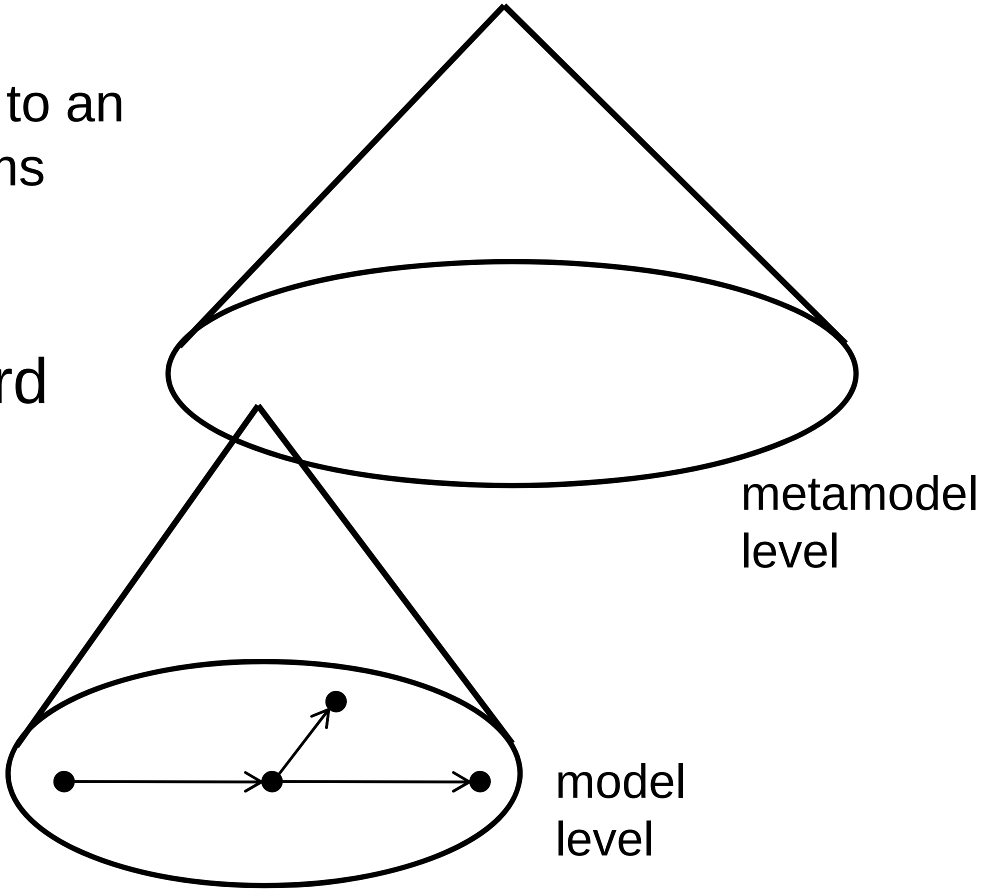
- Implement a set of arrows
  - by transformations, superposition, or whatever
- Feature model defines legal compositions of arrows
- Yields a product line



Recursion

- SPLs can appear at any level of an MDE architecture
    - arrow adds same feature to an infinite domain of programs

- **Superposition** is a standard technique, but not always sufficient
    - Kästner's CIDE (preprocessors)



Essential Distinctions of SPL and MDE

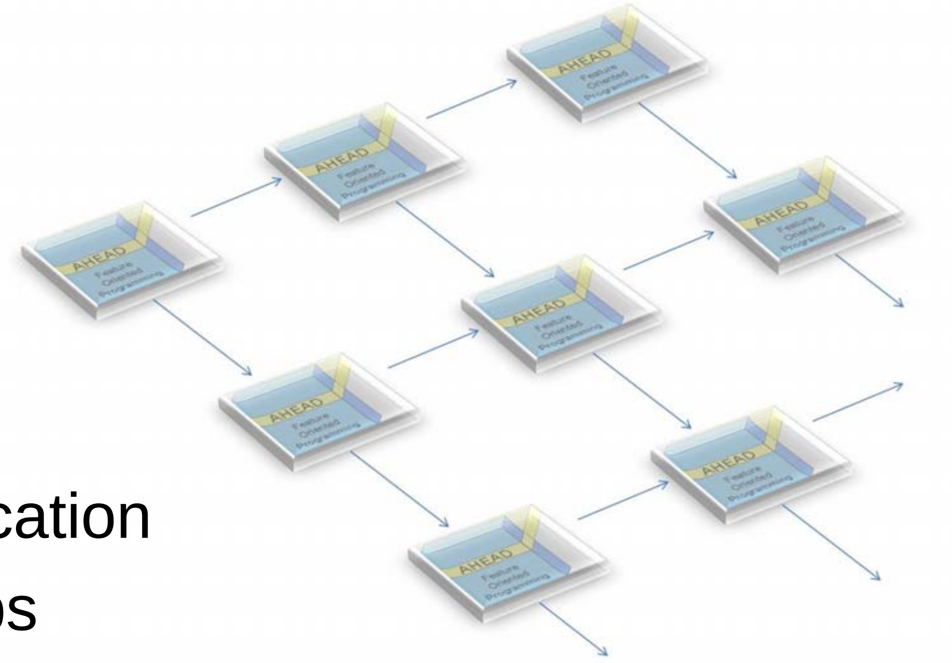
- An MDE “design” is a category with objects (domains) that are **infinite** in size
  - ex: metamodel of all class diagrams
  - # of such diagrams is infinite

- An SPL “design” is a category with objects (domains) that are **finite** in size
  - feature model defines a finite set of programs

Recap

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

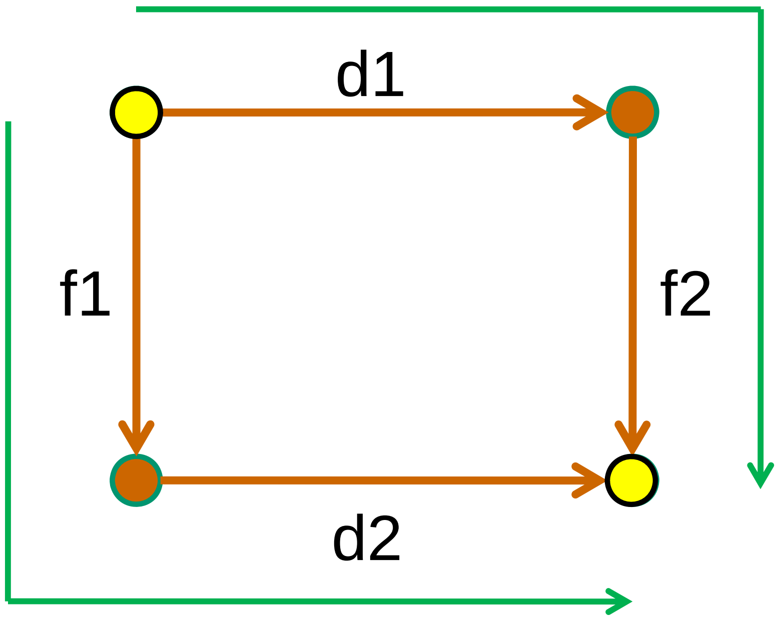
#3: Categories in MDPLs


AHEAD Feature Oriented Programming
AHEAD Feature Oriented Programming
AHEAD Feature Oriented Programming
AHEAD Feature Oriented Programming
AHEAD Feature Oriented Programming
AHEAD Feature Oriented Programming
AHEAD Feature Oriented Programming
AHEAD Feature Oriented Programming
AHEAD Feature Oriented Programming

Exposing fundamental verification
and optimization relationships

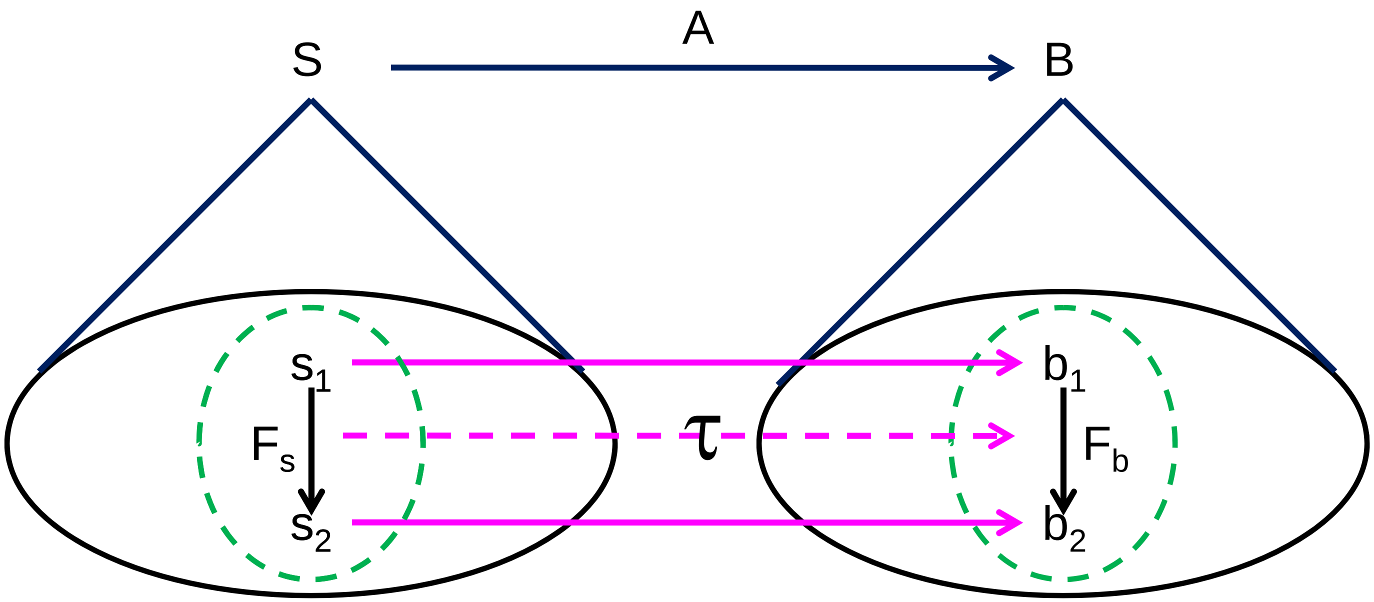
Recall Commuting Diagrams

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



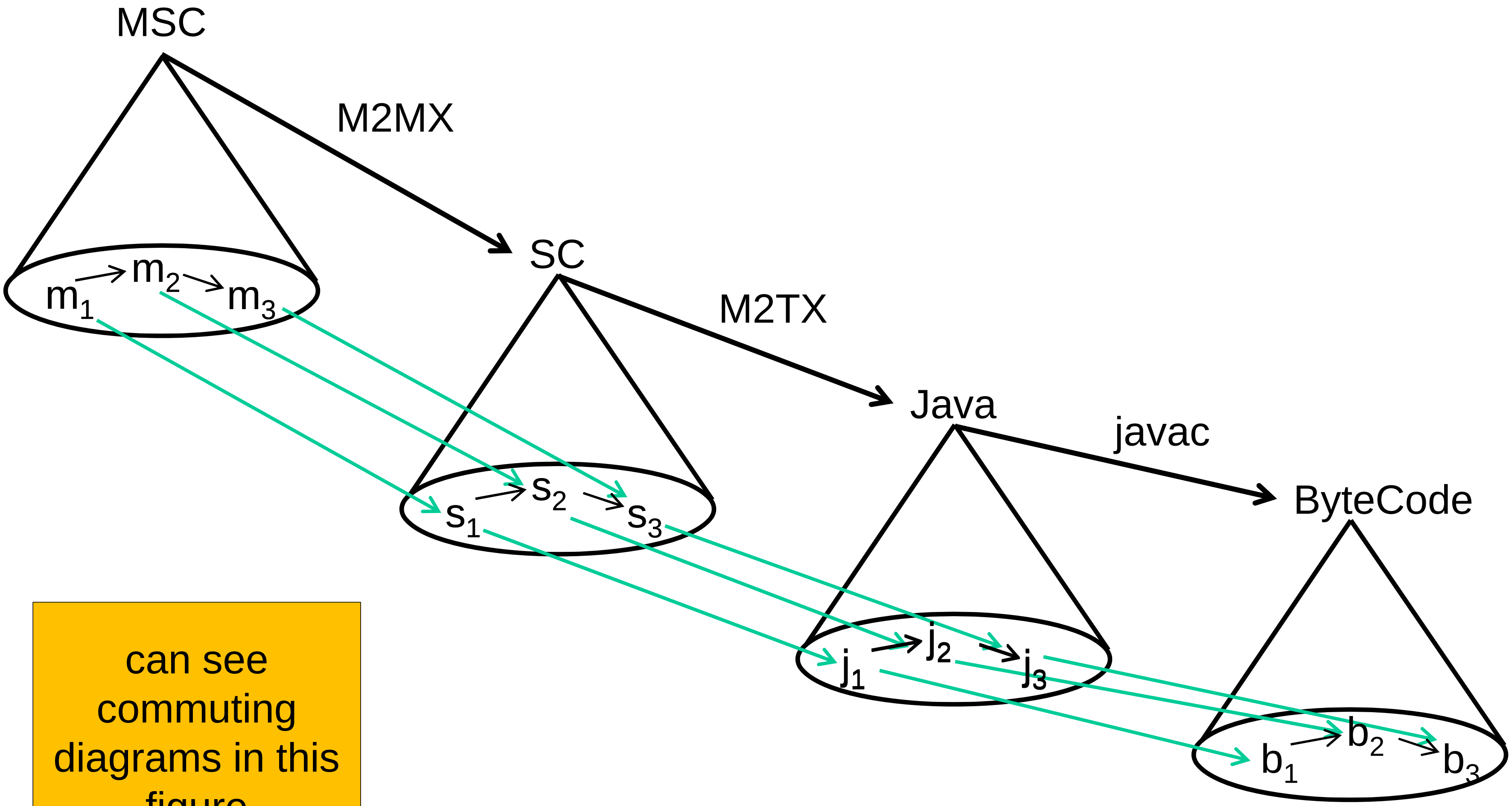
$$f1 \bullet d2 = d1 \bullet f2$$

Commuting Diagrams in MDPLs



- Want to map a product line of S models to its corresponding product line of B models
  - typical MDE transformations map **only** points, not arrows
- **Operator** τ maps arrow F_s to arrow F_b: $\tau(F_s) = F_b$

How Commuting Diagrams Arise

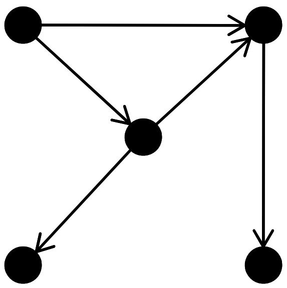


can see commuting diagrams in this figure

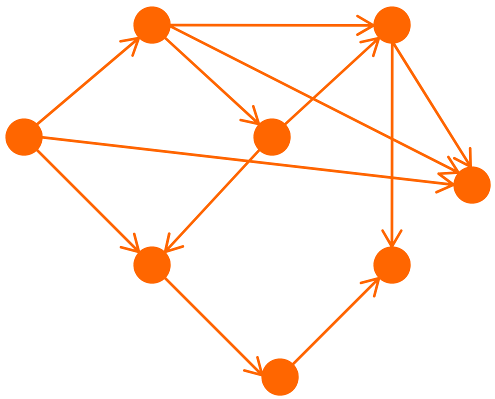
Functors

- Are fundamental to Category Theory
- F:A→B is an embedding of category A into category B
  - each object of A is mapped to an object in B
  - each arrow of A is mapped to an arrow of B
    such that arrow compositions in A are preserved in B

category A

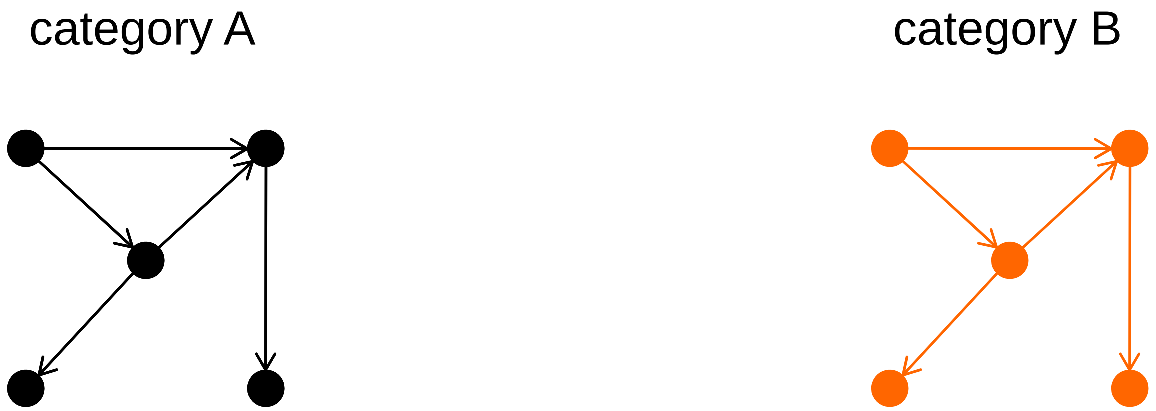


category B



Functors

- I have encountered are isomorphic (A looks just like B)



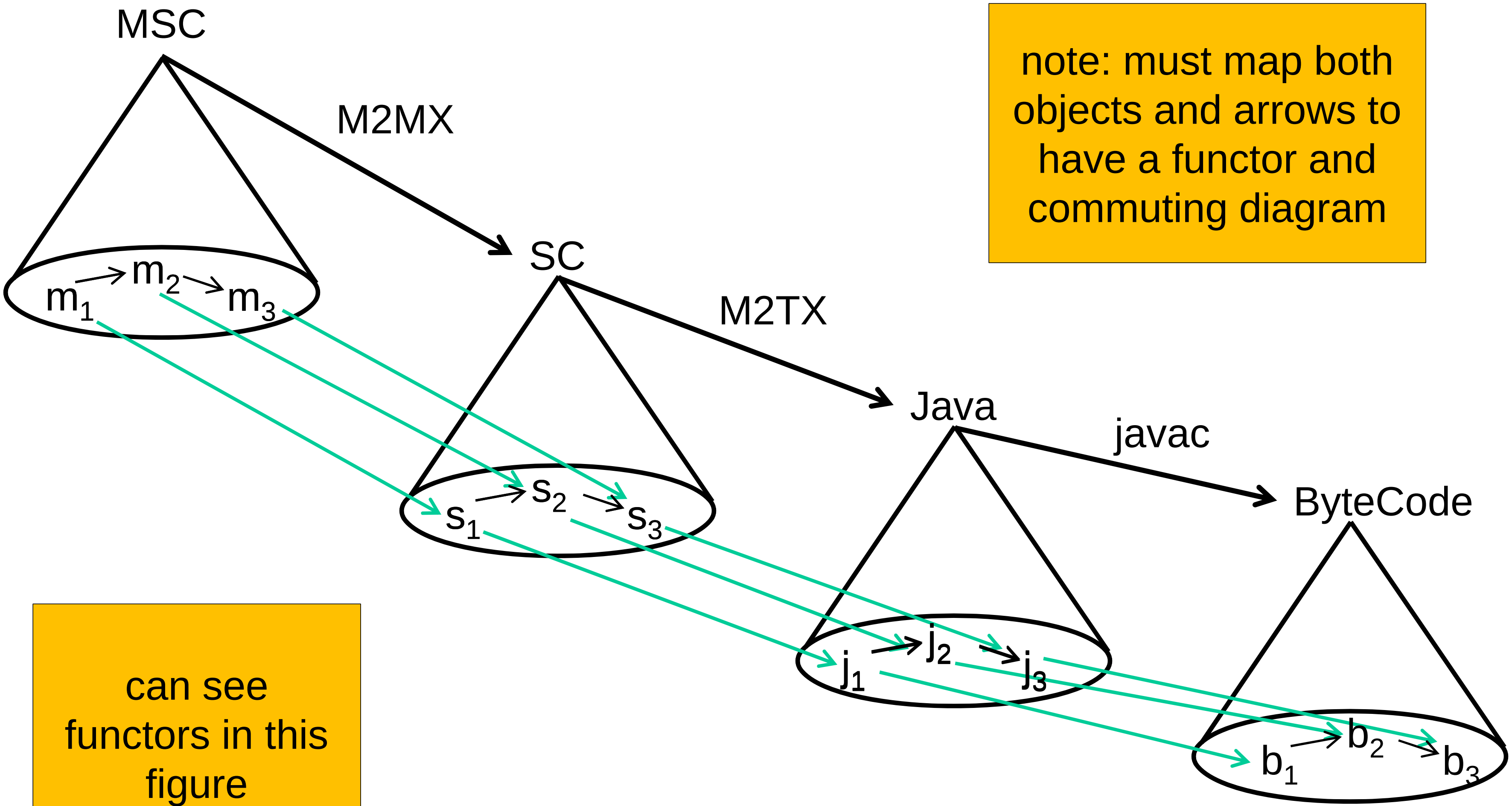
category A

category B

- Product line of Java files → product line of bytecodes

- We have seen functors before in this tutorial

How Functors Arise

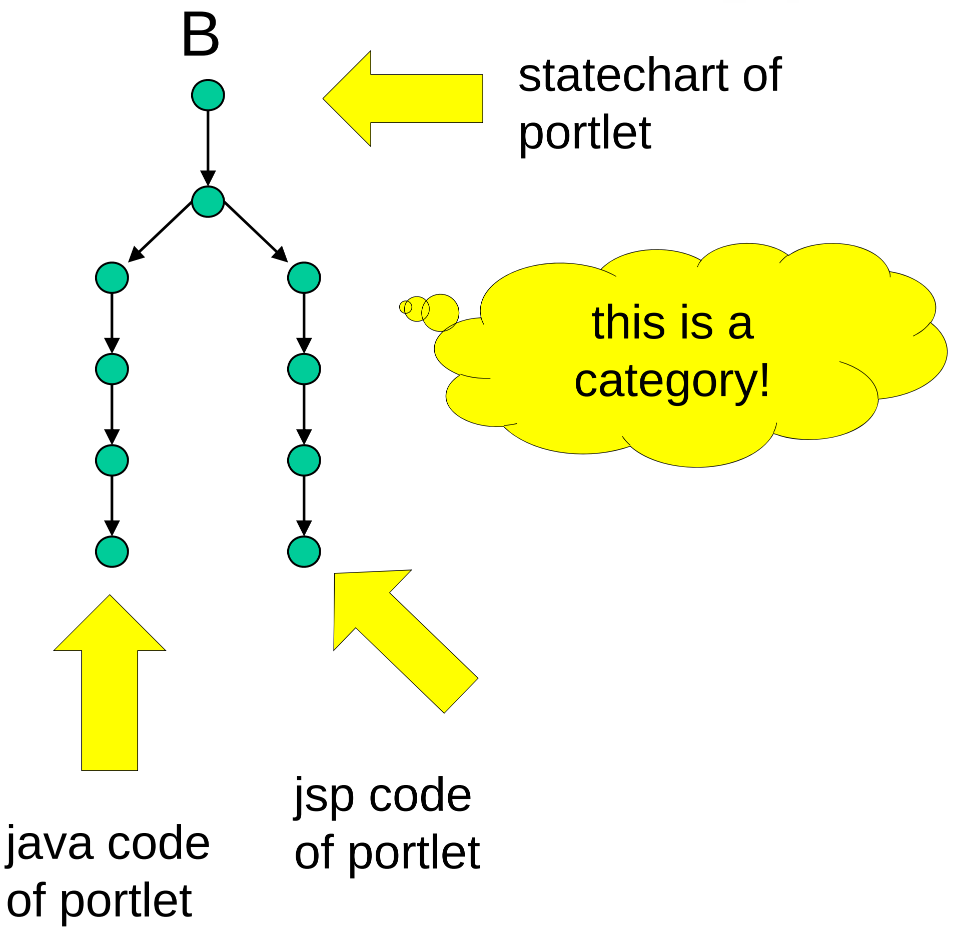


note: must map both objects and arrows to have a functor and commuting diagram

can see functors in this figure

Functors and 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



B

statechart of portlet

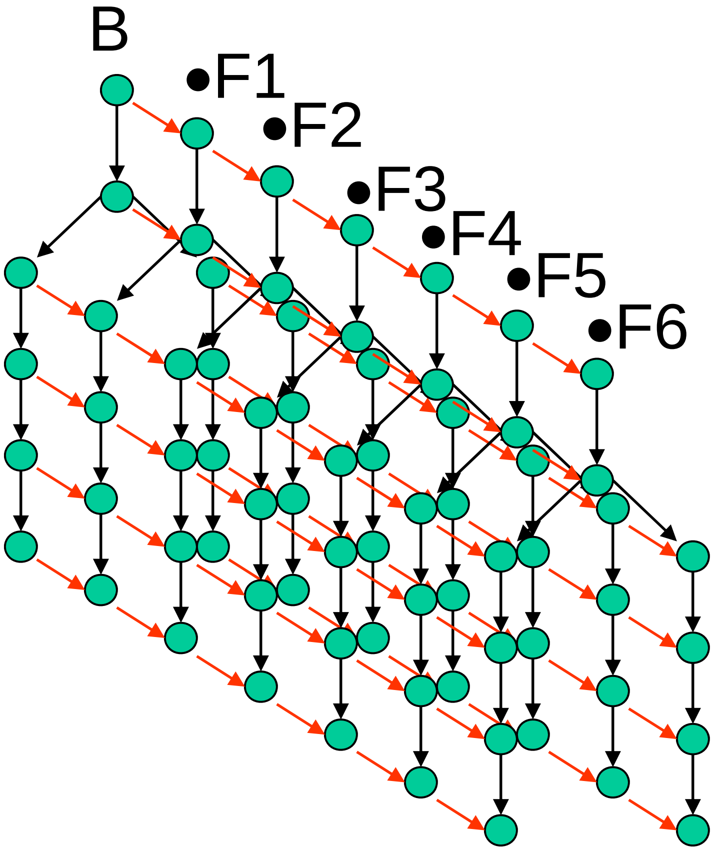
this is a category!

java code of portlet

jsp code of portlet

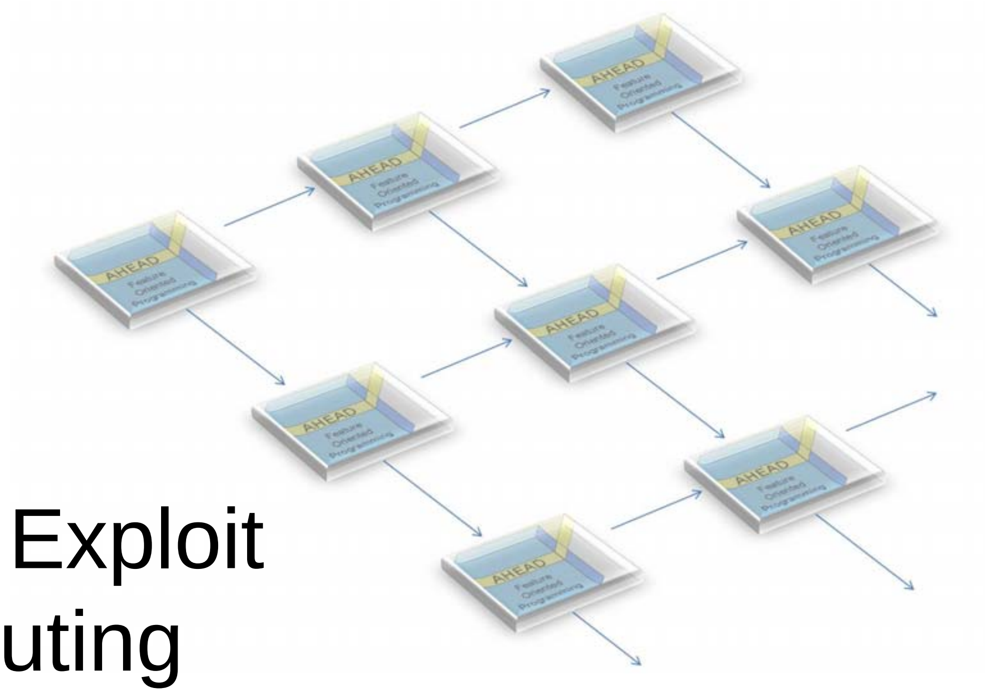
Functors and Commuting Diagrams in PinkCreek

- When a feature is added, each representation is extended (arrows remain the same)
- Features are functors: map each object, arrow of the original category to those of an isomorphic category
- Feature composition = Functor composition



Warning!

- Arrows are 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 arrows
  - 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



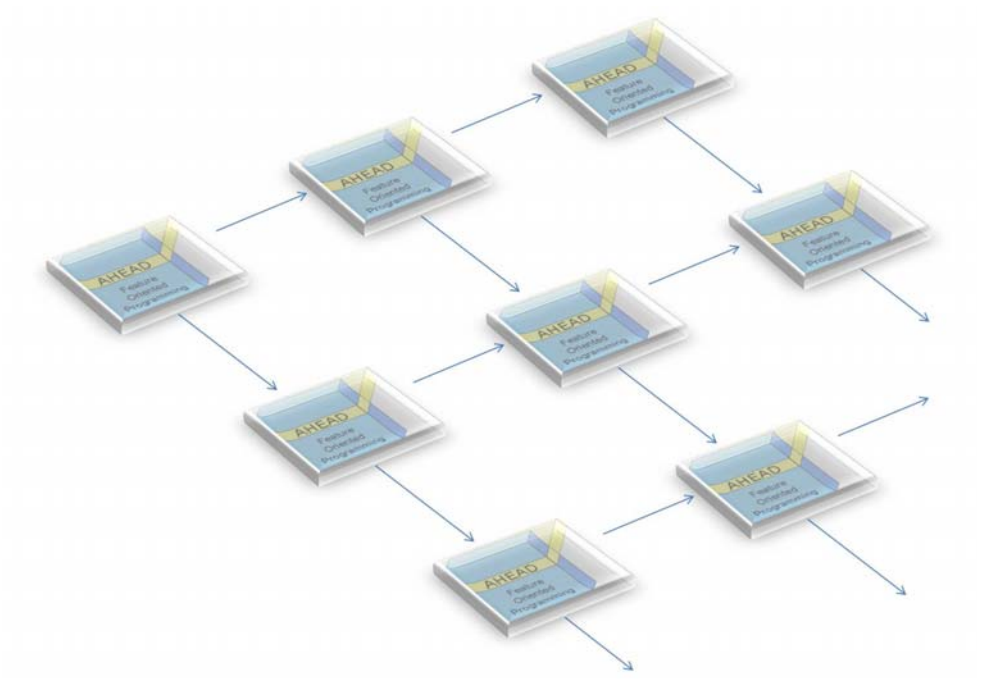
More Examples that Exploit Functors and Commuting Diagrams

Writing Operators

- We found other uses for commuting diagrams and arrow operators in MDPLs:

  - **simplifying implementation (ICMT 2008, SOSYM 2010)**
  - **improving test generation (SIGSOFT 2007, TSE 2010)**
  - understanding feature interactions (GPCE 2008)
  - understanding AHEAD (GPCE 2008)

- Briefly review the first two of these…

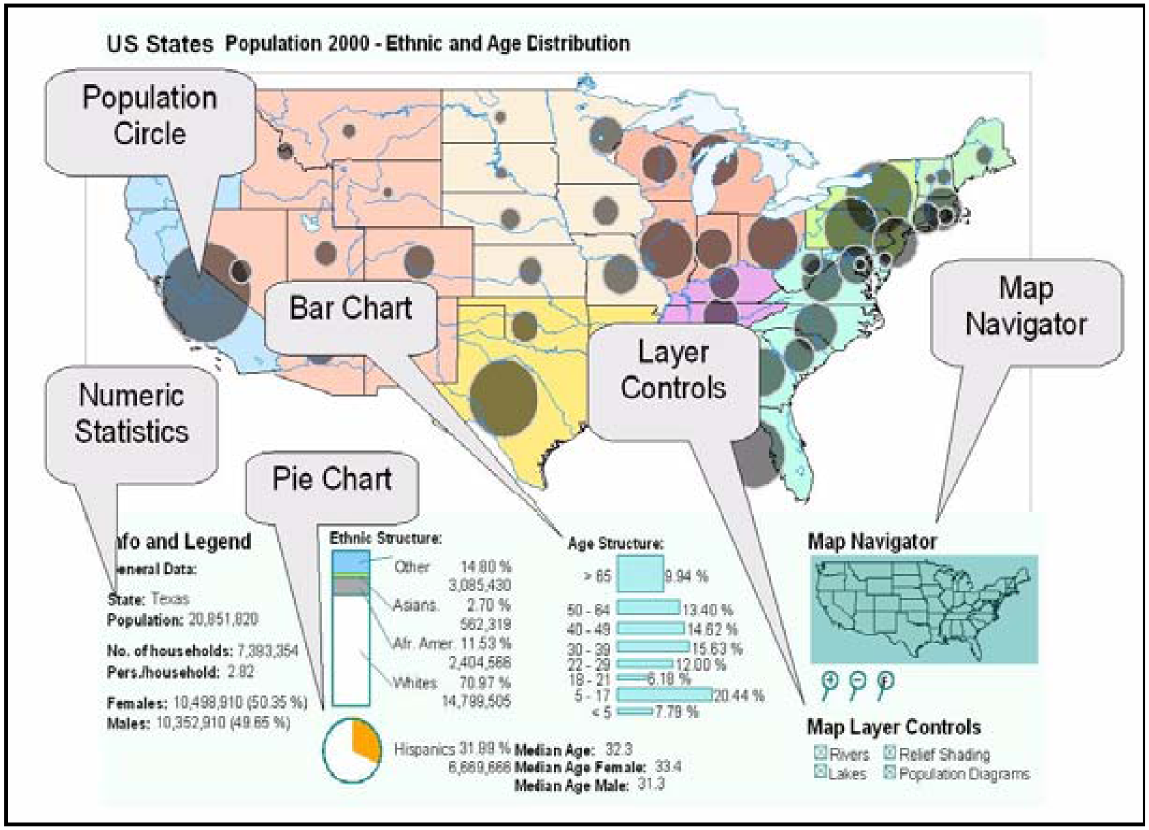


General Technique for Implementing MDPLs

appreciate use of categories to explain what is going on

Example 1: SOSYM 2010 Paper

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



US States Population 2000 - Ethnic and Age Distribution

Info and Legend

General 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 %)

Median Age: 32.3

Median Age Female: 33.4

Median Age Male: 31.3

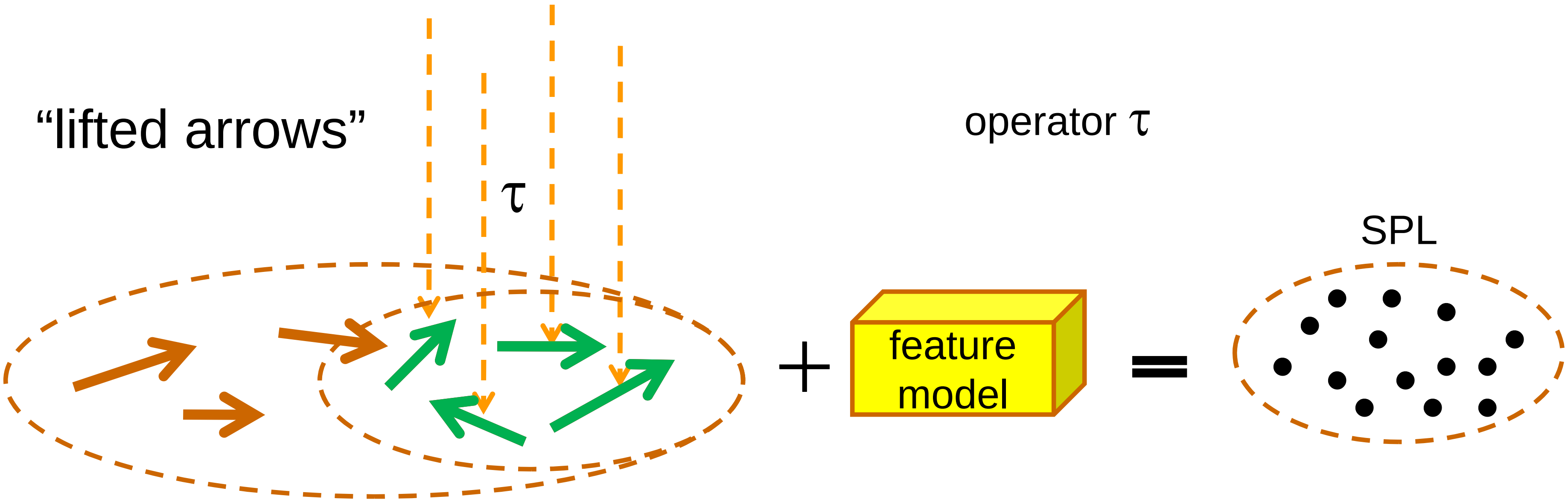
Map Layer Controls

☒ Rivers ☒ Relief Shading
☒ Lakes ☒ Population Diagrams

Example 1: SOSYM 2010 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



“lifted arrows”

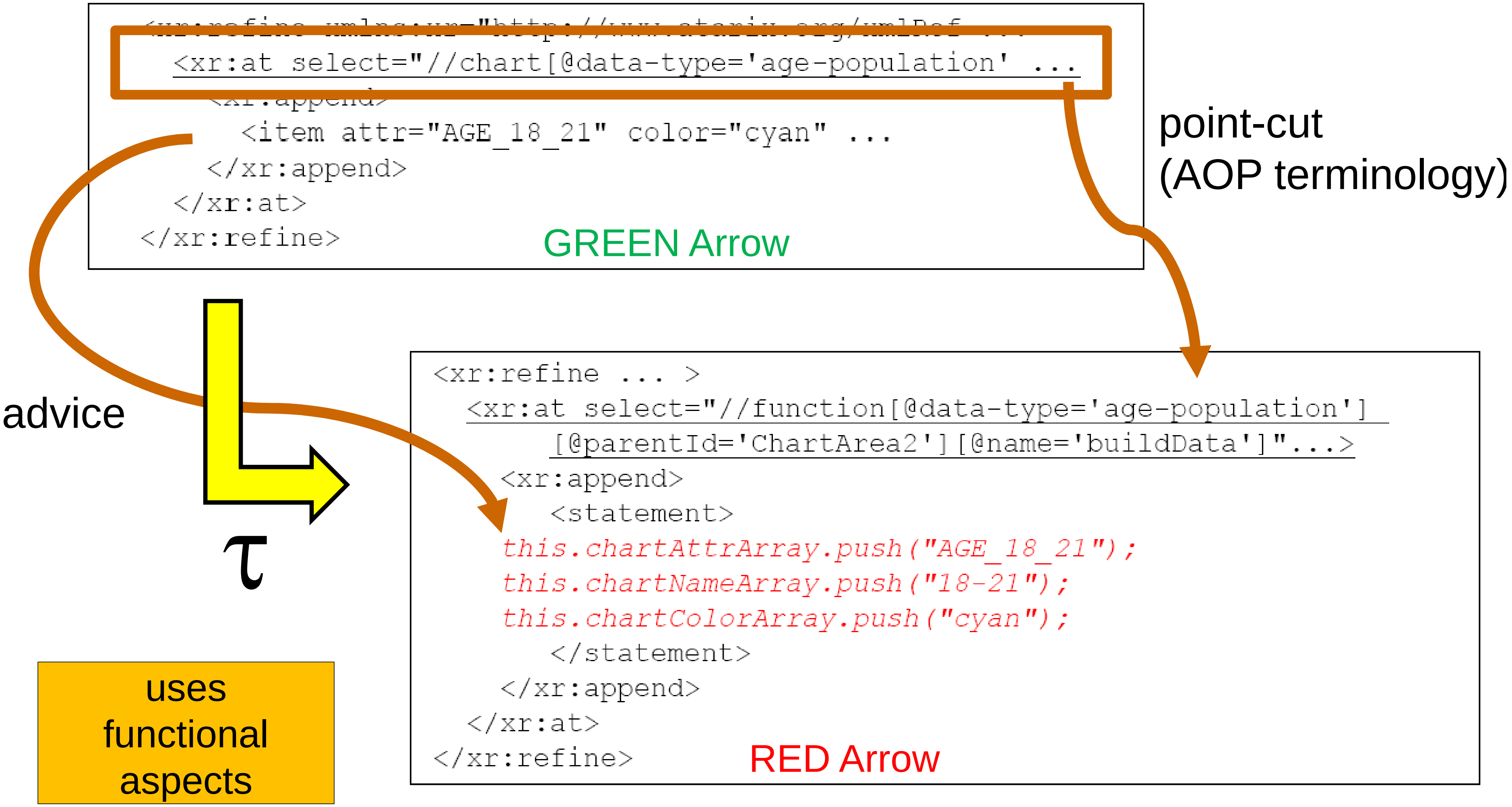
τ

operator τ

SPL

+ feature model =

τ Mapping of Arrow to Arrow



```
<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

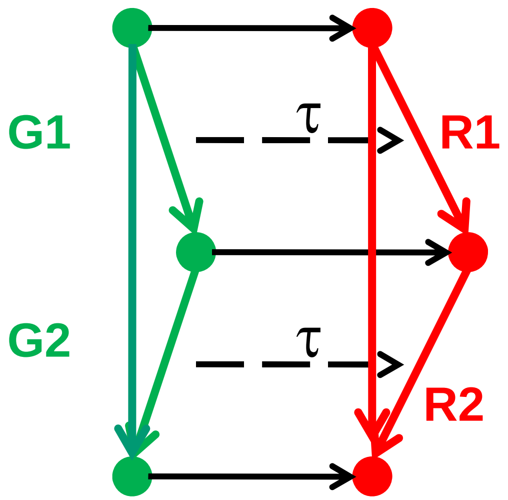
τ

uses functional aspects

```
<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



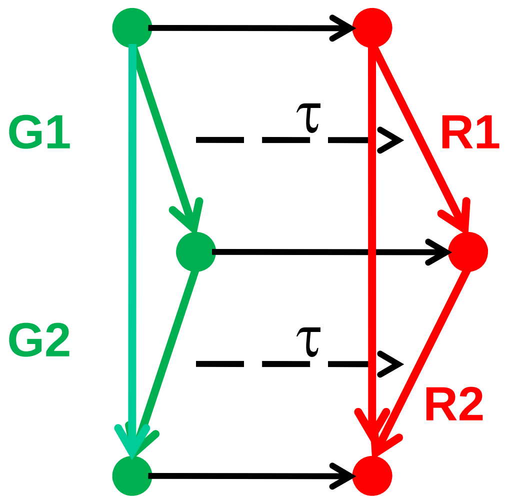
$$\tau(\mathbf{G1} \bullet \mathbf{G2}) = \tau(\mathbf{G1}) \bullet \tau(\mathbf{G2})$$

$$= \mathbf{R1} \bullet \mathbf{R2}$$

- Same result if we compose green arrows and translate OR we translate green arrows, and compose red arrows

- **Homomorphism** – mapping of expression in one algebra (**GREEN**) to a corresponding expression in another (**RED**)

Diagram Constraints



$$\tau(\mathbf{G1} \bullet \mathbf{G2}) \;=\; \tau(\mathbf{G1}) \bullet \tau(\mathbf{G2})$$

$$=\; \mathbf{R1} \;\bullet\; \mathbf{R2}$$

- Same ranslate OR we tr rows

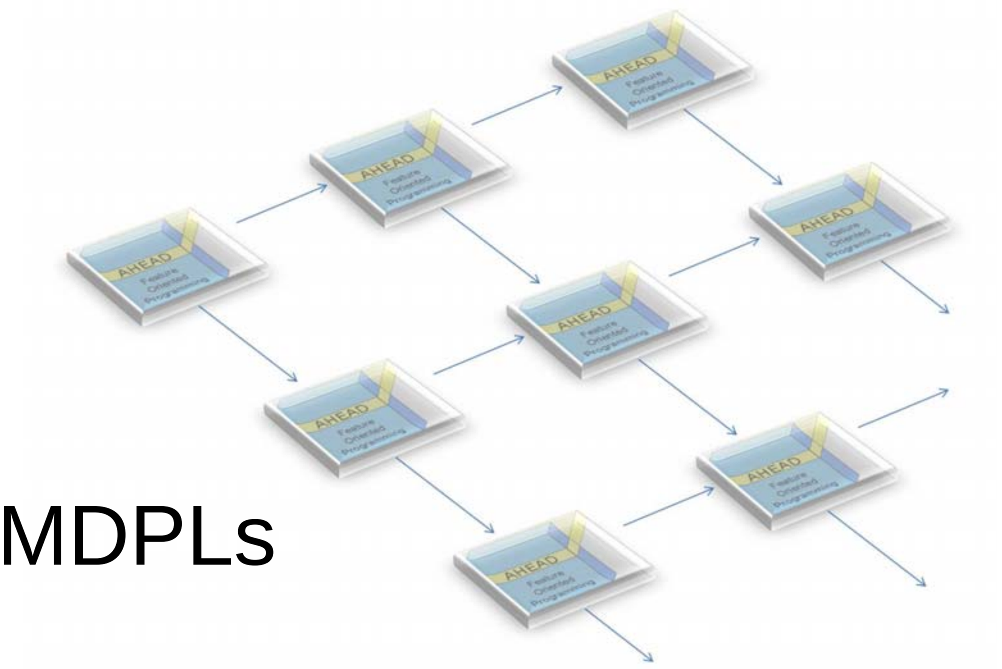
- **Hom** ne algebra (**GRE** ther (**RED**)

Verification condition:
our implementation is correct
if this equality holds!

From Lecture #1

- 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
    - » 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



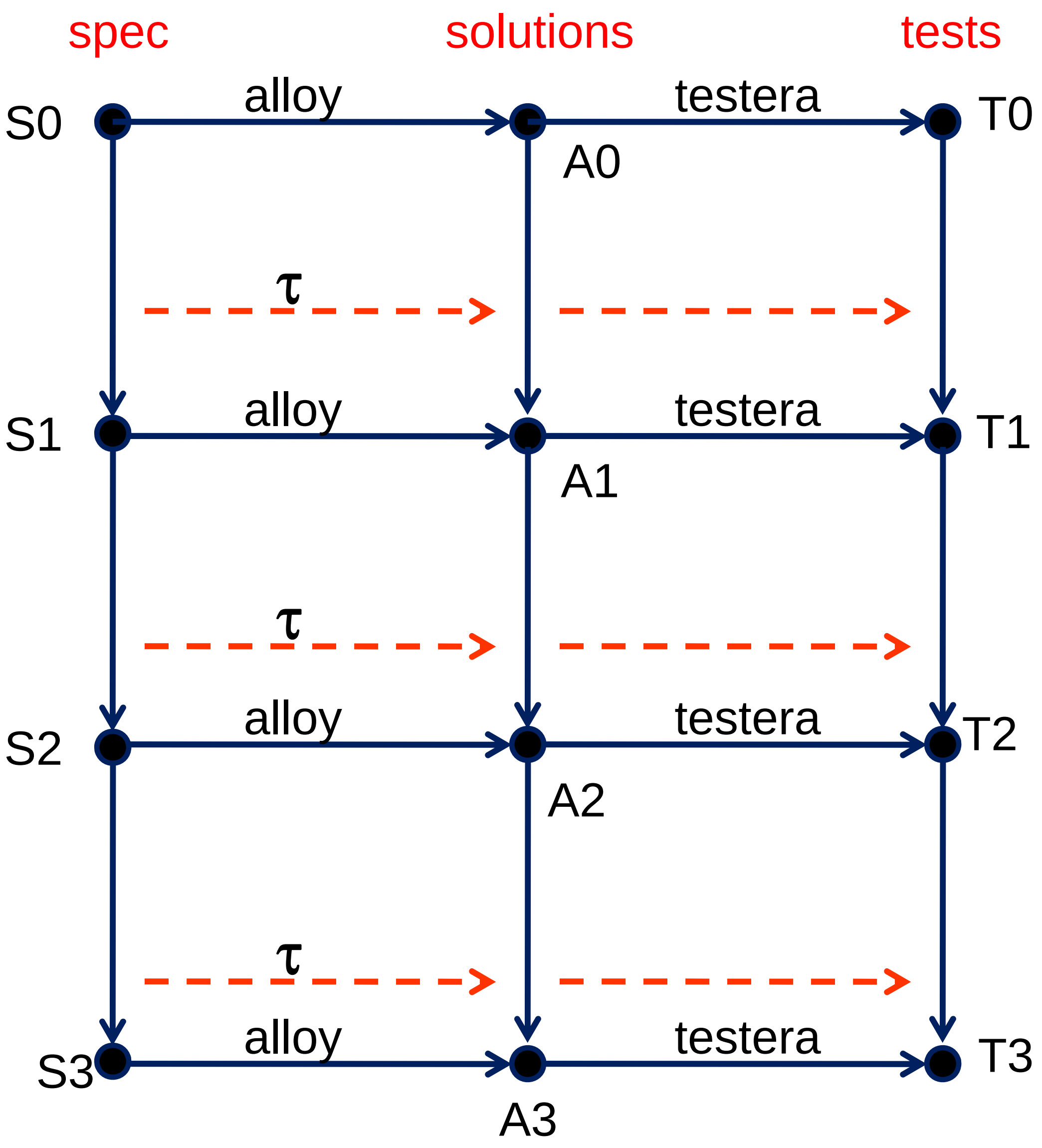
Example 2: TSE 2010 Paper

- 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?

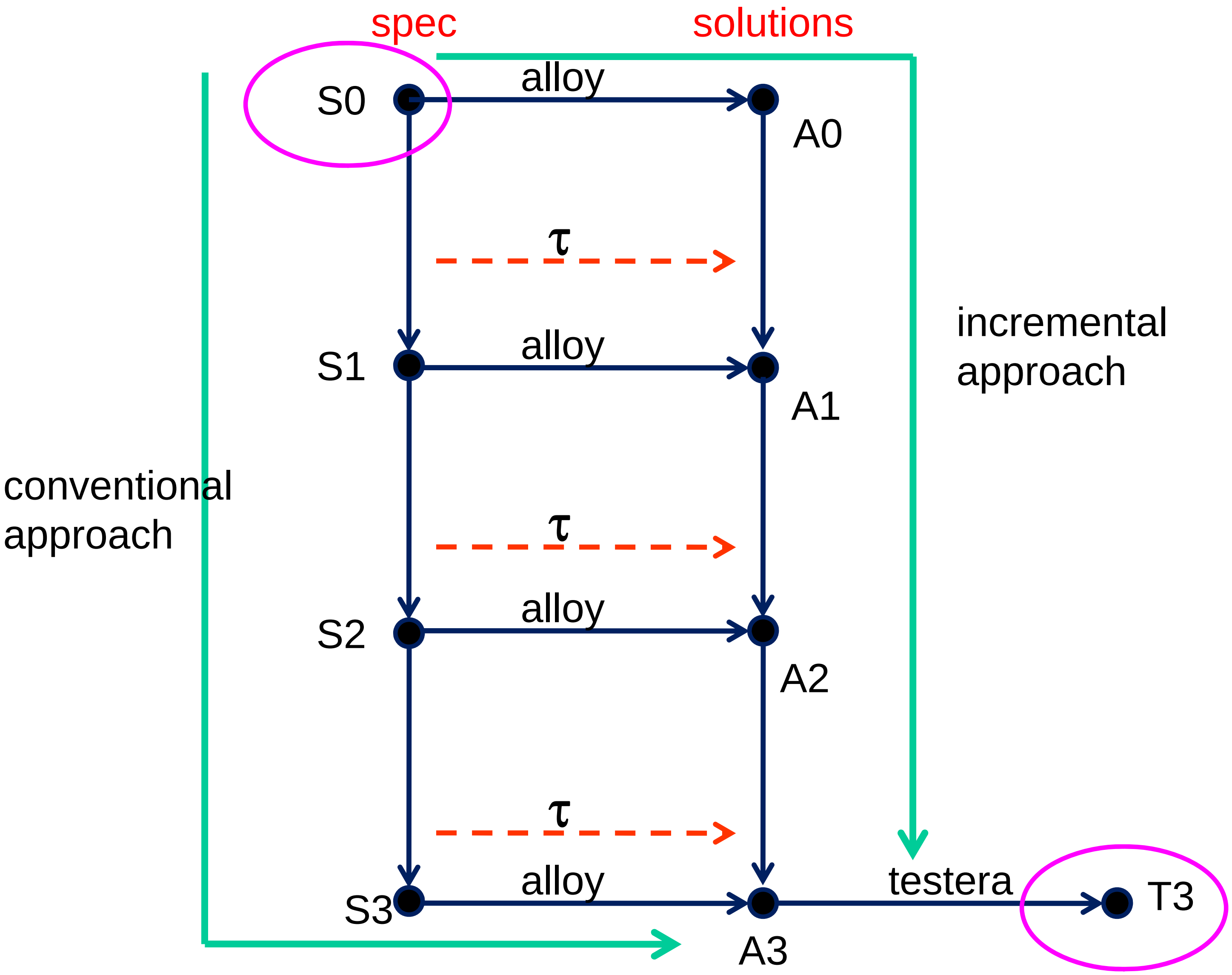
- Specification-based testing can be effective
  - start with a spec (model) of program
  - automatically derive tests
  - Alloy is example

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 are Encouraging

- 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
- See paper(s) for details

Recap

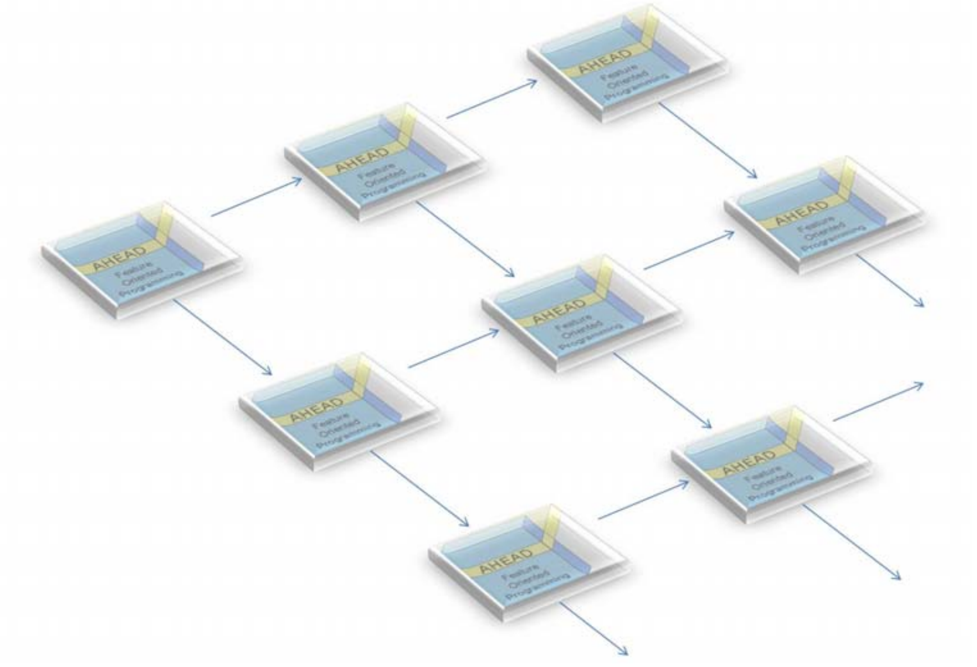
- An SPL or MDE application is an industrial–sized category

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

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

#4: Design Optimization

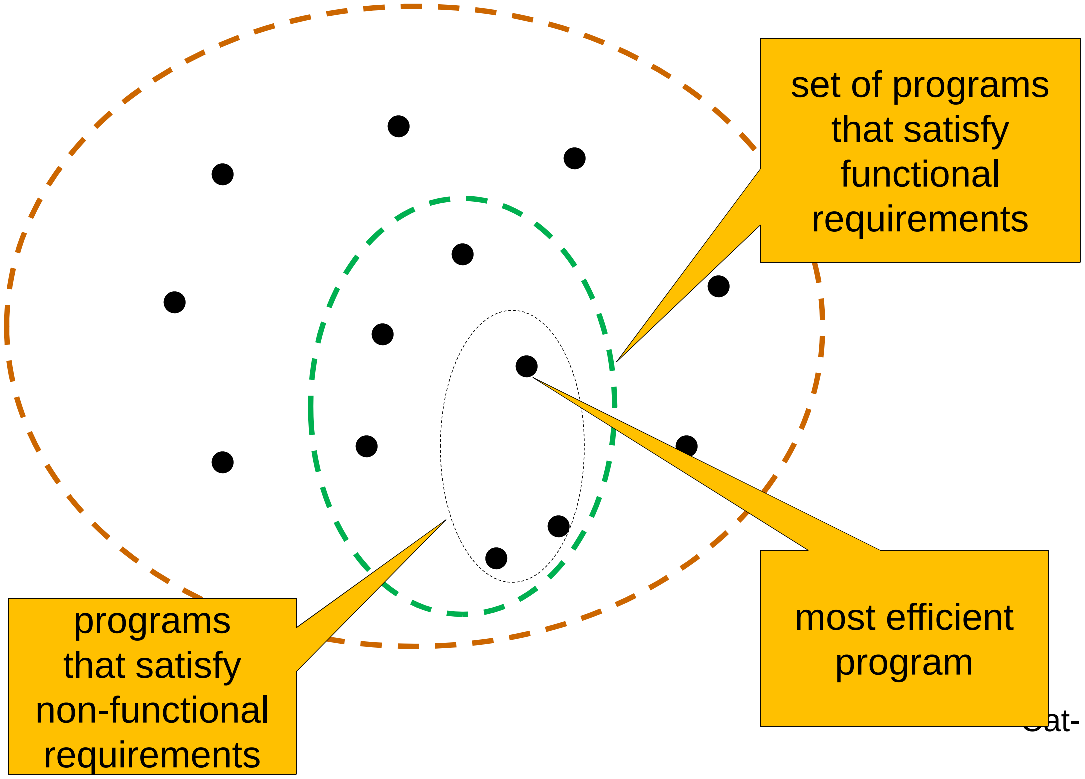
Frontier of D×T



Principles of D×T

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

paradigm of relational query optimization



set of programs that satisfy functional requirements

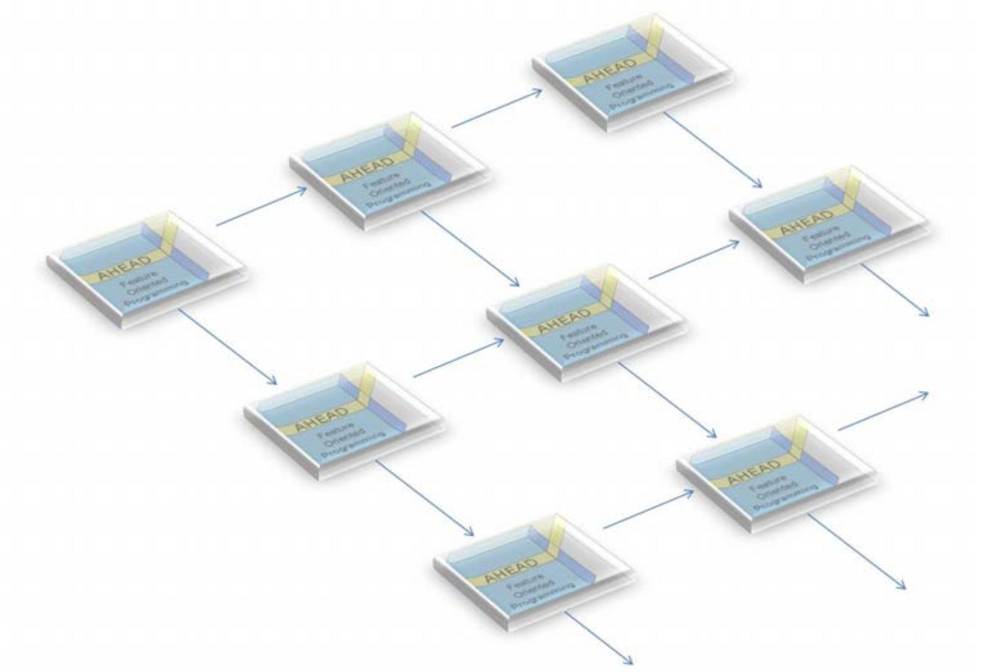
programs that satisfy non-functional requirements

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 & van de Geign's 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

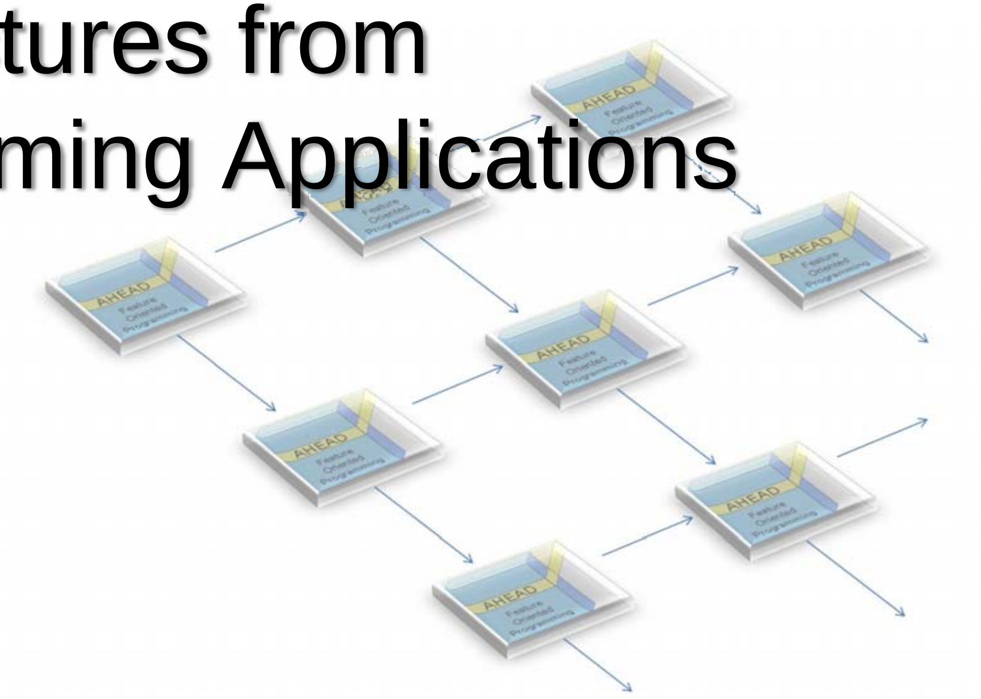
- **D×T** uses category theory
    - provides a language to express our results
    - places research results in context
    - new insight on verification, optimization issues
    - whether theorems from CT are applicable, I don’t know

Key To Success

- Educational benefit of the connection
  - common and simple language
  - offers 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 depends on domain

Look for Them!

Lecture 3:
Extraction of MDE Architectures from Parallel Streaming Applications



work with Taylor Riché

Introduction

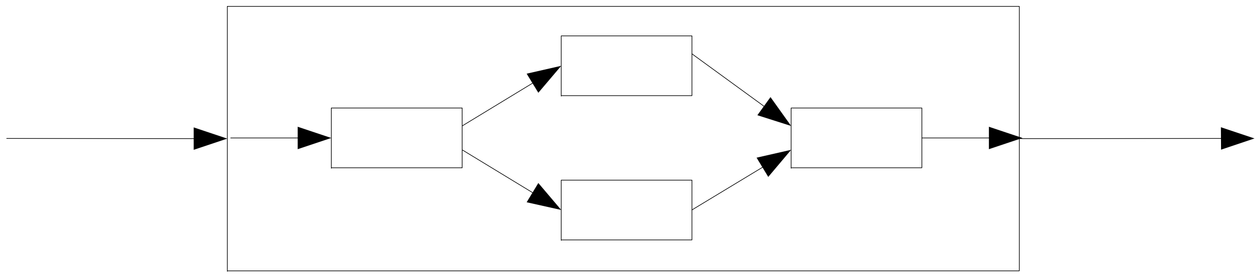
- Challenge of re-engineering complex streaming applications into a component-and-connector architecture
  - to eventually re-implement on a MDE platform

Asynchronous Crash Fault Tolerant (ACFT) servers
Classic Parallel Join of DBMS machines

- They were so complicated, we needed a way to convince ourselves and others that we understood their designs
  - we were not domain experts – not obvious how and why they worked
- We needed a structured way to explain and build our versions of these systems

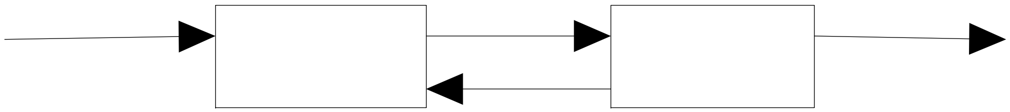
Stepwise Development (SWD)

- Classical & fundamental way to control design complexity
  - our work builds on results of a long line of pioneers (Labview 80, Gorlick 92, Broy 92, Moriconi 94, Garlan 96, Rumpe 97, Kong 03, Clarke 06, …)
  - use a standard component-connector model of application
  - elaborate it by simple transformations called **refinements**

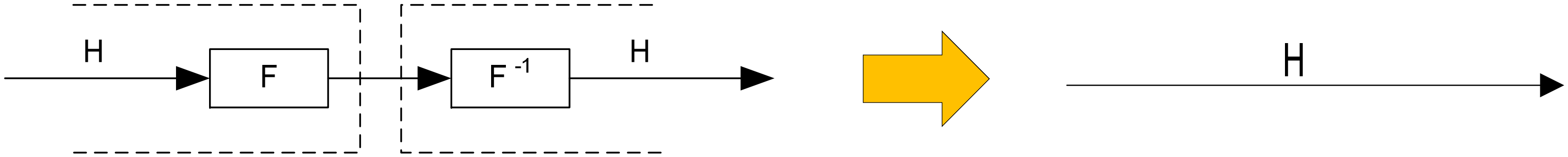


Refinement is Not Enough!

- ***Extend***: extend semantics of an application
  - adding new ports, components, connectors

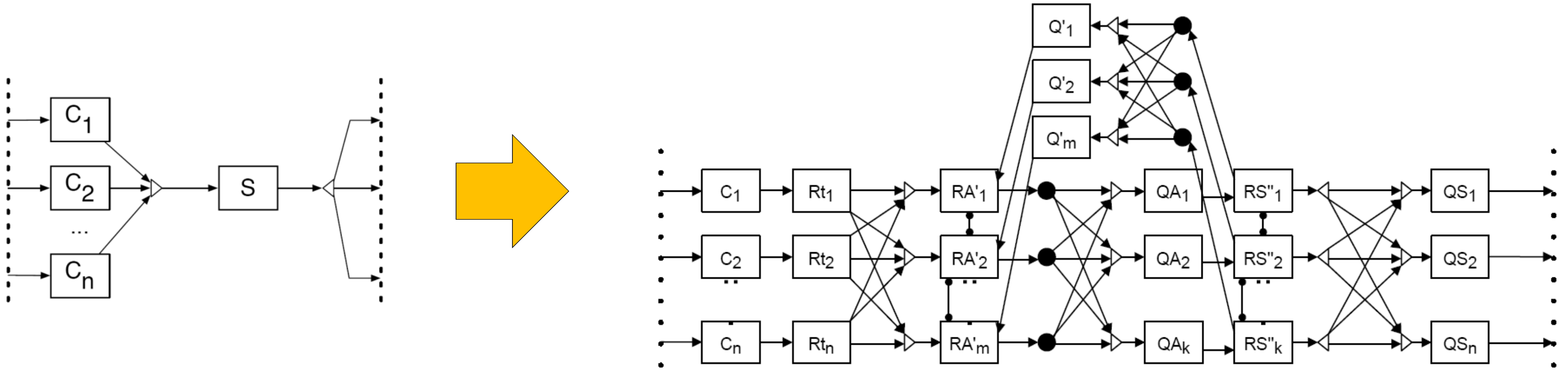


- ***Optimize***: break abstraction boundaries to achieve ***efficiency*** or ***availability***
  - domain-specific optimizations to build modern streaming applications



Re-Engineering Result

- **Model Driven Engineering (MDE) Architecture**
  - start with executable model of a sequential component-connector architecture
  - transform it by **refining**, **optimizing**, **extending** to derive an executable parallel architecture that faithfully captures decisions made by domain experts
  - result is easy-to-understand ***description*** + ***prescription*** to recreate system on an MDE platform



Perspective

- Case Studies are known for their contributions to fault-tolerance and database machines
  - designs were never conceived in terms of transformations
  - novelty of their designs can be expressed by transformations
  - why certain transformations use is part of genius of their designers
- No substitute for domain expertise
  - we use transformations to encode deep domain knowledge
  - express designs by transformations is novel to domain-experts, but the end result is rarely surprising
  - progressively revealing details is so straightforward that even non-domain experts (undergraduates) can follow along
  - although our descriptions are deceptively simple, it takes effort
  - ideal for teaching complex designs to others

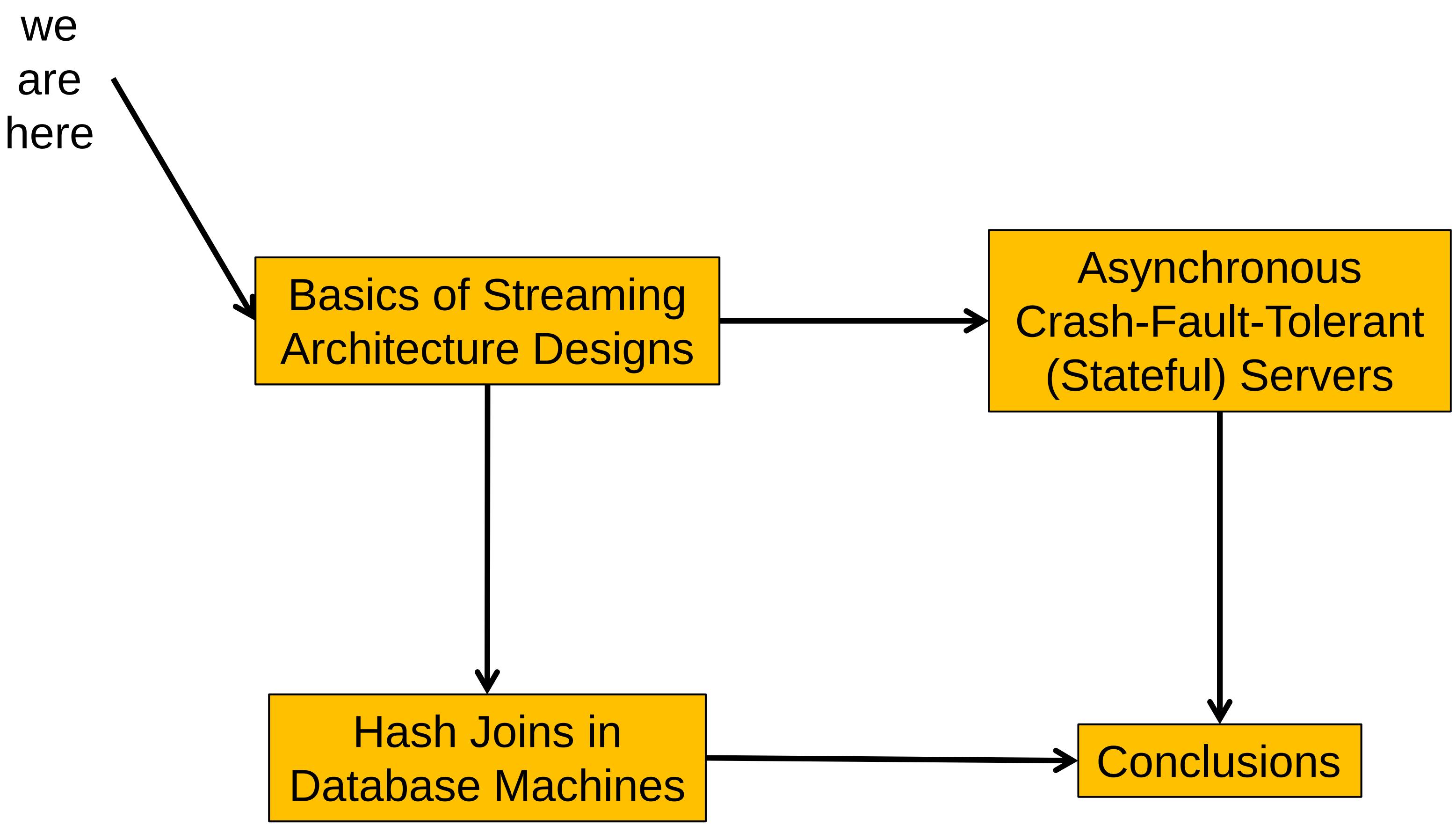
Connection to Prior Lectures

- Incremental Design = SWD
- Express designs by compositions of transformations

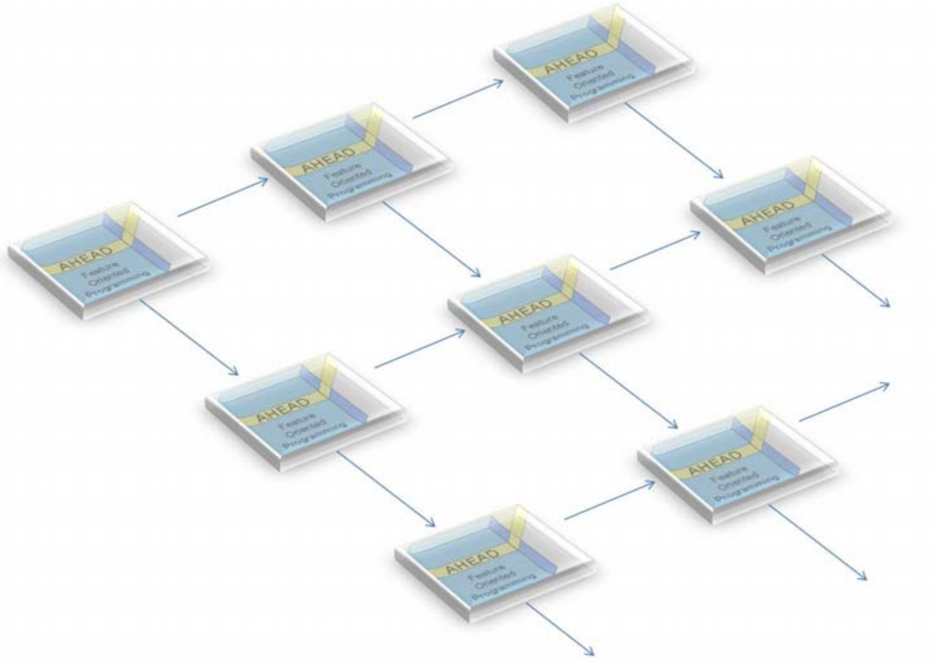
Design by Transformation

- You’ll see elements of product lines, commuting diagrams, and MDE all integrated this lecture

Series of Mini-Presentations


we
are
here
Basics of Streaming Architecture Designs
Asynchronous Crash-Fault-Tolerant (Stateful) Servers
Hash Joins in Database Machines
Conclusions

#1: Basics of Streaming Architectures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Feature Oriented Programming
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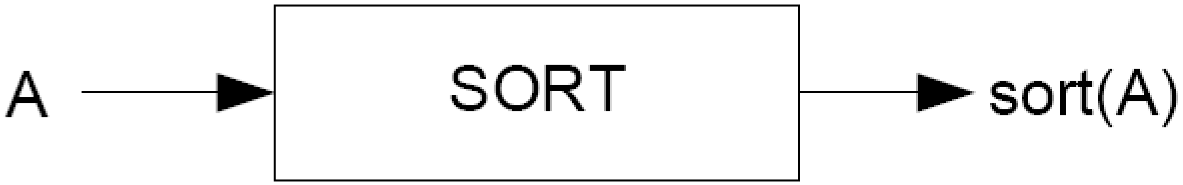
Basics

- **Component-Connector Architecture** is a directed graph
  - box component or computation
  - connector communication path for messages, tuples drawn in direction of data flow

- Semantics of box is clear from context

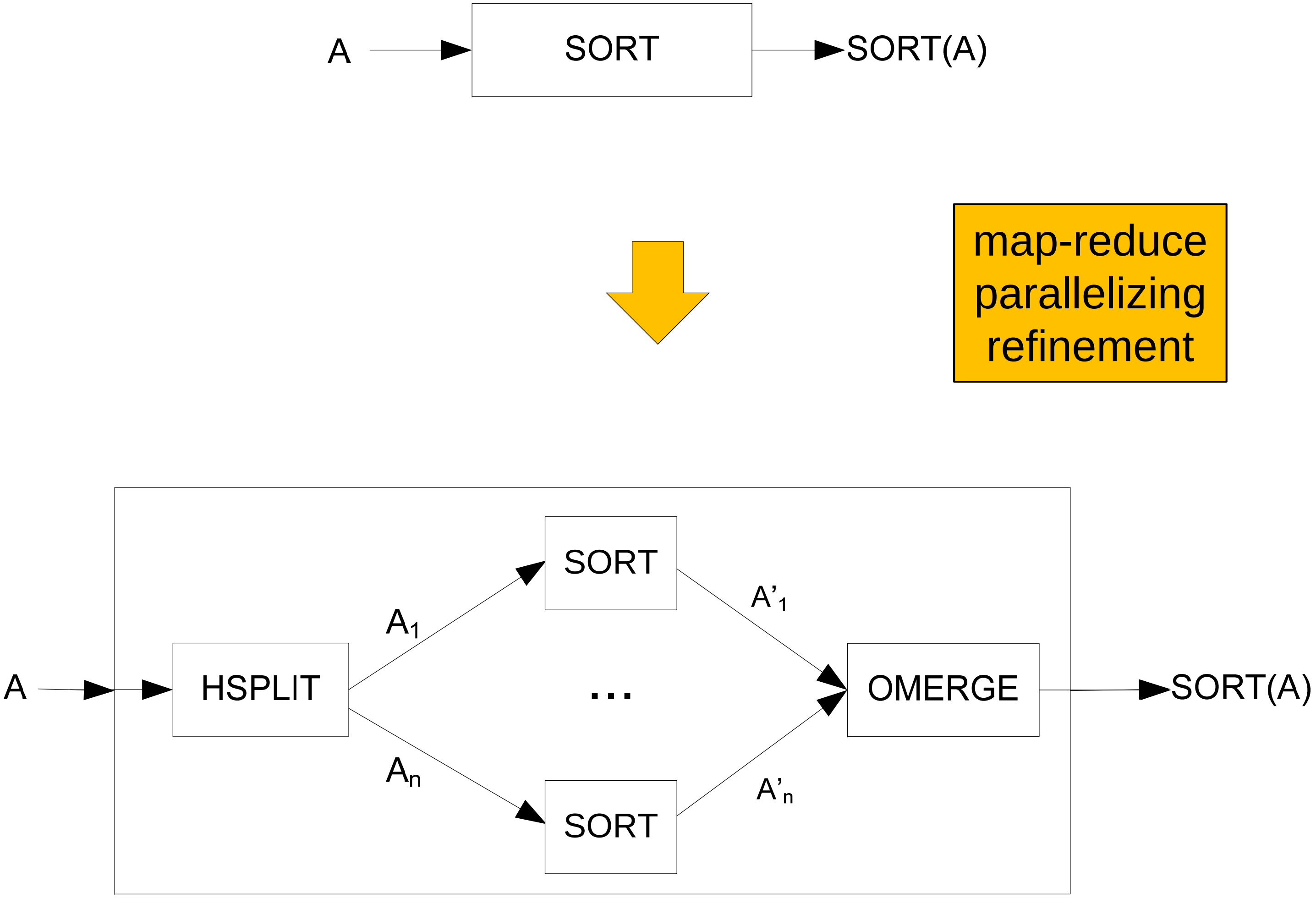


1, 50, 2, 62, 53

1, 2, 50, 53, 62

- Elide unnecessary details (sort key, sort order, sort type)

Refinement



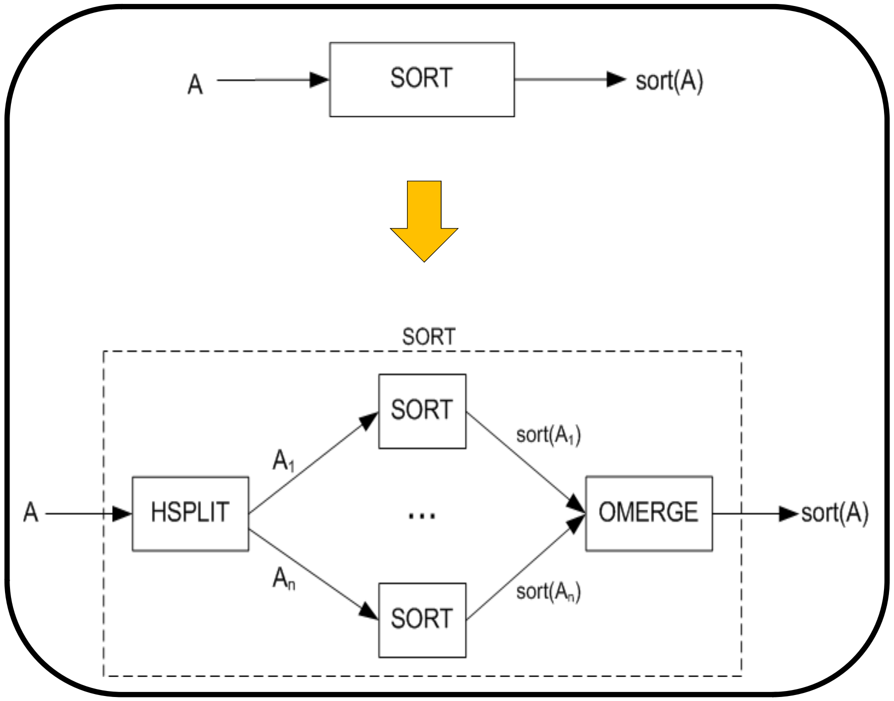
map-reduce parallelizing refinement

Transformations

- Refinement is a **transformation**
    - input pattern → output pattern

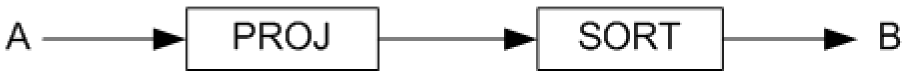
- All **transformations** or compositions of xforms in this talk have been proven correct
    - simple enough that intuition suffices
    - sometimes need Ph.D.

- **Correct by Construction**

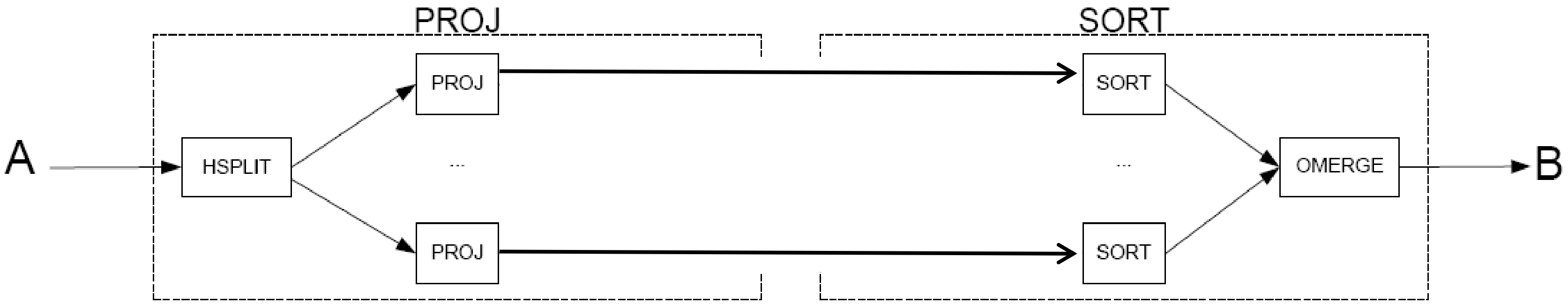


Optimizations

- Break encapsulations to achieve non-functional properties
  - efficiency or availability

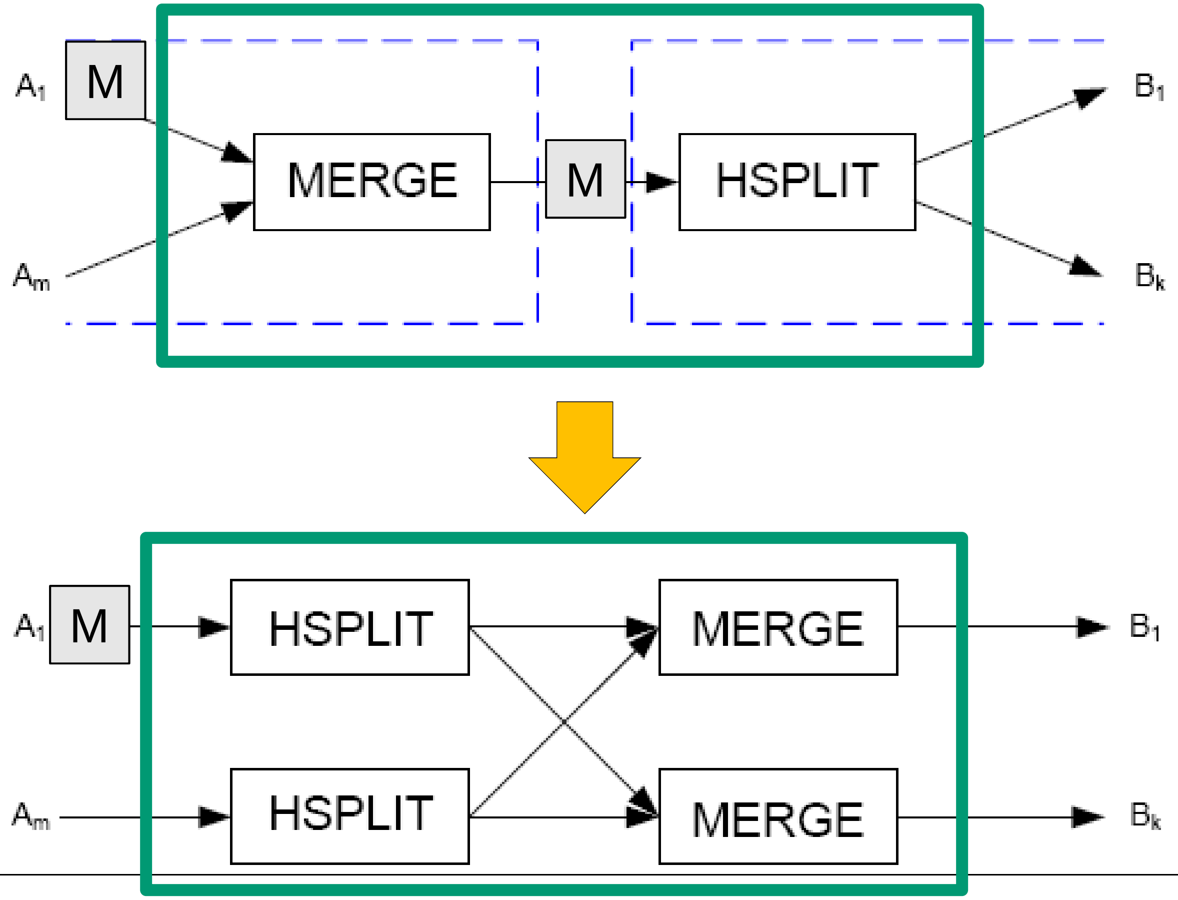


Same HSPLIT box (hash same attributes, same hash function)



Rotations

- Optimizations that reorder *stateless* computations
  - ex: property that each A_i message is assigned to a single B_j stream

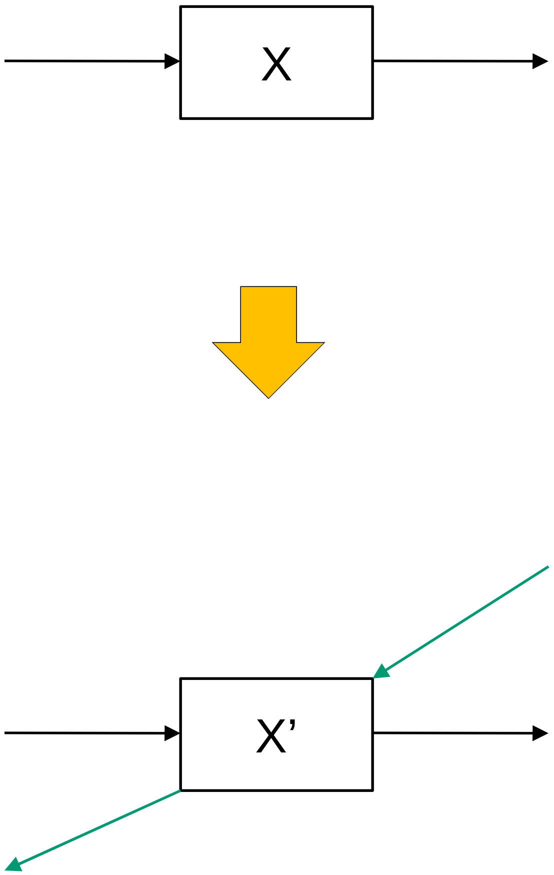


m streams are merged

k streams are produced

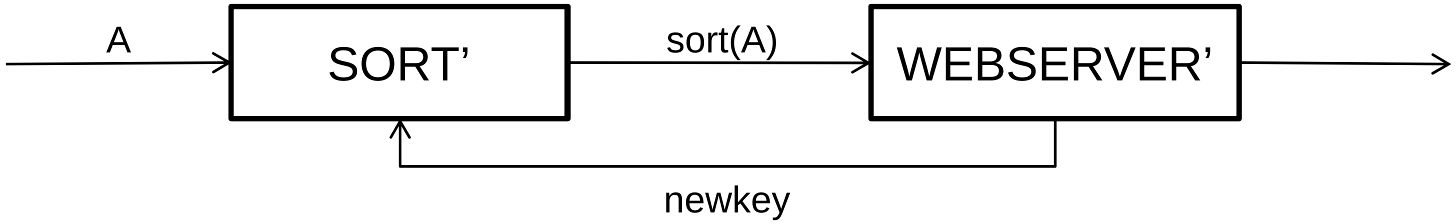
Box Extensions

- Extend the capabilities (semantics) of a box
- Extensions add “features”
- Accomplished by preprocessors #ifdef inclusion of extra code
- Or by more sophisticated means



Model Extensions

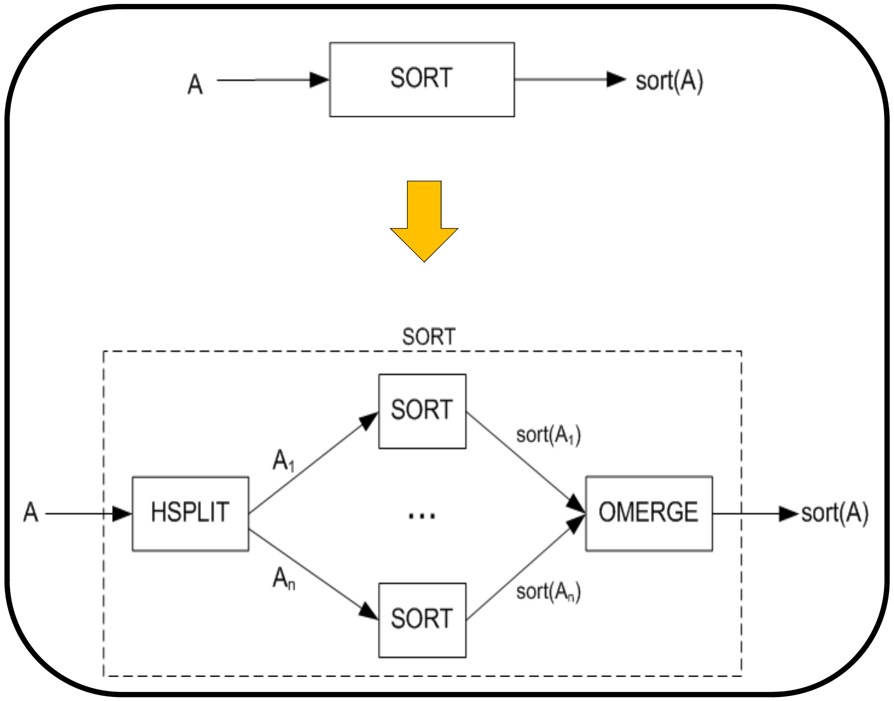
- Example: Webserver takes sorted tuples and creates a web page of sorted results



- Extend Webserver & Sort with new ports and add a feedback data flow called newkey which changes the key that sort uses
  - switching from artist names to album titles
  - switching from last names to SS#

Always Executable

- User supplies boxes and tests for boxes
- Can reuse tests for boxes after refinement
  - logically cannot distinguish input-output response of a single SORT box from its parallel counterpart
- Similar arguments for extensions and optimizations

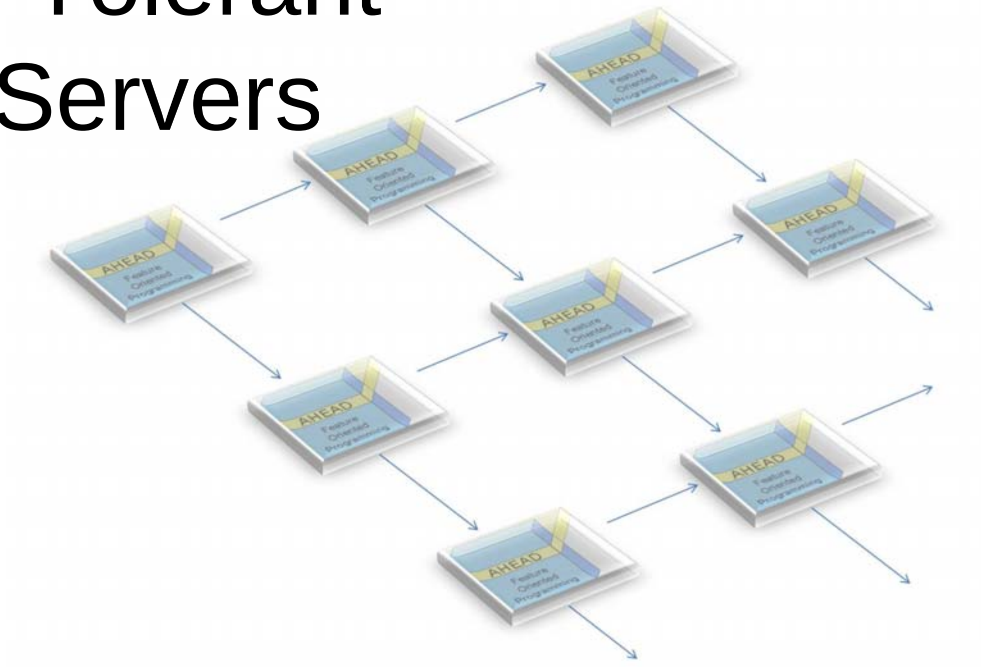


Recap

- Component-connector architecture is implementation model
  - transformations progressively elaborate models
    by refinement, extension, or optimization
  - result is always executable

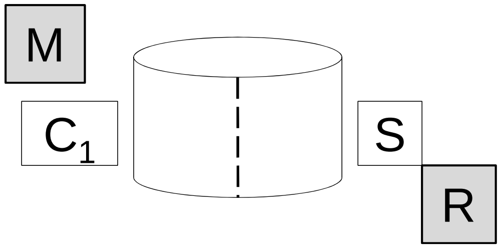
- Now, let look at some examples…

#2: Asynchronous Crash-Fault-Tolerant (Stateful) Servers



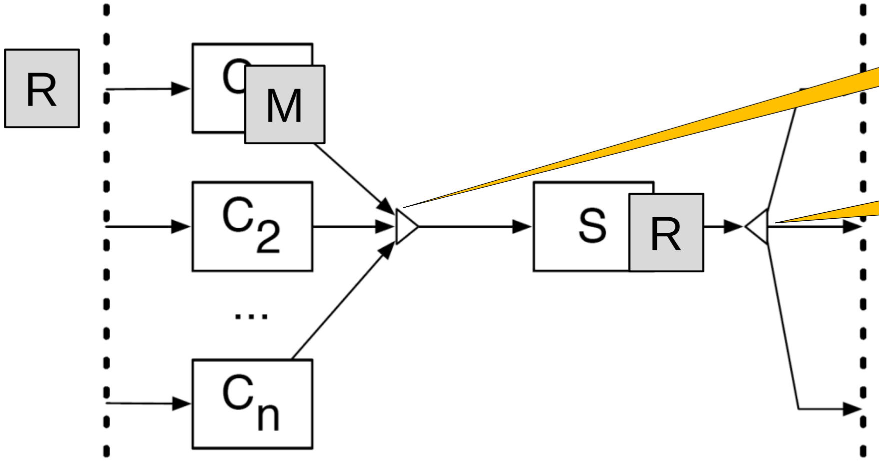
Overview

- Sequential server architecture has a cylinder topology



assume server updates state

- Unroll cylinder by breaking along the seam



serializer

demultiplexor

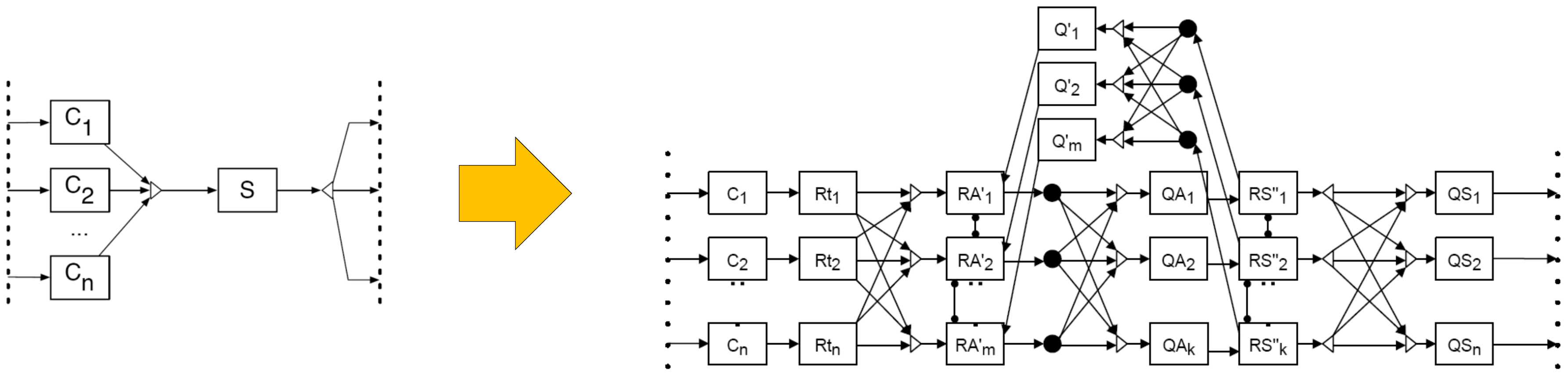
broadcast

Our Goal

- Transform a (stateful) server that works in the ideal world of synchronous networks and no box failures to an

Asynchronous, Crash-Fault-Tolerant (stateful) Server

- consider Synchronous CFT transformations first
- Asynchronous (recovery) transformations last



Basics on Crash-Fault-Tolerance

- Ability of a server to survive a number of failures

- **Failure** – when a box stops processing messages
  - no messages pass through a failed box
  - a failed box cannot create new messages
  - *assume each box executes on its own machine*
    - multiple boxes can run on single machine
    - if machine fails, all boxes on that machine fail
    - failures do not propagate across machine boundaries

Standard Failure Assumptions

- Failures of network components

serializer	(◀)
demultiplexor	(▶)
reliable broadcast	(•)

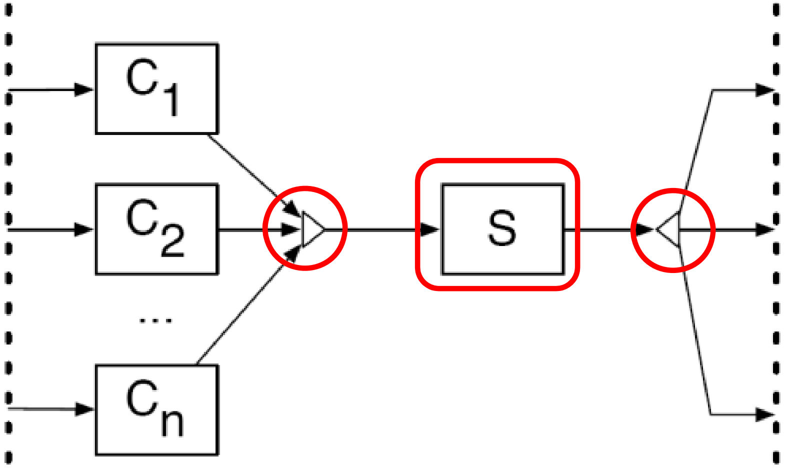
affect a machine the same as pure software boxes

- ex: a machine can't process requests if its network card stops working

- Ultimately we not depend on synchronous networks
  - do expect eventual synchrony
  - use **retransmissions** (in application, network protocol, or both) to deal with transient packet loss
- Requests are benign; BFT removes these assumptions

Technical Goal of CFT

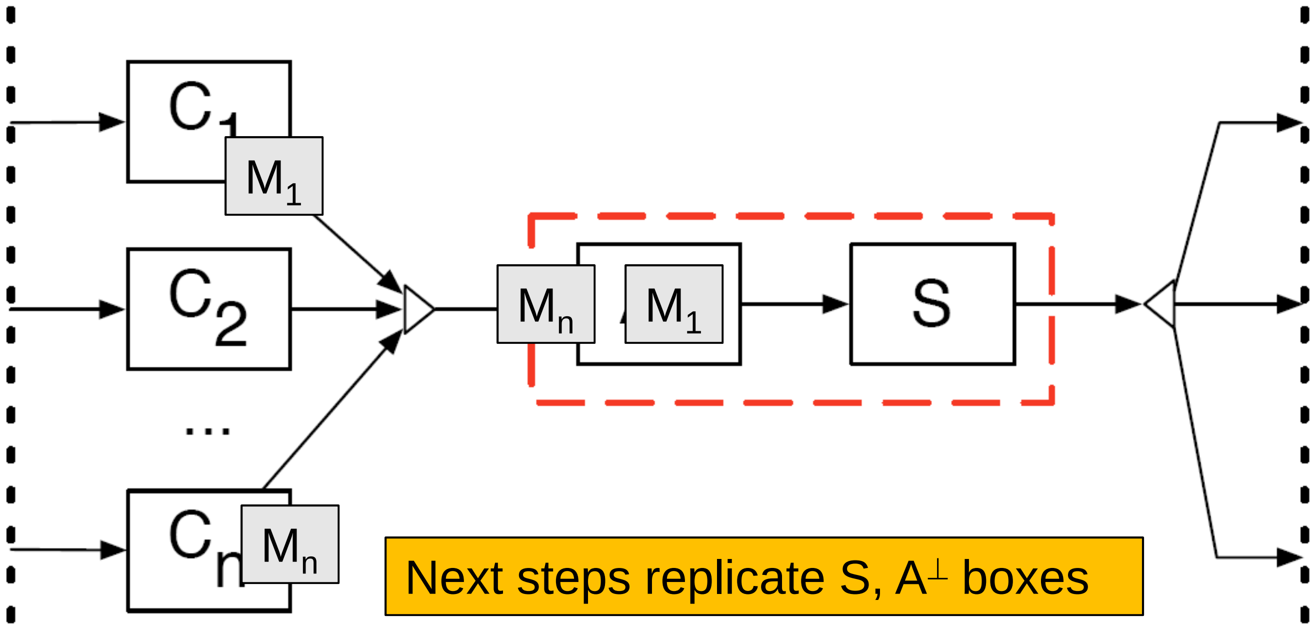
- Eliminate **Single Points of Failure (SPoF)**
  - a failure of a single box (machine) causing the server abstraction to fail
  - our current design has 3 SPoFs



- “Solve” problem by replicating boxes
  - not only solution – we follow most advanced solution to date
  - appeared in SOSP 2009

Step 1: Agreement

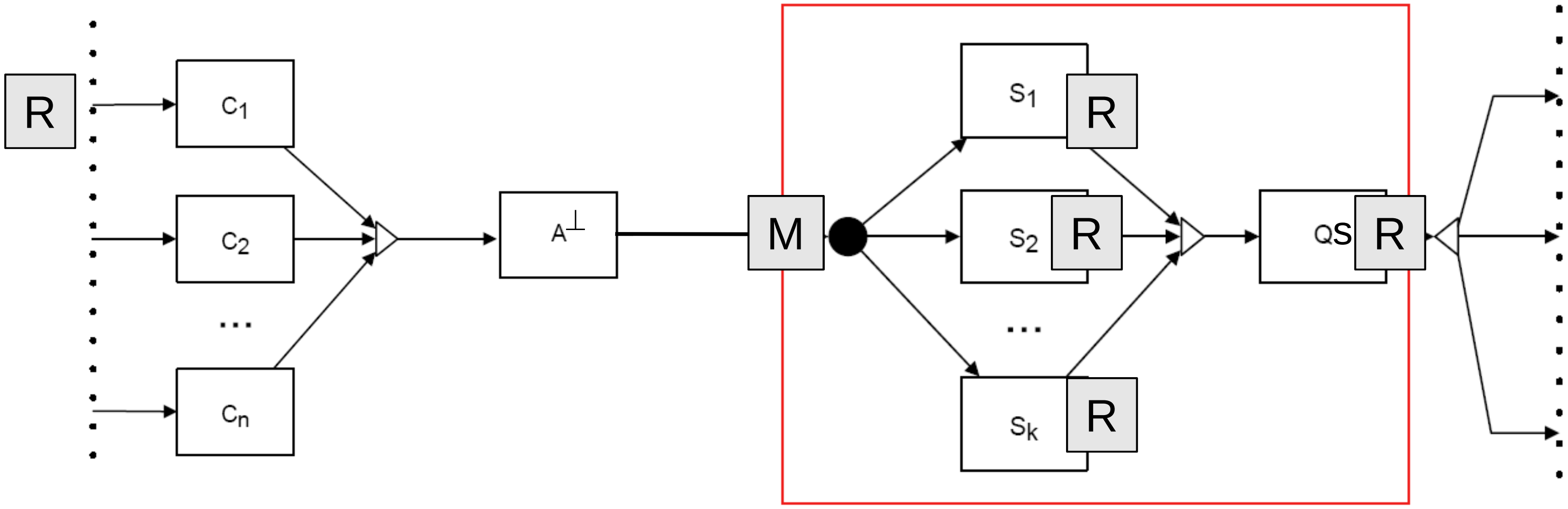
- Add an agreement node $A^{\perp}$
- $A^{\perp}$ materializes implicit network message queue, passing messages one at a time to the server
- In effect, $A^{\perp}$ does nothing it is a place holder for later refinements



Next steps replicate S, $A^{\perp}$ boxes

Step 2a: Replicate Servers

- Make k copies of server
- Each server receives exactly the same sequence of messages from the A⊥ abstraction
- QS collects a quorum of identical messages;
  transmits message when a sufficient number of copies are received
- *Refinement emulates abstraction of a single correct server*



Why are *k* Server Replicas Needed?

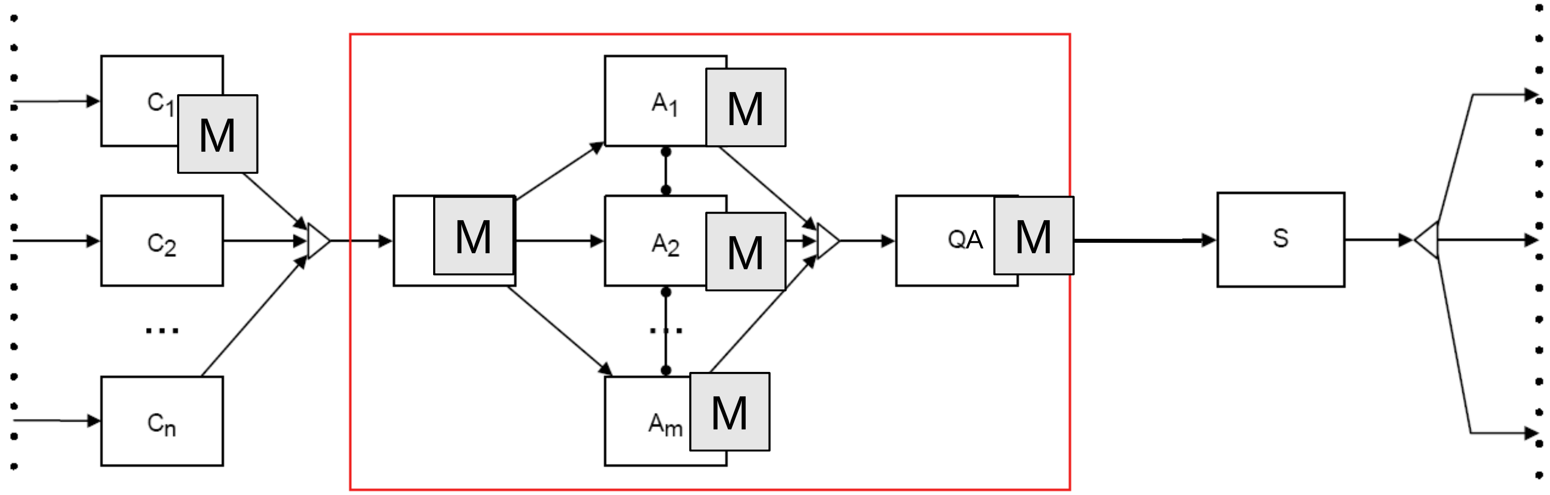
- To tolerate failures of server boxes

  tolerate *f* failures, k = f + 1

- See: *J. Yin, J-P. Martin, A. Venkataramani, L. Alvisi, and M. Dahlin. “Separating Agreement from Execution for Byzantine Fault Tolerant Services”, SOSP 2003.*

Step 2b: Replicate A$^\perp$ Boxes

- Make m copies of A$^\perp$
- Client requests are routed by box Rt to *some or all* A replicas
- A replicas run an **agreement protocol** (Lamport 1998) to decide which is the next client message to process
- A replicas vote and a quorum is taken by QA; when a sufficient number of identical messages is received, QA forwards a single message
- *Refinement emulates abstraction of a single queue*



Why *m* Replicas of A are Needed?

- Ans#1: tolerate failures of A boxes

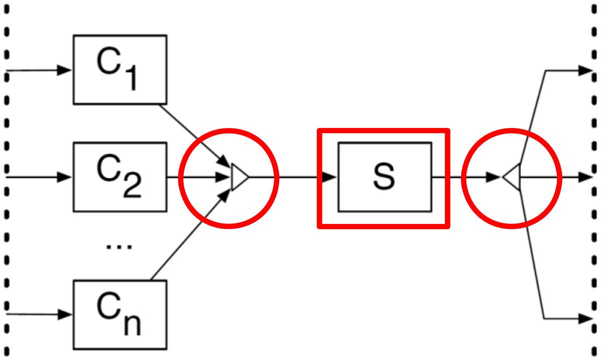
  tolerate *f* failures, need *m = 2f+1*

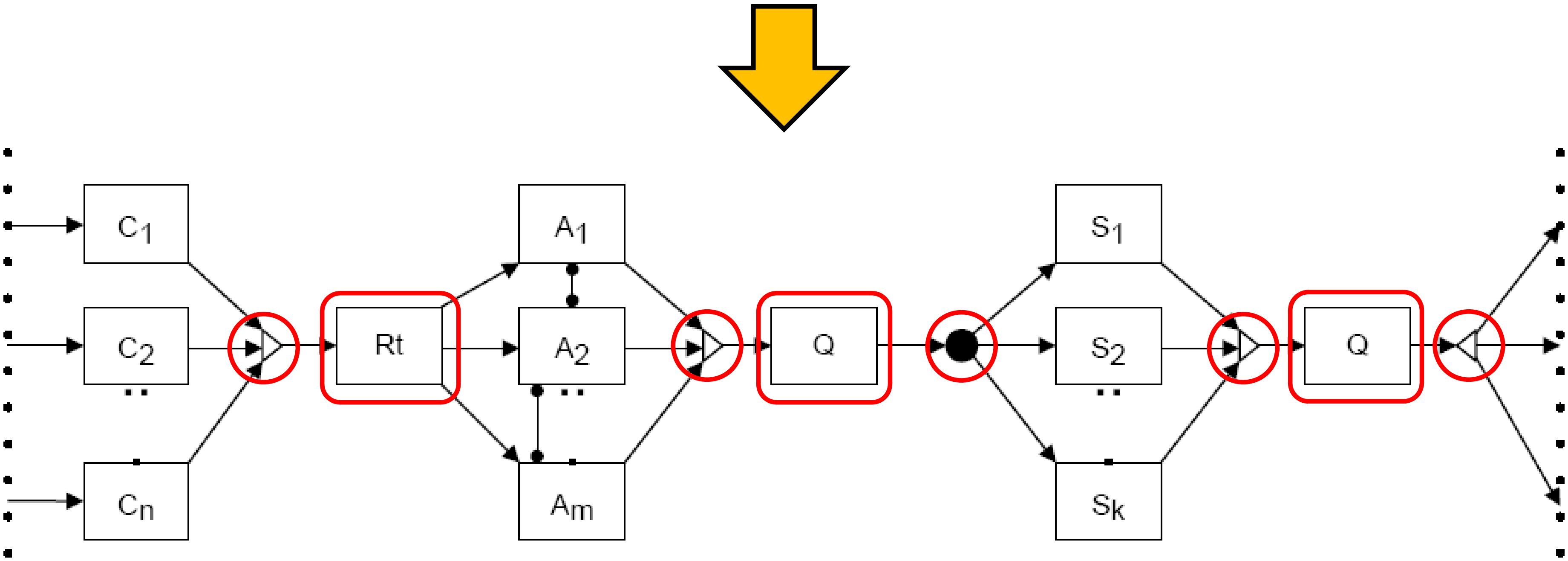
- Ans#2: a consistent order of requests is essential for correct server behavior

- If S replicas processed client requests in different orders, server replica states would diverge and responses from different servers for a single client request would be inconsistent

- Inconsistencies violate the one-correct-server abstraction

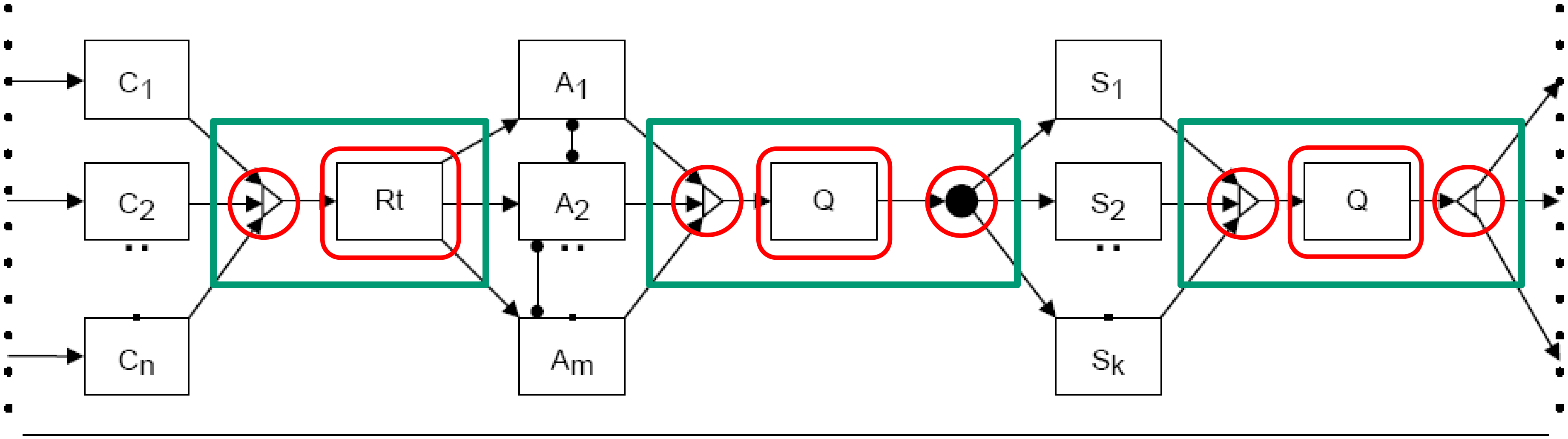
Where We Are…





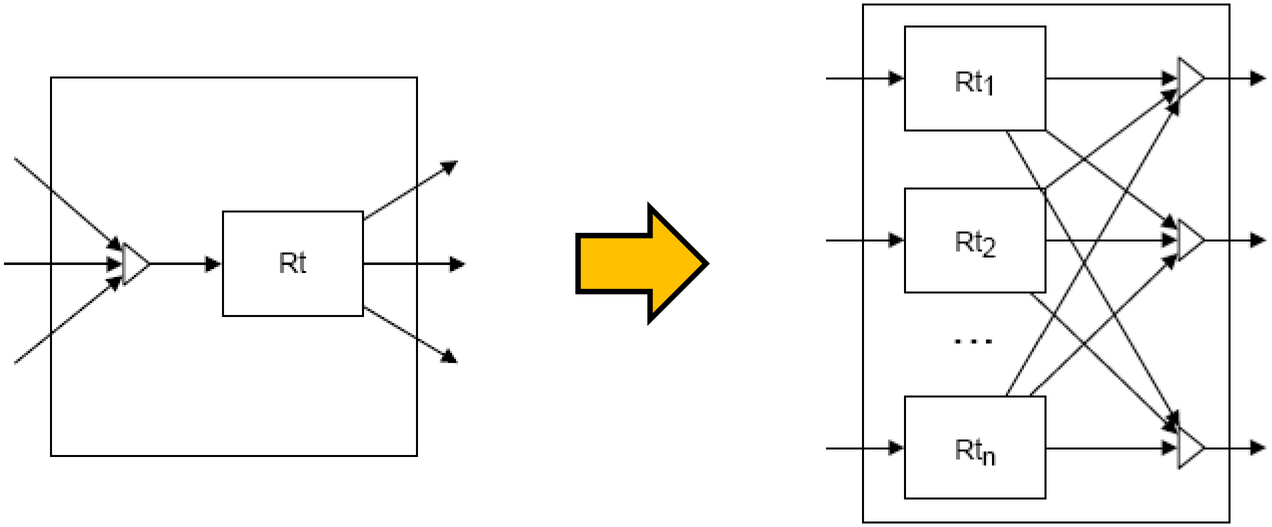
Where We Are Going

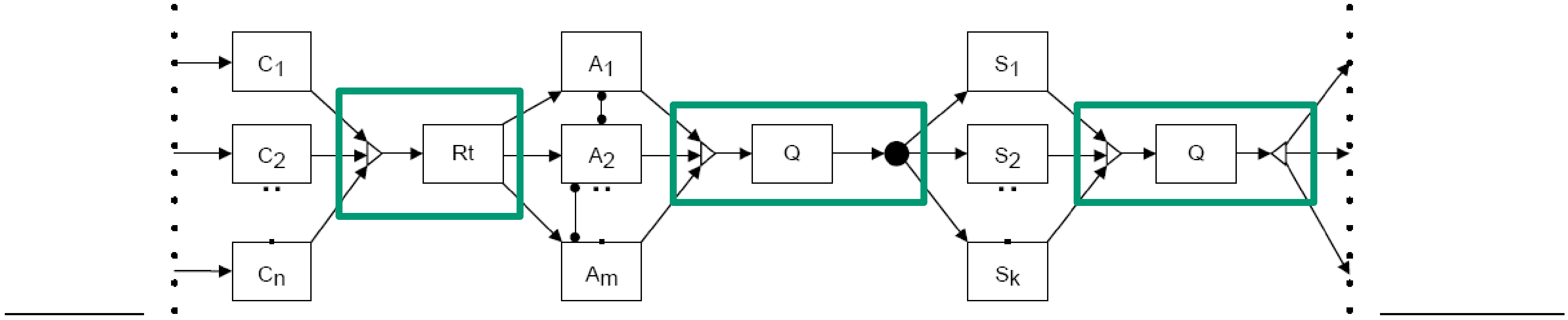
- Dissolve existing module boundaries
- Define new (green) abstractions
- Apply rotations to eliminate SPoFs



Step 3a: (▶,Rt) Rotation

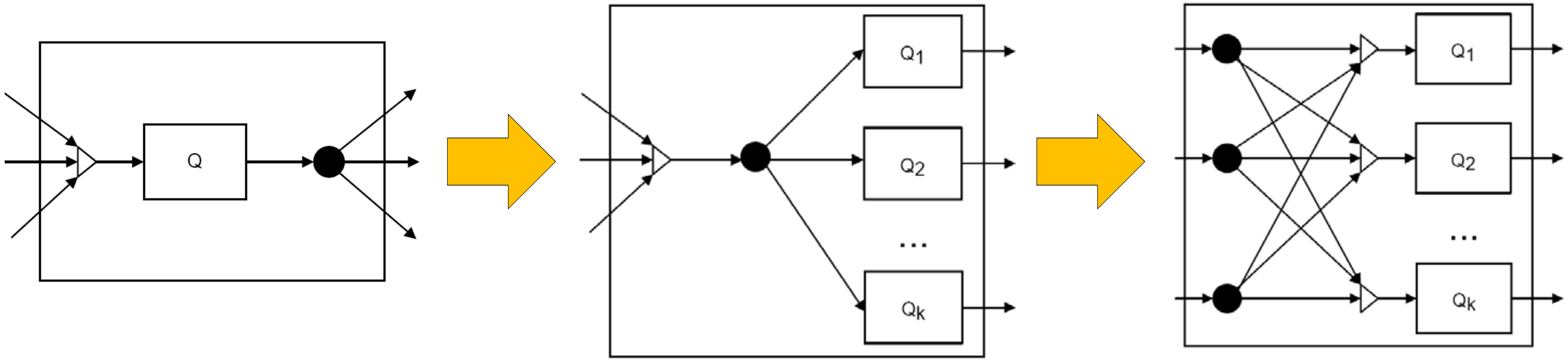
- Each client request is sent to a subset of A replicas

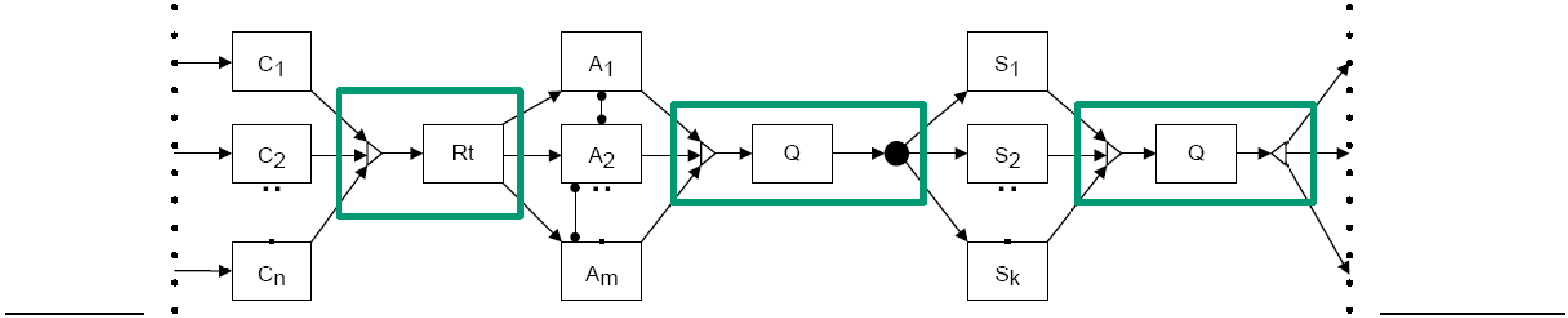




Step 3b: (▶, Q, •) Rotation

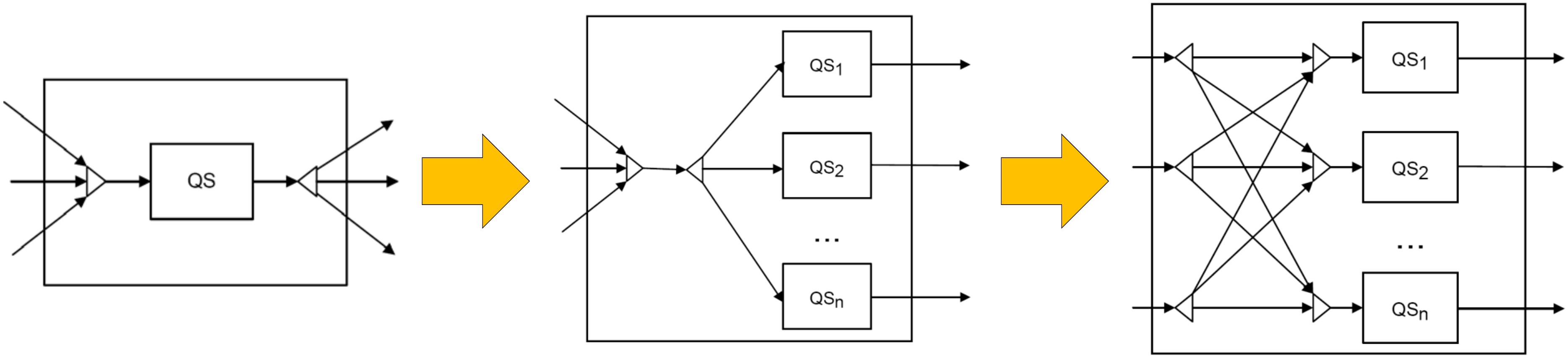
- Each quorum-decided request from replicated A boxes is delivered to all Server replicas

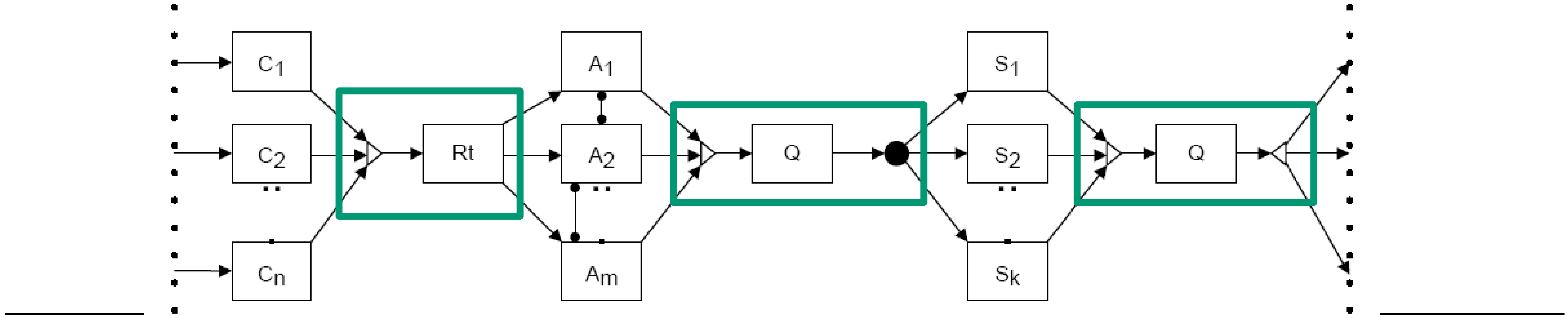




Step 3c: (▶, QS, ◀) Rotation

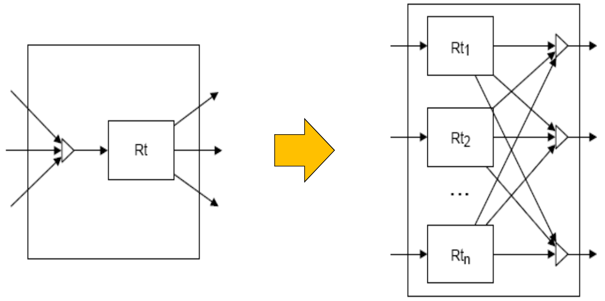
- Each quorum-decided response from replicated S boxes is received by a client box

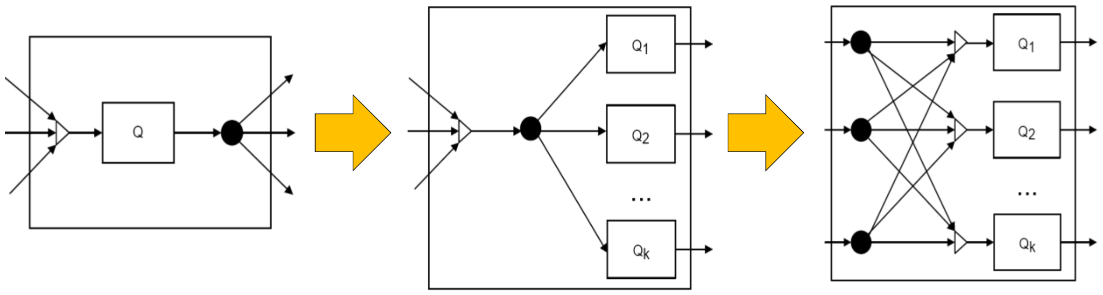


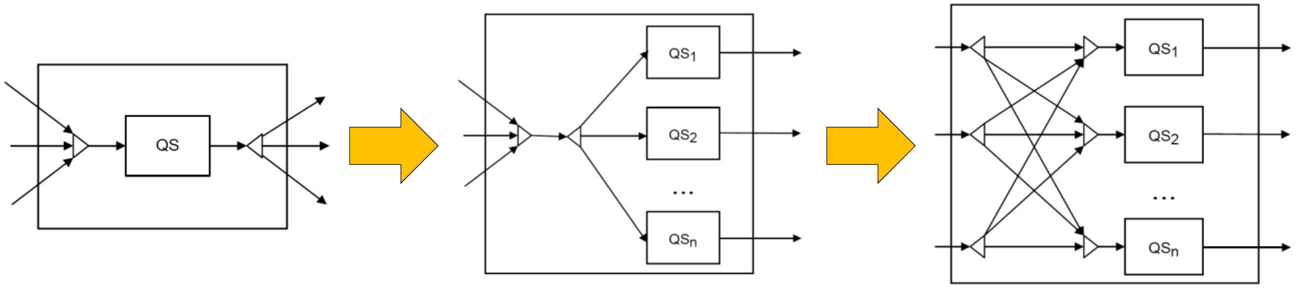


Why So Simple?

- All rotations involve stateless computations
  - state would require a heavy-weight solution (agreements, etc.)

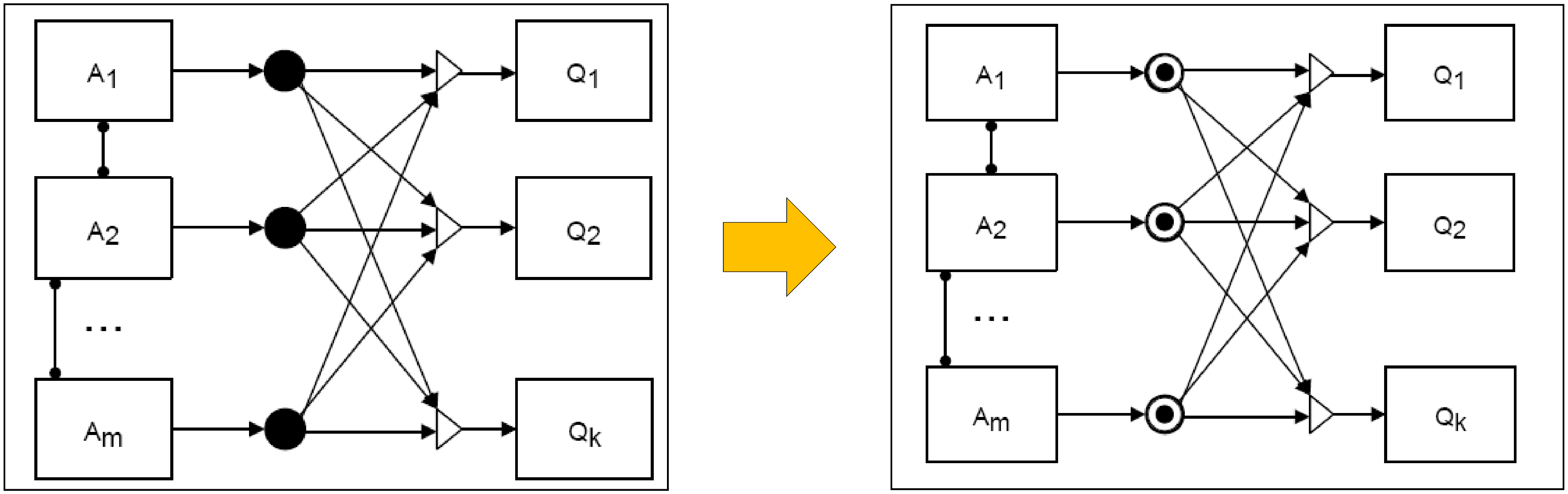






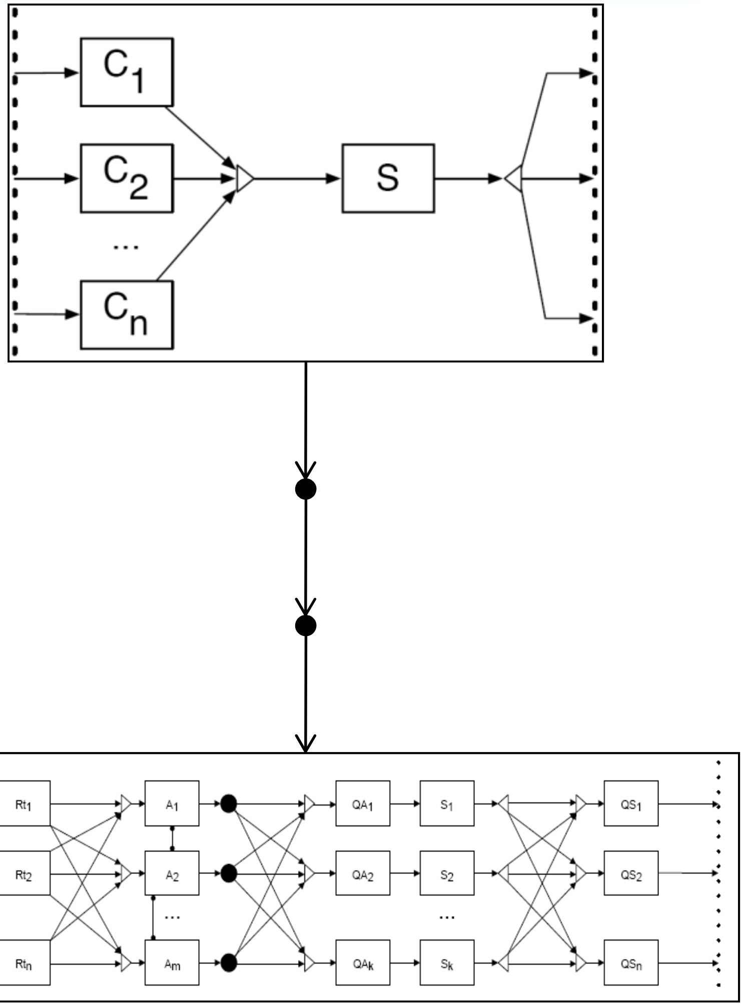
One More Optimization

- Reliable broadcast is very expensive
- Under the right conditions (e.g., quorums) reliable broadcast (●) can be replaced with unreliable broadcast (⦿) which is easy to implement



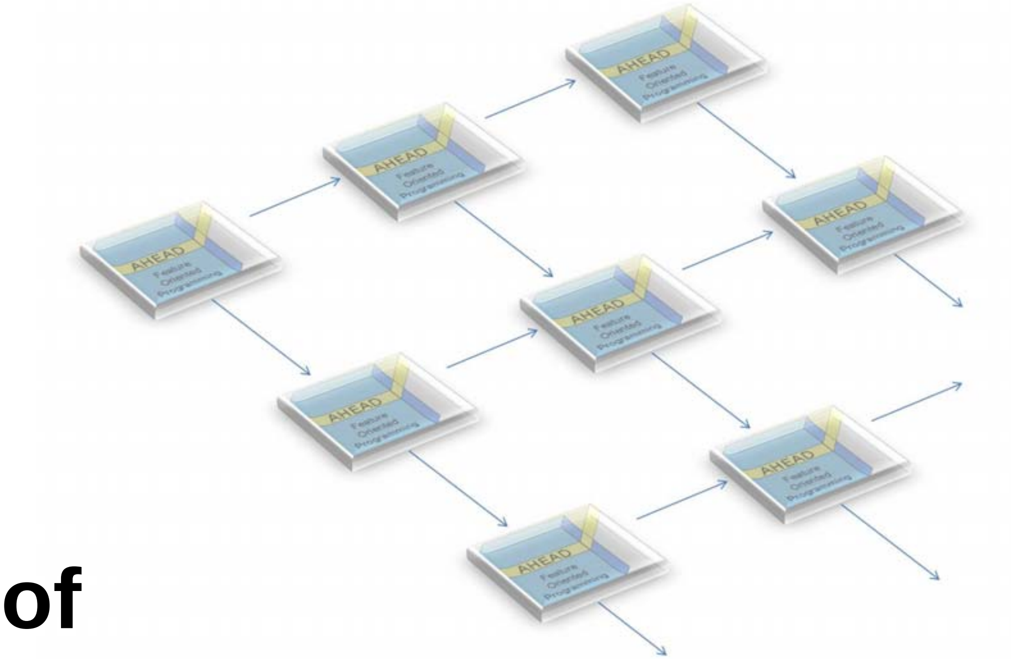
standard way to implement an efficient, reliable crossbar

Final Synchronized CFT Result



No SPoF

SCFT

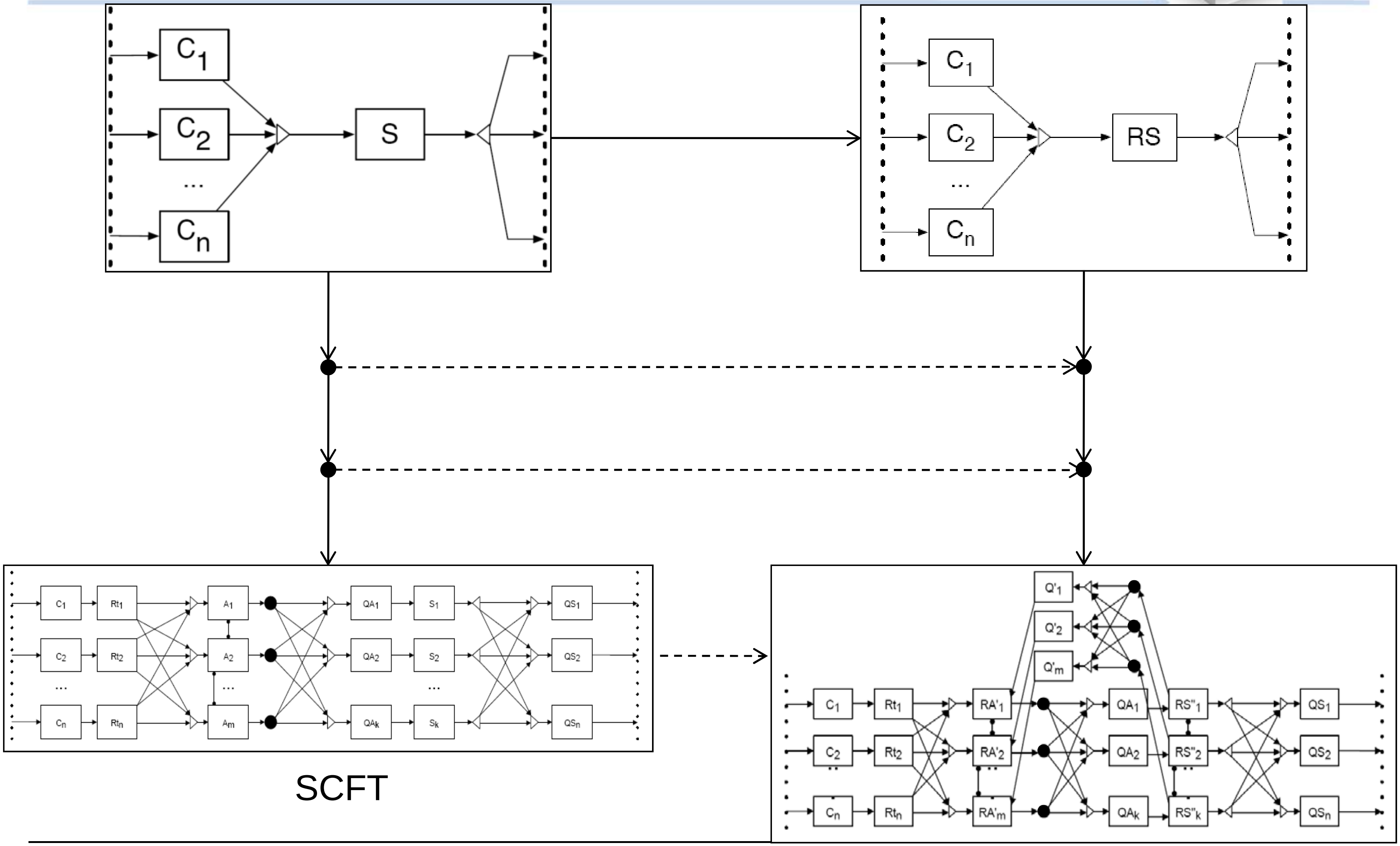


Really Quick Tour of
Recovery (Async) Transformations

Overview

- Just as databases can recover from machine failures, so too can servers
- Recovery limits the situations where clients see unresponsive server abstraction

Where We Are…

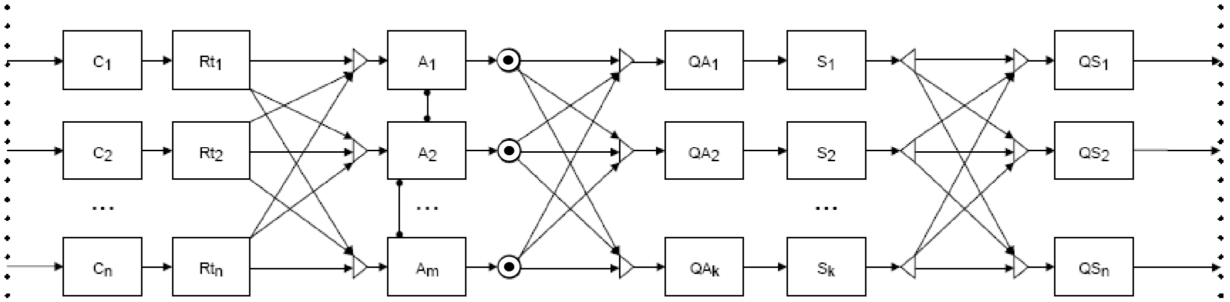


SCFT

ACFT

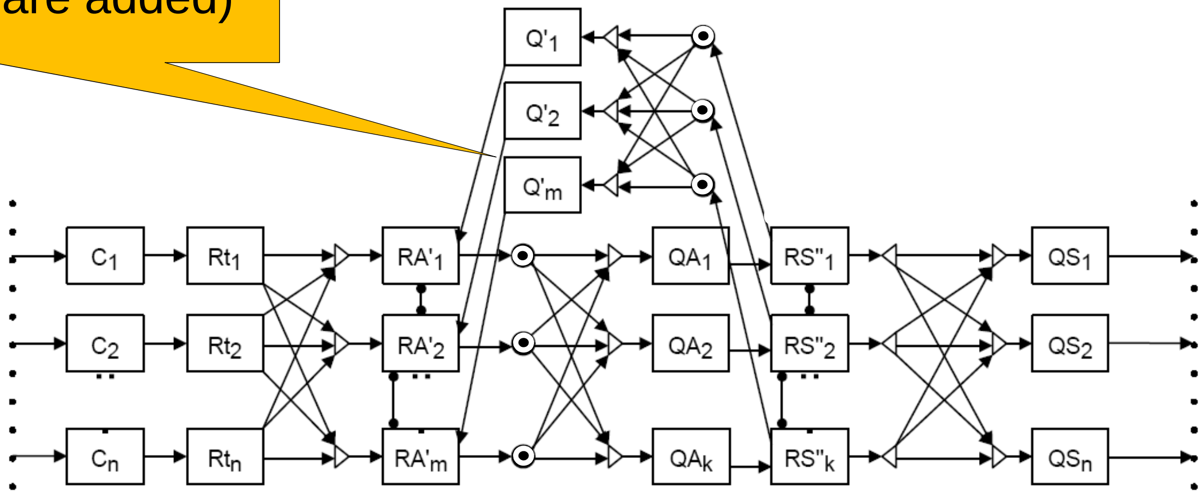
Extension of SCFT to ACFT

SCFT
Server
Architecture



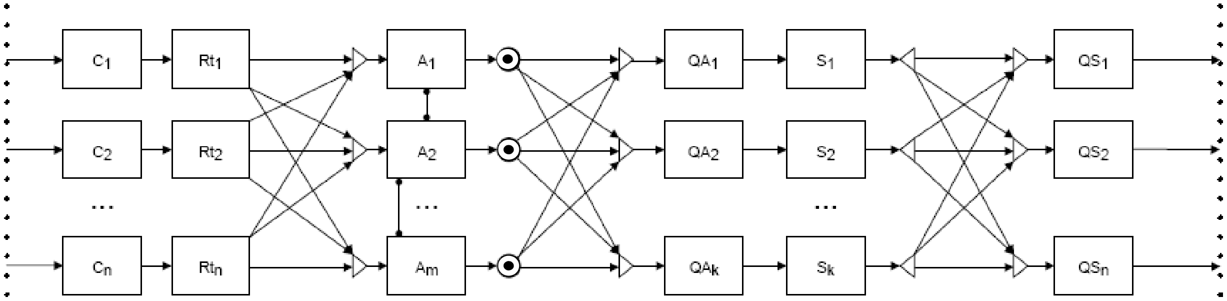
Servers now talk to A boxes
(new connectors are added)

ACFT
Server
Architecture



Extension of SCFT to ACFT

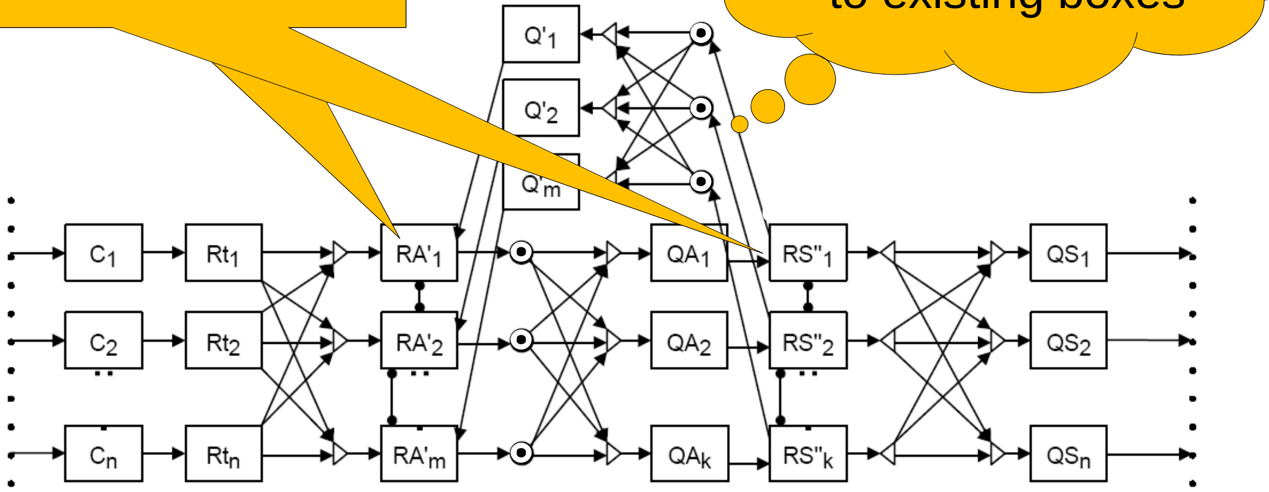
SCFT
Server
Architecture



A and S boxes are extended
(new ports, capabilities added)

incrementally
adding features
to existing boxes

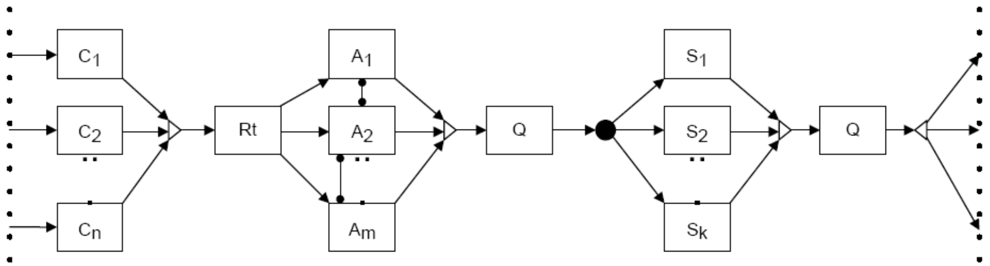
ACFT
Server
Architecture



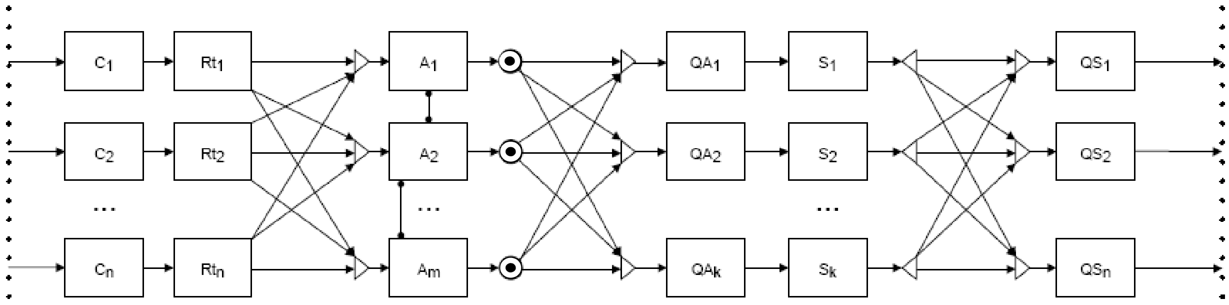
Perspectives

- Rotations were unfamiliar to our domain experts

- Their informal designs jumped directly from



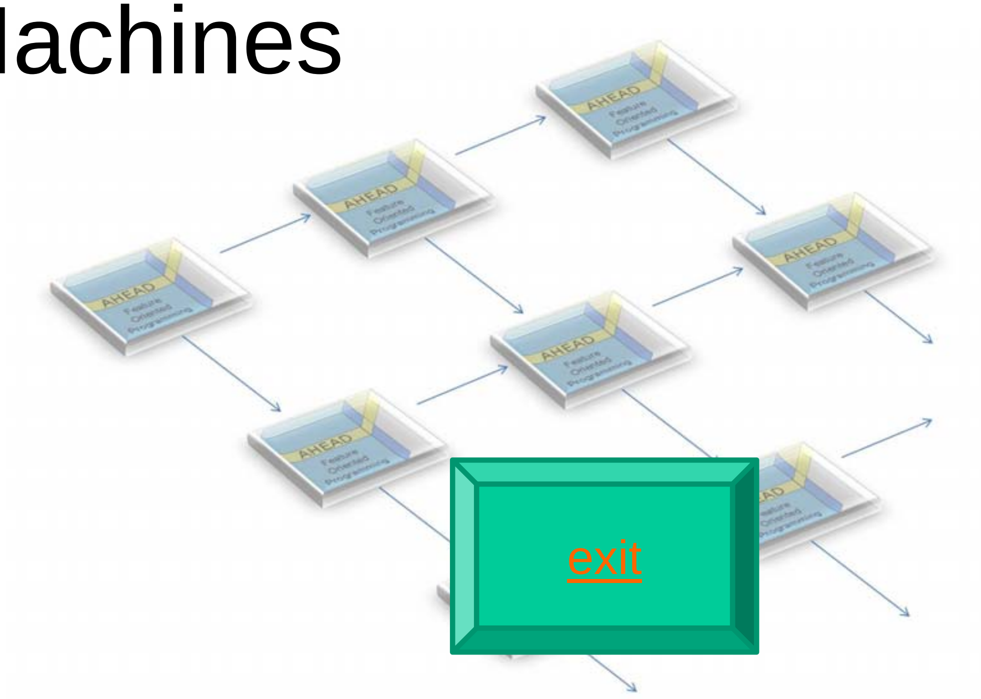
to the one using a reliable crossbar which we derived



Quick Recap

- Incrementally recovered a design created by experts to map a vanilla server to an asynchronous (recoverable), crash-fault-tolerant server
  - starting from a simple client-server model and progressively transforming it into the target architecture
- *LOTS of engineering left*
  - but now we have the architectural plans to recreate it incrementally and in a way that is easy to understand
- Now look at a very different domain where a sequential architecture is mapped to a parallel architecture using *exactly the same principles*

#3: Parallelizing Hash Joins in Database Machines

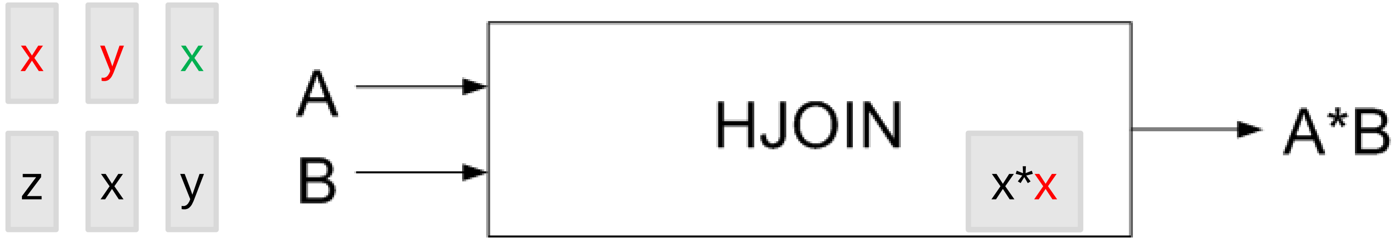


exit

Gamma Database Machine

- Gamma was (maybe still is) the most sophisticated relational database machine ever built in academics
    - University of Wisconsin late 1980’s early 1990s
- Look at how hash joins were parallelized
    - fundamental result in parallelizing joins
    - representative of commercial systems today
    - presented in a new way
    - derive Gamma hash join architecture from first principles

Sequential Hash Join Architecture

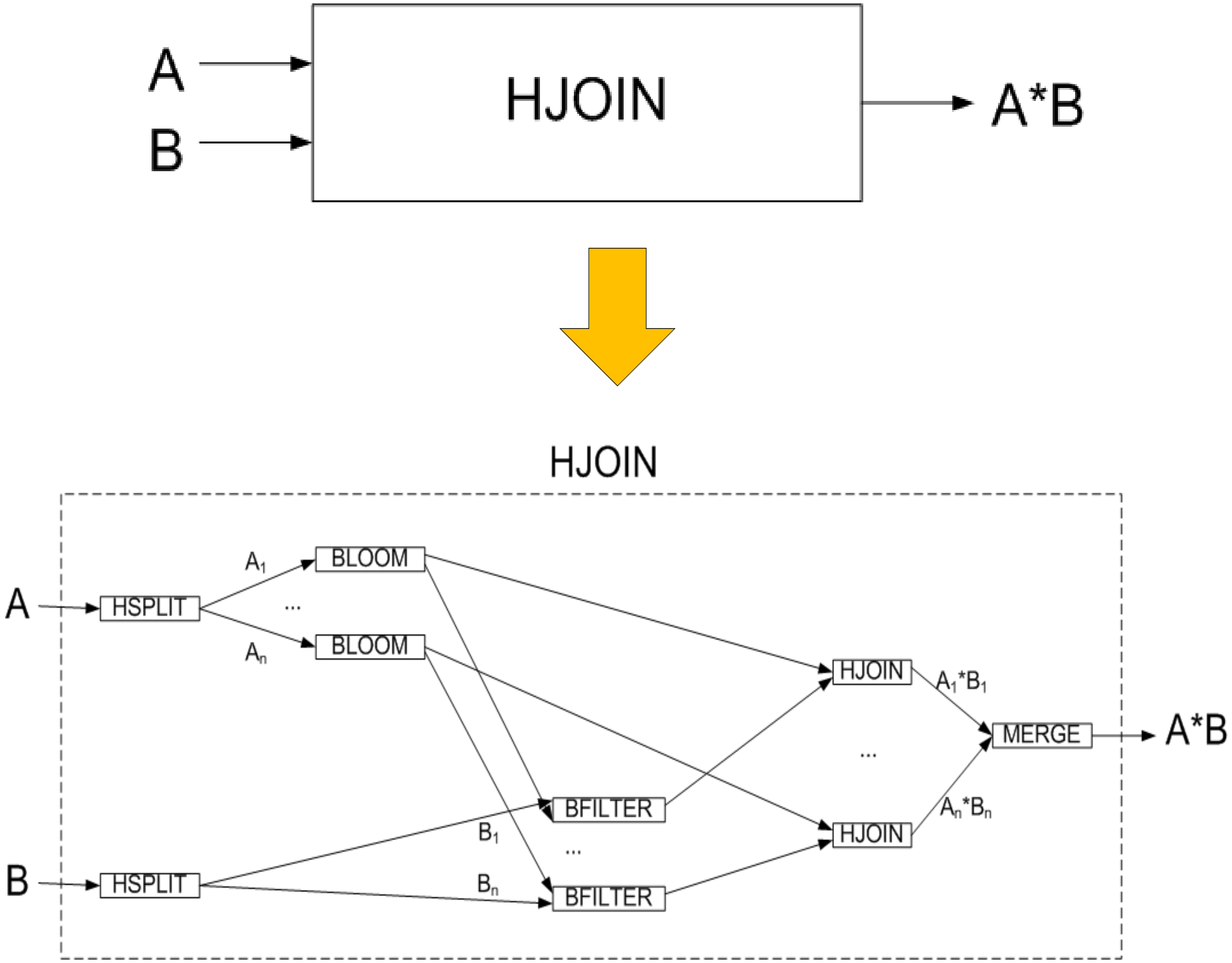


- Hash join takes 2 streams of tuples (A,B) as input and produces the join of these streams (A*B)

- Algorithm:
  - read all of stream A into memory in a hash table
  - read B stream one record at a time;
    hash B's record and join it to all A record's with the same key
  - linear algorithm

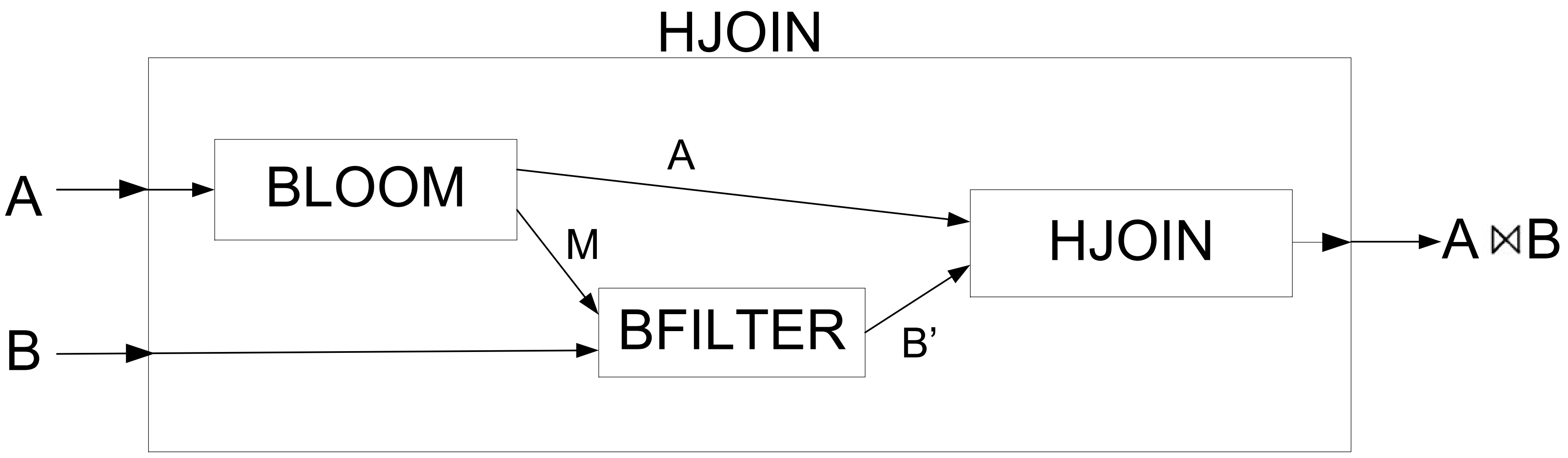
- *How did Gamma's Designers parallelize HJOIN?*

Next Slides Explain Derivation

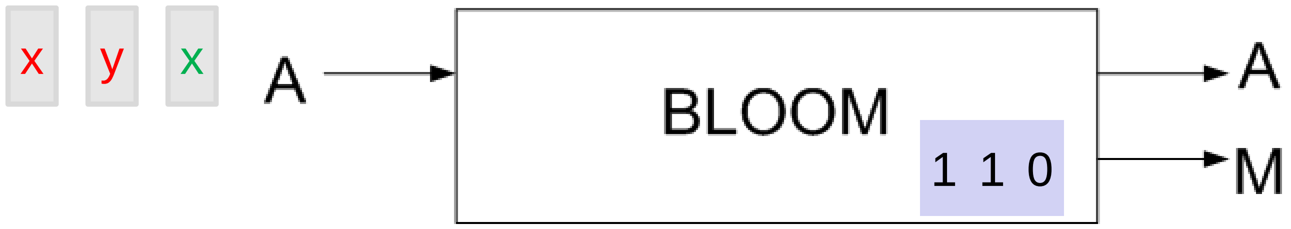


First Refinement

- Because joins are the most complex operator, increase efficiency by reducing the size of its input streams
- Used Bloom filters to eliminate B tuples that do not join with A tuples



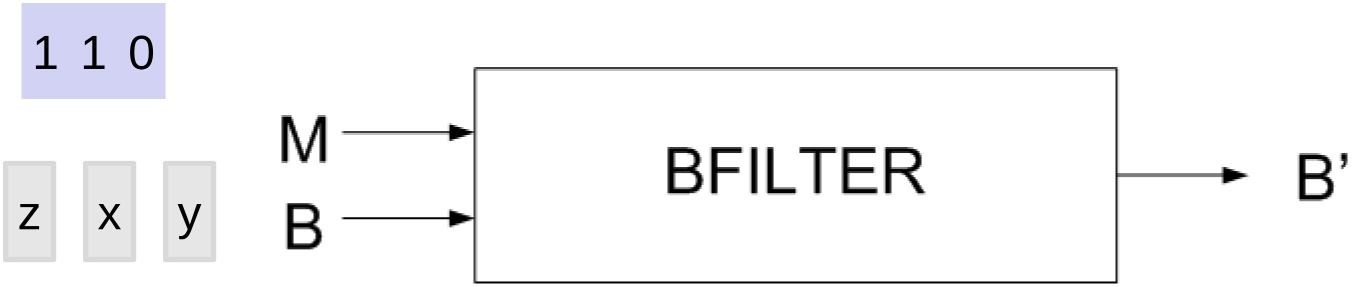
BLOOM Box



- Bloom filtering is a common technique for disqualifying tuples from further processing

- Algorithm:
    - clear bit map M
    - read each A tuple, hash its key, and mark corresponding bit in M
    - output each tuple A
    - after all A tuples read, output M

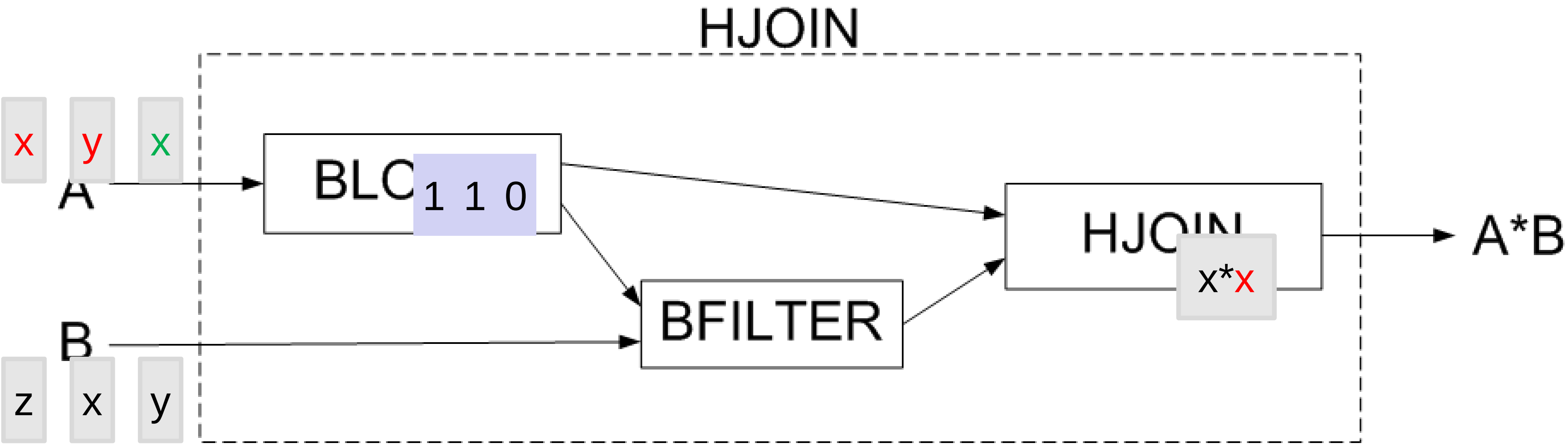
BFILTER Box



- The filtering part of Bloom filters
  - eliminates B tuples that cannot join with A tuples

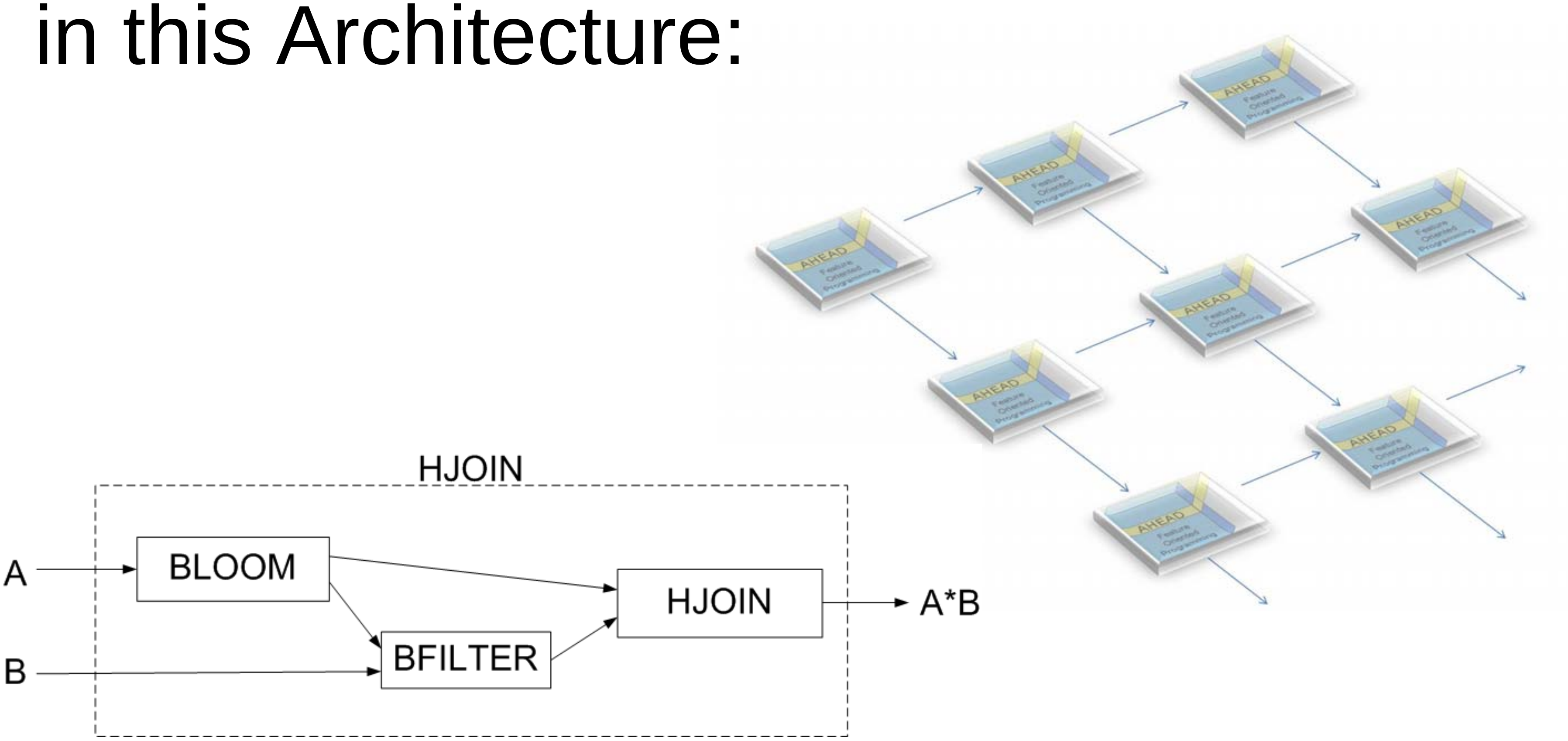
- Algorithm:
  - read bit map M
  - read each tuple of B, hash its key: if corresponding bit in M is not set discard tuple (as it will never join with A tuples)
  - else output tuple

The First Refinement

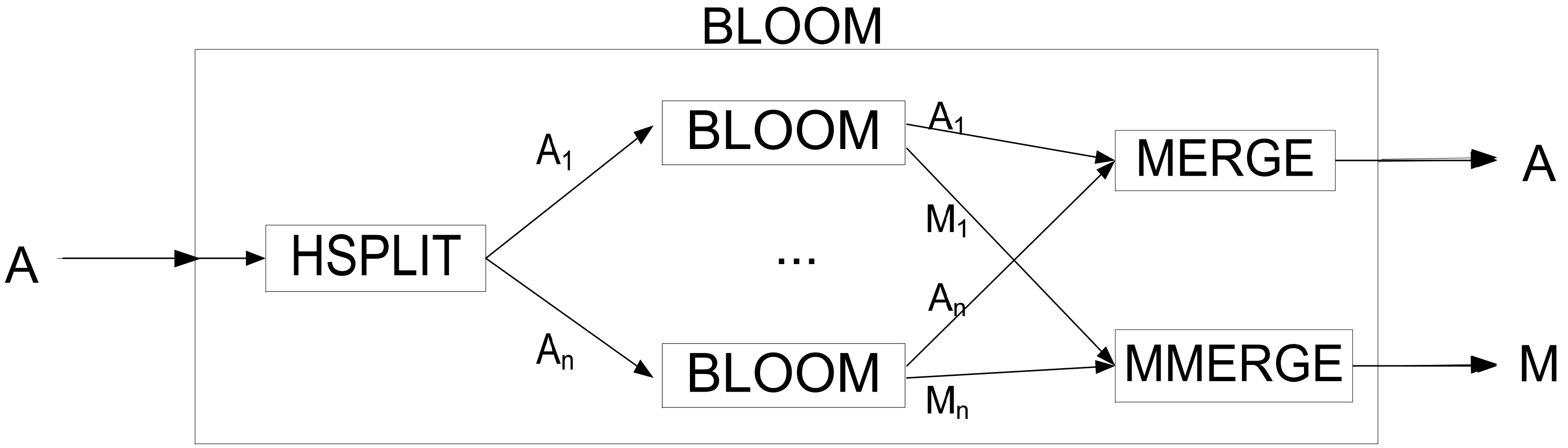


- Expose inner details of HJOIN box
- Can prove correctness of this refinement

Parallelize Each Box in this Architecture:

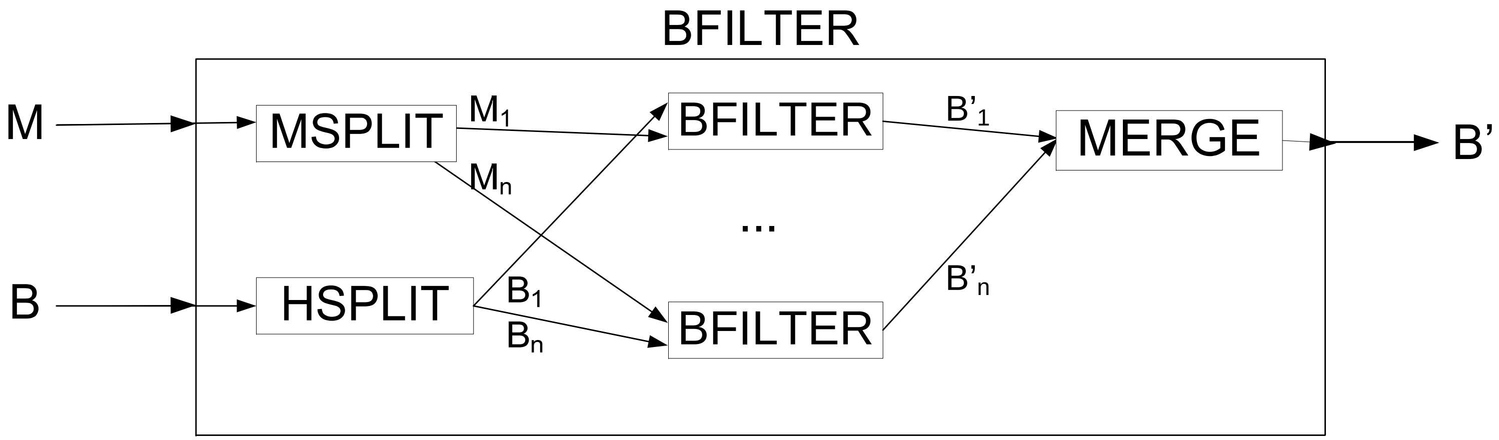


Parallelization of BLOOM Box



- Algorithm:
  - HSPLIT stream A
  - compute Bloom filter on each substream
  - reconstitute stream A
  - form merge bit maps to produce single bit map M

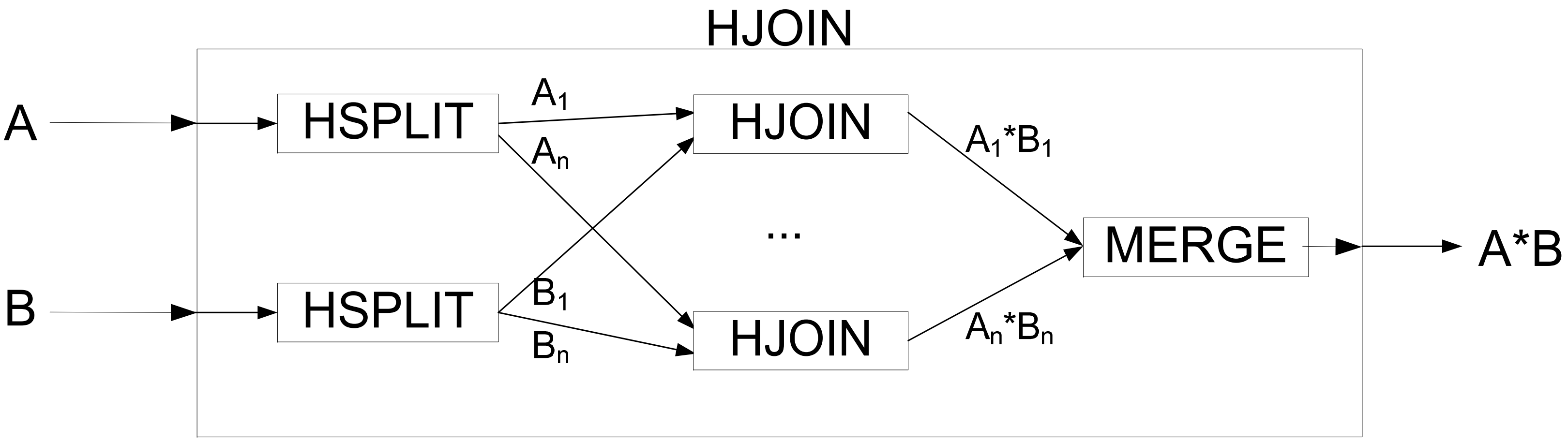
Parallelization of BFILTER Box



- Algorithm:
  - split M into $M_1 \ldots M_n$ and distribute
  - hash split stream B
  - filter B substreams in parallel
  - reconstitute stream B'

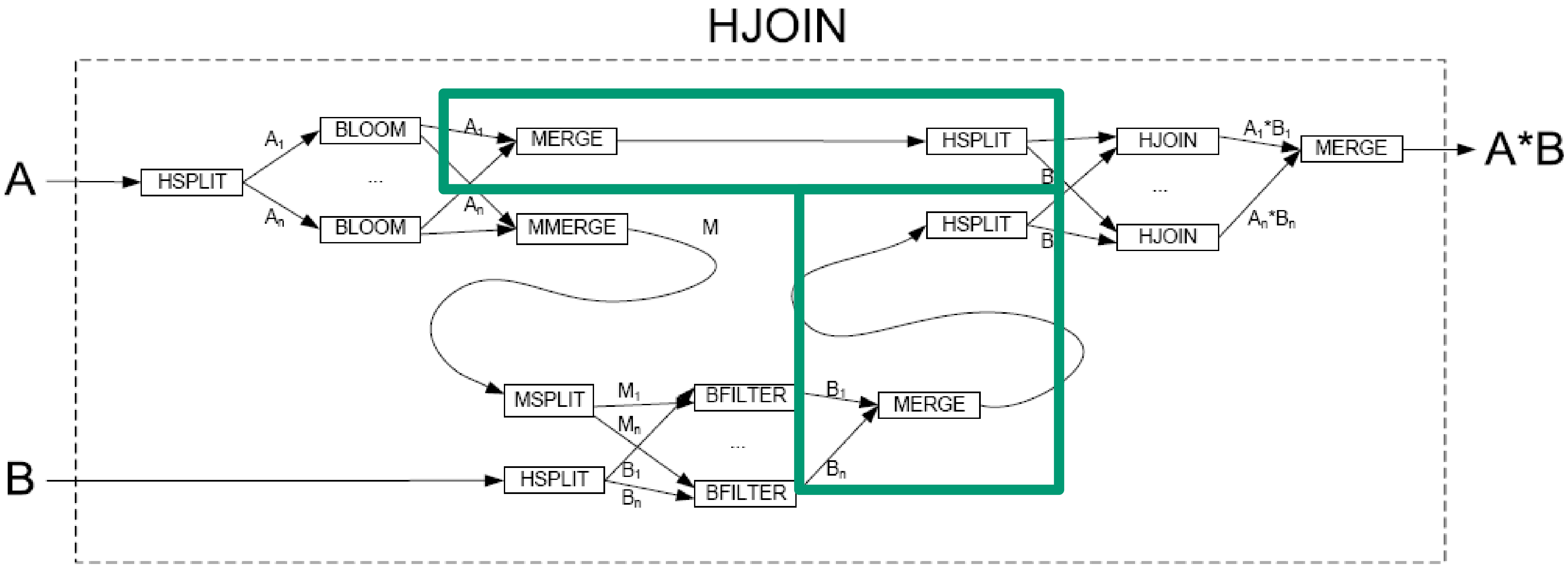
always hash split streams A and B using the same hash function! This gives us properties on which to optimize!

Parallelization of HJOIN Box



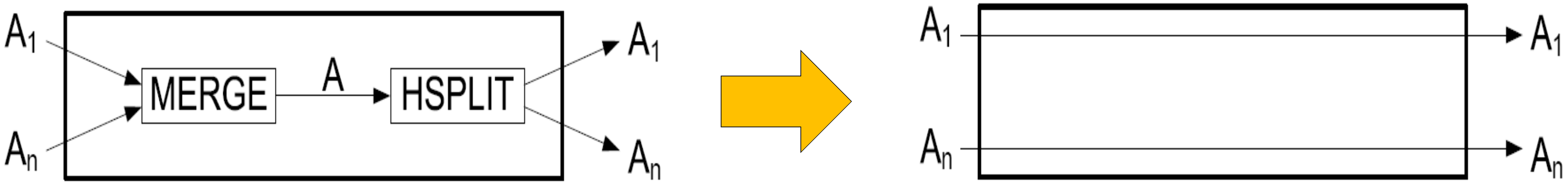
- Algorithm:
  - split both streams using same hash function
  - A and B tuples can join only if they have the same hash key
  - perform *n* joins (rather than n^2) in parallel
  - reconstitute join

Hierarchical Refinement



- Substitute parallel implementations for each box
- Note 3 optimizations are possible
- Here are the first two…

A Better View

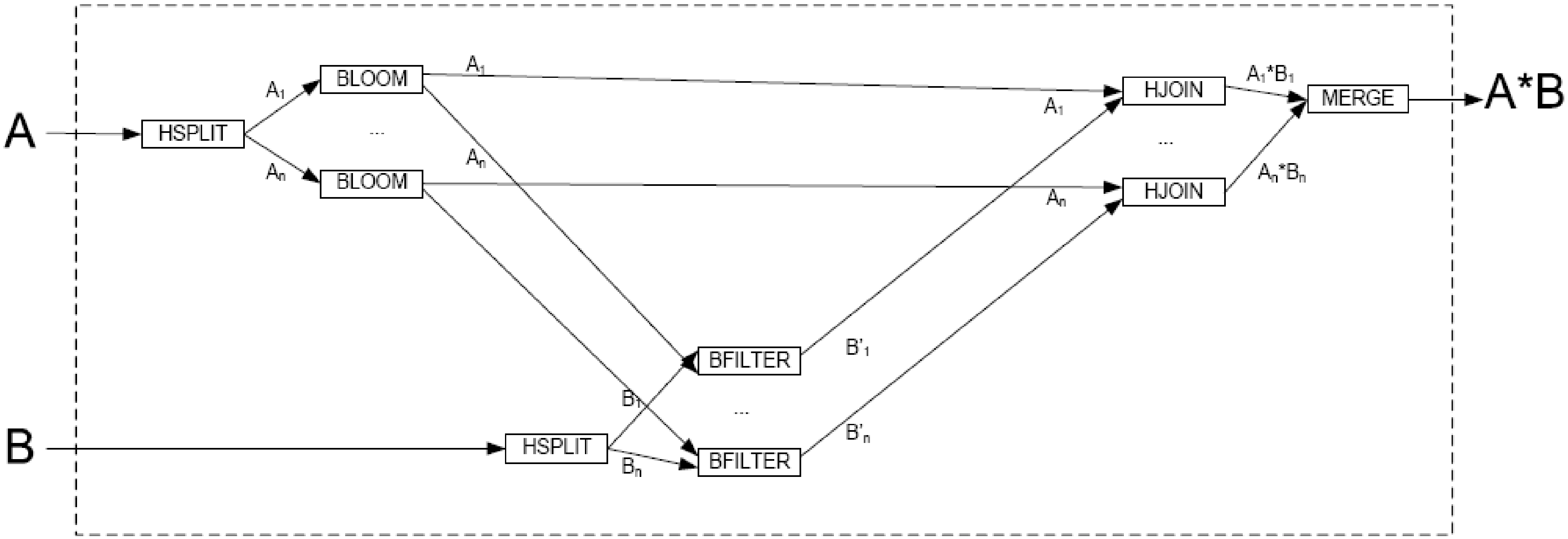


- Stream A is hash split into A_1…A_n, reconstituted, then hash split again
- MERGE – HSPLIT combination is the identity map
- Optimization – get rid of MERGE-HSPLIT

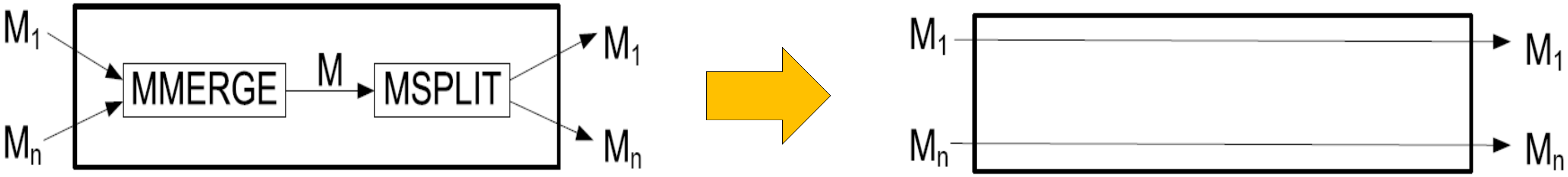
- Same for stream B

Applying Optimizing Rewrite

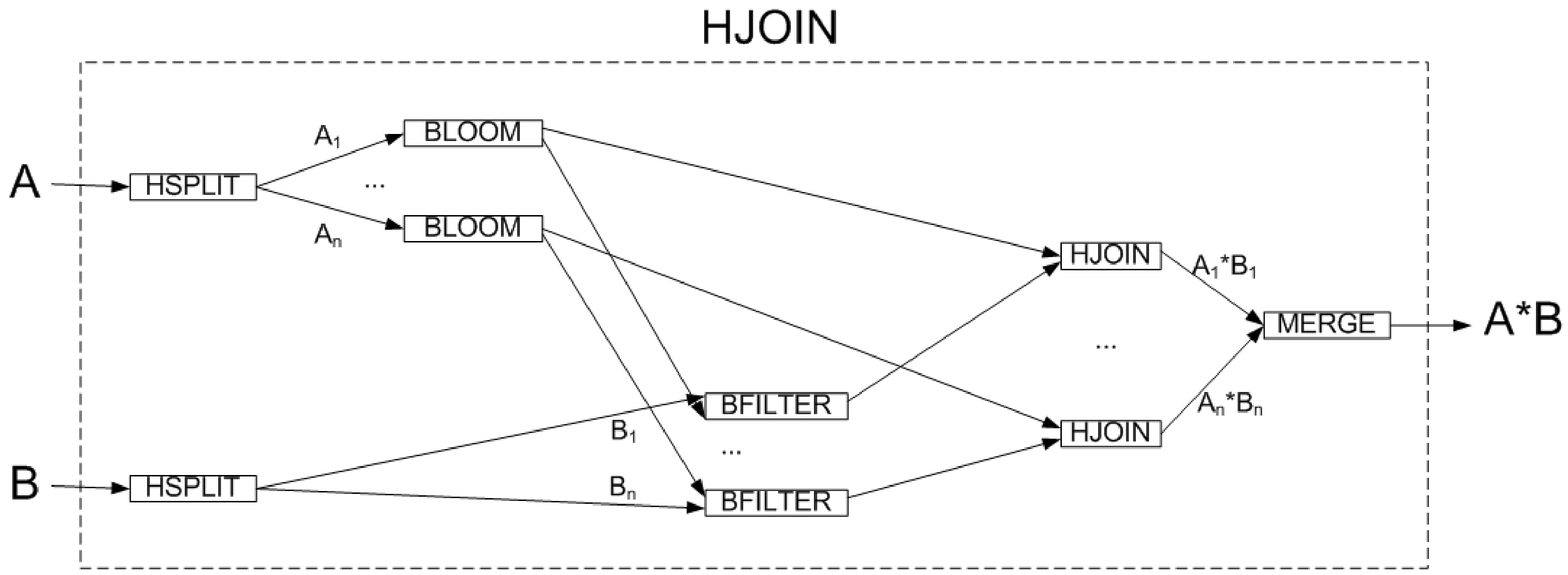
HJOIN



- Still one more optimization to perform…

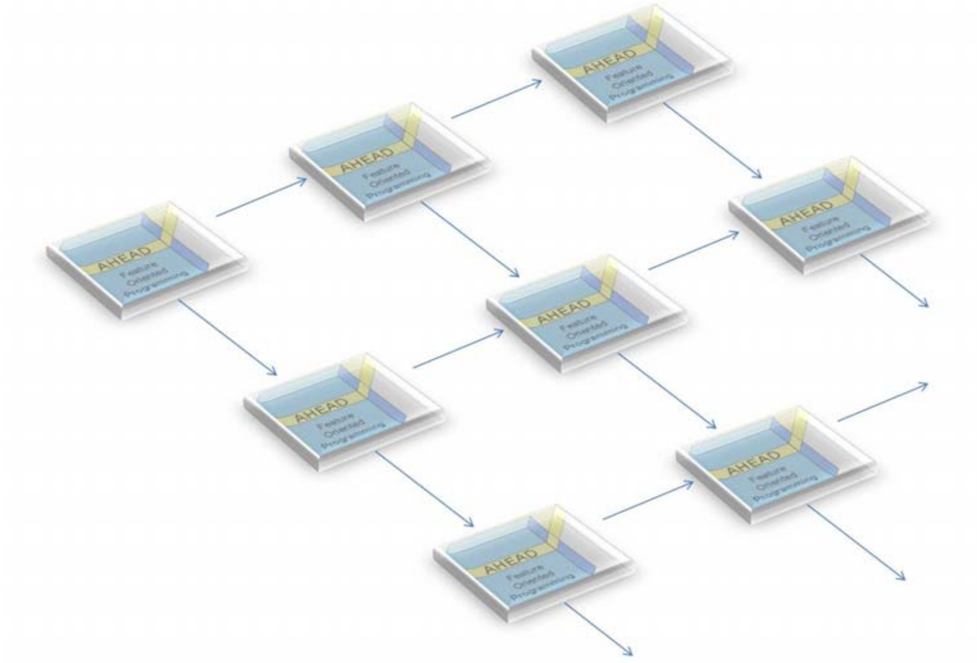


The (Almost) Final Design



- Elegant
- Easier to remember the derivation than the design itself (!)
- Each step can be proven correct, so the final design is **correct**
- *Not whole picture: rotations rewrites are applied when HJOIN boxes are composed see our paper or original Gamma papers*

#4: Conclusions and Future Work



Recap

- Showed how SWD used to extract an MDE architecture from parallel streaming architectures
    - architectures are always executable, derived top-down
    - *architecture is a D×T meta-expression*

- Used traditional technique of refinement + box and model extensions and optimizations – all are needed to explain the complexities of modern streaming architectures

- Encoded deep domain knowledge by simple xforms, demonstrated approach with 2 case studies, and validated our approach by manually re-creating them in the incremental manner in which we presented them

Recap

- Although our MDE architectures look simple
  - it took effort to refresh our domain knowledge
  - polish core abstractions and transformations
- Worth the effort:
  - complex designs can be explained in a simple way
  - can be appreciated by non-experts
  - techniques (and these examples) can be taught to undergraduates
- Incremental Design is not just “cute”
  - ultimately indispensible for future software development technologies that eventually integrate design, construction, verification, and testing
- D×T is at the heart of all of this

Thank You!