ReFlO: An Interactive Tool for Pipe-And-Filter Domain Specification and Program Generation

Rui C. Gonçalves · Don Batory · João L. Sobral

Abstract `ReFlO` is a framework and interactive tool to record and systematize domain knowledge used by experts to derive complex *pipe-and-filter (PnF)* applications. Domain knowledge is encoded as transformations that alter PnF graphs by *refinement* (adding more details), *flattening* (removing modular boundaries), and *optimization* (substituting inefficient PnF graphs with more efficient ones). All three kinds of transformations arise in reverse-engineering legacy PnF applications. We present the conceptual foundation and tool capabilities of `ReFlO`, illustrate how parallel PnF applications are designed and generated, and how domain-specific libraries of transformations are developed.

Keywords MDE, Tools, Software Architectures, Design by Transformation, Refinement, Optimization, Graph Transformations

1 Introduction

Component Based Software Engineering (CBSE) promotes the development of software by graphically wiring together reusable components. CBSE tools foster a circuit analogy to software development and, like actual circuit design tools, can express hierarchical systems by levels of abstraction: a component at level `i` is defined in terms of a circuit of more primitive components at level `i+1`, recursively. CBSE is an early example of *Model Driven Engineering (MDE)* where models (*ie* hierarchical circuit diagrams) are transformed into executables.

Pipe-and-filter (PnF) or *streaming* systems are among the fundamental architecture styles used in CBSE [30,17], where components are functions that process data that is transmitted through wires [68, 32,64,12]. Some time ago, we were given the task to re-engineer expert-created legacy PnF applications: a parallel database query processor and a crash fault-tolerant server. The PnF graphs of these systems were spaghetti diagrams; our understanding of how these systems worked was minimal. We could not explain their PnF graphs nor did we know if they were correct.

Step-wise development provided an answer. We start with an elementary PnF graph that cleanly and abstractly describes the system to be reverse-engineered. In MDE terms, this is a *Platform Independent Model (PIM)*: a model that does not constrain the implementation or target platform and is an abstract specification of what to build. We then *derived* the target PnF graph (a *Platform Specific Model (PSM)* [28]) by applying a series of transformations that are well-known to engineers in that domain. Further, each transformation was simple enough to be demonstratably correct (by proof or other means). Our derivations were *correct by construction* [36].

We had to depart from contemporary CBSE tools to admit *architectural optimizations*—the ability to replace a PnF subgraph with another PnF subgraph that implements the same functionality, but in a different way (to yield improved quality metrics, like performance). Optimizations were essential to our re-engineering tasks; *we could not derive legacy PnF graphs without them.* With *Model-to-Text (M2T)* trans-

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formations, we reproduced these legacy applications from our models.

Our critical insight was to recognize that *the transformations used to derive a PnF graph are building-blocks just as important as the components used in the application itself.*

This paper presents ReFlO, an interactive tool that embodies a derivational approach to PnF graphs. Initially we used ReFlO to reverse-engineer the design of legacy applications—an example of which we illustrate in this paper. Over time, the library of transformations that are used in deriving a family or domain of similar applications becomes extensive enough for forward-engineering. That is, given a PIM of an application, cataloged transformations can be used to mechanically derive the space of all PSMs and automatically select the most efficient. Our work on forward-engineering is not the focus of this paper and is detailed elsewhere [47]. Nonetheless, the strong connection of ReFlO to forward-engineering demonstrates the significance of derivational approaches.

The contributions of this paper are:

- a simple way to encode domain knowledge of PnF graph construction as transformations;
- how ReFlO can be used as an interactive design tool to derive custom PnF graphs;
- an explanation why the Perry Substitution Principle, rather than the Liskov Substitution Principle, is central to derivational development of optimized PnF programs;
- how ReFlO provides a framework to allow different interpretations of PnF graphs to compute properties about them (besides producing executables); and
- how multiple derivations of a PSM can expose new transformation rules of a domain.

2 Foundational Concepts: Part I

2.1 PnF Graphs, Refinements, and Optimizations

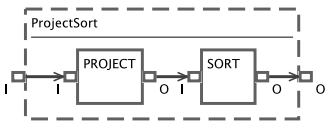


Fig. 2.1 The PnF graph ProjectSort.

A *pipe-and-filter (PnF) graph* [30] is a directed multigraph, where boxes (components) process data that is passed to other boxes via connectors (pipes). Boxes may receive inputs from different sources and compute zero or more outputs. Input ports are drawn as nubs on the left-side of boxes; output ports are drawn as nubs on the right. A connector links an input port to an output port. Figure 2.1 shows a PnF graph modeling a program, called ProjectSort, that projects (eliminates) attributes of the tuples of its input stream and then sorts them.

We call boxes PROJECT and SORT *interfaces* as they specify only abstract behavior (their inputs and outputs, and, informally, their semantics). Besides input ports, boxes may have other inputs that are not shown graphically, such as the sort key for the SORT box or the list of attributes to remove for the PROJECT box. We call the former *essential parameters* and the latter *additional parameters* [18].

Figure 2.1 is a PIM as it makes no reference to or demands on its concrete implementation. It is a high-level specification that can be adapted to a particular platform or for particular inputs. Adaptation is accomplished in ReFlO by applying transformations.

A transformation can map an interface directly to a *primitive* box, representing a concrete code implementation. Besides primitives, there are other implementations of an interface that are expressed as a PnF graph, called *algorithms*. Algorithms may reference interfaces. Figure 2.2 is an algorithm. It shows the PnF graph called parallel_sort of a map-reduce implementation of SORT. Each box inside Figure 2.2, namely SPLIT, SORT and SMERGE (sorted merge), is an interface which can be subsequently elaborated.

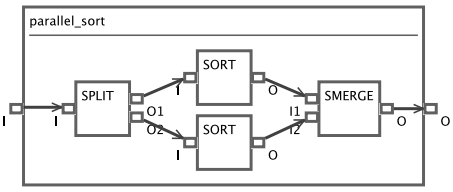


Fig. 2.2 parallel_sort implements SORT by map-reduce.

Refinement [77] is the replacement of an interface with one of its implementations (primitive or algorithm). By repeated refinements, eventually a graph of wired primitives is produced.

Figure 2.1 can be refined by replacing SORT with its parallel_sort algorithm and PROJECT with a similar map-reduce algorithm. Doing so yields the graph of Figure 2.3(a), or equivalently the graph of Figure 2.3(b), obtained by removing modular boundaries. Removing modular boundaries is called *flattening*.

Refinements alone are insufficient to derive complex PnF graphs. Look at Figure 2.3(b). We see a MERGE followed by the SPLIT operation, that is, two streams

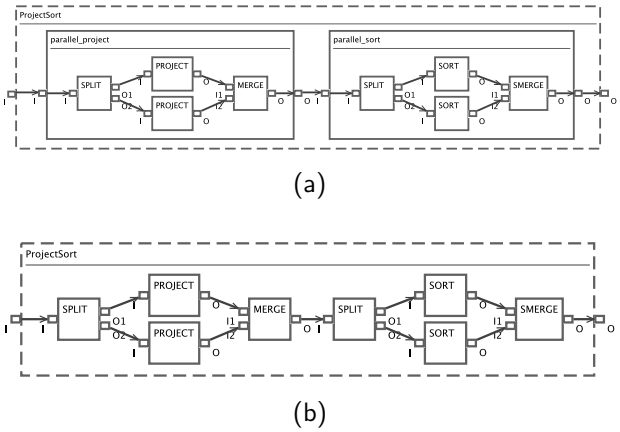


Fig. 2.3 Parallel version of `ProjectSort`.

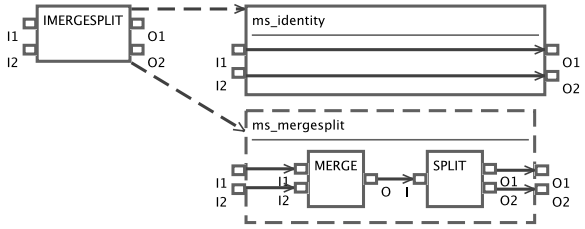


Fig. 2.4 Two implementations of the `IMERGESPLIT` interface.

are merged and the resulting stream is immediately split again. Let interface `IMERGESPLIT` be the operation that receives two input streams, and produces two other streams, with the requirement that the union of the input streams is equal to the union of the output streams (see Figure 2.4). `ms_mergesplit` is one of its implementations. However, the `ms_identity` algorithm provides an alternative implementation that is obviously more efficient than `ms_mergesplit` as it does not require `MERGE` and `SPLIT` computations.[1]

We can use `ms_identity` to optimize `ProjectSort`. The first step is to *abstract* Figure 2.3(b) with the `IMERGESPLIT` interface, obtaining Figure 2.5(a). Then, we refine `IMERGESPLIT` to its `ms_identity` algorithm, to obtain the optimized graph for `ProjectSort` (Figure 2.5(b)). We call the action of abstracting an (inefficient) composition of boxes to an interface, and then refining it to an alternative implementation an *optimization*.[2] This transformation—or rather, composition of transformations—effectively allows inefficient subgraphs that arise after removing the modular boundaries of refinements to be replaced with alternative subgraphs, which provide the same behavior, while improving performance.

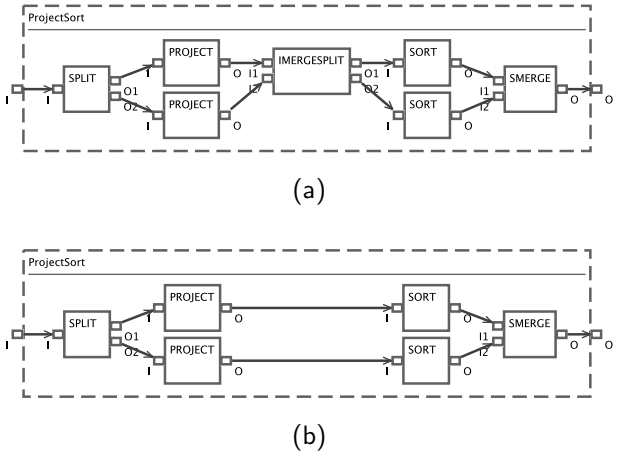


Fig. 2.5 Optimization of `ProjectSort`.

2.2 Perry Substitution Principle

By studying several legacy applications from the same domain, it becomes obvious that there is a set of transformations that are commonly used in derivations. The collected set of transformations contains interface/implementation pairs (`I`, `A`), which we call *rewrite rules*, and specifies two distinct kinds of transformations:

- **Refinement** `I` $\rightsquigarrow$ `A`: An interface `I` is replaced by a graph `A` which represents a primitive or algorithm, and
- **Abstraction** `A` $\rightsquigarrow$ `I`: A graph `A` is replaced by interface `I`.

Under what circumstances is a rewrite rule permitted? A possible answer is based on the *Liskov Substitution Principle (LSP)* [43], which is a foundation of object-oriented design. LSP states that if `A` is a subtype of `I`, then objects of type `A` can be substituted for objects of type `I` without altering the correctness properties of a program. Substituting an interface with an implementing object (component) is standard fare today and is a way to realize refinement in LSP [49, 74]. The technical rationale behind LSP is that preconditions for using subtype `A` can *not* be stronger than preconditions for type `I`, and postconditions for `A` are *not* weaker than that for `I` [43]:

$$\texttt{pre(I)} \Rightarrow \texttt{pre(A)} \tag{2.1}$$

$$\texttt{post(A)} \Rightarrow \texttt{post(I)} \tag{2.2}$$

[1] Readers may notice that algorithms `ms_mergesplit` and `ms_identity` do not necessarily produce the same result. However, both implement the semantics specified by `IMERGESPLIT`, and the result of `ms_identy` is one of the possible results of `ms_mergesplit`, *ie* `ms_identity` removes non-determinism.

[2] Although called *optimizations*, they do not necessarily improve performance, but combinations of them typically do.

To our surprise, LSP is too restrictive when specifying ReFlO graph rewrite rules, as *implementations are often accompanied by preconditions that are not required by their interfaces*. Such implementations are usually more efficient than those that are not as specialized [8].

Example 2.1 Figure 2.6 shows three implementations of the SORT interface: a map-reduce algorithm, a quicksort primitive, and a do_nothing algorithm. do_nothing says: if the input stream is already in sorted order (a precondition not present in SORT but definitely present for do_nothing), then there is no need to sort. The (SORT, do_nothing) rewrite rule violates LSP: do_nothing implementation has *stronger* preconditions than its SORT interface. This is a common situation in graph rewrite rules.

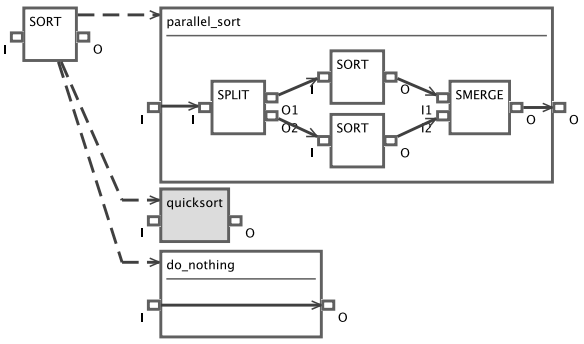


Fig. 2.6 Two algorithms and a primitive implementation of SORT.

Forcing our rewrite rules to comply with LSP, the standard notion of substitutability for object-oriented interface/implementation refinements, *we would not be able to derive the optimized programs that domain experts created manually*. When looking for alternative notions of substitutability, we found an existing precedence for a solution. Let A and I be boxes, and pre and post denote the pre- and postconditions of a box. Perry [54] defined that A is *upward compatible* with I if:

$$\texttt{pre}(\texttt{A}) \Rightarrow \texttt{pre}(\texttt{I}) \tag{2.3}$$

$$\texttt{post}(\texttt{A}) \Rightarrow \texttt{post}(\texttt{I}) \tag{2.4}$$

ie A requires and provides at least the same as I. We call this the *Perry Substitution Principle (PSP)*. It allows the specification of implementations specialized for certain inputs, essential to allow the derivation of optimized program implementations.

Not requiring rewrite rules to conform to LSP, and allowing an interface to be replaced with an implementation with stronger preconditions, means that a rewrite rule is *not always applicable* (it depends on the PnF graph we are refining). To guarantee that the behavior of the PnF graph is preserved when replacing interface I with implementation A, we must guarantee that the preconditions of A are met (in the context of PnF graph being transformed). If not, ReFlO disallows it.

Consider the do_nothing implementation of SORT and ProjectSort of Figure 2.1. Algorithm do_nothing has a precondition that requires its input to be sorted in an appropriate order (*eg* on ascending values of field F). We can use this rewrite rule in ProjectSort (to replace SORT) only if this precondition is met, *ie* if PROJECT has a postcondition specifying its output is sorted in ascending F order. Typically, PROJECT provides no such postcondition, thus ReFlO disallows do_nothing algorithm for ProjectSort. However, if PROJECT exported a postcondition specifying the sort order of its output, the input of SORT was in ascending F order, do_nothing would be a valid replacement of the SORT interface. In this scenario, even though do_nothing has stronger preconditions than SORT, it can be used, and the behavior of ProjectSort would be preserved.

If we assure the preconditions of the implementation being added (A) are met in the PnF graph being transformed (taking into account the postconditions of the boxes that compute the inputs of A), we guarantee that the transformation preserves the behavior of the PnF graph being transformed (*ie* no precondition is added to the PnF graph, and the postconditions are preserved).

Rewrite rules used in abstraction transformations $\texttt{A} \rightsquigarrow \texttt{I}$ have stronger constraints. An abstraction implies that a graph A must implement I, *ie* $\texttt{I} \rightsquigarrow \texttt{A}$. For both constraints to hold, the pre- and postconditions of A and I must be equivalent:

$$\texttt{pre}(\texttt{I}) \Leftrightarrow \texttt{pre}(\texttt{A}) \tag{2.5}$$

$$\texttt{post}(\texttt{I}) \Leftrightarrow \texttt{post}(\texttt{A}) \tag{2.6}$$

To summarize, refinement is a general concept [53]. In object-oriented designs, refinement is often realized by LSP, substituting an interface with an implementing object. In MDE, a refinement typically corresponds to mapping of a model of one type (metamodel) to that of another. In the world of ReFlO graph rewrites, refinement is expressed by rewrite rules satisfying PSP. Differences in the rules followed in MDE and object-oriented worlds have also been documented before. Wimmer *et al.* noticed that inheritance in model transformations require covariant input types, whereas in object-oriented world contravariant input types is required for methods' inheritance [75, 42].

3 Domain Model Specification

ReFlO (**Re**fine, **Fl**atten, and **O**ptimize) is an interactive tool to draw and derive PnF graphs, built upon the ideas of *Design by Transformation (DxT)* [60]. The rewrites that ReFlO applies are taken from a *domain model*—a library of graph transformations whose structure we explained in Section 2. ReFlO provides support for experts build such models.

3.1 Basic Features of a Domain Model

A ReFlO *Domain Model (RDM)* is a set of ordered pairs that associate an interface with an implementing algorithm or primitive. That is, a RDM encodes a library of transformations that can be applied to programs in a given domain. ReFlO provides the following objects to create RDMs: interfaces, primitives, algorithms, input/output ports, connectors, implementation links, and patterns. The UML class diagram of the RDM metamodel is Figure 3.1.

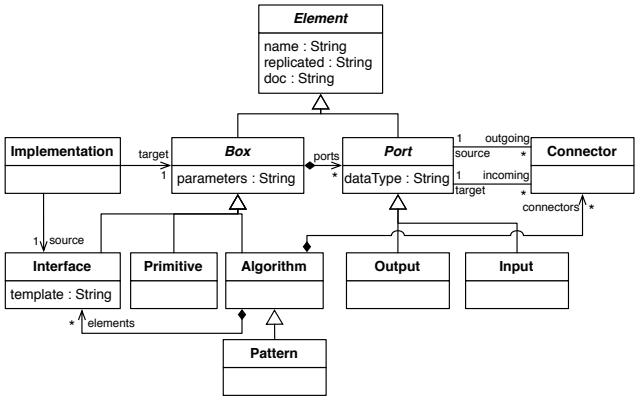


Fig. 3.1 RDM UML class diagram.

An *interface* is a named box with input and output ports. A *primitive* is drawn identically, except that primitives have a gray background whereas interfaces are white (Figure 2.6). Every *port* of a box has a unique name (to distinguish it from other ports) and a data type. A *connector* links a source port to a target port.

An *algorithm* is a named box with I/O ports that encloses a PnF graph.[3] A *pattern* is a special algorithm that not only implements its interface, but also specifies that its graph can be replaced with (or abstracted to) an interface, as part of an optimization. ReFlO graphically distinguishes patterns as dashed-line boxes from algorithms that are solid-line boxes (see Figure 2.4).

[3] We refer to the interfaces (boxes) contained inside an algorithm as *internal interfaces (boxes)*, and to the algorithm as the *parent box* of those interfaces.

A domain model is specified in ReFlO by defining each interface, primitive, and algorithm. A *rewrite rule* is an ordered pair (interface, primitive) or (interface, algorithm) which is drawn/specified by an *implementation* link (a dashed arrow) connecting an interface to an implementation.

Example 3.1 Figure 2.6 defined three implementations of the SORT interface: the `parallel_sort` algorithm, the `quicksort` primitive, and the `do_nothing` algorithm.

Example 3.2 Figure 2.4 specified that pattern `ms_mergesplit` can be abstracted to the IMERGESPLIT interface, which can then be refined to the `ms_identity` algorithm. This compound rewrite was the optimization that we used earlier.

3.2 Advanced Features

3.2.1 Additional Parameters

Every box has a *parameters* attribute which holds a comma-separated list of names, data types and values that specify the box's additional parameters. The value of an additional parameter may be a constant or the value of a parameter of its parent box. Additional parameters keep ReFlO diagrams simpler, allowing developers to focus on the essential parts of the model.

3.2.2 RDM Documentation

Transformation rules must be documented so that others who inspect PnF graphs can understand the rules that were used to derive it. ReFlO boxes and ports have the *doc* attribute, where designers can place a textual description of model elements. ReFlO generates HTML documentation that contains the figures of boxes and their descriptions. This allows users to reference HTML pages for rule definitions. The HTML documentation for the rules that we use later in our case study is at `http://www.cs.utexas.edu/users/schwartz/DxT/case-studies/gamma/models/databases.html`.

3.2.3 Templates

Many rewrite rules are parameterized clones of each other. ReFlO was designed so that any rewrite rule could be used as a template. Every rewrite rule has a *template* attribute; if its value is `null`, the rule is not a template. A non-`null` value specifies (template box name, concrete box name) bindings to create a new instance of the rewrite rule. Typically, a non-`null` value specifies

multiple groups of bindings, one binding for every new instance of a rule. Details are given in [31].

Example 3.3 The rewrite rules of Figure 3.2 define an optimization. Whenever box $\texttt{x}_1$ is followed by box $\texttt{x}_2$, where $\texttt{x}_2 = \texttt{x}_1^{-1}$ (the inverse operation of `x1`), box $\texttt{x}_2$ can be removed, yielding algorithm `idx1`.

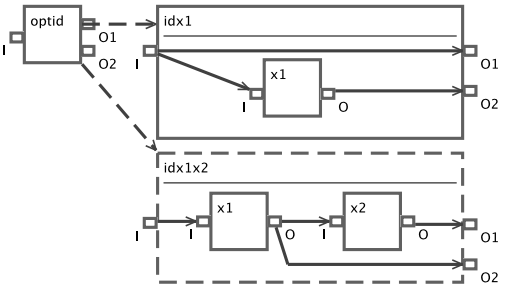


Fig. 3.2 A template with parameters `optid`, `x1` and `x2`.

Figure 3.2 is a template for stamping out customized copies of itself. Using these bindings $\{(\texttt{optid}, \texttt{OptIdF}), (\texttt{x1}, \texttt{F1}), (\texttt{x2}, \texttt{F2})\}$ where $\texttt{F2} = \texttt{F1}^{-1}$, `ReFlO` produces the customized rewrite rules of Figure 3.3. Additional bindings can produce other instances. Templates provide an elementary form of high-order transformations that reduce modeling effort [71].

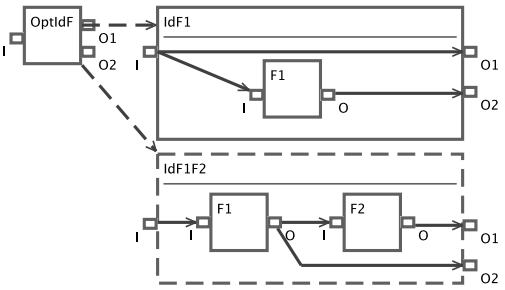


Fig. 3.3 A template instance.

3.2.4 Replicated Elements

Figure 2.2 showed the `parallel_sort` algorithm where two instances of `SORT` are performed in parallel. We want to specify a rewrite with an arbitrary number of instances. We use *replicated elements*. Ports and boxes have a [bracketed attribute] that specifies replication. If brackets are absent, the element is not replicated. If a bracket contains an upper case letter, that is interpreted as a *replication variable* that specifies how many times the element is replicated.[4] Thus, box `B[N]` means that there are `N` instances of box `B` ($\texttt{B}_\texttt{i}$, for $\texttt{i} \in \{\texttt{1} \ldots \texttt{N}\}$). Similarly for ports.

Example 3.4 Figure 3.4 expresses `parallel_sort` in a more general way. `SPLIT` has `N` output ports $\{\texttt{O}_1 \ldots \texttt{O}_\texttt{N}\}$. There are `N` `SORT` boxes $\{\texttt{SORT}_1 \ldots \texttt{SORT}_\texttt{N}\}$. `SPLIT` output port $\texttt{O}_\texttt{i}$ is connected to input port `I` of $\texttt{SORT}_\texttt{i}$. Finally, the input port `I` of `SMERGE` is replicated $\{\texttt{I}_1 \ldots \texttt{I}_\texttt{N}\}$. The output of $\texttt{SORT}_\texttt{i}$ is connected to `SMERGE` input port $\texttt{I}_\texttt{i}$. Figure 2.2 is produced by setting $\texttt{N} = 2$.

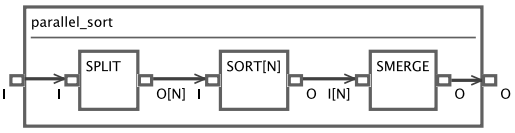


Fig. 3.4 `parallel_sort` with replicated elements.

Example 3.5 Figure 3.5 defines transformations where elements can be replicated a different number of times. The interface has `N` inputs and `M` outputs. Each pattern replicates some elements `N` times and others `M` times.

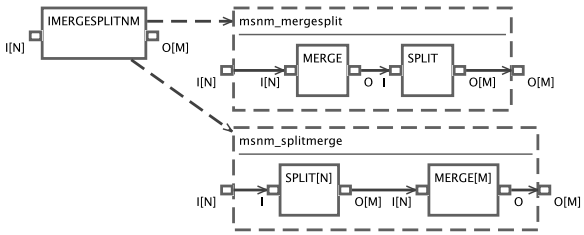


Fig. 3.5 `MERGE` – `SPLIT` cross product.

`ReFlO` has specific rules for replicating connectors (*ie* connectors linking replicated ports or ports of replicated boxes). Using the notation `B.P` to represent port `P` of box `B`, given a connector from output port `O` of box `B` to input port `I` of box `C`, the rules are:

- When `O` is replicated `N` times and `B` is not (which implies that either `I` or `C` is also replicated `N` times), connectors link $\texttt{B.O}_\texttt{i}$ to $\texttt{C.I}_\texttt{i}$ or $\texttt{C}_\texttt{i}\texttt{.I}$ (depending on which is replicated), for $\texttt{i} \in \{\texttt{1} \ldots \texttt{N}\}$.
- When `B` is replicated `N` times and `O` is not (which implies that either `I` or `C` is also replicated `N` times), connectors link $\texttt{B}_\texttt{i}\texttt{.O}$ to $\texttt{C.I}_\texttt{i}$ or $\texttt{C}_\texttt{i}\texttt{.I}$ (depending on which is replicated), for $\texttt{i} \in \{\texttt{1} \ldots \texttt{N}\}$.

[4] At design time, the variable only allow us to determine whether to elements are replicated the same number of times. These variables can be instantiated when generating code.

– When `B` is replicated `N` times and `O` is replicated `M` times (which implies that both `C` and `I` are also replicated), connectors link $\texttt{B}_\texttt{i}.\texttt{O}_\texttt{j}$ to $\texttt{C}_\texttt{j}.\texttt{I}_\texttt{i}$, thereby implementing a *crossbar*, for $\texttt{i} \in \{\texttt{1}\ldots\texttt{N}\}$ and $\texttt{j} \in \{\texttt{1}\ldots\texttt{M}\}$ (this implies that `C` is replicated `M` times, and `I` is replicated `N` times).

Example 3.6 Figure 3.6 is the result of setting `N` and `M` to 2 in algorithm `msnm_splitmerge` from Figure 3.5. Note the crossbar resulting from connectors that link replicated ports of replicated boxes.

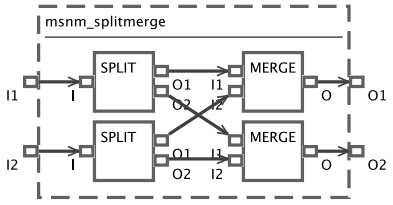


Fig. 3.6 `msnm_splitmerge` pattern without replication.

The mapping of a PIM to a PSM in `ReFlO` is discussed next.

4 Interactive Derivation of PSMs from a PIM

`ReFlO` is an interactive tool that allows designers to (1) define an RDM, (2) define a PIM, and (3) use the transformations of an RDM to progressively rewrite a PIM into a PSM. In the typical use, a domain expert starts by using `ReFlO` to reverse-engineer legacy programs. During this process, he replays the development process, adding to the RDM the transformations that he, sometimes unconsciously, applied to code. The RDM may then be used by other developers to optimize their programs (directly in `ReFlO`, or exporting the RDM to an external tool [46]).

The actions domain experts and developers can invoke when transforming a PnF graph are:

– **Refine** replaces a user selected interface with one of its implementations. `ReFlO` examines each potential refinement and only displays those that satisfy the $\mathcal{I} \rightsquigarrow \mathcal{G}$ constraints of Section 2.2.[5] If only one option is available, `ReFlO` automatically selects it.[6]

– **Flatten** removes the modular boundaries of the selected graph that result from refining a PnF graph. If the graph to be flattened was replicated, this information is pushed down to its internal boxes.

– **Abstract** replaces the selected boxes with the interface they implement. `ReFlO` matches selected boxes with the patterns in the RDM. Unlike in refinements, no preconditions check is needed to decide whether a pattern can be replaced by the interface. However, to decide whether the selected boxes are an instance of the pattern $\mathcal{G}$ we need to put the modular boundaries of $\mathcal{G}$ around the boxes, and verify if $\mathcal{G}$ preconditions are met. That is, it is not enough to verify if the selected boxes have the shape of the pattern. If one match is found, the pattern is replaced by its interface. If multiple patterns match, the user is asked to choose one.[7]

– **Optimize** performs an abstraction, refinement, and flattening as a single step, replacing the selected set of boxes with an equivalent implementation.

Example 4.1 `ReFlO` maps Figure 4.1(a) to 4.1(b) by applying the optimization of Figure 3.5. (Note the replication variables `X` and `Y` of the original graph are used to define the replication variables of the new graph.)

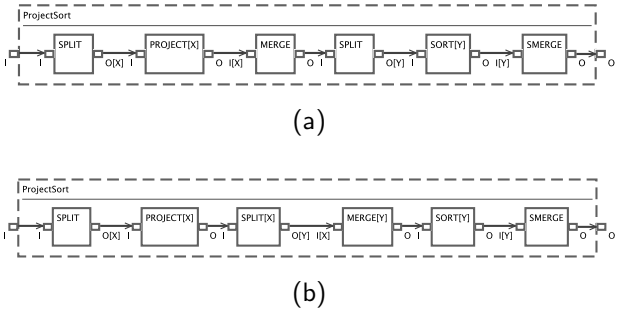


Fig. 4.1 Optimizing a parallel version of `ProjectSort`.

– **Find Optimization** locates all possible matches for the patterns in the RDM that exist inside the selected graph. The interfaces that comprise the matches are identified setting their attribute *label* to contain a tag identifying the match(es).

Example 4.2 Applying find optimization to the `ProjectSort` graph of Figure 2.3b results in the

[5] In Section 5.2 we provide additional details about how `ReFlO` verify these constraints.

[6] Replication parameters of an interface are used to set the replication parameter(s) of an implementation. If an implementation has replication parameters that are not present in the interface, the user is asked to provide a value for the parameter.

[7] The values of replication parameters of the pattern are used to define the replication parameters of the interface. The same is done to define the values of the additional parameters of the new interface.

graph of Figure 4.2, where we can see that two boxes are part of a match (of pattern `ms_mergesplit`).

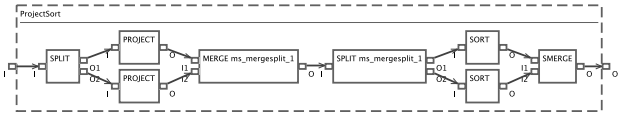


Fig. 4.2 The label shown after the name of boxes `MERGE` and `SPLIT` indicates that they are part of a match of pattern `ms_mergesplit`.

– **Expand** expands replicated boxes and ports of a graph. For each replicated box, a copy is created. For each replicated port, a copy is created (suffixes `1` and `2` are added to names of original port and its copy, respectively, as two ports cannot have the same name). Connectors are copied according to the rules previously defined.

Example 4.3 Figure 4.3 is an expansion of Figure 4.1(b).

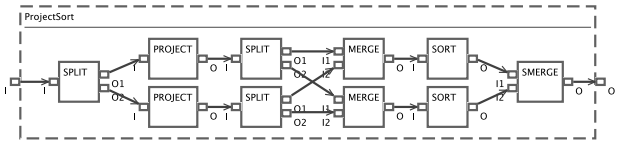


Fig. 4.3 Expanding the parallel, replicated `ProjectSort`.

5 Foundational Concepts: Part II

5.1 Interpretations

A PnF graph `P` may have many interpretations. The default is to interpret each box of `P` as the component it represents. That is, `SORT` means "sort the input stream". We call this the *standard interpretation* $\mathcal{S}$. The standard interpretation of box `B` is denoted $\mathcal{S}$(`B`) or simply `B`, *eg* $\mathcal{S}$(`SORT`) is "sort the input stream". The standard interpretation of graph `P` is $\mathcal{S}$(`P`) or simply `P`.

There are other interpretations of `P`. $\mathcal{ET}$ interprets each box `B` as a computation that *estimates the execution time* of $\mathcal{S}$(`B`), given statistics about $\mathcal{S}$(`B`)'s inputs. So $\mathcal{ET}$(`SORT`) is "return an estimate of the execution time to produce `SORT`'s output stream". Each box `B` $\in$ `P` has exactly the same number of inputs and outputs as $\mathcal{ET}$(`B`) $\in$ $\mathcal{ET}$(`P`), but the meaning of each box as well as the types of each of its I/O ports are different.

Example 5.1 $\mathcal{ET}$(`ProjectSort`) estimates the execution time of `ProjectSort` for an input `I` whose statistics (tuple size, stream length, etc.) is $\mathcal{ET}$(`I`).

Example 5.2 We said in Section 1 that an RDM can be used to forward-engineer (*eg* derive) all possible PSMs from an input PIM. The estimated run-time of a PSM `P` is determined by executing $\mathcal{ET}$(`P`). The most efficient PSM that implements the PIM is the one with the lowest estimated cost [48].

Example 5.3 $\mathcal{M}2\mathcal{T}$(`ProjectSort`) is a model-to-text interpretation that maps `ProjectSort` to executable code.

Example 5.4 Pre- and postconditions guarantee the correctness of `ReFlO` graphs. Each is encoded as a distinct interpretation, discussed further in Section 5.2.

In general, an interpretation $\mathcal{I}$ of graph `P` is an isomorphic graph $\mathcal{I}$(`P`), where each box `b` $\in$ `P` is mapped to a unique box $\mathcal{I}$(`b`) $\in$ $\mathcal{I}$(`P`) and each edge $\mathtt{b}_1 \rightarrow \mathtt{b}_2 \in \mathtt{P}$ is mapped to a unique edge $\mathcal{I}(\mathtt{b}_1) \rightarrow \mathcal{I}(\mathtt{b}_2) \in \mathcal{I}(\mathtt{P})$. In `ReFlO`, graph $\mathcal{I}$(`P`) is identical to `P`, except that the bindings of all boxes to computations are different.

5.1.1 Implementing Interpretations

It is reasonable to expect that each interpretation would be written in its own *domain-specific language (DSL)*. Creating such DSLs was not critical to our goal of developing and demonstrating `ReFlO`. Indeed, this would be an entire research project unto itself. Instead, we chose to write each interpretation in Java. For each interpretation and box, a Java class must be provided by a developer. Every interpretation is represented by a collection of classes, one per box, that is stored in a unique Java package whose name identifies the interpretation. Thus, if there are `n` interpretations, there will be `n` Java packages provided by a domain designer.

Each class has the name of its box and must extend abstract class `AbstractInterpretation` that is provided by `ReFlO` (see Figure 5.1). Interpretations grow in two directions: (i) new boxes can be added to the domain, which requires new classes to be added to each package, and (ii) new interpretations can be added, which requires new packages.

Each interpretation maintains its own data, which we call *properties*. The behavior of an interpretation is specified in method `compute`. It computes and stores properties that are associated with its box or ports. For

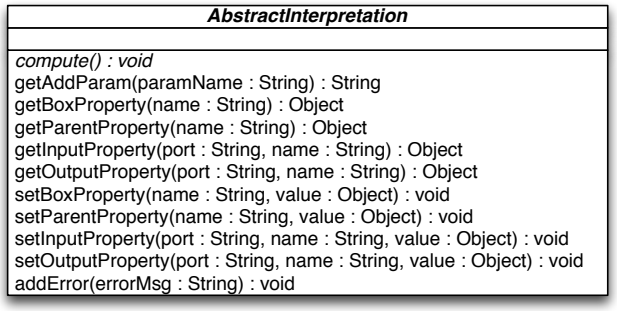


Fig. 5.1 The `AbstractInterpretation` class.

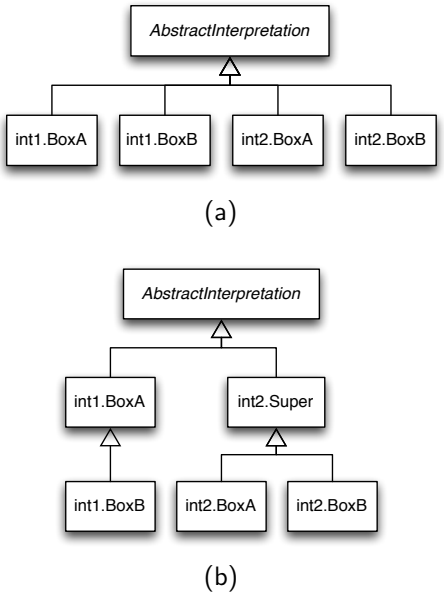


Fig. 5.2 Class diagrams for two interpretations `int1` and `int2`.

each box/port, properties are stored in a map that associates a value with a property identifier.[8] `AbstractInterpretation` provides `get` and `set` methods for accessing and modifying properties.

A typical class structure for interpretations is shown in Figure 5.2(a), where all classes inherit directly from `AbstractInterpretation`. Nevertheless, more complex structures arise. For example, one interpretation may inherit from another (this is common when defining preconditions, as an algorithm has the same preconditions of the interface it implements), or there may be an intermediate class that implements part (or all) of the behavior of several classes (usually of the same interpretation), as depicted in Figure 5.2(b). Besides requiring classes to extend `AbstractInterpretation`, `ReFlO` allows developers to choose the most convenient class structure for the interpretation at hand.

[8] This map is similar to `java.util.Properties` except that values are of type `Object` instead of `String`.

Although `ReFlO` expects a Java class for each box, if none is provided, `ReFlO` automatically selects an appropriate default class with an empty `compute` method. That is, in cases where there are no properties to set, no class needs to be provided.

Example 5.5 `ReFlO` generates complete executables in $\mathcal{M}2\mathcal{T}$ interpretations; so interface boxes have no mappings to code.

Example 5.6 Interpretations that set a ports' property usually do not need to provide a class for algorithms, as the properties of their ports are set when executing the `compute` methods of their internal boxes. This is the case of interpretations that compute postconditions, or interpretations that compute data sizes.

However, there are cases where properties of an algorithm cannot be inferred from its internal boxes. A prime example is the `do_nothing` algorithm—it has preconditions, but its internals suggest nothing. (In such cases, a Java class is written for an algorithm to express its preconditions.)

`ReFlO` executes an interpretation in the following way: for each box in a graph, its `compute` method is executed, with the execution order being determined by the topological order of the boxes (in the case of hierarchical graphs, the interpretation of an algorithm box is executed before the interpretations of its internal boxes). After execution, a developer (or `ReFlO`) may select any box and examine its properties.

5.1.2 Forward and Backward Interpretations

Usually, edges of an interpretation $\mathcal{I}$ have the same direction of the corresponding edge of interpretation $\mathcal{S}$. We have found cases where to compute some property about a graph it is convenient to invert the direction of the edges so that information flows right-to-left. In this case, an edge $\mathtt{b}_1 \rightarrow \mathtt{b}_2 \in \mathtt{P}$ maps to a unique edge $\mathcal{I}(\mathtt{b}_1) \leftarrow \mathcal{I}(\mathtt{b}_2) \in \mathcal{I}(\mathtt{P})$. We call such interpretations *backward* and the others are *forward*.

5.1.3 Composition of Interpretations

To make all of the above work, interpretations must be composable. Each interpretation computes certain properties of a program `P`, and it may need properties that are computed by other interpretations, *eg* to estimate the execution cost of a box, we may need an estimate of the volume of data output by a box. The same property (volume of data) may be needed for other interpretations (*eg* preconditions). Therefore, it is useful

to separate the computation of each property, in order to improve interpretation modularity and reusability.

ReFlO supports the composition of interpretations, where two or more interpretations are executed in sequence. An interpretation has access to the properties computed by previously executed interpretations. For example, an interpretation to compute data sizes ($\mathcal{DS}$) can be composed with one that uses data size estimates to form cost estimates ($\mathcal{ET}$). This is the compound interpretation $(\mathcal{ET} \circ \mathcal{DS})(\mathtt{P}) = \mathcal{ET}(\mathtt{P}) \circ \mathcal{DS}(\mathtt{P})$. This allows interpretation $\mathcal{DS}$ to be composed (reused) with other interpretations that also need data sizes.

5.2 Pre- and Postconditions

We use interpretations to compute box postconditions and then verify their preconditions, rather than providing a custom DSL for this purpose (*ie* pre- and postconditions are specified in the same language/framework used for other interpretations, currently Java).

Postconditions are evaluated by the $\mathcal{POST}$ interpretation. $\mathcal{POST}$ computes the properties that are output by a box given the properties that are input to that box. The postconditions of algorithms and patterns are inferred from the postconditions of their internal boxes.[9]

Preconditions are evaluated by the $\mathcal{PRE}$ interpretation. $\mathcal{PRE}$ reads the values of the properties about box inputs (computed by $\mathcal{POST}$), and checks if the preconditions of that box are satisfied. The method `addError` is used to send a message to ReFlO signaling a failure validating precondition. Thus, ReFlO uses $\mathcal{PRE} \circ \mathcal{POST}$ for computing postconditions and validating preconditions.

When a user tries to apply a transformation, ReFlO builds the list of possible replacements for the selected box(es). The $\mathcal{POST}$ interpretation is then executed, to compute the postconditions for each box in the graph that is to be transformed. ReFlO then evaluates the $\mathcal{PRE}$ interpretation on each replacement graph. If no precondition error is reported, the replacement graph is legal, otherwise it is disallowed.

Example 5.7 In Section 2.2 we mentioned the `do_nothing` implementation of `SORT`. To use such rewrite rule we are required to keep track of how streams are sorted. Thus, we associate a property to output ports, called `SortKey`. When a stream is sorted, `SortKey` is set to the sorting attribute. If unsorted, `SortKey` has an undefined value. The `SORT` box sets this property to its sort key, to specify its output is sorted. Other boxes may change the order of the stream without sorting it, in which case the `SortKey` property is set to undefined. Alternatively, a box may preserve stream order, in which case the sort key property of the input stream is copied to the sort key property of the output stream. The `do_nothing` algorithm reads the value of `SortKey` for its input stream, and compares it to the value of the desired order. If the sort keys are different, the `do_nothing` rewrite is invalid.

[9] ReFlO ignores the specification of explicit postconditions for algorithms or patterns. This prevents postconditions from being specified that are stronger than those computed from its internal boxes.

6 Case Study: Gamma Hash Join

This section serves a dual purpose: (1) to present a case study using DxT to re-engineer a legacy PnF application and (2) to illustrate how an RDM can be populated with rewrites. We have observed that there can be many ways in which a complex PnF graph can be derived; each derivation uses a slightly different or larger set of rewrites than other derivations. By exploring multiple derivations, the RDM is enriched and a better understanding of a design is achieved. *Each of the rewrites that we present in this section have been proven correct [7].*

Gamma was (and perhaps still is) the most sophisticated relational database machine built in academia [19]. It was created in the late 1980s and early 1990s without the aid of modern software architectural models. We focus on Gamma's join parallelization, which is typical of modern relational database machines, and use ReFlO screenshots to incrementally illustrate Gamma's derivations.[10] [11]

6.1 A Modicum of Domain Knowledge

Of course, to appreciate the rewrites that Gamma uses, one needs a modicum of domain knowledge about relational query processing. We assume this, providing references that elaborate such knowledge.

Look at Figure 6.1: it shows interface `HJOIN` (read "hash join") with three different implementations: a primitive, a map-reduce algorithm, and a bloom filter algorithm.

[10] The RDM used in this derivation is available at `http://cs.utexas.edu/users/schwartz/DxT/case-studies/gamma/models/databases.html`.

[11] For simplicity, the derivation presented does not use replication. A derivation using replication is available at `http://cs.utexas.edu/users/schwartz/DxT/case-studies/gamma/architectures/cascadejoin-rep/`.

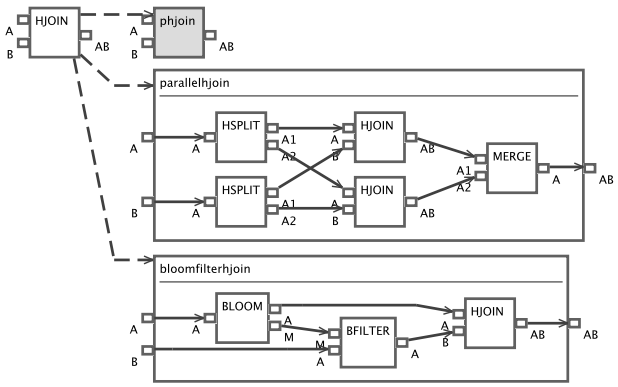


Fig. 6.1 `HJOIN` rewrite rules.

The primitive hash join implementation is simple: read all tuples of stream `A` into a main-memory hash table, where the join key of `A` tuples are hashed. Then read stream `B`, one tuple at a time. By hashing a `B` tuple's join key, one can quickly identify all `A` tuples that join with the `B` tuple. This algorithm has linear complexity in that each `A` and `B` tuple is read once.

The parallelization of `HJOIN` is textbook [5]: both input streams `A`, `B` are hash-split on their join keys using the same hash function. Each stream $\texttt{A}_\texttt{i}$ is joined with stream $\texttt{B}_\texttt{i}$ ($\texttt{i} \in \{1, 2\}$), as we know that $\texttt{A}_\texttt{i} \bowtie \texttt{B}_\texttt{j} = \emptyset$ for all $\texttt{i} \neq \texttt{j}$ (equal keys must hash to the same value). By merging the joins of $\texttt{A}_\texttt{i} \bowtie \texttt{B}_\texttt{i}$ ($\texttt{i} \in \{1, 2\}$), $\texttt{A} \bowtie \texttt{B}$ is produced as output.

A very different `HJOIN` algorithm makes use of Bloom filters to reduce the number of tuples to join [11]. It uses two new boxes: `BLOOM` (to create the filter) and `BFILTER` (to apply the filter). We call this algorithm `bloomfilterhjoin`. Here's how it works: the `BLOOM` box takes a stream of tuples `A` as input and outputs exactly the same stream `A` along with a bitmap `M`. The `BLOOM` box first clears `M`. Each tuple of `A` is read, its join key is hashed, the corresponding bit (indicated by the hash) is set in `M`, and the `A` tuple is output. After all `A` tuples are read, `M` is output. `M` is the *Bloom filter*.

The `BFILTER` box takes Bloom filter `M` and a stream of tuples `A` as input, and eliminates tuples of `A` that cannot join with tuples used to build the Bloom filter. The algorithm begins by reading `M`. Stream `A` is read one tuple at a time; the `A` tuple's join key is hashed, and the corresponding bit in `M` is checked. If the bit is unset, the `A` tuple is discarded as there is no tuple to which it can be joined. Otherwise the `A` tuple is output. A new `A` stream is the result.

Finally, output stream `A` of `BLOOM` and output stream `A` of `BFILTER` are joined. Given the behaviors of the `BLOOM`, `BFILTER`, and `HJOIN` boxes, it is easy to prove that `bloomfilterhjoin` does indeed produce $\texttt{A} \bowtie \texttt{B}$ [7].

We are now ready to present two derivations of Gamma: the first and simplest refines `HJOIN` by map-reduce first and then by bloom filter. The second swaps the order by refining `HJOIN` with bloom filter first, and then map-reduce. This seemingly minor difference yields a surprising wealth of rewrites.

6.2 Gamma – A Short Derivation

A *hash join* is an implementation of a relational equi-join; it takes two streams (`A`, `B`) of tuples as input and produces their equi-join $\texttt{A} \bowtie \texttt{B}$ as output (`AB`). Figure 6.2 is Gamma's PIM. It just uses the `HJOIN` interface to specify the desired behavior.

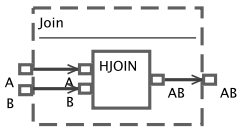


Fig. 6.2 The PIM: `Join`.

Our derivation starts by refining the `HJOIN` interface with its parallel map-reduce algorithm `parallelhjoin` (Figure 6.3).

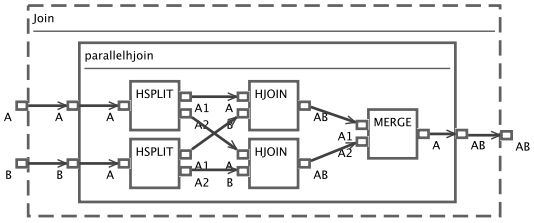


Fig. 6.3 Parallel `Join` graph.

Next, `bloomfilterhjoin` algorithm refines each of the `HJOIN` interfaces of Figure 6.3 to produce Figure 6.4. Flattening Figure 6.4, and refining each interface with

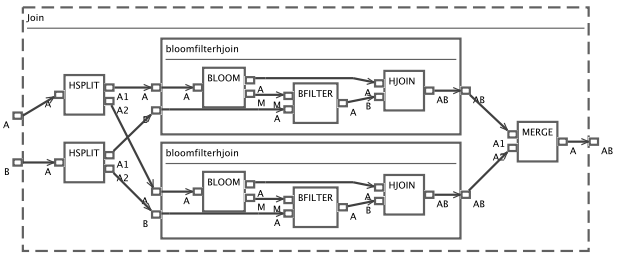


Fig. 6.4 Parallel `Join` graph, using Bloom filters.

its lone primitive yields Gamma's PSM (Figure 6.5).

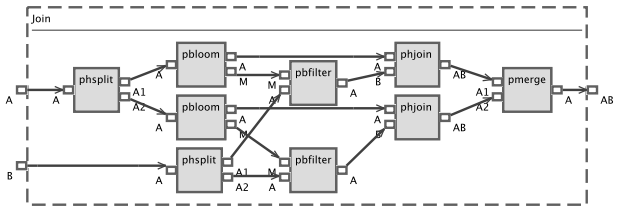


Fig. 6.5 Optimized parallel implementation of Gamma.

6.3 Gamma – An Alternative Derivation

A second, more involved derivation of Figure 6.5 exposes new rewrites. Historically, we discovered this derivation first, and only years later recognized the shorter derivation.

We start by applying the `bloomfilterhjoin` refinement. Doing so, we obtain the graph depicted in Figure 6.6.

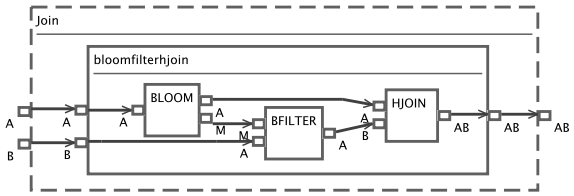


Fig. 6.6 `Join` graph using Bloom filters.

The next step is to parallelize the `BLOOM`, `BFILTER`, and `HJOIN` boxes by refining each with their map-reduce versions (Figure 6.7(a)).

A `BLOOM` box is parallelized by hash-splitting its input stream `A` into substreams $\mathtt{A}_1, \mathtt{A}_2$, creating a Bloom filter $\mathtt{M}_1, \mathtt{M}_2$ for each substream, coalescing $\mathtt{A}_1, \mathtt{A}_2$ back into `A`, and merging bit maps $\mathtt{M}_1, \mathtt{M}_2$ into a single map `M`. A `BFILTER` box is parallelized by hash-splitting its input stream `A` into substreams $\mathtt{A}_1, \mathtt{A}_2$. Map `M` is decomposed into submaps $\mathtt{M}_1, \mathtt{M}_2$ and substream $\mathtt{A}_\mathtt{i}$ is filtered by $\mathtt{M}_\mathtt{i}$. The reduced substreams $\mathtt{A}_1, \mathtt{A}_2$ output by `BFILTER` boxes are coalesced into stream `A`. The same hash function must be used by all algorithms.

This alternative derivation already requires two additional refinements to map interfaces `BLOOM` and `BFILTER` to their map-reduce algorithms. Still, this graph is not yet the optimized Gamma PSM.

In this derivation, refinement is insufficient to produce Gamma's PSM. The graph of Figure 6.7(a) has three *serialization bottlenecks* which degrade performance. Consider the `MERGE` of substreams $\mathtt{A}_1, \mathtt{A}_2$ (produced by `BLOOM`) into `A`, followed by a `HSPLIT` to reconstruct $\mathtt{A}_1, \mathtt{A}_2$. *There is no need to materialize* `A`: the (`MERGE`, `HSPLIT`) pair can also be implemented by the identity map: $\mathtt{A}_\mathtt{i} \rightarrow \mathtt{A}_\mathtt{i}$. The same applies for the (`MERGE`, `HSPLIT`) pair for collapsing and reconstructing substreams produced by `BFILTER`. The removal of (`MERGE`, `HSPLIT`) pairs eliminates two serialization bottlenecks. This optimization is encoded in the graph presented in Figure 6.8(a).

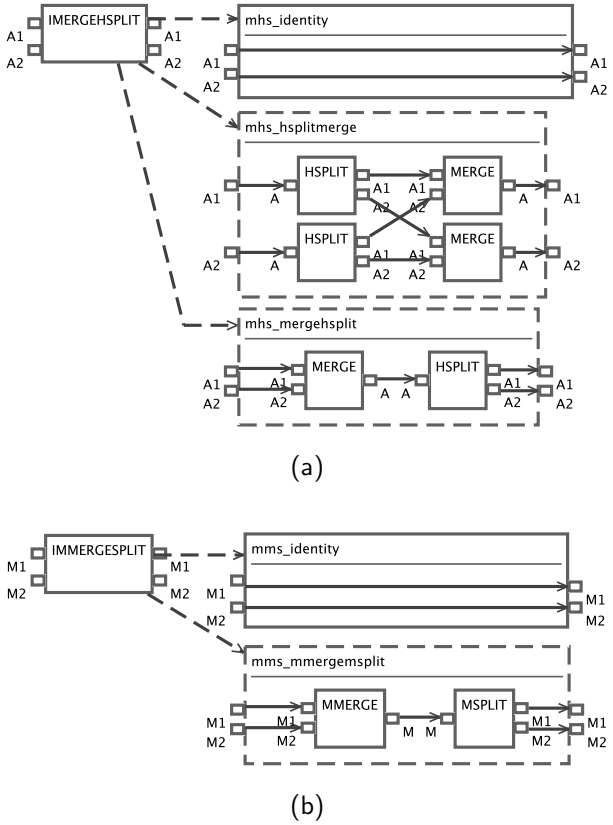


Fig. 6.8 Gamma optimizations.

The third bottleneck combines maps $\mathtt{M}_1, \mathtt{M}_2$ into `M` and then decomposes `M` back into $\mathtt{M}_1, \mathtt{M}_2$. The (`MMERGE`, `MSPLIT`) pair can also be implemented by an identity map: $\mathtt{M}_\mathtt{i} \rightarrow \mathtt{M}_\mathtt{i}$. This optimization removes the (`MMERGE`, `MSPLIT`) boxes and reroutes the streams appropriately.[12] This optimization is encoded in the model presented in Figure 6.8(b).

Using the *Find Optimization* tool available in `ReFlO`, the bottlenecks are identified, as depicted in Figure 6.7(b). After applying the identity optimizations, we can refine the interfaces used with primitive imple-

[12] There are many ways in which `MMERGE` and `MSPLIT` can be realized. The simplest is this: `M` is a $2 \times \mathtt{k}$ bitmap. The join key of an `A` tuple is hashed twice: once to determine the row of `M`, the second to determine the column within the selected row. Thus, all tuples of substream $\mathtt{A}_\mathtt{i}$ hash to row `i` of `M`. `MMERGE` combines $\mathtt{M}_1, \mathtt{M}_2$ into `M` by boolean disjunction. For each `i`, `MSPLIT` extracts row `i` from `M` and zeros out the rest of $\mathtt{M}_\mathtt{i}$.

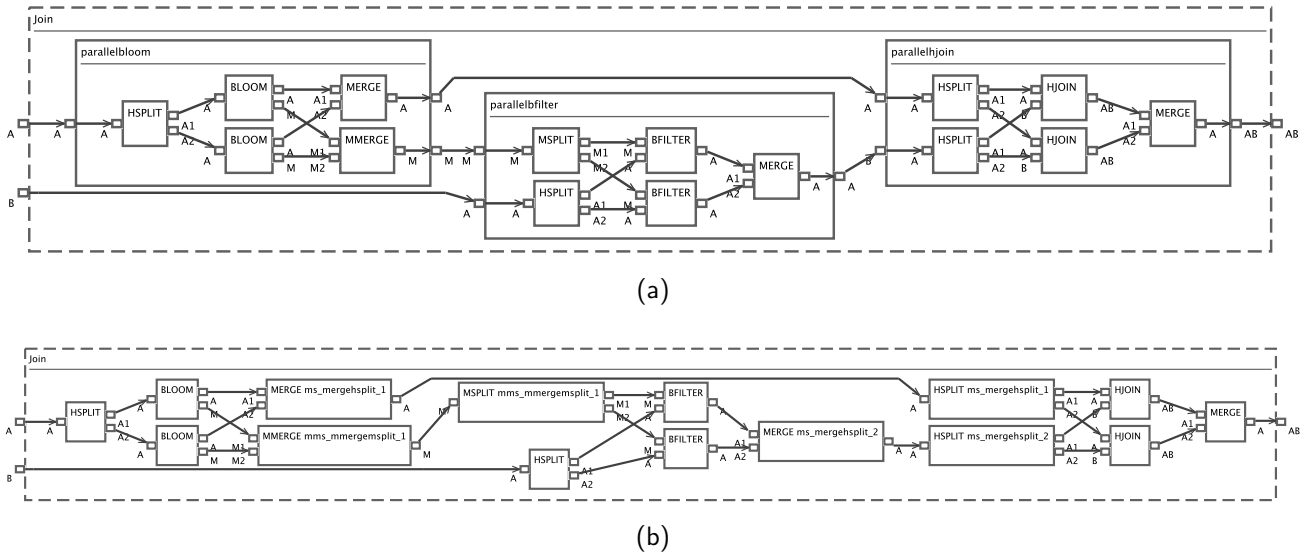


Fig. 6.7 Parallelization of `Join` graph, and its bottlenecks.

mentations, to obtain the optimized Gamma graph, already presented in Figure 6.5.

6.4 An Interpretation Example – Costs Estimates

During the process of deriving a PSM, it is useful for the developers to be able to estimate values of quality attributes they are trying to improve. This is a typical application for interpretations.

For databases, estimates for execution time are computed by adding the execution cost of each interface or primitive present in a graph. The cost of an interface[13] or primitive is computed based on the size of the data being processed. The $\mathcal{DS}$ interpretation takes estimates of input data sizes and computes estimates of output data sizes.

Size estimates are used to build a cost expression representing the cost of executing interfaces and primitives. We build a string containing a cost symbolic expression, as during design time we do not have concrete values for properties needed to compute costs. Thus, we associate a variable (string) to those properties, and we use those strings to build the symbolic expression representing the costs.

Figure 6.9 shows the code used to generate a cost estimate for `phjoin` primitive. `phjoin` is executed by reading each tuple of stream `A` and storing it in a hash table (`cHJoinAItem` is a constant that represents the cost of processing a tuple of stream `A`), and then each tuple of stream `B` is read and joined with tuples of `A` (`cHJoinBItem` is a constant that represents the cost of processing a tuple of stream `B`). Thus, the cost of `phjoin` is given by $\texttt{size}_\texttt{a} * \texttt{cHJoinAItem} + \texttt{size}_\texttt{b} * \texttt{cHJoinBItem}$. As `HJOIN` can always be implemented by `phjoin`, we can use the same cost expression for `HJOIN`. The $\mathcal{COSTS}$ interpretation is backward, as the costs of an algorithm are computed from the costs of its internal boxes (*ie* we need to compute costs of internal boxes first). So the costs are progressively sent to their parent boxes, until they reach the outermost box, where the costs of all boxes are aggregated, providing a cost estimate for the entire graph. Figure 6.10 shows the code used by interpretations of algorithm boxes that simply add their costs to the aggregated costs stored on their parent boxes.

```
public class phjoin extends AbstractInterpretation {
  public void compute() {
    String sizeA=(String)getInputProperty("A","Size");
    String sizeB=(String)getInputProperty("B","Size");
    String cost="("+sizeA+") * cHJoinAItem + ("
        +sizeB+") * cHJoinBItem";
    setBoxProperty("Cost",cost);
    String parentCost=(String)getParentProperty("Cost");
    if(parentCost==null) parentCost=cost;
    else parentCost="("+parentCost+") + ("+cost+")";
    setParentProperty("Cost", parentCost);
  }
}
```

Fig. 6.9 Interpretation that estimates `phjoin` cost.

[13] An interface cost is set to that of its most general primitive implementation.

```
public class Algorithm extends AbstractInterpretation {
  public void compute() {
    String cost=(String) getBoxProperty("Cost");
    String parentCost=(String)getParentProperty("Cost");
    if(parentCost==null) parentCost=cost;
    else parentCost="("+parentCost+") + ("+cost+")";
    setParentProperty("Cost", parentCost);
  }
}
```

Fig. 6.10 Interpretation that processes costs for algorithm boxes.

7 Perspective

To round out our presentation, we sketch a general process on how to use ReFlO effectively and provide some insights on ReFlO's limitations.

7.1 A Process on How to Use ReFlO

ReFlO can be used for different purposes, namely to reverse-engineer existing PnF applications (*ie* to deduce a sequence of transformations that were used in a legacy application to map its PIM to its PSM) or to build new optimized programs, starting from a PIM. In either case, the process starts with a domain analysis [51], where an expert catalogs the fundamental operations of a domain with their implementations. The domain expert also knows that certain compositions of operations are inefficient; thus he needs to identify optimizations as well. It is also his job to provide evidence (*eg* a proof) that each transformation is correct and to specify the pre- and postconditions of each box.

This "minimal" model may be enhanced further. To explore different implementations of a program (*eg* efficiency or availability), additional interpretations are needed to estimate a program's quality attributes.

This knowledge can then be used by developers (or by the domain expert itself) to derive efficient programs. Typically, a developer starts with a PIM of a target application. ReFlO can be used incrementally to apply transformations and derive various PSMs, until a PSM is found that meets desired constraints on quality attributes. The developer may also export a domain model to an external tool to automatically search the space of a given PIM for a desirable PSM [46].

Domain analysis and derivations are often conducted in parallel. The domain model is usually built while reverse engineering existing programs, *ie* domain experts may be using ReFlO to derive programs and to build the domain model at the same time.

Finally, we note that ReFlO was developed specifically with pipe-and-filter software architectures in mind. We believe that ReFlO should be useble in other practical applications, such as dataflow and workflow applications, as well as functional-based application designs.

7.2 Limitations of ReFlO

We have used ReFlO to derive the designs of other applications—*crash fault-tolerant (CFT)* servers [60] and dense linear algebra algorithms [48].

We chose a PnF notation to model programs and transformations that was influenced by the case-studies we explored. Although in certain domains a program's structure easily fits this architecture style (*eg* streaming applications [70], dataflow applications [1]), we are aware that some domains may require more effort to mine than others, and existing code may need to be adapted in order to provide code implementations for domain components. ReFlO seems best suited for mature and well-understood domains, although our use of ReFlO to explore designs of CFT servers is an example of a domain that hardly qualifies as mature. Further, ReFlO is not limited to domains with stateless computations either. The CFT servers that we studied were stateful [60].

The graphical notation (syntax) provided by ReFlO is not sufficient to encode domain knowledge. Pre- and postconditions are specified in Java; quality attribute definitions and computations are also specified in Java. Further, we found that many transformations are simple variations of each other; using templates substantially reduces the effort to encode rule variants. This combination of ideas and representations was sufficient to derive optimized programs in the different domains that we have studied.

It is possible that DSLs may simplify the task of writing different (and standardized) interpretations, rather than writing Java code. We leave this exploration to future work.

ReFlO promotes correct by construction derivations. Providing proofs of correctness for rewrite rules takes effort. Nevertheless, (i) proving individual transformations correct is usually simpler than proving the entire system correct; and (ii) proofs for transformations are reusable, whereas the proof for an entire system is usually not. Moreover, experts are far better able to provide proofs than developers who simply use the components and rewrite rules that experts have defined. *Although having proof of correctness is important,* ReFlO *does not require such proofs.*

Finally, we are hardly the first to notice that implementations of an interface can be specialized for particular inputs and particular conditions [54]. This forced

Perry, and now us, to use PSP. It is worth observing that violations of the LSP are documented in the widely used JDK (*eg* `TreeMap` implementation of `Map` [2]).

8 Related Work

`ReFlO` is a tool to specify model transformations. Common tools/languages for model transformation, such as ATL [3] or Epsilon [26], specify transformations using executable code. Our approach specifies transformations by providing examples, which has two advantages.

First, it makes it easier for domain experts (the ones with the knowledge about the valid domain transformations) to specify transformations [72,4,76,66,62]. Other approaches have been proposed to address this challenge. Baar and Whittle [4] explain how a metamodel (*eg* for PnF graphs) can be extended to also support the specification of transformations over models. In this way, a concrete syntax, similar to the syntax used to define models, is used to define model transformations, making those transformations easier to read and understand by humans. In `ReFlO` transformations are also specified using a concrete syntax.

Model transformation by example (MTBE) [72,76] proposes to (semi-)automatically derive transformation rules based on set of key examples of mappings between source and target models. The approach was improved with the use of Inductive Logic Programming to derive the rules [73]. The rules may later be manually refined. Our rules provide examples in minimal context, and unlike in MTBE, we do not need to relate the objects of the source and target model (ports of interfaces are implicitly related to the ports of their implementations). Additionally, MTBE is more suited for exogenous transformations, whereas we use endogenous transformations [24,39,50].

More recently, a similar approach, *model transformation by demonstration* [66] was proposed, where users show how source models are edited in order to be mapped to the target models. A tool [65] captures the user actions and derives the transformations conditions and the operations needed to perform the transformations. When using `ReFlO` it is enough to provide the original element and its possible replacements.

Graph grammars [61] also provide a declarative way to define model/graph transformations using examples. In particular, our rules are specified in a similar way to productions in the *double-pushout approach* for hypergraphs [38]. AGG [67] is probably the most similar tool to `ReFlO`. It deals with graph rewrite rules, whereas our transformations are better captured by hypergraph rewrite rules, due to the role of ports in the transformations (that specify the gluing points in the transformation). Moreover, it is not clear whether these other approaches would be able to capture pre- and post-conditions, which are essential for correct PnF graph derivation.

Another advantage is that `ReFlO` rewrites make domain knowledge more accessible to non-experts, as `ReFlO` encodes domain knowledge in a graphical and abstract way, relating alternative ways of implementing a particular behavior. Capturing algebraic identities is on the base of algebraic specifications and term rewriting systems. Relational query optimization [44,63] is one of the most successful examples of application of these ideas, where, as in `ReFlO`, the goal is to optimize programs. Program verification tools, such as CafeOBJ [20] or Maude [14], are another common application. `ReFlO` was developed to support DxT approach, where transformations are specified as graph rewrites, instead of term rewriting.

More generally, `ReFlO` provides a framework for program transformation that allows developers to interactively transform high-level program specifications into optimized implementations. SPIRAL [57] and AMPHION [45], are examples of projects with a similar goal, *ie* to synthesize efficient implementations for high-level specifications. Besides the differences in the way as they model the domain knowledge, and the strategies used to transform programs, the focus of these tools was on the automation of the synthesis process, whereas `ReFlO` is a tool for interactive development. Tools such as SPIRAL or AMPHION are useful when we have a complete model of a domain, whereas `ReFlO` is a tool to be used both by domain experts in the process of building those domain models, and later by other developers to optimize their programs. `ReFlO` is able to export its models to code that can be used with DxTer [47,46] a tool that, like SPIRAL and AMPHION, automates the search for the optimized implementation.

Several tools for PnF modeling have been proposed, such as LabVIEW [68], Simulink [64], Weaves [32], Fractal [12], or StreamIt [69]. However, they focus on component specification and construction of systems composing those components. We realized that transformations (in particular optimizations) play an essential role when building efficient architectures using components. LabVIEW does support optimizations, but only when mapping a LabVIEW model to an executable. Users can *not* define refinements and optimizations, but LabVIEW compiler technicians can. More than a tool for the specification of PnF graphs, `ReFlO` provides the ability for users to capture domain-specific graph transformations and to apply them to PnF designs.

The interpretation framework provided by ReFlO offers a way to perform model simulation/animation, which allows developers to predict properties of the system being modeled without having to actually build it. LabVIEW and Simulink are typical examples of tools to simulate PnF architectures. Ptolemy II [25] provides modeling and animation support for heterogeneous models.

Other tools exist for different types of models, such as UML [15,21], or Colored Petri Nets [59]. Our work has some similarities with *Model-Driven Performance Engineering (MDPE)* [29]. However, we focus on endogenous transformations, and how those transformations improve architecture's quality attributes, not exogenous transformations, as it is common in MDPE. Our solution for cost estimation can be compared with the *coupled model transformations* proposed by Becker [9]. However, the cost estimates (as well as other interpretations) are transformed in parallel with the PnF graph, not during M2T transformations. Other solutions have proposed for component based systems [41]. KLAPER [35] provides a language to automate the creation of performance models from component models. Kounev [40] shows how *Queueing Petri Nets* can be used to model systems, allowing prediction of its performance characteristics. The *Palladio Component Model* [10] provides a powerful metamodel to support performance prediction, adapted to the different developer roles. We do not provide a specific framework for cost/performance estimates, as the expressiveness of ReFlO's interpretations framework allow us to support this capability.

ReFlO allows *properties* to be assigned to boxes. Properties are similar to attributes in an *attributed graph* [13]. Those properties are then used to specify pre- and postconditions. Allowing the implementations to have stronger preconditions, we may say that the rewrite rules may have *applicability predicates* [13] or *attribute conditions* [67], which specify a predicate over the attributes of a graph when a match/morphism is not enough to specify whether a transformation can be applied. Pre- and postconditions were used in other component systems, such as Inscape [54], with the goal of validating component compositions. In our case, the main purpose of pre- and postconditions is to decide when transformations can be applied. Nevertheless, they may also be used to validate component compositions.

Abstract interpretations [16,52] define properties about a program's state and specify how instructions affect those properties. The properties are correct, but often imprecise. Still, they provide useful information to allow compilers to perform certain transformations. In ReFlO, postconditions play a similar role. They compute properties about operation outputs based on properties of their inputs, and the properties may be used to decide whether a transformation can be applied or not. As for abstract interpretations, the properties computed by postconditions have to describe output values correctly. In contrast, properties used to compute costs, for example, are often just estimates, and therefore may not be correct, but in this case approximations are usually enough. The Broadway compiler [37] used the same idea of propagating properties about values, to allow the compiler to transform the program. The Broadway compiler separated the compiler infrastructure from domain expertise, and like in ReFlO, the goal was to allow users to specify domain-specific optimizations. Specifying pre- and postconditions as properties that are propagated is also not new. This was the approach used in the Inscape environment [55,56], and later by Batory and Geraci [6], and Feiler and Li [27]. Interpretations provide alternative views of a PnF graph that are synchronized as it is incrementally changed [58].

9 Conclusions

ReFlO was motivated by a lack of technology that would help us understand legacy pipe-and-filter (PnF) applications. Unless PnF graphs are very simple, they are spaghetti diagrams—difficult to understand, impossible to know if they are correct, and without tool support, difficult to analyze. Existing PnF tools, by in large, apply basic checks and convert a PnF graph into an executable, but not much else.

MDE places such tools in context of a much larger paradigm—the ability, indeed desire, to derive PnF applications using domain-specific rewrites that are implicitly used by experts, capturing and systematizing domain knowledge that would otherwise be lost or easily forgotten. Given a legacy PnF application, ReFlO makes it possible to derive its design with rewrite rules that are used by experts, and as we showed in this paper, rules that can be proven correct. To the best of our knowledge, this is the first derivation of Gamma that has been proven correct.

In this paper, we presented the core ideas behind ReFlO. We showed that the Perry Substitution Principle, rather than the Liskov Substitution Principle, is a foundation for ReFlO graph rewrites. We explained how a few basic operations (refine, flatten, abstract, optimize, find optimization, and expand) could be used by designers to derive PnF designs. Further, ReFlO is itself an extensible framework in which different interpretations of a PnF graph (which arise in checking pre- and postconditions, or cost evaluations) can be both added

and composed as needed. Further, we illustrated a technique that we have used to populate ReFlO libraries with domain knowledge—*ie* different derivations of a design utilize different fundamental rewrites of a domain.

We believe ReFlO is a valuable step toward interactive design tools that aid domain-specific program development and knowledge collection.

Availability. ReFlO is available online at `http://www.cs.utexas.edu/users/schwartz/DxT/reflo/`. All PnF figures in this paper are screenshots from ReFlO. ReFlO is a Eclipse [22] plugin. The modeling languages were specified using Ecore [23], and the model editors were implemented using the GEF [33] and GMF [34]. The model transformations and model validation were implemented using the Epsilon [26] family of languages.

Acknowledgements We gratefully acknowledge helpful feedback from B. Marker (Texas), T. Riché (National Instruments), R. Silva (Minho), and the anonymous reviewers. This work was supported by NSF grants CCF 0724979 and OCI-1148125. Rui Gonçalves and João Sobral are funded by ERDF – European Regional Development Fund through the COMPETE Programme (operational programme for competitiveness) and by National Funds through the FCT – Fundação para a Ciência e a Tecnologia (Portuguese Foundation for Science and Technology) within projects FCOMP-01-0124-FEDER-010152 and FCOMP-01-0124-FEDER-011413. Rui Gonçalves is additionally funded by FCT grant SFRH/BD/47800/2008.

References

1. Dataflow application areas. `http://www.ni.com/labview/applications/`, 2013.
2. TreeMap (Java Platform SE 7). `http://docs.oracle.com/javase/7/docs/api/java/util/TreeMap.html`, 2013.
3. ATL - a model transformation technology. `http://www.eclipse.org/atl/`.
4. Thomas Baar and Jon Whittle. On the usage of concrete syntax in model transformation rules. In *PSI '06: Proceedings of the 6th international Andrei Ershov memorial conference on Perspectives of systems informatics*, pages 84–97, 2006.
5. C. K. Baru, G. Fecteau, A. Goyal, H. Hsiao, A. Jhingran, S. Padmanabhan, G. P. Copeland, and W. G. Wilson. DB2 parallel edition. *IBM Systems Journal*, 34(2):292–322, 1995.
6. Don Batory and Bart J. Geraci. Composition validation and subjectivity in genvoca generators. *IEEE Transactions on Software Engineering*, 23(2):67–82, 1997.
7. Don Batory and Bryan Marker. Correctness proofs of the gamma database machine architecture. Technical Report TR-11-17, The University of Texas at Austin, Department of Computer Science, 2011.
8. Don Batory and Sean William O'Malley. The design and implementation of hierarchical software systems with reusable components. *ACM Transactions on Software Engineering and Methodology (TOSEM)*, 1(4):355–398, 1992.
9. Steffen Becker. Coupled model transformations. In *WOSP '08: Proceedings of the 7th international workshop on Software and performance*, pages 103–114, 2008.
10. Steffen Becker, Heiko Koziolek, and Ralf Reussner. The palladio component model for model-driven performance prediction. *Journal of Systems and Software*, 82(1):3–22, 2009.
11. Burton H. Bloom. Space/time trade-offs in hash coding with allowable errors. *Communications of the ACM*, 13(7):422–426, 1970.
12. E. Bruneton, T. Coupaye, and J.B. Stefani. The Fractal Component Model. `http://fractal.ow2.org`, 2004.
13. Horst Bunke. Attributed programmed graph grammars and their application to schematic diagram interpretation. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 4(6):574–582, 1982.
14. M. Clavel, F. Durán, S. Eker, P. Lincoln, N. Martí-Oliet, J. Meseguer, and J. F. Quesada. Maude: specification and programming in rewriting logic. *Theoretical Computer Science*, 285(2):187–243, 2002.
15. Benoit Combemale, Xavier Crégut, Jean-Patrice Giacometti, Pierre Michel, and Marc Pantel. Introducing simulation and model animation in the MDE topcased toolkit. In *ERTS '08: 4th European Congress EMBEDDED REAL TIME SOFTWARE*, 2008.
16. Patrick Cousot and Radhia Cousot. Abstract interpretation: a unified lattice model for static analysis of programs by construction or approximation of fixpoints. In *POPL '77: Proceedings of the 4th ACM SIGACT-SIGPLAN symposium on Principles of programming languages*, pages 238–252, 1977.
17. Ivica Crnkovic. *Building Reliable Component-Based Software Systems*. Artech House, Inc., Norwood, MA, USA, 2002.
18. Dinesh Das. *Making Database Optimizers More Extensible*. PhD thesis, The University of Texas at Austin, 1995.
19. D. J. DeWitt, S. Ghandeharizadeh, D. A. Schneider, A. Bricker, H. I. Hsiao, and R. Rasmussen. The gamma database machine project. *IEEE Transactions on Knowledge and Data Engineering*, 2(1):44–62, 1990.
20. Razvan Diaconescu, Kokichi Futatsugi, and Shusaku Iida. Component-based algebraic specification and verification in CafeOBJ. In *FM '99: Proceedings of the Wold Congress on Formal Methods in the Development of Computing Systems-Volume II*, pages 1644–1663, 1999.
21. Dolev Dotan and Andrei Kirshin. Debugging and testing behavioral UML models. In *OOPSLA '07: Companion to the 22nd ACM SIGPLAN conference on Object-oriented programming systems and applications companion*, pages 838–839, 2007.
22. Eclipse. `http://eclipse.org`.
23. Eclipse Modeling Framework. `http://www.eclipse.org/modeling/emf/`.
24. Alexander Egyed, Nikunj R. Mehta, and Nenad Medvidovic. Software connectors and refinement in family architectures. In *IW-SAPF-3: Proceedings of the International Workshop on Software Architectures for Product Families*, pages 96–106, 2000.
25. Johan Eker, Jorn Janneck, Edward A. Lee, Jie Liu, Xiaojun Liu, Jozsef Ludvig, Sonia Sachs, Yuhong Xiong, and Stephen Neuendorffer. Taming heterogeneity - the ptolemy approach. *Proceedings of the IEEE*, 91(1):127–144, 2003.
26. Epsilon. `http://www.eclipse.org/gmt/epsilon/`.
27. Peter Feiler and Jun Li. Consistency in dynamic reconfiguration. In *ICCDS '98: Proceedings of the Fourth International Conference on Configurable Distributed Systems*, pages 189–196, 1998.

28. David S. Frankel. *Model Driven Architecture: Applying MDA to Enterprise Computing*. John Wiley & Sons, Inc., 2003.
29. Mathias Fritzsche and Jendrik Johannes. Putting performance engineering into model-driven engineering: Model-driven performance engineering. In *Models in Software Engineering*, pages 164–175. Springer-Verlag, 2008.
30. David Garlan and Mary Shaw. An introduction to software architecture. Technical Report CMU-CS-94-166, Carnegie Mellon University, 1994.
31. Rui C. Gonçalves. *Parallel Programming by Transformation*. PhD thesis, Departamento de Informática, Universidade do Minho, (To appear).
32. Michael M. Gorlick and Rami R. Razouk. Using weaves for software construction and analysis. In *ICSE '91: Proceedings of the 13th international conference on Software engineering*, pages 23–34, 1991.
33. Graphical Editing Framework. `http://www.eclipse.org/gef/`.
34. Eclipse graphical modeling framework. `http://www.eclipse.org/gmf/`.
35. Vincenzo Grassi, Raffaela Mirandola, and Antonino Sabetta. From design to analysis models: a kernel language for performance and reliability analysis of component-based systems. In *WOSP '05: Proceedings of the 5th international workshop on Software and performance*, pages 25–36, 2005.
36. C. Green, D. Luckham, R. Balzer, T. Cheatham, and C. Rich. Report on a knowledge-based software assistant. Technical report, Kestrel Institute, 1983.
37. Samuel Z. Guyer and Calvin Lin. Broadway: A compiler for exploiting the domain-specific semantics of software libraries. *Proceedings of the IEEE*, 93(2):342–357, 2005.
38. Annegret Habel. *Hyperedge Replacement: Grammars and Languages*. Springer-Verlag New York, Inc., 1992.
39. Reiko Heckel and Sebastian Thöne. Behavior-preserving refinement relations between dynamic software architectures. In *WADT' 04: Proceedings of the 17th International Workshop on Algebraic Development Techniques*, pages 1–27, 2004.
40. Samuel Kounev. Performance modeling and evaluation of distributed component-based systems using queueing petri nets. *IEEE Transactions on Software Engineering*, 32(7):486–502, 2006.
41. Heiko Koziolek. Performance evaluation of component-based software systems: A survey. *Performance Evaluation*, 67(8):634–658, 2010.
42. Barbara Liskov and Jeannette M. Wing. A new definition of the subtype relation. In *ECOOP '93: Proceedings of the 7th European Conference on Object-Oriented Programming*, pages 118–141, 1993.
43. Barbara H. Liskov and Jeannette M. Wing. A behavioral notion of subtyping. *ACM Transactions on Programming Languages and Systems*, 16(6):1811–1841, 1994.
44. Guy M. Lohman. Grammar-like functional rules for representing query optimization alternatives. In *SIGMOD '88: Proceedings of the 1988 ACM SIGMOD international conference on Management of data*, pages 18–27, 1988.
45. Michael R. Lowry, Andrew Philpot, Thomas Pressburger, and Ian Underwood. Amphion: Automatic programming for scientific subroutine libraries. In *ISMIS '94: Proceedings of the 8th International Symposium on Methodologies for Intelligent Systems*, pages 326–335, 1994.
46. Bryan Marker, Don Batory, and C.T. Shepherd. DxTer: A program synthesizer for dense linear algebra. Technical report, The University of Texas at Austin, Department of Computer Science, 2012.
47. Bryan Marker, Jack Poulson, Don Batory, and Robert van de Geijn. Designing linear algebra algorithms by transformation: Mechanizing the expert developer. In *iWAPT '12: International Workshop on Automatic Performance Tuning*, 2012.
48. Bryan Marker, Andy Terrel, Jack Poulson, Don Batory, and Robert van de Geijn. Mechanizing the expert dense linear algebra developer. In *PPoPP '12: Proceedings of the 17th ACM SIGPLAN symposium on Principles and Practice of Parallel Programming*, pages 289–290, 2012.
49. Nenad Medvidovic, David S. Rosenblum, and Richard N. Taylor. A language and environment for architecture-based software development and evolution. In *ICSE '99: Proceedings of the 21st international conference on Software engineering*, pages 44–53, 1999.
50. Tom Mens and Pieter Van Gorp. A taxonomy of model transformation. *Electronic Notes in Theoretical Computer Science*, 152:125–142, 2006.
51. James M. Neighbors. *Software Construction Using Components*. PhD thesis, Department of Information and Computer Science, University of California, Irvine, 1980.
52. Flemming Nielson, Hanne R. Nielson, and Chris Hankin. *Principles of Program Analysis*. Springer-Verlag, 1999.
53. Richard F. Paige, Dimitrios S. Kolovos, and Fiona A. C. Polack. Refinement via consistency checking in MDA. *Electronic Notes in Theoretical Computer Science*, 137(2):151–161, 2005.
54. Dewayne E. Perry. Version control in the inscape environment. In *ICSE '87: Proceedings of the 9th international conference on Software Engineering*, pages 142–149, 1987.
55. Dewayne E. Perry. The inscape environment. In *ICSE '89: Proceedings of the 11th international conference on Software engineering*, pages 2–11. ACM, 1989.
56. Dewayne E. Perry. The logic of propagation in the inscape environment. *ACM SIGSOFT Software Engineering Notes*, 14(8):114–121, 1989.
57. Markus Püschel, José M. F. Moura, Bryan Singer, Jianxin Xiong, Jeremy Johnson, David Padua, Manuela Veloso, and Robert W. Johnson. Spiral: A generator for platform-adapted libraries of signal processing algorithms. *International Journal of High Performance Computing Applications*, 18(1):21–45, 2004.
58. István Ráth, Gergely Varró, and Dániel Varró. Change-driven model transformations. In *MODELS '09: Proceedings of the 12th International Conference on Model Driven Engineering Languages and Systems*, pages 342–356, 2009.
59. Anne Vinter Ratzer, Lisa Wells, Henry Michael Lassen, Mads Laursen, Jacob Frank Qvortrup, Martin Stig Stissing, Michael Westergaard, Søren Christensen, and Kurt Jensen. CPN tools for editing, simulating, and analysing coloured petri nets. In *ICATPN '03: Proceedings of the 24th international conference on Applications and theory of Petri nets*, pages 450–462, 2003.
60. Taylor. L. Riché, Rui C. Gonçalves, Bryan Marker, and Don Batory. Pushouts in software architecture design. In *GPCE '12: Proceedings of the 11th ACM international conference on Generative programming and component engineering*, pages 84–92, 2012.
61. Grzegorz Rozenberg. *Handbook of Graph Grammars and Computing by Graph Transformation, Vol I: Foundations*. World Scientific, 1997.
62. Hajer Saada, Xavier Dolquesa, Marianne Huchard, Clémentine Nebut, and Houari Sahraoui. Generation of operational transformation rules from examples of model transformations. In *MODELS '12: Proceedings of the 15th International Conference on Model Driven Engineering Languages and Systems*, pages 546–561, 2012.

63. P. Griffiths Selinger, M. M. Astrahan, D. D. Chamberlin, R. A. Lorie, and T. G. Price. Access path selection in a relational database management system. In *SIGMOD '79: Proceedings of the 1979 ACM SIGMOD international conference on Management of data*, pages 23–34, 1979.
64. Simulink - Simulation and Model-Based Design. `http://www.mathworks.com/products/simulink/`.
65. Yu Sun, Jeff Gray, and Jules White. MT-scribe: an end-user approach to automate software model evolution. In *ICSE '11: Proceedings of the 33rd International Conference on Software Engineering*, pages 980–982, 20011.
66. Yu Sun, Jules White, and Jeff Gray. Model transformation by demonstration. In *MODELS '09: Proceedings of the 12th International Conference on Model Driven Engineering Languages and Systems*, pages 712–726, 2009.
67. Gabriele Taentzer. AGG: A graph transformation environment for modeling and validation of software. In *Applications of Graph Transformations with Industrial Relevance*, volume 3062, pages 446–453. Springer Berlin / Heidelberg, 2004.
68. The LabVIEW Environment. `http://www.ni.com/labview/`.
69. William Thies. *Language and Compiler Support for Stream Programs*. PhD thesis, MIT, 2008.
70. William Thies, Michal Karczmarek, and Saman P. Amarasinghe. StreamIt: A language for streaming applications. In *CC '02: Proceedings of the 11th International Conference on Compiler Construction*, pages 179–196, 2002.
71. Massimo Tisi, Frédéric Jouault, Piero Fraternali, Stefano Ceri, and Jean Bézivin. On the use of higher-order model transformations. In *ECMDA-FA '09: Proceedings of the 5th European Conference on Model Driven Architecture - Foundations and Applications*, pages 18–33, 2009.
72. Dániel Varró. Model transformation by example. In *MODELS '06: Proceedings of the 11th international conference on Model Driven Engineering Languages and Systems*, pages 410–424, 2006.
73. Dániel Varró and Zoltán Balogh. Automating model transformation by example using inductive logic programming. In *SAC '07: Proceedings of the 2007 ACM symposium on Applied computing*, pages 978–984, 2007.
74. Wikipedia. Component-based software engineering. `http://en.wikipedia.org/wiki/Component-based_software_engineering`, 2013.
75. Manuel Wimmer, Gerti Kappel, Angelika Kusel, Werner Retschitzegger, Johannes Schönböck, Werner Schwinger, Dimitris Kolovos, Richard Paige, Marius Lauder, Andy Schürr, and Dennis Wagelaar. Surveying rule inheritance in model-to-model transformation languages. *Journal of Object Technology*, 11(2):3:1–46, 2012.
76. Manuel Wimmer, Michael Strommer, Horst Kargl, and Gerhard Kramler. Towards model transformation generation by-example. In *HICSS '07: Proceedings of the 40th Annual Hawaii International Conference on System Sciences*, 2007.
77. Niklaus Wirth. Program development by stepwise refinement. *Communications of the ACM*, 14(4):221–227, 1971.

A Cascading Joins

Figure 6.5 is not the last word on Gamma's graph. Optimizations identical to those presented in Section 3.2.4 are used to optimize the processing of cascading joins, where the output of one join becomes the input of another (see Figure A.1).

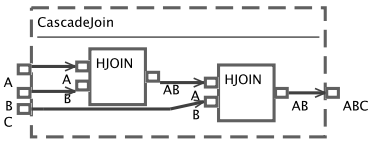
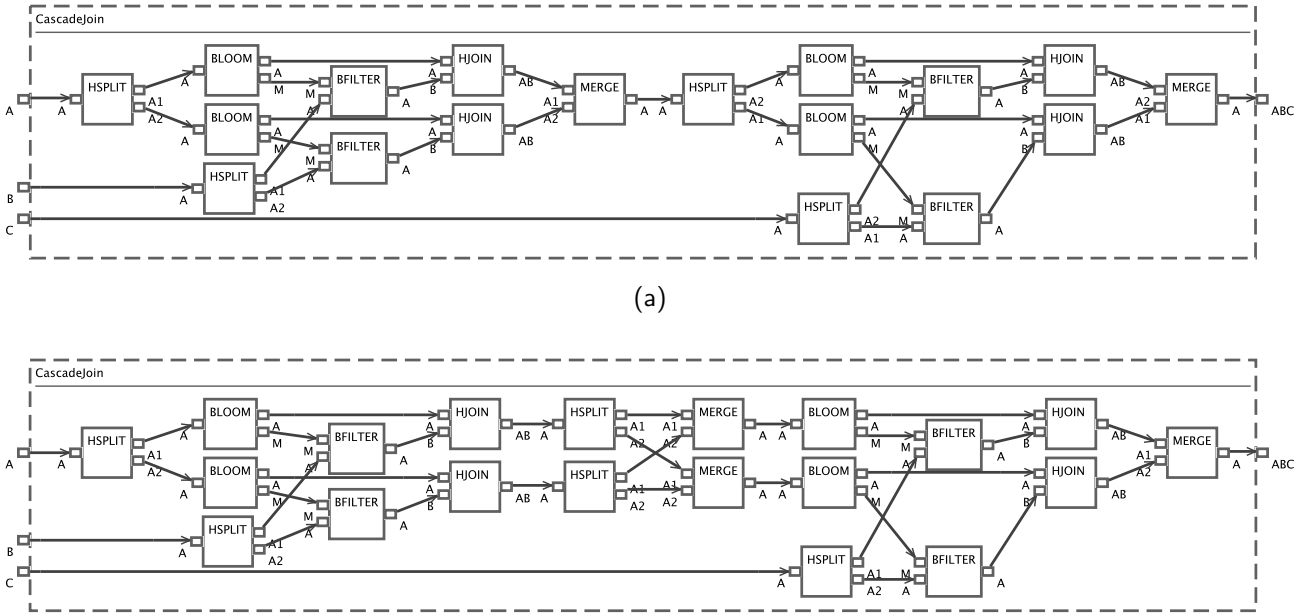


Fig. A.1 `CascadeJoin` graph.

Applying the refinements `parallelhjoin` and `bloomfilter-hjoin`, as described in Section 6.2, we get the graph depicted in Figure A.2(a). This example further shows the importance of deriving the PnF graphs, instead of just using pre-built optimized implementations for the operations present in the initial PIM (in this case, `HJOIN` operations). The use of the optimized implementations for `HJOIN` would have resulted in an implementation equivalent to the one depicted in Figure A.2(a). However, when we compose two (or more) instances of `HJOIN`, new opportunities for optimization arise. We have again a serialization bottleneck, formed by a composition of boxes `MERGE` (that merges the output streams of the first group of `HJOIN`s) and `HSPLIT` (that hash-splits the stream again).

Here again, refinement is insufficient to derive Gamma's graph; encapsulation boundaries must be broken to eliminate serialization bottlenecks. Unlike the bottlenecks in the previous section, cascading joins use different keys to hash the tuples, so the partitioning of the stream *before* its merge is different than the partitioning *after* the hash-split. Therefore, we cannot use algorithm `mhs_identity` to optimize this subgraph.[14] Instead, we use a rewrite that removes these bottlenecks by swapping (`MERGE`, `HSPLIT`) pairs (algorithm `mhs_hsplitmerge`). Each input stream is hash-split into two substreams that are sent to the each `MERGE` box. The substreams with the same hash values are then merged.

[14] We prevent algorithm `mhs_identity` from being chosen using preconditions.



(a)

(b)

Fig. A.2 Rotation of `MERGE` and `HSPLIT`.