ABSTRACT

Title of thesis: DATAFLOW INTERCHANGE FORMAT AND A FRAMEWORK FOR PROCESSING DATAFLOW GRAPHS

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Digital Signal Processing (DSP) applications are often designed with tools based on dataflow graphs and the increasing number of such tools shows the need for a common intermediate graph representation for exchanging dataflow information. In this work, we present the dataflow interchange format (DIF), a platform-independent textual language that is geared towards capturing the semantics of graphical design tools for DSP system design. A key objective of DIF is to facilitate technology transfer across dataflow-based DSP design tools by providing a common, extensible semantics for representing coarse-grain dataflow graphs, and recognizing useful subclasses of dataflow models. This thesis also develops the framework for a Java-based software repository that provides dataflow analysis and optimization algorithms for DIF representations. The featured

framework is accompanied by toolboxes for hierarchical design support and visualization of graphs.

DATAFLOW INTERCHANGE FORMAT AND A FRAMEWORK FOR PROCESSING DATAFLOW GRAPHS

by

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DEDICATION

To my mother, father and brother.

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CHAPTER 1

Introduction

Modeling of DSP applications based on coarse-grain dataflow graphs is widespread in the DSP design community, and a large and growing set of DSP design tools support such dataflow semantics [3]. Since a variety of dataflow modeling styles and accompanying semantic constructs have been developed for DSP design tools (e.g., see [2,5,6,8,12,13]), a critical problem in the process of technology transfer to, from, and across such tools is a common, vendor-independent language and associated suite of intermediate representations and algorithms for DSP-oriented dataflow modeling.

As motivated above, DIF is not centered around any particular form of dataflow, and is designed instead to express different kinds of dataflow semantics. The present version of DIF includes built-in support for synchronous dataflow (SDF) semantics [12], which have emerged as an important common denominator across many DSP design tools and support powerful algorithms for analysis and software synthesis [4]. DIF also includes support for the closely related cyclo-static dataflow (CSDF) model [5], and has specialized support for various restricted versions of SDF, in particular, homogeneous and single-rate dataflow, which are often used in multiprocessor scheduling and hardware synthesis. Additionally, support for dynamic, variable-parameter dataflow quantities (production rates, consumption rates, and delays) is provided in DIF. DIF also captures hierarchy, and arbitrary non-dataflow attributes that can be associated with dataflow graph nodes (also called *actors*), edges, and graphs.

1.1 DIF Package

The *DIF package* is a Java-based software package for DIF that is being developed along with the DIF language. Associated with each of the supported dataflow graph types is an intermediate representation within the DIF package that provides an extensible set of data structures and algorithms for analyzing, manipulating, and optimizing DIF representations. In addition, conversion algorithms between compatible graph types (such as CSDF to SDF or SDF to single-rate conversion) are provided. Presently, the collection of dataflow graph algorithms is based primarily on well-known algorithms (e.g., algorithms for iteration period computation [9], consistency validation [12], and loop scheduling [4]), and the contribution of DIF in this regard is to provide a common repository and front-end through which different DSP tools can have efficient access to these algorithms. This repository is being actively extended with additional dataflow modeling features and additional algorithms, including, for example, more experimental algorithms for data partitioning and hardware synthesis.

1.2 Organization of Thesis

This thesis is organized in six chapters. Chapter2 provides the background on graphs, formal language definitions and the Java programming language. In Chapter3, the formal language definition of DIF is established and a list of supported dataflow graph models is introduced. Chapter 4 describes the DIF software package with code examples. Chapter5 presents a set of applications and examples for DIF and the DIF package. This thesis ends in Chapter 6, with conclusions and recent work.

1.3 Notation

In the notation used in through this thesis, code examples and DIF language keywords are indicated by Arial font. *Italic Arial* font is used for replaceable parts of code examples or in-code comments and *Italic Times New Roman* font is used for examples, definitions, emphasis or terms used for the first time. The special syntax notation of formal language definitions is explained in Section2.3.

CHAPTER 2

Background

2.1 Graphs

Mathematical graphs have been studied for years in many fields of science including computer science. Computer scientists have formulated numerous interesting problems in terms of graphs, including dataflow programming models which are formulated in terms of a special case of graphs called directed graphs. This section reviews types of graphs that will be used throughout this thesis and graph representations in computers.

Definition 2-1 *A simple graph G consists of a finite set V(G) of objects called vertices together with a set E(G) of unordered pairs of vertices; the elements of E(G) are called edges. In an edge definition* $e=(v_i, v_j)$, v_i *and* v_j *are called the endpoints. Two vertices connected with an edge are called adjacent vertices.*

Graphs are usually represented by diagrams, in which a vertex is drawn as a small circle and an edge $e=(v_i, v_j)$ is shown as a line from vertex v_i to v_j. Vertices are also referred as nodes.

Definition 2-2 *A directed simple graph G consists of a finite set V(G) of vertices and a set E(G) of ordered pairs of vertices. In an edge definition* $e=(v_i, v_j)$, v_i *and* v_j *are called the source and the sink respectively.*

Multigraphs are defined in the same way as simple graphs except there may be more than one edge corresponding to the same pair of vertices. Pseudo graph definition adds self-loop edges to this definition. A self-loop edge is an edge of the form (v,v), where both nodes of the pair are the same.

Definition 2-3 *Two graphs G and H are said to be isomorphic if there exists a one-to-one map from V(G) to V(H) with the property that a and b are adjacent vertices in G if and only if maps of a and b are adjacent in H.*

For directed multigraphs, this definition should be extended to include matching edge directions and equal number of edges between mapping nodes. Pseudographs should have the same number of self-loop edges on mapping nodes as well.

Definition 2-4 *A graph H is called a subgraph of a graph G, if and only if* $V(H) \subseteq V(G)$ *and* $E(H) \subseteq E(G)$.

The term *subgraph* is also used in hierarchical designs for indicating a module that is logically associated with a node. This usage is different than the above definition.

Definition 2-5 *Let G be a directed or undirected graph with a vertex set {1, 2, ... , v} and an edge set {(1, 2), (2, 3), ... , (v-1, v), (v, 1)} where* $v \geq 1$ *. Any graph that has an isomorphism of G as a subgraph is called a cyclic graph. Any graph that is not cyclic is called acyclic.*

Note that this definition states that pseudographs are always cyclic.

Directed acyclic graphs (DAG) are especially important in picturing hierarchical relations.

Definition 2-6 *A walk in a graph is a finite sequence of vertices* $v_0, v_1, \ldots, v_n$ *and edges* $e_1, e_2, \ldots, e_n$ *of the form* $v_0, e_1, v_1, e_2, \ldots, e_n, v_n$ *where the endpoints of each* e_i *are* v_{i-1} *and* v_i.

A walk does not consider the edge directions even in a directed graph. The type of walk that considers the edge directions is called a path from v_0 to v_n. Given the definition of *path*,

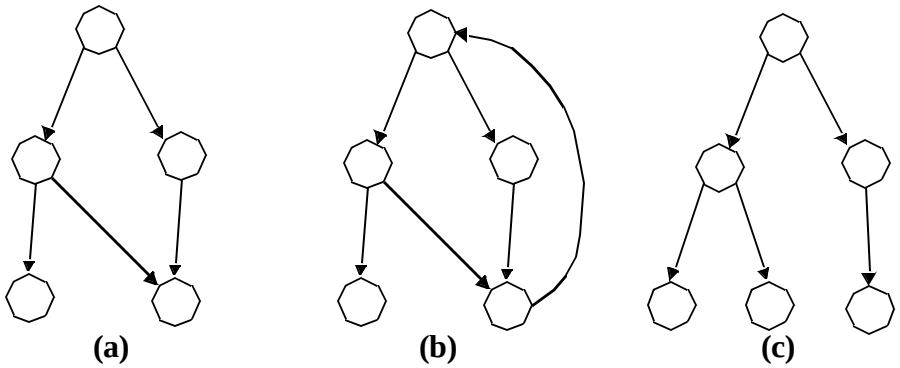


Figure 2-1. Examples of graph types.

a cyclic directed graph can also be defined as a graph with a path that starts and ends at the same node.

Definition 2-7 *If a there exists a walk for graph G that covers all vertices in V(G), G is said to be a connected graph.*

Definition 2-8 *A tree is a connected DAG in which all nodes except one are connected to only one incoming edge. The one node with no incoming edge is called the root of the tree. In a tree, the sink of an edge is called the child of the source. Vertices with no children are called leaves of the tree.*

Figure2-1 demonstrates examples graph types that are commonly mentioned in this thesis: **(a)** A DAG **(b)** A directed cyclic graph **(c)** A tree.

There exist various ways to represent a graph in terms of a programming data structure. The chosen structure often effects the efficiency of algorithms. Two commonly used data structures for this purpose are adjacency lists and adjacency matrices. Both representations only maintain references that contain the adjacency information of nodes. While this is a very efficient method for basic graph algorithms, no compact data structure is provided for

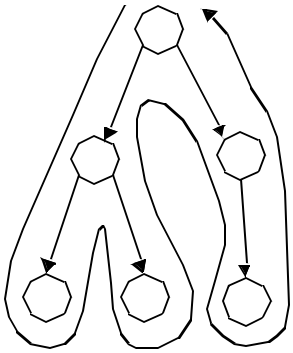


Figure 2-2. Illustration of a depth first tree walk.

additional information that might be associated with nodes or edges. An alternative graph representation in object-oriented languages is to assign an object to each node and edge, by which all node and edge information can be stored in the hierarchy of objects.

Depth First Tree Walk — Many applications, such as compilers, create a tree representation of the input data and then process the nodes in the tree. The order of visiting the nodes of a tree during the process is called a tree walk or a tree traversal. One of the common tree traversals is the *depth-first walk.* In a depth-first walk, nodes are visited following the edges. Starting from the root, the walk starts by going down to one of the children and recursively continues, until a leaf is reached. After a leaf is reached the algorithm walks back one step and checks if there are any unvisited nodes. If there are, the walk continues down the unvisited new path, otherwise algorithm walks back until a node with an unvisited child is found. The walk ends at the tree root when all the children of the root are visited. Every node is visited twice during a depth-first walk: first during the down-walk and second on the walk back. The tree-walks we will consider in this thesis will

assume that always the leftmost unvisited child is selected as the next path to continue from. Figure 2-2 illustrates a such tree-walk.

2.2 Dataflow Graphs

In dataflow programming model, a program is represented as a set of tasks with data precedences. A dataflow graph consists of actors as nodes and unidirectional FIFO channels as edges. In the semantics of dataflow graphs, actors consume, process (fire) and produce data (tokens). The firing of actors is controlled by the actor firing rules. These rules determine when enough data tokens are available to enable the actor. When firing rules are satisfied, the actor fires, consumes a finite number of tokens and produces a finite number of output tokens. Figure2-3 shows a dataflow graph in *(a)* and a firing example on *(b)*.

Differences between dataflow graph types often involve production and consumption rates. In the cyclo-static dataflow model [5], the numbers of tokens produced and consumed by an actor can vary from one firing to the next in a cyclic pattern. In the synchronous

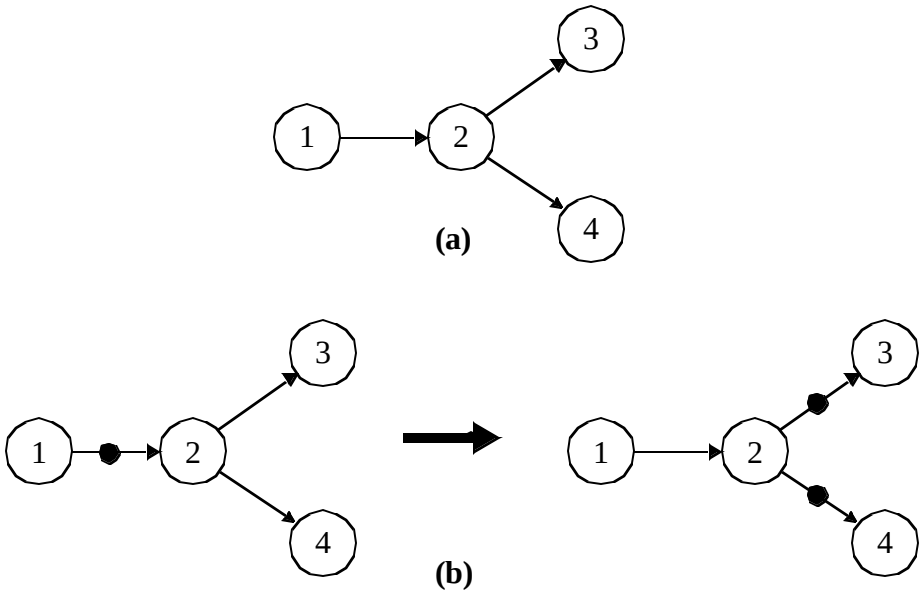


Figure 2-3. A dataflow graph example and firing of a dataflow graph.

dataflow model [12] the rates stay constant. Even more constrained cases are single rate graphs [4] and homogeneous synchronous dataflow graphs (HSDF). Single rate graph actors fire at the same average rate: production and consumption rates on an edge are equal. In HSDF, this rate is set to unity.

2.3 Defining Formal Languages

A formal language is a set of finite length “strings”, over some finite alphabet. The grammar of a formal language is a quadruple (N,T,R,S), where N is a finite set of non-terminals, T is a finite set of terminal symbols, R is a finite set of productions, and $S \in N$ is the *start symbol*.

The set T of terminal symbols is also called the *language alphabet*. These symbols both include the language keywords (see Section3.1.10 for a summary of DIF keywords), operators and other separators. Non-terminals are symbols representing language constructs. The set N should be disjoint from set T.

For *context-free* grammars, which DIF is a part of, productions are rules of the form $\alpha \rightarrow \beta$, where α is a non-terminal symbol and β is a string consisting of terminals or non-terminals. The term context-free comes from the feature that α can always be replaced by β, in no matter what context it occurs. The same α might appear at the left-hand side of more than one production. The notational shortcut for this case is to use the | (pipe) character to combine all such productions.

Example 2-1 *Following is a context-free grammar that can be used to generate simple mathematical expressions that only consist of four basic operations on digits – addition, subtraction, multiplication and division:*

N={S, O, A, B, C} T={a, b,..., z, 0, 1, 2,..., 9 , + , - , * , / , =}

$$S \rightarrow O=B$$
$$O \rightarrow a|b|c|\ldots|z$$
$$A \rightarrow 0|1|2|3|\ldots|9$$
$$B \rightarrow BCA$$
$$B \rightarrow A$$
$$C \rightarrow + \mid - \mid * \mid /$$

*The expression y = 2 * 3 - 5 + 6 is one of the values that S can take, in other words the given grammar can generate the string y = 2 * 3 - 5 + 6.*

Regular Expressions — A regular expression is a string that describes a whole set of strings, or a "language", according to certain syntax rules. Regular expressions can be used to express a language over an alphabet Σ as follows:

- ε is a regular expression that denotes the empty language L()={}.
- If $c \in \Sigma$ then regular expression (c) denotes the language L(c)={c}, which has only one element of length one.

Let r and s be two regular expressions denoting the languages L(r) and L(s).

- (r)(s) is a regular expression that denotes L(r)L(s), concatenation of one element from each language.
- (r)|(s) is a regular expression that denotes $L(r) \cup L(s)$.
- (r)* is a regular expression that denotes (L(r))*, where '*' is the Kleene closure operation:

$$\bigcup_{i=0}^{\infty} L^i, \text{ where } L^i = \underbrace{LLL\ldots}_{i \text{ times}}$$

Frequently, regular expressions are extended with the following two operators.

- (r)+ is a regular expression that denotes L(r)L(r)*.
- (r)? is a regular expression that denotes $L(r) \cup L(\varepsilon)$.

Some additional rules are used in this thesis for conveniently expressing sets of ASCII characters. Let *x* and *y* be two integers and *a* and *b* be two ASCII characters.

- R = x implies that R is the character with the ASCII code ‘x’.
- R = [x .. y] implies that R is the list of all characters with ASCII values starting from x, up to and including y.
- R = [‘a’ .. ‘b’] (with single quotes around a and b) implies that R is the list of ASCII characters starting from a, up to and including b, assuming that characters are ordered according to their ASCII values.
- + and - characters, with no single quotes around, are used as the union and exclusion operators on sets.

Subsets of terminal strings defined through regular expressions are called *tokens*. The DIF specification utilizes the following set of tokens in conjunction with the Backus-Naur form, which is explained next in this section. Note that *eof*, *lf* and *cr* are abbreviations for end-of-line, line feed and carriage return consecutively.

```
all = [0 .. 127]
digit = [‘0’ .. ‘9’]
octal_digit = [‘0’ .. ‘7’]
hex_digit = digit + ['a' .. 'f'] + ['A' .. 'F']
non_digit = [‘A’ .. ‘Z’] + [‘a’ .. ‘z’] + [‘_’]
escape_sequence = simple_escape | hexadecimal_escape |octal_escape
simple_escape = '\' "' | '\"' | '\\' |'\b' | '\f' | '\n' | '\r' | '\t’
hex_escape = '\x' hex_digit+
octal_escape = '\' octal_digit octal_digit? octal_digit?
tab = 9
cr = 13
lf = 10
eol = tab | cr | lf
```

```
string = “” ([all - [“” + ‘\’ + ‘cr’ + ‘lf’]] | escape_sequence)* “”
string_tail = '+' (' ' | eol | tab)* string
```

Backus-Naur Form (BNF) — BNF is a widely used syntax for defining languages with context-free grammars. It was introduced by John Backus and was first used to describe the syntax of the ALGOL 60 programming language [1]. BNF syntax is very similar to the notation used in the *formal languages* part of this section. There are many variants and extensions of BNF, one of which is the Extended BNF (EBNF). EBNF is enhanced with regular expressions. In the DIF specification, regular expressions are integrated in EBNF through tokens.

The following EBNF notation will be used for the formal definition of DIF:

- Language specific terminals, that are language keywords, operators and other separators, will be printed in boldface. If the terminal is a single character, it will appear between double quotes.
- Tokens, including strings, *identifiers* or *numbers* – see Section3.1.1 – are printed as lightface plain text labels.
- Non-terminals will be expressed with a label enclosed between ‘<’and ‘>’ characters.
- The = character will be used to express a production.
- The | character will be used to combine alternative productions with the same left hand side.
- The ‘+’, ‘*’ and ‘?’ operators of regular expressions can also be used with non-terminals.
- The ‘[*label*]:’ notation may be used before terminals for descriptive purposes.
- The ‘{*label*}’ notation may be used before non-terminals for descriptive purposes.

The last two rules are not standard in BNF and they do not contribute to the language definition. They are mainly defined for the reader’s convenience and compiler compatibility, which will be described in Chapter4).

Syntax Trees — A *parse tree* pictorially shows how the start symbol of a grammar derives a particular string in the language. Given a context-free grammar, a parse tree has the following properties:

- The root is the start symbol.
- Each leaf is labeled by a token or by the empty string symbol ε.
- Each interior node is labeled by a non-terminal.
- If A is a non-terminal and X_1, X_2, ..., X_n are the children of node A (terminal or non-terminal) ordered from left to right, this implies the production:

$$A \rightarrow X_1 X_2 \ldots X_n$$

A slightly different version of parse trees is the Abstract Syntax Tree (AST), which eliminates the non-terminals from the tree by replacing them with operators.

Example2-4 shows the **(a)** parse tree and the **(b)** AST for the string y=2*3-5+6 generated by the language in Example2-1.

Parse trees are often generated by the parser stage of compilers for processing the tokens passed from lexer stage. The parse tree can be traversed in various ways depending on the implementation and the desired transformation. The most common tree traversal is the depth-first walk.

2.4 The Java Programming Language

Java [17] is a platform-independent, object-oriented programming language. The DIF package is developed with Java. The following is a list of Java terminology that is used in the subsequent chapters:

- In Java, object types are also named as *classes*. Functions are called *methods* and variables are sometimes referred to as *fields*. Member methods and fields belong to the instance of a class (or *object*) and they produce object specific results. Static

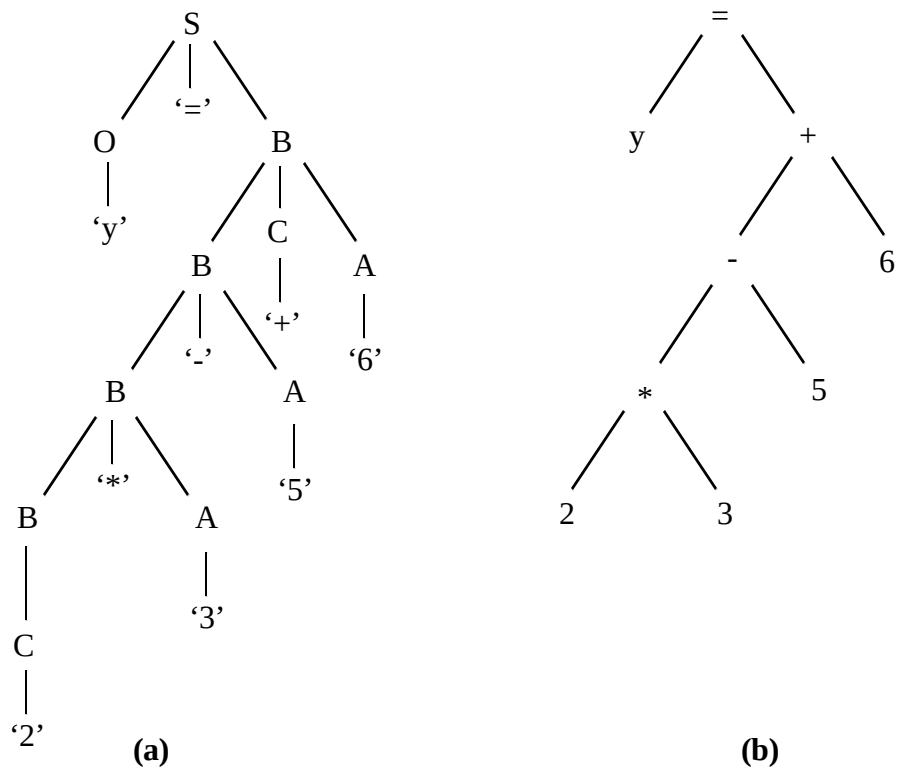


Figure 2-4. Parse tree and the AST for the string `y=2*3-5+6`.

methods are different: rather than belonging to an object, they are accessed from the class name. Their results don't change dynamically depending on the state of an object.

- An object is an *instance* of its class and its super-classes. A special method named the *constructor* is called during *instantiation* of an object that defines the basic properties of the object.
- The phrase "*extending a class"* is used for creating a new class modeled on the original class, overriding some of the methods and fields and possibly imposing more constraints. The *super* and *sub* prefixes denote such hierarchical relationships between classes. Except for the non-default constructors and overridden methods and fields, a graph inherits all the properties from its superclass. Java doesn't allow multiple parents as in C++. All objects have Java *Object* class as the common ancestor.

- A public method or a member can be accessed anywhere unlike protected methods and members, which can only be accessed by package classes and subclasses. The software convention used in this thesis enforces prefixing underscore "_" character to protected method and member names.
- Errors are reported through classes called an *exceptions*. Usually, different kinds of exceptions are *thrown* for different kinds of errors.
- Logically related classes can be collected in a single directory which is called a Java *package*. The *sub*-packages of a Java package are physically stored in sub-directories of the parent package. A full class name is represented in

  package.sub-package.sub-sub-package...Class_Name

  format. Packages do not impose any constraints other than a logical relationship between classes, for example, classes of a sub-package do not necessarily extend the classes of its super package.
- The period "." operator in Java is used for accessing member fields and methods of an object or static methods of a class. It is also used as the separator character in full class names.

CHAPTER 3

Dataflow Interchange Format

DIF captures essential modeling information that is required in dataflow-based analysis and optimization techniques, such as algorithms for consistency analysis, scheduling, memory management, and block processing, while optionally hiding proprietary details such as the actual code that implements the dataflow blocks.

DIF is designed to be exported and imported automatically by tools. However, unlike other interchange formats, DIF is also designed to be read and written by designers who wish to understand the dataflow structure of applications or the dataflow semantics of a particular design tool, or who wish to specify an application model for one or more design tools using the features of DIF. Indeed, DIF provides the programmer a unique, integrated set of semantic features that are relevant to dataflow modeling. As a result, DIF is not based on XML, which is more for pure data exchange applications, and is not well-suited for being read or written by humans. Due to the emphasis on readability, DIF supports C and Java-style comments, allows specifications to be modularized across multiple files (through integration with the standard C preprocessor), and is based on a block-structured syntax.

A dataflow graph definition in DIF consists in general of six blocks of code: *topology*, *interface*, *refinement*, user-defined and built-in *attributes*, and *parameters*. These code blocks are contained in a main block defining the dataflow graph. Using the *basedon* keyword, a graph can inherit the same topology as another graph while overriding arbitrary

attributes and parameters. Figure 3-1 illustrates the general form of a graph definition block. Items in boldface in this figure are DIF keywords, operators and other separators. Italicized words are to be defined by the user. Parts in lightface square brackets are optional. The order of the blocks should not be changed and a block can be excluded if it does not contain any information. The optional keyword on the first line denotes the type (form of

```
[keyword] graph graphID [basedon graphID] {
    params {
        prm1: {-1, 1, 2.2, …};
        prm2: [1, 5] + {8, 9, 10} + [20, 25);
        prm3;
        …
    }
    interface {
        input portID portID ... ;
        output portID portID ... ;
    }
    topology {
        nodes { nodeID[:portID] nodeID[:portID] ...}
        edges {
            edgeID sourceINodeID sinkNodeID;
            edgeID sourceINodeID sinkNodeID;
            ...
        }
    }
    refinement {
        subGraphID nodeID
            subPortID:edgeID, subPortID:portID, … ;
        subGraphID nodeID
            subPortID:portID, subPortID:edgeID, … ;
        …
    }
    attribute attributeName {
        edgeID value;
        nodeID value;
        nodeID;
        …
    }
    …
    builtInAttributeName {...}
    …
}
```

Figure 3-1. A sketch of a dataflow graph definition in DIF.

dataflow). Further details on the different graph types available are described in Section3.2.

3.1 The Language

This section focuses on formally defining DIF in the context of programming languages, providing detailed information on the syntax of the language. It also intends to determine specifications of the required parsing functionality. An implementation of such a parser is explained in Chapter 4.

3.1.1 Lexical Conventions

Syntactical basics of DIF are kept consistent with the syntax of popular programming languages such as C and Java. Identifiers and numbers are defined in the same way as C. Both block comments and line comments are supported.

DIF is a case sensitive language. Not using the correct type case for a language keyword is a syntactical error. Literals with the same spelling but different type cases are considered to represent different entities. White space characters, which are tabs, new lines and form feeds, are ignored except when they separate identifiers, keywords and constants.

The tokens defined in this section are added to the tokens that were previously defined for EBNF.

Numbers — Two types of numbers are used in DIF, signed integers or signed numbers with decimal point (double). `1`, `1.0`, `+0.7`, `-.9` are the examples of valid values.

```
double = (‘+’ | ‘-’)? (digit*) ‘.’ (digit+)
integer = (‘+’ | ‘-’)? (digit*)
number = double | integer
```

Identifiers — An identifier is a sequence of letters and digits. The first character must be a letter or underscore. The maximum length of identifiers is not defined and usually bound

by the compiler implementation. Edge, node and attribute names in DIF are defined as identifiers.

```
identifier = non_digit ( digit | non_digit )*
```

Comments — The characters `/*` introduce a block (long) comment, which terminates with the characters `*/`. The characters `//` introduce a line (short) comment, which terminates with an end-of-line or end-of-file, whichever comes first. Comments do not nest, and they do not occur within string or character literals.

```
not_cr_lf = all - [ cr + lf ]
not_star = all - '*'
not_star_slash = not_star -'/'
short_comment = '//' not_cr_lf* eol
long_comment = '/*' not_star* '*'+ (not_star_slash not_star* '*'+)* '/'
comment = long_comment | short_comment
```

3.1.2 The Body of a DIF Specification

A DIF specification begins with an optional type keyword. Presently, the type keywords include `dif`, `sdf`, `csdf`, `singleRate` and `hsdf`. This list is tentative and will be updated with more keywords as the development on DIF advances.

A graph defaults to type `dif` if the type keyword is not specified. As a type, the `dif` keyword implies the most generic type of dataflow graph supported by DIF. Using a different type keyword usually requires supplying additional information via built-in attributes or accepting the default values for those attributes.

Following the graph type and the `graph` keyword comes an optional `basedon` statement. A *basedon* statement is used for inheriting base features from another graph and in some ways it is analogous to the inheritance operator ":" in C++ or "extends" keyword in Java.

A graph specification can have six types of blocks: parameter definitions, interface declaration, topology definition, refinements and attribute definitions. Blocks should have the same order as in this list. If a block does not contain any *information,* it can be excluded. Two types of attribute definitions exist: *built-in* and *user-defined*. Multiple built-in and user-defined attribute blocks in a graph are allowed.

Edge, node and port identifiers should be unique, for example it is erroneous to define a node label that is already defined as an edge, node or port label. Likewise, an attribute identifier should not be duplicated for using with another attribute.

Following is the EBNF for the highest level definition for a DIF object. The non-terminals at the right hand side of *block* production will be defined in the subsequent sections.

<graph_list> = <graph_block>*

<graph_block> =
[type]:identifier? **graph** [name]:identifier <basedon>? **"{"** <block>* **"}"**

<basedon> = **basedon** identifier

<block> =

{params}	**params** <params_body> |
{interface}	**interface** <interface_body> |
{topology}	**topology** <topology_body> |
{refinement}	**refinement** <refinement_body> |
{fixed_attribute}	**identifier** <attribute_body> |
{attribute}	**attribute** identifier <attribute_body>

3.1.3 Defining the Topology of a Graph

The topology definition of a graph consists of node and edge definition blocks, marked by nodes and edges keywords. These define the sets of nodes and edges, and associate a

unique identifier with each node and each edge. Since dataflow graphs are directed graphs, edges are specified by their source and sink node identifiers. A node definition may also include a port association (described further in Section3.1.4) for interfacing to other graphs. Figure3-2 shows an example of a topology definition block.

The EBNF for a topology definition block is as follows:

<topology body> = **"{"** <topology list>* **"}"**

<topology list> = **nodes "{"** <node definition block>? **"}"** |
edges "{" <edge definition>* **"}"**

<node definition block> = <node definition> <node definition tail>*

<node definition> = identifier | [node:] identifier **":"** [port:] identifier

<node definition tail> = **","** <node definition>

<edge definition> = [edge:] identifier [source:] identifier [sink:] identifier **";"**

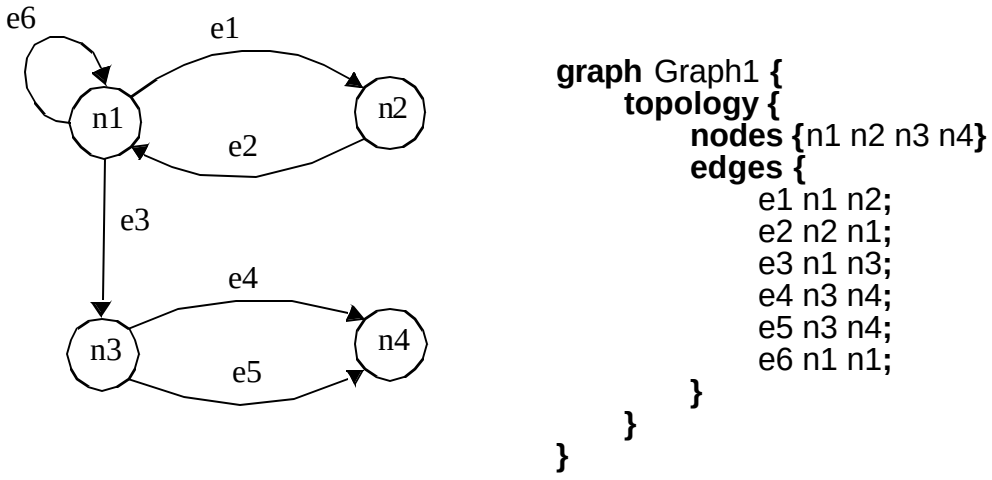


Figure 3-2. An example of a graph and its topology definition specified in DIF.

3.1.4 Hierarchical Graphs

Given the importance of hierarchical design in graphical design tools, a necessary feature of the DIF language is the general ability to assign a node of a graph to a "nested" subgraph. Such hierarchical nodes are called *supernodes* in DIF terminology. In addition to providing for hierarchy, the supernode feature allows for reuse of graph specifications: a topological pattern that appears multiple times in a graph can be defined as a separate module and every occurrence in the original graph (parent graph) or in multiple graphs can be replaced with a single node.

All graph modules, in other words subgraphs, should have an interface block, which contains a list of ports. A listed port will then be associated either with a node in the graph (in the topology/nodes block) or with a port of a subgraph (in the refinement block). Internal association of a port with a node or another port is called an *association.*

Subgraph declarations appear in the refinement block of the parent graph. Every subgraph is assigned to a node, which is called a supernode. A subgraph port can be connected to an edge incident to the supernode or it can be connected to a port of the parent graph. External association of a port with an edge or another port is called a *connection*. Connecting and associating two ports are identical operations.

Ports can be directed (input or output) or bidirectional (inout). Port directions should be consistent with edge directions. An incoming edge can be connected to port types input and inout; an outgoing edge can be connected to port types output and inout. Port relations can only take place between ports of the same type. Undirected hierarchies are created using type inout ports.

Sets of supernodes and port nodes should be disjoint, a node cannot be in both sets in a single graph. Moreover, a supernode can only be assigned to a single subgraph.

Figure3-3 is a detailed example of the hierarchy mechanism in DIF. A dashed line in the figure denotes a port association. The refinement expression in *Graph 2* suggests that n4 will be a supernode for *Graph 1*, for which the connections are defined as e3 to P1 and P3 to P2. Figure3-3*(c)* illustrates *Graph 2* after merging the levels of the hierarchy, which is also referred to as *flattening*. It is not defined how to label the nodes and edges of the subgraph after they are moved into the parent graph. This is left to the particular implementation and applications.

A subgraph should be in the scope of its parent graph during compilation. Graph scopes are explained exclusively in Section3.1.9. Cyclic hierarchy relations are not permitted.

Below is the EBNF for the interface block definition of a graph followed by the refinement block definition:

<interface_body> = **"{"** <interface_expression>* **"}"**

<interface_expression> =
{input} **input** identifier <interface_identifier_tail>* **";"**|
{output} **output** identifier <interface_identifier_tail>* **";"**|
{inout} **inout** identifier <interface_identifier_tail>* **";"**

<interface_identifier_tail> = **","** identifier

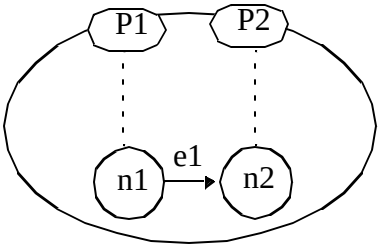
<refinement_body> = **"{"** <refinement_expression>* **"}"**

<refinement_expression> =
[graph]:identifier [node]:identifier <refinement_definitions>? **";"**

<refinement_definitions> =
<refinement_connection> <refinement_connection_tail>*

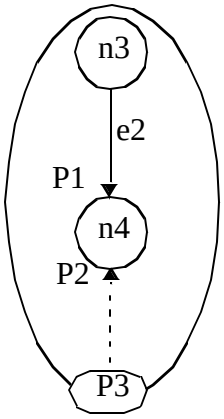
<refinement_connection> = [port]:identifier **":"** [element]:identifier

<refinement_connection_tail> = **","** [port]:identifier **":"** [element]:identifier



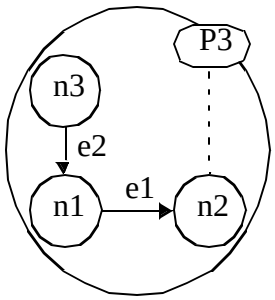
Graph1

```
graph Graph1 {
    …
    interface {
        input P1, P2;
    }                                   (a)
    topology {
        nodes {n1:P1 n2:P2}
    }
    …
}
```



Graph 2

```
graph Graph2 {
    …
    refinement {
        Graph1 n4 P1:e2 P2:P3;
    }                                   (b)
    …
}
```



(c)

Graph 2 after flattening

Figure 3-3. Definition of DIF graphs with interfaces and super nodes.

3.1.5 User-defined and Built-in Attributes

DIF supports assigning attributes to nodes, edges, and graphs. There are two types of attributes: *user-defined* and *built-in.* User-defined attributes bear arbitrary names and can take on any value assigned by the user. Built-in attributes are pre-defined with associated keywords in the DIF language. They are usually handled in a special way by the compiler and have default values even if they are not defined in the graph specification. Depending on the particular semantics of a design tool and the type of the graph, a compiler might read built-in attribute values into special fields of the edge-related data structures and it may perform checks on the value to see if it is acceptable (e.g. positive-valued). An example of a built-in attribute is the *delay* attribute of graph edges.

DIF supports four basic types of attribute values. Attribute types are not required to be consistent within a single attribute block.

- **Number** An attribute value can be a signed integer or a signed double.
- **2-D Number Array** This type is intended for defining matrices. However, comparing rows for matching lengths is not a context-free language operation, therefore the matrix property is not enforced in the formal language definition. Instead, it is handled by the semantics analysis part following the parser. The syntax of 2-D number array is rows of numbers separated by commas. An example is (1 2 3, 4 5 6).
- **List** List is a very flexible type. Elements of a list can be of any type and types are not required to match among elements. Even though the list type is defined to be one dimensional, its elements can be other lists, which in effect enables lists of any dimension. A list example is [[1, 2], [3, (4 5 6)], 7, 8].
- **String** C-language style strings are allowed in attributes. The concatenation operator + can be used to collect multiple lines in a single string.

An attribute can also be parametrized, refer to Section3.1.6 for parametrization. The EBNF for the attribute block definition is as follows:

<attribute_body> = **“{”** <attribute_expression>* **“}”**

<attribute_expression> =
    {element} identifier <value>? **“;”** |
    {graph} **this** <value>? **“;”**

<value> =
    {number} number |
    {param} identifier |
    {concat_string} string string_tail* |
    {array} **“(”** number* <array_row>* **“)”** |
    {list} **“[”** value+ **“]”**

<array_row> = **“,”** number*

If a value is not defined in an attribute expression, the particular attribute is undefined for that element or graph. This is a feature that applies to graphs that are based on other graphs. If the graph definition does not have a basedon statement, a empty-valued attribute expression has no effect.

3.1.6 Parameters

Parameterization of attribute values is possible in DIF with the params block. The capability of defining a possible set of values (domain) for an attribute instead of a specific value provides useful support for analyzing dynamic and reconfigurable dataflow graphs. The domain of a parameter can be an enumerated set of values, an interval, or a composition of both forms. A parameter can be defined only once and the + character should be used for combining different intervals. An example is prm1: {1, 2, 3.5} + [4, 5).

Parameters are defined in EBNF as follows:

<params_body> = **“{”** <params_expression>* **“}”**

<params_expression> =
{normal} identifier **“:”** <range_block> **“;”** |
{blank} identifier **“;”**

<range_block> = <range> <range_tail>*

<range> =
{closed_closed} **“[”** [left]:number **“,”** [right]:number **“]”** |
{open_closed} **“(”** [left]:number **“,”** [right]:number **“]”** |
{closed_open} **“[”** [left]:number **“,”** [right]:number **“)”** |
{open_open} **“)”** [left]:number **“,”** [right]:number **“)”** |
{discrete} **“}”** number <discrete_range_number_tail>* **“}”**

<discrete_range_number_tail> = **“,”** number

<range_tail> = **“+”** <range>

3.1.7 The *basedon* Feature

DIF supports extending a graph definition to create a new graph object that inherits its basic structure from the original model graph. This is a general property of object-oriented languages and it is also suitable to DIF, which essentially defines objects, graphs, nodes and edges, and defines their properties, attributes and parameters. The extended graph inherits its final topology, interface, refinements and type from the model graph. It also inherits all the parameters and attributes, however, overriding and extending these blocks with new values and types are permitted.

Attributes can be undefined by leaving the value blank in a definition, which has no effect if the attribute is not defined or the graph does not have a *basedon* statement. For example, assume that Graph2 is based-on Graph1 and the user-defined size attribute is

assigned to node1 in Graph1. The following code will result in erasing the user-defined size attribute from node1 of Graph2.

```
attribute size {
        node1;
}
```

A *basedon* graph should have its model graph in its scope. Section3.1.9 explains graph scopes in detail. Cyclic basedon relations between graphs are not permitted.

3.1.8 Preprocessor Support

The DIF preprocessor is defined to be the same as the ANSI-C preprocessor as specified in [16]. The include command of the preprocessor is particularly useful in conjunction with the *hierarchy* and *basedon* mechanisms since it can be used to conveniently add graphs to the scope of the current graph.

3.1.9 Scope of a Graph

Two cases in DIF require a graph to be present in the scope of another graph. The first case occurs when a graph is *basedon* a model graph definition, requiring the model graph to be in the scope of the extended graph . The second case is caused by the refinement block. A subgraph should be in the scope of its parent.

There are two methods for including graph *H* in the scope of a graph *G*:

- Define *H* in the same text file following *G*,
- Use the include statement of the preprocessor.

Example 3-1 *Following is a demonstration of both methods on two text files containing a total of three graphs:*

- file1.dif:

```
#include "file2.dif"

dif graph Graph1 {
    …
    refinement {
        Graph1 node1 port1:edge1;
        Graph4 node2 port2:edge2;
    }
}

dif graph Graph2 basedon Graph3 { … }
```

- file2.dif:

```
#include "file3.dif"

dif graph Graph3 {
    …
    refinement {
        Graph4 node3 port3:edge3;
    }
}
```

- file3.dif:

```
dif graph Graph4 { … }
```

In file1.dif, Graph2, Graph3 and Graph4 are in the scope of Graph1: the first one is included by being in the same file, Graph3 is imported by the preprocessor statement and Graph4 is included indirectly through file2.dif. Note that if Graph4 was directly included from file1.dif, the preprocessor would return an error for importing Graph4 twice, therefore it is advisable to use include statements wrapped with ifndef statements. The

scope of Graph3 only includes Graph4, simply because graphs *1* and *2* are not referred to from inside file2.dif, Graph4 does not have any graphs in its scope.

What paths to search and the order to search them for include statements are left to be specified by the particular compiler implementation.

3.1.10 Summary of Keywords

Following is a list of keywords that are used in DIF grouped according to the places they are used. The DIF language is case sensitive, therefore, special attention should be paid to using the keywords with correct case.

- **Top level definition:** graph, dif, sdf, csdf, singleRate, hsdf.
- **Topology definition:** topology, nodes, edges.
- **Interface declaration:** interface, input, output, inout.
- **Subgraph declarations:** refinement.
- **Parameter definitions:** params.
- **Attribute definitions:** this
    - **User-defined:** attribute
    - **Built-in:** production, consumption, delay, transfer.

3.2 Supported Graph Types

The DIF language evolves in parallel with an accompanying the software package, the *DIF package*, that is developed in University of Maryland. Even though this chapter deals with language constructs that are implementation independent, many of the language rules are shaped according to needs that arise during the development of the DIF package. Especially, the supported graph types are open to such development, therefore this section is dedicated to graph types with associated keywords and built-in attributes and compatibility issues of graphs with other graphs for refinement definitions. All graph types

are assumed to be compatible with itself, meaning a graph can be a subgraph of another if their types are the same.

3.2.1 DIF Graphs

DIF graphs are the default and most general class of dataflow graphs supported by DIF. DIF graphs can be specified explicitly using the dif keyword. In DIF graphs, no restriction is made on the rate at which data is produced and consumed on dataflow edges, and other types of specialized assumptions, such as statically-known delay attributes, are avoided as well. Hence an arbitrary attribute type can be attached to each node/edge incidence to represent the associated dataflow properties. In the inheritance hierarchy of the DIF intermediate representations, DIF graphs are the base class of all other forms of dataflow. In this sense, all dataflow graphs modeled in DIF are instances of DIF graph. Furthermore, if a tool cannot export to any of the more specialized versions of dataflow supported by DIF, it should export to DIF graph. Naturally, a DIF graph can have all kinds of graphs as subgraphs in its refinement definition.

3.2.2 CSDF Graphs

In restricted versions of the DIF graph model that are recognized in DIF, the numbers of data values (tokens) produced and consumed by each node may be known statically and edge delays may be fixed integers. For example, *CSDF graphs*, based on the cyclo-static dataflow model [5], are specified by annotating DIF graph definitions with the csdf keyword. In CSDF graphs, production and consumption rates can vary between node executions, as long as the variation forms a certain type of periodic pattern. Consequently,

values of these rates are integer vectors. These vectors are associated with CSDF graph edges using the production and consumption keywords. For example, the code fragment

```
production { e1 [1 1 2 4]; e2 [2 2 3]; }
```

associates the periodic production patterns

1, 1, 2, 4, 1, 1, 2, 4, ... and 2, 2, 3, 2, 2, 3, ...

with edges e1, and e2. If production, consumption and delay values are not defined for a CSDF graph, default values are [1], [1], and 0 respectively. CSDF Graphs are compatible with SDF, single rate and HSDF graphs in refinement definitions.

3.2.3 SDF Graphs

Similar to CSDF graphs, token production and consumption rates of synchronous dataflow (SDF) graphs [12] are known at compile time, but they are fixed rather than periodic integer values. SDF graphs are specified using the sdf keyword, and the arguments of production and consumption specifiers in SDF graphs are required to be integers, as in:

```
production { e1 4; e2 3; }
consumption { e1 5; e2 2; }
delay { e1 1; e2 2; }
```

The last statement, which is permissible in other DIF graph types as well, associates integer-valued delays to the specified edges. If production, consumption and delay values are not defined for an SDF graph, default values are 1, 1, and 0 respectively. SDF graphs can have single rate and HSDF graphs as their subgraphs.

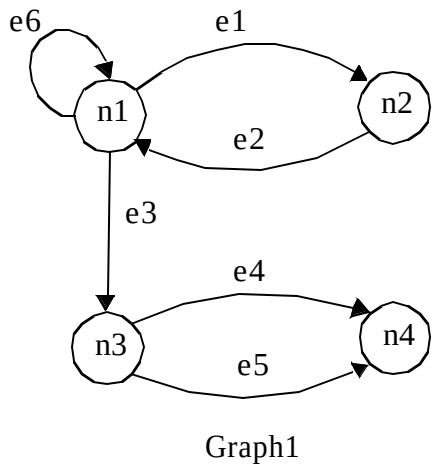
3.2.4 Single Rate and HSDF Graphs

Single rate graphs are a special case of SDF graphs where the production and consumption values on each edge are identical. In single rate graphs, nodes execute (“fire”) at the same average rate. In the slightly more restricted case of homogeneous SDF (HSDF)

graphs, production and consumption values are equal to one for all edges. Instead of production and consumption attributes, DIF uses the transfer keyword for edges in single rate graphs. DIF does not associate an attribute for token transfer volume in HSDF since it is not variable. The default transfer rate for single rate graphs is 1 and the default delay for both single rate and HSDF graphs is 0. HSDF graphs can be defined as subgraphs of single rate graphs.

3.3 A Complete DIFGraph Definition Example

Figures 3-4 and 3-5 demonstrate a complete DIF example that is distributed over three different text files. file1.dif in Figure3-4 defines *Graph 1*, which is the top of the modular



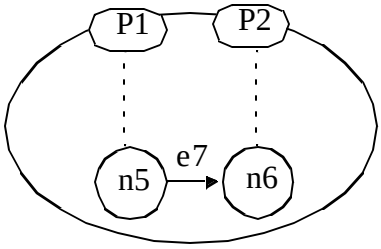
Graph1

file1.dif:

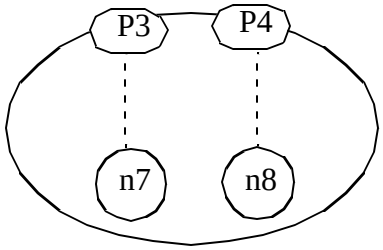
```
#include file2.dif
#include file3.dif

csdf graph Graph1 {
    topology {
        nodes { n1 n2 n3 n4 }
        edges {
            e1 n1 n2; e2 n2 n1;
            e3 n1 n3; e4 n3 n4;
            e5 n3 n4; e6 n1 n1;
        }
    }
    refinement {
        Graph2 n2 P1:e1 P2:e2;
        Graph3 n2 P1:e4 P2:e5;
    }
    production {
        e1 [ 1 2 1 ];
    }
    attribute description {
        this "Top level graph "
            + "with two subgraphs";
    }
}
```

Figure 3-4. Definition of a high level graph with two subgraphs.



Graph2 and Graph3



Graph4

file2.dif:

```
#include file3.dif

sdf graph Graph2 {
      params {
            VAR_DELAY: {0, 1, 2};
            VAR_SIZE: [1, 5] + {7};
      }
      interface { input P1; inout P2; }
      topology {
            nodes { n5:P1 n6:P2 }
            edges { e7 n5 n6; }
      }
      refinement {
            Graph4 n5 P3:P1 P4:e7;
      }
      delay {
            e7 VAR_DELAY;
      }
      attribute size {
            n5 VAR_SIZE;
            n6 VAR_SIZE;
      }
      attribute description {
            this
               [ [0 “parametrized graph”]
               [1 “subgraph”] ];
      }
}

sdf graph Graph4 {
      interface { input P3; output P4; }
      topology {
            nodes { n7:P3 n8:P4 }
      }
}
```

file3.dif:

```
#ifndef file3
#define file3

sdf graph Graph3 basedon Graph2 {
      params {
            VAR_DELAY: {1, 2};
      }
      attribute size {
            n5 7; n6 5;
      }
      attribute description {
            this
              [ [0 “parametrized graph”]
              [1 “subgraph” ]
              [2 “basedon Graph2” ] ];
      }
}

#endif
```

Figure 3-5. Definitions for Graphs 2, 3 and 4.

hierarchy. *Graph 1* requires Graphs *2* and *4* to be in its scope, therefore file2.dif and file3.dif are imported within file1.dif. Graphs *2* and *4* are defined in file2.dif, which automatically puts *Graph 4* in the scope of *Graph 2*. Finally, *Graph 3*, which is based-on *Graph 2,* is defined in file3.dif and file2.dif is imported to add *Graph 2* to its scope. Note that text in file3.dif is wrapped around by an ifndef preprocessor statement. Without this statement *Graph 4* would be imported twice in file1.dif: first, directly by the include statement and then indirectly through file2.dif.

All edge production and consumption rates of *Graph 1* are set to [1] by default, except for the production rate of *e1*, which is set to the array [1 2 1]. A string attribute named *description* is also defined for *Graph 1*. Two parameters are defined and used in *Graph2*, one of which is overridden in *Graph3*.

CHAPTER 4

DIF Package

This chapter introduces the framework in which graph-based algorithms are developed and presents the graph support tools in this framework. In Sections 4.2 and 4.4, internal representations of topologies and hierarchies are discussed in detail, including low level programming considerations. This discussion is followed by the introduction of the DIF parser and writer in Sections 4.5 and 4.6, a front-end for converting DIF files to DIF API objects and a writer for performing the reverse operation. In conclusion, an additional tool for visualizing DIF graphs is explained and discussion about the content of the DIF package is completed (Sections 4.7 and 4.8).

The software explained in this chapter is a subset of an infrastructure for system synthesis research that is being developed by the DSP-CAD Research Group in the University of Maryland at College Park. Generic graph representations used by this package is maintained as a part of Ptolemy II, a set of Java packages supporting heterogeneous, concurrent modeling and design. Ptolemy II is a part of the Ptolemy project [11] conducted in University of California at Berkeley. The rest of the representations and tools reside in the Maryland Package for System Synthesis (MAPSS).

The documentation in this chapter targets two kinds of users: developers and non-developers. Non-developer users typically utilize the provided tools on supported graphs but are not particularly interested in extending the DIF package for any purpose. On the other hand, developers might heed to extend classes for unsupported graph types and other features.

The DIF package is developed using the Java programming language. Extensibility of classes and interface definitions of Java fit well to the layered software design of the DIF package. Platform independence and inherent compatibility with graph notation through object oriented programming are some of the other advantages of Java.

4.1 Organization of Classes

The inheritance hierarchy of dataflow graph types in the DIF API mimics the dataflow graph type-hierarchy explained in Chapter 3 (e.g. CSDF graph is a constrained version of directed graph and SDF graph is derived from CSDF graph with additional constraints, etc). The careful design of the most generic graph type greatly facilitates the inheritance hierarchy chain.

An example is the validNodeWeight method in the Graph class, which checks if a weight object (see *node* in Section4.2.1) associated with a node is an acceptable type while adding the node to a given graph.

```
public boolean validNodeWeight(Object object) {
        return true;
}
```

Clearly, this method will identify all node weights as valid. However, a graph type such as DIFGraph that extends Graph, overrides the validNodeWeight method to require a weight type, DIFNodeWeight, which is specifically defined for DIF graphs.

```
public boolean validNodeWeight(Object object) {
        return object instanceof DIFNodeWeight;
}
```

This is a top-down design methodology equipped by the detailed understanding of similarities and differences of the class types that root from the generic graph. All segments that might possibly deviate from the base class are modeled as methods that can be

overridden. The advantage of a thorough high level definition is the reduction in the complexity of all extending classes and prevention of code duplication in many cases, for example addNode methods do not need to be defined repeatedly in all subclasses since the differences are captured in validNodeWeight method.

The convention used in the DIF package enforces a uniform use of protected and public methods. Public methods are the complete set of functions that are needed by a non-developer user, whereas protected methods are typically used for generic modeling purposes as described above. Protected methods are occasionally used for communication between closely coupled classes in the same Java package as well. Some modeling methods may be defined as public for general convenience. The validNodeWeight method is one such example: it is used internally for node verification and it is also set public so a user can check and filter a set of node weights before adding them to a graph. The combined set of public and protected methods form the developer API.

The logical structure of the Java packages in the DIF package generally follow the hierarchy of the dataflow graph types. Different dataflow graph types are packaged separately and placed into the package hierarchy according to their types. One addition to the dataflow graph types is the DIFGraph which was explained in Chapter 3. The DIFGraph class is developed with the purpose of enhancing the representation capabilities of Graph objects for dataflow support, without changing the topological properties of basic mathematical graphs. It is defined to be the most generic type of dataflow graph in the DIF API. The DIFGraph class is equipped with an advanced data structure for storing dataflow related parameters and attributes.

Figure4-1 summarizes the hierarchical design of the DIF software at the level of Java packages. Presented is a logical diagram, partly based on class inheritance hierarchy, rather than the package hierarchy. An arrow implies that some classes in the package are derived from the classes in the package that the arrow head points to. A diamond shape attached to a package indicates that the package uses classes from the package that is attached to the other end of the connection. The diagram is not exact and aims to present the general structure and highlight important relationships.

4.2 Generic Graphs

Focused around processing graph objects, most structures in the DIF package are developed for either extending the functionality of graph objects or supporting them through additional features. Therefore, one key point relevant to the design of the DIF package is the internal representation of topologies. A graph topology can be expressed in

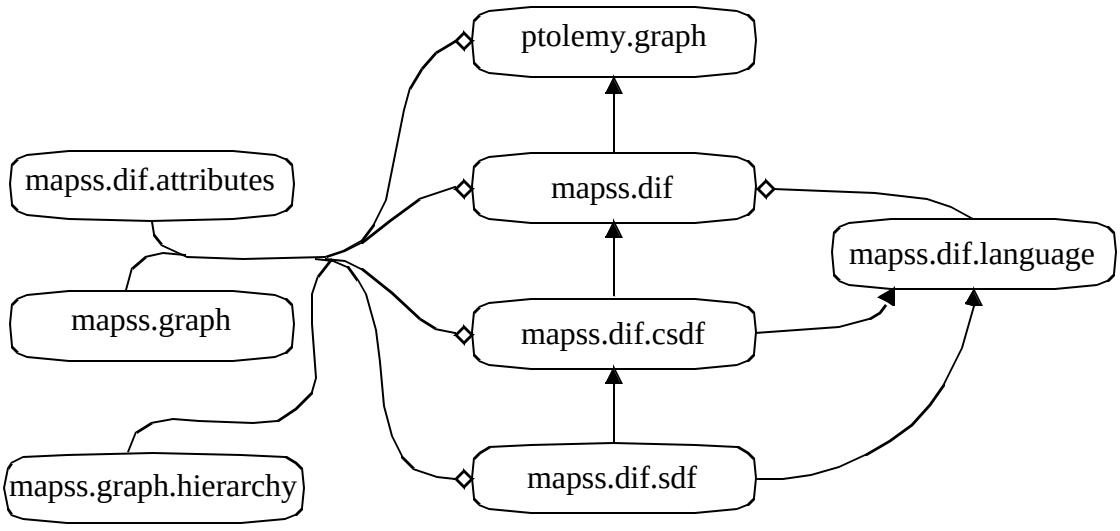


Figure 4-1. DIF package design.

more than one way as described in Section2.1 and the decision on how to represent graphs directly affects the design of algorithms and procedures that operate on graphs.

For many of its representations and manipulations pertaining to generic graphs, DIF employs the ptolemy.graph package from Ptolemy II [11].

4.2.1 Overview of Elementary Classes

This section gives an overview of major features from ptolemy.graph that are used in DIF.

Following are the classes that are used for constructing basic directed and undirected graphs. For the complete package documentation of the base graph package, refer to Ptolemy II documentation.

Element — Element is a base class for the nodes and edges of a graph. Each node and edge in a graph can optionally have a weight object associated with it. While element weights are arbitrary objects in the base graph type, they are typically restricted for the classes that extend Graph class. An element said to be *weighted* if it is assigned a weight and it is referred to as *unweighted* otherwise.

Node — All vertices in a graph are instances of this simple class independent of directed and undirected graph contexts.

Edge — All edges in a graph are instances of the *Edge* class. The connectivity of edges is specified by *source* nodes and *sink* nodes. The graph model does not differentiate between edge types of directed and undirected graphs. In the context of a directed graph, an edge is directed from its source node to its sink node. In case of an undirected graph, there exists no difference between source and sink nodes. This convenient notation simplifies the logical conversion between directed and undirected graph types.

In support of pseudographs, self-loop edges and multiple edges between the same set of nodes are allowed. Source and sink nodes of an edge are immutable: they cannot be changed after being set.

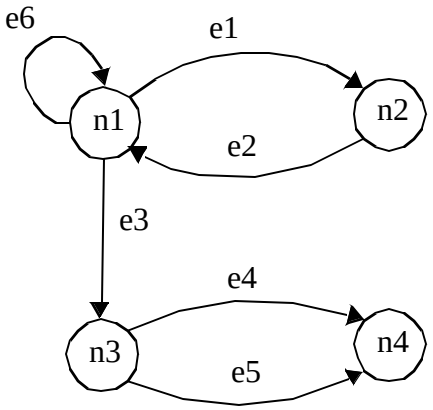
Graph — This class models a graph with optionally-weighted edges and nodes, all of which are instances of the Element class. A collection of edges and nodes does not form a graph until all of them are added to a graph object, which inherently requires the edges and the nodes of a graph to be unique. Both directed and undirected graphs can be implemented using this class due to the combined support in the Edge class.

Each node (edge) is associated with a unique, integer label in a graph. These labels can be used, for example, to index arrays and matrices whose rows/columns correspond to nodes (edges).

A node or an edge can exist as an element in multiple graphs, but any given graph can contain only one instance of the node. Node (or edge) labels, however, are local to individual graphs. Thus, the same node may have different labels in different graphs. Furthermore, the label assigned in a given graph to a node may change if the set of nodes in the graph changes over time. As opposed to elements, weights of graph elements do not need to be distinct. In other words, only one instance of an element can exist in a graph, but distinct elements can share the same weight object.

If an edge will be removed from a graph and be re-added later, it can be *hidden* instead of being removed from the graph. This method is more efficient than removing edges, in terms of algorithm complexity and allows the same label to be used if the edge is restored later.

Directed Graph — The DirectedGraph class implements a transitive closure matrix, which efficiently supports operations such as *strongly connected component decomposition*, or finding *reachable nodes.* The transitive closure matrix is a boolean matrix, whose indexes correspond to node labels. The entry is *(i, j)* true if and only if there exists a path from the node with label *i* to the node with label *j*.



$$\textit{Transitive Closure} = \begin{bmatrix} 1 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

```
import ptolemy.graph.Graph;
import ptolemy.graph.DirectedGraph;
import ptolemy.graph.Edge;
import ptolemy.graph.Node;

public class  Example {

      public Example ( ) {

            // Construct the graph object.
            Graph graph = new Graph( );
            Node n1 = graph.addNode( );
                        ...
            Node n2 = graph.addNode( );
            Edge e1 = addEdge(n1, n2);
            Edge e2 = addEdge(n2, n1);
                        ...
            Edge e6 = addEdge(n1, n1);

            // Convert to DirectedGraph and find transitive closure.
            DirectedGraph graph2 = grap.cloneAs(new DirectedGraph( ));
            boolean[ ][ ] matrix = graph2.transitiveClosure( );
      }
}
```

Figure 4-2. An example of defining a basic graph.

Figure4-2 presents simple Java code that constructs the graph shown in the figure. addNode and addEdge methods are shortcuts for instantiating weightless elements and adding them to the graph. The graph is then copied into a DirectedGraph object which provides a method to find the transitive closure matrix. Note that the cloneAs method requires an empty graph of the desired type as a parameter to clone the current graph. Nodes (and edges) are assigned integer labels starting from 0, in the order they are added to the graph, which are used in the transitive closure matrix.

4.2.2 Cloning and Mirroring Graphs

Graphs can be copied by two methods: *cloning* and *mirroring*. Both methods produce an isomorphic graph, however, they differ in the degree to which information is replicated.

Cloning — The clone of a graph uses the exact same element objects as the original graph, thus original and clone graphs share the same node and edge objects. On the other hand, the data structure that records the nodes and edges contained in the graph is copied. Consequently, the Graph.equals method will return true for the clone and the original graphs, unless the clone graph object is modified by adding, removing, hiding or restoring elements.

The clone method has an extension that can be used to transform a graph into a different type. The Graph.cloneAs method can clone a graph into a subtype of the original graph. For instance, assume that a graph object is of type Graph,

```
DirectedGraph cloneGraph = graph.cloneAs(new DirectedGraph( ))
```

clones the graph object into a new object of type Directed Graph. The parameter in the cloneAs method determines the graph type to clone as.

Mirroring — Mirroring a graph is effectively copying the complete data structure as opposed to only copying the lists that record the edge and node objects in a graph. As a result, the obtained graph object is not equal to the original graph when compared with the Graph.equals method. The MirrorTransformerStrategy class of the ptolemy.graph.analysis.strategy package should be used to mirror graphs. The same class provides a method to search for a particular element that is mirrored from the original class. The following is an example of mirroring a graph. Assume that *graph* is an object of type Graph and e is an edge in *graph*.

```
MirrorTransformerStrategy transformer =
                                new MirrorTransformerStrategy(graph);
Graph mirror = transformer.mirror( );
Edge mirrorEdge = (Edge)transformer.transformedVersionOf(e);
```

It is optional to copy or share the weights between the elements of the original and the mirror graphs. The default behavior is to *share*, which can partly be viewed as a protection against non-cloneable weights.

4.3 The DIFGraph Class and mapss.dif Package

The DIFGraph class caches frequently-used data associated with generic dataflow graphs and acts as the base class of an intermediate representation for performing dataflow graph transformations , analyses, and optimizations.

The Attribute Mechanism

The attribute mechanism of the DIFGraph class can be used to bind arbitrary attributes to elements or to the graph object itself. An attribute is an arbitrary object with a label assigned to it. The object remains arbitrary even in sub-types of DIFGraph unlike weight objects. There is no limit to the number of attributes an element or graph can possess.

Another important feature introduced by the attribute mechanism is element and graph names. Elements and graphs can have string labels as names with the condition that these names, as the rest of the attribute labels, should follow the label convention established in the DIF Language specification. Name attributes are not handled as ordinary attributes, but hard-coded in the DIFGraph class for convenience.

The following classes are involved in the attribute mechanism:

DIF Graph — The DIFGraph class provides the front-end interface for the attribute mechanism, however, the mechanism is externally implemented and is left open for changes. Methods in the DIFGraph class are sufficient for non-developer users.

Attribute Container — The attribute mechanism is implemented in the AttributeContainer class. A separate attribute container is assigned to each graph element and the graph object. Ptolemy II objects from the ptolemy.data package are used internally in the Attribute Container.

mapss.dif.attributes Package — Besides the parameter mechanism classes, the attributes package also contains an enumeration class that can be used to store types of common user defined attributes.

Parametrization of Attributes

The attribute mechanism in DIF is further enhanced by a mechanism that enables parametrization of attribute values. Once parameters are defined for the graph, an attribute value can be set to a reference that points to one of the parameters in the graph. Parameter values can be discrete double numbers, double number intervals or a combination of both. The parameter mechanism is composed of three classes in the mapss.dif.arttributes package:

***Parameter* —** Parameter is an inner class that serves as the parameter reference. A parametrized attribute value is required to instantiate of this class.

***Interval* —** This class represents a double number or a single interval with double number boundaries. Each boundary can be defined to be inclusive or exclusive.

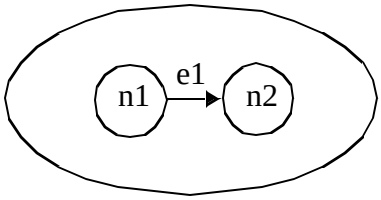
***Interval Collection* —** The domain of a parameter value is modeled as a set of intervals. All Intervals defined for a parameter are collected under a named IntervalCollection object after going through some simple transformations such as merging with neighboring intervals.

4.3.1 DIF Language Conversion from DIFGraph Objects

The DIFGraph class and other classes previously described in this section form the infrastructure that is capable of importing the topology, parameter and attribute information from a DIF specification without any data loss. An example of how a DIF specification can be coded with the DIF package API is presented in Figures 4-3 and 4-4.

The DIF compiler and writer (see Sections 4.5 and 4.6) resolve some of the conversion issues as follows:

- Element, graph, parameter and attribute names should be consistent with the DIF specification of labels as explained in Section3.1.1. All such names in the DIF package are checked by the mapss.util.Conventions class for errors. The default check is consistent with the DIF specification, therefore no ambiguity exists during conversions.
- User-defined attribute value types in the DIF language map to the following Java objects in the DIF API: *String*, *Double*, *2-D double matrix* – double[][] and *List* for object arrays.



Graph1

```
dif graph Graph1 {
    params {
        V_SIZE: [1, 5) + {7} ;
    }
    topology {
        nodes { n1 n2 }
        edges { e1 n1 n2 ; }
    }
    production {
        e1 ( 1 2 1, 2 1 2 );
    }
    attribute size {
        n1 V_SIZE;
        n2 10;
    }
    attribute description {
        this "example graph";
    }
}
```

Figure 4-3. Source DIF specification used in Figure4-4.

- In the conversions from the DIF language to the DIF package objects, user-defined attributes are handled by the attribute mechanism and built-in attributes are usually handled by node and edge weights.

4.3.2 Dataflow Graph Classes

The inheritance hierarchy of dataflow graph classes currently implemented in DIF follows the list below:

1. DIFGraph

2. CSDFGraph

3. SDFGraph

4. SingleRate Graph

5. HSDF Graph

```
import ptolemy.graph.Graph;
import ptolemy.graph.DirectedGraph;
import ptolemy.graph.Edge;
import ptolemy.graph.Node;

public class  Example {

    public Example ( ) {

        // Construct the graph object, set the built-in attribute “production”.
        Graph graph = new Graph( );
        Node n1 = graph.addNode( );
        Node n2 = graph.addNode( );
        DIFEdgeWeight weight =
              new DIFEdgeWeight(new double[ ][ ] { { 1 2 1 }, { 2 1 2 } } )
        Edge e1 = addEdge(n1, n2, weight);

        // Set the graph and element names to the labels.
        graph.setName(“Graph1”); graph.setName(e1, “e1“);
        graph.setName(n1, “n1“); graph.setName(n2, “n2“);

        // Add the parameter values.
        IntervalCollection value = new IntervalCollection(“V_SIZE“);
        value.add(new Interval(1, true, 5, false));
        value.add(new Interval(7));

        // Set the user-defined graph attribute “description”.
        graph.setAttribute(“description”, “example graph“);

        // Set the user-defined element attribute “size”.
        graph.setAttribute(n2, “size”, new Double(10));

        // Set the user-defined element attribute “size” with a parametrized
        // value.
        graph.setAttribute(n1, “size”, new DIFGraph.Parameter(“V_SIZE“);

    }
}
```

Figure 4-4. A conversion from a DIF specification to Java code with the DIF package API.

In this list, every graph extends the previous graph by extending the associated graph class, EdgeWeight class and in some cases the NodeWeight class. Section4.8 includes a list of extended classes for different graph types. Compared to the other extended classes, EdgeWeight is the most distinctive since it contains the production and consumption rates.

4.4 The Hierarchy Package

Modular design support is not provided directly through the Graph class. Instead, subgraph information and hierarchical relations between graphs are captured in the classes of the mapss.graph.hierarchy package, preserving the simplicity of the basic graph type.

The purpose of the Hierarchy package is to form a wrapper around Graph objects to implement hierarchical graphs. Using this package, subgraphs can be defined within graphs, nodes of a subgraph can be connected to its parent graph via ports and supernodes (nodes that contain subgraphs) can be flattened to merge different levels of the hierarchy. A hierarchy-enabled graph is called a *hierarchy* for brevity. The term subgraph is used interchangeably with *subhierarchy.*

Defining a hierarchy requires two steps:

- Constructing a hierarchy object that contains the graph.
- Constructing the ports of the hierarchy object.

Once graphs are hierarchy enabled, they can be modularized. Following are the steps for adding a subgraph to a graph:

- Assigning a node, called a super node of the super-graph, to the subgraph,
- Connecting the ports of the subgraph to edges or ports of the super-graph. Ports can be directed or undirected. Undirected ports can be used as bidirectional ports.

A port can be *connected* to an edge or a port of its parent graph. It can also be *associated* with a node or a subgraph port inside the graph. Figure 4-5 shows all the schemes for port connections. Two possible connections, labeled as *1* and *2* in the figure, and two possible associations, labeled as *a* and *b*, exist for a port. Connection *1* and

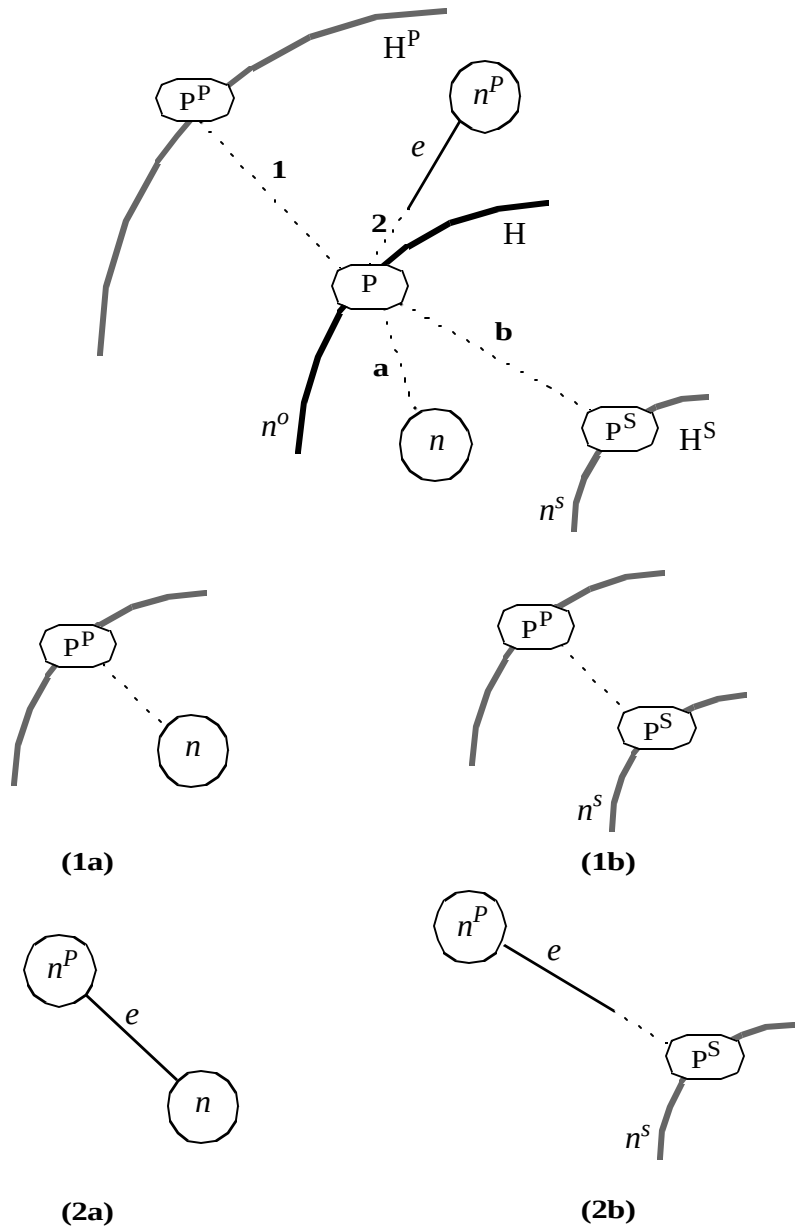


Figure 4-5. A summary of connection schemes for a port.

association *b* are, in fact, identical, i.e. connection *1* is an association to port P^p and association *b* is a connection to port P^S.

Flatten methods are provided in the Hierarchy class for replacing super nodes with their assigned subgraphs. This method places a mirror of the graph object into the parent graph and removes the super node. Port connections are handled as shown in Figure4-5. The top of the figure demonstrates all possible connections and relations on port *P*. Thick lines denote graph boundaries. The letters *P*, *n* and *e* are used for ports, nodes and edges respectively. Superscripts *p* and *s* are abbreviations for parent (outermost) graph and subgraph (innermost graph), n^o is the label of the super-node that contains the graph outlined by the dark contour and n^s is the label of the super-node that contains the innermost subgraph. Dotted lines represent port connections on the outside and port relations on the inside. The sub-figures show how the connection and relations are resolved after flattening the intermediate graph for different cases.

4.4.1 Overview of Classes

The *hierarchy package* contains six classes:

Hierarchy — Hierarchy is the wrapper class that stores the target graph in its data structure. It provides methods to create, delete and flatten super-nodes among other methods, such as clone and mirror.

Port — A hierarchy object interfaces with other hierarchies through Port objects. A port belongs to the hierarchy object that is passed in its constructor. The port-hierarchy association is immutable, meaning a port cannot be used as a port of another hierarchy after it is created. The port class contains *(dis)connect* and *(un)relate* methods to handle

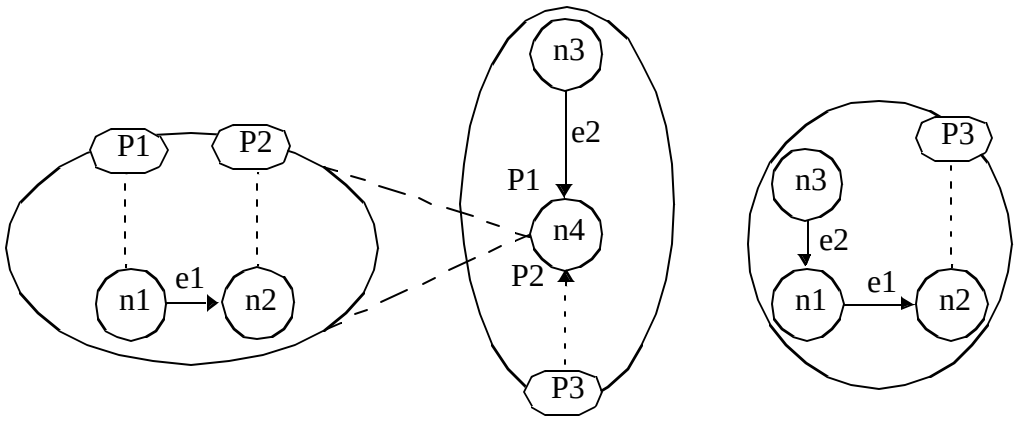
connections and a *dispose* method to remove it from the hierarchy. A disposed port cannot be used any further.

Port List — PortList is an internal class that maintains the list of ports in a hierarchy. It provides methods to check if a port label is previously defined or if an edge is connected to another port prior to a connection. Unused port labels can safely be obtained through the newName method. The order that the ports are added to this list is preserved in getAll and iterator methods.

A port can be of types in, out or inout. Types in and out should be consistent with directions of edges and ports that they are connected and related to. Type inout is compatible with all directions, except that it can only be related to an inout type port.

Super Node Map — Super node map is another class internal to the hierarchy class. It stores supernode/subhierarchy object pairs in a doubly-linked, ordered map. Due to the double-link property both super-nodes and sub-hierarchies can be used as keys to obtain the other pair from the map. The isDefined method is provided to check if a hierarchy name is previously defined. Unused hierarchy names can safely be obtained through the newName method. The order in which the pairs are added to this map is preserved in the getAll and iterator methods.

Cyclic Hierarchy Exception — A cyclic hierarchy exception occurs if a nested hierarchy definition is found to be cyclic, for instance a hierarchy cannot have itself as a subgraph. In addition to being an exception type, this class provides a method to check if a subgraph definition will create a cyclic relationship.



Graph1 Graph 2 Graph 2 after *flatten*

(a) **(b)** **(c)**

```
import mapss.graph.hierarchy.Hierarchy;
import mapss.graph.hierarchy.Port;
                    ...

public class Example2 {

    public Example2 ( ) {
                    ...
        // Graph objects are created here.
                    ...
(a)     // Constructing hierarchy1.
        Hierarchy hierarchy1 = new Hierarchy(graph1, "Graph1");
        Port P1 = new Port(hierarchy1, "P1", Port.IN);
        Port P2 = new Port(hierarchy1, "P2", Port.OUT);

(b)     // Constructing hierarchy2.
        Hierarchy hierarchy2 = new Hierarchy(graph2, "Graph2");
        hierarchy2.addSuperNode(n4, hierarchy1);
        Port P3 = new Port(hierarchy2, "P3", Port.OUT);

        // Connecting ports.
        P1.connect(e2);
        P2.connect(P3);

(c)     // Merging the hierarchy levels.
        hierarchy2.flatten(n4);
    }
}
```

Figure 4-6. The Java code that defines and flattens the nested *hierarchy 2*.

Hierarchy Exception — All hierarchy related errors except the cyclic hierarchy error will cause a *hierarchy exception*. Most of the error checking methods of the Hierarchy package are defined in this class.

4.4.2 Hierarchy Related Functions

Hierarchical and topological structures of modular graphs are distributed over several classes: Graph, Hierarchy, Port, etc. Consistency across these objects can be provided in a strict or loose fashion. Strict consistency is accomplished by continuous verification. The advantage of strict consistency is a persistently valid state, and the trade-off is close coupling between all classes. This conflicts with the philosophy of the Hierarchy package, which is to keep the hierarchy mechanism related code separate from the Graph class since the latter is to be used purely for representing generic mathematical graphs. Therefore, the loose-consistency scheme is found more suitable for DIF hierarchies. In the loose approach, consistency verification is performed less frequently rather than with each operation. In particular, graph operations, such as edge/node addition and removals are not subject to any hierarchy related checks since there is no communication from the Graph class to the Hierarchy class.

This section aims to describe how several functions in the Hierarchy package are achieved while maintaining the desired loose consistency.

Adding a supernode to a hierarchy — Adding a supernode to a hierarchy only assigns a subhierarchy with a node in the hierarchy. No connections or relations are defined at this stage. The subhierarchy is removed from its previous parent, if it exists. The potential supernode is unassigned from its previous subhierarchy as well. Then the supernode-subhierarchy pair is added to the SuperNodeMap object in the Hierarchy and the parent

reference in the subhierarchy object is set. Before this procedure the following checks are performed:

- The parent hierarchy does not contain another subhierarchy with the same name.
- The new supernode definition does not cause a cyclic relationship, i.e. the new subhierarchy is not already an ancestor of the parent hierarchy.

Both of these properties cannot be violated once they are avoided at this step. Note that the supernode is not checked to verify that it is a node in the parent graph, which is not an essential check at this point since the node can later be removed from the graph.

The reverse of this process, called disconnecting, removes the parent reference in a subhierarchy, removes the corresponding entry from the SuperNodeMap of the parent and disconnects all the subhierarchy ports.

Defining a Port — A Port object is added to a Hierarchy through its constructor. In the port constructor, the hierarchy reference and the name of the port is set and the port is added to the PortList of the Hierarchy object. The hierarchy reference and the name field of the Port class are immutable after they are created; a port can be removed from its hierarchy but it cannot be used again (Port.dispose method). Also the port name is checked against other port names in the hierarchy for uniqueness, a property that retains validity since port names are immutable.

The Port.dispose method disconnects all connections and removes the PortList entry in its hierarchy. Any attempt to use the member methods of a disposed port will result in an error.

Connecting a port to an edge — The Port class provides a member method for connecting an edge to a port object. It simply sets the connection field in the port,

overriding it if another connection is defined. When connecting *e* to P (see Figure4-5), the following properties are verified.

- *e* is incident to n^0
- If *e* is not a self-loop edge, it is not connected to another port of n^0.
- If *e* is a self-loop edge, it is not connected to two other ports of n^0.
- The direction of *e* matches the port direction: if n^0 is the source of *e*, P should be of type out, otherwise P should be of type in. If P is type inout both connections are valid.
- If e is a self-loop edge and it is connected to two ports, both ports cannot be of type in or type out at the same time.

Source and sink nodes of Edge objects are immutable, therefore the checks will remain valid after the connection.

Associating a port to a node — Associate method in Port class first removes any previous associations and then sets the node field in the Port object. No checks are performed in this method.

Associating/connecting a port to another port — The port class contains both connect and associate methods for ports. These methods are identical, for example, P.connect(P^P) has the same effect as P^P.associate(P) where P is a port in the subhierarchy and P^P is a port in the parent hierarchy. During this connection, associatedPort and node fields of P^P and the connection field of P are set, overriding all previous field values. All ports in overridden connections and associations are also disconnected/disassociated. Considering the port connection *(1)* in Figure4-5, following statements are verified.

- H is a subhierarchy of H^P.
- P and P^P have the same directions or P is type inout.

Note that type inout ports cannot be related to type in or type out ports.

Flattening a supernode — Following is the algorithm for the Hierarchy.flatten function. It is assumed that n_0 in Figure4-5 is being flattened.

1. For all P store $P^S$and n^0.
2. Add all edges and nodes in H to H^P.
3. Add all supernodes of H to H^P:
   Prefix all H^S names with the name of H followed by a period "."
   For all H^S, store all port-edge connection pairs.
   Add all H^S - n^s pairs to the superNodeMap of H^P.
   Restore edge connections for all H^S.
4. For all P (ports of H) handle the connection/relation:
   connection = P.connection
   N = P.node
   if connection is a Port
      P^P.unrelate( )
      if P is related to a node
         P^S.disconnect( )
         P^S.connect(P^P)
      else
         P^P.relate(n)
   else
      // Means connection is an edge.
      If relation is a node
         Connect the edge to n
      else
         Connect the edge to n^s
         P^S.connect(e)
5. H^P.disconnectSuperNode(n^0)
6. H^P.removeNode(n^0)

The steps labeled "*Connect edge to* ..." are not realizable in the Hierarchy API because edges are immutable. The actual steps include instantiating new edges and replacing the old edges with the new ones. Self-loop edges require special attention during this process.

Before the algorithm is run, the graph and the hierarchy objects are verified for consistency. If an error is found, they are returned with no modification. An alternative is calling the Hierarchy.purge method in advance to remove all faulty connections and

associations. After the purge method is run the Hierarchy object is guaranteed to be free of errors. Below are the conditions that should be verified before flattening.

- n^0 is a node in the graph of H^P and n^0 is a supernode in H^P.
- All ports P of H are connected and related. All related nodes n or n^S are elements in the graph of H. All connected edges *e* are edges in the graph of H^P.

4.4.3 Extending the Hierarchy Class

The Hierarchy class can be extended for handling different kind of graphs. Even though most methods do not depend on the type of the backing graph object, `mirror` and `flatten` methods require graph specific information. All extending classes should provide at least one constructor with exactly two parameters: the graph and the name of the graph. The `_copyEdge` method should be overridden to return an edge with the correct weight object type, the `_mirrorGraph` method should return a `MirrorTransformerStrategy` object that mirrors the backing graph in the desired way and the `_graphType` method should return an empty graph with the graph type supported by this hierarchy.

4.4.4 DIF Language Conversion from DIFHierarchy Objects

The `mapss.dif.language.Writer` class can be used to write a DIFHierarchy object into a DIF text file. This class is discussed in Section4.6. All port labels and the hierarchy name are kept consistent with the DIF conventions. If the hierarchy name is different than the graph name, the graph name is ignored.

4.5 The DIF Compiler

The DIF API provides a complete parser that translates DIF language text into graph and hierarchy objects. This parser is automatically generated by the SableCC [7], a compiler-compiler for building compilers in the Java programming language.

Parser related classes and packages are managed under mapss.dif.language. The list of these classes are is follows:

- **SableCC/compiler.Grammar** SableCC language specification file for DIF.
- **SableCC subpackages** node, lexer, parser and analysis packages compose the SableCC generated compiler framework.
- **Language Analysis** Contains the action code for compiling default DIF graphs. New graph types are added to the compiler API by extending this class. This will be covered in Section 4.5.3.
- **analyzers.txt** Contains the list of full names of default language analysis classes. All default graph types in DIF are associated with an entry in this list. If a class is not found in the JVM path or if an error occurs during initialization of a language analysis, the corresponding graph type will be ignored from subsequent compilations. Whitespaces and line or block comments in analyzers.txt are ignored.
- **Reader** Front-end compiler interface. Accommodates the preprocessor, lexer and parser functions. Compiled objects are accessed through getGraphs and getHierarchies methods of this class.
- **Graph Modifier** A mini-compiler for reduced DIF language files. A reduced DIF graph definition contains only a params block and attributes. It is very similar to the basedon feature in regular DIF files except the graph to be modified is externally loaded in the GraphModifier class.
- **DIF Language Exception** Thrown in case of language related errors.

4.5.1 SableCC

This section is a tutorial on SableCC features that were used in the design of the DIF parser. As opposed to being a complementary guide, some features of SableCC are deliberately ignored for brevity purposes. Refer to [7] for an complete tutorial.

SableCC employs the Visitor Design Pattern and takes advantage of the Java type system to deliver modular, abstract syntax tree (AST) based, object-oriented compilers.

SableCC does not require any action code in specification files, rather it builds the framework, in which actions can be added as Java code. Aside from ease of debugging, this approach benefits from another major advantage: More than one compilers for the same language can share a common framework. For example, the DIF package contains a mini-compiler for reduced DIF, GraphModifier, in addition to the main compiler class.

DIF Parser Design with SableCC

The DIF parser was designed in five major steps:

1. The lexicon and the grammar of the language was defined in a SableCC specification file.
2. The framework was generated by SableCC.
3. Action code was defined in the working-class, LanguageAnalysis, utilizing the SableCC generated AST objects.
4. The main compiler class, Reader, was created to activate the lexer, the parser and the analysis functions.
5. The parser was compiled with Java.

The steps of the design flow with the files or subpackages involved are illustrated in Figure 4-7. Each step in the figure is numbered according to the list above.

The Language Specification File

SableCC language specification input is written in EBNF. As a result, the specification file given in AppendixB is almost identical to the language specification in AppendixA. The only major difference is that the specification file of SableCC contains another section, that is *helpers*. Helpers are logical macros for using in the *tokens* section. Unlike text macros, regular expressions in helpers are evaluated before substitution.

Example 4-1 *Consider the helper h = 'a' | 'b' and the token t = 'a' h 'b'. The set that t represents is {"aab", "abb"} whereas in case of a text macro t would represent 'a' 'a' | 'b' 'b' = {"aa", "bb"}.*

As a general practice, complicated and low-level regular expressions are defined in the helpers section. The language specification file also contains an *ignored tokens* section that lists the tokens, such as whitespaces and comments, to be ignored during parsing.

The AST generating process requires the following conventions for resolving node names.

- If there are alternative productions for a non-terminal, each alternative should be labeled as described in Section2.3 except that one alternative can be left without a label.

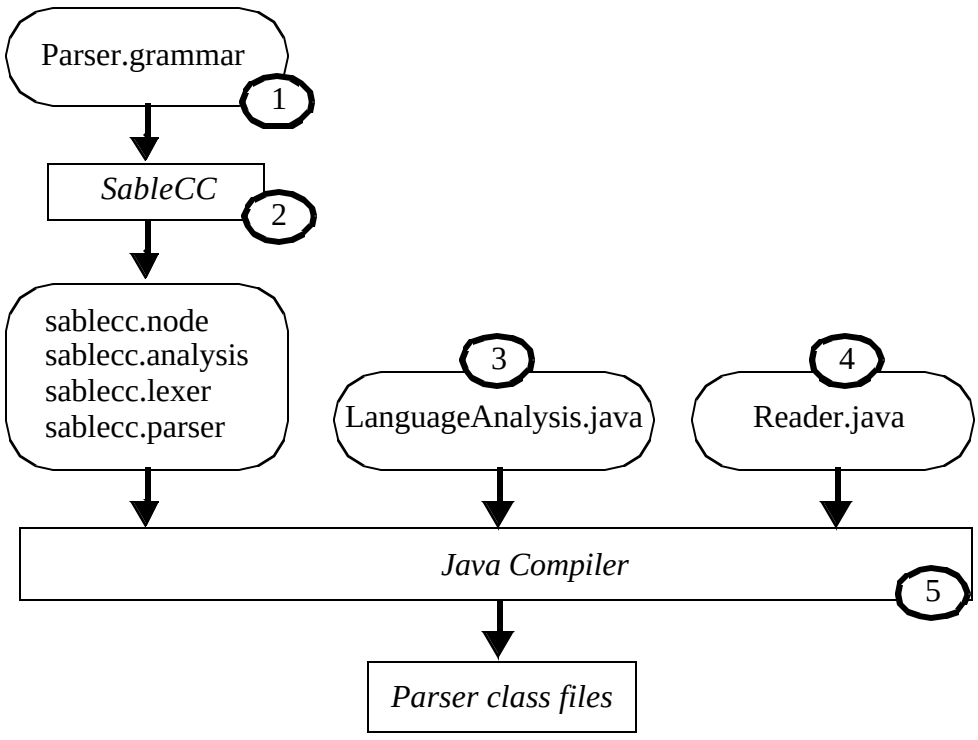


Figure 4-7. DIF parser design flow.

- If the same token is used more than once in a production, each token should be labeled as described in Section2.3, except that only one token can be left unlabeled.

SableCC generates four subpackages to build the compiler framework in the second step of compiler design: lexer, parser, nodes and analysis. Among these, nodes and analysis packages are used in the action code definition.

- ***nodes* package** This package contains the classes that represent the nodes of the AST. Naming conventions for the parse tree are as follows
  - A node representing an unnamed alternative of a production, is named by the production name, prefixed with an uppercase "A", first letter replaced by an uppercase, each letter following an underscore replaced with an uppercase and all underscores removed.
  - Named alternatives translate into similar node names except, the alternative label is placed between the "A" and the production name after the alternative label goes through the same underscore conversion process.
  - Named and unnamed tokens follow the preceding two rules with a minor difference that "T" is used as the first letter.

  AST noes are also equipped with accessor methods that return their children tokens in the tree.
- ***analysis* package** The analysis package provides the tree traversal classes for implementing the action code. The LanguageAnalysis class extends analysis.DepthFirstAdapter for a depth first traversal on the AST. It also inherits a list of node visitor methods, two for each node, which are called by the parser during the first visit and the second visit of a node. These methods are overridden by LanguageAnalysis to implement the action code for nodes. Node objects are passed to the corresponding visitor methods as parameters, this is how the LanguageAnalysis class interacts with the nodes package and accesses the token strings. Visitor method names are obtained from the name of the corresponding node object by adding one of the suffixes *in* (for the first visit) and *out* (for the second visit).

Example 4-2 *Following is the SableCC specification input for the language defined in Example2-1 with a minor improvement. This version allows a string that terminates with an equals sign such as "y=".*

```
Helpers:
        letter = ['a' .. 'z']
        digit = ['0' .. '9']

Tokens:
        label = letter+
        number = digit+\
        operator = '+' | '-' | '*' | '/'
        equals = '='

Productions:
        S =     {defined}       [answer]:label equals B |
                {not_defined}[answer]:label equals
        B = number tail*
        tail = operator number
```

The DepthFirstAdapter class will define the following list of visitor methods. The second method in each entry is the accessor method for accessing the token.

- in/outADefinedS(ADefinedS node) – node.getAnswer( )
- in/outANotDefinedS(ANotDefinedS node) – node.getAnswer( )
- in/outAB(AB node) – node.getNumber( )
- in/outATail(ATail node) – node.getNumber( )

The Compiler

The compiler is a front-end interface for combining the lexer, the parser and the action code. Reader class in the DIF API implements the top-level compiler. The structure of a very simple compiler, reading its input from standard input, is given in Figure4-8.

4.5.2 The Language Analysis Class

This class is normally beyond the scope of a non-developer user and it is of interest to developers for defining new graph types or custom compiler front-ends. The LanguageAnalysis API features three kinds of methods:

- Public methods for compiler front-end use.
- Protected methods for defining new graph types in DIF.
- Public methods inherited from the SableCC adapter class, names starting with *in* or *out*.

The last category of methods is unavoidably defined public even though such methods are supposed to be invisible to the users: Java does not allow overriding a method to have a more constricted scope. These methods contain the basic action code and they do not change unless the language grammar or the semantics change.

```
public class Compiler {
    public static void main(String[ ] args) throws Exception {
        // Create a parser.
        Parser p =
            new Parser(
            new Lexer(
            new PushbackReader(
            new InputStreamReader(System.in), 1024)));
        // Parse the input.
        Start tree = p.parse();
        // Apply the action code.
        tree.apply(new Analysis());
    }
}
```

Figure 4-8. A simple SableCC generated compiler front-end.

The remainder of the public methods, externalHierarchies, getHierarchy and getKeyword are utilized by the compiler front-end. The compiler provides previously read graphs to the parser through the externalHierarchies method. These graphs build the scope of the graph being parsed.

Protected methods in LanguageAnalysis constitute a generic API for defining new graph types in DIF. This is covered in detail in the next section.

4.5.3 Extending the DIF Language For A New Graph Type

In DIF, the differences between graph types typically arise from built-in attributes. Therefore a new graph type definition mainly consists of new built-in attribute definitions. A new graph type is introduced in two steps:

1. Extending the LanguageAnalysis class and overriding the following list of methods:
   - getEmptyXXX methods return an empty graph/edge/node that is of the type that the input topology will be converted to.
   - getKeyword returns the keyword for the new graph type.
   - acceptableSubHierarchy(DIFHiearchy hierarchy) returns true if hierarchy can semantically be a subhierarchy of the parsed graph.
2. Writing the action code to process fixed attributes. _processFixedAttributes method should be overridden with appropriate code for each for each type of built-in attribute. This method returns false if the attribute cannot be processed, which will induce an error thrown by compiler.
3. Adding the full name of the new analysis to analyzers.txt.

4.5.4 The Reader Class – The Front-End Compiler

The reader class of the DIF compiler is more advanced than the front-end in Figure4-8. Default graph analyzers listed by analyzers.txt are initialized by Reader. If desired, custom analyzers can be added through the compile method. The Reader class also contains the preprocessor mechanism of DIF, which is implemented through a system call to the GNU C preprocessor.

A DIF file is compiled by passing the input file name in the constructor, running the compile method and calling the getGraphs or getHierarchies methods for the output.

Following is an informal pseudocode that explains the compile method of Reader. It is assumed that all analyzers are read into a list analyzers during initialization and also cpp is a function that runs the preprocessor on the input. The cpp function reads all the files indicated by the include statements and creates an ordered map of the file names to the DIF file texts. The keys are ordered from the most dependent file to the files with no include statements. This means that given any entry on the list; the scope of the file in the entry consists of the subsequent entries in the list. For this reason, the list is compiled in reverse order.

```
FUNCTION: Reader Main Function
INPUTS: analyzers: LanguageAnalysisList, fileName: String
RETURNS: hierarchies: DIFHierarchyList

    files = cpp ← fileName
    // Start reading files from the least dependent one.
    for (name, text) in files following reverse order
        // Pass each text through lexer & parser for error check.
        // If error check is performed later, file names and line
        // numbers will be lost and errors will be harder to
        // track by the user.
        parser ← lexer ← text
```

```
        for graphText in test following order
            if graphText.keyword == null then
                graphText. keyword = dif
            analyzer = analyzers.find(keyword)
            if "basedon modelName" exists in graphText
                if modelName == graphText.name then
                    throw "Graph cannot be based on itself"
                modelObj = hierarchies.find(modelName)
                if modelObj == null then
                    throw "Model graph not found"
                mirrorObj = modelObj.mirror( )
                GraphModifier.modify(mirrorObj, graphText)
                hierarchies.add(mirrorObj)
            else
                // All semantic checks on the input is performed
                // by the analyzer in the action-code.
                graphObj = analyzer ← parser ← lexer ← text
                hieracrchies.add(graphObj)
    return hierarchies
```

4.6 The DIF Writer

DIF conversion considerations involving DIFGraph and Hierarchy objects were discussed in Sections 4.3.1 and Section4.4.4. The DIFWriter class follows the guidelines provided in those sections. Following is a partial list of DIF Language constructs in Figure 3-1 and the methods they are obtained from in DIFWriter. Types of the values returned by some of the methods are indicated in italic font.

keyword → DIFWriter._graphType( )
graphID → DIFGraph.getName( )
prm$_i$ → *List* DIFGraph.getParameterNames( )
parameter values →
IntervalCollection DIFGraph._getParameterValue(prm$_i$)
IntervalCollection.toString( )

portID → *PortList* Hierarchy.getPorts( ) and Port class methods
node/edgeID → DIFGraph.getName(node/edge)
refinement block → *SuperNodeMap* Hierarchy.getSuperNodes( ) and SuperNodeMap class methods
attribute name and values → AttributeContainer class methods

The AttributeContainer.objectToString method defines which attribute values are convertible to the DIF language. Built-in attributes, such as EdgeWeight information are handled in the DIFWriter._readBuiltInAttributes method.

A new graph writer class can be defined by extending the DIFWriter class and overriding the following methods:

- A new type keyword should be added to the isKeyword method.
- _getEmptyGraph should return an empty graph for type-checking the input graphs.
- _graphType should return the type keyword.
- _readBuiltInAttributes should be overridden to process the built-in attributes in the graph.

4.7 Graph Visualization

DIF specifications and hierarchy/graph objects of the DIF API can also be converted automatically into the input format of *dot* [10], a well known graph-visualization tool. dot is distributed by AT&T Research Labs as a part of GraphViz - open source graph drawing software.

The mapss.graph package provides default dot generators for Graph objects and Hierarchy objects. These classes can be extended to define type specific *dot* generators. A tutorial example of dot generator classes can be found in Section5.2.1.

4.8 Summary of DIF API Packages and Classes

- **Graph Classes** Graph classes for dataflow models presently supported in DIF are collected under three packages.
  - mapss.dif DIF graph classes.
  - mapss.csdf CSDF graph classes.
  - mapss.sdf SDF graph, single rate graph, and hsdf graph classes

  Every graph type may consist of up to nine kinds of classes at its core:

  1. xxxGraph
  2. xxxEdgeWeight
  3. xxxNodeWeight
  4. xxxHierarchy
  5. xxxToDot
  6. xxxHierarchyToDot
  7. xxxMirrorTransformation
  8. xxxLanguageAnalysis
  9. xxxToDIFWriter

"xxx" in these class names is replaced by the specific graph type name. Following is a list of graph types with defined classes, ordered according to the type hierarchy. Numbers denote classes according to the previous list.

- DIF 1, 2, 3, 4, 5, 6, 7
- CSDF 1, 2, 3, 5, 8, 9
- SDF 1, 2, 3, 5, 8, 9
- SingleRate 1, 2, 8, 9
- HSDF 1, 2, 8, 9

For CSDF, SDF, SingleRate and HSDF, the classes that are not present are used from the closest parent in the hierarchy that owns that class type. For example, HSDF does not possess a HSDFNodeWeight class, instead SDFNodeWeight class is used.

LanguageAnalysis and ToDIFWriter classes for DIF graph are placed under mapss.dif.language.

- **Attribute Mechanism** mapss.dif.attributes package and mapss.dif.AttributeContainer class.
- **Hierarchy Mechanism** mapss.graph.hierarchy package.
- **DIF Compiler and Writer** mapss.dif.language package and mapss.dif.language.sablecc package.
- **Graph Visualization Base Classes** mapss.graph package.
- **DIF Naming Conventions** mapss.util.Conventions class.
- **Demo Utilities** mapss.util.demo package.
- **Demos** mapss.graph.demo, mapss.graph.hierarchy.demo, mapss.dif.attributes.demo, mapss.dif.language.demo packages.

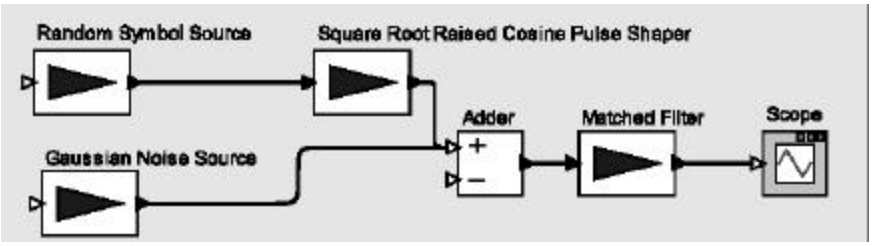
CHAPTER 5

Application Examples and Tutorials

5.1 Applications

5.1.1 Ptolemy

We have developed a back-end for Ptolemy II that generates DIF graphs from dataflow-based Ptolemy II models. An example of Ptolemy-to-DIF conversion through this back-end is shown in Figure5-1. This example represents the functionality of each node as a *computation* attribute, which is derived from the Ptolemy II library definition. A front-end that converts DIF specifications into Ptolemy II models is under development.




```
sdf graph _graph {
    topology {
        nodes {
            n0 n1 n2 n3 n4 n5
        }
        edges {
            e0 n0 n1;
            e1 n1 n2;
            e2 n2 n4;
            e3 n3 n2;
            e4 n4 n5;
        }
    }
    production {
        e0 1;    e1 16;
        e2 1;    e3 1;
        e4 1;
    }
    consumption {
        e0 1;    e1 1;
        e2 1;    e3 1;
        e4 1;
    }
    delay {
        e0 0;    e1 0;
        e2 0;    e3 0;
        e4 0;
    }
    computation {
        n0 DiscreteRandomSource;
        n1 RaisedCosine;
        n2 AddSubtract;
        n3 Gaussian;
        n4 RaisedCosine;
        n5 SequenceScope;
    }
}
```

Figure 5-1. Ptolemy II model of a pulse amplitude modulation system that is exported to DIF.

5.1.2 MCCI Autocoding Toolset

Another application example of DIF is in the Autocoding Toolset of Management, Communications, and Control Inc. (MCCI) [14]. This tool is designed for mapping large, complex signal processing applications onto high-performance multiprocessor platforms. Through a DIF-generating back-end developed by MCCI, the Autocoding Toolset supports generation of DIF specifications after partitioning the application.

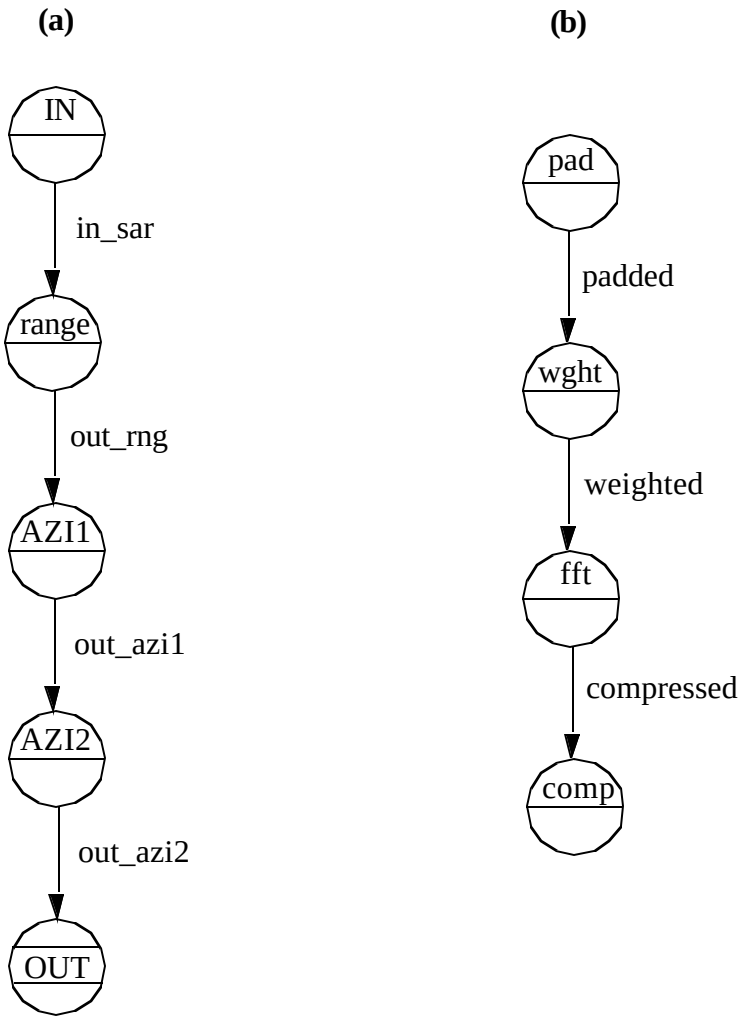


Figure 5-2. The top-level partitioned application graph of a SAR application and a range processing graph in the MCCI Autocoding Toolset.

(a)

```
graph rangeGraph {
    interface {
        input rng_in;
        output rng_out;
    }
    topology {
        nodes {
            pad:rng_in
            wght fft comp:rng_out
        }
        edges {
            padded pad wght;
            weighted wght fft;
            compressed fft comp;
        }
    }
    production {
        padded 1048576;
        weighted 1048576;
        compressed 1048576;
    }
    consumption {
        padded 1048576;
        weighted 1048576;
        compressed 1048576;
    }
    delay {
        padded 0;      weighted 0;
        compressed 0;
    }
}
```

(b)

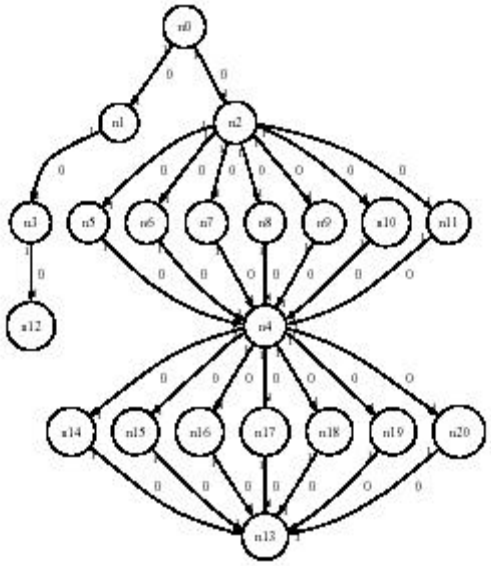
```
graph SAR {
    ...
    refinement {
        rangeGraph range
            rng_in:in_sar rng_out:out_rng;
    }
    ...
}
```

Figure 5-3. Range processing and range processing instantiation in SAR.

Figure5-2 shows a synthetic aperture radar (SAR) application developed in the Autocoding Toolset. The functional requirements of SAR processing consist of four logical processes: data input and conditioning, range processing, azimuth processing and data output. The Autocoding Toolset partitions the application into five parts dividing the azimuth processing into two parts. Figure5-2*(a)* shows the top level functional definition graph and Figure5-2*(b)* shows the *range* subgraph. DIF definitions of these graphs can be found in Figure5-3. Range processing of data includes conversion to complex floating point numbers, padding the end of each data row with zeros, multiplying by a weighting function, computing the FFT, and multiplying the data by the radar cross-section compensation. Note that although Figure5-3*(a)* is a single rate graph, the Autocoding Toolset presently exports this in the more general form of a DIF graph. This example is adapted due to space constraints.

5.1.3 Benchmark Generation

The DIF package contains facilities to generate DIF specifications of randomly-generated, synthetic benchmarks. This can be useful for more extensive testing of tools and algorithms beyond the set of available application models. The benchmark generator is based on an implementation of Sih's dataflow graph generation algorithm [15], which constructs application-like graphs by mimicking patterns found in practical dataflow models. Figure5-4 shows a synthetic DIFGraph generated by the DIF package and laid-out through the *dot* generator.



```
sdf graph _graph {
    topology {
        nodes {
            n0  n1  n2
            n3  n4  n5
            n6  n7  n8
            n9  n10 n11
            n12 n13 n14
            n15 n16 n17
            n18 n19 n20
        }
        edges {
            e0 n0 n1;
            e1 n0 n2;
            e2 n1 n3;
            e3 n2 n5;
            e4 n5 n4;
            ...
            e31 n20 n13;
        }
    }
    production {
        e0 1;
        ...
        e31 1;
    }
    consumption {
        e0 1;
        ...
        e31 1;
    }
    delay {
        e0 0;
        ...
        e31 0;
    }
}
```

Figure 5-4. A synthetic DIFGraph generated by the DIF package and *dot* generator output for the graph.

5.2 Tutorials

5.2.1 A Tutorial Example for the Visualization Tool

The mapss.graph package contains a tutorial example for the graph visualization tool, provided by the DotGenerator class. DotGenerator generates *dot* files for the

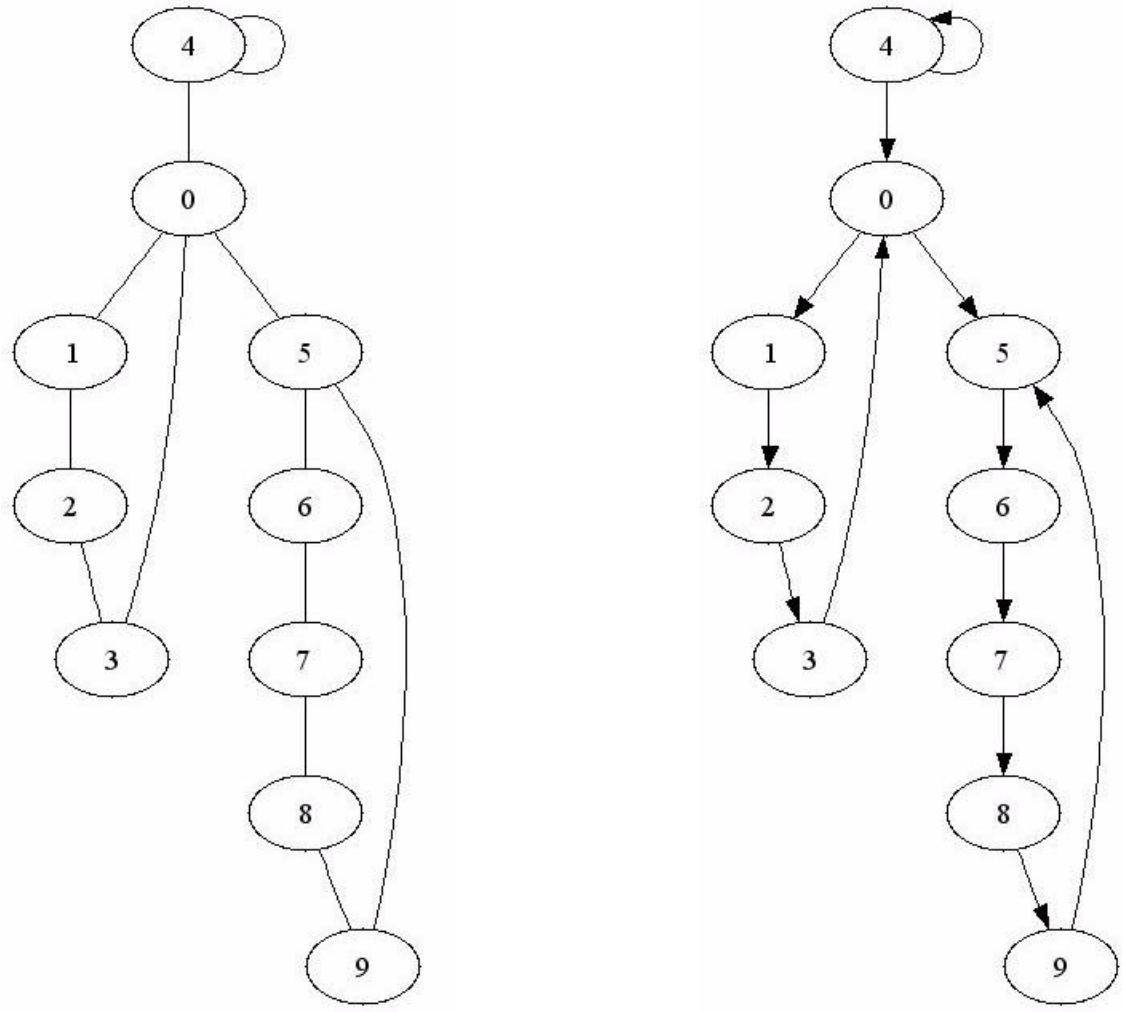


Figure 5-5. Undirected and directed layouts of the same graph with false and true options set in DotGenerator.toFile method.

GraphViz tool. This tutorial is created using the Demo API of the graph.util.demo package.

1. The DotGenerator class provides a one-step static function for generating directed or undirected *dot* files. This method can be used draw graphs with default settings of GraphViz. The following code is for generating directed and undirected graph

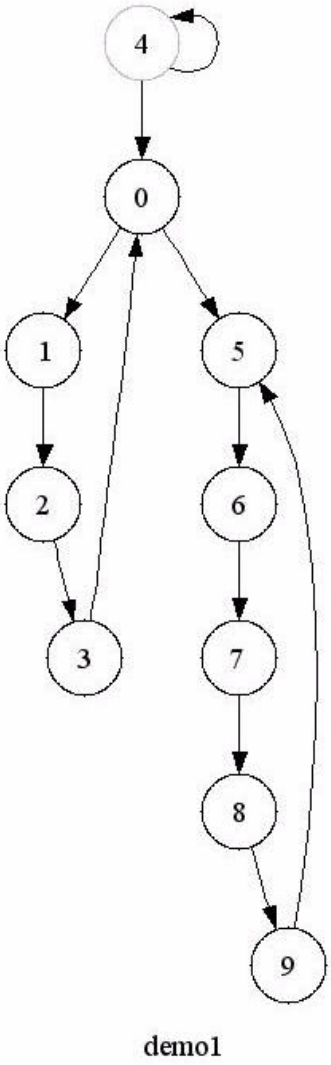


Figure 5-6. A customized graph with circular and colored nodes.

visualization files for a hypothetical Graph object named graph0. The last parameter should be set to true for a directed output.

```
DotGenerator.toFile(graph0, fileName, true or false);
```

2. DotGenerator can be configured for a customized look. For changing default options of the tool, a DotGenerator object is required to be created instead of using the static function. The following is the code that generates the look in Figure5-6.

```
// Create the DotGenerator object.
DotGenerator dot = new DotGenerator(myGraph);

// Add some attributes to the graph to make it look nicer.
// Note that attributes that belong to the graph (not specific
// to an edge or a node) should be added with addLine method.
dot.setGraphName("demo1");
dot.addLine("node[shape = circle];");
dot.addLine("center = true;");

// Add an attribute to a node in the graph.
dot.setAttribute(node4, "color", "red");

// Set the graph as directed.
dot.setAsDirected(true);

// Call toFile function to create the file.
dot.toFile(path + "demo1");
```

3. GraphViz can also cluster graph nodes. Invisible nodes can be used to fine-tune the alignment of nodes in clusters. In the graph of Figure5-7, invisible edges connect

nodes 2 and 5 to an invisible node at the bottom of the figure, which helps GraphViz to place cluster nodes in two rows.

```
// Add a dummy node and two dummy edges to the graph for alignment
// purposes.
myGraph2.addNode(node7);
Edge edge2_7 = myGraph2.addEdge(node2, node7);
Edge edge5_7 = myGraph2.addEdge(node5, node7);

// Cluster the nodes after creating the DotGenerator object.
DotGenerator dot2 = new DotGenerator(myGraph2);
Collection cluster1 =
Arrays.asList(new Node[] {node0, node1, node2});
Collection cluster2 =
Arrays.asList(new Node[] {node3, node4, node5});
dot2.setCluster(cluster1);
dot2.setCluster(cluster2);

// Set some attributes for a nice look.
dot2.setAttribute(cluster1, "label = \"cluster1\"");
dot2.setAttribute(cluster1, "color = blue");
dot2.setAttribute(cluster2, "label = \"cluster2\"");
dot2.setAttribute(cluster2, "color = red");

// Use this part of the graph for alignment purposes so set it
// invisible.
dot2.setAttribute(node7, "style", "\"invis\"");
dot2.setAttribute(edge2_7, "style", "\"invis\"");
dot2.setAttribute(edge5_7, "style", "\"invis\"");

// Set as directed.
dot2.setAsDirected(true);

// Call toFile function to create the file.
dot2.toFile(path + "clusterExample");
```

5.2.2 Tutorial Examples for the Hierarchy Mechanism

The mapss.graph.hierarchy package contains a tutorial example for the hierarchy mechanism. This tutorial is created using the Demo API of the graph.util.demo package.

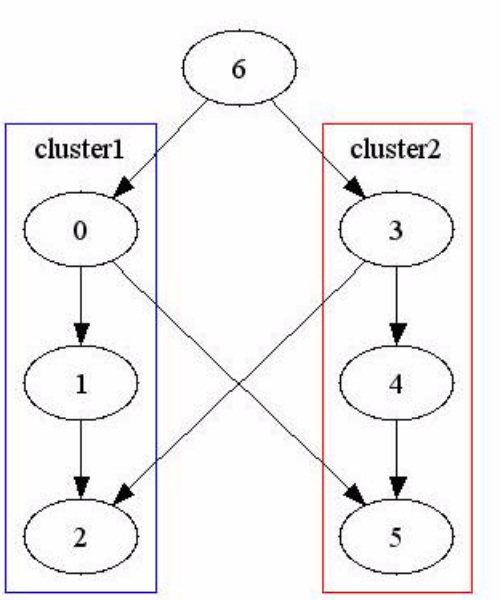


Figure 5-7. A clustered graph example.

All graph and hierarchy figures related to this example are generated by the *dot* generator and GraphViz tool. The dot generator automatically places a list of ports with associations and supernodes under each figure.

Hierarchy Example

1. Setting up a hierarchy and its ports. A hierarchy object is built on a previously constructed graph object. Two kinds of connections can be made to a port from inside the hierarchy: A node or a port of a subhierarchy. In this example, all ports are connected to nodes inside the hierarchy, which is also called relating a port with a node. The code that generates *hierarchy 0* is as follows:

```
// Define Hierarchy0.
Hierarchy h0 = new Hierarchy(g0, "Hierarchy0");
```

```
// Set up ports for Hierarchy0.
Port p01 = new Port("P01", h0);
p01.relate(n01);
Port p02 = new Port("P02", h0);
p02.relate(n02);
Port p03 = new Port("P03", h0);
p03.relate(n03);
```

2. Defining a subhierarchy, *hierarchy 0*, and connecting it to its parent hierarchy, *hierarchy 1*. *Hierarchy 0* is placed in super node, n13. Two kinds of connections can be made to a port from the outside: An edge or a port of the parent hierarchy. In this case, P03 is connected to P13 and other ports of *hierarchy 0* are connected to edges. Note that only the self loop edge of n13 is connected to the ports of the subhierarchy and other incident edges are left unconnected. This leads to removal of those upon flatten of n13. The code that generates *hierarchy1* is below:

```
// Construct Hierarchy1.
Hierarchy h1 = new Hierarchy(g1, "Hierarchy1");

// Define a subhierarchy.
h1.addSuperNode(n13, h0);
```

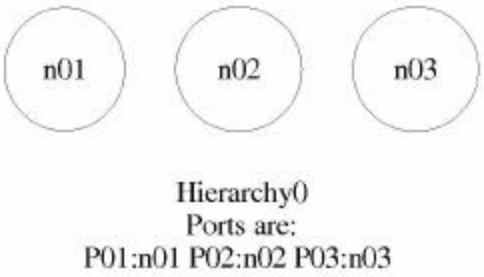


Figure 5-8. *Dot* output for *hierarchy 0*.

```
// Make connections from outside (Hierarchy1) to the subhierarchy
// (Hierarchy0).
p01.connect(e15);
p02.connect(e15);

// Set up ports for Hierarchy1 and connect them with nodes
// from the inside.
Port p11 = new Port("P11", h1);
p11.relate(n11);
Port p12 = new Port("P12", h1);
p12.relate(n14);

// The following port is connected to a port from a subhierarchy instead
// of a node.
Port p13 = new Port("P13", h1);
p13.relate(p03);
```

3. This time *hierarchy 1* is defined as a subhierarchy of *hierarchy 2* in the code example below.

```
// Construct Hierarchy2
Hierarchy h2 = new Hierarchy(g2, "Hierarchy2");

// Define a subhierarchy.
h2.addSuperNode(n23, h1);

// Make connections from outside (Hierarchy2) to the subhierarchy
// (Hierarchy1).
p11.connect(e22);
p12.connect(e23);

// Set up ports for Hierarchy2 and connect them with nodes
// from the inside.
Port p21 = new Port("P21", h2);
p21.relate(n21);
Port p22 = new Port("P22", h2);
p22.relate(n22);
```

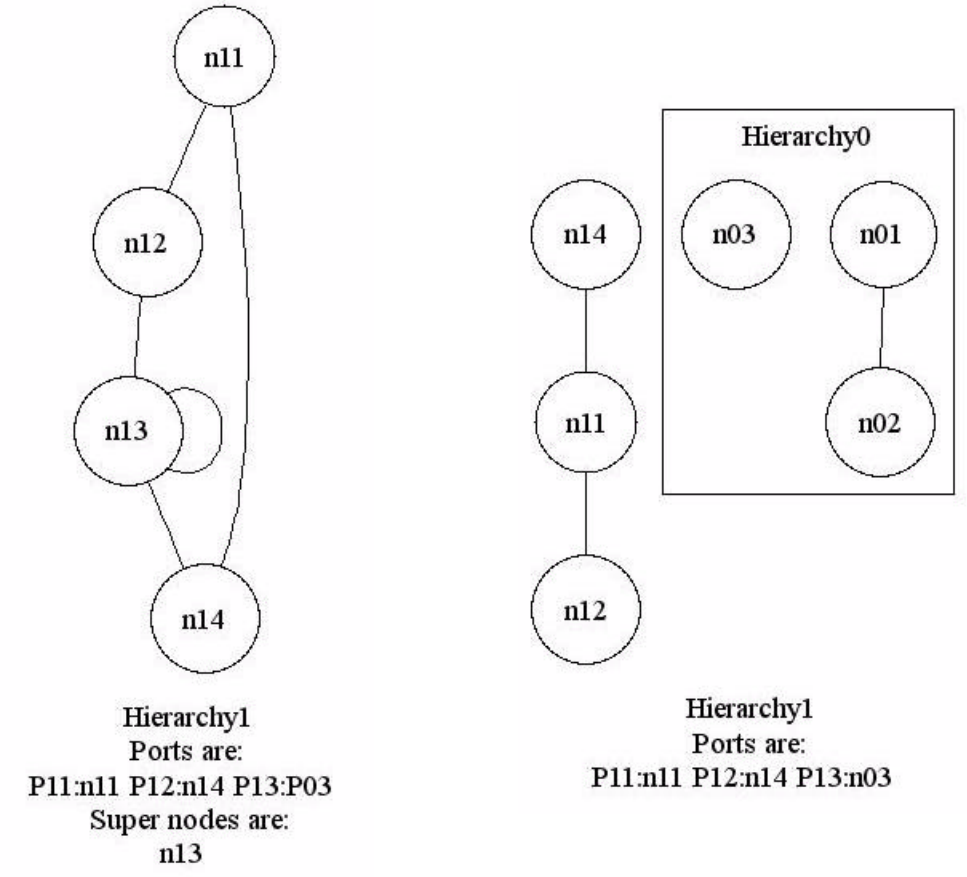


Figure 5-9. *Dot* outputs for *hierarchy 1* before and after it is flattened.

```
// The following port is connected to a port from a subhierarchy instead
// of a node.
Port p23 = new Port("P23", h2);
p23.relate(p13);
```

4. Defining a more complicated hierarchy structure: hierarchies *2* and *0* are to be defined as subhierarchies of *hierarchy 3*. It is not allowed to have multiple parents

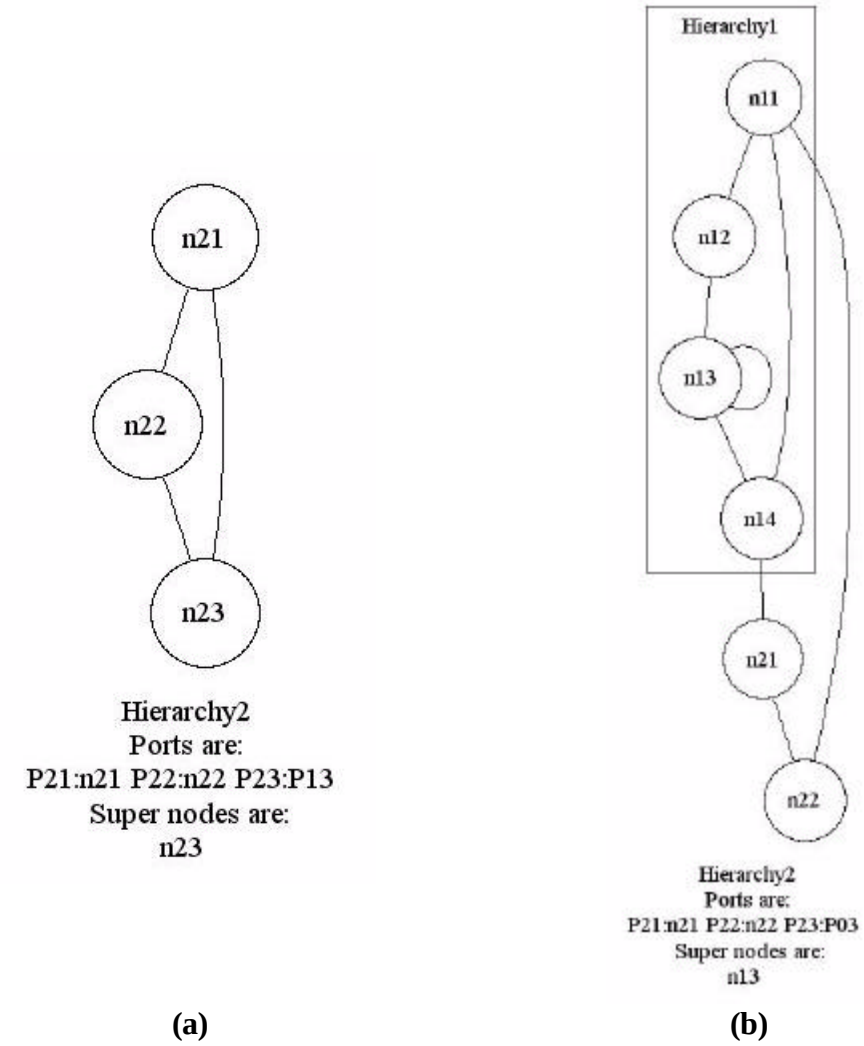


Figure 5-10. *Dot* outputs for *hierarchy 2* before and after it is flattened.

therefore hierarchies *2* and *0* cannot be defined as subhierarchies again. Instead, their mirrors are used.

```
// Construct Hierarchy3.
Hierarchy h3 = new Hierarchy(g3, "Hierarchy3");

// Define a port.
Port p31 = new Port("P31", h3);
```

```
// Mirror Hierarchy0 and Hierarchy2 for reusing in Hierarchy3.
Hierarchy m0 = h0.mirror(false);
m0.setName("Mirror0");
Hierarchy m2 = h2.mirror(false);
m2.setName("Mirror2");

// Define sub-hierarchies.
h3.addSuperNode(n31, h2);
h3.addSuperNode(n32, m0);
h3.addSuperNode(n33, m2);

// Make connections from outside (Hierarchy3) to the sub-hierarchies
// (mirrors of Hierarchy0 and Hierarchy2).
p21.connect(e31);
p22.connect(e33);
p23.connect(e32);

m2.getPorts().get("P21").connect(e33);
m2.getPorts().get("P22").connect(e32);
// Following line is an alternative
// to "p31.relate(m2.getPorts().get("P23"))"
m2.getPorts().get("P23").connect(p31);

m0.getPorts().get("P01").connect(e31);
m0.getPorts().get("P02").connect(e34);
m0.getPorts().get("P03").connect(e34);
```

5. Listing the hierarchical relationship between hierarchy objects can be achieved by the following line of code:

```
ptolemy.graph.DirectedAcyclicGraph relations = h3.hierarchyGraph();
```

To get a *dot* representation of these relations following code can be used:

```
HierarchyToDot.hierarchyGraphToDot(h3, fileName);
```

In Figure5-12, even though hierarchies 1 and 0 seem to be used twice, it is only because names of the mirrors are not changed.

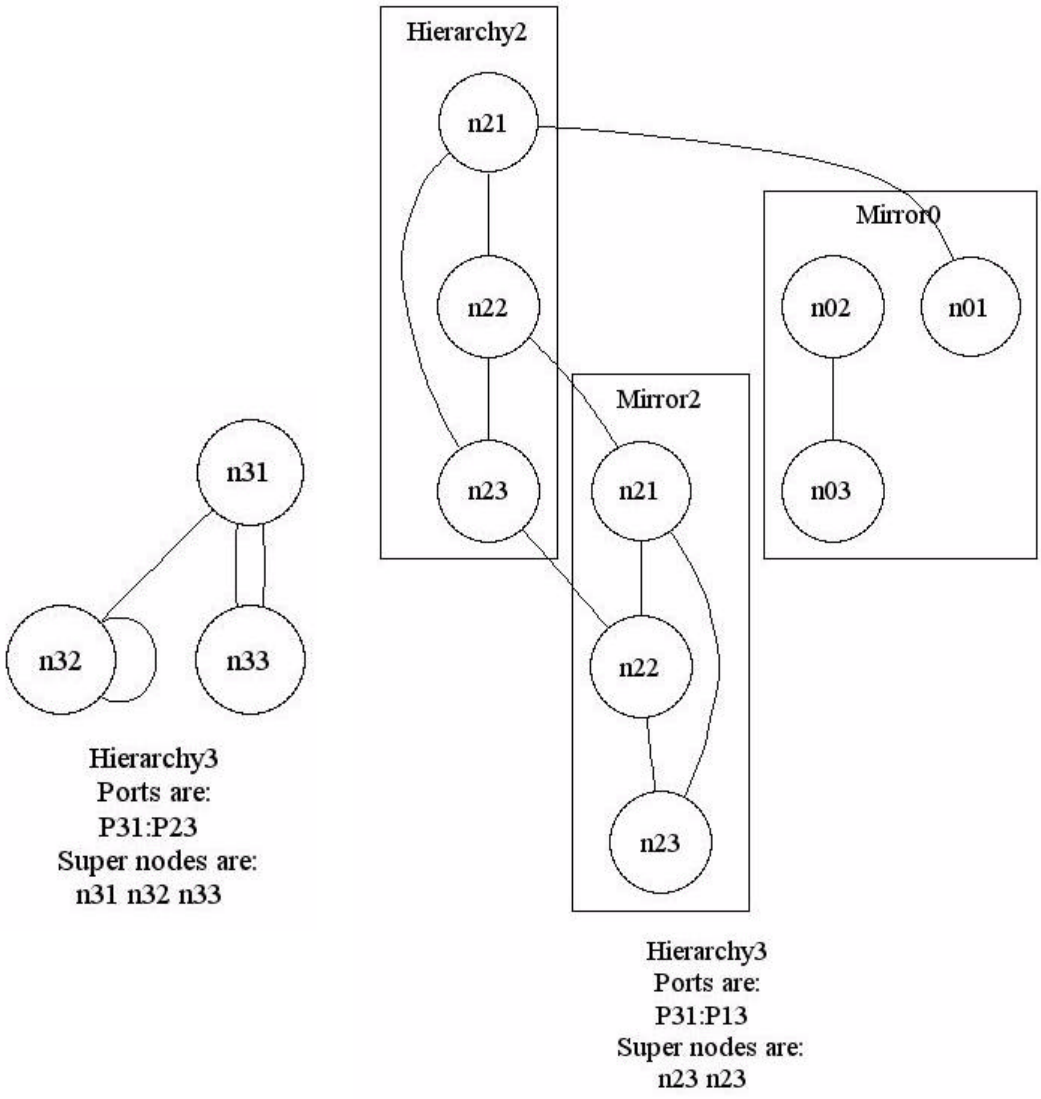


Figure 5-11. *Dot* outputs for *hierarchy 3* before and after it is flattened.

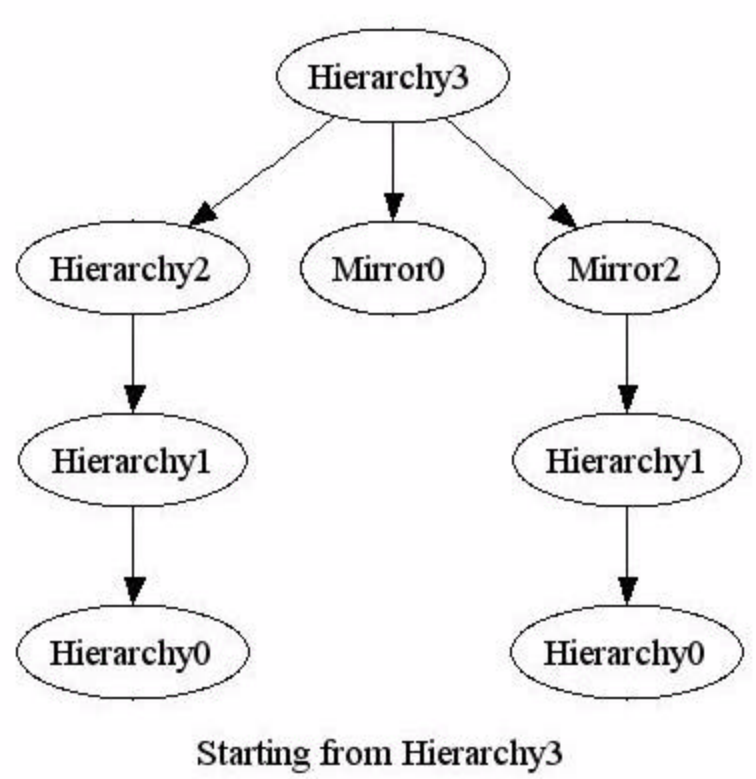


Figure 5-12. *Dot* outputs for hierarchy tree graph.

Directed Hierarchy Example

1. Directed hierarchies are defined in the same way as hierarchies. The difference is the additional direction parameter in the Port constructor and also the visualization tool is configured to show edge directions as well. The code that defines a directed port is

```
Port directedPort = new Port("Name", hierarchy, direction);
```

where the values that the direction parameter can take are Port.IN are Port.OUT. An undirected port can be used as a bidirectional port. This example uses the same graphs as the previous example.

2. Directed hierarchies require extra attention to maintain consistency between connections and port directions. Trying to connect an incoming edge to an output port or vice versa will result in an error. Likewise, if ports are connected together, their directions should be the same, with the exception of undirected ports. A bidirectional (or undirected) port can be connected to an edge or port regardless of the direction, however it cannot be related to a directed port. One example of port direction matching is P01 of *hierarchy 0* (Figure 5-13*(a)*). Despite the fact that P01 is an OUT port in the original hierarchy, the same port in the mirror of *hierarchy 0* is connected to an incoming edge of Hierarchy 3. This is only possible by manually removing that port and defining another port with IN or no direction (Figure5-13*(b)*):

```
// Remove Port 01 in the mirror.
Port oldPort = mirror0.getPorts().get("P01");
Node relatedNode = oldPort.getNode();
oldPort.dispose();

// Replace the old port with a new port with no direction.
(new Port("P01", mirror0)).relate(relatedNode);

// Connect the port to the incoming edge.
mirror0.getPorts().get("P01").connect(e31);
```

Finally, hierarchy 3 is deep-flattened, merging all levels of the hierarchy in a single graph. Note that some of the node labels are duplicated. This is because same node

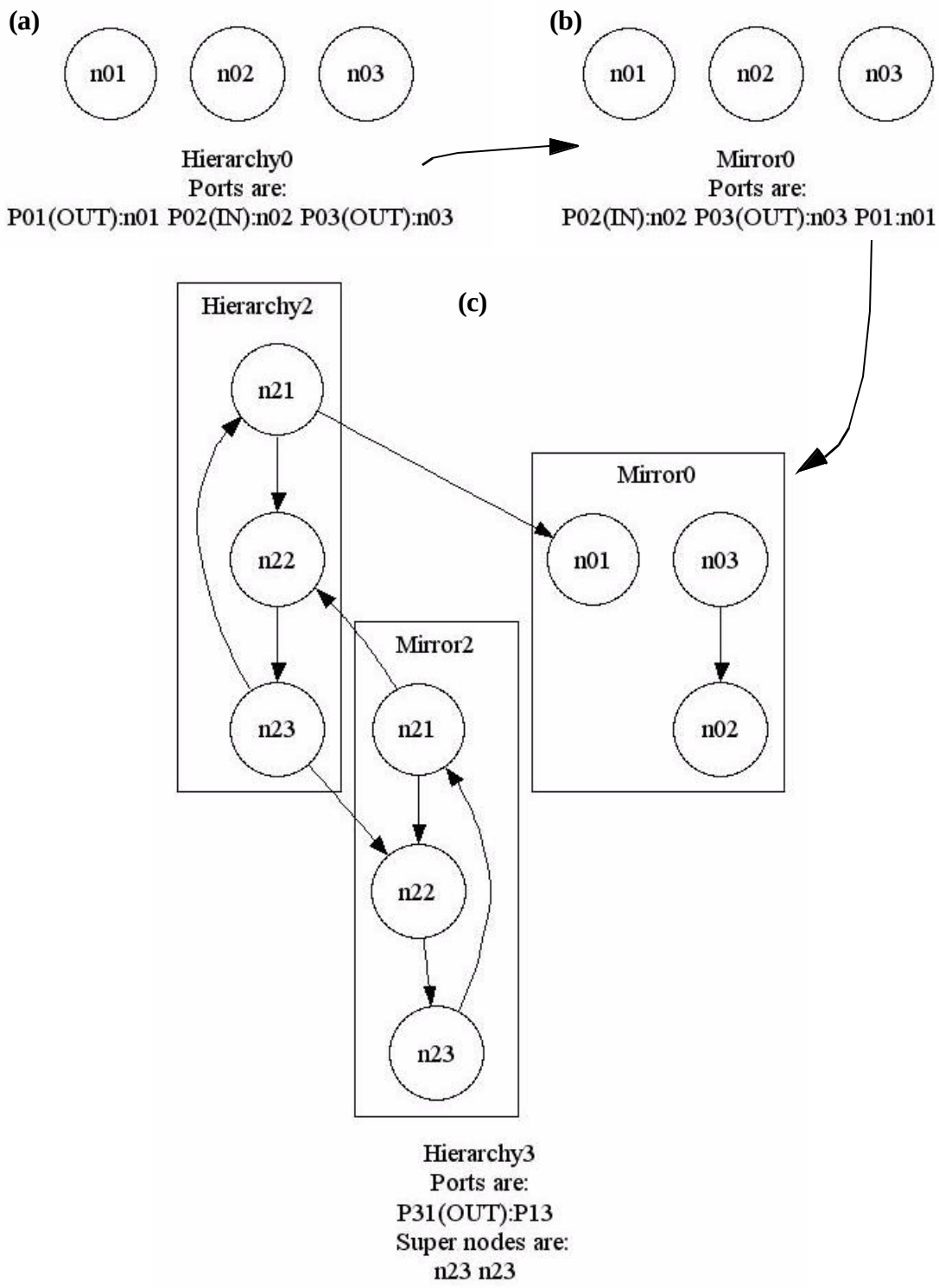


Figure 5-13. Hierarchy 3 with its first level subgraphs.

names are imported from mirror graphs. The Graph class API does not impose any restrictions on node name duplication.

```
h3.deepFlatten();
```

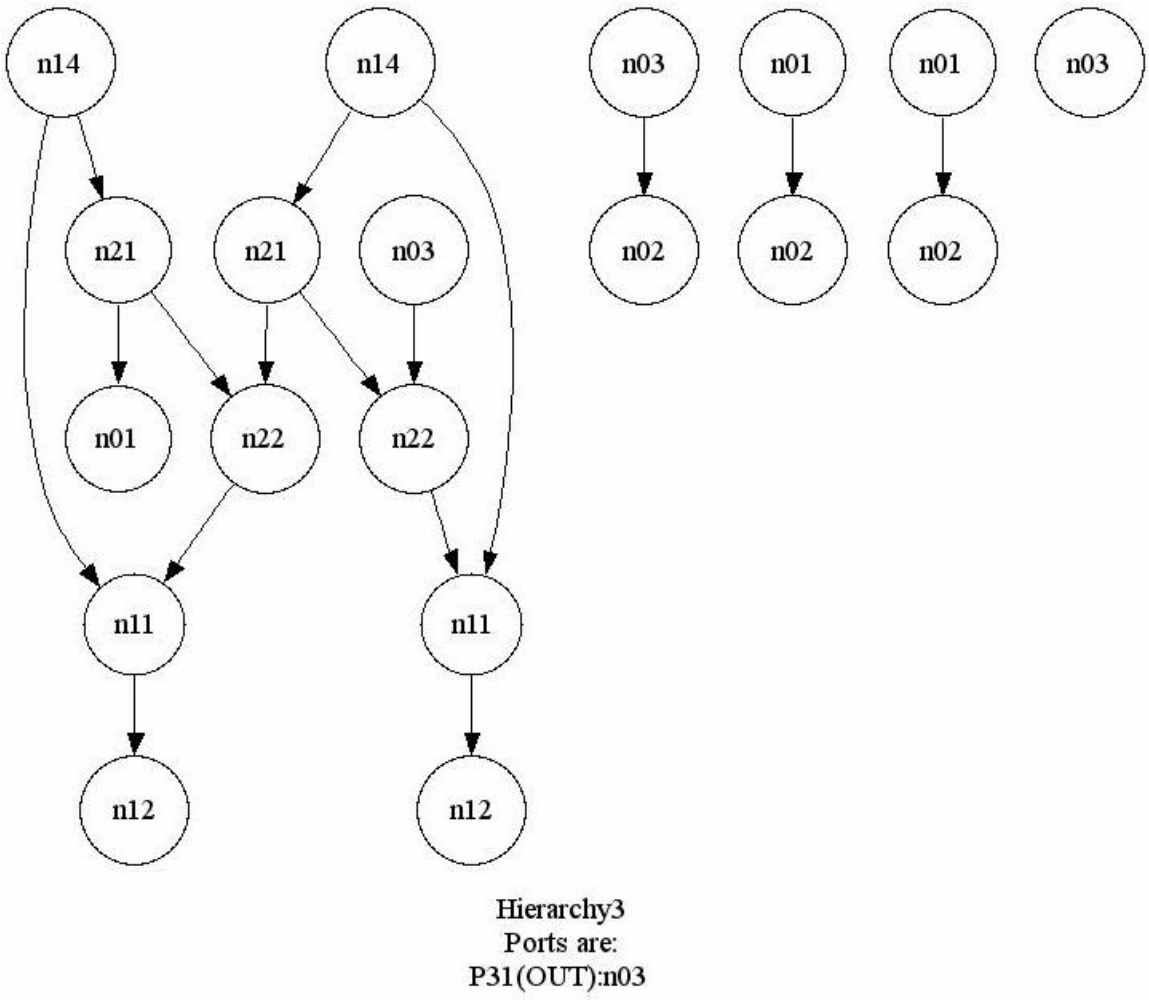


Figure 5-14. Hierarchy 3 after the deep-flatten command.

5.2.3 A Tutorial Example for the DIF Compiler

Following is a tutorial example on the compiler features of the DIF API. The input files used in this example are listed in AppendixD. This demo can also be accessed in the mapss.dif.language.demo package.

1. This demo is an example of how to read and write a text file in DIF. DIF allows usage of C preprocessor commands in files so definitions are divided into files that start from graph1.dif going up to graph5.dif.

2. Compiling graph4.dif which has direct or indirect references to all graph*i*.dif files.

```
Reader reader = new Reader("files\\graph4.dif");
reader.compile();
```

3. Reading the graphs and hierarchies from the reader object.

```
Collection hierarchyCollection = reader.getHierarchies();
Collection graphCollection = reader.getGraphs();
```

4. Creating dot files from all hierarchies for displaying the graphs with GraphViz.

```
for(Iterator hierarchies = hierarchyCollection.iterator();
                                                hierarchies.hasNext(); ) {
DIFHierarchy hierarchy = (DIFHierarchy)hierarchies.next();
(new HierarchyToDot(
        hierarchy,
        hierarchy.getSuperNodes().getNodes(),
        false)).toFile(directoryPath + "//" + hierarchy.getName());
}
```

5. Reading the attributes of the graphs.

```
out.append("Parameters:\n\n");
for(Iterator parameters = graph.getParameterNames().iterator();
                                                    parameters.hasNext(); ) {
    String name = (String)parameters.next();
    out.append(  name + ": "
                + graph.getParameterValue(name).toString()
                + "\n");
}
```

```
out.append("\nGraph attributes:\n\n");
out.append(graph.getAttributeDescriptions() + "\n");
out.append("Node attributes:\n\n");
for(Iterator nodes = graph.nodes().iterator(); nodes.hasNext(); ) {
    Node node = (Node)nodes.next();
    out.append(graph.getAttributeDescriptions(node) + "\n");
}
out.append("Edge attributes:\n\n");
for(Iterator edges = graph.edges().iterator(); edges.hasNext(); ) {
    Edge edge = (Edge)edges.next();
    out.append(graph.getAttributeDescriptions(edge));
    out.append(graph.getName(edge.source()) + " -> "
                        + graph.getName(edge.sink()) + "\n\n");
}
return out.toString();
```

The output of this code for only _graph1 is given below:

```
Parameters:

PRM1: {1.0} + (-1.0,0.0] + [2.0,3.0)
PRM2: {0.0, 0.1}
PRM3:

Graph attributes:

Name: _graph1
Attribute name: codeSize
Value: "Sum of n1 and n2"
Attribute name: totalSize
Value: "Unknown"

Node attributes:

Name: n1
Attribute name: attb1
Value: "\"n1\n\\n1\"\\\\"
Attribute name: attb2
Value: "n1"
Attribute name: codeSize
Value: PRM1
```

Name: n2
Attribute name: attb1
Value: 5.0
Attribute name: attb2
Value: 5.0
Attribute name: codeSize
Value: PRM2

Name: n3
Attribute name: attb1
Value: "n3"
Attribute name: attb2
Value: "n2"

Name: n4
Attribute name: attb1
Value: [[(3.9 -4.0 0.5) [3.0 "n4" ["n4" "n4"]]] [10.0 11.0 "n4"]]

Edge attributes:

Name: e1
n1 -> n2

Name: e2
n2 -> n3

Name: e3
Attribute name: attb1
Value: (0.0 1.0 2.0 3.456,1.0 2.0 3.0 4.0,5.0 6.0 7.0 8.0)
Attribute name: attb2
Value: [0.0 1.0 2.0]
n3 -> n4

Name: e4
Attribute name: attb1
Value: ()
n4 -> n1

6. All graphs that are read are now written to a single file. Note that SDF graph requires an SDFToDIFWriter.

```
for(Iterator graphs = reader.getHierarchies().iterator();
                                                graphs.hasNext(); ) {
    DIFHierarchy hierarchy = (DIFHierarchy)graphs.next();
    if(hierarchy.getGraph() instanceof SDFGraph) {
        out.println((new SDFToDIFWriter(hierarchy)).toString());
    } else {
        out.println((new Writer(hierarchy)).toString());
    }
}
```

7. One feature of the compiler is the ability of changing the parameters and attributes of a DIFGraph without defining a new one. The GraphModifier class is created for this purpose. It is a limited version of the compiler with no preprocessor. It will ignore all fields except the parameter and attribute fields in a DIF file and change the input graph accordingly. This provides a fast way of dynamically modifying graphs.

```
(new GraphModifier(graph1))
        .modifyGraph(new FileReader("./files/graph1Modify.dif"));
```

8. A feature similar to the GraphModifer is the *basedon* keyword in the DIF language. A graph can be accepted as a model for topology and hierarchy and its parameters and attributes can be defined differently in a separate file. This is different than the usage of GraphModifier since it is not dynamic but carried out at the compile time instead. The example file for this example is graph1Modify2.dif.

CHAPTER 6

Conclusion

This thesis has presented the first version (version 0.1) of dataflow interchange format (DIF), a textual language for writing coarse-grain, dataflow-based models of DSP applications, and for communicating such models between DSP design tools. The objectives of DIF are to accommodate a variety of dataflow-related modeling constructs, and to facilitate experimentation with and technology transfer involving such constructs. The DIF language is actively being extended, including the set of supported dataflow modeling semantics, language features and repository of intermediate representations and algorithms. Many of these extensions will be contained in the forthcoming next version, DIF 0.2. Support for DIF has already been incorporated in an individual dataflow-based design tool - the MCCI Autocoding Toolset [14].

APPENDIX A

The Complete DIF Language

Below is a complete definition of the DIF language version 0.1. The tokens part specifies the regular expression tokens to be used with the productions and the productions part defines the language rules in Extended Backus-Naur Form. For more information on formal language definitions, refer to Chapter 2.

- Tokens:

```
all = [0 .. 127]
digit = [‘0’ .. ‘9’]
octal_digit = [‘0’ .. ‘7’]
hex_digit = digit + ['a' .. 'f'] + ['A' .. 'F']
non_digit = [‘A’ .. ‘Z’] + [‘a’ .. ‘z’] + [‘_’]
escape_sequence = simple_escape | hexadecimal_escape |octal_escape
simple_escape = '\' "' | '\"' | '\\' |'\b' | '\f' | '\n' | '\r' | '\t’
hex_escape = '\x' hex_digit+
octal_escape = '\' octal_digit octal_digit? octal_digit?
tab = 9
cr = 13
lf = 10
eol = tab | cr | lf
string = ‘”’ ([all - [‘”’ + ‘\’ + ‘cr’ + ‘lf’]] | escape_sequence)* ‘”’
string_tail = '+' (' ' | eol | tab)* string



double = (‘+’ | ‘-’)? (digit*) ‘.’ (digit+)
integer = (‘+’ | ‘-’)? (digit*)
number = double | integer



identifier = non_digit ( digit | non_digit )*
```

```
not_cr_lf = all - [ cr + lf ]
not_star = all - '*'
not_star_slash = not_star -'/'
short_comment = '//' not_cr_lf* eol
long_comment = '/*' not_star* '*'+ (not_star_slash not_star* '*'+)* '/'
comment = long_comment | short_comment
```

- Productions:

// Defining graph blocks in a file:

<graph_list> = <graph_block>*

<graph_block> =
[type]:identifier? **graph** [name]:identifier <basedon>? **“{”** <block>* **“}”**

<basedon> = **basedon** identifier

<block> = {params} **params** <params_body> |
{interface} **interface** <interface_body> |
{topology} **topology** <topology_body> |
{refinement} **refinement** <refinement_body> |
{fixed_attribute} **identifier** <attribute_body> |
{attribute} **attribute** identifier <attribute_body>

// Defining the topology:

<topology body> = **“{”** <topology list>* **“}”**

<topology list> = **nodes “{”** <node definition block>? **“}”** |
edges “{” <edge definition>* **“}”**

<node definition block> = <node definition> <node definition tail>*

<node definition> = identifier | [node:] identifier **“:”** [port:] identifier

<node definition tail> = **“,”** <node definition>

<edge definition> = [edge:] identifier [source:] identifier [sink:] identifier **“;”**

// Defining the interface:

<interface_body> = **“{”** <interface_expression>* **“}”**

<interface_expression> =
{input} **input** identifier <interface_identifier_tail>* **“;”**|
{output} **output** identifier <interface_identifier_tail>* **“;”**|
{inout} **inout** identifier <interface_identifier_tail>* **“;”**

<interface_identifier_tail> = **“,”** identifier

// Defining the refinement:

<refinement_body> = **“{”** <refinement_expression>* **“}”**

<refinement_expression> =
[graph]:identifier [node]:identifier <refinement_definitions>? **“;”**

<refinement_definitions> =
<refinement_connection> <refinement_connection_tail>*

<refinement_connection> = [port]:identifier **“:”** [element]:identifier

<refinement_connection_tail> = **“,”** [port]:identifier **“:”** [element]:identifier

// Defining attributes:

<attribute_body> = **“{”** <attribute_expression>* **“}”**

<attribute_expression> = {element} identifier <value>? **“;”** |
{graph} **this** <value>? **“;”**

<value> = {number} number |
{param} identifier |
{concat_string} string string_tail* |
{array} **“(”** number* <array_row>* **“)”** |
{list} **“[”** value+ **“]”**

<array_row> = **“,”** number*

// Defining the parameters

<params_body> = **“{”** <params_expression>* **“}”**

<params_expression> = {normal} identifier **“:”** <range_block> **“;”** |
{blank} identifier **“;”**

<range_block> = <range> <range_tail>*

<range> =
{closed_closed} **“[”** [left]:number **“,”** [right]:number **“]”** |
{open_closed} **“(”** [left]:number **“,”** [right]:number **“]”** |
{closed_open} **“[”** [left]:number **“,”** [right]:number **“)”** |
{open_open} **“)”** [left]:number **“,”** [right]:number **“)”** |
{discrete} **“}”** number <discrete_range_number_tail>* **“}”**

<discrete_range_number_tail> = **“,”** number
<range_tail> = **“+”** <range>

APPENDIX B

SableCC Language Specification Input

```
Package mapss.dif.language.sablecc;

Helpers
  all = [0 .. 127];
  digit = ['0' .. '9'];
  non_digit = [[['a' .. 'z'] + ['A' .. 'Z']] + '_'];
  double = ( ( '+' | '-' )? ) (digit*) '.' (digit+);
  integer = ( ( '+' | '-' )? ) digit+;

  tab = 9;
  cr = 13;
  lf = 10;
  eol = cr lf | cr | lf; // This takes care of different platforms

  not_cr_lf = [all -[cr + lf]];
  not_star = [all -'*'];
  not_star_slash = [not_star -'/'];

  short_comment = '//' not_cr_lf* eol;
  long_comment = '/*' not_star* '*'+ (not_star_slash not_star* '*'+)* '/';
  comment = long_comment | short_comment;

  simple_escape_sequence = '\' ''' | '\"' | '\\' |
    '\b' | '\f' | '\n' | '\r' | '\t';
  octal_digit = ['0' .. '7'];
  octal_escape_sequence = '\' octal_digit octal_digit? octal_digit?;
  hexadecimal_digit = [digit + [['a' .. 'f'] + ['A' .. 'F']]];
  hexadecimal_escape_sequence = '\x' hexadecimal_digit+;
  escape_sequence = simple_escape_sequence | octal_escape_sequence |
  hexadecimal_escape_sequence;
  s_char = [all -[[''' + ['\' + [10 + 13]]]] | escape_sequence;
  s_char_sequence = s_char*;
  string = ''' s_char_sequence ''';

Tokens

  blank = (' ' | tab | eol);
  comment = comment;

  l_bkt = '{';
  r_bkt = '}';

  l_par = '(';
  r_par = ')';

  l_sqr = '[';
  r_sqr = ']';
```

```
  semicolon = ';';
  colon = ':';
  comma = ',';
  s_qte = '"';
  plus = '+';

  graph = 'graph';

  attribute = 'attribute';
  interface = 'interface';
  params = 'params';
  refinement = 'refinement';
  topology = 'topology';

  input = 'input';
  output = 'output';
  inout = 'inout';
  param = 'param';
  domain = 'domain';
  nodes = 'nodes';
  edges = 'edges';
  this = 'this';
  basedon = 'basedon';

  identifier = non_digit (digit | non_digit)*;
  number = double | integer;

  string = string;
  string_tail = '+' (' ' | eol | tab)* string;

Ignored Tokens

  blank,
  comment;

Productions

  graph_list = graph_block*;

  graph_block = [type]:identifier? graph [name]:identifier basedon_definition?
                                                l_bkt block* r_bkt;

  basedon_definition = basedon identifier;

  block =
    {params}          params params_body |
    {interface}       interface interface_body |
    {topology}        topology topology_body |
    {refinement}      refinement refinement_body |
    {fixed_attribute} identifier attribute_body |
    {attribute}       attribute identifier attribute_body;
```

```
/************************************
 * Definitions for params block:
 */

params_body = l_bkt params_expression* r_bkt;

params_expression =
  {normal}   identifier colon range_block  semicolon|
  {blank}    identifier semicolon;

range_block = range range_tail*;

range =
  {closed_closed} l_sqr [left]:number comma [right]:number r_sqr |
  {open_closed} l_par [left]:number comma [right]:number r_sqr |
  {closed_open} l_sqr [left]:number comma [right]:number r_par |
  {open_open} l_par [left]:number comma [right]:number r_par |
  {discrete}   l_bkt number discrete_range_number_tail* r_bkt;

discrete_range_number_tail = comma number;

range_tail = plus range;

/************************************
 * Definitions for interface block:
 */

interface_body = l_bkt interface_expression* r_bkt;

interface_expression =
  {input}    input identifier interface_identifier_tail* semicolon |
  {output}   output identifier interface_identifier_tail* semicolon |
  {inout}   inout identifier interface_identifier_tail* semicolon;

interface_identifier_tail = comma identifier;

/************************************
 * Definitions for topology block:
 */

topology_body = l_bkt topology_list* r_bkt;

topology_list =
  {nodes}  nodes l_bkt node_definition_block? r_bkt |
  {edges}  edges l_bkt edge_definition* r_bkt;

node_definition_block = node_definition node_definition_tail*;

node_definition = {plain} identifier |
                  {port}  [node]:identifier colon [port]:identifier;

node_definition_tail = comma node_definition;
```

```
edge_definition = [edge]:identifier
                  [source]:identifier
                  [sink]:identifier
                  semicolon;

/***********************************
 * Definitions for refinement block:
 */

refinement_body = l_bkt refinement_expression* r_bkt;

refinement_expression = [graph]:identifier
                        [node]:identifier
                        refinement_definitions?
                        semicolon;

refinement_definitions = refinement_connection refinement_connection_tail*;

refinement_connection = [port]:identifier colon [element]:identifier;

refinement_connection_tail = comma
                             [port]:identifier
                             colon
                             [element]:identifier;

/***********************************
 * Definitions for attribute block:
 */

attribute_body = l_bkt attribute_expression* r_bkt;

attribute_expression =
  {element} identifier value semicolon |
  {graph} this value semicolon;

value =
  {number} number |
  {param} identifier |
  {string} concatenated_string_value |
  {array_of_numbers} l_par number* array_row* r_par |
  {list_of_values} l_sqr value+ r_sqr;

array_row = comma number*;

concatenated_string_value = string string_tail*;
```

APPENDIX C

Class Designs in the Unified Modeling Language

UML (the unified modeling language) defines a suite of visual syntaxes for describing various aspects of software architecture. This appendix will use the *class diagram* syntax of UML to visualize the class structures and relationships between classes of the DIF API. In these diagrams, classes will be denoted by boxes. The class name is at the top of each box, class variables are below that and methods are the last segment. Public variable or methods are prefixed by a "+" symbol and protected ones are prefixed by "#". Static methods are underlined.

Subclasses are indicated by lines with arrow heads. The class on the side of the arrowhead is the *superclass* and the class on the other end is the *subclass*. Normally, classes are grouped according to their packages however an empty dashed class box with only a name can be placed in a UML diagram if it is extended by any of the classes in that package.

Aggregations are shown with diamonds instead of arrow heads. For example, a Graph is an aggregation of any number (0..n) instances of Edge. More strongly, a Port is contained by 0 or 1 instances of Graph.

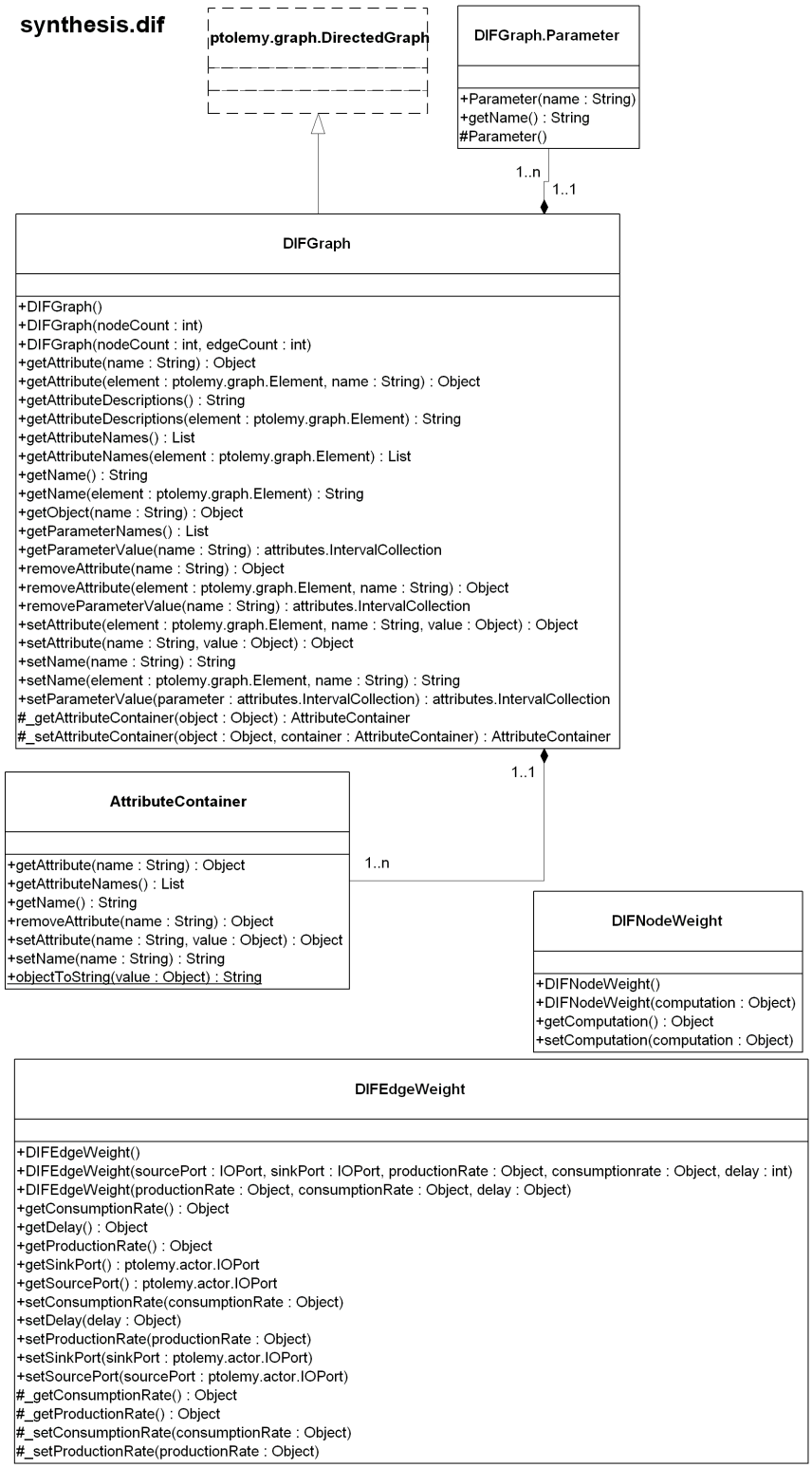


Figure C-1. UML diagram for the basic classes of mapss.dif.

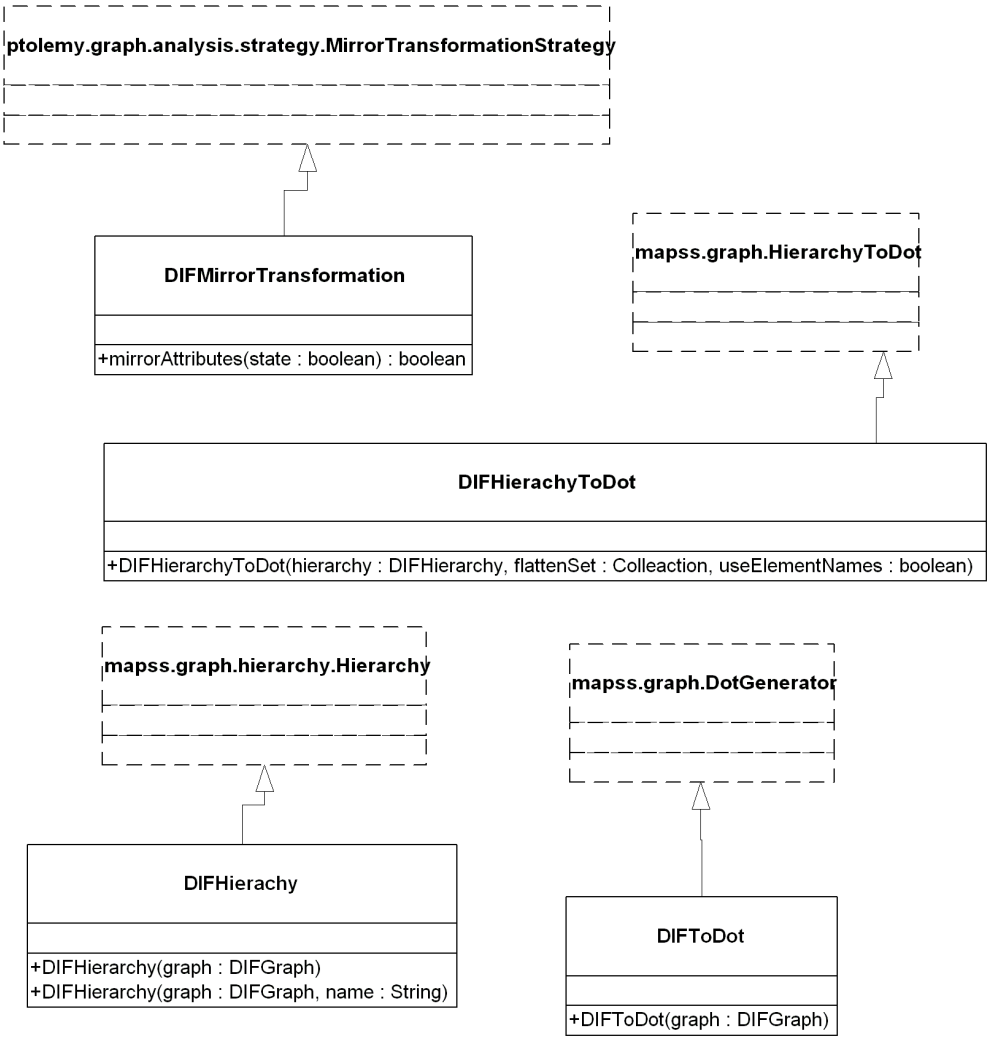


Figure C-2. UML diagram for the utility classes of mapss.dif.

synthesis.dif.language

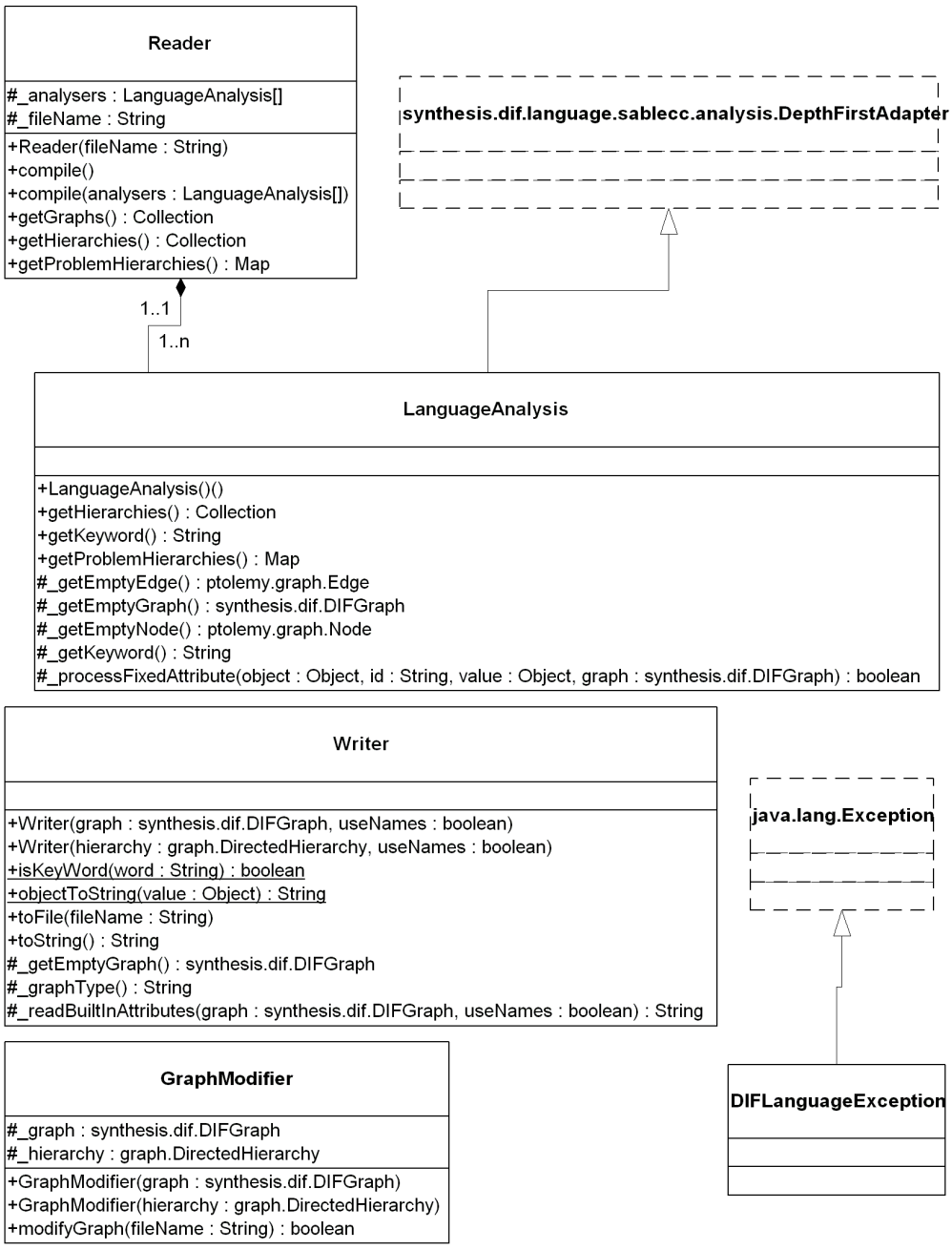


Figure C-3. UML diagram for the classes of mapss.dif.language.

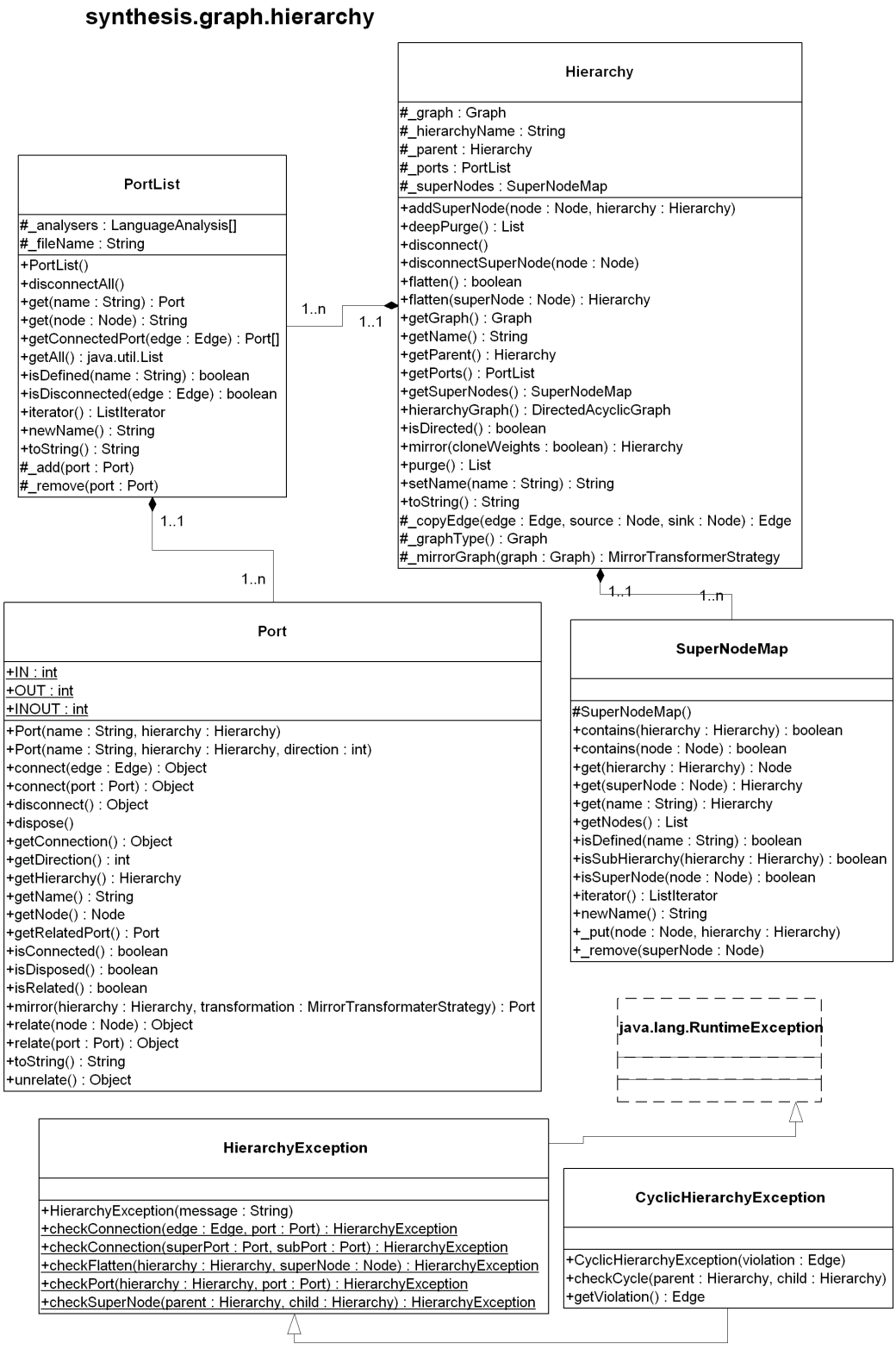


Figure C-4. UML diagram for the classes of mapss.graph.hierarchy.

synthesis.graph

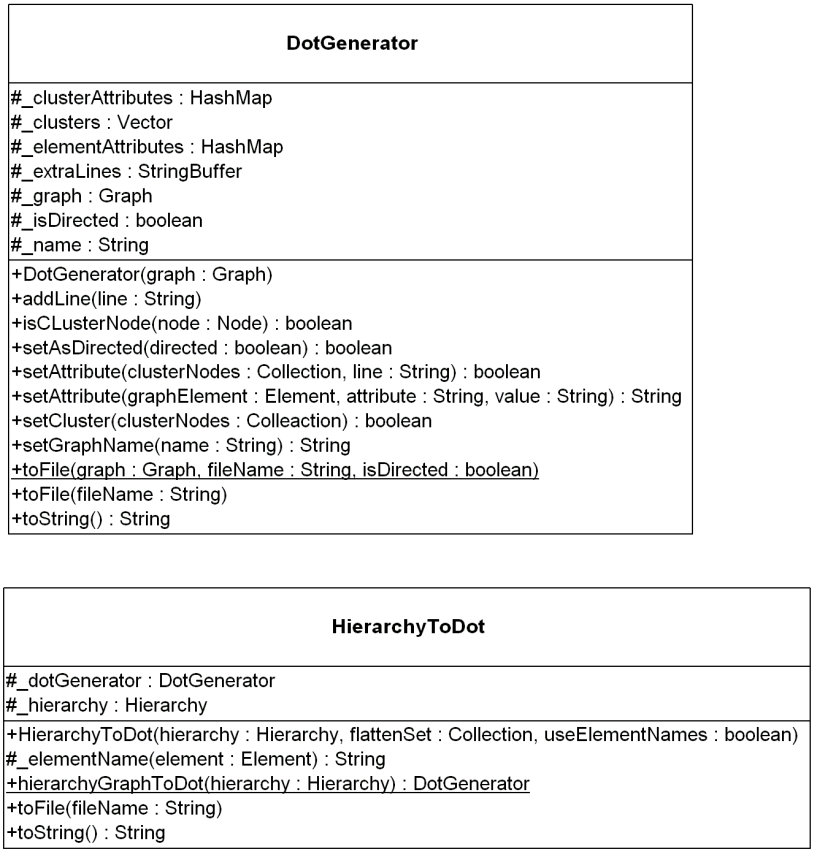


Figure C-5. UML diagram for the classes of mapss.graph.

APPENDIX D

DIF Graph and Hierarchy Specification Examples

- ***graph1.dif***

```
/* A graph definition with an interface.
 */
dif graph _graph1 {
  params {
    PRM1: {1.0} + (-1.0 , 0.0] + [2.0 , 3.0);
    PRM2: {0.0, 0.1};
  }

  interface {
    // You can use labels for interfaces as in the following line.
    // Node n3 is labeled as _N3 and n4 is labeled as _N4.
    input _N3;
    output _N4;
  }

  topology {
    nodes { n1, n2, n3:_N3, n4:_N4 }
    edges {
      e1 n1 n2;
      e2 n2 n3;
      e3 n3 n4;
      e4 n4 n1;
    }
  }

  // This is a user defined attribute.
  attribute attb1 {
    // String attribute. (Concatenation of strings is allowed)
    n1 "\"n1\n" + "\\n1\"\\\\" ;
    // Double attribute.
    n2 5;
    // Double matrix attribute.
    e3 (0 1 2 3.456, 1 2 3 4, 5 6 7 8);
    e4 ( );
```

```
  // Another string attribute.
  n3 "n3";
  // Object array attribute.
  n4 [ [(3.9 -4 +.5) [3 "n4" ["n4" "n4"]]] [10 11 "n4"]];
}

// Another attribute block.
attribute attb2 {
  n1 "n1";
  n2 5;
  e3 [0 1 2];
  n3 "n2";
}

// Some parametrized attributes.
attribute codeSize {
  n1 PRM1;
  n2 PRM2;
  this "Sum of n1 and n2";
}

// One more graph attribute.
attribute totalSize {
  this "Unknown";
 }
}
```

- ***graph1Modify.dif***

```
/* A modified graph is parsed by the graph modifier tool instead of the
 * default parser.
 */
dif graph _graph1Modified {
  params {
    PRM3: {10};
  }

  // User defined attributes.
  attribute attb1 {
    n1 ["Changed attribute" 100] ;
    e1 (1 2, 3 4);
```

```
    e4 "Another changed attribute";
  }

  attribute attb3 {
    n1 "Defined new";
  }

  attribute codeSize {
    n1 "changed";
    n2 PRM1;
  }

  attribute totalSize {
    this "Changed graph attribute";
  }
}
```

- ***graph1Modify2.dif***

```
/* Modifying the graph using the basedon feature of DIF. This gives
 * the same result as graph1Modify.dif however this is a feature defined
 * in the DIF parser.
 */
#include "graph1.dif"
dif graph _graph1Modified basedon _graph1 {
  params {
    PRM3: {10};
  }

  // User defined attributes.
  attribute attb1 {
    n1 ["Changed attribute" 100] ;
    e1 (1 2, 3 4);
    e4 "Another changed attribute";
  }

  attribute attb3 {
    n1 "Defined new";
  }
```

```
  attribute codeSize {
    n1 "changed";
    n2 PRM1;
  }

  attribute totalSize {
    this "Changed graph attribute";
  }
}
```

- ***graph2.dif***

```
#include "graph1.dif"
#define DELAY 3.0
dif graph _graph2 {
  interface {
    inout _N21;
  }

  topology {
    nodes { n21:_N21, n22, n23 }
    edges {
      e21 n21 n22;
      e22 n22 n23;
      e23 n23 n21;
    }
  }

  // An example of a refinement expression.
  // n23 is connected to _graph1 via edges e22 and e23.
  refinement {
    _graph1 n23 _N3:e22, _N4:e23;
  }

  // The following three blocks are built-in attribute definitions
  // for an edge: production/consumption rates and delay of the edge are
  // defined.
  production {
    e21 [2 ["1" "2"] (1 2 3)];
  }
```

```
  consumption {
    e21 2.0;
  }

  delay {
    e21 DELAY;
  }
}
```

- ***graph3.dif***

```
#include "graph2.dif"
dif graph _graph3 {
  interface {
    input _N31;
  }

  topology {
    nodes { n31, n32, n33 }
    edges {
      e31 n31 n32;
      e32 n33 n31;
    }
  }

  refinement {
    _graph2 n32 _N21:e31;
    _graph1 n33 _N3:_N31, _N4:e32;
  }
}
```

- ***graph4.dif***

```
#include "graph3.dif"
#include "graph5.dif"
dif graph _graph4 {
  topology {
    nodes { n41, n42}
    edges {
      e41 n41 n42;
    }
  }
```

```
  refinement {
    _graph3 n42 _N31:e41;
    _graph5 n41 _N51:e41;
  }
}
```

- ***graph5.dif***

```
sdf graph _graph5 {
  interface {
    output _N51;
  }

  topology {
    nodes { n51:_N51}
  }
}
```

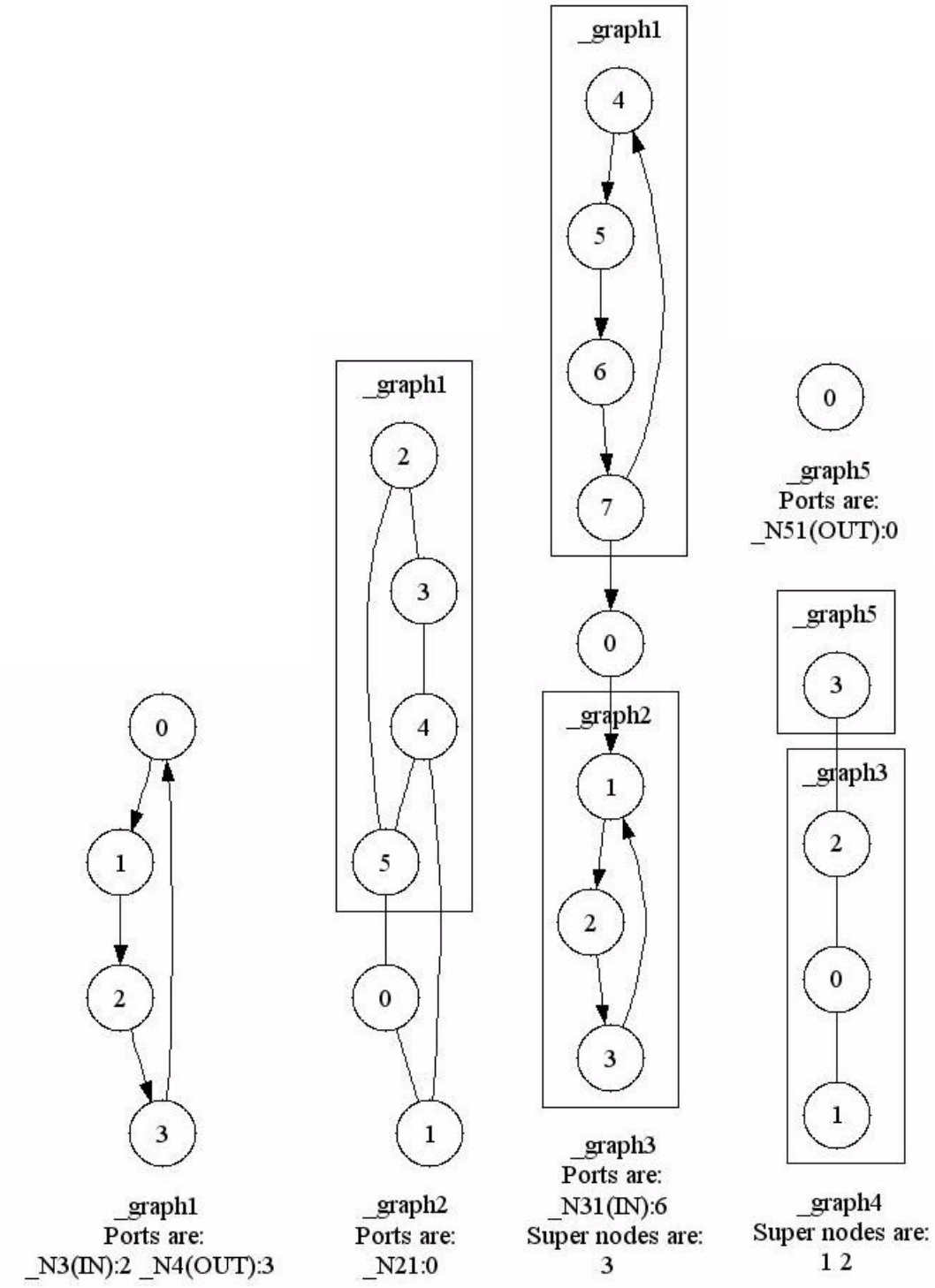


Figure D-1. GraphViz outputs for the hierarchies defined in this appendix - all hierarchies are flattened one level.

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