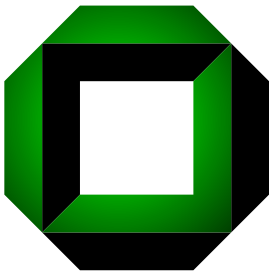

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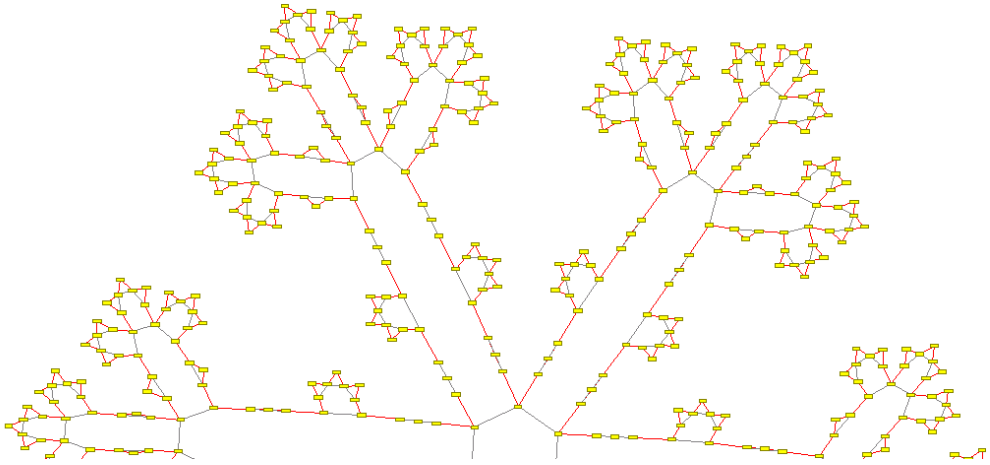
Lehrstuhl Prof. Goos

The GrGen.NET User Manual

Refers to GrGen.NET Release 1.0

www.grgen.net



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ABSTRACT

GrGen.NET is a graph rewrite system enabling elegant and convenient development of applications with comparable performance to conventionally developed ones. GrGen.NET uses attributed, typed, and directed multigraphs with multiple inheritance on node and edge types. Extensive graphical debugging integrated into an interactive shell complements the feature highlights of GrGen.NET. This user manual contains both: Normative statements in the sense of a reference manual as well as an informal guide to the features and usage of GrGen.NET.

FOREWORD

We whish all readers of the manual and especially all users of GrGen.NET a pleasant graph rewrite experience.

If you find that any statements in this manual needs improvement, we encourage you to write the maintainer of GrGen.NET: rubino@ipd.uni-karlsruhe.de. Thank you for using GrGen.NET.

The authors of GrGen.NET

CONTENTS

CHAPTER 1

INTRODUCTION

1.1 What is GrGen.NET?

GrGen (Graph Rewrite GENerator) is a generative programming system for graph rewriting. For the potentially expensive matching problem, GrGen applies several novel heuristic optimizations. According to Varró's benchmark it is at least one order of magnitude faster than any other tool known to us.

In order to accelerate the matching step, we internally introduce *search plans* to represent different *matching strategies* and equip these search plans with a cost model, taking the present host graph into account. The task of selecting a good search plan is then considered as an optimization problem [**?**, **?**]. For the rewrite step, our tool implements the well-founded *single-pushout approach* (SPO, for explanation see [**?**]).

For ease of use, GrGen features an expressive specification language and generates program code with a convenient interface. In contrast to systems like Fujaba [**?**] our pattern matching algorithm is fully automatic and does not need to be tuned or partly be implemented by hand. GrGen.NET [**?**] is the successor of the GrGen tool presented at ICGT 2006 [**?**]. The ".NET" postfix of the new name indicates that GrGen has been reimplemented in C# for the Microsoft .NET or Mono environment [**?**, **?**].

1.2 Features of GrGen.NET

The process of graph rewriting can be divided into four steps: Representing a graph according to a model, searching a pattern aka finding a match, performing changes to the matched spot in the host graph, and, finally, selecting the next rule(s) for application. We have organized the features of GrGen.NET according to this breakdown of graph rewriting.

- The graph model (meta-model) supports:
  - Directed graphs
  - Typed nodes and edges, with multiple inheritance on types
  - Node and edge types can be equipped with typed attributes (like structs)
  - Multigraphs (including multiple edges of the same type)
  - Connection assertions to restrict the "shape" of graphs
- The pattern language supports:
  - Plain isomorphic subgraph matching (injective mapping)
  - Homomorphic matching for a selectable set of nodes/edges, so that the matching is not injective
  - Attribute conditions (including arithmetic operations on the attributes)
  - Type conditions (including powerful instanceof-like type expressions)

  - Parameter passing to rules
  - Dynamic patterns with iterative or recursive paths and graphs (yet to be implemented)

- The rewrite language supports:
  - Attribute re-calculation (using arithmetic operations on the attributes)
  - Retyping of nodes/edges (a stronger version of casts of common programming languages)
  - Creation of new nodes/edges of statically as well as dynamically computed types (some kind of generic templates)
  - Two modes of specification: A rule can either express changes to be made to the match or replace the whole match (the semantics is always mapped to SPO)
  - Returning certain edges/nodes for further computations
  - Copying (duplicating) of elements form the match—comparable with sesqui-pushout rewriting [**?**] (yet to be implemented)

- The rule application language (GrShell) supports:
  - Composing several rules with logical and iterative sequence control (called graph rewrite sequences, GRS)
  - Various methods for creation/deletion/input/output of graphs/nodes/edges
  - Stepwise and graphic debugging of rule application
  - Graph rewrite sequences that can contain nested transactions (yet to be implemented)

- Alternatively to GrShell, you can access the match and rewrite facility through libGr. In this way you can build your own algorithmic rule applications in a .NET language of your choice.

1.3 System Overview

Figure 1.1 gives an overview of the GrGen.NET system components. Table 1.1 shows the GrGen.NET directory structure.

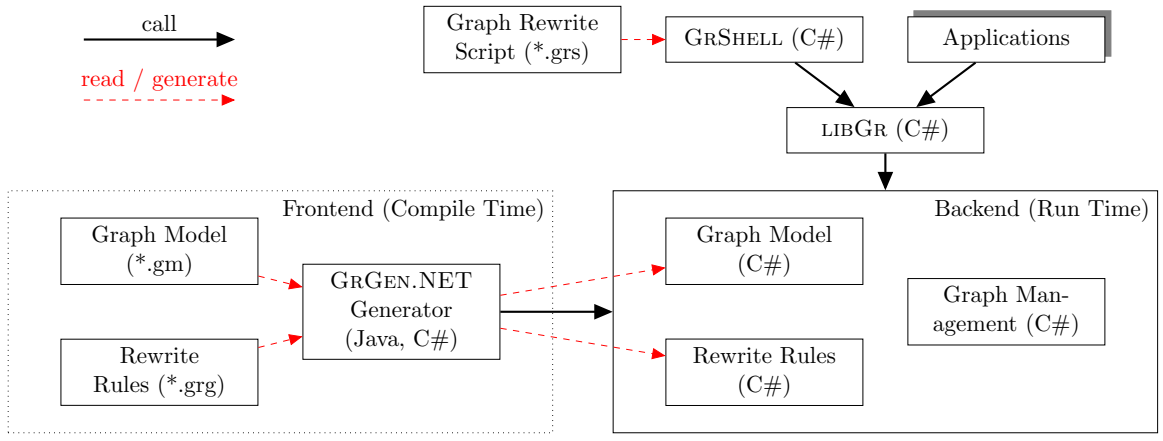


Figure 1.1: GrGen.NET system components [**?**]

bin	Contains the .NET assemblies, in particular GrGen.exe (the graph rewrite system generator), LGSPBackend.dll (a GrGen.NET backend), LibGr.dll (the backend API), and the shell GrShell.exe.
lib	Contains the GrGen.NET generated assemblies (*.dll).
specs	Contains the graph rewrite system source documents (*.gm and *.grg).

Table 1.1: GrGen.NET directory structure

A graph rewrite system[1] is defined by a rule set file (*.grg) and zero or more graph model description files (*.gm). Such a graph rewrite system is generated from these specifications by GrGen.exe and can be used by applications such as GrShell. Figure 1.2 shows the generation process.

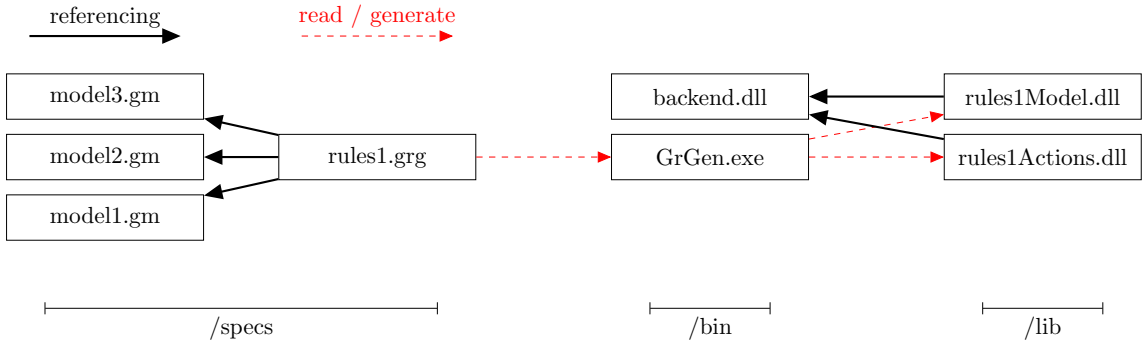


Figure 1.2: Generating a graph rewrite system

In general you have to distinguish carefully between a graph model (meta level), a host graph, a pattern graph and a rewrite rule. In GrGen.NET pattern graphs are implicitly defined by rules, i.e. each rule defines its pattern. On the technical side, specification documents for a graph rewrite system can be available as source documents for graph models and rule sets (plain text *.gm and *.grg files) or as their translated .NET modules, either C# source files or their compiled assemblies (*.dll).

Generating a GrGen.NET graph rewrite system may be considered as preliminary task. The actual process of rewriting as well as dealing with host graphs is performed by GrGen.NET's backend. GrGen.NET provides a backend API—the .NET library libGr. For most issues—in particular for experimental purposes—you might rather want to work with the GrShell because of its more convenient interface. However, GrShell does not provide the full power of the libGr; see also note 6 on page 20.

1.4 What is Graph Rewriting?

The notion of graph rewriting as understood by GrGen.NET is a method for declaratively specifying "changes" to a graph. This is comparable to the well-known term rewriting. Normally you use one or more *graph rewrite rules* to accomplish a certain task. GrGen.NET implements an SPO-based approach. In the simplest case such a graph rewrite rule consists of a tuple $L \rightarrow R$, whereas L—the *left hand side* of the rule—is called *pattern graph* and R—the *right hand side* of the rule—is the *replacement graph*.

Moreover we need to identify graph elements (nodes or edges) of L and R for preserving them during rewrite. This is done by a *preservation morphism* r mapping elements from L to R; the morphism r is injective, but needs to be neither surjective nor total. Together with a rule name p we have $p : L \xrightarrow{r} R$.

[1] In this context, system is not a CH0-like grammar rewrite system, but rather a set of interacting software components.

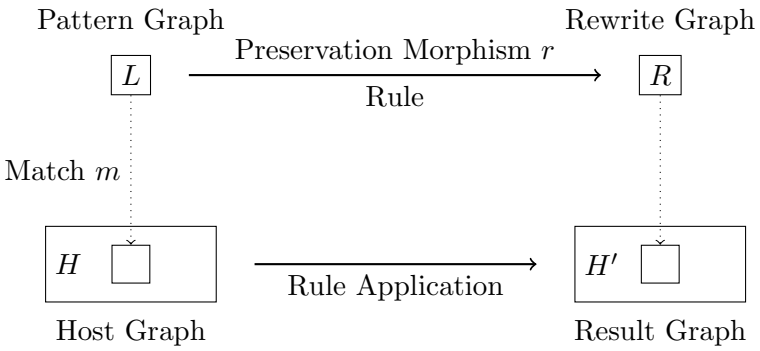
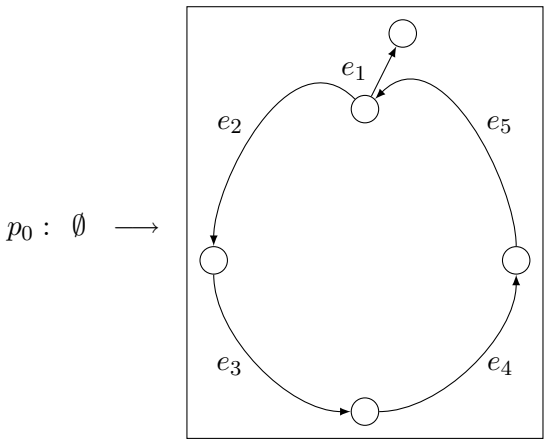


Figure 1.3: Basic Idea of Graph Rewriting

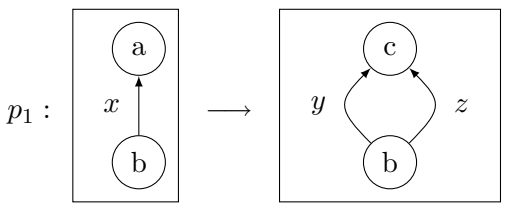
The transformation is done by *application* of a rule to a *host graph* H. To do so, we have to find an occurrence of the pattern graph in the host graph. Mathematically speaking, such a *match* m is an isomorphism from L to a subgraph of H. This morphism may not be unique, i.e. there may be several matches. Afterwards we change the matched spot $m(L)$ of the host graph, such that it becomes an isomorphic subgraph of the replacement graph R. Elements of L not mapped by r are deleted from $m(L)$ during rewrite. Elements of R not in the image of r are inserted into H, all others (elements that are mapped by r) are retained. The outcome of these steps is the resulting graph H'. In symbolic language: $H \overset{m,p}{\Longrightarrow} H'$.

1.5 An Example

We'll have a look at a small example. We start using a special case to construct our host graph: an empty pattern always produces exactly one[2] match (independent of the host graph). So we construct an apple by applying

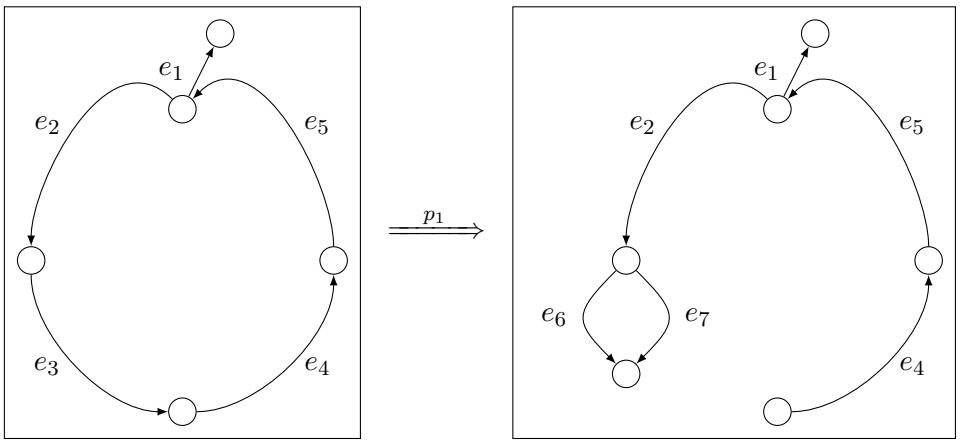


to the empty host graph. As the result we get an apple as new host graph H. Now we want to rewrite our apple with stem to an apple with a leaflet. So we apply

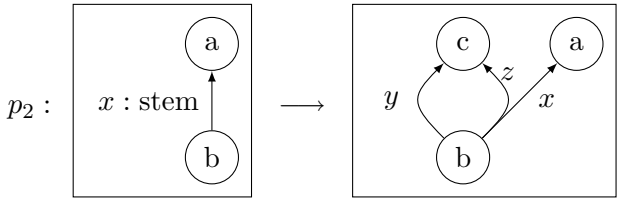


[2]Because of the uniqueness of the total and totally undefined morphism.

to H and get the new host graph H_1, something like this:

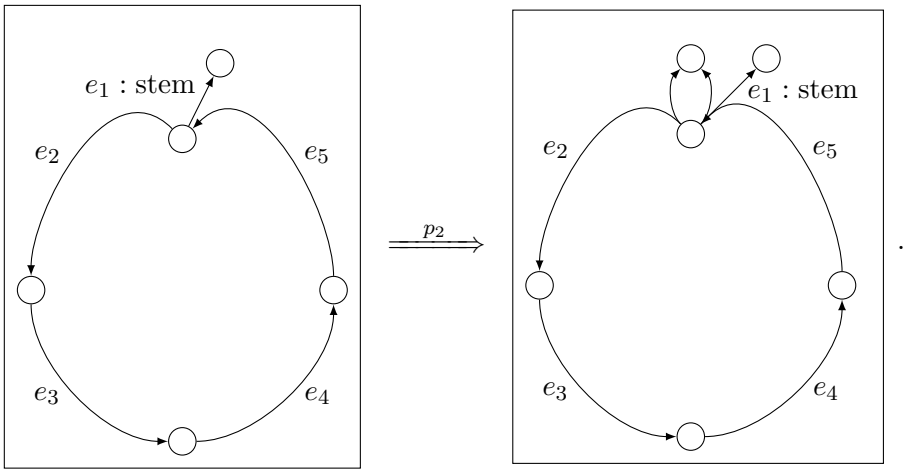


What happened? GrGen.NET has arbitrarily chosen one match out of the set of possible matches, because x matches edge e_3 as well as e_1. A correct solution could make use of edge type information. We have to change rule p_0 to generate the edge e_1 with a special type "stem". And this time we'll even keep the stem. So let



.

If we apply p_2 to the modified H_1 this leads to



.

1.6 The Tools

All the programs and libraries of GrGen.NET are licensed under LGPL. Notice that the yComp graph viewer is not a part of GrGen.NET; yComp ships with its own license. Although yComp is not free software, it's free for use in academic and non-commercial areas.

1.6.1 `GrGen.exe`

The `GrGen.exe` assembly implements the GrGen.NET generator. The GrGen.NET generator parses a rule set and its model files and compiles them into .NET assemblies. The compiled assemblies interact with the GrGen.NET backend.

Usage

`[mono] GrGen.exe [-use <existing-dir>] [-d] <rule-set> [<output-dir>]`

rule-set is a file containing a rule set specification according to chapter 3. Usually such a file has the suffix `.grg`. The suffix `.grg` may be omitted. By default GrGen.NET tries to write the compiled assemblies to the directory `../lib` relative to the path of `GrGen.exe`. This can be changed by the optional parameter *output-dir*.

Options

`-d` Enable debug output. A subdirectory `tmpgrgen`n[3] within the current directory will be created. This directory contains:

- `printOutput.txt`—a snapshot of `stdout` during program execution.
- *Name*`Actions.cs`—the C# source file of the *rule-set*`Actions.dll` assembly.
- *Name*`Model.cs`—the C# source file(s) of the *rule-set*`Modell.dll` assembly.

`-use` Don't re-generate C# source files. Instead use the files in *existing-dir* to build the assemblies.

Requires

.NET 2.0 (or above) or Mono 1.2.2 (or above). Java Runtime Environment 1.5 (or above).

1.6.2 `GrShell.exe`

The GrShell is a shell application of the libGr. GrShell is capable of creating, manipulating, and dumping graphs as well as performing graph rewriting with graphical debug support. For further information about the GrShell language see chapter 5.

Usage

`[mono] grShell.exe [-c "<commands>" | <grshell-script>]`

Opens the interactive shell. The GrShell will execute the commands in *grshell-script* (usually a `*.grs` file) immediately.

Options

`-c` Execute the quoted GrShell commands immediately. Instead of a line break use a double semicolon `;;` as command separation terminal.

Requires

.NET 2.0 (or above) or Mono 1.2.2 (or above).

1.6.3 `LibGr.dll`

The libGr is a .NET assembly implementing GrGen.NET's API. See the extracted HTML documentation for interface descriptions.

1.6.4 `yComp.jar`

yComp[?] is a graph visualization tool based on yFiles[?]. It is well integrated in GrGen.NET, but it's not a part of GrGen.NET. yComp implements several graph layout algorithms and has file format support for VCG, GML and YGF among others.

[3] n is an increasing number.

Usage

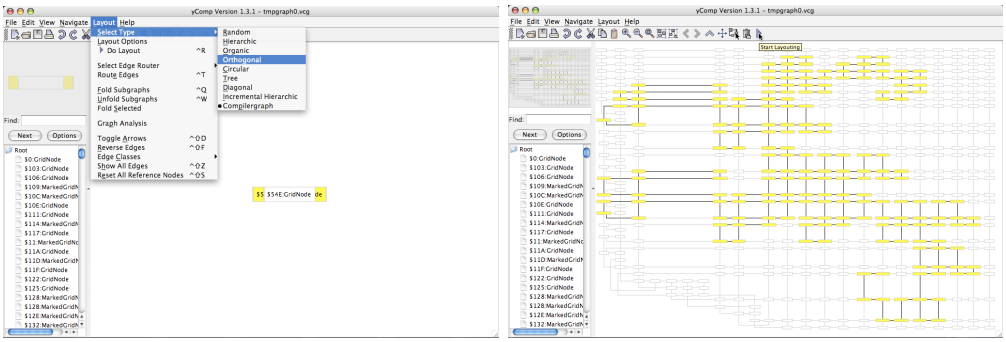
Usually yComp will be loaded by the GrShell. You might want to open yComp manually by typing

```
java -jar yComp.jar [<graph-file>]
```

The *graph-file* may be any graph file in a supported format. yComp will open this file on startup.

Hints

Do not use the compiler graph layout algorithm (yComp's default setting). Instead `Organic` or `Orthogonal` might be good choices. Use the rightmost blue play button to start layout process. This may take a while, depending on the graph size:



Requires

Java Runtime Environment 1.5 (or above).

CHAPTER 2

GRAPH MODEL LANGUAGE

The key features of GrGen.NET *graph models* as described by Geiß et al. [**?**, **?**]:

Types
: Nodes and edges are typed. This is similar to classes in common programming languages, except for the concept of methods that GrGen.NET nodes and edges don't support.

Attributes
: Nodes and edges can possess attributes. The set of attributes assigned to a node or edge is determined by its type. The attributes themselves are typed, too.

Inheritance
: Node and edge types (classes) can be composed by multiple inheritance. `Node` and `Edge` are built-in root types of node and edge types, respectively. Inheritance eases the specification of attributes because subtypes inherit the attributes of their super types. Note that GrGen.NET lacks a concept of overwriting. On a path in the type hierarchy graph from a type up to the built-in root type there must be exactly one declaration for each attribute identifier. Furthermore if multiple paths from a type up to the built-in root type exist, the declaring types for an attribute identifier must be the same on all such paths.

Connection Assertions
: To specify that certain edge types should only connect specific nodes, we include connection assertions. Furthermore the number of outgoing and incoming edges can be constrained.

In this chapter as well as in chapter 5 (GrShell) we use excerpts of example 1 (the `Map` model) for illustration purposes.

2.1 Building Blocks

NOTE (1)

The following syntax specifications make heavy use of *syntax diagrams* (also known as rail diagrams). Syntax diagrams provide a visualization of EBNF[a] grammars. Follow a path along the arrows through a diagram to get a valid sentence (or sub sentence) of the language. Ellipses represent terminals whereas rectangles represent non-terminals. For further information on syntax diagrams see [**?**].

[a] Extended Backus–Naur Form.

EXAMPLE (1)

The following toy example of a model of road maps gives a rough picture of the language:

```
model Map;

enum resident {village = 500, town = 5000, city = 50000}

node class sight;

node class city {
   size: resident;
}

const node class metropolis extends city {
  river: string;
}

abstract node class abandoned_city extends city;
node class ghost_town extends abandoned_city;

edge class street;
edge class trail extends street;
edge class highway extends street
    connect metropolis [+] -> metropolis [+]
{
    jam: boolean;
}
```

Basic elements of the GrGen.NET graph model language are identifiers to denominate types, attributes, and the model itself. The GrGen.NET graph model language is case sensitive.

Ident, *IdentDecl*
A non-empty character sequence of arbitrary length consisting of letters, digits, or underscores. The first character must not be a digit. *Ident* and *IdentDecl* differ in their role: While *IdentDecl* is a *defining* occurrence of an identifier, *Ident* is a *using* occurrence. An *IdentDecl* non-terminal can be annotated. See 4.4 for annotations of declarations.

NOTE (2)

The GrGen.NET model language does not distinguish between declarations and definitions. More precisely, every declaration is also a definition. For instance, the following C-like pseudo GrGen.NET model language code is illegal:

```
node class t_node;
node class t_node {
  ...
}
```

Using an identifier before defining it is allowed. Every used identifier has to be defined exactly once.

NodeType, *EdgeType*, *EnumType*

These are (semantic) specializations of *Ident* to restrict an identifier to denote a node type, an edge type, or an enum type, respectively.

2.2 Type Declarations

???

The graph model consists of its name *IdentDecl* and type declarations defining specific node and edge types as well as enums.

???

ClassDeclaration defines a node type or an edge type. *EnumDeclaration* defines an enum type for use as attribute of nodes or edges. Like all identifier definitions, types do not need to be declared before they are used.

???

Defines an enum type.

EXAMPLE (2)

```
enum Color {red, green, blue}
enum Resident {village = 500, town = 5000, city = 50000}
enum AsInC {a = 2, b, c = 1, d, e = (int)Resident::village + c}
```

The semantics is as in C [?]. So, the following holds: `red` = 0, `green` = 1, `blue` = 2, `a` = 2, `b` = 3, `c` = 1, `d` = 2, and `e` = 501.

???

Defines a new node type or edge type. The keyword `abstract` indicates that you cannot instantiate graph elements of this type. Instead you have to derive non-abstract types to create graph elements. The abstract-property will not be inherited by subclasses, of course.

EXAMPLE (3)

We adjust our map model and make `city` abstract:

```
abstract node class city {
   size: int;
}
abstract node class abandoned_city extends city;
node class ghost_town extends abandoned_city;
```

You will be able to create nodes of type `ghost_town`, but not of type `city` or `abandoned_city`. However, nodes of type `ghost_town` are also of type `abandoned_city` as well as of type `city` and they have the attribute `size`, hence.

The keyword `const` indicates that rules may not write to attributes (see also section 3.4, `eval`). However, such attributes are still writable by LIBGR and GRSHELL directly. This property applies to attributes defined in the current class, only. It does not apply to inherited attributes. The `const` property will not be inherited by subclasses, either. If you want a subclass to have the `const` property, you have to set the `const` modifier explicitly.

???

Defines a new node type. Node types can inherit from other node types defined within the same file. If the `extends` clause is omitted, *NodeType* will inherit from the built-in type `Node`. Optionally nodes can possess attributes.

???

Defines a new edge type. Edge types can inherit from other edge types defined within the same file. If the `extends` clause is omitted, *EdgeType* will inherit from the built-in type `Edge`. Optionally edges can possess attributes. A *connection assertion* specifies that certain edge types should only connect specific nodes and, moreover, the number of outgoing and incoming edges can be constrained.

NOTE (3)

It is not forbidden to create graphs that are invalid according to connection assertions. GRGEN.NET just enables you to check, whether a graph is valid or not. See also section 5.2.2, `validate`.

???

A connection assertion is denoted as a pair of node types in conjunction with their multiplicities. A corresponding edge may connect a node of the first node type or one of its subtypes (source) with a node of the second node type or one of its subtypes (target). The multiplicity is a constraint on the out-degree and in-degree of the source and target node type, respectively. *Number* is an `int` constant as defined in section 4.2. See 5.2.2, `validate`, for an example. Table 2.1 describes the multiplicity definitions.

`[`n`:*]`	The number of edges, nodes of that type are incident to, is unbounded. At least n edges must be incident to nodes of that type.
`[`n`:`m`]`	At least n edges must be incident to nodes of that type, but at most m edges may be incident to nodes of that type ($m \geq n$ must hold).
`[*]`	Abbreviation for `[0:*]`.
`[+]`	Abbreviation for `[1:*]`.
`[`n`]`	Abbreviation for `[`n`:`n`]`.

Table 2.1: GRGEN.NET node constraint multiplicities

???

Defines a node or edge attribute. Possible types are enumeration types (`enum`) and primitive types. See section 4.1 for a list of built-in primitive types.

CHAPTER 3

RULE SET LANGUAGE

The rule set language forms the core of GrGen.NET. Rule files refer to zero[1] or more graph models and specify a set of rewrite rules. The rule language covers the pattern specification and the replace/modify specification. Attributes of graph elements can be re-evaluated during an application of a rule. The following rewrite rule by Geiß et al. [**?**] gives a rough picture of the language:

EXAMPLE (4)

```
1  actions SomeActions using SomeModel;
2
3  rule SomeRule {
4    pattern {
5      n1 : NodeTypeA;
6      n2 : NodeTypeA;
7      hom(n1, n2);
8      n1 --> n2;
9      n3: NodeTypeB;
10     negative {
11       n3 -e1:EdgeTypeA-> n1;
12       if {n3.a1 == 42*n2.a1;}
13     }
14     negative {
15       n4: Node \ (NodeTypeB);
16       n3 -e1:EdgeTypeB-> n4;
17       if {typeof(e1) >= EdgeTypeA;}
18     }
19   }
20   replace {
21     n5: NodeTypeC<n1>;
22     n3 -e1:EdgeTypeB-> n5;
23     eval {
24       n5.a3 = n3.a1*n1.a2;
25     }
26   }
27 }
```

In this chapter we use excerpts of example 4 (`SomeRule`) for illustration purposes.

[1] Omitting a graph meta model means that GrGen.NET uses a default graph model. The default model consists of the base type `Node` for vertices and the base type `Edge` for edges.

3.1 Building Blocks

The GrGen.NET rule set language is case sensitive. The language makes use of several identifier specializations in order to denominate all the GrGen.NET entities.

Ident, *IdentDecl*
A non-empty character sequence of arbitrary length consisting of letters, digits, or underscores. The first character must not be a digit. *Ident* may be an identifier defined in a graph model (see 2.1). *Ident* and *IdentDecl* differ in their role: While *IdentDecl* is a *defining* occurrence of an identifier, *Ident* is a *using* occurrence. An *IdentDecl* non-terminal can be annotated. See 4.4 for annotations of declarations.

NOTE (4)

As in the GrGen.NET model language (see note 2) every declaration is also a definition. Using an identifier before defining it is allowed. Every used identifier has to be defined exactly once.

ModelIdent, *TypeIdent*, *NodeType*, *EdgeType*
These are (semantic) specializations of *Ident*. *TypeIdent* matches every type identifier, i.e. a node type, an edge type, an enumeration type or a primitive type. All the type identifiers are actually type *expressions*. See 4.3 for the use of type expressions.

???

A graphlet specifies a connected subgraph. GrGen.NET provides graphlets as a descriptive notation to define both, patterns to search for as well as the subgraphs that replace or modify matched spots in a host graph. A graph is specified piecewise by graphlets. In example 4, line 8, the statement `n1 --> n2` is the node identifier `n1` followed by the continuation graphlet `--> n2`.

All the graph elements of a graphlet have *name*s. The name is either user assigned or a unique internal, non-accessible name. In the second case the graph element is called *anonymous*. For illustration purposes we use a `$<number>` notation to denote anonymous graph elements in this document. For example the graphlet `n1 --> n2` contains an anonymous edge; thus can be understood as `n1 -$1:Edge-> n2`. Names must not be redefined; once defined, a name is *bound* to a graph element. We use the term "binding of names" because a name not only denotes a graph element of a graphlet but also denotes the mapping of the abstract graph element of a graphlet to a concrete graph element of a host graph. So graph elements of different names are pair wise distinct except for homomorphically matched graph elements (see section 3.3). For instance `v:NodeType1 -e:EdgeType-> w:NodeType2` selects some node of type `NodeType1` that is connected to a node of type `NodeType1` by an edge of type `EdgeType` and binds the names `v`, `w`, and `e`. If `v` and `w` are not explicitly marked as homomorphic, they are distinct. Binding of names allows for splitting a single graphlet into multiple graphlets as well as defining cyclic structures.

EXAMPLE (5)

The following graphlet (`n1`, `n2`, and `n3` are defined somewhere else)

```
1 n1 --> n2 --> n3 <-- n1;
```

is equivalent to

```
1 n2 --> n3;
2 n1 --> n2;
3 n3 <-- n1;
```

and `n1 --> n3` is equivalent to `n3 <-- n1`, of course.

The visibility of names is determined by scopes. Scopes can be nested. Names of surrounding scopes are visible in inner scopes. Usually a scope is defined by { and }. In contrast to pure syntactic scoping, the replace/modify part is a direct inner scope of the pattern part. In example 4, lines 14 to 18, the negative condition uses `n3` from the surrounding scope and defines `n4` and `e1`. We may safely reuse the variable name `e1` in the replace part.

???

Specifies a node of type *NodeType* with respect to *TypeConstraint* (see section 4.3, *TypeConstraint*). Type constraints are allowed in the pattern part only. The `.` is an anonymous node of the base type `Node`. Remember that every node type has `Node` as super type. The `<>` operator retypes a node. Retyping is allowed in the replace/modify part only (see section 3.4, *Retyping*).

Graphlet	Meaning
`x:NodeType;`	The name `x` is bound to a node of type `NodeType` or one of its subtypes.
`:NodeType;`	`$1:NodeType`
`.;`	`$1:Node`
`x;`	The node, `x` is bound to.

???

Specifies an edge. Anonymous edges are specified by `-->` or `<--` resp. `-:T->` or `<-:T-` for an edge type `T`. For a more detailed specification you can use the inplace notated *EdgeRefinement* clause. Type constraints are allowed in the pattern part only (see section 4.3, *TypeConstraint*). The `<>` operator retypes an edge. Retyping is allowed in the replace/-modify part only (see section 3.4, *Retyping*).

Graphlet	Meaning
`-e:EdgeType-> ;`	The name `e` is bound to an edge of type `EdgeType` or one of its subtypes.
`-:EdgeType-> ;`	`-$1:EdgeType-> ;`
`--> ;`	`-$1:Edge-> ;`
`-e-> ;`	The edge, `e` is bound to.

As the above table shows, edges can be defined and used separately, i.e. without their incident nodes. Beware of accidentally "redirecting"[2] an edge: The graphlets

[2]You cannot directly express the redirection of edges. This a direct consquence of the SPO approach. Redirection of edges can be "simulated" by either deleting and re-inserting an edge, or more indirect by re-typing of nodes.

```
-e:Edge-> .;
x:Node -e-> y:Node;
```

are illegal, because the edge `e` would have two destinations: an anonymous node and `y`. However, the graphlets

```
-e-> ;
x:Node -e:Edge-> y:Node;
```

are allowed, but the second graphlet `-e->` is pointless. In particular this graphlet does not identify or create any "copies", neither if the graphlet occurs in the pattern part nor if it occurs in the replace part.

EXAMPLE (6)

Some attempts to specify a loop edge:

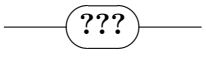
Graphlet	Meaning
`x:Node -e:Edge-> x;`	The edge `e` is a loop.
`x:Node -e:Edge-> ; -e-> x;`	The edge `e` is a loop.
`-e:Edge-> x:Node;`	The edge `e` may or may not be a loop.
`. -e:Edge-> .;`	The edge `e` is certainly not a loop.

NOTE (5)

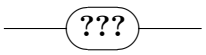
Although both, the pattern part and the replace/modify part, use graphlets, there are subtle differences between them. It concerns the *TypeConstraint* clause, the retype operator `<>`, and the scope of defined graph element names: Names defined within the pattern part are valid in the pattern part as well as in the replace/modify part. Names defined within the replace/modify part are unknown to the pattern part.

3.2 Rules and Tests

The structure of a rule set file is as follows:



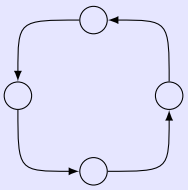
A rule set consists of the underlying graph models and several rewrite rules. In case of multiple graph models GrGen.NET uses the union of these models. In this case beware of conflicting declarations. There is no built-in conflict resolution mechanism like packages or namespaces for models. If necessary you could use prefixes as you might do in C.



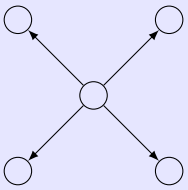
Declares a single rewrite rule such as `SomeRule`. It consists of a pattern part (see section 3.3) in conjunction with its rewrite/modify part (see section 3.4). A *test* has no rewrite specification. It's intended to check whether (and maybe how many times) a pattern occurs.

EXAMPLE (7)

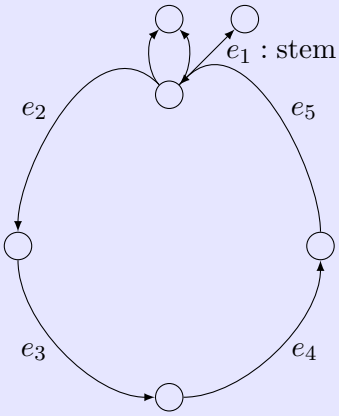
Some graphlets:



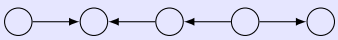
```
x:Node --> . --> . --> . --> x;
```



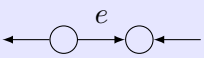
```
. <-- x:Node --> .;
. <-- x --> .;
```




```
. <-e1:stem- n1:Node -e2:Edge-> . -e3:Edge-> .
  -e4:Edge-> . -e5:Edge-> n1;
n1 --> n2:Node;
n1 --> n2;
```



```
. --> . <-- . <-- . --> .;
```




```
-e:Edge->
<-- . -e-> . <-- ;
```

And some illegal graphlets:

`. -e:Edge-> .; . -e-> .;`	Would affect redirecting of edge `e`.
`x -e:T-> y; x -e-> x;`	Would affect redirecting of edge `e`.
`x:Node; negative {y:Node; hom(x,y)}`	Here `x` must not occur in the `hom` statement. See section 3.3 for further information.
`<-- --> ;`	There must be at least a node between the edges.

EXAMPLE (8)

We define a test `SomeCond`

```
1 test SomeCond {
2   pattern {
3     n: SeldomNodeType;
4   }
5 }
```

and execute in GrShell:

```
1   grs SomeCond & SomeRule
```

SomeRule will only be executed, if a node of type `SeldomNodeType` exists. For graph rewrite sequences in GrShell see 5.2.6.

???

The signature sets the name of a rewrite rule to *IdentDecl* and optionally names and types of formal parameters as well as a list of return types. Parameters and return types provide users with the ability to exchange graph elements with rule. This is similar to parameters of procedural languages.

???

Within a rule parameters are treated as (predefined) graph elements of the pattern. Even if a supplied parameter value is undefined, it is treated as valid node or edge definition. So in any case a graph element of the specified type has to be mapped. GrGen.NET assumes the lookup operation for parameters to be in $\mathcal{O}(1)$. In case of an undefined parameter value this might lead to bad search plans, because GrGen.NET has to actually search for such a graph element.

EXAMPLE (9)

Assume the following test that checks whether the edge `e` is not incident to `x`:

```
1  test r(-e:Edge->, x:Node) {
2    pattern {
3      negative {
4        -e-> x;
5      }
6      negative {
7        x <-e-;
8      }
9    }
10 }
```

If `x` and `e` are undefined, test `r` is equivalent to test `s`:

```
1  test s {
2    pattern {
3      x:Node;
4      -e:Edge->;
5      negative {
6        -e-> x;
7      }
8      negative {
9        x <-e-;
10     }
11   }
12 }
```

In particular test `s` is successful if there is *any* edge present in the host graph that is not incident to `x`.

The return types specify edge and node types of graph elements that are returned by the replace/modify part. If return types are specified, the `return` statement is mandatory. Otherwise no `return` statement must occur. See also section 3.4, `return`.

EXAMPLE (10)

We extend `SomeRule` (example 4) with a user defined node to match and we want it to return the rewritten graph elements `n5` and `e1`.

```
1    rule SomeRuleExt(varnode: Node): (Node, EdgeTypeB) {
2      pattern {
3        n1: NodeTypeA;
4        ...
5      }
6      replace {
7        varnode;
8        ...
9        return(n5, e1);
10       eval {
11         ...
```

We don't define `varnode` within the pattern part because this is already covered by the parameter specification itself.

3.3 Pattern Part

???

A pattern consists of zero or more pattern statements. All the pattern statements must be fulfilled by a subgraph of the host graph in order to form a match. An empty pattern always produces exactly one (empty) match. This is caused by the uniqueness of the total and totally undefined function.

Names defined for graph elements may be used by other pattern statements as well as by replace/modify statements. Like all identifier definitions, such names may be used before their declaration. See section 3.1 for a detailed explanation of names and graphlets.

NOTE (6)

The application of a rule is not deterministic (remember the introductionary example in 1.5); in particular there may be more than one subgraph that matches the pattern. Whereas the GrShell selects one of them arbitrarily (without further abilities to control the selection), the underlying libGr provides a mechanism to deal with such ambiguities. libGr allows for splitting a rule application into two steps: Find all the subgraphs of the host graph that match the pattern and rewrite one of these matches. By returning a collection of all matches, the libGr retains the complete graph rewrite process under control. As a libGr user use the following methods of the `IAction` interface:

```
IMatches Match(IGraph graph, int maxMatches, IGraphElement[] parameters);
IGraphElement[] Modify(IGraph graph, IMatch match);
```

This might look like this in C#:

```
IMatches myMatches = myAction.Match(myGraph, -1, null); /* -1: get all the matches */
for (int i = 0;  i < myMatches.NumMatches; i++)
{
   if (inspectCarefully(myMatches.GetMatch(i))
   {
      myAction.Modify(myGraph, myMatches.GetMatch(i));
      break;
   }
}
```

Also notice that graph rewrite sequences introduce a further variant of non-determinism on rule application level: The `$<op>` flag marks the operator `<op>` as commutative, i.e. the execution order of its operands (rules) is non-deterministic. See section 5.2.6 for further information on graph rewrite sequences.

???

The semantics of the various pattern statements:

Graphlet.
: Graphlets specify connected subgraphs. See section 3.1 for a detailed explanation of graphlets.

Isomorphic/Homomorphic Matching.
The `hom` operator specifies the nodes or edges that may be matched homomorphically. In contrast to the default isomorphic matching, the specified graph elements *may* be mapped to the same graph element in the host graph. Note that the graph elements shall have a common subtype. Several homomorphically matched graph elements will be mapped to a graph element of a common subtype. In example 4 nodes `n1` and `n2` may be the same node. This is possible because they are of the same type (`NodeTypeA`). A name may not occur in multiple `hom` statements. For instance it's illegal to write `hom(a, b); hom(b, c);`. Instead write `hom(a, b, c);`. Inside a NAC the `hom` operator may only operate on graph elements that are either defined or used in the NAC.

Negative Application Conditions (NACs).
With negative application conditions (keyword `negative`) we can specify graph patterns which forbid the application of a rule if any of them is present in the host graph (cf. [**?**]). NACs must not be nested. NACs possess a scope of their own. Names defined within a NAC does not exist outside the NAC. Identifiers from surrounding scopes must not be redefined. In general NACs do not care about bindings within the outer scope. Nevertheless, if you use an identifier that is defined in the outer scope, this specifies exactly the graph element, the identifier is bound to in the outer scope.

EXAMPLE (11)

We specify a node `x` with out-degree of exactly 2:

```
1 pattern {
2   <-- x:Node -->;
3   negative {
4     <-- x -->;
5     x -->;
6   }
7 }
```

Attribute Conditions.
The Java-like attribute conditions (keyword `if`) in the pattern part allow for further restriction of the applicability of a rule.

Return values.
The return statement is only allowed for tests. Otherwise the `return` statement belongs to the replace part. See 3.4, *Return Values*.

Keep in mind that using type constraints or the `typeof` operator might be helpful. See section 4.3 for further information.

3.4 Replace/Modify Part

For the task of rewriting GrGen.NET provides two different modes: A *replace mode* and a *modify mode*.

3.4.1 Implicit Definition of the Preservation Morphism r

Besides specifying the pattern, a main task of a rule is to specify the transformation of a matched subgraph within the host graph. The transformation specification defines the transition from the left hand side (LHS) to the right hand side (RHS), i.e. which graph

elements of a match will be kept, which of them will be deleted and which graph elements have to be newly created. In theory this is done by defining the preservation morphism r. In

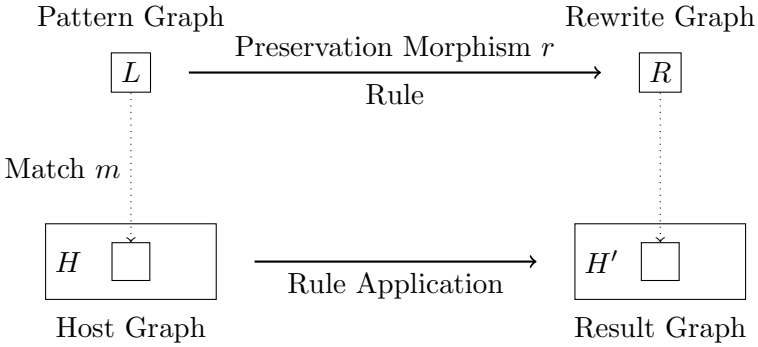


Figure 3.1: Process of Graph Transformation

GrGen.NET the preservation morphism r is defined implicitly by using names in pattern graphlets and replace graphlets. (We don't need to care about the the differences of the replace part and the modify part at the moment.) Remember that each of the graph elements of a match have got a name bound to them, either user defined or internally defined. If such a name is used in a replace graphlet, the denoted graph element will be kept. Otherwise the graph element will be deleted. By defining a name in a replace graphlet a corresponding graph element will be newly created. So in a replace pattern anonymous graph elements will be created, always. Using a name multiple times has the same effect as a single using occurrence. In case of a conflict between deletion and preservation, deletion is prioritized. If an incident node of an edge gets deleted, the edge will be deleted as well (in compliance to the SPO semantics).

Pattern (LHS)	**Replace (RHS)**	$r : L \longrightarrow R$	**Meaning**
`x:T;`	`x;`	$r : \text{lhs}.x \mapsto \text{rhs}.x$	Preservation
`x:T;`		$\text{lhs}.x \notin \text{def}(r)$	Deletion
	`x:T;`	$\text{rhs}.x \notin \text{ran}(r)$	Creation
`x:T;`	`x:T;`	—	Illegal, redefinition of `x`
`-e:T->;`	`-e-> x:Node;`	—	Illegal, redirection of `e`
`x:N -e:E-> y:N;`	`x -e->;`	$r : \{\text{lhs}.x\} \mapsto \{\text{rhs}.x\}$	Deletion of `y`. Hence deletion of `e`.

Table 3.1: Definition of the preservation morphism r

3.4.2 Specification Modes for Graph Transformation

Replace mode.

The semantics of this mode is to delete every graph element of the pattern that is not used (denoted) in the replace part, keep every graph element that is used, and create every additionally defined graph elements. "Using" means denoting a graph element in a graphlet. Attribute calculations are no using occurrences.

In example 10 the nodes `varnode` and `n3` will be kept. The node `n1` is replaced by the node `n5` preserving `n1`'s edges. The anonymous edge instance between `n1` and `n2` only occurs in the pattern and therefore gets deleted.

See section 3.4.1 for a detailed explanation of the transformation semantics.

Modify mode.

The modify mode can be regarded as a replace part in replace mode, where every pattern graph element is added (denoted) before the first replace statement. In particular all

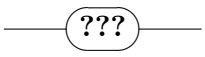
the anonymous graph elements are kept. Additionally this mode supports the `delete` operator that deletes every element given as an argument. Deletion takes place after all other rewrite operations. Multiple deletion of the same graph element is allowed (but pointless) as well as deletion of just created elements (pointless, too).

EXAMPLE (12)

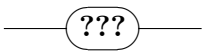
How might example 10 look in modify mode? We have to denominate the anonymous edge between `n1` and `n2` in order to delete it. The node `varnode` should be kept and does not need to appear in the modify part. So we have

```
1  rule SomeRuleExtModify(varnode: Node): (Node, EdgeTypeB)  {
2    pattern {
3      ...
4      n1 -e0:Edge-> n2;
5      ...
6    }
7    modify {
8      n5 : NodeTypeC<n1>;
9      n3 -e1:EdgeTypeB-> n5;
10     delete(e0);
11     eval {
12       ...
```

3.4.3 Syntax



Selects whether the replace mode or the modify mode is used. Several replace statements describe the transformation from the pattern subgraph to the destination subgraph.



The semantics of the various pattern statements:

Graphlet.
Analogous to a pattern graphlet, a specification of a connected subgraph. Its graph elements are either kept because they are elements of the pattern or added otherwise. Names defined in the pattern part must not be redefined in the replace graphlet. See section 3.1 for a detailed explanation of graphlets.

Deletion.
The `delete` operator is only available in the modify mode. It deletes the specified pattern graph elements. Multiple occurrences of `delete` statements are allowed. Deletion statements are executed after all other replace statements. Multiple deletion of the same graph element is allowed (but pointless) as well as deletion of just created elements (pointless, too).

Attribute Evaluation.
If a rule is applied, then the attributes of matched and inserted graph elements will be recalculated according to the `eval` statements.

Return Values.
Graph elements of the replace/modify part can be returned according to the return types in the signature (see 3.2, `ActionSignature`). The `return` statement must not occur multiple times. The graph element names have to be in the same order as the corresponding return types in the signature. The named elements must be compatible to the declared type.

Retyping.
Retyping enables us to keep all adjacent nodes and all attributes stemming from common super types of a graph element while changing its type. Retyping differs from a type cast: During replacement both of the graph elements are alive. Specifically both of them are available for evaluation. Furthermore the source and destination types need not to be on a path in the directed type hierarchy graph, rather their relation can be arbitrary. The edge specification as well as *ReplaceNode* supports retyping. In example 4 node `n5` is a retyped node stemming from node `n1`.

???

Several evaluation parts are allowed within the replace part. Multiple evaluation statements will be internally concatenated, preserving their order. Evaluation statements have imperative semantics. In particular, GrGen.NET does not care about data dependencies. Evaluation takes place before any graph element gets deleted and after all the new elements have been created. You may read (and write, although this is pointless) attributes of graph elements to be deleted.

EXAMPLE (13)

```
...
modify {
  ...
  eval {y.i = 40;}
  eval {y.j = 0;}
  x: IJNode;
  y: IJNode;
  delete(x);
  eval {
    x.i = 1;
    y.j = x.i;
    x.i = x.i + 1;
    y.i = y.i + x.i;
  }
```

This nonsense example yields `y.i` = 42, `y.j` = 1.

CHAPTER 4

TYPES AND EXPRESSIONS

In the following sections *Ident* refers to an identifier of the graph model language (see section 2.1) or the rule set language (see section 3.1). *TypeIdent* is an identifier of a node type or an edge type, *NodeOrEdge* is an identifier of a node or an edge.

4.1 Built-In Types

Besides user-defined node types, edge types and enumeration types, GrGen supports the built-in primitive types in table 4.1. The exact type format is backend specific. The LGSPBackend maps the GrGen.NET primitive types to the corresponding C# primitive types. Table 4.2

`boolean`	Covers the values `true` and `false`.
`int`	A signed integer with at least 32 bits.
`float`, `double`	A floating-point number with single precision or double precision respectively.
`string`	A character sequence of arbitrary length.

Table 4.1: GrGen.NET built-in primitive types

lists GrGen.NET's implicit type casts and the allowed explicit type casts. Of course you are free to express an implicit type cast by an explicit type cast as well as "cast" a type to itself, except for enum types. The cast operator does never accept an enum type.

EXAMPLE (14)

`myfloat = myint; mydouble = (float)myint; mystring = (string)mybool` is allowed, `myenum = (myenum)int; myfloat = mydouble; myint = (int)mybool` is forbidden.

to \ from	`enum`	`boolean`	`int`	`float`	`double`	`string`
`enum`	=/—					
`boolean`		=				
`int`	`(int)`		=	`(int)`	`(int)`	
`float`	`(float)`		implicit	=	`(float)`	
`double`	`(double)`		implicit	implicit	=	
`string`	`(string)`	`(string)`	`(string)`	`(string)`	`(string)`	=

Table 4.2: GrGen.NET type casts.

4.2 Expressions

???

As in C [?], `!` negates a Boolean. Table 4.4 lists the binary operators for Boolean expressions. The `?` operator is a simple if-then-else: if the first *BoolExpr* is evaluated to `true`, the operator returns the second *BoolExpr*, otherwise it returns the third *BoolExpr*. The *CompareOperator* is one of the following operators:

```
<   <=   ==   !=   >=   >
```

These operators are supported by enum types, `int` types, and `float`/`double` types. `String` types and `boolean` types support only the `==` and the `!=` operators. Table 4.3 describes the semantics of compare operators on type expressions. The *BinBoolOperator* is one of the operators in table 4.4.

`A == B`	True, iff A and B are identical. Different types in a type hierarchy are *not* identical.
`A != B`	True, iff A and B are not identical.
`A < B`	True, iff A is a supertype of B, but A and B are not identical.
`A > B`	True, iff A is a subtype of B, but A and B are not identical.
`A <= B`	True, iff A is a supertype of B or A and B are identical.
`A >= B`	True, iff A is a subtype of B or A and B are identical.

Table 4.3: Compare operators on type expressions

NOTE (7)

`A < B` corresponds to the direction of the arrow in an UML class diagram.

`^`	Logical XOR. True, iff either the first or the second Boolean expression is true.
`&&` `||`	Logical AND and OR. Lazy evaluation.
`&` `|`	Logical AND and OR. Strict evaluation.

Table 4.4: Binary Boolean operators, in ascending order of precedence

???

The $\sim$ operator is the bitwise complement. That means every bit of an integer value will be flipped. The `?` operator is a simple if-then-else: if the *BoolExpr* is evaluated to `true`, the operator returns the first *IntExpr*, otherwise it returns the second *IntExpr*. The *BinIntOperator* is one of the operators in table 4.5.

???

^ & |	Bitwise XOR, AND and OR
<< >> >>>	Bitwise shift left, bitwise shift right and bitwise shift right preserving the sign
+ -	Addition and subtraction
* / %	Multiplication, integer division and modulo

Table 4.5: Binary integer operators, in ascending order of precedence

+ -	Addition and subtraction
* / %	Multiplication, division and modulo

Table 4.6: Binary float operators, in ascending order of precedence

The `?` operator is a simple if-then-else: if the *BoolExpr* is evaluated to `true`, the operator returns the first *FloatExpr*, otherwise it returns the second *FloatExpr*. The *BinFloatOperator* is one of the operators in table 4.6.

NOTE (8)

The `%` operator works analogous to the integer modulo operator. For instance `4.5 % 2.3 == 2.2`. GrGen.NET implements the Java semantics.

???

The operator `+` concatenates two strings.

???

Number.
Is an `int`, `float` or `double` constant in decimal notation.

HexNumber.
Is an `int` constant in hexadecimal notation starting with `0x`.

QuotedText.
Is a string constant. It consists of a sequence of characters, enclosed by double quotes.

4.3 Type Related Conditions

???

A type expression identifies a type (and—in terms of matching—also its subtypes). A type expression is either a type identifier itself or the type of a graph element.

EXAMPLE (15)

The following rule will add a reverse edge to a one-way street.

```
1  rule oneway {
2      pattern {
3          a:Node -x:street-> y:Node;
4          negative{
5              y -:typeof(x)-> a;
6          }
7      }
8      replace {
9          a -x-> y;
10         y -:typeof(x)-> a;
11     }
12 }
```

Remember that we have several subtypes of `street`. By the aid of the `typeof` operator, the reverse edge will be automatically typed correctly (the same type as the one-way edge). This behavior is not possible without the `typeof` operator.

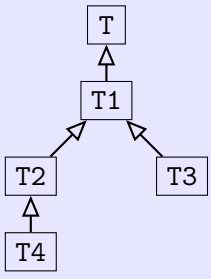
???

A type constraint is used to exclude parts of the type hierarchy. The operator `+` is used to create a union of its operand types. So the following pattern statements are identical:

```
x:T \ (T1 + ··· + Tn);
```

```
x:T;
if {!(typeof(x) <= T1) && ···
    && !(typeof(x) <= Tn)}
```

EXAMPLE (16)



The expression `T\(T2+T3)` applied to the type hierarchy on the left side yields only the types `T` and `T1` as valid.

4.4 Annotations

Identifier definitions can be annotated by pragmas. Annotations are key-value pairs.

???

Although you can use any key-value pairs between the brackets, only the identifier `prio` has an effect so far.

Key	Value Type	Applies to	Meaning
`prio`	int	node, edge	Changes the ranking of a graph element for search plans. The default is `prio`=1000. Graph elements with high values are likely to appear prior to graph elements with low values in search plans.

Table 4.7: Annotations

EXAMPLE (17)

We search the pattern `v:NodeTypeA -e:EdgeType-> w:NodeTypeB`. We have a host graph with about 100 nodes of `NodeTypeA`, 1,000 nodes of `NodeTypeB` and 10,000 edges of `EdgeType`. Furthermore we know that between each pair of `NodeTypeA` and `NodeTypeB` there exists at most one edge of `EdgeType`. GrGen.NET can use this information to improve the initial search plan, if we adjust the pattern like `v[prio=10000]:NodeTypeA -e[prio=5000]:EdgeType-> w:NodeTypeB`.

CHAPTER 5

GRSHELL LANGUAGE

GrShell is a shell application of libGr. It belongs to GrGen.NET's standard equipment. GrShell is capable of creating, manipulating, and dumping graphs as well as performing graph rewriting and debugging graph rewriting. The GrShell provides a line oriented scripting language. GrShell scripts are structured by simple statements separated by line breaks.

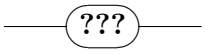
5.1 Building Blocks

GrShell is case sensitive. A comment starts with a `#` and is terminated by end-of-line or end-of-file. Any text left of the `#` will be treated as a statement. The following items are required for representing text, numbers, and rule parameters.

Text
May be one of the following:

- A non-empty character sequence consisting of letters, digits, and underscores. The first character must not be a digit.
- Arbitrary text enclosed by double quotes (`""`).
- Arbitrary text enclosed by single quotes (`''`).

Number
Is an `int` or `float` constant in decimal notation (see also section 4.1).



In order to describe the commands more precisely, the following (semantic) specializations of *Text* are defined:

Filename
: A fully qualified file name without spaces (e.g. `/Users/Bob/amazing_file.txt`) or a single quoted or double quoted fully qualified file name that may contain spaces (`"/Users/Bob/amazing_file.txt"`).

Variable
: Identifier of a variable that contains a graph element.

NodeType, EdgeType
: Identifier of a node type resp. edge type defined in the model of the current graph.

AttributeName
: Identifier of an attribute.

Graph
: Identifies a graph by its name.

Action
: Identifies a rule by its name.

Color
: One of the following color identifiers: `Black`, `Blue`, `Green`, `Cyan`, `Red`, `Purple`, `Brown`, `Grey`, `LightGrey`, `LightBlue`, `LightGreen`, `LightCyan`, `LightRed`, `LightPurple`, `Yellow`, `White`, `DarkBlue`, `DarkRed`, `DarkGreen`, `DarkYellow`, `DarkMagenta`, `DarkCyan`, `Gold`, `Lilac`, `Turquoise`, `Aquamarine`, `Khaki`, `Pink`, `Orange`, `Orchid`. These are the same color identifiers as in VCG/yComp files.

???

The elements of a graph (nodes and edges) can be accessed both by their variable identifier and by their *persistent name* specified through a constructor (see section 5.2.3). The specializations *Node* and *Edge* of *GraphElement* requires the corresponding graph element to be a node or an edge respectively.

EXAMPLE (18)

We insert a node, anonymously and with a constructor:

```
1  > select backend lgspBackend.dll
2  Backend selected successfully.
3  > new graph "../lib/lgsp-TuringModel.dll" G
4  New graph "G" of model "Turing" created.
5
6  # insert an anonymous node...
7  # it will get a persistent pseudo name
8  > new :State
9  New node "$0" of type "State" has been created.
10 > delete node @("$0")
11
12 # and now with constructor
13 > new v:State($=start)
14 new node "start" of type "State" has been created.
15 # Now we have a node named "start" and a variable v assigned to "start"
```

NOTE (9)

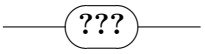
Persistent names belong to a specific graph, whereas variables belong to the current GrShell environment. Persistent names will be saved (`save graph...`, see 5.2.5) and, if you visualize a graph (`dump graph...`, see 5.2.5), graph elements will be labeled with their persistent names. Persistent names have to be unique for a graph.

???

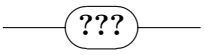
Assigns the variable or persistent name *GraphElement* to *Variable*. If *Variable* has not been defined yet, it will be defined implicitly. As usual for scripting languages, variables have neither types nor declarations.

5.2 GrShell Commands

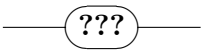
This section describes the GrShell commands. Commands are assembled from basic elements. As stated before commands are terminated by a line breaks. Alternatively commands can be terminated by the `;;` symbol.



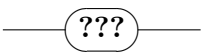
5.2.1 Common Commands



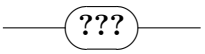
Displays an information message describing supported commands.



Quits GrShell. If GrShell is opened in debug mode, currently active graph displayers (such as yComp) will be closed as well.

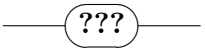


Selects a backend that handles graph and rules representation. *Filename* has to be a .NET assembly (e.g. `lgspBackend.dll`). Comma-separated parameters can be supplied optionally. If so, the backend must support these parameters.

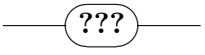


List all the parameters supported by the currently selected backend. The parameters can be provided to the `select backend` command.

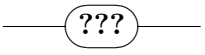
Executes the GrShell script *Filename*. A GrShell script is just a plain text file containing GrShell commands. They are treated as they would be entered interactively, except for parser errors. If a parser error occurs, execution of the script will stop immediately.



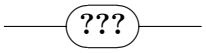
Enables and disables the debug mode. The debug mode shows the current working graph in a yComp window. All changes to the working graph are tracked by yComp immediately.



Sets the default graph layout algorithm to *Text*. If *Text* is omitted, a list of available layout algorithms is displayed. See section 1.6.4 on yComp layouters.



Prints *Text* onto the GrShell command prompt.



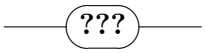
Passes *CommandLine* to the operating system. *CommandLine* is an arbitrary text the operating system attempts to execute.

EXAMPLE (19)

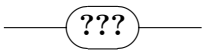
On a Linux machine you might execute

```
1 !sh -C "ls␣|␣grep␣stuff"
```

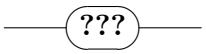
5.2.2 Graph Commands



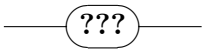
Creates a new graph with the model specified in *Filename*. Its name is set to *Text*. The model file can be either source code (e.g. `turing_machineModel.cs`) or a .NET assembly (e.g. `lgsp-turing_machineModel.dll`).



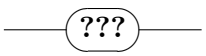
Opens the graph *Text* stored in the backend. However, the *LGSPBackend* doesn't support persistent graphs. *LGSPBackend* is the only backend so far. Therefore this command is currently useless.



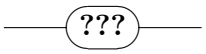
Displays a list of currently available graphs.



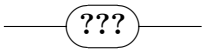
Selects the current working graph. This graph acts as *host graph* for graph rewrite sequences (see also sections 1.4 and 5.2.6). Though you can define multiple graphs, only one graph can be the active "working graph".



Deletes all graph elements of the current working graph resp. the graph *Graph*.



Deletes the graph *Graph* from the backend storage.



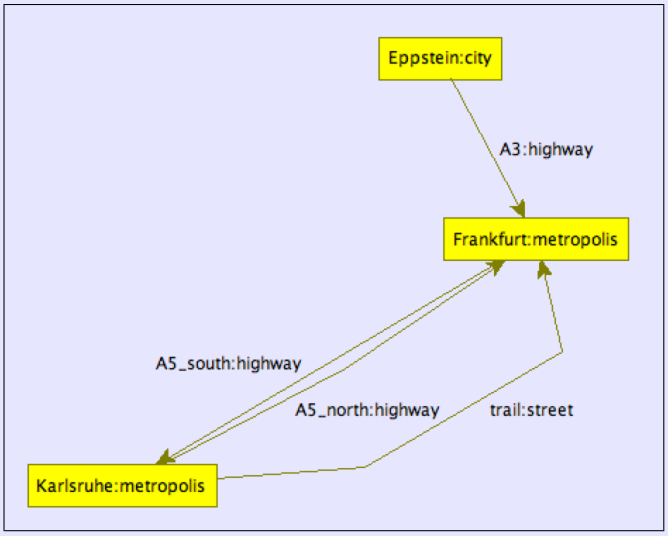
Validates if the current working graph fulfills the connection assertion specified in the corresponding graph model. The *strict* mode additionally requires all the edges of the working graph to be specified in order to get a "valid". Otherwise edges between nodes without specified constraints are ignored.

EXAMPLE (20)

We reuse a simplified version of the street map model from chapter 2:

```
1 model Map;
2
3 node class city;
4 node class metropolis;
5
6 edge class street;
7 edge class highway
8       connect metropolis [+] -> metropolis [+];
```

The node constraint on *highway* requires all the metropolises to be connected by highways. Now have a look at the following graph:



This graph is valid, but not strict valid.

```
1 > validate
2 The graph is valid.
3 > validate strict
4 The graph is NOT valid:
5   CAE: city "Eppstein" -- highway "A3" --> metropolis "Frankfurt" not specified
6   CAE: metropolis "Karlsruhe" -- street "trail" --> metropolis "Frankfurt" not specified
7 >
```

???

Executes a command specific to the current backend. If *SpacedParameters* is omitted, a list of available commands will be displayed (for the LGSP backend see 5.3).

5.2.3 Graph Manipulation Commands

Graph manipulation commands alter existing graphs including creating and deleting graph elements and setting attributes.

???

A constructor is used to initialize a new graph element (see `new ...` below). A comma separated list of attribute declarations is supplied to the constructor. Available attribute names are specified by the graph model of the current working graph. All the undeclared attributes will be initialized with default values, depending on their type (int, enum ← 0; boolean ← false; float, double ← 0.0; string ← “”).
The `$` is a special attribute name: a unique identifier of the new graph element. This identifier is also called *persistent name* (see example 18). This name can be specified by a constructor only.

???

Creates a new node within the current graph. Optionally a variable *Text* is assigned to the new node. If *NodeType* is supplied, the new node will be of type *NodeType* and attributes can be initialized by a constructor. Otherwise the node will be of the base node class type *Node*.

NOTE (10)

The GrShell can reassign variables. This is in contrast to the rule language (chapter 3), where we use *names*.

???

Creates a new edge within the current graph between the specified nodes, directed towards the second *Node*. Optionally a variable *Text* is assigned to the new edge. If *EdgeType* is supplied, the new edge will be of type *EdgeType* and attributes can be initialized by a constructor. Otherwise the edge will be of the base edge class type *Edge*.

???

Set the attribute *AttributeName* of the graph element *GraphElement* to the value of *Text* or *Number*.

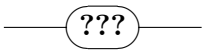
???

Deletes the node *Node* from the current graph. Incident edges will be deleted as well.

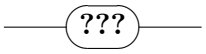
???

Deletes the edge *Edge* from the current graph.

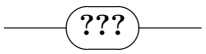
5.2.4 Graph Query Commands



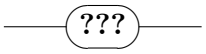
Gets the persistent names and the types of all the nodes/edges of the current graph. If a node type or edge type is supplied, only elements compatible to this type are considered. The `only` keyword excludes subtypes. Nodes/edges without persistent names are shown with a pseudo-name. If the command is specified with `num`, only the number of nodes/edges will be displayed.



Gets the node/edge types of the current graph model.



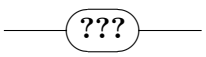
Gets the inherited/descended types of *NodeType*/*EdgeType*.



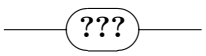
Gets the available node/edge attribute types. If *NodeType*/*EdgeType* is supplied, only attributes defined in *NodeType*/*EdgeType*. The `only` keyword excludes inherited attributes.

NOTE (11)

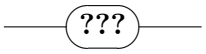
The `show nodes/edges attributes...` command covers types and *inherited* types. This is in contrast to the other `show...` commands where types and *sub*types are specified resp. the direction in the type hierarchy is specified explicitly.



Gets the attribute types and values of a specific graph element.



Gets the value of a specific attribute.



Gets the information, whether the first element is type-compatible to the second element.

5.2.5 Graph Output Commands

???

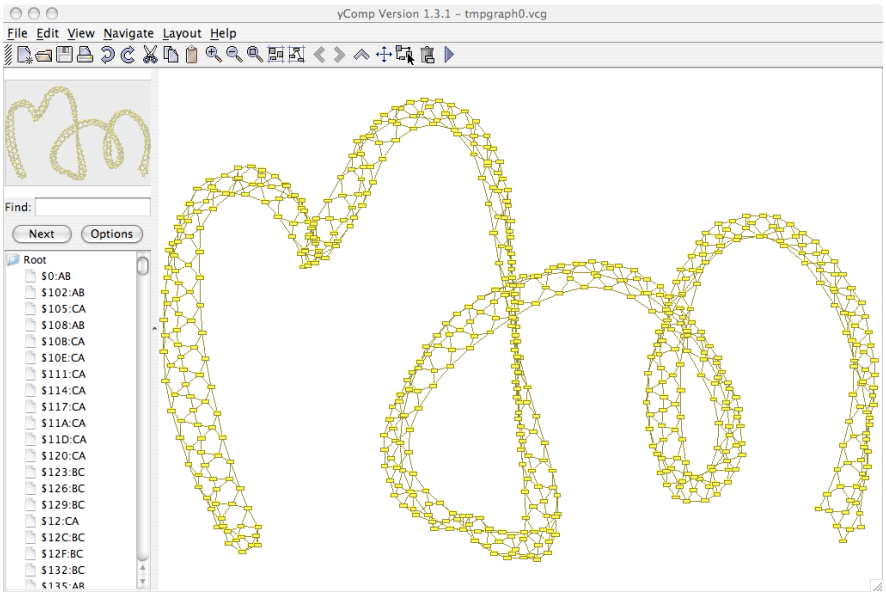
Dumps the current graph as GrShell script into *Filename*. The created script includes

- selecting the backend
- creating all nodes and edges
- restoring the persistent names (see 5.2.3),

but not necessarily using the same commands you typed in during construction. Such a script can be loaded and executed by the `include` command (see section 5.2.1).

???

Dumps the current graph as VCG formatted file into a temporary file. *Filename* specifies an executable. The temporary VCG file will be passed to *Filename* as last parameter. Additional parameters, such as program options, can be specified by *Text*. If you use yComp[1] as executable, this may look like



The temporary file will be deleted, when the application *Filename* is terminated, if GrShell is still running at this time.

???

Dumps the current graph formatted as VCG into the file *Filename*.

[1] See section 1.6.4.

Visualization Styles

The following commands control the style of the VCG output. This affects `dump graph`, `show graph` and `enable debug`.

???

Sets the color or text color or border color resp. the shape of the nodes of type *NodeType* and all of its subtypes. The keyword `only` excludes the subtypes. The following shapes are supported: `box`, `triangle`, `circle`, `ellipse`, `rhom`, `hexagon`, `trapeze`, `uptrapeze`, `lparallelogram`, `rparallelogram`. Those are shape names of yComp (for VCG definition see [?]).

???

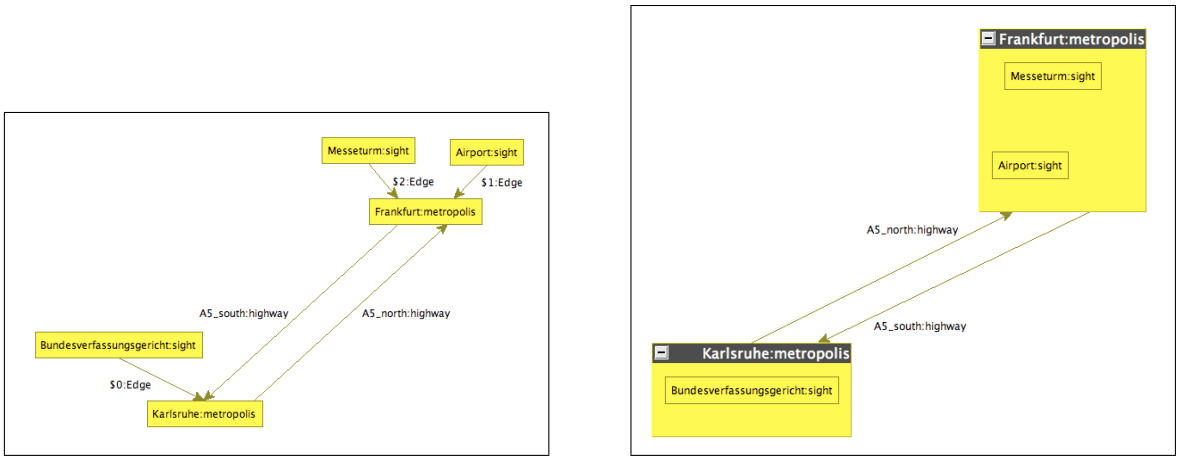
Sets the color or text color of the edges of type *EdgeType* and all of its subtypes. The keyword `only` excludes the subtypes.

???

Excludes nodes of type *NodeType* and all of its subtypes as well as their incident edges from output. The keyword `only` excludes the subtypes.

???

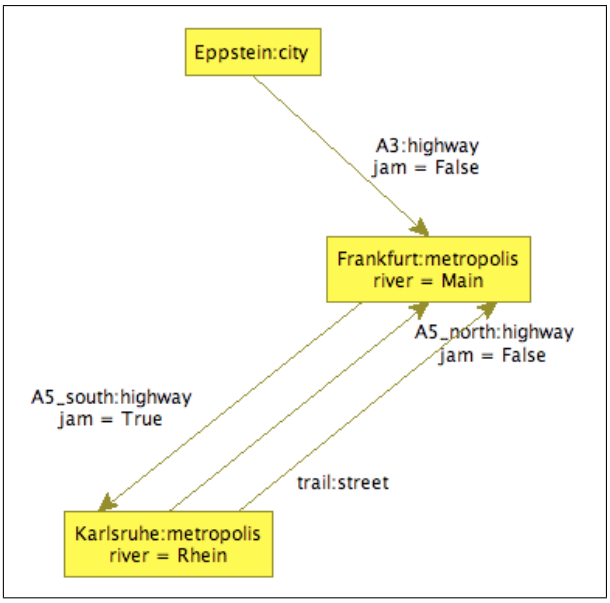
Declares *NodeType* and subtypes of *NodeType* as group node type. All the different typed nodes that points to a node of type *NodeType* (i.e. there is a directed edge between such nodes) will be grouped and visibly enclosed by the *NodeType*-node. The following example shows *metropolis* ungrouped and grouped:



right side: dumped with `dump add node metropolis group`

???

Declares the attribute *AttributeName* to be an "info tag". Info tags are displayed like additional node/edge labels. The keyword `only` excludes the subtypes of *NodeType* resp. *EdgeType*. In the following example *river* and *jam* are info tags:



???

Specifies, whether edge labels will be displayed or not (default to "on").

???

Reset all style options (`dump set...`) to their default values.

5.2.6 Action Commands (GRS)

An *action* denotes a graph rewrite rule.

???

Selects a rule set. *Filename* can either be a .NET assembly (e.g. "rules.dll") or a source file ("rules.cs"). Only one rule set can be loaded simultaneously.

???

Lists all the rules of the loaded rule set, their parameters, and their return values. Rules can return a set of graph elements.

???

Executes an action specific to the current backend. If *SpacedParameters* is omitted, a list of available commands will be displayed (for the LGSPBackend see section 5.3).

???

This executes the graph rewrite sequence *SimpleRewriteSequence*.

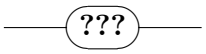


Table 5.1 lists graph rewrite expressions at a glance. The operators hold the following order of precedence, starting with the lowest precedence:

```
;    |    &
```

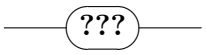
Variables can be assigned to graph elements returned by rules using `(Parameters) = Action`. The desired variable identifiers have to be listed in *Parameters*. Graph elements required by rules must be provided using `Action (Parameters)`, where *Parameters* is a list of variable identifiers. For undefined variables see section 3.2, *Parameters*.

Use the `debug` option to trace the rewriting process step-by-step. During execution yComp will display every single step[2]. The debugger can be controlled by GrShell. The debug commands are shown in table 5.2.

5.3 LGSPBackend Custom Commands

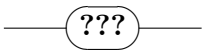
The LGSPBackend supports the following custom commands:

5.3.1 Graph Related Commands

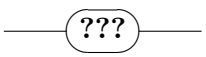


Analyzes the current working graph. The analysis data provides vital information for efficient search plans. Analysis data are available as long as GrShell is running, i.e. when the working graph changes the analysis data is still available but maybe obsolete.

5.3.2 Action Related Commands



Creates a search plan for each rewrite rule *Action* using a heuristic method and the analyze data (if the graph has been analyzed by `custom graph analyze_graph`). Otherwise a default search plan is used. For efficiency reasons it is recommended to do analyzing and search plan creation during the rewriting procedure. Therefore the host graph should be in a stage "similar" to the final result. In deed there might be some trial-and-error steps necessary to get a efficient search plan. A search plan is available as long as the current rule set remains loaded. Specify multiple rewrite rules instead of using multiple commands for each rule to improve the search plan generation performance.



Sets the maximum amount of possible pattern matches to *Number*. This command affects the expression `[Rule]`. For *Number* less or equal to zero, the constraint is reset.

[2]Make sure, that the path to your `yComp.jar` package is set correctly in the `ycomp` shell script within GrGen.NET's `/bin` directory.

`s ; t`	**Concatenation.** First, `s` is executed, afterwards `t` is executed. The sequence `s ; t` is *successfully* executed iff `s` or `t` is successfully executed.
`s | t`	**XOR.** First, `s` is executed. Only if `s` fails, `t` is executed. The sequence `s | t` is successfully executed iff `s` or `t` is successfully executed.
`s & t`	**Transactional AND.** First, `s` is executed, afterwards `t` is executed. If `s` or `t` fails, the action will be terminated and a rollback to the state before `s & t` is performed.
`$<op>`	Flags the operator `<op>` as commutative. Usually operands are executed / evaluated from left to right with respect to bracketing (left-associative). But the sequences `s`, `t`, `u` in `s $<op> t $<op> u` are executed / evaluated in arbitrary order.
`s *`	Executes `s` repeatedly as long as its execution does not fail.
`s {n}`	Executes `s` repeatedly as long as its execution does not fail, but anyway `n` times at most.
`!`	Found matches are dumped into VCG formatted files. Every match produces three files within the current directory: 1. The complete graph that has the matched graph elements marked 2. The complete graph with additional information about matching details 3. A subgraph containing only the matched graph elements
`Rule`	Only the first pattern match produced by the action *Rule* will be rewritten.
`[`*`Rule`*`]`	Every pattern match produced by the action *Rule* will be rewritten. **Note:** This operator is mainly added for benchmark purposes. Its semantic is not equal to `Rule*`. Instead this operator collects all the matches first before starting rewritings. In particular one needs to avoid deleting a graph element that is bound by another match.
`v = w`	The variable `v` is assigned to `w`. If `w` is undefined, `v` will be undefined, too.
`v = @(x)`	The variable `v` is assigned to the graph element identified by `x`. If `x` is not defined any more, `v` will be undefined, too.
`def(`*`Parameters`*`)`	Is *successful* if all the graph elements in *Parameters* exist, i.e. if all the variables are defined.
`true`	A constant acting as a successful match.
`false`	A constant acting as a failed match.

Let `s`, `t`, `u` be graph rewriting sequences, `v`, `w` variable identifiers, `x` an identifier of a graph element, `<op>` $\in \{;, |, \&\}$ and `n` $\in \mathbb{N}_0$.

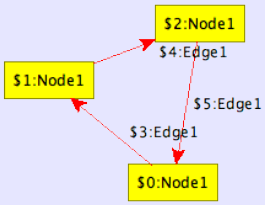
Table 5.1: Graph rewriting expressions

EXAMPLE (21)

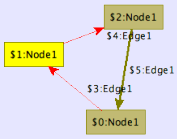
We demonstrate the debug commands with a slightly adjusted script for the Koch snowflake from GrGen.NET's examples (see also 6.1). The graph rewriting sequence is

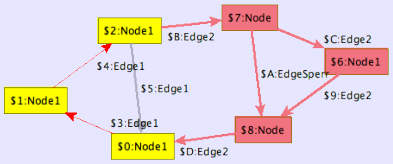
```
1 debug grs (makeFlake1* ; (beautify ; doNothing)* ; makeFlake2* ; beautify*){1}
```

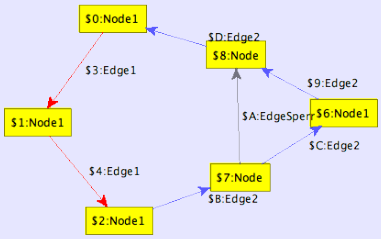
yComp will be opened with an initial graph (resulting from `grs init`):



We type `d`(etailed step) to apply `makeFlake1` step by step resulting in the following graphs:







The following table shows the "break points" of further debug commands, entered one after another:

Command	Active rule
s	makeFlake1
o	beautify
s	doNothing
s	beautify
n	beautify
o	makeFlake2
r	—

`s`(tep)	Executes the next rewriting rule (match and rewrite)
`d`(etailed step)	Executes a rewriting rule in a three-step procedure: matching, highlighting elements to be changed, doing rewriting
`n`(ext)	Ascends one level up within the Kantorowitsch tree of the current rewrite sequence
(step) `o`(ut)	Continues a rewriting sequence until the end of the current loop. If the execution is not in a loop at this moment, the complete sequence will be executed
`r`(un)	Continues execution without further stops
`a`(bort)	Cancels the execution immediately

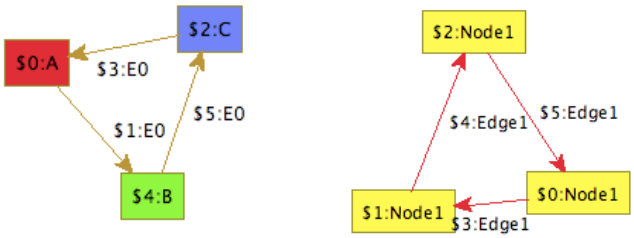
Table 5.2: GrShell debug commands

CHAPTER 6

EXAMPLES

6.1 Fractals

The GrGen.NET package ships with samples for fractal generation. We will construct the Sierpinski triangle and the Koch snowflake. They are created by consecutive rule applications starting with the initial host graphs



for the Sierpinski triangle resp. the Koch snowflake. First of all we have to compile the model and rule set files. So execute in GrGen.NET's `bin` directory

```
GrGen.exe ..\specs\sierpinski.grg
GrGen.exe ..\specs\snowflake.grg
```

or

```
mono GrGen.exe ../specs/sierpinski.grg
mono GrGen.exe ../specs/snowflake.grg
```

respectively. If you are on a Unix-like system you have to adjust the path separators of the GrShell scripts. Just edit the first three lines of `/test/Sierpinski.grs` and `/test/Snowflake.grs`. And as we have the file `Sierpinski.grs` already opened, we can increase the number of iterations to get even more beautiful graphs. Just follow the comments. Be careful when increasing the number of iterations of Koch's snowflake—yComp's layout algorithm might need some time and attempts to layout it nicely. We execute the Sierpinski script by

```
GrShell.exe ..\test\Sierpinski.grs
```

or

```
mono GrShell.exe ../test/Sierpinski.grs
```

respectively. Because both of the scripts are using the debug mode, we complete execution by typing `r`(un). See 5.2.6 for further information. The resulting graphs should look like figures 6.1 and 6.2.

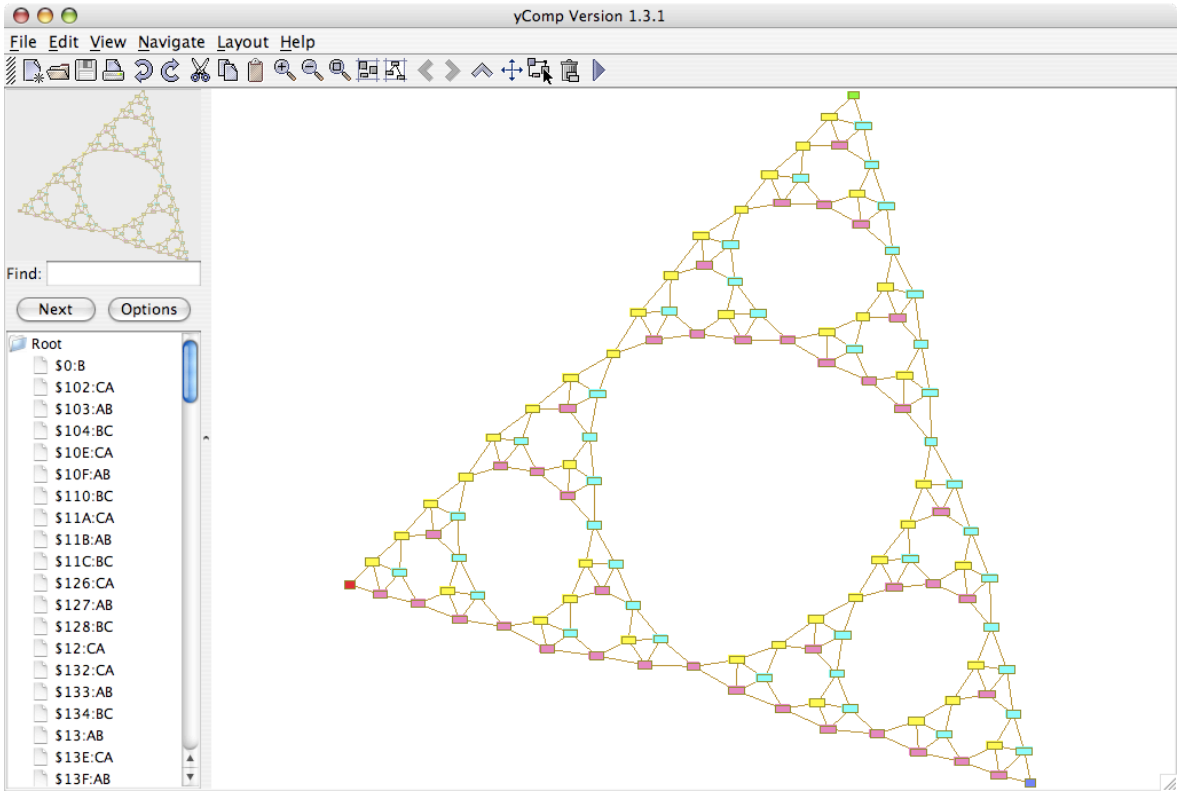


Figure 6.1: Sierpinski triangle

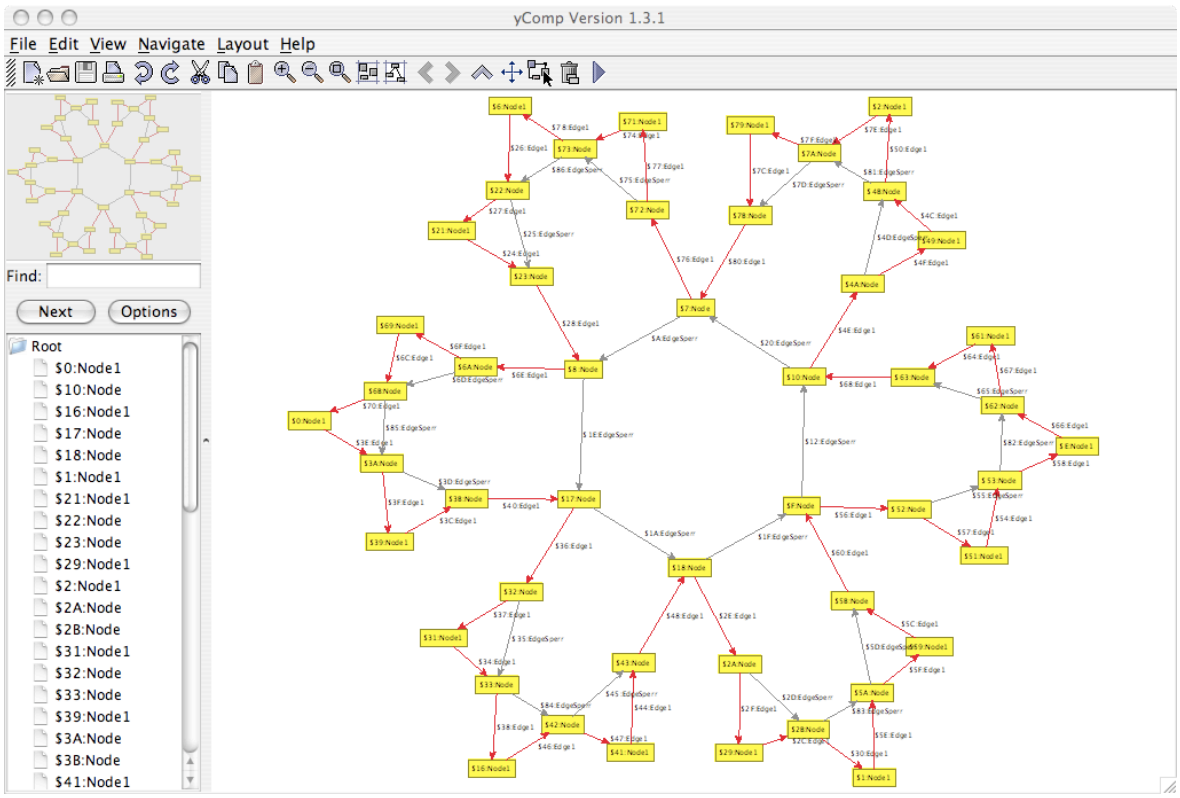


Figure 6.2: Koch snowflake

6.2 Busy Beaver

We want GrGen.NET to work as hard as a busy beaver [**?**, **?**]. Our busy beaver is a Turing machine, that has got five states plus a "halt"-state, writes 1,471 bars onto the tape and terminates [**?**]. So first of all we design a Turing machine as graph model. Besides this example shows that GrGen.NET is Turing complete.
We use the graph model and the rewrite rules to define a general Turing machine. Our approach is to basically draw the machine as a graph. The busy beaver logic is implemented by rule applications in GrShell.

6.2.1 Graph Model

Let's start the model file *TuringModel.gm* with

```
1 model TuringModel;
```

The tape will be a chain of *TapePosition* nodes connected by right edges. A cell value is modeled by a reflexive *value* edge, attached to a *TapePosition* node. The leftmost and the rightmost cell (*TapePosition*) does not have an incoming and outgoing edge respectively. Therefore we have the node constraint [0 : 1].

```
2  node class TapePosition;
3  edge class right
4    connect TapePosition[0:1] -> TapePosition[0:1];
5
6  edge class value
7    connect TapePosition[1] -> TapePosition[1];
8  edge class zero extends value;
9  edge class one extends value;
10 edge class empty extends value;
```

Finally we need states and transitions. The current configuration is modeled with a *RWHead* edge pointing to a *TapePosition* node. *State* nodes are connected with *WriteValue* nodes via *value* edges and from a *WriteValue* node a *moveLeft*/*moveRight* edge leads to the next state.

```
11 node class RWHead;
12
13 node class State;
14
15 node class WriteValue;
16 node class WriteZero extends WriteValue;
17 node class WriteOne extends WriteValue;
18 node class WriteEmpty extends WriteValue;
19
20 edge class moveLeft;
21 edge class moveRight;
22 edge class dontMove;
```

6.2.2 Rule Set

Now the rule set: we begin the rule set file *Turing.grg* with

```
1 actions Turing using TuringModel;
```

We need rewrite rules for the following steps of the Turing machine:

1. Read the value of the current tape cell and select an outgoing edge of the current state.
2. Write a new value into the current cell, according to the sub type of the *WriteValue* node.

3. Move the read-write-head along the tape and propagate a new state as current state.

As you can see a transition of the Turing machine is split into two graph rewriting steps: Writing the new value onto the tape and performing the state transition. We need eleven rules, three rules for each step (for "zero", "one" and "empty") and two rules for extending the tape to the left and the right, respectively.

```
rule readZeroRule {
   pattern {
      s:State -:RWHead-> tp:TapePosition -zv:zero-> tp;
      s -zr:zero-> wv:WriteValue;
   }
   replace {
      s -zr-> wv;
      tp -zv-> tp;
      wv -:RWHead-> tp;
   }
}
```

We take the current state *s* and the current cell *tp* implicitly given by the unique *RWHead* edge and check, whether the cell value is zero. Furthermore we check if the state has a transition for zero. The replacement part deletes the *RWHead* edge between *s* and *tp* and adds it between *wv* and *tp*. The remaining rules are analogous:

```
rule readOneRule {
   pattern {
      s:State -:RWHead-> tp:TapePosition -ov:one-> tp;
      s -or:one-> wv:WriteValue;
   }
   replace {
      s -or-> wv;
      tp -ov-> tp;
      wv -:RWHead-> tp;
   }
}

rule readEmptyRule {
   pattern {
      s:State -:RWHead-> tp:TapePosition -ev:empty-> tp;
      s -er:empty-> wv:WriteValue;
   }
   replace {
      s -er-> wv;
      tp -ev-> tp;
      wv -:RWHead-> tp;
   }
}

rule writeZeroRule {
   pattern {
      wv:WriteZero -rw:RWHead-> tp:TapePosition -:value-> tp;
   }
   replace {
      wv -rw-> tp -:zero-> tp;
   }
}

rule writeOneRule {
   pattern {
      wv:WriteOne -rw:RWHead-> tp:TapePosition -:value-> tp;
```

```
49    }
50    replace {
51       wv -rw-> tp -:one-> tp;
52    }
53 }
54
55 rule writeEmptyRule {
56    pattern {
57       wv:WriteEmpty -rw:RWHead-> tp:TapePosition -:value-> tp;
58    }
59    replace {
60       wv -rw-> tp -:empty-> tp;
61    }
62 }
63
64 rule moveLeftRule {
65    pattern {
66       wv:WriteValue -m:moveLeft-> s:State;
67       wv -:RWHead-> tp:TapePosition <-r:right- ltp:TapePosition;
68    }
69    replace {
70       wv -m-> s;
71       s -:RWHead-> ltp -r-> tp;
72    }
73 }
74
75 rule moveRightRule {
76    pattern {
77       wv:WriteValue -m:moveRight-> s:State;
78       wv -:RWHead-> tp:TapePosition -r:right-> rtp:TapePosition;
79    }
80    replace {
81       wv -m-> s;
82       s -:RWHead-> rtp <-r- tp;
83    }
84 }
85
86 rule dontMoveRule {
87    pattern {
88       wv:WriteValue -m:dontMove-> s:State;
89       wv -:RWHead-> tp:TapePosition;
90    }
91    replace {
92       tp;
93       wv -m-> s;
94       s -:RWHead-> tp;
95    }
96 }
97
98 rule ensureMoveLeftValidRule {
99    pattern {
100      wv:WriteValue -m:moveLeft-> s:State;
101      wv -rw:RWHead-> tp:TapePosition;
102      negative {
103         tp <-:right- ltp:TapePosition;
104      }
105   }
106   replace {
107      wv -m-> s;
```

```
108         wv -rw-> tp <-:right- ltp:TapePosition -:empty-> ltp;
109     }
110 }
111
112 rule ensureMoveRightValidRule {
113     pattern {
114         wv:WriteValue -m:moveRight-> s:State;
115         wv -rw:RWHead-> tp:TapePosition;
116         negative {
117             tp -:right-> rtp:TapePosition;
118         }
119     }
120     replace {
121         wv -m-> s;
122         wv -rw-> tp -:right-> rtp:TapePosition -:empty-> rtp;
123     }
124 }
```

Have a look at the negative conditions within the *ensureMove...* rules. They ensure that the current cell is indeed at the end of the tape: An edge to a right/left neighboring cell must not exist. Now don't forget to compile your model and the rule set with `GrGen.exe` (see 6.1).

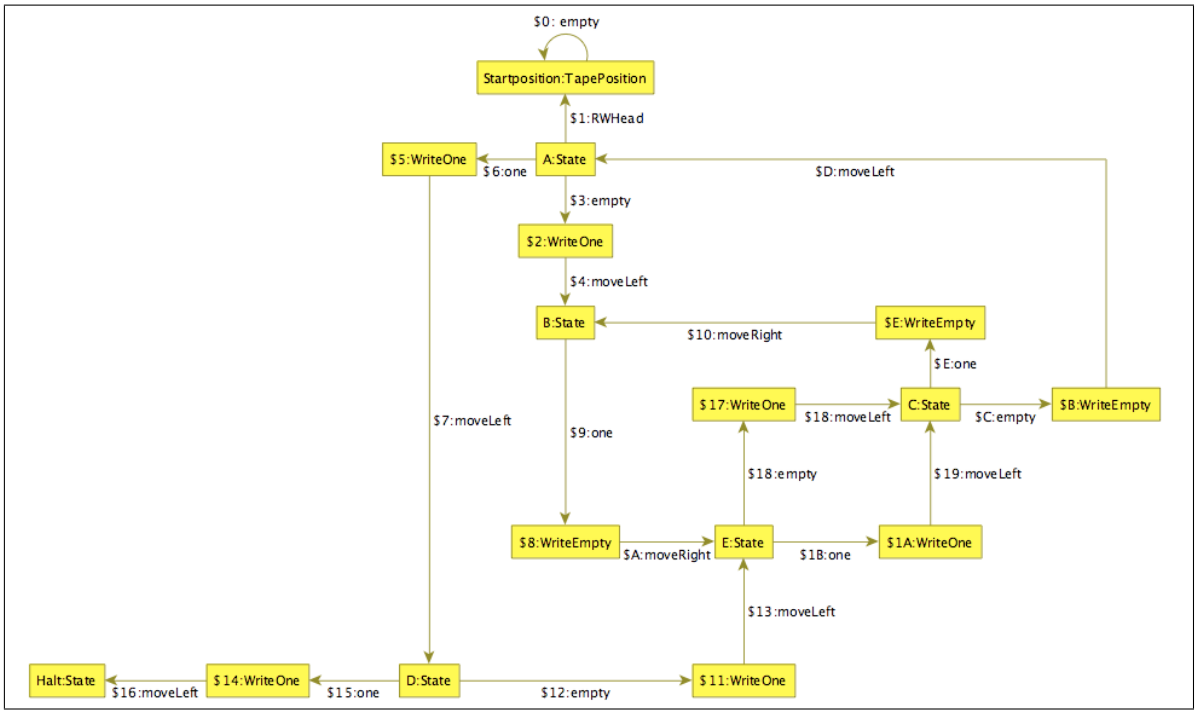
6.2.3 Rule Execution with GrShell

Finally we construct the busy beaver and let it work with GrShell. The following script starts with building the Turing machine that is modeling the 6 states with their transitions in our Turing machine model:

```
1  select backend "lgspBackend.dll"
2  new graph "../lib/lgsp-TuringModel.dll" "Busy␣Beaver"
3  select actions "../lib/lgsp-TuringActions.dll"
4
5  # Initialize tape
6  new tp:TapePosition($="Startposition")
7  new tp -:empty-> tp
8
9  # States
10 new sA:State($="A")
11 new sB:State($="B")
12 new sC:State($="C")
13 new sD:State($="D")
14 new sE:State($="E")
15 new sH:State($ = "Halt")
16
17 new sA -:RWHead-> tp
18
19 # Transitions: three lines per state and input symbol for
20 #   - updating cell value
21 #   - moving read-write-head
22 # respectively
23
24 new sA_0: WriteOne
25 new sA -:empty-> sA_0
26 new sA_0 -:moveLeft-> sB
27
28 new sA_1: WriteOne
29 new sA -:one-> sA_1
30 new sA_1 -:moveLeft-> sD
31
```

```
32 new sB_0: WriteOne
33 new sB -:empty-> sB_0
34 new sB_0 -:moveRight-> sC
35
36 new sB_1: WriteEmpty
37 new sB -:one-> sB_1
38 new sB_1 -:moveRight-> sE
39
40 new sC_0: WriteEmpty
41 new sC -:empty-> sC_0
42 new sC_0 -:moveLeft-> sA
43
44 new sC_1: WriteEmpty
45 new sC -:one-> sC_1
46 new sC_1 -:moveRight-> sB
47
48 new sD_0: WriteOne
49 new sD -:empty-> sD_0
50 new sD_0 -:moveLeft->sE
51
52 new sD_1: WriteOne
53 new sD -:one-> sD_1
54 new sD_1 -:moveLeft-> sH
55
56 new sE_0: WriteOne
57 new sE -:empty-> sE_0
58 new sE_0 -:moveRight-> sC
59
60 new sE_1: WriteOne
61 new sE -:one-> sE_1
62 new sE_1 -:moveLeft-> sC
```

Our busy beaver looks like this:

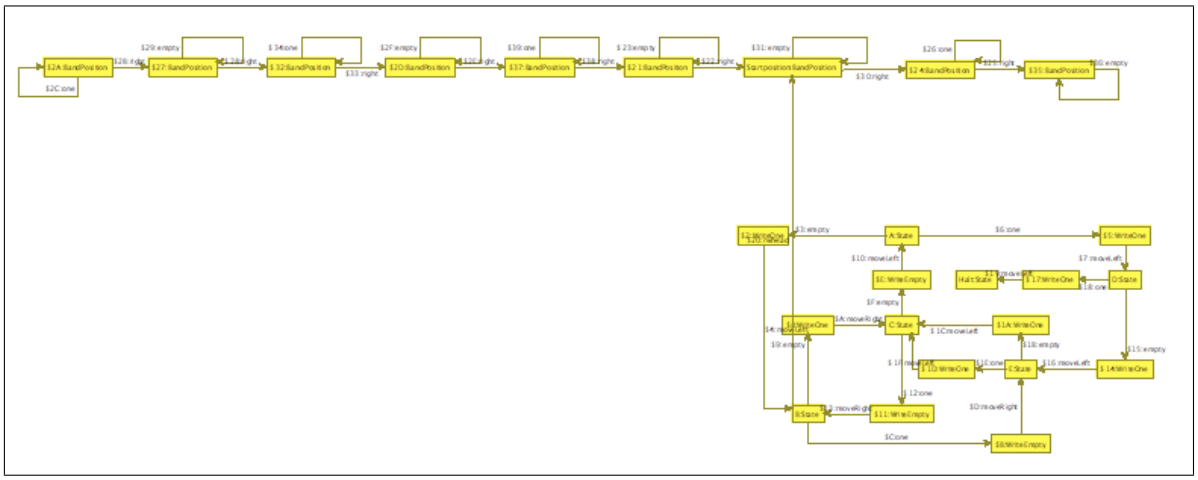


We have an initial host graph now. The graph rewrite sequence is quite straight forward and generic to the Turing graph model. Note that for each state the "*. . . Empty. . .* — *. . . One. . .*"

selection is unambiguous.

```
63  grs ((readOneRule | readEmptyRule) ; (writeOneRule | writeEmptyRule) ;
        (ensureMoveLeftValidRule | ensureMoveRightValidRule) ; (moveLeftRule |
        moveRightRule)){32}
```

We interrupt the machine after 32 iterations and look at the result so far:



In order to improve the performance we generate better search plans. This is a crucial step for execution time: With the initial search plans the beaver runs for 1 minute and 30 seconds. With improved search plans after the first 32 steps he takes about 8.5 seconds[1].

```
64 custom graph analyze_graph
65 custom actions gen_searchplan readOneRule readEmptyRule writeOneRule writeEmptyRule
       ensureMoveLeftValidRule ensureMoveRightValidRule moveLeftRule moveRightRule
```

Let the beaver run:

```
66  grs ((readOneRule | readEmptyRule) ; (writeOneRule | writeEmptyRule) ;
        (ensureMoveLeftValidRule | ensureMoveRightValidRule) ; (moveLeftRule |
        moveRightRule))*
```

[1] On a Pentium 4, 3.2Ghz, with 2GiB RAM.