
Chapter 1. EASY Meta-Programming with Rascal

Leveraging the Extract-Analyze-Synthesize Paradigm for Meta-Programming

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Rascal is a work in progress both regarding implementation and documentation. The current version of this document is a preview version only. Comments labelled "Warning" (like this one) or other *remarks* (like this one) are temporary notes that will disappear in the final version.

A New Language for Meta-Programming

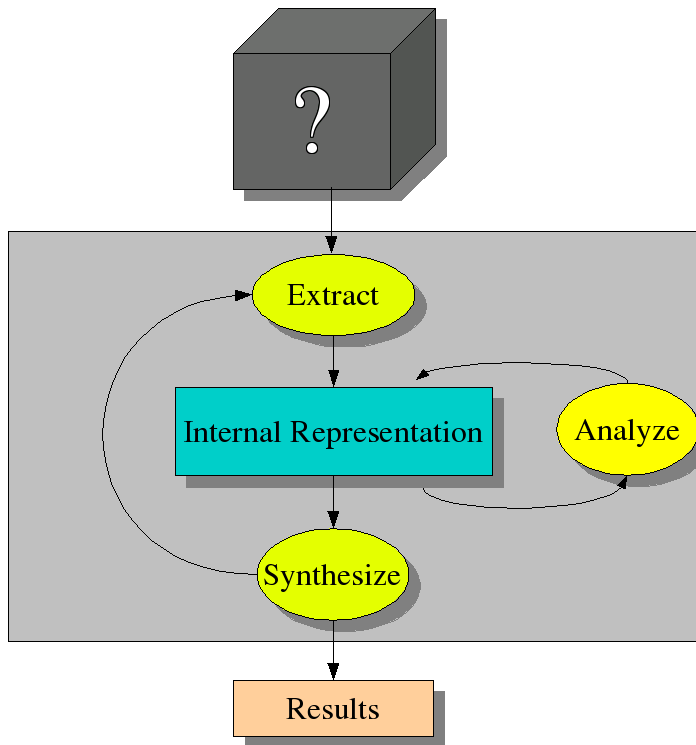
Meta-programs are programs that analyze, transform or generate other programs. Ordinary programs work on data; meta-programs work on programs. The range of programs to which meta-programming can be applied is large: from programs in standard languages like C and Java to domain-specific languages for describing high-level system models or applications in specialized areas like gaming or finance. In some cases, even test results or performance data are used as input for meta-programs.

Rascal is a new language for *meta-programming*, this is the activity of writing meta-programs.

The EASY Paradigm

Many meta-programming problems follow a fixed pattern. Starting with some input system (a black box that we usually call *system-of-interest*), first relevant information is extracted from it and stored in an internal representation. This internal representation is then analyzed and used to synthesize results. If the synthesis indicates this, these steps can be repeated over and over again. These steps are shown in Figure 1.1, “EASY: the Extract-Analyze-Synthesize Paradigm” (page 3).

Figure 1.1. EASY: the Extract-Analyze-Synthesize Paradigm



This is an abstract view on solving meta-programming problems, but is it uncommon? No, so let's illustrate it with a few examples.

Example 1.1. Finding security breaches

Alice is system administrator of a large online marketplace and she is looking for security breaches in her system. The objects-of-interest are the system's log files. First relevant entries are extracted. This will include, for instance, messages from the SecureShell demon that reports failed login attempts. From each entry login name and originating IP address are extracted and put in a table (the internal representation in this example). These data are analyzed by detecting duplicates and counting frequencies. Finally results are synthesized by listing the most frequently used login names and IP addresses.

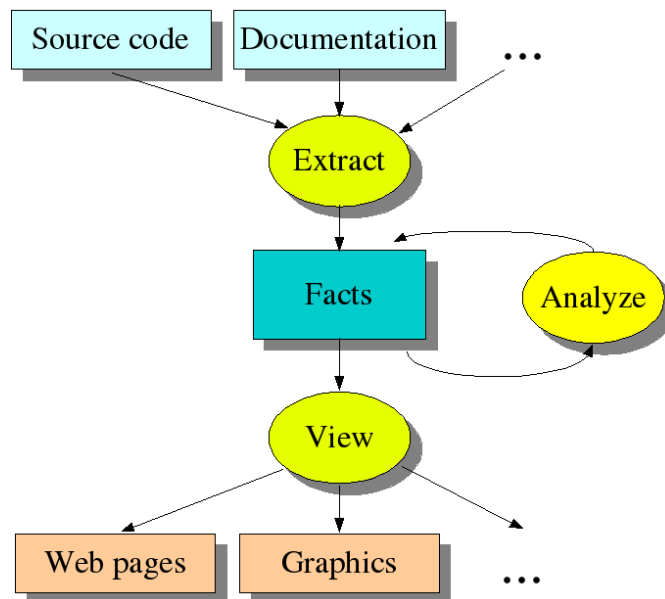
Example 1.2. A Forensic DSL compiler

Bernd is a senior software engineer working at the Berlin headquarters of a forensic investigation lab of the German government. His daily work is to find common patterns in files stored on digital media that have been confiscated during criminal investigations. Text, audio and video files are stored in zillions of different data formats and each data format requires its own analysis technique. For each new investigation ad hoc combinations of tools are used. This makes the process very labour-intensive and error-prone. Bernd convinces his manager that designing a new domain-specific language (DSL) for forensic investigations may relieve the pressure on their lab. After designing the DSL---let's call it DERRICK---he makes an EASY implementation for it. Given a DERRICK program for a specific case under investigation, he first extracts relevant information from it and analyzes it: which media formats are relevant? Which patterns to look for? How should search results be combined? Given this new information, Java code is synthesized that uses the various existing tools and combines their results.

Example 1.3. Renovating Financial Software

Charlotte is software engineer at a large financial institution in Paris and she is looking for options to connect an old and dusty software system to a web interface. She will need to analyze the sources of that system to understand how it can be changed to meet the new requirements. The objects-of-interest are in this case the source files, documentation, test scripts and any other available information. They have to be parsed in some way in order to extract relevant information, say the calls between various parts of the system. The call information can be represented as a binary relation between caller and callee (the internal representation in this example). This relation with 1-step calls is analyzed and further extended with 2-step calls, 3-step calls and so on. In this way call chains of arbitrary length become available. With this new information, we can synthesize results by determining the entry points of the software system, i.e., the points where calls from the outside world enter the system. Having completed this first cycle, Charlotte may be interested in which procedures can be called from the entry points and so on and so forth. Results will be typically represented as pictures that display the relationships that were found. In the case of source code analysis, a variation of our workflow scheme is quite common. It is then called the extract-analyze-view paradigm and is shown in Figure 1.2, “The extract-analyze-view paradigm” (page 4).

Figure 1.2. The extract-analyze-view paradigm



Example 1.4. Finding Concurrency Errors

Daniel is concurrency researcher at one of the largest hardware manufacturers worldwide. He is working from an office in the Bay Area. Concurrency is the big issue for his company: it is becoming harder and harder to make CPUs faster, therefore more and more of them are bundled on a single chip. Programming these multi-core chips is difficult and many programs that worked fine on a single CPU contain hard to detect concurrency errors due to subtle differences in the order of execution that results from executing the code on more than one CPU. Here is where Daniel enters the picture. He is working on tools for finding concurrency errors. First he extracts facts from the code that are relevant for concurrency problems and have to do with calls, threads, shared variables and locks. Next, he analyzes these facts and synthesizes an abstract model that captures the essentials of the concurrency behaviour of the program. Finally he runs a third-party verification tool with this model as input to do the actual verification.

Example 1.5. Model driven engineering

Elisabeth is a software architect at a large airplane manufacturer and her concern is reliability and dependability of airplane control software. She and her team have designed a UML model of the control software and have extended it with annotations that describe the reliability of individual components. She will use this annotated model in two ways: (a) to extract relevant information from it to synthesize input for a statistical tool that will compute overall system reliability from the reliability of individual components; (b) to generate executable code that takes the reliability issues into account.

Rascal

With these examples in mind, you have a pretty good picture how EASY applies in different use cases. All these cases involve a form of *meta-programming*: software programs (in a wide sense) are the objects-of-interest that are being analyzed, transformed or generated. The Rascal language you are about to learn is designed for meta-programming following the EASY paradigm. It can be applied in domains ranging from compiler construction and implementing domain-specific languages to constraint solving and software renovation.

Since representation of information is central to the approach, Rascal provides a rich set of built-in data types. To support extraction and analysis, parsing and advanced pattern matching are provided. High-level control structures make analysis and synthesis of complex datastructures simple.

Benefits of Rascal

Before you spend your time on studying the Rascal language it may help to first hear our elevator pitch about the main benefits offered by the language:

- **Familiar syntax** in a *what-you-see is-what-you-get* style is used even for sophisticated concepts and this makes the language easy to learn and easy to use.
- **Sophisticated built-in data types** provide standard solutions for many meta-programming problems.
- **Safety** is achieved by finding most errors before the program is executed and by making common errors like missing initializations or invalid pointers impossible. *At the time of writing, this checking is done during execution.*
- **Local type inference** makes local variable declarations redundant.
- **Pattern matching** can be used to analyze all complex datastructures.
- **Syntax definitions** make it possible to define new and existing languages and to write tools for them.

- **Visiting** makes it easy to traverse datastructures and to extract information from them or to synthesize results.
- **Templates** enable easy code generation.
- **Functions as values** permit programming styles with high re-use.
- **Generic types** allow writing functions that are applicable for many different types.
- **Eclipse integration** makes Rascal programming a breeze. All familiar tools are at your fingertips.

Interested? Read on!

Aim and Scope of this Book

Aim. The aim of this book is to give an easy to understand but comprehensive overview of the Rascal language and to offer problem solving strategies to handle realistic problems that require meta-programming. Problems may range from security analysis and model extraction to software renovation, domain-specific languages and code generation.

Audience. The book is intended for students, practitioners and researchers who want to solve meta-programming problems.

Background. Readers should have some background in computer science, software engineering or programming languages. Familiarity with several main stream programming languages and experience with larger software projects will make it easier to appreciate the relevance of the meta-programming domain that Rascal is addressing. Some familiarity with concepts like sets, relations and pattern matching is assumed.

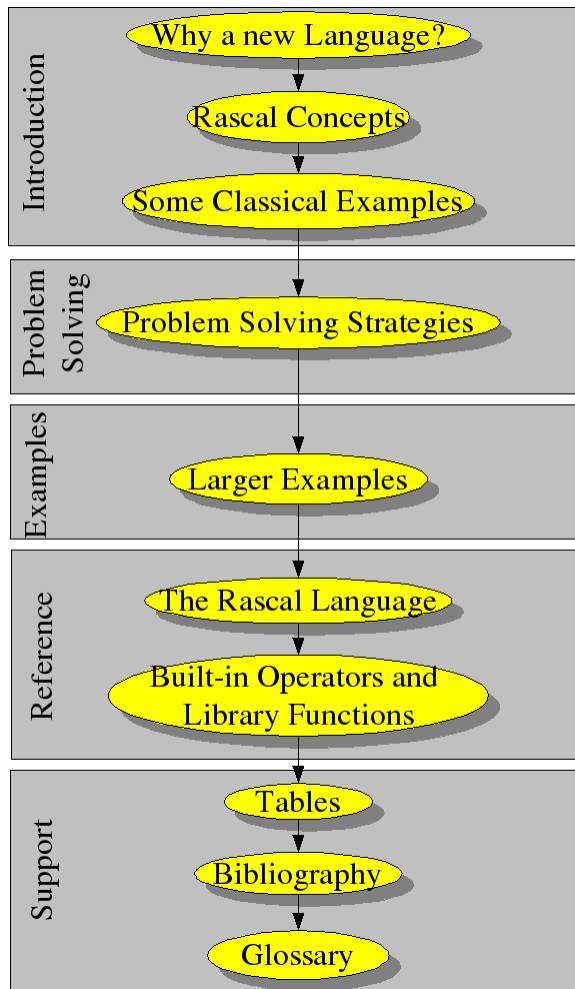
Scope. The scope of the book is limited to the Rascal language and its applications but does not address implementation aspects of the language.

Installing and Running Rascal

See <http://www.meta-environment.org/Meta-Environment/Rascal> for information.

Reading Guide

Figure 1.3. Structure of this Book



The structure of this book is shown in Figure 1.3, “Structure of this Book” (page 7) It consists of five parts:

- **Introduction:** gives a high-level overview of Rascal and consists of the section called “A New Language for Meta-Programming” (page 2) and the section called “Rascal Concepts” (page 9). It also presents some simple examples in the section called “Some Classical Examples” (page 16).
- **Problem Solving:** describes the major problem solving strategies in Rascal's application domain, see the section called “Problem Solving Strategies” (page 24).
- **Examples:** gives a collection of larger examples, see the section called “Larger Examples” (page 31).
- **Reference:** gives a detailed description of the Rascal language, see the section called “The Rascal Language” (page 50) and all built-in operators and library functions, see the section called “Built-in Operators and Library Functions” (page 90).
- **Support:** gives tables with operators, see Table 1.44, “All Operators” (page 122) and library functions, see Table 1.45, “All Functions” (page 124) a bibliography, see the section called “Bibliography” (page 127) and a glossary, see Glossary of Terminology (page 128) that explains many concepts that are used in this book and tries to make the book self-contained.

Typographic Conventions

Rascal code fragments are always shown as a listing like this:

```
.. here is some Rascal code ...
```

Interactive sessions are shown as a screen like this:

```
rascal> Command;  
Type: Value
```

where:

- `rascal>` is the prompt of the Rascal system.
- **Command** is an arbitrary Rascal statement or declaration typed in by the user.
- `Type: Value` is the type of the answer followed by the value of the answer as computed by Rascal. In some cases, the response will simply be `ok` when there is no other meaningful answer to give.



For typographic reasons the output is abbreviated or slightly edited in some examples.

Rascal Concepts

Before explaining the Rascal language in more detail, we detail our elevator pitch a bit and give you a general understanding of the concepts on which the language is based.

Values

Values are the basic building blocks of a language and the type of values determines how they may be used.

Rascal is a value-oriented language. This means that values are immutable and are always freshly constructed from existing parts and that sharing and aliasing problems are completely avoided. The language also provides variables. A value can be associated with a variable as the result of an explicit assignment statement: during the lifetime of a variable different (immutable) values may be assignment to it. Other ways to associate a value with a variable is by way of function calls (binding of formal parameters to actual values) and as the result of a successful pattern match.

Data structures

Rascal provides a rich set of datatypes. From Booleans (bool), infinite precision integers (int) and reals (real) to strings (str) that can act as templates with embedded expressions and statements. From source code locations (loc) based on an extension of Universal Resource Identifiers (URI) that allow precise description of text areas in local and remote files to lists (list), optionally labelled tuples (tuple), sets (set), and optionally labelled maps (map) and relations (rel). From untyped tree structures (node) to fully typed datastructures. Syntax trees that are the result of parsing source files are represented as datatypes (Tree). There is a wealth of built-in operators and library functions available on the standard datatypes. The basic Rascal datatypes are illustrated in Table 1.1, “Basic Rascal Types” (page 9).

These builtin datatypes are closely related to each other:

- In a list all elements have the same static type and the order of elements matters. A list may contain the same value more than once.
- In a set all elements have the same static type and the order of elements does not matter. A set contains an element only once. In other words, duplicate elements are eliminated and no matter how many times an element is added to a set, it will occur in it only once.
- In a tuple all elements (may) have a different static type. Each element of a tuple may have a label that can be used to select that element of the tuple.
- A relation is a set of tuples which all have the same static tuple type.
- A map is an associative table of (key, value) pairs. Key and value (may) have different static type and a key can only be associated with a value once

Untyped trees can be constructed with the builtin type **node**. User-defined algebraic datatypes allow the introduction of problem-specific types and are a subtype of **node**. A fragment of the abstract syntax for statements (assignment, if, while) in a programming language would look as follows:

```
data STAT = asgStat(Id name, EXP exp)
           | ifStat(EXP exp, list[STAT] thenpart,
                   list[STAT] elsepart)
           | whileStat(EXP exp, list[STAT] body)
           ;
```

Table 1.1. Basic Rascal Types

Type	Examples
bool	true, false

Type	Examples
int	1, 0, -1, 123456789
real	1.0, 1.0232e20, -25.5
str	"abc", "first\nnext", "result: <X>"
loc	file:///etc/passwd
tuple[T_1, \dots, T_n]	<1,2>, <"john", 43, true>
list[T]	[], [1], [1,2,3], [true, 2, "abc"]
set[T]	{}, {1,2,3,5,7}, {"john", 4.0}
rel[T_1, \dots, T_n]	{<1,2>, <2,3>, <1,3>}, {<1,10,100>, <2,20,200>}
map[T, U]	(), (1:true, 2:false), ("a":1, "b":2)
node	f(), add(x,y), g("abc", [2,3,4])

Pattern Matching

Pattern matching determines whether a given pattern matches a given value. The outcome can be false (no match) or true (a match). A pattern match that succeeds may bind values to variables.

Pattern matching is *the* mechanism for case distinction (switch statement) and search (visit statement) in Rascal. Patterns can also be used in an explicit match operator `:=` and can then be part of larger boolean expressions. Since a pattern match may have more than one solution, local backtracking over the alternatives of a match is provided. Patterns can also be used in enumerators and control structures like `for` and `while` statement.

A very rich pattern language is provided that includes string matching based on regular expressions, matching of abstract patterns, and matching of concrete syntax patterns. Some of the features that are provided are list (associative) matching, set (associative, commutative, idempotent) matching, and deep matching of descendant patterns. All these forms of matching can be used in a single pattern and can be nested. Patterns may contain variables that are bound when the match is successful. Anonymous (don't care) positions are indicated by the underscore (`_`).

Here is a *regular expression* that matches a line of text, finds the first alphanumeric word in it, and extracts the word itself as well as the before and after it (`\W` matches all non-word characters; `\w` matches all word characters):

```
/^<before:\W*><word:\w+><after:.*$>/
```

Regular expressions follow the Java regular expression syntax with one exception: instead of using numbered groups to refer to parts of the subject string that have been matched by a part of the regular expression we use the notation:

```
<Name:RegularExpression>
```

If *RegularExpression* matches, the matched substring is assigned to string variable *Name*.

The following *abstract pattern* matches the abstract syntax of a while statement defined earlier:

```
whileStat(EXP Exp, list[STAT] Stats)
```

Variables in a pattern are either explicitly declared in the pattern itself---as done in the example---or they may be declared in the context in which the pattern occurs. So-called *multi-variables* in list and set patterns are declared by a `*` suffix: `X*` is thus an abbreviation for `list[...] X` or `set[...] X`, where the precise element type depends on the context. The above pattern can then be written as

```
whileStat(EXP Exp, Stats*)
```

or, if you are not interested in the actual value of the statements as

```
whileStat(EXP Exp, _*)
```

When there is a grammar for this example language (in the form of an imported SDF definition), we can also write *concrete patterns* as we will see below.

Enumerators

Enumerators enumerate the values in a given (finite) domain, be it the elements in a list, the substrings of a string, or all the nodes in a tree. Each value that is enumerated is first matched against a pattern before it can possibly contribute to the result of the enumerator. Examples are:

```
int x <- { 1, 3, 5, 7, 11 }  
int x <- [ 1 .. 10 ]  
/asgStat(Id name, _) <- P
```

The first two produce the integer elements of a set of integers, respectively, a range of integers. Observe that the left-hand side of an enumerator is a pattern, of which `int x` is a specific instance. The use of more general patterns is illustrated by the third enumerator that does a deep traversal (as denoted by the descendant operator `/`) of the complete program `P` (that is assumed to have a `PROGRAM` as value) and only yields statements that match the assignment pattern (`asgStat`) we have seen earlier. Note the use of an anonymous variable at the `EXP` position in the pattern.

Comprehensions

Comprehensions are a notation inspired by mathematical set-builder notation that helps to write succinct definitions of lists and sets. They are also inspired by queries as found in a language like SQL.

Rascal generalizes comprehensions in various ways. Comprehensions exist for lists, sets and maps. A comprehension consists of an expression that determines the successive elements to be included in the result and a list of enumerators and tests (boolean expressions). The enumerators produce values and the tests filter them. A standard example is

```
{ x * x | int x <- [1 .. 10], x % 3 == 0 }
```

which returns the set {9, 36, 81}, i.e., the squares of the integers in the range [1 .. 10] that are divisible by 3. A more intriguing example is

```
{name | /asgStat(Id name, _) <- P}
```

which traverses program `P` and constructs a set of all identifiers that occur on the left hand side of assignment statements in `P`.

Control structures

Control structures like `if` and `while` statement are driven by Boolean expressions, for instance

```
if(N <= 0)  
    return 1;  
else  
    return N * fac(N - 1);
```

Actually, combinations of generators and Boolean expressions can be used to drive the control structures. For instance,

```
for(/asgStat(Id name, _) <- P, size(name) > 10){  
    println(name);  
}
```

prints all identifiers in assignment statements (`asgStat`) that consist of more than 10 characters.

Case Distinction

The switch statement as known from C and Java is generalized: the subject value to switch on may be an arbitrary value and the cases are arbitrary patterns followed by a statement. Each case is comparable to a *transaction*: when the pattern succeeds and the following statement is executed successfully, all changes to variables made by the statement are *committed* and thus become permanent. The variables bound by the pattern are always local to the statement associated with the case. When a match fails or when the associated statement fails, a *rollback* takes place and all side-effects are undone. External side-effects like I/O and side-effects in user-defined Java code are not undone. Here is an example where we take a program `P` and distinguish two cases for while and if statement:

```
switch (P){
case whileStat(_, _):
    println("A while statement");
case ifStat(_, _, _):
    println("An if statement");
}
```

Visiting

Visiting the elements of a datastructure is one of the most common operations in our domain and the visitor design pattern is a solution known to every software engineer. Given a tree-like datastructure we want to perform an operation on some (or all) nodes of the tree. The purpose of the visitor design pattern is to decouple the logistics of visiting each node from the actual operation on each node. In Rascal the logistics of visiting is completely automated.

Visiting is achieved by way of visit expressions that resemble the switch statement. A visit expressions traverses an arbitrarily complex subject value and applies a number of cases to all its subtrees. All the elements of the subject are visited and when one of the cases matches the statements associated with that case are executed. These cases may:

- cause some side effect, i.e., assign a value to local or global variables;
- execute an `insert` statement that replaces the current element;
- execute a `fail` statement that causes the match for the current case to fail (and undoing all side-effects due to the successful match itself and the execution of the statements so far).

The value of a visit expression is the original subject value with all replacements made as dictated by matching cases. The traversal order in a visit expressions can be explicitly defined by the programmer. An example of visiting is given below and in the section called “Colored Trees” (page 17).

Functions

Functions allow the definition of frequently used operations. They have a name and formal parameters. They are explicitly declared and are fully typed. Here is an example of a function that counts the number of assignment statements in a program:

```
int countAssignments(PROGRAM P){
    int n = 0;
    visit (P){
        case asgStat(_, _):
            n += 1;
    }
    return n;
}
```

Functions can also be used as values thus enabling higher-order functions. Consider the following declarations:

```
int double(int x) { return 2 * x; }

int triple(int x) { return 3 * x; }

int f(int x, int (int) multi){ return multi(x); }
```

The functions `double` and `triple` simply multiply their argument with a constant. Function `f` is, however, more interesting. It takes an integer `x` and a function `multi` (with integer argument and integer result) as argument and applies `multi` to its own argument. `f(5, triple)` will hence return 15. Function values can also be created anonymously as illustrated by the following, alternative, manner of writing this same call to `f`:

```
f(5, int (int y){return 3 * y;});
```

Here the second argument of `f` is an anonymous function.

Rascal is a higher-order language in which functions are first-class values.

Syntax Definition and Parsing

All source code analysis projects need to extract information directly from the source code. There are two main approaches to this:

- *Lexical information*: Use regular expressions to extract useful, but somewhat superficial, flat, information. This can be achieved using regular expression patterns.
- *Structured information*: Use syntax analysis to extract the complete, nested, structure of the source code in the form of a syntax tree.

In Rascal, we reuse the Syntax Definition Formalism (SDF) and its tooling. See <http://www.meta-environment.org/Meta-Environment/Documentation> for tutorials and manuals for SDF.

SDF modules define grammars and these modules can be imported in a Rascal module. These grammar rules can be applied in writing concrete patterns to match parts of parsed source code. Here is an example of the same pattern we saw above, but now in concrete form:

```
while <Exp> do <Stats> od
```

Importing an SDF module has the following effects:

- All non-terminals (*sorts* in SDF jargon) that are used in the imported grammar are implicitly declared as Rascal types. For each SDF sort `S` also composite symbols like `S*`, `{S " , " }+` also become available as type. This makes it possible to handle parse trees and parse tree fragments as fully typed values and assign them to variables, store them in larger datastructures or pass them as arguments to functions and use them in pattern matching.
- For all *start symbols* of the grammar *parse functions* are implicitly declared that can parse source files according to a specific start symbol.
- Concrete syntax patterns for that specific grammar can be used.
- Concrete syntax constructors can be used that allow the construction of new parse trees.

The following example parses a Java compilation unit from a text file and counts the number of method declarations:

```
module Count
import languages::java::syntax::Java;
```

```
import ParseTree;

public int countMethods(loc file){
    int n = 0;
    for(/MethodDeclaration md <- parse(#CompilationUnit, file))
        n += 1;
    return n;
}
```

First observe that importing the Java grammar has as effect that non-terminals like `MethodDeclaration` and `CompilationUnit` become available as type in the Rascal program.

The implicitly declared function `parse` takes a reified type (`#CompilationUnit`) and a location as arguments and parses the contents of the location according to the given non-terminal. Next, a match for embedded `MethodDeclarations` is done in the enumerator of the `for` statement. This example ignores many potential error conditions but does illustrate some of Rascal's syntax and parsing features.

Rewrite Rules

A *rewrite rule* is a recipe on how to simplify values. Remember: $(a + b)^2 = a^2 + 2ab + b^2$? A rewrite rule has a pattern as left-hand side (here: $(a + b)^2$) and a replacement as right-hand side (here: $a^2 + 2ab + b^2$). Given a value and a set of rewrite rules the patterns are tried on every subpart of the value and replacements are made if a match is successful. This is repeated as long as some pattern matches.

Rewrite rules are the only implicit control mechanism in the language and are used to maintain invariants during computations. For example, in a package for symbolic differentiation it is desirable to keep expressions in simplified form in order to avoid intermediate results like `sum(product(num(1), x), product(num(0), y))` that can be simplified to `x`. The following rules achieve this:

```
rule simplify1 product(num(1), Expression e) => e;
rule simplify2 product(Expression e, num(1)) => e;
rule simplify3 product(num(0), Expression e) => num(0);
rule simplify4 product(Expression e, num(0)) => num(0);
rule simplify5 sum(num(0), Expression e)      => e;
rule simplify6 sum(Expression e, num(0))      => e;
```

Whenever a new expression is constructed during symbolic differentiation, these rules are *implicitly* applied to that expression and all its subexpressions and when a pattern at the left-hand side of a rule applies the matching subexpression is replaced by the right-hand side of the rule. This is repeated as long as any rule can be applied.

Since rewrite rules are activated automatically, one may always assume that expressions are in simplified form.

Rewrite rules are *Turing complete*, in other words any computable function can be defined using rewrite rules, including functions that do not terminate. This is a point of attention when using rewrite rules.

Equation Solving

Many problems can be solved by forms of *constraint solving*. This is a declarative way of programming: specify the constraints that a problem solution should satisfy and how potential solutions can be generated. The actual solution (if any) is found by enumerating solutions and testing their compliance with the constraints.

Rascal provides a `solve` statement that helps writing constraint solvers. A typical example is dataflow analysis where the propagation of values through a program can be described by a set of equations.

Their solution can be found with the `solve` statement. See the section called “Dataflow Analysis” (page 39) for examples.

Other features

All language features (including the ones just mentioned) are described in more detail later on in this book. Some features we have not yet mentioned are:

- Rascal programs consist of modules that are organized in packages.
- Modules can import other modules.
- The visibility of entities declared in modules can be controlled using public/private modifiers.
- Datastructures may have annotations that can be explicitly used and modified.
- There is an extensive library for builtin datatypes, input/output, fact extraction from Java source code, visualization, and more.

Typechecking and Execution

Rascal has a statically checked type system that prevents type errors and uninitialized variables at runtime. There are no runtime type casts as in Java and there are therefore less opportunities for run-time errors. The language provides *higher-order*, *parametric polymorphism*. A type aliasing mechanism allows documenting specific uses of a type. Built-in operators are heavily overloaded. For instance, the operator `+` is used for addition on integers and reals but also for list concatenation, set union etc.

The flow of Rascal program execution is completely explicit. Boolean expressions determine choices that drive the control structures. Rewrite rules form the only exception to the explicit control flow principle. Only local backtracking is provided in the context of boolean expressions and pattern matching; side effects are undone in case of backtracking.

Some Classical Examples

The following simple examples will help you to grasp the main features of Rascal quickly. You can also look ahead and consult the section called “The Rascal Language”(page 50)for details of the language or the section called “Built-in Operators and Library Functions”(page 90)for specific operators or functions.

Hello

The ubiquitous hello world program looks in Rascal as follows:

```
rascal> import IO;
ok

rascal> println("Hello world, this is my first Rascal program");
Hello world, this is my first Rascal program
ok
```

First, the library module IO (see the section called “IO” (page 94) is imported since hello world requires printing. Next, we call `println` and proudly observe our first Rascal output!

A slightly more audacious approach is to wrap the print statement in a function and call it:

```
rascal> void hello() {
    println("Hello world, this is my first Rascal program");
}
void (): void hello();

rascal> hello();
Hello world, this is my first Rascal program
ok
```

Don't get scared by the `void (): void hello();` that you get back when typing in the `hello` function. The first `void ()` part says the result is a function that returns nothing, and the second part `void hello()` summarizes its value (or would you prefer a hex dump?).

The summit of hello-engineering can be reached by placing all the above in a separate module:

```
module demo::Hello
import IO;

public void hello() {
    println("Hello world, this is my first Rascal program");
}
```

Note that we added a public modifier to the definition of `hello`, since we want it to be visible outside the `Hello` module. Using this `Hello` module is now simple:

```
rascal> import demo::Hello;
ok

rascal> hello();
Hello world, this is my first Rascal program
ok
```



All examples in this book can be found in the `demo` directory of the Rascal distribution. That is why we must prefix all names of examples modules with `demo::`.

Factorial

Here is another classical example, computing the factorial function:

```
module demo::Factorial

public int fac(int N)
{
    if(N <= 0)
        return 1;
    else
        return N * fac(N - 1);
}
```

It uses a conditional statement to distinguish cases and here is how to use it:

```
rascal> import demo::Factorial;
ok

rascal> fac(47);
int: 258623241511168180642964355153611979969197632389120000000000
```

Indeed, Rascal has arbitrary length integers.

Colored Trees

Suppose we have binary trees---trees with exactly two children--that have integers as their leaves. Also suppose that our trees can have red and black nodes. Such trees can be defined as follows:

```
module demo::ColoredTrees

data ColoredTree =
    leaf(int N)
  | red(ColoredTree left, ColoredTree right)
  | black(ColoredTree left, ColoredTree right);
```

We can use them as follows:

```
rascal> import demo::ColoredTrees;
ok

rascal> rb = red(black(leaf(1), red(leaf(2),leaf(3))),
                black(leaf(3), leaf(4)));
ColoredTree: red(black(leaf(1),red(leaf(2),leaf(3))),
                black(leaf(3),leaf(4)))
```

Observe that the type of variable `rb` was automatically inferred to be `ColoredTree`.

We define two operations on `ColoredTrees`, one to count the red nodes, and one to sum the values contained in all leaves:

```
// continuing module demo::ColoredTrees

public int cntRed(ColoredTree t){
    int c = 0;
    visit(t) {
        case red(_,_): c = c + 1;❶
    };
    return c;
```

```

}

public int addLeaves(ColoredTree t){
    int c = 0;
    visit(t) {
        case leaf(int N): c = c + N;❷
    };
    return c;
}

```

- ❶ Visit all the nodes of the tree and increment the counter `c` for each red node.
- ❷ Visit all nodes of the tree and add the integers in the leaf nodes.

This can be used as follows:

```

rascal> cntRed(rb);
int: 2
rascal> addLeaves(rb);
int: 13

```

A final touch to this example is to introduce green nodes and to replace all red nodes by green ones:

```

// continuing module demo::ColoredTrees

data ColoredTree = green(ColoredTree left,
                        ColoredTree right);❶

public ColoredTree makeGreen(ColoredTree t){
    return visit(t) {
        case red(l, r) => green(l, r)    ❷
    };
}

```

- ❶ Extend the `ColoredTree` datatype with a new green constructor.
- ❷ Visit all nodes in the tree and replace red nodes by green ones. Note that the variables `l` and `r` are introduced here without a declaration.

This is used as follows:

```

rascal> makeGreen(rb);
ColoredTree: green(black(leaf(1),green(leaf(2),leaf(3))),
                  black(leaf(3),leaf(4)))

```

Word Replacement

Suppose you are in the publishing business and are responsible for the systematic layout of publications. Authors do not systematically capitalize words in titles---"Word replacement" instead of "Word Replacement"--- and you want to correct this. Here is one way to solve this problem:

```

module demo::WordReplacement
import String;

public str capitalize(str word)
{
    if(/^<letter:[a-z]><rest:.*$/ := word) ❶
        return toUpperCase(letter) + rest;❷
    else
        return word;❸
}

```

- ❶ The function `capitalize` takes a string as input and capitalizes its first character if that is a letter. This is done using a regular expression match that anchors the match at the beginning (^), expects a single letter and assigns it to the variable `letter` (`letter:[a-z]`) followed by an arbitrary sequence of letters until the end of the string that is assigned to the variable `rest` (`<rest:.*$>`).
- ❷ If the regular expression matches we return a new string with the first letter capitalized.
- ❸ Otherwise we return the word unmodified.

The next challenge is how to capitalize all the words in a string. Here are two solutions:

```
// continuing module demo::WordReplacement

public str capAll1(str S)
{
    result = "";
    while (/^<before:\W*><word:\w*><after:.*$>/ := S) { ❶
        result += before + capitalize(word);
        S = after;
    }
    return result;
}

public str capAll2(str S)
{
    return visit(S){❷
        case /<word:\w*>/i ❸ => capitalize(word)❹
    };
}
```

- ❶ In the first solution `capAll1` we just loop over all the words in the string and capitalize each word. The variable `result` is used to collect the successive capitalized words. Here we use `\W` to denote non-word characters and `\w` for word characters.
- ❷ In the second solution we use a visit expression to visit all the substrings of `S`. Each matching case advances the substring by the length of the pattern it matches and replaces that pattern by another string. If no case matches the next substring is tried.
- ❸ The single case matches a word (note that `\w` matches a word character).
- ❹ When the case matches a word, it is replaced by a capitalized version. The modifier `i` at the end of the regular expressions denotes case-insensitive matching.

We can apply this all as follows:

```
rascal> import demo::WordReplacement;
ok

rascal> capitalize("rascal");
str: "rascal"

rascal> capAll1("rascal is great");
str: "Rascal Is Great"
```

Template Programming

Many websites and code generators use template-based code generation. They start from a text template that contains embedded variables and code. The template is "executed" by replacing the embedded variables and code by their string value. A language like PHP is popular for this feature. Let's see how we can do this in Rascal. Given a mapping from field names to their type, the task at hand is to generate a Java class that contains those fields and corresponding getters and setters. Given a mapping

```
public map[str, str] fields = (
```

```
"name" : "String",  
"age" : "Integer",  
"address" : "String"  
);
```

we expect the call

```
genClass("Person", fields)
```

to produce the following output:

```
public class Person {  
  
    private Integer age;  
    public void setAge(Integer age) {  
        this.age = age;  
    }  
    public Integer getAge() {  
        return age;  
    }  
  
    private String name;  
    public void setName(String name) {  
        this.name = name;  
    }  
    public String getName() {  
        return name;  
    }  
  
    private String address;  
    public void setAddress(String address) {  
        this.address = address;  
    }  
    public String getAddress() {  
        return address;  
    }  
  
}
```

This is achieved by the following definition of `genClass`:

```
module demo::StringTemplate  
  
import String;  
  
public str capitalize(str s) {  
    return toUpperCase(substring(s, 0, 1)) + substring(s, 1);  
}  
  
public str genClass(str name, map[str,str] fields) {  
    return "  
    public class <name> {  
        <for (x <- fields)> {  
            str t = fields[x];  
            str n = capitalize(x);>  
            private <t> <x>;  
            public void set<n>(<t> <x>) {  
                this.<x> = <x>;  
            }  
        }  
    }"
```

```

        public <t> get<n>() {
            return <x>;
        }
    <>>
}
";
}

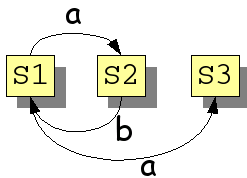
```

Observe how the for statement and expressions that access the map fields that are embedded in the string constant customize the given template for a Java class. The details of string interpolation are explained in the section called “String” (page 51).

A Domain-Specific Language for Finite State Machines

Finite State Machines (FSMs) are a universal device in Computer Science and are used to model problems ranging from lexical tokens to concurrent processes. An FSM consists of named states and labeled transitions between states. An example is shown in Figure 1.4, “Example of a Finite State Machine” (page 21). This example was suggested by Goerel Hedin at GTTSE09.

Figure 1.4. Example of a Finite State Machine



This same information can be represented in textual form as follows:

```

finite-state machine
  state S1;
  state S2;
  state S3;
  trans a: S1 -> S2;
  trans b: S2 -> S1;
  trans a: S1 -> S3

```

and here is where the idea is born to design a Domain-Specific Language for finite state machines (aptly called FSM). This always proceeds in three steps:

1. **Do domain analysis.** Explore the domain and make an inventory of the relevant concepts and their interactions.
2. **Define syntax.** Design a textual syntax to represent these concepts and interactions.
3. **Define operations.** Define operations on DSL programs. This maybe, for example, be typechecking, validation, or execution.

We will now apply these steps to the FSM domain.

Do domain analysis. We assume that the FSM domain is sufficiently known. The concepts are states and labeled transitions.

Define syntax. We define a textual syntax for FSMs. This syntax is written in the Syntax Definition Formalism SDF. See <http://www.meta-environment.org/Meta-Environment/Documentation> for tutorials and manuals for SDF. The syntax definition looks as follows:

```

module demo/StateMachine/Syntax

```

```

imports basic/Whitespace
imports basic/IdentifierCon

exports
  context-free start-symbols
    FSM

  sorts FSM Decl Trans State IdCon

  context-free syntax
    "state" IdCon          -> State
    "trans" IdCon ":" IdCon "->" IdCon -> Trans
    State                  -> Decl
    Trans                  -> Decl
    "finite-state" "machine" {Decl ";" }+ -> FSM

```

Two standard modules for whitespace and identifiers are imported and next a fairly standard grammar for state machines is defined. Observe that in SDF rules are written in reverse order as compared to standard BNF notation.

Define Operations. There are various operations one could define on a FSM: executing it for given input tokens, reducing a non-deterministic automaton to a deterministic one, and so on. Here we select a reachability check on FSMs as example.

We start with the usual imports and define a function `getTransitions` that extracts all transitions from an FSM:

```

module demo::StateMachine::CanReach

import demo::StateMachine::Syntax;
import Relation;
import Map;
import IO;

// Extract from a give FSM all transitions as a relation

public rel[str, str] getTransitions(FSM fsm){
  return { "<from>", "<to>" |
    /\`trans <IdCon a>: <IdCon from> -> <IdCon to>` <- fsm };
}

```

The function `getTransitions` illustrates several issues. Given a concrete fsm, a deep pattern match (/) is done searching for `trans` constructs. For each match three identifiers (`IdCon`) are extracted from it and assigned to the variables `a`, `from`, respectively, `to`. Next `from` and `to` are converted to a string (using the string interpolations "`<from>`" and "`<to>`") and finally they are placed in a tuple in the resulting relation. The net effect is that transitions encoded in the syntax tree of `fsm` are collected in a relation for further processing.

Next, we compute all reachable states in the function `canReach`:

```

// continuing module demo::StateMachine::CanReach

public map[str, set[str]] canReach(FSM fsm){
  transitions = getTransitions(fsm);
  return ( s: (transitions+)[s] | str s <- carrier(transitions) );
}

```

Here `str s <- carrier(transitions)` enumerates all elements that occur in the relations that is extracted from `fsm`. A map comprehension is used to construct a map from each state to all

states that can be reached it. Here `transitions+` is the transitive closure of the transition relation and `(transitions+)[s]` gives the image of that closure for a given state; in other words all states that can be reached from it.

Finally, we declare an example FSM (observe that it uses FSM syntax in Rascal code!):

```
// continuing module demo::StateMachine::CanReach

public FSM example =
    finite-state machine
        state S1;
        state S2;
        state S3;
        trans a: S1 -> S2;
        trans b: S2 -> S1;
        trans a: S1 -> S3;
```

Testing the above functions gives the following results:

```
rascal> import demo::StateMachine::CanReach;
ok

rascal> getTransitions(example);

rel[str,str]: {<"S1", "S2">, <"S2", "S1">, <"S1", "S3">}
rascal> canReach(example);

map[str: set[str]: ("S1" : {"S1", "S2", "S3"},
                        "S2" : {"S1", "S2", "S3"},
                        "S3" : {})]
```

Problem Solving Strategies

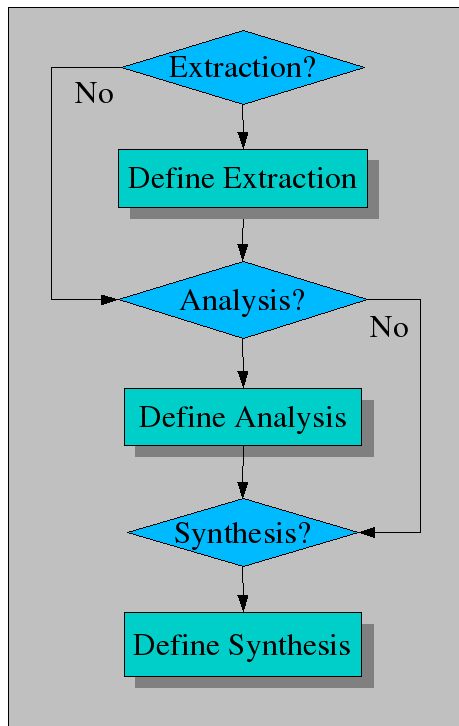
Before we study more complicated examples, it is useful to discuss some general problem solving strategies that are relevant in Rascal's application domain.

To appreciate these general strategies, it is good to keep some specific problem areas in mind:

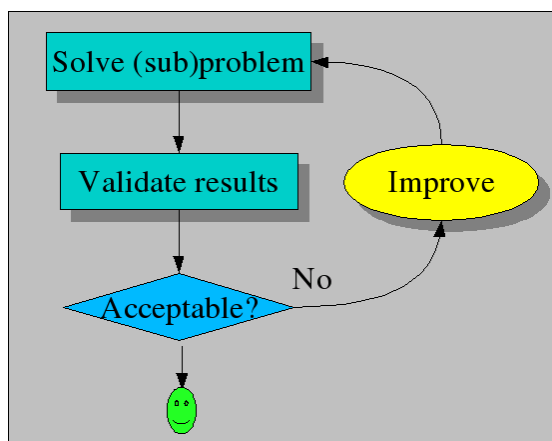
- **Documentation generation:** extract facts from source code and use them to generate textual documentation. A typical example is generating web-based documentation for legacy languages like Cobol and PL/I.
- **Metrics calculation:** extract facts from source code (and possibly other sources like test runs) and use them to calculate code metrics. Examples are cohesion and coupling of modules and test coverage.
- **Model extraction:** extract facts from source code and use them to build an abstract model of the source code. An example is extracting lock and unlock calls from source code and to build an automaton that guarantees that lock/unlock occurs in pairs along every control flow path.
- **Model-based code generation:** given a high-level model of a software system, described in UML or some other modelling language, transform this model into executable code. UML-to-Java code generation falls in this category.
- **Source-to-source transformation:** large-scale, fully automated, source code transformation with certain objectives like removing deprecated language features, upgrading to newer APIs and the like.
- **Interactive refactoring:** given known "code smells" a user can interactively indicate how these smells should be removed. The refactoring features in Eclipse and Visual Studio are examples.

With these examples in mind, we can study the overall problem solving workflow as shown in Figure 1.5, "General 3-Phased Problem Solving Workflow"(page 25) It consists of three optional phases:

- Is **extraction needed** to solve the problem, then define the extraction phase, see the section called "Defining Extraction" (page 26).
- Is **analysis needed**, then define the analysis phase, see the section called "Defining Analysis" (page 28).
- Is **synthesis needed**, then define the synthesis phase, see the section called "Defining Synthesis" (page 29).

Figure 1.5. General 3-Phased Problem Solving Workflow

Each phase is subject to a validation and improvement workflow as shown in Figure 1.6, “Validation and Improvement Workflow” (page 25). Each individual phase as well as the combination of phases may introduce errors and has thus to be carefully validated. In combination with the detailed strategies for each phase, this forms a complete approach for problem solving and validation using Rascal.

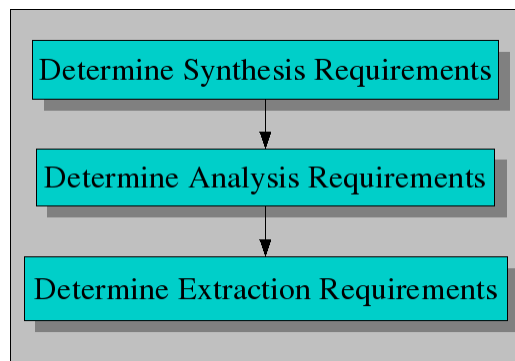
Figure 1.6. Validation and Improvement Workflow

A major question in every problem solving situation is how to determine the requirements for each phase of the solution. For instance, how do we know what to extract from the source code if we do not know what the desired end results of the project are? The standard solution is to use a workflow for requirements gathering that is the inverse of the phases needed to solve the complete problem. This is shown in Figure 1.7, “Requirements Workflow” (page 26) and amounts to the phases:

- **Requirements of the synthesis phase.** This amounts to making an inventory of the desired results of the whole project and may include generated source code, abstract models, or visualizations.

- **Requirements of the analysis phase.** Once these results of the synthesis phase are known, it is possible to list the analysis results that are needed to synthesize desired results. Possible results of the analysis phase include type information, structural information of the original source.
- **Requirements of the extraction phase.** As a last step, one can make an inventory of the facts that have to be extracted to form the starting point for the analysis phase. Typical facts include method calls, inheritance relations, control flow graphs, usage patterns of specific library functions or language constructs.

Figure 1.7. Requirements Workflow



You will have no problem in identifying requirements for each phase when you apply them to a specific example from the list given earlier.

When these requirements have been established, it becomes much easier to actually carry out the project using the three phases of Figure 1.5, “General 3-Phased Problem Solving Workflow” (page 25).

Defining Extraction

How can we extract facts from the *System under Investigation* (SUI) that we are interested in? The extraction workflow is shown in Figure 1.8, “Extraction Workflow” (page 28) and consists of the following steps:

- First and foremost we have to determine which facts we need. This sounds trivial, but it is not. The problem is that we have to anticipate which facts will be needed in the next---not yet defined---analysis phase. A common approach is to use look-ahead and to sketch the queries that are likely to be used in the analysis phase and to determine which facts are needed for them. Start with extracting these facts and refine the extraction phase when the analysis phase is completely defined.
- If relevant facts are already available (and they are reliable!) then we are done. This may happen when you are working on a system that has already been analyzed by others.
- Otherwise you need the source code of the SUI. This requires:
 - Checking that all sources are available (and can be compiled by the host system on which they are usually compiled and executed). Due to missing or unreliable configuration management on the original system this may be a labour-intensive step that requires many iterations.
 - Determining in which languages the sources are written. In larger systems it is common that three or more different languages are being used.
- If there are reliable third-party extraction tools available for this language mix, then we only have to apply them and we are done. Here again, validation is needed that the extracted facts are as expected.
- The extraction may require syntax analysis. This is the case when more structural properties of the source code are needed such as the flow-of-control, nesting of declarations, and the like. There two approaches here:

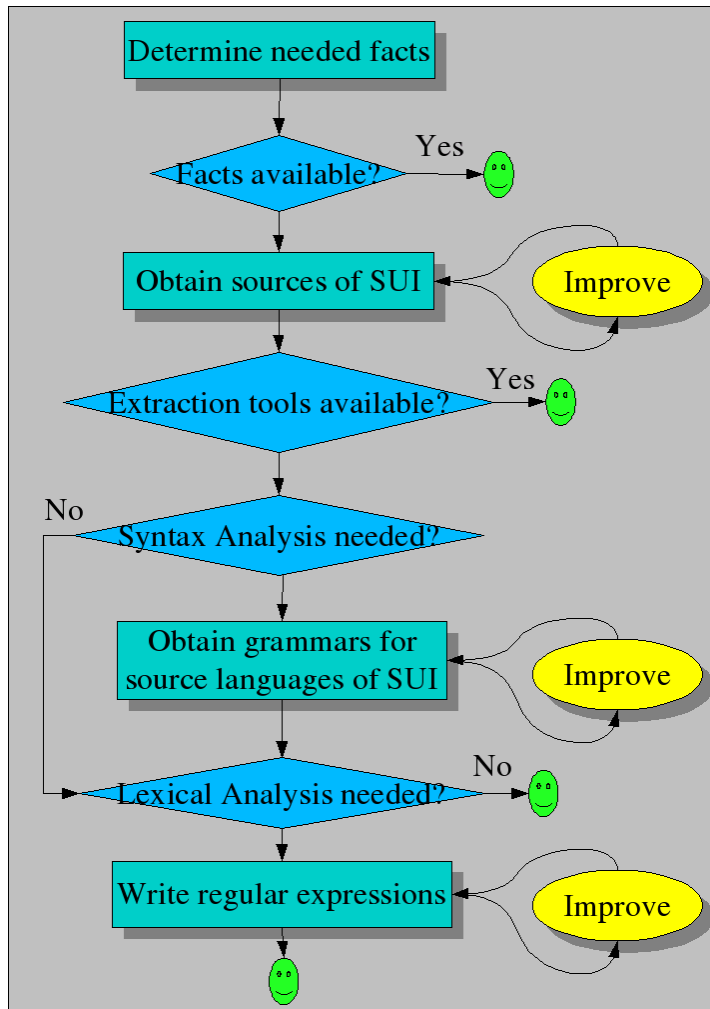
- Use a third-party parser, convert the source code to parse trees and do the further processing of these parse trees in Rascal. The advantage is that the parser can be re-used, the disadvantage is that data conversion is needed to adapt the generated parse tree to Rascal. Validate that the parser indeed accepts the language the SUI is written in, since you will not be the first who has been bitten by the language dialect monster when it turns out that the SUI uses a local variant that slightly deviates from a mainstream language.
- Use an existing SDF definition of the source language or write your own definition. In both cases you can profit from Rascal's seamless integration with SDF. Be aware, however, that writing a grammar for a non-trivial language is a major undertaking and may require weeks to month of work. Whatever approach you choose, validate that the result.
- The extraction phase may only require lexical analysis. This happens when more superficial, textual, facts have to be extracted like procedure calls, counts of certain statements and the like. Use Rascal's full regular expression facilities to do the lexical analysis.

It may happen that the facts extracted from the source code are *wrong*. Typical error classes are:

- Extracted facts are *wrong*: the extracted facts incorrectly state that procedure P calls procedure Q but this is contradicted by a source code inspection. This may happen when the fact extractor uses a conservative approximation when precise information is not statically available. In the language C, when procedure P performs an indirect call via a pointer variable, the approximation may be that P calls all procedures in the procedures.
- Extracted facts are *incomplete*: the inheritance between certain classes in Java code is missing.

The strategy to validate extracted facts differ per case but here are three strategies:

- Post process the extracted facts (using Rascal, of course) to obtain trivial facts about the source code such as total lines of source code and number of procedures, classes, interfaces and the like. Next validate these trivial facts with tools like `wc` (word and line count), `grep` (regular expression matching) and others.
- Do a manual fact extraction on a small subset of the code and compare this with the automatically extracted facts.
- Use another tool on the same source and compare results whenever possible. A typical example is a comparison of a call relation extracted with different tools.

Figure 1.8. Extraction Workflow

The Rascal features that are most frequently used for extraction are:

- Regular expression patterns to extract textual facts from source code.
- Syntax definitions and concrete patterns to match syntactic structures in source code.
- Pattern matching (used in many Rascal statements).
- Visits to traverse syntax trees and to locally extract information.
- The repertoire of built-in datatypes (like lists, maps, sets and relations) to represent the extracted facts.

Defining Analysis

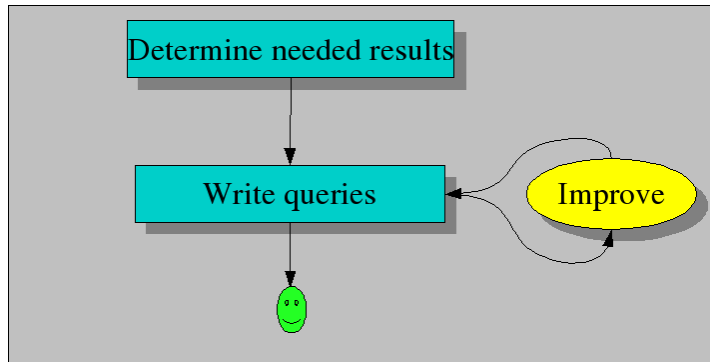
The analysis workflow is shown in Figure 1.9, “Analysis Workflow” (page 29) and consists of two steps:

- Determine the results that are needed for the synthesis phase.
- Write the Rascal code to perform the analysis. This may amount to:
 - Reordering extracted facts to make them more suitable for the synthesis phase.

- Enriching extracted facts. Examples are computing transitive closures of extracted facts (e.g., A may call B in one or more calls), or performing data reduction by abstracting away details (i.e., reducing a program to a finite automaton).
- Combining enriched, extracted, facts to create new facts.

As before, validate, validate and validate the results of analysis. Essentially the same approach can be used as for validating the facts. Manual checking of answers on random samples of the SUI may be mandatory. It also happens frequently that answers inspire new queries that lead to new answers, and so on.

Figure 1.9. Analysis Workflow



The Rascal features that are frequently used for analysis are:

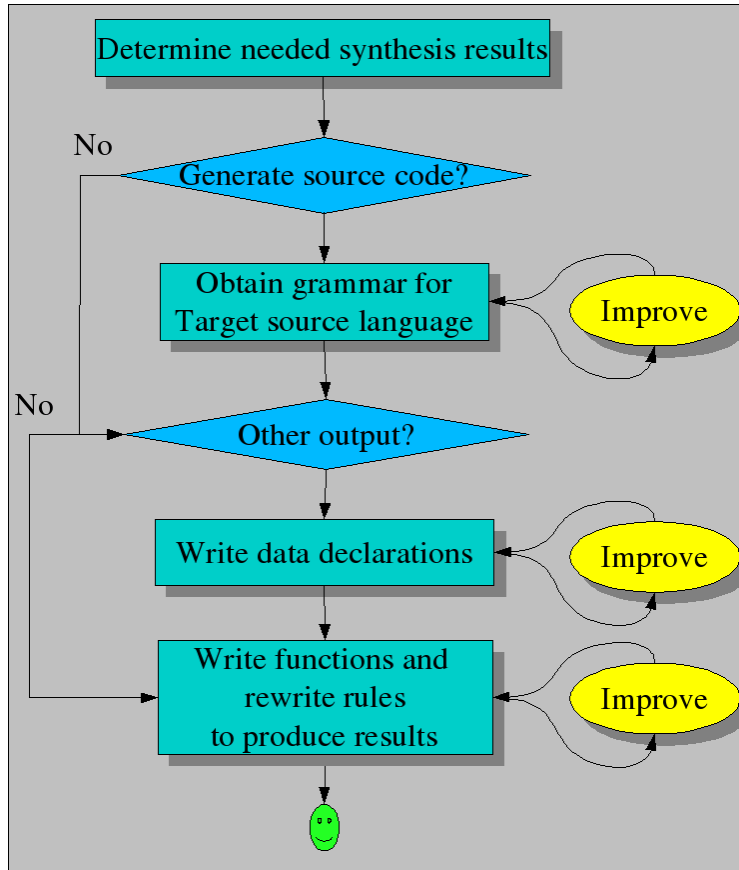
- List, set and map comprehensions.
- The built-in operators and library functions, in particular for lists, maps, sets and relations.
- Pattern matching (used in many Rascal statements).
- Visits and switches to further process extracted facts.
- The solve statement for constraint solving.
- Rewrite rules to simplify results and to enforce constraints.

Defining Synthesis

Results are synthesized as shown in Figure 1.10, “Synthesis Workflow” (page 30) This consists of the following steps:

- Determine the results of the synthesis phase. Wide range of results is possible including:
 - Generated source code.
 - Generated abstract representations, like finite automata or other formal models that capture properties of the SUI.
 - Generated data for visualizations that will be used by visualization tools.
- If source code is to be generated, there are various options.
 - Print strings with embedded variables.
 - Convert abstract syntax trees to strings (perhaps using forms of pretty printing).

- Use a grammar of the target source language, also for code generation. Note that this approach guarantees the generation of syntactically correct source code as opposed to code generation using print statements or string templates.
- If other output is needed (e.g., an automaton or other formal structure) write data declarations to represent that output.
- Finally, write functions and rewrite rules that generate the desired results.

Figure 1.10. Synthesis Workflow

The Rascal features that are frequently used for synthesis are:

- Syntax definitions or data declarations to define output formats.
- Pattern matching (used in many Rascal statements).
- Visits of datastructures and on-the-fly code generation.
- Rewrite rules.

Larger Examples

Now we will have a closer look at some larger applications of Rascal. We start with a call graph analysis in the section called “Call Graph Analysis”(page 31)and then continue with the analysis of the component structure of an application in the section called “Analyzing the Component Structure of an Application” (page 35)and of Java systems in the section called “Analyzing the Structure of Java Systems” (page 36) Next we move on to the detection of uninitialized variables in the section called “Finding Uninitialized and Unused Variables in a Program”(page 37) As an example of computing code metrics, we describe the calculation of McCabe's cyclomatic complexity in the section called “McCabe Cyclomatic Complexity”. Several examples of dataflow analysis follow in the section called “Dataflow Analysis” (page 39) A description of program slicing concludes the chapter, see the section called “Program Slicing” (page 46).



The examples in this section are biased towards pure analysis. We intend to add more extraction and synthesis examples.

Call Graph Analysis

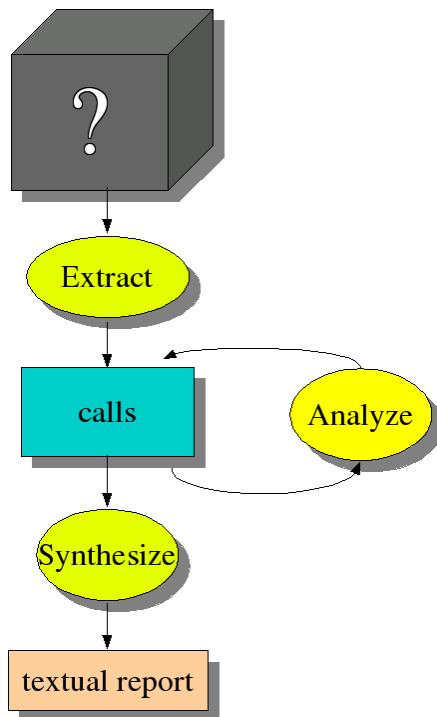
Suppose a mystery box ends up on your desk. When you open it, it contains a huge software system with several questions attached to it:

- How many procedure calls occur in this system?
- How many procedures does it contains?
- What are the entry points for this system, i.e., procedures that call others but are not called themselves?
- What are the leaves of this application, i.e., procedures that are called but do not make any calls themselves?
- Which procedures call each other indirectly?
- Which procedures are called directly or indirectly from each entry point?
- Which procedures are called from all entry points?

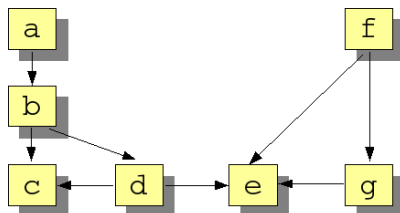
Let's see how these questions can be answered using Rascal.

Preparations

To illustrate this process consider the workflow in Figure 1.11, “Workflow for analyzing mystery box” (page 32) First we have to extract the calls from the source code. Rascal is very good at this, but to simplify this example we assume that this call graph has already been extracted. Also keep in mind that a real call graph of a real application will contain thousands and thousands of calls. Drawing it in the way we do later on in Figure 1.12, “Graphical representation of the `calls` relation”(page 32) makes no sense since we get a uniformly black picture due to all the call dependencies. After the extraction phase, we try to understand the extracted facts by writing queries to explore their properties. For instance, we may want to know *how many calls* there are, or *how many procedures*. We may also want to enrich these facts, for instance, by computing who calls who in more than one step. Finally, we produce a simple textual report giving answers to the questions we are interested in.

Figure 1.11. Workflow for analyzing mystery box

Now consider the call graph shown in Figure 1.12, “Graphical representation of the `calls` relation” (page 32). This section is intended to give you a first impression what can be done with Rascal. Please return to this example when you have digested the detailed description of Rascal in the section called “The Rascal Language” (page 50) and the section called “Built-in Operators and Library Functions” (page 90).

Figure 1.12. Graphical representation of the `calls` relation

Rascal supports basic data types like integers and strings which are sufficient to formulate and answer the questions at hand. However, we can gain readability by introducing separately named types for the items we are describing. First, we introduce therefore a new type `proc` (an alias for strings) to denote procedures:

```
rascal> alias proc = str;
ok
```

Suppose that the following facts have been extracted from the source code and are represented by the relation `Calls`:



Here we should illustrate how to do this.

```
rascal> rel[proc, proc] Calls =
{ <"a", "b">, <"b", "c">, <"b", "d">, <"d", "c">,
```



```
    <"d", "e">, <"f", "e">, <"f", "g">, <"g", "e">
  };
rel[proc,proc]: { <"a", "b">, <"b", "c">, <"b", "d">,
                  <"d", "c">, <"d", "e">, <"f", "e">,
                  <"f", "g">, <"g", "e"> }
```

This concludes the preparatory steps and now we move on to answer the questions.

Questions

How many procedure calls occur in this system?

To determine the numbers of calls, we simply determine the number of tuples in the `Calls` relation, as follows. First, we need the Relation library (described in the section called “Relation” (page 104)) so we import it:

```
rascal> import Relation;
ok
```

next we describe a new variable and calculate the number of tuples:

```
rascal> nCalls = size(Calls);
int: 8
```

The library function `size` determines the number of elements in a set or relation and is explained in the section called “Relation” (page 104). In this example, `nCalls` will get the value 8.

How many procedures are contained in it?

We get the number of procedures by determining which names occur in the tuples in the relation `Calls` and then determining the number of names:

```
rascal> procs = carrier(Calls);
set[proc]: {"a", "b", "c", "d", "e", "f", "g"}

rascal> nprocs = size(procs);
int: 7
```

The built-in function `carrier` determines all the values that occur in the tuples of a relation. In this case, `procs` will get the value `{"a", "b", "c", "d", "e", "f", "g"}` and `nprocs` will thus get value 7. A more concise way of expressing this would be to combine both steps:

```
rascal> nprocs = size(carrier(Calls));
int: 7
```

What are the entry points for this system?

The next step in the analysis is to determine which *entry points* this application has, i.e., procedures which call others but are not called themselves. Entry points are useful since they define the external interface of a system and may also be used as guidance to split a system in parts. The top of a relation contains those left-hand sides of tuples in a relation that do not occur in any right-hand side. When a relation is viewed as a graph, its top corresponds to the root nodes of that graph. Similarly, the bottom of a relation corresponds to the leaf nodes of the graph. See the section called “Graph” (page 93) for more details. Using this knowledge, the entry points can be computed by determining the top of the `Calls` relation:

```
rascal> import Graph;
ok
```

```
rascal> entryPoints = top(Calls);
set[proc]: {"a", "f"}
```

In this case, `entryPoints` is equal to `{"a", "f"}`. In other words, procedures "a" and "f" are the entry points of this application.

What are the leaves of this application?

In a similar spirit, we can determine the *leaves* of this application, i.e., procedures that are being called but do not make any calls themselves:

```
rascal> bottomCalls = bottom(Calls);
set[proc]: {"c", "e"}
```

In this case, `bottomCalls` is equal to `{"c", "e"}`.

Which procedures call each other indirectly?

We can also determine the *indirect calls* between procedures, by taking the transitive closure of the `Calls` relation, written as `Calls+`. Observe that the transitive closure will contain both the direct and the indirect calls.

```
rascal> closureCalls = Calls+;
rel[proc, proc]: {<"a", "b">, <"b", "c">, <"b", "d">,
                  <"d", "c">, <"d", "e">, <"f", "e">,
                  <"f", "g">, <"g", "e">, <"a", "c">,
                  <"a", "d">, <"b", "e">, <"a", "e">}
```

Which procedures are called directly or indirectly from each entry point?

We now know the entry points for this application ("a" and "f") and the indirect call relations. Combining this information, we can determine which procedures are called from each entry point. This is done by indexing `closureCalls` with appropriate procedure name. The index operator yields all right-hand sides of tuples that have a given value as left-hand side. This gives the following:

```
rascal> calledFromA = closureCalls["a"];
set[proc]: {"b", "c", "d", "e"}
```

and

```
rascal> calledFromF = closureCalls["f"];
set[proc]: {"e", "g"}
```

Which procedures are called from all entry points?

Finally, we can determine which procedures are called from both entry points by taking the intersection of the two sets `calledFromA` and `calledFromF`:

```
rascal> commonProcs = calledFromA & calledFromF;
set[proc]: {"e"}
```

In other words, the procedures called from both entry points are mostly disjoint except for the common procedure "e".

Wrap-up

These findings can be verified by inspecting a graph view of the calls relation as shown in Figure 1.12, "Graphical representation of the `calls` relation" (page 32). Such a visual inspection does *not*

scale very well to large graphs and this makes the above form of analysis particularly suited for studying large systems.

Analyzing the Component Structure of an Application

A frequently occurring problem is that we know the call relation of a system but that we want to understand it at the component level rather than at the procedure level. If it is known to which component each procedure belongs, it is possible to *lift* the call relation to the component level as proposed in [Kri99]. Actual lifting amounts to translating each call between procedures by a call between components. This is described in the following module:

```
module demo::Lift

alias proc = str;
alias comp = str;

public rel[comp,comp] lift(rel[proc,proc] aCalls,
                          rel[proc,comp] aPartOf){
    return { <C1, C2> | <proc P1, proc P2> <- aCalls,
                      <comp C1, comp C2> <- aPartOf[P1] *
                                      aPartOf[P2]
    };
}
```

For each pair $\langle P1, P2 \rangle$ in the Calls relation we compose the corresponding parts $aPartOf[P1]$ and $aPartOf[P2]$ (each yielding a set of components) into a new relation of calls between components. This relation is added pair by pair to the result.

Let's now apply this. First import the above module, and define a call relation and a partof relation:

```
rascal> import demo::Lift;
ok

rascal> Calls = {<"main", "a">, <"main", "b">, <"a", "b">,
               <"a", "c">, <"a", "d">, <"b", "d">
               };
rel[str,str] : {<"main", "a">, <"main", "b">, <"a", "b">,
               <"a", "c">, <"a", "d">, <"b", "d">
               }

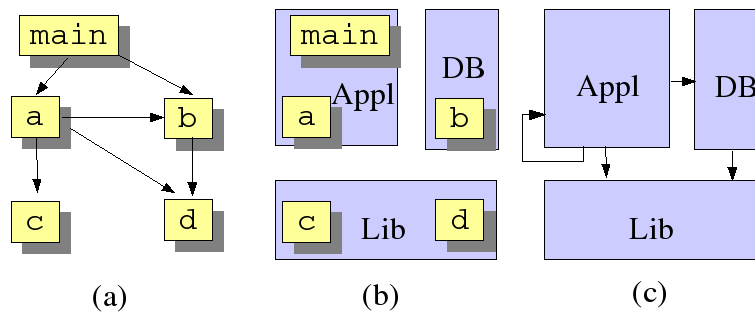
rascal> Components = {"Appl", "DB", "Lib"};
set[str] : {"Appl", "DB", "Lib"}

rascal> PartOf = {<"main", "Appl">, <"a", "Appl">,
                 <"b", "DB">, <"c", "Lib">,
                 <"d", "Lib">};
rel[str,str] : {<"main", "Appl">, <"a", "Appl">,
               <"b", "DB">, <"c", "Lib">,
               <"d", "Lib">}
```

The lifted call relation between components is now obtained by:

```
rascal> ComponentCalls = lift(Calls, PartOf);
rel[str,str] : {<"DB", "Lib">, <"Appl", "Lib">,
               <"Appl", "DB">, <"Appl", "Appl">}
```

The relevant relations for this example are shown in Figure 1.13, “(a) Calls; (b) PartOf; (c) ComponentCalls.” (page 36).

Figure 1.13. (a) Calls; (b) PartOf; (c) ComponentCalls.

Analyzing the Structure of Java Systems

Now we consider the analysis of Java systems (inspired by ???). Suppose that the type `class` is defined as follows

```
alias class = str;
```

and that the following relations are available about a Java application:

- `rel[class, class] CALL`: If $\langle C_1, C_2 \rangle$ is an element of `CALL`, then some method of C_2 is called from C_1 .
- `rel[class, class] INHERITANCE`: If $\langle C_1, C_2 \rangle$ is an element of `INHERITANCE`, then class C_1 either extends class C_2 or C_1 implements interface C_2 .
- `rel[class, class] CONTAINMENT`: If $\langle C_1, C_2 \rangle$ is an element of `CONTAINMENT`, then one of the fields of class C_1 is of type C_2 .

To make this more explicit, consider the class `LocatorHandle` from the `JHotDraw` application (version 5.2) as shown here:

```
package CH.ifa.draw.standard;

import java.awt.Point;
import CH.ifa.draw.framework.*;
/**
 * A LocatorHandle implements a Handle by delegating the
 * location requests to a Locator object.
 */
public class LocatorHandle extends AbstractHandle {
    private Locator    fLocator;
    /**
     * Initializes the LocatorHandle with the
     * given Locator.
     */
    public LocatorHandle(Figure owner, Locator l) {
        super(owner);
        fLocator = l;
    }
    /**
     * Locates the handle on the figure by forwarding
     * the request to its figure.
     */
    public Point locate() {
        return fLocator.locate(owner());
    }
}
```

It leads to the addition to the above relations of the following tuples:

- To CALL the pairs `<"LocatorHandle", "AbstractHandle">` and `<"LocatorHandle", "Locator">` will be added.
- To INHERITANCE the pair `<"LocatorHandle", "AbstractHandle">` will be added.
- To CONTAINMENT the pair `<"LocatorHandle", "Locator">` will be added.

Cyclic structures in object-oriented systems makes understanding hard. Therefore it is interesting to spot classes that occur as part of a cyclic dependency. Here we determine cyclic uses of classes that include calls, inheritance and containment. This is achieved as follows:

```
rel[class,class] USE = CALL + CONTAINMENT + INHERITANCE;
set[str] ClassesInCycle =
  {C1 | <class C1, class C2> <- USE+, C1 == C2};
```

First, we define the USE relation as the union of the three available relations CALL, CONTAINMENT and INHERITANCE. Next, we consider all pairs `<C1, C2>` in the transitive closure of the USE relation such that C₁ and C₂ are equal. Those are precisely the cases of a class with a cyclic dependency on itself. Probably, we do not only want to know which classes occur in a cyclic dependency, but we also want to know which classes are involved in such a cycle. In other words, we want to associate with each class a set of classes that are responsible for the cyclic dependency. This can be done as follows.

```
rel[class,class] USE = CALL + CONTAINMENT + INHERITANCE;
set[class] CLASSES = carrier(USE);
rel[class,class] USETRANS = USE+;
rel[class,set[class]] ClassCycles =
  {<C, USETRANS[C]> | class C <- CLASSES,
    <C, C> in USETRANS };
```

First, we introduce two new shorthands: CLASSES and USETRANS. Next, we consider all classes C with a cyclic dependency and add the pair `<C, USETRANS[C]>` to the relation ClassCycles. Note that USETRANS[C] is the right image of the relation USETRANS for element C, i.e., all classes that can be called transitively from class C.

Finding Uninitialized and Unused Variables in a Program

Consider the following program in the toy language Pico: (This is an extended version of the example presented earlier in [Kli03].)

```
[ 1] begin declare x : natural, y : natural,
[ 2]           z : natural, p : natural;
[ 3]   x := 3;
[ 4]   p := 4;
[ 5]   if q then
[ 6]     z := y + x
[ 7]   else
[ 8]     x := 4
[ 9]   fi;
[10]   y := z
[11] end
```

Inspection of this program learns that some of the variables are being used before they have been initialized. The variables in question are q (line 5), y (line 6), and z (line 10). It is also clear that variable p is initialized (line 4), but is never used. How can we automate these kinds of analysis? Recall from the section called “The EASY Paradigm” (page 3) that we follow the Extract-Analyze-SYNthesize paradigm to approach such a problem. The first step is to determine which elementary

facts we need about the program. For this and many other kinds of program analysis, we need at least the following:

- The *control flow graph* of the program. We represent it by a graph PRED (for predecessor) which relates each statement with its predecessors.
- The *definitions* of each variable, i.e., the program statements where a value is assigned to the variable. It is represented by the relation DEFS.
- The *uses* of each variable, i.e., the program statements where the value of the variable is used. It is represented by the relation USES.

In this example, we will use line numbers to identify the statements in the program. Assuming that there is a tool to extract the above information from a program text, we get the following for the above example:

```
module demo::Uninit
import Relation;
import Graph;

alias expr = int;
alias varname = str;

public expr ROOT = 1;

public graph[expr] PRED = { <1,3>, <3,4>, <4,5>, <5,6>,
                           <5,8>, <6,10>, <8,10> };

public rel[varname,expr] DEFS = { <"x", 3>, <"p", 4>,
                                  <"z", 6>, <"x", 8>,
                                  <"y", 10> };

public rel[varname, expr] USES = { <"q", 5>, <"y", 6>,
                                   <"x", 6>, <"z", 10> };
```

This concludes the extraction phase. Next, we have to enrich these basic facts to obtain the initialized variables in the program. So, when is a variable V in some statement S initialized? If we execute the program (starting in ROOT), there may be several possible execution paths that can reach statement S . All is well if *all* these execution path contain a definition of V . However, if one or more of these path do *not* contain a definition of V , then V may be uninitialized in statement S . This can be formalized as follows:

```
// module demo::Unit continued
public rel[varname,expr] UNINIT =
  { <V,E> | <varname V, expr E> <- USES,
          E in reachX(PRED, {ROOT}, DEFS[V])
  };
```

We analyze this definition in detail:

- $\langle \text{varname } V, \text{expr } E \rangle$: USES enumerates all tuples in the USES relation. In other words, we consider the use of each variable in turn.
- $E \text{ in reachX}(\text{PRED}, \{\text{ROOT}\}, \text{DEFS}[V])$ is a test that determines whether expression E is reachable from the ROOT without encountering a definition of variable V .
 - $\{\text{ROOT}\}$ represents the initial set of nodes from which all path should start.
 - $\text{DEFS}[V]$ yields the set of all statements in which a definition of variable V occurs. These nodes form the exclusion set for reachX: no path will be extended beyond an element in this set.

- PRED is the relation for which the reachability has to be determined.
- The result of `reachX(PRED, {ROOT}, DEFS[V])` is a set that contains all nodes that are reachable from the ROOT (as well as all intermediate nodes on each path).
- Finally, `E in reachX(PRED, {ROOT}, DEFS[V])` tests whether expression E can be reached from the ROOT.
- The net effect is that UNINIT will only contain pairs that satisfy the test just described.

When we execute the resulting Rascal code (i.e., the declarations of ROOT, PRED, DEFS, USES and UNINIT), we get as value for UNINIT:

```
rascal> import demo::Uninit;
ok

rascal> UNINIT;
rel[varname,expr]: {<"q", 5>, <"y", 6>, <"z", 10>}
```

and this is in concordance with the informal analysis given at the beginning of this example.

As a bonus, we can also determine the *unused* variables in a program, i.e., variables that are defined but are used nowhere. This is done as follows:

```
// module demo::Unit continued

public set[varname] UNUSED = domain(DEFS) - domain(USES);
```

Taking the domain of the relations DEFS and USES yields the variables that are defined, respectively, used in the program. The difference of these two sets yields the unused variables, in this case { "p" }.

McCabe Cyclomatic Complexity

The *cyclomatic complexity* of a program is defined as $e - n + 2$, where e and n are the number of edges and nodes in the control flow graph, respectively. It was proposed by McCabe [McC76] as a measure of program complexity. Experiments have shown that programs with a higher cyclomatic complexity are more difficult to understand and test and have more errors. It is generally accepted that a program, module or procedure with a cyclomatic complexity larger than 15 is *too complex*. Essentially, cyclomatic complexity measures the number of decision points in a program and can be computed by counting all if statement, case branches in switch statements and the number of conditional loops. Given a control flow in the form of a predecessor graph `Graph[&T] PRED` between elements of arbitrary type &T, the cyclomatic complexity can be computed in Rascal as follows:

```
module demo::McCabe
import Graph;

public int cyclomaticComplexity(Graph[&T] PRED){
    return size(PRED) - size(carrier(PRED)) + 2;
}
```

The number of edges e is equal to the number of tuples in PRED. The number of nodes n is equal to the number of elements in the carrier of PRED, i.e., all elements that occur in a tuple in PRED.

Dataflow Analysis

Dataflow analysis is a program analysis technique that forms the basis for many compiler optimizations. It is described in any text book on compiler construction, e.g. [ASU86]. The goal of dataflow analysis is to determine the effect of statements on their surroundings. Typical examples are:

- Dominators (the section called “Dominators” (page 40): which nodes in the flow dominate the execution of other nodes?
- Reaching definitions (the section called “Reaching Definitions” (page 42): which definitions of variables are still valid at each statement?
- Live variables (the section called “Live Variables” (page 45): of which variables will the values be used by successors of a statement?
- Available expressions: an expression is available if it is computed along each path from the start of the program to the current statement.

Dominators

A node d of a flow graph *dominates* a node n , if every path from the initial node of the flow graph to n goes through d [ASU86] (Section 10.4). Dominators play a role in the analysis of conditional statements and loops. The function `dominators` that computes the dominators for a given flow graph `PRED` and an entry node `ROOT` is defined as follows:

```
module demo::Dominators
import Set;
import Relation;
import Graph;

public rel[&T, set[&T]] dominators(rel[&T,&T] PRED,
                                   &T ROOT)
{
    set[&T] VERTICES = carrier(PRED);
    return { <V, (VERTICES - {V, ROOT}) -
              reachX(PRED, {ROOT}, {V})>
            | &T V <- VERTICES
            };
}
```

First, the auxiliary set `VERTICES` (all the statements) is computed. The relation `DOMINATES` consists of all pairs $\langle S, \{S_1, \dots, S_n\} \rangle$ such that

- S_i is not an initial node or equal to S .
- S_i cannot be reached from the initial node without going through S .

First import the above module and consider the sample flow graph `PRED`:

```
rascal> import demo::Dominators;
ok

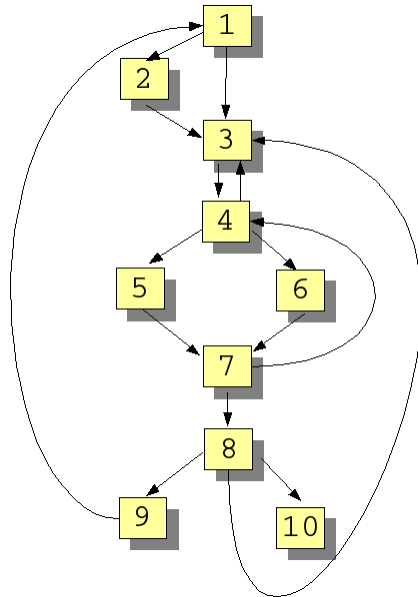
rascal> rel[int,int] PRED = {
<1,2>, <1,3>,
<2,3>,
<3,4>,
<4,3>,<4,5>, <4,6>,
<5,7>,
<6,7>,
<7,4>,<7,8>,
<8,9>,<8,10>,<8,3>,
<9,1>,
<10,7>
};
```



```
rel[int,int]: { <1,2>, <1,3>, ...
```

It is illustrated in Figure 1.14, “Flow graph” (page 41)

Figure 1.14. Flow graph

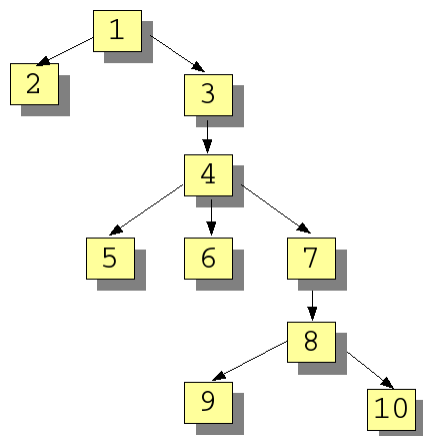


The result of applying dominators to it is as follows:

```
rascal> dominators(PRED);
rel[int,int]: {<1, {2, 3, 4, 5, 6, 7, 8, 9, 10}>,
<2, {}>,
<3, {4, 5, 6, 7, 8, 9, 10}>,
<4, {5, 6, 7, 8, 9, 10}>,
<5, {}>,
<6, {}>,
<7, {8, 9, 10}>,
<8, {9, 10}>,
<9, {}>,
<10, {}>}
```

The resulting *dominator tree* is shown in Figure 1.15, “Dominator tree” (page 41) The dominator tree has the initial node as root and each node d in the tree only dominates its descendants in the tree.

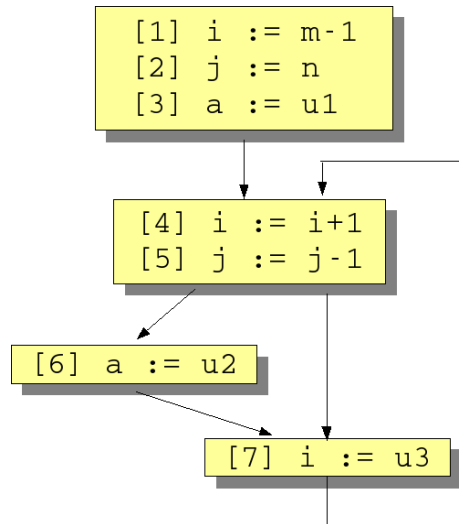
Figure 1.15. Dominator tree



Reaching Definitions

We illustrate the calculation of reaching definitions using the example in Figure 1.16, “Flow graph for various dataflow problems” (page 42) which was inspired by [ASU86] (Example 10.15).

Figure 1.16. Flow graph for various dataflow problems



We assume the following basic definitions to represent information about the program:

```

module demo::ReachingDefs

import Relation;
import Graph;
import IO;

public alias stat = int;
public alias var = str;
public alias def = tuple[stat, var];
public alias use = tuple[stat, var];

public rel[stat, def] definition(rel[stat, var] DEFS){
  return {<S, <S, V> | <stat S, var V> <- DEFS};
}

public rel[stat, def] use(rel[stat, var] USES){
  return {<S, <S, V> | <stat S, var V> <- USES};
}

```

Let's use the following values to represent our example:

```

rascal> rel[stat, stat] PRED = { <1, 2>, <2, 3>, <3, 4>,
                                <4, 5>, <5, 6>, <5, 7>,
                                <6, 7>, <7, 4> };
rel[stat, stat]: { <1, 2>, <2, 3>, ...

rascal> rel[stat, var] DEFS = { <1, "i">, <2, "j">,
                                <3, "a">, <4, "i">,
                                <5, "j">, <6, "a">,
                                <7, "i"> };
rel[stat, var]: { <1, "i">, <2, "j">, ...

```

```
rascal> rel[stat,var] USES = { <1, "m">, <2, "n">,
                             <3, "u1">, <4, "i">,
                             <5, "j">, <6, "u2">,
                             <7, "u3"> };
rel[stat,var]: { <1, "m">, <2, "n">, ...
```

For convenience, we have introduced above a notion `def` that describes that a certain statement defines some variable and we revamp the basic relations into a more convenient format using this new type and the auxiliary functions `definition` and `use`:

```
rascal> definition(DEFS);
rel[stat,def]: { <1, <1, "i">>, <2, <2, "j">>,
                 <3, <3, "a">>, <4, <4, "i">>,
                 <5, <5, "j">>, <6, <6, "a">>,
                 <7, <7, "i">> }

rascal> use(USES);
rel[stat,def]: { <1, <1, "m">>, <2, <2, "n">>,
                 <3, <3, "u1">>, <4, <4, "i">>,
                 <5, <5, "j">>, <6, <6, "u2">>,
                 <7, <7, "u3">> }
```

Now we are ready to define an important new relation `KILL`. `KILL` defines which variable definitions are undone (killed) at each statement and is defined by the following function `kill`:

```
// continuing module demo::ReachingDefs

public rel[stat,def] kill(rel[stat,var] DEFS) {
    return {<S1, <S2, V>> | <stat S1, var V> <- DEFS,
                        <stat S2, V> <- DEFS,
                        S1 != S2};
}
```

In this definition, all variable definitions are compared with each other, and for each variable definition all *other* definitions of the same variable are placed in its kill set. In the example, `KILL` gets the value

```
rascal> kill(DEFS);
rel[stat,def]:
{ <1, <4, "i">>, <1, <7, "i">>, <2, <5, "j">>,
  <3, <6, "a">>, <4, <1, "i">>, <4, <7, "i">>,
  <5, <2, "j">>, <6, <3, "a">>, <7, <1, "i">>,
  <7, <4, "i">>
}
```

and, for instance, the definition of variable `i` in statement 1 kills the definitions of `i` in statements 4 and 7.

After these preparations, we are ready to formulate the reaching definitions problem in terms of two relations `IN` and `OUT`. `IN` captures all the variable definitions that are valid at the entry of each statement and `OUT` captures the definitions that are still valid after execution of each statement. Intuitively, for each statement `S`, `IN[S]` is equal to the union of the `OUT` of all the predecessors of `S`. `OUT[S]`, on the other hand, is equal to the definitions generated by `S` to which we add `IN[S]` minus the definitions that are killed in `S`. Mathematically, the following set of equations captures this idea for each statement:

$$IN[S] = \text{UNION}_{P \text{ in predecessors of } S} OUT[P]$$

$$OUT[S] = DEF[S] + (IN[S] - KILL[S])$$

This idea can be expressed in Rascal quite literally:

```

public rel[stat, def] reachingDefinitions(
    rel[stat,var] DEFS,
    rel[stat,stat] PRED){
    set[stat] STATEMENT = carrier(PRED);
    rel[stat,def] DEF = definition(DEFS);
    rel[stat,def] KILL = kill(DEFS);

    // The set of mutually recursive dataflow equations
    // that has to be solved:

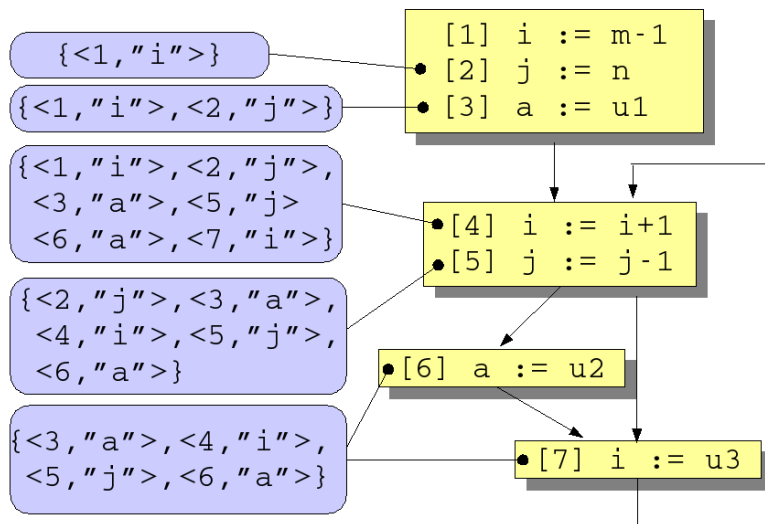
    rel[stat,def] IN = {};
    rel[stat,def] OUT = DEF;

    solve (IN, OUT) {
        IN = {<S, D> | int S <- STATEMENT,
                      stat P <- predecessors(PRED,S),
                      def D <- OUT[P]};
        OUT = {<S, D> | int S <- STATEMENT,
                      def D <- DEF[S] + (IN[S] - KILL[S])};
    };
    return IN;
}

```

First, the relations IN and OUT are declared and initialized. Next follows a solve statement that uses IN and OUT as variables and contains two equations that resemble the mathematical equations given above. Note the use of the library function predecessors to obtain the predecessors of a statement for a given control flow graph.

Figure 1.17. Reaching definitions for flow graph in Figure 1.16, “Flow graph for various dataflow problems” (page 42)



For our running example (Figure 1.17, “Reaching definitions for flow graph in Figure 1.16, “Flow graph for various dataflow problems”” (page 44) the results are as follows (see Figure 1.17, “Reaching definitions for flow graph in Figure 1.16, “Flow graph for various dataflow problems”” (page 44)). Relation IN has as value:

```

{ <2, <1, "i">>, <3, <2, "j">>, <3, <1, "i">>,
  <4, <3, "a">>, <4, <2, "j">>, <4, <1, "i">>,
  <4, <7, "i">>, <4, <5, "j">>, <4, <6, "a">>,
  <5, <4, "i">>, <5, <3, "a">>, <5, <2, "j">>,
  <5, <5, "j">>, <5, <6, "a">>, <6, <5, "j">>,

```

```

<6, <4, "i">>, <6, <3, "a">>, <6, <6, "a">>,
<7, <5, "j">>, <7, <4, "i">>, <7, <3, "a">>,
<7, <6, "a">>
}

```

If we consider statement 3, then the definitions of variables *i* and *j* from the preceding two statements are still valid. A more interesting case are the definitions that can reach statement 4:

- The definitions of variables *a*, *j* and *i* from, respectively, statements 3, 2 and 1.
- The definition of variable *i* from statement 7 (via the backward control flow path from 7 to 4).
- The definition of variable *j* from statement 5 (via the path 5, 7, 4).
- The definition of variable *a* from statement 6 (via the path 6, 7, 4).

Relation OUT has as value:

```

{ <1, <1, "i">>, <2, <2, "j">>, <2, <1, "i">>,
  <3, <3, "a">>, <3, <2, "j">>, <3, <1, "i">>,
  <4, <4, "i">>, <4, <3, "a">>, <4, <2, "j">>,
  <4, <5, "j">>, <4, <6, "a">>, <5, <5, "j">>,
  <5, <4, "i">>, <5, <3, "a">>, <5, <6, "a">>,
  <6, <6, "a">>, <6, <5, "j">>, <6, <4, "i">>,
  <7, <7, "i">>, <7, <5, "j">>, <7, <3, "a">>,
  <7, <6, "a">>
}

```

Observe, again for statement 4, that all definitions of variable *i* are missing in OUT[4] since they are killed by the definition of *i* in statement 4 itself. Definitions for *a* and *j* are, however, contained in OUT[4]. The result of reaching definitions computation is illustrated in Figure 1.17, “Reaching definitions for flow graph in Figure 1.16, “Flow graph for various dataflow problems” (page 44)

We will use the function `reachingDefinitions` later on in the section called “Program Slicing” (page 46) when defining program slicing.

Live Variables

The live variables of a statement are those variables whose value will be used by the current statement or some successor of it. The mathematical formulation of this problem is as follows:

$$IN[S] = USE[S] + (OUT[S] - DEF[S])$$

$$OUT[S] = \text{UNION}_{S' \text{ in successors of } S} IN[S']$$

The first equation says that a variable is live coming into a statement if either it is used before redefinition in that statement or it is live coming out of the statement and is not redefined in it. The second equation says that a variable is live coming out of a statement if and only if it is live coming into one of its successors.

This can be expressed in Rascal as follows:

```

public rel[stat,def] liveVariables(rel[stat, var] DEFS,
                                   rel[stat, var] USES,
                                   rel[stat,stat] PRED){
    set[stat] STATEMENT = carrier(PRED);
    rel[stat,def] DEF = definition(DEFS);
    rel[stat,def] USE = use(USES);

    rel[stat,def] LIN = {};
    rel[stat,def] LOUT = DEF;
}

```

```

solve(LIN, LOUT) {
  LIN = { <S, D> | stat S <- STATEMENT,
                def D <- USE[S] +
                    (LOUT[S] - (DEF[S]))};

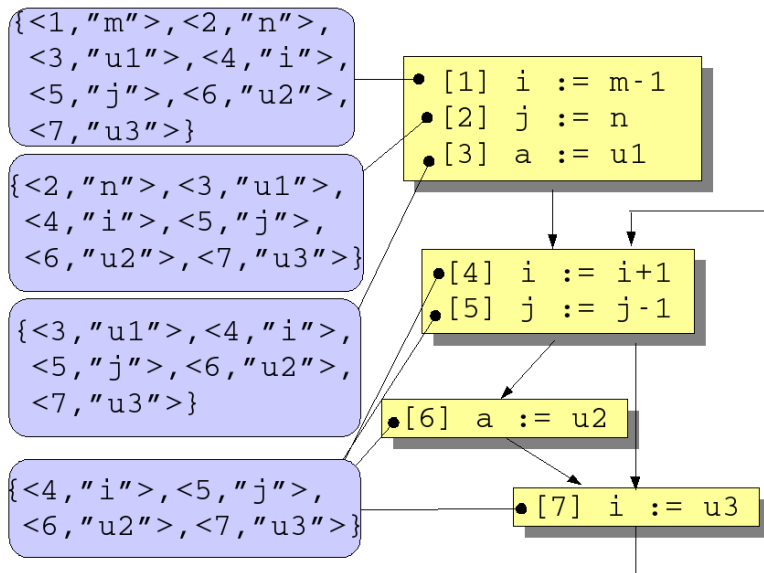
  LOUT = { <S, D> | stat S <- STATEMENT,
                 stat Succ <- successors(PRED,S),
                 def D <- LIN[Succ] };

}
return LIN;
}

```

The results of live variable analysis for our running example are illustrated in Figure 1.18, “Live variables for flow graph in Figure 1.16, “Flow graph for various dataflow problems”” (page 46).

Figure 1.18. Live variables for flow graph in Figure 1.16, “Flow graph for various dataflow problems” (page 42)



Program Slicing

Program slicing is a technique proposed by Weiser [Wei84] for automatically decomposing programs in parts by analyzing their data flow and control flow. Typically, a given statement in a program is selected as the *slicing criterion* and the original program is reduced to an independent subprogram, called a *slice*, that is guaranteed to represent faithfully the behavior of the original program at the slicing criterion. An example will illustrate this (we use line numbers for later reference):

[1] read(n)	[1] read(n)	[1] read(n)
[2] i := 1	[2] i := 1	[2] i := 1
[3] sum := 0	[3] sum := 0	
[4] product := 1		[4] product := 1
[5] while i<= n	[5] while i<= n	[5] while i<= n
do	do	do
begin	begin	begin
[6] sum :=	[6] sum :=	
sum + i	sum + i	
[7] product :=		[7] product :=
product * i		product * i
[8] i := i + 1	[8] i := i + 1	[8] i := i + 1
end	end	end

[9] write(sum)	[9] write(sum)	
[10] write(product)		[10] write(product)
(a) Sample program	(b) Slice for statement [9]	(c) Slice for statement [10]

The initial program is given as (a). The slice with statement [9] as slicing criterion is shown in (b): statements [4] and [7] are irrelevant for computing statement [9] and do not occur in the slice. Similarly, (c) shows the slice with statement [10] as slicing criterion. This particular form of slicing is called *backward slicing*. Slicing can be used for debugging and program understanding, optimization and more. An overview of slicing techniques and applications can be found in [Tip95]. Here we will explore a relational formulation of slicing adapted from a proposal in [JR94]. The basic ingredients of the approach are as follows:

- We assume the relations `PRED`, `DEFS` and `USES` as before.
- We assume an additional set `CONTROL-STATEMENT` that defines which statements are control statements.
- To tie together dataflow and control flow, three auxiliary variables are introduced:
 - The variable `TEST` represents the outcome of a specific test of some conditional statement. The conditional statement defines `TEST` and all statements that are control dependent on this conditional statement will use `TEST`.
 - The variable `EXEC` represents the potential execution dependence of a statement on some conditional statement. The dependent statement defines `EXEC` and an explicit (control) dependence is made between `EXEC` and the corresponding `TEST`.
 - The variable `CONST` represents an arbitrary constant.

The calculation of a (backward) slice now proceeds in six steps:

- Compute the relation `rel[use,def]` `use-def` that relates all uses to their corresponding definitions. The function `reaching-definitions` as shown earlier in the section called “Reaching Definitions” (page 42) does most of the work.
- Compute the relation `rel[def,use]` `def-use-per-stat` that relates the *internal* definitions and uses of a statement.
- Compute the relation `rel[def,use]` `control-dependence` that links all `EXECs` to the corresponding `TESTs`.
- Compute the relation `rel[use,def]` `use-control-def` combines use/def dependencies with control dependencies.
- After these preparations, compute the relation `rel[use,use]` `USE-USE` that contains dependencies of uses on uses.
- The backward slice for a given slicing criterion (a use) is now simply the projection of `USE-USE` for the slicing criterion.

This informal description of backward slicing can now be expressed in Rascal:

```
module demo::Slicing

import Set;
import Relation;
import demo::ReachingDefs;
import demo::Dominators;
import UnitTest;
```

```

set[use] BackwardSlice(set[stat] CONTROLSTATEMENT,
                      rel[stat,stat] PRED,
                      rel[stat,var] USES,
                      rel[stat,var] DEFS,
                      use Criterion) {

    rel[stat, def] REACH = reachingDefinitions(DEFS, PRED);

    // Compute the relation between each use and
    // corresponding definitions: use_def

    rel[use,def] use_def =
    {<<S1,V>, <S2,V>> | <stat S1, var V> <- USES,
                        <stat S2, V> <- REACH[S1]};

    // Internal dependencies per statement

    rel[def,use] def_use_per_stat =
        {<<S,V1>, <S,V2>> | <stat S, var V1> <- DEFS,
                                <S, var V2> <- USES}
        +
        {<<S,V>, <S,"EXEC">> | <stat S, var V> <- DEFS}
        +
        {<<S,"TEST">, <S,V>> | stat S <- CONTROLSTATEMENT,
                                <S, var V> <-
                                    domainR(USES, {S})});

    // Control dependence: control-dependence

    rel[stat, set[stat]] CONTROLDOMINATOR =
    domainR(dominators(PRED, 1), CONTROLSTATEMENT);

    rel[def,use] control_dependence =
    { <<S2, "EXEC">, <S1,"TEST">>
      | <stat S1, stat S2> <- CONTROLDOMINATOR};

    // Control and data dependence: use-control-def

    rel[use,def] use_control_def =
        use_def + control_dependence;
    rel[use,use] USE_USE =
        (use_control_def o def_use_per_stat)*;

    return USE_USE[Criterion];
}

```

Let's apply this to the example from the start of this section and assume the following:

```

rascal> import demo::Slicing;
ok

rascal> rel[stat,stat] PRED = { <1,2>, <2,3>, <3,4>,
                                <4,5>, <5,6>, <5,9>,
                                <6,7>, <7,8>, <8,5>,
                                <8,9>, <9,10> };

rel[stat,stat]: {<1,2>, ...

```



```
rascal> rel[stat,var] DEFS = { <1, "n">, <2, "i">,
                             <3, "sum">,
                             <4, "product">,
                             <6, "sum">,
                             <7, "product">,
                             <8, "i"> };
rel[stat,var]: {<1, "n">, ...

rascal> rel[stat,var] USES = { <5, "i">, <5, "n">,
                             <6, "sum">, <6, "i">,
                             <7, "product">, <7, "i">,
                             <8, "i">, <9, "sum">,
                             <10, "product">
                             };
rel[stat,var]; { <5, "i"> ...

rascal> set[int] CONTROL-STATEMENT = { 5 };
set[int]: {5}

rascal> BackwardSlice(CONTROL-STATEMENT,
                      PRED, USES, DEFS, <9, "sum">);
set[use]: { <1, "EXEC">, <2, "EXEC">, <3, "EXEC">,
            <5, "i">, <5, "n">, <6, "sum">, <6, "i">,
            <6, "EXEC">, <8, "i">, <8, "EXEC">,
            <9, "sum"> }
```

Take the domain of this result and we get exactly the statements in (b) of the example.

The Rascal Language

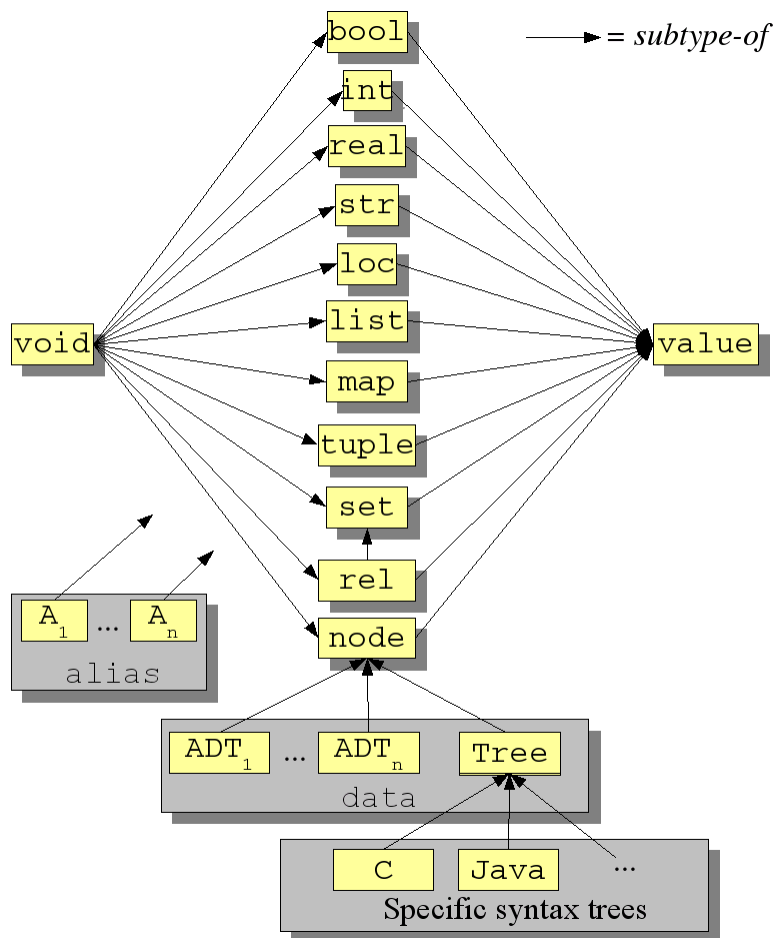
A Rascal program consists of one or more modules. Each module may import other modules and declare data types, variables, functions or rewrite rules. We now describe the basic ingredients of Rascal in more detail:

- Types and values, see the section called “Types and Values” (page 50).
- Declarations, see the section called “Declarations” (page 59).
- Expressions, see the section called “Expressions” (page 65).
- Statements, see the section called “Statements” (page 82).

Types and Values

Typing

Rascal is based on static typing, this means that as many errors and inconsistencies as possible are spotted before the program is executed. The types (to be explained in more detail later) are ordered in a so-called *type lattice* shown in Figure 1.19, “The Rascal Type Lattice” (page 51) The arrows describe a *subtype-of* relation between types. The type `void` is the *smallest* type and is included in all other types and the type `value` is the *largest* type that includes all other types. We also see that `rel` is a subtype of `set` and that each ADT is a subtype of `node`. A special role is played by the datatype `Tree` that is the generic type of syntax trees. Syntax trees for specific languages are all subtypes of `Tree`. As a result, syntax trees can be addressed at two levels: in a generic fashion as `Tree` and in a specific fashion as a more precisely typed syntax tree. Finally, each alias is structurally equivalent to one or more specific other types.

Figure 1.19. The Rascal Type Lattice

Void

Void stands for *nothing* and is represented by the type `void`. It is a type without any values.

Value

Value stands for all possible Rascal values and is represented by the type `value`. This type is a container for all other types and does not have any values itself.

Boolean

The Booleans are represented by the type `bool` which has two values: `true` and `false`.

Integer

The integer values are represented by the type `int` and are written as usual, e.g., 0, 1, or 123. They can be arbitrarily large.

Real

The real values are represented by the type `real` and are written as usual, e.g., 1.5, or 3.14e-123. They can have arbitrary size and precision.

String

The string values are represented by the type `str` and consist of character sequences surrounded by double quotes. e.g., "a" or "a\nlong\tstring".

String literals support so-called *string interpolation*: inside string constants text between angle brackets (< and >) is first executed and then replaced by its string value. Let's try this:

```
rascal> N = 13;
int : 13

rascal> "The value of N is <N>";
str: "The value of N is 13"

rascal> "The value of N*N is <N*N>";
str: "The value of N*N is 169"

rascal> "The value is <(N < 10) ? 10 : N*N>";
str: "The value of 169"
```

As you can see the string value of variables and expressions is interpolated in the result as expected. As we will see later on, various statements (if, for, while, do) also return a value and can be used in this way. In the interpolation variant of these statements the block or blocks that are part of the statement become arbitrary text (that may itself contain interpolations). Their forms are:

```
<if(Exp){> ... Text ... <>
<if(Exp){> ... Text ... <> else {> ... Text ... <>}
<for(Exp){>... Text ... <>
<while(Exp){> ... Text ... <>
<do {>... Text ... <> while (Exp)>
```

Here *Text* is arbitrary text that may itself contain again contain interpolations.

Let's apply this to some examples:

```
rascal> "N is <if(N < 10){> small <> else {> large <>}>";
str: "N is large "

rascal> "N is <if(N < 10){> small <> else {> large (<N><>}>";
str: "N is large (13)"

rascal> "before <for(x<-[1..5]){>a <x> b <>}>after";
str: "before a 1 b a 2 b a 3 b a 4 b a 5 b after"
```

String interpolation enables very flexible template-based text generation.

Location

Location values are represented by the type `loc` and serve as text coordinates in a specific local or remote source file. It is very handy to associate a source code location which extracted facts.

Source locations have the following syntax:

```
|Uri| (O,L,<BL,BC>,<EL,EC>)
```

where:

- *Uri* is an arbitrary Uniform Resource Identifier (URI).
- *O* and *L* are integer expressions giving the offset of this location to the begin of file, respectively, its length.
- *BL* and *BC* are integers expressions giving the begin line and begin column.

separated by comma's and enclosed in bracket as in $[E_1, E_2, \dots, E_n]$, where the E_n ($1 \leq i \leq n$) are expressions that yield the desired element type. For example,

- $[1, 2, 3]$ is of type `list[int]`,
- $\{<1,10>, <2,20>, <3,30>\}$ is of type `set[tuple[int,int]]`,
- $[1, "b", 3]$ is of type `list[value]`,
- $[<"a",10>, <"b",20>, <"c",30>]$ is of type `list[tuple[str,int]]`, and
- $[["a", "b"], ["c", "d", "e"]]$ is of type `list[list[str]]`.



$[1, 2, 3]$ and $[3, 2, 1]$ are different lists.



$[1, 2, 3]$ and $[1, 2, 3, 1]$ are also different lists.

When variables of type `list` occur inside a list, their elements are automatically *spliced* into the surrounding list. This can be prevented by surrounding them with extra `[` and `]` brackets. Note that this approach is atypical: in Rascal splicing is implicit while in other languages it has to be indicated explicitly by the programmer.

```
rascal> L = [1, 2, 3];
list[int]: [1,2,3]

rascal> [10, L, 20];
list[int]: [10, 1, 2, 3, 20]

rascal> [10, [L], 20];
list[value]: [10, [1,2,3], 20]
```

Range

For lists of integers, a special shorthand exists to describe ranges of integers:

- $[F \dots L]$ ranges from first element F up to (and including) last element L with increments of 1.
- $[F, S, \dots E]$, ranges from first element F , second element S up to (and including) last element E with increments of $S - F$.

Set

A set is an unordered sequence of values and has the following properties:

- All elements have the same static type.
- The order of the elements does not matter.
- A set contains an element only once. In other words, duplicate elements are eliminated and no matter how many times an element is added to a set, it will occur in it only once.

Sets are represented by the type `set[T]`, where T is an arbitrary type. Examples are `set[int]`, `set[tuple[int,int]]` and `set[set[str]]`. Sets are denoted by a list of elements, separated

by comma's and enclosed in braces as in $\{E_1, E_2, \dots, E_n\}$, where the E_n ($1 \leq i \leq n$) are expressions that yield the desired element type. For example,

- $\{1, 2, 3\}$ is of type `set[int]`,
- $\{<1,10>, <2,20>, <3,30>\}$ is of type `set[tuple[int,int]]`,
- $\{1, "b", 3\}$ is of type `set[value]`,
- $\{<"a",10>, <"b",20>, <"c",30>\}$ is of type `set[tuple[str,int]]`, and
- $\{\{"a", "b"\}, \{"c", "d", "e"\}\}$ is of type `set[set[str]]`.



$\{1, 2, 3\}$ and $\{3, 2, 1\}$ are identical sets.



$\{1, 2, 3\}$ and $\{1, 2, 3, 1\}$ are also identical sets.

In a similar fashion as with lists, set variables are automatically spliced into a surrounding set. This can be prevented by surrounding them with extra `{}` and `}` brackets.

```
rascal> s = {1, 2, 3};
set[int]: {1,2,3}

rascal> {10, s, 20};
set[int]: {10, 1, 2, 3, 20}

rascal> {10, {s}, 20};
set[value]: {10, {1,2,3}, 20}
```

Map

A map is a set of `key : value` pairs and has the following properties:

- Key and value may have different static types.
- A key can only occur once.

Maps are represented by the type `map[T1, T2]`, where T_1 and T_2 are arbitrary types. Examples are `map[int,int]`, and `map[str,int]`. Maps are denoted by a list of pairs, separated by comma's and enclosed in parentheses as in $(K_1 : V_1, \dots, K_n : V_n)$, where the K_n ($1 \leq i \leq n$) are expressions that yield the keys of the map and V_n ($1 \leq i \leq n$) are expressions that yield the values for each key. Maps resemble functions rather than relations in the sense that only a single value can be associated with each key. For example,

- $(\text{"pear"} : 1, \text{"apple"} : 3, \text{"banana"} : 0)$ is of type `map[str,int]`.

Tuple

A tuple is a sequence of elements with the following properties:

- Each element in a tuple (may) have a different type.
- Each element of a tuple may have a label that can be used to select that element of the tuple.

- Each tuple is *fixed-width*, i.e., has the same number of elements.

Tuples are represented by the type `tuple[$T_1L_1, T_2L_2, \dots, T_nL_n$]`, where T_1, T_2, \dots, T_n are arbitrary types and L_1, L_2, \dots, L_n are optional labels. An example of a tuple type is `tuple[str name, int freq]`. Examples are:

- `<1, 2>` is of type `tuple[int, int]`,
- `<1, 2, 3>` is of type `tuple[int, int, int]`,
- `<"a", 3>` is of type `tuple[str name, int freq]`.

The elements of a tuple can also be labelled and can then be accessed using the field selection operator (`.`). Fields can be changed (yielding a new tuple value) by a combination of field selection and assignment. For instance,

```
rascal> tuple[str first, str last, int age] P = <"Jo","Jones",35>;
tuple[str first, str last, int age] P = <"Jo", "Jones", 35>;

rascal> P.first;
str: "Jo"

rascal> P.first = "Bo";
tuple[str first, str last, int age]: <"Bo","Jones",35>
```

Relation

A relation is a set of elements with the following property:

- All elements have the same static tuple type.

Relations are thus nothing more than sets of tuples, but since they are used so often we provide a shorthand notation for them. Relations are represented by the type `rel[$T_1L_1, T_2L_2, \dots, T_nL_n$]`, where T_1, T_2, \dots, T_n are arbitrary types and L_1, L_2, \dots, L_n are optional labels. It is a shorthand for `set[tuple[$T_1L_1, T_2L_2, \dots, T_nL_n$]]`. Examples are `rel[int, str]` and `rel[int, set[str]]`. An n -ary relations with m tuples is denoted by $\{\langle E_{11}, E_{12}, \dots, E_{1n} \rangle, \langle E_{21}, E_{22}, \dots, E_{2n} \rangle, \dots, \langle E_{m1}, E_{m2}, \dots, E_{mn} \rangle\}$, where the E_{ij} are expressions that yield the desired element type. For example, $\{\langle 1, "a" \rangle, \langle 2, "b" \rangle, \langle 3, "c" \rangle\}$ is of type `rel[int, str]`. Examples are:

- $\{\langle 1, 10 \rangle, \langle 2, 20 \rangle, \langle 3, 30 \rangle\}$ is of type `rel[int, int]` (yes indeed, you saw this same example before and then we gave `set[tuple[int, int]]` as its type; remember that these types are interchangeable.),
- $\{\langle "a", 10 \rangle, \langle "b", 20 \rangle, \langle "c", 30 \rangle\}$ is of type `rel[str, int]`, and
- $\{\langle "a", 1, "b" \rangle, \langle "c", 2, "d" \rangle\}$ is of type `rel[str, int, str]`.

Type Aliases

Everything can be expressed using the elementary types and values that are provided by Rascal. However, for the purpose of documentation and readability it is sometimes better to use a descriptive name as type indication, rather than an elementary type. The alias declaration

```
alias Name = Type;
```

states that *Name* can be used everywhere instead of the already defined type *Type*. Both types are thus structurally equivalent. For instance,


```
alias ModuleId = str;  
alias Frequency = int;
```

introduces two new type names `ModuleId` and `Frequency`, both an alias for the type `str`. The use of type aliases is a good way to document your intentions. Another example is an alias definition for a graph containing integer nodes:

```
alias IntGraph = rel[int,int];
```

Note that Rascal Standard Library provides a graph data type that is defined as follows:

```
alias Graph[&T] = rel[&T, &T];
```

In other words the standard graph datatype can be parameterized with any element type. See the section called “Graph” (page 93) for details.

Algebraic Data Type (ADT)

In ordinary programming languages record types or classes exist to introduce a new type name for a collection of related, named, values and to provide access to the elements of such a collection through their name. In Rascal, data declarations provide this facility. The type declaration

```
data Name = Alt1 | Alt2 | ...
```

introduces a new datatype *Name* and its alternative forms *Alt₁*, *Alt₂*, The description of an alternative is identical in form to the type declaration of a function. For instance,

```
data Bool =  
    tt() | ff() | conj(Bool L, Bool R) | disj(Bool L, Bool R);
```

defines the datatype `Bool` that contains various constants (`tt()` and `ff()`) and constructor functions `conj` and `disj`.

Type Parameters, Type Constraints and Parameterized Types and Type Aliases

In addition to the types that we have already discussed, a type may also be a *type parameter* of the form

```
&Name
```

A type parameter may occur at every syntactic position where a type is required and turns an ordinary type into a parameterized type. Parameterized types are used to define polymorphic functions and data types, i.e., functions and data types that are applicable for more than one type. Type parameters are bound to an actual type when the function or data type is applied and further uses of the type parameter are consistently replaced by the actual type.

The following syntactic positions are *binding occurrences* for type parameters:

- Type parameters in the type declaration of a function are bound to the types of the actual parameters in the call of that function. Type parameters that occur in the body of the function are replaced by the corresponding actual types.
- The left-hand side of an alias. The type parameters are bound when the alias is used and occurrences of type parameters in the right hand side are replaced by corresponding actual types.
- The alternatives of a data type. Binding and replacement is identical to that of function declarations.

All other occurrences of type parameters are *using occurrences*. The following rules apply:

- When the same type parameter is used at different binding occurrences it should be bound to the same actual type.
- For every using occurrence of a type parameter there should be a binding occurrence of a type parameter with the same name.

As a final refinement, constraints can be imposed on the actual types to which a type parameter may be bound. This is expressed by a subtype constraint of the form:

```
&Name <: Type
```

which expresses that actual types bound to *Name* should be a subtype of *Type*. More on subtyping in the section called “Typing” (page 50).

Let's consider a small example of the use of function parameters in a function declaration, we refer to the section called “Function Declaration” (page 60) for a full description of function declarations. The following function `swap` returns a tuple in which its arguments are swapped and can be applied to arbitrary values in a type safe manner:

```
rascal> tuple[&B, &A] swap(&A a, &B b) { return <b, a>; }
ok

rascal> swap(1,2);
tuple[int,int]: <2,1>

rascal> swap("abc", 3);
tuple[int,str]: <3, "abc">
```

Observe that the type parameters that are used in the return type should be defined in the declarations of the formal parameter of the function.

An alias definition may also be parameterized. So we can generalize graphs as follows:

```
rascal> alias Graph[&Node] = rel[&Node, &Node];
ok

rascal> Graph[int] GI = {<1,2>, <3,4>, <4,1>};
Graph[int] : {<1,2>, <3,4>, <4,1>}

rascal> Graph[str] GS = {<"a", "b">, <"c","d">, <"d", "a">};
Graph[str] : {<"a", "b">, <"c", "d">, <"d", "a">}
```

The type parameters that are used in the type in the right part of the alias declaration should be defined in the left part of the alias definition.

Reified Types

Usually one declares functions that have arguments that have a type that corresponds to one of the many forms of values in Rascal. In exceptional circumstances it is desirable to define functions that have a type itself as argument. The prototypical example is a parse function: how to write a type safe parse function that expresses the type of the result we expect? Suppose we want to parse a language that has the non-terminals `EXP`, `STAT` and `PROGRAM`. A first, naive, solution introduces a parse function for each non-terminal:

```
EXP parseEXP(str s) { ... }
STAT parsePROGRAM(str s) { ... }
PROGRAM parsePROGRAM(str s) { ... }
```

Unfortunately this solution does not scale well to large languages with many non-terminals and it breaks down completely when we do not know the non-terminals before hand.

To solve this problem in a more general manner something special has to be done. Types are not values and without an additional mechanism they cannot be passed as arguments to functions. To achieve this effect we introduce *reified types* that are denoted by the type `type`. Now we can write:

```
&T parse(type[&T] start, str s) { ... }
```

and use the `parse` by giving it a type as argument:

```
parse(#EXP, "1+3");
```

In other words, reified types make it possible to use values as types.

Declarations

Rascal Program

A Rascal program consists of a number of modules that may import each other.

Module

A module declaration has the following form:

```
module Name
Imports;
Declaration1;
...
Declarationn;
```

and consists of a *Name* and zero or more imports of other modules, see the section called “Import” (page 60), and declarations for

- Data type, see the section called “Algebraic Data Type (ADT)” (page 57).
- Alias, see the section called “Type Aliases” (page 56).
- Variable, see the section called “Variable Declaration” (page 61).
- Function, see the section called “Function Declaration” (page 60).
- Rewrite rule, see the section called “Rewrite Rule Declaration” (page 64).
- Node annotation, see the section called “Node Annotation Declaration” (page 63).
- Declaration tag, see the section called “Declaration Tag” (page 62).

The module name *Name* will be used when the current module is imported in another module. A module is usually a qualified name of the form:

```
Name1::Name2:: ... ::Namen
```

which corresponds to a path relative to the root of the current workspace.

The constituents of a module are also shown in Figure 1.20, “Constituents of a Module” (page 60). The less familiar features are shown in a separate color.

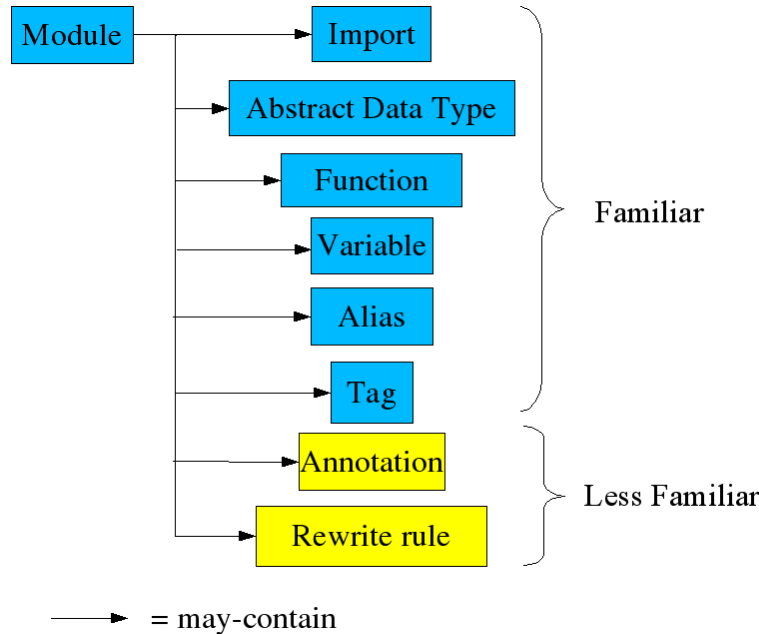
The entities that are *visible* inside a module are

- The private or public entities declared in the module itself.
- The public entities declared in any imported module.

The only entities that are visible outside the module, are the public entities declared in the module itself. If different imported modules declare the same visible name, it can be disambiguated by explicitly qualifying it with its module name:

```
Module :: Name
```

Figure 1.20. Constituents of a Module



Import

An import has the form:

```
import QualifiedName;
```

and has as effect that all public entities declared in module *QualifiedName* are made available to the importing module. Circular imports are allowed. Two kinds of imported modules are supported:

- Another Rascal module.
- An SDF module that defines the syntax of some language, say *L*.

In the former case, all publicly visible entities in the imported module become available in the importing module. In the latter case, all non-terminals (symbols in SDF parlance) that are declared in *L* become available as types in the importing module. In addition, concrete syntax patterns and parse functions can be used for any non-terminal that is defined in *L*.

Import is *non-transitive*, i.e., the visible entities from an imported module are not re-exported by the importing module.

Function Declaration

A function declaration has the form

```
Type Name (Type1 Var1, ..., Typen Varn) Statement
```

Here *Type* is the result type of the function and this should be equal to the type of the result of *Statement* (using the return statement, see the section called “Return Statement” (page 86).

Each $Type_i Var_i$ represents a typed formal parameter of the function. The formal parameters may be used in *Statement* and get their value when function *Name* is invoked. Example:

```
rascal> rel[int, int] invert(rel[int,int] R){
        return {<Y, X> | <int X, int Y> <- R }
      }
ok

rascal> invert({<1,10>, <2,20>});
rel[int,int] : {<10,1>, <20,2>}
```

Variable argument lists. A function may have a variable list of arguments, this has the form:

```
Type Name(ordinary parameters, Type Var...) Statement
```

The last parameter of a function may be followed by `...` and this has as effect that all remaining actual parameters that occur in a call to this function are collected as list value of the last formal parameter. Inside the function body, the type of this parameter will therefore be `list[Type]`.

Exceptions. The exceptions that can be thrown by a function can be (optionally) declared as follows:

```
Type Name(Type1 Var1, ..., Typen Varn)
      throws Exception1, Exception2, ...
```

See the section called “Try Catch Statement” (page 87) and the section called “Throw Statement” (page 88) for details.

Parameterized types in function declaration. The types that occur in function declarations may also contain *type variables* that are written as `&TypeVar`. In this way functions can be defined for arbitrary types. In the following example, we declare an inversion function that is applicable to any binary relation. :

```
rascal> rel[&T2, &T1] invert2(rel[&T1,&T2] R){
        return {<Y, X> | <&T1 X, &T2 Y> <- R };
      }
ok

rascal> invert2({<1,10>, <2,20>});
rel[int,int] : {<10,1>, <20,2>}

rascal> invert2({<"mon", 1>, <"tue", 2>});
rel[int,str] : {<1, "mon">, <2, "tue">}
```

Here we declare a function that can be used to swap the elements of pairs of arbitrary types:

```
rascal> tuple[&T2, &T1] swap(&T1 A, &T2 B) { return <B, A>; }
ok

rascal> swap(<1, 2>);
tuple[int,int] : <2,1>

rascal> swap(<"wed", 3>);
tuple[int,str] : <3, "wed">
```

Variable Declaration

A variable declaration has the form

```
Type Var = Exp
```

where *Type* is a type, *Var* is a variable name, and *Exp* is an expression that should have type *Type*. The effect is that the value of expression *Exp* is assigned to *Var* and can be used later on as *Var*'s value. The following rules apply:

- Double declarations in the same scope are not allowed.
- The type of *Exp* should be compatible with *Type*, i.e., it should be a subtype of *Type*.

As a convenience, also declarations without an initialization expression are permitted inside functions (but not at the module level) and have the form

```
Type Var
```

and only introduce the variable *Var*. When a variable is declared, it has as scope the nearest enclosing block, see the section called “Block Statement” (page 82).

Rascal provides *local type inference*, which allows the implicit declaration of variables that are used locally in functions. The following rules apply:

- An implicitly declared variable is declared at the level of the current scope, this may be the whole function body or a block nested in it.
- An implicitly declared variable gets as type the type of the first value that is assigned to it.
- If a variable is implicitly declared in different execution paths of a function, all these implicit declarations should result in the same type.
- All uses of an implicitly declared variable must be compatible with its implicit type.

Examples.

```
rascal> int max = 100;
int: 100

rascal> min = 0;
int : 0

rascal> day = {<"mon", 1>, <"tue", 2>, <"wed",3>,
               <"thu", 4>, <"fri", 5>, <"sat",6>, <"sun",7>}
rel[str,int]: {<"mon", 1>, <"tue", 2>, <"wed",3>,
               <"thu", 4>, <"fri", 5>, <"sat",6>, <"sun",7>}
```

Declaration Tag



Tags declarations are not yet implemented.



The syntax of tags has to be aligned with the syntax of annotations.

Tags are intended to add meta data to a Rascal program and allow to influence the execution of the Rascal program, for instance, by adding memoization hints or database mappings for relations.

All declarations in a Rascal program may contain (in fixed positions depending on the declaration type) one or more declaration tags (*tag*). A tag is defined by declaring its name, the declaration type to which it can be attached, and the name and type of the annotation. The declaration type `all`, makes

the declaration tag applicable for all possible declaration types. All declaration tags have the generic format `@Name{ ... }`, with arbitrary text between the brackets that is further constrained by the declared type. Here is an example of a license tag:

```
tag str license on module;
```

This will allow to write things like:

```
@license{This module is distributed under the BSD license}
module Booleans
...
```

Other examples of declaration tags are:

```
tag str todo on all          %% todo note for all types
tag void deprecated on function %% marks a deprecated function
tag int memo on function      %% bounded memoization of
                              %% function calls
tag str doc on all           %% documentation string
```

Here is an example of a documentation string as used in the Rascal standard library:

```
@doc{Maximum of a set: max}
public &T max(set[&T] R)
{
    &T result = arb(R);
    for(&T E : R){
        result = max(result, E);
    }
    return result;
}
```

Although user-defined tags are not yet available, the following tags are currently provided:

```
tag str doc on function      %% documentation string
tag str javaClass on function %% implementation class of library
                              %% function
tag void reflective on function %% library function with access to
                              %% interpreter state
tag str javaImports on function %% imports needed by a Rascal
                              %% function with Java body
tag str deprecated on function %% deprecated function
```

Node Annotation Declaration

An annotation may be associated with any node value. Annotations are intended to attach application data to values, like adding position information or control flow information to source code or adding visualization information to a relation. An annotation has a name and the type of its value is explicitly declared. Any value of any named type can be annotated and the type of these annotations can be declared precisely.

For instance, we can add to certain syntactic constructs of programs (e.g., `EXPRESSION`) an annotation with name `posinfo` that contains location information:

```
anno loc EXPRESSION @ posinfo;
```

or location information could be added for all syntax trees:

```
anno loc Tree @ posinfo;
```

We can add to the graph datatype introduced earlier, the annotation with name `LayoutStrategy` that defines which graph layout algorithm to apply to a particular graph, e.g.,

```
data LayoutStrategy = dot() | tree() | force() |
                    hierarchy() | fisheye();

anno LayoutStrategy Graph @ strategy;
```

The following constructs are provided for handling annotations:

- `Val @ Anno`: is an expression that retrieves the value of annotation *Anno* of value *Val* (may be undefined!).
- `Val1[@Anno = Val2]`: is an expression that sets the value of annotation *Anno* of the value *Val1* to *Val2* and returns *Val1* with the new annotation value as result.
- `Var @ Anno = Val`: is an assignment statement that sets the value of annotation *Anno* of the value of variable *Var* to *Val*.

Rewrite Rule Declaration

Functions are the workhorses of Rascal. They can have any value as parameter or result and are explicitly called by the user. Also, functions are declared inside modules and their visibility can be controlled.

Rewrite rules, on the other hand, operate only on nodes and abstract datatypes (ADTs), they are implicitly applied when a new value (we refer to this as the *subject value*) is constructed. The scope of rewrite rules is the whole Rascal program. Rewrite rules are applied to the subject value in a bottom-up fashion. As a result, the subject value may be changed. This process is repeated as long as there are rules that can be applied to the current subject value. Technically, this is called *innermost rewriting*. When done, the result of rewriting the original subject value is used instead of that original value.

Rules have the general form:

```
rule Name PatternWithAction
```

where *Name* is the name of the rule and *PatternWithAction* is the body of the rule consisting of a pattern and an associated action, see the section called “PatternWithAction” (page 77) for a detailed description.

Here is an example for a user-defined type Booleans:

```
rascal>
data Bool = btrue;
data Bool = bfalse;
data Bool = band(Bool left, Bool right);
data Bool = bor(Bool left, Bool right);

rule a1 band(btrue, Bool B)    => B;
rule a2 band(bfalse, Bool B)   => bfalse;
ok

rascal> band(band(btrue,btrue),band(btrue, bfalse));
Bool: bfalse
```

During execution of rules the following applies:

- Rules are applied non-deterministically, and in any order of matching.

- The right-hand side of rules can contain fail statements, which cause backtracking over the alternative matches or alternative rules for a certain constructor.
- When the right-hand side is a statement, an `insert` statement determines the value of the actual replacement. The insert statement is explained in the section called “Visit Expression” (page 80).

You may wonder why we write `btrue` and `bfalse` instead of `true` and `false`. The explanation is that the latter are reserved words that cannot be used as ordinary names. Reserved words can, however, be used as ordinary names by escaping them; this is done by prefixing them with a backslash (`\`), e.g. `\true` and `\false`.

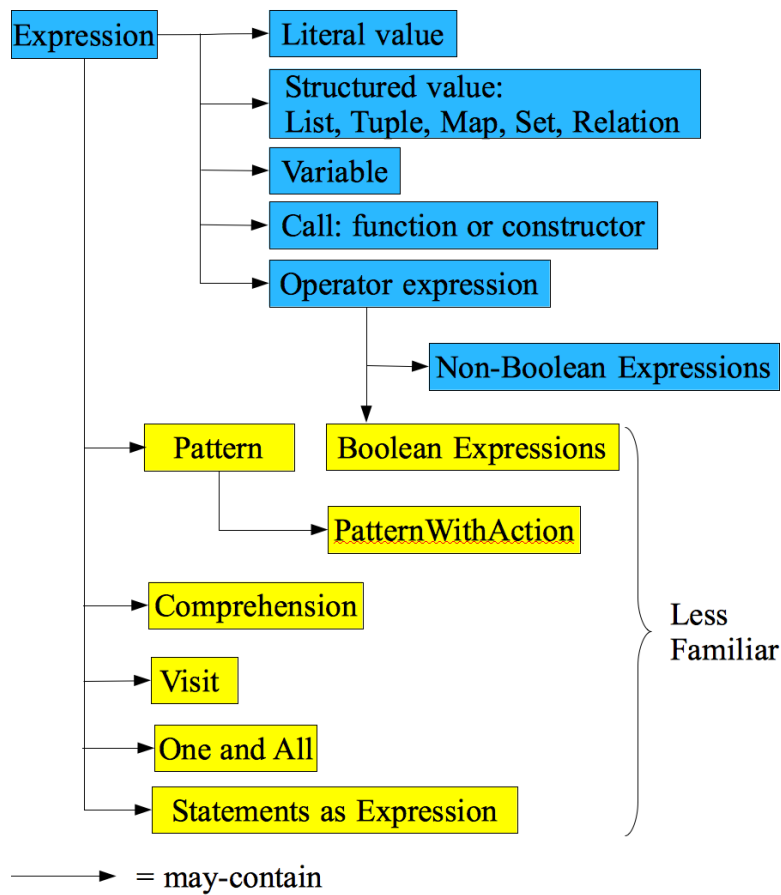
Expressions

The Expression is the basic unit of evaluation and may consist of the ingredients shown in Figure 1.21, “Expression Forms” (page 66):

- An *elementary literal value*, e.g., constants of type `bool`, `int`, `real`, `str` or `loc`. Elementary literals evaluate to themselves.
- A *structured value* for `list`, `set`, `map`, `tuple`, or `rel`. The elements are first evaluated before the structured value is built.
- A *variable*, evaluates to its current value.
- A call to a function or constructor:
 - A *function call*. First the arguments are evaluated and the corresponding function is called. The value returned by the function is used as value of the function call.
 - A *constructor*. First the arguments are evaluated and then a data value is constructed for the corresponding type. This data value is used as value of the constructor. Constructors are functions that can be used in all contexts where functions can be used.
- An *operator expression*. The operator is applied to the arguments; the evaluation order of the arguments depends on the operator. The result returned by the operator is used as value of the operator expression. We distinguish:
 - non-Boolean expressions, see the section called “Non-Boolean Operator Expressions” (page 66).
 - Boolean expressions, see the section called “Boolean Operator Expressions” (page 69).
- A pattern, see the section called “Patterns” (page 71).
- A pattern with associated action, see the section called “PatternWithAction” (page 77).
- A comprehension, see the section called “Comprehension Expression” (page 78).
- A visit expression, see the section called “Visit Expression” (page 80).
- A one expression, see the section called “One Expression” (page 81).
- An all expression, see the section called “All Expression” (page 81).
- Some statements like `if`, `for`, `while` and `do` can also be used in expressions, see the section called “Statement as Expression” (page 81).



Only the `for` statement is currently implemented in this way.

Figure 1.21. Expression Forms

Non-Boolean Operator Expressions

The non-Boolean operators are summarized in Table 1.2, “Non-Boolean Operators” (page 66). All operators are highly overloaded and we refer to the section called “Built-in Operators and Library Functions” (page 90) for a description of their meaning for each specific type. The following rules apply:

- All *name* arguments stand for themselves and are not evaluated.
- For all operators, except, `IfThenElse`, the argument expressions are first evaluated before the operator is applied.
- The operators in Table 1.2, “Non-Boolean Operators” (page 66) are listed from high precedence to low precedence. In other words, operators listed higher in the table bind stronger.

Table 1.2. Non-Boolean Operators

Operator	Name	Description
<i>Exp</i> . <i>Name</i>	Field selection	<i>Exp</i> should evaluate to a tuple or datatype with field <i>Name</i> ; return the value of that field

Operator	Name	Description
$Exp_1 [Name = Exp_2]$	Field assignment	Exp_1 should evaluate to a tuple or datatype with a field $Name$; assign value Exp_2 to that field
$Exp < field, \dots >$	Field projection	Exp should evaluate to a tuple or relation, and field should be a field name or an integer constant. A new tuple or relation is returned that only contains the listed fields.
$Exp_1 [Exp_2, Exp_3, \dots]$	Subscription	The value of Exp_2, Exp_3, \dots are used as index in Exp_1 's value. On list, tuple return the element with given (single!) index value; for map return the value associated with Exp_2 's value. On relations more than one index is allowed. All tuples are returned that have the values of Exp_2, Exp_3, \dots as first elements. These values are removed from each tuple.
$- Exp$	Negation	Negative of Exp 's integer or real value
$Exp +$	Transitive closure	Transitive closure on relation
$Exp *$	Reflexive transitive closure	Reflexive transitive closure on relation
$Exp @ Name$	Annotation selection	Value of annotation $Name$ of Exp 's value
$Exp_1 [@ Name = Exp_2]$	Annotation replacement	Assign value of Exp_2 to annotation $Name$ of Exp_1 's value
$Exp_1 \circ Exp_2$	Composition	Exp_1 and Exp_2 should evaluate to a relation; return their composition. Note: the letter "o" is thus a keyword!
Exp_1 / Exp_2	Division	Divide two integers and reals
$Exp_1 \% Exp_2$	Modulo	Modulo on integer
$Exp_1 * Exp_2$	Multiplication / Product	Multiply integers or real; product of list, set, relation
$Exp_1 \& Exp_2$	Intersection	Intersection of list, set, map or relation
$Exp_1 + Exp_2$	Addition / concatenation / union	Add integer and real; concatenate string, list or tuple; union on set, map, or relation
$Exp_1 - Exp_2$	Subtraction / difference	Subtract integer or real; difference of list, set, map, or relation
$Exp_1 \text{ join } Exp_2$	Join	Join on relation

Most of these operators are described in detail in the section called “Built-in Operators and Library Functions” (page 90) for specific types. Here we describe the remaining generic operators.

Field Selection and Field Assignment. Field selection and field assignment apply to all values that have named components like tuples and relations with named elements, data types, and locations. Field selection returns the value of the named component and Field assignment returns a new value in which the named component has been replaced by a new value. We illustrate this for tuples:

```
rascal> tuple[int key, str val] T = <1, "abc">;
tuple[int, str] : <1, "abc">

rascal> T.val;
str : "abc"
```

```
rascal> T[val = "def"];
tuple[int, str] : <1, "def">

rascal> T;
tuple[int, str] : <1, "abc">
```

Observe that field assignment creates a *new* value with an updated field. The old value remains unchanged as can be seen from the unchanged value of `T` in the above example. In the section called “Assignment Statement” (page 82) we explain how to change a field of variable value.

Field projection. Field projection applies to tuples and relations and may contain element names or integer constants that refer to elements in the order in which they occur in the original value (counting from 0). A field projection returns a new value that consists of the selected elements. Suppose we have a relation with traffic information that records the name of the day, the day number, and the length of the traffic jams at that day.

```
rascal> rel[str day, int daynum, int length] Traffic =
    {<"mon", 1, 100>, <"tue", 2, 150>, <"wed", 3, 125>,
     <"thur", 4, 110>, <"fri", 5, 90>};
rel[str, int, int]: {<"thur", 4, 110>, <"tue", 2, 150>, <"wed", 3, 125>,
                    <"fri", 5, 90>, <"mon", 1, 100>}

rascal> Traffic<length, daynum>;
rel[int, int]: {<110, 4>, <150, 2>, <90, 5>, <100, 1>, <125, 3>}

rascal> Traffic<2, day>;
rel[int, str]: {<125, "wed">, <110, "thur">, <100, "mon">, <90, "fri">,
                <150, "tue">}
```

Field projection thus selects parts from a larger value that has a fixed number of parts. The selection is based on position and not on value and can be used to completely reorder or remove the parts of a larger value.

Subscription. Subscription selects values with a given computed index from a larger value that has a variable number of elements. For lists and tuples a single integer expression is allowed as index and the returned value is the element with that index (counting from 0). For maps, the index type should correspond to the key type of the map and the value associated with the index is returned. For relations, more than one index expression is allowed and as value a new, reduced, relation is returned with all elements that contained the index values at the corresponding tuples positions (but these values are removed, hence a reduced relation). Some examples illustrate this:

```
rascal> L = [10, 20, 30];
list[int] : [10, 20, 30]

rascal> L[1];
int : 20

rascal> T = <"mon", 1>;
tuple[str, int] : <"mon", 1>;

rascal> T[0];
str : "mon"

rascal> colors = ("hearts": "red", "clover": "black",
                  "trumps": "black", "clubs": "red");
map[str, str] : ("hearts": "red", "clover": "black",
                 "trumps": "black", "clubs": "red")
```

```

rascal> colors["trumps"];
str: "black"

rascal> colors[0];
Static Error: -:1,0: Expected str, but got int

rascal> colors["square"];
Uncaught Rascal Exception: -:1,0: NoSuchKey("square")

rascal> rel[str country, int year, int amount] GDP =
    {<"US", 2008, 14264600>, <"EU", 2008, 18394115>,
     <"Japan", 2008, 4923761>, <"US", 2007, 13811200>,
     <"EU", 2007, 13811200>, <"Japan", 2007, 4376705>};
rel[str,int,int] :
    {<"US", 2008, 14264600>, <"EU", 2008, 18394115>,
     <"Japan", 2008, 4923761>, <"US", 2007, 13811200>,
     <"EU", 2007, 13811200>, <"Japan", 2007, 4376705>}

rascal> GDP["Japan"];
rel[int,int] : {<2008, 4923761>, <2007, 4376705>}

rascal> GDP["Japan", 2008];
set[int] : {4923761}

```

Other Non-Boolean Operator Expressions. The other non-Boolean operator expressions are explained in more detail for each datatype, see the section called “Built-in Operators and Library Functions” (page 90).

Boolean Operator Expressions

The Boolean operators are summarized in Table 1.3, “Boolean Operators” (page 70) All operators are highly overloaded and we refer to the section called “Built-in Operators and Library Functions” (page 90) for a description of their meaning for each specific type. The Boolean operators have short-circuit semantics. Most operator are self-explanatory except the match (`:=`) and no match (`!:=`) operators that are also the main reason to treat Boolean operator expressions separately. Although we describe patterns in full detail in the section called “Patterns” (page 71) a preview is useful here. A pattern can

- match (or not match) any arbitrary value (that we will call the *subject value*);
- during the match variables may be bound to subvalues of the subject value.

Match Operator. The match operator

```
Pat := Exp
```

is evaluated as follows:

- *Exp* is evaluated, the result is a subject value;
- the subject value is matched against the pattern *pat*;
- if the match succeeds, any variables in the pattern are bound to subvalues of the subject value and the match expression yields `true`;
- if the match fails, no variables are bound and the match expression yields `false`.

This looks and *is* nice and dandy, so why all this fuss about Boolean operators? The catch is that-- as we will see in detail in the section called “Patterns” (page 71)--a match need not be unique.

This means that there may be more than one way of matching the subject value resulting in different variable bindings. A quick example. Consider the following match of a list

```
[1, list[int] L, 2, list[int] M] := [1,2,3,2,4]
```

By definition `list[int] L` and `list[int] M` match list elements that are part of the enclosing list in which they occur. If they should match a nested list each should be enclosed in list brackets.

There are two solutions for the above match:

- `L = []` and `M = [2, 3, 2, 4]`; and
- `L = [2, 3]` and `M = [4]`.

Depending on the context, only the first solution of a match expression is used, respectively all solutions are used. If a match expression occurs in a larger Boolean expression, a subsequent subexpression may yield false and -- depending on the actual operator -- evaluation *backtracks* to a previously evaluated match operator to try a next solution. Let's illustrate this by extending the above example:

```
[1, list[int] L, 2, list[int] M] := [1,2,3,2,4] && size(L) > 0
```

where we are looking for a solution in which `L` has a non-empty list as value. Evaluation proceeds as follows:

- The left argument of the `&&` operator is evaluated: the match expression is evaluated resulting in the bindings `L = []` and `M = [2, 3, 2, 4]`;
- The right argument of the `&&` operator is evaluated: `size(L) > 0` yields false;
- Backtrack to the left argument of the `&&` operator to check for more solutions: indeed there are more solutions resulting in the bindings `L = [2, 3]` and `M = [4]`;
- Proceed to the right operator of `&&`: this time `size(L) > 0` yields true;
- The result of evaluating the complete expression is true.

This behaviour is applicable in the context of all Rascal constructs where a pattern match determines the flow of control of the program, in particular:

- Boolean expressions: when a pattern match fails that is part of a Boolean expression, further solutions are tried in order to try to make the Boolean expression true.
- Tests in `for`, `while`, `do` statements.
- Tests in `one` and `all` expressions.
- Tests and enumerators in comprehensions.
- Pattern matches in `visit` expression and `switch` statement.
- Pattern matches during rewriting.

Table 1.3. Boolean Operators

Operator	Name	Description
<code>! Exp</code>	Negation	Negate <i>Exp</i> 's boolean value
<code>Exp ?</code>	IsDefined	true if <i>Exp</i> has a well-defined value, i.e., is the result of expression evaluation that ended without raising an exception
<code>Exp₁ in Exp₂</code>	ElementOf	Element of

Operator	Name	Description
$Exp_1 \text{ not in } Exp_2$	NotElementOf	Not element of
$Exp_1 \leq Exp_2$	LessThanOrEqual	Less than or equal on bool, int, real or string; sublist on list; subset on set, map or relation
$Exp_1 < Exp_2$	LessThan	Less than on bool, int, real or string; strict sublist on list; strict subset on set, map or relation
$Exp_1 \geq Exp_2$	GreaterThanOrEqual	Greater than or equal on bool, int, real or string; superlist on list; superset on set, map or relation
$Exp_1 > Exp_2$	GreaterThan	Greater than on bool, int, real or string; strict superlist on list; strict superset on set, map or relation
$Pat := Exp$	Match	Value of Exp matches with pattern Pat
$Pat !:= Exp$	NoMatch	Value of Exp does not match with pattern Pat
$Exp_1 == Exp_2$	Equal	Equality
$Exp_1 != Exp_2$	NotEqual	Inequality
$Exp_1 ? Exp_2$	IfDefinedElse	The value of Exp_1 if that is defined (i.e., is the result of expression evaluation that ended without raising an exception thus excluding, for instance, uninitialized variables and undefined map elements) otherwise the value of Exp_2
$Exp_1 ? Exp_2 : Exp_3$	IfThenElse	Conditional expression
$Exp_1 ==> Exp_2$	Implication	true, unless the value of Exp_1 is true and that of Exp_2 is false
$Exp_1 <==> Exp_2$	Equivalence	true if Exp_1 and Exp_2 have the same value
$Exp_1 \&\& Exp_2$	And	true if the value of both Exp_1 and Exp_2 is true
$Exp_1, Exp_2, \dots, Exp_n$	MultiCondition	Equivalent to: $Exp_1 \&\& Exp_2 \&\& \dots \&\& Exp_n$
$Exp_1 Exp_2$	Or	true if the value of either Exp_1 or Exp_2 is true
$Pat <- Exp$	Enumerator	true for every element in Exp 's value (set/list element, direct subtree) that matches Pat

Patterns

Patterns come in three flavours:

- *Regular expression patterns* to do string matching with regular expressions, see the section called “Regular Expression Patterns” (page 72).
- *Abstract patterns* to do matching on arbitrary values, see the section called “Abstract Patterns” (page 74).
- *Concrete syntax patterns* to match syntax trees that are the result of parsing, see the section called “Concrete Syntax Patterns” (page 76).

Regular Expression Patterns

Regular expression patterns are ordinary regular expressions that are used to match a string value and to decompose it in parts and also to compose new strings. Regular expression patterns bind variables of type `str` when the match succeeds, otherwise they do not bind anything. Their syntax and semantics parallels abstract and concrete syntax patterns as much as possible. This means that they can occur in cases of `visit` and `switch` statements, on the left-hand side of the match operator (`:=` or `!:=`) and as declarator in enumerators.

Here are some examples of regular expression patterns.

```
/\brascal\b/i
```

does a case-insensitive match (`i`) of the word `rascal` between word boundaries (`\b`). And

```
/^.*?<word:\w+><rest:.*$>/m
```

does a multi-line match (`m`), matches the first consecutive word characters (`\w`) and assigns them to the variable `word`. The remainder of the string is assigned to the variable `rest`. Constructs of the form `<Name:Regex>` are called variable **introductions**. They introduce a new variable for the duration of the regular expression match.

Regular expressions may also contain **references** to variables: their string value is used at the position of the variable reference. This can be used to define so-called **non-linear** patterns. This example

```
/<x:[a-z]+>---<x>/
```

matches strings like `abc---abc` that consist of two identical sequences of letters separated by three dashes. Variables that are referenced in a regular expression may also come from the context in which the regular expression occurs. For instance,

```
/<x><n>/
```

will use the current values of `x` and `n` as regular expression. For values `"abc"`, respectively, `3` this would be equivalent to the regular expression:

```
/abc3/
```

Observe that context variables may be of arbitrary type and that their value is first converted to a string before it is inserted in the regular expression. This can be used in many ways. For instance, regular expressions may contain restrictions on the number of repetitions of an element: `/a{3}/` will match exactly three letters `a`. Also minimum and maximum number of occurrences can be defined. Here is how the repetition count can be inserted by a variable reference (where `n` is assumed to have an integer value):

```
/a{<n>}/
```

Taking this example one step further, we can even write

```
/<x:a{<n>}>/
```

in other words, we introduce variable `x` and its defining regular expression contains a reference to a context variable.

We use a regular expression language that slightly extends/modifies the Java Regexp language:

- Regular expression are delimited by `/` and `/` optionally followed by modifiers (see below).
- We allow variable introductions, syntax `<Name:Regex>`, which introduce a variable of type `str` named `Name`. A variable introduction corresponds to a group in a Java regexp. Each variable that is introduced should be unique, but may be referenced more than once later in the regular expression.

- Java regular expressions allow optional groups, which may introduce null bindings. Since uninitialized variables are not allowed in Rascal, we limit the kinds of expressions one can write here by not allowing nesting of variable introductions.
- We allow variable references in a regular expression of the form: `<Name>` which inserts the string value of *Name* in the pattern. Name should have been introduced in the regular expression itself or in the context in which the regular expression occurs.
- In Perl matching options *follow* the regular expression, but Java uses the notation `(?Option)` at the *beginning* of the regular expression to set matching options. We support both styles. The following modifiers are supported:
 - multi-line matching: `(?m)` at the start of the regular expression or the modifier `m` at the end of the regular expression. The anchors `^` and `$` usually only match at the beginning and end of the subject string. When this option is set they also match any begin or end of line that is embedded in the subject string. Examples:

```
rascal> /XX$/ := "lineoneXX\nlinetwo";
bool: false
rascal> /XX$/m := "lineoneXX\nlinetwo";
bool: true
rascal> /(?m)XX$/ := "lineoneXX\nlinetwo";
bool: true
```

- case-insensitive matching: `(?i)` or modifier `i`. Match characters irrespective of their case. Examples:

```
rascal> /XX/ := "some xx";
bool: false
rascal> /XX/i := "some xx";
bool: true
rascal> /(?i)XX/ := "some xx";
bool: true
```

- single-line mode: `(?s)` or modifier `s`. The `.` expression does usually not match line terminators. When single-line mode is set, it will match any character including line terminators.

```
rascal> /a.c/ := "abc";
bool: true
rascal> /a.c/ := "a\nc";
bool: false
rascal> /a.c/s := "a\nc";
bool: true
rascal> /(?s)a.c/ := "a\nc";
bool: true
```

- unix lines: `(?d)` or modifier `d`. Usually newlines (`\n`), carriage return (`\r`) and new line carriage return (`\n\r`) sequences are all considered line terminators. When this option is set, only newline is considered to be a line terminator.



Further discuss here:

- grouping versus variable introduction.
- Quoting issues.
- Multiple matches.

For convenience, we summarize the most frequently used constructs in regular expressions in Table 1.4, “Frequently used elements of Regular Expression Syntax” (page 74).

Table 1.4. Frequently used elements of Regular Expression Syntax

Operator	Description
x	The single character x as long as it is not a punctuation character with a special meaning in the regular expression syntax
$\backslash p$	The punctuation character p
$\backslash \backslash$	The backslash character
$\backslash n$	Newline character
$\backslash t$	Tab character
$[\dots]$	One of the characters between the brackets (also known as character class). Character ranges and set operations on character classes may be used.
$[^ \dots]$	Any one character not between the brackets.
$[a-z0-9]$	Character range: character between a and z or 0 and 9 .
$\backslash d$	Digit: $[0-9]$
$\backslash D$	Non-digit: $[^0-9]$
$\backslash s$	Whitespace
$\backslash S$	Anything but whitespace.
$\backslash w$	A word: $[a-zA-Z0-9_]$
$\backslash W$	A non-word: $[^\backslash w]$
xy	Match x followed by y
$x y$	Match x or y
$x?$	Optional occurrence of x
x^*	Zero or more occurrences of x
x^+	One or more occurrences of x
$x\{n\}$	Exactly n occurrences of x
$x\{n, \}$	n or more occurrences of x
$x\{n, m\}$	At least n , at most m occurrences of x
$^$	The beginning of the subject string
$\$$	The end of the input string
$\backslash b$	Word boundary: position between a word and a non-word character
$\backslash B$	Non-word boundary: position that is not a word boundary

Abstract Patterns

An abstract pattern is recursively defined and may contain the following elements:

- *Literal* of one of the basic types `bool`, `int`, `real`, `str`, or `loc`. A literal pattern matches with a value that is identical to the literal.
- *A variable declaration pattern*

Type Var

A variable declaration introduces a new variable that matches any value of the given type. That value is assigned to `Var` when the whole match succeeds.

- *A multi-variable pattern*

*Var**

A multi-variable is an abbreviation for a variable declaration pattern. It can occur in a list pattern or set pattern and can match zero or more list or set elements.

- A *variable pattern*

```
Var
```

A variable pattern can act in two roles:

- If *Var* has already a defined value then it matches with that value.
- If *Var* has not been defined before (or it has been declared but not initialized) then it matches any value. That value is assigned to *Var*. *Explain scope*.

- A *list pattern*

```
[ Pat1, Pat2, ..., Patn ]
```

A list pattern matches a list value, provided that *Pat*₁, *Pat*₂, ..., *Pat*_n match the elements of that list in order. Two special cases exist when one of the patterns *Pat*_i is

- a variable declaration pattern with a list type that is identical to the type of the list that is being matched.
- a variable pattern, where the variable has been declared, but not initialized, outside the pattern with a list type that is identical to the type of the list that is being matched.

In both cases list matching is applied and the variable can match an arbitrary number of elements of the subject list.

- A *set pattern*

```
{ Pat1, Pat2, ..., Patn }
```

A set pattern matches a set value, provided that *Pat*₁, *Pat*₂, ..., *Pat*_n match the elements of that set in any order. Completely analogous to list patterns, there are two special cases when one of the patterns *Pat*_i is

- a variable declaration pattern with a set type that is identical to the type of the set that is being matched.
- a variable pattern, where the variable has been declared, but not initialized, outside the pattern with a set type that is identical to the type of the set that is being matched.

In both cases set matching is applied and the variable can match an arbitrary number (in arbitrary order!) of elements of the subject set.

- A *tuple pattern*

```
< Pat1, Pat2, ..., Patn >
```

A tuple pattern matches a tuple value, provided that *Pat*₁, *Pat*₂, ..., *Pat*_n match the elements of that tuple in order.

- A *node pattern*

```
Name ( Pat1, Pat2, ..., Patn )
```

A node pattern matches a node value or a datatype value, provided that *Name* matches with the constructor symbol of that value and *Pat*₁, *Pat*₂, ..., *Pat*_n match the children of that value in order.

- A *descendant pattern*

```
/ Pat
```

performs a deep match of the pattern *Pat*. In other words, it matches when any element of the subject at any depth matches *Pat* and is used to match, for instance, tree nodes at an arbitrary distance from the root.

- A *labelled pattern*

```
Var : Pat
```

A labelled pattern matches the same values as *Pat*, but has as side-effect that the matched value is assigned to *Var*.

- A *typed, labelled, pattern*

```
Type Var : Pat
```

A typed, labelled, pattern matches when the subject value has type *Type* and *Pat* matches. The matched value is assigned to *Var*.

- A *type constrained pattern*

```
[Type] Pat
```

matches provided that the subject has type *Type* and *Pat* matches.



Map patterns are currently not supported.

Concrete Syntax Patterns

Suppose we want to manipulate text written in some hypothetical language LANG. Then first the concrete syntax of LANG has to be defined by importing an SDF module that declares the non-terminals and syntax rules for LANG. Next LANG programs have to be parsed. LANG programs made come from text files or they may be included in the Rascal program as literals. In both cases the text is parsed according to the defined syntax and the result is a parse tree in the form of a value of type *Tree*. Concrete patterns operate on these trees.

A *concrete pattern* is a (possibly quoted) concrete syntax fragment that may contain variables. The syntax that is used to parse the concrete pattern may come from any SDF module that has been imported in the module in which the concrete pattern occurs. The

We want to cover the whole spectrum from maximally quoted patterns that can unambiguously describe **any** syntax fragment to minimally quoted patterns as we are used to in ASF+SDF. A concrete pattern may have the following forms:

- A *Quoted pattern*

```
` Token1 Token2 ... Tokenn `
```

Inside a quoted pattern arbitrary lexical tokens may occur. Quoted patterns may contain variable declaration patterns and variable patterns (see below).

- A *typed quoted pattern*

```
(Symbol) ` Token1 Token2 ... Tokenn `
```

is a quoted pattern that is preceded by an SDF symbol to define its desired syntactic type.

- An *unquoted pattern*

```
Token1 Token2 ... Tokenn
```

is a quoted pattern without the surrounding quotes.

- A *typed variable pattern*

```
<Type Var>
```

- A *variable pattern*

```
<Var>
```

- Inside syntax patterns, layout is ignored.

Examples (in a context where an SDF module has been imported that defines the appropriate syntax):

- Quoted syntax pattern with two pattern variable declarations:

```
` while <EXP Exp> do <{STATEMENT ";"}* Stats> od `
```

Two observations can be made about this example:

- The non-terminals (sorts in SDF parlance) `EXP` and `{STATEMENT ";"}* Stats` are declared in the imported SDF module and can be used as types in the Rascal program.
- When this pattern is matched successfully against a subject, the variables `Exp` and `Stats` will be bound.
- Quoted syntax pattern with two pattern variable uses (`Exp` and `Stats` should already have a value):

```
` while <Exp> do <Stats> od `
```

- Identical to the previous example, but with a declaration of the desired syntactic type:

```
STATEMENT ` while <Exp> do <Stats> od `
```

- Unquoted syntax pattern with two pattern variable declarations:

```
while <EXP Exp> do <{STATEMENT ";"}* Stats> od
```

- Unquoted syntax pattern with two pattern variable uses (`Exp` and `Stats` should already have a value):

```
while <Exp> do <Stats> od
```

Obviously, with less quoting and type information, the probability of ambiguities increases. These ambiguities may have the following sources:

- The most common situation is that the concrete pattern interferes with other imported SDF modules or with the syntax of Rascal itself. In this case, adding more quotes and declaring the type of pattern variables and patterns will ultimately resolve the ambiguity. Our assumption is that better type checkers for Rascal can resolve many of them.
- The imported SDF module defines an ambiguous language. In this case the only possible approach is to remove the ambiguities from that SDF definition. This is a black art and may require advanced skills in grammar engineering.

PatternWithAction

Patterns can be used in various contexts, but a common context is a *PatternWithAction*, which in its turn, may be used in a switch statement, visit expression or rewrite rule.

A *PatternWithAction* can have one of the following two forms:

- *Pat => Exp*

When the subject matches *Pat*, the expression *Exp* is evaluated and the subject is replaced with the result.

- *Pat : Statement*

When the subject matches *Pat*, the *Statement* is executed.

In switch statements, only the form *Pat : Statement* is allowed. When the subject matches *Pat*, the *Statement* is executed and the execution of the switch statement is complete. However, when a fail statement is executed in *Statement* all its side effects are undone and further alternatives of *Pat* are tried. If no alternatives remain, *PatternWithAction* as a whole fails and subsequent cases of the switch statement are tried. Also see the section called “Switch Statement” (page 85).

In visit expressions, the form *Pat => Exp* describes subtree replacement: the current subtree of the subject of the visit expression is replaced by the value of *Exp*. The form *Pat : Statement* is as described for switch statements, with the addition that execution of an insert statement will replace the current subtree. After both success or failure of the *PatternWithAction*, the traversal of the subject continues. Also see the section called “Visit Expression” (page 80).

In rewrite rules, both forms are allowed. The form *Pat => Exp* behaves as described for visit expressions. The form *Pat : Statement* is as described for switch statement. If the *PatternWithAction* fails another rule will be tried. Also see the section called “Rewrite Rule Declaration” (page 64).

Comprehension Expression

Comprehensions provide a concise notation to conditionally generate new values. We will use the familiar notation for *list comprehension*

```
[Exp1, ..., Expn | Gen1, ..., Genm]
```

to denote the construction of a list consisting of the successive values of the *contributing expressions* *Exp₁, ..., Exp_n*. The value of the resulting list is determined by *Exp₁, ..., Exp_n* and the *generators* *Gen₁, ..., Gen_m*. *Exp₁, ..., Exp_n* are computed for all possible combinations of values produced by the generators. Each generator may introduce new variables that can be used in subsequent generators as well as in the expressions. A generator can use the variables introduced by preceding generators. Generators may enumerate all the values in a subject value.

Generators may also perform an arbitrary test. When the test fails, execution continues with the preceding generator (if any).

In addition to list comprehensions, Rascal also supports *set comprehension*

```
{Exp1, ..., Expn | Gen1, ..., Genm}
```

that also serve as relation comprehension in the case that *Exp* is of a tuple type.

Finally, *map comprehensions* are written as:

```
(Exp1 : Exp2 | Gen1, ..., Genm)
```

Since the entries in a map require both a key and a value for each entry, always two expressions are needed in this case.

Enumerator

The first of the two possible forms of a generator is an *enumerator* that generates all the values in a given subject value. For elementary types (bool, int, real, loc, str) this is just a singleton. For composite

types (list, set, map, tuple, rel, node) the values of their elements, respectively, their direct children are enumerated. An enumerator has the following form:

```
Pat <- Exp
```

where *Pat* is a pattern and *Exp* is an expression. An enumerator is evaluated as follows:

- Expression *Exp* is evaluated and may have an arbitrary value *V*.
- The elements of *V* are enumerated one by one.
- Each element value is matched against the pattern *Pat*. There are two cases:
 - The match succeeds, any variables in *Pat* are bound, and the next generator in the comprehension is evaluated. The variables that are introduced by an enumerator are only available to generators that appear later (i.e., to the right) in the comprehension. When this enumerator is the last generator in the comprehension, the contributing expressions of the comprehension are evaluated.
 - The match fails, no variables are bound. If *V* has more elements, a next element is tried. Otherwise, a previous generator (i.e., to the left) is tried. If this enumerator is the first generator in the comprehension, the evaluation of the comprehension is complete.

These are examples of enumerators:

- `int N <- {1, 2, 3, 4, 5},`
- `str K <- KEYWORDS`, where `KEYWORDS` should evaluate to a value of `set[str]`.
- `<str K, int N> <- {"a",10>, <"b",20>, <"c",30>}`.
- `<str K, int N> <- FREQUENCIES`, where `FREQUENCIES` should evaluate to a value of type `rel[str,int]`.
- `<str K, 10> <- FREQUENCIES`, will only generate pairs with 10 as second element.
- `int N <- 17`, will only generate the value 17.



Type information is used to check the validity of an enumerator and guard you against mistakes. An impossible enumerator like `int N <- {"apples", "oranges"}` will be flagged as an error since the pattern can never match.

Test

The second of the two possible forms of a generator is a *test*, a boolean-valued expression. If the evaluation of the test gives `true` this indicates that the current combination of generated values up to this test is still desired and execution continues with subsequent generators. If the evaluation gives `false` this indicates that the current combination of values is undesired, and that another combination should be tried by going back to the previous generator.

Examples:

- `N >= 3` tests whether `N` has a value greater than or equal 3.
- `S == "coffee"` tests whether `S` is equal to the string `"coffee"`.

In both examples, the variable (`N`, respectively, `S`) should have been introduced by a generator that occurs earlier in the comprehension.

Examples of Comprehensions

Here are some examples of comprehensions:

```

rascal> {x | int x <- {1, 2, 3, 4, 5}, x >= 3};
set[int] : {3,4,5}

rascal> {<x, y> | int x <- {1, 2, 3}, int y : {2, 3, 4}, x >= y};
rel[int,int] : {<2, 2>, <3, 2>, <3, 3>}

rascal> {<y, x> | <int x, int y> <- {<1,10>, <2,20>}};
rel[int,int] : {<10,1>, <20,2>}

rascal> {x, x * x | int x <- {1, 2, 3, 4, 5}, x >= 3};
set[int] : {3,4,5,9,16,25}

```

Visit Expression

Visiting the nodes in a tree is a very common task in the EASY domain. In many cases (but certainly not all) the tree is a syntax tree of some source code file and the nodes correspond to expressions or statements. Computing metrics or refactoring are examples of tasks that require a tree visit. In object-oriented programming, the *visitor pattern* is in common use for this. There are three frequently occurring scenarios:

- Accumulator: traverse the tree and collect information.
- Transformer: traverse the tree and transform it into another tree.
- Accumulating Transformer: traverse the tree, collect information and also transform the tree.

The `visit` expression in Rascal can accommodate all these (and more) use cases and has the form:

```

Strategy visit ( Exp ) {
case PatternWithAction1;
case PatternWithAction2;
...
default: ...
}

```

Given a subject term (the current value of *Exp*) and a list of cases (consisting of *PatternWithActions*, see the section called “*PatternWithAction*” (page 77) it traverses the term. Depending on the precise actions it may perform replacement (mimicking a transformer), update local variables (mimicking an accumulator) or a combination of these two (accumulating transformer). If **any** of the actions contains an `insert` statement, the value of the visit expression is a new value that is obtained by successive insertions in the subject term by executing one or more cases. Otherwise, the original value of the subject term is returned.

The visit expression is optionally preceded by one of the following strategy indications that determine the traversal order of the subject:

- top-down: visit the subject from root to leaves.
- top-down-break: visit the subject from root to leaves, but stop at the current path when a case matches.
- bottom-up: visit the subject from leaves to root (this is the default).
- bottom-up-break: visit the subject from leaves to root, but stop at the current path when a case matches.
- innermost: repeat a bottom-up traversal as long as the traversal changes the resulting value (compute a fixed-point).
- outermost: repeat a top-down traversal as long as the traversal changes the resulting value (compute a fixed-point).

The execution of the cases has the following effect:

- A *PatternWithAction* of the form *Pat* => *Exp* replaces the current subtree of the subject by the value of *Exp*. Note that a copy of the subject is created at the start of the visit statement and all replacements are made in this copy. As a consequence, modifications made during the visit cannot influence matches later on. The modified copy of the subject is ultimately returned by the visit expression.
- A *PatternWithAction* of the form *Pat* : *Statement* executes *Statement* and this should lead to one of the following:
 - Execution of an `insert` statement of the form

```
insert Exp2
```

The value of *Exp2* replaces the subtree of the subject that is currently being visited. Once again, this modification takes place in a copy of the original subject (see above).



An `insert` statement may only occur in a *PatternWithAction* in a visit expression or a rule.



Pat => *Exp* is equivalent with *Pat* : `insert Exp`;

- Execution of a `fail` statement: all side effects of *Statement* are undone, no insertion is made, and the next case is tried.
- Execution of a `return` statement that returns a value from the enclosing function.

The precise behaviour of the visit expression depends on the type of the subject:

- For type `node` or `ADT`, all nodes of the tree are visited (in the order determined by the strategy). Concrete patterns and abstract patterns directly match tree nodes. Regular expression patterns match only values of type `string`.
- For other structured types (`list`, `set`, `map`, `tuple`, `rel`), the elements of the structured type are visited and matched against the cases. When inserts are made, a new structured value is created. In these cases a strategy does not have any effect.

One Expression

```
one ( Exp1 , Exp2 , ... , Expn )
```

The one expression yields true when one combination of values of *Exp_i* is true.

All Expression

```
all ( Exp1 , Exp2 , ... , Expn )
```

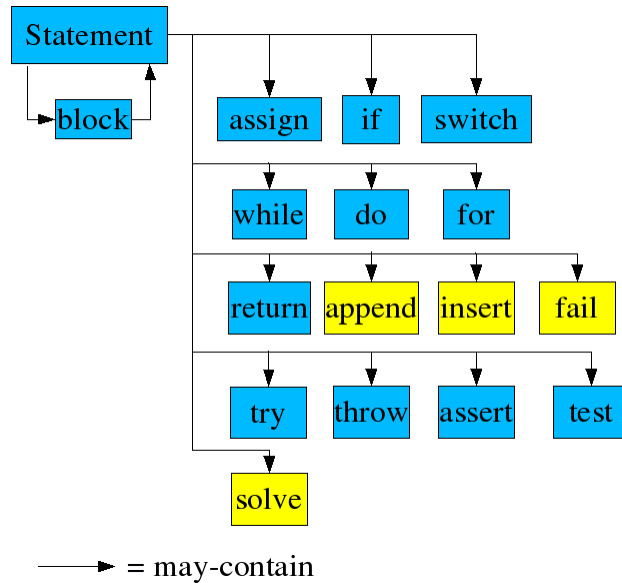
The all expression yields true when all combinations of values of *Exp_i* are true.

Statement as Expression

Several forms of statements produce a value and can be used as expression. This is further explained in the sections for the relevant statements, see the section called “If Statement” (page 85) the section called “While Statement” (page 85) the section called “Do Statement” (page 86) and the section called “For Statement” (page 86).

Statements

Figure 1.22. Various Statement Forms



The various statements forms are summarized in Figure 1.22, “Various Statement Forms” (page 82). The less familiar statements are shown in a different color.

Block Statement

A block consists of a sequence of statements separated by semi-colons:

```
{ Statement1 ... Statementn }
```

Since a block is itself a statement, it may be used in all places where a statement is required. A block also introduces a new scope and variables that are declared in the block are local to that block. The value produced by a block is the value produced by its last statement.

Assignment Statement

The purpose of an assignment is to assign a new value to a simple variable or to an element of a more complex data structure. The most general form of an assignment statement is

```
Assignable AssignmentOp Exp
```

where *AssignmentOp* may be =, +=, -=, *=, /=, or ?=. Here = is the ordinary assignment operators and the other forms can be derived from it according to Table 1.5, “Assignment Operators” (page 82).

Table 1.5. Assignment Operators

Assignment Operator	Equivalent to
<i>Assignable</i> += <i>Exp</i>	<i>Assignable</i> = <i>Assignable</i> + <i>Exp</i>
<i>Assignable</i> -= <i>Exp</i>	<i>Assignable</i> = <i>Assignable</i> - <i>Exp</i>
<i>Assignable</i> *= <i>Exp</i>	<i>Assignable</i> = <i>Assignable</i> * <i>Exp</i>
<i>Assignable</i> /= <i>Exp</i>	<i>Assignable</i> = <i>Assignable</i> / <i>Exp</i>
<i>Assignable</i> &= <i>Exp</i>	<i>Assignable</i> = <i>Assignable</i> & <i>Exp</i>
<i>Assignable</i> ?= <i>Exp</i>	<i>Assignable</i> = <i>Assignable</i> ? <i>Exp</i>

An assignable is either a single variable, (the *base variable*), optionally followed by subscriptions or field selections. The assignment statement always results in assigning a *completely new value* to the base variable. We distinguish the following forms of assignment:

- `Var = Exp`

The expression *Exp* is evaluated and its value is assigned to the base variable *Var*.

- `Assignable [Exp1] = Exp2`

First the value *V* of *Assignable* is determined. Next the value of *Exp₁* is used as index in *V* and the value of *Exp₂* replaces the original value at that index position. The result is a new value *V'* that is assigned to the *Assignable*.

- `Assignable . Name = Exp`

The value *V* of *Assignable* is determined and should be of a type that has a field *Name*. The value of that field is replaced in *V* by the value of *Exp* resulting in a new value *V'* that is assigned to *Assignable*.

- `< Assignable1, Assignable2, ..., Assignablen > = Exp`

First the value *Exp* is determined and should be a tuple of the form $\langle V_1, V_2, \dots, V_n \rangle$. Next the assignments $Assignable_i = V_i$ are performed for $1 \leq i \leq n$.

- `Assignable ? Exp1 = Exp2`

First the value of *Exp₂* is determined and if that is defined it is assigned to *Assignable*. Otherwise, the value of *Exp₁* is assigned to *Assignable*.



Does not seem to work

- `Assignable @ Name = Exp`

The value *V* of *Assignable* is determined and should be of a type that has an annotation *Name*. The value of that annotation is replaced in *V* by the value of *Exp* resulting in a new value *V'* that is assigned to *Assignable*.

- `Name (Assignable1, Assignable2, ...) = Exp`

First the value *Exp* is determined and should be a data value of the form $Name(V_1, V_2, \dots, V_n)$. Next the assignments $Assignable_i = V_i$ are performed for $1 \leq i \leq n$.



Constructor assignable is not yet implemented.

Here are some examples:

```
rascal> N = 3;
int : 3

rascal> N;
int : 3

rascal> L = [10,20,30];
list[int] : [10,20,30]

rascal> P = L;
```

```

list[int] : [10,20,30]

rascal> L[1] = 200;
list[int] : [10,200,30]

rascal> P; // Value of P is unchanged!
list[int] : [10,20,30]

rascal> M = ("abc": 1, "def" : 2);
map[str,int] : ("abc": 1, "def" : 2)

rascal> M["def"] = 3;
map[str,int] : ("abc": 1, "def" : 3)

rascal> T = <1, "abc", true>;
tuple[int,str,bool] : <1, "abc", true>

rascal> T[1] = "def";
tuple[int,str,bool] : <1, "def", true>

rascal> data FREQ = wf(str word, int freq);
ok

rascal> W = wf("rascal", 1000);
FREQ : wf("rascal", 1000)

rascal> W.freq = 100000;
FREQ : wf("rascal",100000)

rascal> <A, B, C> = <"abc", 2.5, [1,2,3]>;
tuple[str,real,list[int]] : <"abc", 2.5, [1,2,3]>

rascal> A;
str : "abc"

rascal> B;
real : 2.5

rascal> C;
list[int] : [1,2,3]

rascal> T = ("a" : 1);
map[str, int]: ("a":1)

rascal> T["b"] ? 1 += 5;
map[str, int]: ("b":6,"a":1)

rascal> anno str FREQ@color;
ok

rascal> W @ color = "red";
FREQ: wf("rascal",100000)[@color="red"]

rascal> wf(S, I) = W;
ok

rascal> S;
str : "rascal"

```

```
rascal> I;  
int : 100000
```

If Statement

The if-statement comes in an if-then and an if-then-else variant:

```
if ( Bool ) Statement
```

```
if ( Bool ) Statement1 else Statement2
```

In both cases the test *Bool* is evaluated and its outcome determines the statement to be executed. Recall from the section called “Boolean Operator Expressions”(page 69)that boolean expression maybe multi-valued. In this case only the first true value (if any) is used. The value of an if-then statement is always void. The value of an if-then-else statement is the value of the statement executed in the then or else branch.

Switch Statement

A switch statement is similar to a switch statement in C or Java and has the form:

```
switch ( Exp ) {  
case PatternWithAction1;  
case PatternWithAction2;  
...  
default: ...  
}
```

The value of the expression *Exp* is the subject term that will be matched by the successive *PatternWithActions* (see the section called “PatternWithAction” (page 77) in the switch statement. The switch statement provides **only** matching at the top level of the subject term and does not traverse it. The type of the pattern in each case must be identical to the type of the subject term (or be a supertype of it). If no case matches, the switch acts as a dummy statement. There is no fall through from one case to the next.



The switch statement does not yet return a value, this will be changed.

While Statement

The while-statement has the form:

```
while ( Bool ) Statement
```

The test *Bool* is evaluated repeatedly and *Statement* is executed when the test is true. Execution ends the first time that the test yields false. The test *Bool* is executed from scratch in each repetition and only the first true value (if any) is used.

By default, the value of a while statement is the empty list. In general, the value of a while statement consists of all values contributed by append statements that are executed during the repeated execution of its body *Statement*.



Append is not yet implemented for this statement.

Do Statement

The do-while-statement has the form:

```
do Statement while ( Bool )
```

Statement is executed repeatedly, as long as the test *Bool* yields true. The test *Bool* is executed from scratch in each repetition and only the first true value (if any) is used.

By default, the value of a do statement is the empty list. In general, the value of a do statement consists of all values contributed by append statements that are executed during the repeated execution of its body *Statement*.



Append is not yet implemented for this statement.

For Statement

The for-statement has the form:

```
for ( Exp1 , Exp2 , ... , Expn ) Statement
```

It executes *Statement* for all possible combinations of values of the expressions *Exp*_i. Note that if one of the expressions is a boolean expression, we do try all its possible values.

By default, the value of a for statement is the empty list. In general, the value of a for statement consists of all values contributed by append statements that are executed during the repeated execution of its body *Statement*.

Return Statement

A return statement has either the form

```
return;
```

or

```
return Exp;
```

both end the execution of the current function. The first form applies to functions with `void` as return type. The second form applies to non-void functions and returns the value of *Exp* as result of the function. The following rules apply:

- The static type of *Exp* should be compatible with the declared return type of the function in which the return statement occurs.
- In each function with a return type that is not `void`, every possible execution path through the body of the function should end in a return statement.



This rule is not yet enforced.

- In each function with a return type that is `void`, a return statement is implicitly assumed at the end of each execution path through the function body.

Append Statement

An append statement may only occur in the body of a while, do or for statement. It has the form

```
append Exp;
```

and appends the value of *Exp* to the resulting list value of the loop construct in which it occurs.

Insert Statement

An insert statement has the form

```
insert Exp;
```

and replaces the value of the *current subject* (see below) by the value of *Exp*. An insert statement may only occur in the action part of a `PatternWithAction` (see the section called “`PatternWithAction`” (page 77)), more precisely in

- A case in a visit expression, see the section called “Visit Expression” (page 80) The current subject is the value matched by the pattern of this case.
- An action of a rewrite rule, see the section called “Rewrite Rule Declaration” (page 64) The current subject is the value matched by the pattern of the rewrite rule.

The following rule applies:

- The static type of *Exp* should be a subtype of the type of the current subject.

Fail Statement

A fail statement has the form

```
fail;
```

and may only occur in the action of `PatternWithAction` (see the section called “`PatternWithAction`” (page 77)). The fail statement forces the failure of that action. Any bindings caused by the pattern or side-effects caused by the action are undone.

Try Catch Statement

A try catch statement has the form

```
try
  Statement1;
catch PatternWithAction1;
catch PatternWithAction2;
...
catch: Statement2;
finally: Statement3;
```

and has as purpose to catch any exceptions that are raised during the execution of *Statement*₁. These exceptions may be caused by:

- The execution of an explicit throw statement, see the section called “Throw Statement” (page 88).
- The Rascal system that discovers an abnormal condition, e.g., an out of bounds error when accessing a list element.

Note that all elements of the try catch statement are optional but that at least one has to be present. Their meaning is as follows:

- If a pattern of some *PatternWithAction*_{*i*} matches, the corresponding action is executed.
- Otherwise, *Statement*₂ is executed (when present).

- Before leaving the try catch statement *Statement*₃ is always executed (when present).

Throw Statement

A throw statement has the form

```
throw Exp;
```

and causes the immediate abortion of the execution of the current function with *Exp*'s value as exception value. The exception can be caught by a try catch statement (the section called “Try Catch Statement” (page 87) in the current function or in one of its callers. If the exception is not caught, the execution of the Rascal program is terminated. The following rules apply:

- The static type of *Exp* should be `RuntimeException`, see the section called “Exception” (page 92).
- The Rascal program may contain data declarations that extend the type `RuntimeException`.

Assert Statement

An assert statement may occur everywhere where a declaration is allowed. It has two forms:

```
assert Exp1
```

and

```
assert Exp1 : Exp2
```

where *Exp*₁ is a boolean-value expression and *Exp*₂ is a string-valued expression that serves as a identifying message for this assertion. When *Exp*₁ evaluates to false, an `AssertionFailed` exception is thrown.

Example:

```
rascal> assert 1==2 : "is never true";
Uncaught Rascal Exception: -:1,0: AssertionFailed("is never true")

rascal> int div(int x, int y) {
    assert y != 0 : "y must be non-zero";
    return x / y;
}
int (int, int): int div(int, int);

rascal> div(4,0);
Uncaught Rascal Exception: -:2,2: AssertionFailed("y must be non-zero")
:1,0: div
```

Test Statement

A test statement forms the basis for Rascal's unit-testing framework and may occur everywhere where a declaration is allowed. It has two forms:

```
test Exp1
```

and

```
test Exp1 : Exp2
```

where *Exp*₁ is a boolean-value expression and *Exp*₂ is a string-valued expression that serves as a identifying message for this test.

During normal execution tests are ignored and the test statement has no affect. When the script is executed as a *test suite* all tests in the current module and all its imported modules are executed and a summary of succeeded/failed tests is shown to the user.

```
rascal>test 1==2;      ❶
ok
rascal>:test          ❷
failed : test 1==2
ok
```

- ❶ The test is ignored during standard execution.
- ❷ There are two ways to execute as test suite. By executing the `:test` directive of the Rascal shell (shown here) or by setting the option `rascal.options.testsuite` (*not yet implemented*).

Solve Statement

Rascal provides a solve statement for performing arbitrary fixed-point computations. This means, repeating a certain computation as long as it causes changes. This can, for instance, be used for the solution of sets of simultaneous linear equations but has much wider applicability. The format is:

```
solve(Var1, Var2, ..., Varn)
    Statement
```

The solve statement consists of the variables for which a fixed point will be computed and a statement. These variables should already exist in the context of the solve statement. Optionally, an expression directly following the list of variables gives an upper bound on the number of iterations. The format then becomes:

```
solve(Var1, Var2, ..., Varn; Exp)
    Statement
```

Statement can use and modify the listed variables *Var_i*. The statement is executed, assigning new values to the variables *Var_i*, and this is repeated as long as the value of any of the variables was changed compared to the previous repetition. Note that this computation will only terminate if the variables range over a so-called bounded monotonic lattice, in which values can only become larger until a fixed upperbound or become smaller until a fixed lower bound.

Let's consider transitive closure as an example (transitive closure is already available as built-in operator, we use it here just as a simple illustration). Transitive closure of a relation is usually defined as:

$$R^+ = R + (R \circ R) + (R \circ R \circ R) + \dots$$

In other words, it is the union of successive compositions of the relation *R* with itself. This can be expressed as follows:

```
rascal> rel[int,int] R = {<1,2>, <2,3>, <3,4>};
rel[int,int] : {<1,2>, <2,3>, <3,4>}
rascal> T = R;
rel[int,int] : {<1,2>, <2,3>, <3,4>}
rascal> solve (T) {
    T = T + (T o R);
}
rel[int,int] : {<1,2>, <1,3>, <1,4>, <2,3>, <2,4>, <3,4>}
```

Built-in Operators and Library Functions

The built-in operators and library functions can be subdivided in the following categories:

- ATermIO: reading and writing values in the ATerm format, see the section called “ATermIO” (page 91).
- Benchmark: measuring functions, see the section called “Benchmark” (page 91).
- Boolean: operators and functions on Boolean values, see the section called “Boolean” (page 92).
- Exception: data definition of all soft exceptions that can be caught by Rascal programs, see the section called “Exception” (page 92).
- Graph: graphs are a special kind of binary relation, see the section called “Graph” (page 93).
- Integer: operators and functions on integers, see the section called “Integer” (page 94).
- IO: simple print functions, see the section called “IO” (page 94).
- JDT: Java fact extraction functions, see the section called “JDT (Eclipse only)” (page 95).
- Labelled Graph: labelled graphs with addition edge information, see the section called “Labeled Graph” (page 98).
- List: operators and functions on lists, see the section called “List” (page 99).
- Location: operators and functions on source locations, see the section called “Location” (page 100).
- Map: operators and functions on maps, see the section called “Map” (page 101).
- Node: operators and functions on nodes, see the section called “Node” (page 102).
- PriorityQueu: functions on priority queues, see the section called “PriorityQueue” (page 103).
- Real: operators and functions on reals, see the section called “Real” (page 103).
- Relation: operators and functions on relations, see the section called “Relation” (page 104).
- Resource: functions to retrieve resources from an Eclipse workspace, see the section called “Resources (Eclipse only)” (page 107).
- RSF: function for reading files in Rigi Standard Format, see the section called “RSF” (page 107).
- Set: operators and functions on sets, see the section called “Set” (page 108).
- String: operators and functions on strings, see the section called “String” (page 110).
- Tree: functions on parse trees, see the section called “Tree” (page 112).
- Tuple: operators and functions on tuples, see the section called “Tuple” (page 112).
- ValueIO: functions for reading and writing Rascal values, both in textual and in binary form, see the section called “ValueIO” (page 113).
- viz::Basic: basic visualization functions for graphical display of values in Eclipse, see the section called “viz::Basic (Eclipse only)” (page 113).
- viz::Chart: functions to draw various charts, see the section called “viz::Figure::Chart” (page 118).

All operators are directly available for each program, but library functions have to be imported in each module that uses them.

We use some notational conventions to describe the argument of operators, as shown in Table 1.6, “Notational conventions” (page 91) When an operator has more than one argument of the same type, they are distinguished by subscripts.

Table 1.6. Notational conventions

Argument	Describes expression of type
<i>Bool</i>	bool
<i>Int</i>	int
<i>Real</i>	real
<i>Number</i>	int or real
<i>Str</i>	str
<i>Loc</i>	loc
<i>Node</i>	node
<i>List</i>	Any list type
<i>Set</i>	Any set type
<i>Map</i>	Any map type
<i>Tuple</i>	Any tuple type
<i>Rel</i>	Any rel type
<i>Value</i>	value
<i>Elm</i>	Compatible with element type of list, set, map, relation

ATermIO

ATerms are a general data format for exchanging tree structured data between programs. ATerms are language and computer architecture neutral and can thus be used to exchange data between programs that are written in different programming languages and that run on different, incompatible, computers. ATerms are extensively used in the ToolBus, the ASF+SDF Meta-Environment, Stratego, TOM, and other systems. The ATermIO library provides functions to convert a Rascal value to an ATerm and to write that ATerm to a text file and also to read an ATerm from a text file and to convert that ATerm to a Rascal value.

Table 1.7. ATermIO Functions

Function	Description
public &T readTextATermFile(type[&T] start, loc location)	Read a value in ATerm format from a text file and convert it to a specific type
public value readTextATermFile(loc location)	Read a value in ATerm format from a text file
public void java writeTextATermFile(loc location, value v)	Convert a value to ATerm format and write it to a text file

Benchmark

Benchmark provides a rudimentary benchmarking framework.



Check benchmark function

Table 1.8. Benchmark Functions

Function	Description
<code>real currentTimeMillis()</code>	Current time in milliseconds since January 1, 1970 GMT.
<code>public void benchmark(map[str, void()] Cases)</code>	Measure and report the execution time of name:void-closure pairs.

Boolean

Table 1.9. Boolean Operators

Operator	Description
$Bool_1 == Bool_2$	Yields true if both arguments are identical
$Bool_1 != Bool_2$	Yields true if both arguments are not identical
$Bool_1 <= Bool_2$	Yields true if both arguments are identical or $Bool_1$ is false and $Bool_2$ is true
$Bool_1 < Bool_2$	Yields true if $Bool_1$ is false and $Bool_2$ is true
$Bool_1 >= Bool_2$	Yields true if both arguments are identical or $Bool_1$ is true and $Bool_2$ is false
$Bool_1 > Bool_2$	Yields true if $Bool_1$ is true and $Bool_2$ is false
$Bool_1 \&\& Bool_2$	Yields true if both arguments have the value true and false otherwise
$Bool_1 Bool_2$	Yields true if either argument has the value true and false otherwise
$Bool_1 ==> Bool_2$	Yields false if $Bool_1$ has the value true and $Bool_2$ has value false, and true otherwise
$! Bool$	Yields true if Bool is false and true otherwise
$Bool_1 ? Bool_2 : Bool_3$	If $Bool_1$ is true then $Bool_2$ else $Bool_3$

Table 1.10. Boolean Functions

Function	Description
<code>bool arbBool()</code>	Arbitrary boolean value
<code>bool fromInt(int i)</code>	Convert an integer to a bool
<code>bool fromString(str s)</code>	Convert the strings "true" or "false" to a bool
<code>int toInt(bool b)</code>	Convert a boolean value to integer
<code>real toReal(bool b)</code>	Convert a boolean value to a real value
<code>str toString(bool b)</code>	Convert a boolean value to a string

Exception

The following "soft" exceptions can be caught by the Rascal program:

```
data RuntimeException =
  EmptyList()
  | EmptyMap()
  | EmptySet()
  | IndexOutOfBounds(int index)
  | AssertionFailed()
  | AssertionFailed(str label)
```

```

NoSuchElement(value v)
IllegalArgument(value v)
IllegalArgument()
IO(str message)
PathNotFound(loc l)
SchemeNotSupported(loc l)
HostNotFound(loc l)
AccessDenied(loc l)
PermissionDenied()
PermissionDenied(str message)
ModuleNotFound(str name)
NoSuchKey(value key)
NoSuchAnnotation(str label)
Java(str message)
ParseError(loc location)
IllegalIdentifier(str name)
;

```

Graph

The graph datatype is a special form of binary relation defined as follows:

```
alias Graph[&T] = rel[&T from, &T to];
```

All operators and functions on relations are applicable to graphs, see the section called “Relation” (page 104). Also see the section called “Labeled Graph” (page 98).

Table 1.11. Graph Functions

Function	Description
set[&T] bottom(Graph[&T] G)	Leaf nodes of a graph
set[&T] predecessors(Graph[&T], &T From)	Direct predecessors of node From
set[&T] reach(Graph[&T] G, set[&T] Start)	Reachability from set of start nodes.
set[&T] reachR(Graph[&T] G, set[&T] Start, set[&T] Restr)	Reachability from set of start nodes with restriction to certain nodes.
set[&T] reachX(Graph[&T] G, set[&T] Start, set[&T] Excl)	Reachability from set of start nodes with exclusion of certain nodes
list[&T] shortestPathPair(Graph[&T] G, &T From, &T To)	Shortest path between pair of nodes
set[&T] successors(Graph[&T], &T From)	Direct successors of node From
set[&T] top(Graph[&T] G)	Root nodes of a graph

The following examples illustrate these functions:

```

rascal> top(<{<1,2>, <1,3>, <2,4>, <3,4>}>);
set[int] : {1}

rascal> bottom(<{<1,2>, <1,3>, <2,4>, <3,4>}>);
set[int] : {4}

rascal> reachR(<{<1,2>, <1,3>, <2,4>, <3,4>}>, {1}, {1, 2, 3});
set[int] : {2, 3}

```

```
rascal> reachX(<{<1,2>, <1,3>, <2,4>, <3,4>}, {1}, {2});
set[int,int] : {3, 4}
```

Integer

Rascal integers are unbounded in size.

Table 1.12. Integer Operators

Operator	Description
$Int_1 == Int_2$	Yields true if both arguments are numerically equal and false otherwise
$Int_1 != Int_2$	Yields true if both arguments are numerically unequal and false otherwise
$Int_1 <= Int_2$	Yields true if Int_1 is numerically less than or equal to Int_2 and false otherwise
$Int_1 < Int_2$	Yields true if Int_1 is numerically less than Int_2 and false otherwise
$Int_1 >= Int_2$	Yields true if Int_1 is numerically greater than or equal than Int_2 and false otherwise
$Int_1 > Int_2$	Yields true if Int_1 is numerically greater than Int_2 and false otherwise
$Int_1 + Int_2$	Sum of Int_1 and Int_2
$Int_1 - Int_2$	Difference of Int_1 and Int_2
$Int_1 * Int_2$	Int_1 multiplied by Int_2
Int_1 / Int_2	Int_1 divided by Int_2
$Int_1 \% Int_2$	Remainder of dividing Int_1 by Int_2
$- Int$	Negate sign of Int
$Bool ? Int_1 : Int_2$	If $Bool$ is true then Int_1 else Int_2

Table 1.13. Integer Functions

Function	Description
<code>int abs(int N)</code>	Absolute value of integer N
<code>int arbInt()</code>	Arbitrary integer value
<code>int arbInt(int limit)</code>	Arbitrary integer value in the interval [0, limit)
<code>int max(int n, int m)</code>	Largest of two integers
<code>int min(int n, int m)</code>	Smallest of two integers
<code>real toReal(int n)</code>	Convert an integer value to a real value
<code>str toString(int n)</code>	Convert an integer value to a string

IO

Table 1.14. IO Functions

Function	Description
<code>void println(value V...)</code>	Print a list of values on the output stream
<code>bool print(value V...)</code>	Print a list of values on the output stream and return true (used for debugging).

Function	Description
<code>void rawPrintln(value V...)</code>	Print a list of values on the output stream, but do not convert parse trees or remove quotes from strings (used for debugging)
<code>list[str] readFile(str filename) throws NoSuchFileError(str msg), IO(str msg)</code>	Read a named file as list of strings
<code>str readFile(loc file) throws UnsupportedScheme(loc file), PathNotFound(loc file), IOError(str msg)</code>	Read the contents of a file location as single string
<code>list[str] readFileLines(loc file) throws UnsupportedScheme(loc file), PathNotFound(loc file), IOError(str msg)</code>	Read the contents of a file location as a list of lines
<code>void writeFile(loc file, value V...) throws UnsupportedScheme(loc file), PathNotFound(loc file), IOError(str msg)</code>	Write a textual representation of some values to a file

JDT (Eclipse only)

Detailed information can be extracted from Java projects in the current Eclipse workspace. The JDT library module depends heavily on the Resources library module.

The access to facts about Java files proceeds in two steps:

- First all facts are extracted from given projects or files. The result is a `Resource` that is annotated with all kinds of interesting information about that specific `Resource`, and usually also about `Resources` that are contained inside that resource. The project/file annotation declarations are shown below.
- Next, specific facts about the Java source code can be retrieved from the annotations. These annotations are shown in Table 1.15, “JDT Project/File Extraction Functions”(page 97) They all represent values of type `BindingRel` or `EntityRel` that are explained below.

The Java constructs that may occur in extracted facts are represented by the datatype `Entity` that is defined in the library module `Java` (not further described here). An "Entity" represents a fully qualified identifier pointing to a very specific part of a Java source code file. Entity is therefore a nested data-type, defined as follows:

```
data Entity = entity(list[Id] id);

data Id = package(str name)
        | class(str name)
        | class(str name, list[Entity] params)
        | interface(str name)
        | interface(str name, list[Entity] params)
        | anonymousClass(int nr)
        | enum(str name)

        | method(str name, list[Entity] params, Entity returnType)
        | constructor(list[Entity] params)
        | initializer
        | initializer(int nr)
```

```

        | field(str name)
        | parameter(str name)
        | variable(str name)
        | enumConstant(str name)

        | primitive(PrimitiveType type)
        | array(Entity elementType)

        | typeParameter(str name)
        | wildcard
        | wildcard(Bound bound)
        ;

data PrimitiveType =
    byte
    | short
    | \int
    | long
    | float
    | double
    | char
    | boolean
    | \void
    | null
    ;

data Bound =
    extends(Entity type)
    | super(Entity type)
    ;

```



Observe how the Rascal keywords `int` and `void` are used to construct symbols in the above data definition by escaping them as `\int` and `\void`.

```

// mMps locations to qualified names in the form of Entities
public alias BindingRel = rel[loc, Entity];

// A short-hand for any relation between two Entities
public alias EntityRel = rel[Entity, Entity];

// A short-hand for mappings from Entities to their declared Modifiers
public alias ModifierRel = rel[Entity entity, Modifier modifier];

```

A `BindingRel` is thus always used to map a source code location to a fully qualified Entity label of that part of the source code. `EntityRel` is simply a short hand for any kind of relation between entities.

The following annotations declare the kind of information that the JDT library module provides after retrieving it from an Eclipse Java project:

```

// All type declarations
anno BindingRel Resource@types;

// All method declarations
anno BindingRel Resource@methods;

// All constructor declarations
anno BindingRel Resource@constructors;

```



```

// All field declarations
anno BindingRel Resource@fields;

// All declarations for local variables and method parameters

anno BindingRel Resource@variables;

// All Package declarations
anno BindingRel Resource@packages;

// All the modifiers that have been declared for each entity
anno ModifierRel Resource@modifiers;

// Which type implements which interfaces
anno EntityRel Resource@implements;

// Which class extends which other classes
anno EntityRel Resource@extends;

// All declarations of top-level classes
anno EntitySet Resource@declaredTopTypes;

// All declarations of inner classes

anno EntityRel Resource@declaredSubTypes;

// Which class defines which methods
anno EntityRel Resource@declaredMethods;

// Which class defines which fields
anno EntityRel Resource@declaredFields;

// Which methods call which other methods, and which
// class initialization code calls which methods
anno EntityRel Resource@calls;

```

To get access to all this information, please use the following functions:

Table 1.15. JDT Project/File Extraction Functions

Function	Description
Resource extractClass(loc javaFile)	Import JDT facts from file
Resource extractProject(loc project)	Import JDT facts from a project
FactMap extractFactsTransitive(loc project)	Extracts facts from a project and all projects it depends on
tuple[rel[&T1, &T2] found, rel[JDTlocation, &T2] notfound] matchLocations(rel[&T1, loc] RSClocs, rel[JDTlocation, &T2] JDTlocs)	Compose two relations by matching JDT locations with Rascal locations and return a tuple with the composition result and the locations that could not be matched. The source code locations of the JDT AST nodes might not always be the same as the ones in your own parse tree. This function picks the 'best fitting' user provided locations for JDT locations that don't have a

Function	Description
	direct match. It works correctly for the Java 1.4 grammar in the sdf-library, but other grammars might need a specific implementation.
<code>str readable(Entity entity)</code>	Will compute a readable representation of a string for use in debugging output or visualizations
<code>Resource unionFacts(Resource m1, Resource m2)</code>	Take all facts annotated on m1 and m2, merge them and return m1 annotated with the unified results

This is the implementation of `extractFacts(set[str] projects)`, showing how to use the `unionFacts()` function :

Here is an example function that extracts the sub-type relation from a given project:

```
EntityRel getSubTypeInfoInformation(loc project){
    fm = extractProject(project);
    return fm@extends + fm@implements +
           {class("Object") x top(fm@extends + fm@implements);
}
```

The following example shows how to link the JDT type bindings to your own parse tree nodes. Suppose you have a relation `nodeLocations` that links your parse tree nodes to their location, you can get the type information of each node (if any) as follows:

```
Resource fm = extractProject(myProject);
BindingRel jdtTypeBindings = fm@types;

rel[node, Entity] myTypeBindings;
BindingRel unmatchedBindings;
<myTypeBindings, unmatchedBindings> =
    matchLocations(nodeLocations, jdtTypeBindings);
```

Labeled Graph

The labeled graph datatype is a special form of binary relation with labelled edges and is defined as follows:

```
alias LGraph[&T,&L] = rel[&T from, &L label, &T to];
```

All operators and functions on relations are applicable to labeled graphs, see the section called “Relation” (page 104).

Table 1.16. Labeled Graph Functions

Function	Description
<code>set[&T] bottom(LGraph[&T] G)</code>	Bottom nodes of a labelled graph
<code>set[&T] predecessors(LGraph[&T], &T From)</code>	Direct predecessors of node From
<code>set[&T] reach(LGraph[&T] G, set[&T] Start)</code>	Reachability from set of start nodes.
<code>set[&T] reachR(LGraph[&T] G, set[&T] Start, set[&T] Restr)</code>	Reachability from set of start nodes with restriction to certain nodes.
<code>set[&T] reachX(LGraph[&T] G, set[&T] Start, set[&T] Excl)</code>	Reachability from set of start nodes with exclusion of certain nodes

Function	Description
<code>list[&T] shortestPathPair(LGraph[&T] G, &T From, &T To)</code>	Shortest path between pair of nodes
<code>set[&T] successors(LGraph[&T] G, &T From)</code>	Direct successors of node From
<code>set[&T] top(LGraph[&T] G)</code>	Top nodes of a labelled graph



`shortestPathPair` not yet implemented for `LGraph`.

List

Table 1.17. List Operators

Operator	Description
<code>List₁ == List₂</code>	Yields <code>true</code> if both arguments have the same elements in the same order
<code>List₁ != List₂</code>	Yields <code>true</code> if both arguments have different elements
<code>List₁ <= List₂</code>	Yields <code>true</code> if both lists are equal or <code>List₁</code> is a sublist of <code>List₂</code>
<code>List₁ < List₂</code>	Yields <code>true</code> if <code>List₁</code> is a sublist of <code>List₂</code>
<code>List₁ >= List₂</code>	Yields <code>true</code> if both lists are equal or <code>List₂</code> is a sublist of <code>List₁</code>
<code>List₁ > List₂</code>	Yields <code>true</code> if <code>List₂</code> is a sublist of <code>List₁</code>
<code>List₁ + List₂</code>	Concatenation of <code>List₁</code> and <code>List₂</code>
<code>List₁ - List₂</code>	List consisting of all elements in <code>List₁</code> that do not occur in <code>List₂</code>
<code>List₁ * List₂</code>	List consisting of tuples with first element from <code>List₁</code> and second element from <code>List₂</code>
<code>Elm in List</code>	Yields <code>true</code> if <code>Elm</code> occurs as element in <code>List</code>
<code>Elm not in List</code>	Yields <code>true</code> if <code>Elm</code> does not occur as element in <code>List</code>
<code>Bool ? List₁ : List₂</code>	If <code>bool</code> is true then <code>List₁</code> else <code>List₂</code>
<code>List [int]</code>	Element at position <code>int</code> in <code>List</code>

Table 1.18. List Functions

Function	Description
<code>&T average(list[&T] lst, &T zero)</code>	Average of elements of a list
<code>list[&T] delete(list[&T] lst, int n)</code> <code>throws IndexOutOfBounds(int index)</code>	Delete <code>nth</code> element from list
<code>set[int] domain(list[&T] lst)</code>	Set of all legal index values for a list
<code>&T head(list[&T] lst) throws EmptyList</code>	Get the first element of a list
<code>list[&T] head(list[&T] lst, int n)</code> <code>throws IndexOutOfBounds(int index)</code>	Get the first <code>n</code> elements of a list
<code>&T getOneFrom(list[&T] lst) throws EmptyList</code>	Get an arbitrary element from a list
<code>list[&T] insertAt(list[&T] lst, int n, &T elm) throws IndexOutOfBounds(int index)</code>	Add an element at a specific position in a list

Function	Description
<code>bool isEmpty(list[&T] lst)</code>	Is list empty?
<code>list[&T] mapper(list[&T] lst, &T (&T) fn)</code>	Apply a function to each element of a list
<code>&T max(list[&T] lst)</code>	Largest element of a list
<code>&T min(list[&T] lst)</code>	Smallest element of a list
<code>set[list[&T]] permutations(list[&T] lst)</code>	All permutations of a list
<code>&T reducer(list[&T] lst, &T (&T, &T) fn, &T unit)</code>	Apply function <code>fn</code> to successive elements of a list, with given unit element.
<code>list[&T] reverse(list[&T] lst)</code>	Elements of a list in reverse order
<code>int size(list[&T] lst)</code>	Number of elements in a list
<code>list[&T] slice(list[&T] lst, int start, int len) throws IndexOutOfBoundsException(int index)</code>	Sublist from start of length <code>len</code>
<code>list[&T] sort(list[&T] lst)</code>	Sort the elements of a list
<code>list[&T] tail(list[&T] lst) throws EmptyList</code>	All but the first element of a list
<code>list[&T] tail(list[&T] lst, int len) throws IndexOutOfBoundsException(int index)</code>	Last <code>n</code> elements of a list
<code>tuple[&T, list[&T]] takeOneFrom(list[&T] lst) throws EmptyList</code>	Remove an arbitrary element from a list, returns the element and the modified list
<code>map[&A, set[&B]] toMap(list[tuple[&A, &B]] lst) throws DuplicateKey</code>	Convert a list of tuples to a map in which the first element of each tuple is associated with the set of second elements from all tuples with the same first element Keys should be unique.
<code>map[&A, &B] toMapUnique(list[tuple[&A, &B]] lst) throws DuplicateKey</code>	Convert a list of tuples to a map; result must be a map
<code>set[&T] toSet(list[&T] lst)</code>	Convert a list to a set
<code>str toString(list[&T] lst)</code>	Convert a list to a string

Location

Table 1.19. Operations on Locations

Operator	Description
$LOC_1 == LOC_2$	Yield true if both arguments are identical and false otherwise
$LOC_1 != LOC_2$	Yield true if both arguments are not identical and false otherwise
$LOC_1 <= LOC_2$	Yield true if LOC_1 is textually contained in or equal to LOC_2 and false otherwise
$LOC_1 < LOC_2$	Yield true if LOC_1 is strictly textually contained in LOC_2 and false otherwise
$LOC_1 >= LOC_2$	Yield true if LOC_1 textually encloses or is equal to LOC_2 and false otherwise
$LOC_1 > LOC_2$	Yield true if LOC_1 textually encloses LOC_2 and false otherwise

Operator	Description
<i>Loc</i> . <i>Field</i>	Retrieve one of the fields of location value <i>Loc</i>

The field names for locations are:

- `uri`: the URI of the location. Also subfields of the URI can be accessed:
 - `scheme`: the scheme (or protocol) like `http` or `file`. Also supported is `cwd`: for current working directory (the directory from which Rascal was started).
 - `authority`: the domain where the data are located.
 - `host`: the host where the URI is hosted (part of authority).
 - `port`: port on host (part of authority).
 - `path`: path name of file on host.
 - `extension`: file name extension.
 - `query`: query data
 - `fragment`: the fragment name following the path name and query data.
 - `user`: user info (only present in schemes like `mailto`).
- `offset`: start of text area.
- `length`: length of text area
- `begin.line`, `begin.column`: begin line and column of text area.
- `end.line`, `end.column`: end line and column of text area.

Map

Table 1.20. Map Operators

Operator	Description
$Map_1 == Map_2$	Yield <code>true</code> if both arguments consist of the same pairs
$Map_1 != Map_2$	Yield <code>true</code> if both arguments have different pairs
$Map_1 \leq Map_2$	Yield <code>true</code> if all pairs in Map_1 occur in Map_2 or Map_1 and Map_2 are equal
$Map_1 < Map_2$	Yield <code>true</code> if all pairs in Map_1 occur in Map_2 but Map_1 and Map_2 are not equal
$Map_1 \geq Map_2$	Yield <code>true</code> if all pairs in Map_2 occur in Map_1 or Map_1 and Map_2 are equal
$Map_1 > Map_2$	Yield <code>true</code> if all pairs in Map_2 occur in Map_1 but Map_1 and Map_2 are not equal
$Map_1 + Map_2$	Union of Map_1 and Map_2
$Map_1 - Map_2$	Difference of Map_1 and Map_2
$Key \text{ in } Map$	Yield <code>true</code> if <i>Key</i> occurs in a key:value pair in <i>Map</i>
$Key_1 \text{ not in } Map_2$	Yield <code>true</code> if <i>Key</i> does not occur in a key:value pair in <i>map</i>
$Bool ? Map_1 : Map_2$	If <i>Bool</i> is true then Map_1 else Map_2

Operator	Description
<i>Map</i> [<i>Key</i>]	The value associated with <i>Key</i> in <i>Map</i> if that exists, undefined otherwise

Table 1.21. Map Functions

Function	Description
<code>set[&K] domain(map[&K, &V] M)</code>	The domain (keys) of a map
<code>map[&K, &V] domainR(map[&K, &V] M, set[&K] S)</code>	Restrict the map to elements with keys in S
<code>map[&K, &V] domainX(map[&K, &V] M, set[&K] S)</code>	Restrict the map to elements with keys not in S
<code>&K getOneFrom(map[&K, &V] M) throws emptyMap</code>	Arbitrary key of a map
<code>map[&V, set[&K]] invert(map[&K, &V] M)</code>	Inverted map in which each value in the old map is associated with a set of key values from the old map
<code>map[&V, &K] invertUnique(map[&K, &V] M) throws MultipleKey</code>	Map with key and value inverted; result should be a map
<code>bool isEmpty(map[&K, &V] M)</code>	Is map empty?
<code>map[&K, &V] mapper(map[&K, &V] M, &K (&K) F, &V (&V) G)</code>	Apply two functions to each key/value pair in a map.
<code>set[&V] range(map[&K, &V] M)</code>	The range (values) of a map
<code>map[&K, &V] rangeR(map[&K, &V] M, set[&V] S)</code>	Restrict the map to elements with value in S
<code>map[&K, &V] rangeX(map[&K, &V] M, set[&V] S)</code>	Restrict the map to elements with value not in S
<code>int size(map[&K, &V] M)</code>	Number of elements in a map.
<code>list[tuple[&K, &V]] toList(map[&K, &V] M)</code>	Convert a map to a list
<code>rel[&K, &V] toRel(map[&K, &V] M)</code>	Convert a map to a relation
<code>str toString(map[&K, &V] M)</code>	Convert a map to a string.

Node

Table 1.22. Node Operators

Operator	Description
<code>Node₁ == Node₂</code>	true if both arguments are identical
<code>Node₁ != Node₂</code>	true if both arguments are not identical
<code>Node₁ <= Node₂</code>	Node ₁ is less than or equal to Node ₂
<code>Node₁ < Node₂</code>	Node ₁ is less than Node ₂
<code>Node₁ >= Node₂</code>	Node ₂ is less than or equal to Node ₁
<code>Node₁ > Node₂</code>	Node ₂ is less than Node ₁
<code>Bool ? Node₁ : Node₂</code>	if Bool is true then Node ₁ else Node ₂
<code>Node [Int]</code>	child of Node at position Int

Comparison of nodes is defined by a lexicographic ordering. Node $N = F(N_1, \dots, N_k)$ is less than node $M = G(M_1, \dots, M_l)$ when:

- N is not equal to M , and
- F is lexicographically less than G , or F is equal to G and $k < l$.

Table 1.23. Node Functions

Function	Description
<code>int arity(node T)</code>	Number of children of a node
<code>map[str, value]</code> <code>getAnnotations(node x)</code>	Retrieve the annotations of a node value as a map
<code>list[value]</code> <code>getChildren(node T)</code>	The children of a node
<code>str getName(node T)</code>	The function name of a node
<code>node makeNode(str N, value V...)</code>	Create a node given its function name and arguments
<code>&T <: node java</code> <code>setAnnotations(&T <: node x,</code> <code>map[str, value] annotations)</code>	Set a map of annotations on a value.

PriorityQueue

Priority queues maintain (value, priority) pairs in sorted order. They are implemented using a binomial heap, see http://en.wikipedia.org/wiki/Binomial_heap. Priority queue are, for instance, used to implement shortest path algorithms.

Table 1.24. PriorityQueue Functions

Function	Description
<code>tuple[int, int, PriorityQueue]</code> <code>extractMinimum(PriorityQueue Q):</code>	Find the (value, priority) pair with minimum priority and delete it
<code>int findMinimum(PriorityQueue Q)</code>	Find the minimum priority.
<code>PriorityQueue</code> <code>insertElement(PriorityQueue Q,</code> <code>int priority, int val):</code>	Insert a (value, priority) pair
<code>bool isEmpty(PriorityQueue Q):</code>	Is queue empty?
<code>PriorityQueue priorityQueue():</code>	Create an empty queue.
<code>PriorityQueue priorityQueue(int</code> <code>priority, int val):</code>	Create queue with one (value, priority) pair.

Real

Rascal reals are unbounded in size and precision.

Table 1.25. Real Operators

Operator	Description
<code>Real₁ == Real₂</code>	true if both arguments are numerically equal and false otherwise
<code>Real₁ != Real₂</code>	true if both arguments are numerically unequal and false otherwise
<code>Real₁ <= Real₂</code>	true if $Real_1$ is numerically less than or equal to $Real_2$ and false otherwise
<code>Real₁ < Real₂</code>	true if $Real_1$ is numerically less than $Real_2$ and false otherwise

Operator	Description
$Real_1 \geq Real_2$	true if $Real_1$ is numerically greater than or equal than $Real_2$ and false otherwise
$Real_1 > Real_2$	true if $Real_1$ is numerically greater than $Real_2$ and false otherwise
$Real_1 + Real_2$	Sum of $Real_1$ and $Real_2$
$Real_1 - Real_2$	Difference of $Real_1$ and $Real_2$
$Real_1 * Real_2$	$Real_1$ multiplied by $Real_2$
$Real_1 / Real_2$	$Real_1$ divided by $Real_2$
$- Real$	Negate sign of $Real$
$Real_1 \% Real_2$	Remainder of dividing $Real_1$ by $Real_2$
$Bool ? Real_1 : Real_2$	If $Bool$ is true then $Real_1$ else $Real_2$

Table 1.26. Real Functions

Function	Description
<code>real arbReal()</code>	Arbitrary real value in the interval [0.0,1.0).
<code>real max(real n, real m)</code>	Largest of two reals
<code>real min(real n, real m)</code>	Smallest of two reals
<code>int toInt(real d)</code>	Converts this real (implemented as BigDecimal) to an integer (implemented as BigInteger). This conversion is analogous to a narrowing primitive conversion from double to long as defined in the Java Language Specification: any fractional part of this BigDecimal will be discarded. Note that this conversion can lose information about the precision of the BigDecimal value.
<code>str toString(real d)</code>	Convert a real to a string.

Relation

Relation are sets of tuples, therefore all set operators apply to relations as well, see, Table 1.31, “Set Operators” (page 108) Graph and labeled graph are a special forms of relation, see the section called “Graph” (page 93) and the section called “Labeled Graph” (page 98).

Table 1.27. Operations on Relations

Operator	Description
$Rel_1 \circ Rel_2$	Relation resulting from the composition of the two arguments
$Set_1 \times Set_2$	Relation resulting from the Cartesian product of the two arguments
$Rel +$	Relation resulting from the transitive closure of Rel . Rel should be a binary relation of type <code>rel [&T, &T]</code> .
$Rel *$	Relation resulting from the reflexive transitive closure of Rel . Rel should be a binary relation of type <code>rel [&T, &T]</code> .
$Rel [Exp_1, Exp_2, \dots]$	Relation resulting from subscription of Rel with the index values of Exp_1, Exp_2, \dots . The result is a relation with all tuples that have these index values as first elements with the index values removed from the tuple. If the resulting tuple has only a single element, a set is returned instead of a relation. A wildcard <code>_</code> as index value matches all possible values at that index position.

Operator	Description
$Rel [Set]$	Relation resulting from subscription of Rel with all elements of Set .
$Rel < Index_1, Index_2, \dots >$	Relation resulting from restricting Rel to the columns described by $Index_1, Index_2, \dots$

Examples:

```

rascal> {<1,10>, <2,20>, <3,15>} o {<10,100>, <20,200>};
rel[int,int] : {<1,100>, <2,200>}

rascal> {1, 2, 3} x {9};
rel[int,int] : {<1, 9>, <2, 9>, <3, 9>}

rascal> {<1,2>, <2,3>, <3,4>}+;
rel[int,int]: {<1,2>, <2,3>, <3,4>, <1, 3>, <2, 4>, <1, 4>}

rascal> {<1,2>, <2,3>, <3,4>}*;
rel[int,int]: {<1,2>, <2,3>, <3,4>, <1, 3>, <2, 4>, <1, 4>,
               <1, 1>, <2, 2>, <3, 3>, <4, 4>}

rascal> R = {<1,10>, <2,20>, <1,11>, <3,30>, <2,21>};
rel[int,int] : {<1,10>, <2,20>, <1,11>, <3,30>, <2,21>}

rascal> R[1];
set[int] : {10, 11}

rascal> R[{1}];
set[int] : {10, 11}

rascal> R[{1, 2}];
set[int] : {10, 11, 20, 21}

rascal> RR = {<1,10,100>,<1,11,101>,<2,20,200>,<2,22,202>,
              <3,30,300>};
rel[int,int,int]:{<1,10,100>,<1,11,101>,<2,20,200>,<2,22,202>,
                  <3,30,300>}

rascal> RR[1];
rel[int,int]: {<10,100>,<11,101>};

rascal> RR[1,_];
set[int]: {100,101}

rascal> RR<2,0,1>;
rel[int,int,int]: {<101,1,11>,<200,2,20>,<100,1,10>,
                  <300,3,30>,<202,2,22>} ;

rascal> RR<2.0,1>[100];
rel[int,int]: {<1,10>}

```

Table 1.28. Relation Functions

Function	Description
<code>set[&T] carrier (rel[&T,&T] R)</code>	All elements in any tuple in a relation
<code>rel[&T,&T] carrierR (rel[&T,&T] R, set[&T] S)</code>	Relation restricted to tuples with elements in a set S

Function	Description
<code>rel[&T,&T] carrierX (rel[&T,&T] R, set[&T] S)</code>	Relation excluded tuples with some element in S
<code>rel[&T0, &T1] complement(rel[&T0, &T1] R)</code>	Complement of relation
<code>set[&T0] domain (rel[&T0,&T1] R)</code>	First element of each tuple in binary relation
<code>rel[&T0,&T1] domainR (rel[&T0,&T1] R, set[&T0] S)</code>	Restriction of a relation to tuples with first element in S
<code>rel[&T0,&T1] domainX (rel[&T0,&T1] R, set[&T0] S)</code>	Relation excluded tuples with first element in S
<code>rel[&T,&T] ident(set[&T] S)</code>	The identity relation for set S.
<code>rel[&T1, &T0] invert (rel[&T0, &T1] R)</code>	Inverse the tuples in a relation
<code>set[&T1] range (rel[&T0,&T1] R)</code>	The range of a binary relation
<code>rel[&T0,&T1] rangeR (rel[&T0,&T1] R, set[&T2] S)</code>	Restriction of a binary relation to tuples with second element in set S
<code>rel[&T0,&T1] rangeX (rel[&T0,&T1] R, set[&T2] S)</code>	Restriction of a binary relation to tuples with second element not in set S

Examples:

```

rascal> id({1,2,3});
rel[int,int] : {<1,1>, <2,2>, <3,3>}

rascal> id({"mon", "tue", "wed"});
rel[str,str] : {<"mon","mon">, <"tue","tue">, <"wed","wed">}

rascal> invert({<1,10>, <2,20>});
rel[int,int] : {<10,1>, <20,2>}

rascal> compl({<1,10>});
rel[int,int] : {<1, 1>, <10, 1>, <10, 10>}

rascal> domain({<1,10>, <2,20>});
set[int] : {1, 2}

rascal> domain({<"mon", 1>, <"tue", 2>});
set[str] : {"mon", "tue"}

rascal> range({<1,10>, <2,20>});
set[int] : {10, 20}

rascal> range({<"mon", 1>, <"tue", 2>});
set[int] : {1, 2}

rascal> carrier({<1,10>, <2,20>});
set[int] : {1, 10, 2, 20}

rascal> domainR({<1,10>, <2,20>, <3,30>}, {3, 1});
rel[int,int] : {<1,10>, <3,30>}

rascal> rangeR({<1,10>, <2,20>, <3,30>}, {30, 10});
rel[int,int] : {<1,10>, <3,30>}

```

```

rascal> carrierR({<1,10>, <2,20>, <3,30>}, {10, 1, 20});
rel[int,int] : {<1,10>}

rascal> domainX({<1,10>, <2,20>, <3,30>}, {3, 1});
rel[int,int] : {<2, 20>}

rascal> rangeX({<1,10>, <2,20>, <3,30>}, {30, 10});
rel[int,int] : {<2, 20>}

rascal> carrierX({<1,10>, <2,20>, <3,30>}, {10, 1, 20});
rel[int,int] : {<3,30>}

```



Further support for n-ary relations is being considered.

RSF

Rigi Standard Format (RSF) is a textual format to represent binary relations and is used to exchange relational facts between different tools. The following functions allows reading in RSF data.

Table 1.29. RSF Functions

Function	Description
map[str, rel[str,str]] readRSF(str nameRSFFile) throws IO(str msg)	Read a file in Rigi Standard Format (RSF).

Resources (Eclipse only)

The Resources library provides direct access to Eclipse projects and the resources they contain. A Resource is the Rascal representation of an Eclipse project, or a folder or a file in an Eclipse project. In combination with the IO library module, users of the Resources library gain access to the contents of any file that is in an Eclipse project.

```

data Resource = root(set[Resource] projects)
                | project(loc id, set[Resource] contents)
                | folder(loc id, set[Resource] contents)
                | file(loc id);

```

Resource is a recursive data-type, where recursion indicates "containment". I.e. a folder contains many other resources, a project also contains other resources. The root of an Eclipse workspace also contains other resources, in particular "projects".

Each Resource, but the root, has an 'id' field that explains the exact location of the resource. Examples of Eclipse Resource locations are:

```

// A location that points to a project in the Eclipse workspace
// named "myProject"
|project://myProject|

// A location that points to a file named Main.java in the src
// folder of the myProject project in the workspace
|project://myProject/src/Main.java|

// A location that points to a part of the previous file,

```

```
// namely the first 10 characters on the first line.
|project://myProject/src/Main.java|(0,10,1,0,1,10)
```

Using the IO library, one can easily read the contents of a such an Eclipse project location:

```
import IO;
str contents = readFile(|project://myProject/src/Main.java|);
```

Other library functions in the Resource library provide more information about resources:

Table 1.30. Resources Functions

Function	Description
set[loc] dependencies(loc project);	Computes referenced projects transitively
public Resource getProject(loc project);	Retrieves the hierarchical representation of a single named project
set[loc] projects()	Convenience function to retrieve a set of project locations of the Eclipse workspace
set[loc] references(loc project);	Find out which other projects this project references (depends on)
Resource root()	Retrieve a full hierarchical representation of all resources in the Eclipse workspace

Set

Table 1.31. Set Operators

Operator	Description
$Set_1 == Set_2$	true if both arguments are equal sets and false otherwise
$Set_1 != Set_2$	true if both arguments are unequal sets and false otherwise
$Set_1 \leq Set_2$	true if Set_1 is a subset of Set_2 and false otherwise
$Set_1 < Set_2$	true if Set_1 is a strict subset of Set_2 and false otherwise
$Set_1 \geq Set_2$	true if Set_1 is a superset of Set_2 and false otherwise
$Set_1 > Set_2$	true if Set_1 is a strict superset of Set_2 and false otherwise
$Set_1 + Set_2$	Set resulting from the union of the two arguments
$Set_1 - Set_2$	Set resulting from the difference of the two arguments
$Set_1 * Set_2$	Relation resulting from the product of the two arguments. It contains a tuple for each combination of values from both arguments
$Set_1 \& Set_2$	Set resulting from the intersection of the two arguments
$Elm \text{ in } Set$	true if Elm occurs as element in Set and false otherwise
$Elm \text{ not in } Set$	false if Elm occurs as element in Set and false otherwise
$Set_1 \text{ join } Set_2$	Relation resulting from the natural join of the two arguments. It contains tuples that are the result from concatenating the elements from both arguments
$Bool ? Set_1 : Set_2$	If $Bool$ is true then Set_1 else Set_2

Examples:

```
rascal> {1, 2, 3} + {4, 5, 6};
set[int] : {1, 2, 3, 4, 5, 6}
```

```

rascal> {1, 2, 3} + {1, 2, 3};
set[int] : {1, 2, 3}

rascal> {1, 2, 3, 4} - {1, 2, 3};
set[int] : {4}

rascal> {1, 2, 3} - {4, 5, 6};
set[int] : {1, 2, 3}

rascal> {1,2,3} * {4,5,6};
rel[int,int]: {<1,4>,<1,5>,<1,6>,<3,4>,<3,5>,<3,6>,<2,4>,<2,5>,<2,6>}

rascal> {1, 2, 3} & {4, 5, 6};
set[int] : { }

rascal> {1, 2, 3} & {1, 2, 3};
set[int] : {1, 2, 3}

rascal> 3 in {1, 2, 3};
bool : true

rascal> 4 in {1, 2, 3};
bool : false

rascal> 3 notin {1, 2, 3};
bool : false

rascal> 4 notin {1, 2, 3};
bool : true

rascal> <2,20> in {<1,10>, <2,20>, <3,30>};
bool : true

rascal> <4,40> notin {<1,10>, <2,20>, <3,30>};
bool : true

rascal> {<1,2>, <10,20>} join {<2,3>};
rel[int, int, int, int]: {<1,2,2,3>,<10,20,2,3>}

rascal> {<1,2>} join {3, 4};
rel[int, int, int]: {<1,2,3>,<1,2,4>}

```

Table 1.32. Set Functions

Function	Description
<code>&T getOneFrom(set[&T] st) throws emptySet</code>	Pick a random element from a set
<code>bool isEmpty(set[&T] st)</code>	Is set empty?
<code>set[&T] mapper(set[&T] st, &T (&T,&T) fn)</code>	Apply a function to each element of a set
<code>&T max(set[&T] st)</code>	Largest element of a set
<code>&T min(set[&T] st)</code>	Smallest element of a set
<code>set[set[&T]] power(set[&T] st)</code>	All subsets of a set
<code>set[set[&T]] power1(set[&T] st)</code>	All subsets (excluding empty set) of a set

Function	Description
<code>&T reducer(set[&T] st, &T (&T,&T) fn, &T unit)</code>	Apply function F to successive elements of a set
<code>int size(set[&T] st)</code>	Number of elements in a set
<code>tuple[&T, set[&T]] takeOneFrom(set[&T] st) throws emptySet</code>	Remove an arbitrary element from a set, returns the element and the modified set
<code>list[&T] toList(set[&T] st)</code>	Convert a set to a list
<code>map[&A, set[&B]] toMap(rel[&A, &B] st)</code>	Convert a set of tuples to a map in which the first element of each tuple is associated with the set of second elements from all tuples with the same first element
<code>map[&A, &B] toMapUnique(rel[&A, &B] st) throws DuplicateKey</code>	Convert a set of tuples to a map; the result should be a legal map
<code>str toString(set[&T] st)</code>	Convert a set to a string

Examples:

```
rascal> power({1, 2, 3, 4});
set[set[int]] : { {}, {1}, {2}, {3}, {4}, {1,2}, {1,3}, {1,4},
                  {2,3}, {2,4}, {3,4}, {1,2,3}, {1,2,4},
                  {1,3,4}, {2,3,4}, {1,2,3,4}
                }

rascal> power1({1, 2, 3, 4});
set[set[int]] : { {1}, {2}, {3}, {4}, {1,2}, {1,3}, {1,4}, {2,3},
                  {2,4}, {3,4}, {1,2,3}, {1,2,4}, {1,3,4},
                  {2,3,4}, {1,2,3,4}
                }

rascal> size({1,2,3});
int : 3

rascal> size(<1,10>, <2,20>, <3,30>);
int : 3
```

String

Table 1.33. Operations on Strings

Operator	Description
$Str_1 == Str_2$	Yields true if both arguments are equal and false otherwise
$Str_1 != Str_2$	Yields true if both arguments are unequal and false otherwise
$Str_1 \leq Str_2$	Yields true if Str_1 is lexicographically less than or equal to Str_2 and false otherwise
$Str_1 < Str_2$	Yields true if Str_1 is lexicographically less than Str_2 and false otherwise
$Str_1 \geq Str_2$	Yields true if Str_1 is lexicographically greater than or equal to Str_2 and false otherwise
$Str_1 > Str_2$	Yields true if Str_1 is lexicographically greater than Str_2 and false otherwise
$Str_1 + Str_2$	Concatenates Str_1 and Str_2

Operator	Description
<code>Bool ? Str₁ : Str₂</code>	If <i>Bool</i> is true then <i>Str₁</i> else <i>Str₂</i>

Table 1.34. String Functions

Function	Description
<code>int charAt(str s, int i) throws IndexOutOfBounds(int index)</code>	Character at position <i>i</i> in string <i>s</i> .
<code>bool endsWith(str s, str suffix)</code>	Yields <code>true</code> if string <i>s</i> ends with given string <i>suffix</i> .
<code>str center(str s, int n)</code>	Center <i>s</i> in string of length <i>n</i> using spaces
<code>str center(str s, int n, str pad)</code>	Center <i>s</i> in string of length <i>n</i> using a pad character
<code>bool isEmpty(str s)</code>	Is string empty?
<code>str left(str s, int n)</code>	Left align <i>s</i> in string of length <i>n</i> using spaces
<code>str left(str s, int n, str pad)</code>	Left align <i>s</i> in string of length <i>n</i> using pad character
<code>str replaceAll(str input, str find, str replacement)</code>	Replace all occurrences of (regex) <i>find</i> in <i>input</i> by <i>replacement</i>
<code>str replaceFirst(str input, str find, str replacement)</code>	Replace the first occurrence of (regex) <i>find</i> in <i>input</i> by <i>replacement</i>
<code>str replaceLast(str input, str find, str replacement)</code>	Replace the last occurrence of (regex) <i>find</i> in <i>input</i> by <i>replacement</i>
<code>str right(str s, int n)</code>	Right align <i>s</i> in string of length <i>n</i> using spaces
<code>str reverse(str s)</code>	String with all characters in reverse order.
<code>int size(str s)</code>	Length of string <i>s</i> .
<code>bool startsWith(str s, str prefix)</code>	Yields <code>true</code> if string <i>s</i> starts with the string <i>prefix</i> .
<code>str substring(str s, int begin) throws IndexOutOfBounds(int index)</code>	Yields substring of <i>s</i> from index <i>begin</i> to the end of the string
<code>str substring(str s, int begin, int end) throws IndexOutOfBounds(int index)</code>	Yields substring of <i>s</i> from index <i>begin</i> to (but not including) index <i>end</i>
<code>int toInt(str s) throws IllegalArgumentException(value v)</code>	Convert string <i>s</i> to integer. Throws <code>IllegalArgumentException</code> when <i>s</i> cannot be converted.
<code>str toLowerCase(str s)</code>	Convert all characters in string <i>s</i> to lowercase.
<code>real toReal(str s) throws IllegalArgumentException(value v)</code>	Convert <i>s</i> to a real. Throws <code>IllegalArgumentException</code> when <i>s</i> cannot be converted.
<code>str toUpperCase(str s)</code>	Convert all characters in string <i>s</i> to uppercase.



Remove `charAt` when string subscript is implemented.

Tree

Tree is the universal parse tree data type and can be used to parse text in any language. We do not give its full declaration here since internal details are never needed by Rascal users. The following is noteworthy:

- Tree is a subtype of the type node.
- All parse trees for a specific language are a subtype of Tree.
- Trees are annotated with location annotations defined as follows:

```
anno loc Tree@\loc;
```



For historical reasons the name of the annotation is "loc" and this interferes with the Rascal keyword loc. Therefore the annotation name has to be escaped as \loc when it is declared or used.

Table 1.35. Tree Functions

Function	Description
<code>&T<:Tree java parse(type[&T<:Tree] start, loc input);</code>	Parse the contents of a resource pointed to by the input parameter and return a parse tree
<code>&T<:Tree java parse(type[&T<:Tree] start, str input)</code>	Parse a string and return a parse tree.

These declarations use type reification as explained in the section called “Reified Types” (page 58).

Tuple

Table 1.36. Tuple Operators

Operator	Description
<code><i>Tuple</i>₁ == <i>Tuple</i>₂</code>	true if both arguments are identical
<code><i>Tuple</i>₁ != <i>Tuple</i>₂</code>	true if both arguments are not identical
<code><i>Tuple</i>₁ <= <i>Tuple</i>₂</code>	true if both arguments are identical or if the leftmost element in <i>Tuple</i> ₁ that differs from the corresponding in <i>Tuple</i> ₂ is smaller than that element in <i>Tuple</i> ₂
<code><i>Tuple</i>₁ < <i>Tuple</i>₂</code>	true if both arguments are not identical and the leftmost element in <i>Tuple</i> ₁ that differs from the corresponding in <i>Tuple</i> ₂ is smaller than that element in <i>Tuple</i> ₂
<code><i>Tuple</i>₁ >= <i>Tuple</i>₂</code>	true if both arguments are identical or if the leftmost element in <i>Tuple</i> ₁ that differs from the corresponding in <i>Tuple</i> ₂ is greater than that element in <i>Tuple</i> ₂
<code><i>Tuple</i>₁ > <i>Tuple</i>₂</code>	true if both arguments are not identical and the leftmost element in <i>Tuple</i> ₁ that differs from the corresponding in <i>Tuple</i> ₂ is greater than that element in <i>Tuple</i> ₂
<code><i>Tuple</i>₁ + <i>Tuple</i>₂</code>	Concatenates <i>Tuple</i> ₁ and <i>Tuple</i> ₂
<code><i>Bool</i> ? <i>Tuple</i>₁ : <i>Tuple</i>₂</code>	If <i>Bool</i> is true then <i>Tuple</i> ₁ else <i>Tuple</i> ₂
<code><i>Tuple</i> . <i>Name</i></code>	Select field <i>Name</i> from <i>Tuple</i>

Operator	Description
<i>Tuple</i> [<i>Int</i>]	Select field at position <i>int</i> from <i>Tuple</i>

Value

Table 1.37. Value Operators

Operator	Description
$Value_1 == Value_2$	true if both arguments are identical
$Value_1 != Value_2$	true if both arguments are not identical
$Value_1 \leq Value_2$	$Value_1$ is less than or equal to $Value_2$
$Value_1 < Value_2$	$Value_1$ is less than $Value_2$
$Value_1 \geq Value_2$	$Value_2$ is less than or equal to $Value_1$
$Value_1 > Value_2$	$Value_2$ is less than $Value_1$
$Bool ? Value_1 : Value_2$	if $Bool$ is true then $Value_1$ else $Value_2$

By brute force, a total less than operator between two values $V1$ and $V2$ of arbitrary types $T1$ and $T2$ is defined:

- If the types $T1$ and $T2$ can be compared then $V1$ less than $V2$ is used.
- Otherwise values are ordered according their type name, i.e., `int` is smaller than `list`, and `map` is smaller than `rel`.

ValueIO

Table 1.38. ValueIO Functions

Function	Description
<code>value readValueFile(loc file) throws IO(str msg)</code>	Read a value from a binary file in PBF format
<code>&T readBinaryValueFile(type[&T] result, loc file) throws IO(str msg)</code>	Read a typed value from a binary file.
<code>value readBinaryValueFile(loc file) throws IO(str msg)</code>	Read a value from a binary file.
<code>&T readTextValueFile(type[&T] result, loc file) throws IO(str msg)</code>	Read a typed value from a text file
<code>value readTextValueFile(loc file) throws IO(str msg)</code>	Read a value from a text file
<code>void writeBinaryValueFile(loc file, value val)</code>	Write a value to a file using an efficient binary file format (PBF)
<code>void writeTextValueFile(loc file, value val)</code>	Write a value to a file using a textual file format

viz::Basic (Eclipse only)

The Eclipse version of the Rascal provides various view on values:

- A graph view displays a value as graph (when applicable).

- A text view displays a value in its textual representation.
- A tree view displays a value in a tree-structured, expandable and collapsible, textual representation.



There is an overlap between the viz::Basic functions and the viz::Figure functions that will be eliminated in the future.

Table 1.39. viz::Basic Functions

Function	Description
<code>void graphView(value v)</code>	Display value <code>v</code> as a graph
<code>void textView(value v)</code>	Display value <code>v</code> as text
<code>void treeView(value v)</code>	Display value <code>v</code> as a expandable/collapsible tree

viz::Figure

The viz::Figure library is a general visualization library. A visualisation is described by creating a value of the data type Figure. A Figure can be primitive (rectangular box, ellipse, text) or composite (horizontal/vertical composition, placement on grid, tree or graph). The visual appearance of a Figure may be influenced by setting properties like color, size and the like. The actually display of a Figure is done by a render function.

viz::Figure::Core

The core of the viz::Figure library consists of two parts:

- Figure properties (FProperty), and
- the Figure data type itself.

Figure properties are defined as follows:

```
alias FProperties = list[FProperty];

data FProperty =
/* sizes */
    width(real width)           // set width of element
  | width(int iwidth)
  | height(real height)        // set height of element
  | height(int iheight)
  | size(real size)            // set width/height to same value
  | size(int isize)
  | size(real hor, real vert)  // set width and height to separate
                               // values
  | size(int ihor, int iver)
  | gap(real amount)           // set hor/vert gap between
                               // elements in composition to
                               // same value
  | gap(int iamount)
  | gap(real hor, real vert)   // set hor/vert gap between
                               // elements in composition to
                               // separate values
  | gap(int ihor, int iver)

/* alignment */
  | anchor(real h, real v)     // horizontal (0=left; 1=right) &
```

```

// vertical anchor (0=top,1=bottom)
| hanchor(real h)
| vanchor(real v)

/* line and border properties */
| lineWidth(int lineWidth) // line width
| lineColor(Color lineColor) // line color
| lineColor(str colorName) // named line color

| fillColor(Color fillColor) // fill color of shapes and text
| fillColor(str colorName) // named fill color

/* wedge properties */
| fromAngle(real angle)
| fromAngle(int iangle)
| toAngle(real angle)
| toAngle(int iangle)
| innerRadius(real radius)
| innerRadius(int iradius)

/* font and text properties */
| font(str fontName) // named font
| fontSize(int isize) // font size
| fontColor(Color textColor) // font color
| fontColor(str colorName)
| textAngle(real angle) // text rotation
| textAngle(int iangle)

/* interaction properties */
| mouseOver(FProperties props)
// switch to new properties when
// mouse is over element
| mouseOver(FProperties props, Figure inner)
// display new inner element when
// mouse is over current element

/* other properties */
| id(str name) // name of elem (used in edges and
// various layouts)
| connected() // shape consist of connected
// points
| closed() // closed shapes
| curved() // use curves instead of
// straight lines
;

```

The Figure data type itself is defined as follows:

```

alias Figures = list[Figure];

data Figure =
/* atomic primitives */

    text(FProperties props, str s) // text label
  | text(str s) // text label

/* primitives/containers */

```

```

| box(FProperties props)                // rectangular box
| box(FProperties props, Figure inner)  // rectangular box
|                                     // with inner element

| ellipse(FProperties props)           // ellipse
| ellipse(FProperties props, Figure inner) // ellipse with inner
|                                     // element

| wedge(FProperties props)              // wedge
| wedge(FProperties props, Figure inner) // wedge with inner
|                                     // element

| space(FProperties props)              // invisible box
|                                     // (used for spacing)
| space(FProperties props, Figure inner) // invisible box with
|                                     // visible inner
|                                     // element

/* composition */

| use(Figure elem)                     // use another elem
| use(FProperties props, Figure elem)

| hcat(Figures elems)                 // hor concatenation
| hcat(FProperties props, Figures elems)

| vcat(Figures elems)                 // vert concatenation
| vcat(FProperties props, Figures elems)

| align(Figures elems)                // hor/vert
|                                     // composition
| align(FProperties props, Figures elems)

| overlay(Figures elems)              // overlay (stacked)
|                                     // composition
| overlay(FProperties props, Figures elems)

| shape(list[Vertex] points)           // shape of to be
|                                     // connected vertices
| shape(FProperties props, list[Vertex] points)

| grid(Figures elems)                 // placement on
|                                     // fixed grid
| grid(FProperties props, Figures elems)

| pack(Figures elems)                 // composition by
|                                     // 2D packing
| pack(FProperties props, Figures elems)

| graph(Figures nodes, list[Edge] edges) // composition of
|                                     // nodes and edges
|                                     // as graph
| graph(FProperties, Figures nodes, list[Edge] edges)
|                                     // composition of
|                                     // nodes and edges
|                                     // as tree
| tree(Figures nodes, list[Edge] edges, str root)

```

```

| tree(FProperties, Figures nodes, list[Edge] edges, str root)
/* transformation */

| rotate(real angle, Figure elem)           // Rotate element
                                           // around anchor point
| scale(real perc, Figure)                 // Scale element
                                           // (same for h and v)
| scale(real xperc, real yperc, Figure elem)
                                           // Scale element
                                           // (different for
                                           // h and v)
;

```

Table 1.40. viz::Figure::Core Functions

Function	Description
public Color gray(int gray)	Gray value (0-255)
public Color gray(int gray, real alpha)	Gray value (0-255) with transparency (0-100%)
public Color gray(real perc)	Gray value (0-100%)
public Color gray(real perc, real alpha)	Gray value (0-100%) with transparency (0-100%)
public Color color(str colorName)	Named color (from SVG standard) http://www.w3.org/TR/SVG/types.html#ColorKeywords
public Color color(str colorName, real alpha)	Named color with transparency (0-100%)
public Color rgb(int r, int g, int b)	Color based on red (r), green (g) and blue (b)
public Color rgb(int r, int g, int b, real alpha)	RGB color with transparency
public list[Color] interpolateColor(Color from, Color to, real percentage)	Interpolate between two colors (in RGB space)
public list[Color] colorSteps(Color from, Color to, int steps)	Interpolate between two colors (in RGB space)
public Color(int) colorScale(list[int] values, Color from, Color to)	Interpolate between two colors (in RGB space)
public Color(real) colorScale(list[real] values, Color from, Color to)	Interpolate between two colors (in RGB space)
public str palette(int n)	Pick color from 12-color palette

viz::Figure::Render

The render function displays a figure depending on the context. When called from the REPL, a top-level window is created to display the figure. When called from Eclipse, a graphics pane is created as part of the Eclipse GUI.

Table 1.41. viz::Figure::Render Function

Function	Description
public void render(Figure fig)	Render a figure

viz::Figure::Chart

These functions provide chart drawing facilities and are based on JFreeChart. In the Eclipse context the module embeds the charts in an Eclipse window, while the commandline version will show a popup window. Different charts need their input data in different formats that can be summarized as follows:

```
// A named series of int or real values

public alias intTuples =
    tuple[str name, list[tuple[int, int]] values];

public alias intSeries =
    tuple[str name, list[int] values];
```

All chart drawing functions take as arguments:

- A title string.
- A single value that is to be displayed as a chart.
- Some functions may have one or two additional arguments.
- Finally, zero or more ChartSettings that give control over the way in which the chart is drawn.

Table 1.42. viz::Chart Functions

Function	Description
public void barChart(str title, map[str,int] facts, ChartSetting settings...)	Draw a bar chart for integers
public void barChart(str title, map[str,real] facts, ChartSetting settings...)	Draw a bar chart for reals (not yet implemented)
public void barChart(str title, list[str] categories, list[intSeries] facts, ChartSetting settings...)	Draw a bar chart for multiple series of integers
public void barChart(str title, list[str] categories, list[realSeries] facts, ChartSetting settings...)	Draw a bar chart for multiple series of reals (not yet implemented)
public void pieChart(str title, map[str, int] facts, ChartSetting settings...)	Draw a pieChart for integers
public void pieChart(str title, map[str, real] facts, ChartSetting settings...)	Draw a pieChart for reals (not yet implemented)
public void xyChart(str title, list[intSeries], ChartSetting settings...)	Draw an xyChart for integers
public void xyChart(str title, list[realSeries], ChartSetting settings...)	Draw an xyChart for reals

In its simplest form, a *barChart* displays a map of integer or real values. Vertical bars are drawn with length according to the values and the associated keys in the map acts as labels. A *barChart* may also display several series of integer or real values. In this case a list of category names and a list of int or real series are needed. The *n*-th category name corresponds with the *n*-th element in each series. Names of series act thus as row names and category names act as column names. Each series is grouped together in the bar chart and corresponding category elements in different series get the same color. See http://en.wikipedia.org/wiki/Bar_chart for further details



BoxPlots and Histograms are not yet available.

BoxPlots are also known as box-and-whisker diagrams and are useful to display statistical data. One of the most famous box plots stems from the Michelson-Morley Experiment in 1887, see http://en.wikipedia.org/wiki/Box_plot for further details. For each named subseries of data, the following characteristics are shown:

- The sample minimum.
- The lower quartile (Q1).
- The median (Q2).
- The upper quartile (Q3).
- The sample maximum.

The values from minimum to maximum are indicated by a vertical line. Values between Q1 and Q3 are indicated by a small box superimposed on this vertical line. A horizontal line inside the box indicates the median. Outliers are explicitly indicated in the plot.

A histogram displays observations in a fixed number of bins, see <http://en.wikipedia.org/wiki/Histogram> for details.

PieCharts essentially take maps of integers or reals as input. The strings are used to label each sector of the pieChart and the number determines the relative size of the sector. See http://en.wikipedia.org/wiki/Pie_chart for further details.

An *xyChart* plots the graph of one or more functions on the same grid. Each series is interpreted as a list of (x,y) values; the name of the series acts as function name.

All chart functions can have zero or more *ChartSettings* that give control over the way in which the chart is drawn. A *ChartSetting* can be one of the following:

```
data ChartSetting =
  | areaPlot()
  | chartSize(int w, int h)
  | curvePlot()
  | horizontal()
  | linePlot()
  | ring(int h)
  | stackedBars()
  | subtitle(str txt)
  | vertical()
  | xLabel(str txt)
  | yLabel(str txt)
  ;
```

The applicability and meaning of these settings is as follows.

Table 1.43. Chart Settings

Function	Applicable for	Description
<code>areaPlot()</code>	<code>xyChart</code>	Changes an <code>xyChart</code> from a line graph into an area graph, i.e., all surface below the line graph is colored.
<code>chartSize(int w, int h)</code>	<code>barChart</code> , <code>pieChart</code> , <code>xyChart</code>	Width and height of chart

Function	Applicable for	Description
<code>curvePlot()</code>	<code>xyChart</code>	Connect the points in an <code>xyChart</code> with a curve
<code>horizontal()</code>	<code>barChart</code> , <code>xyChart</code>	Default, horizontal, drawing mode
<code>linePlot()</code>	<code>xyChart</code>	Connect the points in an <code>xyChart</code> with lines
<code>ring(int h)</code>	<code>pieChart</code>	Draw <code>pieChart</code> as a ring with inner radius <code>n</code>
<code>stackedBars()</code>	<code>barChart</code>	Draw <code>barChart</code> in stacked fashion
<code>subtitle(str txt)</code>	<code>barChart</code> , <code>pieChart</code> <code>xyChart</code>	At the top of the chart, draw a subtitle below the title
<code>vertical()</code>	<code>barChart</code> , <code>xyChart</code>	Vertical drawing mode.
<code>xLabel(str txt)</code>	<code>barChart</code> , <code>xyPlot</code>	Draw a label at the bottom (domain, x-axis) of the chart
<code>yLabel(str txt)</code>	<code>barChart</code> , <code>xyPlot</code>	Draw a label at the left (range, y-axis) of the chart

Running Rascal

The Rascal system comes in two flavours: a command line version and a version integrated in Eclipse.

Rascal at the Command Line

At the command line the Rascal system can be invoked by typing the command **rascal**. Next, the Rascal prompt `rascal>` appears and you can start typing commands (declarations, statements, expressions). To simplify interactive use, semicolons (`;`) that end commands may be omitted at the top level.

In addition to Rascal expressions and statements, the command line interface also supports some additional directives that you can find by typing `:help` as show here:

```
rascal> :help
Welcome to the Rascal command shell.

Shell commands:
:help                Prints this message
:quit or EOF         Quits the shell
:list                Lists all visible rules, functions and
                    variables
:set <option> <expression> Sets an option
:edit <modulename>   Opens an editor for that module
:modules             Lists all imported modules
:test               Runs all unit tests currently loaded
:unimport <modulename> Undo an import
:undeclare <name>    Undeclares a variable or function
                    introduced in the shell
:history             Print the command history

Example rascal statements and declarations:
1 + 1;              Expressions simply print their output
                    and (static) type
int a;              Declarations allocate a name in the
                    current scope
a = 1;              Assignments store a value in a
                    (optionally previously declared)
                    variable
int a = 1;          Declaration with initialization
import IO;           Importing a module makes its public
                    members available
println("Hello World") Function calling

Please read the manual for further information
ok
rascal>
```



Further discuss here arguments of the rascal command.

Rascal in Eclipse



To be written

Table of Built-in Operators

Table 1.44. All Operators

Operator	Description	See Library Module/Section
$Exp_1[Name = Exp_2]$	Field assignment	Non-Boolean Operator Expressions (page 66)
$Exp . Name$	Field selection	Non-Boolean Operator Expressions (page 66), Location (page 100), Tuple (page 112)
$Exp < field, \dots >$	Field projection	Non-Boolean Operator Expressions (page 66), Relation (page 104)
$Exp_1[Exp_2, Exp_3, \dots]$	Index	Non-Boolean Operator Expressions (page 66), List (page 99), Map (page 101), Node (page 102), Relation (page 104), Tuple (page 112)
$Exp ?$	Isdefined: true if Exp has a defined value	Boolean Operator Expressions (page 69)
$! Exp$	Negation	Boolean Operator Expressions (page 69), Boolean (page 92)
$- Exp$	Negation	Integer (page 94), Real (page 103)
$Exp +$	Transitive closure	Relation (page 104)
$Exp *$	Reflexive transitive	Relation (page 104)
$Exp @ Name$	Annotation value	
$Exp_1[@Name = Exp_2]$	Assign annotation value	
$Exp_1 \circ Exp_2$	Composition	Relation (page 104)
$Exp_1 \times Exp_2$	Cartesian product	Relation (page 104)
Exp_1 / Exp_2	Division	Integer (page 94), Real (page 103)
$Exp_1 \% Exp_2$	Modulo	Integer (page 94), Real (page 103)
$Exp_1 * Exp_2$	Multiplication/product	Integer (page 94), List (page 99), Real (page 103), Set (page 108)
$Exp_1 \& Exp_2$	Intersection	Set (page 108)
$Exp_1 + Exp_2$	Addition/ concatenation/union	Integer (page 94), List (page 99), Map (page 101), Real (page 103), Set (page 108), String (page 110), Tuple (page 112)
$Exp_1 - Exp_2$	Subtraction/difference	Integer (page 94), List (page 99), Map (page 101), Real (page 103), Set (page 108)
$Exp_1 \text{ join } Exp_2$	Join	Set (page 108)
$Exp_1 \text{ in } Exp_2$	Element of	Boolean Operator Expressions (page 69), List (page 99), Map (page 101), Set (page 108)
$Exp_1 \text{ not in } Exp_2$	Not element of	Boolean Operator Expressions (page 69), List (page 99), Map (page 101), Set (page 108)
$Exp_1 \leq Exp_2$	Less than/sublist / subset	Boolean Operator Expressions (page 69), Boolean (page 92), Integer (page 94), List

Operator	Description	See Library Module/Section
		(page 99), Location (page 100), Map (page 101), Node (page 102), Real (page 103), Set (page 108), String (page 110), Tuple (page 112), Value (page 113)
$Exp_1 < Exp_2$	Less than/strict sublist/ strict subset	Boolean Operator Expressions (page 69), Boolean (page 92), Integer (page 94), List (page 99), Location (page 100), Map (page 101), Node (page 102), Real (page 103), Set (page 108), String (page 110), Tuple (page 112), Value (page 113)
$Exp_1 >= Exp_2$	Greater than/superlist/ superset	Boolean Operator Expressions (page 69), Boolean (page 92), Integer (page 94), List (page 99), Location (page 100), Map (page 101), Node (page 102), Real (page 103), Set (page 108), String (page 110), Tuple (page 112), Value (page 113)
$Exp_1 > Exp_2$	Greater than/strict superlist/ strict superset	Boolean Operator Expressions (page 69), Boolean (page 92), Integer (page 94), List (page 99), Location (page 100), Map (page 101), Node (page 102), Real (page 103), Set (page 108), String (page 110), Tuple (page 112), Value (page 113)
$Pat := Exp$	Match	Boolean Operator Expressions (page 69)
$Pat !:= Exp$	No Match	Boolean Operator Expressions (page 69)
$Exp_1 == Exp_2$	Equality	Boolean Operator Expressions (page 69), Boolean (page 92), Integer (page 94), List (page 99), Location (page 100), Map (page 101), Node (page 102), Real (page 103), Set (page 108), String (page 110), Tuple (page 112), Value (page 113)
$Exp_1 != Exp_2$	Inequality	Boolean Operator Expressions (page 69), Boolean (page 92), Integer (page 94), List (page 99), Location (page 100), Map (page 101), Node (page 102), Real (page 103), Set (page 108), String (page 110), Tuple (page 112), Value (page 113)
$Exp_1 ? Exp_2$	Ifdefined Otherwise	Boolean Operator Expressions (page 69)
$Exp_1 ? Exp_2 : Exp_3$	Conditional Expression	Boolean Operator Expressions (page 69), Boolean (page 92), Integer (page 94), List (page 99), Map (page 101), Node (page 102), Real (page 103), Set (page 108), String (page 110), Tuple (page 112), Value (page 113)
$Exp_1 ==> Exp_2$	Implication	Boolean Operator Expressions (page 69), Boolean (page 92)
$Exp_1 <==> Exp_2$	Equivalence	Boolean Operator Expressions (page 69), Boolean (page 92)
$Exp_1 \&\& Exp_2$	Boolean and	Boolean Operator Expressions (page 69), Boolean (page 92)
$Exp_1 Exp_2$	Boolean or	Boolean Operator Expressions (page 69), Boolean (page 92)

Table of Built-in Functions

Table 1.45. All Functions

Function	See Library Module
abs	Integer (page 94)
arbBool	Boolean (page 92)
arbInt	Integer (page 94)
arbReal	Real (page 103)
area	viz::Figure::Chart (page 118)
arity	Node (page 102)
average	List (page 99), Set (page 108)
barChart	viz::Figure::Chart (page 118)
bottom	Graph (page 93), Labeled Graph (page 98)
boxPl	viz::Figure::Chart (page 118)
carrier	Relation (page 104)
carrierR	Relation (page 104)
carrierX	Relation (page 104)
center	String (page 110)
charAt	String (page 110)
complement	Relation (page 104)
currentTimeMillis	Benchmark (page 91)
delete	List (page 99)
dependencies	Resources (Eclipse only) (page 107)
dim3	viz::Figure::Chart (page 118)
domain	List (page 99), Map (page 101), Relation (page 104)
domainLabel	viz::Figure::Chart (page 118)
domainR	Relation (page 104)
domainX	Relation (page 104)
endsWith	String (page 110)
extractClass	JDT (Eclipse only) (page 95)
extractFactsTransitive	JDT (Eclipse only) (page 95)
extractProject	JDT (Eclipse only) (page 95)
fromInt	Boolean (page 92)
fromString	Boolean (page 92)
getChildren	Node (page 102)
getName	Node (page 102)
getOneFrom	List (page 99), Map (page 101), Set (page 108)
graphView	viz::Basic (Eclipse only) (page 113)
head	List (page 99)
histogram	viz::Figure::Chart (page 118)
horizontal	viz::Figure::Chart (page 118)

Function	See Library Module
ident	Relation (page 104)
insertAt	List (page 99)
invert	Map (page 101), Relation (page 104)
invertUnique	Map (page 101)
isEmpty	List (page 99), Map (page 101), Set (page 108), String (page 110)
left	String (page 110)
makeNode	Node (page 102)
mapper	List (page 99), Map (page 101), Set (page 108)
matchLocations	JDT (Eclipse only) (page 95)
max	Integer (page 94), List (page 99), Real (page 103), Set (page 108)
min	Integer (page 94), List (page 99), Real (page 103), Set (page 108)
noSectionLabels	viz::Figure::Chart (page 118)
permutations	List (page 99)
pieChart	viz::Figure::Chart (page 118)
power	Set (page 108)
power1	Set (page 108)
predecessors	Graph (page 93), Labeled Graph (page 98)
println	IO (page 94)
projects	Resources (Eclipse only) (page 107)
range	Map (page 101)
rangeLabel	viz::Figure::Chart (page 118)
rangeR	Relation (page 104)
reach	Graph (page 93), Labeled Graph (page 98)
reachR	Graph (page 93), Labeled Graph (page 98)
reachX	Graph (page 93), Labeled Graph (page 98)
readable	JDT (Eclipse only) (page 95)
readFile	IO (page 94)
readRSF	RSF (page 107)
readValueFromBinaryFile	ValueIO (page 113)
readValueFromTextFile	ValueIO (page 113)
reducer	List (page 99), Set (page 108)
references	Resources (Eclipse only) (page 107)
reverse	List (page 99), String (page 110)
right	String (page 110)
ring	viz::Figure::Chart (page 118)
root	Resources (Eclipse only) (page 107)
shortestPathPair	Graph (page 93), Labeled Graph (page 98)
size	List (page 99), Map (page 101), Set (page 108), String (page 110)

Function	See Library Module
slice	List (page 99)
sort	List (page 99)
scatter	viz::Figure::Chart (page 118)
stacked	viz::Figure::Chart (page 118)
startsWith	String (page 110)
subtitle	viz::Figure::Chart (page 118)
successors	Graph (page 93), Labeled Graph (page 98)
tail	List (page 99)
takeOneFrom	List (page 99), Set (page 108)
textView	viz::Basic (Eclipse only) (page 113)
treeView	viz::Basic (Eclipse only) (page 113)
toReal	String (page 110)
toInt	Boolean (page 92), Real (page 103), String (page 110)
toList	Map (page 101), Set (page 108)
toLowerCase	String (page 110)
toMap	List (page 99), Set (page 108)
toMapUnique	List (page 99), Set (page 108)
top	Graph (page 93), Labeled Graph (page 98)
toReal	Boolean (page 92), Integer (page 94)
toRel	Map (page 101)
toSet	List (page 99)
toString	Boolean (page 92), Integer (page 94), List (page 99), Map (page 101), Real (page 103), Set (page 108)
toUpperCase	String (page 110)
unionFacts	JDT (Eclipse only) (page 95)
vertical	viz::Figure::Chart (page 118)
writeValueToBinaryFile	ValueIO (page 113)
writeValueToTextFile	ValueIO (page 113)
xyChart	viz::Figure::Chart (page 118)

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Arnold Lankamp implemented a very efficient version of the Program Data Base (PDB), added a binary streaming format, implemented the SGLR invoker, and takes care of deployment issues.

Karel Pieterse used Rascal as topic for a usability study in his Master's thesis. The results will be included in the final version of this document.

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Glossary of Terminology

Annotation	An annotation is a (name, value) pair that can be attached to a datatype value. The value can be retrieved and changed via the name. One datatype value can have more than one annotation.
ASF	Algebraic Specification Formalism. This a notation for describing rewrite rules and is mostly used for defining software analysis, fact extraction, and software transformation. It is the predecessor of Rascal.
ASF+SDF	The combination of the formalisms ASF and SDF. ASF+SDF can describe both the syntax of a language and the operations on that language (checking, execution, analysis, transformation). It is the predecessor of Rascal.
AsFix	<p>ASF+SDF Fixed format. A dataformat used to represent parse trees. AsFix is a specialized view on ATerms. Important features are:</p> <ul style="list-style-type: none">• The AsFix format is a full parse tree that contains all the original layout and comments from the original source code program that was parsed.• The AsFix format is self-descriptive: each subtree contains information about the exact grammar production that has been used to parse the text that has resulted in that parse tree.• The AsFix format does not contain source code coordinates per se, but a separate tool can easily compute these coordinates and add them to the parse tree in the form of annotations. <p>AsFix is the predecessor of the ParseTree format used by Rascal</p>
ATerm	<p>Annotated terms. A dataformat used for the internal representation of all data. Distinguishing features are:</p> <ul style="list-style-type: none">• ATerms are language-independent and can be processed by programs in any language.• ATerms can be annotated with auxiliary information that does not affect the tree structure.• ATerms preserve <i>maximal subterm sharing</i>. This means that common parts of the data are not duplicated but shared. This leads to considerable size-reduction of the data. <p>ATerms are the predecessors of the shared PDB implementation used in Rascal.</p>
Backtracking	Backtracking is a general algorithmic method for finding all (or some) solutions to some computational problem, in the case of Rascal for pattern matching. It incrementally builds candidate matches, and abandons each partial match ("backtracks") as soon as it determines that it cannot possibly be completed to a valid match.

Bag	A bag can contain arbitrary values, without any particular order, and possibly repeated elements. All elements of a bag have the same type. <i>Rascal does not (yet?) support bags.</i>
Comprehension	An algorithmic schema for computing lists, sets or relations.
Constraint solving	The process of finding solutions to a problem that is only specified by the boundary conditions (constraints) that a solution should satisfy.
Control flow	The order in which the statements in a program can be executed. Usually represented as a control flow graph.
Debugger	A debugger allows the step-by-step execution of a program.
Dataflow	The order in which values may be assigned to variables during program execution. Usually represented as a data flow graph.
Eclipse	Interactive Development Environment (IDE) for Java and other languages. The Rascal IDE is built on top of Eclipse and IMP.
Enumerator	A Rascal construct that enumerates all the elements of a given value.
Function (higher order)	A function is a computational entity with typed formal parameters and a typed result. When applied to actual parameters, the function is applied and the result replaces the function call. A higher-order function is a function that has one or more functions as parameter.
Graph	In mathematics a graph is a set of objects (nodes) that may be pairwise connected with links (edges). In Rascal, a graph is a binary relation in which each tuple represents an edge in the corresponding (mathematical) graph.
Interactive Development Environment (IDE)	A programming environment for the interactive design, development, debugging and testing of programs. Eclipse is an example of an IDE.
IDE Meta Platform (IMP)	IMP is an extension of Eclipse and is intended to make it easier to add support for new languages to Eclipse. The Rascal implementation is part of IMP.
Location	Data format to describe locations in source code.
List	A list can contain arbitrary values, with a particular order, and possibly repeated elements. All elements of a list have the same type.
Map	A map is a binary relation consisting of 2-tuples (pairs) of the form (key, value) that associate each key with a unique value.
Meta-Environment	The ASF+SDF Meta-Environment is the IDE for writing ASF+SDF specifications.
Meta-programming	The activity of writing programs that manipulate other programs as data.
Parser	A program that performs syntactic analysis on a given input text and builds a parse tree.

Parse table	A parse table is produced by a parse table generator and is an efficient representation of grammar that can be used by a parser.
Parse table generator	A parse table generator takes a grammar as input and converts it to a parse table to be used by a parser.
Parse tree	Tree-structured representation of a text that has been analyzed by a parser.
ParseTree	The ParseTree datatype is the parse tree format used in Rascal. It is the successor of AsFix.
Pattern	A structural description of values that is used for matching.
Pattern matching	Matching is an algorithmic method for determining the structural similarity of a pattern and a subject value. The pattern may contain variables that are bound to corresponding parts of the subject value when the match succeeds.
Program Data Base (PDB)	Subsystem of IMP that is responsible for implementing Rascal's datatypes.
Polymorphism	Functions and datatypes that can handle values of different types in a uniform manner.
Prettyprinter	A prettyprinter converts parse trees to text. The prettyprinter uses default rules to insert layout in a parse tree so that its corresponding text is presented in a uniform way. Optionally, user-defined formatting rules can replace this default behaviour.
Relation	A relation is a set of tuples. All tuples of a relation have the same type.
Rscript	A small scripting language for defining relational expressions. Used for the analysis of facts extracted from software. Predecessor of Rascal.
Relational Algebra	An algebra on relations that provides operators on relations that yield new relations. Relational algebra uses no variables and provides an operational view on relations.
Relational calculus	Relational calculus provides a more declarative and descriptive way to formulate operations on relations and depends on the use of variables.
Read-Eval-Print-Loop (REPL)	Command-line loop that reads user input, evaluates it and prints the result.
Rewrite rule	A rewrite rule consists of a pattern and a replacement. A rewrite rule is applied to all subparts of a datastructure and when the pattern matches the matching subpart is replaced. Pattern and replacement may contain variables and variables in the replacement are first replaced by their value before the replacement is applied.
SDF	Syntax Definition Formalism. A notation for describing the grammar of programming and application languages. SDF definitions can be imported in Rascal.
Set	A set can contain arbitrary values, without any particular order, and no repeated elements. All elements of a set have the same type.

Side-effect	In imperative programming languages like C and Java, assignments cause changes in a global state that are visible for other statements and procedures.
Syntax tree	Tree-structured representation of a text that has been analyzed by a parser.
Summary	An error or message summary. A dataformat for the internal representation of errors and messages. Summaries are produced by checker and compilers and are used by the GUI.
Term rewriting	Term rewriting is the act of applying a set of rewrite rules to a subject value. The rules are applied as long as any pattern in some rule matches. The result is the subject value with replacements made as prescribed by the matching rules.
Traversal	The process of visiting all the sub-elements of a larger datastructure. The <code>visit</code> expression and enumerators provide traversal functionality in Rascal.
Tuple	A tuple is an ordered list of values of possibly different type. An element of a tuple may have a label by which that element can be selected or modified.
Type checking	The activity to check that all entities in a program are declared and are used in a way that is consistent with their declared type.
Type inference	The activity to infer the type of program entities from their use.