Degc Language

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Contents

1 Language Specification

1.1 Lexical Grammar

1.1.1 Overview

Lexical grammar is similar to the *Python* language.

The Degc tokenizer always returns the longest possible token which can be produced from the input. Tokens are delimited by non-matching characters and by whitespace. An unrecognized character or sequence is treated as an error.

In Degc, whitespace is syntactically significant. Four (4) spaces are used to indent blocks, and other whitespace characters are ignored. Spaces are also ignored inside parenthesized (,) and bracketed [,] code.

Line comments are indicated with a hash # symbol. All input from the hash sign to the end of the current line is ignored.

1.1.2 Identifiers

Types and functions are designated by a string identifier. Valid identifiers may begin with an underscore, or any upper- or lower-case English letter. Identifiers may not begin with numbers, but numbers are permitted in the remainder of the identifier.

Identifiers which begin with a number, or contain any symbols other than English letters, numbers, and underscores, are invalid.

1.1.3 Literals

Degc includes the Boolean literal values *true* and *false*.

Numeric literals denote fractional decimal numbers, and may contain any Arabic number from 0 to 9, and optionally a single decimal . which must be followed by additional numbers. Degc supports fixed-precision numbers with $\varepsilon = 0.0001$.

1.1.4 Keywords and Punctuators

The Degc lexicon contains the following keywords: *all, and, any, assert, as, best, by, either, else, embed, enum, exists, extends, for, from, function, if, import, intersect, in, limit, module, not, or, panic, program, record, setminus, set, take, union, with.*

The Degc lexicon also contains the following punctuators: *@ : , . -> + - * / < <= > >= = != ( ) [ ] { } |*

1.2 Syntax and Semantics

1.2.1 Overview

Degc is a declarative language for describing academic programs. As such, Degc programs are written to model the given problem, rather than written to execute specific computations.

Degc programs operate over an input *ontology* - a set of facts, which are described using records. Degc programs do not have direct access to the contents of records. Instead, Degc programs contain assertions about the ontology. A Degc program evaluates *true* when all of its assertions are true, and *false* otherwise.

1.2.2 Modules

Degc definitions are stored inside modules. Each module is a self-contained namespace. In order to access a symbol from a different namespace, it must be manually imported into the current module.

1.2.2.1 Module declaration

The first line of a Degc translation unit must be a module declaration.

```
module ca.ualberta.science
```

Module declarations are non-unique. By standard convention, module names should reflect the organizational structure of the authoring institution (generally, a fully-qualified domain name in reverse order).

A typical convention will be {country code}.{parent institution}.{faculty}.{department}.

1.2.2.2 Importing symbols

Symbols from the current module (including those defined in other translation units) are automatically imported. Symbols from other modules may be imported using an *import* directive.

```
from ca.ualberta import TakenCourse
from ca.ualberta.science import (Honors, General as BScGeneral,)
```

Import directives are optional. If used, they must immediately follow the module declaration (not including comments and whitespace).

1.2.3 Types

Degc is strongly and statically typed, with three distinct forms of typename.

In the following, a type is *assignment-compatible* with a target type if that type can be transparently treated as an instance of the target type (for the purposes of, for example, passing as a function argument).

1.2.3.1 Boolean types

All values of Boolean type are either *true* or *false*. Boolean types are assignment-compatible only with the boolean type.

The Boolean typename is:

```
bool
```

1.2.3.2 Numeric types

The Degc numeric type is a fixed-precision number with four decimal places ($\varepsilon = 0.0001$). The number type is assignment-compatible only with the number type.

The number type has two typenames:

```
number
quantity
```

For the purposes of the type system, *number* and *quantity* are indistinct. The *quantity* type differs semantically only when used as a record field.

1.2.3.3 Enumeration and Record types

The enumeration and record types reference user-defined enumerations and records. The typenames of these types are simply the identifiers used to name or import these types.

Enumeration and record types are assignment-compatible only with their own type.

1.2.3.4 Program types

Program types reference user-defined programs. The typenames of these types are the identifiers used to name or import these types.

Program types are assignment-compatible with any base program type. For example, if the program *ChildProgram* inherits from *BaseProgram*, then any value of type *Child-Program* is assignment-compatible with the *BaseProgram* type. However, a value of type *BaseProgram* is *not* assignment-compatible with the *ChildProgram* type.

1.2.3.5 Set types

Set types reference subsets of the ontology. All set types are specialized with a record type, denoting the element type of the subset.

Set typenames feature a record typename, in the following format:

```
set(TakenCourse)
```

A value of a set type is assignment-compatible only with the identical set type.

1.2.3.6 Function types

Function types are normally only invoked for implementing higher-order functions. All function types

Function typenames include argument and return typenames:

```
function({arg1}, {arg2}, ..., {argN})->{return typename}
function()->bool
function(number, number)->set(TakenCourse)
function(function(number, number)->bool, set(TakenCourse))->bool
```

A function is assignment-compatible only with another function type, and only if the return values and arguments are also assignment-compatible.

1.2.4 Declarations

1.2.4.1 Records

A record is a quantum of the input ontology. Records contain relevant facts, such as courses or certifications taken, student status, etc.

A record may optionally have one *quantity* field. A record type must have a quantity field to use *take* and *limit* statements.

Example:

```
record TakenCourse:
    Faculty faculty
    Subject subject
    number level
    quantity credits
```

1.2.4.2 Enumerations

Enumerations are a list of options.
Example:

```
enum Subject:
    CMPUT
    MATH
    ENGL
    PHIL
```

1.2.4.3 Functions

Degc contains an embedded functional programming language which can be accessed by writing functions. Degc supports higher-order functions, but not lexical closures.
Example:

```
function SubjectLevelCourse(Subject sub, number lev) -> set(TakenCourse):
    { TakenCourse | subject = sub and level >= lev and level < (lev + 100) }
```

1.2.4.4 Programs

Degc programs describe statements about the ontology. Programs may inherit from other programs. Programs may be parameterized, but are restricted to enumeration arguments.
Example:

```
program ExampleProgram:
    take 6 in { TakenCourse | subject = Subject.CMPUT }
program ExampleChildProgram extends BaseProgram:
    take 6 in { TakenCourse | subject = Subject.CMPUT }
program ExampleParameterizedProgram(Subject majorSubject):
    take 6 in { TakenCourse | subject = majorSubject }
program ExampleChildProgram(Subject sub) extends BaseProgram(sub):
    take 6 in { TakenCourse | subject = majorSubject }
```

1.2.5 Expressions

1.2.5.1 Overview

Deg expressions are similar to those in other languages. As is typical, function calls have the highest precedence, followed by member access, unary operators (arithmetic and boolean negation), multiplication, addition, relations, equality, logical and, and logical or. A higher precedence may be imposed with parentheses.

1.2.5.2 Logical and Arithmetic

Degc supports the usual arithmetic operators for number types: *+,-,*,/*.

Degc also supports the following logical operations: *and, or, not*.

1.2.5.3 Relational

Degc supports the following relational operators: *=,!=,>,>=,<,<=*.

Nominal types - enumerations and booleans - support the identity relations.

The ordinal numeric type supports all relational operators.

1.2.5.4 Set

Set expressions are used to describe a portion of the ontology. They are constructed using a typical set builder notation.

Example:

```
{ TakenCourse }
```

This code describes a set of all records with the type *TakenCourse*.

```
{ TakenCourse | subject = Subject.CMPUT and level < 200 }
```

This code describes a set of all records with the type *`TakenCourse`*`, a subject of` *`CMPUT`*`, and a level which is below` 200.

It must be possible to represent the constructed set as a union of orthogonal ranges. As a result, set clause relations must each depend on a single record member, and that member must be isolated on a single side of the relational operator.

Sets support the *exists, union, intersect,* and *setminus* operators. The *exists* operator returns true if and only if there is at least one record matching the input set. The other operators function as expected.

1.2.5.5 Selection

The selection, or *if/else* expression, is used for predicated branching inside expressions. *If/else* can only be used inside functions.

```
if x = 5:
    true
else if x > 10:
    true
else:
    false
```

The type of the selection expression is the nearest assignment-compatible type common to all branches of the expression.

1.2.5.6 Panic

Degc supports a rudimentary exception mechanism. A panic expression will immediately cause the executing program to terminate with a result of *false*.
Example:

```
function AbortIfTrue(bool predicate)->bool:
    if predicate:
        panic
    else:
        true
```

1.2.6 Statements

1.2.6.1 Overview

Program statements are used to describe facts about the ontology. In the following, an asterisk (*) indicates that the statement type is planned but not currently supported by the reference implementation.

1.2.6.2 Assertions

Assertions execute a boolean expression. If the expression evaluates as *false*, the current execution is rejected.
Example:

```
assert exists { RoyalConservatoryPiano | grade >= 6 }
```

1.2.6.3 Embed

Embed statements include, in-line, the contents of another program.
Example:

```
embed ComputingScienceMajor
```

Parameterized programs may also be embedded with included arguments.
Example:

```
embed MajorProgramMap(majorSubject) with (minorSubject,)
```

The embed keyword may also be used to enclose program statements in a nested block:
Example:

```
take 6 in { TakenCourse | subject = majorSubject }
embed:
    assert exists { StudentRegistered }
    take 6 in { TakenCourse | subject = minorSubject }
take 3 in { TakenCourse }
```

1.2.6.4 Disjunction

Disjunctions are used to indicate a non-discriminated branch. Program execution is successful if at least one branch may be taken.

Example:

```
either:
    assert exists { TakenCourse | subject = Subject.MUS and level = 110 }
or:
    assert exists { PianoExemptionExam | grade >= 0.8 }
or:
    assert exists { RoyalConservatoryPiano | grade >= 6 }
```

1.2.6.5 For All*

For All loops execute the statement body for each record in the matching set. This allows programs to make assertions about all records in the ontology.

For All loops may not contain *take* or *limit* statements.

Example:

```
for all course in { TakenCourse | subject = Subject.CMPUT }:
    assert course.grade >= 2.7
```

1.2.6.6 For Any*

For Any loops execute the statement body for any one, arbitrarily-chosen record in the ontology.

For Any loops may not contain *take* or *limit* statements.

Example:

```
for any status in { RegistrationStatus }:
    assert status.registered
```

1.2.6.7 For Best*

For Best loops execute the statement body for the best matching record, where the best record is identified with an order predicate.

For Best loops may not contain *take* or *limit* statements.

Example:

```
function HighestGrade(TakenCourse a, TakenCourse b)->bool:
    a.grade >= b.grade
for best course by HighestGrade in { TakenCourse }:
    assert course.grade >= 4.0
```

1.2.6.8 Conditional

Conditional statements are used to indicate a discriminated branch. Conditional statements are used to branch program execution predicated upon the value of a boolean expression.

Example:

```
if exists { RoyalConservatoryPiano | grade >= 6 }:
    assert not exists { PianoExemptionExam }
else:
    assert exists { PianoExemptionExam }
```

1.2.6.9 Take

Take statements are used to allocate a specified quantity from a set. Once taken, the quantity cannot be used to fulfill another *take* requirement.

For example, an academic program may require 6 credits from art courses and 3 additional credits in free options. Although art credits may be applied toward the free option requirement, art credits may not simultaneously be applied to both requirements.

```
take 6 in { TakenCourse | faculty = Faculty.AR }
take 3 in { TakenCourse }
```

In this example, the student always requires at least 9 credits in taken courses.

1.2.6.10 Limit

Limit statements are used to constrain the quantity which may be taken from a set.

For example, a typical academic program will apply a restriction on the number of introductory-level courses which may be applied to a program of study. Limit statements allow these types of requirements to be imposed while still maximizing the assignment of credits.

```
limit 42 in { TakenCourse | level < 200 }
```

Due to the algorithm used for solving programs, limit sets must either be point-wise disjoint or a sub/super-set. Compliant Degc compilers must produce an error when a program contains limit statements which do not satisfy this restriction.

2 Execution Model

2.1 Overview

Degc uses a hybrid execution model which combines an integer program with assertions defined using a programming language.

Due to the specific form of integer programs written in Degc, it is possible to describe the integer program portions as an instance of network max-flow. This correspondence allows a larger amount of preprocessing and a guaranteed polynomial execution time. The disadvantage to this approach is a greater demand for storage space: since branches may produce significantly different networks, each possible branch and combination of program parameters must be enumerated into a separate network. See section 2.2.5 for a detailed discussion of alternative approaches.

The accompanying bytecode program serves to prune the set of feasible networks which must be tested. Any branch which contains a failing assertion is flagged as infeasible, and it is excluded during program execution.

Programs are thus executed in three major stages:

1. The fully specified program is selected based on the input parameters.
2. The bytecode program is executed, masking impossible branches.
3. The max-flow is computed for each possible branch.
   a) Credit quantities are computed from the ontology and assigned to the network inputs.
   b) The max-flow is computed with the Edmonds-Karp algorithm.
   c) If the max-flow is sufficient, the program has been satisfied and returns immediately.

2.2 Integer Program - Network Correspondence

2.2.1 Overview

The *take* and *limit* statements of a Degc program describe an integer program of a particular form.

Let $S_1, \ldots, S_n$ be disjoint subsets of the ontology of a single common type. A Degc integer program consists of some number of variables, $\alpha_1, \ldots, \alpha_\ell \in \mathbb{Z}$, which we may intuitively understand as an assignment of credits from the $S_1, \dots S_n$ input subsets to the requirements that must be satisfied. Since the goal is to fully satisfy all requirements, $\alpha_1 + \alpha_2 + \cdots + \alpha_\ell$ should be maximized, subject to three types of constraints: *supply* constraints, *demand* constraints, and *limit* constraints.

Supply constraints are imposed implicitly by the input. Suppose $\alpha_{b_1}, \dots, \alpha_{b_k}$ represent the amounts of quantity assigned from the ontology subset S_b to various requirements. If the input ontology only has some $c_b \in \mathbb{Z}$ quantity in subset S_b, it follows that $\alpha_{b_1} + \alpha_{b_2} + \cdots + \alpha_{b_k} \leq c_b$, since the total amount of quantity consumed from S_b cannot exceed c_b.

Demand constraints are imposed by the program. Suppose a requirement R_d for $c_d \in \mathbb{Z}$ quantity takes $\alpha_{d_1}, \dots, \alpha_{d_j}$ quantity respectively from each of $S_{e_1}, S_{e_2}, \dots, S_{e_j}$. Then, $\alpha_{d_1} + \alpha_{d_2} + \cdots + \alpha_{d_j} \geq c_d$, since at least c_d quantity must be consumed by such a requirement for it to be satisfied.

Limits are imposed by constraining the total amount of quantity which may be consumed from some subsets. Suppose L_g is a limit of $c_g \in \mathbb{Z}$ imposed upon some collection of subsets which respectively contribute $\alpha_{g_1}, \alpha_{g_2}, \dots, \alpha_{g_p}$ quantity to some number of requirements. Then, $\alpha_{g_1} + \alpha_{g_2} + \cdots + \alpha_{g_p} \leq c_g$.

With the exception of limit constraints, each of these constraints can be directly represented as a network flow. Limit constraints require some modification, which is discussed below.

2.2.2 Supply Constraints

As discussed previously, suppose $\alpha_{b_1}, \alpha_{b_2}, \dots, \alpha_{b_k}$ represent the amounts of quantity consumed from an ontology subset S_b. Then, $\alpha_{b_1} + \alpha_{b_2} + \cdots + \alpha_{b_k} \leq c_b$, where $c_b \in \mathbb{Z}$ is the total amount of quantity contained within S_b.

This constraint can be represented directly in a network: let S_b be represented by a graph node, with outbound arcs to requirements representing $\alpha_{b_1}, \dots, \alpha_{b_k}$. Then, the total flow through S_b is constrained by adding a c_b-capacity arc from the S_b node to the network source node (see figure 2.2.1).

2.2.3 Demand Constraints

As discussed previously, suppose $\alpha_{d_1}, \alpha_{d_2}, \dots, \alpha_{d_\ell}$ represent the amounts of quantity consumed by a requirement R_d. Then, $\alpha_{d_1} + \alpha_{d_2} + \cdots + \alpha_{d_\ell} \geq c_d$, where $c_d \in \mathbb{Z}$ is the total amount of quantity demanded by the requirement.

As before, this constraint can be represented directly in a network: let R_d be represented by a graph node, with inbound arcs from the disjoint subsets representing $\alpha_{d_1}, \dots, \alpha_{d_\ell}$, and an additional infinite-capacity arc from the requirement node to the network sink node. Since the solver computes max-flow, the $\alpha_{d_1}, \dots, \alpha_{d_i}$ are maximized, with the requirement successfully satisfied iff $\alpha_{d_1} + \cdots + \alpha_{d_i} \geq c_d$ (see figure 2.2.2).

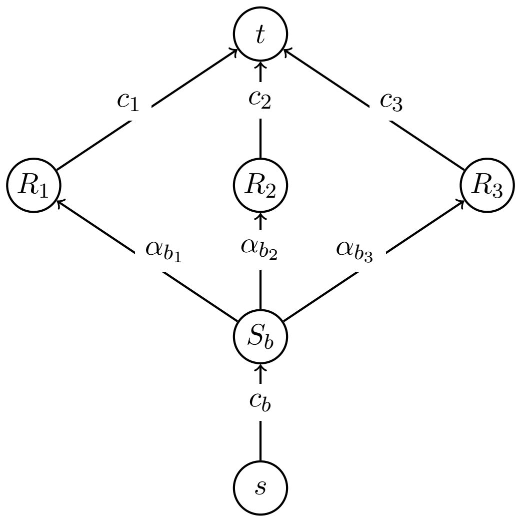

Figure 2.2.1: Illustrates the network flow analogue to the implicit supply constraint.

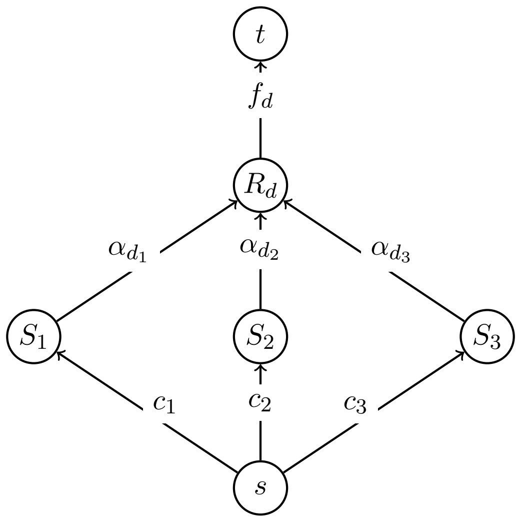

Figure 2.2.2: Illustrates the network flow analogue to the implicit supply constraint.

2.2.4 Limit Constraints

In general, limit constraints cannot be represented in a network. The exception is when every limit is either a subset, a superset, or disjoint from every other set involved in a limit.

2.2.4.1 Disjoint

Suppose L is a disjoint limit constraint, imposing a constraint c on a family of ontology subsets $S_1, S_2, \ldots, S_n$, which are constrained to supply maximum quantities of $s_1, s_2, \ldots, s_n$, respectively. Suppose also $\alpha_1, \alpha_2, \ldots, \alpha_n \in \mathbb{Z}$, where α_i represents the amount of quantity S_i provides to any number of requirements. Then, L has an equivalent *demand constraint* representation.

Proof. Let $\beta_i = s_i - \alpha_i$, for any $1 \leq i \leq n$.

$$\begin{aligned}
& \sum_{i=1}^{n} \alpha_i \leq c \\
\iff \quad & -\sum_{i=1}^{n} \alpha_i \geq -c \\
\iff \quad & \sum_{i=1}^{n} s_i - \sum_{i=1}^{n} \alpha_i \geq \sum_{i=1}^{n} s_i - c \\
\iff \quad & \sum_{i=1}^{n} \beta_i \geq \sum_{i=1}^{n} s_i - c
\end{aligned}$$

Which is, indeed, the form needed for a demand constraint. □

Therefore, disjoint limit constraints are constructed as demand constraints, where the sum of all incoming quantity is greater than the difference between the sum of all possible quantity and the limit constraint value.

(Note that all of the β_i are positive. Therefore, when the supplied quantity is less than the limit amount, all of the $\beta_i = 0$.)

2.2.4.2 Superset/Subset

Subset limit constraints are constructed similar to disjoint limit constraints, with the zero-clamped requirement constraint of each subset subtracted from the requirement constraint of the next-largest superset.

Proof. Let L_1, L_2 be limit constraints, such that L_1 is the largest subset of L_2 among all limit constraints. Suppose the corresponding limit for L_1 is $\sum_{i=1}^{n} \beta_i \geq \sum_{i=1}^{n} s_i - c$, while the corresponding limit for L_2 is $\sum_{i=1}^{m} \beta_i \geq \sum_{i=1}^{m} s_i - d$ (where, clearly, $m > n$).

Case 1: Suppose $\sum_{i=1}^{n} s_i - c$ is non-positive. Then, $\sum_{i=1}^{n} \beta_i = 0$, and the constraint is valid and applies only to $L_2 \setminus L_1$.

Case 2: Suppose $\sum_{i=1}^{n} s_i - c$ is positive.

$$\begin{aligned} & \sum_{i=1}^{m} \beta_i \geq \sum_{i=1}^{m} s_i - d \\ \iff \quad & \sum_{i=1}^{m} \beta_i - \sum_{i=1}^{n} \beta_i \geq \sum_{i=1}^{m} s_i - d - \sum_{i=1}^{n} s_i + c \\ \iff \quad & \sum_{i=n+1}^{m} \beta_i \geq \sum_{i=n+1}^{m} s_i - (d + c) \end{aligned}$$

Therefore, subtracting the subset limit constraint from the superset limit constraint yields a new demand constraint, implicating only the ontology subsets of $L_2 \setminus L_1$. $\square$

2.2.5 Alternative Approaches

There are several possible alternative approaches which may warrant consideration in the future.

2.2.5.1 Depth-first exploration with backtracking

It is possible to directly evaluate program requirements. This approach offers a reduced implementation complexity, more flexibility, and has already been successfully prototyped. Unfortunately, repeated backtracking implies a potentially-exponential number of expensive queries against the input ontology, which may not be reasonable in a production setting.

2.2.5.2 Integer program solver

This model was chosen specifically to guarantee a polynomial execution time. In practice, however, a general integer program solver may be superior to the Edmonds-Karp solver, while simultaneously eliminating the unfortunate disjoint/subset restriction on the limit constraints.

3 Implementation

3.1 Compiling Degc

3.1.1 Requirements

Degc has been built and tested using Ubuntu 12.10. This is currently the only supported platform.

Degc requires the following additional libraries and tools:

- GCC 4.7 or Clang 3.3
- Make 3.8
- Bison 2.5
- Flex 2.5
- Boost 1.49
- NullUnit 0.3 (available here: http://code.google.com/p/nullunit)

3.1.2 Compiling

Navigate to the directory where Degc has been extracted and run the following command:

```
$ make
```

This command will automatically compile Degc and run the test cases.

3.2 Development Guide

3.2.1 Overview

This portion of the document contains a high-level description of the major namespaces and components in the Degc implementation.

The Degc compiler is a multi-pass design, translating the input text to executable code over 8 self-contained stages. This design simplifies the implementation of new features, as the behavior of each stage can be implemented and tested separately.

The recommended approach for introducing new features is to write failing test cases. The compiler will automatically generate unimplemented feature errors, letting you know what files must be modified to support your feature.

3.2.2 compiler::ast

The *ast* namespace contains the Abstract Syntax Tree implementation. The parser output consists of AST nodes, which encode the language in a tree structure.

- FACTORY - An AST node factory, used by the parser rules to generate AST nodes.
- NODE - Contains declarations of AST node types.
- VISITOR - An abstract visitor interface used by later compiler stages to inspect the AST.

3.2.3 compiler::diagnostics

The *diagnostics* namespace contains utilities and helper functions for error reporting.

- ERROR - Container object describing a single error.
- ERRORCODE - Names error codes.
- ERRORLEVEL - Names error levels.
- ERRORLOCATION - Container object describing the filename and position of an error.
- REPORT - Abstract error report interface.
- STOREDREPORT - Error reporter which stores Error objects.
- STREAMREPORT - Error reporter which prints errors to a provided std::ostream&.

3.2.4 compiler::grammar

The *grammar* namespace contains the parser and lexical analyzer.

- INSTANCE - Encapsulates an instance of the parser.
- LEXER.LEX - GNU Flex lexer rules.
- PARSER.Y - GNU Bison parser rules.

3.2.5 compiler::ir

The *ir* namespace contains helper classes for generating bytecode.

- PRINTER - Abstract interface for a bytecode printer.
- CODEPRINTER - Prints executable bytecode.
- TEXTPRINTER - Prints human-readable text.
- SPLITPRINTER - Prints to multiple printer implementations.

3.2.6 compiler::sg

The *sg* namespace contains the Semantic Graph implementation. The first compiler stages convert the Abstract Syntax Tree to the Semantic Graph data structure, which is more useful for performing semantic analysis.

- ERROR_HELPER - Contains helper functions for reporting semantic errors.
- MODULE - Records all of the symbols contained within a single module.
- NODE - Contains declarations of Semantic Graph node types.
- SCOPE_STACK - Contains a stack of scopes, allowing argument look-up within nested scopes.
- SCOPE - A single scope containing symbols (e.g. function arguments, record members).
- TABLE - Semantic Graph root node.
- VISITOR - An abstract visitor interface used by later compiler stages to inspect the SG.

3.2.7 compiler::stages

The *stages* namespace contains the transformation rules used for translating the input program into the bytecode and network output.

3.2.7.1 generate_ast

Constructs an Abstract Syntax Tree from an input source file.

3.2.7.2 generate_sg

Constructs a basic Semantic Graph from the Abstract Syntax Tree generated in the previous stage.

The basic SG contains built-in types, along with user-defined modules and symbols, although the contents of type, function, and program symbols are not yet initialized.

3.2.7.3 resolve_imports

Associates named imports with the actual symbol nodes generated in the previous stage.

3.2.7.4 generate_members

Populates user-defined type symbols - records, enumerations, and function arguments.

3.2.7.5 generate_expr

Generates expressions from the AST, replacing names with SG node references, and performs semantic analysis.

3.2.7.6 constant_folding

Performs any possible off-line computation, converting constant expressions into constant values.

3.2.7.7 generate_set_expr

Normalizes set filter expressions, verifying that set filters can be expressed as a union of orthogonal ranges.

3.2.7.8 generate_code

Generates networks and bytecode for programs and functions.

3.2.8 runtime::code

The *code* namespace contains data structures used to record facts about an executable program.

- CODEBUFFER - Contains an executable bytecode stream.
- CODEBUFFERREADSTREAM - Reads from a CodeBuffer at a specified offset.
- CODEBUFFERWRITESTREAM - Appends to a CodeBuffer, used by COMPILER::IR::CODEPRINTER.
- FUNCTIONTABLE - Uniquely associates function names with a CodeBuffer offset.
- PROGRAMTABLE - Uniquely associates program names with a program data structure.
- RECORDTYPETABLE - Uniquely associates record names with an integer identifier.

3.2.9 runtime::math

The *math* namespace contains utility classes used for compiling and solving programs.

- FIXED - Defines a fixed-point decimal data type.
- INTERVAL - Defines an interval on a data type. Used by SET.
- RELATION - Defines the relations used by SET to construct intervals.
- SET - Defines a set on the ontology as a union of orthogonal ranges.

3.2.10 runtime::solver

The *solver* namespace contains utility classes used for solving programs.

- RECORD - Describes the contents of a single record field.
- RECORDTABLE - Abstract interface for a collection of records of a particular type.
- LINEARRECORDTABLE - Implementation of RecordTable which uses linear search.
- RECORDINDEX - Collection of RecordTable instances, one for each type in the ontology.
- NETWORK - Network data structure and implementation of Edmonds-Karp algorithm.
- PROGRAM - Program data structure.

3.2.11 runtime::vm

The *vm* namespace contains the bytecode virtual machine implementation.

- OPCODE - Defines the opcodes which can be executed by the virtual machine.
- VIRTUALMACHINE - The virtual machine implementation. Executes programs via bytecode interpretation.