

Oliver Graf

THE

DROMEDAR

PROGRAMMING LANGUAGE

Contents

1	Introduction	3
2	Typing System	3
3	Expressions	4
4	Handling Whitespace	4
5	Buildup of a Program	5
6	Garbage Collection	6
7	Formal Typing Rules	6
8	Formal Grammar	14

1 Introduction

1.1 Hello, World!

```
fn main -> void
    print_str("Hello, World!")
```

2 Typing System

Dromedar uses a static, strong and sound typing system – typing errors cannot happen at runtime. It knows primitive and reference types.

2.1 Primitives

There are four primitive types:

- **int** represents 64-bit 2's complement (signed) integers.
- **flt** represents 64-bit IEEE-754 standard floating point numbers.
- **char** represents 8-bit UTF-8 characters.
- **bool** represents a 1-bit value: **true** and **false**.

2.2 Reference Types

Reference types represent data structures that are laid over pointers to objects stored in the heap. References come in two types: Maybe-**null** and Definitely-not-**null** types. Operations like array subscript access are only possible with non-**null** types to ensure **null** safety.

With a non-null-type **t**, the type **t?** represents a reference type that allows **null** values. Primitives are non-nullable.

The following are reference types:

- **string** represents lists of characters.
- **[t]** represents an array with elements of type **t**.

Thus, e.g. **[[int]?)** represents a two-dimensional array of integers which is definitely non-**null**, whereas its rows may be **null**.

2.3 Mutability

In general, variables declared with the **let** keyword are immutable, whereas **mut** declarations create mutable variables.

For references, Dromedar uses a different notion of mutability: Allowing the object to point to new objects is handled with the **mut** declaration. However, even immutable objects are allowed to call methods which alter their internal state – for example changing an array's element.

2.4 Subtyping

Generally, variables and objects can be assigned values of *subtypes*. Every type is a subtype of itself, and e.g. **t** is a subtype of **t?**. Generally, a subtype is a restricted value set of its supertype – any subtype expression can be assigned to a variable of its supertype.

3 Expressions

Because Dromedar has a strong type system, it generally disallows any operations with operands of a non-specified type unless they are explicitly cast to the correct type before. This means that integer and floating point numbers cannot be added, multiplied, etc.

The following table describes precedence and type of all operators:

Operator	Name	Prec.	Assoc.	Types
-	Unary Negation	100	non-assoc.	int -> int flt -> flt
!	Logical Negation			bool -> bool
**	Exponentiation	90	right	int,int -> int flt,flt -> flt int,flt -> flt flt,int -> flt
*	Multiplication	80	left	int,int -> int flt,flt -> flt int,flt -> flt flt,int -> flt
+	String Addition	70	left	string,string -> string
+, -	Addition Subtraction	70	left	int,int -> int flt,flt -> flt int,flt -> flt flt,int -> flt char,int -> char int,char -> char
<<, >>, >>>	Left Shift Logical Right Shift Arithmetic Right Shift	60	left	int,int -> int
&	Bitwise And	60	left	int,int -> int
^	Bitwise Xor	50	left	int,int -> int
	Bitwise Or	40	left	int,int -> int
=, !=, >, <, >=, <=	Comparison	30	non-assoc.	[int/flt] -> bool [char] -> bool
=, !=, >, <, >=, <=	Structural Comparison	30	non-assoc.	[string] -> bool
==, !=	Reference Comparison	30	non-assoc.	[rt1...rtN] -> bool
&&	Logical And	20	left	bool,bool -> bool
	Logical Or	10	left	bool,bool -> bool

Consider the following example:

The expression `1+18-18+'a'` is well-typed (of type **char**) and gets parsed as `((1+18)-18)+'a'` and evaluated to `'b'`. `10 - 0.0` on the other hand is not well-typed as `-` cannot take an **int** and a **flt** operand as arguments.

Comparison operators work differently to other (binary) operators: Instead of comparing just two expressions, Dromedar allows chaining expressions to create one final boolean value: For example, `1 < 2 != 5 >= 5` holds because every single sub-expression (`1 < 2`, `2 != 5` and `5 >= 5`) holds. Every expression is only evaluated once for its side-effect.

Thus, `A op B op C` is not necessarily semantically equivalent to `A op B && B op C`.

4 Handling Whitespace

In order to keep the code simple and easy to look at, Dromedar uses significant whitespace: Blocks of code (such as bodies of **if**) statements, are denoted by adding a level of indentation.

Every line is either empty (this includes lines containing only comments), or it contains code.

If a line contains code, the level of its indentation is determined by its relationship to the previous line and its environment:

Two neighboring lines of code within the same block of code must have exactly matching whitespace characters before their respective code starts. If a following line has a deeper level of indentation, it must match the whitespace characters of the previous line and then add a number of additional whitespace characters (space(s) and/or tab(s)).

A line of code can only have a deeper indentation level of one step compared to the previous line. The first line of code is always a global instruction and as such has the lowest level of indentation. If it is indented, this level of indentation corresponds to a baseline indentation that every line of code must share.

Consider this valid example:

```
global x := 3           # baseline indentation of two spaces
                        # empty line -> indentation doesn't matter
fn main : args:[string] -> int
    Stdio.println("Hello, World!") # deeper indentation level
    return 0                    # same indentation level
```

Blocks with the same level of indentation can have different indentation strings, but they must still match their environments, as follows:

```
if <condition>
    BLOCK A
else
    BLOCK B
```

The two blocks have a different indentation level, but from context it is still clear that **BLOCK A** is a sub-block of the **if**-statement, whereas **BLOCK B** belongs to the **else**-statement.

5 Buildup of a Program

A program consists of a series of global statements – global variable declarations and function definitions.

5.1 Global Declarations

Global variables are all assigned a value at the point of their declaration. This value is evaluated statically – declaration expressions can only contain literals and global variables that were already declared previously.

Functions are also declared globally. They can call each other and themselves recursively within their respective function bodies.

5.2 Standard Library

The Dromedar standard library includes the following functions and objects:

5.2.1 Str: String Operations

Name	Type	Effect
Str.of_int	int -> string	transforms an integer into a string
Str.of_flt	flt -> string	transforms a decimal number into a string

5.2.2 IO: Standard I/O Operations

Printing operations are always preceded by the **IO** library name.

Name	Type	Effect
IO.print_str	string -> void	prints a string to the console
IO.print_int	int -> void	prints an integer to the console
IO.print_flt	flt -> void	prints a real number to the console
IO.print_char	char -> void	prints a character to the console
IO.print_bool	bool -> void	prints <i>"true"</i> or <i>"false"</i> to the console

5.2.3 File: File I/O

Name	Type	Effect
<code>File.readall</code>	string -> [string]	returns all lines from the file with the given input name

5.2.4 Math : Mathematical Operations

Name	Type	Effect
<code>Math.sin</code>	flt -> flt	sine function
<code>Math.cos</code>	flt -> flt	cosine function
<code>Math.tan</code>	flt -> flt	tangent function
<code>Math.e</code>	flt	Euler's constant
<code>Math.pi</code>	flt	π constant

6 Garbage Collection

Dromedar uses an algorithm that combines the mark/sweep and reference counting approaches. It is a *precise* garbage collection algorithm, meaning that it is capable of collecting all non-reachable objects and it will only attempt to GC exactly these (as opposed to conservative GC algorithms like the Boehm-Demers-Weiser garbage collector for C/C++).

Internally, each reference object is stored in a central garbage collection table that counts the numbers of program references that can reach a program, as well as the set of its children.

When a garbage collection run is triggered, the collector will free all objects that are not reachable. An object is deemed **reachable** if either its count of program references is nonzero, or if it is the child of a reachable object.

7 Formal Typing Rules

A typing rule takes the following shape:

$$\frac{\text{Hypotheses}}{S, \dots \vdash_{\text{type}} \text{grammar spec}} \text{NAME}$$

Here, S represents a list of stacks (resp. a stack) of symbol definitions: $S \in (\text{id} \times \text{type} \times \{c, m\})^n$ for some block depth n at any given point. In global context, S has only one layer. id corresponds to the set of names that variables can have (related to the Lexer symbol `%Identifier`), type to the set of types in a given program (related to the Parser symbol `Type`), and $\{c, m\}$ to the mutability of the object: c represents an immutable value (as declared by **let**), and m a mutable one (declared by **mut**).

Writing S in a proof rule enables access to functions and variables within the same module M , whereas S_N corresponds to the context from module N .

The symbol \in is defined as follows: $s \in S \Leftrightarrow s$ is contained in *any* layer of S , whereas \in_0 is true only if the symbol is at the top level of the symbol stack (i.e. defined in the same block). The operator \cup on S adds another binding to the top layer of the stack, whereas \sqcup adds another layer to the stack.

The following are the typing rules for Dromedar programs:

7.1 Subtyping Rules

7.1.1 Cross-Typing

Cross types are types which aren't related by the subtype relation \preceq but still allow for some typesafe interaction – e.g. by assigning variables of one type to variables of another.

The crosstype relation, denoted by the \asymp operator, commutes.

$$\overline{\vdash_{\text{T}} \text{int} \asymp \text{flt}} \text{CROSSTyINTFLT}, \quad \overline{\vdash_{\text{T}} \text{flt} \asymp \text{int}} \text{CROSSTyFLTINT}$$

7.1.2 Trivial Rule

$$\overline{\vdash_{\text{T}} t \preceq t} \text{SUBTyTRIVIAL}$$

7.1.3 References

$$\frac{\vdash_{\mathcal{T}} t1 \preceq t2}{\vdash_{\mathcal{T}} t1 \preceq t2?} \text{SUBTYREFS}, \quad \frac{\vdash_{\mathcal{T}} t1 \preceq t2}{\vdash_{\mathcal{T}} t1? \preceq t2?} \text{SUBTYREFS}$$

7.1.4 Arrays

$$\frac{\vdash_{\mathcal{T}} t1 \preceq t2}{\vdash_{\mathcal{T}} [t1] \preceq [t2]} \text{SUBTYFUNS}$$

7.1.5 Functions

$$\frac{\vdash_{\mathcal{T}} u1 \preceq t1, \dots, \vdash_{\mathcal{T}} un \preceq tn \quad \vdash_{\mathcal{T}} rt \preceq ru}{\vdash_{\mathcal{T}} (t1, \dots, tn) \rightarrow rt \preceq (u1, \dots, un) \rightarrow ru} \text{SUBTYFUNCS}$$

7.1.6 Subtypes and Supertypes

The functions `subtys` and `suptys` of types $\rightarrow \mathcal{P}(\text{types})$ compute the sub- and supertype set of the input type, respectively.

They are used – among others – in the `EXPLITARR` rule.

$$\begin{aligned} \text{subtys} := & \begin{cases} \text{int} & \mapsto \{\text{int}\} \\ \text{flt} & \mapsto \{\text{flt}\} \\ \text{char} & \mapsto \{\text{char}\} \\ \text{bool} & \mapsto \{\text{bool}\} \\ \text{string} & \mapsto \{\text{string}\} \\ t? & \mapsto \{u, u? \mid u \in \text{subtys}(t)\} \\ [t] & \mapsto \{[u] \mid u \in \text{subtys}(t)\} \\ (t1 \dots tn) \rightarrow rt & \mapsto \{(u1 \dots un) \rightarrow st \mid u1 \dots un \in \text{suptys}(t1 \dots tn), st \in \text{subtys}(rt)\} \end{cases} \\ \text{suptys} := & \begin{cases} \text{int} & \mapsto \{\text{int}\} \\ \text{flt} & \mapsto \{\text{flt}\} \\ \text{char} & \mapsto \{\text{char}\} \\ \text{bool} & \mapsto \{\text{bool}\} \\ \text{string} & \mapsto \{\text{string}, \text{string}?\} \\ t? & \mapsto \{u? \mid u \in \text{suptys}(t)\} \\ [t] & \mapsto \{[u], [u]? \mid u \in \text{suptys}(t)\} \\ (t1 \dots tn) \rightarrow rt & \mapsto \left[\begin{array}{l} \{(u1 \dots un) \rightarrow st, (u1 \dots un) \rightarrow st)? \\ \mid u1 \dots un \in \text{subtys}(t1 \dots tn), st \in \text{suptys}(rt)\} \end{array} \right] \end{cases} \end{aligned}$$

7.2 Builtin Operators

Many builtin operators are overloaded, providing functionality for multiple input types.

7.2.1 Unary Operators

7.2.1.1 Arithmetic Negation

$$\overline{\vdash_0 - :: \text{int} \rightarrow \text{int}}^{\text{TYUOPNEGINT}}, \quad \overline{\vdash_0 - :: \text{flt} \rightarrow \text{flt}}^{\text{TYUOPNEGINT}}$$

7.2.1.2 Logical Negation

$$\overline{\vdash_0 ! :: \text{bool} \rightarrow \text{bool}}^{\text{TYUOPNOT}}$$

7.2.2 Binary Operators

7.2.2.1 Power

$$\begin{aligned} & \overline{\vdash_0 ** :: (\text{int}, \text{int}) \rightarrow \text{int}}^{\text{TYBOPPOWINT}}, \quad \overline{\vdash_0 ** :: (\text{flt}, \text{flt}) \rightarrow \text{flt}}^{\text{TYBOPPOWFLT}} \\ & \overline{\vdash_0 ** :: (\text{int}, \text{flt}) \rightarrow \text{flt}}^{\text{TYBOPPOWINTFLT}}, \quad \overline{\vdash_0 ** :: (\text{flt}, \text{int}) \rightarrow \text{flt}}^{\text{TYBOPPOWFLTINT}} \end{aligned}$$

7.2.2.2 Multiplication, Division, Modulo

$$\begin{array}{c}
\frac{}{\vdash_0 * :: (\mathbf{int}, \mathbf{int}) \rightarrow \mathbf{int}} \text{TyBopMulInt}, \quad \frac{}{\vdash_0 * :: (\mathbf{flt}, \mathbf{flt}) \rightarrow \mathbf{flt}} \text{TyBopMulInt} \\
\frac{}{\vdash_0 * :: (\mathbf{int}, \mathbf{flt}) \rightarrow \mathbf{flt}} \text{TyBopMulIntFlt}, \quad \frac{}{\vdash_0 * :: (\mathbf{flt}, \mathbf{int}) \rightarrow \mathbf{flt}} \text{TyBopMulFltInt} \\
\\
\frac{}{\vdash_0 / :: (\mathbf{int}, \mathbf{int}) \rightarrow \mathbf{int}} \text{TyBopDivInt}, \quad \frac{}{\vdash_0 / :: (\mathbf{flt}, \mathbf{flt}) \rightarrow \mathbf{flt}} \text{TyBopDivInt} \\
\frac{}{\vdash_0 / :: (\mathbf{int}, \mathbf{flt}) \rightarrow \mathbf{flt}} \text{TyBopDivIntFlt}, \quad \frac{}{\vdash_0 / :: (\mathbf{flt}, \mathbf{int}) \rightarrow \mathbf{flt}} \text{TyBopDivFltInt} \\
\\
\frac{}{\vdash_0 \% :: (\mathbf{int}, \mathbf{int}) \rightarrow \mathbf{int}} \text{TyBopModInt}
\end{array}$$

7.2.2.3 Addition and Subtraction

•

$$\begin{array}{c}
\frac{}{\vdash_0 + :: (\mathbf{int}, \mathbf{int}) \rightarrow \mathbf{int}} \text{TyBopAddInt}, \quad \frac{}{\vdash_0 + :: (\mathbf{flt}, \mathbf{flt}) \rightarrow \mathbf{flt}} \text{TyBopAddFlt}, \\
\frac{}{\vdash_0 + :: (\mathbf{int}, \mathbf{flt}) \rightarrow \mathbf{flt}} \text{TyBopAddIntFlt}, \quad \frac{}{\vdash_0 + :: (\mathbf{flt}, \mathbf{int}) \rightarrow \mathbf{flt}} \text{TyBopAddFltInt} \\
\frac{}{\vdash_0 + :: (\mathbf{int}, \mathbf{char}) \rightarrow \mathbf{char}} \text{TyBopAddCharR}, \quad \frac{}{\vdash_0 + :: (\mathbf{char}, \mathbf{int}) \rightarrow \mathbf{char}} \text{TyBopAddCharL} \\
\\
\frac{}{\vdash_0 + :: (\mathbf{string}, \mathbf{string}) \rightarrow \mathbf{string}} \text{TyBopAddString} \\
\\
\frac{\mathbf{t} = \min_{\leq}(\text{suptys}(\mathbf{t1}) \cap \text{suptys}(\mathbf{t2}))}{\vdash_0 + :: ([\mathbf{t1}], [\mathbf{t2}]) \rightarrow [\mathbf{t}]} \text{TyBopAddArr}
\end{array}$$

•

$$\begin{array}{c}
\frac{}{\vdash_0 - :: (\mathbf{int}, \mathbf{int}) \rightarrow \mathbf{int}} \text{TyBopSubInt}, \quad \frac{}{\vdash_0 - :: (\mathbf{flt}, \mathbf{flt}) \rightarrow \mathbf{flt}} \text{TyBopSubFlt}, \\
\frac{}{\vdash_0 - :: (\mathbf{int}, \mathbf{flt}) \rightarrow \mathbf{flt}} \text{TyBopSubIntFlt}, \quad \frac{}{\vdash_0 - :: (\mathbf{flt}, \mathbf{int}) \rightarrow \mathbf{flt}} \text{TyBopSubFltInt} \\
\frac{}{\vdash_0 - :: (\mathbf{int}, \mathbf{char}) \rightarrow \mathbf{char}} \text{TyBopSubCharR}, \quad \frac{}{\vdash_0 - :: (\mathbf{char}, \mathbf{int}) \rightarrow \mathbf{char}} \text{TyBopSubCharL}
\end{array}$$

7.2.2.4 Shift Operators

•

$$\frac{}{\vdash_0 << :: (\mathbf{int}, \mathbf{int}) \rightarrow \mathbf{int}} \text{TyBopLShift}$$

•

$$\frac{}{\vdash_0 >> :: (\mathbf{int}, \mathbf{int}) \rightarrow \mathbf{int}} \text{TyBopBitRShift}$$

•

$$\frac{}{\vdash_0 >>> :: (\mathbf{int}, \mathbf{int}) \rightarrow \mathbf{int}} \text{TyBopBitAShift}$$

7.2.2.5 Bitwise Operators

•

$$\frac{}{\vdash_0 \& :: (\mathbf{int}, \mathbf{int}) \rightarrow \mathbf{int}} \text{TyBopBitAnd}$$

•

$$\frac{}{\vdash_0 \wedge :: (\mathbf{int}, \mathbf{int}) \rightarrow \mathbf{int}} \text{TyBopXor}$$

•

$$\frac{}{\vdash_0 | :: (\mathbf{int}, \mathbf{int}) \rightarrow \mathbf{int}} \text{TyBopBitOr}$$

7.2.2.6 Logical Operators

•

$$\frac{}{\vdash_O \&\& :: (\mathbf{bool}, \mathbf{bool}) \rightarrow \mathbf{bool}} \text{TyBopLogAnd}$$

•

$$\frac{}{\vdash_O \wedge\wedge :: (\mathbf{bool}, \mathbf{bool}) \rightarrow \mathbf{bool}} \text{TyBopLogXor}$$

•

$$\frac{}{\vdash_O || :: (\mathbf{bool}, \mathbf{bool}) \rightarrow \mathbf{bool}} \text{TyBopLogOr}$$

7.2.2.7 Comparison Operators

$$\frac{}{\vdash_O \{=, !=, >, <, >=, <= \} :: (\mathbf{int}, \dots, \mathbf{int}) \rightarrow \mathbf{bool}} \text{TyCmpListInt}$$

$$\frac{}{\vdash_O \{=, !=, >, <, >=, <= \} :: (\mathbf{flt}, \dots, \mathbf{flt}) \rightarrow \mathbf{bool}} \text{TyCmpListFlt}$$

$$\frac{}{\vdash_O \{=, !=, >, <, >=, <= \} :: (\mathbf{char}, \dots, \mathbf{char}) \rightarrow \mathbf{bool}} \text{TyCmpListChar}$$

$$\frac{\vdash_T t_1 \preceq \mathbf{string}, \dots, \vdash_T t_n \preceq \mathbf{string}}{\vdash_O \{=, !=, >, <, >=, <= \} :: (t_1, \dots, t_n) \rightarrow \mathbf{bool}} \text{TyCmpListRefStr}$$

$$\frac{\vdash_T t_1 \preceq / \succeq t_2, \dots, \vdash_T t_{(n-1)} \preceq / \succeq t_n \quad t_1, \dots, t_n \text{ reference types}}{\vdash_O \{==, != \} :: (t_1, \dots, t_n) \rightarrow \mathbf{bool}} \text{TyCmpListRefVal}$$

7.3 Expressions

7.3.1 Subtyping Expression Rule

To reduce proof rule size, define the following rules:

$$\frac{S \vdash_E \text{exp} :: t_1 \quad \vdash_T t_1 \preceq t}{S \vdash_{ET} \text{exp} \trianglelefteq t} \text{EXPSUBLOCAL}, \quad \frac{S \vdash_G \text{exp} :: t_1 \quad \vdash_T t_1 \preceq t}{S \vdash_{GT} \text{exp} \trianglelefteq t} \text{EXPSUBGLOBAL}$$

$$\frac{S \vdash_E \text{exp} :: t_1, \quad \vdash_T t_1 \asymp t}{S \vdash_{ET} \text{exp} \bowtie t} \text{EXPCROSSLOCAL}, \quad \frac{S \vdash_E \text{exp} :: t_1, \quad \vdash_T t_1 \asymp t}{S \vdash_{GT} \text{exp} \bowtie t} \text{EXPCROSSGLOBAL}$$

7.3.2 Assignability

The rule \vdash_A defines when an expression can be assigned a value; \vdash_{AC} is equivalent to \vdash_A – except that it also allows immutable objects whose children (e.g. array elements) can still be modified.

$$\frac{(\mathbf{id}, _, m) \in S}{S \vdash_A \mathbf{id}} \text{EXPASSNID} \quad \frac{S \vdash_{AC} e_1}{S \vdash_A e_1[e_2]} \text{EXPASSNSUB}$$

$$\frac{(\mathbf{id}, _, _) \in S}{S \vdash_{AC} \mathbf{id}} \text{EXPASSNID}', \quad \frac{S \vdash_{AC} e_1}{S \vdash_{AC} e_1[e_2]} \text{EXPASSNSUB}'$$

7.3.3 Global Expressions

The rule \vdash_G describes global expressions, which are restricted in a way that they can be computed at compile time. Global variables are also strictly non-**null**.

The following copied rules use \vdash_G instead of \vdash_E

7.3.3.1 Literals

- $\text{GEXPLITINT} := \text{EXPLITINT}$
- $\text{GEXPLITFLT} := \text{EXPLITFLT}$
- $\text{GEXPLITCHAR} := \text{EXPLITCHAR}$
- $\text{GEXPLITBOOL} := \text{EXPLITBOOL}$

7.3.3.2 Other Rules

- $\text{GEXPID} := \text{EXPID}$
- $\text{GEXPUP} := \text{EXPUP}$
- $\text{GEXPBOP} := \text{EXPBOP}$
- $\text{GEXPCMLIST} := \text{EXPCMLIST}$

Note that global variable declarations cannot feature function calls or **null** declarations.

7.3.4 Literals

•

$$\frac{}{\vdash_E n :: \mathbf{int}} \text{EXPLITINT}$$

•

$$\frac{}{\vdash_E f :: \mathbf{flt}} \text{EXPLITFLT}$$

•

$$\frac{}{\vdash_E c :: \mathbf{char}} \text{EXPLITCHAR}$$

•

$$\frac{}{\vdash_E \mathbf{true} :: \mathbf{bool}} \text{EXPLITBOOLTRUE}, \frac{}{\vdash_E \mathbf{false} :: \mathbf{bool}} \text{EXPLITBOOLFALSE}$$

•

$$\frac{}{\vdash_E s :: \mathbf{string}} \text{EXPLITSTRING}$$

- In arrays, the typechecker looks for the common subtypes of all array literal elements and looks for the one type \mathbf{t} that is a supertype of all elements and which is a subtype of all other such subtypes (the minimum of the subtypes given the \preceq relation on types).

$$\frac{S \vdash_E e_1 :: \mathbf{t}_1, \dots, S \vdash_E e_n :: \mathbf{t}_n \quad \mathbf{t} = \min_{\preceq}(\bigcap_{i=1}^n \text{suptys}(\mathbf{t}_i))}{S \vdash_E [e_1, \dots, e_n] :: [\mathbf{t}]} \text{EXPLITARR}$$

Because the graph connecting types and subtypes is a forest of trees, if the intersection of supertypes is nonempty there is a unique solution \mathbf{t} .

7.3.5 Range List

$$\frac{S \vdash_E e_1 :: \mathbf{int} \quad S \vdash_E e_2 :: \mathbf{int}}{S \vdash_E [e_1 \text{ \%RangeSpecifier } e_2] :: [\mathbf{int}]} \text{EXPRANGEARR}$$

7.3.6 List Comprehension

$$\frac{S \vdash_E l_1 :: [\mathbf{t}_1], S_1 := S \cup \{(l_1, \mathbf{t}_1, c)\} \vdash_E l_2 :: [\mathbf{t}_2], \dots, S_{n-1} \vdash_E l_n :: [\mathbf{t}_n] \quad S_n \vdash_E (e, c) :: (\mathbf{t}, \mathbf{bool})}{S \vdash_E [e : x_1 \mathbf{in} l_1, \dots, x_n \mathbf{in} l_n : c] :: [\mathbf{t}]} \text{EXPLC}$$

7.3.7 Null

$$\frac{t \text{ is a non-null ref. type}}{S \vdash_E \mathbf{null\ of\ } t :: t?} \text{EXPNULL}$$

7.3.8 Dangerous Dereference

$$\frac{S \vdash_E \text{exp} :: t?}{S \vdash_E \mathbf{assert\ exp} :: t} \text{EXPDEREF}$$

7.3.9 Ternary Operator

$$\frac{S \vdash_E c :: \mathbf{bool} \quad S \vdash_E e1 :: t1, S \vdash_E e2 :: t2 \quad t = \min_{\leq}(\text{suptys}(t1) \cap \text{suptys}(t2))}{S \vdash_E ?c \rightarrow e1 : e2 :: t} \text{EXPTERN}$$

7.3.10 Identifiers

$$\frac{(id, t, _) \in S}{S \vdash_E id :: t} \text{EXPID}$$

7.3.11 Unary Operations

Unary and Binary Operations do not need to do subtype checking, as they operate only on primitives.

$$\frac{S \vdash_E \text{exp} :: t1 \quad \vdash_O \text{op} :: t1 \rightarrow t}{S \vdash_E \text{op\ exp} :: t} \text{EXPUOP}$$

7.3.12 Binary Operations

$$\frac{S \vdash_E e1 :: t1 \quad S \vdash_{ET} e2 :: t2 \quad \vdash_O \text{op} :: (t1, t2) \rightarrow t}{S \vdash_E e1 \text{ op } e2 :: t} \text{EXPBOP}$$

7.3.13 Function Calls

$$\frac{S \vdash_E f :: (t1, \dots, tn) \rightarrow rt \quad rt \neq \mathbf{void} \quad S \vdash_{ET} e1 \leq t1 \vee e1 \bowtie t1, \dots, S \vdash_{ET} en \leq tn \vee en \bowtie tn}{S \vdash_E f(e1, \dots, en) :: rt} \text{EXPFUNC}$$

7.3.14 **sprintf** call

Because Dromedar is typesafe, a construct like **sprintf** is not possible within the standard framework of the language. Instead, it uses the **sprintf** keyword that generates a string from the input string and its arguments.

First, define the rule to decide whether an object type is *printable*:

$$\overline{\vdash_P \mathbf{int}}^{\text{PRTINT}}, \quad \overline{\vdash_P \mathbf{flt}}^{\text{PRTFLT}}, \quad \overline{\vdash_P \mathbf{char}}^{\text{PRTCHAR}}, \quad \overline{\vdash_P \mathbf{bool}}^{\text{PRTBOOL}}, \quad \overline{\vdash_P \mathbf{string}}^{\text{PRTSTRING}}$$

$$\frac{\vdash_P t}{\vdash_P [t]} \text{PRTARR}$$

$$\frac{0 \leq j1 < n, \dots, 0 \leq jm < n \quad S \vdash_E e1 :: t1, \dots, S \vdash_E en :: tn \quad \vdash_P t1, \dots, \vdash_P tn}{S \vdash_E \mathbf{sprintf}(\dots\{j1\}\dots\{jm\}\dots, e1, \dots, en) :: \mathbf{string}} \text{EXPSPRINTF}$$

7.3.15 Subscript Access

•

$$\frac{S \vdash_E s :: \mathbf{string} \quad S \vdash_E i :: \mathbf{int}}{S \vdash_E s[i] :: \mathbf{char}} \text{EXPARRSUB}$$

•

$$\frac{S \vdash_E e :: [t] \quad S \vdash_E i :: \mathbf{int}}{S \vdash_E e[i] :: t} \text{EXPARRSUB}$$

7.3.16 Projection

$$\frac{(f, t, _) \in S_{\text{Id}}}{S \vdash_E \text{Id}.f :: t} \text{EXP PROJMODULE}$$

$$\frac{S \vdash_E e :: [t]}{S \vdash_E e.\text{length} :: \mathbf{int}} \text{EXP PROJLISTLENGTH}$$

7.3.17 Comparison Lists

$$\frac{\vdash_O \text{op1} :: (t_0, t_1) \rightarrow t, \dots, \vdash_O \text{opn} :: (t_{(n-1)}, t_n) \rightarrow t \quad S \vdash_{\text{ET}} (e_0, \dots, e_n) [\leq | \bowtie] (t_0, \dots, t_n)}{S \vdash_E e_0 \text{ op1 } \dots \text{ opn } e_n :: t} \text{EXPCMPLIST}$$

7.4 Statements

In the statement typing rules, a statement rule produces a tuple (S, r) where S stands for the newly updated context, and $r \in \{\perp, \top\}$, where \perp means that a statement might not return and \top means that a statement definitely returns.

To prevent potential mistakes, the typechecker prevents statements which are deemed unreachable at compile time. The logical operators \vee and \wedge operate as if $\perp \equiv 0$ and $\top \equiv 1$.

7.4.1 Local Variable Declarations

$$\begin{aligned} & \frac{(id, _, _) \notin_0 S \quad S \vdash_E \text{exp} :: t}{S, rt \vdash_S \mathbf{let} \text{id} := \text{exp} \Rightarrow (S \cup (id, t, c)), \perp} \text{STMTVDECLCONST} \\ & \frac{(id, _, _) \notin_0 S \quad S \vdash_{\text{ET}} \text{exp} \leq t \vee \text{exp} \bowtie t}{S, rt \vdash_S \mathbf{let} \text{id}:t := \text{exp} \Rightarrow (S \cup (id, t, c)), \perp} \text{STMTVTDECLCONST} \\ & \frac{(id, _, _) \notin_0 S \quad S \vdash_E \text{exp} :: t}{S, rt \vdash_S \mathbf{mut} \text{id} := \text{exp} \Rightarrow (S \cup (id, t, m)), \perp} \text{STMTVDECLMUT} \\ & \frac{(id, _, _) \notin_0 S \quad S \vdash_{\text{ET}} \text{exp} \leq t \vee \text{exp} \bowtie t}{S, rt \vdash_S \mathbf{mut} \text{id}:t := \text{exp} \Rightarrow (S \cup (id, t, m)), \perp} \text{STMTVTDECLMUT} \end{aligned}$$

7.4.2 Assignments

$$\frac{S \vdash_A \text{lhs} \quad S \vdash_E \text{lhs} :: t \quad S \vdash_{\text{ET}} \text{exp} \leq t \vee \text{exp} \bowtie t}{S, rt \vdash_S \text{lhs} := \text{exp} \Rightarrow S, \perp} \text{STMTASSN}$$

7.4.3 Expression Statements

$$\frac{S \vdash_E \text{exp} :: t}{S, rt \vdash_S \text{exp} \Rightarrow S, \perp} \text{STMTEXPR} \quad \frac{S \vdash_E (t_1, \dots, t_n) \rightarrow \mathbf{void}}{S, rt \vdash_S \text{exp}(a_1, \dots, a_n) \Rightarrow S, \perp} \text{STMTEXPRVOID}$$

7.4.4 printf Call

$$\frac{S \vdash_E \mathbf{sprintf}(\dots \{j1\} \dots \{jm\} \dots, e_1, \dots, e_n) :: \mathbf{string}}{S \vdash_S \mathbf{printf}(\dots \{j1\} \dots \{jm\} \dots, e_1, \dots, e_n) \Rightarrow S, \perp} \text{STMTPRINTF}$$

7.4.5 assert Call

$$\frac{S \vdash_E \text{exp} :: \mathbf{bool}}{S \vdash_S \mathbf{assert} \text{exp} \Rightarrow S, \perp} \text{STMTASSERT}$$

7.4.6 If Statements

$$\frac{S \vdash_E c :: \mathbf{bool} \quad S, \text{rt} \vdash_S b1 \Rightarrow S_1, R_1 \quad S, \text{rt} \vdash_S b2 \Rightarrow S_2, R_2}{S, \text{rt} \vdash_S \mathbf{if} \ c \ b1 \ \mathbf{else} \ b2 \Rightarrow S, R_1 \wedge R_2} \text{STMTIF}$$

7.4.7 Checked Null Casts

$$\frac{S \vdash_E \text{exp} :: \mathbf{t?} \quad S \cup \{(r, \mathbf{t}, c)\}, \text{rt} \vdash_S b1 \Rightarrow S', R_1 \quad S, \text{rt} \vdash_S b2 \Rightarrow S'', R_2}{S, \text{rt} \vdash_S \mathbf{dennull} \ r := \text{exp} \ b1 \ \mathbf{else} \ b2 \Rightarrow S, R_1 \wedge R_2} \text{STMTNULLCAST}$$

7.4.8 While Statements

$$\frac{S \vdash_E c :: \mathbf{bool} \quad S, \text{rt} \vdash_S b \Rightarrow S', R}{S, \text{rt} \vdash_S \mathbf{while} \ c \ b \Rightarrow S, \perp} \text{STMTWHILE}$$

7.4.9 Do-While Statements

$$\frac{S \vdash_E c :: \mathbf{bool} \quad S, \text{rt} \vdash_S b \Rightarrow S', R}{S, \text{rt} \vdash_S \mathbf{do} \ b \ \mathbf{while} \ c \Rightarrow S, R} \text{STMTDOWHILE}$$

7.4.10 For Statements

$$\frac{S \vdash_E \text{estart} :: \mathbf{int} \quad S \vdash_E \text{eend} :: \mathbf{int} \quad S \cup \{(\text{id}, \mathbf{int}, c)\}, \text{rt} \vdash_S b \Rightarrow S', R}{S, \text{rt} \vdash_S \mathbf{for} \ \text{id} := \text{estart} \% \text{RangeSpecifier} \ \text{eend} \ b \Rightarrow S, \perp} \text{STMTFOR}$$

7.4.11 Return Statements

$$\frac{S \vdash_{ET} \text{exp} \trianglelefteq \text{rt} \vee \text{exp} \bowtie \text{rt}}{S, \text{rt} \vdash_S \mathbf{return} \ \text{exp} \Rightarrow S, \top} \text{STMTRETURNEXP}, \quad \frac{}{S, \mathbf{void} \vdash_S \mathbf{return} \Rightarrow S, \top} \text{STMTRETURN}$$

7.4.12 Blocks

$$\frac{S \sqcup \{\}, \text{rt} \vdash_S s1 \Rightarrow S_1, \perp, \quad S_1, \text{rt} \vdash_S s2 \Rightarrow S_2, \perp, \quad \dots, \quad S_{n-1}, \text{rt} \vdash_S s_n \Rightarrow S_n, R}{S, \text{rt} \vdash_S s1 \ \dots \ s_n \Rightarrow S_n, R} \text{STMTBLOCK}$$

7.5 Global Statements

7.5.1 Global Function Declaration

$$\frac{S \sqcup \{(a1, \mathbf{t1}, c), \dots, (a_n, \mathbf{tn}, c)\}, \text{rt} \vdash_S b \Rightarrow S', \top \text{ (or } \text{rt} = \mathbf{void}) \quad a1, \dots, a_n \text{ distinct}}{S \vdash_G \mathbf{fn} \ \text{id} : a1:\mathbf{t1}, \dots, a_n:\mathbf{tn} \rightarrow \text{rt} \ b \Rightarrow S} \text{GSTMTFDECL}$$

7.5.2 Global Variable Declaration

$$\begin{aligned} & \frac{(id, _, _) \notin S \quad S \vdash_G \text{exp} :: \mathbf{t} \ \mathbf{t} \text{ non-}\mathbf{null}}{S \vdash_G \mathbf{global} \ \text{id} := \text{exp} \Rightarrow S \cup \{(id, \mathbf{t}, c)\}} \text{GSTMTVDECLCONST} \\ & \frac{(id, _, _) \notin S \quad S \vdash_{GT} \text{exp} \trianglelefteq \mathbf{t} \ \mathbf{t} \text{ non-}\mathbf{null}}{S \vdash_G \mathbf{global} \ \text{id}:\mathbf{t} := \text{exp} \Rightarrow S \cup \{(id, \mathbf{t}, c)\}} \text{GSTMTVDECLCONST} \\ & \frac{(id, _, _) \notin S \quad S \vdash_G \text{exp} :: \mathbf{t} \ \mathbf{t} \text{ non-}\mathbf{null}}{S \vdash_G \mathbf{global} \ \mathbf{mut} \ \text{id} := \text{exp} \Rightarrow S \cup \{(id, \mathbf{t}, m)\}} \text{GSTMTVDECLMUT} \\ & \frac{(id, _, _) \notin S \quad S \vdash_{GT} \text{exp} \trianglelefteq \mathbf{t} \ \mathbf{t} \text{ non-}\mathbf{null}}{S \vdash_G \mathbf{global} \ \mathbf{mut} \ \text{id}:\mathbf{t} := \text{exp} \Rightarrow S \cup \{(id, \mathbf{t}, m)\}} \text{GSTMTVDECLMUT} \end{aligned}$$

7.5.3 Module Header

$$\frac{}{S \vdash_G \mathbf{module} \ M \Rightarrow S \text{ where } S_M = S \text{ with } M \text{ as the only active module}} \text{GSTMTMODULE}$$

7.5.4 Program

$$\frac{S_0 \vdash_G \mathbf{gs1} \Rightarrow S_1, \dots, S_{n-1} \vdash_G \mathbf{gsn} \Rightarrow S_n}{S_0 \vdash_G \mathbf{gs1} \dots \mathbf{gsn} \Rightarrow S_n} \text{GSTMTPROGRAM}$$

7.6 Context Buildup

7.6.1 Global Function Declarations

$$\frac{(\mathbf{id}, _) \notin S}{S \vdash_{\text{GCF}} \mathbf{fn} \ \mathbf{id} : \mathbf{a1:t1}, \dots, \mathbf{an:tn} \rightarrow \mathbf{rt} \ b \Rightarrow S \cup (\mathbf{id}, (\mathbf{t1}, \dots, \mathbf{tn}) \rightarrow \mathbf{rt}, c)} \text{GSTMTFCtxtFDECL}$$

$$\frac{}{S \vdash_{\text{GCF}} \mathbf{global} \ X := Y \Rightarrow S} \text{GSTMTFCtxtVDECL}$$

$$\frac{}{S \vdash_{\text{GCF}} \mathbf{module} \ M \Rightarrow S \text{ where } S_M = S \text{ with } M \text{ as the only active module}} \text{GSTMTFCtxtMODULE}$$

7.6.2 Program: Functions

$$\frac{S_0 \vdash_{\text{GCF}} \mathbf{gs1} \Rightarrow S_1, \dots, S_{n-1} \vdash_{\text{GCF}} \mathbf{gsn} \Rightarrow S_n}{S_0 \vdash_{\text{GC}} \mathbf{gs1} \dots \mathbf{gsn} \Rightarrow S_n \text{ with no active module}} \text{GSTMTCTXTFUNCS}$$

7.7 Rule for Program Typechecking

Let S^* be the starting context which contains the builtin context. It looks as follows:

$$S^* := \{\} \sqcup \left\{ \begin{array}{lll} (\mathbf{string_of_int}, & \mathbf{int} \rightarrow \mathbf{string}, & c), \\ (\mathbf{string_of_flt}, & \mathbf{flt} \rightarrow \mathbf{string}, & c), \\ (\mathbf{string_concat}, & (\mathbf{string}, \mathbf{string}) \rightarrow \mathbf{string}, & c), \\ (\mathbf{io_print}, & \mathbf{string} \rightarrow \mathbf{void}, & c) \end{array} \right\}$$

Let maintys be the legal set of types of main functions – one of which must be contained in a program.

$$\text{maintys} := \left\{ \begin{array}{ll} \mathbf{void} \rightarrow \mathbf{void}, & \mathbf{void} \rightarrow \mathbf{int}, \\ [\mathbf{string}] \rightarrow \mathbf{void}, & [\mathbf{string}] \rightarrow \mathbf{int} \end{array} \right\}$$

Then, the program rule **PROG** shall be:

$$\frac{S^* \vdash_{\text{GC}} \mathbf{prog} \Rightarrow S' \ \exists! \mathbf{ft} \in \text{maintys} : (\mathbf{main}, \mathbf{ft}, c) \in S' \ S' \vdash_{\text{G}} \mathbf{prog} \Rightarrow S}{\vdash \mathbf{prog}} \text{PROG}$$

8 Formal Grammar

8.1 Lexer Grammar

The Lexer Grammar is specified using **regular expressions**:

```
LiteralInt    ::= /[1-9]\d*/
LiteralFlt    ::= /\d+\.\d+/
LiteralChar   ::= /'([^\\"|\\([\nrt']))'/
LiteralBool   ::= /true|false/
LiteralStr    ::= /"([^\\"|\\([\nrt"]))*"/
```

Identifier	::= /[a-zA-Z][a-zA-Z0-9_]*/
module	::= /module/
global	::= /global/
fn	::= /fn/
let	::= /let/
mut	::= /mut/
int	::= /int/
flt	::= /flt/
char	::= /char/
bool	::= /bool/
string	::= /string/
void	::= /void/
null	::= /null/
dennull	::= /dennull/
of	::= /of/
in	::= /in/
if	::= /if/
elif	::= /elif/
else	::= /else/
do	::= /do/
while	::= /while/
for	::= /for/
printf	::= /printf/
sprintf	::= /sprintf/
assert	::= /assert/
return	::= /return/
Dash	::= /\-/
Bang	::= /!/
Star	::= /*/
Plus	::= /\+/
LShift	::= /<</
RShift	::= />>/
AShift	::= />>>/
Bitand	::= /&/
Xor	::= /\^/
Bitor	::= /\ /
Logand	::= /&&/
Logor	::= /\ \ /
Equal	::= /=/
NotEqual	::= /!=/
Greater	::= />/
Less	::= /</
GreaterEq	::= />=/
LessEq	::= /<=/
RefEqual	::= /==/
RefNotEqual	::= /!=/
Assign	::= /:=/

```

Colon      ::= /:/
Arrow      ::= /\->/

Dot        ::= /\./
Comma      ::= /\,/

Dots       ::= /\.\.\./
DotsPipe   ::= /\.\.\|/
PipeDots   ::= /\|\.\.\./
PipeDotPipe ::= /\|\.\.\|/

LParen     ::= /\(/
RParen     ::= /\)/
LBrack     ::= /\[/
RBrack     ::= /\]/

QuestionMark ::= /\?/

```

8.2 Parser Grammar

The following grammar specification uses a preceding % for lexer tokens.

```

Program      ::=
| €
| GlobalStatement Program

GlobalStatement ::=
| GVDeclaration
| GFDeclaration
| %Module %Identifier

GVDeclaration ::=
| %Global      %Identifier          %Assign GlobalExpression
| %Global      %Identifier %Colon Type %Assign GlobalExpression
| %Global %Mut %Identifier          %Assign GlobalExpression
| %Global %Mut %Identifier %Colon Type %Assign GlobalExpression

GFDeclaration ::=
| %Fn %Identifier          %Arrow ReturnType Block
| %Fn %Identifier %Colon FArguments %Arrow ReturnType Block

FArguments ::=
| %Identifier %Colon Type
| %Identifier %Colon Type %Comma FArguments

ReturnType ::=
| %Void
| Type

Block ::=
| €
| Statement Block

Statement ::=
| VDeclaration
| AssignStmt
| IfStmt
| NullCastStmt
| WhileStmt
| DoWhileStmt
| ForStmt

```


	ExprStmt
	ReturnStmt
VDeclaration	::= %Let %Identifier %Assign Expression %Let %Identifier %Colon Type %Assign Expression %Mut %Identifier %Assign Expression %Mut %Identifier %Colon Type %Assign Expression
AssignStmt	::= LHS %Assign Expression
IfStmt	::= %If Expression Block ElifStmt
ElifStmt	::= %Elif Expression Block ElifStmt %Else Block €
NullCastStmt	::= %Dnull %Id %Assign Expression Block %Dnull %Id %Assign Expression Block %Else Block
WhileStmt	::= %While Expression Block
DoWhileStmt	::= %Do Block %While Expression
ForStmt	::= %For %Id %Assign Expr RangeSpecifier Expr Block
RangeSpecifier	::= %Dots %DotsPipe %PipeDots %PipeDotPipe
ExprStmt	::= Expression %Printf %LParen %LiteralStr PrintfArglist %RParen %Assert Expression
ReturnStmt	::= %Return %Return Expression
LHS	::= %Identifier
Type	::= %Int %Flt %Char %Bool RefType RefType %QuestionMark
RefType	::= %String

```

| %LBrack Type %RBrack
| %Identifier
| %Identifier %Dot %Identifier

GlobalExpression ::= Expression*

Expression ::=
| %Null %Of RefType
| %LBrack %RBrack %Of Type
| %QuestionMark Expression %Arrow Expression %Colon Expression
| ExprPrec30

ExprPrec20 ::=
| ExprPrec30
| ExprPrec30 %Equal ExprPrec20
| ExprPrec30 %NotEqual ExprPrec20
| ExprPrec30 %Greater ExprPrec20
| ExprPrec30 %Less ExprPrec20
| ExprPrec30 %GreaterEq ExprPrec20
| ExprPrec30 %LessEq ExprPrec20
| ExprPrec30 %RefEqual ExprPrec20
| ExprPrec30 %RefNotEqual ExprPrec20

ExprPrec30 ::=
| ExprPrec40
| ExprPrec40 %Bitor ExprPrec30

ExprPrec40 ::=
| ExprPrec50
| ExprPrec50 %Xor ExprPrec40

ExprPrec50 ::=
| ExprPrec60
| ExprPrec60 %Bitand ExprPrec50

ExprPrec60 ::=
| ExprPrec70
| ExprPrec70 %LShift ExprPrec60
| ExprPrec70 %RShift ExprPrec60
| ExprPrec70 %AShift ExprPrec60

ExprPrec70 ::=
| ExprPrec80
| ExprPrec80 %Plus ExprPrec70
| ExprPrec80 %Minus ExprPrec70

ExprPrec80 ::=
| ExprPrec90
| ExprPrec90 %Star ExprPrec80

ExprPrec90 ::=
| ExprPrec100
| ExprPrec100 %StarStar ExprPrec90

ExprPrec100 ::=
| SimpleExpression
| %Dash ExprPrec100
| %Bang ExprPrec100

SimpleExpression ::=
| BaseExpression Application
| BaseExpression

BaseExpression ::=
| %LParen Expression %RParen
| %LBrack CommaExpList %RBrack
| %LBrack Expression RangeSpecifier Expression %RBrack
| %LBrack Expression %Colon ListCmpVars %RBrack
| %LBrack Expression %Colon ListCmpVars %Colon Expression %RBrack

```

	%LiteralInt
	%LiteralFlt
	%LiteralChar
	%LiteralBool
	%LiteralStr
	%Identifier
	%Sprintf %LParen %LiteralStr PrintfArgList %RParen
	%Assert Expression
PrintfArgList	::=
	€
	%Comma Expression PrintfArgList
ListCmpVars	::=
	€
	ListCmpVarsNE
ListCmpVarsNE	::=
	%Identifier %In Expression
	%Identifier %In Expression %Comma ListCmpVarsNE
Application	::=
	%LParen CommaExpList %RParen
	%LParen CommaExpList %RParen Application
	%LBrack Expression %RBrack
	%LBrack Expression %RBrack Application
	%Dot Identifier
	%Dot Identifier Application
CommaExpList	::=
	€
	CommaExpListNE
CommaExpListNE	::=
	Expression
	Expression %Comma CommaExpListNE