C∀ (Cforall) User Manual
Version 1.0

“describe not prescribe”

C∀ Team (past and present)
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1 Introduction

C\textsuperscript{\textcopyright} is a modern general-purpose concurrent programming-language, designed as an evolutionary step forward for the C programming language. The syntax of C\textsuperscript{\textcopyright} builds from C and should look immediately familiar to C/C++ programmers. C\textsuperscript{\textcopyright} adds many modern features that directly lead to increased safety and productivity, while maintaining interoperability with existing C programs and achieving similar performance. Like C, C\textsuperscript{\textcopyright} is a statically typed, procedural (non-object-oriented) language with a low-overhead runtime, meaning there is no global garbage-collection, but regional garbage-collection is possible. The primary new features include polymorphic routines and types, exceptions, concurrency, and modules.

One of the main design philosophies of C\textsuperscript{\textcopyright} is to “describe not prescribe”, which means C\textsuperscript{\textcopyright} tries to provide a pathway from low-level C programming to high-level C\textsuperscript{\textcopyright} programming, but it does not force programmers to “do the right thing”. Programmers can cautiously add C\textsuperscript{\textcopyright} extensions to their C programs in any order and at any time to incrementally move towards safer, higher-level programming. A programmer is always free to reach back to C from C\textsuperscript{\textcopyright}, for any reason, and in many cases, new C\textsuperscript{\textcopyright} features can be locally switched back to their C counterpart. There is no notion or requirement for rewriting a legacy C program to C\textsuperscript{\textcopyright}; instead, a programmer evolves a legacy program into C\textsuperscript{\textcopyright} by incrementally incorporating C\textsuperscript{\textcopyright} features. As well, new programs can be written in C\textsuperscript{\textcopyright} using a combination of C and C\textsuperscript{\textcopyright} features. In many ways, C\textsuperscript{\textcopyright} is to C as Scala \cite{Scala} is to Java, providing a vehicle for new typing and control-flow capabilities on top of a highly popular programming language allowing immediate dissemination.

C++ \cite{C++} had a similar goal 30 years ago, allowing object-oriented programming to be incrementally added to C. However, C++ currently has the disadvantages of a strong object-oriented bias, multiple legacy design-choices that are difficult to update, and active divergence of the language model from C, requiring significant effort and training to incrementally add C++ to a C-based project. In contrast, C\textsuperscript{\textcopyright} has 30 years of hindsight and a clean starting point. Like C++, there may be both old and new ways to achieve the same effect. For example, the following programs compare the C, C\textsuperscript{\textcopyright}, and C++ I/O mechanisms, where the programs output the same result.

\begin{verbatim}
C
#include <stdio.h>
int main( void ) {
  int x = 0, y = 1, z = 2;
  printf("%d %d %d\n", x, y, z);
}

C\textsuperscript{\textcopyright}
#include <fstream>
int main( void ) {
  int x = 0, y = 1, z = 2;
  std::cout << x << y << z << std::endl;
}

C++
#include <iostream>
int main() {
  int x = 0, y = 1, z = 2;
  std::cout << x << ' ' << y << ' ' << z;
}
\end{verbatim}

While C\textsuperscript{\textcopyright} I/O (see Section 21, p. 42) looks similar to C++, there are important differences, such as automatic spacing between variables and an implicit newline at the end of the expression list, similar to Python \cite{Python}.

1.1 Background

This document is a programmer reference-manual for the C\textsuperscript{\textcopyright} programming language. The manual covers the core features of the language and runtime-system, with simple examples illustrating syntax and semantics of features. The manual does not teach programming, \textit{i.e.}, how to combine the new constructs to build complex programs. The reader must have an intermediate knowledge of control flow, data structures, and concurrency issues to understand the ideas presented, as well as some experience programming in C/C++. Implementers should refer to the C\textsuperscript{\textcopyright} Programming Language Specification for details about the language syntax and semantics. Changes to the syntax and additional features are expected to be included in later revisions.

2 Why fix C?  

The C programming language is a foundational technology for modern computing with billions of lines of code implementing everything from hobby projects to commercial operating-systems. This installation base and the programmers producing it represent a massive software-engineering investment spanning decades and likely to continue for decades more. Even with all its problems, C continues to be popular because it allows writing software at virtually any level in a computer system without restriction. For system programming, where direct access to hardware, storage management, and real-time issues are a requirement, C is the only language of choice. The TIOBE index \cite{TIOBE} for February 2021 ranks the top six most \textit{popular} programming languages as C 17.4\%, Java 12\%, Python 12\%, C++ 7.6\%, C\# 4\%,

\textsuperscript{1}Pronounced “C-for-all”, and written C\textsuperscript{\textcopyright}, CFA, or Cforall.
Visual Basic 3.8% = 56.8%, where the next 50 languages are less than 2% each, with a long tail. The top 4 rankings over the past 35 years are:

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Hence, C is still an extremely important programming language, with double the usage of C++; in many cases, C++ is often used solely as a better C. Love it or hate it, C has been an important and influential part of computer science for 40 years and its appeal is not diminishing. Nevertheless, C has many problems and omissions that make it an unacceptable programming language for modern needs.

As stated, the goal of the C programming language. Fortran [13], Cobol [5], and Ada [?] are examples of programming languages that took an evolutionary approach, where modern language-features (e.g., objects, concurrency) are added and problems fixed within the framework of the existing language. Java [17], Go [18], Rust [27] and D [2] are examples of the revolutionary approach for modernizing C/C++, resulting in a new language rather than an extension of the descendent. These languages have different syntax and semantics from C, do not interoperate directly with C, and are not systems languages because of restrictive memory-management or garbage collection. As a result, there is a significant learning curve to move to these languages, and C legacy-code must be rewritten. These costs can be prohibitive for many companies with a large software-base in C/C++, and a significant number of programmers require retraining in the new programming language.

The result of this project is a language that is largely backwards compatible with C11 [20], but fixes many of the well known C problems while adding modern language-features. To achieve these goals required a significant engineering exercise, i.e., “thinking inside the C box”. Considering the large body of existing C code and programmers, there is significant impetus to ensure C is transformed into a modern language. While C11 made a few simple extensions to the language, nothing was added to address existing problems in the language or to augment the language with modern language-features. While some may argue that modern language-features may make C complex and inefficient, it is clear a language without modern capabilities is insufficient for the advanced programming problems existing today.

### 3 History

The C project started with Dave Till’s K-W C [4, 30], which extended C with new declaration syntax, multiple return values from routines, and advanced assignment capabilities using the notion of tuples (see [32] for similar work in C++). The first C implementation of these extensions was by Rodolfo Esteves [12].

The signature feature of C is overloading (giving the language its name):

```c
forall( T ) T identity( T val ) { return val; }

int forty_two = identity( 42 ); // T is bound to int, forty_two == 42
```

C’s polymorphism was originally formalized by Glen Ditchfield [8], and first implemented by Richard Bilson [1]. However, at that time, there was little interesting in extending C, so work did not continue. As the saying goes, “What goes around, comes around.”, and there is now renewed interest in the C programming language because of the legacy code-base, so the C project was restarted in 2015.

### 4 Interoperability

C is designed to integrate directly with existing C programs and libraries. The most important feature of interoperability is using the same calling conventions, so there is no complex interface or overhead to call existing C routines.

This feature allows C programmers to take advantage of the existing panoply of C libraries to access thousands of external software features. Language developers often state that adequate library support takes more work than

---

2 Two important existing problems addressed were changing the type of character literals from int to char and enumerator from int to the type of its enumerators.
designing and implementing the language itself. Fortunately, C++, like C, starts with immediate access to all exiting C libraries, and in many cases, can easily wrap library routines with simpler and safer interfaces, at zero or very low cost. Hence, C++ begins by leveraging the large repository of C libraries, and then allows programmers to incrementally augment their C programs with modern backward-compatible features.

However, it is necessary to differentiate between C and C++ code because of name overloading, as for C++. For example, the C math-library provides the following routines for computing the absolute value of the basic types: abs, labs, llabs, fabs, fabsf, fabsl, cabs, cabsf, and cabsl. Whereas, C++ wraps each of these routines into one overloaded name abs:

```cpp
char abs(char );
extern "C" { int abs( int ); } // use default C routine for int
long int abs( long int );
long long int abs( long long int );
float abs( float );
double abs( double );
long double abs( long double );
float _Complex abs( float _Complex );
double _Complex abs( double _Complex );
long double _Complex abs( long double _Complex );
```

The problem is a name clash between the C name abs and the C++ names abs, resulting in two name linkages: extern "C" and extern "C++" (default). Overloaded names must use name mangling to create unique names that are different from unmangled C names. Hence, there is the same need as in C++ to know if a name is a C or C++ name, so it can be correctly formed. The only way around this problem is C’s approach of creating unique names for each pairing of operation and type.

This example illustrates a core idea in C++: the power of a name. The name “abs” evokes the notion of absolute value, and many mathematical types provide the notion of absolute value. Hence, knowing the name abs is sufficient to apply it to any type where it is applicable. The time savings and safety of using one name uniformly versus N unique names cannot be underestimated.

## 5 C++ Compilation

The command `c++` is used to compile a C++ program and is based on the GNU `gcc` command, e.g.:

```
c++ [ gcc/C++ options ] [ C/C++ source-files ] [ assembler/loader files ]
```

There is no ordering among options (flags) and files, unless an option has an argument, which must appear immediately after the option possibly with or without a space separating option and argument.

C++ has the following `gcc` flags turned on:

- `-std=gnu11` The 2011 C standard plus GNU extensions.
- `-g` Use the traditional GNU semantics for inline routines in C11 mode, which allows inline routines in header files.
- `-CFA` Only the C preprocessor (flag `-E`) and the C++ translator steps are performed and the transformed program is written to standard output, which makes it possible to examine the code generated by the C++ translator. The generated code starts with the standard C++ prelude.
- `-XCFA` Pass next flag as-is to the `c++-cpp` translator (see details below).
- `-debug` The program is linked with the debugging version of the runtime system. The debug version performs runtime checks to aid the debugging phase of a C++ program, but can substantially slow program execution. The runtime checks should only be removed after a program is completely debugged. **This option is the default.**
- `-nodebug` The program is linked with the non-debugging version of the runtime system, so the execution of the program is faster. **However, no runtime checks or asserts are performed so errors usually result in abnormal program behaviour or termination.**
- `-help` Information about the set of C++ compilation flags is printed.
- `-nohelp` Information about the set of C++ compilation flags is not printed. **This option is the default.**
- `-quiet` The C++ compilation message is not printed at the beginning of a compilation.
The C preprocessor allows only integer values in a preprocessor variable so a value like “1.0.0” is not allowed. Hence, the need to have three variables for the major, minor and patch version number.
// include file uses the CFA keyword "with".
#if !defined(with)                   // nesting ?
#define with "with"                   // make keyword an identifier
#endif
#include <bfdlink.h>                 // must have internal check for multiple expansion
#if defined(with) && defined(CFA_BFD_H)  // reset only if set
#undef with
#undef CFA_BFD_H
#endif

Figure 1: Header-File Interposition

tuple  print AST after tuple expansion
instgen print AST after instantiate generics
bbox   print AST before box pass
bcodegen print AST before code generation
--prelude-dir <directory> prelude directory for debug/nodebug
-S, --statistics <option-list> enable profiling information: counters, heap, time, all, none
-t, --tree build in tree

6 Backquote Identifiers

CFA introduces several new keywords (see Section C, p. 65) that can clash with existing C variable-names in legacy code. Keyword clashes are accommodated by syntactic transformations using the CFA backquote escape-mechanism:

```c
int `coroutine' = 3;         // make keyword an identifier
double `forall' = 3.5;
```

Existing C programs with keyword clashes can be converted by prefixing the keyword identifiers with double backquotes, and eventually the identifier name can be changed to a non-keyword name. Figure 1 shows how clashes in existing C header-files (see Section D, p. 65) can be handled using preprocessor interposition: `include_next and I filename. Several common C header-files with keyword clashes are fixed in the standard CFA header-library, so there is a seamless programming-experience.

7 Constant Underscores

Numeric constants are extended to allow underscores as a separator, e.g.:

```c
2_147_483_648;                // decimal constant
56_ul;                       // decimal unsigned long constant
0_377;                       // octal constant
0x_ff_ff;                     // hexadecimal constant
0x_ef3d_aa5c;                 // hexadecimal constant
3.141_592_654;               // floating constant
10_e_+1_00;                   // floating constant
0x_fff_ff_f_p_3;             // hexadecimal floating
0x_1_ffff_ffff_p_128_l;      // hexadecimal floating long constant
L_"\x_ffe_feee";              // wide character constant
```

The rules for placement of underscores are:

1. A sequence of underscores is disallowed, e.g., 12____34 is invalid.
2. Underscores may only appear within a sequence of digits (regardless of the digit radix). In other words, an underscore cannot start or end a sequence of digits, e.g., _1, 1_ and _1_ are invalid (actually, the 1st and 3rd examples are identifier names).
3. A numeric prefix may end with an underscore; a numeric infix may begin and/or end with an underscore; a numeric suffix may begin with an underscore. For example, the octal 0 or hexadecimal 0x prefix may end with
8 Exponentiation Operator

C, C++, and Java (and other programming languages) have no exponentiation operator, i.e., $x^y$, and instead use a routine, like $\text{pow}(x,y)$, to perform the exponentiation operation. C++ extends the basic operators with the exponentiation operator $??$ and $??=$, as in, $x \backslash \backslash y$ and $x \leftarrow y$, which means $x^y$ and $x ← x^y$. The priority of the exponentiation operator is between the cast and multiplicative operators, so that $w * (\text{int}x) \backslash (\text{int}y) * z$ is parenthesized as $(w * (((\text{int}x)) \backslash (\text{int}y))) * z$.

There are exponentiation operators for integral and floating types, including the built-in complex types. Integral exponentiation is performed with repeated multiplication4 (or shifting if the exponent is 2). Overflow for a large exponent or negative exponent returns zero. Floating exponentiation is performed using logarithms, so the exponent cannot be negative.

9 Control Structures

C++ identifies inconsistent, problematic, and missing control structures in C, and extends, modifies, and adds control structures to increase functionality and safety.

9.1 if / while Statement

The if/while expression allows declarations, similar to for declaration expression.5

4The multiplication computation is $O(\log y)$.

5Declarations in the do-while condition are not useful because they appear after the loop body.
9.2  case Clause

\texttt{C}\ restricts the case clause of a switch statement to a single value. For multiple case clauses associated with the same statement, it is necessary to have multiple case clauses rather than multiple values. Requiring a case clause for each value is not in the spirit of brevity normally associated with \texttt{C}. Therefore, the case clause is extended with a list of values.

\begin{verbatim}
C
switch ( i ) {
  case 1, 3, 5:  // odd values
  ...            
  case 2, 4, 6:  // even values
  ...            
}                   
\end{verbatim}

In addition, subranges are allowed to specify case values.\footnote{\texttt{gcc} has the same mechanism but awkward syntax, \texttt{2 ... 42}, because a space is required after a number, otherwise the period is a decimal point.}

\begin{verbatim}
switch ( i ) {
  case 1~5:      // 1, 2, 3, 4, 5
  ...           
  case 10~15:    // 10, 11, 12, 13, 14, 15
  ...           
}                   
\end{verbatim}

Lists of subranges are also allowed.

\begin{verbatim}
case 1~5, 12~21, 35~42:
\end{verbatim}

9.3  switch Statement

\texttt{C}\ allows a number of questionable forms for the switch statement:

1. By default, the end of a case clause\footnote{In this section, the term case clause refers to either a case or default clause.} \texttt{falls through} to the next case clause in the switch statement; to exit a switch statement from a case clause requires explicitly terminating the clause with a transfer statement, most commonly \texttt{break}:

\begin{verbatim}
switch ( i ) {
  case 1:
    ...  // fall-through
  case 2:
    ...
    break;  // exit switch statement
}
\end{verbatim}

The ability to fall-through to the next clause is a useful form of control flow, specifically when a sequence of case actions compound:

\begin{verbatim}
switch ( argc ) {
  case 3:
    if ( argc == 3 ) {
    // open output file  // open output file
    // fall-through  // open input file
    }
  case 2:
    } else if ( argc == 2 ) {
    // open input file  // open input file (duplicate)
    break;  // exit switch statement
  default:
    } else {
    // usage message  // usage message
    }
}
\end{verbatim}

In this example, case 2 is always done if case 3 is done. This control flow is difficult to simulate with \texttt{if} statements or a switch statement without fall-through as code must be duplicated or placed in a separate routine. \texttt{C} also uses fall-through to handle multiple case-values resulting in the same action:
switch (i) {
  case 1: case 3: case 5: // odd values
      // odd action
      break;
  case 2: case 4: case 6: // even values
      // even action
      break;
}

This situation is better handled by a list of case values (see Section 9.2). While fall-through itself is not a
problem, the problem occurs when fall-through is the default, as this semantics is unintuitive to many program-
ners and is different from most programming languages with a switch statement. Hence, default fall-through
semantics results in a large number of programming errors as programmers often forget the break statement at
the end of a case clause, resulting in inadvertent fall-through.

2. It is possible to place case clauses on statements nested within the body of the switch statement:

switch (i) {
  case 0:
    if (j < k) {
      ...
      case 1: // transfer into "if" statement
      ...
    } // if
}

This usage branches into control structures, which is known to cause both comprehension and technical diffi-
culties. The comprehension problem results from the inability to determine how control reaches a particular
point due to the number of branches leading to it. The technical problem results from the inability to ensure
declaration and initialization of variables when blocks are not entered at the beginning. There are few arguments
for this kind of control flow, and therefore, there is a strong impetus to eliminate it.

This C idiom is known as “Duff’s device” [9], from this example:

register int n = (count + 7) / 8;
switch (count % 8) {
  case 0: do{ *to = *from++; }while ( n > 0 );
  case 1: // transfer into "if" statement
    ...
  ...
} // if

which unrolls a loop N times (N = 8 above) and uses the switch statement to deal with any iterations not a
multiple of N. While efficient, this sort of special purpose usage is questionable:

Disgusting, no? But it compiles and runs just fine. I feel a combination of pride and revulsion at this
discovery. [9]

3. It is possible to place the default clause anywhere in the list of labelled clauses for a switch statement, rather than
only at the end. Most programming languages with a switch statement require the default clause to appear last in
the case-clause list. The logic for this semantics is that after checking all the case clauses without success, the
default clause is selected; hence, physically placing the default clause at the end of the case clause list matches
with this semantics. This physical placement can be compared to the physical placement of an else clause at the
end of a series of connected if/else statements.

4. It is possible to place unreachable code at the start of a switch statement, as in:

switch (x) {
  int y = 1;       // unreachable initialization
  x = 7;          // unreachable code without label/branch
  case 0: ...
}
9.3 switch Statement

```c
int z = 0; // unreachable initialization, cannot appear after case
z = 2;
case 1:
    x = z; // without fall through, z is uninitialized
}
```

While the declaration of the local variable `y` is useful with a scope across all case clauses, the initialization for such a variable is defined to never be executed because control always transfers over it. Furthermore, any statements before the first case clause can only be executed if labelled and transferred to using a goto, either from outside or inside of the switch, where both are problematic. As well, the declaration of `z` cannot occur after the case because a label can only be attached to a statement, and without a fall-through to case 3, `z` is uninitialized.

The key observation is that the switch statement branches into a control structure, i.e., there are multiple entry points into its statement body.

Before discussing potential language changes to deal with these problems, it is worth observing that in a typical C program:

- the number of switch statements is small,
- most switch statements are well formed (i.e., no Duff’s device),
- the default clause is usually written as the last case-clause,
- and there is only a medium amount of fall-through from one case clause to the next, and most of these result from a list of case values executing common code, rather than a sequence of case actions that compound.

These observations put into perspective the CAV changes to the switch.

1. Eliminating default fall-through has the greatest potential for affecting existing code. However, even if fall-through is removed, most switch statements would continue to work because of the explicit transfers already present at the end of each case clause, the common placement of the default clause at the end of the case list, and the most common use of fall-through, i.e., a list of case clauses executing common code, e.g.:

```c
case 1: case 2: case 3: ...
```

still works. Nevertheless, reversing the default action would have a non-trivial effect on case actions that compound, such as the above example of processing shell arguments. Therefore, to preserve backwards compatibility, it is necessary to introduce a new kind of switch statement, called choose, with no implicit fall-through semantics and an explicit fall-through if the last statement of a case-clause ends with the new keyword fallthrough/-fallthru, e.g.:

```c
choose ( i ) {
    case 1: case 2: case 3:
    ...
    // implicit end of switch (break)
    case 5:
    ...
    fallthru; // explicit fall through
    case 7:
    ...
    break // explicit end of switch (redundant)
    default:
        j = 3;
}
```

Like the switch statement, the choose statement retains the fall-through semantics for a list of case clauses. An implicit break is applied only at the end of the statements following a case clause. An explicit fallthru is retained because it is a C-idiom most C programmers expect, and its absence might discourage programmers from using the choose statement. As well, allowing an explicit break from the choose is a carry over from the switch statement, and expected by C programmers.

2. Duff’s device is eliminated from both switch and choose statements, and only invalidates a small amount of very questionable code. Hence, the case clause must appear at the same nesting level as the switch/choose body, as is done in most other programming languages with switch statements.

3. The issue of default at locations other than at the end of the cause clause can be solved by using good program-
9.5 Loop Control

Looping a fixed number of times, possibly with a loop index, occurs frequently. C++ condenses simply looping to facilitate coding speed and safety (see examples in Figure 2).

The for, while, and do loop-control allow an empty conditional, which implies a comparison value of 1 (true).

```cpp
while (/*empty*/ ) // while (true)
for (/*empty*/ ) // for (; true; )
do ... while (/*empty*/ ) // do ... while (true)
```

The for control has 4 new loop-control operators that are not overloadable:

- ∼ (tilde) up-to exclusive range,
- ∼= (tilde equal) up-to inclusive range,
- ∼− (minus tilde) down-to exclusive range,

Essentially, these declarations are hoisted before the switch/choose statement and both declarations and statement are surrounded by a compound statement.
9.5 Loop Control

<table>
<thead>
<tr>
<th>loop control</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>while () { sout</td>
<td>&quot;empty&quot;; break; }</td>
</tr>
<tr>
<td>do { sout</td>
<td>&quot;empty&quot;; break; } while ();</td>
</tr>
<tr>
<td>for () { sout</td>
<td>&quot;empty&quot;; break; }</td>
</tr>
<tr>
<td>for (0) { sout</td>
<td>&quot;A&quot;; } sout</td>
</tr>
<tr>
<td>for (1) { sout</td>
<td>&quot;A&quot;; } sout</td>
</tr>
<tr>
<td>for (10) { sout</td>
<td>&quot;A&quot;; } sout</td>
</tr>
<tr>
<td>for (i = 0 to 10) { sout</td>
<td>&quot;B&quot;; } sout</td>
</tr>
<tr>
<td>for (i = 10 to 2) { sout</td>
<td>&quot;C&quot;; } sout</td>
</tr>
<tr>
<td>for (i = 0.5 to 5.5) { sout</td>
<td>&quot;D&quot;; } sout</td>
</tr>
<tr>
<td>for (i = 0.5 to 5.5) { sout</td>
<td>&quot;E&quot;; } sout</td>
</tr>
<tr>
<td>for (i = 10) { sout</td>
<td>i; } sout</td>
</tr>
<tr>
<td>for (i = -10) { sout</td>
<td>i; } sout</td>
</tr>
<tr>
<td>for (i = 10 to 2) { sout</td>
<td>i; } sout</td>
</tr>
<tr>
<td>for (i = 0.5 to 5.5) { sout</td>
<td>i; } sout</td>
</tr>
<tr>
<td>for (ui = 2u = 2u to 10u) { sout</td>
<td>ui; } sout</td>
</tr>
<tr>
<td>for (ui = 2u to 10u) { sout</td>
<td>ui; } sout</td>
</tr>
</tbody>
</table>

enum { N = 10; }
| for (N) { sout | "N"; } sout | nl; } | N | N | N | N | N | N | N | N | N |
| for (i = N) { sout | i; } sout | nl; } | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| for (i = -N) { sout | i; } sout | nl/ nl/ nl/ } | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 |

const int low = 3, high = 10, inc = 2;
| for (i = low to high) { i = i + inc; } { sout | i; } sout | nl; } | 3 | 6 | 9 |
| for (i = low to high) { i = i + inc; } { sout | i; } sout | nl; } | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| for (i = low to high) { i = i + inc; } { sout | i; } sout | nl; } | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 |
| for (i = low to high) { i = i + inc; } { sout | i; } sout | nl; } | 2.1 | 3.8 | 5.5 | 7.2 | 8.9 |
| for (i = low to high) { i = i + inc; } { sout | i; } sout | nl; } | 2.1 | 3.8 | 5.5 | 7.2 | 8.9 |
| for (i = low to high) { i = i + inc; } { sout | i; } sout | nl; } | 12.1 | 10.4 | 8.7 | 7.5 | 3.6 |
| for (i = low to high) { i = i + inc; } { sout | i; } sout | nl; } | 12.1 | 10.4 | 8.7 | 7.5 | 3.6 |
| for (i = low to high) { i = i + inc; } { sout | i; } sout | nl; } | 0 | -5 | 1 | -2 | 3 | -2 | 4 | -1 |
| for (i = low to high) { i = i + inc; } { sout | i; } sout | nl; } | 0 | -5 | 1 | -2 | 3 | -2 | 4 | -1 |
| for (i = low to high) { i = i + inc; } { sout | i; } sout | nl; } | 0 | -5 | 1 | -2 | 3 | -2 | 4 | -1 |
| for (i = low to high) { i = i + inc; } { sout | i; } sout | nl; } | 0 | -5 | 1 | -2 | 3 | -2 | 4 | -1 |
| for (i = low to high) { i = i + inc; } { sout | i; } sout | nl; } | 0 | -5 | 1 | -2 | 3 | -2 | 4 | -1 |
| for (i = low to high) { i = i + inc; } { sout | i; } sout | nl; } | 0 | -5 | 1 | -2 | 3 | -2 | 4 | -1 |

Figure 2: Loop Control Examples
9.6 Labelled continue / break Statement

The for index components, low (L), high (H), and increment (I), are optional. If missing:

- 0 is the implicit low value.
- 1 is the implicit increment value.
- The up-to range uses operator += for increment.
- The down-to range uses operator -= for decrement.

If no type is specified for the loop index, it is the type of the high value H (when the low value is implicit) or the low value L.

```c
for (5) // typeof(5) anonymous-index; 5 is high value
for (i; 1.5 ~ 5.5 ) // typeof(1.5) i; 1.5 is low value
for (int i; 0 ~ 10 ~ 2 ) // int i; type is explicit
```

The following are examples for constructing different for-control:

- H is implicit up-to exclusive range \([0, H)\).
- \(~=\) H is implicit up-to inclusive range \([0, H]\).
- L ~ H is explicit up-to exclusive range \([L, H)\).
- L ~ H is explicit up-to inclusive range \([L, H]\).
- L ~ H is explicit down-to exclusive range \([H, L)\), where L and H are implicitly interchanged to make the range down-to.
- L ~ H is explicit down-to inclusive range \([H, L]\), where L and H are implicitly interchanged to make the range down-to.
- \@ means put nothing in this field.

```c
for (1 ; i = 1, j = 2; i < 5 && j < 12; i += 1, j += 3 ) // for ( typeof(i) i = 1, j = 2; i < 5 && j < 12; i += 1, j += 3 )
```

Warning: specifying the down-to range maybe unexpected because the loop control implicitly switches the L and H values (and toggles the increment/decrement for I):

```c
for (i; 1 ~ 10 ) // up range
for (i; 1 ~ 10 ) // down range
for (i; 10 ~ 1 ) // WRONG down range!
```

The reason for this semantics is that the range direction can be toggled by adding/removing the minus, ‘~’, versus interchanging the L and H expressions, which has a greater chance of introducing errors.

9.6 Labelled continue / break Statement

C continue and break statements, for altering control flow, are restricted to one level of nesting for a particular control structure. This restriction forces programmers to use goto to achieve the equivalent control-flow for more than one level of nesting. To prevent having to switch to the goto, C++ extends the continue and break with a target label to support static multi-level exit [3], as in Java. For both continue and break, the target label must be directly associated
with a for, while or do statement; for break, the target label can also be associated with a switch, if or compound ({} ) statement. Figure 3 shows a comparison between labelled continue and break and the corresponding C equivalent using goto and labels. The innermost loop has 8 exit points, which cause continuation or termination of one or more of the 7 nested control-structures.

Both labelled continue and break are a goto restricted in the following ways:

- They cannot create a loop, which means only the looping constructs cause looping. This restriction means all situations resulting in repeated execution are clearly delineated.
- They cannot branch into a control structure. This restriction prevents missing declarations and/or initializations at the start of a control structure resulting in undefined behaviour.

The advantage of the labelled continue/break is allowing static multi-level exits without having to use the goto statement, and tying control flow to the target control structure rather than an arbitrary point in a program via a label. Furthermore, the location of the label at the beginning of the target control structure informs the reader (eye candy) that complex control-flow is occurring in the body of the control structure. With goto, the label is at the end of the control structure, which fails to convey this important clue early enough to the reader. Finally, using an explicit target for the transfer instead of an implicit target allows new constructs to be added or removed without affecting existing constructs. Otherwise, the implicit targets of the current continue and break, i.e., the closest enclosing loop or switch, change as certain constructs are added or removed.

The if statement has an optional else clause executed if the conditional is false. This concept is extended to the while, for, and do looping constructs (like Python). Hence, if the loop conditional becomes false, looping stops and the corresponding else clause is executed, if present.

The following example is a linear search for the key 3 in an array, where finding the key is handled with a break and not finding with the else clause on the loop construct.
int a[10];

while (int i = 0; i < 10 ) {
    for (i; i < 10 ) {
        do {
            if ( a[i] == 3 ) break; // found
        } else { // i == 10
            // i += 1;
            sout | "not found";
        }
    }
}

Note, dangling else now occurs with if, while, for, do, and waitfor.

### 9.8 with Statement

Grouping heterogeneous data into an aggregate (structure/union) is a common programming practice, and aggregates may be nested:

```c
struct Person {  // aggregate
    struct Name { char first[20], last[20]; } name  // nesting
    struct Address { ... } address  // nesting
    int sex;
};
```

Functions manipulating aggregates must repeat the aggregate name to access its containing fields.

```c
Person p
p.name; p.address; p.sex;  // access containing fields
```

which extends to multiple levels of qualification for nested aggregates and multiple aggregates.

```c
struct Ticket { ... } t;
```

Repeated aggregate qualification is tedious and makes code difficult to read. Therefore, reducing aggregate qualification is a useful language design goal.

C partially addresses the problem by eliminating qualification for enumerated types and unnamed nested aggregates, which open their scope into the containing aggregate. This feature is used to group fields for attributes and/or with union aggregates.

```c
struct S {
    struct /* unnamed */ { int g, h; } __attribute__((aligned(64)));  // implicit "this" parameter
    int tag;
    union /* unnamed */ {
        struct { char c1, c2; } __attribute__((aligned(128)));  // this->c; this->i; this->d;
        struct { int i1, i2;);
        struct { double d1, d2;};
    };
    enum { R, G, B };  // derived class variables
    s.g; s.h; s.tag = R; s.c1; s.c2; s.i1 = G; s.i2 = B; s.d1; s.d2;
};
```

Object-oriented languages reduce qualification for class variables within member functions, e.g., C++:

```c
struct S {
    char c; int i; double d;
    void f( /* S * this */) {  // this->c; this->i; this->d;
    }
};
```

In general, qualification is elided for the variables and functions in the lexical scopes visible from a member function. However, qualification is necessary for name shadowing and explicit aggregate parameters.

```c
struct T {
    char m; int i; double n;  // derived class variables
};
struct S : public T {
```
9.8 \texttt{with} Statement

```
char c; int i; double d;  // class variables

void g( double d, T & t ) {
    d; t.m; t.i; t.n;  // function parameter
    c; i; this->d; S::d;  // class S variables
    m; T::i; n;  // class T variables
}
```

Note the three different forms of qualification syntax in C++, \texttt{.., \rightarrow, ::}, which is confusing.

Since CV in not object-oriented, it has no implicit parameter with its implicit qualification. Instead CV introduces a general mechanism using the \texttt{with} statement (see Pascal \citep[§ 4.F]{pascal}) to explicitly elide aggregate qualification by opening a scope containing the field identifiers. Hence, the qualified fields become variables with the side-effect that it is simpler to write, easier to read, and optimize field references in a block.

```
void f( S & this ) \texttt{with ( this )} {  // with statement
    c; i; d;  // this.c, this.i, this.d
}
```

with the generality of opening multiple aggregate-parameters:

```
void g( S & s, T & t ) \texttt{with ( s, t )} {  // multiple aggregate parameters
    c; s.i; d;  // s.c, s.i, s.d
    m; t.i; n;  // t.m, t.i, t.n
}
```

where qualification is only necessary to disambiguate the shadowed variable \texttt{i}. In detail, the \texttt{with} statement may form a function body or be nested within a function body.

The \texttt{with} clause takes a list of expressions, where each expression provides an aggregate type and object. (Enumerations are already opened.) To open a pointer type, the pointer must be dereferenced to obtain a reference to the aggregate type.

```
S * sp;
\texttt{with ( *sp )} { ... }
```

The expression object is the implicit qualifier for the open structure-fields.

CV’s ability to overload variables (see Section \ref{sec:overload}, p. 56) and use the left-side of assignment in type resolution means most fields with the same name but different types are automatically disambiguated, eliminating qualification. All expressions in the expression list are open in parallel within the compound statement. This semantic is different from Pascal, which nests the openings from left to right. The difference between parallel and nesting occurs for fields with the same name and type:

```
struct Q { int i; int k; int m; } q, w;
struct R { int i; int j; double m; } r, w;
with ( r, q ) {  // unambiguous, \texttt{r} + q.k
    j + k;
    m = 5.0;  // unambiguous, q.m = 5.0
    m = 1;  // unambiguous, \texttt{r.m} = 1
    int a = m;  // unambiguous, a = \texttt{r}.
    \texttt{double b} = m;  // unambiguous, b = q.m
    int c = r.i + q.i;  // disambiguate with qualification
    \texttt{(double)m};  // disambiguate with cast
}
```

For parallel semantics, both \texttt{r.i} and \texttt{q.i} are visible, so \texttt{i} is ambiguous without qualification; for nested semantics, \texttt{q.i} hides \texttt{r.i}, so \texttt{i} implies \texttt{q.i}. Pascal nested-semantics is possible by nesting with statements.

```
with ( r ) {  // unambiguous, \texttt{r.i}
    i;
    with ( q ) {  // unambiguous, q.i
        i;
    }
}
```

A cast or qualification can be used to disambiguate variables within a \texttt{with statement}. A cast can also be used to disambiguate among overload variables in a \texttt{with expression}:
with \( w \) \{ ... \} // ambiguous, same name and no context

with \( \{Q\} w \) \{ ... \} // unambiguous, cast

Because there is no left-side in the with expression to implicitly disambiguate between the \( w \) variables, it is necessary to explicitly disambiguate by casting \( w \) to type \( Q \) or \( R \).

Finally, there is an interesting problem between parameters and the function-body with, e.g.:

void f( S & s, char c ) with ( s ) {
    s.c = c; i = 3; d = 5.5; // initialize fields
}

Here, the assignment \( s.c = c \) means \( s.c = s.c \), which is meaningless, and there is no mechanism to qualify the parameter \( c \), making the assignment impossible using the function-body with. To solve this problem, parameters not explicitly opened are treated like an initialized aggregate:

struct Params {
    char c;
} params;

and implicitly opened after a function-body open, to give them higher priority:

void f( S & s, char c ) with( params ) \{ // syntax not allowed, illustration only
    s.c = c; i = 3; d = 5.5;
}

This implicit semantic matches with programmer expectation.

\section{Exception Handling}

Exception handling provides two mechanisms: change of control flow from a raise to a handler, and communication from the raise to the handler. Transfer of control can be local, within a routine, or non-local, among routines. Non-local transfer can cause stack unwinding, i.e., non-local routine termination, depending on the kind of raise.

```
exception_t E {};

void f(...) {
    ... throw E(); ...
        // termination
    ...
    ... throwResume E(); ...
        // resumption
}
```

The kind of raise and handler match: throw with catch and throwResume with catchResume. Then the exception type must match along with any additional predicate must be true. The catch and catchResume handlers may appear in any order. However, the finally clause must appear at the end of the try statement.

\subsection{Exception Hierarchy}

An exception type can be derived from another exception type, just like deriving a subclass from a class, providing a kind of polymorphism among exception types. The exception-type hierarchy that is created is used to organize exception types, similar to a class hierarchy in object-oriented languages, e.g.:
A programmer can then choose to handle an exception at different degrees of specificity along the hierarchy; derived exception-types support a more flexible programming style. For example, higher-level code should catch general exceptions to reduce coupling to the specific implementation at the lower levels; unnecessary coupling may force changes in higher-level code when low-level code changes. A consequence of derived exception-types is that multiple exceptions may match, e.g.:

```
catch( Arithmetic )
```

matches all three derived exception-types: DivideByZero, Overflow, and Underflow. Because the propagation mechanisms perform a simple linear search of the handler clause for a guarded block, and selects the first matching handler, the order of catch clauses in the handler clause becomes important, e.g.:

```
try {
  ...
} catch( Overflow ) { // must appear first
  // handle overflow
} catch( Arithmetic )
  // handle other arithmetic issues
}
```

Multiple derivation among exception is not supported.

### 11 Alternative Declarations

C declaration syntax is notoriously confusing and error prone. For example, many C programmers are confused by a declaration as simple as:

```
int * x[5]
```

Is this an array of 5 pointers to integers or a pointer to an array of 5 integers? If there is any doubt, it implies productivity and safety issues even for basic programs. Another example of confusion results from the fact that a routine name and its parameters are embedded within the return type, mimicking the way the return value is used at the routine’s call site. For example, a routine returning a pointer to an array of integers is defined and used in the following way:

```
int (*f())[5];  // definition
... (*f())[3] += 1;  // usage
```

Essentially, the return type is wrapped around the routine name in successive layers (like an onion). While attempting to make the two contexts consistent is a laudable goal, it has not worked out in practice, even though Dennis Richie believed otherwise:

```
In spite of its difficulties, I believe that the C’s approach to declarations remains plausible, and am comfortable with it; it is a useful unifying principle. [26, p. 12]
```

C provides its own type, variable and routine declarations, using a different syntax. The new declarations place qualifiers to the left of the base type, while C declarations place qualifiers to the right of the base type. In the following example, red is the base type and blue is qualifiers. The C declarations move the qualifiers to the left of the base type, i.e., move the blue to the left of the red, while the qualifiers have the same meaning but are ordered left to right to specify a variable’s type.

```
C

[5] * int x1;  int * x1[5];
* [5] int x2;  int (*x2)[5];
[5] [5] int f( int p );  int (*f( int p ))[5];
```

The only exception is bit field specification, which always appear to the right of the base type. However, unlike C, C\* type declaration tokens are distributed across all variables in the declaration list. For instance, variables x and y of type pointer to integer are defined in C\* as follows:

```
C\*

* int x, y;  int *x, *y;
```
The downside of this semantics is the need to separate regular and pointer declarations:

```
void* x;  int *x, y;
int y;
```

which is prescribing a safety benefit. Other examples are:

```
void z[5];  int z[5]; // array of 5 integers
char w[5];  char *w[5]; // array of 5 pointers to char
double v[5];  double (*v)[5]; // pointer to array of 5 doubles
struct s {
    int f0;  int *f1;
    [5] int f2;
};
```

The new declaration syntax can be used in other contexts where types are required, e.g., casts and the pseudo-routine `sizeof`:

```
y = (*int)x;
y = (int*)x;
i = sizeof([5]int);
i = sizeof(int*[5]);
```

Finally, new CV declarations may appear together with C declarations in the same program block, but cannot be mixed within a specific declaration. Therefore, a programmer has the option of either continuing to use traditional C declarations or take advantage of the new style. Clearly, both styles need to be supported for some time due to existing C-style header-files, particularly for UNIX-like systems.

12 Pointer / Reference

C provides a pointer type; CV adds a reference type. These types may be derived from an object or routine type, called the referenced type. Objects of these types contain an address, which is normally a location in memory, but may also address memory-mapped registers in hardware devices. An integer constant expression with the value 0, or such an expression cast to type `void*`, is called a null-pointer constant. An address is sound, if it points to a valid memory location in scope, i.e., within the program’s execution-environment and has not been freed. Dereferencing an unsound address, including the null pointer, is undefined, often resulting in a memory fault.

A program object is a region of data storage in the execution environment, the contents of which can represent values. In most cases, objects are located in memory at an address, and the variable name for an object is an implicit address to the object generated by the compiler and automatically dereferenced, as in:

9 The placement of a storage-class specifier other than at the beginning of the declaration specifiers in a declaration is an obsolescent feature. [20, §6.11.5(1)]
10 One way to conceptualize the null pointer is that no variable is placed at this address, so the null-pointer address can be used to denote an uninitialized pointer/reference object; i.e., the null pointer is guaranteed to compare unequal to a pointer to any object or routine. In general, a value with special meaning among a set of values is called a sentinel value, e.g., -1 as a return code value.
where the right example is how the compiler logically interprets the variables in the left example. Since a variable name only points to one address during its lifetime, it is an immutable pointer; hence, the implicit type of pointer variables \( x \) and \( y \) are constant pointers in the compiler interpretation. In general, variable addresses are stored in instructions instead of loaded from memory, and hence may not occupy storage. These approaches are contrasted in the following:

<table>
<thead>
<tr>
<th>explicit variable address</th>
<th>implicit variable address</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>lda r1,100</code> // load address of ( x )</td>
<td><code>ld r2,(r1)</code> // load value of ( x )</td>
</tr>
<tr>
<td><code>lda r3,104</code> // load address of ( y )</td>
<td><code>st r2,(r3)</code> // store ( x ) into ( y )</td>
</tr>
</tbody>
</table>

Finally, the immutable nature of a variable’s address and the fact that there is no storage for the variable pointer means pointer assignment is impossible. Therefore, the expression \( x = y \) has only one meaning, \( *x = *y \), i.e., manipulate values, which is why explicitly writing the dereferences is unnecessary even though it occurs implicitly as part of instruction decoding.

A pointer/reference object is a generalization of an object variable-name, i.e., a mutable address that can point to more than one memory location during its lifetime. (Similarly, an integer variable can contain multiple integer literals during its lifetime versus an integer constant representing a single literal during its lifetime, and like a variable name, may not occupy storage if the literal is embedded directly into instructions.) Hence, a pointer occupies memory to store its current address, and the pointer’s value is loaded by dereferencing, e.g.:

```
int x, y, *p1, *p2, **p3;
p1 = &x; // p1 points to x
p2 = p1; // p2 points to x
p1 = &y; // p1 points to y
p3 = &p2; // p3 points to p2
```

Notice, an address has a duality: a location in memory or the value at that location. In many cases, a compiler might be able to infer the best meaning for these two cases. For example, Algol68 [23] infers pointer dereferencing to select the best meaning for each pointer usage

\[
p2 = p1 + x; \quad // \text{compiler infers } *p2 = *p1 + x;
\]

Algol68 infers the following dereferencing \( *p2 = *p1 + x \), because adding the arbitrary integer value in \( x \) to the address of \( p1 \) and storing the resulting address into \( p2 \) is an unlikely operation. Unfortunately, automatic dereferencing does not work in all cases, and so some mechanism is necessary to fix incorrect choices.

Rather than inferring dereference, most programming languages pick one implicit dereferencing semantics, and the programmer explicitly indicates the other to resolve address-duality. In C, objects of pointer type always manipulate the pointer object’s address:

\[
p2 = p1; \quad // p2 = p1 rather than *p2 = *p1 \quad \text{and the programmer probably meant:}
\]

```
p1 = p2;
*p2 = *p1 + x; // pointer address assignment
```

The C semantics work well for situations where manipulation of addresses is the primary meaning and data is rarely accessed, such as storage management (malloc/free).

However, in most other situations, the pointed-to value is requested more often than the pointer address.

\[
*p2 = ((p1 + p2) * (p3 - p1)) / (p3 - 15);
\]

In this case, it is tedious to explicitly write the dereferencing, and error prone when pointer arithmetic is allowed. It is better to have the compiler generate the dereferencing and have no implicit pointer arithmetic:

\[
p2 = ((p1 + p2) * (p3 - p1)) / (p3 - 15);
\]

To support this common case, a reference type is introduced in C#, denoted by &, which is the opposite dereference
semantics to a pointer type, making the value at the pointed-to location the implicit semantics for dereferencing (similar
but not the same as C++ reference types).

```c
int x, y, &r1, & r2, &&r3;
&r1 = &x;  // r1 points to x
&r2 = &r1; // r2 points to x
&r1 = &y;  // r1 points to y
& &r3 = & &r2; // r3 points to r2
r2 = ((r1 + r2) * (r3 - r1)) / (r3 - 15); // implicit dereferencing
```

Except for auto-dereferencing by the compiler, this reference example is the same as the previous pointer example.

Hence, a reference behaves like the variable name for the current variable it is pointing-to. One way to conceptualize a
reference is via a rewrite rule, where the compiler inserts a dereference operator before the reference variable for each
reference qualifier in a declaration, so the previous example becomes:

```c
*r2 = ((*r1 + *r2) * (**r3 - *r1)) / (**r3 - 15);
```

When a reference operation appears beside a dereference operation, e.g., &, they cancel out. However, in C, the cancel-
lution always yields a value (rvalue). For a C# reference type, the cancellation on the left-hand side of assignment
leaves the reference as an address (lvalue):

```c
(&&)r1 = &x;  // (&&) cancel giving address in r1 not variable pointed-to by r1
```

Similarly, the address of a reference can be obtained for assignment or computation (rvalue):

```c
(&(&&))r3 = (&(&&))r2; // (&&) cancel giving address in r2, (&(&&)) cancel giving a address in r3
```

Cancellation works to arbitrary depth.

Fundamentally, pointer and reference objects are functionally interchangeable because both contain addresses.

```c
int x, *p1 = &x, **p2 = &p1, ***p3 = &p2,
& r1 = &x,  & & r2 = r1,  & & & r3 = r2;
***p3 = 3;    // change x
r3 = 3;       // change x, **r3
* &p3 = ...;  // change p1
& &r3 = ...;  // change r1, (&&)**r3, 1 cancellation
*p3 = ...;    // change p2
& & &r3 = p3; // change r2, (&(&&))**r3, 2 cancellations
& & & &r3 = p3; // change r3 to p3, (&(&&(&&)))*r3, 3 cancellations
```

Furthermore, both types are equally performant, as the same amount of dereferencing occurs for both types. Therefore,
the choice between them is based solely on whether the address is dereferenced frequently or infrequently, which
dictates the amount of implicit dereferencing aid from the compiler.

As for a pointer type, a reference type may have qualifiers:

```c
const int cx = 5;    // cannot change cx;
const int & cr = cx; // cannot change what cr points to
& cr = &cx;        // can change cr
cr = 7;            // error, cannot change cx
int & const rc = x; // must be initialized
& rc = &x;         // error, cannot change rc
const int & const crc = cx;  // must be initialized
crc = 7;           // error, cannot change cx
&crc = &cx;        // error, cannot change crc
```

Hence, for type & const, there is no pointer assignment, so & rc = & x is disallowed, and the address value cannot be the
null pointer unless an arbitrary pointer is coerced into the reference:

```c
int & const cr = *0;  // where 0 is the int * zero
```

Note, constant reference-types do not prevent addressing errors because of explicit storage-management:

```c
int & const cr = *malloc();
```

```c
cr = 5;
free( &cr );
```

11 The unary & operator yields the address of its operand. If the operand has type “type”, the result has type “pointer to type”. If the operand is the
result of a unary * operator, neither that operator nor the & operator is evaluated and the result is as if both were omitted, except that the constraints
on the operators still apply and the result is not an lvalue. [20, § 6.5.3.2–3]
12.1 Initialization

Initialization is different than assignment because initialization occurs on the empty (uninitialized) storage on an object, while assignment occurs on possibly initialized storage of an object. There are three initialization contexts in C\+\+: declaration initialization, argument/parameter binding, return/temporary binding. Because the object being initialized has no value, there is only one meaningful semantics with respect to address duality: it must mean address as there is no pointed-to value. In contrast, the left-hand side of assignment has an address that has a duality. Therefore, for pointer/reference initialization, the initializing value must be an address not a value.

Like the previous example with C pointer-arithmetic, it is unlikely assigning the value of x into a pointer is meaningful (again, a warning is usually given). Therefore, for safety, this context requires an address, so it is superfluous to require explicitly taking the address of the initialization object, even though the type is incorrect. Note, this is strictly a convenience and safety feature for a programmer. Hence, C\+\+ allows r to be assigned x because it infers a reference for x, by implicitly inserting a address-of operator, \&, and it is an error to put an & because the types no longer match due to the implicit dereference. Unfortunately, C allows p to be assigned with \&x (address) or x (value), but most compilers warn about the latter assignment as being potentially incorrect. Similarly, when a reference type is used for a parameter/return type, the call-site argument does not require a reference operator for the same reason.

Within routine f, it is possible to change the argument by changing the corresponding parameter, and parameter r can be locally reassigned within f. Since operator routine ?+? takes its arguments by value, the references returned from f are used to initialize compiler generated temporaries with value semantics that copy from the references. This implicit referencing is crucial for reducing the syntactic burden for programmers when using references; otherwise references have the same syntactic burden as pointers in these contexts.

When a pointer/reference parameter has a const value (immutable), it is possible to pass literals and expressions.

---

12 The reason for disallowing arrays of reference is unknown, but possibly comes from references being ethereal (like a textual macro), and hence, replaceable by the referent object.
void f(const int & cr);
void g(const int * cp);
f(3);        g(&3);
f(x + y);    g(&x + y);

Here, the compiler passes the address to the literal 3 or the temporary for the expression x + y, knowing the argument cannot be changed through the parameter. The & before the constant/expression for the pointer-type parameter (g) is a CV extension necessary to type match and is a common requirement before a variable in C (e.g., scanf). Importantly, &3 may not be equal to &3, where the references occur across calls because the temporaries maybe different on each call.

CV extends this semantics to a mutable pointer/reference parameter, and the compiler implicitly creates the necessary temporary (copying the argument), which is subsequently pointed-to by the reference parameter and can be changed.13

void f(int & r);
void g(int * p);
f(3);        g(&3);       // compiler implicit generates temporaries
f(x + y);    g(&x + y);   // compiler implicit generates temporaries

Essentially, there is an implicit rvalue to lvalue conversion in this case.14 The implicit conversion allows seamless calls to any routine without having to explicitly name/copy the literal/expression to allow the call.

Finally, C handles routine objects in an inconsistent way. A routine object is both a pointer and a reference (particle and wave).

void f(int i);
void (*fp)(int);
fp = f;
fp = &f;
fp = *fp;
fp(3);
(*fp)(3);

While C’s treatment of routine objects has similarity to inferring a reference type in initialization contexts, the examples are assignment not initialization, and all possible forms of assignment are possible (f, &f, *f) without regard for type. Instead, a routine object should be referenced by a const reference:

const void (&fr)(int) = f;       // routine reference
fr = ...;                       // error, cannot change code
&fr = ...;                      // changing routine reference
fr(3);                          // reference call to f
(*fr)(3);                       // error, incorrect type

because the value of the routine object is a routine literal, i.e., the routine code is normally immutable during execution.15 CV allows this additional use of references for routine objects in an attempt to give a more consistent meaning for them.

12.2 Address-of Semantics

In C, &E is an rvalue for any expression E. CV extends the & (address-of) operator as follows:

• if R is an rvalue of type T &1 · · · &r, where r ≥ 1 references (& symbols), than &R has type T * &2 · · · &r, i.e., T pointer with r − 1 references (& symbols).
• if L is an lvalue of type T &1 · · · &l, where l ≥ 0 references (& symbols), than &L has type T * &1 · · · &l, i.e., T pointer with l references (& symbols).

The following example shows the first rule applied to different value contexts:

int x, *px, **ppx, ***pppx, ****ppppx;
int &rx = x, & &rrx = rx, && &rrrx = rrx ;

13If whole program analysis is possible, and shows the parameter is not assigned, i.e., it is const, the temporary is unnecessary.

14This conversion attempts to address the const hell problem, when the innocent addition of a const qualifier causes a cascade of type failures, requiring an unknown number of additional const qualifiers, until it is discovered a const qualifier cannot be added and all the const qualifiers must be removed.

15Dynamic code rewriting is possible but only in special circumstances.
12.3 Conversions

C provides a basic implicit conversion to simplify variable usage:

0. lvalue to rvalue conversion: \( cv \ T \) converts to \( T \), which allows implicit variable dereferencing.

\begin{verbatim}
int x;
\end{verbatim}

An rvalue has no type qualifiers (\( cv \)), so the lvalue qualifiers are dropped.

\( cv \) provides three new implicit conversion for reference types to simplify reference usage.

1. reference to rvalue conversion: \( cv \ T \& \) converts to \( T \), which allows implicit reference dereferencing.

\begin{verbatim}
int x, &r = x, f( int p );
\end{verbatim}

An rvalue has no type qualifiers (\( cv \)), so the reference qualifiers are dropped.

2. lvalue to reference conversion: lvalue-type \( cv1 \ T \) converts to \( cv2 \ T \& \), which allows implicitly converting variables to references.

\begin{verbatim}
int x, &r = x, f( int &p );
f( x );
\end{verbatim}

An rvalue has no type qualifiers (\( cv \)), so the reference qualifiers are dropped.

Conversion can restrict a type, where \( cv1 \leq cv2 \), e.g., passing an int to a const volatile int & \& has low cost.

Conversion can expand a type, where \( cv1 > cv2 \), e.g., passing a const volatile int to an int & \& has high cost (warning); furthermore, if \( cv1 \) has const but not \( cv2 \), a temporary variable is created to preserve the immutable lvalue.

3. rvalue to reference conversion: \( T \) converts to \( cv \ T \& \), which allows binding references to temporaries.

\begin{verbatim}
int x, &r = x, f( int &p );
f( x + 3 );
\end{verbatim}

In both case, modifications to the temporary are inaccessible (warning). Conversion expands the temporary-type with \( cv \), which is low cost since the temporary is inaccessible.

13 Enumeration

An enumeration is a compile-time mechanism to alias names to constants, like typedef is a mechanism to alias names to types. Its purpose is to define a restricted-value type providing code-readability and maintenance – changing an enum’s value automatically updates all name usages during compilation.

An enumeration type is a set of names, each called an enumeration constant (shortened to enum) aliased to a fixed value (constant).

\begin{verbatim}
enum Days { Mon, Tue, Wed, Thu, Fri, Sat, Sun }; // enumeration type definition, set of 7 names & values
\end{verbatim}

The set of enums is injected into the variable namespace at the definition scope. Hence, enums may be overloaded with variable, enum, and function names.
13.1 Enum type

The type of enums can be any type, and an enum’s value comes from this type. Because an enum is a constant, it cannot appear in a mutable context, e.g., `Mon = Sun` is disallowed, and has no address (it is an rvalue). Therefore, an enum is automatically converted to its constant’s base-type, e.g., comparing/printing an enum compares/prints its value rather than the enum name; there is no mechanism to print the enum name.

The default enum type is `int`. Hence, `Days` is the set type `Mon, Tue, ..., Sun`, while the type of each enum is `int` and each enum represents a fixed integral value. If no values are specified for an integral enum type, the enums are automatically numbered by one from left to right starting at zero. Hence, the value of enum `Mon` is 0, `Tue` is 1, ..., `Sun` is 6. If an enum value is specified, numbering continues by one from that value for subsequent unnumbered enums. If an enum value is a constant expression, the compiler performs constant-folding to obtain a constant value.

CV allows other integral types with associated values.

```
enum (char) Letter { A = 'A', B, C, I = 'I', J, K);
enum (long long int) BigNum { X = 123_456_789_012_345, Y = 345_012_789_456_123 };
```

For enumeration `Letter`, enum `A`’s value is explicitly set to `'A'`, with `B` and `C` implicitly numbered with increasing values from `'A'`, and similarly for enums `I`, `J`, and `K`.

Non-integral enum types must be explicitly initialized, e.g., `double` is not automatically numbered by one.

```
enum (double) Math { PI_2 = 1.570796, PI = 3.141597, E = 2.718282 } // non-integral numeric
enum (char *) Name { Fred = "Fred", Mary = "Mary", Jane = "Jane" };
enum (int *) ptr { I = &i, J = &j, K = &k };
enum (int &) ref { I = i, J = j, K = k };
enum (int, int) { T = [ 1, 2 ] };
enum (void (*)()) funs { F = f, F = g };
```

// aggregate
```
struct S { int i, j; };
enum (S) s { A = { 3, 4 }, B = { 7, 8 } };
```

// enumeration
```
enum (Letter) Greek { Alph = A, Beta = B, /* more enums */ } // alphabet intersection
```

Enumeration `Greek` may have more or less enums than `Letter`, but the enum values must be from `Letter`. Therefore, `Greek` enums are a subset of type `Letter` and are type compatible with enumeration `Letter`, but `Letter` enums are not type compatible with enumeration `Greek`.

The following examples illustrate the difference between the enumeration type and the type of its enums.

```
Math m = PI; // allowed
double d = PI; // allowed, conversion to base type
m = E; // allowed
```
13.2 Inheritance

Plan-9 inheritance may be used with enumerations.

```c
enum ( struct vec3 ) Axis { Up @= { 1, 0, 0 }, Left @= { 0, 1, 0 }, Front @= { 0, 0, 1 } }
```

Finally, enumeration variables are assignable and comparable only if the appropriate operators are defined for its enum type.

### 13.2 Inheritance

Enumerations can inherit from a base type, including other enumerations and integral types.

```c
enum ( char * ) Name2 { inline Name, Jack = "Jack", Jill = "Jill" }
enum /* inferred */ Name3 { inline Name2, Sue = "Sue", Tom = "Tom" }
```

An enumeration inherits all the values of its base type, but the names of the inherited values are only available if they are explicitly defined. If the base type is an integer, automatic numbering may be used.

```c
void f( Name );
void g( Name2 );
void h( Name3 );
void j( const char * );
```

The following calls are valid:

```c
f( Fred );
g( Fred ); g( Jill );
h( Fred ); h( Jill ); h( Sue );
j( Fred ); j( Jill ); j( Sue ); j( "W" );
```

Note, the validity of calls is the same for call-by-reference as for call-by-value, and `const` restrictions are the same as for other types.

Enums cannot be created at runtime, so inheritance problems, such as contra-variance do not apply. Only instances of the enum base-type may be created at runtime.

### 14 Routine Definition

C9 supports a new syntax for routine definition, as well as C11 and K&R routine syntax. The point of the new syntax is to allow returning multiple values from a routine [15, 24], e.g.:

```c
[ int o1, int o2, char o3 ] f( int i1, char i2, char i3 ) {
routine body
}
```

where routine f has three output (return values) and three input parameters. Existing C syntax cannot be extended with multiple return types because it is impossible to embed a single routine name within multiple return type specifications.

In detail, the brackets, [], enclose the result type, where each return value is named and that name is a local variable.
Named Return Values

of the particular return type. The value of each local return variable is automatically returned at routine termination. Declaration qualifiers can only appear at the start of a routine definition, e.g.:

```
extern [ int x ] g ( int y ) { }
```

Lastly, if there are no output parameters or input parameters, the brackets and/or parentheses must still be specified; in both cases the type is assumed to be void as opposed to old style C defaults of int return type and unknown parameter types, respectively, as in:

```
[ ] g( ) ;               // no input or output parameters
[ void ] g ( void ) ;   // no input or output parameters
```

Routine f is called as follows:

```
[ i, j, ch ] = f ( 3, ' a ', ch );
```

The list of return values from f and the grouping on the left-hand side of the assignment is called a return list and discussed in Section 12.

Cy style declarations cannot be used to declare parameters for K&R style routine definitions because of the following ambiguity:

```
int ( *f(x))[ 5 ] int x ;
```

The string "int ( *f(x))[ 5 ]" declares a K&R style routine of type returning a pointer to an array of 5 integers, while the string "[ 5 ] int x" declares a Cy style parameter x of type array of 5 integers. Since the strings overlap starting with the open bracket, [ , there is an ambiguous interpretation for the string. As well, Cy-style declarations cannot be used to declare parameters for C-style routine-definitions because of the following ambiguity:

```
typedef int foo ;
int f ( int ( * foo ) );               // foo is redefined as a parameter name
```

The string "int ( * foo )" declares a C-style named-parameter of type pointer to an integer (the parenthesis are superfluous), while the same string declares a Cy style unnamed parameter of type routine returning integer with unnamed parameter of type pointer to foo. The redefinition of a type name in a parameter list is the only context in C where the character * can appear to the left of a type name, and Cy relies on all type qualifier characters appearing to the right of the type name. The inability to use Cy declarations in these two contexts is probably a blessing because it precludes programmers from arbitrarily switching between declarations forms within a declaration contexts.

C-style declarations can be used to declare parameters for Cy style routine definitions, e.g.:

```
[ int ] f ( int ( * foo ) );               // returns an integer, accepts 2 pointers to integers
[ * int, int * ] f ( int ) ;              // returns 2 pointers to integers, accepts an integer
```

The reason for allowing both declaration styles in the new context is for backwards compatibility with existing preprocessor macros that generate C-style declaration-syntax, as in:

```
#define ptoa ( n, d ) int ( *n)[ d ]
int f ( ptoa ( p, 5 ) ) ...                // expands to int f ( int ( *p)[ 5 ] )
[ int ] f ( ptoa ( p, 5 ) ) ...            // expands to [ int ] f ( int ( *p)[ 5 ] )
```

Again, programmers are highly encouraged to use one declaration form or the other, rather than mixing the forms.

14.1 Named Return Values

Named return values handle the case where it is necessary to define a local variable whose value is then returned in a return statement, as in:

```
int f () {
    int x ;
    ... x = 0 ; ... x = y ; ...
    return x ;
}
```

Because the value in the return variable is automatically returned when a Cy routine terminates, the return statement does not contain an expression, as in:

---

16 Michael Tiemann, with help from Doug Lea, provided named return values in g++, circa 1989.
When the return is encountered, the current values of \( x \) and \( y \) are returned to the calling routine. As well, “falling off the end” of a routine without a return statement is permitted, as in:

```
[ int x, int y ] f() {
  int z;
  ... x = 0; ... y = z; ...  // implicitly return x, y
  return;
}
```

In this case, the current values of \( x \) and \( y \) are returned to the calling routine just as if a return had been encountered.

Named return values may be used in conjunction with named parameter values; specifically, a return and parameter can have the same name.

```
[ int x, int y ] f( int, x, int y ) {
  ...    // implicitly return x, y
}
```

This notation allows the compiler to eliminate temporary variables in nested routine calls.

```
[ int x, int y ] f( int, x, int y );  // prototype declaration
int a, b;
[a, b] = f( f( f( a, b ) ) );
```

While the compiler normally ignores parameters names in prototype declarations, here they are used to eliminate temporary return-values by inferring that the results of each call are the inputs of the next call, and ultimately, the left-hand side of the assignment. Hence, even without the body of routine \( f \) (separate compilation), it is possible to perform a global optimization across routine calls. The compiler warns about naming inconsistencies between routine prototype and definition in this case, and behaviour is undefined if the programmer is inconsistent.

### 14.2 Routine Prototype

The syntax of the new routine prototype declaration follows directly from the new routine definition syntax; as well, parameter names are optional, e.g.:

```
[ int x ] f();    // returning int with no parameters
[ * int ] g( int y);   // returning pointer to int with int parameter
[ ] h( int, char );    // returning no result with int and char parameters
[ * int, int ] ]( int ); // returning pointer to int and int, with int parameter
```

This syntax allows a prototype declaration to be created by cutting and pasting source text from the routine definition header (or vice versa). Like C, it is possible to declare multiple routine-prototypes in a single declaration, where the return type is distributed across all routine names in the declaration list (see Section 11, p. 17), e.g.:

```
C :    const double bar1(), bar2( int ), bar3( double );
C\# :  [const double] foo0(), foo0( int ), foo0( double ) { return 3.0; }
```

\( C\# \) allows the last routine in the list to define its body.

Declaration qualifiers can only appear at the start of a \( C\# \) routine declaration, e.g.:

```
extern [ int ] f( int );
static [ int ] g( int );
```

### 15 Routine Pointers

The syntax for pointers to \( C\# \) routines specifies the pointer name on the right, e.g.:

```
* [ int x ] ]( ) fp;    // pointer to routine returning int with no parameters
* [ * int ] (int y) gp;  // pointer to routine returning pointer to int with int parameter
* [ ] (int,char) hp;     // pointer to routine returning no result with int and char parameters
* [ * int, int ] (int) jp; // pointer to routine returning pointer to int and int, with int parameter
```

While parameter names are optional, a routine name cannot be specified; for example, the following is incorrect:

```
* [ int x ] f( ) fp;  // routine name "f" is not allowed
```
16 Named and Default Arguments

Named and default arguments [19]'17 are two mechanisms to simplify routine call. Both mechanisms are discussed with respect to C/V.

**Named (or Keyword) Arguments**: provide the ability to specify an argument to a routine call using the parameter name rather than the position of the parameter. For example, given the routine:

```c
void p(int x, int y, int z) {...}
```

a positional call is:
```
p(4, 7, 3);
```

whereas a named (keyword) call may be:
```
p(z:3, x:4, y:7);
// rewrite => p(4, 7, 3)
```

Here the order of the arguments is unimportant, and the names of the parameters are used to associate argument values with the corresponding parameters. The compiler rewrites a named call into a positional call. The advantages of named parameters are:

- Remembering the names of the parameters may be easier than the order in the routine definition.
- Parameter names provide documentation at the call site (assuming the names are descriptive).
- Changes can be made to the order or number of parameters without affecting the call (although the call must still be recompiled).

Unfortunately, named arguments do not work in C-style programming-languages because a routine prototype is not required to specify parameter names, nor do the names in the prototype have to match with the actual definition. For example, the following routine prototypes and definition are all valid.

```c
void p(int, int, int);
// equivalent prototypes
void p(int x, int y, int z);
void p(int y, int x, int z);
void p(int z, int y, int x);
void p(int q, int r, int s) {} // match with this definition
```

Forcing matching parameter names in routine prototypes with corresponding routine definitions is possible, but goes against a strong tradition in C programming. Alternatively, prototype definitions can be eliminated by using a two-pass compilation, and implicitly creating header files for exports. The former is easy to do, while the latter is more complex.

Furthermore, named arguments do not work well in a C/V-style programming-languages because they potentially introduces a new criteria for type matching. For example, it is technically possible to disambiguate between these two overloaded definitions of \( f \) based on named arguments at the call site:

```c
int f(int i, int j);
int f(int x, double y);
```

However, named arguments compound routine resolution in conjunction with conversions:

```c
f(j:3, i:4); // 1st f
f(x:7, y:8.1); // 2nd f
f(4, 5); // ambiguous call
```

Depending on the cost associated with named arguments, this call could be resolvable or ambiguous. Adding named argument into the routine resolution algorithm does not seem worth the complexity. Therefore, C/V does **not** attempt to support named arguments.

**Default Arguments** provide the ability to associate a default value with a parameter so it can be optionally specified in the argument list. For example, given the routine:

```c
f(i:3, 5.7); // ambiguous call?
```

17 Francez [14] proposed a further extension to the named-parameter passing style, which specifies what type of communication (by value, by reference, by name) the argument is passed to the routine.
void p( int x = 1, int y = 2, int z = 3 ) {...}

the allowable positional calls are:

1. p(); // rewrite ⇒ p( 1, 2, 3 )
2. p( 4 ); // rewrite ⇒ p( 4, 2, 3 )
3. p( 4, 4 ); // rewrite ⇒ p( 4, 4, 3 )
4. p( 4, 4, 4 ); // rewrite ⇒ p( 4, 4, 4 )

// empty arguments
5. p( , 4, 4 ); // rewrite ⇒ p( 1, 4, 4 )
6. p( 4, , 4 ); // rewrite ⇒ p( 4, 2, 4 )
7. p( 4, 4, ); // rewrite ⇒ p( 4, 4, 3 )
8. p( 4, , ); // rewrite ⇒ p( 4, 2, 3 )
9. p( , 4, ); // rewrite ⇒ p( 1, 2, 4 )
10. p( , , 4 ); // rewrite ⇒ p( 1, 2, 4 )
11. p( , , ); // rewrite ⇒ p( 1, 2, 3 )

Here the missing arguments are inserted from the default values in the parameter list. The compiler rewrites missing default values into explicit positional arguments. The advantages of default values are:

- Routines with a large number of parameters are often very generalized, giving a programmer a number of different options on how a computation is performed. For many of these kinds of routines, there are standard or default settings that work for the majority of computations. Without default values for parameters, a programmer is forced to specify these common values all the time, resulting in long argument lists that are error prone.

- When a routine's interface is augmented with new parameters, it extends the interface providing generalizability (somewhat like the generalization provided by inheritance for classes). That is, all existing calls are still valid, although the call must still be recompiled.

The only disadvantage of default arguments is that unintentional omission of an argument may not result in a compiler-time error. Instead, a default value is used, which may not be the programmer's intent.

Default values may only appear in a prototype versus definition context:

void p( int x, int y = 2, int z = 3 ); // prototype: allowed
void p( int, int, y = 2, int z = 3 ); // prototype: allowed
void p( int x, int, int y = 2, int z = 3 ) {} // definition: not allowed

The reason for this restriction is to allow separate compilation. Multiple prototypes with different default values is an error.

Ellipse ("...") arguments present problems when used with default arguments. The conflict occurs because both named and ellipse arguments must appear after positional arguments, giving two possibilities:

p( /* positional */ , ..., /* named */ );
p( /* positional */ , /* named */ , ... );

While it is possible to implement both approaches, the first possibly is more complex than the second, e.g.:

p( int x, int y, int z, ... );
p( 1, 4, 5, 6, z : 3, y : 2 ); // assume p( /* positional */ , ..., /* named */ );
p( 1, z : 3, y : 2, 4, 5, 6 ); // assume p( /* positional */ , /* named */ , ... );

In the first call, it is necessary for the programmer to conceptually rewrite the call, changing named arguments into positional, before knowing where the ellipse arguments begin. Hence, this approach seems significantly more difficult, and hence, confusing and error prone. In the second call, the named arguments separate the positional and ellipse arguments, making it trivial to read the call.

The problem is exacerbated with default arguments, e.g.:

void p( int x, int y = 2, int z = 3... );

---

18 "It should be possible for the implementor of an abstraction to increase its generality. So long as the modified abstraction is a generalization of the original, existing uses of the abstraction will not require change. It might be possible to modify an abstraction in a manner which is not a generalization without affecting existing uses, but, without inspecting the modules in which the uses occur, this possibility cannot be determined. This criterion precludes the addition of parameters, unless these parameters have default or inferred values that are valid for all possible existing applications." [7, p. 128]
The first call is an error because arguments 4 and 5 are actually positional not ellipse arguments; therefore, argument 5 subsequently conflicts with the named argument $z : 3$. In the second call, the default value for $y$ is implicitly inserted after argument 1 and the named arguments separate the positional and ellipse arguments, making it trivial to read the call. For these reasons, CV requires named arguments before ellipse arguments. Finally, while ellipse arguments are needed for a small set of existing C routines, like `printf`, the extended CV type system largely eliminates the need for ellipse arguments (see Section 25, p. 54), making much of this discussion moot.

Default arguments and overloading (see Section 25, p. 54) are complementary. While in theory default arguments can be simulated with overloading, as in:

```c
    default arguments overloading
    void p( int x, int $y = 2$, int $z = 3$ ) {...} // rewrite ⇒ void p( int x, int $y$, int $z$ ) {...}
    void p( int $x$ ) { p( $x$, 2, 3 ); }
    void p( int $x$, int $y$ ) { p( $x$, $y$, 3 ); }
```

the number of required overloaded routines is linear in the number of default values, which is unacceptable growth. In general, overloading should only be used over default arguments if the body of the routine is significantly different. Furthermore, overloading cannot handle accessing default arguments in the middle of a positional list, via a missing argument, such as:

```c
    p( 1, /* default */ $5$ ); // rewrite ⇒ p( 1, 2, 5 )
```

Given the CV restrictions above, both named and default arguments are backwards compatible. C++ only supports default arguments; Ada supports both named and default arguments.

### 17 Unnamed Structure Fields

C requires each field of a structure to have a name, except for a bit field associated with a basic type, e.g.:

```c
 struct {  
    int $f_1$; // named field  
    int $f_2 : 4$; // named field with bit field size  
    int $3$; // unnamed field for basic type with bit field size  
    int ; // disallowed, unnamed field  
    int $*$; // disallowed, unnamed field  
    int $()$( int ); // disallowed, unnamed field  
};
```

This requirement is relaxed by making the field name optional for all field declarations; therefore, all the field declarations in the example are allowed. As for unnamed bit fields, an unnamed field is used for padding a structure to a particular size. A list of unnamed fields is also supported, e.g.:

```c
 struct {  
    int , , ; // 3 unnamed fields  
}
```

### 18 Nesting

Nesting of types and routines is useful for controlling name visibility (name hiding).

#### 18.1 Type Nesting

CV allows type nesting, and type qualification of the nested types (see Figure 4), where as C hoists (refactors) nested types into the enclosing scope and has no type qualification. In the left example in C, types $C$, $U$ and $T$ are implicitly hoisted outside of type $S$ into the containing block scope. In the right example in CV, the types are not hoisted and accessed using the field-selection operator ":." for type qualification, as does Java, rather than the C++ type-selection operator ":=".
18.2 Routine Nesting

While C∀ does not provide object programming by putting routines into structures, it does rely heavily on locally nested routines to redefine operations at or close to a call site. For example, the C quick-sort is wrapped into the following polymorphic C∀ routine:

```c
forall( T | { int $?<?( T, T ); } )
void qsort( const T * arr, size_t dimension );
```

which can be used to sort in ascending and descending order by locally redefining the less-than operator into greater-than.

```c
class unsigned int size = 5;
int ia[size];
...                             // assign values to array ia
qsort( ia, size );             // sort ascending order using builtin $?<?
{
    int $?<?( int x, int y ) { return x > y; }   // nested routine
    qsort( ia, size );                           // sort descending order by local redefinition
}
```

Nested routines are not first-class, meaning a nested routine cannot be returned if it has references to variables in its enclosing blocks; the only exception is references to the external block of the translation unit, as these variables persist for the duration of the program. The following program in undefined in C∀ (and Indexcgcc)

```c
[…][int( int )] foo() {  // int (* foo)( int )
    int i = 7;
    int bar( int p ) {  // dependent on local variable
        i += 1;
        sout | i;
    }
    return bar;         // undefined because of local dependence
}
int main() {  // int (*)( int ) fp = foo();
    sout | fp( 3 );
}
```

because

Currently, there are no lambda expressions, i.e., unnamed routines because routine names are very important to properly select the correct routine.
19 Tuple

In C and C++, lists of elements appear in several contexts, such as the parameter list of a routine call.

\[
f(2, x, 3 + i); \quad // \text{element list}
\]

A list of elements is called a tuple, and is different from a comma expression.

19.1 Multiple-Return-Value Functions

In C and most programming languages, functions return at most one value; however, many operations have multiple outcomes, some exceptional (see Section 10, p. 16). To emulate functions with multiple return values, aggregation and/or aliasing is used.

In the former approach, a record type is created combining all of the return values. For example, consider C’s `div` function, which returns the quotient and remainder for a division of an integer value.

\[
\text{typedef struct}\{\text{int} \text{ quot, rem;}\} \text{ div_t}; \quad // \text{from include stdlib.h}
\]

\[
\text{div_t qr = div( 13, 5 );} \quad // \text{return quotient/remainder aggregate}
\]

This approach requires a name for the return type and fields, where naming is a common programming-language issue. That is, naming creates an association that must be managed when reading and writing code. While effective when used sparingly, this approach does not scale when functions need to return multiple combinations of types.

In the latter approach, additional return values are passed as pointer parameters. A pointer parameter is assigned inside the routine to emulate a return. For example, consider C’s `modf` function, which returns the integral and fractional part of a floating value.

\[
\text{double modf( double x, double * i );} \quad // \text{from include math.h}
\]

\[
\text{double intp, frac = modf( 13.5, &intp );} \quad // \text{return integral and fractional components}
\]

This approach requires allocating storage for the return values, which complicates the call site with a sequence of variable declarations leading to the call. Also, while a disciplined use of `const` can give clues about whether a pointer parameter is used as an out parameter, it is not obvious from the routine signature whether the callee expects such a parameter to be initialized before the call. Furthermore, while many C routines that accept pointers are safe for a NULL argument, there are many C routines that are not null-safe. Finally, C does not provide a mechanism to state that a parameter is going to be used as an additional return value, which makes the job of ensuring that a value is returned more difficult for the compiler. Still, not every routine with multiple return values should be required to return an error code, and error codes are easily ignored, so this is not a satisfying solution. As with the previous approach, this technique can simulate multiple return values, but in practice it is verbose and error prone.

C++ allows functions to return multiple values by extending the function declaration syntax. Multiple return values are declared as a comma-separated list of types in square brackets in the same location that the return type appears in standard C function declarations.

\[
[\text{char, int, double }] f(\ldots);
\]

The ability to return multiple values from a function requires a new syntax for the return statement. For consistency, the return statement in C++ accepts a comma-separated list of expressions in square brackets.

\[
\text{return } [c, i, d];
\]

The expression resolution ensures the correct form is used depending on the values being returned and the return type of the current function. A multiple-returning function with return type `T` can return any expression that is implicitly convertible to `T`.

A common use of a function’s output is input to another function. C++ allows this case, without any new syntax; a multiple-returning function can be used in any of the contexts where an expression is allowed. When a function call is passed as an argument to another call, the best match of actual arguments to formal parameters is evaluated given all possible expression interpretations in the current scope.
19.2 Expressions

In this case, there are two overloaded g routines. Both calls to g expect two arguments that are matched by the two return values from div and modl respectively, which are fed directly to the first and second parameters of g. As well, both calls to g have exact type matches for the two different versions of g, so these exact matches are chosen. When type matches are not exact, conversions are used to find a best match.

The previous examples can be rewritten passing the multiple returned-values directly to the printf function call.

```c
[ int, int ] div( int x, int y );        // from include stdlib
printf( "%d %d\n", div( 13, 5 ) );   // print quotient/remainder
```

```c
[ double, double ] modf( double x );    // from include math
printf( "%g %g\n", modf( 13.5 ) ); // print integral/fractional components
```

This approach provides the benefits of compile-time checking for appropriate return statements as in aggregation, but without the required verbosity of declaring a new named type.

Finally, the addition of multiple-return-value functions necessitates a syntax for retaining the multiple values at the call-site versus their temporary existence during a call. The simplest mechanism for retaining a return value in C is variable assignment. By assigning the multiple return-values into multiple variables, the values can be retrieved later.

As such, C allows assigning multiple values from a function into multiple variables, using a square-bracketed list of lvalue expressions on the left side.

```c
int quot, rem;
[ quot, rem ] = div( 13, 5 );          // assign multiple variables
printf( "%d %d\n", quot, rem );       // print quotient/remainder
```

Here, the multiple return-values are matched in much the same way as passing multiple return-values to multiple parameters in a call.

19.2 Expressions

Multiple-return-value functions provide C with a new syntax for expressing a combination of expressions in the return statement and a combination of types in a function signature. These notions are generalized to provide C with tuple expressions and tuple types. A tuple expression is an expression producing a fixed-size, ordered list of values of heterogeneous types. The type of a tuple expression is the tuple of the subexpression types, or a tuple type.

In C, a tuple expression is denoted by a comma-separated list of expressions enclosed in square brackets. For example, the expression [5, 'x', 10.5] has type [int, char, double]. The previous expression has 3 components. Each component in a tuple expression can be any C expression, including another tuple expression. The order of evaluation of the components in a tuple expression is unspecified, to allow a compiler the greatest flexibility for program optimization. It is, however, guaranteed that each component of a tuple expression is evaluated for side-effects, even if the result is not used. Multiple-return-value functions can equivalently be called tuple-returning functions.

19.3 Variables

The previous call of div still requires the preallocation of multiple return-variables in a manner similar to the aliasing example. In C, it is possible to overcome this restriction by declaring a tuple variable.

```c
[ int, int ] qr = div( 13, 5 );        // initialize tuple variable
printf( "%d %d\n", qr );             // print quotient/remainder
```

It is now possible to match the multiple return-values to a single variable, in much the same way as aggregation. As well, the components of the tuple value are passed as separate parameters to printf, allowing direct printing of tuple variables. One way to access the individual components of a tuple variable is with assignment.

```c
[ quot, rem ] = qr;                  // assign multiple variables
```

In addition to variables of tuple type, it is also possible to have pointers to tuples, and arrays of tuples. Tuple types can be composed of any types, except for array types, since array assignment is disallowed, which makes tuple assignment difficult when a tuple contains an array.

```c
[ double, int ] * pdi;
[ double, int ] * adi[10];
```

This examples declares a variable of type [double, int], a variable of type pointer to [double, int], and an array of ten [double, int].
19.4 Indexing

It is also possible to access a single component of a tuple-valued expression without creating temporary variables. Given a tuple-valued expression \( e \) and a compile-time constant integer \( i \) where \( 0 \leq i < n \), where \( n \) is the number of components in \( e \), \( e_i \) accesses the \( i^{th} \) component of \( e \), e.g.:

```c
[int, double] x;
[char *, int] f();
void g(double, int);
[int, double] * p;

int y = x.0; // access int component of x
y = f().1; // access int component of f
p->0 = 5; // access int component of tuple pointed-to by p
int f1(int, int);
g(x.1, x.0); // rearrange x to pass to g
double z = [x, f()].0.1; // access second component of first component of tuple expression
```

Tuple-index expressions can occur on any tuple-typed expression, including tuple-returning functions, square-bracketed tuple expressions, and other tuple-index expressions, provided the retrieved component is also a tuple. This feature was proposed for K-W C but never implemented [30, p. 45].

19.5 Flattening and Structuring

As evident in previous examples, tuples in \( C\) do not have a rigid structure. In function call contexts, tuples support implicit flattening and restructuring conversions. Tuple flattening recursively expands a tuple into the list of its basic components. Tuple structuring packages a list of expressions into a value of tuple type.

```c
int f(int, int);
int g([int, int]):
int h([int, [int, int]]);
[int, int] x;
int y;

f(x); // flatten
g(y, 10); // structure
h(x, y); // flatten & structure
```

In \( C\), each of these calls is valid. In the call to \( f \), \( x \) is implicitly flattened so that the components of \( x \) are passed as the two arguments to \( f \). For the call to \( g \), the values \( y \) and \( 10 \) are structured into a single argument of type \([int, int]\) to match the type of the parameter of \( g \). Finally, in the call to \( h \), \( x \) is flattened to yield an argument list of length 3, of which the first component of \( x \) is passed as the first parameter of \( h \), and the second component of \( x \) and \( y \) are structured into the second argument of type \([int, int]\). The flexible structure of tuples permits a simple and expressive function-call syntax to work seamlessly with both single- and multiple-return-value functions, and with any number of arguments of arbitrarily complex structure.

In K-W C [4, 30], there were 4 tuple coercions: opening, closing, flattening, and structuring. Opening coerces a nested tuple into a tuple of values, while closing converts a tuple of values into a single tuple value. Flattening coerces a nested tuple into a flat tuple, \( i.e. \), it takes a tuple with tuple components and expands it into a tuple with only non-tuple components. Structuring moves in the opposite direction, \( i.e. \), it takes a flat tuple value and provides structure by introducing nested tuple components.

In \( C\), the design has been simplified to require only the two conversions previously described, which trigger only in function call and return situations. This simplification is a primary contribution of this thesis to the design of tuples in \( C\). Specifically, the expression resolution algorithm examines all of the possible alternatives for an expression to determine the best match. In resolving a function call expression, each combination of function value and list of argument alternatives is examined. Given a particular argument list and function value, the list of argument alternatives is flattened to produce a list of non-tuple valued expressions. Then the flattened list of expressions is compared with each value in the function’s parameter list. If the parameter’s type is not a tuple type, then the current argument value is unified with the parameter type, and on success the next argument and parameter are examined. If the parameter’s type is a tuple type, then the structuring conversion takes effect, recursively applying the parameter matching algorithm using the tuple’s component types as the parameter list types. Assuming a successful unification, eventually the algorithm gets to the end of the tuple type, which causes all of the matching expressions to be consumed.
19.6 Assignment

An assignment where the left side of the assignment operator has a tuple type is called tuple assignment. There are two kinds of tuple assignment depending on whether the right side of the assignment operator has a non-tuple or tuple type, called mass and multiple assignment, respectively.

```c
int x;
double y;
[int, double] z;
[y, x] = 3.14; // mass assignment
[x, y] = z;   // multiple assignment
Z = 10;      // mass assignment
Z = [x, y];  // multiple assignment
```

Let $L_i$ for $i$ in $[0, n]$ represent each component of the flattened left side, $R_i$ represent each component of the flattened right side of a multiple assignment, and $R$ represent the right side of a mass assignment.

For a multiple assignment to be valid, both tuples must have the same number of elements when flattened. For example, the following is invalid because the number of components on the left does not match the number of components on the right.

```c
[int, int] x, y, z; // multiple assignment, invalid 4 != 2
```

Multiple assignment assigns $R_i$ to $L_i$ for each $i$. That is, $a=b=c$ in that conversions are applied to $R$ in each individual assignment, which prevents data loss from the chain of conversions that can happen during a cascading assignment. For example, $[y, x] = 3.14$ performs the assignments $y = 3.14$ and $x = 3.14$, which results in the value $3.14$ in $y$ and the value $3$ in $x$. On the other hand, the C cascading assignment $y = x = 3.14$ performs the assignments $x = 3.14$ and $y = x$, which results in the value $3$ in $x$, and as a result the value $3$ in $y$ as well.

Both kinds of tuple assignment have parallel semantics, such that each value on the left side and right side is evaluated before any assignments occur. As a result, it is possible to swap the values in two variables without explicitly creating any temporary variables or calling a function.

```c
int x = 10, y = 20;
[x, y] = [y, x];
```

After executing this code, $x$ has the value $20$ and $y$ has the value $10$.

In C', tuple assignment is an expression where the result type is the type of the left side of the assignment, as in normal assignment. That is, a tuple assignment produces the value of the left-hand side after assignment. These semantics allow cascading tuple assignment to work out naturally in any context where a tuple is permitted. These semantics are a change from the original tuple design in K-W C [30], wherein tuple assignment was a statement that allows cascading assignments as a special case. Restricting tuple assignment to statements was an attempt to fix what was seen as a problem with side-effects, wherein assignment can be used in many different locations, such as in function-call argument position. While permitting assignment as an expression does introduce the potential for subtle complexities, it is impossible to remove assignment expressions from C' without affecting backwards compatibility.

Furthermore, there are situations where permitting assignment as an expression improves readability by keeping code succinct and reducing repetition, and complicating the definition of tuple assignment puts a greater cognitive burden...
on the user. In another language, tuple assignment as a statement could be reasonable, but it would be inconsistent for tuple assignment to be the only kind of assignment that is not an expression. In addition, K-W C permits the compiler to optimize tuple assignment as a block copy, since it does not support user-defined assignment operators. This optimization could be implemented in C, but it requires the compiler to verify that the selected assignment operator is trivial.

The following example shows multiple, mass, and cascading assignments used in one expression

```c
int a, b;
double c, d;
[ void f( [ int, int ];
   f( [ c, a ] = [ b, d ] = 1.5 ); // assignments in parameter list

The tuple expression begins with a mass assignment of 1.5 into [b, d], which assigns 1.5 into b, which is truncated to 1, and 1.5 into d, producing the tuple [1, 1.5] as a result. That tuple is used as the right side of the multiple assignment (i.e., [c, a] = [1, 1.5]) that assigns 1 into c and 1.5 into a, which is truncated to 1, producing the result [1, 1]. Finally, the tuple [1, 1] is used as an expression in the call to f.
```

19.7 Construction

Tuple construction and destruction follow the same rules and semantics as tuple assignment, except that in the case where there is no right side, the default constructor or destructor is called on each component of the tuple. As constructors and destructors did not exist in previous versions of C or in K-W C, this is a primary contribution of this thesis to the design of tuples.

```c
struct S;
void ?{}(S *);
   // (1)
void ?{}(S *, int);
   // (2)
void ?{}(S * double);
   // (3)
void ?{}(S *, S);
   // (4)

[S, S] x = [3, 6.28]; // uses (2), (3), specialized constructors
[S, S] y;
   // uses (1), (1), default constructor
[S, S] z = x.0;
   // uses (4), (4), copy constructor
```

In this example, x is initialized by the multiple constructor calls ?{}(&x.0, 3) and ?{}(&x.1, 6.28), while y is initialized by two default constructor calls ?{}(&y.0) and ?{}(&y.1). z is initialized by mass copy constructor calls ?{}(&z.0, x.0) and ?{}(&z.1, x.0). Finally, x, y, and z are destructed, i.e., the calls ?{}(&x.0), ?{}(&x.1), ?{}(&y.0), ?{}(&y.1), ?{}(&z.0), and ?{}(&z.1).

It is possible to define constructors and assignment functions for tuple types that provide new semantics, if the existing semantics do not fit the needs of an application. For example, the function void ?{}([T, U] *, S) can be defined to allow a tuple variable to be constructed from a value of type S.

```c
struct S { [ int x; double y; ];
void ?{}([int, double] * this, S s) {
   this->0 = s.x;
   this->1 = s.y;
}
```

Due to the structure of generated constructors, it is possible to pass a tuple to a generated constructor for a type with a member prefix that matches the type of the tuple. For example,

```c
struct S { [ int x; double y; int z ];
   [int, double] t;
   S s = t;
```

The initialization of s with t works by default because t is flattened into its components, which satisfies the generated field constructor ?{}([S *, int, double]) to initialize the first two values.

19.8 Member-Access Expression

Tuples may be used to select multiple fields of a record by field name. The result is a single tuple-valued expression whose type is the tuple of the types of the members. For example,
A member-access tuple may be used anywhere a tuple can be used, e.g.:

```c
s.[y, z, x] = [3, 3.2, 'x'];  // equivalent to s.y = 3, s.z = 3.2
f(s.[y, z]);                  // equivalent to f(s.y, s.z)
```

Note, the fields appearing in a record-field tuple may be specified in any order; also, it is unnecessary to specify all the fields of a struct in a multiple record-field tuple.

Since tuple-index expressions are a form of member-access expression, it is possible to use tuple-index expressions in conjunction with member-access expressions to restructure a tuple (e.g., rearrange components, drop components, duplicate components, etc.).

```c
[ int, int, long, double ] x;
void f( double, long );
```

```c
f(x.[0, 3]);                     // f(x.0, x.3)
x.[0, 1] = x.[1, 0];             // [x.0, x.1] = [x.1, x.0]
```

It is possible for a member tuple expression to contain other member access expressions, e.g.:

```c
struct A { double i; int j;};
struct B { int * k; short l;};
struct C { int x; A y; B z; } v;
v.[x, y.[i, j], z.k];
```

This expression is equivalent to [v.x, [v.y.i, v.y.j], v.z.k]. That is, the aggregate expression is effectively distributed across the tuple allowing simple and easy access to multiple components in an aggregate without repetition. It is guaranteed that the aggregate expression to the left of the . in a member tuple expression is evaluated exactly once. As such, it is safe to use member tuple expressions on the result of a function with side-effects.

```c
[ int, float, double ] f();
[ double, float ] x = f().[2, 1];   // f() called once
```

In K-W C, member tuple expressions are known as record field tuples [30]. Since C/ permits these tuple-access expressions using structures, unions, and tuples, member tuple expression or field tuple expression is more appropriate.

### 19.9 Casting

In C, the cast operator is used to explicitly convert between types. In C/, the cast operator has a secondary use, which is type ascription, since it forces the expression resolution algorithm to choose the lowest cost conversion to the target type. That is, a cast can be used to select the type of an expression when it is ambiguous, as in the call to an overloaded function.

```c
int f();                     // (1)
double f();                  // (2)
f();                        // ambiguous - (1),(2) both equally viable
(int)f();                   // choose (2)
```

Since casting is a fundamental operation in C/, casts need to be given a meaningful interpretation in the context of tuples. Taking a look at standard C provides some guidance with respect to the way casts should work with tuples.

```c
int f();                     // (1)
void g();
(int)g();                   // invalid, void cannot be converted to int
(struct A)f();              // invalid, int cannot be converted to A
```
In C, line 4 is a valid cast, which calls f and discards its result. On the other hand, line 5 is invalid, because g does not produce a result, so requesting an int to materialize from nothing is nonsensical. Finally, line 8 is also invalid, because in C casts only provide conversion between scalar types [20, p. 91]. For consistency, this implies that any case wherein the number of components increases as a result of the cast is invalid, while casts that have the same or fewer number of components may be valid.

Formally, a cast to tuple type is valid when $T_n \leq S_m$, where $T_n$ is the number of components in the target type and $S_m$ is the number of components in the source type, and for each $i$ in $[0, n)$, $S_i$ can be cast to $T_i$. Excess elements ($S_j$ for all $j$ in $[n, m)$) are evaluated, but their values are discarded so that they are not included in the result expression. This discarding naturally follows the way that a cast to void works in C.

For example,

```c
[int, int, int] f();
[int, [int, int], int] g();
```

(1) discards the last element of the return value and converts the second element to type double. Since int is effectively a 1-element tuple, (2) discards the second component of the second element of the return value of g. If g is free of side effects, this is equivalent to $[(\text{int})(\text{g}().0), (\text{int})(\text{g}().1.0), (\text{int})(\text{g}().2)]$. Since void is effectively a 0-element tuple, (3) discards the first and third return values, which is effectively equivalent to $[(\text{int})(\text{g}().1.0), (\text{int})(\text{g}().1.1)]$. Note that a cast is not a function call in C, so flattening and structuring conversions do not occur for cast expressions. As such, (4) is invalid because the cast target type contains 4 components, while the source type contains only 3. Similarly, (5) is invalid because the cast $[(\text{int}, \text{int}, \text{int})](\text{g}().1)$ is invalid. That is, it is invalid to cast $\text{int, int}$ to $\text{int, int, int}$.

### 19.10 Polymorphism

Due to the implicit flattening and structuring conversions involved in argument passing, dtype and dtype parameters are restricted to matching only with non-tuple types. The integration of polymorphism, type assertions, and monomorphic specialization of tuple-assertions are a primary contribution of this thesis to the design of tuples.

```c
forall(T, dtype U)
void f(T x, U * y);
```

```c
f(5, "hello");
```

In this example, [5, "hello"] is flattened, so that the argument list appears as 5, "hello". The argument matching algorithm binds T to int and U to const char, and calls the function as normal.

Tuples can contain polymorphic types. For example, a plus operator can be written to add two triples of a type together.

```c
forall(T | (T ?+?(T, T));)
  return [x.0+y.0, x.1+y.1, x.2+y.2];
}
```

```c
[int, int, int] x;
int i1, i2, i3;
[i1, i2, i3] = x + ([10, 20, 30]);
```

Note that due to the implicit tuple conversions, this function is not restricted to the addition of two triples. A call to this plus operator type checks as long as a total of 6 non-tuple arguments are passed as flattening, and all of the arguments have a common type that can bind to T, with a pairwise ?+? over T. For example, these expressions also succeed and produce the same value.

```c
([x.0, x.1]) + ([x.2, 10, 20, 30]); // x + ([10, 20, 30])
x.0 + ([x.1, x.2, 10, 20, 30]); // x + ([10, 20, 30])
```

This presents a potential problem if structure is important, as these three expressions look like they should have different meanings. Furthermore, these calls can be made ambiguous by introducing seemingly different functions.
It is also important to note that these calls could be disambiguated if the function return types were different, as they likely would be for a reasonable implementation of \(?+?\), since the return type is used in overload resolution. Still, these semantics are a deficiency of the current argument matching algorithm, and depending on the function, differing return values may not always be appropriate. These issues could be rectified by applying an appropriate conversion cost to the structuring and flattening conversions, which are currently 0-cost conversions in the expression resolver. Care would be needed in this case to ensure that exact matches do not incur such a cost.

\begin{verbatim}
void f([int, int], int, int);

f([0, 0], 0, 0); // no cost
f(0, 0, 0); // cost for structuring
f([0, 0], [0, 0]); // cost for flattening
f([0, 0, 0], 0); // cost for flattening and structuring
\end{verbatim}

Until this point, it has been assumed that assertion arguments must match the parameter type exactly, modulo polymorphic specialization (i.e., no implicit conversions are applied to assertion arguments). This decision presents a conflict with the flexibility of tuples.

\subsection{Assertion Inference}

If assertion arguments must match exactly, then the call to \(g\) cannot be resolved, since the expected type of \(f\) is flat, while the only \(f\) in scope requires a tuple type. Since tuples are fluid, this requirement reduces the usability of tuples in polymorphic code. To ease this pain point, function parameter and return lists are flattened for the purposes of type unification, which allows the previous example to pass expression resolution.

This relaxation is made possible by extending the existing thunk generation scheme, as described by Bilson [1]. Now, whenever a candidate’s parameter structure does not exactly match the formal parameter’s structure, a thunk is generated to specialize calls to the actual function.

\begin{verbatim}
int thunk(int p0, double p1, double p2) {
  return f([p0, p1], p2);
}
\end{verbatim}

Essentially, this provides flattening and structuring conversions to inferred functions, improving the compatibility of tuples and polymorphism.

\section{Tuples}

In C and CV, lists of elements appear in several contexts, such as the parameter list for a routine call. (More contexts are added shortly.) A list of such elements is called a \textit{lexical list}. The general syntax of a lexical list is:

\begin{verbatim}
[ exprlist ]
\end{verbatim}

where $\texttt{exprlist}$ is a list of one or more expressions separated by commas. The brackets, [], allow differentiating between lexical lists and expressions containing the C comma operator. The following are examples of lexical lists:

\begin{verbatim}
[ x, y, z ]
[ 2 ]
[ v+w, x*y, 3.14159, f() ]
\end{verbatim}

Tuples are permitted to contain sub-tuples (i.e., nesting), such as \([ [ 14, 21 ], 9 ]\), which is a 2-element tuple whose first element is itself a tuple. Note, a tuple is not a record (structure); a record denotes a single value with substructure, whereas a tuple is multiple values with no substructure (see flattening coercion in Section 19.5, p. 34). In essence, tuples are largely a compile time phenomenon, having little or no runtime presence.

Tuples can be organized into compile-time tuple variables; these variables are of \textit{tuple type}. Tuple variables and types can be used anywhere lists of conventional variables and types can be used. The general syntax of a tuple type

\begin{verbatim}
forall(T | { T ?+?(T, T); })
[T, T, T] ?+?([T, T] x, [T, T, T, T]);
forall(T | { T ?+?(T, T); })
[T, T, T] ?+?(T x, [T, T, T, T, T]);
\end{verbatim}
is:

\[
\begin{array}{ll}
\text{[ typelist ]} \\
\text{where } \texttt{typelist} \text{ is a list of one or more legal C or C type specifications separated by commas, which may}
\end{array}
\]

include other tuple type specifications. Examples of tuple types include:

\[
\begin{array}{ll}
\text{[ unsigned int, char ]} \\
\text{[ double, double, double ]} \\
\text{[ \cdot int, int \cdot ]} & \text{ // mix of CFA and ANSI} \\
\text{[ \cdot [5] int, \cdot \cdot char, \cdot [ [int, int] ] [int, int] ]} \\
\end{array}
\]

Like tuples, tuple types may be nested, such as \([ [int, int], int] \), which is a 2-element tuple type whose first element is itself a tuple type.

Examples of declarations using tuple types are:

\[
\begin{array}{ll}
\text{[ int, int ] x;} & \text{ // 2 element tuple, each element of type int} \\
\text{[ \cdot char, char \cdot ] y;} & \text{ // pointer to a 2 element tuple} \\
\text{[ [ int, int ] ] z [ [ int, int ] ];} \\
\end{array}
\]

The last example declares an external routine that expects a 2 element tuple as an input parameter and returns a 2 element tuple as its result.

As mentioned, tuples can appear in contexts requiring a list of value, such as an argument list of a routine call. In unambiguous situations, the tuple brackets may be omitted, e.g., a tuple that appears as an argument may have its square brackets omitted for convenience; therefore, the following routine invocations are equivalent:

\[
\begin{array}{ll}
f([1, x+2, \text{fred()} ]); \\
f(1, x+2, \text{fred}()); \\
\end{array}
\]

Also, a tuple or a tuple variable may be used to supply all or part of an argument list for a routine expecting multiple input parameters or for a routine expecting a tuple as an input parameter. For example, the following are all legal:

\[
\begin{array}{ll}
\text{[ int, int ] w1;} \\
\text{[ int, int, int ] w2;} \\
\text{[ void ] f (int, int,int);} & \text{ // three input parameters of type int} \\
\text{[ void ] g ([int, int, int]);} & \text{ 3 element tuple as input} \\
\text{f([1, 2, 3]);} \\
\text{f(w1, 3);} \\
\text{f(1, w1);} \\
\text{f(w2);} \\
\text{g([1, 2, 3]);} \\
\text{g(w1, 3);} \\
\text{g(1, w1);} \\
\text{g(w2);} \\
\end{array}
\]

Note, in all cases 3 arguments are supplied even though the syntax may appear to supply less than 3. As mentioned, a tuple does not have structure like a record; a tuple is simply converted into a list of components.

The present implementation of C\(\nu\) does not support nested routine calls when the inner routine returns multiple values; i.e., a statement such as \(g(f())\) is not supported. Using a temporary variable to store the results of the inner routine and then passing this variable to the outer routine works, however.

A tuple can contain a C comma expression, provided the expression containing the comma operator is enclosed in parentheses. For instance, the following tuples are equivalent:

\[
\begin{array}{ll}
\text{[ 1, 3, 5 ]} \\
\text{[ 1, (2, 3), 5 ]} \\
\end{array}
\]

The second element of the second tuple is the expression \((2, 3)\), which yields the result 3. This requirement is the same as for comma expressions in argument lists.

Type qualifiers, i.e., \texttt{const} and \texttt{volatile}, may modify a tuple type. The meaning is to distribute the qualifier across all of the types in the tuple, e.g.:

\[
\begin{array}{ll}
\text{const volatile [ int, float, const int ] } x; \\
\end{array}
\]

is equivalent to:

\[
\begin{array}{ll}
\text{[ const volatile int, const volatile float, const volatile int ] } x; \\
\end{array}
\]

Declaration qualifiers can only appear at the start of a C\(\nu\) tuple declaration, e.g.,

\[
\begin{array}{ll}
\end{array}
\]
20.1 Tuple Coercions

There are four coercions that can be performed on tuples and tuple variables: closing, opening, flattening and structuring. In addition, the coercion of dereferencing can be performed on a tuple variable to yield its value(s), as for other variables. A closing coercion takes a set of values and converts it into a tuple value, which is a contiguous set of values, as in:

```c
[ int, int, int, int ] w;
```

```c
w = [ 1, 2, 3, 4 ];
```

First the right-hand tuple is closed into a tuple value and then the tuple value is assigned.

An opening coercion is the opposite of closing; a tuple value is converted into a tuple of values, as in:

```c
[ a, b, c, d ] = w
```

w is implicitly opened to yield a tuple of four values, which are then assigned individually.

A flattening coercion coerces a nested tuple, i.e., a tuple with one or more components, which are themselves tuples, into a flattened tuple, which is a tuple whose components are not tuples, as in:

```c
[ a, b, c, d ] = [ [ 1, 2, 3 ], 4 ];
```

First the right-hand tuple is flattened and then the values are assigned individually. Flattening is also performed on tuple types. For example, the type [ int, [ int, int ] ] can be coerced, using flattening, into the type [ int, int, int, int ],

A structuring coercion is the opposite of flattening; a tuple is structured into a more complex nested tuple. For example, structuring the tuple [ 1, 2, 3, 4 ] into the tuple [ 1, [ 2, 3 ], 4 ] or the tuple type [ int, int, int, int ] into the tuple type [ int, [ int, int ], int ]. In the following example, the last assignment illustrates all the tuple coercions:

```c
[ int, int, int, int ] w = [ 1, 2, 3, 4 ];
```

```c
int x = 5;
```

```c
[ x, w ] = [ w, x ];  // all four tuple coercions
```

Starting on the right-hand tuple in the last assignment statement, w is opened, producing a tuple of four values; therefore, the right-hand tuple is now the tuple [ [ 1, 2, 3, 4 ], 5 ]. This tuple is then flattened, yielding [ 1, 2, 3, 4, 5 ], which is structured into [ 1, [ 2, 3, 4, 5 ] ] to match the tuple type of the left-hand side. The tuple [ 2, 3, 4, 5 ] is then closed to create a tuple value. Finally, x is assigned 1 and w is assigned the tuple value using multiple assignment (see Section 19.6, p. 35).

A possible additional language extension is to use the structuring coercion for tuples to initialize a complex record with a tuple.

20.2 Mass Assignment

C allows assignment to several variables at once using mass assignment [24]. Mass assignment has the following form:

```c
[ lvalue, ... , lvalue ] = expr;
```

The left-hand side is a tuple of lvalues, which is a list of expressions each yielding an address, i.e., any data object that can appear on the left-hand side of a conventional assignment statement. Any arithmetic expression. Clearly, the types of the entities being assigned must be type compatible with the value of the expression. Mass assignment has parallel semantics, e.g., the statement:

```c
[ x, y, z ] = 1.5;
```

is equivalent to:

```c
x = 1.5; y = 1.5; z = 1.5;
```

This semantics is not the same as the following in C:

```c
extern [ int, int ] w1;
static [ int, int, int ] w2;

Unfortunately, C's syntax for subscripts precluded treating them as tuples. The C subscript list has the form [i][j]... and not [i, j, ...]. Therefore, there is no syntactic way for a routine returning multiple values to specify the different subscript values, e.g., f[g()] always means a single subscript value because there is only one set of brackets. Fixing this requires a major change to C because the syntactic form M[i, j, k] already has a particular meaning: i, j, k is a comma expression.

A possible additional language extension is to use the structuring coercion for tuples to initialize a complex record with a tuple.
as conversions between intermediate assignments may lose information. A more complex example is:

\[ \text{int } x = y = z = 1.5; \]

\[ [i, y[i], z] = a + b; \]

which is equivalent to:

\[ t = a + b; \]
\[ a1 = \&i; a2 = \&y[i]; a3 = \&z; \]
\[ *a1 = t; *a2 = t; *a3 = t; \]

The temporary \( t \) is necessary to store the value of the expression to eliminate conversion issues. The temporaries for the addresses are needed so that locations on the left-hand side do not change as the values are assigned. In this case, \( y[i] \) uses the previous value of \( i \) and not the new value set at the beginning of the mass assignment.

### 20.3 Multiple Assignment

\( \text{CV} \) also supports the assignment of several values at once, known as multiple assignment [24, 15]. Multiple assignment has the following form:

\[ \text{[lvalue, ..., lvalue]} = \text{[expr, ..., expr]}; \]

The left-hand side is a tuple of \( \text{lvalues} \), and the right-hand side is a tuple of \( \text{exprs} \). Each \( \text{expr} \) appearing on the right-hand side of a multiple assignment statement is assigned to the corresponding \( \text{lvalues} \) on the left-hand side of the statement using parallel semantics for each assignment. An example of multiple assignment is:

\[ [x, y, z] = [1, 2, 3]; \]

Here, the values 1, 2 and 3 are assigned, respectively, to the variables \( x, y \) and \( z \). A more complex example is:

\[ [i, y[i], z] = [1, i, a + b]; \]

Here, the values 1, \( i \) and \( a + b \) are assigned to the variables \( i, y[i] \) and \( z \), respectively. Note, the parallel semantics of multiple assignment ensures:

\[ [x, y] = [y, x]; \]

correctly interchanges (swaps) the values stored in \( x \) and \( y \). The following cases are errors:

\[ [a, b, c] = [1, 2, 3, 4]; \]
\[ [a, b, c] = [1, 2]; \]

because the number of entities in the left-hand tuple is unequal with the right-hand tuple.

As for all tuple contexts in C, side effects should not be used because C does not define an ordering for the evaluation of the elements of a tuple; both these examples produce indeterminate results:

\[ f(x++, x++); \] // C routine call with side effects in arguments
\[ [v1, v2] = [x++, x++]; \] // side effects in right-hand side of multiple assignment

### 20.4 Cascade Assignment

As in C, \( \text{CV} \) mass and multiple assignments can be cascaded, producing cascade assignment. Cascade assignment has the following form:

\[ \text{tuple = tuple = ... = tuple}; \]

and it has the same parallel semantics as for mass and multiple assignment. Some examples of cascade assignment are:

\[ x1 = y1 = x2 = y2 = 0; \]
\[ [x1, y1] = [x2, y2] = [x3, y3]; \]
\[ [x1, y1] = [x2, y2] = 0; \]
\[ [x1, y1] = z = 0; \]

As in C, the rightmost assignment is performed first, \( i.e. \), assignment parses right to left.

### 21 Stream I/O Library

The goal of \( \text{CV} \) stream input/output (I/O) is to simplify the common cases, while fully supporting polymorphism and user defined types in a consistent way. Stream I/O can be implicitly or explicitly formatted. Implicit formatting means \( \text{CV} \) selects the output or input format for values that matches the variable’s type. Explicit formatting means additional
information is specified to augment how an output or input of value is interpreted. CV formatting incorporates ideas from C printf, C++ stream manipulators, and Python implicit spacing and newline. Specifically:

- print/Python format codes are dense, making them difficult to read and remember. CV/C++ format manipulators are named, making them easier to read and remember.
- print/Python separates format codes from associated variables, making it difficult to match codes with variables.
- CV/C++ co-locate codes with associated variables, where CV has the tighter binding.
- Format manipulators in CV have local effect, whereas C++ have global effect, except setw. Hence, it is common programming practice to toggle manipulators on and then back to the default to prevent downstream side-effects. Without this programming style, errors occur when moving prints, as manipulator effects incorrectly flow into the new location. Furthermore, to guarantee no side-effects, manipulator values must be saved and restored across function calls.
- CV has more sophisticated implicit value spacing than Python, plus implicit newline at the end of a print.

The standard polymorphic I/Os stream are stdin/sin (input), stdout/sout and stderr/serr (output) (like C++ cin/cout/cerr).

Polymorphic streams exit and abort provide implicit program termination without and with generating a stack trace and core file. Stream exit implicitly returns EXIT_FAILURE to the shell.

```
exit | "x (" | x | ") negative value."; // terminate and return EXIT_FAILURE to shell
abort | "x (" | x | ") negative value."; // terminate and generate stack trace and core file
```

Note, CV stream variables stdin, stdout, stderr, exit, and abort overload C variables stdin, stdout, stderr, and functions exit and abort, respectively. The CV header file for the I/O library is fstream.h.

## 21.1 Basic I/O

For implicit formatted output, the common case is printing a series of variables separated by whitespace.

```
// CV
int x = 1, y = 2, z = 3;
std::cout << x << " " << y << " " << z << "endl; // print (x,y,z)

// C++
scanf("%d %d %d", &x, &y, &z);

// Python
print(x, y, z)
```

The CV form has half the characters of the C++ form, and is similar to Python I/O with respect to implicit separators and newline. Similar simplification occurs for tuple I/O, which flattens the tuple and prints each value separated by comma space.

```
// CV
std::cout | x | y | z;

// C++
scanf("%d %d %d", &x, &y, &z);

// Python
print(x, y, z)
```

```
[ int, [ int, int ] ] t1 = [ 1, [ 2, 3 ] ], t2 = [ 4, [ 5, 6 ] ];

// CV
std::cout | t1 | t2;

// C++
sout | t1 | t2;

// Python
print(t1, t2)
```

Finally, CV uses the logical-or operator for I/O as it is the lowest-priority overloader operator, other than assignment.

Therefore, fewer output expressions require parenthesis.

```
// CV: std::cout | x * 3 | y + 1 | z << 2 | x == y | (x | y) | (x || y) | (x > z ? 1 : 2);

// C++: std::cout | x * 3 | y + 1 | z << 2 | (x == y) | (x | y) | (x || y) | (x > z ? 1 : 2)

// Python
print(x * 3, y + 1, z << 2, x == y, x | y, x | y, x > z ? 1 : 2)
```

There is a weak similarity between the CV logical-or operator and the Shell pipe-operator for moving data, where data flows in the correct direction for input but the opposite direction for output. Input and output use a uniform operator, |, rather than C++’s << and >> input/output operators, which prevents this common error in C++:

```
cin << i; // why is this generating a lot of error messages?
```

For implicit formatted input, the common case is reading a sequence of values separated by whitespace, where the type of an input constant must match with the type of the input variable.

```
// CV
int x; double y; char z;

// C++
scanf("%d %f %c", &x, &y, &z);

// Python
x = int(input()); y = float(input()); z = input();
```
#include <fstream.h>

int main(int argc, char * argv[]) {
    ifstream in = stdin; // copy default files
    ofstream out = stdout;
    try {
        choose(argc) {
            case 2, 3:
                open(in, argv[1]); // open input file first as output creates file
                if (argc == 3) open(out, argv[2]); // do not create output unless input opens
            case 1: ; // use default files
                default:
                    exit("Usage" | argv[0]| "{ [ input-file (default stdin) "
                                "[ output-file (default stdout) ] ] ");
            } // choose
            } catch(open_failure * ex; ex>istream == &in) { // input file errors
                exit("Unable to open input file" | argv[1];
            } catch(open_failure * ex; ex>ostream == &out) { // output file errors
                close(in); // optional
                exit("Unable to open output file" | argv[2];
            } // try
            out | nlOff; // turn off auto newline
            in | nlOn; // turn on reading newline
            char ch;
            for () { // read/write characters
                in | ch;
                if (eof(in) ) break; // eof ?
                out | ch;
            } // for
        } // main
    }

Figure 5: CÆ Command-Line Processing

Figure 5 shows idiomatic CÆ command-line processing and copying an input file to an output file. Note, a stream variable may be copied because it is a reference to an underlying stream data-structures. All I/O errors are handles as exceptions, but end-of-file is not an exception as C programmers are use to explicitly checking for it.

Figure 6 shows the stream operations.

• fail tests the stream error-indicator, returning nonzero if it is set.
• clear resets the stream error-indicator.
• flush (ofstream only) causes any unwritten data for a stream to be written to the file.
• eof (ifstream only) tests the end-of-file indicator for the stream pointed to by stream. Returns true if the end-of-file indicator is set, otherwise false.
• open binds the file with name to a stream accessed with mode (see fopen).
• close flushes the stream and closes the file.
• write (ofstream only) writes size bytes to the stream. The bytes are written lazily when an internal buffer fills. Eager buffer writes are done with flush
• read (ifstream only) reads size bytes from the stream.
• ungetc (ifstream only) pushes the character back to the input stream. Pushed-back characters returned by subsequent reads in the reverse order of pushing.

The constructor functions:

• create an unbound stream, which is subsequently bound to a file with open.
• create a bound stream to the associated file with given mode.
21.2 Implicit Separator

The implicit separator character (space/blank) is a separator not a terminator for output. The rules for implicitly adding the separator are:

1. A separator does not appear at the start or end of a line.
   ```cpp
   sout | 1 | 2 | 3;
   1 2 3
   ``

2. A separator does not appear before or after a character literal or variable.
   ```cpp
   sout | '1' | '2' | '3';
   123
   ``

3. A separator does not appear before or after a null (empty) C string, which is a local mechanism to disable insertion of the separator character.
   ```cpp
   sout | 1 | " | 2 | " | 3;
   123
   ``

4. A separator does not appear before a C string starting with the (extended) ASCII characters: ` ere ! ? } ] \ _ ^ \" where ` is a closing citation mark.
   ```cpp
   sout | 1 | " | x" | 2 | " . x" | 3 | " ; | x" | 4 | ! | x" | 5 | ? | x" | 6 | " | x" |
   7 | " | x | 8 | " | x" | 9 | " | x" | 10 | " | x" | 11 | " | x"
   123
   ``

5. A separator does not appear after a C string ending with the (extended) ASCII characters: ` ere ! ? } ] \ _ ^ \" where ` is inverted opening exclamation and question marks, and ` is an opening citation mark.
   ```cpp
   sout | "x " | 1 | "x " | 2 | "x " | 3 | "x " | 4 | "x " | 5 | "x " | 6 | "x " |
   7 | "x " | 8 | "x " | 9 | "x " | 10;
   ```

The destructor closes the stream.
21.3 Separation Manipulators

The following manipulators control implicit output separation. The effect of these manipulators is global for an output stream (except `sep` and `nosep`).

1. `sepSet` and `sepVal`/`sepGet` set and get the separator string. The separator string can be at most 16 characters including the `\0` string terminator (15 printable characters).

   ```
   sepSet( sout, "", ");  // set separator from " " to " 
   sout [1] [2] [3] " ";  // get separator
   1 "2 3"
   ```

   `sepGet` can be used to store a separator and then restore it:

   ```
   char store[sepSize];  // sepSize is the maximum separator size
   strcpy( store, sepGet( sout ) );  // copy current separator
   sepSet( sout, "_\"\"\" );  // change separator to underscore
   sout [1] [2] [3];  // get separator
   1 "2 3"
   ```

2. `sepTupleSet` and `sepTupleVal`/`sepTupleGet` set and get the tuple separator-string. The tuple separator-string can be at most 16 characters including the `\0` string terminator (15 printable characters).

   ```
   sepTupleSet( sout, "\"\"\"\" );  // set tuple separator from " " to " "
   1 "2 3"
   ```

   As for `sepGet`, `sepTupleGet` can be used to store a tuple separator and then restore it.

3. `sepOff` and `sepOn` globally toggle printing the separator.

   ```
   sout [1] [2] [3];  // turn off implicit separator
   123
   ```

4. `sep` and `nosep` locally toggle printing the separator with respect to the next printed item, and then return to the global separator setting.

   ```
   sout [1] [nosep] [2] [3];  // turn off implicit separator for the next item
   123
   ```

   ```
   sout [1] [sep] [2] [3];  // turn on implicit separator for the next item
   123
   ```
21.4 Newline Manipulators

The tuple separator also responds to being turned on and off.

```plaintext
sout | t1 | nosep | t2;  // turn off implicit separator for the next item
1, 2, 34, 5, 6
```

Use `sep` to accomplish this functionality.

```plaintext
sout | t1 | nosep | t2;
// turn off implicit separator for the next item
1, 2, 3
```

```
sep cannot be used to start/end a line with a separator because separators do not appear at the start/end of a line.
```

Use `sep` to accomplish this functionality.

```plaintext
sout | sep | 1 | 2 | 3 | sep;
// sep does nothing at start/end of line
```

```plaintext
sout | sepVal | 1 | 2 | 3 | sepVal;
// use sepVal to print separator at start/end of line
```

21.4 Newline Manipulators

The following manipulators control newline separation for input and output.

For input:

1. `nlOn` reads the newline character, when reading single characters.
2. `nlOff` does not read the newline character, when reading single characters.
3. `nl` scans characters until the next newline character, *i.e.*, ignore the remaining characters in the line. If `nlOn` is enabled, the `nl` is also consumed.

For example, in:

```plaintext
sin | i | nl | j;
```

variable `i` is assigned 1, the 2 is skipped, and variable `j` is assigned 3.

For output:

1. `nlOn` implicitly prints a newline at the end of each output expression.
2. `nlOff` does not implicitly print a newline at the end of each output expression.
3. `nl` inserts a newline.

```plaintext
sout | nl;  // only print newline
sout | 2;  // implicit newline
sout | 3 | nl | 4 | nl;  // terminating nl merged with implicit newline
sout | 5 | nl | nl;  // again terminating nl merged with implicit newline
sout | 6;  // implicit newline
```

2
3
4
5
6

Note, a terminating `nl` is merged with (overrides) the implicit newline at the end of the `sout` expression, otherwise it is impossible to print a single newline

21.5 Output Value Manipulators

The following manipulators control formatting (printing) of the argument output values.

1. `bin( integer )` print value in base 2 preceded by `0b/0B`.

```plaintext
sout | bin( 0 ) | bin( 27HH ) | bin( 27H ) | bin( 27 ) | bin( 27L );
0b0 0b11011 0b11011 0b11011 0b11011
```

```plaintext
sout | bin( -27HH ) | bin( -27H ) | bin( -27 ) | bin( -27L );
0b111111111111111111111111111111101 0b(58 1s)100101
```

2. `oct( integer )` print value in base 8 preceded by 0.

```plaintext
sout | oct( 0 ) | oct( 27HH ) | oct( 27H ) | oct( 27 ) | oct( 27L );
0 033 033 033 033
```

```plaintext
sout | oct( -27HH ) | oct( -27H ) | oct( -27 ) | oct( -27L );
```
3. **hex(integer/floating-point)** print value in base 16 preceded by 0x/0X.

```
sout | hex( 0 ) | hex( 27HH ) | hex( 27H ) | hex( 27 ) | hex( 27L );
0x0 0x1b 0x1b 0x1b 0x1b
sout | hex( −27HH ) | hex( −27H ) | hex( −27 ) | hex( −27L );
0xe5 0xffe5 0xffffffe5 0xffffffffffffffe5
```

4. **sci(floating-point)** print value in scientific notation with exponent. Default is 6 digits of precision.

```
sout | sci( 0.0 ) | sci( 27.5 ) | sci( −27.5 );
0.000000e+00 2.750000e+01
```

5. **eng(floating-point)** print value in engineering notation with exponent, which means the exponent is adjusted to a multiple of 3.

```
sout | eng( 0.0 ) | eng( 27000.5 ) | eng( −27.5e7 );
0 27.0005M −275M
```

6. **unit(engineering-notation)** print engineering exponent as a letter between the range $10^{-24}$ and $10^{24}$:

- $z \Rightarrow 10^{-24}$
- $z \Rightarrow 10^{-21}$
- $x \Rightarrow 10^{-18}$
- $x \Rightarrow 10^{-15}$
- $x \Rightarrow 10^{-12}$
- $x \Rightarrow 10^{-9}$
- $x \Rightarrow 10^{-6}$
- $x \Rightarrow 10^{-3}$
- $x \Rightarrow 10^3$
- $x \Rightarrow 10^6$
- $x \Rightarrow 10^9$
- $x \Rightarrow 10^{12}$
- $x \Rightarrow 10^{15}$
- $x \Rightarrow 10^{18}$
- $x \Rightarrow 10^{21}$
- $x \Rightarrow 10^{24}$

```
sout | unit(eng( 0.0 )) | unit(eng( 27000.5 )) | unit(eng( −27.5e7 ));
0 27.0005K −275M
```

7. **upcase(bin/hex/floating-point)** print letters in a value in uppercase. Lower case is the default.

```
sout | upcase( bin( 27 ) ) | upcase( hex( 27 ) ) | upcase( 27.5e10 ) | upcase( hex( 27.5 ) );
0B11011 0X1B.27E−09 0X1.B8F+4
```

8. **nobase(integer)** do not precede bin, oct, hex with 0b/0B, 0, or 0x/0X. Printing the base is the default.

```
sout | nobase( bin( 27 ) ) | nobase( oct( 27 ) ) | nobase( hex( 27 ) );
11011 33 1b
```

9. **nodp(floating-point)** do not print a decimal point if there are no fractional digits. Printing a decimal point is the default, if there are no fractional digits.

```
sout | 0. | nodp( 0. ) | 27.0 | nodp( 27.0 ) | nodp( 27.5 );
0.0 27.0 27.5
```

10. **sign(integer/floating-point)** prefix with plus or minus sign (+ or −). Only printing the minus sign is the default.

```
sout | sign( 27 ) | sign( −27 ) | sign( 27. ) | sign( −27. ) | sign( 27.5 ) | sign( −27.5 );
+27 −27 +27.0 −27.0 +27.5 −27.5
```

11. **wd(minimum, value), wd(minimum, precision, value)** For all types, minimum is the number of printed characters. If the value is shorter than the minimum, it is padded on the right with spaces.

```
sout | wd( 4, 34 ) | wd( 3, 34 ) | wd( 2, 34 );
sout | wd( 10, 4. ) | wd( 9, 4. ) | wd( 8, 4. );
sout | wd( 4, "ab" ) | wd( 3, "ab" ) | wd( 2, "ab" );

```

```
0.000000 4.000000 4.000000
```

```
If the value is larger, it is printed without truncation, ignoring the minimum.
```

```
sout | wd( 4, 34567 ) | wd( 3, 34567 ) | wd( 2, 34567 );
sout | wd( 4, 3456. ) | wd( 3, 3456. ) | wd( 2, 3456. );
sout | wd( 4, "abcdef" ) | wd( 3, "abcdef" ) | wd( 2, "abcdef" );
34567 34567 34567 34567
3456 3456 3456.
```

```
abcdefghijklmnopqrstuvwxyz
```
For integer types, precision is the minimum number of printed digits. If the value is shorter, it is padded on the left with leading zeros.

```c
sout | wd( 4.3, 34 ) | wd( 8.4, 34 ) | wd( 10.10, 34 );
```

```
   03400034_000000034
```

If the value is larger, it is printed without truncation, ignoring the precision.

```c
sout | wd( 4.1, 3456 ) | wd( 8.2, 3456 ) | wd( 10.3, 3456 );
```

```
3456_3456_3456_3456
```

If precision is 0, nothing is printed for zero. If precision is greater than the minimum, it becomes the minimum.

```c
sout | wd( 4.0, 0 ) | wd( 3.10, 34 );
```

```
_00000000_0000
```

For floating-point types, precision is the minimum number of digits after the decimal point.

```c
sout | wd( 6.3, 27.5 ) | wd( 8.1, 27.5 ) | wd( 8.0, 27.5 ) | wd( 3.8, 27.5 );
```

```
3456_3456_3456_3456
```

For the C-string type, precision is the maximum number of printed characters, so the string is truncated if it exceeds the maximum.

```c
sout | wd( 6.3, "abcd") | wd( 6.8, "abcdefg hi j k") | wd( 6.3, "abcd") | wd( 10, """) | 'X';
```

```
_0_0_0_0_0_0X
```

Note, printing the null string with minimum width L pads with L spaces.

12. ws (minimum, significant, floating-point) For floating-point types, minimum is the same as for manipulator \texttt{wd}, but significant is the maximum number of significant digits to be printed for both the integer and fractions (versus only the fraction for \texttt{wd}). If a value’s significant digits is greater than significant, the last significant digit is rounded up.

```c
sout | ws(6,6, 234567.) | ws(6,5, 234567.) | ws(6,4, 234567.) | ws(6,3, 234567.);
```

```
234567_234567_234567_234567
```

If a value’s magnitude is greater than significant, the value is printed in scientific notation with the specified number of significant digits.

```c
sout | ws(6.6, 234567.) | ws(6.5, 234567.) | ws(6.4, 234567.) | ws(6.3, 234567.);
```

```
234567_234567_234567_234567
```

If significant is greater than minimum, it defines the number of printed characters.

```c
sout | ws(3.6, 234567.) | ws(4.6, 234567.) | ws(5.6, 234567.) | ws(6.6, 234567.);
```

```
234567_234567_234567_234567
```

13. \texttt{left(field-width)} left justify within the given field.

```c
sout | left(1d(34), 27) | left(1d(10, 27.5)) | left(1d(4.3, 27)) | left(1d(10,3.27.5));
```

```
27_27.000000_27.500000_027_27.500000
```

14. \texttt{pad0(field-width)} left pad with zeroes (0).

```c
sout | pad0( 1d(4, 27) ) | pad0( 1d(4.3, 27) ) | pad0( 1d(8.3, 27.5) );
```

```
0027 027 027.500
```

21.6 Input Value Manipulators

The format of numeric input values in the same as C constants without a trailing type suffix, as the input value-type is denoted by the input variable. For bool type, the constants are \texttt{true} and \texttt{false}. For integral types, any number of digits, optionally preceded by a sign (+ or -), where a

- 1-9 prefix introduces a decimal value (0-9),
- 0 prefix introduces an octal value (0-7), and
- 0x or 0X prefix introduces a hexadecimal value (0-f) with lower or upper case letters.

For floating-point types, any number of decimal digits, optionally preceded by a sign (+ or -), optionally containing a decimal point, and optionally followed by an exponent, e or E, with signed (optional) decimal digits. Floating-point values can also be written in hexadecimal format preceded by 0x or 0X with hexadecimal digits and exponent denoted by p or P.

For the C-string type, the input values are not the same as C-string constants, \textit{i.e.}, double quotes bracketing arbitrary
text with escape sequences. Instead, the next sequence of non-whitespace characters are read, and the input sequence is terminated with delimiter '0'. The string variable must be large enough to contain the input sequence. To force programmers to consider buffer overruns for C-string input, C-strings can only be read with a width field, which should specify a size less than or equal to the C-string size, e.g.:

```c
char line[64];
sin | wdi( sizeof(line), line ); // must specify size
```

A scanset is a simple regular expression, where the matching set contains any Latin-1 character (8-bits) or character ranges using minus. For example, the scanset "a-zA-Z/?§" matches characters between 'a' and 'z', between 'A' and 'Z', between space and '/', and characters '?' and (Latin-1) '§'. The following string is matched by this scanset:

```
!&% abAA () ZZZ ?? xx§§§
```

To match a minus, put it as the first character, "-0-9". Other complex forms of regular-expression matching are not supported.

The following manipulators control scanning of input values (reading), and only affect the format of the argument.

1. `skip( pattern ), skip( length )` The pattern is composed of white-space and non-white-space characters, where any white-space character matches 0 or more input white-space characters (hence, consecutive white-space characters in the pattern are combined), and each non-white-space character matches exactly with an input character. The length is composed of the next \( N \) characters, including the newline character. If the match succeeds, the input characters are discarded, and input continues with the next character. If the match fails, the input characters are left unread.

```c
char sk[] = "abc";
sin | "abc " | skip( sk ) | skip( 5 ); // match input sequence
abc
abc
xx
```

2. `wdi( maximum, reference-value )` For all types except char, maximum is the maximum number of characters read for the current operation.

```c
char s[10]; int i; double d;
sin | wdi( 4, s ) | wdi( 3, i ) | wdi( 8, d ); // c == "abcd", i == 123, d == 3.456E+2
abcd123.456E+2
```

Note, input wdi cannot be overloaded with output wd because both have the same parameters but return different types. Currently, CyC cannot distinguish between these two manipulators in the middle of an sout/sin expression based on return type.

3. `ignore( reference-value )` For all types, the data is read from the stream depending on the argument type but ignored, i.e., it is not stored in the argument.

```c
double d;
sin | ignore( d ); // d is unchanged
```

4. `incl( scanset, wdi-input-string )` For C-string types only, the scanset matches any number of characters in the set. Matching characters are read into the C input-string and null terminated.

```c
char s[10];
sin | incl( "abc", s );
bcaxyz
```

5. `excl( scanset, wdi-input-string )` For C-string types, the scanset matches any number of characters not in the set. Non-matching characters are read into the C input-string and null terminated.

```c
char s[10];
sin | excl( "abc", s );
xyzbca
```

6. `getline( char delimit, wdi-input-string )` Is an @excl@ with scanset "delimit", which consumes all characters up to the delimit character. If the delimit character is omitted, it defaults to 'n' (newline).
21.7 Concurrent Stream Access

When a stream is shared by multiple threads, input or output characters can be intermixed or cause failure. For example, if two threads execute the following:

\begin{verbatim}
thread1 : sout | "abc " | "def ";
thread2 : sout | "uvw " | "xyz ";
\end{verbatim}

possible outputs are:

<table>
<thead>
<tr>
<th>abc def</th>
<th>abc uvw xyz</th>
<th>uvw abc xyz def</th>
<th>abuvw def</th>
<th>uvw abc def</th>
</tr>
</thead>
<tbody>
<tr>
<td>uvw xyz</td>
<td>uvw abc def</td>
<td>abuvw def xyz</td>
<td>uvw abc def</td>
<td></td>
</tr>
</tbody>
</table>

Concurrent operations can even corrupt the internal state of the stream resulting in failure. As a result, some form of mutual exclusion is required for concurrent stream access.

A coarse-grained solution is to perform all stream operations via a single thread or within a monitor providing the necessary mutual exclusion for the stream. A fine-grained solution is to have a lock for each stream, which is acquired and released around stream operations by each thread. C++ provides a fine-grained solution where a recursive lock is acquired and released indirectly via a manipulator `acquire` or instantiating an RAII type specific for the kind of stream: `osacquire` for output streams and `isacquire` for input streams.

The common usage is the short form of the mutex statement to lock a stream during a single cascaded I/O expression, e.g.:

\begin{verbatim}
thread1 : mutex(sout) sout | "abc " | "def ";
thread2 : mutex(sout) sout | "uvw " | "xyz ";
\end{verbatim}

Now, the order of the thread execution is still non-deterministic, but the output is constrained to two possible lines in either order.

<table>
<thead>
<tr>
<th>abc def</th>
<th>uvw xyz</th>
</tr>
</thead>
<tbody>
<tr>
<td>uvw xyz</td>
<td>abc def</td>
</tr>
</tbody>
</table>

In summary, the stream lock is acquired by the `acquire` manipulator and implicitly released at the end of the cascaded I/O expression ensuring all operations in the expression occur atomically.

To lock a stream across multiple I/O operations, the long form of the mutex statement is used, e.g.:

\begin{verbatim}
mutex(sout) {
  sout | 1;
  mutex(sout) sout | 2 | 3; // unnecessary, but ok because of recursive lock
  sout | 4;
} // implicitly release sout lock
\end{verbatim}

Note, the unnecessary `mutex` in the middle of the mutex statement, works because the recursive stream-lock can be acquired/released multiple times by the owner thread. Hence, calls to functions that also acquire a stream lock for their output do not result in deadlock.

The previous values written by threads 1 and 2 can be read in concurrently:

\begin{verbatim}
mutex(sin) {
  int x, y, z, w;
  sin | x;
  mutex(sin) sin | y | z; // unnecessary, but ok because of recursive lock
  sin | w;
} // implicitly release sin lock
\end{verbatim}

Again, the order of the reading threads is non-deterministic. Note, non-deterministic reading is rare.

**WARNING:** The general problem of nested locking can occur if routines are called in an I/O sequence that block, e.g.:

\begin{verbatim}
mutex(sout) sout | "data:" | rtn(mon); // mutex call on monitor
\end{verbatim}

If the thread executing the I/O expression blocks in the monitor with the `sout` lock, other threads writing to `sout` also block until the thread holding the lock is unblocked and releases it. This scenario can lead to deadlock, if the thread that is going to unblock the thread waiting in the monitor first writes to `sout` (deadly embrace). To prevent nested locking, a simple precaution is to factor out the blocking call from the expression, e.g.:

\begin{verbatim}
int data = rtn(mon);
mutex(sout) sout | "data:" | data;
\end{verbatim}
#include <fstream.h>
#include <locale.h>  // setlocale
#include <stdlib.h>  // getenv

int main() {
    void print() {
        sout | 12 | 123 | 1234 | 12345 | 123456 | 1234567;
        sout | 12. | 123.1 | 1234.12 | 12345.123 | 123456.1234 | 1234567.12345;
        sout | nl;
    }
    sout | "Default locale off";
    print();
    sout | "Locale on" | setlocale( LC_NUMERIC, getenv("LANG")); // enable local locale
    print();
    sout | "German" | setlocale( LC_NUMERIC, "de_DE.UTF-8"); // enable German locale
    print();
    sout | "Ukraine" | setlocale( LC_NUMERIC, "uk_UA.utf8"); // enable Ukraine locale
    print();
    sout | "Default locale off" | setlocale( LC_NUMERIC, "C"); // disable locale
    print();
}

Default locale off
12 123 1234 12345 123456 1234567
12. 123.1 1234.12 12345.123 123456.1234 1234567.12345

Locale on en_US.UTF-8
12 123 1.234 12.345 123.456 1234.567
12. 123.1 1.234.12 12.345.123 123.456.1234 1234.567.12345

German de_DE.UTF-8
12 123 1.234 12.345 123.456 1234.567
12. 123.1 1.234.12 12.345.123 123.456.1234 1234.567.12345

Ukraine uk_UA.utf8
12 123 1.234 12.345 123.456 1234.567

Default locale off C
12 123 1234 12345 123456 1234567
12. 123.1 1234.12 12345.123 123456.1234 1234567.12345

Figure 7: Stream Locale

21.8 Locale

Cultures use different syntax, called a locale, for printing numbers so they are easier to read, e.g.:

12,345.123  // comma separator, period decimal-point
12.345,123  // period separator, comma decimal-point
1 2,345.123.  // space separator, comma decimal-point, period terminator

A locale is selected with function setlocale, and the corresponding locale package must be installed on the underlying system; setlocale returns 0 if the requested locale is unavailable. Furthermore, a locale covers the syntax for many cultural items, e.g., address, measurement, money, etc. This discussion applies to item LC_NUMERIC for formatting non-monetary integral and floating-point values. Figure 7 shows selecting different cultural syntax, which may be associated with one or more countries.
```c
#include <fstream.hfa>
#include <strstream.hfa>

int main() {
    enum { size = 256 }; // output buffer
    char buf[size];
    ostrstream osstr = { buf, size }; // bind output buffer/size
    int i = 3, j = 5, k = 7;
    double x = 12345678.9, y = 98765.4321e-11;

    osstr | i | hex(j) | wd(10, k) | sci(x) | unit(eng(y)) | "abc";
    write( osstr ); // write string to stdout
    printf("%s", buf); // same lines of output
    sout | i | hex(j) | wd(10, k) | sci(x) | unit(eng(y)) | "abc";

    char buf2["12 14 15 3.5 7e4 abc"]; // input buffer
    istrstream isstr = { buf2 };
    char s[10];
    isstr | i | j | k | x | y | s;
    sout | i | j | k | x | y | s;
}
```

Figure 8: String Stream Processing

22 String Stream

The stream types `ostrstream` and `istrstream` provide all the stream formatting capabilities to/from a C string rather than a stream file. Figure 8 shows writing (output) to and reading (input) from a C string. The only string stream operations different from a file stream are:

- Constructors to create a stream that writes to a write buffer (`ostrstream`) of size, or reads from a read buffer (`istrstream`) containing a C string terminated with '0'.

```c
void ?{}( ostrstream & osstr &, char buf[], size_t size );
void ?{}( istrstream & isstr & is, char buf[] );
```

- Write (`ostrstream only`) writes all the buffered characters to the specified stream (stdout default).

```c
ostrstream & write( ostrstream & os, FILE * stream = stdout );
```

There is no read for `istrstream`.

23 Structures

Structures in C++ are basically the same as structures in C. A structure is defined with the same syntax as in C. When referring to a structure in C++, users may omit the struct keyword.

```c
struct Point {
    double x;
    double y;
};
```

C++ does not support inheritance among types, but instead uses composition to enable reuse of structure fields. Composition is achieved by embedding one type into another. When type A is embedded in type B, an object with type B may be used as an object of type A, and the fields of type A are directly accessible. Embedding types is
achieved using anonymous members. For example, using Point from above:

```c
void foo(Point p);
```

```c
struct ColoredPoint {
    Point; // anonymous member (no identifier)
    int Color;
};
```

```c
ColoredPoint cp = ...;
```

```c
// x from Point is accessed directly
```

```c
// color is accessed normally
```

```c
foo(cp); // cp can be used directly as a Point
```

### 24 Constructors and Destructors

CV supports C initialization of structures, but it also adds constructors for more advanced initialization. Additionally, CV adds destructors that are called when a variable is deallocated (variable goes out of scope or object is deleted). These functions take a reference to the structure as a parameter (see Section 12, p. 18 for more information).

### 25 Overloading

Overloading refers to the capability of a programmer to define and use multiple objects in a program with the same name. In CV, a declaration may overload declarations from outer scopes with the same name, instead of hiding them as is the case in C. This may cause identical C and CV programs to behave differently. The compiler selects the appropriate object (overload resolution) based on context information at the place where it is used. Overloading allows programmers to give functions with different signatures but similar semantics the same name, simplifying the interface to users. Disadvantages of overloading are that it can be used to give functions with different semantics the same name, causing confusion, or that the compiler may resolve to a different function from what the programmer expected.

The compiler follows some overload resolution rules to determine the best interpretation of all of these overloads. The best valid interpretations are the valid interpretations that use the fewest unsafe conversions. Of these, the best are those where the functions and objects involved are the least polymorphic. Of these, the best have the lowest total conversion cost, including all implicit conversions in the argument expressions. Of these, the best have the highest total conversion cost for the implicit conversions (if any) applied to the argument expressions. If there is no single best valid interpretation, or if the best valid interpretation is ambiguous, then the resulting interpretation is ambiguous. For details about type inference and overload resolution, please see the CV Language Specification.

```c
int foo(int a, int b) {
    float sum = 0.0;
    float special = 1.0;
    {
        int sum = 0;
        // both the float and int versions of sum are available
        float special = 4.0;
        // this inner special hides the outer version
        ...
    }
    ...
}
```

### 25.1 Constant

The constants 0 and 1 have special meaning. In CV, as in C, all scalar types can be incremented and decremented, which is defined in terms of adding or subtracting 1. The operations &&, ||, and ! can be applied to any scalar arguments and are defined in terms of comparison against 0 (ex. (a && b) becomes (a != 0 && b != 0)).

In C, the integer constants 0 and 1 suffice because the integer promotion rules can convert them to any arithmetic type, and the rules for pointer expressions treat constant expressions evaluating to 0 as a special case. However, user-
defined arithmetic types often need the equivalent of a 1 or 0 for their functions or operators, polymorphic functions
often need 0 and 1 constants of a type matching their polymorphic parameters, and user-defined pointer-like types may
need a null value. Defining special constants for a user-defined type is more efficient than defining a conversion to the
type from bool.

Why just 0 and 1? Why not other integers? No other integers have special status in C. A facility that let program-
ners declare specific constants...const Rational 12, for instance, would not be much of an improvement. Some facility
for defining the creation of values of programmer-defined types from arbitrary integer tokens would be needed. The
complexity of such a feature does not seem worth the gain.

For example, to define the constants for a complex type, the programmer would define the following:

```c
struct Complex {
    double real;
    double imaginary;
}

const Complex 0 = {0, 0};
```
```c
const Complex 1 = {1, 0};
...
Complex a = 0;
...
a++;
...
if (a) { // same as if (a == 0)
...
}
```

### 25.2 Variable

The overload rules of CÆ allow a programmer to define multiple variables with the same name, but different types. Allowing overloading of variable names enables programmers to use the same name across multiple types, simplifying naming conventions and is compatible with the other overloading that is allowed. For example, a developer may want to do the following:

```c
int pi = 3;
float pi = 3.14;
char pi = .p.;
```

### 25.3 Function Overloading

Overloaded functions in CÆ are resolved based on the number and type of arguments, type of return value, and the level of specialization required (specialized functions are preferred over generic).

The examples below give some basic intuition about how the resolution works.

```c
// Choose the one with less conversions
int doSomething(int value) {...} // option 1
int doSomething(short value) {...} // option 2
int a, b = 4;
short c = 2;
a = doSomething(b); // chooses option 1
a = doSomething(c); // chooses option 2
```

```c
// Choose the specialized version over the generic
generic(type T)
T bar(T rhs, T lhs) {...} // option 3
float bar(float rhs, float lhs){...} // option 4
float a, b, c;
double d, e, f;
c = bar(a, b); // chooses option 4
```

```c
// specialization is preferred over unsafe conversions
t = bar(d, e); // chooses option 5
```

### 25.4 Operator

CÆ also allows operators to be overloaded, to simplify the use of user-defined types. Overloading the operators allows the users to use the same syntax for their custom types that they use for built-in types, increasing readability and improving productivity. CÆ uses the following special identifiers to name overloaded operators:

These identifiers are defined such that the question marks in the name identify the location of the operands. These operands represent the parameters to the functions, and define how the operands are mapped to the function call. For example, a + b becomes ?+(a, b).
In the example below, a new type, myComplex, is defined with an overloaded constructor, + operator, and string operator. These operators are called using the normal C syntax.

type Complex = struct { // define a Complex type
double real;
double imag;
} // Constructor with default values

void {}(Complex &c, double real = 0.0, double imag = 0.0) {
    c.real = real;
c.imag = imag;
}

Complex +(Complex lhs, Complex rhs) {
    Complex sum;
    sum.real = lhs.real + rhs.real;
    sum.imag = lhs.imag + rhs.imag;
    return sum;
}

String ()?{const Complex c} { // use the string conversions for the structure members
    return (String)c.real + . + . + (String)c.imag + .i.;
}

Complex a, b, c = {1.0}; // constructor for c w/ default imag
... c = a + b;
print(.sum = . + c);

Auto type-inferencing occurs in a declaration where a variable’s type is inferred from its initialization expression type.
The two important capabilities are:

- not determining or writing long generic types,
- ensuring secondary variables, related to a primary variable, always have the same type.

In C++, `typedef` provides a mechanism to alias long type names with short ones, both globally and locally, but not eliminate the use of the short name. `gcc` provides `typeof` to declare a secondary variable from a primary variable. C++ also relies heavily on the specification of the left-hand side of assignment for type inferencing, so in many cases it is crucial to specify the type of the left-hand side to select the correct type of the right-hand expression. Only for overloaded routines with the same return type is variable type-inferencing possible. Finally, auto presents the programming problem of tracking down a type when the type is actually needed. For example, given

```c++
auto j = ...;
void rtn( ... parm );
rtn( j );
```

A programmer must work backwards to determine the type of `j`'s initialization expression, reconstructing the possibly long generic type-name. In this situation, having the type name or a short alias is very useful.

There is also the conundrum in type inferencing of when to brand a type. That is, when is the type of the variable more important than the type of its initialization expression. For example, if a change is made in an initialization expression, it can cause cascading type changes and/or errors. At some point, a variable type needs to remain constant and the expression to be in error when it changes.

Given `typedef` and `typeof` in C++, and the strong need to use the type of left-hand side in inferencing, auto type-inferencing is not supported at this time. Should a significant need arise, this feature can be revisited.

### 27 Concurrency

Concurrency support in C++ is implemented on top of a highly efficient runtime system of light-weight, M:N, user level threads. The model integrates concurrency features into the language by making the structure type the core unit of concurrency. All communication occurs through method calls, where data is sent via method arguments, and received via the return value. This enables a very familiar interface to all programmers, even those with no parallel programming experience. It also allows the compiler to do static type checking of all communication, a very important safety feature. This controlled communication with type safety has some similarities with channels in Go, and can actually implement channels exactly, as well as create additional communication patterns that channels cannot. Mutex objects, monitors, are used to contain mutual exclusion within an object and synchronization across concurrent threads.

#### 27.1 Coroutine

Coroutine are the precursor to threads. Figure 10 shows a coroutine that computes the Fibonacci numbers.

#### 27.2 Monitors

A monitor is a structure in C++ which includes implicit locking of its fields. Users of a monitor interact with it just like any structure, but the compiler handles code as needed to ensure mutual exclusion. An example of the definition of a monitor is shown here:

```c++
type Account = monitor {
   const unsigned long number; // account number
   float balance; // account balance
};
```
#include <fstream.hfa>
#include <coroutine.hfa>

coroutine Fibonacci {
    int fn;                       // used for communication
}

void main( Fibonacci & fib ) {
    int fn1, fn2;               // retained between resumes
    fn = 0; fn1 = fn;           // 1st case
    suspend;                    // restart last resume
    fn = 1; fn2 = fn1; fn1 = fn; // 2nd case
    suspend;                    // restart last resume
    for () {
        fn = fn1 + fn2; fn2 = fn1; fn1 = fn; // general case
        suspend; // restart last resume
    }
}

int next( Fibonacci & fib ) {     // restart last suspend
    resume( fib );
    return fn;
}

int main() {
    Fibonacci f1, f2;
    for ( 10 ) {
        sout | next( f1 ) | next( f2 );
    }
}

Figure 10: Fibonacci Coroutine

27.3 Threads

C finally provides a simple mechanism for creating and utilizing user level threads. A thread provides mutual exclusion
like a monitor, and also has its own execution state and a thread of control. Similar to a monitor, a thread is defined
like a structure:

28 Language Comparisons

CA is one of many languages that attempts to improve upon C. In developing CA, many other languages were consulted
for ideas, constructs, and syntax. Therefore, it is important to show how these languages each compare with Do. In
this section, CA is compared with what the writers of this document consider to be the closest competitors of Do: C++,
Go, Rust, and D.

28.1 C++

C++ is a general-purpose programming language. It has imperative, object-oriented and generic programming features,
while also providing facilities for low-level memory manipulation. (Wikipedia)

The primary focus of C++ seems to be adding object-oriented programming to C, and this is the primary difference
between C++ and Do. C++ uses classes to encapsulate data and the functions that operate on that data, and to hide the
internal representation of the data. CA uses modules instead to perform these same tasks. Classes in C++ also enable
inheritance among types. Instead of inheritance, CA embraces composition and interfaces to achieve the same goals
with more flexibility. There are many studies and articles comparing inheritance and composition (or is-a versus has-a
relationships), so we will not go into more detail here (Venner, 1998) (Pike, Go at Google: Language Design in the

Overloading in CA is very similar to overloading in C++, with the exception of the additional use, in CA, of the
return type to differentiate between overloaded functions. References and exceptions in CA are heavily based on the
Go

28.2 Go

Go, also commonly referred to as golang, is a programming language developed at Google in 2007 [\]. It is a statically typed language with syntax loosely derived from that of C, adding garbage collection, type safety, some structural typing capabilities, additional built-in types such as variable-length arrays and key-value maps, and a large standard library. (Wikipedia)

Go and C\# differ significantly in syntax and implementation, but the underlying core concepts of the two languages are aligned. Both Go and C\# use composition and interfaces as opposed to inheritance to enable encapsulation and abstraction. Both languages (along with their tooling ecosystem) provide a simple packaging mechanism for building units of code for easy sharing and reuse. Both languages also include built-in lightweight, user-level threading concurrency features that attempt to simplify the effort and thought process required for writing parallel programs while maintaining high performance.

Go has a significant runtime which handles the scheduling of its lightweight threads, and performs garbage collection, among other tasks. C\# uses a cooperative scheduling algorithm for its tasks, and uses automatic reference counting to enable advanced memory management without garbage collection. This results in Go requiring significant overhead to interface with C libraries while C\# has no overhead.
28.3 Rust

Rust is a general-purpose, multi-paradigm, compiled programming language developed by Mozilla Research. It is designed to be a "safe, concurrent, practical language", supporting pure-functional, concurrent-actor[dubious . discuss][citation needed], imperative-procedural, and object-oriented styles.

The primary focus of Rust is in safety, especially in concurrent programs. To enforce a high level of safety, Rust has added ownership as a core feature of the language to guarantee memory safety. This safety comes at the cost of a difficult learning curve, a change in the thought model of the program, and often some runtime overhead.

Aside from those key differences, Rust and C also have several similarities. Both languages support no overhead interoperability with C and have minimal runtimes. Both languages support inheritance and polymorphism through the use of interfaces (traits).

28.4 D

The D programming language is an object-oriented, imperative, multi-paradigm system programming language created by Walter Bright of Digital Mars and released in 2001. [.] Though it originated as a re-engineering of C++, D is
a distinct language, having redesigned some core C++ features while also taking inspiration from other languages, notably Java, Python, Ruby, C#, and Eiffel.

D and C both start with C and add productivity features. The obvious difference is that D uses classes and inheritance while C uses composition and interfaces. D is closer to C than C++ since it is limited to single inheritance and also supports interfaces. Like C++, and unlike C, D uses garbage collection and has compile-time expanded templates. D does not have any built-in concurrency constructs in the language, though it does have a standard library for concurrency which includes the low-level primitives for concurrency.

A Syntax Ambiguities

C has a number of syntax ambiguities, which are resolved by taking the longest sequence of overlapping characters that constitute a token. For example, the program fragment x+++++y is parsed as x++ y because operator tokens ++ and + overlap. Unfortunately, the longest sequence violates a constraint on increment operators, even though the parse x++ y might yield a correct expression. Hence, C programmers are aware that spaces have to be added to disambiguate certain syntactic cases.

In C#, there are ambiguous cases with dereference and operator identifiers, e.g., int *?*?(), where the string *?*? can be interpreted as:

```
  *?*? // dereference operator, dereference operator
```

By default, the first interpretation is selected, which does not yield a meaningful parse. Therefore, C# does a lexical look-ahead for the second case, and backtracks to return the leading unary operator and reparses the trailing operator identifier. Otherwise a space is needed between the unary operator and operator identifier to disambiguate this common case.

A similar issue occurs with the dereference, *?(...), and routine-call, ?(,...) identifiers. The ambiguity occurs when the dereference operator has no parameters:

```
  *?(...);
  *?(...);
```

requiring arbitrary whitespace look-ahead for the routine-call parameter-list to disambiguate. However, the dereference operator must have a parameter/argument to dereference *?(...). Hence, always interpreting the string *?() as *?() does not preclude any meaningful program.

The remaining cases are with the increment/decrement operators and conditional expression, e.g.:

```
i++?(...);
i?++(...);
```

requiring arbitrary whitespace look-ahead for the operator parameter-list, even though that interpretation is an incorrect expression (juxtaposed identifiers). Therefore, it is necessary to disambiguate these cases with a space:

```
i++?i : 0;
i?++i : 0;
```

B C Incompatibles

The following incompatibles exist between C# and C, and are similar to Annex C for C++ [21].

1. **Change**: add new keywords

   New keywords are added to C# (see Section C, p. 65).

   **Rationale**: keywords added to implement new semantics of C#.

   **Effect on original feature**: change to semantics of well-defined feature.

   Any C11 programs using these keywords as identifiers are invalid C# programs.

   **Difficulty of converting**: keyword clashes are accommodated by syntactic transformations using the C# backquote escape-mechanism (see Section 6, p. 5).

   **How widely used**: clashes among new C# keywords and existing identifiers are rare.

2. **Change**: drop K&R C declarations

   K&R declarations allow an implicit base-type of int, if no type is specified, plus an alternate syntax for declaring parameters. e.g.:
C Incompatibles

1. \texttt{x; // int x}
2. \texttt{*y; // int *y}
3. \texttt{f(p1, p2); // int f(int p1, int p2);}
4. \texttt{g(p1, p2) int p1, p2; // int g(int p1, int p2);}

\texttt{CV} continues to support K&R routine definitions:
5. \texttt{f(a, b, c) // default int return}
6. \texttt{int a, b; char c // K&R parameter declarations}
7. \{
8. ...
9. \}

\textbf{Rationale:} dropped from C11 standard.\footnote{At least one type specifier shall be given in the declaration specifiers in each declaration, and in the specifier-qualifier list in each structure declaration and type name \cite[§ 6.7.2(2)]{ISO-C}}

\textbf{Effect on original feature:} original feature is deprecated.

Any old C programs using these K&R declarations are invalid \texttt{CV} programs.

\textbf{Difficulty of converting:} trivial to convert to \texttt{CV}.

\textbf{How widely used:} existing usages are rare.

3. \textbf{Change:} type of character literal int to char to allow more intuitive overloading:

\begin{verbatim}
  int rtn(int i);
  int rtn(char c);
  rtn('x'); // programmer expects 2nd rtn to be called
\end{verbatim}

\textbf{Rationale:} it is more intuitive for the call to \texttt{rtn} to match the second version of definition of \texttt{rtn} rather than the first. In particular, output of char variable now print a character rather than the decimal ASCII value of the character.

\begin{verbatim}
  sout | 'x' | " " | (int)'x';
  x 120
\end{verbatim}

Having to cast 'x' to char is non-intuitive.

\textbf{Effect on original feature:} change to semantics of well-defined feature that depend on:

\begin{verbatim}
  sizeof('x') == sizeof(int)
\end{verbatim}

no long work the same in \texttt{CV} programs.

\textbf{Difficulty of converting:} simple

\textbf{How widely used:} programs that depend upon \texttt{sizeof('x')} are rare and can be changed to \texttt{sizeof(char)}.

4. \textbf{Change:} make string literals const:

\begin{verbatim}
  char *p = "abc"; // valid in C, deprecated in CV
  char *q = expr ? "abc" : "de"; // valid in C, invalid in CV
\end{verbatim}

The type of a string literal is changed from [] char to const [] char. Similarly, the type of a wide string literal is changed from [] wchar_t to const [] wchar_t.

\textbf{Rationale:} This change is a safety issue:

\begin{verbatim}
  char *p = "abc";
  p[0] = 'w'; // segment fault or change constant literal
\end{verbatim}

The same problem occurs when passing a string literal to a routine that changes its argument.

\textbf{Effect on original feature:} change to semantics of well-defined feature.

\textbf{Difficulty of converting:} simple syntactic transformation, because string literals can be converted to char *.

\textbf{How widely used:} programs that have a legitimate reason to treat string literals as pointers to potentially modifiable memory are rare.

5. \textbf{Change:} remove tentative definitions, which only occurs at file scope:

\begin{verbatim}
  int; // forward definition
  int *i = &i; // forward reference, valid in C, invalid in CV
  int i = 0; // definition
\end{verbatim}

\cite[At least one type specifier shall be given in the declaration specifiers in each declaration, and in the specifier-qualifier list in each structure declaration and type name \cite[§ 6.7.2(2)]{ISO-C}]}
is valid in C, and invalid in C\textit{\texttt{A}} because duplicate overloaded object definitions at the same scope level are disallowed. This change makes it impossible to define mutually referential file-local static objects, if initializers are restricted to the syntactic forms of C. For example,

```c
struct X { int i; struct X *next; }; // forward definition
static struct X a;                  // forward reference, valid in C, invalid in C\textit{\texttt{A}}
static struct X b = { 0, &a };      // definition
static struct X a = { 1, &b };      // definition
```

**Rationale:** avoids having different initialization rules for built-in types and user-defined types.

**Effect on original feature:** change to semantics of well-defined feature.

**Difficulty of converting:** the initializer for one of a set of mutually-referential file-local static objects must invoke a routine call to achieve the initialization.

**How widely used:** seldom

6. **Change:** have \texttt{struct} introduce a scope for nested types:

```c
enum Colour { R, G, B, Y, C, M };
struct Person {
    enum Colour { R, G, B };    // nested type
    struct Face {              // nested type
        Colour Eyes, Hair;    // type defined outside (1 level)
    };                        // type defined outside (top level)
    Colour Eyes;              // type defined same level
    Colour Hair;              // type defined same level
    Face looks[10];           // type defined same level
};
 Colour c = R;              // type/enum defined same level
Person.Colour pc = Person.R; // type/enum defined inside
Person.Face pretty;        // type defined inside
```

In C, the name of the nested types belongs to the same scope as the name of the outermost enclosing structure, \textit{i.e.}, the nested types are hoisted to the scope of the outer-most type, which is not useful and confusing. C\textit{\texttt{A}} is \textit{C incompatible} on this issue, and provides semantics similar to C++. Nested types are not hoisted and can be referenced using the field selection operator ".", unlike the C++ scope-resolution operator ":.:

**Rationale:** \texttt{struct} scope is crucial to C\textit{\texttt{A}} as an information structuring and hiding mechanism.

**Effect on original feature:** change to semantics of well-defined feature.

**Difficulty of converting:** Semantic transformation.

**How widely used:** C programs rarely have nest types because they are equivalent to the hoisted version.

7. **Change:** In C++, the name of a nested class is local to its enclosing class.

**Rationale:** C++ classes have member functions which require that classes establish scopes.

**Difficulty of converting:** Semantic transformation. To make the struct type name visible in the scope of the enclosing struct, the struct tag could be declared in the scope of the enclosing struct, before the enclosing struct is defined. Example:

```c
struct Y;                   // struct Y and struct X are at the same scope
struct X {
    struct Y { /* ... */ } y;
};
```

All the definitions of C struct types enclosed in other struct definitions and accessed outside the scope of the enclosing struct could be exported to the scope of the enclosing struct. Note: this is a consequence of the difference in scope rules, which is documented in 3.3.

**How widely used:** Seldom.

8. **Change:** remove implicit conversion of \texttt{void *} to or from any \texttt{T *} pointer:

```c
void foo() {
    int * b = malloc( sizeof(int) );    // implicitly convert void * to int *
    char * c = b;                        // implicitly convert int * to void *, and then void * to char *
}
```
**C**  

**C  Keywords**

```c
int * b = (int *)malloc( sizeof(int) );
char * c = (char *)b;
```

**Rationale:**  
increase type safety

**Effect on original feature:** deletion of semantically well-defined feature.

**Difficulty of converting:** requires adding a cast (see Section E.1 for better alternatives):

```c
int * b = (int *)malloc( sizeof(int) );
char * c = (char *)b;
```

**How widely used:** Significant. Some C translators already give a warning if the cast is not used.

**Change:** Types must be declared in declarations, not in expressions In C, a sizeof expression or cast expression may create a new type. For example,

```c
p = (void*) (struct int {} *) 0;
```

**Rationale:** This prohibition helps to clarify the location of declarations in the source code.

**Effect on original feature:** Deletion of a semantically well-defined feature.

**Difficulty of converting:** Syntactic transformation.

**How widely used:** Seldom.

**Change:** comma expression is disallowed as subscript

**Rationale:** safety issue to prevent subscripting error for multidimensional arrays: `x[i,j]` instead of `x[i][j]`, and this syntactic form then taken by C for new style arrays.

**Effect on original feature:** change to semantics of well-defined feature.

**Difficulty of converting:** semantic transformation of `x[i,j]` to `x[(i,j)]`

**How widely used:** Seldom.

**C  Keywords**

C  introduces the following new keywords, which cannot be used as identifiers.

```c
basetypeof enable finally int128 report trait when
choose exception fimup monitor suspend try with
coroutine fallback forall mutex throw virtual zero_t
disable fallback generator one_t throwResume waitfor
```

C  introduces the following new quasi-keywords, which can be used as identifiers.

```c
catch fixup
catchResume or
finally timeout
```

**D**  

**Standard Headers**

C11 prescribes the following standard header-files [20, § 7.1.2] and C  adds to this list:

<table>
<thead>
<tr>
<th>C11</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>assert.h</td>
<td>gmp.h</td>
</tr>
<tr>
<td>float.h</td>
<td>malloc.h</td>
</tr>
<tr>
<td>math.h</td>
<td>wchar.h</td>
</tr>
<tr>
<td>stdatomic.h</td>
<td>wchar.h</td>
</tr>
<tr>
<td>stdlib.h</td>
<td>wchar.h</td>
</tr>
<tr>
<td>time.h</td>
<td>wchar.h</td>
</tr>
<tr>
<td>complex.h</td>
<td>unistd.h</td>
</tr>
<tr>
<td>inttypes.h</td>
<td>unistd.h</td>
</tr>
<tr>
<td>setjmp.h</td>
<td>unistd.h</td>
</tr>
<tr>
<td>stdbool.h</td>
<td>unistd.h</td>
</tr>
<tr>
<td>stddef.h</td>
<td>unistd.h</td>
</tr>
<tr>
<td>string.h</td>
<td>unistd.h</td>
</tr>
<tr>
<td>unwind.h</td>
<td>unistd.h</td>
</tr>
<tr>
<td>limits.h</td>
<td>unistd.h</td>
</tr>
<tr>
<td>stdalign.h</td>
<td>unistd.h</td>
</tr>
<tr>
<td>stdint.h</td>
<td>unistd.h</td>
</tr>
<tr>
<td>tgmath.h</td>
<td>unistd.h</td>
</tr>
<tr>
<td>wchar.h</td>
<td>unistd.h</td>
</tr>
<tr>
<td>wctype.h</td>
<td>unistd.h</td>
</tr>
</tbody>
</table>

For the prescribed head-files, C  uses header interposition to wraps these includes in an extern "C"; hence, names in these include files are not mangled (see Section 4, p. 2). All other C header files must be explicitly wrapped in extern "C" to prevent name mangling. This approach is different from C++ where the name-mangling issue is handled internally in C header-files through checks for preprocessor variable `__cplusplus`, which adds appropriate extern "C" qualifiers.

**E**  

**Standard Library**

The C  standard-library wraps explicitly-polymorphic C routines into implicitly-polymorphic versions.
The storage-management routines extend their C equivalents by overloading, alternate names, providing shallow type-safety, and removing the need to specify the allocation size for non-array types.

C storage management provides the following capabilities:

- filled after allocation with a specified character or value.
- resize an existing allocation to decreased or increased its size. In either case, new storage may or may not be allocated and, if there is a new allocation, as much data from the existing allocation is copied into the new allocation. For an increase in storage size, new storage after the copied data may be filled.
- align an allocation on a specified memory boundary, e.g., an address multiple of 64 or 128 for cache-line purposes.
- array the allocation size is scaled to the specified number of array elements. An array may be filled, resized, or aligned.

Table 2 shows allocation routines supporting different combinations of storage-management capabilities.

C memory management extends the type safety of all allocations by using the type of the left-hand-side type to determine the allocation size and return a matching type for the new storage. Type-safe allocation is provided for all C allocation routines and new C alloc allocation routines, e.g., in

```
int * ip = (int *)malloc( sizeof(int) );  // C
int * ip = malloc();                     // CV type-safe version of C malloc
int * ip = alloc();                     // CV type-safe uniform alloc
```

the latter two allocations determine the allocation size from the type of p (int) and cast the pointer to the allocated storage to int *.

CV memory management extends allocation safety by implicitly honouring all alignment requirements, e.g., in

```
struct S { int i; } __attribute__((aligned(128)))); // cache-line alignment
S * sp = malloc();                               // honour type alignment
```

the storage allocation is implicitly aligned to 128 rather than the default 16. The alignment check is performed at compile time so there is no runtime cost.

CV memory management extends the resize capability with the notion of sticky properties. Hence, initial allocation capabilities are remembered and maintained when resize requires copying. For example, an initial alignment and fill capability are preserved during a resize copy so the copy has the same alignment and extended storage is filled.

Without sticky properties it is dangerous to use realloc, resulting in an idiom of manually performing the reallocation to maintain correctness.
E.1 Storage Management

CV memory management extends allocation to support constructors for initialization of allocated storage, e.g., in

```c
struct S { int i; };  // cache-line alignment
void f({ S & s, int i }) { s.i = i; }
// assume f operator for printing an S
S & sp = new( S );  // call constructor after allocation
sout << sp.i;
delete( &sp );
S * spa = anew( S, 10, 5 );  // allocate array and initialize each array element
for ( i; 10 ) sout << spa[i] << endl;
sout << endl;
delete( 10, spa );
```

Allocation routines `new/anev` allocate a variable/array and initialize storage using the allocated type’s constructor.

Note, the matching deallocation routines `delete/adelete`.

```c
extern "C" {
    // C unsafe allocation
    void * malloc( size_t size );
    void * calloc( size_t dim, size_t size );
    void * realloc( void * ptr, size_t size );
    void * memalign( size_t align, size_t size );
    int posix_memalign( void ** ptr, size_t align, size_t size ); // CFA

    // C unsafe initialization/copy
    void * memset( void * dest, int c, size_t size );
    void * memcpy( void * dest, const void * src, size_t size );
}
```

```c
forall( dtype T | sized(T) ) {
    // CV safe equivalents, i.e., implicit size specification
    T * malloc( void );
    T * calloc( size_t dim );
    T * realloc( T * ptr, size_t size );
    T * memalign( size_t align );
    T * cmemalign( size_t alignment, size_t noOfElems, size_t elemSize ); // CFA

    // C unsafe general allocation, fill, resize, alignment, array
    T * alloc( void );  // variable, T size
    T * alloc( size_t dim );  // array[dim], T size elements
    T * alloc( T ptr[], size_t dim );  // realloc array[dim], T size elements
    T * alloc_set( char fill );  // variable, T size, fill bytes with value
    T * alloc_set( T fill );  // variable, T size, fill with value
    T * alloc_set( size_t dim, char fill );  // array[dim], T size elements, fill bytes with value
    T * alloc_set( size_t dim, T fill );  // array[dim], T size elements, fill elements with value
    T * alloc_set( size_t dim, const T fill[] );  // array[dim], T size elements, fill elements with array
    T * alloc_set( T ptr[], size_t dim, char fill );  // realloc array[dim], T size elements, fill bytes with value
    T * alloc_align( size_t align );  // aligned variable, T size
    T * alloc_align( size_t align, size_t dim );  // aligned array[dim], T size elements
    T * alloc_align( T ptr[], size_t align );  // realloc new aligned array
    T * alloc_align( T ptr[], size_t align, size_t dim );  // realloc new aligned array[dim]
```
T * alloc_align_set( size_t align, char fill );  // aligned variable, T size, fill bytes with value
T * alloc_align_set( size_t align, T fill );  // aligned variable, T size, fill with value
T * alloc_align_set( size_t align, size_t dim, char fill );  // aligned array[dim], T size elements, fill bytes with value
T * alloc_align_set( size_t align, size_t dim, T fill );  // aligned array[dim], T size elements, fill elements with value
T * alloc_align_set( size_t align, size_t dim, const T fill[] );  // aligned array[dim], T size elements, fill elements with array
T * alloc_align_set( T ptr[], size_t align, size_t dim, char fill );  // realloc new aligned array[dim], fill new bytes with value

T * memset( T * dest, char fill );
T * memcpy( T * dest, const T * src );

T * amemset( T dest[], char fill, size_t dim );
T * amemcpy( T dest[], const T src[], size_t dim );

forall( dtype T | sized(T), ttype Params | {
    void ?{}( T &, Params ); } ) T * new( Params p );
forall( dtype T | sized(T) | {
    void ∧{}( T & ); } ) void delete( T * ptr );
forall( dtype T | sized(T) | {
    void ∧{}( T & ); }, ttype Params | {
    void adelete( Params ); } )
void delete( size_t dim, T arr[], Params rest );
forall( dtype T | sized(T), ttype Params |{
    void ?{}( T &, Params ); } ) T * anew( size_t dim, Params p );
forall( dtype T | sized(T) | {
    void ∧{}( T & ); } ) void adelete( size_t dim, T arr[] );
forall( dtype T | sized(T) | {
    void ∧{}( T & ); }, ttype Params | {
    void adelete( Params ); } )
void adelete( size_t dim, T arr[], Params rest );

int ato( const char * ptr );
unsigned int ato( const char * ptr );
long int ato( const char * ptr );
unsigned long int ato( const char * ptr );
long long int ato( const char * ptr );
float ato( const char * ptr );
double ato( const char * ptr );
long double ato( const char * ptr );
float _Complex ato( const char * ptr );
double _Complex ato( const char * ptr );
long double _Complex ato( const char * ptr );

int strto( const char * sptr, char ** eptr, int base );
unsigned int strto( const char * sptr, char ** eptr, int base );
long int strto( const char * sptr, char ** eptr, int base );
unsigned long int strto( const char * sptr, char ** eptr, int base );
long long int strto( const char * sptr, char ** eptr, int base );
float strto( const char * sptr, char ** eptr );
double strto( const char * sptr, char ** eptr );
long double strto( const char * sptr, char ** eptr );
float _Complex strto( const char * sptr, char ** eptr );
double _Complex strto( const char * sptr, char ** eptr );
long double _Complex strto( const char * sptr, char ** eptr );
E.4 Absolute Value

```
T * bsearch( T key, const T * arr, size_t dim );

forall( T | { int ?<( T, T ); } ) // position
unsigned int bsearch( T key, const T * arr, size_t dim );
forall( T | { int ?<( T, T ); } )
void qsort( const T * arr, size_t dim );
forall( E | { int ?<( E, E ); } ) {
E * bsearch( E key, const E * vals, size_t dim ); // location
size_t bsearch( E key, const E * vals, size_t dim ); // position
E * bsearchl( E key, const E * vals, size_t dim );
size_t bsearchl( E key, const E * vals, size_t dim );
E * bsearchu( E key, const E * vals, size_t dim );
size_t bsearchu( E key, const E * vals, size_t dim );
}
forall( K, E | { int ?<( K, K ); } ) {
E * bsearch( K key, const E * vals, size_t dim );
size_t bsearch( K key, const E * vals, size_t dim );
E * bsearchl( K key, const E * vals, size_t dim );
size_t bsearchl( K key, const E * vals, size_t dim );
E * bsearchu( K key, const E * vals, size_t dim );
size_t bsearchu( K key, const E * vals, size_t dim );
}
forall( E | { int ?<( E, E ); } ) {
void qsort( E * vals, size_t dim );
}
```

E.4 Absolute Value

```
unsigned char abs( signed char );
int abs( int );
unsigned long int abs( long int );
unsigned long long int abs( long long int );
float abs( float );
double abs( double );
long double abs( long double );
float abs( float _Complex );
double abs( double _Complex );
long double abs( long double _Complex );
forall( T | { void ?()( T *, zero_t); int ?<( T, T ); T -?( T ); } )
T abs( T );
```

E.5 Random Numbers

```
void srandom( unsigned int seed );
char random( void );
char random( char u ); // [0,u)
char random( char l, char u ); // [l,u]
int random( void );
int random( int u ); // [0,u)
int random( int l, int u ); // [l,u]
unsigned int random( void );
unsigned int random( unsigned int u ); // [0,u)
unsigned int random( unsigned int l, unsigned int u ); // [l,u]
long int random( void );
long int random( long int u ); // [0,u)
long int random( long int l, long int u ); // [l,u]
```
E.6 Algorithms

forall( T | { int ?<?( T, T ); } ) T min( T t1, T t2 );
forall( T | { int ?>?( T, T ); } ) T max( T t1, T t2 );
forall( T | { T min( T, T ); T max( T, T ); } ) T clamp( T value, T min_val, T max_val );
forall( T ) void swap( T * t1, T * t2 );

F Math Library

The C\textsuperscript{11} math-library wraps explicitly-polymorphic C math-routines into implicitly-polymorphic versions.

F.1 General

float ?%? ( float, float );
float fmod( float, float );
double ?%? ( double, double );
double fmod( double, double );
long double ?%? ( long double, long double );
long double fmod( long double, long double );
float remainder( float, float );
double remainder( double, double );
long double remainder( long double, long double );
float remquo( float, float, int * );
double remquo( double, double, int * );
long double remquo( long double, long double, int * );
[ int, float ] remquo( float, float );
[ int, double ] remquo( double, double );
[ int, long double ] remquo( long double, long double );
[ int, float ] div( float, float );
[ int, double ] div( double, double );
[ int, long double ] div( long double, long double );
float fma( float, float, float );
double fma( double, double, double );
long double fma( long double, long double, long double );
float fdim( float, float );
double fdim( double, double );
long double fdim( long double, long double );
float nan( const char * );
double nan( const char * );
long double nan( const char * );

F.2 Exponential

float exp( float );
double exp( double );
long double exp( long double );
float _Complex exp( float _Complex );
double _Complex exp( double _Complex );
long double _Complex exp( long double _Complex );

float exp2( float );
double exp2( double );
long double exp2( long double );
// float _Complex exp2( float _Complex );
// double _Complex exp2( double _Complex );
// long double _Complex exp2( long double _Complex );

float expm1( float );
double expm1( double );
long double expm1( long double );
// float _Complex expm1( float _Complex );
// double _Complex expm1( double _Complex );
// long double _Complex expm1( long double _Complex );

float pow( float, float );
double pow( double, double );
long double pow( long double, long double );
float _Complex pow( float _Complex, float _Complex );
double _Complex pow( double _Complex, double _Complex );
long double _Complex pow( long double _Complex, long double _Complex );

float log( float );
double log( double );
long double log( long double );
float _Complex log( float _Complex );
double _Complex log( double _Complex );
long double _Complex log( long double _Complex );

int log2( unsigned int );
long int log2( unsigned long int );
long long int log2( unsigned long long int );
float log2( float );
double log2( double );
long double log2( long double );
// float _Complex log2( float _Complex );
// double _Complex log2( double _Complex );
// long double _Complex log2( long double _Complex );

float log10( float );
double log10( double );
long double log10( long double );
// float _Complex log10( float _Complex );
// double _Complex log10( double _Complex );
// long double _Complex log10( long double _Complex );

float log1p( float );
double log1p( double );
long double log1p( long double );

int ilogb( float );
int ilogb( double );
int ilogb( long double );

float logb( float );
double logb( double );
long double logb( long double );
F.4 Trigonometric

float sqrt(float);
double sqrt(double);
long double sqrt(long double);
float_Complex sqrt(float_Complex);
double_Complex sqrt(double_Complex);
long double_Complex sqrt(long double_Complex);

float cbrt(float);
double cbrt(double);
long double cbrt(long double);
float_Complex cbrt(float_Complex);
double_Complex cbrt(double_Complex);
long double_Complex cbrt(long double_Complex);

float hypot(float, float);
double hypot(double, double);
long double hypot(long double, long double);

float sin(float);
double sin(double);
long double sin(long double);
float_Complex sin(float_Complex);
double_Complex sin(double_Complex);
long double_Complex sin(long double_Complex);

float cos(float);
double cos(double);
long double cos(long double);
float_Complex cos(float_Complex);
double_Complex cos(double_Complex);
long double_Complex cos(long double_Complex);

float tan(float);
double tan(double);
long double tan(long double);
float_Complex tan(float_Complex);
double_Complex tan(double_Complex);
long double_Complex tan(long double_Complex);

float asin(float);
double asin(double);
long double asin(long double);
float_Complex asin(float_Complex);
double_Complex asin(double_Complex);
long double_Complex asin(long double_Complex);

float acos(float);
double acos(double);
long double acos(long double);
float_Complex acos(float_Complex);
double_Complex acos(double_Complex);
long double_Complex acos(long double_Complex);

float atan(float);
double atan(double);
long double atan(long double);
float_Complex atan(float_Complex);
double_Complex atan(double_Complex);
long double_Complex atan(long double_Complex);
F.5  Hyperbolic

```c
float atan2( float, float );
double atan2( double, double );
long double atan2( long double, long double );
float atan( float, float );
double atan( double, double );
long double atan( long double, long double );

F.5  Hyperbolic

float sinh( float );
double sinh( double );
long double sinh( long double );
float _Complex sinh( float _Complex );
double _Complex sinh( double _Complex );
long double _Complex sinh( long double _Complex );
float cosh( float );
double cosh( double );
long double cosh( long double );
float _Complex cosh( float _Complex );
double _Complex cosh( double _Complex );
long double _Complex cosh( long double _Complex );
float tanh( float );
double tanh( double );
long double tanh( long double );
float _Complex tanh( float _Complex );
double _Complex tanh( double _Complex );
long double _Complex tanh( long double _Complex );
float asinh( float );
double asinh( double );
long double asinh( long double );
float _Complex asinh( float _Complex );
double _Complex asinh( double _Complex );
long double _Complex asinh( long double _Complex );
float acosh( float );
double acosh( double );
long double acosh( long double );
float _Complex acosh( float _Complex );
double _Complex acosh( double _Complex );
long double _Complex acosh( long double _Complex );
float atanh( float );
double atanh( double );
long double atanh( long double );
float _Complex atanh( float _Complex );
double _Complex atanh( double _Complex );
long double _Complex atanh( long double _Complex );

F.6  Error / Gamma

float erf( float );
double erf( double );
long double erf( long double );
float _Complex erf( float _Complex );
double _Complex erf( double _Complex );
long double _Complex erf( long double _Complex );
```
F.7 Nearest Integer

// n / align - align
signed char floor( signed char n, signed char align );
unsigned char floor( unsigned char n, unsigned char align );
short int floor( short int n, short int align );
unsigned short int floor( unsigned short int n, unsigned short int align );
int floor( int n, int align );
unsigned int floor( unsigned int n, unsigned int align );
long int floor( long int n, long int align );
unsigned long int floor( unsigned long int n, unsigned long int align );
unsigned long long int floor( unsigned long long int n, unsigned long long int align );

// (n + (align - 1)) / align
signed char ceiling_div( signed char n, char align );
unsigned char ceiling_div( unsigned char n, unsigned char align );
short int ceiling_div( short int n, short int align );
unsigned short int ceiling_div( unsigned short int n, unsigned short int align );
int ceiling_div( int n, int align );
unsigned int ceiling_div( unsigned int n, unsigned int align );
long int ceiling_div( long int n, long int align );
unsigned long int ceiling_div( unsigned long int n, unsigned long int align );
long int ceiling_div( long long int n, long long int align );
unsigned long int ceiling_div( unsigned long long int n, unsigned long long int align );

// floor( n + (n % align != 0 ? align - 1 : 0), align )
signed char ceiling( signed char n, signed char align );
unsigned char ceiling( unsigned char n, unsigned char align );
short int ceiling( short int n, short int align );
unsigned short int ceiling( unsigned short int n, unsigned short int align );
int ceiling( int n, int align );
unsigned int ceiling( unsigned int n, unsigned int align );
long int ceiling( long int n, long int align );
unsigned long int ceiling( unsigned long int n, unsigned long int align );
long int ceiling( long long int n, long long int align );
unsigned long int ceiling( unsigned long long int n, unsigned long long int align );

float floor( float );
double floor( double );
long double floor( long double );
F.8  Manipulation

float ceil( float );
double ceil( double );
long double ceil( long double );

float trunc( float );
double trunc( double );
long double trunc( long double );

float rint( float );
long double rint( long double );
long int rint( float );
long int rint( double );
long long int rint( float );
long long int rint( double );
long long int rint( long double );

long int lrint( float );
long int lrint( double );
long int lrint( long double );

float nearbyint( float );
double nearbyint( double );
long double nearbyint( long double );

float round( float );
long double round( long double );
long int round( float );
long int round( double );
long int round( long double );
long long int round( float );
long long int round( double );
long long int round( long double );

long int lround( float );
long int lround( double );
long int lround( long double );

long long int llround( float );
long long int llround( double );
long long int llround( long double );

float copysign( float, float );
double copysign( double, double );
long double copysign( long double, long double );

float frexp( float, int * );
double frexp( double, int * );
long double frexp( long double, int * );

float ldexp( float, int );
double ldexp( double, int );
long double ldexp( long double, int );

[ float, float ] modf( float );
float modf(float, float *);
[double, double] modf(double);
double modf(double, double *);
[long double, long double] modf(long double);
long double modf(long double, long double *);

float nextafter(float, float);
double nextafter(double, double);
long double nextafter(long double, long double);

float scalbn(float, int);
double scalbn(double, int);
long double scalbn(long double, int);

float scalbln(float, long int);
double scalbln(double, long int);
long double scalbln(long double, long int);

G Time Keeping

G.1 Duration

struct Duration {
    int64_t tn;  // nanoseconds
};

void {}( Duration & dur );
void {}( Duration & dur, zero_t );
void {}( Duration & dur, timeval t )
void {}( Duration & dur, timespec t )
Duration ==?( Duration & dur, zero_t );
Duration ==?( Duration & dur, timeval t )
Duration ==?( Duration & dur, timespec t )
Duration +?( Duration rhs );
Duration +?( Duration & lhs, Duration rhs );
Duration +=?( Duration & lhs, Duration rhs );
Duration -?( Duration rhs );
Duration -?( Duration & lhs, Duration rhs );
Duration -=?( Duration & lhs, Duration rhs );
Duration *?( Duration rhs );
Duration *?( int64_t lhs, Duration rhs );
Duration *=?( Duration & lhs, int64_t rhs );
Duration /?( Duration lhs, Duration rhs );
Duration /?( Duration lhs, int64_t rhs );
Duration /=?( Duration & lhs, int64_t rhs );
double div(Duration lhs, Duration rhs );
Duration %=?( Duration lhs, Duration rhs );
Duration %=?( Duration & lhs, Duration rhs );
bool ==?( Duration lhs, zero_t );
bool ?!=? ( Duration lhs, zero_t );
bool ?<? ( Duration lhs, zero_t );
bool ?<=?( Duration lhs, zero_t );
bool ?>? ( Duration lhs, zero_t );
bool ?>=?( Duration lhs, zero_t );
bool ?==?( Duration lhs, Duration rhs );
bool ?!=?( Duration lhs, Duration rhs );
bool ?<? ( Duration lhs, Duration rhs );
bool ?<=?( Duration lhs, Duration rhs );
bool ?>? ( Duration lhs, Duration rhs );
bool ?>=?( Duration lhs, Duration rhs );

Duration abs( Duration rhs );

Duration ?'ns( int64_t nsec );
Duration ?'us( int64_t usec );
Duration ?'ms( int64_t msec );
Duration ?'s( int64_t sec );
Duration ?'h( int64_t hours );
Duration ?'m( int64_t min );
Duration ?'m( double min );
Duration ?'h( double hours );
Duration ?'d( int64_t days );
Duration ?'d( double days );
Duration ?'w( int64_t weeks );
Duration ?'w( double weeks );

int64_t ?'ns( Duration dur );
int64_t ?'us( Duration dur );
int64_t ?'ms( Duration dur );
int64_t ?'s( Duration dur );
int64_t ?'m( Duration dur );
int64_t ?'h( Duration dur );
int64_t ?'d( Duration dur );
int64_t ?'w( Duration dur );

double ?'dns( Duration dur );
double ?'dus( Duration dur );
double ?'dms( Duration dur );
double ?'ds( Duration dur );
double ?'dm( Duration dur );
double ?'dh( Duration dur );
double ?'dd( Duration dur );
double ?'dw( Duration dur );

Duration max( Duration lhs, Duration rhs );
Duration min( Duration lhs, Duration rhs );

forall( ostream( ostype ) ) ostype & ?{}( ostype & os, Duration dur );

G.2 timeval

void ?{}( timeval & t );
void ?{}( timeval & t, zero_t );
void ?{}( timeval & t, time_t sec, suseconds_t usec );
void ?{}( timeval & t, time_t sec );
void ?{}( timeval & t, Time time );
timeval ?=?( timeval & t, .zero_t );
    timeval ?+?( timeval & lhs, timeval rhs );
    timeval ?-?( timeval & lhs, timeval rhs );
    bool ?==?( timeval lhs, timeval rhs );
    bool ?!=?( timeval lhs, timeval rhs );

G.3 timespec
void ?( timespec & t );
void ?( timespec & t, .zero_t );
void ?( timespec & t, time_j sec, __syscall_ulong_t nsec );
void ?( timespec & t, time_j sec );
void ?( timespec & t, Time time );
timespec ?=?( timespec & t, .zero_t );
timespec ?+?( timespec & lhs, timespec rhs );
timespec ?-?( timespec & lhs, timespec rhs );
bool ?==?( timespec lhs, timespec rhs );
bool ?!=?( timespec lhs, timespec rhs );

G.4 itimerval
void ?( itimerval & itv, Duration alarm );
void ?( itimerval & itv, Duration alarm, Duration interval );

G.5 Time
struct Time {
    uint64_t tn; // nanoseconds since UNIX epoch
};
void ?( Time & time );
void ?( Time & time, .zero_t );
void ?( Time & time, timeval t );
void ?( Time & time, timespec t );
Time ?=?( Time & time, .zero_t );
Time ?=?( Time & time, timeval t );
Time ?=?( Time & time, timespec t );
Time ?+?( Time & lhs, Duration rhs );
Time ?+?( Duration lhs, Time rhs );
Time ?+?( Time & lhs, Duration rhs );
Time ?-?( Time lhs, Time rhs );
Time ?-?( Time lhs, Duration rhs );
Time ?-?( Time & lhs, Duration rhs );
bool ?==?( Time lhs, Time rhs );
bool ?==?( Time lhs, Time rhs );
bool ?<=?( Time lhs, Time rhs );
bool ?>=( Time lhs, Time rhs );
bool ?>=( Time lhs, Time rhs );

int64_t ?*ns( Time t );
char * yy_mm_dd( Time time, char * buf );
char * ?*ymd( Time time, char * buf ); // short form
char * mm_dd_yy( Time time, char * buf );
char * ?*mdy( Time time, char * buf ); // short form
H Clock

H.1 C time

char * ctime( Time tp );
char * ctime_r( Time tp, char * buf );
tm * gmtime( Time tp );
tm * gmtime_r( Time tp, tm * result );
tm * localtime( Time tp );
tm * localtime_r( Time tp, tm * result );

H.2 Clock

struct Clock {
    // virtual clock
    Duration offset;
};

void {}( Clock & clk );
void {}( Clock & clk, Duration adj );
void reset( Clock & clk, Duration adj );

Duration resolutionHi();
Duration resolution();
Time timeHiRes();
Time time();
Time time( Clock & clk );
Time {}( Clock & clk );
timeval time( Clock & clk );
tm time( Clock & clk );
Duration processor();
Duration program();
Duration boot();

I Pseudo Random Number Generator

Random numbers are values generated independently, i.e., new values do not depend on previous values (independent trials), e.g., lottery numbers, shuffled cards, dice roll, coin flip. While a primary goal of programming is computing values that are not random, random values are useful in simulation, cryptography, games, etc. A random-number generator is an algorithm that computes independent values. If the algorithm uses deterministic computation (a predictable sequence of values), it generates pseudo random numbers versus true random numbers.

All pseudo random-number generators (PRNG) involve some technique to scramble bits of a value, e.g., multiplicative recurrence:

\[
\text{rand} = 36973 \times (\text{rand} \& 65535) + (\text{rand} \gg 16) ; \quad \text{// scramble bits}
\]

Multiplication of large values adds new least-significant bits and drops most-significant bits.
PRNG prng1, prng2;
set_seed( prng1, 1009 );  set_seed( prng2, 1009 );
for ( 10 ) {
  // Do not cascade prng calls because side-effect functions called in arbitrary order.
  sout | nlOff | prng( prng1 );  sout | prng( prng1, 5 );  sout | prng( prng1, 0, 5 ) | ' \t ';
  sout | prng( prng2 );  sout | prng( prng2, 5 );  sout | prng( prng2, 0, 5 ) | nlOn;
}

37301721 2 2  37301721 2 2
1681308562 1 3 1681308562 1 3
290112364 3 2 290112364 3 2
1852700364 4 3 1852700364 4 3
733221210 1 3 733221210 1 3
1775396023 2 3 1775396023 2 3
123981445 2 3 123981445 2 3
2062557687 2 0 2062557687 2 0
283934808 1 0 283934808 1 0
672325890 1 3 672325890 1 3

Figure 13: Sequential PRNG

<table>
<thead>
<tr>
<th>bits 63–32 (most)</th>
<th>bits 31–0 (least)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x0</td>
<td>0x3e8e36</td>
</tr>
<tr>
<td>0x5f</td>
<td>0x718c25e1</td>
</tr>
<tr>
<td>0xad3e</td>
<td>0x7b5f1dbe</td>
</tr>
<tr>
<td>0xbc3b</td>
<td>0xac69ff19</td>
</tr>
<tr>
<td>0x1070f</td>
<td>0x2d258dc6</td>
</tr>
</tbody>
</table>

By dropping bits 63–32, bits 31–0 become scrambled after each multiply. The least-significant bits appear random but the same bits are always generated given a fixed starting value, called the seed (value 0x3e8e36 above). Hence, if a program uses the same seed, the same sequence of pseudo-random values is generated from the PRNG. Often the seed is set to another random value like a program's process identifier (getpid) or time when the program is run; hence, one random value bootstraps another. Finally, a PRNG usually generates a range of large values, e.g., [0, UINT_MAX], which are scaled using the modulus operator, e.g., prng() % 5 produces random values in the range 0–4.

CAY provides a sequential PRNG type only accessible by a single thread (not thread-safe) and a set of global and companion thread PRNG functions accessible by multiple threads without contention.

- The PRNG type is for sequential programs, like corouting:

  ```
  struct PRNG { ... }; // opaque type
  void ?(PRNG & prng);  // random seed
  void ?(PRNG & prng, uint32_t seed); // fixed seed
  void set_seed( PRNG & prng, uint32_t seed ); // set seed
  uint32_t get_seed( PRNG & prng ); // get seed
  uint32_t prng( PRNG & prng ); // [0,UINT_MAX]
  uint32_t prng( PRNG & prng, uint32_t u ); // [0,u]
  uint32_t prng( PRNG & prng, uint32_t l, uint32_t u ); // [l,u]
  uint32_t calls( PRNG & prng ); // number of calls
  ```

A PRNG object is used to randomize behaviour or values during execution, e.g., in games, a character makes a random move or an object takes on a random value. In this scenario, it is useful to have multiple PRNG objects, e.g., one per player or object. However, sequential execution is still repeatable given the same starting seeds for all PRNGs. Figure 13 shows an example that creates two sequential PRNGs, sets both to the same seed (1009), and illustrates the three forms for generating random values, where both PRNGs generate the same sequence of values.

- The PRNG global and companion thread functions are for concurrent programming, such as randomizing execution in short-running programs, e.g., yield( prng() % 5 ).

  ```
  void set_seed( uint32_t seed ); // set global seed
  uint32_t get_seed(); // get global seed
  ```


```cpp

thread T {
void main(T & th) { // thread address
    for (i, 10) {
        sout | nlOff | prng(); sout | prng(5); sout | prng(0, 5) | ' \t '; // SLOWER
        sout | nlOff | prng(th); sout | prng(th, 5); sout | prng(th, 0, 5) | nlOn; // FASTER
    }
}

int main() {
    set_seed(1009);
    thread & th = *active_thread(); // program main thread address
    for (i, 10) {
        sout | nlOff | prng(); sout | prng(5); sout | prng(0, 5) | ' \t '; // SLOWER
        sout | nlOff | prng(th); sout | prng(th, 5); sout | prng(th, 0, 5) | nlOn; // FASTER
    }
    sout | nl;
    T t; // run thread
}

37301721 2 2 1681308562 1 3
290112364 3 2 1852700364 4 3
73222121 1 3 177596023 2 3
123981445 2 3 2062557687 2 0
283934808 1 0 672325890 1 3
1414344101 1 3 873424536 3 4
871831898 3 4 866783532 0 1
2142057611 4 4 173102562 5
802117363 0 4 492964499 0 0
2346353643 1 3 2143013105 3 2
// same output as above from thread t

Figure 14: Concurrent PRNG

// SLOWER
uint32_t prng();       // [0,UINT_MAX]
uint32_t prng( uint32_t u ); // [0,u)
uint32_t prng( uint32_t l, uint32_t u ); // [l,u]

// FASTER
uint32_t prng( thread & th );       // [0,UINT_MAX]
uint32_t prng( thread & th, uint32_t u ); // [0,u)
uint32_t prng( thread & th, uint32_t l, uint32_t u ); // [l,u]

The only difference between the two sets of prng routines is performance.

Because concurrent execution is non-deterministic, seeding the concurrent PRNG is less important, as repeat-
able execution is impossible. Hence, there is one system-wide PRNG (global seed) but each CPU thread has its
own non-contended PRNG state. If the global seed is set, threads start with this seed, until it is reset and then
threads start with the reset seed. Hence, these threads generate the same sequence of random numbers from their
specific starting seed. If the global seed is not set, threads start with a random seed, until the global seed is set.
Hence, these threads generate different sequences of random numbers. If each thread needs its own seed, use a
sequential PRNG in each thread. The slower prng functions without a thread argument call active_thread internally
to indirectly access the current thread’s PRNG state, while the faster prng functions with a thread argument directly
access the thread through the thread parameter. If a thread pointer is available, e.g., in thread main, eliminating
the call to active_thread significantly reduces the cost of accessing the thread’s PRNG state. Figure 14 shows an
example using the slower/faster concurrent PRNG in the program main and a thread.
Multi-precision Integers

C++ has an interface to the GMP multi-precision signed-integers [16], similar to the C++ interface provided by GMP. The C++ interface wraps GMP routines into operator routines to make programming with multi-precision integers identical to using fixed-sized integers. The C++ type name for multi-precision signed-integers is Int and the header file is gmp.

```
void Int( Int * this ); // constructor/destructor
void Int( Int * this, Int init );
void Int( Int * this, zero_t );
void Int( Int * this, one_t );
void Int( Int * this, signed long int init );
void Int( Int * this, unsigned long int init );
void Int( Int * this, const char * val );
void Int( Int * this );

Int =?( Int * lhs, Int rhs ); // assignment
Int =?( Int * lhs, long int rhs );
Int =?( Int * lhs, unsigned long int rhs );
Int =?( Int * lhs, const char * rhs );

char =?( char * lhs, Int rhs );
short int =?( short int * lhs, Int rhs );
int =?( int * lhs, Int rhs );
long int =?( long int * lhs, Int rhs );
unsigned char =?( unsigned char * lhs, Int rhs );
unsigned short int =?( unsigned short int * lhs, Int rhs );
unsigned int =?( unsigned int * lhs, Int rhs );
unsigned long int =?( unsigned long int * lhs, Int rhs );

long int narrow( Int val );
unsigned long int narrow( Int val );

int =?( Int oper1, Int oper2 ); // comparison
int =?( Int oper1, long int oper2 );
int =?( long int oper2, Int oper1 );
int =?( Int oper1, unsigned long int oper2 );
int =?( unsigned long int oper2, Int oper1 );
int !=?( Int oper1, Int oper2 );
int !=?( Int oper1, long int oper2 );
int !=?( long int oper1, Int oper2 );
int !=?( Int oper1, unsigned long int oper2 );
int !=?( unsigned long int oper1, Int oper2 );

int <?( Int oper1, Int oper2 );
int <?( Int oper1, long int oper2 );
int <?( long int oper2, Int oper1 );
int <?( Int oper1, unsigned long int oper2 );
int <?( unsigned long int oper2, Int oper1 );
int <=?( Int oper1, Int oper2 );
int <=?( Int oper1, long int oper2 );
int <=?( long int oper2, Int oper1 );
int <=?( Int oper1, unsigned long int oper2 );
int <=?( unsigned long int oper2, Int oper1 );

int >?( Int oper1, Int oper2 );
int >?( Int oper1, long int oper2 );
int >?( long int oper2, Int oper1 );
int >?( Int oper1, unsigned long int oper2 );
int >?( unsigned long int oper2, Int oper1 );
```
int >?( unsigned long int oper1, Int oper2 );
int >=?( Int oper1, Int oper2 );
int >=?( Int oper1, long int oper2 );
int >=?( long int oper1, Int oper2 );
int >=?( Int oper1, unsigned long int oper2 );
int >=?( unsigned long int oper1, Int oper2 );

int +( Int oper ); // arithmetic
int -( Int oper );
int ~ ?( Int oper );

int ?&?( Int oper1, Int oper2 );
int ?&?( Int oper1, long int oper2 );
int ?&?( long int oper1, Int oper2 );
int ?&?( Int oper1, unsigned long int oper2 );
int ?&?( unsigned long int oper1, Int oper2 );
int ?&=( Int * lhs, Int rhs );

int ?|?( Int oper1, Int oper2 );
int ?|?( Int oper1, long int oper2 );
int ?|?( long int oper1, Int oper2 );
int ?|?( Int oper1, unsigned long int oper2 );
int ?|?( unsigned long int oper1, Int oper2 );
int ?|=?( Int * lhs, Int rhs );

int ?∧?( Int oper1, Int oper2 );
int ?∧?( Int oper1, long int oper2 );
int ?∧?( long int oper1, Int oper2 );
int ?∧?( Int oper1, unsigned long int oper2 );
int ?∧?( unsigned long int oper1, Int oper2 );
int ?∧=?( Int * lhs, Int rhs );

int ?+?( Int addend1, Int addend2 );
int ?+?( Int addend1, long int addend2 );
int ?+?( long int addend2, Int addend1 );
int ?+?( Int addend1, unsigned long int addend2 );
int ?+?( unsigned long int addend2, Int addend1 );
int ?+=?( Int * lhs, Int rhs );
int ?+=?( Int * lhs, long int rhs );
int ?+=?( Int * lhs, unsigned long int rhs );
int ?++?( Int * lhs );
int ?++( Int * lhs );

int ?−?( Int minuend, Int subtrahend );
int ?−?( Int minuend, long int subtrahend );
int ?−?( long int minuend, Int subtrahend );
int ?−?( Int minuend, unsigned long int subtrahend );
int ?−?( unsigned long int minuend, Int subtrahend );
int ?−=( Int * lhs, Int rhs );
int ?−=( Int * lhs, long int rhs );
int ?−=( Int * lhs, unsigned long int rhs );
int ?−−?( Int * lhs );
int ?−−( Int * lhs );

int ?∗?( Int multiplicator, Int multiplicand );
int ?∗?( Int multiplicator, long int multiplicand );
int ?∗?( long int multiplicand, Int multiplicator );
int ?∗?( Int multiplicator, unsigned long int multiplicand );
int ?∗?( unsigned long int multiplicand, Int multiplicator );
K Rational Numbers

Rational numbers are numbers written as a ratio, i.e., as a fraction, where the numerator (top number) and the denominator (bottom number) are whole numbers. When creating and computing with rational numbers, results are constantly reduced to keep the numerator and denominator as small as possible.

```c
struct Rational {
    long int numerator, denominator;  // invariant: denominator > 0
}; // Rational
Rational rational();  // constructors
Rational rational( long int n );
```

Figure 15 shows C and C factorial programs using the GMP interfaces. (Compile with flag -lgmp to link with the GMP library.)

K Rational Numbers

Rational numbers are numbers written as a ratio, i.e., as a fraction, where the numerator (top number) and the denominator (bottom number) are whole numbers. When creating and computing with rational numbers, results are constantly reduced to keep the numerator and denominator as small as possible.
```c
#include <gmp.hfa>
int main(void) {
    sout | "Factorial Numbers";
    Int fact = 1;

    sout | 0 | fact;
    for ( i; 40 ) {
        fact *= i;
        sout | i | fact;
    }
}
```

```c
#include <gmp.h>
int main(void) {
    gmp_printf("Factorial Numbers
");
    mpz_t fact;
    mpz_init_set_ui(fact, 1);
    gmp_printf("%d %Zd", 0, fact);
    for (unsigned int i = 1; i <= 40; i += 1) {
        mpz_mul_ui(fact, fact, i);
        gmp_printf("%d %Zd", i, fact);
    }
}
```

Factorial Numbers
0 1
1 1
2 2
3 6
4 24
5 120
6 720
7 5040
8 40320
9 362880
10 3628800
11 39916800
12 479001600
13 6227020800
14 87178291200
15 1307674368000
16 20922789888000
17 355687428096000
18 6402373705728000
19 12164510040883200
20 2432902008176640000
21 51090942171709440000
22 11240007277777607680000
23 25852016738884976640000
24 620448401733239439360000
25 1551121004330985984000000
26 4032914611266056358400000
27 10888869450418352160768000000
28 3048883446117138605015040000000
29 8841761937397019545436160000000
30 26525285981219158636308480000000
31 82228368541779228177255628800000000
32 26313083693369353016721801216000000000
33 868331761881188469551819440128000000000
34 2952327990396041408476186096352000000000
35 10333147966386449266666513375232000000000
36 37199332678990121746799944815083520000000000
37 1376375309122634504631597958158090240000000000
38 523022617466601117600722410007429120000000000
39 20397882081197443358640828173990289735680000000000
40 8159152832478977343456112695961158942720000000000

Figure 15: Multi-precision Factorials
Rational rational( long int n, long int d );
void ?()[ Rational r, zero_t );
void ?()[ Rational r, one_t );

long int numerator( Rational r );  // numerator/denominator getter/setter
long int numerator( Rational r, long int n );
long int denominator( Rational r );
long int denominator( Rational r, long int d );

int ?==?( Rational l, Rational r );  // comparison
int ?!=?( Rational l, Rational r );
int ?<?( Rational l, Rational r );
int ?<=?( Rational l, Rational r );
int ?>?( Rational l, Rational r );
int ?>=( Rational l, Rational r );

Rational -?( Rational r );  // arithmetic
Rational +?( Rational l, Rational r );
Rational -?( Rational l, Rational r );
Rational *?( Rational l, Rational r );
Rational /?( Rational l, Rational r );

double widen( Rational r );  // conversion
Rational narrow( double f, long int md );

forall( dtype istype | istream( istype ) ) istype * ?|?( istype *, Rational * ); // I/O
forall( dtype ostype | ostream( ostype ) ) ostype * ?|?( ostype *, Rational );

References

REFERENCES


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