C∀ (Cforall) User Manual
Version 1.0

"describe not prescribe"

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1 Introduction

C∀[1] is a modern general-purpose programming-language, designed as an evolutionary step forward for the C programming language. The syntax of C∀ builds from C and should look immediately familiar to C/C++ programmers. C∀ adds many modern programming-language features that directly lead to increased *safety* and *productivity*, while maintaining interoperability with existing C programs and achieving similar performance. Like C, C∀ 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∀ is to "describe not prescribe", which means C∀ tries to provide a pathway from low-level C programming to high-level C∀ programming, but it does not force programmers to "do the right thing". Programmers can cautiously add C∀ 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∀, for any reason, and in many cases, new C∀ features can be locally switched back to there C counterpart. There is no notion or requirement for *rewriting* a legacy C program in C∀; instead, a programmer evolves a legacy program into C∀ by incrementally incorporating C∀ features. As well, new programs can be written in C∀ using a combination of C and C∀ features.

C++ [27] 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 cannot be updated, 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∀ has 30 years of hindsight and a clean starting point.

Like C++, there may be both an old and new ways to achieve the same effect. For example, the following programs compare the C, C∀, and C++ I/O mechanisms, where the programs output the same result.

C

```
#include <stdio.h>

int main( void ) {
    int x = 0, y = 1, z = 2;
    printf( "%d %d %d\n", x, y, z );
}
```

C∀

```
#include <fstream>

int main( void ) {
    int x = 0, y = 1, z = 2;
    sout | x | y | z | endl;
}
```

C++

```
#include <iostream>
using namespace std;
int main() {
    int x = 0, y = 1, z = 2;
    cout<<x<<" "<<y<<" "<<z<<endl;
}
```

While the C∀ I/O looks similar to the C++ output style, there are important differences, such as automatic spacing between variables as in Python (see Section 21, p. 44).

1.1 Background

This document is a programmer reference-manual for the C∀ 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, *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∀ 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.

[1] Pronounced "C-for-all", and written C∀, CFA, or Cforall.

2 Why fix C?

The C programming language is a foundational technology for modern computing with millions 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 usually the only language of choice. The TIOBE index [29] for July 2018 ranks the top five most *popular* programming languages as Java 16%, C 14%, C++ 7.5%, Python 6%, Visual Basic 4% = 47.5%, where the next 50 languages are less than 4% each, with a long tail. The top 3 rankings over the past 30 years are:

	2018	2013	2008	2003	1998	1993	1988
Java	1	2	1	1	16	-	-
C	**2**	**1**	**2**	**2**	**1**	**1**	**1**
C++	3	4	3	3	2	2	5

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∀ project is to engineer modern language-features into C in an evolutionary rather than revolutionary way. C++ [7, 14] is an example of a similar project; however, it largely extended the C language, and did not address most of C's existing problems.[2] Fortran [16], Ada [1], and Cobol [8] 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 [20], Go [21], Rust [26] and D [3] 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 [6], but fixes many of the well known C problems while adding modern language-features. To achieve these goals required a significant engineering exercise, where we had to "think inside the existing C box". Without these significant extension to C, it is unable to cope with the needs of modern programming problems and programmers; as a result, it will fade into disuse. Considering the large body of existing C code and programmers, there is significant impetus to ensure C is transformed into a modern programming 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.

[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.

3 History

The C∀ project started with Dave Till's K-W C [5, 28], which extended C with new declaration syntax, multiple return values from routines, and advanced assignment capabilities using the notion of tuples. (See [30] for similar work in C++.) The first C∀ implementation of these extensions was by Rodolfo Esteves [15].

The signature feature of C∀ is *overloadable* parametric-polymorphic functions [9, 10, 13] with functions generalized using a **forall** clause (giving the language its name):

```
forall( otype 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 [11], and first implemented by Richard Bilson [2]. 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 legacy code-bases, so the C∀ project has been restarted.

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 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 very low cost. Hence, C∀ begins by leveraging the large repository of C libraries, and than 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, cabsf, cabs, and cabsl. Whereas, C∀ wraps each of these routines into ones with the overloaded name abs:

```
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 the name clash between the library routine abs and the C∀ names abs. Hence, names appearing in an **extern** "C" block have *C linkage*. Then overloading polymorphism uses a mechanism called *name mangling* to create unique names that are different from C names, which are not mangled. 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. There is no way around this problem, other than C's approach of creating unique names for each pairing of operation and types.

This example strongly 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 Compiling a C∀ Program

The command cfa is used to compile a C∀ program and is based on the GNU gcc command, *e.g.*:

```
cfa [ gcc-options ] [ C/C∀ source-files ] [ assembler/loader files ]
```

C∀ programs having the following gcc flags turned on:

-std=gnu11 The 2011 C standard plus GNU extensions.

-fgnu89-inline Use the traditional GNU semantics for inline routines in C11 mode, which allows inline routines in header files.

The following new C∀ options are available:

-CFA Only the C preprocessor 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.

-debug The program is linked with the debugging version of the runtime system. The debug version performs runtime checks to help during the debugging phase of a C∀ program, but can substantially slow program execution. The runtime checks should only be removed after the 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* assert*s 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.

-noquiet The C∀ compilation message is printed at the beginning of a compilation. **This option is the default.**

The following preprocessor variables are available:

__CFA_MAJOR__ is available during preprocessing and its value is the major version number of C∀.[3]

__CFA_MINOR__ is available during preprocessing and its value is the minor version number of C∀.

__CFA_PATCH__ is available during preprocessing and its value is the patch level number of C∀.

__CFA__, __CFORALL__, and __cforall are always available during preprocessing and have no value.

These preprocessor variables allow conditional compilation of programs that must work differently in these situations. For example, to toggle between C and C∀ extensions, use the following:

```
#ifndef __CFORALL__
#include <stdio.h>              // C header file
#else
#include <fstream>              // C∀ header file
#endif
```

which conditionally includes the correct header file, if the program is compiled using gcc or cfa.

[3] The C preprocessor allows only integer values in a preprocessor variable so a value like "1.0.0.0 " 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
#define __CFA_BFD_H__
#endif

#include_next <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

6 Backquote Identifiers

C∀ introduces several new keywords (see Section C, p. 62) that can clash with existing C variable-names in legacy code. Keyword clashes are accommodated by syntactic transformations using the C∀ backquote escape-mechanism:

```
int `otype` = 3;                        // make keyword an identifier
double `forall` = 3.5;
```

Existing C programs with keyword clashes can be converted by enclosing keyword identifiers in 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. 63) can be handled using preprocessor *interposition*: **#include_next** and **-I** filename. Several common C header-files with keyword clashes are fixed in the standard C∀ header-library, so there is a seamless programming-experience.

7 Constant Underscores

Numeric constants are extended to allow underscores, *e.g.*:

```
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_ff_ff_p_3;                           // hexadecimal floating
0x_1.ffff_ffff_p_128_l;                 // hexadecimal floating long constant
L_"\x_ff_ee";                           // 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 an underscore 0_377 or 0x_ff; the exponent infix E may start or end with an underscore 1.0_E10, 1.0E_10 or 1.0_E_10; the type suffixes U, L, etc. may start with an underscore 1_U, 1_ll or 1.0E10_f.

It is significantly easier to read and enter long constants when they are broken up into smaller groupings (many cultures use comma and/or period among digits for the same purpose). This extension is backwards compatible, matches with the use of underscore in variable names, and appears in Ada and Java 8.

8 Exponentiation Operator

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

As for division, there are exponentiation operators for integral and floating types, including the builtin complex types. Unsigned integral exponentiation is performed with repeated multiplication[4] (or shifting if the base is 2). Signed integral exponentiation is performed with repeated multiplication (or shifting if the base is 2), but yields a floating result because $x^{-y} = 1/x^y$. Hence, it is important to designate exponent integral-constants as unsigned or signed: 3 \ 3u return an integral result, while 3 \ 3 returns a floating result. Floating exponentiation is performed using logarithms, so the base cannot be negative.

```
sout | 2 \ 8u | 4 \ 3u | -4 \ 3u | 4 \ -3 | -4 \ -3 | 4.0 \ 2.1 | (1.0f+2.0fi) \ (3.0f+2.0fi) | endl;
256 64 -64 0.015625 -0.015625 18.3791736799526 0.264715-1.1922i
```

Parenthesis are necessary for complex constants or the expression is parsed as 1.0f+(2.0fi \ 3.0f)+2.0fi. The exponentiation operator is available for all the basic types, but for user-defined types, only the integral-computation versions are available. For returning an integral value, the user type T must define multiplication, *, and one, 1; for returning a floating value, an additional divide of type T into a **double** returning a **double** (**double** ?/?(**double**, T)) is necessary for negative exponents.

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. (Does not make sense for **do-while**.)

```
if ( int x = f() ) ...                    // x != 0
if ( int x = f(), y = g() ) ...           // x != 0 && y != 0
if ( int x = f(), y = g(); x < y ) ...    // relational expression
if ( struct S { int i; } x = { f() }; x.i < 4 ) // relational expression

while ( int x = f() ) ...                 // x != 0
while ( int x = f(), y = g() ) ...        // x != 0 && y != 0
while ( int x = f(), y = g(); x < y ) ... // relational expression
while ( struct S { int i; } x = { f() }; x.i < 4 ) ... // relational expression
```

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

Unless a relational expression is specified, each variable is compared not equal to 0, which is the standard semantics for the **if/while** expression, and the results are combined using the logical && operator.[5] The scope of the declaration(s) is local to the @if@ statement but exist within both the "then" and "else" clauses.

9.2 Loop Control

The **for/while/do–while** loop-control allows empty or simplified ranges. An empty conditional implies 1. The up-to range ~ means exclusive range [M,N); the up-to range ~= means inclusive range [M,N]. The down-to range –~ means exclusive range [N,M); the down-to range –~= means inclusive range [N,M]. 0 is the implicit start value; 1 is the implicit increment value. The up-to range uses += for increment; the down-to range uses –= for decrement. The loop index is polymorphic in the type of the start value or comparison value when start is implicitly 0.

loop control		output
while () { sout | "empty"; **break**; }	sout | endl;	empty
do { sout | "empty"; **break**; } **while** ();	sout | endl;	empty
for () { sout | "empty"; **break**; }	sout | endl;	empty
for (0) { sout | "A"; }	sout | "zero" | endl;	zero
for (1) { sout | "A"; }	sout | endl;	A
for (10) { sout | "A"; }	sout | endl;	A A A A A A A A A A
for (1 ~= 10 ~ 2) { sout | "B"; }	sout | endl;	B B B B B
for (10 –~= 1 ~ 2) { sout | "C"; }	sout | endl;	C C C C C
for (0.5 ~ 5.5) { sout | "D"; }	sout | endl;	D D D D D
for (5.5 –~ 0.5) { sout | "E"; }	sout | endl;	E E E E E
for (i; 10) { sout | i; }	sout | endl;	0 1 2 3 4 5 6 7 8 9
for (i; 1 ~= 10 ~ 2) { sout | i; }	sout | endl;	1 3 5 7 9
for (i; 10 –~= 1 ~ 2) { sout | i; }	sout | endl;	10 8 6 4 2
for (i; 0.5 ~ 5.5) { sout | i; }	sout | endl;	0.5 1.5 2.5 3.5 4.5
for (i; 5.5 –~ 0.5) { sout | i; }	sout | endl;	5.5 4.5 3.5 2.5 1.5
for (ui; 2u ~= 10u ~ 2u) { sout | ui; }	sout | endl;	2 4 6 8 10
for (ui; 10u –~= 2u ~ 2u) { sout | ui; }	sout | endl | endl;	10 8 6 4 2
int start = 3, comp = 10, inc = 2;		
for (i; start ~ comp ~ inc + 1) { sout | i; }	sout | endl;	3 6 9

9.3 switch Statement

C allows a number of questionable forms for the **switch** statement:

1. By default, the end of a **case** clause[6] *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 **break**:

```
switch ( i ) {
  case 1:
    ...
    // fall–through
  case 2:
    ...
    break;   // exit switch statement
}
```

[5] C++ only provides a single declaration always compared not equal to 0.

[6] In this section, the term *case clause* refers to either a **case** or **default** clause.

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

```
switch ( argc ) {
  case 3:
    // open output file
    // fall–through
  case 2:
    // open input file
    break;   // exit switch statement
  default:
    // usage message
}
```

```
if ( argc == 3 ) {
    // open output file
    // open input file
} else if ( argc == 2 ) {
    // open input file (duplicate)

} else {
    // usage message
}
```

In this example, case 2 is always done if case 3 is done. This control flow is difficult to simulate with if statements or a **switch** statement without fall-through as code must be duplicated or placed in a separate routine. 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;
}
```

However, this situation is handled in other languages without fall-through by allowing a list of case values. While fall-through itself is not a problem, the problem occurs when fall-through is the default, as this semantics is unintuitive to many programmers and is different from virtually all other 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
  case 2:
    while ( j < 5 ) {
        ...
      case 3:     // transfer into "while" statement
        ...
    } // while
} // switch
```

The problem with this usage is branching into control structures, which is known to cause both comprehension and technical difficulties. The comprehension problem occurs 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 no positive arguments for this kind of control flow, and therefore, there is a strong impetus to eliminate it. Nevertheless, C does have an idiom where this capability is used, known as "Duff's device" [12]:

```
register int n = (count + 7) / 8;
switch ( count % 8 ) {
case 0: do{ *to = *from++;
case 7:     *to = *from++;
case 6:     *to = *from++;
case 5:     *to = *from++;
case 4:     *to = *from++;
case 3:     *to = *from++;
case 2:     *to = *from++;
case 1:     *to = *from++;
        } while ( --n > 0 );
}
```

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. [12]

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. Virtually all 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: ...
    ...
    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**, both of which 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 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 C∀ 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.*:

```
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.*:

```
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 programming style, and there are a few reasonable situations involving fall-through where the **default** clause needs to appear is locations other than at the end. Therefore, no change is made for this issue.

4. Dealing with unreachable code in a **switch/choose** body is solved by restricting declarations and associated initialization to the start of statement body, which is executed *before* the transfer to the appropriate **case** clause[7] and precluding statements before the first **case** clause. Further declarations at the same nesting level as the statement body are disallowed to ensure every transfer into the body is sound.

```
switch ( x ) {
    int i = 0;                          // allowed only at start
  case 0:
    ...
    int j = 0;                          // disallowed
  case 1:
    {
        int k = 0;                      // allowed at different nesting levels
        ...
      case 2:                           // disallow case in nested statements
    }
  ...
}
```

9.4 case Statement

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 does not seem to be in the spirit of brevity normally associated with C. Therefore, the **case** clause is extended with a list of values, as in:

C∀	**C**
`switch ( i ) {`	`switch ( i ) {`
`  case 1, 3, 5:`	`  case 1: case 3 : case 5:  // odd values`
`    ...`	`    ...`
`  case 2, 4, 6:`	`  case 2: case 4 : case 6:  // even values`
`    ...`	`    ...`
`}`	`}`

In addition, subranges are allowed to specify case values.[8]

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

Lists of subranges are also allowed.

```
  case 1~5, 12~21, 35~42:
```

[7] Essentially, these declarations are hoisted before the **switch/choose** statement and both declarations and statement are surrounded by a compound statement.

[8] gcc has the same mechanism but awkward syntax, `2 ...42`, because a space is required after a number, otherwise the period is a decimal point.

C∀

```
LC: {
    ... declarations ...
    LS: switch ( ... ) {
      case 3:
        LIF: if ( ... ) {
            LF: for ( ... ) {
                LW: while ( ... ) {
                    ... break LC; ...
                    ... break LS; ...
                    ... break LIF; ...
                    ... continue LF; ...
                    ... break LF; ...
                    ... continue LW; ...
                    ... break LW; ...
                } // while
            } // for
        } else {
            ... break LIF; ...
        } // if
    } // switch
} // compound
```

C

```
{
    ... declarations ...
    switch ( ... ) {
      case 3:
        if ( ... ) {
            for ( ... ) {
                while ( ... ) {
                    ... goto LC; ...        // terminate compound
                    ... goto LS; ...        // terminate switch
                    ... goto LIF; ...       // terminate if
                    ... goto LFC; ...       // continue loop
                    ... goto LFB; ...       // terminate loop
                    ... goto LWC; ...       // continue loop
                    ... goto LWB; ...       // terminate loop
                LWC: ; } LWB: ;
            LFC: ; } LFB: ;
        } else {
            ... goto LIF; ...               // terminate if
        } L3: ;
    } LS: ;
} LC: ;
```

Figure 2: Multi-level Exit

9.5 Labelled continue / break Statement

While C provides **continue** and **break** statements for altering control flow, both are restricted to one level of nesting for a particular control structure. Unfortunately, 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 [4], 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 2 shows **continue** and **break** indicating the specific control structure, and the corresponding C program using only **goto** and labels. The innermost loop has 7 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. 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.

10 with Statement

Grouping heterogeneous data into *aggregate*s (structure/union) is a common programming practice, and an aggregate can be further organized into more complex structures, such as arrays and containers:

```
struct S {                              // aggregate
    char c;                             // fields
    int i;
    double d;
};
S s, as[10];
```

However, functions manipulating aggregates must repeat the aggregate name to access its containing fields:

```
void f( S s ) {
    s.c; s.i; s.d;                      // access containing fields
}
```

which extends to multiple levels of qualification for nested aggregates. A similar situation occurs in object-oriented programming, *e.g.*, C++:

```
struct S {
    char c;                             // fields
    int i;
    double d;
    void f() {                          // implicit "this" aggregate
        this->c; this->i; this->d;      // access containing fields
    }
}
```

Object-oriented nesting of member functions in a **class**/**struct** allows eliding **this**-> because of lexical scoping. However, for other aggregate parameters, qualification is necessary:

```
struct T { double m, n; };
int S::f( T & t ) {                     // multiple aggregate parameters
    c; i; d;                            // this->.c, this->.i, this->.d
    t.m; t.n;                           // must qualify
}
```

To simplify the programmer experience, C∀ provides a **with** statement (see Pascal [23, § 4.F]) to elide aggregate qualification to fields by opening a scope containing the field identifiers. Hence, the qualified fields become variables with the side-effect that it is easier to optimizing field references in a block.

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

with the generality of opening multiple aggregate-parameters:

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

In detail, the **with** statement has the form:

with-statement:
    `'with' '(' expression-list ')' compound-statement`

and may appear as the body of a function or nested within a function body. Each expression in the expression-list provides a type and object. The type must be an aggregate type. (Enumerations are already opened.) The object is the implicit qualifier for the open structure-fields.

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 S { int i; int j; double m; } s, w;
struct T { int i; int k; int m; } t, w;
with ( s, t ) {
    j + k;                          // unambiguous, s.j + t.k
    m = 5.0;                        // unambiguous, t.m = 5.0
    m = 1;                          // unambiguous, s.m = 1
    int a = m;                      // unambiguous, a = s.i
    double b = m;                   // unambiguous, b = t.m
    int c = s.i + t.i;              // unambiguous, qualification
    (double)m;                      // unambiguous, cast
}
```

For parallel semantics, both s.i and t.i are visible, so i is ambiguous without qualification; for nested semantics, t.i hides s.i, so i implies t.i. C∀'s ability to overload variables means fields with the same name but different types are automatically disambiguated, eliminating most qualification when opening multiple aggregates. Qualification or a cast is used to disambiguate.

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

```
void ?{}( S & s, int i ) with ( s ) {       // constructor
    s.i = i;  j = 3;  m = 5.5;              // initialize fields
}
```

Here, the assignment s.i = i means s.i = s.i, which is meaningless, and there is no mechanism to qualify the parameter i, making the assignment impossible using the function-body **with**. To solve this problem, parameters are treated like an initialized aggregate:

```
struct Params {
    S & s;
    int i;
} params;
```

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

```
void ?{}( S & s, int i ) with ( s ) with( params ) {
    s.i = i; j = 3; m = 5.5;
}
```

Finally, a cast may be used to disambiguate among overload variables in a **with** expression:

```
with ( w ) { ... }                  // ambiguous, same name and no context
with ( (S)w ) { ... }               // unambiguous, cast
```

and **with** expressions may be complex expressions with type reference (see Section **??**) to aggregate:

In object-oriented programming, there is an implicit first parameter, often names self or this, which is elided.

```
class C {
    int i, j;
    int mem() {                     // implicit "this" parameter
        i = 1;                      // this->i
        j = 2;                      // this->j
    }
```

```
}
```

Since C∀ is non-object-oriented, the equivalent object-oriented program looks like:

```
struct S { int i, j; };
int mem( S & this ) {                   // explicit "this" parameter
    this.i = 1;                         // "this" is not elided
    this.j = 2;
}
```

but it is cumbersome having to write "this." many times in a member.

C∀ provides a **with** clause/statement (see Pascal [23, § 4.F]) to elided the "this." by opening a scope containing field identifiers, changing the qualified fields into variables and giving an opportunity for optimizing qualified references.

```
int mem( S & this ) with( this ) {      // with clause
    i = 1;                              // this.i
    j = 2;                              // this.j
}
```

which extends to multiple routine parameters:

```
struct T { double m, n; };
int mem2( S & this1, T & this2 ) with( this1, this2 ) {
    i = 1; j = 2;
    m = 1.0; n = 2.0;
}
```

The statement form is used within a block:

```
int foo() {
    struct S1 { ... } s1;
    struct S2 { ... } s2;
    with( s1 ) {                        // with statement
        // access fields of s1 without qualification
        with s2 {                       // nesting
            // access fields of s1 and s2 without qualification
        }
    }
    with s1, s2 {
        // access unambiguous fields of s1 and s2 without qualification
    }
}
```

When opening multiple structures, fields with the same name and type are ambiguous and must be fully qualified. For fields with the same name but different type, context/cast can be used to disambiguate.

```
struct S { int i; int j; double m; } a, c;
struct T { int i; int k; int m } b, c;
with( a, b )
{
}
```

11 Exception Handling

Exception handling provides two mechanism: 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

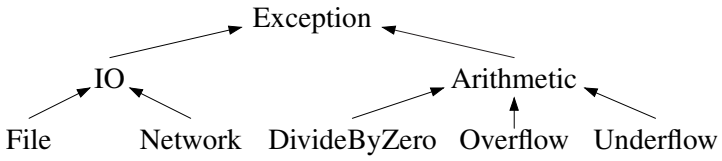
the kind of raise.

```
exception_t E {};                       // exception type
void f(...) {
    ... throw E{}; ...                  // termination
    ... throwResume E{}; ...            // resumption
}
try {
    f(...);
} catch( E e ; boolean-predicate ) {            // termination handler
    // recover and continue
} catchResume( E e ; boolean-predicate ) {      // resumption handler
    // repair and return
} finally {
    // always executed
}
```

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

11.1 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.*:

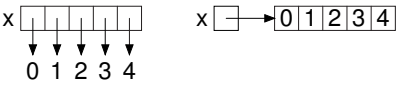
```
try {
    ...
} catch( Overflow ) {    // must appear first
    // handle overflow
} catch( Arithmetic )
    // handle other arithmetic issues
}
```

Multiple derivation among exception is not supported.

12 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.

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∀	C
`[5] * int x1;`	`int * x1 [5];`
`* [5] int x2;`	`int (*x2)[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∀	C
`* int x, y;`	`int *x, *y;`

The downside of this semantics is the need to separate regular and pointer declarations:

C∀	C
`* int x;` `int y;`	`int *x, y;`

which is prescribing a safety benefit. Other examples are:

C∀	C	
`[ 5 ] int z;`	`int z[ 5 ];`	*// array of 5 integers*
`[ 5 ] * char w;`	`char * w[ 5 ];`	*// array of 5 pointers to char*
`* [ 5 ] double v;`	`double (* v)[ 5 ];`	*// pointer to array of 5 doubles*
`struct s {`	`struct s {`	
`  int f0:3;`	`  int f0:3;`	*// common bit field syntax*
`  * int f1;`	`  int * f1;`	
`  [ 5 ] * int f2;`	`  int * f2[ 5 ]`	
`};`	`};`	

All type qualifiers, *e.g.*, **const**, **volatile**, etc., are used in the normal way with the new declarations and also appear left to right, *e.g.*:

C∀	C	
`const * const int x;`	`int const * const x;`	*// const pointer to const integer*
`const * [ 5 ] const int y;`	`const int (* const y)[ 5 ]`	*// const pointer to array of 5 const integers*

All declaration qualifiers, *e.g.*, **extern**, **static**, etc., are used in the normal way with the new declarations but can only appear at the start of a C∀ routine declaration,[9] *e.g.*:

C∀	C	
`extern [ 5 ] int x;`	`int extern x[ 5 ];`	*// externally visible array of 5 integers*
`static * const int y;`	`const int static * y;`	*// internally visible pointer to constant int*

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

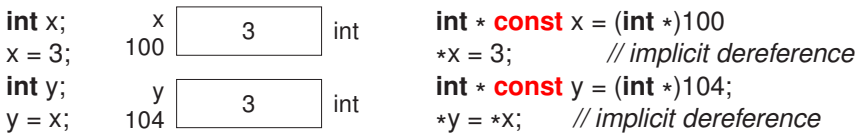
C∀	C
`y = (* int)x;`	`y = (int *)x;`
`i = sizeof([ 5 ] * int);`	`i = sizeof(int * [ 5 ]);`

Finally, new C∀ 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.

13 Pointer / Reference

C provides a *pointer type*; C∀ 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*.[10] 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:



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:

[9] The placement of a storage-class specifier other than at the beginning of the declaration specifiers in a declaration is an obsolescent feature. [6, § 6.11.5(1)]

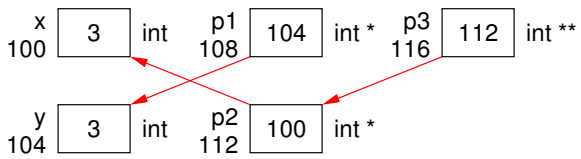
[10] One way to conceptualize the null pointer is that no variable is placed at this address, so the null-pointer address can be used to denote an uninitialized pointer/reference object; *i.e.*, the null pointer is guaranteed to compare unequal to a pointer to any object or routine. In general, a value with special meaning among a set of values is called a *sentinel value*, *e.g.*, −1 as a return code value.

explicit variable address			implicit variable address		
lda	r1,100	// load address of x			
ld	r2,(r1)	// load value of x	ld	r2,(100)	// load value of x
lda	r3,104	// load address of y			
st	r2,(r3)	// store x into y	st	r2,(104)	// store x into y

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 [24] infers pointer dereferencing to select the best meaning for each pointer usage

```
p2 = p1 + x;                    // 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:

```
p1 = p2;                        // p1 = p2  rather than  *p1 = *p2
p2 = p1 + x;                    // p2 = p1 + x  rather than  *p2 = *p1 + x
```

even though the assignment to p2 is likely incorrect, and the programmer probably meant:

```
p1 = p2;                        // pointer address assignment
*p2 = *p1 + x;                  // pointed-to value assignment / operation
```

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).

```
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:

```
*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 cancellation always yields a value (rvalue).[11] For a C∀ reference type, the cancellation on the left-hand side of assignment leaves the reference as an address (lvalue):

```
(&*)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):

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

Cancellation works to arbitrary depth.

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

```
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 = ...;                                 // 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:

```
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*:

[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. [6, § 6.5.3.2–3]

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

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

```
int & const cr = *malloc();
cr = 5;
free( &cr );
cr = 7;                                 // unsound pointer dereference
```

The position of the **const** qualifier *after* the pointer/reference qualifier causes confuse for C programmers. The **const** qualifier cannot be moved before the pointer/reference qualifier for C style-declarations; C∀-style declarations (see Section 12, p. 17) attempt to address this issue:

C∀	C
const * **const** * **const int** ccp; **const** & **const** & **const int** ccr;	**const int** * **const** * **const** ccp;

where the C∀ declaration is read left-to-right.

Finally, like pointers, references are usable and composable with other type operators and generators.

```
int w, x, y, z, & ar[3] = { x, y, z };  // initialize array of references
&ar[1] = &w;                            // change reference array element
typeof( ar[1] ) p;                      // (gcc) is int, i.e., the type of referenced object
typeof( &ar[1] ) q;                     // (gcc) is int &, i.e., the type of reference
sizeof( ar[1] ) == sizeof( int );       // is true, i.e., the size of referenced object
sizeof( &ar[1] ) == sizeof( int *)      // is true, i.e., the size of a reference
```

In contrast to C∀ reference types, C++'s reference types are all **const** references, preventing changes to the reference address, so only value assignment is possible, which eliminates half of the address duality. Also, C++ does not allow arrays of reference[12] Java's reference types to objects (all Java objects are on the heap) are like C pointers, which always manipulate the address, and there is no (bit-wise) object assignment, so objects are explicitly cloned by shallow or deep copying, which eliminates half of the address duality.

13.1 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.

```
int * p = &x;                           // assign address of x
int * p = x;                            // assign value of x
int & r = x;                            // must have address of x
```

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

[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 referant object.

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.

```
int & f( int & r );                     // reference parameter and return
z = f( x ) + f( y );                    // reference operator added, temporaries needed for call results
```

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.

```
int temp1 = f( x ), temp2 = f( y );
z = temp1 + temp2;
```

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.

```
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 C∀ 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.

C∀ *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 );                     // routine pointer
fp = f;                                 // reference initialization
fp = &f;                                // pointer initialization
fp = *f;                                // reference initialization
fp(3);                                  // reference invocation
(*fp)(3);                               // pointer invocation
```

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)

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

[14] This 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.

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] C∀ allows this additional use of references for routine objects in an attempt to give a more consistent meaning for them.

13.2 Address-of Semantics

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

- if R is an rvalue of type T $\&_1 \cdots \&_r$, where $r \geq 1$ references (& symbols), than &R has type T $*\&_2 \cdots \&_r$, *i.e.*, T pointer with $r-1$ references (& symbols).
- if L is an lvalue of type T $\&_1 \cdots \&_l$, where $l \geq 0$ references (& symbols), than &L has type T $*\&_1 \cdots \&_l$, *i.e.*, T pointer with l references (& symbols).

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

```
int x, * px, ** ppx, *** pppx, **** ppppx;
int & rx = x, && rrx = rx, &&& rrrx = rrx ;
x = rrrx;      // rrrx is an lvalue with type int &&& (equivalent to x)
px = &rrrx;        // starting from rrrx, &rrrx is an rvalue with type int *&&& (&x)
ppx = &&rrrx;  // starting from &rrrx, &&rrrx is an rvalue with type int **&& (&rx)
pppx = &&&rrrx;    // starting from &&rrrx, &&&rrrx is an rvalue with type int ***& (&rrx)
ppppx = &&&&rrrx; // starting from &&&rrrx, &&&&rrrx is an rvalue with type int **** (&rrrx)
```

The following example shows the second rule applied to different lvalue contexts:

```
int x, * px, ** ppx, *** pppx;
int & rx = x, && rrx = rx, &&& rrrx = rrx ;
rrrx = 2;      // rrrx is an lvalue with type int &&& (equivalent to x)
&rrrx = px;        // starting from rrrx, &rrrx is an rvalue with type int *&&& (rx)
&&rrrx = ppx;  // starting from &rrrx, &&rrrx is an rvalue with type int **&& (rrx)
&&&rrrx = pppx;    // starting from &&rrrx, &&&rrrx is an rvalue with type int ***& (rrrx)
```

13.3 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.

```
int x;
x + 1;          // lvalue variable (int) converts to rvalue for expression
```

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

C∀ 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.

```
int x, &r = x, f( int p );
x = r + f( r );  // lvalue reference converts to rvalue
```

[15] Dynamic code rewriting is possible but only in special circumstances.

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.

```
int x, &r = x, f( int & p ); // lvalue variable (int) convert to reference (int &)
f( x );      // lvalue variable (int) convert to reference (int &)
```

Conversion can restrict a type, where cv1 $\leq$ cv2, *e.g.*, passing an **int** to a **const volatile int** &, which has low cost. Conversion can expand a type, where cv1 $>$ cv2, *e.g.*, passing a **const volatile int** to an **int** &, which 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.

```
int x, & f( int & p );
f( x + 3 );   // rvalue parameter (int) implicitly converts to lvalue temporary reference (int &)
&f(...) = &x;  // rvalue result (int &) implicitly converts to lvalue temporary reference (int &)
```

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.

14 Routine Definition

C∀ also 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 [18, 25], *e.g.*:

```
[ 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 of the particular return type.[16] 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.

C∀ 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; {}
```

[16] Michael Tiemann, with help from Doug Lea, provided named return values in g++, circa 1989.

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 C∀ 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, C∀-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 C∀ 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 C∀ relies on all type qualifier characters appearing to the right of the type name. The inability to use C∀ 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 C∀ style routine definitions, *e.g.*:

```
[ int ] f( * int, int * );             // 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 C∀ routine terminates, the **return** statement *does not* contain an expression, as in:

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

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() {
    ...
}                                      // implicitly return x, y
```

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 ] j ( 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 12, p. 17), *e.g.*:

```
C :     const double bar1(), bar2( int ), bar3( double );
C∀ :    [const double] foo(), foo( int ), foo( 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,[9] *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 [22][17] are two mechanisms to simplify routine call. Both mechanisms are discussed with respect to C∀.

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:

```
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.

```
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∀-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:

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

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

[17] Francez [17] 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.

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

```
f( i : 3, 5.7 );                        // 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∀ 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:

```
void p( int x = 1, int y = 2, int z = 3 ) {...}
```

the allowable positional calls are:

```
p();                                    // rewrite ⇒ p( 1, 2, 3 )
p( 4 );                                 // rewrite ⇒ p( 4, 2, 3 )
p( 4, 4 );                              // rewrite ⇒ p( 4, 4, 3 )
p( 4, 4, 4 );                           // rewrite ⇒ p( 4, 4, 4 )
// empty arguments
p(  , 4, 4 );                           // rewrite ⇒ p( 1, 4, 4 )
p( 4,  , 4 );                           // rewrite ⇒ p( 4, 2, 4 )
p( 4, 4,   );                           // rewrite ⇒ p( 4, 4, 3 )
p( 4,  ,   );                           // rewrite ⇒ p( 4, 2, 3 )
p(  , 4,   );                           // rewrite ⇒ p( 1, 4, 3 )
p(  ,  , 4 );                           // rewrite ⇒ p( 1, 2, 4 )
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[18] (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 = 2, int = 3 );            // prototype: allowed
void p( int x, 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.

[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." [10, p. 128]

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... );
p( 1, 4, 5, 6, z : 3 );                 // assume p( /* positional */, ... , /* named */ );
p( 1, z : 3, 4, 5, 6 );                 // assume p( /* positional */, /* named */, ... );
```

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, C∀ requires named arguments before ellipse arguments. Finally, while ellipse arguments are needed for a small set of existing C routines, like printf, the extended C∀ type system largely eliminates the need for ellipse arguments (see Section 24), making much of this discussion moot.

Default arguments and overloading (see Section 24) are complementary. While in theory default arguments can be simulated with overloading, as in:

default arguments	overloading

`void p( int x, int y = 2, int z = 3 ) {...}`	`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:

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

Given the C∀ 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.*:

```
struct {
    int f1;                             // named field
    int f2 : 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
```

C Type Nesting	C Implicit Hoisting	C∀

struct S {
  enum C { R, G, B };
  struct T {
  union U { **int** i, j; };
  enum C c;
  short int i, j;
  };
  struct T t;
} s;
 	
int fred() {
  s.t.c = R;
  struct T t = { R, 1, 2 };
  enum C c;
  union U u;
}
	enum C { R, G, B };
	union U { **int** i, j; };
	struct T {
	  enum C c;
	  short int i, j;
	};
	struct S {
	  struct T t;
	} s;
		struct S {
		  enum C { R, G, B };
		  struct T {
		  union U { **int** i, j; };
		  enum C c;
		  short int i, j;
		  };
		  struct T t;
		} s;
		
		int fred() {
		  s.t.c = S.R; *// type qualification*
		  struct S.T t = { S.R, 1, 2 };
		  enum S.C c;
		  union S.T.U u;
		}

Figure 3: Type Nesting / Qualification

```
        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.*:

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

18 Nesting

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

18.1 Type Nesting

C∀ allows type nesting, and type qualification of the nested types (see Figure 3), 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 C∀, 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:

```
    forall( otype 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.

```
const 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)

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

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 );                       // 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 11, p. 15). 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.

```
typedef struct { int quot, rem; } div_t;    // from include stdlib.h
div_t div( int num, int den );
div_t qr = div( 13, 5 );                    // return quotient/remainder aggregate
printf( "%d %d\n", qr.quot, qr.rem );       // print quotient/remainder
```

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.

```
double modf( double x, double * i );      // from include math.h
double intp, frac = modf( 13.5, &intp );  // return integral and fractional components
printf( "%g %g\n", intp, frac );          // print integral/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.

```
[ char, int, double ] f( ... );
```

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.

```
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.

```
void g( int, int );                       // 1
void g( double, double );                 // 2
g( div( 13, 5 ) );                        // select 1
g( modf( 13.5 ) );                        // select 2
```

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 modf. 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.

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

```
    [ 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.

```
    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 expression*s and *tuple type*s. 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*.

```
    [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.

```
    [ 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.

```
    [ double, int ] di;
    [ 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*np 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.*:

```
[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
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 [28, 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.

```
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 [5, 28], there were 4 tuple coercions: opening, closing, flattening, and structuring. Opening coerces a tuple value 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 and structured into a tuple expression. For example, in

```
int f(int, [double, int]);
f([5, 10.2], 4);
```

There is only a single definition of f, and 3 arguments with only single interpretations. First, the argument alternative list [5, 10.2], 4 is flattened to produce the argument list 5, 10.2, 4. Next, the parameter matching algorithm begins, with $P =$ **int** and $A =$ **int**, which unifies exactly. Moving to the next parameter and argument, $P =$ [**double**, **int**] and $A =$ **double**. This time, the parameter is a tuple type, so the algorithm applies recursively with $P' =$ **double** and $A =$ **double**, which unifies exactly. Then $P' =$ **int** and $A =$ **double**, which again unifies exactly. At this point, the end of P' has been reached, so the arguments 10.2, 4 are structured into the tuple expression [10.2, 4]. Finally, the end of the parameter list P has also been reached, so the final expression is f(5, [10.2, 4]).

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.

```
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.

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

Multiple assignment assigns R_i to L_i for each i. That is, ?=?(&L_i, R_i) must be a well-typed expression. In the previous example, [x, y] = z, z is flattened into z.0, z.1, and the assignments x = z.0 and y = z.1 happen.

A mass assignment assigns the value R to each L_i. For a mass assignment to be valid, ?=?(&L_i, R) must be a well-typed expression. These semantics differ from C cascading assignment (*e.g.*, 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.

```
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 [28], wherein tuple assignment was a statement that allows cascading assignments as a special case. Restricting tuple assignment to statements was an attempt to 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 assignment used in one expression

```
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.

```
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.

```
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,

```
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,

```
struct S { char x; int y; double z; } s;
s.[x, y, z];
```

Here, the type of s.[x, y, z] is [**char**, **int**, **double**]. A member tuple expression has the form *e*.[x, y, z]; where *e* is an expression with type T, where T supports member access expressions, and x, y, z are all members of T with types T_x, T_y, and T_z respectively. Then the type of *e*.[x, y, z] is [T_x, T_y, T_z].

A member-access tuple may be used anywhere a tuple can be used, *e.g.*:

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

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

f( x.[ 0, 3 ] );                        // f( x.0, x.3 )
x.[ 0, 1 ] = x.[ 1, 0 ];                // [ x.0, x.1 ] = [ x.1, x.0 ]
[ long, int, long ] y = x.[ 2, 0, 2 ];
```

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

```
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.

```
[ 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* [28]. 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.

```
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.

```
1  int f();
2  void g();
3
4  (void)f(); // valid, ignore results
5  (int)g();  // invalid, void cannot be converted to int
6
7  struct A { int x; };
8  (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 [6, 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,

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

([int, double])f();          // (1) valid
([int, int, int])g();        // (2) valid
([void, [int, int]])g();     // (3) valid
([int, int, int, int])g();   // (4) invalid
([int, [int, int, int]])g(); // (5) invalid
```

(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 [(**int**)(g().0), (**int**)(g().1.0), (**int**)(g().2)]. Since **void** is effectively a 0-element tuple, (3) discards the first and third return values, which is effectively equivalent to [(**int**)(g().1.0), (**int**)(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 ([**int**, **int**, **int**])(g().1) is invalid. That is, it is invalid to cast [**int**, **int**] to [**int**, **int**, **int**].

19.10 Polymorphism

Due to the implicit flattening and structuring conversions involved in argument passing, **otype** 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.

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

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 otype and dtype components. For example, a plus operator can be written to add two triples of a type together.

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

```
([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.

```
forall(otype T | { T ?+?(T, T); })
```

```
[T, T, T] ?+?([T, T] x, [T, T, T, T]);
forall(otype T | { T ?+?(T, T); })
[T, T, T] ?+?(T x, [T, T, T, T, T]);
```

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.

```
void f([int, int], int, int);

f([0, 0], 0, 0);    // no cost
f(0, 0, 0, 0);      // cost for structuring
f([0, 0,], [0, 0]); // cost for flattening
f([0, 0, 0], 0);    // cost for flattening and structuring
```

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.

19.10.1 Assertion Inference

```
int f([int, double], double);
forall(otype T, otype U | { T f(T, U, U); })
void g(T, U);
g(5, 10.21);
```

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 [2]. 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.

```
int _thunk(int _p0, double _p1, double _p2) {
    return f([_p0, _p1], _p2);
}
```

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

20 Tuples

In C and C∀, 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 *lexical list*. The general syntax of a lexical list is:

```
[ exprlist ]
```

where *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:

```
[ x, y, z ]
[ 2 ]
[ v+w, x*y, 3.14159, f() ]
```

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 12.1). 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 *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 is:

```
[ typelist ]
```

where *typelist* is a list of one or more legal C∀ or C type specifications separated by commas, which may include other tuple type specifications. Examples of tuple types include:

```
[ unsigned int, char ]
[ double, double, double ]
[ * int, int * ]                        // mix of CFA and ANSI
[ * [ 5 ] int, * * char, * [ [ int, int ] ] (int, int) ]
```

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:

```
[ int, int ] x;                         // 2 element tuple, each element of type int
* [ char, char ] y;                     // pointer to a 2 element tuple
[ [ int, int ] ] z ([ int, int ]);
```

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:

```
f( [ 1, x+2, fred() ] );
f( 1, x+2, fred() );
```

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:

```
[ int, int ] w1;
[ int, int, int ] w2;
[ void ] f (int, int, int); /* three input parameters of type int */
[ void ] g ([ int, int, int ]); /* 3 element tuple as input */
f( [ 1, 2, 3 ] );
f( w1, 3 );
f( 1, w1 );
f( w2 );
g( [ 1, 2, 3 ] );
g( w1, 3 );
g( 1, w1 );
g( w2 );
```

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∀ 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:

```
[ 1, 3, 5 ]
[ 1, (2, 3), 5 ]
```

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.*, const and volatile, may modify a tuple type. The meaning is the same as for a type qualifier modifying an aggregate type [Int99, x 6.5.2.3(7),x 6.7.3(11)], *i.e.*, the qualifier is distributed across all of the types in the tuple, *e.g.*:

```
const volatile [ int, float, const int ] x;
```

is equivalent to:

```
[ const volatile int, const volatile float, const volatile int ] x;
```

Declaration qualifiers can only appear at the start of a C∀ tuple declaration4, *e.g.*:

```
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. □

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:

```
[ int, int, int, int ] w;
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:

```
[ 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:

```
[ 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], 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:

```
[ int, int, int, int ] w = [ 1, 2, 3, 4 ];
int x = 5;
[ 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 14).

□ 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∀ permits assignment to several variables at once using mass assignment [25]. Mass assignment has the following form:

```
[ 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. *expr* is any standard 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:

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

is equivalent to:

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

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

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

as conversions between intermediate assignments may lose information. A more complex example is:

```
[ 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

C∀ also supports the assignment of several values at once, known as multiple assignment [25, 18]. Multiple assignment has the following form:

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

The left-hand side is a tuple of *lvalues*, and the right-hand side is a tuple of *expr*s. Each *expr* appearing on the right-hand side of a multiple assignment statement is assigned to the corresponding *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 righthand side of multiple assignment
```

20.4 Cascade Assignment

As in C, C∀ mass and multiple assignments can be cascaded, producing cascade assignment. Cascade assignment has the following form:

```
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 I/O Library

The goal of C∀ I/O is to simplify the common cases, while fully supporting polymorphism and user defined types in a consistent way. The approach combines ideas from C++ and Python. The C∀ header file for the I/O library is fstream.

The common case is printing out a sequence of variables separated by whitespace.

C∀

```
int x = 1, y = 2, z = 3;
sout | x | y | z | endl;
1␣2␣3
```

C++

```
cout << x << "  " << y << "  " << z << endl;
1␣2␣3
```

The C∀ form has half the characters of the C++ form, and is similar to Python I/O with respect to implicit separators. Similar simplification occurs for tuple I/O, which prints all tuple values separated by ",␣".

```
[int, [ int, int ] ] t1 = [ 1, [ 2, 3 ] ], t2 = [ 4, [ 5, 6 ] ];
sout | t1 | t2 | endl;                    // print tuples
1␣2␣3␣4␣5␣6
```

Finally, C∀ uses the logical-or operator for I/O as it is the lowest-priority overloadable operator, other than assignment. Therefore, fewer output expressions require parenthesis.

```
C∀:   sout | x * 3 | y + 1 | z << 2 | x == y | (x | y) | (x || y) | (x > z ? 1 : 2) | endl;
C++:  cout << x * 3 << y + 1 << (z << 2) << (x == y) << (x | y) << (x || y) << (x > z ? 1 : 2) << endl;
      3␣3␣12␣0␣3␣1␣2
```

There is a weak similarity between the C∀ 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.

21.1 Implicit Separator

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

1. A separator does not appear at the start or end of a line.

```
sout | 1 | 2 | 3 | endl;
1␣2␣3
```

2. A separator does not appear before or after a character literal or variable.

```
sout | '1' | '2' | '3' | endl;
123
```

3. A separator does not appear before or after a null (empty) C string.

```
sout | 1 | "" | 2 | "" | 3 | endl;
123
```

   which is a local mechanism to disable insertion of the separator character.

4. A separator does not appear before a C string starting with the (extended) ASCII characters: `([{=$£¥¡¿«`

```
sout | "x (" | 1 | "x [" | 2 | "x {" | 3 | "x =" | 4 | "x $" | 5 | "x £" | 6 | "x ¥"
     | 7 | "x ¡" | 8 | "x ¿" | 9 | "x «" | 10 | endl;
x␣(1␣x␣[2␣x␣{3␣x␣=4␣x␣$5␣x␣£6␣x␣¥7␣x␣¡8␣x␣¿9␣x␣«10
```

   where ¡¿ are inverted opening exclamation and question marks, and « is an opening citation mark.

5. A seperator does not appear after a C string ending with the (extended) ASCII characters: `,.;!?)]}%¢»`

```
sout | 1 | ", x" | 2 | ". x" | 3 | "; x" | 4 | "! x" | 5 | "? x" | 6 | "% x"
     | 7 | "¢ x" | 8 | "» x" | 9 | ") x" | 10 | "] x" | 11 | "} x" | endl;
1,␣x␣2.␣x␣3;␣x␣4!␣x␣5?␣x␣6%␣x␣7¢␣x␣8»␣x␣9)␣x␣10]␣x␣11}␣x
```

   where » is a closing citation mark.

6. A seperator does not appear before or after a C string begining/ending with the ASCII quote or whitespace characters: `'":␣\t\v\f\r\n`

```
sout | "x'" | 1 | "'x'" | 2 | "'x\"" | 3 | "\"x:" | 4 | ":x " | 5 | " x\t" | 6 | "\tx" | endl;
```

```
x'1'x'2'x"3"x:4:x␣5␣x␣␣6␣␣␣x
```

7. If a space is desired before or after one of the special string start/end characters, simply insert a space.

```
sout | "x  (␣" | 1 | "␣)  x" | 2 | "␣,  x" | 3 | "␣:x:␣" | 4 | endl;
x␣(␣1␣)␣x␣2␣,␣x␣3␣:x:␣4
```

21.2 Manipulator

The following C++-style manipulators and routines control implicit seperation.

1. Routines sepSet and sep/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 | "  \"" | sep | "\"" | endl;
1,␣$2,␣$3␣",␣$"

sepSet( sout, "  " );                     // reset separator to " "
sout | 1 | 2 | 3 | "  \"" | sepGet( sout ) | "\"" | endl;
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 | endl;
1_2_3

sepSet( sout, store );                    // change separator back to original
sout | 1 | 2 | 3 | endl;
1␣2␣3
```

2. Routine sepSetTuple and sepTuple/sepGetTuple get and set the tuple separator-string. The tuple separator-string can be at most 16 characters including the '\0' string terminator (15 printable characters).

```
sepSetTuple( sout, "  " );                // set tuple separator from ", " to "  "
sout | t1 | t2 | "  \"" | sepTuple | "\"" | endl;
1␣2␣3␣4␣5␣6␣"␣"

sepSetTuple( sout, ",  " );               // reset tuple separator to ",  "
sout | t1 | t2 | "  \"" | sepGetTuple( sout ) | "\"" | endl;
1,␣2,␣3␣4,␣5,␣6␣",␣"
```

As for sepGet, sepGetTuple can be use to store a tuple separator and then restore it.

3. Manipulators sepDisable and sepEnable *globally* toggle printing the separator, *i.e.*, the seperator is adjusted with respect to all subsequent printed items.

```
sout | sepDisable | 1 | 2 | 3 | endl;     // globally turn off implicit separator
123

sout | sepEnable | 1 | 2 | 3 | endl;      // globally turn on implicit separator
1␣2␣3
```

4. Manipulators sepOn and sepOff *locally* toggle printing the separator, *i.e.*, the seperator is adjusted only with respect to the next printed item.

```
sout | 1 | sepOff | 2 | 3 | endl;          // locally turn off implicit separator
12␣3
sout | sepDisable | 1 | sepOn | 2 | 3 | endl; // locally turn on implicit separator
1␣23
```

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

```
sout | t1 | sepOff | t2 | endl;              // locally turn on/off implicit separator
1,␣2,␣34,␣5,␣6
```

sepOn *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.

```
sout | sepOn | 1 | 2 | 3 | sepOn | endl ;   // sepOn does nothing at start/end of line
1␣2␣3
sout | sep | 1 | 2 | 3 | sep | endl ;       // use sep to print separator at start/end of line
␣1␣2␣3␣
```

22 Types

22.1 Type Definitions

C∀ allows users to define new types using the keyword type.

```
// SensorValue is a distinct type and represented as an int
type SensorValue = int;
```

A type definition is different from a typedef in C because a typedef just creates an alias for a type, while Do.s type definition creates a distinct type. This means that users can define distinct function overloads for the new type (see Overloading for more information). For example:

```
type SensorValue = int;
void printValue(int v) {...}
void printValue(SensorValue v) {...}
void process(int v) {...}

SensorValue s = ...;

printValue(s); // calls version with SensorValue argument

printValue((int) s); // calls version with int argument

process(s); // implicit conversion to int
```

If SensorValue was defined with a typedef, then these two print functions would not have unique signatures. This can be very useful to create a distinct type that has the same representation as another type.

The compiler will assume it can safely convert from the old type to the new type, implicitly. Users may override this and define a function that must be called to convert from one type to another.

```
type SensorValue = int;
// ()? is the overloaded conversion operator identifier
// This function converts an int to a SensorValue
SensorValue ()?(int val) {
    ...
}
void process(int v) {...}
```

```
SensorValue s = ...;
process(s); // implicit call to conversion operator
```

In many cases, it is not desired for the compiler to do this implicit conversion. To avoid that, the user can use the explicit modifier on the conversion operator. Any places where the conversion is needed but not explicit (with a cast), will result in a compile-time error.

```
type SensorValue = int;

// conversion from int to SensorValue; must be explicit
explicit SensorValue ()?(int val) {
    ...
}

void process(int v) {...}

SensorValue s = ...;
process(s); // implicit cast to int: compile-time error
process((int) s); // explicit cast to int: calls conversion func
```

The conversion may not require any code, but still need to be explicit; in that case, the syntax can be simplified to:

```
type SensorValue = int;
explicit SensorValue ()?(int);
void process(int v) {...}

SensorValue s = ...;
process(s); // compile-time error
process((int) s); // type is converted, no function is called
```

22.2 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.

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

Point p = {0.0, 0.0};
```

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:

```
void foo(Point p);

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

```
    cp.x = 10.3; // x from Point is accessed directly
    cp.color = 0x33aaff; // color is accessed normally
    foo(cp); // cp can be used directly as a Point
```

23 Constructors and Destructors

C∀ supports C initialization of structures, but it also adds constructors for more advanced initialization. Additionally, C∀ 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 References for more information).

24 Overloading

Overloading refers to the capability of a programmer to define and use multiple objects in a program with the same name. In C∀, 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 C∀ 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. C∀ allows overloading of functions, operators, variables, and even the constants 0 and 1.

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 C∀ Language Specification.

```
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
        ...
    }
    ...
}
```

24.1 Overloaded Constant

The constants 0 and 1 have special meaning. In C∀, 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)).

```
struct Widget {
    int id;
    float size;
    Parts * optionalParts;
};

// ?{} is the constructor operator identifier
// The first argument is a reference to the type to initialize
// Subsequent arguments can be specified for initialization

void ?{}(Widget &w) { // default constructor
    w.id = -1;
    w.size = 0.0;
    w.optionalParts = 0;
}

// constructor with values (does not need to include all fields)
void ?{}(Widget &w, int id, float size) {
    w.id = id;
    w.size = size;
    w.optionalParts = 0;
}

//^? is the destructor operator identifier
void ^?(Widget &w) { // destructor
    w.id = 0;
    w.size = 0.0;
    if (w.optionalParts != 0) {
    // This is the only pointer to optionalParts, free it
    free(w.optionalParts);
    w.optionalParts = 0;
    }
}

Widget baz; // reserve space only
Widget foo{}; // calls default constructor
Widget bar{23, 2.45}; // calls constructor with values
baz{24, 0.91}; // calls constructor with values
?{}(baz, 24, 0.91}; // explicit call to constructor
^bar; // explicit call to destructor
^?(bar); // explicit call to destructor
```

Figure 4: Constructors and Destructors

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 programmers 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:

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

const Complex 0 = {0, 0};
const Complex 1 = {1, 0};
...

    Complex a = 0;
...

    a++;
...
    if (a) { // same as if (a == 0)
...
}
```

24.2 Variable Overloading

The overload rules of C∀ 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:

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

24.3 Function Overloading

Overloaded functions in C∀ 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.

```
// 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

    // 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

    // specialization is preferred over unsafe conversions

    f = bar(d, e); // chooses option 5
```

24.4 Operator Overloading

C∀ 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. C∀ uses the following special identifiers to name overloaded operators:

?[?]	subscripting	?+?	addition	?=?	simple assignment
?()	function call	?−?	subtraction	?\=?	exponentiation assignment
?++	postfix increment	?<<?	left shift	?*=?	multiplication assignment
?−−	postfix decrement	?>>?	right shift	?/=?	division assignment
++?	prefix increment	?<?	less than	?%=?	remainder assignment
−−?	prefix decrement	?<=?	less than or equal	?+=?	addition assignment
*?	dereference	?>=?	greater than or equal	?−=?	subtraction assignment
+?	unary plus	?>?	greater than	?<<=?	left-shift assignment
−?	arithmetic negation	?==?	equality	?>>=?	right-shift assignment
~?	bitwise negation	?!=?	inequality	?&=?	bitwise AND assignment
!?	logical complement	?&?	bitwise AND	?^=?	exclusive OR assignment
?\?	exponentiation	?^?	exclusive OR	?|=?	inclusive OR assignment
?*?	multiplication	?|?	inclusive OR		
?/?	division				
?%?	remainder				

Table 1: Operator Identifiers

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);
```

25 Auto Type-Inferencing

Auto type-inferencing occurs in a declaration where a variable's type is inferred from its initialization expression type.

C++	gcc	
	`#define expr 3.0 * i`	
`auto j = 3.0 * 4;`	`typeof(expr) j = expr;`	`// use type of initialization expression`
`int i;`	`int i;`	
`auto k = i;`	`typeof(i) k = i;`	`// use type of primary variable`

The two important capabilities are:

- preventing having to determine or write long generic types,
- ensure 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

```
auto j = ...
```

and the need to write a routine to compute using 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 significant 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.

26 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.

26.1 Coroutine

Coroutines are the precursor to tasks. Figure 5 shows a coroutine that computes the Fibonacci numbers.

26.2 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:

```
type Account = monitor {
    const unsigned long number; // account number
    float balance; // account balance
};
```

26.3 Tasks

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

27 Language Comparisons

C∀ is one of many languages that attempts to improve upon C. In developing C∀, 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, C∀ is compared with what the writers of this document consider to be the closest competitors of Do: C++, Go, Rust, and D.

```
#include <fstream>
#include <coroutine>

coroutine Fibonacci {
    int fn;                             // used for communication
};
void ?{}( Fibonacci * this ) {
    this->fn = 0;
}
void main( Fibonacci * this ) {
    int fn1, fn2;                       // retained between resumes
    this->fn = 0;                       // case 0
    fn1 = this->fn;
    suspend();                          // return to last resume

    this->fn = 1;                       // case 1
    fn2 = fn1;
    fn1 = this->fn;
    suspend();                          // return to last resume

    for ( ;; ) {                        // general case
        this->fn = fn1 + fn2;
        fn2 = fn1;
        fn1 = this->fn;
        suspend();                      // return to last resume
    } // for
}
int next( Fibonacci * this ) {
    resume( this );                     // transfer to last suspend
    return this->fn;
}
int main() {
    Fibonacci f1, f2;
    for ( int i = 1; i <= 10; i += 1 ) {
        sout | next( &f1 ) | '  ' | next( &f2 ) | endl;
    } // for
}
```

Figure 5: Fibonacci Coroutine

27.1 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. C∀ uses modules instead to perform these same tasks. Classes in C++ also enable inheritance among types. Instead of inheritance, C∀ 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 (Venners, 1998) (Pike, Go at Google: Language Design in the Service of Software Engineering , 2012).

```
#include <fstream>
#include <kernel>
#include <monitor>
#include <thread>

monitor global_t {
    int value;
};

void ?{}(global_t * this) {
    this->value = 0;
}

static global_t global;

void increment3( global_t * mutex this ) {
    this->value += 1;
}
void increment2( global_t * mutex this ) {
    increment3( this );
}
void increment( global_t * mutex this ) {
    increment2( this );
}

thread MyThread {};

void main( MyThread* this ) {
    for(int i = 0; i < 1_000_000; i++) {
        increment( &global );
    }
}
int main(int argc, char* argv[]) {
    processor p;
    {
        MyThread f[4];
    }
    sout | global.value | endl;
}
```

Figure 6: Atomic-Counter Monitor

Figure 7: f:AtomicCounterMonitor

```
#include <fstream>
#include <kernel>
#include <stdlib>
#include <thread>

thread First  { signal_once * lock; };
thread Second { signal_once * lock; };

void ?{}( First * this, signal_once* lock ) { this->lock = lock; }
void ?{}( Second * this, signal_once* lock ) { this->lock = lock; }

void main( First * this ) {
    for ( int i = 0; i < 10; i += 1 ) {
        sout | "First : Suspend No." | i + 1 | endl;
        yield();
    }
    signal( this->lock );
}

void main( Second * this ) {
    wait( this->lock );
    for ( int i = 0; i < 10; i += 1 ) {
        sout | "Second : Suspend No." | i + 1 | endl;
        yield();
    }
}

int main( void ) {
    signal_once lock;
    sout | "User main begin" | endl;
    {
        processor p;
        {
            First  f = { &lock };
            Second s = { &lock };
        }
    }
    sout | "User main end" | endl;
}
```

Figure 8: Simple Tasks

Overloading in C∀ is very similar to overloading in C++, with the exception of the additional use, in C∀, of the return type to differentiate between overloaded functions. References and exceptions in C∀ are heavily based on the same features from C++. The mechanism for interoperating with C code in C∀ is also borrowed from C++.

Both C∀ and C++ provide generics, and the syntax is quite similar. The key difference between the two, is that in C++ templates are expanded at compile time for each type for which the template is instantiated, while in C∀, function pointers are used to make the generic fully compilable. This means that a generic function can be defined in a compiled library, and still be used as expected from source.

27.2 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 light weight, 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 light weight 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.

27.3 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).

27.4 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 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
*␣?*?                    // dereference, multiplication 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 deference 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++ [7].

1. **Change:** add new keywords
   New keywords are added to C∀ (see Section C, p. 62).
   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.*:

```
x;                       // int x
*y;                      // int *y
f( p1, p2 );             // int f( int p1, int p2 );
g( p1, p2 ) int p1, p2;  // int g( int p1, int p2 );
```

C∀ continues to support K&R routine definitions:

```
f( a, b, c )                    // default int return
    int a, b; char c            // K&R parameter declarations
{
    ...
}
```

Rationale: dropped from C11 standard.[19]

Effect on original feature: original feature is deprecated.
Any old C programs using these K&R declarations are invalid C∀ programs.

Difficulty of converting: trivial to convert to C∀.

How widely used: existing usages are rare.

3. **Change:** type of character literal **int** to **char** to allow more intuitive overloading:

```
int rtn( int i );
int rtn( char c );
rtn( 'x' );                     // programmer expects 2nd rtn to be called
```

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

```
sout | 'x' | "  " | (int)'x' | endl;
x 120
```

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

Effect on original feature: change to semantics of well-defined feature that depend on:

```
sizeof( 'x' ) == sizeof( int )
```

no long work the same in C∀ programs.

Difficulty of converting: simple

How widely used: programs that depend upon **sizeof**(`'x'`) are rare and can be changed to **sizeof**(**char**).

4. **Change:** make string literals **const**:

```
char * p = "abc";               // valid in C, deprecated in C∀
char * q = expr ? "abc" : "de"; // valid in C, invalid in C∀
```

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.

Rationale: This change is a safety issue:

```
char * p = "abc";
p[0] = 'w';                     // segment fault or change constant literal
```

The same problem occurs when passing a string literal to a routine that changes its argument.

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

Difficulty of converting: simple syntactic transformation, because string literals can be converted to **char** *.

How widely used: programs that have a legitimate reason to treat string literals as pointers to potentially modifiable memory are rare.

[19] 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 [6, § 6.7.2(2)]

5. **Change:** remove *tentative definitions*, which only occurs at file scope:

```
int i;                  // forward definition
int *j = &i;            // forward reference, valid in C, invalid in C∀
int i = 0;              // definition
```

is valid in C, and invalid in C∀ 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,

```
struct X { int i; struct X *next; };
static struct X a;              // forward definition
static struct X b = { 0, &a };// forward reference, valid in C, invalid in C∀
static struct X a = { 1, &b };    // definition
```

Rationale: avoids having different initialization rules for builtin 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 **struct** introduce a scope for nested types:

```
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)
    };
    .Colour shirt;                // type defined outside (top level)
    Colour pants;                 // 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, *i.e.*, the nested types are hoisted to the scope of the outer-most type, which is not useful and confusing. C∀ is 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: **struct** scope is crucial to C∀ 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:

```
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 **void** * to or from any T * pointer:

```
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 *
}
```

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):

```
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.

9. **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,

```
p = (void*)(struct x {int i;} *)0;
```

declares a new type, struct x .

Rationale: This prohibition helps to clarify the location of declarations in the source code.

Effect on original feature: Deletion of a semantically welldefined feature.

Difficulty of converting: Syntactic transformation.

How widely used: Seldom.

10. **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 C∀ Keywords

C∀ introduces the following new keywords.

catch	**dtype**	**finally**	**one_t**	**try**	**with**
catchResume	**enable**	**forall**	**otype**	**ttype**	**zero_t**
choose	**exception**	**ftype**	**throw**	**virtual**	
coroutine	**fallthrough**	**monitor**	**throwResume**	**waitfor**	
disable	**fallthru**	**mutex**	**trait**	**when**	

D Standard Headers

C11 prescribes the following standard header-files [6, § 7.1.2] and C∀ adds to this list:

C11						C∀
assert.h	float.h	math.h	stdatomic.h	stdlib.h	time.h	gmp.h
complex.h	inttypes.h	setjmp.h	stdbool.h	stdnoreturn.h	uchar.h	malloc.h
ctype.h	iso646.h	signal.h	stddef.h	string.h	wchar.h	unistd.h
errno.h	limits.h	stdalign.h	stdint.h	tgmath.h	wctype.h	
fenv.h	locale.h	stdarg.h	stdio.h	threads.h		

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. 3). All other C header files must be explicitly wrapped in **extern** `"C"` to prevent name mangling. For C++, the name-mangling issue is often handled internally in many 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.

E.1 Storage Management

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.

Storage management provides the following capabilities:

fill after allocation the storage is filled with a specified character.

resize an existing allocation is decreased or increased in 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. For an increase in storage size, new storage after the copied data may be filled.

alignment an allocation starts 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.

The table shows allocation routines supporting different combinations of storage-management capabilities:

		fill	resize	alignment	array
C	malloc	no	no	no	no
	calloc	yes (0 only)	no	no	yes
	realloc	no/copy	yes	no	no
	memalign	no	no	yes	no
	posix_memalign	no	no	yes	no
C11	aligned_alloc	no	no	yes	no
C∀	alloc	no/copy/yes	no/yes	no	yes
	align_alloc	no/yes	no	yes	yes

It is impossible to resize with alignment because the underlying realloc allocates storage if more space is needed, and it does not honour alignment from the original allocation.

```
1   // C unsafe allocation
2   extern "C" {
3   void * malloc( size_t size );
4   void * calloc( size_t dim, size_t size );
5   void * realloc( void * ptr, size_t size );
6   void * memalign( size_t align, size_t size );
7   int posix_memalign( void ** ptr, size_t align, size_t size );
8
9   // C unsafe initialization/copy
10  void * memset( void * dest, int c, size_t size );
11  void * memcpy( void * dest, const void * src, size_t size );
12  }
13
14  forall( dtype T | sized(T) ) {
15  // C∀  safe equivalents, i.e., implicit size specification
16      T * malloc( void );
17      T * calloc( size_t dim );
18      T * realloc( T * ptr, size_t size );
19      T * memalign( size_t align );
20      T * aligned_alloc( size_t align );
21      int posix_memalign( T ** ptr, size_t align );
22
23  // C∀  safe general allocation, fill, resize, array
24      T * alloc( void );
25      T * alloc( char fill );
26      T * alloc( size_t dim );
27      T * alloc( size_t dim, char fill );
28      T * alloc( T ptr[], size_t dim );
29      T * alloc( T ptr[], size_t dim, char fill );
30
31  // C∀  safe general allocation, align, fill, array
32      T * align_alloc( size_t align );
33      T * align_alloc( size_t align, char fill );
34      T * align_alloc( size_t align, size_t dim );
35      T * align_alloc( size_t align, size_t dim, char fill );
36
37  // C∀  safe initialization/copy, i.e., implicit size specification
38      T * memset( T * dest, char c );
39      T * memcpy( T * dest, const T * src );
40
41  // C∀  safe initialization/copy array
42      T * amemset( T dest[], char c, size_t dim );
43      T * amemcpy( T dest[], const T src[], size_t dim );
44  }
45
46  // C∀  allocation/deallocation and constructor/destructor
47  forall( dtype T | sized(T), ttype Params | { void ?{}( T *, Params ); } ) T * new( Params p );
48  forall( dtype T | { void ^?{}( T * ); } ) void delete( T * ptr );
49  forall( dtype T, ttype Params | { void ^?{}( T * ); void delete( Params ); } )
50    void delete( T * ptr, Params rest );
51
52  // C∀  allocation/deallocation and constructor/destructor, array
53  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 );
```

E.2 String to Value Conversion

```
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 );
unsigned 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 );
unsigned 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.3 Search / Sort

```
forall( otype T | { int ?<?( T, T ); } )    // location
T * bsearch( T key, const T * arr, size_t dim );

forall( otype T | { int ?<?( T, T ); } )    // position
unsigned int bsearch( T key, const T * arr, size_t dim );

forall( otype T | { int ?<?( T, T ); } )
void qsort( const T * arr, size_t dim );

forall( otype 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( otype K, otype E | { int ?<?( K, K ); K getKey( const E & ); } ) {
```

```
        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( otype 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( otype 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)
    unsigned long int random( void );
    unsigned long int random( unsigned long int u ); // [0,u)
    unsigned long int random( unsigned long int l, unsigned long int u ); // [l,u)
    float random( void );                           // [0.0, 1.0)
    double random( void );                          // [0.0, 1.0)
    float _Complex random( void );                  // [0.0, 1.0)+[0.0, 1.0)i
    double _Complex random( void );                 // [0.0, 1.0)+[0.0, 1.0)i
    long double _Complex random( void );            // [0.0, 1.0)+[0.0, 1.0)i
```

E.6 Algorithms

```
forall( otype T | { int ?<?( T, T ); } ) T min( T t1, T t2 );
forall( otype T | { int ?>?( T, T ); } ) T max( T t1, T t2 );
forall( otype T | { T min( T, T ); T max( T, T ); } ) T clamp( T value, T min_val, T max_val );
forall( otype T ) void swap( T * t1, T * t2 );
```

F Math Library

The C∀ 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 );

float div( float, float, int * );           // alternative name for remquo
double div( double, double, int * );
long double div( long double, long double, int * );
[ 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 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 );
```

F.3 Logarithm

```
    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 );

    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 );
```

```
1
2       float logb( float );
3       double logb( double );
4       long double logb( long double );
5
6       float sqrt( float );
7       double sqrt( double );
8       long double sqrt( long double );
9       float _Complex sqrt( float _Complex );
10      double _Complex sqrt( double _Complex );
11      long double _Complex sqrt( long double _Complex );
12
13      float cbrt( float );
14      double cbrt( double );
15      long double cbrt( long double );
16
17      float hypot( float, float );
18      double hypot( double, double );
19      long double hypot( long double, long double );
```

20 F.4 Trigonometric

```
21      float sin( float );
22      double sin( double );
23      long double sin( long double );
24      float _Complex sin( float _Complex );
25      double _Complex sin( double _Complex );
26      long double _Complex sin( long double _Complex );
27
28      float cos( float );
29      double cos( double );
30      long double cos( long double );
31      float _Complex cos( float _Complex );
32      double _Complex cos( double _Complex );
33      long double _Complex cos( long double _Complex );
34
35      float tan( float );
36      double tan( double );
37      long double tan( long double );
38      float _Complex tan( float _Complex );
39      double _Complex tan( double _Complex );
40      long double _Complex tan( long double _Complex );
41
42      float asin( float );
43      double asin( double );
44      long double asin( long double );
45      float _Complex asin( float _Complex );
46      double _Complex asin( double _Complex );
47      long double _Complex asin( long double _Complex );
48
49      float acos( float );
50      double acos( double );
51      long double acos( long double );
```

```
1   float _Complex acos( float _Complex );
2   double _Complex acos( double _Complex );
3   long double _Complex acos( long double _Complex );
4
5   float atan( float );
6   double atan( double );
7   long double atan( long double );
8   float _Complex atan( float _Complex );
9   double _Complex atan( double _Complex );
10  long double _Complex atan( long double _Complex );
11
12  float atan2( float, float );
13  double atan2( double, double );
14  long double atan2( long double, long double );
15
16  float atan( float, float );                 // alternative name for atan2
17  double atan( double, double );
18  long double atan( long double, long double );
```

19 F.5 Hyperbolic

```
20  float sinh( float );
21  double sinh( double );
22  long double sinh( long double );
23  float _Complex sinh( float _Complex );
24  double _Complex sinh( double _Complex );
25  long double _Complex sinh( long double _Complex );
26
27  float cosh( float );
28  double cosh( double );
29  long double cosh( long double );
30  float _Complex cosh( float _Complex );
31  double _Complex cosh( double _Complex );
32  long double _Complex cosh( long double _Complex );
33
34  float tanh( float );
35  double tanh( double );
36  long double tanh( long double );
37  float _Complex tanh( float _Complex );
38  double _Complex tanh( double _Complex );
39  long double _Complex tanh( long double _Complex );
40
41  float asinh( float );
42  double asinh( double );
43  long double asinh( long double );
44  float _Complex asinh( float _Complex );
45  double _Complex asinh( double _Complex );
46  long double _Complex asinh( long double _Complex );
47
48  float acosh( float );
49  double acosh( double );
50  long double acosh( long double );
51  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 );

float erfc( float );
double erfc( double );
long double erfc( long double );
float _Complex erfc( float _Complex );
double _Complex erfc( double _Complex );
long double _Complex erfc( long double _Complex );

float lgamma( float );
double lgamma( double );
long double lgamma( long double );
float lgamma( float, int * );
double lgamma( double, int * );
long double lgamma( long double, int * );

float tgamma( float );
double tgamma( double );
long double tgamma( long double );
```

F.7 Nearest Integer

```
float floor( float );
double floor( double );
long double floor( long double );

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 int rint( long 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 );
long long int llrint( float );
long long int llrint( double );
long long int llrint( 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 );
```

F.8 Manipulation

```
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 nexttoward( float, long double );
    double nexttoward( double, long double );
    long double nexttoward( 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 tv;                             // nanoseconds
    };

    void ?{}( Duration & dur );
    void ?{}( Duration & dur, zero_t );

    Duration ?=?( Duration & dur, zero_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 lhs, int64_t rhs );
    Duration ?*?( int64_t lhs, Duration rhs );
    Duration ?*=?( Duration & lhs, int64_t rhs );

    int64_t ?/?( 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, 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 );

    _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 );

    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 ?`s( double sec );
    Duration ?`m( int64_t min );
    Duration ?`m( double min );
    Duration ?`h( int64_t hours );
    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 );

    Duration max( Duration lhs, Duration rhs );
    Duration min( Duration lhs, Duration rhs );
```

G.2 timeval

```
    void ?{}( timeval & t );
    void ?{}( timeval & t, time_t sec, suseconds_t usec );
    void ?{}( timeval & t, time_t sec );
    void ?{}( timeval & t, zero_t );
    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, time_t sec, __syscall_slong_t nsec );
void ?{}( timespec & t, time_t sec );
void ?{}( timespec & t, zero_t );
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 tv;                        // nanoseconds since UNIX epoch
};

void ?{}( Time & time );
void ?{}( Time & time, zero_t );

Time ?=?( Time & time, zero_t );

void ?{}( Time & time, timeval t );
Time ?=?( Time & time, timeval t );

void ?{}( Time & time, timespec t );
Time ?=?( Time & time, timespec t );

Time ?+?( Time & lhs, Duration rhs );
Time ?+?( Duration lhs, Time rhs );
Time ?+=?( Time & lhs, Duration rhs );

Duration ?-?( 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 );
_Bool ?>=?( Time lhs, Time rhs );

char * yy_mm_dd( Time time, char * buf );
char * ?`ymd( Time time, char * buf ) { // short form
    return yy_mm_dd( time, buf );
```

```
    } // ymd

    char * mm_dd_yy( Time time, char * buf );
    char * ?`mdy( Time time, char * buf ) { // short form
        return mm_dd_yy( time, buf );
    } // mdy

    char * dd_mm_yy( Time time, char * buf );
    char * ?`dmy( Time time, char * buf ) { // short form
        return dd_mm_yy( time, buf );;
    } // dmy

    size_t strftime( char * buf, size_t size, const char * fmt, Time time );
    forall( dtype ostype | ostream( ostype ) ) ostype & ?|?( ostype & os, Time time );
```

H Clock

H.1 C time

```
    char * ctime( time_t tp );
    char * ctime_r( time_t tp, char * buf );
    tm * gmtime( time_t tp );
    tm * gmtime_r( time_t tp, tm * result );
    tm * localtime( time_t tp );
    tm * localtime_r( time_t tp, tm * result );
```

H.2 Clock

```
    struct Clock {
        Duration offset;                // for virtual clock: contains offset from real-time
        int clocktype;                  // implementation only -1 (virtual), CLOCK_REALTIME
    };

    void resetClock( Clock & clk );
    void resetClock( Clock & clk, Duration adj );
    void ?{}( Clock & clk );
    void ?{}( Clock & clk, Duration adj );

    Duration getResNsec();              // with nanoseconds
    Duration getRes();                  // without nanoseconds

    Time getTimeNsec();                 // with nanoseconds
    Time getTime();                     // without nanoseconds
    Time getTime( Clock & clk );
    Time ?()( Clock & clk );
    timeval getTime( Clock & clk );
    tm getTime( Clock & clk );
```

I Multi-precision Integers

C∀ has an interface to the GMP multi-precision signed-integers [19], 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 * this );                         // constructor/destructor
void ?{}( Int * this, Int init );
void ?{}( Int * this, zero_t );
void ?{}( Int * this, one_t );
void ?{}( Int * this, signed long int init );
void ?{}( Int * this, unsigned long int init );
void ?{}( Int * this, const char * val );
void ^?{}( 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 );
```

```
1   int ?>?( Int oper1, Int oper2 );
2   int ?>?( Int oper1, long int oper2 );
3   int ?>?( long int oper1, Int oper2 );
4   int ?>?( Int oper1, unsigned long int oper2 );
5   int ?>?( unsigned long int oper1, Int oper2 );
6
7   int ?>=?( Int oper1, Int oper2 );
8   int ?>=?( Int oper1, long int oper2 );
9   int ?>=?( long int oper1, Int oper2 );
10  int ?>=?( Int oper1, unsigned long int oper2 );
11  int ?>=?( unsigned long int oper1, Int oper2 );
12
13  Int +?( Int oper );                    // arithmetic
14  Int -?( Int oper );
15  Int ~?( Int oper );
16
17  Int ?&?( Int oper1, Int oper2 );
18  Int ?&?( Int oper1, long int oper2 );
19  Int ?&?( long int oper1, Int oper2 );
20  Int ?&?( Int oper1, unsigned long int oper2 );
21  Int ?&?( unsigned long int oper1, Int oper2 );
22  Int ?&=?( Int * lhs, Int rhs );
23
24  Int ?|?( Int oper1, Int oper2 );
25  Int ?|?( Int oper1, long int oper2 );
26  Int ?|?( long int oper1, Int oper2 );
27  Int ?|?( Int oper1, unsigned long int oper2 );
28  Int ?|?( unsigned long int oper1, Int oper2 );
29  Int ?|=?( Int * lhs, Int rhs );
30
31  Int ?^?( Int oper1, Int oper2 );
32  Int ?^?( Int oper1, long int oper2 );
33  Int ?^?( long int oper1, Int oper2 );
34  Int ?^?( Int oper1, unsigned long int oper2 );
35  Int ?^?( unsigned long int oper1, Int oper2 );
36  Int ?^=?( Int * lhs, Int rhs );
37
38  Int ?+?( Int addend1, Int addend2 );
39  Int ?+?( Int addend1, long int addend2 );
40  Int ?+?( long int addend2, Int addend1 );
41  Int ?+?( Int addend1, unsigned long int addend2 );
42  Int ?+?( unsigned long int addend2, Int addend1 );
43  Int ?+=?( Int * lhs, Int rhs );
44  Int ?+=?( Int * lhs, long int rhs );
45  Int ?+=?( Int * lhs, unsigned long int rhs );
46  Int ++?( Int * lhs );
47  Int ?++( Int * lhs );
48
49  Int ?-?( Int minuend, Int subtrahend );
50  Int ?-?( Int minuend, long int subtrahend );
51  Int ?-?( long int minuend, Int subtrahend );
52  Int ?-?( Int minuend, unsigned long int subtrahend );
53  Int ?-?( unsigned long int minuend, Int subtrahend );
```

```
1   Int ?-=?( Int * lhs, Int rhs );
2   Int ?-=?( Int * lhs, long int rhs );
3   Int ?-=?( Int * lhs, unsigned long int rhs );
4   Int --?( Int * lhs );
5   Int ?--( Int * lhs );
6
7   Int ?*?( Int multiplicator, Int multiplicand );
8   Int ?*?( Int multiplicator, long int multiplicand );
9   Int ?*?( long int multiplicand, Int multiplicator );
10  Int ?*?( Int multiplicator, unsigned long int multiplicand );
11  Int ?*?( unsigned long int multiplicand, Int multiplicator );
12  Int ?*=?( Int * lhs, Int rhs );
13  Int ?*=?( Int * lhs, long int rhs );
14  Int ?*=?( Int * lhs, unsigned long int rhs );
15
16  Int ?/?( Int dividend, Int divisor );
17  Int ?/?( Int dividend, unsigned long int divisor );
18  Int ?/?( unsigned long int dividend, Int divisor );
19  Int ?/?( Int dividend, long int divisor );
20  Int ?/?( long int dividend, Int divisor );
21  Int ?/=?( Int * lhs, Int rhs );
22  Int ?/=?( Int * lhs, long int rhs );
23  Int ?/=?( Int * lhs, unsigned long int rhs );
24
25  [ Int, Int ] div( Int dividend, Int divisor );
26  [ Int, Int ] div( Int dividend, unsigned long int divisor );
27
28  Int ?%?( Int dividend, Int divisor );
29  Int ?%?( Int dividend, unsigned long int divisor );
30  Int ?%?( unsigned long int dividend, Int divisor );
31  Int ?%?( Int dividend, long int divisor );
32  Int ?%?( long int dividend, Int divisor );
33  Int ?%=?( Int * lhs, Int rhs );
34  Int ?%=?( Int * lhs, long int rhs );
35  Int ?%=?( Int * lhs, unsigned long int rhs );
36
37  Int ?<<?( Int shiften, mp_bitcnt_t shift );
38  Int ?<<=?( Int * lhs, mp_bitcnt_t shift );
39  Int ?>>?( Int shiften, mp_bitcnt_t shift );
40  Int ?>>=?( Int * lhs, mp_bitcnt_t shift );
41
42  Int abs( Int oper );                    // number functions
43  Int fact( unsigned long int N );
44  Int gcd( Int oper1, Int oper2 );
45  Int pow( Int base, unsigned long int exponent );
46  Int pow( unsigned long int base, unsigned long int exponent );
47  void srandom( gmp_randstate_t state );
48  Int random( gmp_randstate_t state, mp_bitcnt_t n );
49  Int random( gmp_randstate_t state, Int n );
50  Int random( gmp_randstate_t state, mp_size_t max_size );
51  int sgn( Int oper );
52  Int sqrt( Int oper );
53
```

```
forall( dtype istype | istream( istype ) ) istype * ?|?( istype * is, lnt * mp );  // I/O
forall( dtype ostype | ostream( ostype ) ) ostype * ?|?( ostype * os, lnt mp );
```

The following factorial programs contrast using GMP with the C∀ and C interfaces, where the output from these programs appears in Figure 9. (Compile with flag –lgmp to link with the GMP library.)

C∀

```
#include <gmp>
int main( void ) {
    sout | "Factorial Numbers" | endl;
    Int fact = 1;

    sout | 0 | fact | endl;
    for ( unsigned int i = 1; i <= 40; i += 1 ) {
        fact *= i;
        sout | i | fact | endl;
    }
}
```

C

```
#include <gmp.h>
int main( void ) {
    gmp_printf( "Factorial Numbers\n" );
    mpz_t fact;
    mpz_init_set_ui( fact, 1 );
    gmp_printf( "%d %Zd\n", 0, fact );
    for ( unsigned int i = 1; i <= 40; i += 1 ) {
        mpz_mul_ui( fact, fact, i );
        gmp_printf( "%d %Zd\n", i, fact );
    }
}
```

J 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.

```
// implementation
struct Rational {
    long int numerator, denominator;  // invariant: denominator > 0
}; // Rational

Rational rational();                          // constructors
Rational rational( long int n );
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 );
```

```
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 121645100408832000
20 2432902008176640000
21 51090942171709440000
22 1124000727777607680000
23 25852016738884976640000
24 620448401733239439360000
25 15511210043330985984000000
26 403291461126605635584000000
27 10888869450418352160768000000
28 304888344611713860501504000000
29 8841761993739701954543616000000
30 265252859812191058636308480000000
31 8222838654177922817725562880000000
32 263130836933693530167218012160000000
33 8683317618811886495518194401280000000
34 295232799039604140847618609643520000000
35 10333147966386144929666651337523200000000
36 371993326789901217467999448150835200000000
37 13763753091226345046315979581580902400000000
38 523022617466601111760007224100074291200000000
39 20397882081197443358640281739902897356800000000
40 815915283247897734345611269596115894272000000000
```

Figure 9: Multi-precision Factorials

```
    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 );
```

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