

# The Co-dfns Compiler

Aaron W. Hsu

June 10, 2022

Co-dfns Compiler: High-performance, Parallel APL Compiler  
Copyright © 2011-2022 Aaron W. Hsu <arcfide@sacrideo.us>

This program is free software: you can redistribute it and/or modify it under the terms of the GNU Affero General Public License as published by the Free Software Foundation, either version 3 of the License, or (at your option) any later version.

This program is distributed in the hope that it will be useful, but WITHOUT ANY WARRANTY; without even the implied warranty of MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the GNU Affero General Public License for more details.

You should have received a copy of the GNU Affero General Public License along with this program. If not, see <http://gnu.org/licenses>.

*This program is available under other license terms. Please contact Aaron W. Hsu <arcfide@sacrideo.us> for more information.*

## Contents

|          |   |           |
|----------|---|-----------|
| <b>1</b> | <b>Introduction</b>                                   | <b>4</b>  |
| <b>2</b> | <b>User’s Guide</b>                                   | <b>4</b>  |
| <b>3</b> | <b>Co-dfns Architecture</b>                           | <b>4</b>  |
| 3.1      | Global Settings . . . . .                             | 8         |
| 3.2      | The Fix API . . . . .                                 | 11        |
| 3.3      | The User Command API . . . . .                        | 13        |
| 3.4      | AST Record Structure . . . . .                        | 13        |
| 3.5      | Converters between parent and depth vectors . . . . . | 13        |
| <b>4</b> | <b>Testing</b>  | <b>14</b> |
| <b>5</b> | <b>Co-dfns Compiler</b>                               | <b>15</b> |
| 5.1      | Parser . . . . .                                      | 15        |
| 5.1.1    | Output of the Parser . . . . .                        | 16        |
| 5.1.2    | Handling Parsing Errors . . . . .                     | 19        |
| 5.1.3    | Tokenizing the Input . . . . .                        | 20        |
| 5.1.4    | Parsing Token Stream . . . . .                        | 23        |
| 5.2      | Compiler Transformations . . . . .                    | 30        |
| 5.3      | Code Generator . . . . .                              | 31        |
| 5.4      | Backend C Compiler Interface . . . . .                | 36        |
| 5.5      | Linking with Dyalog . . . . .                         | 37        |
| 5.6      | Runtime . . . . .                                     | 37        |
| <b>6</b> | <b>Language Features</b>                              | <b>38</b> |
| <b>7</b> | <b>Runtime Primitives</b>                             | <b>38</b> |
| <b>8</b> | <b>Utilities</b>                                      | <b>38</b> |
| 8.1      | Must haves . . . . .                                  | 38        |
| 8.2      | AST Pretty-printing . . . . .                         | 39        |
| 8.3      | Debugging utilities . . . . .                         | 40        |
| 8.4      | Reading and Writing Files . . . . .                   | 42        |
| 8.5      | XML Rendering . . . . .                               | 42        |
| 8.6      | Detecting the Operating System . . . . .              | 42        |
| <b>9</b> | <b>Developer Infrastructure</b>                       | <b>43</b> |
| 9.1      | Building the Compiler . . . . .                       | 43        |
| 9.1.1    | Tangling the Source . . . . .                         | 43        |
| 9.1.2    | Weaving the Source . . . . .                          | 45        |
| 9.2      | Building the Runtime . . . . .                        | 47        |
| 9.3      | Loading the Compiler . . . . .                        | 50        |

June 10, 2022

codfns.nw 3

|   |           |
|---|-----------|
| <b>10 Index</b>                             | <b>51</b> |
| 10.1 Chunks . . . . .                       | 51        |
| 10.2 Identifiers . . . . .                  | 52        |
| <b>11 GNU AFFERO GENERAL PUBLIC LICENSE</b> | <b>54</b> |

## 1 Introduction

## 2 User's Guide

## 3 Co-dfns Architecture

This section describes the “big picture” parts of the Co-*dfns* compiler. The intent here is to try to show how all of the various moving parts of the compiler fit together, to provide a sort of road map that will give you a precise plan for understanding how the various components affect one another. One of the most important things to understand in any compiler is the net effect a local change in the code can have on the rest of the system, so I hope that this section will help to clarify this.

The design of the Co-*dfns* compiler is one of austerity and minimalism. My intent is, was, and hopefully shall remain that of producing an exceptionally clear design that avoids or eliminates unnecessary code and complexity within the design. I attack this problem in many ways, but I primarily attempt to do this by both reducing the size of the code surface in total, that is, write less code, as well as reducing the number of entry points and paths through that code. In other words, my ideal design is one in which you enter the compiler in some limited, but well defined and useful set of entry points, and then proceed in a linear fashion through the code as the execution path, resulting finally in your result. This is the “ultimate” in data flow, functionally oriented programming.

The ramifications of this design choice implies a few important things. Firstly, it implies that I reduce and eliminate any code that represents boilerplate or that does not actively contribute to the “big picture” of the code. This is required in an extreme degree if I am to reduce the overall complexity of the design. This also implies that there is very little intentional redundancy in the shape and style of the source, making it very terse and compact. Since there are intentionally very few entry and exit points through the control flow of the code, this reduces the number of dependencies for me to be aware of when dealing with a single piece of code, but this also comes at the cost of not being able to see many examples of the interfaces with that code. Often, there will be one, and only one place, in which a given piece of code is used, and I do not want the code to needlessly store excess information in its source that doesn't need to be there.

This all culminates in something that can be quite shocking at first: making a change to the source is almost always a big deal. If all the source code is meaningful and carefully constructed, this also means that making changes to this code are almost always non-trivial,

because if the code represented something trivial, I would have tried to remove it from the code so that only the “big things” were in the code itself. Thus, anyone who wishes to view and read the compiler code should take it upon themselves to appreciate the way in which the code flows together, and how the flow of the program runs, as doing so will be essential to understanding how to make changes to the source without breaking something. Fortunately, this does come with the intended benefits of a very short and simple codebase that has clear flow through the system, it just means that if you want to change something, make sure you realize that you are almost always likely to be working at the “architectural” level, rather than at the small and trivial level of details.

The compiler is designed to fit into a single Dyalog APL namespace, and importantly, we do not define additional nested namespaces or other forms of name hiding. I intentionally want to restrict the namespace to a single global one. This single global namespace should therefore contain the carefully curated names that matter, and any that do not matter should, ideally, not be defined or used. The namespace itself can be divided into three main groupings: the public facing entry-points into the system, the compiler logic itself, and the utilities or other elements that serve to support the others. This gives use the following code outline.

```
5  ⟨* 5⟩≡
    :Namespace codfns

        ⟨Global Settings 8a⟩
        ⟨The Fix API 11⟩
        ⟨User-command API 13a⟩

        ⟨Parser 15⟩
        ⟨Compiler 30⟩
        ⟨Code Generator 31⟩
        ⟨Interface to the backend C compiler 36⟩
        ⟨Linking with Dyalog 37a⟩

        ⟨Must Have APL Utilities 38c⟩
        ⟨AST Record Structure 13b⟩
        ⟨Converters between parent and depth vectors 13c⟩
        ⟨XML Rendering 42b⟩
        ⟨Pretty-printing AST trees 39⟩
```

```
    :EndNamespace
```

Root chunk (not used in this document).

Defines:

codfns, used in chunks 6, 14b, 31, 36, 41b, and 43–49.

This  $\langle * 5 \rangle$  chunk is meant to be stored to a file. We have a build system for doing this that depends on the contents of the  $\langle \textit{Tangle Commands 6} \rangle$  chunk. Thus, we follow the convention here of updating the contents of the  $\langle \textit{Tangle Commands 6} \rangle$  chunk each time that we initially define a new chunk that is intended to be output to a file during the tangling process. See more about the build infrastructure later in this document.

```
6   $\langle \textit{Tangle Commands 6} \rangle \equiv$   
    echo "Tangling codfns.apln..."  
    notangle codfns.nw > src/codfns.apln
```

This definition is continued in chunks 14b, 41b, 44, 46, and 47c.

This code is used in chunk 43.

Defines:

codfns.apln, never used.

Uses codfns 5 and src 48.

The primary user-facing interfaces into the compiler are *⟨The Fix API 11⟩* and the *⟨User-command API 13a⟩*. These are the ways that you primarily drive the entire compiler. I intentionally expose the rest of the compiler interfaces without hiding them so that people who wish to leverage these other parts of the system without using the “entire” compiler pipeline are able to do so, but I do not consider this a public interface.

This distinction matters because of our testing philosophy and our version numbering. Generally speaking, our version numbering scheme only tracks a major or minor change in the compiler when the externally facing interfaces receive some fundamental changes. Changes to the internal changes are *not* considered for this versioning scheme. Moreover, since I intend for there to be great freedom in changing and altering the behavior of these internal pipeline interfaces, these interfaces are not directly tested, and the test suite should *not* include testing against these internal interfaces. We philosophically only test against the external interfaces, and eschew internal unit tests.<sup>1</sup>

The utility functions defined below the core compiler pipeline represent functionality that is tangential to the main compiler operation. However, these utilities also tend to represent some specific insight into the design of the compiler. Understanding the core AST structure and design as well as getting a grip on how to manipulate the core tree manipulation structures are vital to understanding the rest of the code. Therefore, this section spends more time on discussing these topics before the upcoming sections dealing with a more detailed exposition of the compiler itself. However, there are utilities that we consider more advanced, such as the pretty-printing functions and XML rendering that are topics of interest to advanced users of the compiler, but which are not part of the main compiler pipeline. Even though these functions have intentionally general application and are likely to be useful not only to those working on the compiler itself but also to those who are using more advanced compiler features, these utilities are not critical to a deep understanding of the compiler, so these are not discussed in this section. Instead, we discuss those topics in the section on developer tooling and infrastructure concerns.

The remaining parts of this section will describe the external facing interfaces to the compiler as well as the core underlying data structures and idioms that form the underlying skeleton and foundation for writing and working with any aspect of the compiler. These are all feature and component agnostic elements of the system that do not belong solely to only a single part, but that impact all other

---

<sup>1</sup>You can read more of my opinions on this matter in my article, “The Fallacy of Unit Testing”.

elements of the compiler source code, and so it pays especially well to pay attention and understand this code to a high degree.

### 3.1 Global Settings

There are some global options that we assume to exist throughout the compiler. These set the standard behaviors as well as serve as knobs that can be tweaked in some cases to identify what behaviors we want from the rest of the compiler.

First, we have a set of read-only global constants that are defined to configure our APL environment. These are the typical ones, and we try to stick to the defaults, except that we are sane, and thus we use `⎕IO` set to 0.

8a `<Global Settings 8a>≡`  
`⎕IO ⎕ML ⎕WX←0 1 3`

This definition is continued in chunks 8–10.

This code is used in chunk 5.

Defines:

`⎕IO`, used in chunk 40.

`⎕ML`, used in chunk 40.

`⎕WX`, never used.

Additionally, we set a `VERSION` constant to track changes to the system through the distributions. We use semantic versioning<sup>2</sup> as our versioning scheme. That being said, we also do not have particular qualms about changing the public API at a rapid pace, provided that we document this.

8b `<Global Settings 8a>+≡`  
`VERSION←4 1 0`

This code is used in chunk 5.

Defines:

`VERSION`, never used.

---

<sup>2</sup><https://semver.org/>



We depend on ArrayFire<sup>3</sup> for much of our GPU backend functionality. This means we need to know two things, where ArrayFire is installed and which ArrayFire backend we should use when compiling. We only really need to know where ArrayFire is installed on UNIX style systems, as these systems seem to be much more variable in this regard, and there is an environment variable that we can use in Windows to find out where ArrayFire is installed more conveniently on that platform. We default to using 'cuda' as our main option, but we also support the following options for `AF_LIB`:

```
cuda opengl cpu
```

Using '' for `AF_LIB` will use ArrayFire's unified backend, but we don't default to this because we have seen some issues on some platforms with reliability problems. To avoid this, we choose to use `cuda` as the default, which tends to either work or fail explicitly, which allows the user to respond rather than crashing ungracefully in the case of the unified backend.

The least reliable backend we have seen is the `opengl` one, which seems to be more hit or miss depending on the underlying stability of the OpenCL drivers that are installed on the user's system. In particular, some Linux OpenCL installations seem to be particularly fragile. In such cases, always make sure that a good, solid OpenCL library is being used.

```
9 <Global Settings 8a>+≡
  AF_PREFIX←'/opt/arrayfire'
  AF_LIB←'cuda'
```

This code is used in chunk 5.

Defines:

`AF_LIB`, used in chunks 13a, 36, and 49a.  
`AF_PREFIX`, used in chunk 36.

---

<sup>3</sup><https://arrayfire.com/>

On Windows, we rely on the Visual Studio C/C++ compiler to build our runtime and user code. We have settled on trying to stay as up to date with this as possible. However, there are many different installation paths used by Visual Studio, which can make it difficult to know where to look unless we hardcode each location. Instead, we assume that Visual Studio will not be a primary interest to our users, making it likely that they will be installing Visual Studio only as a dependency for using Co-dfns. In this case, it is likely that they will be using the Community version. Thus, we default to using the latest version of Visual Studio of which we are aware and using the Community version of this, which Microsoft does not charge for.

If a different version of Visual Studio is installed, then it is important to figure out what the right path should be to locate the Visual Studio installation. The main thing we need to get from this path is access to the `vcvarsall.bat` batch file. This file configures the `cmd.exe` environment to be able to find the Visual Studio compiler and work in the right way. In the 2002 Community addition, and apparently most new versions of Visual Studio, this is located in the `VC\Auxiliary\Build\` subdirectory of the main installation folder. When changing this path, we want to make sure that the following path points to the correct `vcvarsall.bat` file:

```
VSΔPATH, '\VC\Auxiliary\Build\vcvarsall.bat'
```

Most users will simply need to alter `Community` to match the edition of Visual Studio 2022 that they have installed on their system.

```
10 <Global Settings 8a>+≡
    VSΔPATH←'\Program Files\Microsoft Visual Studio'
    VSΔPATH,←'\2022\Community'
```

This code is used in chunk 5.

Defines:

VSΔPATH, used in chunks 36 and 49a.

### 3.2 The Fix API

One of the core entry points into the compiler is through the `Fix` function. This function is designed to mimic and more or less replace the use of the `FIX` function found in Dyalog APL. Its design models that behavior, and it is important as an entry-point because it exercises most of the core elements of the compiler. In particular, the design of the compiler’s pipeline is demonstrated most fully in this function.

*Parse → Compile → Generate → Backend → Link*

The interfaces to the `FIX` function and the Co-dfns `Fix` function differ in a few key ways. The left argument to `Fix` is a character vector giving the name to use when generating files and other artifacts. This does *not* affect the name of the resulting namespace, since that is defined, if at all, in the file source itself. The  $\alpha$  argument only affects the name of the files and other outputs that `Fix` generates.

We also print out which part of the compiler we are in when we enter that “phase”. Doing this helps to give us an intuitive sense of how fast each phase is and whether one phase is taking an abnormally long time or not. It also helps in debugging.

```
11 <The Fix API 11>≡
    Fix←{
        _←a n s src←PS ω←⎵←'P'
        _←          TT _←⎵←'C'
        _←          GC _←⎵←'G'
        _←          α CC _←⎵←'B'
        _←          n NS _←⎵←'L'
    }
```

This code is used in chunk 5.

Defines:

`Fix`, used in chunk 13a.

Uses `PS` 15 and `src` 48.

The input requirements for `Fix` are not listed in the definition itself, because both the parser `PS` and the `Fix` function need to use the same basic checks, and since the `Fix` function calls the parser as its first entry point, it doesn't make much sense to duplicate that work in both places. The requirements are as follows:

- Scalar/Vector
- Character type
- Simple or Vector of Vectors

We generate a `DOMAIN ERROR` if the inputs are not well-formed.

12a *<Verify source input  $\omega$ , set IN 12a>*≡  
`IN← $\omega$`   
  
`err←'PARSER EXPECTS SCALAR OR VECTOR INPUT'`  
`1<≠pIN:err □SIGNAL 11`  
  
`err←'PARSER EXPECTS SIMPLE OR VECTOR OF VECTOR INPUT'`  
`2<|≡IN:err □SIGNAL 11`  
  
*<Normalize the input formatting 12b>*  
  
`err←'PARSER EXPECTS CHARACTER ARRAY'`  
`0≠10|□DR IN:err □SIGNAL 11`

This code is used in chunk 15.  
 Uses `SIGNAL 19b`.

The input formatting that is accepted means that newlines could be denoted either with `LF`, `CR`, or `CRLF` sequences inside of the vectors themselves or they could be denoted by having separate vectors for the various lines, or even a mixture of both. To simplify this situation we want to normalize them so that we are always dealing with some combination of `LF`, `CR`, and `CRLF` sequences within the file itself, rather than dealing with the nested situation. This ensures that after verification of the input, everything will work off of the same format. We intentionally put a newline at the end of the file even if we may not require one because it is possible that we are dealing with a file that is missing its final newline. By always adding one, we ensure that every line in the input is always terminated by a line ending. Life is also simpler if we just use `LF` as our line ending instead of something else, this means that future code must be aware that there could be mixed line endings in the file.

12b *<Normalize the input formatting 12b>*≡  
`IN← $\epsilon(\subseteq IN)$ , ""UCS 10`  
 This code is used in chunk 12a.

### 3.3 The User Command API

```

13a  ⟨User-command API 13a⟩≡
      ∇Z←Help _
      Z←'Usage: <object> <target> [-af={cpu,opencl,cuda}]'
      ∇

      ∇r←List
      r←NS"1p<Θ ⋄ r.Name←,"c'Compile' ⋄ r.Group←c'CODFNS'
      r[0].Desc←'Compile an object using Co-dfns'
      r.Parse←c'2S -af=cpu opencl cuda '
      ∇

      ∇ Run(C I);Convert;in;out
      A Parameters
      A      AFΔLIB      ArrayFire backend to use
      Convert←{α(□SE.SALT.Load'[SALT]/lib/NStoScript -noname').ntgennscode ω}
      in out←I.Arguments ⋄ AFΔLIB←I.af''>~I.af≡0
      S←(c':Namespace ',out),2↓0 0 0 out Convert ##.THIS.⊕in
      →0/~/~'Compile'≠C
      {##.THIS.⊕out,'←ω'}out Fix S←□EX'##.THIS.',out
      ∇

```

This code is used in chunk 5.  
Uses AFΔLIB 9 and Fix 11.

### 3.4 AST Record Structure

```

13b  ⟨AST Record Structure 13b⟩≡
      fΔ←'ptknfsrdx'
      NΔ←'ABCEFGKLMNOPSVZ'
      A B C E F G K L M N O P S V Z←1+ι15

```

This code is used in chunk 5.

### 3.5 Converters between parent and depth vectors

```

13c  ⟨Converters between parent and depth vectors 13c⟩≡
      P2D←{z←;ι≠ω ⋄ d←ω≠,z ⋄ _←{p↦d+←ω≠p←α[z,←ω]}*≡~ω ⋄ d(Δ(-1+d)↑÷0 1-ϕz)}
      D2P←{0≠ω:Θ ⋄ p↦2{p[ω]←α[α⊥ω]}↗↦◦◻ω↦p←ι≠ω}

```

This code is used in chunk 5.

## 4 Testing

We use the APLUnit testing framework to facilitate our testing of the Co-dfns compiler. The test harness is designed around a testing philosophy in which we ever only write black-box tests that work on the whole compiler using inputs that could be created or are expected to be creatable by end-users. That is, we do no “unit testing” of our source code, but only whole program testing.

The testing framework is provided by the `ut.apln` file, which is not part of this literate program and so is not included in this document. In order to make some of the testing more convenient, we define the function `TEST` to run the tests that exist in the `tests\` sub-directory. Each of these tests has a specific number which defines the test, and we refer to the tests by number when running them. Both of these testing functions assume that we are running inside of the `tests\` directory or one configured identically to it.

The `TEST` function takes either `'ALL'` as its input or a test number in the form of an integer. Given an integer, we call the test matching that number in the current working directory.

The `'ALL'` option causes `TEST` to run all of the tests that are defined in the current working directory. This command is a nicety, since we can technically do all of this by iterating the `TEST` function over the range of test numbers, but this would not create the aggregate statistics that we would like to see at the end of the testing report. By using `'ALL'` we get to see a complete summary of the results of testing all the code, rather than just the individual testing results on a per testing group/number basis.

```
14a <TEST 14a>≡
    TEST←{
        #.UT.(print_passed print_summary)←1
        'ALL'≡ω:#.UT.run './'
        path←'./t',(1 0⌞(4p10)⌞ω),'*_tests.dyalog'
        #.UT.run ⍵0⌞NINFO⌞1⌞path
    }
```

Root chunk (not used in this document).

Defines:

`TEST`, used in chunks 14b and 23.

The `TEST` function is part of the utilities that exist outside of the `codfns` namespace, so we define a file for it.

```
14b <Tangle Commands 6>+≡
    echo "Tangling src/TEST.aplf..."
    notangle -R'[[TEST]]' codfns.nw > src/TEST.aplf
```

This code is used in chunk 43.

Defines:

`TEST.aplf`, never used.

Uses `codfns 5`, `src 48`, and `TEST 14a`.

## 5 Co-dfns Compiler

### 5.1 Parser

The first, and in many ways, the most complex element of the compiler is the parser. APL has a number of unique issues when it comes to adequately parsing the language, but the most important is handling the context-sensitive nature of parsing variables: depending on the type of a variable, the parse tree can look very different. To manage this, we make use of a linear, multi-pass style of parser in which the parsing process consists of numerous small passes over the input, each time refining the input into something more like the final result. The parser should take some input that matches the input requirements of the `Fix` function and produce a suitable output AST.

$$PS :: Source \rightarrow AST \times ExportTypes \times SymbolTable \times Source$$

We can think of the parser as starting with a forest of trees, each of which contains a single root node that represents a single character in from the input source, with all trees arranged in the source order. During each pass of the parser, we progressively combine these trees into more complex trees until we end up at the end with a single tree per parsed module. In other words, we take a fully flat forest of single-node trees and progressively increase the depth while reducing the number of root-nodes until we have our desired AST structure.

We divide the parsing roughly into two main phases, the tokenization phase and the parsing phase. Unlike most compilers, we don't have a strict division in these two phases, so, as they say, think of them more like guidelines than actual rules<sup>4</sup>.

```

15  ⟨Parser 15⟩≡
    PS←{
        ⟨Verify source input ω, set IN 12a⟩

        ⟨Parsing Constants 16a⟩
        ⟨Line and error reporting utilities 19b⟩

        ⟨Tokenize input 20⟩
        ⟨Parse token stream 23⟩

        ⟨Adjust AST for output 16b⟩
    }

```

---

<sup>4</sup><https://www.youtube.com/watch?v=WJVBvvS57j0>

This code is used in chunk 5.

Defines:

PS, used in chunks 11 and 48.

When parsing, it's very helpful to have names for line endings.

16a  $\langle \text{Parsing Constants } 16a \rangle \equiv$

CR LF  $\leftarrow$  UCS 13 10

This code is used in chunk 15.

### 5.1.1 Output of the Parser

After we finish all of our parsing, we need to take the resulting AST and convert that into something that is suitable for output to the rest of the system. We do this in a few ways.

When we finish parsing, we expect the following fields:

| Field | Description                             |
|-------|---|
| d     | Depth vector                            |
| t     | Node type                               |
| k     | Node sub-class or “kind”                |
| n     | Name/value field                        |
| pos   | Starting index for source position      |
| end   | Exclusive index for source end position |
| xn    | Names of top-level exported bindings    |
| xt    | Types of top-level exported bindings    |
| sym   | Symbol Table                            |
| IN    | Canonical source code                   |

The xn and xt fields are not part of the AST proper, but form an auxiliary analysis that is exceptionally useful, and so we include this as a part of the output of the parser. After parsing a module, we want to extract out the top-level bindings and what their types are, which we can then use to feed into things like the linker and other areas that might need to know what names are available in a given module. Top-level bindings are identified as bindings that appear as a part of an initialization function, also known as F0.

16b  $\langle \text{Adjust AST for output } 16b \rangle \equiv$

msk  $\leftarrow$  (t=B)  $\wedge$  k[I@{t[ $\omega$ ]  $\neq$  F}  $\times$   $\equiv$  p]=0  
 xn  $\leftarrow$  (Op < ' '), msk  $\neq$  n  $\diamond$  xt  $\leftarrow$  msk  $\neq$  k

This definition is continued in chunks 17–19.

This code is used in chunk 15.

Defines:

xn, used in chunk 19a.

xt, used in chunk 19a.



We also want to convert the AST to an order that follows a depth-first, preorder traversal order, so that we can switch from using the parent vector to the depth vector. We use this output as our main output because it is space efficient for storage, and it works well as a canonical form to use. Because applications may want to only use the parser and not the rest of the compiler, we want to choose an output format that is suitable for external as well as internal use. This has some performance overheads, but it is probably worth it regardless, as reordering at this point to allow a depth vector enables some nice assumptions in the rest of the compiler. We use the P2D utility to reorder all of our AST columns. Note that things like the exported bindings and the symbol table are not strictly part of the AST structure, because they are of a different length and type than the other columns.

17 *(Adjust AST for output 16b)+≡*  
     d i←P2D p ♦ d n t k pos end I◦←←i

This code is used in chunk 15.

There is an inefficiency in the AST representation at this point, where the `n` field contains character vectors. This inefficiency was necessary while building up the AST because we were not sure what symbols would be created before we parsed them, but at this point, we know the full set of symbols that we have in the AST. This means that we can convert the `n` field to a symbol table representation. In this case, we want the `n` field to pair with a `sym` list that contains all the unique symbols in the source. We want `old_n ≡ sym[|new_n]` to hold for this new `n` field. In other words, we want the new `n` field to contain negative integers whose magnitudes are valid indices into the `sym` symbol table. This means that there is only one character vector per unique symbol or numeric literal in the source code, which can greatly reduce memory usage. Moreover, it is much faster to compare symbols that are represented by numeric index rather than character vector. Most of the work we expect to be done on the `n` field, so that we never have to pull in `sym` unless we want to know the actual value of the symbol. This actually mimics the feature of symbols in other languages like Scheme, but it comes with an additional efficiency benefit in that we do not require the use of a full generalized pointer to represent a symbol if we have fewer symbols. This means that we are very likely only going to need a single byte or a couple of bytes per symbol to represent it in the `n` field.

The choice to make all of our symbols negative in value is somewhat strange, but we have a good reason for doing so. The `n` field is a single field that we use to contain general data for every node, and as such, it represents a sort of union type of all sorts of different data. In particular, we also want to be able to support using the `n` field to point to other nodes in the AST, which is a feature we rely heavily on in the compiler transformations. However, this feature would conflict with using the `n` field as an index into the `sym` table, rather than as an index into the AST. By making symbol pointers negative, we put them into a separate space than the positive AST node pointers, allowing us to store both pointers in the same field. This may seem like a little bit of a strange hack, but it actually makes reasoning about things a little easier, because we can tend to think of `n` as a name, even if that name is pointing to an AST or a symbol, and avoids needless space duplication or the need to remember to update multiple fields that are only relevant for some nodes.

We map the 0th index to be a null or empty symbol. We also want to reserve the first four symbol slots [1, 4] so that they will *always* refer to the same symbols, namely,  $\omega$ ,  $\alpha$ ,  $\alpha\alpha$ , and  $\omega\omega$ .

This gives us the following definitions for `sym` and `n`.

```
18  (Adjust AST for output 16b) +=
    sym ← v('')(, 'ω')(, 'α') 'αα' 'ωω', n
    n ← -sym | n
```

Finally, we want to return our AST structure in a meaningful way. Logically, we have the AST proper, which consists of these fields:

The above fields are returned as an inverted table, where each column is a vector of the same length. We also want to return the variable environment, which gives the names of our top-level bindings and their types, also as an inverted table. Finally, we must return a canonical representation of the source code that is suitable as an indexing target for the `pos` and `end` fields, as well as the symbol table. Thus, we have a four element vector as the return value:

Which gives us the following return value.

This code is used in chunk 15.  
Uses xn 16b and xt 16b.

```

19b) <Line and error reporting utilities 19b>≡
    linestarts←(⊔1,2>≠IN∈CR LF);≠IN
    mkdm←{α+2 ⋄ line←linestarts⊔ω ⋄ no←['', (⊗1+line), '']
        i←(≠IN[i]∈CR LF)≠i←beg+⊔linestarts[line+1]-beg←linestarts[line]
        (⊔EM α)(no, IN[i])(' ^'[i∈ω], ~' 'p~≠no)}
    quotelines←{
        lines←⊔linestarts⊔ω
        nos←(1 0p~2×≠lines)⋈['', (⊗1+lines), ⋈1-']
        beg←linestarts[lines] ⋄ end←linestarts[lines+1]
        m←εω''i''end-beg
        ~1⊔enos, (≠CR LF'', (IN∘I''i), ~' '-'∘I''m), CR}
    SIGNAL←{α+2 '' ⋄ en msg←α ⋄ EN∘←en ⋄ DM∘←en mkdm ⋄ω
        dmx←('EN' en)('Category' 'Compiler')('Vendor' 'Co-dfns')
        dmx, ←c'Message'(msg, CR, quotelines ω)
        ⊔SIGNAL←dmx}

```

lines, never used.  
mkdm, never used.  
quotelines, used in chunk 20.  
SIGNAL, used in chunks 12a, 20, 23, 31, 36–38, and 42a.

```

20 {Tokenize input 20}=
    A Group input into lines as a nested vector
      pos←(i≠IN)⊆~IN∈CR LF

    A Mask strings
      0≠#lin←1▷◊φ~msk←≠λ~''''=IN◊I~pos:{
        EM←'SYNTAX ERROR: UNBALANCED STRING',( 'S'≠2≤#lin),CR
        EM,←quotelines ∈(msk≠~pos)[lin]
        EM [SIGNAL 2]θ

    A Remove comments
      pos msk≠~~←cλ~''(~msk←mskv~1φ~msk)~λ'⊃'=IN◊I~pos

    A Remove leading and trailing whitespace
      WS←[UCS 9 32 ◊ pos msk≠~~←c~(λλvλλUφ)◊(WS∈~IN◊I)~pos

    A Flatten and separate lines and ◊ with Z type
      t←0ρ<pos ◊ t pos msk(ε,◊,~)←Z(▷~pos)0 ◊ t[1'◊'=IN[pos]]←Z

    A Tokenize Strings
      end←1+pos ◊ t[i←12<≠0;msk]←C ◊ end[i]←end[12>≠msk;0]
      t pos end≠~~←c(t≠0)v~msk

    A Verify that all open characters are part of the valid character set
      alp←'ABCDEFGHIJKLMNOPQRSTUVWXYZ_abcdefghijklmnopqrstuvwxyz'
      alp,←'ÀÁÂÃÄÅÆÇÈÉÊËÌÍÎÏÐÑÒÓÔÕÖØÙÚÛÜÝßàáâãäåæçèéêëìíîïðóôõöøùúûüþ'
      alp,←'ΔΔABCDEF GHIJKLMNOPQRSTUVWXYZ'
      num←[D
      synb←'~[]{}()''':αω◊;'
      syna←'θ□#~'
      prmf←'+-×÷|/[ *%! ?~Λv~λ~<≤=>≥≡≠ρ,;φθq↑↓<≤>ε∈∩∪12□ΔΨ±∓1T~1-⊞∇↔'
      prmd←'◊.~⊞⊞ö@' ◊ prmmo←'~~&I⊞' ◊ prmfo←'≠/λ~'
      prms←prmf,prmd,prmmo,prmfo
      x←' '@{t≠0}IN[pos] A The spaces produce nice invariants
      v≠msk←~xεalp,num,syna,synb,prms,WS:{
        EM←'SYNTAX ERROR: INVALID CHARACTER(S) IN SOURCE',CR
        EM,←quotelines 1msk
        EM [SIGNAL 2]θ

    A Tokenize numbers
      _←{dm[ω]←λλdm[ω]}~(dmv×εalp)⊆1≠dm×xenum
      dmv←('.' =x)^(~1φdm)∨1φdm
      dmv←('-' =x)∧1φdm
      dmv←(x∈'EeJj')^(~1φdm)∧1φdm

```

```

v/mask←(dm=0)∧x='-' : 2 'ORPHANED -' SIGNAL pos/mask
v/{1<+ω='j'}''dp←C''dm=x:'MULTIPLE J IN NUMBER'□SIGNAL 2
v/{1<+ω='e'}''dp←;/{ω≠ω≠'j'}''dp:'MULTIPLE E IN NUMBER'□SIGNAL 2
v/'e'='⇒'dp:'MISSING MANTISSA'□SIGNAL 2
v/'e'='⇒'φ''dp:'MISSING EXPONENT'□SIGNAL 2
mn ex←↓φ↑{2↑(ω≠ω≠'e'),<''}''dp
v/{1<+ω='.'ω}''mn,ex:'MULTIPLE . IN NUMBER'□SIGNAL 2
v/'.'ε''ex:'REAL NUMBER IN EXPONENT'□SIGNAL 2
v/{v↑1↓ωε'-''}''mn,ex:'MISPLACED -'□SIGNAL 2
t[i←12<≠0;dm]←N ◇ end[i]←end/m2>≠dm;0

```

#### A Tokenize Variables

```

t[i←12<≠0;vm]←(~dm)∧x∈alp,num]←V ◇ end[i]←end/m2>≠vm;0

```

#### A Tokenize α, ω formals

```

fm←{mm←φ>(;>,>,>)/φm←α=' ',ω ◇ 1↓''(mm∧~m1)(mm∧m1←1φm)}
am aam←'α'fm x ◇ wm wwm←'ω'fm x
((amvwm)/t)←A ◇ ((aamvwm)/t)←P ◇ ((aamvwm)/end)←end/m-1φaamvwm

```

#### A Tokenize Primitives, Atoms

```

t[1(~dm)∧x∈prms]←P ◇ t[1x∈syna]←A

```

#### A Compute dfns regions and type, include } as a child

```

t[1{'='x]←F ◇ 0≠d←-1φ+λ1 -1 0['{'ιx]:'UNBALANCED DFNS'□SIGNAL 2

```

#### A Check for out of context dfns formals

```

v/(d=0)∧(t=P)∧IN[pos]∈'αω':'DFN FORMAL REFERENCED OUTSIDE DFNS'□SIGNAL

```

#### A Compute trad-fns regions

```

v/Z≠t/m-1φ≠λ(d=0)∧'∇'='x:'TRAD-FNS START/END LINES MUST BEGIN WITH ∇'□SIGNAL 2

```

```

0≠tm←-1φ≠λ(d=0)∧'∇'='x:'UNBALANCED TRAD-FNS'□SIGNAL 2

```

```

v/Z≠t/m-1∇.φ<(2>≠tm);0:'TRAD-FNS END LINE MUST CONTAIN ∇ ALONE'□SIGNAL

```

#### A Identify Label colons versus others

```

t[1tm∧(d=0)∧((~>)∧(<λvλ))''':'=(t=Z)∈IN[pos]]←L

```

#### A Tokenize Keywords

```

ki←1(t=0)∧(d=0)∧(':'=IN[pos])∧1φt=V
t[ki]←K ◇ end[ki]←end[ki+1] ◇ t[ki+1]←0
ERR←'EMPTY COLON IN NON-DFNS CONTEXT, EXPECTED LABEL OR KEYWORD'
v/(t=0)∧(d=0)∧':':IN[pos]:ERR □SIGNAL 2

```

#### A Tokenize System Variables

```

si←1('□'=IN[pos])∧1φt=V
t[si]←S ◇ end[si]←end[si+1] ◇ t[si+1]←0

```

```

A Delete all characters we no longer need from the tree
  d tm t pos end( $\tilde{f}$ ) $\leftarrow$ c( $t \neq 0$ ) $\vee x \in '()$ ][{}:;'
```

```

A Tokenize Labels
  ERR $\leftarrow$ 'LABEL MUST CONSIST OF A SINGLE NAME'
   $\vee f(Z \neq t[li-1]) \vee (V \neq t[li-1] \wedge msk \leftarrow t=L)$ :ERR  $\square$  SIGNAL 2
  t[li] $\leftarrow$ L  $\diamond$  end[li] $\leftarrow$ end[li+1]
  d tm t pos end( $\tilde{f}$ ) $\leftarrow$ c~msk
```

This code is used in chunk 15.

Uses quotelines 19b and SIGNAL 19b.

### 5.1.4 Parsing Token Stream

23

*(Parse token stream 23)*≡

A Now that all compound data is tokenized, reify n field before tree-building  
 $n \leftarrow \{1 \downarrow \pm ''0', \omega\} @ \{t=N\} (c='') @ \{t \in Z\} F\} 1 \quad \square C @ \{t \in K\} S\} IN \circ I''pos + i''end-pos$

A Verify that keywords are defined and scoped correctly

```
KW ← 'NAMESPACE' 'ENDNAMESPACE' 'END' 'IF' 'ELSEIF' 'ANDIF' 'ORIF' 'ENDIF'
KW, ← 'WHILE' 'ENDWHILE' 'UNTIL' 'REPEAT' 'ENDREPEAT' 'LEAVE' 'FOR' 'ENDFOR'
KW, ← 'IN' 'INEACH' 'SELECT' 'ENDSELECT' 'CASE' 'CASELIST' 'ELSE' 'WITH'
KW, ← 'ENDWITH' 'HOLD' 'ENDHOLD' 'TRAP' 'ENDTRAP' 'GOTO' 'RETURN' 'CONTINUE'
KW, ← 'SECTION' 'ENDSECTION' 'DISPOSABLE' 'ENDDISPOSABLE'
KW, '' ← ':'
msk ← KW ∈ kws ← n / km ← t = K
v / msk: ('UNRECOGNIZED KEYWORD ', kws → '' → lmsk) □ SIGNAL 2
msk ← kw ∈ ':NAMESPACE' ':ENDNAMESPACE'
v / msk ^ km / tm: 'NAMESPACE SCRIPTS MUST APPEAR AT THE TOP LEVEL' □ SIGNAL 2
msk ← kw ∈ KW ~ ':NAMESPACE' ':ENDNAMESPACE' ':SECTION' ':ENDSECTION'
v / msk ← msk ^ km / tm: {msg ← 2 'STRUCTURED STATEMENTS MUST APPEAR WITHIN TRAD-FNS'
msg SIGNAL ∈ {x + l end[ω] - x ← pos[ω]} '' lkm \msk} θ
```

A Verify system variables are valid

```
SYSV ←, '' 'Á' 'A' 'AI' 'AN' 'AV' 'AVU' 'BASE' 'CT' 'D' 'DCT' 'DIV' 'DM'
SYSV, ←, '' 'DMX' 'EXCEPTION' 'FAVAIL' 'FNAMES' 'FNUMS' 'FR' 'IO' 'LC' 'LX'
SYSV, ←, '' 'ML' 'NNAMES' 'NNUMS' 'NSI' 'NULL' 'PATH' 'PP' 'PW' 'RL' 'RSI'
SYSV, ←, '' 'RTL' 'SD' 'SE' 'SI' 'SM' 'STACK' 'TC' 'THIS' 'TID' 'TNAME' 'TNUMS'
SYSV, ←, '' 'TPOOL' 'TRACE' 'TRAP' 'TS' 'USING' 'WA' 'WSID' 'WX' 'XSI'
SYSF ←, '' 'ARBIN' 'ARBOU' 'AT' 'C' 'CLASS' 'CLEAR' 'CMD' 'CONV' 'CR' 'CS' 'CSV'
SYSF, ←, '' 'CY' 'DF' 'DL' 'DQ' 'DR' 'DT' 'ED' 'EM' 'EN' 'EX' 'EXPORT'
SYSF, ←, '' 'FAPPEND' 'FCHK' 'FCOPY' 'FCREATE' 'FDROP' 'FERASE' 'FFT' 'IFFT'
SYSF, ←, '' 'FHIST' 'FHOLD' 'FIX' 'FLIB' 'FMT' 'FPROPS' 'FRDAC' 'FRDCI' 'FREAD'
SYSF, ←, '' 'FRENAME' 'FREPLACE' 'FRESIZE' 'FSIZE' 'FSTAC' 'FSTIE' 'FTIE'
SYSF, ←, '' 'FUNTIE' 'FX' 'INSTANCES' 'JSON' 'KL' 'LOAD' 'LOCK' 'MAP' 'MKDIR'
SYSF, ←, '' 'MONITOR' 'NA' 'NAPPEND' 'NC' 'NCOPY' 'NCREATE' 'NDELETE' 'NERASE'
SYSF, ←, '' 'NEW' 'NEXISTS' 'NGET' 'NINFO' 'NL' 'NLOCK' 'NMOVE' 'NPARTS'
SYSF, ←, '' 'NPUT' 'NQ' 'NR' 'NREAD' 'NRENAME' 'NREPLACE' 'NRESIZE' 'NS'
SYSF, ←, '' 'NSIZE' 'NTIE' 'NUNTIE' 'NXLATE' 'OFF' 'OR' 'PFKEY' 'PROFILE'
SYSF, ←, '' 'REFS' 'SAVE' 'SH' 'SHADOW' 'SIGNAL' 'SIZE' 'SR' 'SRC' 'STATE'
SYSF, ←, '' 'STOP' 'SVC' 'SVO' 'SVQ' 'SVR' 'SVS' 'TCNUMS' 'TGET' 'TKILL' 'TPUT'
SYSF, ←, '' 'TREQ' 'TSYNC' 'UCS' 'VR' 'VFI' 'WC' 'WG' 'WN' 'WS' 'XML' 'XT'
SYSD ←, '' 'OPT' 'R' 'S'
v / msk ← (t = S) ^ ~ n ∈ □, '' SYSV, SYSF, SYSD: {
ERR ← 2 'INVALID SYSTEM VARIABLE, FUNCTION, OR OPERATOR'
ERR SIGNAL ∈ pos[ω] {α + l ω - α} '' end[ω]
} lmsk
```

```

A Compute parent vector from d
  p ← D2P d

A Compute nameclass of dfns
  k ← 2 × t ∈ F ◊ k[upfz(t=P) ∧ n ∈ c'αα'] ← 3 ◊ k[upfz(t=P) ∧ n ∈ c'ωω'] ← 4

A We will often wrap a set of nodes as children under a Z node
  gz ← {z ← ω ↑ z - 0 ≠ ω ◊ ks ← -1 ↓ ω
        t[z] ← Z ◊ p[ks] ← z ◊ pos[z] ← pos[ω] ◊ end[z] ← end[ϕz, ks] ◊ z}

A Nest top-level root lines as Z nodes
  _ ← (gz 1ϕ)''(t[i]=Z) < i ← 1 d = 0
  'Non-Z top-level node' assert t[1p=i≠p]=Z:

A Nest all dfns expression bodies as Z nodes
  _ ← p[i]{end[α] ← end[ϕω] ◊ gz''ω < 1, -1 ↓ t[ω]=Z} ∩ i ← 1 t[p]=F
  'Non-Z dfns body node' assert t[1t[p]=F]=Z:

A Drop/eliminate any Z nodes that are empty or blank
  _ ← p[i]{msk[α, ω] ← ~ ∧ / IN[pos[ω]] ∈ WS} ∩ i ← 1 (t[p]=Z) ∧ p ≠ i ≠ p → msk ← t ≠ Z
  t m n t k pos end(fz) ← msk ◊ p ← (1 ~ msk)(t - 1 + 1) msk / p

A Parse Keyword structures
  nss ← n ∈ c':NAMESPACE' ◊ nse ← n ∈ c':ENDNAMESPACE'
  ERR ← ':NAMESPACE KEYWORD MAY ONLY APPEAR AT BEGINNING OF A LINE'
  Z v. ≠ t / z - 1 φ nss:ERR □ SIGNAL 2
  ERR ← 'NAMESPACE DECLARATION MAY HAVE ONLY A NAME OR BE EMPTY'
  v / (Z ≠ t / z - 1 φ nss) ∧ (V ≠ t / z - 1 φ nss) v Z ≠ t / z - 2 φ nss:ERR □ SIGNAL 2
  ERR ← ':ENDNAMESPACE KEYWORD MUST APPEAR ALONE ON A LINE'
  v / Z ≠ t / z - 1 - 1 v. φ < nse:ERR □ SIGNAL 2
  t[nsi ← 1 φ nss] ← M ◊ t[nei ← 1 φ nse] ← -M
  n[i] ← n[1 + i ← 1 (t=M) ∧ V=1 φ t] ◊ end[nsi] ← end[nei]
  x ← 1 p = i ≠ p ◊ d ← + λ (t[x]=M) + - t[x] = -M
  0 ≠ ϕ d:':NAMESPACE KEYWORD MISSING :ENDNAMESPACE PAIR' □ SIGNAL 2
  p[x] ← x[D2P -1 φ d]

A Delete unnecessary namespace nodes from the tree, leave only M's
  msk ← ~ nss v (~ 1 φ nss) ∧ t = V) v nse v 1 φ nse
  t k n pos end(fz) ← msk ◊ p ← (1 ~ msk)(t - 1 + 1) msk / p

A PARSE LABELS ◊◊◊

A Map guard statements to (G (Z ...) (Z ...))
  _ ← p[i]{
    0 = + / m ← ': '= IN[pos[ω]]:θ
    > m: 'EMPTY GUARD TEST EXPRESSION' □ SIGNAL 2
  }

```



```

1<+fm:'TOO MANY GUARDS'[] SIGNAL 2
t[α]←G ◇ p[ti←gz>tx cq←2↑(cθ);ω<1,-1↓m]←α ◇ k[ti]←1
ci←#p ◇ p,←α ◇ t k pos end;←0 ◇ n,←c' ' ◇ k[gz cq,ci]←1
0)⊞i←1t[p[p]]=F

A Parse brackets and parentheses into -1 and Z nodes
_←p[i]{
  x←IN[pos[ω]] ◇ bd←+bm←(bo←['=x]+bc←')'=x ◇ pd←+pm←(po←['=x]+
pc←')'=x
  0≠φbd:2'UNBALANCED BRACKETS'SIGNAL pos[ω]{x+1(↑fω)}
x←[fα]ö{ωfω≠bd}end[ω]
  0≠φpd:2'UNBALANCED PARENTHESES'SIGNAL pos[ω]{x+1(↑fω)}
x←[fα]ö{ωfω≠pd}end[ω]
  (po≠bd)∨.≠φpc≠bd:'OVERLAPPING BRACKETS AND PARENTHESES'[] SIGNAL
  p[ω]←(α,ω)[1+1@{ω=1≠ω}D2P +1-1φbm+pm] ◇ t[bo≠ω]←-1 ◇ t[po≠ω]←
  end[po≠ω]←end[φpc≠ω] ◇ end[bo≠ω]←end[φbc≠ω]
0)⊞i←1(t[p]=Z)∧p≠i≠p
  t k n pos endfω←msk←IN[pos]ε')' ◇ p←(1~msk)(t-1+1)mskf p

A Convert semi-colon indexing into Z nodes in the -1 nodes
_←p[i]{k[z←,f gz''g←ω<1-1φIN[pos[ω]]ε';']←1 ◇ t[z]←Z P[1≠'g]}⊞i←1t[p]=

A Mark bindable nodes
bm←(t=V)∨(t=A)∧nε,'''
bm←{bm→p[i]{bm[α]←(V -1≡t[ω])∨∧f bm[ω]}⊞i←1(~bm[p])∧t[p]=Z}*≡bm

A Binding nodes
_←p[i]{
  t[ωfω(n[ω]ε<,'←')∧0,-1↓bm[ω]]←B
  b v←{(≡'x)(1↓'x←ωfω{t[≡ω]=B}''ω)}-1φ''ω<1,-1↓t[ω]εP B
  v≠bm[εv]:'CANNOT BIND ASSIGNMENT VALUE'[] SIGNAL 2
  p[ω]←(α,b)[0,-1↓+t[ω]=B]
  n[b]←n[εv] ◇ t[εv]←-7 ◇ pos[b]←pos[εv] ◇ end[b]←end[≡φω]
0)⊞i←1(t[p]=Z)∧p≠i≠p
  t k n pos endfω←msk←t≠-7 ◇ p←(1~msk)(t-1+1)mskf p

A Mark unambiguous primitive kinds
k[1(t=S)∧nε'[]',''SYSV]←1 ◇ k[1(t=S)∧nε'[]',''SYSF]←2 ◇ k[1(t=S)∧nε'[]',''SYSD]←
t[1t=S]←P
k[1tεA C N]←1 ◇ k[1nε,'prmf s]←2 ◇ k[1nε,'prmmo]←3 ◇ k[1nε,'prmdo]←4
k[1nε,'prmf o]←5
k[i←1msk←(nε<,'o')∧1φnε<,'.']←3 ◇ end[i]←end[i+1] ◇ n[i]←c,'o.'
t k n pos endfω←msk←-1φmsk ◇ p←(1~msk)(t-1+1)mskf p

A Anchor variables to earliest binding in matching frame
rf←-1@{~t[ω]εF G M}p[rz←I@{~(t[ω]=Z)∧(t[p[ω]]εF G M)∨p[ω]=ω}*≡≡p]

```

```

rf[i]←p[i←1t=G] ◇ rz[i]←i ◇ rf←rf I@{rzεp[i]→∃i←1t[p]=G}rf
mk←{α[ω],;n[ω]}
fr←rf mk←fb←fb[1←rf mk←fb←fb I◦(1←)U◦rz mk←fb←1t=B] ◇ fb,←1
vb←fb[fr←rf mk i]@(i←1t=V)→1p≠p
vb[i≠(rz[i]<rz[b])∨(rz[i]=rz[b])∧i≥b+vb[i+i≠vb[i]≠1]]←1
_←{z/≠1=vb[1][z]←fb[fr←n I@1→z←rf I@0→ω]}≠Q{rf[ω],;ω}1(t=V)∧vb=1
v≠msk←(t=V)∧vb=1:{
  6'ALL VARIABLES MUST REFERENCE A BINDING'SIGNALεpos[ω]{α+1ω-α}''end[ω]
}1msk
}

A α/ω → V ; M → F0 ; αα/ωω → P2
  t←V@(i←1(t=A)∧nε,``αω')→F@{t=M}t ◇ vb[i]←i ◇ k[1(t=P)∧nε'αα' 'ωω']←2

A Infer types of bindings, groups, and variables
  z x←1Qp[i]{αω}∃i←1(t[p]εB Z)∧p≠i≠p
  x←{ω≠1→1t[ω]=1}UΦ``x
  0v.=≠``x:'BRACKET SYNTAX REQUIRES FUNCTION OR ARRAY TO ITS LEFT'□SIGNAL
  _←{
    k[msk≠z]←k[x≠msk←(k[≠``x]≠0)∧1=≠``x] ◇ z x≠←c~msk
    k[z≠msk←k[≠``x]=4]←3 ◇ z x≠←c~msk
    k[z≠msk←{(2 3 5ε≠k[≠ω])∨4=(ω,≠k)[01≠1k[ω]=1]□k,0}◦Φ``x]←2 ◇ z x≠←c~msk
    k[z≠msk←k[≠◦Φ``x]=1]←1 ◇ z x≠←c~msk
    k[i]←k[vb[i←1t=V]]
  }
  ≠z}≠(=v0=→)≠z
  'FAILED TO INFER ALL BINDING TYPES'assert 0=≠z:

A Strand arrays into atoms
  i←|i→km→0<i←i[Δ|(i,≠←up[i]),p[i←1t[p]εB Z]]
  msk←(t[i]εC N)∨msk∧1→1v.Φ<msk+km∧(t[i]εA C N V Z)∧k[i]=1
  np←(≠p)+i≠ai+i≠am→2>≠msk;0 ◇ p←(np@ai≠p)[p] ◇ p,←ai ◇ km→2<≠0;msk
  t k n pos end(→,I)←c ai ◇ k[ai]←1 6[v≠msk≤t[i]≠N]
  t n pos(→@ai≠)←A(c'')(pos[km≠i]) ◇ p[msk≠i]←ai[(msk←msk∧~am)≠1++≠km]
  i←1(t[p]=A)∧(k[p]=6)∧t=N
  p,←i ◇ t k n pos end(→,I)←c i ◇ t k n(→@i≠)←A 1(c'')

A PARSE B→D...
A PARSE B←...D

A Rationalize F[X]
  _←p[i]{
    ≡m←t[ω]=1: 'SYNTAX ERROR:NOTHING TO INDEX'□SIGNAL 2
    k[ω≠m∧1Φ(k[ω]ε2 3 5)∨1Φk[ω]=4]←4
    0}∃i←1(t[p]εB Z)∧(p≠i≠p)∧k[p]ε1 2
    i←1(t=1)∧k=4 ◇ j←1(t[p]=1)∧k[p]=4
    (≠i)≠≠j:{
      2'AXIS REQUIRES SINGLE AXIS EXPRESSION'SIGNAL εpos[ω]+1''end[ω]-pos[ω]
    }
  }

```

```

    }>,{<α≠1<≠ω}⊔p[j]
    v≠msk←t[j]≠Z:{
        2'AXIS REQUIRES NON-EMPTY AXIS EXPRESSION'SIGNAL εpos[ω]+ι''end[ω]
pos[ω]
    }msk≠p[j]
    p[j]←p[i] ♦ t[i]←P ♦ end[i]←1+pos[i]

A Group function and value expressions
    i km←,{p[i]}{(α,ω)(0,1vω)}⊔i←1(t[p]∈B Z)^(p≠ι≠p)∧k[p]∈1 2

A Mask and verify dyadic operator right operands
    (dm←1φ(k[i]=4)∧t[i]∈F P V Z)∨.∧(∼km)∨k[i]∈0 3 4:{
        'MISSING RIGHT OPERAND'SIGNAL 2
    }θ

A Refine schizophrenic types
    k[i]≠(k[i]=5)∧dm∨1φ(∼km)∨(∼dm)∧k[i]∈1 6]←2 ♦ k[i]≠k[i]=5]←3

A Rationalize ∘.
    jm←(t[i]=P)∧n[i]∈c, ' ∘. '
    jm∨.∧1φ(∼km)∨k[i]∈3 4:'MISSING OPERAND TO ∘.'SIGNAL 2
p←((ji←jm≠i)@(jj←i≠1φjm)ι≠p)[p] ♦ t[ji,jj]←t[jj,ji] ♦ k[ji,jj]←k[jj,ji]
n[ji,jj]←n[jj,ji] ♦ pos[ji,jj]←pos[ji,ji] ♦ end[ji,jj]←end[jj,jj]

A Mask and verify monadic and dyadic operator left operands
    v≠msk←(dm∧2φ∼km)∨(1φ∼km)∧mm←(k[i]=3)∧t[i]∈F P V Z:{
        2'MISSING LEFT OPERAND'SIGNAL εpos[ω]+ι''end[ω]-pos[ω]
    }i≠msk
    msk←dm∨mm

A Parse function expressions
    np←(≠p)+ιxc←≠oi←msk≠i ♦ p←(np@oiι≠p)[p] ♦ p,←oi ♦ t k n pos end(ι,I)←co
    p[g≠i]←oi[(g←(∼msk)∧(1φmsk)∨2φdm)≠xc-φ+λφmsk]
    p[g≠oi]←(g←msk≠(1φmm)∨2φdm)≠1φoi ♦ t[oi]←0 ♦ n[oi]←c''
    pos[oi]←pos[g≠i][msk≠1++λg←(∼msk)∧(1φmm)∨2φdm]
    ol←1+(k[i]≠(2φmm)∨3φdm)=4)∨k[i]≠(1φmm)∨2φdm]∈2 3
    or←(msk≠dm)λ1+k[dm≠i]=2
    k[oi]←3 3ιfor ol

A Wrap all assignment values as Z nodes
    i km←,{p[i]}{(α,ω)(0,1vω)}⊔i←1(t[p]∈B Z)^(p≠ι≠p)∧k[p]∈1
    j←i≠msk←(t[i]=P)∧n[i]∈c, ' ← ' ♦ nz←(≠p)+ιzc←≠msk
    p,←nz ♦ t k n,←zcp''Z 1(c'') ♦ pos,←1+pos[j] ♦ end,←end[p[j]]
    zm←1φmsk ♦ p[km≠i]←(zpm≠(i∼km)+zmλnz)[km≠1++λzpm←zm∨∼km]

A This is the definition of a function value at this point

```

```
isfn←{(t[ω]∈O F)∨(t[ω]∈B P V Z)∧k[ω]=2}
```

```
A Parse modified assignment to E4(V, F, Z)
```

```
j←i≠m←msk∧(¬1φisfn i)∧¬2φ(t[i]=V)∧k[i]=1 ♦ p[zi←nz≠msk/m]←j
p[i≠(1φm)∨2φm]←2≠j ♦ t k(¬@j≠)←E 4 ♦ pos end n{α[ω]@j¬α}←vi zi,cvi←i≠2φ
```

```
A Parse bracket modified assignment to E4(E6, O2(F, P3(←)), Z)
```

```
j←i≠m←msk∧(¬1φisfn i)∧(¬2φt[i]=¬1)∧¬3φ(t[i]=V)∧k[i]=1
p[zi←nz≠msk/m]←ei←i≠3φm ♦ t k end(¬@ei≠)←E 4(end[zi])
p t k n(¬@(i≠2φm)≠)←ei E 6(c'')
p,←j ♦ t,←Pp≠j ♦ k,←3p≠j ♦ n,←(≠j)p c, '←' ♦ pos,←pos[j] ♦ end,←end[j]
p t k n pos(¬@j≠)←ei O 2(c'')(pos[fi←i≠1φm]) ♦ p[fi]←j
```

```
A Parse bracket assignment to E4(E6, P2(←), Z)
```

```
j←i≠m←msk∧(¬1φt[i]=¬1)∧¬2φ(t[i]=V)∧k[i]=1 ♦ p[zi←nz≠msk/m]←ei←i≠2φm
t k end(¬@ei≠)←E 4(end[zi]) ♦ p t k n(¬@(i≠1φm)≠)←ei E 6(c'')
p t k(¬@j≠)←ei P 2
```

```
A Parse modified strand assignment
```

```
A Parse strand assignment
```

```
A SELECTIVE MODIFIED ASSIGNMENT
```

```
A SELECTIVE ASSIGNMENT
```

```
A Enclose V[X;...] for expression parsing
```

```
i←i[Ap[i←L(t[p]∈B Z)∧(k[p]=1)∧p≠i≠p]] ♦ j←i≠jm←t[i]=¬1
t[j]←A ♦ k[j]←¬1 ♦ p[i≠1φjm]←j
```

```
A TRAINS
```

```
A Parse expression sequences
```

```
i km←,≠p[i]{(α;ω)(0,(2≤≠ω)∧1∨ω)}⊕i←L(t[p]∈B Z)∧(k[p]=1)∧p≠i≠p
msk←m2∨fm∧¬1φm2←km∧(1φkm)∧¬fm←(t[i]=O)∨(t[i]≠A)∧k[i]=2
t,←Ep≠xc←≠msk ♦ k,←msk/mask+m2 ♦ n,←xc p c''
pos,←pos[msk/i] ♦ end,←end[p[msk/i]]
p,←msk≠1φ(i×~km)+km×x←¬1+(≠p)++\msk ♦ p[km/i]←km/x
```

```
A Rationalize V[X;...]
```

```
i←i[Ap[i←L(t[p]=A)∧k[p]=¬1]] ♦ msk←~2≠¬1,ip←p[i] ♦ ip←vip ♦ nc←2×≠ip
t[ip]←E ♦ k[ip]←2 ♦ n[ip]←c'' ♦ p[msk/i]←msk/≠p)+1+2×¬1++\~msk
p,←2≠ip ♦ t,←ncp P E ♦ k,←ncp 2 6 ♦ n,←ncp, ''[' '']
pos,←2≠pos[ip] ♦ end,←ε(1+pos[ip]),≠end[ip] ♦ pos[ip]←pos[i≠~msk]
```

```
A Sanity check
```

```
ERR←'INVARIANT ERROR: Z node with multiple children'
ERR assert(≠(t[p]=Z)∧p≠i≠p)=≠t=Z:
```

```

A Count parentheses in source information
  ip ← p[i ← 1(t[p]=Z) ∧ n[p] ∈ c, '('] ♦ pos[i] ← pos[ip] ♦ end[i] ← end[ip]

A VERIFY Z/B NODE TYPES MATCH ACTUAL TYPE

A Eliminate Z nodes from the tree
  zi ← p I@{t[p[ω]]=Z} * ≡ ki ← 1msk ← (t[p]=Z) ∧ t ≠ Z
  p ← (zi@ki ≠ p)[p] ♦ t k n pos end(¬@zi) ← t k n pos end I''c ki
  t k n pos end / ← cmsk ← ~msk vt = Z ♦ p ← (1~msk)(t-1+1)msk / p

```

This code is used in chunk 15.

Uses `assert 38c`, `SIGNAL 19b`, and `TEST 14a`.

## 5.2 Compiler Transformations

```

30  <Compiler 30>≡
      TT←{((d t k n ss se)exp sym src)←ω ◊ I←{(cω)[]α}
      A B C E F G K L M N O P S V Z←1+ι15

      A Compute parent vector and reference scope
      r←I@{t[ω]≠F}*≡p-2{p[ω]←α[α_ω]} / - ◊ c ⊞ d - p - ι ≠ d

      A Lift Functions to top-level
      p, ← n[i] ← (≠p) + ι ≠ i + _ (t=F) ∧ p ≠ ι ≠ p ◊ t k n r (ι, I) ← c i ◊ p r I ← c n[i] @ i - ι ≠ p
      t[i] ← C

      A Wrap expressions as binding or return statements
      i ← (_ (t ∈ F G) ∧ t[p]=F), {ω / ~ 2 | ι ≠ ω} _ t[p]=G ◊ p t k n r / ~ ← c m - 2 @ i - 1 p ~ ≠ p
      p r i I ← c j ← (+m) - 1 ◊ n ← j I @ (0 ≤ ι) n ◊ p[i] ← j ← i - 1
      k[j] ← - (k[r[j]]=0) ∨ 0 @ ({>φω} ⊞ p[j]) - (t[j]=B) ∨ (t[j]=E) ∧ k[j]=4 ◊ t[j] ← E

      A Lift guard tests
      p[i] ← p[x ← -1 + i ← {ω / ~ 2 | ι ≠ ω} _ t[p]=G] ◊ t[i, x] ← t[x, i] ◊ k[i, x] ← k[x, i]
      n[x] ← n[i] ◊ p ← ((x, i) @ (i, x) - ι ≠ p) [p]

      A Count strand and indexing children
      n[_ (t ∈ A E) ∧ k=6] ← 0 ◊ n[p / ~ (t[p] ∈ A E) ∧ k[p]=6] ← +1

      A Lift and flatten expressions
      p[i] ← p[x ← p I @ {~ t[p[ω]] ∈ F G} * ≡ i ← _ t ∈ G A B C E O P V] ◊ j ← (φ i) [Δ φ x]
      p t k n r {α[ω] @ i - α} ← c j ◊ p ← (i @ j - ι ≠ p) [p]

      A Compute slots for each frame
      s ← -1, ~ ∈ ι " n [ux] ← - ◊ ≠ ⊞ x ← 0 [] qe ← u I ◊ Δ ~ r n ← r [b], ; n [b ← _ t = B]

      A Compute frame depths
      d ← (≠p) ↑ d ◊ d [i ← _ t = F] ← 0 ◊ _ ← {z - d [i] + ← ω ≠ z ← r [ω]} * ≡ i ◊ f ← d [0 [] qe], -1

      A Record exported top-level bindings
      xi ← _ (t = B) ∧ k[r] = 0

      p t k n f s r d xi sym}

```

This code is used in chunk 5.  
Uses src 48.

### 5.3 Code Generator

31      $\langle \textit{Code Generator } 31 \rangle \equiv$   
           GC  $\leftarrow \{$

```
p t k n fr sl rf fd xi sym←w ◊ A B C E F G K L M N O P S V Z←1+ι15
I←{(←w)[]α} ◊ com←{>{α, ' , ' , w}/w}
ks←{w←[0]~(←w)=w[;0]} ◊ nam←{'Δ'□R'__'◊φ''sym[|w]}
```

|               |        |        |       |       |       |       |       |       |       |
|---------------|--------|--------|-------|-------|-------|-------|-------|-------|-------|
| syms, ←, '+'  | '_'    | 'x'    | '÷'   | '*'   | '@'   |       |       |       |       |
| nams, ←       | 'add'  | 'sub'  | 'mul' | 'div' | 'exp' | 'log' | 'res' | 'cir' | 'min' |
| syms, ←, '<'  | '≤'    | '='    | '≥'   | '>'   | '≠'   |       |       |       |       |
| nams, ←       | 'lth'  | 'lte'  | 'eq'  | 'gte' | 'gth' | 'neq' | 'not' | 'and' | 'lor' |
| syms, ←, '[]' | '['    | '\r'   | '\r'  | '\r'  | '\r'  | '\r'  | '\r'  | '\r'  | '\r'  |
| nams, ←       | 'sqd'  | 'brk'  | 'iot' | 'rho' | 'cat' | 'ctf' | 'rot' | 'trn' | 'rtf' |
| syms, ←, '≡'  | '≠'    | '\r'   | '\r'  | '\r'  | '\r'  | '\r'  | '\r'  | '\r'  | '\r'  |
| nams, ←       | 'eqv'  | 'nqv'  | 'rgt' | 'lft' | 'enc' | 'dec' | 'red' | 'rdf' | 'scn' |
| syms, ←, '↑'  | '↓'    | '\r'   | '\r'  | '\r'  | '\r'  | '\r'  | '\r'  | '\r'  | '\r'  |
| nams, ←       | 'tke'  | 'drp'  | 'map' | 'com' | 'dot' | 'rnk' | 'pow' | 'jot' | 'unq' |
| syms, ←, 'Δ'  | '\r'   | '\r'   | '\r'  | '\r'  | '\r'  | '\r'  | '\r'  | '\r'  | '\r'  |
| nams, ←       | 'gdu'  | 'gdd'  | 'oup' | 'fnd' | 'par' | 'mdv' | 'fft' | 'ift' | 'scl' |
| syms, ←, '∇'  | '\r'   | '\r'   | '\r'  | '\r'  | '\r'  | '\r'  | '\r'  | '\r'  | '\r'  |
| nams, ←       | 'this' | 'span' | 'l'   |       | 'r'   |       | 'aa'  | 'ww'  |       |

```

gck← (A 1)(A 6)
gcv← 'Aa' 'As'
gck←(B 1)(B 2)(B 3)(B 4)
gcv←'Bv' 'Bf' 'Bo' 'Bo'
gck←(C 1)(C 2)
gcv←'Ca' 'Cf'
gck←(E -2)(E -1)(E 0)(E 1)(E 2)(E 4)(E 6)
gcv←'Ec' 'Ek' 'Er' 'Em' 'Ed' 'Eb' 'Ei'
gck←(F 0)(F 2)(F 3)(F 4)
gcv←'Fz' 'Fn' 'Fm' 'Fd'
gck←(G 0)(N 1)
gcv←'Gd' 'Na'
gck←(O 1)(O 2)(O 4) (O 5) (O 7) (O 8)
gcv←'Ov' 'Of' 'Ovv' 'Ofv' 'Ovf' 'Off'
gck←(P 0)(P 1)(P 2)(P 3)(P 4)
gcv←'Pv' 'Pv' 'Pf' 'Po' 'Po'
gck←(V 0)(V 1)(V 2)(V 3)(V 4)
gcv←'Va' 'Va' 'Vf' 'Vo' 'Vo'
gcv←c{' '* Unhandled ','(⌘α),' */'',NL}'
NL←␣UCS 13 10

```

```
pref <- '#include "codfns.h" '
pref, <- ' '
```

```

pref,<-c'EXPORT int'
pref,<-c'DyalogGetInterpreterFunctions(void *p)'
pref,<-c{'
pref,<-c'    return set_dwafns(p);'
pref,<-c'}'
pref,<-c''

Bf<-{id<-sym>~|4>α
      z <-id,' = retain_cell(stkhd[-1]);'
z}

Cf<-{id<-~4>α
      z <-c'mk_closure((struct closure **)stkhd++, fn',id,', 0);'
z}

Ek<-{
      z <-c'release_cell(*--stkhd);'
      z,<-c''
z}

Em<-{
      z <-c'c = *--stkhd;'
      z,<-c'w = *--stkhd;'
      z,<-c'(c->fn)((struct array **)stkhd++, NULL, w, c->fv);'
      z,<-c'release_cell(c);'
      z,<-c'release_cell(w);'
z}

Er<-{
      z <-c'*z = *--stkhd;'
      z,<-c'goto cleanup;'
      z,<-c''
z}

Fn<-{id<-~5>α ◊ x<-~>~ω ◊ t<-2[]x ◊ k<-3[]x
      hsw<-(t=0)∨(t=E)∧k∈1 2 ◊ hsa<-((t=E)∧k=2)∨(t=0)∧k∈4 5 7 8
      z <-c'int'
      z,<-c'fn',id,'(struct array **z, struct array *l, struct array *r, void *fv[])'
      z,<-c{'
      z,<-c'    void    *stk[128];'
      z,<-c'    void    **stkhd;'
      z,<-c'    void    *w;'
      z,<-c'    void    *a;'
      z,<-c'    struct  closure *c;'
      z,<-c''

```



```

z,←c'          stkhd = &stk[0];'
z,←c' '
z,←c' ' ,''>,fdis''ω
z,←c'          *z = NULL;'
z,←c' '
z,←c'cleanup:'
z,←c'          return 0;'
z,←c'}'
z,←c' '
z}

Fz←{id←⌈5>α ⋄ awc←v/(3[]x){(ω∈A 0)∨(ω=E)∧α>0}2[]x←⊘>,fω
z ←c'int init',id,' = 0;'
z,←c' '
z,←c'EXPORT int'
z,←c'init(void)'
z,←c'{'
z,←c' return fn',id,'(NULL, NULL, NULL, NULL);'
z,←c'}'
z,←c' '
z,←c'int'
z,←c'fn',id,'(struct array **z, struct array *l, struct array *r, void *fv[])'
z,←c'{'
z,←c'          void      *stk[128];'
z,←c'          void      **stkhd;'
z,←c'          void      *a, *w;'
z,←c'          struct    closure *c;'
z,←c' '
z,←c'          if (init',id,')'
z,←c'              return 0;'
z,←c' '
z,←c'          stkhd = &stk[0];'
z,←c'          init',id,' = 1;'
z,←c'          cdf_init();'
z,←c' '
z,←c' ' ,''>,fdis''ω
z,←c'          return 0;'
z,←c'}'
z,←c' '
z}

Pf←{id←(syms⊔sym[|4>α])>nams
z ←c'*stkhd++ = retain_cell(',id,');'
z}

```

```

Va←{id←(|4>α)>' ' 'r' 'l' 'aa' 'ww',5↓sym
    z ←c'*stkhd++ = retain_cell(',id,');'
z}

Zp←{n←'fn',⌘ω
    k[ω]∈0 2:{
        z ←c'int'
        z,←c'n, '(struct array **z, struct array *l, struct array *r, void *fv[]);'
        z,←c'
    }ω
    'UNKNOWN FUNCTION TYPE'␣SIGNAL 16
}

Zx←{n←sym>⌘|n[ω] ⋄ rid←⌘rf[ω]
    k[ω]=0:c'
    k[ω]=1:{
        z ←c'struct array *',n,',';
    }ω
    k[ω]=2:{
        z ←c'struct closure *',n,',';
        z,←c'
        z,←c'EXPORT int'
        z,←c'n, '_dwa(struct localp *zp, struct localp *lp, struct localp *rp)'
        z,←c'{
            z,←c'
            z,←c'        struct array *z, *l, *r;'
            z,←c'        int err;'
            z,←c'
            z,←c'        l = NULL;'
            z,←c'        r = NULL;'
            z,←c'
            z,←c'        fn',rid, '(NULL, NULL, NULL, NULL);'
            z,←c'
            z,←c'        err = 0;'
            z,←c'
            z,←c'        if (lp)'
            z,←c'            err = dwa2array(&l, lp->pocket);'
            z,←c'
            z,←c'        if (err)'
            z,←c'            dwa_error(err);;'
            z,←c'
            z,←c'        if (rp)'
            z,←c'            dwa2array(&r, rp->pocket);'
            z,←c'
            z,←c'        if (err) {'

```

June 10, 2022

codfns.nw 35

```
z,←c'                                release_array(l);'
z,←c'                                dwa_error(err);'
z,←c'                                }'
z,←c'                                '
z,←c'                                err = ('n,->fn)(&z, l, r, 'n,->fv);'
z,←c'                                '
z,←c'                                release_array(l);'
z,←c'                                release_array(r);'
z,←c'                                '
z,←c'                                if (err)'
z,←c'                                dwa_error(err);'
z,←c'                                '
z,←c'                                err = array2dwa(NULL, z, zp);'
z,←c'                                release_array(z);'
z,←c'                                '
z,←c'                                if (err)'
z,←c'                                dwa_error(err);'
z,←c'                                '
z,←c'                                return 0;'
z,←c'                                '
z,←c'                                '
z}ω
⊥'''UNKNOWN EXPORT TYPE''⊠SIGNAL 16'
}

d i←P2D p ⊠ ast←(⊠td p t k n(ι≠p)fr sl fd)[i;]
NOTFOUND←{('[GC] UNSUPPORTED NODE TYPE ',NΔ[ω],⌘⊢ϕω)⊠SIGNAL 16}
dis←{0=2>h←,1↑ω:'' ⊠ (≠gck)=i←gckι<h[2 3]:NOTFOUND h[2 3] ⊠ h(⊥i>gcv)ks 1↑ω
z←ε,∘NL''pref,⊃,⌘(,⌘Zp''⊥t=F),(,⌘Zx''xi),(c<''),dis''ks ast
z}
```

This code is used in chunk 5.  
Uses codfns 5 and SIGNAL 19b.

## 5.4 Backend C Compiler Interface

36

*⟨Interface to the backend C compiler 36⟩≡*

CC←{

```

    vsbat←VSΔPATH, '\VC\Auxiliary\Build\vcvarsall.bat'
    tie←{0:~SIGNAL EN ⋄ 22:~ω NCREATE 0 ⋄ 0 NRESIZE ω NTIE 0}
    put←{s←(−128+256|128+'UTF-8'UCS α)NAPPEND(t←tie ω)83 ⋄ 1:r←s~NUNTIE t
    ⟨The opsys utility 42c⟩
    soext←{opsys'.dll' '.so' '.dylib'}
    ccf←{' -o ',ω, '.',α, ' ',ω, '.c' -laf',AFΔLIB, ' > ',ω, '.log 2>&1'}
    cci←{'-I',AFΔPREFIX, '/include' -L',AFΔPREFIX, opsys ' ' /lib64 ' ' /
    cco←'-std=c99 -Ofast -g -Wall -fPIC -shared -Wno-parentheses '
    cco,←'-Wno-misleading-indentation '
    ucc←{ωω(ΔSH αα, ' ',cco,cci,ccf)ω}
    gcc←'gcc'ucc'so'
    clang←'clang'ucc'dylib'
    vsco←{z←'/W3 /wd4102 /wd4275 /O2 /Zc:inline /Zi /FS /Fd"',ω, '.pdb' '
        z,←'/WX /MD /EHsc /nologo '
        z, '/I"%AF_PATH%\include" /D "NOMINMAX" /D "AF_DEBUG" '}
    vslo←{z←'/link /DLL /OPT:REF /INCREMENTAL:NO /SUBSYSTEM:WINDOWS '
        z,←'/LIBPATH:"%AF_PATH%\lib" /OPT:ICF /ERRORREPORT:PROMPT /TLBID:1
        z, '/DYNAMICBASE "af', AFΔLIB, '.lib" "codfns.lib" '}
    vsc0←{~NEXISTS vsbat:'VISUAL C?'~SIGNAL 99 ⋄ ' ',vsbat, ' amd64'}
    vsc1←{' && cd ',(ΔCMD'echo %CD%'),' && cl ',(vsco ω), ' ',ω, '.c' '}
    vsc2←{(vslo ω), '/OUT:"',ω, '.dll' > ' ',ω, '.log'""}
    vsc←{ΔCMD ('%comspec% /C ',vsc0,vsc1,vsc2)ω}
    _←(Δopsys'vsc' 'gcc' 'clang')α~ω put α, '.c'~1 NDELETE f←α,soextθ
    _←,ΔNGET(α, '.log')1
    NEXISTS f:f ⋄ 'COMPILE ERROR' SIGNAL 22}

```

This code is used in chunk 5.

Uses AFΔLIB 9, AFΔPREFIX 9, codfns 5, put 42a, SIGNAL 19b, tie 42a, vsbat 49a, vsc 49a, and VSΔPATH 10.

## 5.5 Linking with Dyalog

37a

⟨Linking with Dyalog 37a⟩≡

NS←{

```

MKA←{mka←ω} ⋄ EXA←{exa ⋄ ω}
Display←{α←'Co-dfns' ⋄ W←w_new←α ⋄ 777::w_del W
      w_del W←W αα{w_close α:⌈'⌈SIGNAL 777' ⋄ α αα ω}*ωω←ω}
LoadImage←{α←1 ⋄ ~⌈NEXISTS ω:⌈SIGNAL 22 ⋄ loading ⋄ ω α}
SaveImage←{α←'image.png' ⋄ saveimg ω α}
Image←{~2 3v.=≠pω:⌈SIGNAL 4 ⋄ (3≠pω)^3=≠pω:⌈SIGNAL 5 ⋄ ω←w_img ω α}
Plot←{2≠pω:⌈SIGNAL 4 ⋄ ~2 3v.=1pω:⌈SIGNAL 5 ⋄ ω←w_plot (⋄ω) α}
Histogram←{ω←w_hist ω,α}
RtmΔInit←{
  _←'w_new'      ⌈NA'P' ,ω,'|w_new          <C[]'
  _←'w_close'⌈NA'I' ,ω,'|w_close P'
  _←'w_del'      ⌈NA          ω,'|w_del          P'
  _←'w_img'      ⌈NA          ω,'|w_img          <PP P'
  _←'w_plot'     ⌈NA          ω,'|w_plot        <PP P'
  _←'w_hist'     ⌈NA          ω,'|w_hist        <PP F8      F8 P'
  _←'loading'    ⌈NA          ω,'|loading >PP <C[] I'
  _←'saveimg'    ⌈NA          ω,'|saveimg <PP <C[]'
  _←'exa'        ⌈NA          ω,'|exarray >PP P'
  _←'mka'        ⌈NA'P' ,ω,'|mkarray <PP'
  _←'FREA'       ⌈NA          ω,'|frea          P'
  _←'Sync'       ⌈NA          ω,'|cd_sync'
  0 0 ρ θ}
mkna←{α,'|',('Δ'⌈R'__'←ω),'_cdf P P P'}
mkf←{fn←α,'|',('Δ'⌈R'__'←ω),'_dwa ' ⋄ mon dya←ω°,''_mon' '_dya'
      z←('Z←{A}',ω,' W')(':If 0=⌈NC' 'Δ.',mon,'')
      z,←(mon dya{'',α,' 'Δ.⌈NA'',fn,ω,' <PP'''}''>PP P' '>PP <PP'),c':E
      z,':If 0=⌈NC' 'A'('Z←Δ.',mon,' 0 0 W')':Else'('Z←Δ.',dya,' 0 A W')':
ns←#.⌈NSθ ⋄ _←'ΔΔ'ns.⌈NS''cθ ⋄ Δ Δ←ns.(Δ Δ) ⋄ Δ.names←(0ρ<''),(2=1>α)≠0=
fns←'RtmΔInit' 'MKA' 'EXA' 'Display' 'LoadImage' 'SaveImage' 'Image' 'Plot
fns,←'Histogram' 'soext' 'opsys' 'mkna'
_←Δ.⌈FX∘⌈CR''fns ⋄ Δ.(decls←ω∘mkna''names) ⋄ _←ns.⌈FX''(c''),ω∘mkf''Δ.name
_←Δ.⌈FX'Z←Init'('Z←RtmΔInit ''',ω,'')'→0≠0=≠names' 'names ##.Δ.⌈NA''dec
ns}

```

This code is used in chunk 5.

Uses PP 41a and SIGNAL 19b.

## 5.6 Runtime

37b

⟨Implementation of APL Primitives 37b⟩≡

⌈ TBW

Root chunk (not used in this document).

38a  $\langle C Runtime Support 38a \rangle \equiv$   
`/* TBW */`  
 Root chunk (not used in this document).

38b  $\langle C Runtime Header 38b \rangle \equiv$   
`/* TBW */`  
 Root chunk (not used in this document).

## 6 Language Features

## 7 Runtime Primitives

## 8 Utilities

### 8.1 Must haves

There are some APL functions that are so critical as to be worthy of primitive status.

- Indexing
- Under
- Assert

38c  $\langle Must Have APL Utilities 38c \rangle \equiv$   
`I←{(⊂ω)⌈α}`  
`U←{α←⌈ ⋄ ωω×-1⌈α ααöωω ω}`  
`assert←{α←'assertion failure' ⋄ 0∈ω:⊥'α ⌈ SIGNAL 8' ⋄ shy←0}`  
 This code is used in chunk 5.  
 Defines:  
`assert`, used in chunk 23.  
 Uses SIGNAL 19b.

## 8.2 AST Pretty-printing

```

39  <Pretty-printing AST trees 39>≡
    dct←{α[(2×2≠/n,0)+(1↑≠m)+m+n←φv\φm←' ≠αα ω]ωω ω}
    dlk←{((x□ρω)↑[x←2|1+ωω]α),[ωω]αα@(c0 0)×('┐'⇒ω)┐ω}
    dwh←{ω('┐'dlk 1)' |┐┐┐'(0□□)dct,⊃;/(≠''α),''c[≠□□α)↑''α}
    dwv←{ω('┐'dlk 0)' ┐┐┐┐'(0□┐)dct(┐;1┐┐)⊃{α,' ',ω)/(1+┐[≠''α){α↑ω;''┐'┐↑≠□ω}''α}

    pp3←{α←'o' ◊ d←(ι≠ω)≠ω ◊ _←{z┐d+←ω≠z←α[ω]}×≡≡ω ◊ lbl←αρ≠ω
        lyr←{i←ια=d ◊ k v←┐□ωω[i],◊c□i ◊ (ω◊{α[ω]}''v)αα''@k┐ω}ω
        (ω=ι≠ω)≠αα lyr≠(1+ι┐/d),c□◊;◊□''lbl}

    lb3←{α←ι≠ω
        '(',''')',''{α,';',',ω}≠''(NΔ{α[ω]}@2┐(2>ω){α[|ω]}@{0>ω}@4↑>ω)[α;]}

```

This code is used in chunk 5.

Defines:

dct, never used.  
 dlk, never used.  
 dwh, never used.  
 dwv, never used.  
 lb3, never used.  
 pp3, never used.

### 8.3 Debugging utilities

The following utilities help to improve quality of life when working with the Co-dfns source code.

The `DISPLAY` function is taken from <https://dfns.dyalog.com> and helps to make debugging easier by allowing us to thread `DISPLAY` calls into expressions. I prefer to do something like this:

```
... {ω←⊖#.DISPLAY ω} ...
```

The function itself returns the character rendering of the code, so the above little expression is one that I use to insert and do debugging within an expression.

```
40 (DISPLAY Utility 40)≡
    DISPLAY←{⊖IO ⊖ML←0
    play of array.

    α←1 ⋄ chars←α>'..''''|- ' '⊖|-'
    A α: 0-clunky, 1-smooth

    tl tr bl br vt hz←chars
    A Top left

    box←{
        vrt hrz←(-1+ρω)ρ⋄vt hz
        top←(hz,'⊖→')[-1⊖α],hrz
        A Vert. an
        A Up
    per border with axis.
        bot←(α),hrz
    der with type.
        rgt←tr,vt,vrt,br
        lax←(vt,'⊖⊖')[-1⊖1⊖α],⋄cvt
        A Left side(s) wi
        A
        lft←⊖tl,(⊖lax),bl
        lft,(top;ω;bot),rgt
        A
    }

    deco←{α←type open ω ⋄ α,axes ω}
    axes←{(-2⌈ρω)⊖1+×ρω}
    A Type and axes vector
    A An
    ray axis types.
    open←{(1⌈ρω)ρω}
    pose null axes.
    trim←{(~1 1⊖⊖ω=' ')/ω}
    A Re
    move extra blank cols.
    type←{{(1=ρω)⊖'+ω}⊖,char''ω}
    char←{⊖≡ρω:hz ⋄ (αω∈'-',⊖D)⊖'#~'}⊖⊖
    A Simple array type
    A Simple scalar type.
    line←{(6≠10|⊖DR' 'ω)⊖' -'}
    A un
    derline for atom.

    {
    cursively box arrays:
```



```

0≡ω:' ';(open □FMT ω);line ω
1 θ≡(≡ω)(ρω):'▽' 0 0 box □FMT ω
    1≡ω:(deco ω)box open □FMT open ω
    ('ε'deco ω)box trim □FMT ▽"open ω
}ω
}

```

A Simple scalar  
 A Object rep: □OR  
 A Simple array.  
 A Nested array.

Root chunk (not used in this document).

Defines:

DISPLAY, used in chunk 41.

Uses □IO 8a and □ML 8a.

I also define a function PP that encapsulates the above usage pattern that I like to use, making the whole thing less verbose and a little more convenient.

41a *⟨PP Utility 41a⟩*≡  
 PP←{ω→□←#.DISPLAY ω}

Root chunk (not used in this document).

Defines:

PP, used in chunks 37a and 41b.

Uses DISPLAY 40.

Both of these function exist outside of the codfns namespace and so they get their own files inside of the src\ directory.

41b *⟨Tangle Commands 6⟩*+≡  
 echo "Tangling src/DISPLAY.aplf..."  
 notangle -R'[[DISPLAY]] Utility' codfns.nw > src/DISPLAY.aplf  
  
 echo "Tangling src/PP.aplf..."  
 notangle -R'[[PP]] Utility' codfns.nw > src/PP.aplf

This code is used in chunk 43.

Defines:

DIRECTORY, never used.

PP.aplf, never used.

Uses codfns 5, DISPLAY 40, PP 41a, and src 48.

## 8.4 Reading and Writing Files

It is helpful to be able to easily write files to disk, and the following `put` and `tie` utilities help us to do so when we want to. These are pretty standard, but they could maybe be replaced by `INPUT` or something like that.

```
42a  ⟨Basic tie and put utilities 42a⟩≡
      tie←{
          0::SIGNAL EN
          22::ω NCREATE 0
          0 NRESIZE ω NTIE 0
      }

      put←{
          s←(¯128+256|128+'UTF-8'UCS ω)NAPPEND(t←tie α)83
          1:r←sNUNTIE t
      }
```

This code is used in chunk 47b.

Defines:

`put`, used in chunks 36, 47b, and 48.

`tie`, used in chunks 36 and 47b.

Uses `SIGNAL` 19b.

## 8.5 XML Rendering

```
42b  ⟨XML Rendering 42b⟩≡
      Xml←{α←0 ♦ ast←α{d i←P2Dω ♦ i◦{ω[α]}''(c d),1↓α↓ω}* (0≠α)⊢ω ♦ d t k n←4†ast
          cls←NΔ[t],''('-. '[1+×k]),''⌘''|k ♦ fld←{((≠ω)†3↓fΔ),;ω}''↓Q†3↓ast
          XMLQ†d cls(c')fld}
```

This code is used in chunk 5.

Defines:

`Xml`, never used.

## 8.6 Detecting the Operating System

It is quite helpful to be able to easily detect the operating system that we are on. This turns out to be helpful in more areas than just the compiler.

```
42c  ⟨The opsys utility 42c⟩≡
      opsys←{ω∼'Win' 'Lin' 'Mac'⊢c3†>'.'WG'APLVersion'}
```

This code is used in chunks 36, 44c, and 46d.

Defines:

`opsys`, used in chunks 44c and 46d.

## 9 Developer Infrastructure

### 9.1 Building the Compiler

The Co-dfns compiler is written, developed, and distributed as a literate program. For more information about literate programming, see the resources available at <http://literateprogramming.com/>. We use noweb as our preferred literate programming tool because it is eminently simple, while still handling the majority of our needs and producing high quality output in L<sup>A</sup>T<sub>E</sub>X format with all the important elements of literate programming, including live hyperlinking and cross-references.

#### 9.1.1 Tangling the Source

The process of tangling produces the executable source code for the compiler. Importantly, the tangled output is *not* meant to be used as the primary means of reading or debugging the source. Instead, it is meant primarily as the machine readable version of the code only.

With noweb, we need to invoke `notangle` once for each of the chunks that we wish to use to produce an output file. To make this easy, we build up a script to do this work for us.

For Linux and Mac, the following bash script creates these files. We use a separate chunk that we build up incrementally throughout the rest of this document as a record of all the chunks that we should create. Notice that we explicitly tangle the `TANGLE.sh` file as the last thing that we do; this helps to ensure that we are reliably executing the rest of the script before changing the contents of the file, as some systems will be affected and change execution behavior in strange ways if we change the `TANGLE.sh` file early on in the execution of the file.

```
43 <TANGLE.sh 43>≡
    #!/bin/bash

    <Tangle Commands 6>

    echo "Tangling TANGLE.sh..."
    notangle -R'[[TANGLE.sh]]' codfns.nw > TANGLE.sh
Root chunk (not used in this document).
Defines:
    TANGLE.sh, used in chunk 44a.
Uses codfns 5 and TANGLE 44c.
```

On Windows, the best way that we have found to do this is by installing noweb using the Cygwin project and then calling `TANGLE.sh` from a local `TANGLE.bat` file. This document assumes that you have already successfully built and installed via Cygwin a working Icon-driven noweb installation.

Users who prefer to work in a UNIX fashion via Cygwin or some other subsystem on Windows can follow the build scripts directly. For developers who prefer to work in a primarily Windows environment, the following `TANGLE.bat` build script assists in handling the calls into Cygwin so that you do not need to have a Cygwin terminal open all the time.

44a `<TANGLE.bat 44a>≡`  
`set SH=C:\cygwin64\bin\bash.exe -l -c`  
`%SH% "cd $OLDPWD && ./TANGLE.sh"`

Root chunk (not used in this document).

Defines:

`TANGLE.bat`, used in chunk 44b.

Uses `TANGLE 44c` and `TANGLE.sh 43`.

44b `<Tangle Commands 6>+≡`  
`echo "Tangling TANGLE.bat..."`  
`notangle -R'[[TANGLE.bat]]' codfns.nw > TANGLE.bat`

This code is used in chunk 43.

Uses `codfns 5`, `TANGLE 44c`, and `TANGLE.bat 44a`.

When tangled to the `TANGLE.aplf` file, the following script enables the user to simply type `TANGLE` within a Dyalog APL session to update the code tree from within Dyalog itself. This is much more convenient than keeping a Cygwin Terminal session open along with a Dyalog APL session while programming.

*Note: this command expects to be run from within the root of the repository, not from, say, within the testing directory.*

44c `<TANGLE 44c>≡`  
`TANGLE;opsys`  
`<The opsys utility 42c>`  
`□CMD opsys '.\TANGLE.bat' './TANGLE.sh' './TANGLE.sh'`

Root chunk (not used in this document).

Defines:

`TANGLE`, used in chunks 43 and 44.

Uses `opsys 42c`.

44d `<Tangle Commands 6>+≡`  
`echo "Tangling TANGLE.aplf..."`  
`notangle -R'[[TANGLE]]' codfns.nw > src/TANGLE.aplf`

This code is used in chunk 43.

Defines:

`TANGLE.aplf`, never used.

Uses `codfns 5`, `src 48`, and `TANGLE 44c`.

### 9.1.2 Weaving the Source

Weaving is the process by which we produce the final printed output of this document, intended for reading and general human consumption. We rely on the  $\text{\LaTeX}$  typesetting system to do this. Moreover, because we make heavy use of UTF-8 and prefer to have our own fonts installed and used, it is necessary to use the `xelatex` system instead of the typical  $\text{\LaTeX}$  engine. In order to get the indexing right, we must run the engine twice. The first run will update the indexing files that will be picked up on the second run and incorporated into the final document. Note, we have tried to use the `lua-latex` engine, which in theory should work just as well as the `xelatex` engine, but we get a strange error relating to noweb's style file, so we stick with `xelatex` for now.

Running this script also depends on having the appropriate fonts installed. In this case, please ensure that the following fonts are installed in your Windows font system so that they can be picked up by the  $\text{\TeX}$  engine.

- Libre Baskerville (Regular, Italic, Bold)
- APL385 Unicode
- Lucida Sans Unicode
- Cambria Math

If you do not wish to use these fonts, then see the top of the `codfns.nw` file and edit the font specifications to the fonts that you do wish to use.

Note the use of `-delay -index` for options. We want to generate indexing, but we also need to make sure that we can use some of our own packages in the system,

*Note: this command expects to be run from within the root of the repository, not from, say, within the testing directory.*

```
45 <WEAVE.sh 45>≡
    #!/bin/bash
    mkdir -p woven
    noweave -delay -index codfns.nw > woven/codfns.tex
    cd woven
    xelatex codfns
    xelatex codfns
```

Root chunk (not used in this document).

Defines:

`WEAVE.sh`, used in chunk 46.

Uses `codfns.5`.

46a *⟨Tangle Commands 6⟩*+≡  
 echo "Tangling WEAVE.sh..."  
 notangle -R'[[WEAVE.sh]]' codfns.nw > WEAVE.sh

This code is used in chunk 43.  
 Uses codfns 5, WEAVE 46d, and WEAVE.sh 45.

And just like the tangling code, we want to define a TANGLE.bat batch file to call the Cygwin environment from Windows.

46b *⟨WEAVE.bat 46b⟩*≡  
 set SH=C:\cygwin64\bin\bash.exe -l -c  
 %SH% "cd \$OLDPWD && ./WEAVE.sh"

Root chunk (not used in this document).  
 Defines:  
 WEAVE.bat, used in chunk 46c.  
 Uses WEAVE 46d and WEAVE.sh 45.

46c *⟨Tangle Commands 6⟩*+≡  
 echo "Tangling WEAVE.bat..."  
 notangle -R'[[WEAVE.bat]]' codfns.nw > WEAVE.bat

This code is used in chunk 43.  
 Uses codfns 5, WEAVE 46d, and WEAVE.bat 46b.

Like the *⟨TANGLE Command (never defined)⟩*, the following command, when tangled to the WEAVE.aplf file enables weaving in a the Dyalog APL session by executing the WEAVE command.

46d *⟨WEAVE 46d⟩*≡  
 WEAVE;opsys  
*⟨The opsys utility 42c⟩*  
 □CMD opsys '.\WEAVE.bat' './WEAVE.sh' './WEAVE.sh'

Root chunk (not used in this document).  
 Defines:  
 WEAVE, used in chunk 46.  
 Uses opsys 42c.

46e *⟨Tangle Commands 6⟩*+≡  
 echo "Tangling src/WEAVE.aplf..."  
 notangle -R'[[WEAVE]]' codfns.nw > src/WEAVE.aplf

This code is used in chunk 43.  
 Defines:  
 WEAVE.aplf, never used.  
 Uses codfns 5, src 48, and WEAVE 46d.

## 9.2 Building the Runtime

One of our goals with the Co-dfns runtime is to write as much of it as possible in APL. This means that we want to have at minimum a very small kernel that has been written in C, while most of the rest of the code is implemented in some APL files. This leads to a three part breakdown of the process to build the runtime.

47a *⟨Build the runtime 47a⟩*≡  
     *⟨Compile the primitives in prim.apln 48⟩*  
     *⟨Build codfns.dll DLL 49a⟩*  
     *⟨Copy the runtime files into tests\ 49b⟩*

This code is used in chunk 47b.

We define the command `MKΔRTM` to build the runtime. This command takes a path to the root directory of the Co-dfns repository; this is to allow us to rebuild the runtime from anywhere in the system if we so choose.

47b *⟨MKΔRTM 47b⟩*≡  
     `MKΔRTM path;put;tie;src;vsbat;vsc;wsd`

*⟨Basic tie and put utilities 42a⟩*  
*⟨Build the runtime 47a⟩*

Root chunk (not used in this document).

Defines:

`MKΔRTM`, used in chunk 47c.

Uses `put` 42a, `src` 48, `tie` 42a, `vsbat` 49a, `vsc` 49a, and `wsd` 49a.

This file is another of our external utilities that exists outside of the `codfns` namespace, so it gets its own file in `src\`.

47c *⟨Tangle Commands 6⟩*+≡  
     `echo "Tangling src/MKΔRTM.aplf..."`  
     `notangle -R'[[MKΔRTM]]' codfns.nw > src/MKΔRTM.aplf`

This code is used in chunk 48.

Defines:

`MKΔRTM.aplf`, never used.

Uses `codfns` 5, `MKΔRTM` 47b, and `src` 48.

The first step we must take is producing an appropriate C file that contains the primitives that we have defined in `prim.apln`. This means that we want to only compile the code in `prim.apln` as far as producing the C code. Since we do not have a full blown runtime yet, we will be compiling the `prim.c` file along with the rest of the runtime code, instead of the normal build process, which assumes that we already have a working runtime. This means that we only invoke the GC TT PS passes of the compiler pipeline, while avoiding the CC pass. We use the SALT system to load the source from `prim.apln` and then run the compiler passes that we want before storing the resulting code in the `rtm\prim.c` file.

48 *<Compile the primitives in prim.apln 48>*≡  
     src←SRC SE.SALT.Load path,'\rtm\prim.apln'  
     (path,'\rtm\prim.c')put codfns.{GC TT PS ω}src

This code is used in chunk 47a.

Defines:

    src, used in chunks 6, 11, 14b, 30, 41b, 44d, 46, and 47.

Uses codfns 5, PS 15, and put 42a.



Once we have the `rtm\prim.c` file written appropriately, we can run the main compiler process. For simplicity, we just compile all of the `.c` files that are found in the `rtm\` subdirectory. We must ensure that we are appropriately invoking our ArrayFire dependencies as well as producing the appropriate debugging symbols most of the time.

```
49a <Build codfns.dll DLL 49a>≡
    vsbat←#.codfns.VSΔPATH
    vsbat,'\\VC\\Auxiliary\\Build\\vcvarsall.bat'
    wsd←path,'\\'

    vsc←'%comspec% /C "',vsbat,'" amd64'
    vsc,←' && cd "',wsd,'\\rtm"'
    vsc,←' && cl /MP /W3 /wd4102 /wd4275'
    vsc,←' /Od /Zc:inline /Zi /FS'
    vsc,←' /Fo".\\\\" /Fd"codfns.pdb"'
    vsc,←' /WX /MD /EHsc /nologo'
    vsc,←' /I"%AF_PATH%\\include"'
    vsc,←' /D"NOMINMAX" /D"AF_DEBUG" /D"EXPORTING"'
    vsc,←' "*.c" /link /DLL /OPT:REF'
    vsc,←' /INCREMENTAL:NO /SUBSYSTEM:WINDOWS'
    vsc,←' /LIBPATH:"%AF_PATH%\\lib"'
    vsc,←' /DYNAMICBASE "af",codfns.AFΔLIB,'.lib"'
    vsc,←' /OPT:ICF /ERRORREPORT:PROMPT'
    vsc,←' /TLBID:1 /OUT:"codfns.dll"'
```

This code is used in chunk 47a.

Defines:

`vsbat`, used in chunks 36 and 47b.

`vsc`, used in chunks 36, 47b, and 49b.

`wsd`, used in chunks 47b and 49b.

Uses `AFΔLIB` 9, `codfns` 5, and `VSΔPATH` 10.

Finally, in order to write up the test harness to work right, we must copy the appropriate runtime files into the `tests\` directory so that we can find them when we finally start running our code there.

```
49b <Copy the runtime files into tests\ 49b>≡
    □CMD □←vsc
    □CMD □←'copy "',wsd,'rtm\codfns.h" "',wsd,'tests\'
    □CMD □←'copy "',wsd,'rtm\codfns.exp" "',wsd,'tests\'
    □CMD □←'copy "',wsd,'rtm\codfns.lib" "',wsd,'tests\'
    □CMD □←'copy "',wsd,'rtm\codfns.pdb" "',wsd,'tests\'
    □CMD □←'copy "',wsd,'rtm\codfns.dll" "',wsd,'tests\'
```

This code is used in chunk 47a.

Uses `codfns` 5, `vsc` 49a, and `wsd` 49a.

### 9.3 Loading the Compiler

In order to load the compiler into an APL session as well as all the development utilities, we assume that you have first managed to either load up a session with a bootstrapped version of the `TANGLE` command or that you already have a tangled `src\` directory. If the `src\` directory has not yet been created by running the `TANGLE` command, then this must be done before loading the compiler system. After tangling, the compiler can be loaded using the provided `LOAD` shortcut. This shortcut is meant to use the Dyalog Link system for hot-loading the files in `src\` into the root namespace. We do so through the following link command:

```
Link.Create # src -source=dir -watch=dir
```

This means that we want to link the `src\` directory into the `#` namespace, but we also want to make sure that we only pull changes that come from the filesystem. This is because we are editing the code via the `WEB` document, and we do not want to risk having some intermediate representation that isn't accurate and that doesn't flow the right way; we want all appropriate changes to begin in the `WEB` document and then, and only then, flow into the session. This also allows us to make some modifications to the code for testing and experimentation inside of the session without consideration for the code outside of the session, and such changes will be removed or forgotten on the next `TANGLE` command.

To set this up, we also ensure that we begin our work within the root Co-dfns repository directory, as this is where we expect to run the `TANGLE` and `WEAVE` commands.

There is unfortunately only a limited range of possibilities for linking in a new directory as we wish to do. The method we choose to use is launching a fresh Dyalog APL session and then using an `LX` expression from the command line to do the actual linking using the `SE.UCMD` functionality. I personally find this to be rather hackish, and I hope that an alternative approach to doing this will show up in the near future. Nonetheless, the arguments that we pass to `dyalog.exe` look something like this:

```
LX="[SE.UCMD'Link.Create # src -source=dir -watch=dir']"
```

If you do not use the `LOAD` shortcut, you can use the above command to do the linking manually.

## 10 Index

### 10.1 Chunks

⟨\* 5⟩  
 ⟨DISPLAY *Utility* 40⟩  
 ⟨MKΔRTM 47b⟩  
 ⟨PP *Utility* 41a⟩  
 ⟨TANGLE.bat 44a⟩  
 ⟨TANGLE.sh 43⟩  
 ⟨TANGLE 44c⟩  
 ⟨TEST 14a⟩  
 ⟨WEAVE.bat 46b⟩  
 ⟨WEAVE.sh 45⟩  
 ⟨WEAVE 46d⟩  
 ⟨*Adjust AST for output* 16b⟩  
 ⟨*AST Record Structure* 13b⟩  
 ⟨*Basic tie and put utilities* 42a⟩  
 ⟨*Build codfns.dll DLL* 49a⟩  
 ⟨*Build the runtime* 47a⟩  
 ⟨*C Runtime Header* 38b⟩  
 ⟨*C Runtime Support* 38a⟩  
 ⟨*Code Generator* 31⟩  
 ⟨*Compile the primitives in prim.apln* 48⟩  
 ⟨*Compiler* 30⟩  
 ⟨*Converters between parent and depth vectors* 13c⟩  
 ⟨*Copy the runtime files into tests\* 49b⟩  
 ⟨*Global Settings* 8a⟩  
 ⟨*Implementation of APL Primitives* 37b⟩  
 ⟨*Interface to the backend C compiler* 36⟩  
 ⟨*Line and error reporting utilities* 19b⟩  
 ⟨*Linking with Dyalog* 37a⟩  
 ⟨*Must Have APL Utilities* 38c⟩  
 ⟨*Normalize the input formatting* 12b⟩  
 ⟨*Parse token stream* 23⟩  
 ⟨*Parser* 15⟩  
 ⟨*Parsing Constants* 16a⟩  
 ⟨*Pretty-printing AST trees* 39⟩  
 ⟨*Tangle Commands* 6⟩  
 ⟨*The opsys utility* 42c⟩  
 ⟨*The Fix API* 11⟩  
 ⟨*Tokenize input* 20⟩  
 ⟨*User-command API* 13a⟩  
 ⟨*Verify source input ω, set IN* 12a⟩  
 ⟨*XML Rendering* 42b⟩

## 10.2 Identifiers

AFΔLIB: 9, 13a, 36, 49a  
 AFΔPREFIX: 9, 36  
 assert: 23, 38c  
 codfns: 5, 6, 14b, 31, 36, 41b, 43, 44b, 44d, 45, 46a, 46c, 46e, 47c, 48, 49a, 49b  
 codfns.apln: 6  
 dct: 39  
 DISPLAY: 40, 41a, 41b  
 DISPLAY.aplf: 41b  
 dlk: 39  
 dwh: 39  
 dwv: 39  
 Fix: 11, 13a  
 lb3: 39  
 linestarts: 19b  
 mkdm: 19b  
 MKΔRTM: 47b, 47c  
 MKΔRTM.aplf: 47c  
 opsys: 42c, 44c, 46d  
 PP: 37a, 41a, 41b  
 PP.aplf: 41b  
 pp3: 39  
 PS: 11, 15, 48  
 put: 36, 42a, 47b, 48  
 quotelines: 19b, 20  
 SIGNAL: 12a, 19b, 20, 23, 31, 36, 37a, 38c, 42a  
 src: 6, 11, 14b, 30, 41b, 44d, 46e, 47b, 47c, 48  
 TANGLE: 43, 44a, 44b, 44c, 44d  
 TANGLE.aplf: 44d  
 TANGLE.bat: 44a, 44b  
 TANGLE.sh: 43, 44a  
 TEST: 14a, 14b, 23  
 TEST.aplf: 14b  
 tie: 36, 42a, 47b  
 VERSION: 8b  
 vsbat: 36, 47b, 49a  
 vsc: 36, 47b, 49a, 49b  
 VSΔPATH: 10, 36, 49a  
 WEAVE: 46a, 46b, 46c, 46d, 46e  
 WEAVE.aplf: 46e  
 WEAVE.bat: 46b, 46c  
 WEAVE.sh: 45, 46a, 46b  
 wsd: 47b, 49a, 49b  
 Xml: 42b

June 10, 2022

codfns.nw 53

xn: 16b, 19a  
xt: 16b, 19a  
□IO: 8a, 40  
□ML: 8a, 40  
□WX: 8a

## 11 GNU AFFERO GENERAL PUBLIC LICENSE

Version 3, 19 November 2007

Copyright © 2007 Free Software Foundation, Inc.

<https://fsf.org/>

Everyone is permitted to copy and distribute verbatim copies of this license document, but changing it is not allowed.

### Preamble

The GNU Affero General Public License is a free, copyleft license for software and other kinds of works, specifically designed to ensure cooperation with the community in the case of network server software.

The licenses for most software and other practical works are designed to take away your freedom to share and change the works. By contrast, our General Public Licenses are intended to guarantee your freedom to share and change all versions of a program—to make sure it remains free software for all its users.

When we speak of free software, we are referring to freedom, not price. Our General Public Licenses are designed to make sure that you have the freedom to distribute copies of free software (and charge for them if you wish), that you receive source code or can get it if you want it, that you can change the software or use pieces of it in new free programs, and that you know you can do these things.

Developers that use our General Public Licenses protect your rights with two steps: (1) assert copyright on the software, and (2) offer you this License which gives you legal permission to copy, distribute and/or modify the software.

A secondary benefit of defending all users' freedom is that improvements made in alternate versions of the program, if they receive widespread use, become available for other developers to incorporate. Many developers of free software are heartened and encouraged by the resulting cooperation. However, in the case of software used on network servers, this result may fail to come about. The GNU General Public License permits making a modified version and letting the public access it on a server without ever releasing its source code to the public.

The GNU Affero General Public License is designed specifically to ensure that, in such cases, the modified source code becomes available to the community. It requires the operator of a network server to provide the source code of the modified version running there to the users of that server. Therefore, public use of a modified version, on a publicly accessible server, gives the public access to the source code of the modified version.

An older license, called the Affero General Public License and published by Affero, was designed to accomplish similar goals. This is a different license, not a version of the Affero GPL, but Affero has released a new version of the Affero GPL which permits relicensing under this license.

The precise terms and conditions for copying, distribution and modification follow.

## Terms and Conditions

### 0. Definitions.

“This License” refers to version 3 of the GNU Affero General Public License.

“Copyright” also means copyright-like laws that apply to other kinds of works, such as semiconductor masks.

“The Program” refers to any copyrightable work licensed under this License. Each licensee is addressed as “you”. “Licensees” and “recipients” may be individuals or organizations.

To “modify” a work means to copy from or adapt all or part of the work in a fashion requiring copyright permission, other than the making of an exact copy. The resulting work is called a “modified version” of the earlier work or a work “based on” the earlier work.

A “covered work” means either the unmodified Program or a work based on the Program.

To “propagate” a work means to do anything with it that, without permission, would make you directly or secondarily liable for infringement under applicable copyright law, except executing it on a computer or modifying a private copy. Propagation includes copying, distribution (with or without modification), making available to the public, and in some countries other activities as well.

To “convey” a work means any kind of propagation that enables other parties to make or receive copies. Mere interaction with a user through a computer network, with no transfer of a copy, is not conveying.

An interactive user interface displays “Appropriate Legal Notices” to the extent that it includes a convenient and prominently visible feature that (1) displays an appropriate copyright notice, and (2) tells the user that there is no warranty for the work (except to the extent that warranties are provided), that licensees may convey the work under this License, and how to view a copy of this License. If the interface presents a list of user

commands or options, such as a menu, a prominent item in the list meets this criterion.

#### 1. Source Code.

The “source code” for a work means the preferred form of the work for making modifications to it. “Object code” means any non-source form of a work.

A “Standard Interface” means an interface that either is an official standard defined by a recognized standards body, or, in the case of interfaces specified for a particular programming language, one that is widely used among developers working in that language.

The “System Libraries” of an executable work include anything, other than the work as a whole, that (a) is included in the normal form of packaging a Major Component, but which is not part of that Major Component, and (b) serves only to enable use of the work with that Major Component, or to implement a Standard Interface for which an implementation is available to the public in source code form. A “Major Component”, in this context, means a major essential component (kernel, window system, and so on) of the specific operating system (if any) on which the executable work runs, or a compiler used to produce the work, or an object code interpreter used to run it.

The “Corresponding Source” for a work in object code form means all the source code needed to generate, install, and (for an executable work) run the object code and to modify the work, including scripts to control those activities. However, it does not include the work’s System Libraries, or general-purpose tools or generally available free programs which are used unmodified in performing those activities but which are not part of the work. For example, Corresponding Source includes interface definition files associated with source files for the work, and the source code for shared libraries and dynamically linked subprograms that the work is specifically designed to require, such as by intimate data communication or control flow between those subprograms and other parts of the work.

The Corresponding Source need not include anything that users can regenerate automatically from other parts of the Corresponding Source.

The Corresponding Source for a work in source code form is that same work.

#### 2. Basic Permissions.

All rights granted under this License are granted for the term of copyright on the Program, and are irrevocable provided the



stated conditions are met. This License explicitly affirms your unlimited permission to run the unmodified Program. The output from running a covered work is covered by this License only if the output, given its content, constitutes a covered work. This License acknowledges your rights of fair use or other equivalent, as provided by copyright law.

You may make, run and propagate covered works that you do not convey, without conditions so long as your license otherwise remains in force. You may convey covered works to others for the sole purpose of having them make modifications exclusively for you, or provide you with facilities for running those works, provided that you comply with the terms of this License in conveying all material for which you do not control copyright. Those thus making or running the covered works for you must do so exclusively on your behalf, under your direction and control, on terms that prohibit them from making any copies of your copyrighted material outside their relationship with you.

Conveying under any other circumstances is permitted solely under the conditions stated below. Sublicensing is not allowed; section 10 makes it unnecessary.

### 3. Protecting Users' Legal Rights From Anti-Circumvention Law.

No covered work shall be deemed part of an effective technological measure under any applicable law fulfilling obligations under article 11 of the WIPO copyright treaty adopted on 20 December 1996, or similar laws prohibiting or restricting circumvention of such measures.

When you convey a covered work, you waive any legal power to forbid circumvention of technological measures to the extent such circumvention is effected by exercising rights under this License with respect to the covered work, and you disclaim any intention to limit operation or modification of the work as a means of enforcing, against the work's users, your or third parties' legal rights to forbid circumvention of technological measures.

### 4. Conveying Verbatim Copies.

You may convey verbatim copies of the Program's source code as you receive it, in any medium, provided that you conspicuously and appropriately publish on each copy an appropriate copyright notice; keep intact all notices stating that this License and any non-permissive terms added in accord with section 7 apply to the code; keep intact all notices of the absence of any warranty; and give all recipients a copy of this License along with the Program.

You may charge any price or no price for each copy that you convey, and you may offer support or warranty protection for a fee.

#### 5. Conveying Modified Source Versions.

You may convey a work based on the Program, or the modifications to produce it from the Program, in the form of source code under the terms of section 4, provided that you also meet all of these conditions:

- (a) The work must carry prominent notices stating that you modified it, and giving a relevant date.
- (b) The work must carry prominent notices stating that it is released under this License and any conditions added under section 7. This requirement modifies the requirement in section 4 to “keep intact all notices”.
- (c) You must license the entire work, as a whole, under this License to anyone who comes into possession of a copy. This License will therefore apply, along with any applicable section 7 additional terms, to the whole of the work, and all its parts, regardless of how they are packaged. This License gives no permission to license the work in any other way, but it does not invalidate such permission if you have separately received it.
- (d) If the work has interactive user interfaces, each must display Appropriate Legal Notices; however, if the Program has interactive interfaces that do not display Appropriate Legal Notices, your work need not make them do so.

A compilation of a covered work with other separate and independent works, which are not by their nature extensions of the covered work, and which are not combined with it such as to form a larger program, in or on a volume of a storage or distribution medium, is called an “aggregate” if the compilation and its resulting copyright are not used to limit the access or legal rights of the compilation’s users beyond what the individual works permit. Inclusion of a covered work in an aggregate does not cause this License to apply to the other parts of the aggregate.

#### 6. Conveying Non-Source Forms.

You may convey a covered work in object code form under the terms of sections 4 and 5, provided that you also convey the machine-readable Corresponding Source under the terms of this License, in one of these ways:

- (a) Convey the object code in, or embodied in, a physical product (including a physical distribution medium), accompanied by the Corresponding Source fixed on a durable physical medium customarily used for software interchange.
- (b) Convey the object code in, or embodied in, a physical product (including a physical distribution medium), accompanied by a written offer, valid for at least three years and valid for as long as you offer spare parts or customer support for that product model, to give anyone who possesses the object code either (1) a copy of the Corresponding Source for all the software in the product that is covered by this License, on a durable physical medium customarily used for software interchange, for a price no more than your reasonable cost of physically performing this conveying of source, or (2) access to copy the Corresponding Source from a network server at no charge.
- (c) Convey individual copies of the object code with a copy of the written offer to provide the Corresponding Source. This alternative is allowed only occasionally and noncommercially, and only if you received the object code with such an offer, in accord with subsection 6b.
- (d) Convey the object code by offering access from a designated place (gratis or for a charge), and offer equivalent access to the Corresponding Source in the same way through the same place at no further charge. You need not require recipients to copy the Corresponding Source along with the object code. If the place to copy the object code is a network server, the Corresponding Source may be on a different server (operated by you or a third party) that supports equivalent copying facilities, provided you maintain clear directions next to the object code saying where to find the Corresponding Source. Regardless of what server hosts the Corresponding Source, you remain obligated to ensure that it is available for as long as needed to satisfy these requirements.
- (e) Convey the object code using peer-to-peer transmission, provided you inform other peers where the object code and Corresponding Source of the work are being offered to the general public at no charge under subsection 6d.

A separable portion of the object code, whose source code is excluded from the Corresponding Source as a System Library, need not be included in conveying the object code work.

A “User Product” is either (1) a “consumer product”, which means any tangible personal property which is normally used for per-

sonal, family, or household purposes, or (2) anything designed or sold for incorporation into a dwelling. In determining whether a product is a consumer product, doubtful cases shall be resolved in favor of coverage. For a particular product received by a particular user, “normally used” refers to a typical or common use of that class of product, regardless of the status of the particular user or of the way in which the particular user actually uses, or expects or is expected to use, the product. A product is a consumer product regardless of whether the product has substantial commercial, industrial or non-consumer uses, unless such uses represent the only significant mode of use of the product.

“Installation Information” for a User Product means any methods, procedures, authorization keys, or other information required to install and execute modified versions of a covered work in that User Product from a modified version of its Corresponding Source. The information must suffice to ensure that the continued functioning of the modified object code is in no case prevented or interfered with solely because modification has been made.

If you convey an object code work under this section in, or with, or specifically for use in, a User Product, and the conveying occurs as part of a transaction in which the right of possession and use of the User Product is transferred to the recipient in perpetuity or for a fixed term (regardless of how the transaction is characterized), the Corresponding Source conveyed under this section must be accompanied by the Installation Information. But this requirement does not apply if neither you nor any third party retains the ability to install modified object code on the User Product (for example, the work has been installed in ROM).

The requirement to provide Installation Information does not include a requirement to continue to provide support service, warranty, or updates for a work that has been modified or installed by the recipient, or for the User Product in which it has been modified or installed. Access to a network may be denied when the modification itself materially and adversely affects the operation of the network or violates the rules and protocols for communication across the network.

Corresponding Source conveyed, and Installation Information provided, in accord with this section must be in a format that is publicly documented (and with an implementation available to the public in source code form), and must require no special password or key for unpacking, reading or copying.

## 7. Additional Terms.

“Additional permissions” are terms that supplement the terms of this License by making exceptions from one or more of its conditions. Additional permissions that are applicable to the entire Program shall be treated as though they were included in this License, to the extent that they are valid under applicable law. If additional permissions apply only to part of the Program, that part may be used separately under those permissions, but the entire Program remains governed by this License without regard to the additional permissions.

When you convey a copy of a covered work, you may at your option remove any additional permissions from that copy, or from any part of it. (Additional permissions may be written to require their own removal in certain cases when you modify the work.) You may place additional permissions on material, added by you to a covered work, for which you have or can give appropriate copyright permission.

Notwithstanding any other provision of this License, for material you add to a covered work, you may (if authorized by the copyright holders of that material) supplement the terms of this License with terms:

- (a) Disclaiming warranty or limiting liability differently from the terms of sections 15 and 16 of this License; or
- (b) Requiring preservation of specified reasonable legal notices or author attributions in that material or in the Appropriate Legal Notices displayed by works containing it; or
- (c) Prohibiting misrepresentation of the origin of that material, or requiring that modified versions of such material be marked in reasonable ways as different from the original version; or
- (d) Limiting the use for publicity purposes of names of licensors or authors of the material; or
- (e) Declining to grant rights under trademark law for use of some trade names, trademarks, or service marks; or
- (f) Requiring indemnification of licensors and authors of that material by anyone who conveys the material (or modified versions of it) with contractual assumptions of liability to the recipient, for any liability that these contractual assumptions directly impose on those licensors and authors.

All other non-permissive additional terms are considered “further restrictions” within the meaning of section 10. If the Program as you received it, or any part of it, contains a notice stating that it is governed by this License along with a term that

is a further restriction, you may remove that term. If a license document contains a further restriction but permits relicensing or conveying under this License, you may add to a covered work material governed by the terms of that license document, provided that the further restriction does not survive such relicensing or conveying.

If you add terms to a covered work in accord with this section, you must place, in the relevant source files, a statement of the additional terms that apply to those files, or a notice indicating where to find the applicable terms.

Additional terms, permissive or non-permissive, may be stated in the form of a separately written license, or stated as exceptions; the above requirements apply either way.

#### 8. Termination.

You may not propagate or modify a covered work except as expressly provided under this License. Any attempt otherwise to propagate or modify it is void, and will automatically terminate your rights under this License (including any patent licenses granted under the third paragraph of section 11).

However, if you cease all violation of this License, then your license from a particular copyright holder is reinstated (a) provisionally, unless and until the copyright holder explicitly and finally terminates your license, and (b) permanently, if the copyright holder fails to notify you of the violation by some reasonable means prior to 60 days after the cessation.

Moreover, your license from a particular copyright holder is reinstated permanently if the copyright holder notifies you of the violation by some reasonable means, this is the first time you have received notice of violation of this License (for any work) from that copyright holder, and you cure the violation prior to 30 days after your receipt of the notice.

Termination of your rights under this section does not terminate the licenses of parties who have received copies or rights from you under this License. If your rights have been terminated and not permanently reinstated, you do not qualify to receive new licenses for the same material under section 10.

#### 9. Acceptance Not Required for Having Copies.

You are not required to accept this License in order to receive or run a copy of the Program. Ancillary propagation of a covered work occurring solely as a consequence of using peer-to-peer transmission to receive a copy likewise does not require acceptance. However, nothing other than this License grants you per-

mission to propagate or modify any covered work. These actions infringe copyright if you do not accept this License. Therefore, by modifying or propagating a covered work, you indicate your acceptance of this License to do so.

#### 10. Automatic Licensing of Downstream Recipients.

Each time you convey a covered work, the recipient automatically receives a license from the original licensors, to run, modify and propagate that work, subject to this License. You are not responsible for enforcing compliance by third parties with this License.

An “entity transaction” is a transaction transferring control of an organization, or substantially all assets of one, or subdividing an organization, or merging organizations. If propagation of a covered work results from an entity transaction, each party to that transaction who receives a copy of the work also receives whatever licenses to the work the party’s predecessor in interest had or could give under the previous paragraph, plus a right to possession of the Corresponding Source of the work from the predecessor in interest, if the predecessor has it or can get it with reasonable efforts.

You may not impose any further restrictions on the exercise of the rights granted or affirmed under this License. For example, you may not impose a license fee, royalty, or other charge for exercise of rights granted under this License, and you may not initiate litigation (including a cross-claim or counterclaim in a lawsuit) alleging that any patent claim is infringed by making, using, selling, offering for sale, or importing the Program or any portion of it.

#### 11. Patents.

A “contributor” is a copyright holder who authorizes use under this License of the Program or a work on which the Program is based. The work thus licensed is called the contributor’s “contributor version”.

A contributor’s “essential patent claims” are all patent claims owned or controlled by the contributor, whether already acquired or hereafter acquired, that would be infringed by some manner, permitted by this License, of making, using, or selling its contributor version, but do not include claims that would be infringed only as a consequence of further modification of the contributor version. For purposes of this definition, “control” includes the right to grant patent sublicenses in a manner consistent with the requirements of this License.

Each contributor grants you a non-exclusive, worldwide, royalty-free patent license under the contributor's essential patent claims, to make, use, sell, offer for sale, import and otherwise run, modify and propagate the contents of its contributor version.

In the following three paragraphs, a "patent license" is any express agreement or commitment, however denominated, not to enforce a patent (such as an express permission to practice a patent or covenant not to sue for patent infringement). To "grant" such a patent license to a party means to make such an agreement or commitment not to enforce a patent against the party.

If you convey a covered work, knowingly relying on a patent license, and the Corresponding Source of the work is not available for anyone to copy, free of charge and under the terms of this License, through a publicly available network server or other readily accessible means, then you must either (1) cause the Corresponding Source to be so available, or (2) arrange to deprive yourself of the benefit of the patent license for this particular work, or (3) arrange, in a manner consistent with the requirements of this License, to extend the patent license to downstream recipients. "Knowingly relying" means you have actual knowledge that, but for the patent license, your conveying the covered work in a country, or your recipient's use of the covered work in a country, would infringe one or more identifiable patents in that country that you have reason to believe are valid.

If, pursuant to or in connection with a single transaction or arrangement, you convey, or propagate by procuring conveyance of, a covered work, and grant a patent license to some of the parties receiving the covered work authorizing them to use, propagate, modify or convey a specific copy of the covered work, then the patent license you grant is automatically extended to all recipients of the covered work and works based on it.

A patent license is "discriminatory" if it does not include within the scope of its coverage, prohibits the exercise of, or is conditioned on the non-exercise of one or more of the rights that are specifically granted under this License. You may not convey a covered work if you are a party to an arrangement with a third party that is in the business of distributing software, under which you make payment to the third party based on the extent of your activity of conveying the work, and under which the third party grants, to any of the parties who would receive the covered work from you, a discriminatory patent license (a) in connection with copies of the covered work conveyed by you (or copies made from those copies), or (b) primarily for and in



connection with specific products or compilations that contain the covered work, unless you entered into that arrangement, or that patent license was granted, prior to 28 March 2007.

Nothing in this License shall be construed as excluding or limiting any implied license or other defenses to infringement that may otherwise be available to you under applicable patent law.

12. No Surrender of Others' Freedom.

If conditions are imposed on you (whether by court order, agreement or otherwise) that contradict the conditions of this License, they do not excuse you from the conditions of this License. If you cannot convey a covered work so as to satisfy simultaneously your obligations under this License and any other pertinent obligations, then as a consequence you may not convey it at all. For example, if you agree to terms that obligate you to collect a royalty for further conveying from those to whom you convey the Program, the only way you could satisfy both those terms and this License would be to refrain entirely from conveying the Program.

13. Remote Network Interaction; Use with the GNU General Public License.

Notwithstanding any other provision of this License, if you modify the Program, your modified version must prominently offer all users interacting with it remotely through a computer network (if your version supports such interaction) an opportunity to receive the Corresponding Source of your version by providing access to the Corresponding Source from a network server at no charge, through some standard or customary means of facilitating copying of software. This Corresponding Source shall include the Corresponding Source for any work covered by version 3 of the GNU General Public License that is incorporated pursuant to the following paragraph.

Notwithstanding any other provision of this License, you have permission to link or combine any covered work with a work licensed under version 3 of the GNU General Public License into a single combined work, and to convey the resulting work. The terms of this License will continue to apply to the part which is the covered work, but the work with which it is combined will remain governed by version 3 of the GNU General Public License.

14. Revised Versions of this License.

The Free Software Foundation may publish revised and/or new versions of the GNU Affero General Public License from time to

time. Such new versions will be similar in spirit to the present version, but may differ in detail to address new problems or concerns.

Each version is given a distinguishing version number. If the Program specifies that a certain numbered version of the GNU Affero General Public License “or any later version” applies to it, you have the option of following the terms and conditions either of that numbered version or of any later version published by the Free Software Foundation. If the Program does not specify a version number of the GNU Affero General Public License, you may choose any version ever published by the Free Software Foundation.

If the Program specifies that a proxy can decide which future versions of the GNU Affero General Public License can be used, that proxy’s public statement of acceptance of a version permanently authorizes you to choose that version for the Program.

Later license versions may give you additional or different permissions. However, no additional obligations are imposed on any author or copyright holder as a result of your choosing to follow a later version.

15. Disclaimer of Warranty.

THERE IS NO WARRANTY FOR THE PROGRAM, TO THE EXTENT PERMITTED BY APPLICABLE LAW. EXCEPT WHEN OTHERWISE STATED IN WRITING THE COPYRIGHT HOLDERS AND/OR OTHER PARTIES PROVIDE THE PROGRAM “AS IS” WITHOUT WARRANTY OF ANY KIND, EITHER EXPRESSED OR IMPLIED, INCLUDING, BUT NOT LIMITED TO, THE IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE. THE ENTIRE RISK AS TO THE QUALITY AND PERFORMANCE OF THE PROGRAM IS WITH YOU. SHOULD THE PROGRAM PROVE DEFECTIVE, YOU ASSUME THE COST OF ALL NECESSARY SERVICING, REPAIR OR CORRECTION.

16. Limitation of Liability.

IN NO EVENT UNLESS REQUIRED BY APPLICABLE LAW OR AGREED TO IN WRITING WILL ANY COPYRIGHT HOLDER, OR ANY OTHER PARTY WHO MODIFIES AND/OR CONVEYS THE PROGRAM AS PERMITTED ABOVE, BE LIABLE TO YOU FOR DAMAGES, INCLUDING ANY GENERAL, SPECIAL, INCIDENTAL OR CONSEQUENTIAL DAMAGES ARISING OUT OF THE USE OR INABILITY TO USE THE PROGRAM (INCLUDING BUT NOT LIMITED TO LOSS OF DATA OR DATA

BEING RENDERED INACCURATE OR LOSSES SUSTAINED BY YOU OR THIRD PARTIES OR A FAILURE OF THE PROGRAM TO OPERATE WITH ANY OTHER PROGRAMS), EVEN IF SUCH HOLDER OR OTHER PARTY HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES.

#### 17. Interpretation of Sections 15 and 16.

If the disclaimer of warranty and limitation of liability provided above cannot be given local legal effect according to their terms, reviewing courts shall apply local law that most closely approximates an absolute waiver of all civil liability in connection with the Program, unless a warranty or assumption of liability accompanies a copy of the Program in return for a fee.

## End of Terms and Conditions

### How to Apply These Terms to Your New Programs

If you develop a new program, and you want it to be of the greatest possible use to the public, the best way to achieve this is to make it free software which everyone can redistribute and change under these terms.

To do so, attach the following notices to the program. It is safest to attach them to the start of each source file to most effectively state the exclusion of warranty; and each file should have at least the “copyright” line and a pointer to where the full notice is found.

```
<one line to give the program's name and a brief idea of what it does.>
```

```
Copyright (C) <textyear>          <name of author>
```

```
This program is free software: you can redistribute it and/or modify
it under the terms of the GNU Affero General Public License as published by
the Free Software Foundation, either version 3 of the License, or
(at your option) any later version.
```

```
This program is distributed in the hope that it will be useful,
but WITHOUT ANY WARRANTY; without even the implied warranty of
MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.  See the
GNU Affero General Public License for more details.
```

```
You should have received a copy of the GNU Affero General Public License
along with this program.  If not, see <https://www.gnu.org/licenses/>.
```

Also add information on how to contact you by electronic and paper mail.

If your software can interact with users remotely through a computer network, you should also make sure that it provides a way for users to get its source. For example, if your program is a web application, its interface could display a “Source” link that leads users to an archive of the code. There are many ways you could offer source, and different solutions will be better for different programs; see section 13 for the specific requirements.

You should also get your employer (if you work as a programmer) or school, if any, to sign a “copyright disclaimer” for the program, if necessary. For more information on this, and how to apply and follow the GNU AGPL, see <https://www.gnu.org/licenses/>.