

The Co-dfns Compiler

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June 8, 2022

Co-dfns Compiler: High-performance, Parallel APL Compiler
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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.

```
4  (* 4)≡
    :Namespace codfns

        {Global Settings 6}
        {The Fix API 7}
        {User-command API 9a}

        {Parser 22}
        {Compiler 32}
        {Code Generator 33}
        {Interface to the backend C compiler 38}
        {Linking with Dyalog 39a}

        {AST Record Structure 9b}
        {Converters between parent and depth vectors 9c}
        {XML Rendering 18a}
        {Pretty-printing AST trees 18b}

    :EndNamespace

Root chunk (not used in this document).
Defines:
    codfns, used in chunks 10, 13, 16, 17, 33, and 38.
```

The primary user-facing interfaces into the compiler are *⟨The Fix API 7⟩* and the *⟨User-command API 9a⟩*. 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.¹

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

¹You 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

```
6  <Global Settings 6>=
    □IO □ML □WX←0 1 3
    VERSION←4 1 0
    AFΔPREFIX←'/opt/arrayfire'
    AFΔLIB←'cuda'
    VSΔPATH←'\Program Files\Microsoft Visual Studio\2022\Community'
```

This code is used in chunk 4.

Defines:

- AFΔLIB, used in chunks 9a, 17a, and 38.
- AFΔPREFIX, used in chunk 38.
- VERSION, never used.
- VSΔPATH, used in chunks 17a and 38.
- IO, used in chunk 19.
- ML, used in chunk 19.
- WX, never used.

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 `α` 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.

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

This code is used in chunk 4.

Defines:

`Fix`, used in chunk 9a.

Uses `src 16c`.

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.

8a *⟨Verify input from IN 8a⟩*≡
`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 8b⟩

`err←'PARSER EXPECTS CHARACTER ARRAY'`
`0≠10|□DR IN:err □SIGNAL 11`

This code is used in chunk 22.

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.

8b *⟨Normalize the input formatting 8b⟩*≡
`IN←ε(⊆IN), '□UCS 10`

This code is used in chunk 8a.

3.3 The User Command API

9a $\langle \text{User-command API } 9a \rangle \equiv$

```

  ▽ 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 4.
  Uses AFΔLIB 6 and Fix 7.

```

3.4 AST Record Structure

9b $\langle \text{AST Record Structure } 9b \rangle \equiv$

```

  fΔ ← 'ptknfsrdx'
  NΔ ← 'ABCEFGKLMNOPSVZ'

```

This code is used in chunk 4.

3.5 Converters between parent and depth vectors

9c $\langle \text{Converters between parent and depth vectors } 9c \rangle \equiv$

```

  P2D ← {z ← ∫ ι ≠ ω ◊ d ← ω ≠, z ◊ _ ← {p → d + ← ω ≠ p ← α[z, ← ω]} * ≡ ∼ ω ◊ d(Δ(-1+d)† ∘ 0 1 ⊖ φ z)}
  D2P ← {0 = ≠ ω : θ ◊ p → 2 {p[ω] ← α[α ⊥ ω]} / ∙ ∘ ⊖ ω → p ← ι ≠ ω}

```

This code is used in chunk 4.

4 Developer Infrastructure

4.1 Building the Compiler

4.1.1 Tangling and Weaving the Literate Source

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^AT_EX format with all the important elements of literate programming, including live hyperlinking and cross-references. We intend `codfns.nw` to tangle into the following files based on specific chunks that have been provided in this document.

Chunk	File Output
<code><* 4></code>	<code>src\codfns.apln</code>
<code><C Runtime Support 40a></code>	<code>rtm\runtime.c</code>
<code><C Runtime Header 40b></code>	<code>rtm\codfns.h</code>
<code><Implementation of APL Primitives 39b></code>	<code>rtm\prim.apln</code>
<code><DISPLAY Utility 19></code>	<code>src\DISPLAY.aplf</code>
<code><MKΔRTM Command 16b></code>	<code>src\MKΔRTM.aplf</code>
<code><PP Utility 20a></code>	<code>src\PP.aplf</code>
<code><TANGLE Command 12></code>	<code>src\TANGLE.aplf</code>
<code><TEST Function 21></code>	<code>src\TEST.aplf</code>
<code><WEAVE Command 14></code>	<code>src\WEAVE.aplf</code>
<code><Tangle Script 10></code>	<code>TANGLE.sh</code>
<code><Weave Script 13></code>	<code>WEAVE.sh</code>

The following bash script will create these files.

```

10 <Tangle Script 10>=
    #!/bin/bash
    echo "Tangling src/codfns.apln..."
    notangle codfns.nw > src/codfns.apln

    echo "Tangling src/DISPLAY.aplf..."
    notangle -R'[[DISPLAY]] Utility' codfns.nw > src/DISPLAY.aplf

    echo "Tangling src/MKΔRTM.aplf..."
    notangle -R'[[MKΔRTM]] Command' codfns.nw > src/MKΔRTM.aplf

    echo "Tangling src/PP.aplf..."
    notangle -R'[[PP]] Utility' codfns.nw > src/PP.aplf

```

```
echo "Tangling src/TANGLE.aplf..."
notangle -R'[[TANGLE]] Command' codfns.nw > src/TANGLE.aplf
```

```
echo "Tangling src/TEST.aplf..."
notangle -R'[[TEST]] Function' codfns.nw > src/TEST.aplf
```

```
echo "Tangling src/WEAVE.aplf..."
notangle -R'[[WEAVE]] Command' codfns.nw > src/WEAVE.aplf
```

```
echo "Tangling TANGLE.sh..."
notangle -R'Tangle Script' codfns.nw > TANGLE.sh
```

```
echo "Tangling WEAVE.sh..."
notangle -R'Weave Script' codfns.nw > WEAVE.sh
```

Root chunk (not used in this document).

Uses codfns 4, DISPLAY 19, MKΔRTM 16b, PP 20a, src 16c, TANGLE 12, TEST 21,
and WEAVE 14.

On Windows, the best way that we have found to do this is via the Cygwin project. 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 build scripts assist in handling the calls into Cygwin so that you do not need to have a Cygwin terminal open all the time.

When tangled to the `TANGLE.aplf` file, this script will enable the user simply type `TANGLE` to update the code tree from within a Dyalog APL Session. This is much more convenient than keeping a Cygwin Terminal session open along with a Dyalog APL session while programming. At the moment, this file is only designed to work on Windows with Cygwin, but we should in principle extend this to work on Linux and Mac OS X style machines as well.

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

```
12  (TANGLE Command 12)≡
    TANGLE;SH;CWD;CD
    SH←'C:\cygwin64\bin\bash.exe -l -c '
    CWD↔⍎CMD'C:\cygwin64\bin\bash.exe -c pwd'
    CD←'cd ',CWD, ''

    ⍎CMD SH, '',CD,' && ./TANGLE.sh''
```

Root chunk (not used in this document).

Defines:

`TANGLE`, used in chunk 10.

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 \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 \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 \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.

```
13 <Weave Script 13>≡
    #!/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).
Uses `codfns 4`.

Like the *⟨TANGLE Command 12⟩*, the following command, when tangled to the `WEAVE.aplf` file permits the Windows programmer to simply execute `WEAVE` in a the Dyalog APL session and weave the documents together.

```
14  ⟨WEAVE Command 14⟩≡
    WEAVE;SH;CWD;CD
    SH←'C:\cygwin64\bin\mintty.exe -e C:\cygwin64\bin\bash.exe -l -c '
    CWD←⊞CMD'C:\cygwin64\bin\bash.exe -c pwd'
    CD←'cd ',CWD,' '
```

```
⊞CMD SH, ' ',CD, ' && ./WEAVE.sh" '
```

Root chunk (not used in this document).

Defines:

`WEAVE`, used in chunk 10.

4.2 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.

4.3 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.

16a *⟨Build the runtime 16a⟩*≡
⟨Compile the primitives in prim.apln 16c⟩
⟨Build codfns.dll DLL 17a⟩
⟨Copy the runtime files into tests\ 17b⟩

This code is used in chunk 16b.

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.

16b *⟨MKΔRTM Command 16b⟩*≡
`MKΔRTM path;prim;put;src;tie;vsbat;vsc;wsd`

⟨Basic tie and put utilities 20b⟩
⟨Build the runtime 16a⟩

Root chunk (not used in this document).

Defines:

`MKΔRTM`, used in chunk 10.

Uses `put` 20b, `src` 16c, `tie` 20b, `vsbat` 17a, and `wsd` 17a.

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.

16c *⟨Compile the primitives in prim.apln 16c⟩*≡
`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 16a.

Defines:

`src`, used in chunks 7, 10, 16b, and 32.

Uses `codfns` 4 and `put` 20b.

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.

```
17a <Build codfns.dll DLL 17a>≡
    vsbat←#.codfns.VSΔPATH,'\\VC\\Auxiliary\\Build\\vcvarsall.bat'
    wsd←path,'\ '

    vsc←'%comspec% /C "'',vsbat,'" amd64'
    vsc,←' && cd "'',wsd,'\\rtm"'
    vsc,←' && cl /MP /W3 /wd4102 /wd4275 /Od /Zc:inline /Zi /FS'
    vsc,←' /Fo".\\\" /Fd"codfns.pdb"'
    vsc,←' /WX /MD /EHsc /nologo /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 16a.

Defines:

`vsbat`, used in chunks 16b and 38.

`wsd`, used in chunks 16b and 17b.

Uses `AFΔLIB` 6, `codfns` 4, and `VSΔPATH` 6.

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.

```
17b <Copy the runtime files into tests\ 17b>≡
    □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 16a.

Uses `codfns` 4 and `wsd` 17a.

4.4 XML Rendering

18a $\langle \text{XML Rendering } 18a \rangle \equiv$

$$\begin{aligned} \text{Xml} \leftarrow \{ \alpha \leftarrow 0 \ \diamond \ \text{ast} \leftarrow \alpha \{ d \ i \leftarrow P2D \triangleright \omega \ \diamond \ i \circ \{ \omega[\alpha] \}''(c d), 1 \downarrow \alpha \downarrow \omega \} \ddot{*} (0 \neq \alpha) \vdash \omega \ \diamond \ d \ t \ k \ n \leftarrow 4 \uparrow \text{ast} \\ \text{cls} \leftarrow N\Delta[t], ''(' - . . '[1 + \times k]), ''\text{f}'' | k \ \diamond \ \text{fld} \leftarrow \{ ((\neq \omega) \uparrow 3 \downarrow f \Delta), \text{f} \omega \}'' \downarrow \Phi \uparrow 3 \downarrow \text{ast} \\ \square \text{XML} \Phi \uparrow d \ \text{cls}(c'') \text{fld} \} \end{aligned}$$

This code is used in chunk 4.

4.5 AST Pretty-printing

18b $\langle \text{Pretty-printing AST trees } 18b \rangle \equiv$

$$\begin{aligned} \text{dct} \leftarrow \{ \alpha [(2 \times 2 \neq / n, 0) + (1 \uparrow \ddot{\neq} m) + m + n \leftarrow \phi v \setminus \phi m \leftarrow ' \neq \alpha \alpha \ \omega] \omega \omega \ \omega \} \\ \text{dlk} \leftarrow \{ ((x \square p \omega) \uparrow [x \leftarrow 2 | 1 + \omega \omega] \alpha), [\omega \omega] \alpha \alpha @ (c 0 \ 0) \ddot{*} (' \uparrow' = \triangleright \omega) \vdash \omega \} \\ \text{dwh} \leftarrow \{ \omega (' \uparrow' \text{dlk} \ 1) ' \mid \vdash \Gamma \vdash (0 \square \Phi) \text{dct}, \triangleright \text{f} / ((\neq'' \alpha), ''c \uparrow / \neq \circ \Phi'' \alpha) \uparrow'' \alpha \} \\ \text{dwv} \leftarrow \{ \omega (' \uparrow' \text{dlk} \ 0) ' \vdash \Gamma \mid (0 \square \vdash) \text{dct}(\text{f} \triangleright 1 \downarrow \vdash) \triangleright \{ \alpha, ' \ , \omega \} / (1 + \uparrow / \neq'' \alpha) \{ \alpha \uparrow \omega \text{f} \ddot{\neq} ' \uparrow \ddot{\neq} \Phi \omega \}'' \alpha \} \\ \\ \text{pp3} \leftarrow \{ \alpha \leftarrow ' o ' \ \diamond \ d \leftarrow (i \neq \omega) \neq \omega \ \diamond \ _ \leftarrow \{ z \vdash d \vdash \omega \neq z \leftarrow \alpha[\omega] \} \ddot{*} \equiv \ddot{\neq} \omega \ \diamond \ \text{lbl} \leftarrow \alpha p \ddot{\neq} \omega \\ \text{lyr} \leftarrow \{ i \leftarrow \underline{i} \alpha = d \ \diamond \ k \ v \leftarrow \downarrow \Phi \omega \omega[i], \circ c \square i \ \diamond \ (\omega \circ \{ \alpha[\omega] \}'' v) \alpha \alpha'' @ k \vdash \omega \} \omega \\ (\omega = i \neq \omega) \text{f} \triangleright \alpha \alpha \ \text{lyr} \text{f} (1 + i \uparrow / d), c \Phi \circ \text{f} \circ \text{f} \text{lbl} \} \\ \\ \text{lb3} \leftarrow \{ \alpha \leftarrow i \neq \triangleright \omega \\ ' (' , '' ') ' , '' \ddot{\neq} \{ \alpha , ' ; ' , \omega \} \text{f} \text{f}'' (N\Delta \{ \alpha[\omega] \} @ 2 \vdash (2 \triangleright \omega) \{ \alpha[|\omega] \} @ \{ 0 > \omega \} @ 4 \uparrow \triangleright \omega) [\alpha ;] \} \end{aligned}$$

This code is used in chunk 4.

Defines:

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

4.6 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.

```
19 (DISPLAY Utility 19)≡
    DISPLAY←{⊖IO ⊖ML←0
    play of array.

    α←1 ⋄ chars←α>'..''''|- ' '⊖|-'
    tl tr bl br vt hz←chars

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

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

    {
cursively box arrays:
```

A Bo

A α: 0-clunky, 1-smooth

A Top left

A Vert. an

A Up

A Left side(s) wi

A

A

A Type and axes vector

A An

A Re

A Simple array type

A Simple scalar type.

A un

```

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 chunks 10 and 20a.

Uses □IO 6 and □ML 6.

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.

20a *⟨PP Utility 20a⟩*≡
 PP←{ω→□←#.DISPLAY ω}

Root chunk (not used in this document).

Defines:

PP, used in chunks 10 and 39a.

Uses DISPLAY 19.

4.7 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.

20b *⟨Basic tie and put utilities 20b⟩*≡
 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←s□NUNTIE t
 }

This code is used in chunk 16b.

Defines:

put, used in chunks 16 and 38.

tie, used in chunks 16b and 38.

4.8 Testing Harness

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.

```
21  (TEST Function 21)≡
    TEST←{
        #.UT.(print_passed print_summary)←1
        'ALL'≡ω:#.UT.run './'
        path←'./t',(1 0⌞(4ρ10)⌈ω),'*_tests.dyalog'
        #.UT.run ⍵0⌞NINFO⌈1←path
    }
```

Root chunk (not used in this document).

Defines:

`TEST`, used in chunks 10 and 22.

5 Co-dfns Compiler

5.1 Parser

22

(Parser 22)≡

```
PS←{IN←ω ◊ A B C E F G K L M N O P S V Z←1+ι15
  I←{(cω)[]α} ◊ U←{0=□NC'α':ωω×-1 αα ωω ω ◊ ωω×-1-(ωω α) αα ωω ω}
  assert←{α←'assertion failure' ◊ 0∈ω:±'α □SIGNAL 8' ◊ shy+0}
```

(Verify input from IN 8a)

A Line and error reporting utilities

```
CR LF←□UCS 13 10
linestarts←(ι1;2>≠IN∈CR LF);≠IN
mkdm←{α←2 ◊ line←linestartsιω ◊ no←['',(⌘1+line),'] '
  i←(≠IN[i]∈CR LF)≠i←beg+ιlinestarts[line+1]-beg+linestarts[line]
  (□EM α)(no,IN[i])(' ^'[i∈ω],~' 'p~≠no)}
quotelines←{
  lines←ulinestartsιω
  nos←(1 0p~2×≠lines)λ['',(⌘1+lines),ö1-'] '
  beg←linestarts[lines] ◊ end←linestarts[lines+1]
  m←εω~i←beg+ιend-beg
  -1↓∈nos,(~◊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}
```

A Group input into lines as a nested vector

```
pos←(ι≠IN)ε~≠IN∈CR LF
```

A Mask strings

```
0≠≠lin←ι⊃◊φ~msk←≠λ~''''=IN◊I~pos:{
  EM←'SYNTAX ERROR: UNBALANCED STRING',('S'≠~2≤≠lin),CR
  EM,←quotelines ε(msk≠~pos)[lin]
  EM □SIGNAL 2}θ
```

A Remove comments

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

A Remove leading and trailing whitespace

```
WS←□UCS 9 32 ◊ pos msk≠~~←c~(λλvλλUφ)◊(WSε~IN◊I)~pos
```

A Flatten and separate lines and ◊ with Z type

```
t←⊃0p<pos ◊ t pos msk(ε,◊;~)←Z(⊃~pos)0 ◊ t[ι'◊'=IN[pos]]←Z
```

codfns.nw 23

```
end+=1+pos < t[i+12<70;msk]+C < end[i]+end[12>7msk;0]
t pos end+=<(t!=0)^~msk
```

```

_←{dm[ω]←Λλdm[ω]}*(dmvxεalp)≤i≠dm←xεnum
dmv←('.'=x)^(1φdm)∨1φdm
dmv←('−'=x)∧1φdm
dmv←(x∈'EeJj')^(1φdm)∧1φdm
v≠msk←(dm=0)∧x='−':2'ORPHANED −'SIGNAL pos≠msk
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'==0φ**dp:'MISSING EXPONENT'□SIGNAL 2
mn ex←1λt{2t(ω≤≠ω≠'e'),<''}**dp
v≠{1<+≠'.'=ω)**mn,ex:'MULTIPLE . IN NUMBER'□SIGNAL 2
v≠'.'ε**ex:'REAL NUMBER IN EXPONENT'□SIGNAL 2
v≠{v≠1λω∈'−'}**mn,ex:'MISPLACED −'□SIGNAL 2
t[i←i2<≠0;dm]←N ♦ end[i]←end≠2>≠dm;0

```

```
t[i+12<#0;vm<(~dm)^xεalp,num]←V ♦ end[i]←endf~2>#vm;0
```

```
f ← (mm ← φ) (▷ ◦ ◦, ⊢) ⊢ φm ← α = ' ', ω ◊ 1 ↓ ** (mm ∧ m1) (mm ∧ m1 ⊢ φm) }
am aam ← 'α' fm x ◊ wm wwm ← 'ω' fm x
((am ∨ wm) ⊢ t) ← A ◊ ((aam ∨ wwm) ⊢ t) ← P ◊ ((aam ∨ wwm) ⊢ end) ← end ⊢ ~ - 1 φ aam ∨ wwm
```

A Tokenize Primitives, Atoms

```

t[1(~dm)^xεprms]←P ♦ t[1xεsyna]←A

A Compute dfns regions and type, include } as a child
t[1{'='x]←F ♦ 0≠d←1φ+λ1 -1 0[{'}'lx]:'UNBALANCED DFNS'□SIGNAL 2

A Check for out of context dfns formals
v≠(d=0)^(t=P)^(IN[pos]ε'αω':'DFN FORMAL REFERENCED OUTSIDE DFNS'□SIGNAL

A Compute trad-fns regions
v≠Z≠t≠1φmsk←(d=0)^(∇'='x:'TRAD-FNS START/END LINES MUST BEGIN WITH ∇'□SIGNAL
NAL 2
0≠tm←1φ≠λ(d=0)^(∇'='x:'UNBALANCED TRAD-FNS'□SIGNAL 2
v≠Z≠t≠1 -1v.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(≠)←<(t≠0)vxε'()[{}:;]'

A Tokenize Labels
ERR←'LABEL MUST CONSIST OF A SINGLE NAME'
v≠(Z≠t[li-1])v(V≠t[li←1φmsk←t=L]):ERR □SIGNAL 2
t[li]←L ♦ end[li]←end[li+1]
d tm t pos end(≠)←<~msk

A Now that all compound data is tokenized, reify n field before tree-building
n←{1↓_''0',ω}@{t=N}{<'')@{t∈Z F}1 □C@{t∈K S}IN◦I''pos+1''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←~KWε~kws←nf~km←t=K
v/msk:('UNRECOGNIZED KEYWORD ',kws▷~>_msk)[]SIGNAL 2
msk←kwsε':NAMESPACE' ':ENDNAMESPACE'
v/msk^km/ftm:'NAMESPACE SCRIPTS MUST APPEAR AT THE TOP LEVEL'[]SIGNAL 2
msk←kwsεKW~':NAMESPACE' ':ENDNAMESPACE' ':SECTION' ':ENDSECTION'
v/msk←msk^~km/ftm:{msg←2'STRUCTURED STATEMENTS MUST APPEAR WITHIN TRAD-FNS'
msg SIGNAL ε{x+ιend[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)^~nε[]',~SYSV,SYSF,SYSD:{
ERR←2'INVALID SYSTEM VARIABLE, FUNCTION, OR OPERATOR'
ERR SIGNALεpos[ω]{α+ιω-α}~end[ω]
}_lmsk

```

A Compute parent vector from d

```
p←D2P d
```

A Compute nameclass of dfns

```
k←2×tεF ♦ k[upf~(t=P)^nε<'αα']←3 ♦ k[upf~(t=P)^nε<'ωω']←4
```

A We will often wrap a set of nodes as children under a Z node

```
gz←{z←ω↑~0≠ω ♦ ks←~1↓ω
t[z]←Z ♦ p[ks]←z ♦ pos[z]←pos[ω] ♦ end[z]←end[ωφz,ks] ♦ z}
```

A Nest top-level root lines as Z nodes

```
_←(gz 1φ~)'(t[i]=Z)<i←_d=0
'Non-Z top-level node'assert t[_p=ι≠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←_t[p]=F
'Non-Z dfns body node'assert t[_t[p]=F]=Z:
```

A Drop/eliminate any Z nodes that are empty or blank

```
_←p[i]{msk[α,ω]←~^fIN[pos[ω]]∈WS}⊞i←_t[p]=Z)∧p≠i≠p~msk←t≠Z
tm n t k pos end(f~)←cmsk ◇ p←(_~msk)(t-1+_t)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'
Zv.≠t≠~1φnss:ERR □SIGNAL 2
ERR←':NAMESPACE DECLARATION MAY HAVE ONLY A NAME OR BE EMPTY'
v≠(Z≠t≠~1φnss)^(V≠t≠~1φnss)∨Z≠t≠~2φnss:ERR □SIGNAL 2
ERR←':ENDNAMESPACE KEYWORD MUST APPEAR ALONE ON A LINE'
v≠Z≠t≠~>1 ~1v.φ<nse:ERR □SIGNAL 2
t[nsi←_t1φnss]←M ◇ t[nei←_t1φnse]←-M
n[i]←n[1+i←_t(t=M)∧V=1φt] ◇ end[nsi]←end[nei]
x←_tp=i≠p ◇ d←+λ(t[x]=M)+-t[x]=-M
0≠φd:':NAMESPACE KEYWORD MISSING :ENDNAMESPACE PAIR'□SIGNAL 2
p[x]←x[D2P ~1φd]
```

A Delete unnecessary namespace nodes from the tree, leave only M's

```
msk←~nssv((~1φnss)∧t=V)∨nsev1φnse
t k n pos endf~←cmsk ◇ p←(_~msk)(t-1+_t)msk/p
```

A PARSE LABELS ○○○

A Map guard statements to (G (Z ...) (Z ...))

```
_←p[i]{
  0=+f m←': '=IN[pos[ω]]:θ
  >m:'EMPTY GUARD TEST EXPRESSION'□SIGNAL 2
  1<+f m:'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←_t[p[p]]=F
```

A Parse brackets and parentheses into ~1 and Z nodes

```
_←p[i]{
  x←IN[pos[ω]] ◇ bd←+λbm←(bo←[' '=x)+-bc←'] '=x ◇ pd←+λpm←(po←[' '=x)+
  pc←') '=x
  0≠φbd:2'UNBALANCED BRACKETS'SIGNAL pos[ω]{x+ι([fω)
  x←[fα}ö{ωf~0≠bd}end[ω]
  0≠φpd:2'UNBALANCED PARENTHESES'SIGNAL pos[ω]{x+ι([fω)
  x←[fα}ö{ωf~0≠pd}end[ω]
```

```

(po/bd)∨.≠φpc/bd: 'OVERLAPPING BRACKETS AND PARENTHESES' □ SIGNAL
p[ω]←(α,ω)[1+-1@{ω=ι≠ω}D2P +-1φbm+pm] ◇ t[bo/ω]←-1 ◇ t[po/ω]←
end[po/ω]←end[φpc/ω] ◇ end[bo/ω]←end[φbc/ω]
0}∃i+l(t[p]=Z)∧p≠ι≠p
t k n pos endf↗←msk←~IN[pos]ε')' ◇ p←(l~msk)(t-1+l)msk/p

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

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

A Binding nodes
_←p[i]{
t[ωf↗(n[ω]ε<, '←')∧0, -1↓bm[ω]]←B
b v←{(↔'x)(1↓'x←ωf↗{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↓+-1t[ω]=B]
n[b]+n[εv] ◇ t[εv]←-7 ◇ pos[b]←pos[εv] ◇ end[b]←end[↔φω]
0}∃i+l(t[p]=Z)∧p≠ι≠p
t k n pos endf↗←msk←t≠-7 ◇ p←(l~msk)(t-1+l)msk/p

A Mark unambiguous primitive kinds
k[l(t=S)∧nε'□', 'SYSV'] +1 ◇ k[l(t=S)∧nε'□', 'SYSF'] +2 ◇ k[l(t=S)∧nε'□', 'SYSD'] +
t[lt=S] +P
k[lt∈A C N] +1 ◇ k[lnε, 'prmf s'] +2 ◇ k[lnε, 'prmmo'] +3 ◇ k[lnε, 'prmdo'] +4
k[lnε, 'prmf o'] +5
k[i+lmsk←(nε<, 'o')∧1φnε<, '.'] +3 ◇ end[i]←end[i+1] ◇ n[i]←<, 'o.'
t k n pos endf↗←msk←~-1φmsk ◇ p←(l~msk)(t-1+l)msk/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+lt=G] ◇ rz[i]←i ◇ rf←rf I@{rzεp[i]t→∃i+lt[p]=G}rf
mk←{α[ω], ;n[ω]}
fr←rf mkf←fb←fb[ι↗rf mkf←fb←fb I o(ι↗)Uθrz mkf←fb+lt=B] ◇ fb, ←-1
vb←fb[fri rf mk i]@ (i+lt=V) t-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[fri↗n I@1t←rf I@0t←ω]}*≡↗{rf[ω], ;ω}l(t=V)∧vb=-1
v/mask←(t=V)∧vb=-1: {
6 'ALL VARIABLES MUST REFERENCE A BINDING' SIGNALεpos[ω]{α+ιω-α}''end[ω]
}lmsk

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

```

A Infer types of bindings, groups, and variables

```

z x ← ↓ p[i] {αω} ∃ i ← ⊥ (t[p] ∈ B Z) ∧ p ≠ i ≠ p
x ← {ω ≠ ⊥ ∧ t[ω] = -1} ∪ φ''x
0 v. = ≠ ''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 5 ∈ ≠ k[≠ ω]) ∨ 4 = (ω, ≠ k)[0 ≠ ∧ ≠ k[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 ← ⊥ t = V]]
  ≠ z } * ( = v 0 = ⊥ ) ≠ z
'FAILED TO INFER ALL BINDING TYPES' assert 0 = ≠ z:

```

A Strand arrays into atoms

```

i ← | i - km ← 0 < i - i [⊥] (i, ≠ ← - up[i]), p[i ← ⊥ t[p] ∈ B Z]]
msk ← (t[i] ∈ C N) ∨ msk ∧ ⊃ 1 - 1 v. φ < msk ← km ∧ (t[i] ∈ A 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 ← ⊥ (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 ∧ - 1 φ (k[ω] ∈ 2 3 5) ∨ - 1 φ k[ω] = 4] ← 4
  0} ∃ i ← ⊥ (t[p] ∈ B Z) ∧ (p ≠ i ≠ p) ∧ k[p] ∈ 1 2
  i ← ⊥ (t = -1) ∧ k = 4 ◇ j ← ⊥ (t[p] = -1) ∧ k[p] = 4
  (≠ i) ≠ ≠ j: {
    2 'AXIS REQUIRES SINGLE AXIS EXPRESSION' SIGNAL ε pos[ω] + i '' end[ω] - pos[ω]
  } ⊃, ≠ {c α ≠ 1 < ≠ ω} ∃ p[j]
  v ≠ msk ← t[j] ≠ Z: {
    2 'AXIS REQUIRES NON-EMPTY AXIS EXPRESSION' SIGNAL ε pos[ω] + i '' 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, 1 ∨ ω) } ∃ i ← ⊥ (t[p] ∈ B Z) ∧ (p ≠ i ≠ p) ∧ k[p] ∈ 1 2

```

A Mask and verify dyadic operator right operands

```

(dm ← - 1 φ (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

$k[i \neq (k[i]=5) \wedge dm \vee \neg 1\phi(\sim km) \vee (\sim dm) \wedge k[i] \in 1 \ 6] \leftarrow 2 \diamond k[i \neq k[i]=5] \leftarrow 3$

A Rationalize o.

$jm \leftarrow (t[i]=P) \wedge n[i] \in c, 'o.'$
 $jm \vee . \wedge 1\phi(\sim km) \vee k[i] \in 3 \ 4: 'MISSING OPERAND TO o.'$ SIGNAL 2
 $p \leftarrow ((ji \leftarrow jm \neq i) @ (jj \leftarrow i \neq \neg 1\phi jm) \neq p)[p] \diamond t[ji, jj] \leftarrow t[jj, ji] \diamond k[ji, jj] \leftarrow k[jj, ji]$
 $n[ji, jj] \leftarrow n[jj, ji] \diamond pos[ji, jj] \leftarrow pos[ji, ji] \diamond end[ji, jj] \leftarrow end[jj, jj]$

A Mask and verify monadic and dyadic operator left operands

$\neq msk \leftarrow (dm \wedge \neg 2\phi \sim km) \vee (\neg 1\phi \sim km) \wedge mm \leftarrow (k[i]=3) \wedge t[i] \in F \ P \ V \ Z: \{$
 $2 'MISSING LEFT OPERAND' \text{ SIGNAL } \epsilon pos[\omega] + i'' end[\omega] - pos[\omega]$
 $\} i \neq msk$
 $msk \leftarrow dm \vee mm$

A Parse function expressions

$np \leftarrow (\neq p) + i \neq c \leftarrow \neq oi \leftarrow msk \neq i \diamond p \leftarrow (np @ oi \neq p)[p] \diamond p, \neq oi \diamond t \ k \ n \ pos \ end(\neg, I) \leftarrow co$
 $p[g \neq i] \leftarrow oi[(g \leftarrow (\sim msk) \wedge (1\phi msk) \vee 2\phi dm) \neq xc - \phi + \lambda \phi msk]$
 $p[g \neq oi] \leftarrow (g \leftarrow msk \neq (1\phi mm) \vee 2\phi dm) \neq 1\phi oi \diamond t[oi] \leftarrow 0 \diamond n[oi] \leftarrow c'$
 $pos[oi] \leftarrow pos[g \neq i][msk \neq 1 + \lambda g \leftarrow (\sim msk) \wedge (1\phi mm) \vee 2\phi dm]$
 $ol \leftarrow 1 + (k[i \neq (2\phi mm) \vee 3\phi dm] = 4) \vee k[i \neq (1\phi mm) \vee 2\phi dm] \in 2 \ 3$
 $or \leftarrow (msk \neq dm) \wedge 1 + k[dm \neq i] = 2$
 $k[oi] \leftarrow 3 \ 3 \uparrow \text{ for } ol$

A Wrap all assignment values as Z nodes

$i \ km \leftarrow \neq p[i] \{(\alpha, \omega)(0, 1 \vee \omega)\} \exists i \leftarrow 1 (t[p] \in B \ Z) \wedge (p \neq i \neq p) \wedge k[p] \in 1$
 $j \leftarrow i \neq msk \leftarrow (t[i]=P) \wedge n[i] \in c, ' \leftarrow ' \diamond nz \leftarrow (\neq p) + i \neq c \leftarrow \neq msk$
 $p, \neq nz \diamond t \ k \ n, \neq zcp''Z \ 1(c'') \diamond pos, \neq 1 + pos[j] \diamond end, \neq end[p[j]]$
 $zm \leftarrow \neg 1\phi msk \diamond p[km \neq i] \leftarrow (zpm \neq (i \times \sim km) + zm \wedge nz)[km \neq 1 + \lambda zpm \leftarrow zmv \sim km]$

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

$isfn \leftarrow \{(t[\omega] \in O \ F) \vee (t[\omega] \in B \ P \ V \ Z) \wedge k[\omega] = 2\}$

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

$j \leftarrow i \neq m \leftarrow msk \wedge (\neg 1\phi isfn \ i) \wedge \neg 2\phi(t[i]=V) \wedge k[i] = 1 \diamond p[zi \leftarrow nz \neq msk \neq m] \leftarrow j$
 $p[i \neq (1\phi m) \vee 2\phi m] \leftarrow 2 \neq j \diamond t \ k(\neg @ j \neq) \leftarrow E \ 4 \diamond pos \ end \ n\{\alpha[\omega] @ j \neg \alpha\} \leftarrow vi \ zi, cvi \leftarrow i \neq 2\phi$

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

$j \leftarrow i \neq m \leftarrow msk \wedge (\neg 1\phi isfn \ i) \wedge (\neg 2\phi t[i] = \neg 1) \wedge \neg 3\phi(t[i]=V) \wedge k[i] = 1$
 $p[zi \leftarrow nz \neq msk \neq m] \leftarrow ei \leftarrow i \neq 3\phi m \diamond t \ k \ end(\neg @ ei \neq) \leftarrow E \ 4(end[zi])$
 $p \ t \ k \ n(\neg @ (i \neq 2\phi m) \neq) \leftarrow ei \ E \ 6(c'')$
 $p, \neq j \diamond t, \neq Pp \neq j \diamond k, \neq 3p \neq j \diamond n, \neq (\neq j)p \leftarrow c, ' \leftarrow ' \diamond pos, \neq pos[j] \diamond end, \neq end[j]$
 $p \ t \ k \ n \ pos(\neg @ j \neq) \leftarrow ei \ O \ 2(c'')(pos[fi \leftarrow i \neq 1\phi m]) \diamond p[fi] \leftarrow j$

```

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÷2φ
  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[⊥p[i←⊥(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←⊥(t[p]∈B Z)^(k[p]=1)^(p≠i≠p
  msk←m2∨fm^(¬1φm2←km^(1φkm)^(fm←(t[i]=0)∨(t[i]≠A)^(k[i]=2
  t,←E÷xc←÷msk ◇ k,←msk÷msk+m2 ◇ n,←xcpc''
  pos,←pos[msk÷i] ◇ end,←end[p[msk÷i]]
  p,←msk÷1φ(i×~km)+km×x←¬1+(≠p)++λmsk ◇ p[km÷i]←km÷x

A Rationalize V[X;...]
  i←i[⊥p[i←⊥(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++λ~msk
  p,←2÷ip ◇ t,←ncpP E ◇ k,←ncp2 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←⊥(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←⊥msk←(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÷←msk←~mskvt=Z ◇ p←(⊥~msk)(¬¬1+⊥)msk÷p

A Compute Exports
  msk←(t=B)^(k[I@{t[ω]≠F}×≡~p]=0

```

```
xn←(Op<''),msk/n ♦ xt←msk/k
```

```
d i←P2D p ♦ d n t k pos end I←t←ci ♦ sym←u('')('ω')('α')'αα' 'ωω',n
(d t k(-sym/n)pos end)(xn xt)sym IN}
```

This code is used in chunk 4.

Uses TEST 21.

5.2 Compiler Transformations

```

32  <Compiler 32>≡
    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[α1ω]}7◊c⊖d-1p-ι≠d

    A Lift Functions to top-level
      p,←n[i]←(≠p)+ι≠i+1(t=F)∧p≠ι≠p ◊ t k n r(ι,I)←ci ◊ p r I↪←cn[i]@ι-ι≠p
      t[i]←C

    A Wrap expressions as binding or return statements
      i←(1(~t∈F G)∧t[p]=F),{ω↪~2|ι≠ω}1t[p]=G ◊ p t k n r↪←cm-2@ι-1p↪≠p
      p r i I↪←cj←(+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}1t[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(1(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+1t∈G A B C E O P V] ◊ j←(ϕi)[Δϕx]
      p t k n r{α[ω]@ι-α}←cj ◊ p←(i@j-ι≠p)[p]

    A Compute slots for each frame
      s←-1,↪←ι''n[ux]←ι◊≠⊖x←0[]⊖e←ι◊Δ↪rn←r[b],;n[b←1t=B]

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

    A Record exported top-level bindings
      xi←1(t=B)∧k[r]=0

      p t k n f s r d xi sym}

```

This code is used in chunk 4.
Uses src 16c.

5.3 Code Generator

33 $\langle \text{Code Generator } 33 \rangle \equiv$
 GC $\leftarrow\{$

```
p t k n fr sl rf fd xi sym $\leftarrow\omega$   $\diamond$  A B C E F G K L M N O P S V Z $\leftarrow 1+i15$ 
I $\leftarrow\{(\omega)\alpha\}$   $\diamond$  com $\leftarrow\{>\{\alpha, ', ', \omega\}/\omega\}$ 
ks $\leftarrow\{\omega\in[0]\ddot{~}(>\omega)=\omega[;0]\}$   $\diamond$  nam $\leftarrow\{'\Delta'\square R' \_\_\circ\mathbb{F}'\text{sym}[|\omega]\}$ 
```

```
syms  $\leftarrow$ , "'+'      '-'      'x'      '÷'      '*'      '⊗'
nams  $\leftarrow$       'add'      'sub'      'mul'      'div'      'exp'      'log'      'res'      'cir'      'min'      'max'
syms  $\leftarrow$ , "'<'      '≤'      '='      '≥'      '>'      '≠'
nams  $\leftarrow$       'lth'      'lte'      'eq'      'gte'      'gth'      'neq'      'not'      'and'      'lor'      'nan'
syms  $\leftarrow$ , "'[]'      '['      ']'      'ρ'      '⊂'      '⊃'      '⊆'      '⊇'
nams  $\leftarrow$       'sqd'      'brk'      'iot'      'rho'      'cat'      'ctf'      'rot'      'trn'      'rtf'      'mem'
syms  $\leftarrow$ , "'≡'      '≠'      '⊂'      '⊃'      '⊆'      '⊇'
nams  $\leftarrow$       'eqv'      'nqv'      'rgt'      'lft'      'enc'      'dec'      'red'      'rdf'      'scn'      'scf'
syms  $\leftarrow$ , "'↑'      '↓'      '⋮'      '⋈'      '⋉'      '⋊'      '⋋'      '⋌'
nams  $\leftarrow$       'tke'      'drp'      'map'      'com'      'dot'      'rnk'      'pow'      'jot'      'unq'      'int'
syms  $\leftarrow$ , "'Δ'      'Ψ'      '∘'      '⊕'      '⊗'      '⊙'      '⊚'      '⊛'
nams  $\leftarrow$       'gdu'      'gdd'      'oup'      'fnd'      'par'      'mdv'      'fft'      'ift'      'scl'      'nst'
syms  $\leftarrow$ , "'∇'      ';'      'α'      'ω'      'αα'      'ωω'
nams  $\leftarrow$       'this'      'span'      'l'      'r'      'aa'      'ww'
```

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

```
pref  $\leftarrow$ <'#include "codfns.h"'
pref, $\leftarrow$ <''
```

```

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' ' ,''>,≠dis''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←⊘>≠ω
z ←c'init 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' ' ,''>,≠dis''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'
            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)'
                err = dwa2array(&l, lp->pocket);'
        z,←c' '
        z,←c'
            if (err)'
                dwa_error(err);;'
        z,←c' '
        z,←c'
            if (rp)'
                dwa2array(&r, rp->pocket);'
        z,←c' '
        z,←c'
            if (err) {'

```

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```
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 4.
Uses codfns 4.

5.4 Backend C Compiler Interface

38

⟨Interface to the backend C compiler 38⟩≡

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
    opsys←{ω>~'Win' 'Lin' 'Mac'ι<3↑>'. '□WG'APLVersion'}
    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(□SH 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 "',(=□CMD'echo %CD%'),' && cl ',(vsco ω),' ',ω,','.',c' '}
    vsc2←{(vslo ω),'/OUT:"',ω,','.dll' > "',ω,','.log'""'}
    vsc←{□CMD ('%comspec% /C ',vsc0,vsc1,vsc2)ω}
    _←(⊞opsys'vsc' 'gcc' 'clang')α→ω put α, '.c'→1 □NDELETE f←α,soextθ
    □←,→□NGET(α, '.log')1
    □NEXISTS f:f ◇ 'COMPILE ERROR' □SIGNAL 22}

```

This code is used in chunk 4.

Uses AFΔLIB 6, AFΔPREFIX 6, codfns 4, put 20b, tie 20b, vsbat 17a, and VSΔPATH 6.

5.5 Linking with Dyalog

39a

(Linking with Dyalog 39a)≡

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 4.

Uses PP 20a.

6 Co-dfns Runtime

39b

(Implementation of APL Primitives 39b)≡

⌈ TBW

Root chunk (not used in this document).

- 40a *⟨C Runtime Support 40a⟩*≡
 /* TBW */
 Root chunk (not used in this document).
- 40b *⟨C Runtime Header 40b⟩*≡
 /* TBW */
 Root chunk (not used in this document).

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7.2 Identifiers

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Version 3, 19 November 2007

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