The Co-dfns Compiler

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Contents

1 Introduction

1.1 How to Read a WEB

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 23⟩
         ⟨Code Generator 24⟩
         ⟨Interface to the backend C compiler 29⟩
         ⟨Linking with Dyalog 30a⟩

         ⟨Must Have APL Utilities 43c⟩
         ⟨AST Record Structure 13b⟩
         ⟨Converters between parent and depth vectors 13c⟩
         ⟨XML Rendering 47b⟩
         ⟨Pretty-printing AST trees 44⟩

:EndNamespace
```

Root chunk (not used in this document).
Defines:

`codfns`, used in chunks 6, 14b, 24, 29, 46b, and 48–54.

This ⟨* 5⟩ chunk is meant to be stored to a file. We have a build system for doing this that depends on the contents of the ⟨*Tangle Commands* 6⟩ chunk. Thus, we follow the convention here of updating the contents of the ⟨*Tangle Commands* 6⟩ 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 ⟨*Tangle Commands* 6⟩≡

```
echo "Tangling codfns.apln..."
notangle codfns.nw > src/codfns.apln
```

This definition is continued in chunks 14b, 46b, 49, 51, and 52c.
This code is used in chunk 48.
Defines:
`codfns.apln`, never used.
Uses `codfns` 5 and `src` 53.

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.[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

[1] 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 45.
`⎕ML`, used in chunk 45.
`⎕WX`, never used.

Additionally, we set a `VERSION` constant to track changes to the system through the distributions. We use semantic versioning[2] 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.

[2]https://semver.org/

We depend on ArrayFire[3] 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 opencl 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 `opencl` 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, 29, and 54a.
`AF∆PREFIX`, used in chunk 29.

[3] 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:

```
VS∆PATH,'\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⟩+≡

```
VS∆PATH←'\Program Files\Microsoft Visual Studio'
VS∆PATH,←'\2022\Community'
```

This code is used in chunk 5.
Defines:
`VS∆PATH`, used in chunks 29 and 54a.

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.

$$Parse \rightarrow Compile \rightarrow Generate \rightarrow Backend \rightarrow Link$$

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 `⍺` 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 ⍵⊣⍞←'P'
          _←            TT _⊣⍞←'C'
          _←            GC _⊣⍞←'G'
          _←          ⍺ CC _⊣⍞←'B'
                      n NS _⊣⍞←'L'
}
```

This code is used in chunk 5.
Defines:
`Fix`, used in chunk 13a.
Uses `PS` 15 and `src` 53.

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* ⍵*, set* `IN` 12a⟩≡

```
IN←⍵

err←'PARSER EXPECTS SCALAR OR VECTOR INPUT'
1<≢⍴IN: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←∊(⊆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¨1⍴⊂⍬ ⋄ r.Name←,¨⊂'Compile' ⋄ r.Group←⊂'CODFNS'
 r[0].Desc←'Compile an object using Co-dfns'
 r.Parse←⊂'2S -af=cpu opencl cuda '
∇

∇ Run(C I);Convert;in;out
⍝ Parameters
⍝     AF∆LIB        ArrayFire backend to use
 Convert←{⍺(⎕SE.SALT.Load'[SALT]/lib/NStoScript -noname').ntgennscode ⍵}
 in out←I.Arguments ⋄ AF∆LIB←I.af''⊃⍨I.af≡0
 S←(⊂':Namespace ',out),2↓0 0 0 out Convert ##.THIS.⍎in
 →0/⍨'Compile'≢C
 {##.THIS.⍎out,'←⍵'}out Fix S⊣⎕EX'##.THIS.',out
∇
```
This code is used in chunk 5.
Uses `AF∆LIB` 9 and `Fix` 11.

3.4 AST Record Structure

13b ⟨*AST Record Structure* 13b⟩≡
```
f∆←'ptknfsrdx'
N∆←'ABCEFGKLMNOPSVZ'
A B C E F G K L M N O P S V Z←1+⍳15
```
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←⍪⍳≢⍵ ⋄ d←⍵≠,z ⋄ _←{p⊣d+←⍵≠p←⍺[z,←⍵]}⍣≡⍨⍵ ⋄ d(⍋(-1+d)↑⍤0 1⊢⌽z)}
D2P←{0=≢⍵:⍬ ⋄ p⊣2{p[⍵]←⍺[⍺⍸⍵]}⌿⊢∘⊂⌸⍵⊣p←⍳≢⍵}
```
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\` subdirectory. 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⍕(4⍴10)⊤ω),'_*_tests.dyalog'
        #.UT.run ⊃⊃0⎕NINFO⍠1⊢path
}
```
Root chunk (not used in this document).
Defines:
`TEST`, used in chunks 14b and 40d.

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 48.
Defines:
`TEST.aplf`, never used.
Uses `codfns` 5, `src` 53, 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.

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

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[4].

15 ⟨*Parser* 15⟩≡

```
PS←{
        ⟨Verify source input ⍵, set IN 12a⟩

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

        ⟨Tokenize input 20⟩
        ⟨Parse token stream 21⟩

        ⟨Adjust AST for output 16b⟩
}
```

[4] https://www.youtube.com/watch?v=WJVBvvS57j0

This code is used in chunk 5.
Defines:
`PS`, used in chunks 11 and 53.

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

16a ⟨*Parsing Constants* 16a⟩≡

```
CR LF←⎕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`	Exclussive 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 ⟨*Adjust AST for output* 16b⟩≡

```
msk←(t=B)∧k[I@{t[ω]≠F}⍣≡⍨p]=0
xn←(0⍴⊂''),msk⌿n ⋄ xt←msk⌿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 `0`th 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, `⍵`, `⍺`, `⍺⍺`, and `⍵⍵`.

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

18 ⟨*Adjust AST for output* 16b⟩+≡
```
sym←∪(,'')(,'⍵')(,'⍺')'⍺⍺' '⍵⍵',n
n←-sym⍳n
```

This code is used in chunk 15.

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

```
d t k n pos end
```

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:

```
AST TopBindingTypes SymbolTable InputSource
```

Which gives us the following return value.

19a ⟨*Adjust AST for output* 16b⟩+≡

```
  (d t k n pos end)(xn xt)sym IN
```

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

5.1.2 Handling Parsing Errors

19b ⟨*Line and error reporting utilities* 19b⟩≡

```
  linestarts←(⍸1⍪2>⌿IN∊CR LF)⍪≢IN
  mkdm←{⍺←2 ⋄ line←linestarts⍸⍵ ⋄ no←'[',(⍕1+line),'] '
          i←(~IN[i]∊CR LF)⌿i←beg+⍳linestarts[line+1]-beg←linestarts[line]
          (⎕EM ⍺)(no,IN[i])(' ^'[i∊⍵],⍨' 'ρ⍨≢no)}
  quotelines←{
          lines←∪linestarts⍸⍵
          nos←(1 0ρ⍨2×≢lines)⍀'[',(⍕⍪1+lines),⍤1⊢'] '
          beg←linestarts[lines] ⋄ end←linestarts[lines+1]
          m←∊∘⍵¨i←beg+⍳¨end-beg
          ¯1↓∊nos,(~∘CR LF¨⍪,(IN∘I¨i),⍪' ‾'∘I¨m),CR}
  SIGNAL←{⍺←2 '' ⋄ en msg←⍺ ⋄ EN∘←en ⋄ DM∘←en mkdm ⊃⍵
          dmx←('EN' en)('Category' 'Compiler')('Vendor' 'Co-dfns')
          dmx,←⊂'Message'(msg,CR,quotelines ⍵)
          ⎕SIGNAL⊂dmx}
```

This code is used in chunk 15.
Defines:
- `linestarts`, never used.
- `mkdm`, never used.
- `quotelines`, used in chunks 31c and 32b.
- `SIGNAL`, used in chunks 12a, 24, 29–36, 38–43, and 47a.

5.1.3 Tokenizing the Input

20 ⟨*Tokenize input* 20⟩≡

```
⍝ Group input into lines as a nested vector
pos←(⍳≢IN)⊆⍨~IN∊CR LF

⟨Check and mask the strings 32b⟩
⟨Unify whitespace and comments 31d⟩
⟨Tokenize strings 32c⟩
⟨Verify that all open characters are valid 31c⟩
⟨Tokenize numbers 32a⟩
⟨Tokenize variables 32d⟩
⟨Tokenize primitives and atoms 33f⟩
⟨Compute dfns regions and type, with } as a child 40a⟩
⟨Check for out of context dfns formals 33a⟩
⟨Compute trad-fns regions 41a⟩
⟨Identify label colons vs. others 41b⟩
⟨Tokenize keywords 41e⟩
⟨Tokenize system variables 34a⟩

⍝ Delete all characters we no longer need from the tree
d tm t pos end(⌿⍨)←⊂(t≠0)∨x∊'()[]{}:;'

⟨Tokenize labels 41c⟩
```

This code is used in chunk 15.

5.1.4 Parsing Token Stream

21 ⟨*Parse token stream* 21⟩≡

```
⍝ 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+ι¨end-pos

⟨Check that all keywords are valid 42a⟩
⟨Check that namespaces are at the top level 42b⟩
⟨Verify that all structured statements appear within trad-fns 43a⟩
⟨Verify that system variables are defined 34b⟩

⍝ Compute parent vector from d
p←D2P d

⟨Compute the nameclass of dfns 40b⟩

⍝ 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[⊃⌽z,ks]
        z
}

⟨Nest top-level root lines as Z nodes 42c⟩
⟨Wrap all dfns expression bodies as Z nodes 40c⟩

⍝ Drop/eliminate any Z nodes that are empty or blank
_←p[i]{msk[α,ω]←~∧⌿IN[pos[ω]]∊WS}⌸i←⍸(t[p]=Z)∧p≠ι≢p⊣msk←t≠Z
tm n t k pos end(⌿⍨)←⊂msk ⋄ p←(⍸~msk)(⊢-1+⍸)msk⌿p

⟨Parse :Namespace syntax 42d⟩
⟨Parse guards to (G (Z ...) (Z ...)) 40d⟩
⟨Parse brackets and parentheses into ¯1 and Z nodes 38a⟩
⟨Convert ; groups within brackets into Z nodes 34d⟩
⟨Parse Binding nodes 36a⟩
⟨Mark system variables as P nodes with appropriate kinds 34c⟩
⟨Mark atoms, characters, and numbers as kind 1 33d⟩
⟨Mark APL primitives with appropriate kinds 33g⟩
⟨Anchor variables to earliest binding in the matching frame 40e⟩
⟨Convert M nodes to FO nodes 43b⟩
⟨Convert α and ω to V nodes 33b⟩
⟨Convert αα and ωω to P2 nodes 33c⟩
⟨Infer the type of bindings, groups, and variables 36b⟩
⟨Strand arrays into atoms 33e⟩
⟨Parse dyadic operator bindings 36c⟩
⟨Rationalize F[X] syntax 35d⟩
```

```
⟨Group function and value expressions 38b⟩
⟨Parse function expressions 39a⟩
⟨Parse assignments 37⟩
⟨Enclose V[X;...] for expression parsing 35b⟩
⟨Parse trains 39b⟩
⟨Parse value expressions 38c⟩
⟨Rationalize V[X;...] 35c⟩

⍝ Sanity check
ERR←'INVARIANT ERROR: Z node with multiple children'
ERR assert(+⌿(t[p]=Z)∧p≠ι≢p)=+⌿t=Z:

⍝ Count parentheses in source information
ip←p[i←⍸(t[p]=Z)∧n[p]∊⊂,'(')] ⋄ pos[i]←pos[ip] ⋄ end[i]←end[ip]

⍝ VERIFY Z/B NODE TYPES MATCH ACTUAL TYPE

⍝ Eliminate Z nodes from the tree
zi←p I@{t[p[ω]]=Z}⍣≡ki←⍸msk←(t[p]=Z)∧t≠Z
p←(zi@kiι≢p)[p] ⋄ t k n pos end(⊣@zi⍨)←t k n pos end I¨⊂ki
t k n pos end⌿⍨←⊂msk←~msk∨t=Z ⋄ p←(⍸~msk)(⊢-1+⍸)msk⌿p
```

This code is used in chunk 15.
Uses `assert` 43c.

5.2 Compiler Transformations

23 ⟨*Compiler* 23⟩≡
```
  TT←{((d t k n ss se)exp sym src)←⍵ ⋄ I←{(⊂⍵)⌷⍺}
         A B C E F G K L M N O P S V Z←1+⍳15

 ⍝ Compute parent vector and reference scope
         r←I@{t[⍵]≠F}⍣≡⍨p⊣2{p[⍵]←⍺[⍺⍸⍵]}⌿⊢∘⊂⌸d⊣p←⍳≢d

 ⍝ Lift Functions to top-level
         p,←n[i]←(≢p)+⍳≢i←⍸(t=F)∧p≠⍳≢p ⋄ t k n r(⊣,I)←⊂i ⋄ p r I⍨←⊂n[i]@i⊢⍳≢p
         t[i]←C

 ⍝ Wrap expressions as binding or return statements
         i←(⍸(~t∊F G)∧t[p]=F),{⍵⌿⍨2|⍳≢⍵}⍸t[p]=G ⋄ p t k n r⌿⍨←⊂m←2@i⊢1⍴⍨≢p
         p r i I⍨←⊂j←(+⍀m)-1 ⋄ n←j I@(0≤⊢)n ⋄ p[i]←j←i-1
         k[j]←-(k[r[j]]=0)∨0@({⊃⌽⍵}⌸p[j])⊢(t[j]=B)∨(t[j]=E)∧k[j]=4 ⋄ t[j]←E

 ⍝ Lift guard tests
         p[i]←p[x←¯1+i←{⍵⌿⍨~2|⍳≢⍵}⍸t[p]=G] ⋄ t[i,x]←t[x,i] ⋄ k[i,x]←k[x,i]
         n[x]←n[i] ⋄ p←((x,i)@(i,x)⊢⍳≢p)[p]

 ⍝ Count strand and indexing children
         n[⍸(t∊A E)∧k=6]←0 ⋄ n[p⌿⍨(t[p]∊A E)∧k[p]=6]+←1

 ⍝ Lift and flatten expressions
         p[i]←p[x←p I@{~t[p[⍵]]∊F G}⍣≡i←⍸t∊G A B C E O P V] ⋄ j←(⌽i)[⍋⌽x]
         p t k n r{⍺[⍵]@i⊢⍺}←⊂j ⋄ p←(i@j⊢⍳≢p)[p]

 ⍝ Compute slots for each frame
         s←¯1,⍨∊⍳¨n[∪x]←⊢∘≢⌸x←0⌷⍉e←∪I∘⍋⍨rn←r[b],⍪n[b←⍸t=B]

 ⍝ Compute frame depths
         d←(≢p)↑d ⋄ d[i←⍸t=F]←0 ⋄ _←{z⊣d[i]+←⍵≠z←r[⍵]}⍣≡i ⋄ f←d[0⌷⍉e],¯1

 ⍝ 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` 53.

5.3 Code Generator

24 ⟨*Code Generator* 24⟩≡

```
GC←{
        p t k n fr sl rf fd xi sym←ω ⋄ A B C E F G K L M N O P S V Z←1+⍳15
        I←{(⊂ω)⌷α} ⋄ com←{⊃{α,',',ω}/ω}
        ks←{ω⊂[0]⍨(⊃ω)=ω[;0]} ⋄ nam←{'∆'⎕R'__'∘⍕¨sym[|ω]}

     syms ←,¨'+'         '-'          '×'          '÷'          '*'           '⍟'
     nams ←      'add'   'sub'  'mul' 'div' 'exp' 'log' 'res'   'cir'   'min'  'max
     syms,←,¨'<'         '≤'         '='           '≥'          '>'           '≠'          '
     nams,←      'lth'   'lte'  'eql' 'gte' 'gth' 'neq' 'not'   'and'   'lor'  'nan
     syms,←,¨'⌷'             '['           'ι'          'ρ'          ','           '⍪'
     nams,←      'sqd'   'brk'  'iot' 'rho' 'cat' 'ctf' 'rot'   'trn'   'rtf'  'mem
     syms,←,¨'≡'             '≢'         '⊢'          '⊣'          '⊤'          '⊥'
     nams,←      'eqv'   'nqv'  'rgt' 'lft' 'enc' 'dec' 'red'   'rdf'   'scn'  'scf
     syms,←,¨'↑'             '↓'         '¨'          '⍨'          '.'           '⍤'
     nams,←      'tke'   'drp'  'map' 'com' 'dot' 'rnk' 'pow'   'jot'   'unq'  'int
     syms,←,¨'⍋'             '⍒'         '∘.'  '⍷'          '⊂'          '⌹'          '⎕FFT
     nams,←      'gdu'   'gdd'  'oup' 'fnd' 'par' 'mdv' 'fft'   'ift'   'scl'  'nst
     syms,←,¨'∇'             ';'           'α'          'ω'          'αα'        'ωω'
      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,←⊂'{''/* Unhandled '',(⍕α),'' */'',NL}'
        NL←⎕UCS 13 10

        pref ←⊂'#include "codfns.h"'
        pref,←⊂''
```

```
        pref,←⊂'EXPORT int'
        pref,←⊂'DyalogGetInterpreterFunctions(void *p)'
        pref,←⊂'{'
        pref,←⊂'    return set_dwafns(p);'
        pref,←⊂'}'
        pref,←⊂''

        Bf←{id←sym⊃⍨|4⊃α
                z ←⊂id,' = retain_cell(stkhd[-1]);'
        z}

        Cf←{id←⍕4⊃α
                z ←⊂'mk_closure((struct closure **)stkhd++, fn',id,', 0);'
        z}

        Ek←{
                z ←⊂'release_cell(*--stkhd);'
                z,←⊂''
        z}

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

        Er←{
                z ←⊂'*z = *--stkhd;'
                z,←⊂'goto cleanup;'
                z,←⊂''
        z}

        Fn←{id←⍕5⊃α ⋄ x←⍉⊃⍪⌿⍵ ⋄ t←2⌷x ⋄ k←3⌷x
                hsw←(t=O)∨(t=E)∧k∊1 2 ⋄ hsa←((t=E)∧k=2)∨(t=O)∧k∊4 5 7 8
                z ←⊂'int'
                   z,←⊂'fn',id,'(struct array **z, struct array *l, struct ar
  ray *r, void *fv[])'
                z,←⊂'{'
                z,←⊂'         void    *stk[128];'
                z,←⊂'         void    **stkhd;'
                z,←hsw/⊂' void    *w;'
                z,←hsa/⊂' void    *a;'
                z,←hsw/⊂' struct  closure *c;'
                z,←⊂''
```

```
                z,←⊂'       stkhd = &stk[0];'
                z,←⊂''
                z,← ' ',¨⊃,⌿dis¨ω
                z,←⊂'       *z = NULL;'
                z,←⊂''
                z,←⊂'cleanup:'
                z,←⊂'       return 0;'
                z,←⊂'}'
                z,←⊂''
        z}

        Fz←{id←⍕5⊃α ⋄ awc←∨⌿(3⌷x){(ω∊A O)∨(ω=E)∧α>0}2⌷x←⍉⊃⍪⌿ω
                z ←⊂'int init',id,' = 0;'
                z,←⊂''
                z,←⊂'EXPORT int'
                z,←⊂'init(void)'
                z,←⊂'{'
                z,←⊂' return fn',id,'(NULL, NULL, NULL, NULL);'
                z,←⊂'}'
                z,←⊂''
                z,←⊂'int'
                   z,←⊂'fn',id,'(struct array **z, struct array *l, struct ar
 ray *r, void *fv[])'
                z,←⊂'{'
                z,←⊂'       void    *stk[128];'
                z,←⊂'       void    **stkhd;'
                z,← awc⌿⊂'       void    *a, *w;'
                z,← awc⌿⊂'       struct  closure *c;'
                z,←⊂''
                z,←⊂'       if (init',id,')'
                z,←⊂'               return 0;'
                z,←⊂''
                z,←⊂'       stkhd = &stk[0];'
                z,←⊂'       init',id,' = 1;'
                z,←⊂'       cdf_init();'
                z,←⊂''
                z,← ' ',¨⊃,⌿dis¨ω
                z,←⊂'       return 0;'
                z,←⊂'}'
                z,←⊂''
        z}

        Pf←{id←(syms⍳sym[|4⊃α])⊃nams
                z ←⊂'*stkhd++ = retain_cell(',id,');'
        z}
```

```
        Va←{id←(|4⊃⍺)⊃'' 'r' 'l' 'aa' 'ww',5↓sym
                z ←⊂'*stkhd++ = retain_cell(',id,');'
        z}

        Zp←{n←'fn',⍕⍵
                k[⍵]∊0 2:{
                        z ←⊂'int'
                          z,←⊂n,'(struct array **z, struct array *l, struct ar
 ray *r, void *fv[]);'
                        z,←⊂''
                z}⍵
                'UNKNOWN FUNCTION TYPE'⎕SIGNAL 16
        }

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

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

  d i←P2D p ⋄ ast←(⍉↑d p t k n(⍳≢p)fr sl fd)[i;]
  NOTFOUND←{('[GC] UNSUPPORTED NODE TYPE ',N∆[⊃ω],⍕⊃⌽ω)⎕SIGNAL 16}
dis←{0=2⊃h←,1↑ω:'' ⋄ (≢gck)=i←gck⍳⊂h[2 3]:NOTFOUND h[2 3] ⋄ h(⍎i⊃gcv)ks 1↓ω
  z←∊,∘NL¨pref,⊃,⌿(,⌿Zp¨⍸t=F),(,⌿Zx¨xi),(⊂⊂''),dis¨ks ast
  z}
```

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

5.4 Backend C Compiler Interface

29 ⟨*Interface to the backend C compiler* 29⟩≡

```
  CC←{
           vsbat←VS∆PATH,'\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 47c⟩
           soext←{opsys'.dll' '.so' '.dylib'}
           ccf←{' -o ''',ω,'.',α,''' ''',ω,'.c'' -laf',AF∆LIB,' > ',ω,'.log 2>&1'}
        cci←{'-I''',AF∆PREFIX,'/include'' -L''',AF∆PREFIX,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', AF∆LIB, '.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,soext⍬
           ⎕←⍪⊃⎕NGET(α,'.log')1
           ⎕NEXISTS f:f ⋄ 'COMPILE ERROR' ⎕SIGNAL 22}
```

This code is used in chunk 5.

Uses AF∆LIB 9, AF∆PREFIX 9, codfns 5, put 47a, SIGNAL 19b, tie 47a, vsbat 54a, vsc 54a, and VS∆PATH 10.

5.5 Linking with Dyalog

30a ⟨*Linking with Dyalog* 30a⟩≡

```
  NS←{
          MKA←{mka⊂ω} ⋄ EXA←{exa θ 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 ⋄ loadimg θ ω α}
          SaveImage←{α←'image.png' ⋄ saveimg ω α}
          Image←{~2 3∨.=≢⍴ω:⎕SIGNAL 4 ⋄ (3≠⊃⍴ω)∧3=≢⍴ω:⎕SIGNAL 5 ⋄ ω⊣w_img ω α}
          Plot←{2≠≢⍴ω:⎕SIGNAL 4 ⋄ ~2 3∨.=1⊃⍴ω:⎕SIGNAL 5 ⋄ ω⊣w_plot (⍉ω) α}
          Histogram←{ω⊣w_hist ω,α}
          Rtm∆Init←{
                  _←'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
                  _←'loadimg'⎕NA                     ω,'|loadimg >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 ⍴ θ}
          mkna←{α,'|',('∆'⎕R'__'⊢ω),'_cdf P P P'}
          mkf←{fn←α,'|',('∆'⎕R'__'⊢ω),'_dwa ' ⋄ mon dya←ω∘,¨'_mon' '_dya'
                  z←('Z←{A}',ω,' W')(':If 0=⎕NC''⍙.',mon,'''')
             z,←(mon dya{'''',α,'''⍙.⎕NA''',fn,ω,' <PP'''}¨'>PP P' '>PP <PP'),⊂':E
             z,':If 0=⎕NC''A'''('Z←⍙.',mon,' 0 0 W')':Else'('Z←⍙.',dya,' 0 A W')':
         ns←#.⎕NSθ ⋄ _←'∆⍙'ns.⎕NS¨⊂θ ⋄ ∆ ⍙←ns.(∆ ⍙) ⋄ ∆.names←(0⍴⊂''),(2=1⊃α)≠0=
        fns←'Rtm∆Init' 'MKA' 'EXA' 'Display' 'LoadImage' 'SaveImage' 'Image' 'Plot
          fns,←'Histogram' 'soext' 'opsys' 'mkna'
          _←∆.⎕FX∘⎕CR¨fns ⋄ ∆.(decls←ω∘mkna¨names) ⋄ _←ns.⎕FX¨(⊂''),ω∘mkf¨∆.name
       _←∆.⎕FX'Z←Init'('Z←Rtm∆Init ''',ω,'''')'→0⌿⍨0=≢names' 'names ##.⍙.⎕NA¨dec
          ns}
```

This code is used in chunk 5.
Uses PP 46a and SIGNAL 19b.

5.6 Runtime

30b ⟨*Implementation of APL Primitives* 30b⟩≡

```
  ⍝ TBW
```

Root chunk (not used in this document).

31a ⟨*C Runtime Support* 31a⟩≡
```
/* TBW */
```
Root chunk (not used in this document).

31b ⟨*C Runtime Header* 31b⟩≡
```
/* TBW */
```
Root chunk (not used in this document).

6 Language Features

6.1 Valid source input character set

31c ⟨*Verify that all open characters are valid* 31c⟩≡
```
alp←'ABCDEFGHIJKLMNOPQRSTUVWXYZ_abcdefghijklmnopqrstuvwxyz'
alp,←'ÀÁÂÃÄÅÆÇÈÉÊËÌÍÎÏÐÑÒÓÔÕÖØÙÚÛÜÝßàáâãäåæçèéêëìíîïðñòóôõöøùúûüþ'
alp,←'∆⍙ⒶⒷⒸⒹⒺⒻⒼⒽⒾⒿⓀⓁⓂⓃⓄⓅⓆⓇⓈⓉⓊⓋⓌⓍⓎⓏ'
num←⎕D
synb←'¯[]{}()'':⍺⍵⋄;'
syna←'⍬⎕⍞#'
prmfs←'+-×÷|⌈⌊*⍟○!?~∧∨⍲⍱<≤=>≥≠≡≢⍴,⍪⌽⊖⍉↑↓⊂⊆⊃∊⍷∩∪⍳⍸⌷⍋⍒⍎⍕⊥⊤⊣⊢⌹∇←→'
prmdo←'∘.⍣⍠⌺⍤⍥@' ⋄ prmmo←'¨⍨&⌶⌸' ⋄ prmfo←'/⌿\⍀'
prms←prmfs,prmdo,prmmo,prmfo
x←' '@{t≠0}IN[pos] ⍝ The spaces produce nice invariants
∨⌿msk←~x∊alp,num,syna,synb,prms,WS:{
        EM←'SYNTAX ERROR: INVALID CHARACTER(S) IN SOURCE',CR
        EM,←quotelines ⍸msk
        EM ⎕SIGNAL 2
}⍬
```
This code is used in chunk 20.
Uses `quotelines` 19b and `SIGNAL` 19b.

6.2 Comments and Whitespace

31d ⟨*Unify whitespace and comments* 31d⟩≡
```
⍝ Remove comments
pos msk⌿¨⍨←⊂∧⍀¨(~msk←msk∨¯1⌽¨msk)⍲'⍝'=IN∘I¨pos

⍝ Remove leading and trailing whitespace
WS←⎕UCS 9 32 ⋄ pos msk⌿¨⍨←⊂~(∧⍀∨∧⍀U⌽)∘(WS∊⍨IN∘I)¨pos

⍝ Flatten and separate lines and ⋄ with Z type
t←⊃0⍴⊂pos ⋄ t pos msk(∊,∘⍪⍨)←Z(⊃¨pos)0 ⋄ t[⍸'⋄'=IN[pos]]←Z
```
This code is used in chunk 20.

6.3 Numbers

32a ⟨*Tokenize numbers* 32a⟩≡

```
_←{dm[⍵]←∧⍀dm[⍵]}¨(dm∨x∊alp)⊆⍳≢dm←x∊num
dm∨←('.'=x)∧(¯1⌽dm)∨1⌽dm
dm∨←('¯'=x)∧1⌽dm
dm∨←(x∊'EeJj')∧(¯1⌽dm)∧1⌽dm
∨⌿msk←(dm=0)∧x='¯':2'ORPHANED ¯'SIGNAL pos⌿⍨msk
∨⌿{1<+⌿⍵='j'}¨dp←⎕C¨dm⊆x:'MULTIPLE J IN NUMBER'⎕SIGNAL 2
∨⌿{1<+⌿⍵='e'}¨dp←⊃⍪/{⍵⊆⍨⍵≠'j'}¨dp:'MULTIPLE E IN NUMBER'⎕SIGNAL 2
∨⌿'e'=⊃¨dp:'MISSING MANTISSA'⎕SIGNAL 2
∨⌿'e'=⊃∘⌽¨dp:'MISSING EXPONENT'⎕SIGNAL 2
mn ex←↓⍉↑{2↑(⍵⊆⍨⍵≠'e'),⊂''}¨dp
∨⌿{1<+⌿'.'=⍵}¨mn,ex:'MULTIPLE . IN NUMBER'⎕SIGNAL 2
∨⌿'.'∊¨ex:'REAL NUMBER IN EXPONENT'⎕SIGNAL 2
∨⌿{∨⌿1↓⍵∊'¯'}¨mn,ex:'MISPLACED ¯'⎕SIGNAL 2
t[i←⍸2<⌿0⍪dm]←N ⋄ end[i]←end⌿⍨2>⌿dm⍪0
```

This code is used in chunk 20.
Uses `SIGNAL` 19b.

6.4 Strings and characters

32b ⟨*Check and mask the strings* 32b⟩≡

```
0≠≢lin←⍸⊃∘⌽¨msk←≠⍀¨''''=IN∘I¨pos:{
        EM←'SYNTAX ERROR: UNBALANCED STRING',('S'⌿⍨2≤≢lin),CR
        EM,←quotelines ∊(msk⌿¨pos)[lin]
        EM ⎕SIGNAL 2
}⍬
```

This code is used in chunk 20.
Uses `quotelines` 19b and `SIGNAL` 19b.

32c ⟨*Tokenize strings* 32c⟩≡

```
end←1+pos ⋄ t[i←⍸2<⌿0⍪msk]←C ⋄ end[i]←end[⍸2>⌿msk⍪0]
t pos end⌿⍨←⊂(t≠0)∨~msk
```

This code is used in chunk 20.

6.5 Variables

32d ⟨*Tokenize variables* 32d⟩≡

```
t[i←⍸2<⌿0⍪vm←(~dm)∧x∊alp,num]←V ⋄ end[i]←end⌿⍨2>⌿vm⍪0

⍝ Tokenize α, ω formals
fm←{mm←⌽⊃(>∘⊃,⊢)⌿⌽m←α=' ',⍵ ⋄ 1↓¨(mm∧~m1)(mm∧m1←1⌽m)}
am aam←'α'fm x ⋄ wm wwm←'ω'fm x
((am∨wm)⌿t)←A ⋄ ((aam∨wwm)⌿t)←P ⋄ ((aam∨wwm)⌿end)←end⌿⍨¯1⌽aam∨wwm
```

This code is used in chunk 20.

33a ⟨*Check for out of context dfns formals* 33a⟩≡
```
∨⌿(d=0)∧(t=P)∧IN[pos]∊'αω':'DFN FORMAL REFERENCED OUTSIDE DFNS'⎕SIGNAL 2
```
This code is used in chunk 20.
Uses SIGNAL 19b.

33b ⟨*Convert* α *and* ω *to* V *nodes* 33b⟩≡
```
t←V@(i←⍸(t=A)∧n∊,¨'αω')⊢t ⋄ vb[i]←i
```
This code is used in chunk 21.

33c ⟨*Convert* αα *and* ωω *to* P2 *nodes* 33c⟩≡
```
k[⍸(t=P)∧n∊'αα' 'ωω']←2
```
This code is used in chunk 21.

6.6 Arrays

33d ⟨*Mark atoms, characters, and numbers as kind* 1 33d⟩≡
```
k[⍸t∊A C N]←1
```
This code is used in chunk 21.

33e ⟨*Strand arrays into atoms* 33e⟩≡
```
i←|i⊣km←0<i←i[⍋|(i,⍨←-∪p[i]),p[i←⍸t[p]∊B Z]]
msk←(t[i]∊C N)∨msk∧⊃1 ¯1∨.⌽⊂msk←km∧(t[i]∊A C N V Z)∧k[i]=1
np←(≢p)+⍳≢ai←i⌿⍨am←2>⌿msk⍪0 ⋄ p←(np@ai⍳≢p)[p] ⋄ p,←ai ⋄ km←2<⌿0⍪msk
t k n pos end(⊣,I)←⊂ai ⋄ k[ai]←1 6[∨⌿¨msk⊆t[i]≠N]
t n pos(⊣@ai⍨)←A(⊂'')(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)←⊂i ⋄ t k n(⊣@i⍨)←A 1(⊂'')
```
This code is used in chunk 21.

6.7 Primitives

6.7.1 APL Primitives

33f ⟨*Tokenize primitives and atoms* 33f⟩≡
```
t[⍸(~dm)∧x∊prms]←P ⋄ t[⍸x∊syna]←A
```
This code is used in chunk 20.

33g ⟨*Mark APL primitives with appropriate kinds* 33g⟩≡
```
k[⍸n∊,¨prmfs]←2 ⋄ k[⍸n∊,¨prmmo]←3 ⋄ k[⍸n∊,¨prmdo]←4
k[⍸n∊,¨prmfo]←5
k[i←⍸msk←(n∊⊂,'∘')∧1⌽n∊⊂,'.']←3 ⋄ end[i]←end[i+1] ⋄ n[i]←⊂,'∘.'
t k n pos end⌿⍨←⊂msk←~¯1⌽msk ⋄ p←(⍸~msk)(⊢-1+⍸)msk⌿p
```
This code is used in chunk 21.

6.7.2 System Functions and Variables

34a ⟨*Tokenize system variables* 34a⟩≡
```
si←⍸('⎕'=IN[pos])∧1⌽t=V
t[si]←S ⋄ end[si]←end[si+1] ⋄ t[si+1]←0
```
This code is used in chunk 20.

34b ⟨*Verify that system variables are defined* 34b⟩≡
```
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' 'ARBOUT' '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'
∨⌿msk←(t=S)∧~n∊'⎕',¨SYSV,SYSF,SYSD:{
        ERR←2'INVALID SYSTEM VARIABLE, FUNCTION, OR OPERATOR'
        ERR SIGNAL∊pos[ω]{α+⍳ω-α}¨end[ω]
}⍸msk
```
This code is used in chunk 21.
Uses `SIGNAL` 19b.

34c ⟨*Mark system variables as* `P` *nodes with appropriate kinds* 34c⟩≡
```
k[⍸(t=S)∧n∊'⎕',¨SYSV]←1 ⋄ k[⍸(t=S)∧n∊'⎕',¨SYSF]←2 ⋄ k[⍸(t=S)∧n∊'⎕',¨SYSD]←4
t[⍸t=S]←P
```
This code is used in chunk 21.

6.8 Brackets

6.8.1 Indexing

34d ⟨*Convert* `;` *groups within brackets into* `Z` *nodes* 34d⟩≡
```
_←p[i]{k[z←⊃⍪⌿gz¨g←ω⊂⍨¯1⌽IN[pos[ω]]∊';]']←1 ⋄ t[z]←Z P[1=≢¨g]}⌸i←⍸t[p]=¯1
```
This code is used in chunk 21.

35a ⟨*Verify brackets have function/array target* 35a⟩≡
```
x←{⍵/⍨~∧\t[⍵]=¯1}∪⌽¨x
0∨.=≢¨x:'BRACKET SYNTAX REQUIRES FUNCTION OR ARRAY TO ITS LEFT'⎕SIGNAL 2
```
This code is used in chunk 36b.
Uses `SIGNAL` 19b.

35b ⟨*Enclose* `V[X;...]` *for expression parsing* 35b⟩≡
```
i←i[⍋p[i←⍸(t[p]∊B Z)∧(k[p]=1)∧p≠⍳≢p]] ⋄ j←i/⍨jm←t[i]=¯1
t[j]←A ⋄ k[j]←¯1 ⋄ p[i/⍨1⌽jm]←j
```
This code is used in chunk 21.

35c ⟨*Rationalize* `V[X;...]` 35c⟩≡
```
i←i[⍋p[i←⍸(t[p]=A)∧k[p]=¯1]] ⋄ msk←~2≠/¯1,ip←p[i] ⋄ ip←∪ip ⋄ nc←2×≢ip
t[ip]←E ⋄ k[ip]←2 ⋄ n[ip]←⊂'' ⋄ p[msk/i]←msk/(≢p)+1+2×¯1++\~msk
p,←2/ip ⋄ t,←nc⍴P E ⋄ k,←nc⍴2 6 ⋄ n,←nc⍴,¨'[' ''
pos,←2/pos[ip] ⋄ end,←∊(1+pos[ip]),⍪end[ip] ⋄ pos[ip]←pos[i/⍨~msk]
```
This code is used in chunk 21.

6.8.2 Axis Operator

35d ⟨*Rationalize* `F[X]` *syntax* 35d⟩≡
```
_←p[i]{
        ⊃m←t[⍵]=¯1:'SYNTAX ERROR:NOTHING TO INDEX'⎕SIGNAL 2
        k[⍵/⍨m∧¯1⌽(k[⍵]∊2 3 5)∨¯1⌽k[⍵]=4]←4
0}⌸i←⍸(t[p]∊B Z)∧(p≠⍳≢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 ∊pos[⍵]+⍳¨end[⍵]-pos[⍵]
}⊃⍪/{⊂⍺/⍨1<≢⍵}⌸p[j]
∨/msk←t[j]≠Z:{
        2'AXIS REQUIRES NON-EMPTY AXIS EXPRESSION'SIGNAL ∊pos[⍵]+⍳¨end[⍵]-pos[⍵
}msk/p[j]
p[j]←p[i] ⋄ t[i]←P ⋄ end[i]←1+pos[i]
```
This code is used in chunk 21.
Uses `SIGNAL` 19b.

6.9 Bindings and Types

36a ⟨*Parse Binding nodes* 36a⟩≡

```
⍝ Mark bindable nodes
bm←(t=V)∨(t=A)∧n∊,¨'⎕⍞'
bm←{bm⊣p[i]{bm[⍺]←(V ¯1≡t[⍵])∨∧⌿bm[⍵]}⌸i←⍸(~bm[p])∧t[p]=Z}⍣≡bm

⍝ Binding nodes
_←p[i]{
        t[⍵⌿⍨(n[⍵]∊⊂,'←')∧0,¯1↓bm[⍵]]←B
        b v←{(⊃¨x)(1↓¨x←⍵⌿⍨{t[⊃⍵]=B}¨⍵)}¯1⌽¨⍵⊂⍨1,¯1↓t[⍵]∊P B
        ∨⌿~bm[∊v]:'CANNOT BIND ASSIGNMENT VALUE'⎕SIGNAL 2
        p[⍵]←(⍺,b)[0,¯1↓+⍀t[⍵]=B]
        n[b]←n[∊v] ⋄ t[∊v]←¯7 ⋄ pos[b]←pos[∊v] ⋄ end[b]←end[⊃⌽⍵]
0}⌸i←⍸(t[p]=Z)∧p≠⍳≢p
t k n pos end⌿⍨←⊂msk←t≠¯7 ⋄ p←(⍸~msk)(⊢-1+⍸)msk⌿p
```

This code is used in chunk 21.
Uses `SIGNAL` 19b.

36b ⟨*Infer the type of bindings, groups, and variables* 36b⟩≡

```
z x←↓⍉p[i]{⍺⍵}⌸i←⍸(t[p]∊B Z)∧p≠⍳≢p
⟨Verify brackets have function/array target 35a⟩
_←{
        k[msk⌿z]←k[x⌿⍨msk←(k[⊃¨x]≠0)∧1=≢¨x]
        z x⌿⍨←⊂~msk

        k[z⌿⍨msk←k[⊃¨x]=4]←3
        z x⌿⍨←⊂~msk

        k[z⌿⍨msk←{(2 3 5∊⍨k[⊃⍵])∨4=(⍵,≢k)[0⍳⍨∧⍀k[⍵]=1]⌷k,0}∘⌽¨x]←2
        z x⌿⍨←⊂~msk

        k[z⌿⍨msk←k[⊃∘⌽¨x]=1]←1
        z x⌿⍨←⊂~msk

        k[i]←k[vb[i←⍸t=V]]
≢z}⍣(=∨0=⊣)≢z
'FAILED TO INFER ALL BINDING TYPES'assert 0=≢z:
```

This code is used in chunk 21.

36c ⟨*Parse dyadic operator bindings* 36c⟩≡

```
⍝ PARSE B←D...
⍝ PARSE B←...D
```

This code is used in chunk 21.

6.10 Assignments

37 ⟨*Parse assignments* 37⟩≡

```
⍝ Wrap all assignment values as Z nodes
i km←⍪⌿p[i]{(α⍪ω)(0,1∨ω)}⌸i←⍸(t[p]∊B Z)∧(p≠⍳≢p)∧k[p]∊1
j←i⌿⍨msk←(t[i]=P)∧n[i]∊⊂,'←' ⋄ nz←(≢p)+⍳zc←+⌿msk
p,←nz ⋄ t k n,←zc⍴¨Z 1(⊂'') ⋄ pos,←1+pos[j] ⋄ end,←end[p[j]]
zm←¯1⌽msk ⋄ p[km⌿i]←(zpm⌿(i×~km)+zm⍀nz)[km⌿¯1++⍀zpm←zm∨~km]

⍝ 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}

⍝ Parse modified assignment to E4(V, F, Z)
j←i⌿⍨m←msk∧(¯1⌽isfn i)∧¯2⌽(t[i]=V)∧k[i]=1 ⋄ p[zi←nz⌿⍨msk⌿m]←j
p[i⌿⍨(1⌽m)∨2⌽m]←2⌿j ⋄ t k(¬@j⍨)←E 4 ⋄ pos end n{α[ω]@j⊢α}←vi zi,⊂vi←i⌿⍨2⌽m

⍝ Parse bracket modified assignment to E4(E6, O2(F, P3(←)), Z)
j←i⌿⍨m←msk∧(¯1⌽isfn i)∧(¯2⌽t[i]=¯1)∧¯3⌽(t[i]=V)∧k[i]=1
p[zi←nz⌿⍨msk⌿m]←ei←i⌿⍨3⌽m ⋄ t k end(¬@ei⍨)←E 4(end[zi])
p t k n(¬@(i⌿⍨2⌽m)⍨)←ei E 6(⊂'')
p,←j ⋄ t,←P⍴⍨≢j ⋄ k,←3⍴⍨≢j ⋄ n,←(≢j)⍴⊂,'←' ⋄ pos,←pos[j] ⋄ end,←end[j]
p t k n pos(¬@j⍨)←ei O 2(⊂'')(pos[fi←i⌿⍨1⌽m]) ⋄ p[fi]←j

⍝ Parse bracket assignment to E4(E6, P2(←), Z)
j←i⌿⍨m←msk∧(¯1⌽t[i]=¯1)∧¯2⌽(t[i]=V)∧k[i]=1 ⋄ p[zi←nz⌿⍨msk⌿m]←ei←i⌿⍨2⌽m
t k end(¬@ei⍨)←E 4(end[zi]) ⋄ p t k n(¬@(i⌿⍨1⌽m)⍨)←ei E 6(⊂'')
p t k(¬@j⍨)←ei P 2

⍝ Parse modified strand assignment
⍝ Parse strand assignment

⍝ SELECTIVE MODIFIED ASSIGNMENT
⍝ SELECTIVE ASSIGNMENT
```

This code is used in chunk 21.

6.11 Expressions

38a ⟨*Parse brackets and parentheses into* `¯1` *and* `Z` *nodes* 38a⟩≡

```
  _←p[i]{
        x←IN[pos[⍵]] ⋄ bd←+⍀bm←(bo←'['=x)+-bc←']'=x ⋄ pd←+⍀pm←(po←'('=x)+-pc←')'=
       0≠⊃⌽bd:2'UNBALANCED BRACKETS'SIGNAL pos[⍵]{x+⍳(⌈⌿⍵)-x←⌊⌿⍺}⍤{⍵⌿⍨0≠bd}end[⍵
      0≠⊃⌽pd:2'UNBALANCED PARENTHESES'SIGNAL pos[⍵]{x+⍳(⌈⌿⍵)-x←⌊⌿⍺}⍤{⍵⌿⍨0≠pd}end
        (po⌿bd)∨.≠⌽pc⌿bd:'OVERLAPPING BRACKETS AND PARENTHESES'⎕SIGNAL 2
        p[⍵]←(⍺,⍵)[1+¯1@{⍵=⍳≢⍵}D2P +⍀¯1⌽bm+pm] ⋄ t[bo⌿⍵]←¯1 ⋄ t[po⌿⍵]←Z
        end[po⌿⍵]←end[⌽pc⌿⍵] ⋄ end[bo⌿⍵]←end[⌽bc⌿⍵]
  0}⌸i←⍸(t[p]=Z)∧p≠⍳≢p
  t k n pos end⌿⍨←⊂msk←~IN[pos]∊')' ⋄ p←(⍸~msk)(⊢-1+⍸)msk⌿p
```

This code is used in chunk 21.
Uses `SIGNAL` 19b.

38b ⟨*Group function and value expressions* 38b⟩≡

```
  i km←⍪⌿p[i]{(⍺⍪⍵)(0,1∨⍵)}⌸i←⍸(t[p]∊B Z)∧(p≠⍳≢p)∧k[p]∊1 2
```

This code is used in chunk 21.

6.11.1 Value Expressions

38c ⟨*Parse value expressions* 38c⟩≡

```
  i km←⍪⌿p[i]{(⍺⍪⍵)(0,(2≤≢⍵)∧1∨⍵)}⌸i←⍸(t[p]∊B Z)∧(k[p]=1)∧p≠⍳≢p
  msk←m2∨fm∧~¯1⌽m2←km∧(1⌽km)∧~fm←(t[i]=O)∨(t[i]≠A)∧k[i]=2
  t,←E⍴⍨xc←+⌿msk ⋄ k,←msk⌿msk+m2 ⋄ n,←xc⍴⊂''
  pos,←pos[msk⌿i] ⋄ end,←end[p[msk⌿i]]
  p,←msk⌿¯1⌽(i×~km)+km×x←¯1+(≢p)++⍀msk ⋄ p[km⌿i]←km⌿x
```

This code is used in chunk 21.

6.11.2 Function Expressions

39a ⟨*Parse function expressions* 39a⟩≡

```
⍝ Mask and verify dyadic operator right operands
(dm←¯1⌽(k[i]=4)∧t[i]∊F P V Z)∨.∧(~km)∨k[i]∊0 3 4:{
        'MISSING RIGHT OPERAND'⎕SIGNAL 2
}⍬

⍝ Refine schizophrenic types
k[i⌿⍨(k[i]=5)∧dm∨¯1⌽(~km)∨(~dm)∧k[i]∊1 6]←2 ⋄ k[i⌿⍨k[i]=5]←3

⍝ Rationalize ∘.
jm←(t[i]=P)∧n[i]∊⊂,'∘.'
jm∨.∧1⌽(~km)∨k[i]∊3 4:'MISSING OPERAND TO ∘.'⎕SIGNAL 2
p←((ji←jm⌿i)@(jj←i⌿⍨¯1⌽jm)⍳≢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]

⍝ Mask and verify monadic and dyadic operator left operands
∨⌿msk←(dm∧¯2⌽~km)∨(¯1⌽~km)∧mm←(k[i]=3)∧t[i]∊F P V Z:{
        2'MISSING LEFT OPERAND'SIGNAL ∊pos[⍵]+⍳¨end[⍵]-pos[⍵]
}i⌿⍨msk
msk←dm∨mm

⍝ Parse function expressions
np←(≢p)+⍳xc←≢oi←msk⌿i ⋄ p←(np@oi⍳≢p)[p] ⋄ p,←oi ⋄ t k n pos end(⊣,I)←⊂oi
p[g⌿i]←oi[(g←(~msk)∧(1⌽msk)∨2⌽dm)⌿xc-⌽+⍀⌽msk]
p[g⌿oi]←(g←msk⌿(1⌽mm)∨2⌽dm)⌿1⌽oi ⋄ t[oi]←O ⋄ n[oi]←⊂''
pos[oi]←pos[g⌿i][msk⌿¯1++⍀g←(~msk)∧(1⌽mm)∨2⌽dm]
ol←1+(k[i⌿⍨(2⌽mm)∨3⌽dm]=4)∨k[i⌿⍨(1⌽mm)∨2⌽dm]∊2 3
or←(msk⌿dm)⍀1+k[dm⌿i]=2
k[oi]←3 3⊥↑or ol
```

This code is used in chunk 21.
Uses `SIGNAL` 19b.

6.12 Trains

39b ⟨*Parse trains* 39b⟩≡

```
⍝ TRAINS
```

This code is used in chunk 21.

6.13 Functions

6.13.1 D-fns

40a ⟨*Compute dfns regions and type, with* } *as a child* 40a⟩≡

```
t[⍸'{'=x]←F ⋄ 0≠⊃d←¯1⌽+⍀1 ¯1 0['{}'⍳x]:'UNBALANCED DFNS'⎕SIGNAL 2
```

This code is used in chunk 20.
Uses `SIGNAL` 19b.

40b ⟨*Compute the nameclass of dfns* 40b⟩≡

```
k←2×t∊F ⋄ k[∪p⌿⍨(t=P)∧n∊⊂'⍺⍺']←3 ⋄ k[∪p⌿⍨(t=P)∧n∊⊂'⍵⍵']←4
```

This code is used in chunk 21.

40c ⟨*Wrap all dfns expression bodies as* `Z` *nodes* 40c⟩≡

```
_←p[i]{end[⍺]←end[⊃⌽⍵] ⋄ gz¨⍵⊂⍨1,¯1↓t[⍵]=Z}⌸i←⍸t[p]=F
'Non-Z dfns body node'assert t[⍸t[p]=F]=Z:
```

This code is used in chunk 21.

40d ⟨*Parse guards to* `(G (Z ...) (Z ...))` 40d⟩≡

```
_←p[i]{
        0=+⌿m←':'=IN[pos[⍵]]:⍬
        ⊃m:'EMPTY GUARD TEST EXPRESSION'⎕SIGNAL 2
        1<+⌿m:'TOO MANY GUARDS'⎕SIGNAL 2
        t[⍺]←G ⋄ p[ti←gz⊃tx cq←2↑(⊂⍬)⍪⍨⍵⊂⍨1,¯1↓m]←⍺ ⋄ k[ti]←1
        ci←≢p ⋄ p,←⍺ ⋄ t k pos end⍪←0 ⋄ n,←⊂'' ⋄ k[gz cq,ci]←1
0}⌸i←⍸t[p[p]]=F
```

This code is used in chunk 21.
Uses `SIGNAL` 19b and `TEST` 14a.

40e ⟨*Anchor variables to earliest binding in the matching frame* 40e⟩≡

```
rf←¯1@{~t[⍵]∊F G M}p[rz←I@{~(t[⍵]=Z)∧(t[p[⍵]]∊F G M)∨p[⍵]=⍵}⍣≡⍨p]
rf[i]←p[i←⍸t=G] ⋄ rz[i]←i ⋄ rf←rf I@{rz∊p[i]⊢∘⊃⌸i←⍸t[p]=G}rf
mk←{⍺[⍵],⍪n[⍵]}
fr←rf mk⊢fb←fb[⍳⍨rf mk⊢fb←fb I∘(⍳⍨)∪⍬rz mk⊢fb←⍸t=B] ⋄ fb,←¯1
vb←fb[fr⍳rf mk i]@(i←⍸t=V)⊢¯1⍴⍨≢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⊢⍵]}⍣≡⍉{rf[⍵],⍪⍵}⍸(t=V)∧vb=¯1
∨⌿msk←(t=V)∧vb=¯1:{
        6'ALL VARIABLES MUST REFERENCE A BINDING'SIGNAL∊pos[⍵]{⍺+⍳⍵-⍺}¨end[⍵]
}⍸msk
```

This code is used in chunk 21.

6.13.2 Trad-fns

41a ⟨*Compute trad-fns regions* 41a⟩≡
```
∨⌿Z≠t⌿⍤1⌽msk←(d=0)∧'∇'=x:'TRAD-FNS START/END LINES MUST BEGIN WITH ∇'⎕SIGNAL 2
0≠⊃tm←¯1⌽≠⍀(d=0)∧'∇'=x:'UNBALANCED TRAD-FNS'⎕SIGNAL 2
∨⌿Z≠t⌿⍤⊃1 ¯1∨.⌽⊂(2>⌿tm)⍪0:'TRAD-FNS END LINE MUST CONTAIN ∇ ALONE'⎕SIGNAL 2
```
This code is used in chunk 20.
Uses `SIGNAL` 19b.

6.14 Labels

41b ⟨*Identify label colons vs. others* 41b⟩≡
```
t[⍸tm∧(d=0)∧∊((~⊃)∧(<⍀∨⍀))¨':'=(t=Z)⊂IN[pos]]←L
```
This code is used in chunk 20.

41c ⟨*Tokenize labels* 41c⟩≡
```
ERR←'LABEL MUST CONSIST OF A SINGLE NAME'
∨⌿(Z≠t[li-1])∨(V≠t[li←⍸1⌽msk←t=L]):ERR ⎕SIGNAL 2
t[li]←L ⋄ end[li]←end[li+1]
d tm t pos end(⌿⍤)←⊂~msk
```
This code is used in chunk 20.
Uses `SIGNAL` 19b.

41d ⟨*Parse labels* 41d⟩≡
```
⍝ XXX: Parse labels
```
Root chunk (not used in this document).

6.15 Statements

6.15.1 What is a keyword?

41e ⟨*Tokenize keywords* 41e⟩≡
```
ki←⍸(t=0)∧(d=0)∧(':'=IN[pos])∧1⌽t=V
t[ki]←K ⋄ end[ki]←end[ki+1] ⋄ t[ki+1]←0
ERR←'EMPTY COLON IN NON-DFNS CONTEXT, EXPECTED LABEL OR KEYWORD'
∨⌿(t=0)∧(d=0)∧':'=IN[pos]:ERR ⎕SIGNAL 2
```
This code is used in chunk 20.
Uses `SIGNAL` 19b.

42a ⟨*Check that all keywords are valid* 42a⟩≡

```
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
∨⌿msk:('UNRECOGNIZED KEYWORD ',kws⊃⍨⊃⍸msk)⎕SIGNAL 2
```

This code is used in chunk 21.
Uses `SIGNAL` 19b.

6.15.2 Namespaces

42b ⟨*Check that namespaces are at the top level* 42b⟩≡

```
msk←kws∊':NAMESPACE' ':ENDNAMESPACE'
∨⌿msk∧km⌿tm:'NAMESPACE SCRIPTS MUST APPEAR AT THE TOP LEVEL'⎕SIGNAL 2
```

This code is used in chunk 21.
Uses `SIGNAL` 19b.

42c ⟨*Nest top-level root lines as* `Z` *nodes* 42c⟩≡

```
_←(gz 1⌽⊢)¨(t[i]=Z)⊂i←⍸d=0
'Non-Z top-level node'assert t[⍸p=⍳≢p]=Z:
```

This code is used in chunk 21.

42d ⟨*Parse* `:Namespace` *syntax* 42d⟩≡

```
nss←n∊⊂':NAMESPACE' ⋄ nse←n∊⊂':ENDNAMESPACE'
ERR←':NAMESPACE KEYWORD MAY ONLY APPEAR AT BEGINNING OF A LINE'
Z∨.≠t⌿⍨1⌽nss:ERR ⎕SIGNAL 2
ERR←'NAMESPACE DECLARATION MAY HAVE ONLY A NAME OR BE EMPTY'
∨⌿(Z≠t⌿⍨¯1⌽nss)∧(V≠t⌿⍨¯1⌽nss)∨Z≠t⌿⍨¯2⌽nss:ERR ⎕SIGNAL 2
ERR←':ENDNAMESPACE KEYWORD MUST APPEAR ALONE ON A LINE'
∨⌿Z≠t⌿⍨⊃1 ¯1∨.⌽⊂nse:ERR ⎕SIGNAL 2
t[nsi←⍸1⌽nss]←M ⋄ t[nei←⍸1⌽nse]←-M
n[i]←n[1+i←⍸(t=M)∧V=1⌽t] ⋄ end[nsi]←end[nei]
x←⍸p=⍳≢p ⋄ d←+⍀(t[x]=M)+-t[x]=-M
0≠⊃⌽d:':NAMESPACE KEYWORD MISSING :ENDNAMESPACE PAIR'⎕SIGNAL 2
p[x]←x[D2P ¯1⌽d]

⍝ Delete unnecessary namespace nodes from the tree, leave only M's
msk←~nss∨((¯1⌽nss)∧t=V)∨nse∨1⌽nse
t k n pos end⌿⍨←⊂msk ⋄ p←(⍸~msk)(⊢-1+⍸)msk⌿p
```

This code is used in chunk 21.
Uses `SIGNAL` 19b.

6.15.3 Structured Programming Statements

43a ⟨*Verify that all structured statements appear within trad-fns* 43a⟩≡

```
msk←kws∊KW~':NAMESPACE' ':ENDNAMESPACE' ':SECTION' ':ENDSECTION'
∨⌿msk←msk∧~km⌿tm:{
        msg←2'STRUCTURED STATEMENTS MUST APPEAR WITHIN TRAD-FNS'
        msg SIGNAL ∊{x+⍳end[⍵]-x←pos[⍵]}¨⍸km⍀msk
}⍬
```

This code is used in chunk 21.
Uses SIGNAL 19b.

43b ⟨*Convert* M *nodes to* FO *nodes* 43b⟩≡

```
t←F@{t=M}t
```

This code is used in chunk 21.

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

43c ⟨*Must Have APL Utilities* 43c⟩≡

```
I←{(⊂⍵)⌷⍺}
U←{⍺←⊢ ⋄ ⍵⍵⍣¯1⊢⍺ ⍺⍺⍥⍵⍵ ⍵}
assert←{⍺←'assertion failure' ⋄ 0∊⍵:⍎'⍺ ⎕SIGNAL 8' ⋄ shy←0}
```

This code is used in chunk 5.
Defines:
  assert, used in chunk 21.
Uses SIGNAL 19b.

8.2 AST Pretty-printing

44 ⟨*Pretty-printing AST trees* 44⟩≡
```
dct←{α[(2×2≠/n,0)+(1↑⍨≢m)+m+n←⌽∨\⌽m←' '≠αα ω]ωω ω}
dlk←{((x⌷⍴ω)↑[x←2|1+ωω]α),[ωω]αα@(⊂0 0)⍣('┌'=⊃ω)⊢ω}
dwh←{ω('┬'dlk 1)' │├┌└─'(0⌷⍉)dct,⊃⍪/((≢¨α),¨⊂⌈/≢∘⍉¨α)↑¨α}
dwv←{ω('├'dlk 0)' ─┬┌┐│'(0⌷⊢)dct(⊣⍪1↓⊢)⊃{α,' ',ω}/(1+⌈/≢¨α){α↑ω⍪⍨'│'↑⍨≢⍉ω}¨α}

pp3←{α←'○' ⋄ d←(⍳≢ω)≠ω ⋄ _←{z⊣d+←ω≠z←α[ω]}⍣≡⍨ω ⋄ lbl←α⍴⍨≢ω
        lyr←{i←⍸α=d ⋄ k v←↓⍉ωω[i],∘⊂⌸i ⋄ (ω∘{α[ω]}¨v)αα¨@k⊢ω}ω
        (ω=⍳≢ω)⌿⊃αα lyr⌿(1+⍳⌈/d),⊂⍉∘⍪∘⍕¨lbl}

lb3←{α←⍳≢⊃ω
        '(',¨')',¨⍨{α,';',ω}⌿⍕¨(N∆{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.

45 ⟨DISPLAY *Utility* 45⟩≡

```
  DISPLAY←{⎕IO ⎕ML←0                                                          ⍝ Bo
  play of array.

         α←1 ⋄ chars←α⊃'..''''|-' '┌┐└┘│─'                         ⍝ α: 0-clunky, 1-smooth

        tl tr bl br vt hz←chars                                                ⍝ Top left

        box←{
             vrt hrz←(¯1+⍴ω)⍴¨vt hz                                            ⍝ Vert. ar
              top←(hz,'⊖→')[¯1↑α],hrz                                              ⍝ Up
  per border with axis.
             bot←(⊃α),hrz
  der with type.
             rgt←tr,vt,vrt,br
             lax←(vt,'⌽↓')[¯1↓1↓α],¨⊂vrt                                   ⍝ Left side(s) wi
             lft←⍉tl,(↑lax),bl                                                      ⍝
             lft,(top⍪ω⍪bot),rgt                                                    ⍝
           }

         deco←{α←type open ω ⋄ α,axes ω}                                 ⍝ Type and axes vector
        axes←{(-2⌈⍴⍴ω)↑1+×⍴ω}                                                  ⍝ Ar
  ray axis types.
        open←{(1⌈⍴ω)⍴ω}
  pose null axes.
         trim←{(~1 1⍷∧⌿ω=' ')/ω}                                               ⍝ Re
  move extra blank cols.
        type←{{(1=⍴ω)⊃'+'ω}∪,char¨ω}                                   ⍝ Simple array type
          char←{⍬≡⍴ω:hz ⋄ (⊃ω∊'¯',⎕D)⊃'#~'}∘⍕                   ⍝ Simple scalar type.
          line←{(6≠10|⎕DR' 'ω)⊃' -'}                                           ⍝ un
  derline for atom.

        {
  cursively box arrays:
```

```
              0=≡ω:' '⍪(open ⎕FMT ω)⍪line ω                    ⍝ Simple scalar
               1 θ≡(≡ω)(ρω):'∇' 0 0 box ⎕FMT ω               ⍝ Object rep: ⎕OR
                 1=≡ω:(deco ω)box open ⎕FMT open ω           ⍝ Simple array.
                 ('∊'deco ω)box trim ⎕FMT ∇¨open ω          ⍝ Nested array.
          }ω
  }
```

Root chunk (not used in this document).
Defines:
`DISPLAY`, used in chunk 46.
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.

46a ⟨`PP` *Utility* 46a⟩≡

```
PP←{ω⊣⎕←#.DISPLAY ω}
```

Root chunk (not used in this document).
Defines:
`PP`, used in chunks 30a and 46b.
Uses `DISPLAY` 45.

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

46b ⟨*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 48.
Defines:
`DISPLAY.aplf`, never used.
`PP.aplf`, never used.
Uses `codfns` 5, `DISPLAY` 45, `PP` 46a, and `src` 53.

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 `⎕NPUT` or something like that.

47a ⟨*Basic* `tie` *and* `put` *utilities* 47a⟩≡
```
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 52b.
Defines:
  `put`, used in chunks 29, 52b, and 53.
  `tie`, used in chunks 29 and 52b.
Uses `SIGNAL` 19b.

8.5 XML Rendering

47b ⟨*XML Rendering* 47b⟩≡
```
Xml←{α←0 ⋄ ast←α{d i←P2D⊃ω ⋄ i∘{ω[α]}¨(⊂d),1↓α↓ω}⍣(0≠α)⊢ω ⋄ d t k n←4↑ast
        cls←NΔ[t],¨('-..'[1+×k]),¨⍕¨|k ⋄ fld←{((≢ω)↑3↓fΔ),⍪ω}¨↓⍉↑3↓ast
        ⎕XML⍉↑d cls(⊂'')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.

47c ⟨*The* `opsys` *utility* 47c⟩≡
```
opsys←{ω⊃⍨'Win' 'Lin' 'Mac'⍳⊂3↑⊃'.'⎕WG'APLVersion'}
```
This code is used in chunks 29, 49c, and 51d.
Defines:
  `opsys`, used in chunks 49c and 51d.

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 LaTeX 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.

48 ⟨TANGLE.sh 48⟩≡

```
#!/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 49a.
Uses `codfns` 5 and `TANGLE` 49c.

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.

49a ⟨`TANGLE.bat` 49a⟩≡

```
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 49b.
Uses `TANGLE` 49c and `TANGLE.sh` 48.

49b ⟨*Tangle Commands* 6⟩+≡

```
echo "Tangling TANGLE.bat..."
notangle -R'[[TANGLE.bat]]' codfns.nw > TANGLE.bat
```

This code is used in chunk 48.
Uses `codfns` 5, `TANGLE` 49c, and `TANGLE.bat` 49a.

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.*

49c ⟨`TANGLE` 49c⟩≡

```
TANGLE;opsys
⟨The opsys utility 47c⟩
⎕CMD opsys '.\TANGLE.bat' './TANGLE.sh' './TANGLE.sh'
```

Root chunk (not used in this document).
Defines:
`TANGLE`, used in chunks 48 and 49.
Uses `opsys` 47c.

49d ⟨*Tangle Commands* 6⟩+≡

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

This code is used in chunk 48.
Defines:
`TANGLE.aplf`, never used.
Uses `codfns` 5, `src` 53, and `TANGLE` 49c.

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 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 `lualatex` 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.*

50 ⟨`WEAVE.sh` 50⟩≡

```
#!/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 51.
Uses `codfns` 5.

51a ⟨*Tangle Commands* 6⟩+≡
```
echo "Tangling WEAVE.sh..."
notangle -R'[[WEAVE.sh]]' codfns.nw > WEAVE.sh
```
This code is used in chunk 48.
Uses `codfns` 5, `WEAVE` 51d, and `WEAVE.sh` 50.

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

51b ⟨`WEAVE.bat` 51b⟩≡
```
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 51c.
Uses `WEAVE` 51d and `WEAVE.sh` 50.

51c ⟨*Tangle Commands* 6⟩+≡
```
echo "Tangling WEAVE.bat..."
notangle -R'[[WEAVE.bat]]' codfns.nw > WEAVE.bat
```
This code is used in chunk 48.
Uses `codfns` 5, `WEAVE` 51d, and `WEAVE.bat` 51b.

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.

51d ⟨`WEAVE` 51d⟩≡
```
WEAVE;opsys
⟨The opsys utility 47c⟩
⎕CMD opsys '.\WEAVE.bat' './WEAVE.sh' './WEAVE.sh'
```
Root chunk (not used in this document).
Defines:
`WEAVE`, used in chunk 51.
Uses `opsys` 47c.

51e ⟨*Tangle Commands* 6⟩+≡
```
echo "Tangling src/WEAVE.aplf..."
notangle -R'[[WEAVE]]' codfns.nw > src/WEAVE.aplf
```
This code is used in chunk 48.
Defines:
`WEAVE.aplf`, never used.
Uses `codfns` 5, `src` 53, and `WEAVE` 51d.

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.

52a ⟨*Build the runtime* 52a⟩≡
  ⟨*Compile the primitives in* `prim.apln` 53⟩
  ⟨*Build* `codfns.dll` *DLL* 54a⟩
  ⟨*Copy the runtime files into* `tests\` 54b⟩
This code is used in chunk 52b.

We define the command `MK∆RTM` 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.

52b ⟨`MK∆RTM` 52b⟩≡
```
MK∆RTM path;put;tie;src;vsbat;vsc;wsd
```
  ⟨*Basic* `tie` *and* `put` *utilities* 47a⟩
  ⟨*Build the runtime* 52a⟩
Root chunk (not used in this document).
Defines:
  `MK∆RTM`, used in chunk 52c.
Uses `put` 47a, `src` 53, `tie` 47a, `vsbat` 54a, `vsc` 54a, and `wsd` 54a.

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

52c ⟨*Tangle Commands* 6⟩+≡
```
echo "Tangling src/MK∆RTM.aplf..."
notangle -R'[[MK∆RTM]]' codfns.nw > src/MK∆RTM.aplf
```
This code is used in chunk 48.
Defines:
  `MK∆RTM.aplf`, never used.
Uses `codfns` 5, `MK∆RTM` 52b, and `src` 53.

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.

53 ⟨*Compile the primitives in* `prim.apln` 53⟩≡

```
src←⎕SRC ⎕SE.SALT.Load path,'\rtm\prim.apln'
(path,'\rtm\prim.c')put codfns.{GC TT PS ⍵}src
```

This code is used in chunk 52a.
Defines:
`src`, used in chunks 6, 11, 14b, 23, 46b, 49d, 51, and 52.
Uses `codfns` 5, `PS` 15, and `put` 47a.

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 appropriatelly invoking our ArrayFire dependencies as well as producing the appropriate debugging symbols most of the time.

54a ⟨*Build* `codfns.dll` *DLL* 54a⟩≡

```
vsbat←#.codfns.VS∆PATH
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.AF∆LIB,'.lib"'
vsc,←'    /OPT:ICF /ERRORREPORT:PROMPT'
vsc,←'    /TLBID:1 /OUT:"codfns.dll""'
```

This code is used in chunk 52a.
Defines:
`vsbat`, used in chunks 29 and 52b.
`vsc`, used in chunks 29, 52b, and 54b.
`wsd`, used in chunks 52b and 54b.
Uses `AF∆LIB` 9, `codfns` 5, and `VS∆PATH` 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.

54b ⟨*Copy the runtime files into* `tests\` 54b⟩≡

```
⎕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 52a.
Uses `codfns` 5, `vsc` 54a, and `wsd` 54a.

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

10.2 Identifiers

11 GNU AFFERO GENERAL PUBLIC LICENSE

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