The Co-dfns Compiler

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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 changing this code is 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.

7 ⟨* 7⟩≡

```
:Namespace codfns

⟨Global Settings 10a⟩
⟨The Fix API 13⟩
⟨User-command API 15a⟩

⟨Parser 17⟩
⟨Compiler 23⟩
⟨Code Generator 25b⟩
⟨Interface to the backend C compiler 26⟩
⟨Linking with Dyalog 27⟩

⟨Must Have APL Utilities 81c⟩
⟨Basic tie and put utilities 84c⟩
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⟨AST Record Structure 15b⟩
⟨Converters between parent and depth vectors 15c⟩
⟨XML Rendering 85a⟩
⟨Pretty-printing AST trees 82⟩
```

```
:EndNamespace
```

Root chunk (not used in this document).
Defines:
`codfns`, used in chunks 8, 16b, 24d, 26, 32b, 34a, 41, 47b, 58, 64, 71, 84b, and 86–92.

This ⟨* 7⟩ 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* 8⟩ chunk. Thus, we follow the convention here of updating the contents of the ⟨*Tangle Commands* 8⟩ 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.

8 ⟨*Tangle Commands* 8⟩≡

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

This definition is continued in chunks 16b, 32b, 34a, 41b, 47b, 58b, 64b, 71b, 84b, 87, 89, and 90c.
This code is used in chunk 86.
Defines:
`codfns.apln`, never used.
Uses `codfns` 7 and `src` 91.

The primary user-facing interfaces into the compiler are ⟨*The Fix API* 13⟩ and the ⟨*User-command API* 15a⟩. 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`.

10a ⟨*Global Settings* 10a⟩≡

```
⎕IO ⎕ML ⎕WX←0 1 3
```

This definition is continued in chunks 10–12.
This code is used in chunk 7.
Defines:
`⎕IO`, used in chunk 83.
`⎕ML`, used in chunk 83.
`⎕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.

10b ⟨*Global Settings* 10a⟩+≡

```
VERSION←4 1 0
```

This code is used in chunk 7.
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.

11 ⟨*Global Settings* 10a⟩+≡

```
AF∆PREFIX←'/opt/arrayfire'
AF∆LIB←'cuda'
```

This code is used in chunk 7.
Defines:
`AF∆LIB`, used in chunks 15a, 26, and 92a.
`AF∆PREFIX`, used in chunk 26.

[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.

12 ⟨*Global Settings* 10a⟩+≡

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

This code is used in chunk 7.
Defines:
`VS∆PATH`, used in chunks 26 and 92a.

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.

$$\textit{Parse} \rightarrow \textit{Compile} \rightarrow \textit{Generate} \rightarrow \textit{Backend} \rightarrow \textit{Link}$$

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.

13 ⟨*The Fix API* 13⟩≡

```
Fix←{
_←a n s src←PS ⍵⊣⍞←'P'
_←          TT _⊣⍞←'C'
_←          GC _⊣⍞←'G'
_←        ⍺ CC _⊣⍞←'B'
n NS _⊣⍞←'L'
}
```

This code is used in chunk 7.
Defines:
`Fix`, used in chunk 15a.
Uses `PS` 17 and `src` 91.

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.

14a ⟨*Verify source input* ⍵*, set* `IN` 14a⟩≡

```
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 14b⟩

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

This code is used in chunk 17.
Uses `SIGNAL` 20b.

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.

14b ⟨*Normalize the input formatting* 14b⟩≡

```
IN←∊(⊆IN),¨⎕UCS 10
```

This code is used in chunk 14a.

3.3 The User Command API

15a ⟨*User-command API* 15a⟩≡
```
∇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 7.
Uses `AF∆LIB` 11 and `Fix` 13.

3.4 AST Record Structure

15b ⟨*AST Record Structure* 15b⟩≡
```
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 7.

3.5 Converters between parent and depth vectors

15c ⟨*Converters between parent and depth vectors* 15c⟩≡
```
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 7.

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.

16a ⟨`TEST` 16a⟩≡

```
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 16b and 67a.

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

16b ⟨*Tangle Commands* 8⟩+≡

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

This code is used in chunk 86.
Defines:
`TEST.aplf`, never used.
Uses `codfns` 7, `src` 91, and `TEST` 16a.

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].

17 ⟨*Parser* 17⟩≡

```
PS←{
⟨Verify source input ⍵, set IN 14a⟩

⟨Parsing Constants 18a⟩
⟨Line and error reporting utilities 20b⟩

⟨Tokenize input 21⟩
⟨Parse token stream 22⟩

⟨Compute parser exports 69b⟩
⟨Adjust AST for output 18b⟩
}
```

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

This code is used in chunk 7.
Defines:
`PS`, used in chunks 13 and 91.

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

18a ⟨*Parsing Constants* 18a⟩≡

```
CR LF←⎕UCS 13 10
```

This code is used in chunk 17.

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

On parser output, we 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.

18b ⟨*Adjust AST for output* 18b⟩≡

```
d i←P2D p ⋄ d n t k pos end I∘⊢←⊂i
```

This definition is continued in chunks 19 and 20a.
This code is used in chunk 17.

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

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

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

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

19 ⟨*Adjust AST for output* 18b⟩+≡

```
sym←∪('')(,'⍵')(,'⍺')'⍺⍺' '⍵⍵',n
n←-sym⍳n
```

This code is used in chunk 17.

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.

20a ⟨*Adjust AST for output* 18b⟩+≡

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

This code is used in chunk 17.
Uses `xn` 69b and `xt` 69b.

5.1.2 Handling Parsing Errors

20b ⟨*Line and error reporting utilities* 20b⟩≡

```
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∊⍵],⍨' '⍴⍨≢no)}
quotelines←{
lines←∪linestarts⍸⍵
nos←(1 0⍴⍨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 17.
Defines:
`linestarts`, never used.
`mkdm`, never used.
`quotelines`, used in chunks 47c and 49a.
`SIGNAL`, used in chunks 14a, 24–27, 47–49, 52–54, 58c, 60a, 64d, 66–69, 71d, 81c, and 84c.
Uses `dmx` 43a.

5.1.3 Tokenizing the Input

21 ⟨*Tokenize input* 21⟩≡

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

⟨Check and mask the strings 49a⟩
⟨Unify whitespace and comments 48a⟩
⟨Tokenize strings 49b⟩
⟨Verify that all open characters are valid 47c⟩
⟨Tokenize numbers 48b⟩
⟨Tokenize variables 49c⟩
⟨Tokenize primitives and atoms 51b⟩
⟨Compute dfns regions and type, with } as a child 64d⟩
⟨Check for out of context dfns formals 49d⟩
⟨Compute trad-fns regions 66c⟩
⟨Identify label colons vs. others 67d⟩
⟨Tokenize keywords 68a⟩
⟨Tokenize system variables 51d⟩

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

⟨Tokenize labels 67e⟩
```

This code is used in chunk 17.

5.1.4 Parsing Token Stream

22 ⟨*Parse token stream* 22⟩≡

```
⍝ 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+⍳¨end-pos

⟨Check that all keywords are valid 68b⟩
⟨Check that namespaces are at the top level 68c⟩
⟨Verify that all structured statements appear within trad-fns 71d⟩
⟨Verify that system variables are defined 52a⟩

⍝ Compute parent vector from d
p←D2P d

⟨Compute the nameclass of dfns 64e⟩

⍝ 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 68d⟩
⟨Wrap all dfns expression bodies as Z nodes 64f⟩

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

⟨Parse :Namespace syntax 69a⟩
⟨Parse guards to (G (Z ...) (Z ...)) 67a⟩
⟨Parse brackets and parentheses into ¯1 and Z nodes 58c⟩
⟨Convert ; groups within brackets into Z nodes 52c⟩
⟨Parse Binding nodes 54a⟩
⟨Mark system variables as P nodes with appropriate kinds 52b⟩
⟨Mark atoms, characters, and numbers as kind 1 50b⟩
⟨Mark APL primitives with appropriate kinds 51c⟩
⟨Anchor variables to earliest binding in the matching frame 64g⟩
⟨Convert M nodes to FO nodes 71e⟩
⟨Convert α and ω to V nodes 49e⟩
⟨Convert αα and ωω to P2 nodes 49f⟩
⟨Infer the type of bindings, groups, and variables 54b⟩
⟨Strand arrays into atoms 50c⟩
⟨Parse dyadic operator bindings 54c⟩
⟨Rationalize F[X] syntax 53e⟩
```

```
⟨Group function and value expressions 58d⟩
⟨Parse function expressions 60a⟩
⟨Parse assignments 55c⟩
⟨Enclose V[X;...] for expression parsing 53a⟩
⟨Parse trains 60c⟩
⟨Parse value expressions 59b⟩
⟨Rationalize V[X;...] 53b⟩

⍝ Sanity check
ERR←'INVARIANT ERROR: Z node with multiple children'
ERR assert(+⌿(t[p]=Z)∧p≠⍳≢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[⍵]]=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¨⊂ki
t k n pos end⌿⍨←⊂msk←~msk∨t=Z ⋄ p←(⍸~msk)(⊢-1+⍸)msk⌿p
```

This code is used in chunk 17.
Uses `assert` 81c.

5.2 Compiler Transformations

23 ⟨*Compiler* 23⟩≡

```
TT←{
((d t k n ss se)exp sym src)←⍵

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

⟨Lift dfns to the top-level 65a⟩
⟨Wrap expressions as binding or return statements 65b⟩
⟨Lift guard tests 67b⟩
⟨Count strand and indexing children 50d⟩
⟨Lift and flatten expressions 59a⟩
⟨Compute slots and frames 65d⟩
⟨Record exported top-level bindings 69c⟩

p t k n f s r d xi sym
}
```

This code is used in chunk 7.
Uses `src` 91 and `xi` 69c.

5.3 Code Generator

24a ⟨*Map generators over the linearized AST; return* 24a⟩≡

```
d i←P2D p ⋄ ast←(⍉↑d p t k n(⍳≢p)fr sl fd)[i;] ⋄ ks←{ω⊂[0]⍨(⊃ω)=ω[;0]}
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}
∊,∘(⎕UCS 13 10)¨pref,⊃,⌿(,⌿Zp¨⍸t=F),(,⌿Zx¨xi),(⊂⊂''),dis¨ks ast
```

This code is used in chunk 25b.
Uses `SIGNAL` 20b and `xi` 69c.

24b ⟨*Symbol ⟷ Name mapping* 24b⟩≡

```
syms←0⍴⊂'' ⋄ nams←0⍴⊂''
```

This definition is continued in chunks 53c, 56a, 65e, and 72–81.
This code is used in chunk 25b.

24c ⟨*Node ⟷ Generator mapping* 24c⟩≡

```
gck←0⍴⊂0 0 ⋄ gcv←0⍴⊂''
```

This definition is continued in chunks 48–50, 53d, 55a, 56b, 59c, 60b, 65, 67c, and 69d.
This code is used in chunk 25b.

24d ⟨*Prefix code for all generated files* 24d⟩≡

```
pref ←⊂'#include "codfns.h"'
pref,←⊂''
pref,←⊂'EXPORT int'
pref,←⊂'DyalogGetInterpreterFunctions(void *p)'
pref,←⊂'{'
pref,←⊂'    return set_dwafns(p);'
pref,←⊂'}'
pref,←⊂''
```

This code is used in chunk 25b.
Uses `codfns` 7, `codfns.h` 33, and `set_dwafns` 46a.

24e ⟨*Node-specific code generators* 24e⟩≡

```
Zp←{
n←'fn',⍕ω
⟨Declare top-level function bindings 61a⟩
'UNKNOWN FUNCTION TYPE'⎕SIGNAL 16
}
```

This definition is continued in chunks 25a, 50a, 51a, 55b, 59d, 65, 66, and 70.
This code is used in chunk 25b.
Uses `SIGNAL` 20b.

25a ⟨*Node-specific code generators* 24e⟩+≡

```
Zx←{
n←sym⊃⍨|n[ω] ⋄ rid←⍕rf[ω]
k[ω]=0:⊂''
⟨Declare top-level array structures 50f⟩
⟨Declare top-level closures 61b⟩
⍎'''UNKNOWN EXPORT TYPE''⎕SIGNAL 16'
}
```

This code is used in chunk 25b.
Uses `EXPORT` 34b and `SIGNAL` 20b.

25b ⟨*Code Generator* 25b⟩≡

```
GC←{
p t k n fr sl rf fd xi sym←ω

⟨Symbol ⟷ Name mapping 24b⟩
⟨Node ⟷ Generator mapping 24c⟩

⟨Prefix code for all generated files 24d⟩
⟨Node-specific code generators 24e⟩

⟨Map generators over the linearized AST; return 24a⟩
}
```

This code is used in chunk 7.
Uses `xi` 69c.

5.4 Backend C Compiler Interface

26 ⟨*Interface to the backend C compiler* 26⟩≡

```
CC←{
vsbat←VS∆PATH,'\VC\Auxiliary\Build\vcvarsall.bat'
soext←{opsys'.dll' '.so' '.dylib'}
libdir←opsys ''' ' '/lib64'' ' '/lib'' '
ccf←{' -o ''',⍵,'.',⍺,''' ''',⍵,'.c'' -laf',AF∆LIB,' > ',⍵,'.log 2>&1'}
cci←{'-I''',AF∆PREFIX,'/include'' -L''',AF∆PREFIX,libdir}
cco←'-std=c99 -Ofast -g -Wall -fPIC -shared '
cco,←'-Wno-parentheses -Wno-misleading-indentation '
ucc←{⍵⍵(⎕SH ⍺⍺,' ',cco,cci,ccf)⍵}
gcc←'gcc'ucc'so'
clang←'clang'ucc'dylib'
vsco←{z←'/W3 /wd4102 /wd4275 /O2 /Zc:inline /Zi /FS /Fd"',⍵,'.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 ⍵),' "',⍵,'.c" '}
vsc2←{(vslo ⍵),'/OUT:"',⍵,'.dll" > "',⍵,'.log""'}
vsc←{⎕CMD ('%comspec% /C ',vsc0,vsc1,vsc2)⍵}
_←(⍎opsys'vsc' 'gcc' 'clang')⍺⊣⍵ put ⍺,'.c'⊣1 ⎕NDELETE f←⍺,soext⍬
⎕←⍪⊃⎕NGET(⍺,'.log')1
⎕NEXISTS f:f ⋄ 'COMPILE ERROR' ⎕SIGNAL 22}
```

This code is used in chunk 7.
Uses AF∆LIB 11, AF∆PREFIX 11, codfns 7, opsys 85b, put 84c, SIGNAL 20b, vsbat 92a, vsc 92a, and VS∆PATH 12.

5.5 Linking with Dyalog

27 ⟨*Linking with Dyalog* 27⟩≡

```
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 ⋄ loadimg ⍬ 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 ⍴ ⍬}
mkna←{α,'|',('∆'⎕R'__'⊢ω),'_cdf P P P'}
mkf←{
fn←α,'|',('∆'⎕R'__'⊢ω),'_dwa '
z←⊂'Z←{A}',ω,' W'
z,←⊂':If 0=⎕NC''⍙.',ω,'_mon'''
z,←⊂'       ''',ω,'_mon''⍙.⎕NA''',fn,'>PP P <PP'''
z,←⊂'       ''',ω,'_dya''⍙.⎕NA''',fn,'>PP <PP <PP'''
z,←⊂':EndIf'
z,←⊂':If 0=⎕NC''A'''
z,←⊂'       Z←⍙.',ω,'_mon 0 0 W'
z,←⊂':Else'
z,←⊂'       Z←⍙.',ω,'_dya 0 A W'
z,←⊂':EndIf'
z
}
ns←#.⎕NS⍬ ⋄ _←'∆⍙'ns.⎕NS¨⊂⍬ ⋄ ∆ ⍙←ns.(∆ ⍙)
∆.names←(0⍴⊂''),(2=1⊃α)⌿0⊃α
fns←'Rtm∆Init' 'MKA' 'EXA' 'Display'
fns,←'LoadImage' 'SaveImage' 'Image' 'Plot' 'Histogram'
fns,←'soext' 'opsys' 'mkna'
```

```
  _←∆.⎕FX∘⎕CR¨fns
  ∆.(decls←⍵∘mkna¨names)
  _←ns.⎕FX¨(⊂''),⍵∘mkf¨∆.names
  _←'Z←Init'
  _,←⊂'Z←Rtm∆Init ''',⍵,''''
  _,←⊂'→0⌿⍨0=≢names'
  _,←⊂'names ##.⍙.⎕NA¨decls'
  _←∆.⎕FX _
  ns
  }
```

This code is used in chunk 7.
Uses PP 84a and SIGNAL 20b.

29 ⟨*DWA Function Export* 29⟩≡

```
  z,←⊂'EXPORT int'
  z,←⊂n,'_dwa(struct localp *zp, struct localp *lp, struct localp *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,←⊂''
```

This code is used in chunk 61b.

Uses dwa_error 44a.

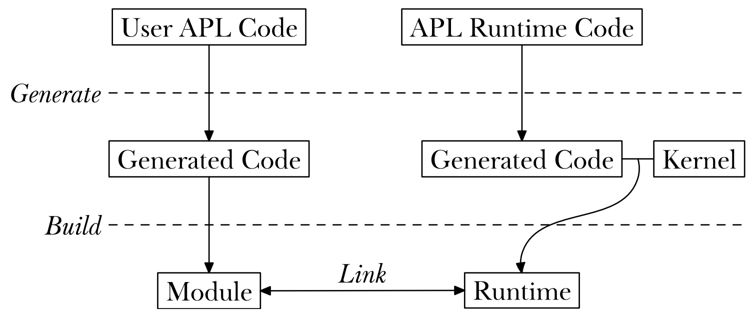

Figure 1: Process of Building and Linking the Runtime

5.6 Runtime

The runtime component of Co-dfns handles the code necessary for the output of the Code Generator to run. This includes support for all the supported language features as well as the runtime code for the built-in APL primitives and system functionality. The design of the runtime is meant to allow for as much of the runtime as possible to be implemented in APL. We also want to make it as easy as possible to target new languages for output from the compiler.

Conceptually, the code generator produces a code module that links against an already built runtime module that provides all the language support. Each module has some “backend target” language. In order to make retargeting the compiler as simple as possible and to implement most of the runtime as APL, we split the runtime code into an APL namespace, containg all the APL code that is applicable to all backends and that can be implemented in APL, and a backend kernel that contains all the backend language-specific code that we must use. We can split the compiler into a frontend *generate* and a backend *build* step. The generate phase takes the input APL source and generates code in the backend target language that depends on a runtime implementation. The build phase takes that code and uses the backend toolchain to link, compile, and otherwise assemble the code into an appropriate redistributable “binary”. The C backend, for instance, takes APL and turns it into C code where a C compiler then builds and links it against a runtime, finally producing a DLL.

To build the runtime, the same basic approach is used. We use the compiler to generate a backend file from the APL runtime code. However, since no runtime exists for the runtime itself, we do *not* continue in the typical manner and build with the standard backend pipeline, which assumes the existence of a runtime. Instead, we merge the generated code with the kernel for that specific backend and build as its own standalone object.

This workflow is illustrated by Figure 1 showing how all of the pieces of the runtime interact with user code.

This architecture has some interesting advantages. First, most of the process for building the runtime is just like building any other piece of APL code. Second, only a small kernel and code generator need to be implemented for a new backend, with most of the work remaining in the APL runtime code. Third, the runtime may be implemented using a different backend language than that used for compiling the user code. All that is required is that the backend for the user code knows how to link to and access the code in the runtime object. This permits, for instance, a Scheme or Javascript backend to depend on a runtime implemented in C, thus enabling greater performance while hiding any integration hassles from the interface exposed by the user module. In theory, any combination of suitable backend languages may be used.

We put all the runtime primitives into a single Co-dfns namespace called `prim.apln`.

32a ⟨*prim.apln* 32a⟩≡

```
:Namespace prim

⟨APL Primitives 80a⟩
⟨System Primitives (never defined)⟩

:EndNamespace
```

Root chunk (not used in this document).
Defines:
`prim`, used in chunks 32b and 91.
`prim.apln`, used in chunk 32b.

32b ⟨*Tangle Commands* 8⟩+≡

```
echo "Tangling rtm/prim.apln..."
notangle -R'prim.apln' codfns.nw > rtm/prim.apln
```

This code is used in chunk 86.
Uses `codfns` 7, `prim` 32a, and `prim.apln` 32a.

Each primitive has its own unique considerations, so we leave the definition of these primitives to section 7.

For each backend we must have a unique kernel and code generator. Most of that content will be defined on a per-language feature basis below. The rest of this section focuses on the more generic and fundamental elements of the kernels, such as general organization, interface, and memory management.

5.6.1 GPU C Runtime Kernel

The main concern of a C runtime is managing memory and adequately handling access to the DWA system. Dyalog's DWA system permits us direct access to the underlying interpreter array format and memory manager. We could use this format directly but this will not work for GPU compute because the DWA interface connects array elements and header information in a way that makes GPU allocating them quite difficult, especially if we only want the elements on the GPU.

DWA has a specific array format, but we will delay specifying utility code for array handling until section 6.6. In this section, we handle the following issues:

- DWA Initialization
- Header Structure
- Memory Management
- Datatype Management
- Error Reporting

We deal with the top-level error signalling behavior in this section, but for error signalling within functions, as well as arrays, module initialization function calls, and so forth, see the appropriate subsection of Language Features (section 6).

The first order of business is the main structure of the C runtime files and API. We could attempt to put all our runtime code into a single `kernel.c` file, but the result would require us to maintain includes in a way that prevents us from easily linking the include statements to each language feature implementation without encouraging needless duplicate includes. Instead, we assume that each langauge feature will be given its own C file and then we can manage includes independently. We will make use of a single `codfns.h` file that contains all the public entry points into the runtime.

33 ⟨*codfns.h* 33⟩≡

```
#pragma once
```

⟨*C runtime includes* (never defined)⟩
⟨*C runtime macros* 34b⟩
⟨*C runtime enumerations* 36b⟩
⟨*C runtime structures* 36a⟩
⟨*C runtime declarations* 38a⟩

Root chunk (not used in this document).
Defines:
`codfns.h`, used in chunks 24d, 34a, 41a, 58a, 64a, 71a, and 92b.

34a ⟨*Tangle Commands* 8⟩+≡

```
echo "Tangling rtm/codfns.h..."
notangle -R'codfns.h' codfns.nw > rtm/codfns.h
```

This code is used in chunk 86.
Uses `codfns` 7 and `codfns.h` 33.

Since we want to use this single header for the runtime code *and* the generated code that will import the runtime, an interesting situation arises regarding exports. Both generated and runtime code must export functions from their respective DLLs, but in the case of the runtime, these exported functions are also the functions that we must import into our generated code, we must annotate the edeclaration of such functions differently if we are importing than when we are exporting. Thus, when we are building the runtime, we want to export all our bindings, but when we are accessing the runtime from generated code we want to import those same bindings while exporting functions that we generate.

To handle this, we rely on three preprocessor definitions. When we are building the runtime, we will define `EXPORTING`, but we expect this to be undefined when building generated code. Then we have an `EXPORT` definition that always maps to the platform specific export decorator, while `DECLSPEC` will be the import spec or export spec depending on `EXPORTING`.

It used to be the case that each platform handled DLL importing and exporting differently, but modern compilers all handle the `__declspec` syntax, so we will use that for all platforms.

34b ⟨*C runtime macros* 34b⟩≡

```
#define EXPORT __declspec(dllexport)
#ifdef EXPORTING
#define DECLSPEC EXPORT
#else
#define DECLSPEC __declspec(dllimport)
#endif
```

This code is used in chunk 33.
Defines:
`DECLSPEC`, used in chunks 37–40, 43, 44, 46a, 57, 62, 63, and 71c.
`EXPORT`, used in chunks 25a and 71a.
`EXPORTING`, used in chunk 92a.

Our next major concern is handling memory and multiple data types. Since the compiler assumes a stack machine model, we have a unified stack that will contain many different objects, such as functions and arrays, so we must have a way of handling the objects in a somewhat generic way.

While some generality is desirable, I must curtail my Scheme-esque impulse towards unnecessary dynamic generality. This is a runtime, after all, and experience shows that extra dynamic annotation can seriously impede scalability of the system and introduce unfortunate performance gotchas. Rather than chase this form of programmability, I am taking a page from Knuth's book and aiming for "re-editable" code that can be easily, but statically, extended. The goal is to avoid excess runtime allocation and indirection while at the same time making it easy to add and manage datatypes.

Any such memory or type management system must address the following questions:

- How do I make an object?
- How do I free an object?
- When do I free an object?
- How do I keep an object alive?
- How do I make new data types?

In APL, most values have a stack lifetime, which would encourage us to make use of a stack semantics in our runtime. However, for more involved APL, this assumption does not hold true. Instead, to manage our objects, we choose to make use of reference counting.[5] This maintains most of the predictability and low-overhead of a stack semantics but gives us the additional power to allow object lifetimes to extend beyond the lifetime of their definition context.

We do not have a requirement in our system for generic object creation (indeed, such a requirement is quite rare), but we do need to generically retain a reference to an object and to release an object. We want to enable this without too much indirection. To implement this, we simply require that all our datatypes be structures that share the following common fields. We call these types cells as a convenient term.

35 ⟨*Common cell fields* 35⟩≡

```
enum cell_type ctyp;
unsigned int refc;
```

This code is used in chunks 36a, 56d, and 61d.
Defines:

[5] `https://en.wikipedia.org/wiki/Reference_counting`

`ctyp`, used in chunks 37, 39a, 57a, and 62.
`refc`, used in chunks 37, 38b, 40a, 57a, and 62.
Uses `cell_type` 36b.

These fields help us to answer the two most important questions we must answer for any cell: what type of cell is it; and, is it currently referenced? By requiring all data structs to have these fields in common, we can cast them about and be basolutely sure that things will continue to work. We define a "void" cell type `struct cell_void` to be our minimal cell type.

36a ⟨*C runtime structures* 36a⟩≡
```
struct cell_void {
⟨Common cell fields 35⟩
};
```
This definition is continued in chunks 56d and 61d.
This code is used in chunk 33.
Defines:
`cell_void`, used in chunks 37–40.

The `enum cell_type` keeps track of all known cell types.

36b ⟨*C runtime enumerations* 36b⟩≡
```
enum cell_type {
⟨Cell type names 36c⟩
};
```
This code is used in chunk 33.
Defines:
`cell_type`, used in chunk 35.

We set the first $0th$ cell type to our void cell.

36c ⟨*Cell type names* 36c⟩≡
```
CELL_VOID
```
This definition is continued in chunks 56c and 61c.
This code is used in chunk 36b.
Defines:
`CELL_VOID`, used in chunks 37 and 39c.

We do not make or define any generic way to create cells; you must make a constructor function suitable to the needs of the data type. At the moment, it is the responsibility of such makers to ensure that the common fields are appropriately initialized. A maker should return a `0` on success and a non-zero error on failure. It should also take a `struct cell_TYPE **` as the first argument to store the allocated cell in. We expect the slot passed to a creator will be a possibly previously utilized slot on a stack or something along these lines. This means that it is the caller's responsibility to ensure that this slot has already been released. Failure to do this would potentially lead to a memory leak. However, attempting to handle this within the cell maker function results in an API that is much too fragile and needlessly complex. We expect to generally follow the stylistic guideline that a function should allocate and own its own data and then release that data in the same function.

The basic cell maker for the `void` cell type looks like this:

37 ⟨*Cell definitions* 37⟩≡
```
DECLSPEC int
mk_void(struct cell_void **cell)
{
struct cell_void *ptr;

ptr = malloc(sizeof(struct cell_void));

if (ptr == NULL)
return 1;

ptr->ctyp = CELL_VOID;
ptr->refc = 1;
*cell = ptr;

return 0;
}
```
This definition is continued in chunks 38–40.
This code is used in chunk 41a.
Defines:
`mk_void`, used in chunk 38a.
Uses `CELL_VOID` 36c, `cell_void` 36a, `ctyp` 35, `DECLSPEC` 34b, and `refc` 35.

A few points of style here. The error codes should try to follow the standard APL codes. Additionally, the target slot should not be mutated until we are sure that all is well and that the object is well-formed.

38a ⟨*C runtime declarations* 38a⟩≡

```
DECLSPEC int mk_void(struct cell_void **);
```

This definition is continued in chunks 38–40, 43, 44, 57b, 63a, 64c, and 71c.
This code is used in chunk 33.
Uses `cell_void` 36a, `DECLSPEC` 34b, and `mk_void` 37.

While we must define unique constructors for the various types, when releasing or freeing a cell of some kind, we *do* want to be able to generically free a cell. However, this must be done with a minimum of runtime overhead. First, we distinguish the terms "release" and "free". If an object is freed, that object's memory is fully returned to the memory manager, whereas releasing is about reducing the number of references to that object. When a cell has no references to it, then it is freed.

Each cell type will require its own unique release function that manages cleanly destroying the cell. The release function for the `void` cell type looks like this:

38b ⟨*Cell definitions* 37⟩+≡

```
DECLSPEC void
release_void(struct cell_void *cell)
{
if (cell == NULL)
return;

if (--cell->refc)
return;

free(cell);
}
```

This code is used in chunk 41a.
Defines:
`release_void`, used in chunks 38c and 39c.
Uses `cell_void` 36a, `DECLSPEC` 34b, and `refc` 35.

38c ⟨*C runtime declarations* 38a⟩+≡

```
DECLSPEC void release_void(struct cell_void *);
```

This code is used in chunk 33.
Uses `cell_void` 36a, `DECLSPEC` 34b, and `release_void` 38b.

To support generic cell release, we define a `release_cell` function.

39a ⟨*Cell definitions* 37⟩+≡
```
DECLSPEC void
release_cell(void *cell)
{
if (cell == NULL)
return;

switch (((struct cell_void *)cell)->ctyp) {
⟨Cell release cases 39c⟩
default:
dwa_error(99);
}
}
```
This code is used in chunk 41a.
Defines:
`release_cell`, used in chunks 39b, 57a, and 62.
Uses `cell_void` 36a, `ctyp` 35, `DECLSPEC` 34b, and `dwa_error` 44a.

39b ⟨*C runtime declarations* 38a⟩+≡
```
DECLSPEC void release_cell(void *);
```
This code is used in chunk 33.
Uses `DECLSPEC` 34b and `release_cell` 39a.

For each cell type, we must plug the type-specific release function into this `release_cell` switch to enable generic releasing for that type. For the `void` type, this looks as follows:

39c ⟨*Cell release cases* 39c⟩≡
```
case CELL_VOID:
release_void(cell);
break;
```
This definition is continued in chunks 57c and 63b.
This code is used in chunk 39a.
Uses `CELL_VOID` 36c and `release_void` 38b.

The above mostly suffices for dealing with cells. However, we also want to conveniently bump the reference count of a cell seamlessly without explicitly setting `refc`. We often encounter the case where we are assigning a cell to a new slot, thus requiring a reference count increment. The following function `retain_cell` lets us do this in a single statment by writing:

```
slot2 = retain_cell(slot1);
```

40a ⟨*Cell definitions* 37⟩+≡

```
DECLSPEC void *
retain_cell(void *cell)
{
if (cell != NULL)
((struct cell_void *)cell)->refc++;

return cell;
}
```

This code is used in chunk 41a.
Defines:
`retain_cell`, used in chunks 40b, 50a, 51a, 55b, and 63c.
Uses `cell_void` 36a, `DECLSPEC` 34b, and `refc` 35.

40b ⟨*C runtime declarations* 38a⟩+≡

```
DECLSPEC void *retain_cell(void *);
```

This code is used in chunk 33.
Uses `DECLSPEC` 34b and `retain_cell` 40a.

Fortunately, this retention function requires no extra code as we extend the system with more data types. This gives us the following steps if we want to add a new data type to the runtime:

1. Add the cell type to ⟨*Cell type names* 36c⟩ as `, CELL_TYPE`.
2. Define the structure in ⟨*C runtime structures* 36a⟩, making sure that ⟨*Common cell fields* 35⟩ are the first fields.
3. Define an `int mk_type(struct cell_type **, ...)` function and declare it in ⟨*C runtime declarations* 38a⟩.
4. Define a `void release_type(struct cell_type *)` function and declare it in ⟨*C runtime declarations* 38a⟩.
5. Add a case to ⟨*Cell release cases* 39c⟩ on `CELL_TYPE` that calls `release_type` on `cell`.

The cell handling we put into a file on its own.

41a ⟨*cell.c* 41a⟩≡

```
#include <stdlib.h>

#include "codfns.h"

⟨Cell definitions 37⟩
```

Root chunk (not used in this document).
Defines:
`cell.c`, used in chunk 41b.
Uses `codfns` 7 and `codfns.h` 33.

41b ⟨*Tangle Commands* 8⟩+≡

```
echo "Tangling rtm/cell.c..."
notangle -R'cell.c' codfns.nw > rtm/cell.c
```

This code is used in chunk 86.
Uses `cell.c` 41a and `codfns` 7.

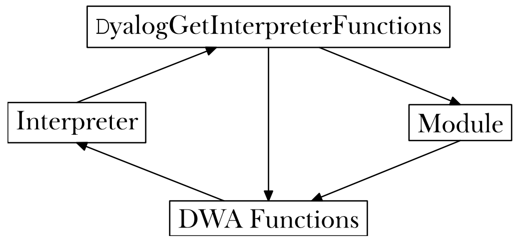

Figure 2: DWA module initialization

Finally, we must handle the DWA connection between a Co-dfns compiled module and the interpreter. One constraint on this design is the need to make a Co-dfns module work with or without a DWA-driven interpreter. If we are interfacing solely with a foreign, C-based system, we still must function somehow.

DWA modules export `DyalogGetInterpreterFns` as a function to link the interpreter and the module.

The function receives a structure from the interpreter populated with function pointers that enable access to various interpreter features. A small design point comes into play here because we do not want to unnecessarily expose our underlying model to the user of the compiled module. In particular, if an user is not a Dyalog interpreter, they should not need to know about the DWA system in order to function. For example, they should not need to know or use `DyalogGetInterpreterFunctions` or the underlying functions. Thus, we must have a way to achieve similar functionality from different systems.

Our approach to this is to provide more generic and explicit function for setting things we want from any system and then to layer DWA initialization on top of that.

Fundamentally, the main thing that we care about for all systems is having some means of making a non-local escaping error report. This main error reporting is meant to mimic the extended signalling functionality of the interpreter documented in the `⎕DMX` object. The DWA equivalent of this structure is given by `struct dwa_dmx`.

42 ⟨*DWA structures and enumerations* 42⟩≡

```
struct dwa_dmx {
unsigned int flags;
unsigned int en;
unsigned int enx;
const wchar_t *vendor;
const wchar_t *message;
const wchar_t *category;
};
```

This definition is continued in chunk 45.
This code is used in chunk 47a.
Defines:
`dwa_dmx`, used in chunks 43a and 44c.

In our APL model at the moment, there is only one main and universal ⎕DMX object at a time, so we define a single `dmx` binding to contain the current data.

43a ⟨*DWA definitions* 43a⟩≡

```
struct dwa_dmx dmx;
```

This definition is continued in chunks 43, 44, and 46a.
This code is used in chunk 47a.
Defines:
`dmx`, used in chunks 20b, 43b, and 44a.
Uses `dwa_dmx` 42.

The reality of many FFI systems is that they do not do a good job of supporting C structs in the form of such global variables, so we must make sure that there is a meaningful way to access the system using nothing but function calls.

In the case of errors we have an interesting situation. In C, handling a long chain of errors demands that we are meticulous about how we handle the interaction of the call stack and any kind of early exit. In our case, this means that any time we finally call the non-local error function that we expect to never return, we may be quite far removed from the original site of the error. Thus, passing any complex data back up a call stack could be quite complex. Instead, we populate most of `dmx` that we care about using setter functions and then only have a very little to worry about passing up a call stack, namely, the error number itself.

we define a setter function `set_dmx_message` to handle setting `dmx.message`.

43b ⟨*DWA definitions* 43a⟩+≡

```
DECLSPEC void
set_dmx_message(wchar_t *msg)
{
dmx.message = msg;
}
```

This code is used in chunk 47a.
Defines:
`set_dmx_message`, used in chunk 43c.
Uses `DECLSPEC` 34b and `dmx` 43a.

43c ⟨*C runtime declarations* 38a⟩+≡

```
DECLSPEC void set_dmx_message(wchar_t *);
```

This code is used in chunk 33.
Uses `DECLSPEC` 34b and `set_dmx_message` 43b.

Our main non-returning function `dwa_error` handles some of the parts of `dmx` that we do not currently change, and then calls the internally initialized error function provided by whatever our interfacing system is.

44a ⟨*DWA definitions* 43a⟩+≡
```
DECLSPEC void
dwa_error(unsigned int n)
{
dmx.flags = 3;
dmx.en = n;
dmx.enx = n;
dmx.vendor = L"Co-dfns";
dmx.category = NULL;

dwa_error_ptr(&dmx);
}
```
This code is used in chunk 47a.
Defines:
`dwa_error`, used in chunks 29, 39a, and 44b.
Uses `DECLSPEC` 34b, `dmx` 43a, and `dwa_error_ptr` 44c.

44b ⟨*C runtime declarations* 38a⟩+≡
```
DECLSPEC void dwa_error(unsigned int);
```
This code is used in chunk 33.
Uses `DECLSPEC` 34b and `dwa_error` 44a.

The above requires the calling interface set `dwa_error_ptr`, which we handle with `set_codfns_error`.

44c ⟨*DWA definitions* 43a⟩+≡
```
void (*dwa_error_ptr)(struct dwa_dmx *);

DECLSPEC void
set_codfns_error(void *fn)
{
dwa_error_ptr = fn;
}
```
This code is used in chunk 47a.
Defines:
`dwa_error_ptr`, used in chunk 44a.
`set_codfns_error`, used in chunks 44d and 46b.
Uses `DECLSPEC` 34b and `dwa_dmx` 42.

44d ⟨*C runtime declarations* 38a⟩+≡
```
DECLSPEC void set_codfns_error(void *);
```
This code is used in chunk 33.
Uses `DECLSPEC` 34b and `set_codfns_error` 44c.

To link this interface into the DWA functionality, we must extract the appropriate function pointers out of the structure passed to `DyalogGetInterpreterFunctions`. We assume that the code generator will create a suitable definition for `DyalogGetInterpreterFunctions` that calls the following `set_dwafns`, such as:

```
EXPORT int
DyalogGetInterpreterFunctions(void *fns)
{
        return set_dwafns(fns);
}
```

This established a link in each compiled module to the runtime DWA handling and allows us to keep the DWA logic inside the runtime. The DWA structure is relatively involved in its full expression, but we do not need the full power, so we can simplify our setup. We also want to talk about the structure more generically here without too much detail that may be more properly handled in the correct language feature section. At its heart, the structure is a set of functions, which we store as an array of `void *` pointers.

45 ⟨*DWA structures and enumerations* 42⟩+≡

```
struct dwa_wsfns {
long long size;
void *fns[18];
};

struct dwa_fns {
long long size;
struct dwa_wsfns *ws;
};
```

This code is used in chunk 47a.
Defines:
`dwa_fns`, used in chunk 46a.
`dwa_wsfns`, never used.

It is the job of the `set_dwafns` function to set the appropriate Codfns interface functions and follow the initialization expectations of the DWA system. On successful initialization, the function should return 0, but we must check compatibility by examining the given structure `size`, return `16` if something is not right.

46a ⟨*DWA definitions* 43a⟩+≡

```
DECLSPEC int
set_dwafns(void *p)
{
struct dwa_fns *dwa;

if (p == NULL)
return 0;

dwa = p;

if (dwa->size < (long long)sizeof(struct dwa_fns))
return 16;

⟨Set DWA interface functions 46b⟩

return 0;
}
```

This code is used in chunk 47a.
Defines:
`set_dwafns`, used in chunk 24d.
Uses `DECLSPEC` 34b and `dwa_fns` 45.

Assuming that the DWA structure seems valid, we want to extract these functions into the appropriate names that we have created for them. An alternative would be to retain the structure and make indirect calls into that structure, but this is a little more awkward and would involve both more storage and more memory indirects for no more clarity and only more entanglement of the code. Instead, setting the correct names at the time of a `set_dwafns` call leads to a much cleaner dependency tree. At this point, only the `dwa_error` function has been designed and defined.

46b ⟨*Set DWA interface functions* 46b⟩≡

```
set_codfns_error(dwa->ws->fns[17]);
```

This code is used in chunk 46a.
Uses `set_codfns_error` 44c.

This covers the main global DWA handling, but we have more to do in other sections to handle DWA arrays and function calling. We benefit from having a few things together in a single C file, so we will store our DWA code in a single C file with an eye to making it easy to add in the appropriate code in later sections.

47a ⟨*dwa.c* 47a⟩≡
⟨*DWA includes* (never defined)⟩
⟨*DWA macros* (never defined)⟩
⟨*DWA structures and enumerations* 42⟩
⟨*DWA definitions* 43a⟩

Root chunk (not used in this document).
Defines:
`dwa.c`, used in chunk 47b.

47b ⟨*Tangle Commands* 8⟩+≡

```
echo "Tangling rtm/dwa.c..."
notangle -R'dwa.c' codfns.nw > rtm/dwa.c
```

This code is used in chunk 86.
Uses `codfns` 7 and `dwa.c` 47a.

6 Language Features

6.1 Valid source input character set

47c ⟨*Verify that all open characters are valid* 47c⟩≡

```
alp←'ABCDEFGHIJKLMNOPQRSTUVWXYZ_abcdefghijklmnopqrstuvwxyz'
alp,←'ÀÁÂÃÄÅÆÇÈÉÊËÌÍÎÏÐÑÒÓÔÕÖØÙÚÛÜÝßàáâãäåæçèéêëìíîïðñòóôõöøùúûüþ'
alp,←'∆⍙A̲B̲C̲D̲E̲F̲G̲H̲I̲J̲K̲L̲M̲N̲O̲P̲Q̲R̲S̲T̲U̲V̲W̲X̲Y̲Z̲'
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 21.
Uses `quotelines` 20b and `SIGNAL` 20b.

6.2 Comments and Whitespace

48a ⟨*Unify whitespace and comments* 48a⟩≡

```
⍝ Remove comments
pos msk⌿¨⍨←⊂∧⍀¨(~msk←msk∨¯1⌽¨msk)⍲'⍝'=IN∘I¨pos

⍝ Remove leading and trailing whitespace
WS←⎕UCS 9 32 ⋄ pos msk⌿¨⍨←⊂~(∧⍀∨∧⍀⍢⌽)∘(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 21.

6.3 Numbers

48b ⟨*Tokenize numbers* 48b⟩≡

```
_←{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 21.
Uses `SIGNAL` 20b.

48c ⟨*Node* ⟷ *Generator mapping* 24c⟩+≡

```
gck,←⊂N 1
gcv,←⊂'Na'
```

This code is used in chunk 25b.

6.4 Strings and characters

49a ⟨*Check and mask the strings* 49a⟩≡

```
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 21.
Uses `quotelines` 20b and `SIGNAL` 20b.

49b ⟨*Tokenize strings* 49b⟩≡

```
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 21.

6.5 Variables

49c ⟨*Tokenize variables* 49c⟩≡

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

⍝ Tokenize α, ω formals
fm←{mm←⌽⊃(>∘⊃,⊢)⌿⌽m←α=' ',ω ⋄ 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 21.

49d ⟨*Check for out of context dfns formals* 49d⟩≡

```
∨⌿(d=0)∧(t=P)∧IN[pos]∊'αω':'DFN FORMAL REFERENCED OUTSIDE DFNS'⎕SIGNAL 2
```

This code is used in chunk 21.
Uses `SIGNAL` 20b.

49e ⟨*Convert* `α` *and* `ω` *to* `V` *nodes* 49e⟩≡

```
t←V@(i←⍸(t=A)∧n∊,¨'αω')⊢t ⋄ vb[i]←i
```

This code is used in chunk 22.

49f ⟨*Convert* `αα` *and* `ωω` *to* `P2` *nodes* 49f⟩≡

```
k[⍸(t=P)∧n∊'αα' 'ωω']←2
```

This code is used in chunk 22.

49g ⟨*Node ⟷ Generator mapping* 24c⟩+≡

```
gck,←(V 0)(V 1)(V 2)(V 3)(V 4)
gcv,←'Va' 'Va' 'Vf' 'Vo' 'Vo'
```

This code is used in chunk 25b.

50a ⟨*Node-specific code generators* 24e⟩+≡

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

This code is used in chunk 25b.
Uses `retain_cell` 40a.

6.6 Arrays

50b ⟨*Mark atoms, characters, and numbers as kind* `1` 50b⟩≡

```
k[⍸t∊A C N]←1
```

This code is used in chunk 22.

50c ⟨*Strand arrays into atoms* 50c⟩≡

```
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 22.

50d ⟨*Count strand and indexing children* 50d⟩≡

```
n[⍸(t∊A E)∧k=6]←0 ⋄ n[p/⍨(t[p]∊A E)∧k[p]=6]+←1
```

This code is used in chunk 23.

50e ⟨*Node ⟷ Generator mapping* 24c⟩+≡

```
gck,←(A 1)(A 6)
gcv,←'Aa' 'As'
```

This code is used in chunk 25b.

50f ⟨*Declare top-level array structures* 50f⟩≡

```
k[⍵]=1:{
z ←⊂'struct array *',n,';'
z}⍵
```

This code is used in chunk 25a.

6.7 Primitives

50g ⟨*Node ⟷ Generator mapping* 24c⟩+≡

```
gck,←(P 0)(P 1)(P 2)(P 3)(P 4)
gcv,←'Pv' 'Pv' 'Pf' 'Po' 'Po'
```

This code is used in chunk 25b.

51a ⟨*Node-specific code generators* 24e⟩+≡
```
Pf←{id←(symsιsym[|4⊃α])⊃nams
z ←⊂'*stkhd++ = retain_cell(',id,');'
z}
```
This code is used in chunk 25b.
Uses `retain_cell` 40a.

6.7.1 APL Primitives

51b ⟨*Tokenize primitives and atoms* 51b⟩≡
```
t[⍸(~dm)∧x∊prms]←P ⋄ t[⍸x∊syna]←A
```
This code is used in chunk 21.

51c ⟨*Mark APL primitives with appropriate kinds* 51c⟩≡
```
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 22.

6.7.2 System Functions and Variables

51d ⟨*Tokenize system variables* 51d⟩≡
```
si←⍸('⎕'=IN[pos])∧1⌽t=V
t[si]←S ⋄ end[si]←end[si+1] ⋄ t[si+1]←0
```
This code is used in chunk 21.

52a ⟨*Verify that system variables are defined* 52a⟩≡

```
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[⍵]{⍺+⍳⍵-⍺}¨end[⍵]
}⍸msk
```

This code is used in chunk 22.
Uses `SIGNAL` 20b.

52b ⟨*Mark system variables as* `P` *nodes with appropriate kinds* 52b⟩≡

```
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 22.

6.8 Brackets

6.8.1 Indexing

52c ⟨*Convert* `;` *groups within brackets into* `Z` *nodes* 52c⟩≡

```
_←p[i]{k[z←⊃⍪⌿gz¨g←⍵⊂⍨¯1⌽IN[pos[⍵]]∊';]']←1 ⋄ t[z]←Z P[1=≢¨g]}⌸i←⍸t[p]=¯1
```

This code is used in chunk 22.

52d ⟨*Verify brackets have function/array target* 52d⟩≡

```
x←{⍵⌿⍨~∧⍀t[⍵]=¯1}∪⌽¨x
0∨.=≢¨x:'BRACKET SYNTAX REQUIRES FUNCTION OR ARRAY TO ITS LEFT'⎕SIGNAL 2
```

This code is used in chunk 54b.
Uses `SIGNAL` 20b.

53a ⟨*Enclose* `V[X;...]` *for expression parsing* 53a⟩≡
```
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 22.

53b ⟨*Rationalize* `V[X;...]` 53b⟩≡
```
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,←ncρP E ⋄ k,←ncρ2 6 ⋄ n,←ncρ,¨'[' ''
pos,←2/pos[ip] ⋄ end,←∊(1+pos[ip]),⍪end[ip] ⋄ pos[ip]←pos[i/⍨~msk]
```
This code is used in chunk 22.

53c ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,';' ⋄ nams,←⊂'span'
```
This code is used in chunk 25b.

53d ⟨*Node* ⟷ *Generator mapping* 24c⟩+≡
```
gck,←⊂E 6
gcv,←⊂'Ei'
```
This code is used in chunk 25b.

6.8.2 Axis Operator

53e ⟨*Rationalize* `F[X]` *syntax* 53e⟩≡
```
_←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 22.
Uses `SIGNAL` 20b.

6.9 Bindings and Types

54a ⟨*Parse Binding nodes* 54a⟩≡
```
⍝ 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
v⌿⍨~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 22.
Uses `SIGNAL` 20b.

54b ⟨*Infer the type of bindings, groups, and variables* 54b⟩≡
```
z x←↓⍉p[i]{⍺⍵}⌸i←⍸(t[p]∊B Z)∧p≠⍳≢p
```
⟨*Verify brackets have function/array target* 52d⟩
```
_←{
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 22.

54c ⟨*Parse dyadic operator bindings* 54c⟩≡
```
⍝ PARSE B←D...
⍝ PARSE B←...D
```
This code is used in chunk 22.

55a ⟨*Node ⟷ Generator mapping* 24c⟩+≡
```
gck,←(B 1)(B 2)(B 3)(B 4)
gcv,←'Bv' 'Bf' 'Bo' 'Bo'
```
This code is used in chunk 25b.

55b ⟨*Node-specific code generators* 24e⟩+≡
```
Bf←{id←sym⊃⍨|4⊃α
z ←⊂id,' = retain_cell(stkhd[-1]);'
z}
```
This code is used in chunk 25b.
Uses `retain_cell` 40a.

6.10 Assignments

55c ⟨*Parse assignments* 55c⟩≡
```
⍝ 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,←Pρ⍨≢j ⋄ k,←3ρ⍨≢j ⋄ n,←(≢j)ρ⊂,'←' ⋄ 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 22.

56a ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'←' ⋄ nams,←⊂'get'
```
This code is used in chunk 25b.

56b ⟨*Node ⟷ Generator mapping* 24c⟩+≡
```
gck,←⊂E 4
gcv,←⊂'Eb'
```
This code is used in chunk 25b.

56c ⟨*Cell type names* 36c⟩+≡
```
, CELL_BOX
```
This code is used in chunk 36b.
Defines:
`CELL_BOX`, used in chunk 57.

56d ⟨*C runtime structures* 36a⟩+≡
```
struct cell_box {
⟨Common cell fields 35⟩
void *value;
};
```
This code is used in chunk 33.
Defines:
`box`, used in chunks 57a, 58b, and 83.

57a ⟨*Box definitions* 57a⟩≡

```
DECLSPEC int
mk_box(struct cell_box **box, void *value)
{
*box = malloc(sizeof(struct cell_box));

if (*box == NULL)
return 1;

(*box)->ctyp    = CELL_BOX;
(*box)->refc    = 1;
(*box)->value   = value;

return 0;
}

DECLSPEC void
release_box(struct cell_box *box)
{
if (box == NULL)
return;

box->refc--;

if (box->refc)
return;

release_cell(box->value);
free(box);
}
```

This code is used in chunk 58a.
Defines:
`mk_box`, used in chunk 57b.
`release_box`, used in chunk 57.
Uses `box` 56d, `CELL_BOX` 56c, `ctyp` 35, `DECLSPEC` 34b, `refc` 35, and `release_cell` 39a.

57b ⟨*C runtime declarations* 38a⟩+≡

```
DECLSPEC int mk_box(struct cell_box **, void *);
DECLSPEC void release_box(struct cell_box *);
```

This code is used in chunk 33.
Uses `DECLSPEC` 34b, `mk_box` 57a, and `release_box` 57a.

57c ⟨*Cell release cases* 39c⟩+≡

```
case CELL_BOX:
release_box(cell);
break;
```

This code is used in chunk 39a.
Uses `CELL_BOX` 56c and `release_box` 57a.

58a ⟨*box.c* 58a⟩≡

```
#include <stdlib.h>

#include "codfns.h"

⟨Box definitions 57a⟩
```

Root chunk (not used in this document).
Defines:
`box.c`, used in chunk 58b.
Uses `codfns` 7 and `codfns.h` 33.

58b ⟨*Tangle Commands* 8⟩+≡

```
echo "Tangling rtm/box.c..."
notangle -R'box.c' codfns.nw > rtm/box.c
```

This code is used in chunk 86.
Uses `box` 56d, `box.c` 58a, and `codfns` 7.

6.11 Expressions

58c ⟨*Parse brackets and parentheses into* `¯1` *and* `Z` *nodes* 58c⟩≡

```
_←p[i]{
x←IN[pos[ω]]
bd←+\bm←(bo←'['=x)+-bc←']'=x
pd←+\pm←(po←'('=x)+-pc←')'=x
0≠⊃⌽bd:{
ix←pos[ω]{x+⍳(⌈/ω)-x←⌊/α}⍥{ω⌿⍨0≠bd}end[ω]
2'UNBALANCED BRACKETS'SIGNAL ix
}ω
0≠⊃⌽pd:{
ix←pos[ω]{x+⍳(⌈/ω)-x←⌊/α}⍥{ω⌿⍨0≠pd}end[ω]
2'UNBALANCED PARENTHESES'SIGNAL ix
}ω
(po⌿bd)∨.≠⌽pc⌿bd:{
'OVERLAPPING BRACKETS AND PARENTHESES'⎕SIGNAL 2
}ω
p[ω]←(α,ω)[1+¯1@{ω=⍳≢ω}D2P +\¯1⌽bm+pm]
t[bo⌿ω]←¯1 ⋄ t[po⌿ω]←Z
end[po⌿ω]←end[⌽pc⌿ω] ⋄ end[bo⌿ω]←end[⌽bc⌿ω]
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 22.
Uses `SIGNAL` 20b.

58d ⟨*Group function and value expressions* 58d⟩≡

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

This code is used in chunk 22.

59a ⟨*Lift and flatten expressions* 59a⟩≡
```
p[i]←p[x←p I@{~t[p[ω]]∊F G}⍣≡i←⍸t∊G A B C E O P V] ⋄ j←(⌽i)[⍋⌽x]
p t k n r{α[ω]@i⊢α}←⊂j ⋄ p←(i@j⊢⍳≢p)[p]
```
This code is used in chunk 23.

6.11.1 Value Expressions

59b ⟨*Parse value expressions* 59b⟩≡
```
i km←⍪⌿p[i]{(α⍪ω)(0,(2≤≢ω)∧1∨ω)}⌸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,←Eρ⍨xc←+⌿msk ⋄ k,←msk⌿msk+m2 ⋄ n,←xcρ⊂''
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 22.

59c ⟨*Node* ⟷ *Generator mapping* 24c⟩+≡
```
gck,←(E 1)(E 2)
gcv,←'Em' 'Ed'
```
This code is used in chunk 25b.

59d ⟨*Node-specific code generators* 24e⟩+≡
```
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}
```
This code is used in chunk 25b.

6.11.2 Function Expressions

60a ⟨*Parse function expressions* 60a⟩≡
```
⍝ 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 22.
Uses SIGNAL 20b.

60b ⟨*Node ⟷ Generator mapping* 24c⟩+≡
```
gck,←(O 1)(O 2)(O 4) (O 5) (O 7) (O 8)
gcv,←'Ov' 'Of' 'Ovv' 'Ofv' 'Ovf' 'Off'
```
This code is used in chunk 25b.

6.12 Trains

60c ⟨*Parse trains* 60c⟩≡
```
⍝ TRAINS
```
This code is used in chunk 22.

6.13 Functions

61a ⟨*Declare top-level function bindings* 61a⟩≡
```
k[ω]∊0 2:{
z ←⊂'int'
z,←⊂n,'(struct array **z, struct array *l, struct array *r, void *fv[]);'
z,←⊂''
z}ω
```
This code is used in chunk 24e.

61b ⟨*Declare top-level closures* 61b⟩≡
```
k[ω]=2:{
z ←⊂'struct closure *',n,';'
z,←⊂''
⟨DWA Function Export 29⟩
z}ω
```
This code is used in chunk 25a.

61c ⟨*Cell type names* 36c⟩+≡
```
, CELL_CLOSURE
```
This code is used in chunk 36b.
Defines:
`CELL_CLOSURE`, used in chunks 62 and 63b.

61d ⟨*C runtime structures* 36a⟩+≡
```
struct cell_closure {
⟨Common cell fields 35⟩
int (*fn)(struct cell_array **,
struct cell_array *, struct cell_array *, void **);
unsigned int fs;
void *fv[];
}
```
This code is used in chunk 33.
Defines:
`cell_closure`, used in chunks 62 and 63.

62 ⟨*Closure definitions* 62⟩≡
```
DECLSPEC int
mk_closure(struct cell_closure **k,
int (*fn)(struct cell_array **,
struct cell_array *, struct cell_array *, void **),
unsigned int fs)
{
size_t sz;
struct cell_closure *ptr;

sz = sizeof(struct cell_closure) + fs * sizeof(void *);
ptr = malloc(sz);

if (ptr == NULL)
return 1;

ptr->ctyp = CELL_CLOSURE;
ptr->refc = 1;
ptr->fn = fn;
ptr->fs = fs;

*k = ptr;

return 0;
}

DECLSPEC void
release_closure(struct cell_closure *k)
{
if (k == NULL)
return;

k->refc--;

if (k->refc)
return;

for (unsigned int i = 0; i < k->fs; i++)
release_cell(k->fv[i]);

free(k);
}
```
This definition is continued in chunk 63c.
This code is used in chunk 64a.
Defines:
`mk_closure`, used in chunk 63.

release_closure, used in chunk 63.
Uses CELL_CLOSURE 61c, cell_closure 61d, ctyp 35, DECLSPEC 34b, refc 35, and release_cell 39a.

63a ⟨*C runtime declarations* 38a⟩+≡

```
DECLSPEC int mk_closure(struct cell_closure **,
int (*)(struct cell_array **,
struct cell_array *, struct cell_array *, void **),
unsigned int);
DECLSPEC void release_closure(struct cell_closure *);
```

This code is used in chunk 33.
Uses cell_closure 61d, DECLSPEC 34b, mk_closure 62, and release_closure 62.

63b ⟨*Cell release cases* 39c⟩+≡

```
case CELL_CLOSURE:
release_closure(cell);
break;
```

This code is used in chunk 39a.
Uses CELL_CLOSURE 61c and release_closure 62.

63c ⟨*Closure definitions* 62⟩+≡

```
DECLSPEC int
apply_dop(struct cell_closure **z,
struct cell_closure *op, void *l, void *r)
{
int err;

err = mk_closure(z, op->fn, op->fs+2);

if (err)
return err;

(*z)->fv[0] = l;
(*z)->fv[1] = r;

memcpy(&(*z)->fv[2], op->fv, op->fs * sizeof(op->fv[0]));

for (unsigned int i = 0; i < (*z)->fs; i++)
retain_cell((*z)->fv[i]);

return 0;
}
```

This code is used in chunk 64a.
Defines:
apply_dop, never used.
apply_mop, never used.
Uses cell_closure 61d, DECLSPEC 34b, mk_closure 62, and retain_cell 40a.

64a ⟨*closure.c* 64a⟩≡
```
#include <stdlib.h>
#include <string.h>

#include "codfns.h"

⟨Closure definitions 62⟩
```
Root chunk (not used in this document).
Defines:
`closure.c`, used in chunk 64b.
Uses `codfns` 7 and `codfns.h` 33.

64b ⟨*Tangle Commands* 8⟩+≡
```
echo "Tangling rtm/closure.c..."
notangle -R'closure.c' codfns.nw > rtm/closure.c
```
This code is used in chunk 86.
Uses `closure.c` 64a and `codfns` 7.

64c ⟨*C runtime declarations* 38a⟩+≡
This code is used in chunk 33.

6.13.1 D-fns

64d ⟨*Compute dfns regions and type, with* } *as a child* 64d⟩≡
```
t[⍸'{'=x]←F ⋄ 0≠⊃d←¯1⌽+⍀1 ¯1 0['{}'⍳x]:'UNBALANCED DFNS'⎕SIGNAL 2
```
This code is used in chunk 21.
Uses `SIGNAL` 20b.

64e ⟨*Compute the nameclass of dfns* 64e⟩≡
```
k←2×t∊F ⋄ k[∪p/⍨(t=P)∧n∊⊂'αα']←3 ⋄ k[∪p/⍨(t=P)∧n∊⊂'ωω']←4
```
This code is used in chunk 22.

64f ⟨*Wrap all dfns expression bodies as* `Z` *nodes* 64f⟩≡
```
_←p[i]{end[α]←end[⊃⌽ω] ⋄ gz¨ω⊂⍨1,¯1↓t[ω]=Z}⌸i←⍸t[p]=F
'Non-Z dfns body node'assert t[⍸t[p]=F]=Z:
```
This code is used in chunk 22.

64g ⟨*Anchor variables to earliest binding in the matching frame* 64g⟩≡
```
rf←¯1@{~t[ω]∊F G M}p[rz←I@{~(t[ω]=Z)∧(t[p[ω]]∊F G M)∨p[ω]=ω}⍣≡⍨p]
rf[i]←p[i←⍸t=G] ⋄ rz[i]←i ⋄ rf←rf I@{rz∊p[i]⊢∘⊃⌸i←⍸t[p]=G}rf
mk←{α[ω],⍪n[ω]}
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⊢ω]}⍣≡⍉{rf[ω],⍪ω}⍸(t=V)∧vb=¯1
∨⌿msk←(t=V)∧vb=¯1:{
6'ALL VARIABLES MUST REFERENCE A BINDING'SIGNAL∊pos[ω]{α+⍳ω-α}¨end[ω]
}⍸msk
```
This code is used in chunk 22.

65a ⟨*Lift dfns to the top-level* 65a⟩≡
```
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
```
This code is used in chunk 23.

65b ⟨*Wrap expressions as binding or return statements* 65b⟩≡
```
i←(⍸(~t∊F G)∧t[p]=F),{ω⌿⍨2|⍳≢ω}⍸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@({⊃⌽ω}⌸p[j])⊢(t[j]=B)∨(t[j]=E)∧k[j]=4 ⋄ t[j]←E
```
This code is used in chunk 23.

65c ⟨*Node* ⟷ *Generator mapping* 24c⟩+≡
```
gck,←(E ¯1)(E 0)
gcv,←'Ek'  'Er'
```
This code is used in chunk 25b.

65d ⟨*Compute slots and frames* 65d⟩≡
```
⍝ 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]+←ω≠z←r[ω]}⍣≡i ⋄ f←d[0⌷⍉e],¯1
```
This code is used in chunk 23.

65e ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'∇' ⋄ nams,←⊂'this'
```
This code is used in chunk 25b.

65f ⟨*Node* ⟷ *Generator mapping* 24c⟩+≡
```
gck,←(C 1)(C 2)(F 2)(F 3)(F 4)
gcv,←'Ca' 'Cf' 'Fn' 'Fm' 'Fd'
```
This code is used in chunk 25b.

65g ⟨*Node-specific code generators* 24e⟩+≡
```
Cf←{id←⍕4⊃⍺
z ←⊂'mk_closure((struct closure **)stkhd++, fn',id,', 0);'
z}
```
This code is used in chunk 25b.

65h ⟨*Node-specific code generators* 24e⟩+≡
```
Ek←{
z ←⊂'release_cell(*--stkhd);'
z,←⊂''
z}
```
This code is used in chunk 25b.

66a ⟨*Node-specific code generators* 24e⟩+≡
```
Er←{
z ←⊂'*z = *--stkhd;'
z,←⊂'goto cleanup;'
z,←⊂''
z}
```
This code is used in chunk 25b.

66b ⟨*Node-specific code generators* 24e⟩+≡
```
Fn←{id←⍕5⊃⍺ ⋄ 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, '
z,←⊂'    struct array *l, struct array *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¨⍵
z,←⊂'       *z = NULL;'
z,←⊂''
z,←⊂'cleanup:'
z,←⊂'       return 0;'
z,←⊂'}'
z,←⊂''
z}
```
This code is used in chunk 25b.

6.13.2 Trad-fns

66c ⟨*Compute trad-fns regions* 66c⟩≡
```
∨⌿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 21.
Uses `SIGNAL` 20b.

6.14 Guards

67a ⟨*Parse guards to* `(G (Z ...) (Z ...))` 67a⟩≡
```
_←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 22.
Uses `SIGNAL` 20b and `TEST` 16a.

67b ⟨*Lift guard tests* 67b⟩≡
```
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]
```
This code is used in chunk 23.

67c ⟨*Node ⟷ Generator mapping* 24c⟩+≡
```
gck,←⊂G 0
gcv,←⊂'Gd'
```
This code is used in chunk 25b.

6.14.1 Error Guards

6.15 Labels

67d ⟨*Identify label colons vs. others* 67d⟩≡
```
t[⍸tm∧(d=0)∧∊((~⊃)∧(<⍀∨⍀))¨':'=(t=Z)⊂IN[pos]]←L
```
This code is used in chunk 21.

67e ⟨*Tokenize labels* 67e⟩≡
```
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 21.
Uses `SIGNAL` 20b.

67f ⟨*Parse labels* 67f⟩≡
```
⍝ XXX: Parse labels
```
Root chunk (not used in this document).

6.16 Statements

6.16.1 What is a keyword?

68a ⟨*Tokenize keywords* 68a⟩≡
```
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 21.
Uses `SIGNAL` 20b.

68b ⟨*Check that all keywords are valid* 68b⟩≡
```
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 22.
Uses `SIGNAL` 20b.

6.16.2 Namespaces

68c ⟨*Check that namespaces are at the top level* 68c⟩≡
```
msk←kws∊':NAMESPACE' ':ENDNAMESPACE'
∨⌿msk∧km⌿tm:'NAMESPACE SCRIPTS MUST APPEAR AT THE TOP LEVEL'⎕SIGNAL 2
```
This code is used in chunk 22.
Uses `SIGNAL` 20b.

68d ⟨*Nest top-level root lines as* `Z` *nodes* 68d⟩≡
```
_←(gz 1⌽⊢)¨(t[i]=Z)⊂i←⍸d=0
'Non-Z top-level node'assert t[⍸p=⍳≢p]=Z:
```
This code is used in chunk 22.

69a ⟨*Parse* `:Namespace` *syntax* 69a⟩≡
```
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 22.
Uses `SIGNAL` 20b.

In the parser, 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`.

69b ⟨*Compute parser exports* 69b⟩≡
```
msk←(t=B)∧k[I@{t[ω]≠F}⍣≡⍨p]=0
xn←(0⍴⊂''),msk⌿n ⋄ xt←msk⌿k
```
This code is used in chunk 17.
Defines:
`xn`, used in chunk 20a.
`xt`, used in chunk 20a.

69c ⟨*Record exported top-level bindings* 69c⟩≡
```
xi←⍸(t=B)∧k[r]=0
```
This code is used in chunk 23.
Defines:
`xi`, used in chunks 23–25.

69d ⟨*Node ⟷ Generator mapping* 24c⟩+≡
```
gck,←⊂F 0
gcv,←⊂'Fz'
```
This code is used in chunk 25b.

70 ⟨*Node-specific code generators* 24e⟩+≡

```
Fz←{id←⍕5⊃⍺ ⋄ awc←∨⌿(3⌷x){(⍵∊A O)∨(⍵=E)∧⍺>0}2⌷x←⍉⊃⍪⌿⍵
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, '
z,←⊂'    struct array *l, struct array *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¨⍵
z,←⊂'       return 0;'
z,←⊂'}'
z,←⊂''
z}
```

This code is used in chunk 25b.

71a ⟨*init.c* 71a⟩≡

```
#include "codfns.h"

int
init(void);

EXPORT int
cdf_init(void)
{
return init();
}
```

Root chunk (not used in this document).
Defines:
`init.c`, used in chunk 71b.
Uses `codfns` 7, `codfns.h` 33, and `EXPORT` 34b.

71b ⟨*Tangle Commands* 8⟩+≡

```
echo "Tangling rtm/init.c..."
notangle -R'init.c' codfns.nw > rtm/init.c
```

This code is used in chunk 86.
Uses `codfns` 7 and `init.c` 71a.

71c ⟨*C runtime declarations* 38a⟩+≡

```
DECLSPEC int cdf_init(void);
```

This code is used in chunk 33.
Uses `DECLSPEC` 34b.

6.16.3 Structured Programming Statements

71d ⟨*Verify that all structured statements appear within trad-fns* 71d⟩≡

```
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 22.
Uses `SIGNAL` 20b.

71e ⟨*Convert* `M` *nodes to* `F0` *nodes* 71e⟩≡

```
t←F@{t=M}t
```

This code is used in chunk 22.

7 Runtime Primitives

7.1 Addition/Identity

72a ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'+' ⋄ nams,←⊂'add'
```
This code is used in chunk 25b.

7.2 And (Logical)

72b ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'∧' ⋄ nams,←⊂'and'
```
This code is used in chunk 25b.

7.3 Bracket

72c ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'[' ⋄ nams,←⊂'brk'
```
This code is used in chunk 25b.

7.4 Catenate (First/Last Axis)

72d ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,',' ⋄ nams,←⊂'cat'
syms,←⊂,'⍪' ⋄ nams,←⊂'ctf'
```
This code is used in chunk 25b.

7.5 Circle/Trigonometrics

72e ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'○' ⋄ nams,←⊂'cir'
```
This code is used in chunk 25b.

7.6 Commute

72f ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'⍨' ⋄ nams,←⊂'com'
```
This code is used in chunk 25b.

7.7 Compose

73a ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'∘' ⋄ nams,←⊂'jot'
```
This code is used in chunk 25b.

7.8 Convolve

73b ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'⎕CONV' ⋄ nams,←⊂'conv'
```
This code is used in chunk 25b.

7.9 Decode

73c ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'⊥' ⋄ nams,←⊂'dec'
```
This code is used in chunk 25b.

7.10 Disclose

73d ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'⊃' ⋄ nams,←⊂'dis'
```
This code is used in chunk 25b.

7.11 Division/Reciprocal

73e ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'÷' ⋄ nams,←⊂'div'
```
This code is used in chunk 25b.

7.12 Drop

73f ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'↓' ⋄ nams,←⊂'drp'
```
This code is used in chunk 25b.

7.13 Each

73g ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'¨' ⋄ nams,←⊂'map'
```
This code is used in chunk 25b.

7.14 Enclose

74a ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'⊂' ⋄ nams,←⊂'par'
```
This code is used in chunk 25b.

7.15 Encode

74b ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'⊤' ⋄ nams,←⊂'enc'
```
This code is used in chunk 25b.

7.16 Equal

74c ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'=' ⋄ nams,←⊂'eql'
```
This code is used in chunk 25b.

7.17 Exponent

74d ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'*' ⋄ nams,←⊂'exp'
```
This code is used in chunk 25b.

7.18 Factorial/Binomial

74e ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'!' ⋄ nams,←⊂'fac'
```
This code is used in chunk 25b.

7.19 Fast Fourier Transforms

74f ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'⎕FFT' ⋄ nams,←⊂'fft'
```
This code is used in chunk 25b.

74g ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'⎕IFFT' ⋄ nams,←⊂'ift'
```
This code is used in chunk 25b.

7.20 Find

75a ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'⍷' ⋄ nams,←⊂'fnd'
```
This code is used in chunk 25b.

7.21 Grade Down

75b ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'⍒' ⋄ nams,←⊂'gdd'
```
This code is used in chunk 25b.

7.22 Grade Up

75c ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'⍋' ⋄ nams,←⊂'gdu'
```
This code is used in chunk 25b.

7.23 Greater Than

75d ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'>' ⋄ nams,←⊂'gth'
```
This code is used in chunk 25b.

7.24 Greater Than or Equal

75e ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'≥' ⋄ nams,←⊂'gte'
```
This code is used in chunk 25b.

7.25 Index

75f ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'⌷' ⋄ nams,←⊂'sqd'
```
This code is used in chunk 25b.

7.26 Index Generator

75g ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'⍳' ⋄ nams,←⊂'iot'
```
This code is used in chunk 25b.

7.27 Inner Product

76a ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'.' ⋄ nams,←⊂'dot'
```
This code is used in chunk 25b.

7.28 Intersection

76b ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'∩' ⋄ nams,←⊂'int'
```
This code is used in chunk 25b.

7.29 Left

76c ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'⊣' ⋄ nams,←⊂'lft'
```
This code is used in chunk 25b.

7.30 Less Than

76d ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'<' ⋄ nams,←⊂'lth'
```
This code is used in chunk 25b.

7.31 Less Than or Equal

76e ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'≤' ⋄ nams,←⊂'lte'
```
This code is used in chunk 25b.

7.32 Logarithm

76f ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'⍟' ⋄ nams,←⊂'log'
```
This code is used in chunk 25b.

7.33 Match

76g ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'≡' ⋄ nams,←⊂'eqv'
```
This code is used in chunk 25b.

7.34 Matrix Division

77a ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'⌹' ⋄ nams,←⊂'mdv'
```
This code is used in chunk 25b.

7.35 Maximum/Ceiling

77b ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'⌈' ⋄ nams,←⊂'max'
```
This code is used in chunk 25b.

7.36 Membership

77c ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'∊' ⋄ nams,←⊂'mem'
```
This code is used in chunk 25b.

7.37 Minimum/Floor

77d ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'⌊' ⋄ nams,←⊂'min'
```
This code is used in chunk 25b.

7.38 Multiplication

77e ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'×' ⋄ nams,←⊂'mul'
```
This code is used in chunk 25b.

7.39 Nest/Partition

77f ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'⊆' ⋄ nams,←⊂'nst'
```
This code is used in chunk 25b.

7.40 Not

77g ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'~' ⋄ nams,←⊂'not'
```
This code is used in chunk 25b.

7.41 Not And (Logical)

78a ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'⍲' ⋄ nams,←⊂'nan'
```
This code is used in chunk 25b.

7.42 Not Equal

78b ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'≠' ⋄ nams,←⊂'neq'
```
This code is used in chunk 25b.

7.43 Not Match

78c ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'≢' ⋄ nams,←⊂'nqv'
```
This code is used in chunk 25b.

7.44 Not Or (Logical)

78d ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'⍱' ⋄ nams,←⊂'nor'
```
This code is used in chunk 25b.

7.45 Or (Logical)

78e ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'∨' ⋄ nams,←⊂'lor'
```
This code is used in chunk 25b.

7.46 Outer Product

78f ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'∘.' ⋄ nams,←⊂'oup'
```
This code is used in chunk 25b.

7.47 Power

78g ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'⍣' ⋄ nams,←⊂'pow'
```
This code is used in chunk 25b.

7.48 Rank

79a ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'⍤' ⋄ nams,←⊂'rnk'
```
This code is used in chunk 25b.

7.49 Reduce

79b ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'/' ⋄ nams,←⊂'red'
```
This code is used in chunk 25b.

79c ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'⌿' ⋄ nams,←⊂'rdf'
```
This code is used in chunk 25b.

7.50 Roll

79d ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'?' ⋄ nams,←⊂'rol'
```
This code is used in chunk 25b.

7.51 Rotate (First/Last Axis)

79e ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'⌽' ⋄ nams,←⊂'rot'
syms,←⊂,'⊖' ⋄ nams,←⊂'rtf'
```
This code is used in chunk 25b.

7.52 Residue

79f ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'|' ⋄ nams,←⊂'res'
```
This code is used in chunk 25b.

7.53 Right

79g ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'⊢' ⋄ nams,←⊂'rgt'
```
This code is used in chunk 25b.

80a ⟨*APL Primitives* 80a⟩≡
```
rgt←{⍵}
```
This code is used in chunk 32a.
Defines:
`rgt`, used in chunk 83.

7.54 Scalar Each

80b ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'%s' ⋄ nams,←⊂'scl'
```
This code is used in chunk 25b.

7.55 Scan

80c ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'\' ⋄ nams,←⊂'scn'
```
This code is used in chunk 25b.

80d ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'⍀' ⋄ nams,←⊂'scf'
```
This code is used in chunk 25b.

7.56 Shape

80e ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'⍴' ⋄ nams,←⊂'rho'
```
This code is used in chunk 25b.

7.57 Subtraction

80f ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'-' ⋄ nams,←⊂'sub'
```
This code is used in chunk 25b.

7.58 Take

80g ⟨*Symbol ⟷ Name mapping* 24b⟩+≡
```
syms,←⊂,'↑' ⋄ nams,←⊂'tke'
```
This code is used in chunk 25b.

7.59 Transpose

81a ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'⍉' ◇ nams,←⊂'trn'
```
This code is used in chunk 25b.

7.60 Union

81b ⟨*Symbol* ⟷ *Name mapping* 24b⟩+≡
```
syms,←⊂,'∪' ◇ nams,←⊂'unq'
```
This code is used in chunk 25b.

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

81c ⟨*Must Have APL Utilities* 81c⟩≡
```
I←{(⊂⍵)⌷⍺}
U←{⍺←⊢ ◇ ⍵⍵⍣¯1⊢⍺ ⍺⍺⍥⍵⍵ ⍵}
assert←{
α←'assertion failure'
0∊⍵:⍎'⍺ ⎕SIGNAL 8'
1:shy←0
}
```
This code is used in chunk 7.
Defines:
`assert`, used in chunk 22.
Uses `SIGNAL` 20b.

8.2 AST Pretty-printing

82 ⟨*Pretty-printing AST trees* 82⟩≡

```
dct←{⍺[(2×2≠/n,0)+(1↑⍨≢m)+m+n←⌽∨\⌽m←' '≠⍺⍺ ⍵]⍵⍵ ⍵}
dlk←{((x⌷⍴⍵)↑[x←2|1+⍵⍵]⍺),[⍵⍵]⍺⍺@(⊂0 0)⍣('┌'=⊃⍵)⊢⍵}

dwh←{
z←⊃⍪/((≢¨⍺),¨⊂⌈/≢∘⍉¨⍺)↑¨⍺
⍵('┬'dlk 1)' │├┌└─'(0⌷⍉)dct,z
}
dwv←{
z←⊃{⍺,'  ',⍵}/(1+⌈/≢¨⍺){⍺↑⍵⍪⍨'│'↑⍨≢⍉⍵}¨⍺
⍵('├'dlk 0)' ─┬┌┐│'(0⌷⊢)dct(⊣⍪1↓⊢)z
}

lb3←{
⍺←⍳≢⊃⍵
z←(N∆{⍺[⍵]}@2⊢(2⊃⍵){⍺[|⍵]}@{0>⍵}@4↑⊃⍵)[⍺;]
'(',¨')',¨⍨{⍺,';',⍵}⌿⍕¨z
}

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

This code is used in chunk 7.
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:

```
... {⍵⊣⎕←#.DISPLAY ⍵} ...
```

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.

83 ⟨`DISPLAY` *Utility* 83⟩≡

```
DISPLAY←{
⎕IO ⎕ML←0
⍺←1 ⋄ chars←⍺⊃'..''''|-' '┌┐└┘│─'
tl tr bl br vt hz←chars
box←{
vrt hrz←(¯1+⍴⍵)⍴¨vt hz
top←(hz,'⊖→')[¯1↑⍺],hrz
bot←(⊃⍺),hrz
rgt←tr,vt,vrt,br
lax←(vt,'⌽↓')[¯1↓1↓⍺],¨⊂vrt
lft←⍉tl,(↑lax),bl
lft,(top⍪⍵⍪bot),rgt
}
deco←{⍺←type open ⍵ ⋄ ⍺,axes ⍵}
axes←{(-2⌈⍴⍴⍵)↑1+×⍴⍵}
open←{(1⌈⍴⍵)⍴⍵}
trim←{(~1 1⍷∧⌿⍵=' ')/⍵}
type←{{(1=⍴⍵)⊃'+'⍵}∪,char¨⍵}
char←{⍬≡⍴⍵:hz ⋄ (⊃⍵∊'¯',⎕D)⊃'#~'}∘⍕
line←{(6≠10|⎕DR' '⍵)⊃' -'}
{
0=≡⍵:' '⍪(open ⎕FMT ⍵)⍪line ⍵
1 ⍬≡(≡⍵)(⍴⍵):'∇' 0 0 box ⎕FMT ⍵
1=≡⍵:(deco ⍵)box open ⎕FMT open ⍵
('∊'deco ⍵)box trim ⎕FMT ∇¨open ⍵
}⍵
}
```

Root chunk (not used in this document).
Defines:
`DISPLAY`, used in chunk 84.
Uses `box` 56d, `rgt` 80a, `⎕IO` 10a, and `⎕ML` 10a.

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.

84a ⟨PP *Utility* 84a⟩≡
```
PP←{ω⊣⎕←#.DISPLAY ω}
```
Root chunk (not used in this document).
Defines:
PP, used in chunks 27 and 84b.
Uses DISPLAY 83.

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

84b ⟨*Tangle Commands* 8⟩+≡
```
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 86.
Defines:
DISPLAY.aplf, never used.
PP.aplf, never used.
Uses codfns 7, DISPLAY 83, PP 84a, and src 91.

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.

84c ⟨*Basic* tie *and* put *utilities* 84c⟩≡
```
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 chunks 7 and 90b.
Defines:
put, used in chunks 26, 90b, and 91.
tie, used in chunk 90b.
Uses SIGNAL 20b.

8.5 XML Rendering

85a ⟨*XML Rendering* 85a⟩≡

```
Xml←{⍺←0
ast←⍺{d i←P2D⊃⍵ ⋄ i∘{⍵[⍺]}¨(⊂d),1↓⍺↓⍵}⍣(0≠⍺)⊢⍵
d t k n←4↑ast
cls←N∆[t],¨('-..'[1+×k]),¨⍕¨|k
fld←{((≢⍵)↑3↓f∆),⍪⍵}¨↓⍉↑3↓ast
⎕XML⍉↑d cls(⊂'')fld
}
```

This code is used in chunk 7.
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.

85b ⟨*The* `opsys` *utility* 85b⟩≡

```
opsys←{⍵⊃⍨'Win' 'Lin' 'Mac'⍳⊂3↑⊃'.'⎕WG'APLVersion'}
```

This code is used in chunks 7, 87c, and 89d.
Defines:
`opsys`, used in chunks 26, 87c, and 89d.

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.

86 ⟨TANGLE.sh 86⟩≡

```
#!/bin/bash

⟨Tangle Commands 8⟩

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 87a.
Uses `codfns` 7 and `TANGLE` 87c.

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.

87a ⟨`TANGLE.bat` 87a⟩≡

```
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 87b.
Uses `TANGLE` 87c and `TANGLE.sh` 86.

87b ⟨*Tangle Commands* 8⟩+≡

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

This code is used in chunk 86.
Uses `codfns` 7, `TANGLE` 87c, and `TANGLE.bat` 87a.

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.*

87c ⟨`TANGLE` 87c⟩≡

```
TANGLE;opsys
⟨The opsys utility 85b⟩
⎕CMD opsys '.\TANGLE.bat' './TANGLE.sh' './TANGLE.sh'
```

Root chunk (not used in this document).
Defines:
`TANGLE`, used in chunks 86 and 87.
Uses `opsys` 85b.

87d ⟨*Tangle Commands* 8⟩+≡

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

This code is used in chunk 86.
Defines:
`TANGLE.aplf`, never used.
Uses `codfns` 7, `src` 91, and `TANGLE` 87c.

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, edit the font specifications at the top of `codfns.nw` 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.*

88 ⟨`WEAVE.sh` 88⟩≡
```
#!/bin/bash
mkdir -p woven
noweave -delay -index codfns.nw > woven/codfns.tex
cd woven
xelatex --shell-escape codfns
xelatex --shell-escape codfns
```
Root chunk (not used in this document).
Defines:
`WEAVE.sh`, used in chunk 89.
Uses `codfns` 7.

89a ⟨*Tangle Commands* 8⟩+≡
```
echo "Tangling WEAVE.sh..."
notangle -R'[[WEAVE.sh]]' codfns.nw > WEAVE.sh
```
This code is used in chunk 86.
Uses `codfns` 7, `WEAVE` 89d, and `WEAVE.sh` 88.

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

89b ⟨`WEAVE.bat` 89b⟩≡
```
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 89c.
Uses `WEAVE` 89d and `WEAVE.sh` 88.

89c ⟨*Tangle Commands* 8⟩+≡
```
echo "Tangling WEAVE.bat..."
notangle -R'[[WEAVE.bat]]' codfns.nw > WEAVE.bat
```
This code is used in chunk 86.
Uses `codfns` 7, `WEAVE` 89d, and `WEAVE.bat` 89b.

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.

89d ⟨`WEAVE` 89d⟩≡
```
WEAVE;opsys
⟨The opsys utility 85b⟩
⎕CMD opsys '.\WEAVE.bat' './WEAVE.sh' './WEAVE.sh'
```
Root chunk (not used in this document).
Defines:
`WEAVE`, used in chunk 89.
Uses `opsys` 85b.

89e ⟨*Tangle Commands* 8⟩+≡
```
echo "Tangling src/WEAVE.aplf..."
notangle -R'[[WEAVE]]' codfns.nw > src/WEAVE.aplf
```
This code is used in chunk 86.
Defines:
`WEAVE.aplf`, never used.
Uses `codfns` 7, `src` 91, and `WEAVE` 89d.

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.

90a ⟨*Build the runtime* 90a⟩≡
  ⟨*Compile the primitives in* `prim.apln` 91⟩
  ⟨*Build* `codfns.dll` *DLL* 92a⟩
  ⟨*Copy the runtime files into* `tests\` 92b⟩
This code is used in chunk 90b.

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.

90b ⟨`MK∆RTM` 90b⟩≡

```
MK∆RTM path;put;tie;src;vsbat;vsc;wsd
```

  ⟨*Basic* `tie` *and* `put` *utilities* 84c⟩
  ⟨*Build the runtime* 90a⟩
Root chunk (not used in this document).
Defines:
  `MK∆RTM`, used in chunk 90c.
Uses `put` 84c, `src` 91, `tie` 84c, `vsbat` 92a, `vsc` 92a, and `wsd` 92a.

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

90c ⟨*Tangle Commands* 8⟩+≡

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

This code is used in chunk 86.
Defines:
  `MK∆RTM.aplf`, never used.
Uses `codfns` 7, `MK∆RTM` 90b, and `src` 91.

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.

91 ⟨*Compile the primitives in* `prim.apln` 91⟩≡

```
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 90a.
Defines:
`src`, used in chunks 8, 13, 16b, 23, 84b, 87d, 89, and 90.
Uses `codfns` 7, `prim` 32a, `PS` 17, and `put` 84c.

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.

92a ⟨*Build* `codfns.dll` *DLL* 92a⟩≡

```
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 90a.
Defines:
`vsbat`, used in chunks 26 and 90b.
`vsc`, used in chunks 26, 90b, and 92b.
`wsd`, used in chunks 90b and 92b.
Uses `AF∆LIB` 11, `codfns` 7, `EXPORTING` 34b, and `VS∆PATH` 12.

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.

92b ⟨*Copy the runtime files into* `tests\` 92b⟩≡

```
⎕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 90a.
Uses `codfns` 7, `codfns.h` 33, `vsc` 92a, and `wsd` 92a.

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.

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Preamble

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