The Co-dfns Compiler

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3a ⟨* 3a⟩≡
```
:Namespace codfns

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:EndNamespace
```
Root chunk (not used in this document).
Defines:
codfns, used in chunks 16, 21, 24, 26, 29, and 30.

3.1 Global Settings

3b ⟨Global Settings 3b⟩≡
```
⎕IO ⎕ML ⎕WX←0 1 3
VERSION←4 1 0
AF∆PREFIX←'/opt/arrayfire'
AF∆LIB←'cuda'
VS∆PATH←'\Program Files\Microsoft Visual Studio\2022\Community'
```
This code is used in chunk 3a.
Defines:
AF∆LIB, used in chunks 4b, 21, and 30a.
AF∆PREFIX, used in chunk 21.
VERSION, never used.
VS∆PATH, used in chunks 21 and 30a.
⎕IO, used in chunk 33.
⎕ML, used in chunk 33.
⎕WX, never used.

3.2 The Fix API

4a ⟨*The Fix API* 4a⟩≡
```
Fix←{n NS{ω⍎⍵←'L'}α CC{ω⍎⍵←'B'}GC{ω⍎⍵←'G'}TT{ω⍎⍵←'C'}a n s src←PS ω⍎⍵←'P'}
```
This code is used in chunk 3a.
Uses src 29c.

3.3 The user-command API

4b ⟨*User-command API* 4b⟩≡
```
∇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←{α(⎕SE.SALT.Load'[SALT]/lib/NStoScript -noname').ntgennscode ω}
 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,'←ω'}out Fix S⍪⎕EX'##.THIS.',out
∇
```
This code is used in chunk 3a.
Uses AF∆LIB 3b.

4 Co-dfns Compiler

4.1 AST Record Structure

4c ⟨*AST Record Structure* 4c⟩≡
```
f∆←'ptknfsrdx'
N∆←'ABCEFGKLMNOPSVZ'
```
This code is used in chunk 3a.

4.2 Converters between parent and depth vectors

5 ⟨*Converters between parent and depth vectors 5*⟩≡

```
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 3a.

4.3 Parser

6 ⟨*Parser* 6⟩≡

```
PS←{IN←⍵ ⋄ A B C E F G K L M N O P S V Z←1+⍳15
  I←{(⊂⍵)[⍺]} ⋄ U←{0=⎕NC'⍺':⍵⍵⍣¯1 ⍺⍺ ⍵⍵ ⍵ ⋄ ⍵⍵⍣¯1⊢(⍵⍵ ⍺) ⍺⍺ ⍵⍵ ⍵}
  assert←{⍺←'assertion failure' ⋄ 0∊⍵:⍺⍺'⍺ ⎕SIGNAL 8' ⋄ shy←0}

  1<≢⍴IN:'PARSER REQUIRES A SCALAR/VECTOR INPUT'⎕SIGNAL 11
  2<|≡IN:'PARSER REQUIRES A SIMPLE OR VECTOR OF VECTOR INPUT'⎕SIGNAL 11
  IN←∊(⊆IN),¨⎕UCS 10
  0≠10|⎕DR IN:'PARSER REQUIRES A CHARACTER ARRAY'⎕SIGNAL 11

⍝ Line and error reporting utilities
  CR LF←⎕UCS 13 10
  linestarts←(⍳1⍪2>≠IN∊CR LF)⌿≢IN
  mkdm←{⍺←2 ⋄ line←linestarts⍸⍵ ⋄ no←'[',(⍕1+line),'] '
    i←(~IN[i]∊CR LF)≠i←beg+⍳⊃linestarts[line+1]-beg←linestarts[line]
    (⎕EM ⍺)(no,IN[i])(' ^'[i∊⍵],¨' 'ρ¨≢no)}
  quotelines←{
    lines←∪linestarts⍸⍵
    nos←(1 0ρ¨2×≢lines)⍀'[',(⍕⍪1+lines),¨'1⊢'] '
    beg←linestarts[lines] ⋄ end←linestarts[lines+1]
    m←∊∘⍵¨i←beg+⍳¨end-beg
    ¯1↓∊nos,(~∘CR LF¨⍪,(IN∘I¨i),⍪' ¯'∘I¨m),CR}
  SIGNAL←{⍺←2 '' ⋄ en msg←⍺ ⋄ EN∘←en ⋄ DM∘←en mkdm ⊃⍵
    dmx←('EN' en)('Category' 'Compiler')('Vendor' 'Co-dfns')
    dmx,←⊂'Message'(msg,CR,quotelines ⍵)
    ⎕SIGNAL⊂dmx}

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

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

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

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

⍝ Flatten and separate lines and ⋄ with Z type
  t←⊃0ρ⊂pos ⋄ t pos msk(∊,∘⍪¨⍨)←Z(⊃¨pos)0 ⋄ t[⍸'⋄'=IN[pos]]←Z
```

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

⍝ Verify that all open characters are part of the valid character set
    alp←'ABCDEFGHIJKLMNOPQRSTUVWXYZ_abcdefghijklmnopqrstuvwxyz'
    alp,←'ÀÁÂÃÄÅÆÇÈÉÊËÌÍÎÏÐÑÒÓÔÕÖØÙÚÛÜÝßàáâãäåæçèéêëìíîïðñòóôõöøùúûüþ'
    alp,←'Δ⍙ABCDEFGHIJKLMNOPQRSTUVWXYZ'
    num←⎕D
    synb←'¯[]{}()'':αω⋄;'
    syna←'θ⎕⍞#'
    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}⍬

⍝ Tokenize numbers
    _←{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

⍝ Tokenize Variables
    t[i←⍸2<⌿0,vm←(~dm)∧x∈alp,num]←V ⋄ end[i]←end⌿⍨2>⌿vm,0

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

⍝ Tokenize Primitives, Atoms
```

```
    t[⍳(~dm)∧x∊prms]←P ⋄ t[⍳x∊syna]←A

  ⍝ Compute dfns regions and type, include } as a child
    t[⍳'{'=x]←F ⋄ 0≠⊃d←¯1⍞+⍀1 ¯1 0['{}'⍳x]:'UNBALANCED DFNS'⎕SIGNAL 2

  ⍝ Check for out of context dfns formals
    ∨⌿(d=0)∧(t=P)∧IN[pos]∊'⍺⍵':'DFN FORMAL REFERENCED OUTSIDE DFNS'⎕SIGNAL 2

  ⍝ Compute trad-fns regions
    ∨⌿Z≠t⌿⍨1⍞msk←(d=0)∧'∇'=x:'TRAD-FNS START/END LINES MUST BEGIN WITH ∇'⎕SIGNAL
    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

  ⍝ Identify Label colons versus others
    t[⍳tm∧(d=0)∧∊((~⊃)∧(<⍀∨⍀))⍨':'=(t=Z)⊂IN[pos]]←L

  ⍝ Tokenize Keywords
    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

  ⍝ Tokenize System Variables
    si←⍳('⎕'=IN[pos])∧1⍞t=V
    t[si]←S ⋄ end[si]←end[si+1] ⋄ t[si+1]←0

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

  ⍝ Tokenize Labels
    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

  ⍝ Now that all compound data is tokenized, reify n field before tree-building
    n←{1↓⍵⍨'0',⍵}@{t=N}(⊂'')@{t∊Z F}1 ⎕C@{t∊K S}IN⍳I⍨pos+⍳⍨end-pos

  ⍝ Verify that keywords are defined and scoped correctly
    KW←'NAMESPACE' 'ENDNAMESPACE' 'END' 'IF' 'ELSEIF' 'ANDIF' 'ORIF' 'ENDIF'
    KW,←'WHILE' 'ENDWHILE' 'UNTIL' 'REPEAT' 'ENDREPEAT' 'LEAVE' 'FOR' 'ENDFOR'
    KW,←'IN' 'INEACH' 'SELECT' 'ENDSELECT' 'CASE' 'CASELIST' 'ELSE' 'WITH'
    KW,←'ENDWITH' 'HOLD' 'ENDHOLD' 'TRAP' 'ENDTRAP' 'GOTO' 'RETURN' 'CONTINUE'
    KW,←'SECTION' 'ENDSECTION' 'DISPOSABLE' 'ENDDISPOSABLE'
    KW,⍨⍨←':'
    msk←~KW∊⍨kws←n⌿⍨km←t=K
```

```
    v≠msk:('UNRECOGNIZED KEYWORD ',kws⊃⍤⊃⍤⊃⍳msk)⎕SIGNAL 2
    msk←kws∊':NAMESPACE' ':ENDNAMESPACE'
    v≠msk∧km≠tm:'NAMESPACE SCRIPTS MUST APPEAR AT THE TOP LEVEL'⎕SIGNAL 2
    msk←kws∊KW~':NAMESPACE' ':ENDNAMESPACE' ':SECTION' ':ENDSECTION'
    v≠msk←msk∧~km≠tm:{msg←2'STRUCTURED STATEMENTS MUST APPEAR WITHIN TRAD-FNS'
      msg SIGNAL ∊{x+⍳end[⍵]-x←pos[⍵]}⍤⊃⍳km⍀msk}⍬

  ⍝ Verify system variables are valid
    SYSV←,⍤⊃'Á' 'A' 'AI' 'AN' 'AV' 'AVU' 'BASE' 'CT' 'D' 'DCT' 'DIV' 'DM'
    SYSV,←,⍤⊃'DMX' 'EXCEPTION' 'FAVAIL' 'FNAMES' 'FNUMS' 'FR' 'IO' 'LC' 'LX'
    SYSV,←,⍤⊃'ML' 'NNAMES' 'NNUMS' 'NSI' 'NULL' 'PATH' 'PP' 'PW' 'RL' 'RSI'
    SYSV,←,⍤⊃'RTL' 'SD' 'SE' 'SI' 'SM' 'STACK' 'TC' 'THIS' 'TID' 'TNAME' 'TNUMS'
    SYSV,←,⍤⊃'TPOOL' 'TRACE' 'TRAP' 'TS' 'USING' 'WA' 'WSID' 'WX' 'XSI'
    SYSF←,⍤⊃'ARBIN' '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'
    v≠msk←(t=S)∧~n∊'⎕',⍤⊃SYSV,SYSF,SYSD:{
      ERR←2'INVALID SYSTEM VARIABLE, FUNCTION, OR OPERATOR'
      ERR SIGNAL∊pos[⍵]{α+⍳⍵-α}⍤⊃end[⍵]
    }⍳msk

  ⍝ Compute parent vector from d
    p←D2P d

  ⍝ Compute nameclass of dfns
    k←2×t∊F ⋄ k[∪p≠⍤⊃(t=P)∧n∊⊂'αα']←3 ⋄ k[∪p≠⍤⊃(t=P)∧n∊⊂'ωω']←4

  ⍝ We will often wrap a set of nodes as children under a Z node
    gz←{z←⍵↑⍤⊃-0≠≠⍵ ⋄ ks←¯1↓⍵
      t[z]←Z ⋄ p[ks]←⊃z ⋄ pos[z]←pos[⊃⍵] ⋄ end[z]←end[⊃⍬z,ks] ⋄ z}

  ⍝ Nest top-level root lines as Z nodes
    _←(gz 1⍬⊢)⍤⊃(t[i]=Z)⊂i←⍳d=0
    'Non-Z top-level node'assert t[⍳p=⍳≠p]=Z:
```

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

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

⍝ Parse Keyword structures
  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

⍝ PARSE LABELS ∘∘∘

⍝ Map guard statements to (G (Z ...) (Z ...))
  _←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

⍝ Parse brackets and parentheses into ¯1 and Z nodes
  _←p[i]{
    x←IN[pos[⍵]] ⋄ bd←+⍀bm←(bo←'['=x)+-bc←']'=x ⋄ pd←+⍀pm←(po←'('=x)+-pc←')'=x
    0≠⊃⌽bd:2'UNBALANCED BRACKETS'SIGNAL pos[⍵]{x+⍳(⌈⌿⍵)-x←⌊⌿⍺}⌸{⍵⌿⍨0≠bd}end[⍵]
   0≠⊃⌽pd:2'UNBALANCED PARENTHESES'SIGNAL pos[⍵]{x+⍳(⌈⌿⍵)-x←⌊⌿⍺}⌸{⍵⌿⍨0≠pd}end[⍵
    (po⌿bd)∨.≠⌽pc⌿bd:'OVERLAPPING BRACKETS AND PARENTHESES'⎕SIGNAL 2
    p[⍵]←(⍺,⍵)[1+¯1@{⍵=⍳≠⍵}D2P +⍀¯1⌽bm+pm] ⋄ t[bo⌿⍵]←¯1 ⋄ t[po⌿⍵]←Z
    end[po⌿⍵]←end[⌽pc⌿⍵] ⋄ end[bo⌿⍵]←end[⌽bc⌿⍵]
  0}⌸i←⍳(t[p]=Z)∧p≠⍳≠p
```

```
    t k n pos end≠⍤¨←⊂msk←~IN[pos]∈')' ⋄ p←(⍳⍤~msk)(⊢-1+⍳)msk⌿p

⍝ Convert semi-colon indexing into Z nodes in the ¯1 nodes
    _←p[i]{k[z←⊃⍪≠gz¨g←⍵⊂⍤¯1⊢IN[pos[⍵]]∈';]']←1 ⋄ t[z]←Z P[1=≠¨g]}⍸i←⍳⍤~t[p]=¯1

⍝ Mark bindable nodes
    bm←(t=V)∨(t=A)∧n∈,¨'⍞⍞'
    bm←{bm⍪p[i]{bm[α]←(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[⍵]←(α,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

⍝ Mark unambiguous primitive kinds
    k[⍳⍤(t=S)∧n∈'⍞',¨'SYSV]←1 ⋄ k[⍳⍤(t=S)∧n∈'⍞',¨'SYSF]←2 ⋄ k[⍳⍤(t=S)∧n∈'⍞',¨'SYSD]←4
    t[⍳⍤t=S]←P
    k[⍳⍤t∈A C N]←1 ⋄ 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

⍝ Anchor variables to earliest binding in matching frame
    rf←¯1@{~t[⍵]∈F G M}p[rz←I@{~(t[⍵]=Z)∧(t[p[⍵]]∈F G M)∨p[⍵]=⍵}⍣≡⍤¨p]
    rf[i]←p[i←⍳⍤t=G] ⋄ rz[i]←i ⋄ rf←rf I@{rz∈p[i]⊢∘⊃⍸i←⍳⍤t[p]=G}rf
    mk←{α[⍵],⍪n[⍵]}
    fr←rf mk⊢fb←fb[⍳⍤rf mk⊢fb←fb I∘(⍳⍤¨)U⍥rz mk⊢fb←⍳⍤t=B] ⋄ fb,←¯1
    vb←fb[frιrf 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[frι⍁n I@1⊢z←rf I@0⊢⍵]}⍣≡⍁{rf[⍵],⍪⍵}⍳⍤(t=V)∧vb=¯1
    v⌿msk←(t=V)∧vb=¯1:{
      6'ALL VARIABLES MUST REFERENCE A BINDING'SIGNAL∈pos[⍵]{α+ι⍵-α}¨end[⍵]
    }⍳msk

⍝ α/ω → V ; M → F0 ; αα/ωω → P2
    t←V@(i←⍳⍤(t=A)∧n∈,¨'αω')⊢F@{t=M}t ⋄ vb[i]←i ⋄ k[⍳⍤(t=P)∧n∈'αα' 'ωω']←2

⍝ Infer types of bindings, groups, and variables
    z x←↓⍁p[i]{αω}⍸i←⍳⍤(t[p]∈B Z)∧p≠⍳≠p
    x←{⍵≠⍤¨~∧⍀t[⍵]=¯1}U⍣¯x
    0∨.=≠¨x:'BRACKET SYNTAX REQUIRES FUNCTION OR ARRAY TO ITS LEFT'⍞SIGNAL 2
```

```
    _←{
      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[⊃ω])∨4=(ω,≠k)[0⍳⍨∧⌿k[ω]=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:

  ⍝ Strand arrays into atoms
    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(⊂'')

  ⍝ PARSE B←D...
  ⍝ PARSE B←...D

  ⍝ Rationalize F[X]
    _←p[i]{
      ⊃m←t[ω]=¯1:'SYNTAX ERROR:NOTHING TO INDEX'⎕SIGNAL 2
      k[ω≠⍨m∧¯1⍋(k[ω]∊2 3 5)∨¯1⍋k[ω]=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[ω]+⍳¨end[ω]-pos[ω]
    }⊃⌿≠{⊂α≠⍨1<≠ω}⌸p[j]
    ∨≠msk←t[j]≠Z:{
      2'AXIS REQUIRES NON-EMPTY AXIS EXPRESSION'SIGNAL ∊pos[ω]+⍳¨end[ω]-pos[ω]
    }msk≠p[j]
    p[j]←p[i] ⋄ t[i]←P ⋄ end[i]←1+pos[i]

  ⍝ Group function and value expressions
    i km←⌿≠p[i]{(α⌿ω)(0,1∨ω)}⌸i←⍸(t[p]∊B Z)∧(p≠⍳≠p)∧k[p]∊1 2

  ⍝ 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

⍝ 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[⍵]∈O F)∨(t[⍵]∈B P V Z)∧k[⍵]=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[⍵]@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

⍝ Enclose V[X;...] for expression parsing
   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

⍝ TRAINS

⍝ Parse expression sequences
   i km←⍪⌿p[i]{(⍺⍪⍵)(0,(2≤≠⍵)∧1∨⍵)}⌸i←⍸(t[p]∊B Z)∧(k[p]=1)∧p≠⍳≠p
   msk←m2∨fm∧~¯1⌽m2←km∧(1⌽km)∧~fm←(t[i]=0)∨(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

⍝ Rationalize V[X;...]
   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]

⍝ 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

⍝ Compute Exports
   msk←(t=B)∧k[I@{t[⍵]≠F}⍤⍸≡⍨p]=0
   xn←(0ρ⊂''),msk⌿n ⋄ xt←msk⌿k

   d i←P2D p ⋄ d n t k pos end I⍤⊢←⊂i ⋄ sym←∪('')(,'ω')(,'α')'αα' 'ωω',n
   (d t k(-sym⍳n)pos end)(xn xt)sym IN}
```

This code is used in chunk 3a.

Uses TEST 31a.

4.4 Compiler Transformations

15 ⟨*Compiler* 15⟩≡

```
TT←{((d t k n ss se)exp sym src)←ω ⋄ I←{(⊂ω)⌷α}
  A B C E F G K L M N O P S V Z←1+⍳15

⍝ Compute parent vector and reference scope
  r←I@{t[ω]≠F}⍤≡⍨p⍪2{p[ω]←α[α⍳ω]}⌿⊢∘⊂⌸d⍪p←⍳≠d

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

⍝ Wrap expressions as binding or return statements
  i←(⍸(~t∈F G)∧t[p]=F),{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

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

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

⍝ Lift and flatten expressions
  p[i]←p[x←p I@{~t[p[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]

⍝ 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

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

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

This code is used in chunk 3a.
Uses src 29c.

4.5 Code Generator

16 ⟨*Code Generator* 16⟩≡

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

  syms ←,¨'+'    '-'    '×'   '÷'   '*'   '⍟'   '|'    '○'     '⌊'    '⌈'   '!
  nams ←  'add'  'sub'  'mul' 'div' 'exp' 'log' 'res'  'cir'   'min'  'max' 'fac
  syms,←,¨'<'    '≤'    '='   '≥'   '>'   '≠'   '~'    '∧'     '∨'    '⍲'   '⍱
  nams,←  'lth'  'lte'  'eql' 'gte' 'gth' 'neq' 'not'  'and'   'lor'  'nan' 'nor
  syms,←,¨'⌷'    '['    'ι'   'ρ'   ','   '⍪'   '⍋'    '⍒'     '⍳'    '∈'   '⊃
  nams,←  'sqd'  'brk'  'iot' 'rho' 'cat' 'ctf' 'rot'  'trn'   'rtf'  'mem' 'dis
  syms,←,¨'≡'    '≢'    '⊢'   '⊣'   '⍉'   '⊥'   '/'    '⌿'     '\'    '⍀'   '?
  nams,←  'eqv'  'nqv'  'rgt' 'lft' 'enc' 'dec' 'red'  'rdf'   'scn'  'scf' 'rol
  syms,←,¨'↑'    '↓'    '⍫'   '⍒'   '.'   '⍤'   '⍣'    '⍥'     '∪'    '∩'   '←
  nams,←  'tke'  'drp'  'map' 'com' 'dot' 'rnk' 'pow'  'jot'   'unq'  'int' 'get
  syms,←,¨'⍋'    '⍒'    '∘.'  '⍷'   '⊂'   '⌸'   '⌻FFT' '⌻IFFT' '%s'   '⊆'   '⌻CONV
  nams,←  'gdu'  'gdd'  'oup' 'fnd' 'par' 'mdv' 'fft'  'ift'   'scl'  'nst' 'conv
  syms,←,¨'∇'    ';'    'α'   'ω'   'αα'  'ωω'  '%u'
  nams,←  'this' 'span' 'l'   'r'   'aa'  'ww'  ''

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

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

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

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

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

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

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

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

Fn←{id←⍕5⊃⍺ ⋄ x←⍵⊃⍨⍸≠⍵ ⋄ t←2⌷x ⋄ k←3⌷x
  hsw←(t=0)∨(t=E)∧k∈1 2 ⋄ hsa←((t=E)∧k=2)∨(t=0)∧k∈4 5 7 8
  z ←⊂'int'
 z,←⊂'fn',id,'(struct array **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}

Fz←{id←⍕5⊃⍺ ⋄ awc←∨≠(3⌷x){(⍵∈A 0)∨(⍵=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, 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}

Pf←{id←(symsɪsym[|4⊃⍺])⊃nams
  z ←⊂'*stkhd++ = retain_cell(',id,');'
z}

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

```
z}

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

Zx←{n←sym⊃⍨¨|n[⍵] ⋄ rid←⍕rf[⍵]
  k[⍵]=0:⊂''
  k[⍵]=1:{
    z ←⊂'struct array *',n,';'
  z}⍵
  k[⍵]=2:{
    z ←⊂'struct closure *',n,';'
    z,←⊂''
    z,←⊂'EXPORT int'
    z,←⊂n,'_dwa(struct localp *zp, struct localp *lp, struct 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,←⊂''
    z}ω
    ⍬'''UNKNOWN EXPORT TYPE''⎕SIGNAL 16'
  }

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

This code is used in chunk 3a.
Uses codfns 3a.

4.6 Backend C Compiler Interface

21 ⟨*Interface to the backend C compiler* 21⟩≡

```
CC←{
  vsbat←VSΔPATH,'\VC\Auxiliary\Build\vcvarsall.bat'
  tie←{0::⎕SIGNAL ⎕EN ⋄ 22::⍵ ⎕NCREATE 0 ⋄ 0 ⎕NRESIZE ⍵ ⎕NTIE 0}
  put←{s←(⍕128+256|128+'UTF-8'⎕UCS ⍺)⎕NAPPEND(t←tie ⍵)83 ⋄ 1:r←s⊣⎕NUNTIE t}
  opsys←{⍵⊃⍨'Win' 'Lin' 'Mac'⍳⊂3↑⊃'.'⎕WG'APLVersion'}
  soext←{opsys'.dll' '.so' '.dylib'}
  ccf←{' -o ''',⍵,'.',⍺,''' ''',⍵,'.c'' -laf',AFΔLIB,' > ',⍵,'.log 2>&1'}
 cci←{'-I''',AFΔPREFIX,'/include'' -L''',AFΔPREFIX,opsys''' ' '/lib64'' ' '/lib'
  cco←'-std=c99 -Ofast -g -Wall -fPIC -shared -Wno-parentheses '
  cco,←'-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", AFΔLIB, '.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 3a.
Uses AFΔLIB 3b, AFΔPREFIX 3b, codfns 3a, put 32b, tie 32b, vsbat 30a, and VSΔPATH 3b.

4.7 Linking with Dyalog

22a ⟨*Linking with Dyalog* 22a⟩≡

```
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}
  RtmΔInit←{
    _←'w_new'  ⎕NA'P ',ω,'|w_new   <C[]'
    _←'w_close'⎕NA'I ',ω,'|w_close P'
    _←'w_del'  ⎕NA     ω,'|w_del   P'
    _←'w_img'  ⎕NA     ω,'|w_img   <PP P'
    _←'w_plot' ⎕NA     ω,'|w_plot  <PP P'
    _←'w_hist' ⎕NA     ω,'|w_hist  <PP F8   F8 P'
    _←'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,'|',('Δ'⎕R'__'⊢ω),'_cdf P P P'}
  mkf←{fn←α,'|',('Δ'⎕R'__'⊢ω),'_dwa ' ⋄ mon dya←ω⍤,⍤⊂'_mon' '_dya'
    z←('Z←{A}',ω,' W')(':If 0=⎕NC''Δ.',mon,'''')
    z,←(mon dya{'''',α,'''Δ.⎕NA''',fn,ω,' <PP'''}⍤⊂⍤1'>PP P' '>PP <PP'),⊂':EndIf
   z,':If 0=⎕NC''A''('Z←Δ.',mon,' 0 0 W')':Else('Z←Δ.',dya,' 0 A W')':EndIf'
  ns←#.⎕NS⍬ ⋄ _←'ΔΔ'ns.⎕NS⍤⊂⍬ ⋄ Δ Δ←ns.(Δ Δ) ⋄ Δ.names←(0⍴⊂''),(2=1⊃⍺)⌿0⊃⍺
  fns←'RtmΔInit' 'MKA' 'EXA' 'Display' 'LoadImage' 'SaveImage' 'Image' 'Plot'
  fns,←'Histogram' 'soext' 'opsys' 'mkna'
  _←Δ.⎕FX⍤⎕CR⍤fns ⋄ Δ.(decls←ω⍤mkna⍤names) ⋄ _←ns.⎕FX⍤(⊂''),ω⍤mkf⍤Δ.names
  _←Δ.⎕FX'Z←Init'('Z←RtmΔInit ''',ω,''''')'→0⌿⍤⍨0=≢names' 'names ##.Δ.⎕NA⍤decls
  ns}
```

This code is used in chunk 3a.
Uses PP 34.

5 Co-dfns Runtime

22b ⟨*Implementation of APL Primitives* 22b⟩≡

```
⍝ TBW
```

Root chunk (not used in this document).

23a ⟨*C Runtime Support* 23a⟩≡
```
/* TBW */
```
Root chunk (not used in this document).

23b ⟨*C Runtime Header* 23b⟩≡
```
/* TBW */
```
Root chunk (not used in this document).

6 Developer's Guide

6.1 Building the Compiler

6.1.1 Tangling and Weaving the Literate Source

The Co-dfns compiler is written, developed, and distributed as a literate program. For more information about literate programming, see the resources available at `http://literateprogramming.com/`. We use noweb as our preferred literate programming tool because it is eminently simple, while still handling the majority of our needs and producing high quality output in LaTeX format with all the important elements of literate programming, including live hyperlinking and cross-references. We intend `codfns.nw` to tangle into the following files based on specific chunks that have been provided in this document.

Chunk	File Output
⟨* 3a⟩	`src\codfns.apln`
⟨*C Runtime Support* 23a⟩	`rtm\runtime.c`
⟨*C Runtime Header* 23b⟩	`rtm\codfns.h`
⟨*Implementation of APL Primitives* 22b⟩	`rtm\prim.apln`
⟨`DISPLAY` *Utility* 33⟩	`src\DISPLAY.aplf`
⟨`MK∆RTM` *Command* 29b⟩	`src\MK∆RTM.aplf`
⟨`PP` *Utility* 34⟩	`src\PP.aplf`
⟨`TANGLE` *Command* 25⟩	`src\TANGLE.aplf`
⟨`TEST` *Function* 31a⟩	`src\TEST.aplf`
⟨`WEAVE` *Command* 27⟩	`src\WEAVE.aplf`
⟨*Tangle Script* 24⟩	`TANGLE.sh`
⟨*Weave Script* 26⟩	`WEAVE.sh`

The following bash script will create these files.

24 ⟨*Tangle Script* 24⟩≡

```
#!/bin/bash
notangle codfns.nw > src/codfns.apln
notangle -R'[[DISPLAY]] Utility' codfns.nw > src/DISPLAY.aplf
notangle -R'[[MK∆RTM]] Command' codfns.nw > src/MK∆RTM.aplf
notangle -R'[[PP]] Utility' codfns.nw > src/PP.aplf
notangle -R'[[TANGLE]] Command' codfns.nw > src/TANGLE.aplf
notangle -R'[[TEST]] Function' codfns.nw > src/TEST.aplf
notangle -R'[[WEAVE]] Command' codfns.nw > src/WEAVE.aplf
notangle -R'Tangle Script' codfns.nw > TANGLE.sh
notangle -R'Weave Script' codfns.nw > WEAVE.sh
```

Root chunk (not used in this document).
Uses `codfns` 3a, `DISPLAY` 33, `MK∆RTM` 29b, `PP` 34, `src` 29c, `TANGLE` 25, `TEST` 31a, and `WEAVE` 27.

On Windows, the best way that we have found to do this is via the Cygwin project. This document assumes that you have already successfully built and installed via Cygwin a working Icon-driven noweb installation.

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

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

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

25 ⟨`TANGLE` *Command* 25⟩≡

```
TANGLE;SH;CWD;CD
SH←'C:\cygwin64\bin\bash.exe -l -c '
CWD←⊃⎕CMD'C:\cygwin64\bin\bash.exe -c pwd'
CD←'cd ''',CWD,''''

⎕CMD SH,'"',CD,' && ./TANGLE.sh"'
```

Root chunk (not used in this document).
Defines:
`TANGLE`, used in chunk 24.

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

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

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

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

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

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

26 ⟨*Weave Script* 26⟩≡

```
#!/bin/bash
mkdir woven
noweave -delay -index codfns.nw > woven/codfns.tex
cd woven
xelatex codfns
xelatex codfns
```

Root chunk (not used in this document).
Uses `codfns` 3a.

Like the ⟨TANGLE *Command* 25⟩, the following command, when tangled to the WEAVE.aplf file permits the Windows programmer to simply execute WEAVE in a the Dyalog APL session and weave the documents together.

27 ⟨WEAVE *Command* 27⟩≡

```
WEAVE;SH;CWD;CD
SH←'C:\cygwin64\bin\bash.exe -l -c '
CWD←⊃⎕CMD'C:\cygwin64\bin\bash.exe -c pwd'
CD←'cd ''',CWD,''''

⎕CMD SH,'"',CD,' && ./WEAVE.sh"'
```

Root chunk (not used in this document).
Defines:
WEAVE, used in chunk 24.

6.2 Loading the Compiler

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

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

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

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

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

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

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

6.3 Building the Runtime

One of our goals with the Co-dfns runtime is to write as much of it as possible in APL. This means that we want to have at minimum a

very small kernel that has been written in C, while most of the rest of the code is implemented in some APL files. This leads to a three part breakdown of the process to build the runtime.

29a ⟨*Build the runtime* 29a⟩≡
```
⟨Compile the primitives in prim.apln 29c⟩
⟨Build codfns.dll DLL 30a⟩
⟨Copy the runtime files into tests\ 30b⟩
```
This code is used in chunk 29b.

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.

29b ⟨`MK∆RTM` *Command* 29b⟩≡
```
MK∆RTM path;prim;put;src;tie;vsbat;vsc;wsd

⟨Basic tie and put utilities 32b⟩
⟨Build the runtime 29a⟩
```
Root chunk (not used in this document).
Defines:
`MK∆RTM`, used in chunk 24.
Uses `put` 32b, `src` 29c, `tie` 32b, `vsbat` 30a, and `wsd` 30a.

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.

29c ⟨*Compile the primitives in* `prim.apln` 29c⟩≡
```
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 29a.
Defines:
`src`, used in chunks 4a, 15, 24, and 29b.
Uses `codfns` 3a and `put` 32b.

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.

30a ⟨*Build* `codfns.dll` *DLL* 30a⟩≡

```
vsbat←#.codfns.VSΔPATH,'\VC\Auxiliary\Build\vcvarsall.bat'
wsd←path,'\'

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

This code is used in chunk 29a.
Defines:
`vsbat`, used in chunks 21 and 29b.
`wsd`, used in chunks 29b and 30b.
Uses `AFΔLIB` 3b, `codfns` 3a, and `VSΔPATH` 3b.

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.

30b ⟨*Copy the runtime files into* `tests\` 30b⟩≡

```
⍞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 29a.
Uses `codfns` 3a and `wsd` 30a.

6.4 Testing Harness

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

The testing framework is provided by the `ut.apln` file, which is not part of this literate program and so is not included in this document. In order to make some of the testing more convenient, we define the function `TEST` to run the tests that exist in the `tests\` 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.

31a ⟨`TEST` *Function* 31a⟩≡

```
TEST←{
  #.UT.(print_passed print_summary)←1
  'ALL'≡⍵:#.UT.run './'
  path←'./t',(1 0⍕(4⍴10)⊤⍵),'_*_tests.dyalog'
  #.UT.run ⊃⊃0⍪⎕NINFO⍠1⊢path
}
```

Root chunk (not used in this document).
Defines:
`TEST`, used in chunks 6 and 24.

6.5 XML Rendering

31b ⟨*XML Rendering* 31b⟩≡

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

This code is used in chunk 3a.

6.6 AST Pretty-printing

32a ⟨*Pretty-printing AST trees* 32a⟩≡

```
dct←{α[(2×2≠/n,0)+(1↑⍨≢≠m)+m+n←⍸⍵\⍸m←' '≠αα ⍵]⍵⍵ ⍵}
dlk←{((x⌷⍴⍵)↑[x←2|1+⍵⍵]α),[⍵⍵]αα@(⊂0 0)⍤('┌'=⊃⍵)⊢⍵}
dwh←{⍵('┬'dlk 1)' │├┌└─'(0⌷⍉)dct,⊃⍪/((≠⍤¨α),⍤⊂⌈/≠∘⍉⍤¨α)↑⍤¨α}
dwv←{⍵('├'dlk 0)' ─┬┐│'(0⌷⊢)dct(⊣⍪1↓⊢)⊃{α,' ',⍵}/(1+⌈/≠⍤¨α){α↑⍵⍪⍤¨' '↑⍤¨≠⍉⍵}⍤¨α}

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

lb3←{α←⍳≠⊃⍵
  '(',⍤¨')',⍤¨⍤⊂{α,';',⍵}⌿⍋⍤¨(NΔ{α[⍵]}@2⊢(2⊃⍵){α[⍸⍵]}@{0>⍵}@4↑⊃⍵)[α;]}
```

This code is used in chunk 3a.
Defines:
`dct`, never used.
`dlk`, never used.
`dwh`, never used.
`dwv`, never used.
`lb3`, never used.
`pp3`, never used.

6.7 Reading and Writing Files

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

32b ⟨*Basic* `tie` *and* `put` *utilities* 32b⟩≡

```
tie←{
  0::⎕SIGNAL ⎕EN
  22::⍵ ⎕NCREATE 0
  0 ⎕NRESIZE ⍵ ⎕NTIE 0
}

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

This code is used in chunk 29b.
Defines:
`put`, used in chunks 21 and 29.
`tie`, used in chunks 21 and 29b.

6.8 Debugging utilities

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

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

```
... {ω⍪⎕←#.DISPLAY ω} ...
```

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

33 ⟨DISPLAY *Utility* 33⟩≡

```
DISPLAY←{⎕IO ⎕ML←0                          ⍝ Boxed display of array.

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

  tl tr bl br vt hz←chars                   ⍝ Top left, top right, ...

  box←{                                     ⍝ Box with type and axes.
    vrt hrz←(¯1+⍴ω)⍴¨vt hz                  ⍝ Vert. and horiz. lines.
    top←(hz,'⊖→')[¯1↑α],hrz                 ⍝ Upper border with axis.
    bot←(⊃α),hrz                            ⍝ Lower border with type.
    rgt←tr,vt,vrt,br                        ⍝ Right side with corners.
    lax←(vt,'⍬↓')[¯1↓1↓α],¨⊂vrt             ⍝ Left side(s) with axes,
    lft←⍪tl,(↑lax),bl                       ⍝ ... and corners.
    lft,(top⍪ω⍪bot),rgt                     ⍝ Fully boxed array.
  }

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

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

Root chunk (not used in this document).

Defines:
  DISPLAY, used in chunks 24 and 34.
Uses ⎕IO 3b and ⎕ML 3b.

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.

34 ⟨PP *Utility* 34⟩≡
```
PP←{⍵⊣⎕←#.DISPLAY ⍵}
```
Root chunk (not used in this document).
Defines:
  PP, used in chunks 22a and 24.
Uses DISPLAY 33.

7 Index

7.1 Chunks

7.2 Identifiers

8 GNU AFFERO GENERAL PUBLIC LICENSE

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(e) Convey the object code using peer-to-peer transmission, provided you inform other peers where the object code and Corresponding Source of the work are being offered to the general public at no charge under subsection 6d.

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

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