PL516, An Algol-like assembly language for the DDP-516

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January 19, 1999

Abstract

This report gives details of a high-level assembly language for a small 16-bit machine. The language is based upon the work of N. Wirth on PL360.

The report is intended as a user's manual, a description of the Algol-like assembler for those not familiar with the idea, and as a compiler-writer's guide to the system.

Contents

1 Introduction

The language described in this report is based upon PL360 by N. Wirth [1]. As far as the hardware allows, the language follows the same conventions as PL360. The short address length is exploited by using the first sector of the machine in a similar way to the Program Reference Table of the B5500 (as will be explained in more detail later).

This report is an attempt to combine (a) a manual for users (b) a description of an Algol-like assembler for other interested parties, and (c) a compiler-writer's description of the language and compiler to assist in future enhancements to the system. Clearly three reports should have been written but the author hopes that this will be adequate.

It must be emphasized that this language is no substitute for Fortran or Algol 60, but rather a more convenient and flexible system for writing large machine-code programs. The main advantage over DAP, the assembler for the DDP-516, is that program texts are largely self-documenting due to their Algol-like structure.

The author would like to thank all those who have contributed to the design and implementation of the system, namely Miss Elizabeth Giles for preparing the compiler text, to D.A. Bell who wrote the compiler in its own language and to G. Alway, F.G.Duncan, R. Scowen, P. Wilkinson and M. Woodger all of whom made many suggestions and criticisms on the basis of the author's rough notes.

The work described in this paper was carried out as part of the research work of the National Physical Laboratory.

2 What is an Algol-like assembly language

The basic idea of PL516 is to provide a facility for writing machine-code which makes the program text look superficially like Algol. This can be done by separating the features of Algol 60 into two classes.

Firstly those which require no subroutines to implement them in the running program. These can be implemented in PL516. For instance, identifiers for naming locations in store. Six characters are significant in this compiler and additional characters can be added although they are ignored. This gives substantially greater flexibility over DAP which only allows up to four characters in an identifier.

Secondly are those features which require subroutines in the program because the machine cannot implement the feature in a straightforward manner. Dynamic storage allocation is such a facility. If the machine had hardware for storage allocation like the B5500 then this would be a feature of the assembler. Since there are no hardware facilities for floating point on the PPD-516, this language uses integers only.

Hence the following table can be constructed:

PL516 contains: identifiers, type-checking, scope to identifiers, procedures, compound statements, conditional statements, simple **for** loops.

PL516 does not contain: dynamic storage allocation, multi-dimensional arrays, more than one parameter to procedures, call by name, expressions involving temporary working store, real variables.

In addition to the Algol-like facilities of the assembler, one can write ordinary machine code (for communicating with peripherals, for instance), refer to constants by identifiers to improve the legibility of the program, and initialise the values of an array (possible because fixed storage is used).

Numerous examples of procedures and programs are given throughout this report and a glance at these will illustrate many of the points made above. Those who prefer to learn by examples may like to start at section 5.

3 The DDP-516

The assembler is, of course, a machine-dependent language. So to describe how the language is implemented it is necessary to understand the addressing mechanism and instruction code. This is given in detail in [2, 3] but this section is added to make the report as complete as possible.

The DDP-516 is a 16-bit machine with two main registers. The first register, called the A register, is the main accumulator of the machine. The second is the X register which is the index register. The X register is also word 0 of the machine.

There are four classes of instructions as follows:

Generic instructions. These addressless instructions usually operate on the contents of the accumulator. An example is TCA (Twos Complement Accumulator) which negates A as a 16-bit signed integer. In referring to machine instructions in this report, the DAP conventions will be used (see [3]).

Shift instructions. These instructions have a six-bit field giving the two's complement of the shift required. Double length shifting can be done using the B register. The B register is not directly accessible by instructions and so will not be mentioned very much in this brief account. Twelve shift orders are available in total from all possible combinations of left, right, logical and cyclic and arithmetic, single and double length.

Input-output instructions. These instructions have a 10-bit address field divided between the device function code and the device address.

Memory reference instructions. (for DXA mode machines having 16K only). These instructions are very important since they determine the addressing structure of the machine. The operation code is 4-bits giving a basic repertoire of instructions for adding, subtracting etc, the accumulator to the word accessed. The remaining 12 bits of the instruction are divided into 3 one-bit flags and a 9-bit address. One flag is the 'this sector bit'. If this is set, then the full 14 bit address is formed by taking the most significant five bits from the current instruction address. This means that the machine is sectored into blocks of 512 words so that one can either address the sector one's instructions are in or sector 0, the first sector of the machine.

The other two flag bits are the 'indirect' bit and the 'index' bit which, together with the 14 bit address, gives one machine word. If the 'index' bit is set then the current contents of the X register are added to the 14 bit address constructed from the instruction. After this, the indirect bit is inspected. If it is not set then the address of the operand has now been calculated. If the indirect bit is set, then the 14 bit address is used to load a 16 bit word which is interpreted as an address with indirect and index bits. This process of indirection can be carried to arbitrary depth. To illustrate this, consider three examples:

1. One of the memory reference instructions is a jump order JMP. Ordinarily in the assembler jumps are within the current sector and so a direct jump can be made. However, jumps to labels not in the current sector can be done by putting in sector 0 the 14 bit address of the label. Then the jump is an indirect jump i.e, with the indirect bit set in the instruction. The instruction points to the word in sector 0. This word in sector 0 does not have the indirect bit set (nor index bit) so the jump is effected to the 14 bit address given by this word.
   This can be represented diagrammatically thus:

```
JMP 'indirect' ->
                | | |........    word in sector 0
                  ->
                    ........   location of label anywhere in store
```

2. One of the memory reference instructions loads the accumulator (LDA). How does one use the addressing to load the *i*th element of an array b into the accumulator? For each array in the assembler there is an 'array word' which has the 14 bit address of the zero-th element of the array together with the index bit set. To load b[i] we do:

```
LDX I  which loads the index register
LDA 'indirect' ->
                | |*|........   'array word' with index bit set in
                                  current sector or sector 0
                  ->
                    ........   b[0]
                  I
                    ........   b[i] anywhere in store.
```

   In the assembler the array word is always directly addressable from the instruction and so is either in the current sector or in sector 0.

3. The third example illustrates how the addressing is used to implement switches. Switches are simpler than in Algol 60 in that each switch element is a label. The 'switch word' s has both the index and the indirect bit set, so diagrammatically this is:

```
LDX I  which loads X register as with arrays
JMP 'indirect' ->
                |*|*|........   'array word' in
                                  current sector or sector 0
                  ->
                    ........        s[0]
                  I
                    | | |........   s[i] address of ith label
                    ->              label corresponding to ith
                                    element of switch
```

   So one level of indirection plus one level with both indirection and indexing is used to do the required jump.

Control instructions. Apart from the unconditional jump other orders exist to transfer program control.

Generic control instructions. Instructions in this category see if a particular condition is **true**. If it is, the next instruction is skipped over. So it is usual to place unconditional jumps after such instructions, the jump being to code which deals with the case where the condition is false. An example of such an instruction is SPL which skips the next instruction if the accumulator is positive. Hence the instructions SPL followed by TCA takes the absolute value of the contents of the accumulator.

Subroutine jump instruction. This instruction, JST, is a memory reference instruction and so the address is calculated in the way described above. In this address is placed one more than the address of the JST instruction itself. Control then passes to the next word in the computer store.

In the assembled code of PL516 the addresses of procedures are kept in sector 0, and so one has diagrammatically:

```
JST 'indirect' ->
                  | | |........   address word of procedure in sector 0
                    ->
                      | | |........  return address planted here
                      ............
                      ............  code of procedure
                      JMP 'indirect' to return address above
```

As illustrated, the return is done by doing an indirect jump to the return address which is planted by the JST instruction.

Note that code cannot be pure on this machine since the return addresses must be stored with the code.

Increment in store instruction. This instruction IRS, is also a memory reference instruction. the operand is incremented by one in the store without affecting the accumulator. If the result of this incrementing is to give zero, then the next instruction is skipped. Frequently one knows from the logic of the program that the result can never be zero so no jump order or special coding is placed after the IRS (beware!). The instruction is very useful for loop control, but the counting goes from $-n, .. - 1$. The jump after the IRS returns control to the beginning of the loop.

The compare instruction. The last instruction CAS is also a memory reference instruction which does not alter the accumulator. It is a control instruction for comparing the accumulator with the operand. If the accumulator > operand the next instruction is executed, with equality one instruction is skipped and with accumulator < operand two instructions are skipped. By inserting appropriate jump instructions after the CAS all various inequalities can be tested for.

4 The language

PL516 will be described in a manner similar to the Algol 60 report [4]. Each feature of the language is given by a formal syntactic description using a variant of the Backus-Naur notation. For those not familiar with this, a verbal explanation is also given as well as many examples. The semantics are given by explaining the code generated by the compiler. This is given in DAP, so the reader is referred to [2, 3] or Section 3 of this report for a shorter account.

4.1 The syntax notation

The notation used is the Backus-Naur form with a number of additions to shorten the description introduced by F.G. Duncan [5]. The cross-reference technique of Coulouris [6] is also used.

The first addition is to abbreviate the fact that a symbol may or may not occur. For instance

$$< a >::= < b >< c >$$

means

$$< a >::=< c > \mid < b >< c >$$

That is an $< a >$ is a $< c >$, or a $< b >$ followed by a $< c >$.

To assist in searching for the appropriate syntax rule, these rules are all numbered and each reference to a rule is preceded by the number. Hence the rule above might be

$$< 1.3a >::= \{< 1.2b >\} < 4.8c >$$

Symbols of the language itself are written in bold or the symbol itself like the Algol 60 Report. A complete list of the symbols is given in Appendix A. Syntax rule $n.r$ is to be found in section 4.2.n.

Another addition to the syntax notation is to deal with repetitions $< a >_1^*$ means one or more $< a >$'s. Similarly $< a >_0^*$ means zero or more $< a >$'s.

The last addition is to deal with lists in a compact manner.

$<< a > list < b >>$ means $< a >< < b >< a >>_0^*$. Usually $< b >$ is a separator such as a comma or semicolon.

4.2 The language elements

4.2.1 Expressions

The purpose of expressions is to do some calculation from values already stored without using temporary working store. All the calculation is done in the accumulator alone.

$< 1.0 expression >$::= $< 1.3 unary\ operator >_0^* < 1.1 term >$
$<< 1.4 binary\ operator >< 1.2 cell >$
$|< 1.5 shift\ operator >< 4.0 constant >>_0^*$

This means that an expression is any number of unary operators followed by a term followed by any number of either a binary operator followed by a cell or a shift operator followed by a constant. The evaluation of the expression is done by first evaluating the term, then applying the unary operators in the reverse order to the appearance in the text, then applying the binary or shift operators in the order left to right. Detailed examples are given later when the other terms have been defined.

$< 1.1 term >$::= **accumulator** |
$< 1.2 cell >$|
$(< 1.0 expression >)$ |
$< 9.0 procedure\ call >$|
zero |
codeword $< 11.5 type\ identifier >$|
if $< 3.0 condition >$ **then** $< 1.0 expression >$ **else** $< 1.0 expression >$

The purpose of term is to do the initial loading operation on the accumulator before the operators are applied to it. This load operation is omitted in the case where the **accumulator** symbol is read. By this means the current contents of the accumulator can be used in an expression (but only by explicitly stating this). When the symbol **zero** is written, then the instruction CRA (CleaR Accumulator) is generated. The possibility of nesting expressions by means of brackets means that quite complex expressions can be done although no temporary working store is used.

$< 1.2 cell >$::= $< 14.1 integer\ identifier >$|
ind $< 14.1 integer\ identifier >$|
$< 14.3 array\ identifier >< 2.0 subscript >$|
$< 4.0 constant >$

All variables in this language are 16-bit integers. A cell is such an integer addressed in one of four ways. Firstly, the integer may be declared as a simple integer and given an identifier, say i1 or int2. Secondly the simple integer 'addi' may contain the address of the integer required. In this case access must be made with the indirect bit set in the instruction (see page 3). The case of arrays is dealt with when describing subscripts. The last case is an explicit constant which is given a location by the compiler as necessary and accessed directly like an ordinary integer.

$< 1.3 unary\ operator >$::= **addc** | **inc** | **neg** |
setsignplus | **setsignminus** | **not** |
changesign | **copysignandsetplus** | **icleft** |
cleft | **swop** | **icright** |
abs | **abug**

These operators act upon the current contents of the accumulator. Except for the last two, they are single generic instructions. The corresponding DAP instructions are:

addc ACA add the C register (a 1 bit overflow register and shift indicator) to the A register (ie, the accumulator)

inc AOA add one to the A register

neg TCA negate the constants of the A register

setsignplus SSP clears the sign bit of the accumulator leaving the other bits unchanged

setsignminus SSM sets the sign bit of the accumulator leaving the other bits unchanged

not CMA all the bits in the A register are changed

changesign CHS change the sign bit of the A register leaving the other bits unchanged

copysignandsetplus CSA the sign bit of A is put into the C register, and the sign bit is cleared

icleft ICL This instruction is for manipulating the A register regarded as two 8 bit characters. The most significant character is moved to the bottom of the A register and the top of the register cleared. Instruction stands for Interchange and Clear Left, ie $(x, y) \rightarrow (0, y)$

cleft ICA Interchange the two characters in the A register ie $(x, y) \rightarrow (y, x)$

swop CAR Clear the least significant character in the A register ie $(x, y) \rightarrow (x, 0)$

icright ICR The least significant character is moved up in the A register and the bottom of the A register cleared, ie $(x, y) \rightarrow (y, 0)$

The penultimate operator is slightly different in that two instructions are generated namely:
abs SPL TCA. This gives the absolute value of the A register (see page 4).
abug is a compiler controlled diagnostic facility. When the appropriate compiling options are set the instruction JST *'776 is generated, otherwise no code is output. The compiling options are explained in the programming notes for the version of the compiler in use.

$< 1.2term >$::= $+ \mid - \mid$ **and** $\mid$ **nev** $\mid * \mid / \mid$ **mod**

It has been pointed out in $< 1.0expression >$ that 'term' caused the accumulator to be loaded, after which the unary operators are applied. At this stage the binary operators can be invoked. The instructions to do this are as follows:

+ ADD $< operand >$

- SUB $< operand >$

and ANA $< operand >$

nev ERA $< operand >$

The last three are somewhat different since more than one instruction is generated:

***** MPY $< operand >$ LLS 15 (long left shift 15 places)

/ LRS 15 (long right shift 15 places) DIV $< operand >$

mod LRS 15 (long right shift 15 places) DIV $< operand >$ IAB (interchange A and B registers)

These instructions are the ones produced by the current version of the compiler. Since MPY and DIV are not available on some machines, they must be replaced by a subroutine call or otherwise removed altogether. The compiler itself does not use these instructions.
Some realistic examples of expressions can now be given.

1. **abs** a + b

   This will generate the machine code:

```
LDA  A  since a is the term
SPL     after the unary operators are
TCA     applied, two instructions for abs
```

2. **not** (a + b) **and** c

   The term (a+b) must be evaluated first, this gives:

```
LDA  A  form the term a
ADD  B  from the binary operator + and cell b
CMA     from the unary operator not
ANA  C  from the binary operator and cell c
```

3. The same expression as above with the brackets missing: **not** a + b **and** c

```
LDA  A
CMA
ADD  B
ANA  C
```

   In other words, the brackets in expressions determine the positioning of the unary operators. Unlike Algol 60 or Fortran all operators have the same priority.

4. For example: a + b * c

   generates the code:

```
LDA  A
ADD  B
MPY  C
LLS  15
```

   since the binary operators are applied in the order left to right. No priority can be given to operators as can be seen from this example. This is because once 'a' has been loaded into the accumulator there is no way of multiplying b and c. Temporary storage would have to be used to preserve the contents of the accumulator but this is excluded.

5. **accumulator** + b * c

   Here the current constants of the accumulator is being referred to so no load operation is done, so the code generated is

```
ADD  B
SUB  C
```

6. **not setsignminus zero**

   Instead of a load operation **zero** clears the accumulator so we have

```
CRA
SSM from setsignminus
CMA from not
```

   Note that the unary operators are applied in the order right to left. The effect of this is to leave in the accumulator the largest positive integer (zero sign bit, the rest all 1's).

7. **neg** (**abs** (**not** a + **ind**b)/c) **mod** d

   Just to illustrate how complex expressions can be. The code generated is

```
LDA  A  since the innermost term is evaluated first
CMA     from the not
ADD* B  * means set the indirect bit in instruction
SPL
TCA     now abs (two instructions)
LRS  15
DIV  C  the /c completes the outermost term
TCA     so now apply neg
LRS  15
DIV  D
IAB     finally the mod d
```

Expressions involving constants, arrays, procedure calls, conditions and type identifiers will be illustrated when the appropriate syntax has been described.

$< 1.5 shift\ operator >$::= **singlerightlogical** | **singleleftlogical** |
singlerightarithmetic | **singleleftarithmetic** |
singlerightcyclic | **singleleftcyclic** |
doublerightlogical | **doubleleftlogical** |
doublerightarithmetic | **doubleleftarithmetic** |
doublerightcyclic | **doubleleftcyclic** |

The number following the shift operator is two's complemented and truncated to 6 bits and then placed in the appropriate instruction. It is only possible to shift by a constant amount, since the amount is placed in the instruction by the compiler.

The above operators generate the shift instruction (in the order above): LGR, LGL, ARS, ALS, ARR, ALR, LRL, LLL, LRS, LLS, LLR and LLR. The double length shifts regard the B register as an extension to the bottom of the A register.

The hardware representation of the shifts (see Appendix A) uses five characters to increase program legibility.

4.2.2 Arrays and subscripting

One dimensional arrays of integers are part of the assembly language. Because of the fixed storage lay-out, the size of the array must be given to the compiler. Array elements are accessed in the manner described on page 4.

The syntax of the subscripting mechanism is:

$< 2.0 subscript >$::= [$<< 14.1 integer\ identifier >$|
$< 4.0 constant >$|
xsymbol $>$]

The purpose of the subscript is the load the X register, so that the appropriate element of the array can be accessed. In the first case the integer is loaded into the register, in the second case the constant is loaded.

In the final case no LDX instruction is generated. This is used if the X register already contains the required value. It will be noted that complex subscript expressions are not allowed. This is a consequence of the fact that no arithmetic operations can be performed in the X register itself. When more complex expressions are required, the relevant calculation must be done in the accumulator and the result assigned to word 0 of the machine (which is the X register). This will be explained in section 4.5.2.

Some examples of expressions involving array accessing can now be given.

1. ar1[i] + ar[j] - ar[k]

   Each subscript gives a LDX operation so the code for this is

```
LDX   I
LDA*  AR1
LDX   J
ADD*  AR
LDX   K
SUB*  AR
```

Note the indirect addressing via the array word in all the instructions accessing the array elements.

2. **not**(ar[i] **and** ar1[**xsymbol**]

   The first subscript loads the X register with i so that the second array element accessed is ar1[i]. The code generated is:

```
LDX   I
LDA*  AR
ANA*  AR1
CMA
```

3. **negabs**(ar[i] * ar1[**xsymbol**]) / ar2[j]

   This generates the code:

```
LDX   I
LDA*  AR    which loads the first array element
MPY*  AR1
LLS   15    multiplying by the second array element
SPL
TCA         from abs
TCA         from neg
LDX   J
LRS   15    note the LDX operation is performed before any of
DIV*  AR2   the divide operation
```

4.2.3 Conditions

There are no boolean variables in PL516. Apart from ordinary jump instructions control is effected by means of conditions. This is done by making use of the test orders which skip one instruction if the condition is true. The instruction which may be skipped over is a jump to the code which deals with the case when the condition is false. This jump order is generated automatically by the compiler and in the examples which follow is written as JMP false.

$$
\begin{aligned}
<3.0 condition> ::= \quad & <1.0 expression><3.3 relational\ operator><1.2 cell> | \\
& <1.0 expression><3.2 accumulator\ condition> | \\
& <9.1 conditional\ procedure\ call> | \\
& <3.1 condition\ operator>
\end{aligned}
$$

The first type of condition uses the CAS instruction (see page pagerefsec354) to compare the current contents of the accumulator (set by expression) with the word in store determined by cell.

The second case is where the expression sets the accumulator and is tested by a single instruction.

Thirdly, a procedure can be a conditional procedure. In this case the procedure may return control in the ordinary position if the condition is false, or one instruction further on if the condition is true. This will be explained in more detail when procedure calls are dealt with in section 4.2.9.

The last case is the simplest, the syntax of which is:

$$
\begin{aligned}
<3.1 conditional\ operator> ::= \quad & \textbf{sense1} \mid \textbf{sense2} \mid \\
& \textbf{sense3} \mid \textbf{sense4} \mid \\
& \textbf{anykey} \mid \textbf{nokey} \mid \\
& \textbf{cset} \mid \textbf{notc}
\end{aligned}
$$

There are four sense keys on the machine, numbered 1 to 4. The instruction SS1 skips the next order if sense key one is set. So the condition operator **sense1** generates the code:

```
SS1
JMP   false
```

and similarly with **sense2**, **sense3** and **sense4**. **anykey** gives SSS, **nokey** gives SSR, **cset** gives SSC and **notc** gives SRC.

The address planted in the JMP **false** instruction will become clear when examples of conditions in pieces of program can be given.

$< 3.2 accumulator\ condition >::=$ **zero** | **plus** |
nonzero | **odd** |
even | **minus**

In this case, after generating code to evaluate the expression, the single instruction (SZE, SPL, SNZ, SLN, SMI, respectively) followed by JMP **false** is generated.

Examples of such conditions are:

1. a + b **zero**

   generates:

   ```
   LDA   A
   ADD   B    from expression
   SZE
   JMP   false
   ```

2. Using the convention **true** $= -1$ and **false**$= 0$ then one would write the booleans expression bool1 **and** bool2 as:

   bool1 **and** bool2 **nonzero** generating:

   ```
   LDA   BOOL1
   ANA   BOOL2
   SNZ
   JMP   false
   ```

3. a + b[i] **minus**

   generates:

   ```
   LDA   A
   LDX   I
   ADD*  B    from expression
   SMI
   JMP   false
   ```

4. **zero zero** is a valid condition since the first zero is from term and the second an accumulator condition. The code is:

   ```
   CRA
   SZE
   JMP   false
   ```

   Clearly the skip is always performed. Confusion is not likely to arise from the double use of A **zero** since the context is clear in practical cases.

$< 3.3 relational\ operator >::= \quad = | \neq | > | < | \geq | \leq$

After the evaluation of the expression and generation of a possible LDX if the cell is an array element the code is:

$=$

```
CAS   cell address
SKP      skips one instruction
SKP
JMP   false
```

$\neq$

```
CAS   cell address
SKP      skips one instruction
JMP   false
```

$>$

```
CAS   cell address
JMP   *+3     this means jump forward three places
NOP           dummy instruction
JMP   false
```

$\geq$

```
CAS   cell address
NOP           dummy instruction
SKP
JMP   false
```

$\leq$

```
CAS   cell address
JMP   false
NOP
```

The details of these instructions need not, of course, be remembered. The effect of the code is clear, control passes according to the usual interpretation of the operators leaving the value of the expression in the accumulator. It is worth remembering that using relational operators generates 3 or 4 instructions, but has the advantage that the accumulator is compared with a word in store without disturbing the accumulator.

1. **accumulator** = a generates

   ```
   CAS   A
   SKP
   SKP
   JMP   false
   ```

   Note there is no code from the expression.

2. a + b $\neq$ c[i] generates

   ```
   LDA   A
   ADD   B   from expression
   LDX   I
   CAS*  C   from c[i]
   SKP
   JMP   false
   ```

3. a / b[i] > c[**xsymbol**] generates

```
LDA   A
LDX   I
LRS   15
DIV*  B
CAS*  C
JMP   *+3
NOP
JMP   false
```

4. a **mod** b < c generates

```
LDA   A
LRS   15
DIV   B
IAB
CAS   C
NOP
JMP   false
```

Some examples can now be given of conditional expressions the syntax of which appeared in $< 1.1 term >$.

The code generated is:

```
<condition code>
JMP   false    --------------------> a
<extra condition code>
JMP            --------------------> b
<code from second expression> a <----
                              b <----
```

So the effect is that if the expression is true the first expression is evaluated otherwise the second expression is executed.

1. **if** xx > yy **then** xx **else** yy

   Code to give the maximum of xx and yy in the accumulator.

   The code generated is:

```
LDA   XX
CAS   YY
JMP   *+3
NOP
JMP   false  ----> a
LDA   XX
JMP          ----> b
LDA   YY     <---- a
             <---- b
```

2. **if** a+b=c **if** d $\neq$ e **then** f[-6] **else** g[8] **else neg** (y+z)

   This generates:

```
LDA   A
ADD   B
CAS   C
SKP
SKP
JMP   false   -----------> a
```

```
LDA   A
CAS   E
SKP
JMP   false   -----> b
LDX   =-6
LDA*  F
JMP           -----> c
LDX   =8    b<-----
LDA*  G
JMP         c<-------->d
LDA   Y     a<------------
ADD   Z
TCA
            d<------
```

4.2.4 Constants

Facilities for constants in the assembler are somewhat different from Algol 60. There is no 'literal' facility in the instruction set for loading constants into the accumulator. Hence at binary machine-code level there is no distinction between constants and ordinary integers. In PL516 however, there are three types of constants. Firstly there are the explicit constants, a string of digits as in Algol 60. Secondly there is a type of entity called constant. This is like an ordinary integer except that an initial value is given to it and the assembler checks (as far as possible) that no assignment is made to it. Such constants are referred to by their identifier. The third type of constant, called a compile constant, is also referred to by an identifier. This, however, is not given any storage in the running program until it is referred to in a context which requires that it should be given storage. The significance of this will become clear when examples of the use of constants in complete programs is given.

The purpose of giving constants identifiers is to improve program legibility and yet preserve the static nature of the constant in the program text. Explicit constants should be used very rarely since altering one declaration of a constant is substantially easier than altering several occurences of the explicit constant appearing throughout the program text.

$$
\begin{aligned}
< 4.0 constant >::= \quad & < 14.4 constant\ identifier > | \\
& < 14.5 compile\ constant\ identifier > | \\
& < 4.1 number > | \\
& \textbf{charsymbol} < string\ character >< string\ character > | \\
& \textbf{addressof}\{\textbf{ind}\}\{\textbf{index}\} < 11.5 type\ identifier > | \\
& \ll < 4.0 constant >, < 4.0 constant > \gg \\
< 4.1 number >::= \quad & \{-\} < \textbf{octalsymbol} < octal\ sequence > | \\
& < digit >_1^* >
\end{aligned}
$$

An octal sequence is of course, a sequence of one or more digits excluding 8 and 9. The minus sign has the usual interpretation, but note that it is **not** an operator. The unary operator written as - in Algol 60 is **neg** in PL516 (see $< 1.3 unary\ operator >$). The accumulator can be regarded as two 8 bit characters so there is a facility to set constants appropriately. A string character is a space or a Teletype 33 graphic character and so excludes control characters.

Indirect and indexed addressing is ordinarily dealt with for the user through the use of arrays (and the layout to be explained later). However 16 bit addresses with the index or indirect bits set can be formed by using the **addressof** type of constant. The form of the address is given in section 4.2.11.

The form of constant appearing in angle brackets (shown as $\ll, \gg$) is to allow each half of the word to be set separately by the appropriate constant. In the example given below, -8 is placed in the most significant 8 bits and octal 70 in the lower 8 bits.

1. Examples of constants

   noinputs
   692
   -84

octalsymbol 123
charsymbol AB
<-8, **octalsymbol** 70 >

2. Examples of constants appearing in expressions

   a + **octalsymbol** 77

   generates

```
LDA  A
ADD  =’77  ’ means octal, the
           = means put address of ’77 in
             the instruction
```

   interrupt **singleleftlogical** clockpulse

   Note in this case ‘clockpulse’ cannot be an integer, since the syntax for expression excludes this. The code generated is

```
LDA  INTERRUPT
LGL  CLOCKPULSE
```

   The two’s complement of the value of the constant ‘clockpulse’ is truncated to 6 bits and placed in the instruction.

3. Constants in conditions

   ar[-6] > b[-2]

   generates

```
LDX   =-6
LDA*  AR
LDX   =-2
CAS*  B
JMP   *+3
NOP
JMP   false
```

   Note that negative constants can be out into subscripts because the minus sign is part of the constant.

   Assume that there is a compile constant ‘minus1’ declared to have the value -1 then

   a + -1 = minus1

   would generate

```
LDA   A
ADD   =-1
CAS   =-1
SKP
SKP
JMP   false
```

   Both the CAS and the ADD instruction refer to a word containing -1. Such repeated references to the same constant use the same word in store. If minus1 was an ordinary constant, however, the CAS operation would address the word set aside for ‘minus1’ on its declaration.

The distinction between compile constants and ordinary named constants can be ignored initially since it is of secondary importance. The point is covered in more detail in section 5.

4.2.5 Assignment statement

The purpose of assignment statements is that same as in Algol 60, namely to give new values to the variables listed on the left-hand side of the statement. The syntax is as follows:

$< 5.0 assignment\ statement >$::= $<< 5.1 lhs > list <,>> \leftarrow < 1.0 expression >$

$< 5.1 lhs >$::= $< 14.1 integer\ identifier >|$
$\{$**ind**$\} < 14.1 integer\ identifier >|$
$< 14.3 array\ identifier >< 2.0 subscript >|$
accumulator

So an assignment statement is one or more 'lhs's separated by commas followed by $\leftarrow$ and then the expression. The code generated is to first evaluate the expression and then to store the contents of the accumulator to the variables listed in the left-hand side in the order left to right.

Various distinct types of element on the left hand side produce the following code:

$< integer\ identifier >$ produces:

```
STA  <integer>
```

ind $< integer\ identifier >$ produces:

```
STA*  <integer>
```

$< array\ identifier >< subscript >$ produces:

```
code for subscript as described in 4.2.2
STA*  <array>
```

accumulator produces no code and so is included if the expression is to be evaluated but no assignment made.

Some examples:

1. Zeroise a number of elements of an array

   ar[i], a[j], a[k] $\leftarrow$ **zero**

   This generates the code

   ```
   CRA      from zero
   LDX   I
   STA*  A  from a[i]
   LDX   J
   STA*  A  from a[j]
   LDX   K
   STA*  A  from a[k]
   ```

   Note that the order of the assignment is the order the variables appear in the text. This can be important if **xsymbol** appears as a subscript, for instance.

2. ar[i], b[**xysymbol**] $\leftarrow$ c[j] + b[**xysymbol**]

   generates

   ```
   LDX   J
   LDA*  C
   ADD*  B  from expression
   LDX   I
   STA*  A  from a[i]
   STA*  B  from b[xsymbol]
   ```

   Hence the assignment above is equivalent to

   ar[i], b[i] $\leftarrow$ c[j] + b[j]

   but requires two fewer LDX instructions.

   Programmers familiar with Algol 60 will no doubt be annoyed with the use of ',' in the assignment statement. The purpose of this is to make the compiler somewhat simpler.

3. To add one to the current contents of the accumulator one writes:

   accumulator ← **accumulator** + 1

   which generates the single instruction

```
ADD   =1
```

4. **ind** addv, i, j ← i + j

   generates

```
LDA   I
ADD   J  from expression
STA*  ADDV
STA   I
STA   J
```

5. How does one write the equivalent of the Algol 60

   a := b[i+j] ?

   Clearly the X register must be loaded with i+j. The X register is word 0 of the machine, so the assembler has a declaration set up for the integer x, which is given the address 0. So the above can be written:

   x ← i + j;
   a ← b[**xsymbol**]

   This generates the code

```
LDA   I
ADD   J
STA   0
LDA*  B
STA   A
```

To summarise, the facility provided by assignment statements in PL516 is very similar to that of Algol 60.

4.2.6 Statements using conditions

One of the distinguishing features of Algol 60 over Fortran is that fewer labels are required. This is because flow of control can be expressed via conditional statements and for loops. This feature of Algol 60 is present in PL516. Three forms of conditional control statements are available.

$< 6.0 if\ statement >$::= **if** $< 3.0 condition >$ **then** $< 10.0 statement >$
else $< 10.0 statement >$

The effect of this statement is similar to the construction in Algol. If the condition is true the the first statement is executed otherwise the second statement is executed. Representing the flow of control with jumps by arrows, the code generated is as follows:

```
<condition code>
JMP false         -------------> a
<extra condition code>
<code from first statement>
JMP               -------------> b
<code from second statement> a<------
                             b<------
```

Examples can be given using assignment statements as statements.

1. **if** a **zero then**
   a ⟵ b + c
   else
   b ⟵ c + d

   This generates the code

```
LDA  A
SZE
JMP  false          -------------> a
LDA  B
ADD  C
STA  A
JMP                 -------------> b
LDA  C                           a<------
ADD  D
STA  B
                                 b<------
```

2. Add 3 to a[i] if a[i] is even, otherwise subtract 6 from a[i].

   if a[i] **even then**
   a[**xsymbol**] ⟵ **accumulator** + 3
   else a[**xsymbol**] ⟵ **accumulator** - 6

   Note the use of **xsymbol** and **accumulator** which reduces the size of code generated, which is:

```
LDX  I
LDA* A
SLZ
JMP  false          -------------> a
ADD  =+3
STA* A
JMP                 -------------> b
SUB  =+6                         a<------
STA* A
                                 b<------
```

3. In the above example two STA* A instructions are generated which would not be produced if it were hand coded. However this can be avoided by writing:

   if a[i] **even then**
   accumulator ⟵ **accumulator** + 3
   else **accumulator** ⟵ **accumulator** - 6;
   a[**xsymbol**] ⟵ **accumulator**

   Which generates

```
LDX  I
LDA* A
SLZ
JMP  false          -------------> a
ADD  =+3
JMP                 -------------> b
SUB  =+6                         a<------
STA* A                           b<------
```

It must be remembered that repeated use of **xsymbol** and **accumulator** especially over a number of statements, makes the program less clear, since the reader must scan the text backwards to work out the value of the X or A register.

4. In fact the above example can be more elegantly coded using a conditional expression. For instance

   a[**xsymbol**] ← **if** a[i] **even then accumulator** + 3 **else accumulator** - 6;

   This produces the same machine code as the previous example.

5. There are no boolean variables, so integers must be used instead. The convention 0 = **false** and -1 = **true** means that **and** and **nev** have the usual meaning.

   Hence the Algol 60 statement

   if a **and** b **then**
   c := ar[i]
   else
   d := ar[j];

   would be written in assembly code as

   if a **and** b **nonzero then**
   c ← ar[i]
   else
   d ← ar[j];

   This generates the code

```
LDA  A
ANA  B
SNZ
JMP  false          -------------> a
LDX  I
LDA* AR
STA  C
JMP                 -------------> b
LDX  J                       a<------
LDA* AR
STA  D
                             b<------
```

   Note that if statements always have an **else**. The reason for this is to avoid the ambiguity that existed in the original Algol 60 report[4]. The revised report overcame this by making the syntax more complex. This was not thought appropriate in this case, since being able to add a new statement type would not be so easy. If no **else** is required then a when statement is written.

$< 6.0 if\ statement >$::= **when** $< 3.0 condition >$ **then** $< 10.0 statement >$

The machine code generated for this is:

```
<condition code>
JMP  false          -------------> a
<extra condition code>
<code from statement>
                             a<------
```

1. **when** xx $\leq$ y **then**
   accumulator $\leftarrow$ y;
   maxxy $\leftarrow$ **accumulator**

   Note that the A register is either set with xx by the condition or by y from the first assignment statement.

   This generates the code

```
LDA  XX
CAS  Y
JMP  false          -------------> a
NOP
LDA  Y
STA  MAXXY                 a<------
```

2. Load into the accumulator the sense key reading as a binary number.

   accumulator $\leftarrow$ **zero**;
   when sense1 then
   accumulator $\leftarrow$ **accumulator** + 1;
   when sense2 then
   accumulator $\leftarrow$ **accumulator** + 2;
   when sense3 then
   accumulator $\leftarrow$ **accumulator** + 4;
   when sense4 then
   accumulator $\leftarrow$ **accumulator** + 8;

   Not surprisingly the **accumulator** symbol is a single character on the Teletype representation (see Appendix A). The code generated for all this is

```
CRA
SS1
JMP  false  ( =+1 )
ADD  =+1
SS2
JMP  false  ( =+1 )
ADD  =+2
SS3
JMP  false  ( =+1 )
ADD  =+4
SS4
JMP  false  ( =+1 )
ADD  =+8
```

   Such repeated use of the accumulator symbol makes this one of the few cases when the DAP is shorter to write than PL516.

The last form of statement using conditions is the while statement - a surprising omission from Algol 60. The syntax is:

$< 6.0 while\ statement >$::= **while** $< 3.0 condition >$ **do** $< 10.0 statement >$

The code generated is:

```
<condition code>            b<-----
JMP  false          -------------> a
<extra condition code>
<code from statement>
JMP                 -------------> b
                            a<------
```

So the statement is repeatedly executed while the condition is true.

1. Find the first non-zero element of an array form a[i] onwards

   while a[i] **zero then**
   i ← i + 1;

   This generates the code

```
LDX   I a<-----
LDA*  A
SZE
JMP   false
LDA   I
ADD   =+1
STA   I
JMP   ------>a
```

   So a[i] now has a non-zero value.

2. Find the first differing elements of the two arrays a and b

   while a[i] = b[**xsymbol**] **then**
   i ← i + 1;

   This generates the code

```
LDX   I a<-----
LDA*  A
CAS*  B
SKP
SKP
JMP   false --->b
LDA   I
ADD   =+1
STA   I
JMP   ------>a
      b<---------
```

4.2.7 Loop control

The machine instruction IRS (IncRement in Store, see page 5) is clearly intended for loop control. If one wishes to go round a loop 3 times, then a word in store 'COUNT' is used for this which is given the value initially of -3. The loop control is then done by:

```
IRS  COUNT
JMP  <to beginning of loop>
```

This mechanism is very crude in that one must always increment by +1 up to -1 and one must always go through the loop once. Nevertheless this mechanism is adequate for the vast majority of ordinary loops. So it is adopted for PL516.

$< 7.0 for\ statement >$::= **for** $<$ {**ind**} $<$ $14.1 integer\ identifier >$←$<$ $1.0 expression >$|
$< 7.1 xassignment\ statement >>$
do $< 10.0 statement >$

$< 7.1 xassignment\ statement >$::= **xsymbol** ←$<$ $1.2 cell >$

A special case is where the count is word 0 of the machine. This is the X register which allows indexing to be performed efficiently. In this case, loop control does not use the accumulator since the initial loading of the X register can be done by an LDX operation. This is reflected in the syntax by the option using the 'xassignment statement'.

The code generated is as follows:

Without the xassignment statement.
```
STA  CONTROL
        a<---------------
<code from statement>
IRS  CONTROL
JMP     ----------------->a
```

The STA and IRS instructions have the indirect bit set if the integer control variable has **ind** in front of it.

with the xassignment statement.
```
LDX  <address of cell>
        a<---------------
<code from statement>
IRS  0
JMP     ----------------->a
```

One important consequence of this method of loop control is that it is convenient if array elements are addressed for $-n$, to -2, -1. Rather than produce arrays in either order (as in DAP) for consistency *all arrays are addressed from -(size of array in words) to -1*. This means that control variables have the opposite sign to what would be usual in Algol 60 and the scanning is in the opposite direction (although in the direction of increasing address).

Examples:

1. Add two vectors element by element putting the result in a third vector. Assume that the number of words in the vectors is -size.

   This simple loop can be coded using the X register as the control variable thus:

   for xsymbol ← size **do**
   a[**xsymbol**] ← b[**xsymbol**] + c[**xsymbol**]

   This generates the machine code

```
LDX   SIZE
        a<---------------
LDA*  B
ADD*  C
STA*  A
IRS   0
JMP     ----------------->a
```

   Note that size is negative, and that -30 (for instance) could have been written instead of size. This would be undesirable since changing the program for a different size of arrays would require going through the entire program text altering all the constants.

2. Find the largest element of an array.

   This might be written in Algol 60 thus:

   j := c[1]; **for** i := 2 **step** 1 **until** size **do**
   if c[i] > j **then** j := c[i]

The straightforward way of coding this in PL516 would be

j ← c[1]; **for** i ← **inc** size **do**
    when c[i] > j **then** j ← **accumulator**

Note that i is used as the control variable since an expression is required initially (since **xsymbol** ← **inc** size is not valid). the **if** in Algol must be changed to **when** since there is no **else** in the statement.

Th code generated is

```
LDX   SIZE
LDA*  C
STA   J     from j <- c[size]
LDA   SIZE
AOA
STA   I     from i <- inc size
        a<---------------
LDX   I
CAS*  C
JMP   *+3
NOP
JMP   false  --->b
STA   J            since c[i] is in the A register
IRS   I     b<----
JMP     ----------------->a
```

3. It is however possible to code this using the X register as the control variable. In this case, the largest element of the array so far is kept in the accumulator.

   This is written as

   accumulator ← c[size]; **for xsymbol** ← **inc** sizep1 **do**
       when accumulator < c[**xsymbol**] **then**
           accumulator ← c[**xsymbol**]

   The code generated is

```
LDX   SIZE
LDA*  C
LDX   SIZEP1
CAS*  C   a<--------------
JMP   *+3
NOP
JMP   false  --->b
LDA*  C
IRS   0     b<----
JMP     ----------------->a
```

   Note that this code is very nearly optimal. This is achieved by use of **xsymbol** and **accumulator** but as a consequence the program is much less intelligible. The new constant ‘sizep1’ has the value one more than size.

More complex **for** loops that exist in Algol 60 must be coded differently in PL516. This can usually be done conveniently with a **while** statement without using labels.

For instance the Algol 60 **for** i := j **step** k **until** n **do**, where n could have a value of zero so that the controlled statement is not executed. This can be code as:

i ← j;
while i ≤ n **do**
    begin
    <controlled statement>;
    i ← i + k
    end

Note that the example 5 given in 4.2.5 could not have been written as

xsymbol ← i + j;
a ← b[**xsymbol**]

Since the first statement is not a valid assignment statement as i+j is not a cell. So x is used when one is using the X register as an ordinary integer but **xsymbol** is used when its special properties as an index register are being exploited.

4.2.8 Goto statements

Because of the generality of statements using conditions very few labels need be written in most programs. Statements can be lebelled in a similar manner to Algol 60 as will be explained in section 4.2.10. Two forms of **goto** are provided as follows:

$< 8.0 goto\ statement >$::= **goto** $<< 14.6 label\ identifier >|$
$< 14.7 switch\ identifier >< 2.0 subscript >>$

The statement **goto** ll would generate the single instruction JMP LL.

Switches are set up in a manner similar to arrays as explained on page 4. As with arrays, the index is negative, so a 3 element switch have index values -3, -2 and -1. Although there is no logical necessity to have them with negative values it is convenient for the mechanism to be the same as arrays.

The code generated from **goto** SS[i] is

```
LDX   I
JMP*  SS
```

The switch word SS has the index and indirect bit set. Assuming i is within range (this is not checked!) the next level of indirection (after indexing) will give the 14 bit address of the label in the switch. The way the switch elements are set up is described in 4.2.12. Note that since the subscripting of switches is the same as arrays, **xsymbol** can appear instead of an integer.

Examples

1. Find an element of an array ‘a’ equal to i, and goto the corresponding element of a switch ‘branch’. Otherwise goto the label ‘error’.

   accumulator ← i;
   for xsymbol ← size **do**
       when accumulator = a[**xsymbol**] **then**
           goto branch[**xsymbol**];
   goto error

   Note that the accumulator has been loaded with i outside the loop.

   The code generated is

```
LDA   I
LDX   SIZE
LDX   SIZEP1
CAS*  A   a<--------------
SKP
```

```
SKP
JMP   false  --->b
JMP*  BRANCH
IRS   0     b<----
JMP     ----------------->a
JMP   ERROR
```

2. There is no designational expressions in PL516, so that the Algol 60

   goto if xx > 0 **then** ll **else** error1

   must be written as

   if xx > 0 **then goto** ll **else goto** error1

   This generates the code

```
LDA   XX
CAS   =0
JMP   *+3
NOP
JMP   false     --->b
JMP   LL
JMP             --->a
JMP   ERROR1    b<---
                a<---
```

   This is one of the few cases where PL516 generates code which is substantially worse than hand coding. Note the non-executable jump round the 'else statement'.

4.2.9 Procedure calls

There are four types of procedures in PL516. A procedure may expect a parameter and it may be a 'conditional' procedure. All four types exist but they may only be called in the appropriate context. All procedures may leave a result in the accumulator. Procedure calls can occur in three different contexts. The first is in $< 1.1 term >$ and the second $< 3.0 condition >$ which have been given. The last context occurs in the next section as a statement. The syntax is:

$< 9.0 procedure\ call >$::= $< 14.1 procedure\ identifier > \{(< 1.0 expression >)\}$

$< 9.1 conditional\ procedure\ call >$::= $< 9.0 procedure\ call >$

the second rule is written down separately to imply a check in the compiler that only conditional procedures can be called in the context of a condition, and that they may not be called in the other two contexts. Apart from being conditional a procedure may have one parameter. This parameter is an expression which is evaluated before entering the procedure. Hence by analogue with Algol 60, one value parameter is allowed in which case the value of the expression is in the accumulator on entry to the procedure.

So the code generated is

```
{<code from expression>}
JST*  <procedure>
```

The procedure call is always indirect since the address of the procedure is kept in sector 0 as explained on page 4.

It is always assumed that procedures leave the A register set appropriately. So the same procedure can be called in $< term >$ (which is clearly expects this) or in $< statement >$. But if a procedure is an **accumulator** procedure then on every call it must have a parameter.

Examples are given of each of the four types of procedure.

1. ‘readn’ is an ordinary procedure which reads a number off a given input device.

   i, j, n ← **neg** readn + 1

   This generates the code

```
JST*    READN
TCA
ADD     =+1
STA     I
STA     J
STA     N
```

2. However readn could be called as a statement producing the single instruction JST* READN. This would merely have the effect of skipping over one number on the input device (assuming the contents of the accumulator was not used).

3. ‘square’ is procedure with one parameter which produces the square of the parameter as the result.

$$y^4 + 2y^2 + 6$$

   can be evaluated by the expression

   square(square(y)+1)+5

   This generates the code

```
LDA     Y
JST*    SQUARE
ADD     =+1
JST*    SQUARE
ADD     =+5
```

4. In the version of the PL516 compiler in its own language there is an **accumulator conditional procedure** ‘bsis’. This determines whether or not the current basic symbol is one of a number of types, that is, unary operator, binary operator etc. This is done by searching a table from a position depending on the particular type.

   For instance, the code to deal with the binary operator or shifts in expression is as follows:

```
morebinorshift: if bsis then
                    begin
                    nbs;
                    cell;
                    <code generation for binary operators>
                    goto morebinorshift;
                    end
                else
                    when bsis(shift) then
                        begin
                        nbs;
                        constant;
                        <code generation for shifts>
                        goto morebinorshifts
                        end;
```

   The routine nbs reads the next basic symbol off the paper tape, and cell and constant deal with the corresponding syntactic units. The details of code generation are omitted.

   This generates the code

```
MOREBINORSHIFT    LDA  BINARY
                  JST* BSIS
                  JMP  false  (to LDA SHIFT)
                  JST* NBS
                  JST* CELL
                  <code generation for binary operator>
                  JMP  MOREBINORSHIFT
                  JMP    jump over else: never executed
                  LDA  SHIFT
                  JST* BSIS
                  JMP  false  (to end)
                  JST* NBS
                  JST* CONSTANT
                  <code generation for shifts>
                  JMP  MOREBINORSHIFTS
```

One can see from this how the compiler keeps scanning the text until a symbol which is not a binary or shift is reached. The parameter to bsis is clearly necessary so that it is known which part of the table to scan.

Thus conditional procedures in PL516 are very similar to boolean procedures of Algol 60.

4.2.10 Statements

Many of the types of statement have already been introduced. The complete list is as follows:

$< 10.0 statement >$::= $< 5.0 assignment\ statement >|$
$< 6.0 if\ statement >|$
$< 6.1 when\ statement >|$
$< 6.2 while\ statement >|$
$< 7.0 for\ statement >|$
$< 7.1 xassignment\ statement >|$
$< 8.0 goto\ statement >|$
$< 9.0 procedure\ call >|$
$< 14.6 label\ identifier >:< 10.0 statement >|$
$< 10.1 null >|$
$< 10.2 compound\ statement >|$
$< 11.0 code\ statement >|$
exittrue
exitfalse
sbug

$< 10.1 null >$::=

$< 10.2 compound\ statement >$::= **begin** $<< 10.0 statement > list <; >>$ **end**

A compound statement is the same as in Algol 60, namely **begin** followed by a list of statement separated by semicolons followed by **end**. The code generated is, of course, just the concatenation of the code from the individual statements.

Most of the statements have already been explained, note that conditional procedures cannot be called as statement.

Any statement can be labelled and within the scope of the label a goto statement can transfer control to that point. Hence it is possible to jump into the middle of a **for** loop (NB not valid in Algol 60). The effect of this would depend on the value of the control variable before executing the goto.

Code statement is dealt with in the next section; it merely provides a convenient method of writing DAP-like instructions within the program.

The instructions **exittrue** and **exitfalse** provide a means of exit from a conditional procedure. Their use other than inside a conditional procedure is regarded as an error by the compiler. The code generated for **exittrue** is

```
IRS   <return address>
JST*  <return address>
```

and for **exitfalse** is

```
JST*  <return address>
```

So **exitfalse** is the ordinary return instruction, but **exittrue** increments the return address by one before returning. (Note: the result can never be zero.) This corresponds to the expected action of conditional procedure calls in conditions (see 4.2.3).

The last statement **sbug** is a diagnostic aid. It is either regarded as a dummy statement or as a call of a procedure whose address word is placed in a fixed position octal 777 in sector 0. Hence the code generated is:

```
JST*  '777
```

The procedure called in this way can be provided by the user, and can usefully print out the position of its call, contents of the accumulator etc. Further details are given in the program notes for the version of the compiler in use.

Examples

1. There is a conditional procedure in the PL516 compiler which is used to tell if a character is a letter. The main coding of this procedure is:

   when accumulator $\leq$ zsymbol **then**
   when accumulator $\geq$ zsymbol **then**
   exittrue

   This produces the DAP

   ```
   CAS  ZSYMBOL
   JMP  false      (to end)
   NOP
   CAS  ASYMBOL
   NOP
   SKP
   JMP  false      (to end)
   IRS  <return address>
   JMP* <return address>
   ```

   If the **exittrue** is not executed, then the ordinary exit is made from the procedure (which is **exitfalse**).

2. A single procedure deals with constants as defined in 4.2.4. The coding of this procedure can now be followed:

   if bs = charsymbol **then**
   begin
   value ← **swop** inchar;
   value ← inchar+value;
   nbs;
   value ← **zero**
   end else if numerical(bs) **then**
   begin
   number;
   vadd ← **zero**
   end else if bs = addsymbol **then**

```
        begin
        nbs;
        if bs = indsymbol then
                begin
                value ← octalsymbol 100000;
                nbs;
                end    else
                value ← zero;
        when bs = indexsymbol then
                begin
                value ← octalsymbol 40000;
                nbs;
                end;
        typeidentifier;
                when add > octalsymbol 777 then
                add ← add - octalsymbol 1000 + sectno;
        value ← value + add;
        vadd ← zero;
        end
else if letter(bs) then
        begin
        identifier;
        if type = const then
                begin
                value ← getcode(add);
                vadd ← add;
                end    else if type - compconst then
                begin
                value ← add;
                vadd ← zero;
                end
        else
                fail(notconst);
        end
else
        fail(badstart)
```

The code closely follows the syntactic definition. 'nbs' (next basic symbol) reads the next compound symbol from the paper tape. 'inchar' reads a character. The coding sets the value of the constant in 'value', and its address (if it has one) in 'vadd', otherwise 'vadd' is set to zero. If the constant is a declared constant then 'getcode' is used to get the value of the constant from the code already generated.

The generated code is not given, since it is straightforward. The example does illustrate the similarity of the coding with Algol 60. Note that each compound statement can be studied in isolation, making it easier to follow the overall structure. The coding is by no means optimal, the **accumulator** sysmbol could be used in a number of places, but this would reduce the clarity of the procedure.

4.2.11 Code statement

Code statements provide a means of writing DAP-like machine code within a PL516 program. This is certainly necessary for input-output instructions since they are not otherwise available. For completeness, the full range of DAP instructions are available (but not the pseudo-instructions). Using these instructions when it is possible to achieve the same effect with ordinary statements loses the point of PL516. For this reason writing code statements should be kept to a minimum except where necessary or (as sometimes happens) a code statement is clearer than the equivalent PL516 coding.

In keeping with the rest of the language, code statement are in free-format, and have the following syntax.

$< 11.0 code\ statement >$::= **codesymbol** $<< 11.1 memory\ reference >|$
$< 11.2 I/O\ or\ shift >|$
$< 11.3 generic >>$

$< 11.1 memory\ reference >$::= $< memory\ reference\ mnemonic >$
$<$ **ind** | **index** | $bfindindex\ |, >< 11.4 address\ field >$

$< 11.2 I/O\ or\ shift >$::=$< I/O\ or\ shift\ mnemonic >, < 4.0 constant >$

$< 11.3 generic >$::=$< generic\ mnemonic >$

$< 11.4 address\ field >$::= $< 11.5 type\ identifier >|< 4.1 number >|$
$* < 4.1 number >$

$< 11.5 type\ identifier >$::= $< 14.1 integer\ identifier >|$
$< 14.2 procedure\ identifier >|$
$< 14.3 array\ identifier >|$
$< 14.4 constant\ identifier >|$
$< 14.6 label\ identifier >|$
$< 14.7 switch\ identifier >$

Hence the syntax depends upon the type of mnemonic encountered. Naturally a generic mnemonic completes the statement. For shift or input-output mnemonics a constant follows. Note that the constant can be declared constant given an appropriate identifier. In the case of shift instructions, the constant is negated and truncated to 6 bits before inserting in the instruction.

The memory reference instructions are more complex. The **ind** and **index** symbols cause the indirect and index bits to be set in the instruction. The address field gives the other 10 bits of the instruction. In the case where this is a number, the value of this is put in the instruction. In the final case of the star proceeding a number, the current instruction address is added to the number and this inserted in the instruction. This convention with numbers is identical to DAP.

The most important address field is a type identifier. In this case the 10 bits inserted in the instruction are the short address of the appropriate variable. For integers and constants this is just the short address of a word in store. For arrays and switches this is the address of the 'array' word. For procedures the address is to the word in sector 0 giving the long address of the link (see page 4). For labels, the address depends upon whether the label is global or local (see 4.1.12) for details. In the case of a global label the address is to a word in sector 0 giving the full address of the label (as for procedures). But with local labels the address gives the address of the labelled statement. No reference is possible to compile constants in memory reference instruction. The reason for this is that the meaning would not be clear - is the value or the address of the constant to be inserted in the instruction? For technical reasons the generic instruction OTK must be written as **codesymbol** OTK,0.

Examples

1. In the compiler, the instruction mnemonics and binary instructions are stored alternately in the array mcode. A linear search is made as follows

```
for xsymbol ← -176 do
    if mcode[xsymbol] = ident1 then
        goto found;
    else        codesymbol IRS, 0;
```

The IRS instruction achieves the same effect that **step** 2 would do in Algol 60. The generated code is

```
LDX   =-76
LDA*  MCODE  a<-----
CAS   IDENT1
SKP
SKP
```

```
JMP   false
JMP   FOUND
JMP       over else, never executed
IRS   0
IRS   0
JMP        -------->a
```

The use of the IRS to increment a word in store (when no skip is expected) is by far the most frequent machine code instruction in code statements.

2. Read a character from the paper tape reader.

codesymbol OCP, 1;
codesymbol INA, **octalsymbol** 1001;
codesymbol JMP, *-1;
codesymbol OCP, **octalsymbol** 101;

Needless to mention **codesymbol** is represented by a single character (%) on the teletype.

3. Output a character to the teletype.

codesymbol SKS, **octalsymbol** 104;
codesymbol JMP, *-1;
codesymbol OCP, **octalsymbol** 104;
codesymbol JMP, *-1;

Type identifier has occurred twice in the syntax already. The first case was in $< 1.1 term >$. The effect of **codeword** $< typeidentifier >$ is to generate the instruction LDA, <type identifier>. By this means, array words may be loaded into the accumulator without using code. The use of this facility is explained in section 5.4.

The second case was in $< 4.0 constant >$. Address constants give a method of setting long addresses. The bottom nine bits of the address is as for <type identifier> in code instructions. The sector number is either 0 (global variables) of the current sector number (local variables). This distinction will become clear when declarations are considered in the next section.

4.2.12 Declarations

The purpose of declarations is the same as in most programming languages, namely to inform the compiler of a new variable. Variables can be declared at one of two levels; either globally so that they can be accessed at any point in the program or locally in which case they can only be accessed in the procedure in which they are declared. All local variables are accessed with the 'this sector bit' set in the memory reference instruction. Consequently no procedure can be more than 512 words nor can a procedure straddle sector boundaries. Similarly global variables or pointers to them are kept in sector 0, so not more than 512 global variables may be declared. Neither of these restrictions have been found to be too severe. The compiler itself uses 150 locations in sector 0. The average length of procedures in the compiler is about 50 words, so the loss due to desectoring is small. Techniques are described in section 5.3 to remove even this loss.

Unlike Algol 60, the scope of a variable is from its declaration until the end of the program or procedure in which it is declared. This is to allow for one-pass translation. Hence all variables must be declared before use (with the exception of local labels as explained below). Space is allocated to a variable on its declaration - either in sector 0 for globals of the current sector for locals. arrays, string, switches and procedures which are declared globally only have their address words in sector 0, the main body being in the current sector.

The syntax of declarations is

$< 12.0 declaration >$ ::= **integer** $<< 14.1 integer\ identifier > list <, >>|$
array $<<< 14.3 array\ identifier >$
$< $ **later** $|< 12.1 array\ values >>> list <, >>|$
constant $<<< 14.4 constant\ identifier >=< 4.0 constant >> list <, >>>|$
compconstant $<<< 14.5 compile\ constant\ identifier >=< 4.0 constant >> list <, >>>|$
switch $<<< 14.7 switch\ identifier >=<< 14.6 label\ identifier > list <, >>>|$
label $<< 14.6 label\ identifier > list <, >>|$
string $<<< 14.3 array\ identifier >=$
$< char1 >< any\ string\ character\ excluding char1 >_0^*< char1 >> list <, >>$
{ **accumulator** } { **conditional** } **procedure** $< 14.2 procedure\ identifier >;$
$< 13.1 procedure\ body >$
list $< 4.0 constant >|$
origin $< 4.0 constant >< + | - >< 4.0 constant >>_0^*|$
global $< 4.0 constant >|$
nextsector |
set $<< 14.3 array\ identifier >< 12.1 array\ values >> list <, >>|$
forward { **accumulator** } { **conditional** } **procedure**
$<< 14.2 procedure\ identifier > list <, >>|$
$< 10.1 null >$

$< 12.1 array\ values >$ ::= $[< 4.0 constant >]$
$\{(<< 4.0 constant >|\ " < string character >_0^*\ " > list <, >>>)\}$

This long syntax is not complex since it divides naturally into syntax for each type of declaration. Each one is taken separately.

Declaration of integers

The syntax merely says that **integer** is followed by a list of integer identifiers separated by commas. The integers are allocated space in sector 0 or the current sector in the order of declaration. The initial value of the integer is undefined (that is, not necessarily zero).

Constants and compile constants

the syntax is identical. Constants are given storage in the same way as integers but are initialised with the value given. no storage is given to compile constants, so this facility is really to provide a mnemonic for explicit constants of a program.

constant i = 10, j = i; is valid giving i and j both the value 10.

All the bounds of array and other such constants should be declared constants or compile constants so that changes can be made merely by altering the declaration.

Arrays

One dimensional arrays are declared by giving the number of words required in square brackets. The option facility in array values allows one to give initial values to the elements of the array. The actual array can be positioned at any point in the core by means of the **later** facility. If the array is to be used it must be declared, but it may not be convenient for the array to be positioned at that point in the code. In this case the array is declared **later** and the storage set aside when the set declaration is reached. The absolute value of the constant in the square brackets is taken as the number of words in the array (which can be zero: a reason for this is given in section 5.5). This means the same constant can be used for **for** loop control ie,

```
constant size = -100;
...
array a[size],
...
        for i ← size do
                begin
                end
```

With global arrays only the array word goes into sector 0, the rest being with the code from procedures etc.

Initial values which are simple constants are assigned in the order of increasing core location. An error is produced if more constants are given than words allocated to the array. The " $< stringcharacter >$ "$^{*}_{0}$ facility is to include arbitrary length strings within an array. The string characters are read and packed two to a word. The last word is filled out with a space if necessary.

Example

array a[-5] (10, **octalsymbol** 764, "ABC")

For words of this array are specified as follows: a[-5] = 10, a[-4] = 500, a[-3] = "AB" (A at the top), a[-2] = "C ", so a[-1] is undefined.

Strings

Except for the declaration, strings are logically the same as arrays. One must have some facility for setting alphanumeric strings without having to work out the length of it in advance (unlike Fortran!). String declarations provide this facility. The string elements are addressed from 0 upwards for obvious reasons. The initial character <char1> acts as a terminator of the string, but is not stored with the string.

Example

string error = /_ERROR_NUMBER./,
linen = /_LINE_NUMBER./

The string 'error' is initialised as follows: error[0]='_E', error[1]='RR', error[2]='OR', error[3]='_N', error[4]='UM', error[5]='BE', error[0]='R.'. The string 'linen' also requires 7 words (plus one for the array word) the extra half-word being filled with a space.

Labels

Unlike Algol, labels must in general, be declared. The only exception is a label local to a procedure which first occurs in a **goto** statement or as a label. It must be declared if a global label with the same identifier has been declared and the first occurrence is in a **goto** statement. In most cases local labels need not be declared, but global labels must always be declared.

Local labels are not allocated any space, since the labelled statement is always referenced in the current sector of code. By means of global labels control can be transferred to any part of a procedure or main program. When a global label is declared a word is set aside for its long address which is set on meeting the labelled statement. Hence a jump to a global label is an indirect jump via the address word in sector 0.

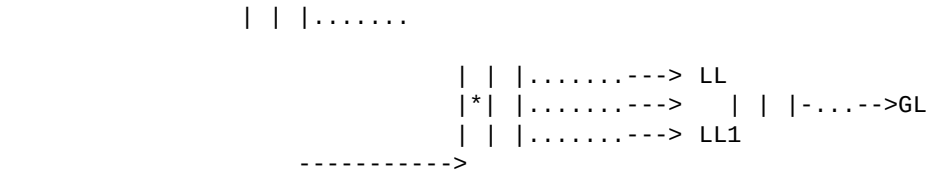
Switches

A switch is an array of labels. These labels must have previously been declared. The mechanism for setting up the switch word is described on page 4. If the label in the switch is global then an extra level of indirection occurs to access the address word of the global label.

Example

switch SS = LL, Gl, LL1

where LL and LL1 are local and GL is global, then **goto** SS[-3] goes to LL, etc. The storage and pointers are as follows:



Note that local labels in the switch have the current sector number incorporated with the address of the label to give the long address. Global labels have the indirect bit set but the sector number is zero.

Procedures

Unlike all the types mentioned so far, procedures can only be declared globally. So procedures may not be nested (a rarely-used feature of Algol 60). The address word of the procedure is set up on the declaration and the address of the link inserted when the procedure coding is reached. As explained in the other sections, procedures can be of our different types. This is specified by the **accumulator** and **conditional** symbols which precede **procedure**. Procedures may be declared forward, ie in advance of the main coding. This is to allow for recursion (the compiler is a recursive program). It can also be used for

the procedures to be placed in any order (alphabetical, for instance) rather than an order depending on the calling structure. A method of using forward declarations for program segmentation is given in section 5.7.

List directive

The constant given controls the information listed during compilation on the teletype. This can include the machine-code generated (printed in DAP-like form) and the name list. Details can be obtained from the programming notes for the version of the compiler in use, together with the default value for the list constant.

Origin directive

This directive can only appear as a global declaration. It performs a similar function to the ORG pseudo-operation code of DAP. The constant expression following **origin** is taken as the long address of the next position for the generating local code. If paper tape output of the generated code has been requested, the local code generated so far will be output. Because explicit constants are always accessed with the 'this sector' bit set, the constant pool is also output at this stage and references to it filled in.

The position of code generation initially is given in the programming notes for the version of the compiler in use - it is ordinarily octal 1000.

The directive **origin** 0 has a special meaning. Here the constant pool is cleared and code generated, but the position for the next generation of code is not advanced (and so is next to the end of the constant pool). This can be used to generate code without gaps at sector boundaries as explained in section 5.

The **origin** directive also divides up the current address for code generation between the sector number and 9 bit displacement within the sector. This must be done before instruction code generation. For instance

array a[1000];
procedure p1;
<procedure body>

would not work since the 1000 words allocated for the array would spill over the sector boundary. So an origin directive must be inserted between the array and procedure declaration. **origin** 0 would be appropriate here if it is known that p1 will not then straddle a sector boundary.

The additional generality of the origin directive is to allow greater flexibility in positioning code. For instance, a program could be arranged as follows

compconstant baseadd = **octalsymbol** 1000;
origin baseadd + **octalsymbol** 2000;
etc

So that altering one compile constant can shift the code into any position in core.

Next sector directive

A disadvantage of the origin directive is that usually one must be placed for each sector of code. So large programs will have several making it awkward to change its position in core. The next sector directive overcomes this by clearing the constant pool and then incrementing the address for local code generation to the beginning of the next free sector. This directive can be used liberally during program testing to avoid any difficulty with procedures straddling sector boundaries.

Global directive

The constant after **global** must be greater than 16 and less than 512. The constant specifies the address in sector 0 at which succeeding words must be taken. So

global octalsymbol 400;
forward procedure p1, p2, p3;

means that the procedure words for p1, p2, p3 would occupy words '400, '401 and '402 respectively. no check is made by the compiler that **global** has not been misused to assign a word twice to the same location in sector 0. This directive is not likely to be very mush used, but is is valuable for program segmentation (see sector 5).

The declarations

global octalsymbol 776;
forward procedure pabug, psbug;
global octalsymbol 400;

at the beginning of the program text allows one to trap calls generated for **abug** and **sbug** and make them enter a user defined procedure.

4.2.13 Program and procedures

Program and procedures have the same structure, but as explained in 4.2.12.7, procedures cannot be nested. The syntax is

$< 13.0 program >$::=$<<$ $12.0 declaration > list <; >><$ $10.2 compound\ statement >$

$< 13.1 procedure\ body >$::=$<<$ $12.0 declaration > list <; >><$ $10.2 compound\ statement >$

Note that the body of the procedure/program coding is a compound statement (unlike Algol 60). This is to simplify the compiler - the **begin** is used to separate the declarations from the statements. Since procedure declarations cannot be nested, this syntax implies that declarations can only be inserted at program level (ie, globally - the address information or value being inserted in sector 0) or at procedure level (locally so that access is with the 'this sector bit' set). Hence blocks in the Algol 60 sense do not exist.

Examples

1. Procedure 'outchar' prints a character on the monitor typewriter leaving the accumulator undisturbed.

   procedure outchar;
   begin
   codesymbol SKS, **octalsymbol** 104; **codesymbol** JMP, *-1;
   codesymbol OCP, **octalsymbol** 104;
   codesymbol OTA, 4; **codesymbol** JMP, *-1;
   end

2. Use the above procedure to print a new line on the monitor.

   procedure newline;
   constant crlf = **octalsymbol** 106612;
   begin
   outchar(**swop** crlf);
   outchar(**swop accumulator**)
   end

   Note that the second call of 'outchar' assumes that the contents of the accumulator has not been changed by outchar. It would be safer to write outchar(crlf) for the second call.

More examples of complete programs are given in section 5.

4.2.14 Identifiers

$< 14.1 integer\ identifier >$::=$< identifier >$

$< 14.2 procedure\ identifier >$::=$< identifier >$

$< 14.3 array\ identifier >$::=$< identifier >$

$< 14.4 constant\ identifier >$::=$< identifier >$

$< 14.5 compile\ constant\ identifier >$::=$< identifier >$

$< 14.6 label\ identifier >$::=$< identifier >$

$< 14.7 switch\ identifier >$::=$< identifier >$

The purpose of adding this to the syntax is to imply a type-check by the compiler. On the declaration a check is made to ensure the identifier has not been used at that level. Note that the first occurrence of a local label may be at a **goto** or the label itself, in which case the declaration is set-up then. On the use of an identifier, the type check is made as implied by the syntax.

Two version of the compiler exist and they differ slightly in the definition of an identifier. The version for the DDP-516 in order to economise in core uses 5 bits for each character (giving 3 per word). This means that the identifier alphabet has to be restricted. The alphabet chosen is A to Z, 1, 2, 3, 4 and 5. this conveniently includes the characters used in DAP mnemonics.

A further economy in the compiler has been to use the same routine for reading an identifier, a basic symbol and a DAP mnemonic. For this reason, internal spaces my not appear in an identifier. Also basic symbols are terminated by a non-identifier character (space, for instance). The hardware representation is given in Appendix A.

5 Further examples and programming advice

In this section all examples are given in the representation of the basic symbols that has been chosen for the teletype. this representation is given in full in Appendix A. The examples have been copied directly from the paper tape. The comment convention is the "&" and all the characters following on that line are ignored.

5.1 Condition test: a simple example

This program was the first one to compile and execute correctly. It tests the relational operators, and in so doing uses quite a number of the language features.

The program listing contains as comments the machine code generated by the compiler. This is in two columns. The first gives the address where the compiled code was placed. The address is either in sector 0 for global simple variables and pointers or in the current sector for the main code. The second column gives the contents of the address given either in instruction format or octal or UNDEFINED (meaning that no assignment is made by the compiler to that location).

Note that only the array word for A goes into sector 0 at 103. This word has the index bit set and points to location 1003 - one word beyond the three elements of the array. A word containing address of the procedure OUT1 goes into sector 0 next. The code of the procedure follows on from the end of the array. Usually code statements would be typed in a more compact manner but one instruction per line is used here to improve the layout. The return link is planted in 1003 by a call of OUT1 and return is done by the indirect jump at 1011. The procedure OUT2 illustrates the procedure call mechanism. On entry to OUT2 the accumulator contains two characters which are to be typed on the control typewriter. OUT1, being an accumulator procedure, has an expression as a parameter. The expression .SWOP @ interchanges the characters in the accumulator to print each character.

The constants are given space in the same way as CASE, I and J but are given the appropriate value, as can be seen from the last column.

The conditional procedure RELATION is the main part of the program. The label declarations merely tell the compiler that LE etc are local labels, so that the switch declaration can be compiled. The switch declaration is a local one so all the words are in the current sector. The switch word itself has both the indirect and index bits set. So each element of the switch is the address of the corresponding label. As with arrays, the switch word points to one beyond the corresponding label. As with arrays, the switch word points to one beyond the last switch element. The .BEGIN signals the start of the code of the procedure to the link word is set aside at 1027.

The coding of the procedure is straightforward. It tests each of the relational operators for all possible cases of numerical inequality. Note that each subscript causes a corresponding LDX operation to be generated. The compiler generates jump orders in conditions and to jump over the statement after the .ELSE. In fact the jumps at 1042, 1055, 1067, 1102, 115 and 1127 cannot be executed since they are preceded by .EXITTRUE. In entry the return address is set in 1027. This is incremented by .EXITTRUE before the indirect jump. .EXITFALSE is the ordinary return and so just generates an indirect jump. The relational operators generate the code that was given in 4.2.3 but the details need not be remembered since the effect follows the conventional usage. The code from the relation follows the LDX and the CAS instruction.

The main program starts at 1132. It consists of three nested for loops. It prints out a matrix of T's and F's for each relation so that each operator can be easily checked. The for loops start by assigning the appropriate constant to the control variable. The CASE and I for loops have a compound statement as the controlled statement. The .BEGIN and .END do not generate any code but merely bracket the internal statements together. The innermost statement prints T on the monitor if the relation is true and F otherwise. This is done by an if statement. Note how the call of RELATION is done. If the condition is true then control is passed to 1143 instead of 1142 because of the IRS instruction in the body of the procedure RELATION. Hence OUT2(TRUE) is executed, after which a jump is performed to avoid executing the statement after the .ELSE. On the other hand, if the condition is false, control will pass to 1142 and hence to 1146 to execute OUT2(FALSE). The semicolon after OUT2(FALSE) marks the end of the J loop, so the control instructions for this are generated. This is the IRS J and then the jump to be beginning of the loop.

At the end of the program after the HLT, the literal constants are generated. This consists of -6 and -3; note that only one -3 is generated although it is referenced twice at 1135 and 1137.

The output of the program on entering it at 1132 appears at the end of the program text.

```
& CONDITION TEST
& LISTING             & COMMENT      &OCTAL & INSTRUCTION
                                     &  ADD &   OR BINARY
.INTEGER
 CASE,                               &  100 & UNDEFINED
 I,                                  &  101 & UNDEFINED
 J;                                  &  102 & UNDEFINED
.ARRAY
 A[-3]                & ARRAY WORD   &  103 &  41003
  ( -1, 0, 1 );                      & 1000 & 177777
                                     & 1001 &      0
                                     & 1002 &      1
@ .PROCEDURE OUT1;  &PROCEDURE WD    &  104 &   1003
 .BEGIN             & LINK WORD      & 1003 &      0
 % SKS, '104;                        & 1004 & SKS  104
 % JMP, *-1;                         & 1005 & JMP 1004
 % OCP, '104;                        & 1006 & OCP  104
 % OTA, 4;                           & 1007 & OTA    4
 % JMP, *-1;                         & 1010 & JMP 1007
 .END;                               & 1011 & JMP*1003
@ .PROCEDURE OUT2;  &PROCEDURE WD    &  105 &   1012
 .BEGIN             & LINK WORD      & 1013 &      0
 OUT1( .SWOP @ );                    & 1013 & ICA
                                     & 1014 & JST* 104
 OUT1( .SWOP @ );                    & 1015 & ICA
                                     & 1016 & JST* 104
 .END;                               & 1017 & JMP*1012
.CONSTANT
 CRLF = '106612;                     &  106 & 106612
 TRUE = $ T,                         &  107 & 120324
 FALSE = $ F;                        &  110 & 120306
.CONDITIONAL .PROCEDURE RELATION;    &  111 &   1027
  .LABEL LE, GE, LT, GT, EQ, NE;
  .SWITCH OPCASE =    & SWITCH WD    & 1020 & 141027
     LE,                             & 1021 &   1032
     GE,                             & 1022 &   1044
     LT,                             & 1023 &   1057
     GT,                             & 1024 &   1071
     EQ,                             & 1025 &   1104
     NE;                             & 1026 &   1117
 .BEGIN                              & 1027 &      0
 .GOTO OPCASE[ CASE];                & 1030 & LDX  100
                                     & 1031 & JMP*1020
 LE: .IF A[I] .LE A[J] .THEN         & 1032 & LDX  101
                                     & 1033 & LDA* 103
                                     & 1034 & LDX  102
                                     & 1035 & CAS* 103
                                     & 1036 & JMP 1043
                                     & 1037 & NOP
      .EXITTRUE                      & 1040 & IRS 1027
                                     & 1041 & JMP*1027
    .ELSE      & JMP NEVER EXEC      & 1042 & JMP 1044
      .EXITFALSE;                    & 1043 & JMP*1027
 GE: .IF A[I] .GE A[J] .THEN         & 1044 & LDX  101
                                     & 1045 & LDA* 103
```

```
                                  & 1046 & LDX  102
                                  & 1047 & CAS* 103
                                  & 1050 & NOP
                                  & 1051 & SKP
                                  & 1052 & JMP 1056
     .EXITTRUE                    & 1053 & IRS 1027
                                  & 1054 & JMP*1027
   .ELSE                          & 1055 & JMP 1057
     .EXITFALSE;                  & 1056 & JMP*1027
LT: .IF A[I] < A[J] .THEN         & 1057 & LDX  101
                                  & 1060 & LDA* 103
                                  & 1061 & LDX  102
                                  & 1062 & CAS* 103
                                  & 1063 & NOP
                                  & 1064 & JMP 1070
     .EXITTRUE                    & 1065 & IRS 1027
                                  & 1066 & JMP*1027
   .ELSE                          & 1067 & JMP 1071
     .EXITFALSE;                  & 1070 & JMP*1027
GT: .IF A[I] > A[J] .THEN         & 1071 & LDX  101
                                  & 1072 & LDA* 103
                                  & 1073 & LDX  102
                                  & 1074 & CAS* 103
                  & JMP *+3       & 1075 & JMP 1100
                                  & 1076 & NOP
                                  & 1077 & JMP 1103
     .EXITTRUE                    & 1100 & IRS 1027
                                  & 1101 & JMP*1027
   .ELSE                          & 1102 & JMP 1104
     .EXITFALSE;                  & 1103 & JMP*1027
EQ: .IF A[I] = A[J] .THEN         & 1104 & LDX  101
                                  & 1105 & LDA* 103
                                  & 1106 & LDX  102
                                  & 1107 & CAS* 103
                                  & 1110 & SKP
                                  & 1111 & SKP
                                  & 1112 & JMP 1116
     .EXITTRUE                    & 1113 & IRS 1027
                                  & 1114 & JMP*1027
   .ELSE                          & 1115 & JMP 1117
     .EXITFALSE;                  & 1116 & JMP*1027
NE: .IF A[I] .NE A[J] .THEN       & 1117 & LDX  101
                                  & 1120 & LDA* 103
                                  & 1121 & LDX  102
                                  & 1122 & CAS* 103
                                  & 1123 & SKP
                                  & 1124 & JMP 1130
     .EXITTRUE                    & 1125 & IRS 1027
                                  & 1126 & JMP*1027
   .ELSE                          & 1127 & JMP 1131
     .EXITFALSE;                  & 1130 & JMP*1027
   .END;                          & 1131 & JMP*1027
.BEGIN         & START OF PROGRAM  & NO CODE
  & INH;                          & 1132 & INH
 .FOR CASE = -6 .DO               & 1133 & LDA 1165
                                  & 1134 & STA  100
  .BEGIN
  .FOR I = -3 .DO                 & 1135 & LDA 1166
```

```
                                  & 1136 & STA  101
     .BEGIN
     .FOR J = -3 .DO              & 1137 & LDA 1166
                                  & 1140 & STA  102
       .IF RELATION .THEN         & 1141 & JST* 111
                                  & 1142 & JMP 1146
          OUT2( TRUE )            & 1143 & LDA  107
                                  & 1144 & JST* 105
       .ELSE                      & 1145 & JMP 1150
          OUT2( FALSE )           & 1146 & LDA  110
                                  & 1147 & JST* 105
                & END J LOOP      & 1150 & IRS  102
                                  & 1151 & JMP 1141
          OUT2( CRLF )            & 1152 & LDA  106
                                  & 1153 & JST* 105
      .END;                       & 1154 & IRS  101
                                  & 1155 & JMP 1137
      OUT2( CRLF );               & 1156 & LDA  106
                                  & 1157 & JST* 105
      OUT2( CRLF );               & 1160 & LDA  106
                                  & 1161 & JST* 105
    .END;        & END CASE LOOP  & 1162 & IRS  100
                                  & 1163 & JMP 1135
  .END;          & END PROGRAM    & 1164 & HLT
                 & CONSTANT -6    & 1165 & 177772
                 & CONSTANT -3    & 1165 & 177775

STARTED AT 1132

 T T T
 F T T
 F F T

 T F F
 T T F
 T T T

 F T T
 F F T
 F F F

 F F F
 T F F
 T T F

 T F F
 F T F
 F F T

 F T T
 T F T
 T T F

HALTED AT 1164
```

5.2 A simple sort program and some input/output routines

(omitted)

5.3 Positioning code in the core

Since the code is generated in two parts, sector 0 and the current sector; different techniques are available for each. Usually the current sector is more important and so this is dealt with first. Control is maintained by the origin and next sector directives. In both cases the literal pool is emptied before the code generation address is altered. Because literals are always accessed with the 'this sector bit' in the memory reference instruction, these directives must be done at least once for every sector of instructions. Remember that the literal pool itself may require quite a bit of space in the sector.

With large programs it is convenient to reposition the whole code without altering all the origin directives. This can be done by always doing .ORIGIN BASEADDRESS + '4000; etc where BASEADDRESS is a compile constant whose value (a multiple of '1000) relocates the entire program code. This does require recompilation of the program but the compiler is sufficiently fast for this not to be a serious drawback.

A consequence of the use of compile constants which are declared globally is that no space is required in sector 0, but space is required in every sector in which they are used in a memory reference instruction. For instance, the error numbers of the PL516 compiler are declared like this. The advantage of this is that the source text giving the declarations automatically lists all the error numbers. Declaring them as constants however would result in far too large a use of sector 0. The other advantage is of course, that the identifier giving the failure number indicates the cause.

The code produced by the compiler is in blocks. These blocks are delimited by the origin and next sector directives. The final special block produced is in sector 0. Blocks which have all their values undefined (like a global array with no values set) are not punched out in the non-load and go version of the compiler. Otherwise the entire block is punched out. As a consequence of this large arrays with no values set should be in a block by themselves so that they are not punched out. No check is made by the compiler that the blocks produced do not overwrite one another.

The directive .ORIGIN 0 has a special meaning. The literal pool is emptied as usual, but the position of code generation is not increased and so the next block starts after the end of the last one. By this means code can be packed without gaps. This is of little use in itself unless one can ensure the code of procedures do not overlap sector boundaries. In any case, .ORIGIN should not be done more than necessary otherwise multiple copies of common literals will be made in one sector. One solution to this problem is to use global arrays as inter-sector buffers. This is illustrated below

```
   Text             Code

<procedures>       instructions
.ORIGIN 0;         literals
.ARRAY             array space
                      ------- sector boundary
                   further array space
.ORIGIN 0;
<procedures>       instructions
```

The second .ORIGIN 0 us required to output the array block (if necessary) and to inform the compiler that a new sector has been reached. One can see that the size of the instruction code can vary quite substantially without forcing the procedure code near the sector boundary. This technique is only really appropriate to programs which have been completely coded so that the rough size of the procedures and arrays are known. Usually it will be necessary to declare the arrays later so that the buffer will be declared by a set declaration.

Programs with multiple entry points (say '2000, '2001 etc) can easily be arranged by placing a succession of goto statements after the appropriate origin directive.

The directive to reposition code generation in sector 0 is .GLOBAL. Again, no check is made by the compiler that the repositioning will not overwrite a word previously set in sector 0. One reason to require .GLOBAL is to use the .ABUG and .SBUG diagnostics. Address of the corresponding procedures must be put at '776 and '777. This can be done by

```
.GLOBAL '776;
.FORWARD .PROCEDURE ABUG, SBUG;
```

```
.GLOBAL '200;
```

The second .GLOBAL is required to avoid sector 0 overflow. When the procedure .ABUG and SBUG are met, the address of the relevant links will be inserted in '776 and '777. With the load and go version of the compiler an error message is output if addresses from '540 to '777 are used in sector 0, although the appropriate repositioning will take place. If .ABUG and .SBUG are used without setting locations '776 and '777 then the load and go version of the compiler will use its own procedures to give diagnostics (see section 6).

Sector 0 is the last block of code to be output, if the code is being punched. Not all the sector is punched, but merely from the lowest to the highest address used.

5.4 A desk calculator program

(omitted)

5.5 A string editor

(omitted)

5.6 Array handling

Programs written in DAP often use absolute addresses to reference words in core. This is rarely the case in PL516 except, of course, for simple variables. The fact that array referencing is always indirect via the address word has many advantages. It has the slight disadvantage in some cases of requiring an extra core cycle.

One advantage of the array word technique has already been given in 5.5 with the procedure TYPEOUT. The method of using .CODEWORD and storing the array word in the procedure implements a primitive type of formal array mechanism.

Dynamic allocation of core for arrays is quite possible in PL516. Initially the global arrays are declared with an arbitrary number of words in one area of core. Whenever one array becomes full, then a routine can be entered to reallocate the available space between the arrays. This can be done by copying the parts of the arrays into new positions and then altering the array words appropriately (using %STA, A). This routine can be quite small but needs to be very carefully written. The rest of the program uses the arrays in the conventional manner resulting in intelligible coding. If this method of dynamic addressing is used, then no absolute address to elements of the array should be made, not should any procedure keep a copy of the array word.

To summarise, the array mechanism should be used to access words other than simple variables. The extra core cycle is more than compensated by the increased flexibility and program intelligibility.

5.7 Program segmentation

In the last section the advantage of the array mechanism was stressed which was due to the use of the array word. Similar advantages accrue with procedures since access is always via the procedure word in sector 0. By means of the .GLOBAL directive and forward declarations the procedure words can be conveniently placed anywhere in sector 0. If a procedure is declared forward but not met an error message is output by the compiler although the machine code produced in valid. In this case the procedure word of the procedure not reached is zero.

One use of these techniques is in binary libraries. The library procedures are compiled with a dummy program and punched out on paper tape. The program using the libraries is compiled with forward procedures in the same position in sector 0. After the binary libraries are read into core the resulting program can be successfully executed. This is because loading sector 0 of the library will set the address words of the required procedures. Care must be taken with any other words used in sector 0 by the library procedures. There is little point in using this technique to minimise compilation times since these are typically very short. It can be used to implement two different libraries as a loading option. The two

libraries must use the same address words for the procedures in sector 0 as the main program. A further use for the technique is for compiling very long programs on a small machine. The binary libraries can overwrite the compiler after the main program has been compiled into core.

A second use of the procedure addressing mechanism could be in program segmentation. Say that two sets of procedures A and B are to use the same instruction space. Both can be compiled independently with the rest of the program and the instructions dumped onto backing store. Each set of procedures will have different addresses for the procedure words in sector 0. At any moment only one set of procedures (say A) will be in core. A call of a B procedure will activate a control routine to swop the two sets. The calling of the control routine is done by writing to the address words of the procedures not in core, the address of the control routine. In consequence, from the program text it appears that both sets of procedures are in core, since the swopping is done automatically by the actual call.

5.8 Use of code statements

code statements are, of course, necessary to provide access to instructions not directly available in the language. Use in other contexts is dangerous since the type-checking and flow of control checking cannot then be done by the compiler. With memory reference instructions where $< 11.4 address\ field >$ is a $< 11.5 type\ identifier >$ it is necessary to check that the address inserted in the instruction is the one required. For integers and constants there is little chance for confusion, but for arrays and switches, the address of the array or switch word is inserted. For procedures, the address is of the word in sector 0 containing the address of the procedure. For labels, the address depends on whether the label is local to the procedure or global. For a local label, the address in the current sector and so this is planted in the instruction. For global labels, the address out in the instruction is to a word in sector 0 containing the 14 bit address of the labelled statement. Clearly, if the level of declaration of the label is altered, code statements using the label will have to be changed.

References to compile constants are not allowed in code statements. The reason for this is that the meaning of such a reference is not clear. Consider

```
.COMPCONSTANT COMMA = '254;
.BEGIN
 @ = '256;
 %STA, COMMA;
.END;
```

To create a constant in the pool would allow assignment to it, as illustrated, which would be disastrous. To interpret this as STA '254 would be equally dangerous.

5.9 Program checking

Many checks are performed by the compiler but others cannot be checked. The most important ones are as follows:

1. Use of @ and #. Check that the A and X registers do have the desired contents. Remember a procedure may overwrite the X register.
2. Array bound checking. Do logical checks to ensure each index is within bounds.
3. Check use of code statements. See section 5.8 for details. With the IRS instruction, a skip must be catered for, or be logically impossible.
4. Check the use of core. The blocks of code should not overwrite on another.
5. For segmented programs or use of binary libraries check that the use of sector 0 is correct.

5.10 Good programming practice

The main purpose of the language - to improve program legibility - can be destroyed by not exploiting the language properly. A summary of the most important programming points is as follows:

1. Use long, meaningful identifiers.
2. Do not use @ and # to the extent that the program becomes obscure.
3. Do not use code statements if they can be easily avoided.
4. Avoid undue complication.
5. Indent the program listing to show scope of the for loops, begin-end brackets, etc.
6. Use conditions rather than labels.

6 A program testing system

Techniques for program testing are likely to be continually revised in the light of experience. Consequently, the only system described here is the first one to be implemented. Considerable improvements are likely to be made in the near future.

After a program has been compiled into core, the core store contains three main blocks. The permanent coding of the compiler, the program just compiled. and the global name list of the compiled program. Clearly the name list gives a lot of details about the compiled program which can be used for diagnostic purposes. If the machine has adequate core store then program execution is possible without overwriting the name list. This is assumed in the system described below.

It is clearly convenient if one can test individual procedures of a large program without writing special test programs for the purpose. This can be done by typing statements ‘one-line’. After the main program has been compiled a special entry can be made to the compiler. At this point input of a further statement is expected from the control typewriter. This statement can refer any of the global entities since information about them has been retained in the name list. It can, of course, be a compound statement which can be several lines of type. It is not advisable to type very much since an error will result in an immediate failure message with no action being taken by the compiler. On successful completion of the statement (followed by the terminator ’;’) the resulting code produced by the compiler will be immediately executed. If the statement execution terminates ordinarily, a further statement can be typed from the control typewriter. Using this facility, values can be given to global integers and array elements, individual procedures can be executed, and values of integers etc, printed out.

This listing below illustrates the technique in testing the string editor program described in 5.5. The -> is the invitation to type by the compiler after the string editor had been compiled. The call of the procedure CONVERT is compiled, executed and another invitation to type is automatically given. The for loop typed next, prints out the contents of the array DEC to test that the conversion was performed successfully. the call of the procedure PRINTDECI prints the array DEC out with initial zero suppression (which in this case is no different from the ordinary print). The next three statements check the procedure DECIMAL for various arguments. The system prints CR, LF both before and after execution of the statement.

The call of the procedure READRULES causes the next four lines to be printed after which replies were made to set up the string edits given in the example in 5.5. To check that READRULES functioned correctly, the relevant parts of the arrays S1 and S2 are printed out. Note the initial error in using I which was not declared. In this case, all the typing since the last -> is lost so one must start again. For this reason only short sequences of code should be typed this way.

(Example omitted)

7 Structure of the compiler

Although the language is inspired by PL360, the compiler does not use the precedence method used by Wirth [1]. The reason for this is that the author finds it difficult to see if a language is a precedence language, and if it is not, what remedy can be taken. Hence a technique has been used which the author finds easier to understand. The method used is one of top-down analysis by a series of recursive routines. This has been used very successfully for compilation of an Algol-like language, Babel, in the National Physical Laboratory (see [8, 9]).

Each syntactic rule is translated by a routine which contains calls of further routines according to the syntax. For instance, the routine 'program' calls 'declaration' and 'compound statement' as given in $< 13.0 program >$. 'compound statement' calls 'statement' which can call 'assignment statement' which can call 'lhs', etc. At each level it is possible for the compiler to decide which alternative in the syntax appears in the program merely on the basis of the next basic symbol or identifier. This is not possible with programming languages in general, but is quite an acceptable restriction on the design of a new language. Alternatively, the syntax of the same language can be altered so as to put it in a 'one track' form (see [10]).

The principle advantage of this method is that the compiler listing is very easy to follow, since it closely follows the syntax rules which defines the language.

7.1 The basic compiler routines

When the routine for a syntactic rule is entered, the first basic symbol or identifier has been read. The routine 'lhs' reads basic symbols and assigns the internal code of 'bs'. For instance, when 'compound statement' is called the **begin** has been read and is set in the variable 'bs'. When this routine is left, the corresponding **end** has been read and the next basic symbol after this is set in 'bs'. The other important convention concerns the translation stack. The level of this stack is the same on exit as it was on the corresponding entry to the routine. This means that the translation stack can be used to dump the return links for the recursive routines. In fact, about 60 words proves adequate for the routines. These working variables are stacked explicitly by an **accumulator procedure** 'stack', and unstacked by a parameterless **procedure** 'unstack' which leaves the value of the top of the stack in the accumulator.

Reading of paper tape takes place at two levels. The highest level is the routine 'nbs', which assigns the value of the next basic sysmbol to 'bs'. This routine uses 'inchar' for reading individual characters off the paper tape. 'inchar' deals with comment removal and also updates an array containing the last few characters read (for error diagnostics). 'nbs' uses the routine 'setident' for reading the characters of the compound symbol (after the decimal point). 'setident' is also used by the syntactic routine 'identifier' to read the characters of the identifier.

7.2 The compiler tables

A number of tables are used in the compiler. Each one must be understood if the compiler listing is to be followed.

'trace' is a cyclic store containing the last 20 characters read off the paper tape. The contents of this array are printed out on a failure.

'mcode' is a fixed array containing the machine code mnemonics and corresponding binary instructions. A five bit code for the characters of the mnemonics (as with identifier characters). Hence one word is required for the mnemonic and one for the instruction.

'complist' is also a fixed array, which contains the characters of each compound sysmbol and the corresponding internal code. Each entry in 'complist' is two or three words long. Only two words are required when the compound has three or fewer characters. When three words are required the sign bit of the first word is set.

'namelist', the array containing the name list of the program being compiled, has entries each of three or four words. The identifier is stored in an identical manner to that in 'complist'. The two words other than the identifier characters contain the type and the 'address' (actually the value in the case of a compile constant). The name list is in three parts separated by a dummy entry. The first part is fixed and contains the declaration of the X register as an integer. The second part is the global name list which is only extended

outside procedure bodies and the main program. The last part is the local name list which is removed at the end of each procedure. This removal is done by the procedure 'local collapse' which also checks that any local label has been reached.

'optable' is an array used to find out if a basic symbol is a unary operator, binary operator, relational operator, condition operator or an accumulator condition. A variable number of words is also stored following each basic symbol, which usually consists of machine code instructions to be generated for each operator. Corresponding to each basic symbol type there is an initial index which is the position in 'optable' at which the search is started. Each entry in 'optable' consists of one word giving the basic symbol in the least significant 8 bits and the number of extra words in the entry in the most significant bits. Each part of 'optable' is terminated by a zero word entry. The procedure 'bsis' which accesses this array is as follows:

```
accumulator conditional procedure bsis;
        begin
            xsymbol ← accumulator
    more:   when icleft optable[xsymbol] = bs then
                begin
                codesymbol STX, addbs;
                exittrue
                end;
            when accumulator nonzero then
                begin
                x ← inc optable[xsymbol]+x;
                goto more
                end
        end;
```

The procedure does **exittrue** if the basic sysmbol is of the required type, setting the variable 'addbs' so that the additional information in 'optable' can be easily accessed.

The array 'code' contains the machine-code generated by the compiler. Word 'la' of the current sector of code being generated is in code[la+lstart] and word 'ga' of sector 0 is in word code[ga+gstart]. With the load and go version of the compiler the array word of 'code' is set up so that code[n] is word n of the core-store. Without load and go, the current sector of code could be punched out on its completion so that only a small area of code would be required by 'code'.

'cpool' is used to administer the addressing of literals and compile constants. Every new literal requires two words in 'cpool' giving the value of the literal and the address of the last memory reference instruction accessing it. References to the same literal are chained so that all the addresses can be filled in correctly when the constant pool is emptied (at **origin** or **nextsector**).

'lhsinst' is used in the translation of assignment statements. The instructions generated from the left hand side of the assignment statement must be stored until the expression code has been generated. These instructions are put in 'lhsinst'. One complication of this process is that literals involved in the left hand side cannot be put in 'cpool' since the address of the memory-reference instruction (LDX) using the literal is not known.

7.3 Some syntactic routines

In order to illustrate the compiling technique a number of short routines of the compiler are given.

The procedure which compiles $< 6.1 when\ statement >$ is as follows:

```
procedure whenstatement;
        begin
        enter;
        nbs;
        condition
        stack(fjadd);
```

```
        failifnot(thensymbol);
        statement;
        x ← unstack + lstart;
        code[xsymbol] ← jmpso+la;
        leave;
        end;
```

The procedure is, of course, recursive (via statement). Since this will not work in the usual manner, the subroutine 'enter' stacks the return address on the translation stack, while 'leave' does the return jump to that address. The procedure can only be called if the current basic sysmbol is **when**. This is removed by 'nbs' so that 'condition' can be called. Apart from generating the code for the condition the routine also sets the variable 'fjadd' with the address of the JMP false as given in 4.2.3. this value must be stacked because of the possible recursion. The procedure 'failifnot' has as parameter the internal code that the current symbol should have. In this case it checks that 'bs' has the internal code of **then** and then calls 'nbs'. After this 'statement' can be called, which generates the code for the statement. The address to which the JMP false instruction should go is now known. So 'fjadd' is unstacked and the X register set appropriately. Now the JMP false can be planted in the already generated code. 'la' is the next instruction with the 'this sector' bit set. The constant 'thensymbol' is a compile constant as are all similar constants and the compiler error numbers. This is because they are global, consequently declaring them as constants would require substantial amount of space in sector 0.

The procedure which implements $< 7.0 for\ statement >$ is as follows:

```
procedure forstatement;
        begin
        enter;
        nbs;
        if bs = xsymbol then
                begin
                assignmentstatement;
                foraddress ← zero;
                end
        else
                begin
                if bs = indsymbol then
                        begin
                        nbs;
                        foraddress ← octalsymbol 100000;
                        end
                else
                        foraddress ← zero;
                identifier;
                when type ≠ int then
                        fail(fornotint);
                foraddress ← add + foraddress;
                failifnot(becomessymbol);
                expression;
                generate(sta+foraddress);
                end;
        failifnot(dosymbol);
        stack(la);
        stack(foraddress);
        statement;
        generate(unstack+irs);
        generate(unstack+jmpso);
```

```
        leave;
        end;
```

The use of long identifiers helps to make the listing self-explanatory, but the following points should be noted. The procedure 'identifier' sets the variables 'type' and 'add'. 'type' contains the internal code of the type of the latest variable or zero it is it not declared. 'add' contains the address of the variable - which for an integer is the 9-bit address ('this sector' bit set for local integers). 'la' is the address of the next free word in the current sector of code being generated, and 'foraddress' is the address of the control variable. Before calling 'statement' to translate the controlled statement, the variables 'la' and 'foraddress' are stacked. 'foraddress' is unstacked to generate the IRS instruction and 'la' is unstacked to generate the JMP to the beginning of the loop.

The procedure for translating $< 3.0 condition >$ is as follows:

```
procedure condition;
label gt, ge, lt, le, eq, ne;
switch rel = gt, ge, lt, le, eq, ne;
integer relopcase;
begin
    enter;
    if bsis(cond) then
        begin
        nbs;
        x ← inc addbs;
        generate(optable[xsymbol];
        setfjadd    end
    else
        if letter(bs) then
            begin
            identifier;
            if (type and octalsymbol 12) = octalsymbol 12 then
                begin
                proccall;
                setfjadd
                end
            else
                begin
                id ← -1;
                goto expr
                end
            end
        else
        expr: begin
            expression;
            if bsis(accond) then
                begin
                nbs;
                x ← inc addbs;
                generate(optable[xsymbol];
                setfjadd
                end
            else if bsis(relop) then
                begin
                x ← inc addbs;
                relopcase ← optable[xsymbol];
```

```
                    nbs;
                    cell;
                    genaddinst(cas);
                    goto rel[relopcase];
               gt:  generate(jmpso+la+3);
                    generate(nop);
                    setfjadd;
                    goto exit;
               ge:  generate(nop);
                    generate(skp);
                    setfjadd;
                    goto exit;
               lt:  generate(nop);
                    setfjadd;
                    goto exit;
               le:  setfjadd;
                    generate(nop);
                    goto exit;
               eq:  generate(skp);
                    generate(skp);
                    setfjadd;
                    goto exit;
               ne:  generate(skp);
                    setfjadd;
               exit: end
               else
                    fail(fcondition);
               end;
    leave;
end;
```

The procedure 'setfjadd' consists of two statements: fjadd ← la; **codesymbol** IRS, la; this it sets 'fjadd' to the current instruction address and leaves a space in the compiled code for the jump instruction. Note the way 'bsis' is used to determine the type of the current basic sysmbol. After calling 'bsis', the variable 'addbs' is used to fetch the machine-code instructions from 'optable'. the variable 'id' is set to -1 before calling expression when the identifier at the beginning of the expression has been read. The call of 'genvaddinst' generates the CAS instruction taking into account that the CAS may refer to an explicit constant whose address is not yet known (and so be noted in 'cpool'). The use of a switch is illustrated although a case statement would be more natural in this instance.

7.4 Some statistics on the compiler

The permanent coding of the compiler is about 4,300 words, including about 150 locations in sector 0. The current version of the compiler is load and go, and so requires space for the name list (3 or 4 words per entry) and the complied code. The compiler listing is about 2,500 lines and is probably about half the length of paper tape of the equivalent size DAP program (reasonably commented). There are about 350 global declarations.

The compiler compiles itself into core in about 70 seconds. At least 55 seconds of this is paper tape reading time, so about 15 seconds of computing time is required.

The compiler was originally written in a subset of Algol 60 for KDF9. The subset was, of course, the parts of Algol 60 which could be easily converted to PL516. It took about two man-months to write and debug this version of the compiler. Then D.A. Bell recoded the compiler in its own language. Unfortunately the changes required, although not very substantial, were too much to do automatically. The only major change was that identifiers in the array 'namelist' and 'complist' took up only one word (48 bits) on KDF9

as opposed to one or two on the 516. This recoding took a further two man-months. The KDF9 compiler took 5 minutes (processor time) to compile the version of the compiler in its own language.

Writing this manual and coding various enhancements (like statements on-line) means that the total effort has been about six man-months spread over the period May 1969 to April 1970.

8 Comments on machine design

Wirth [1] makes some comments on inconsistencies in the 360 series architecture which became apparent in the design of PL360. In a similar manner various features in the DDP-516 order code do not match the rest of the structure.

For instance, it has not proved possible to use various instructions in PL516. The memory reference instruction STX (store the X register) could have been added by a special statement. This would be no clearer than **codesymbol** STX, variable. In any case, since no arithmetic can be done in the X register, storing the contents of the X register is unlikely to prove very useful. Similarly the instruction IAB is not used. The instruction IMA interchanges the contents of the A register and the memory reference location. No high level language syntax naturally uses such an instruction; for instance, the CPL swop interchanges the value of two variables (and does not involve an expression which could be evaluated in the accumulator).

The IRS instruction is conveniently exploited in the for loop but has the annoying requirement of using a negative count. In fact, only quite sophisticated computer (like KDF9) have single instructions for loop control which match the requirements of conventional high level languages. The CAS instruction is awkward in that control can pass to one of the three following locations (a la Fortran). The difficulty that this presents is reflected in the code for 'condition' given in 7.3. All the other test instructions skip only one instruction if the condition is true. This uniformity of structure is exploited in conditional procedures which mirror the simple test instructions but allow the computation of more complex conditions. The negative tests on the sense keys have not been used as $< 3.1 condition\ operators >$ since the double negative involved in some cases would not be clear.

The JST instruction has the facility that the index and indirect bits are preserved in the word containing the link. This means that those word can be used to indirectly access parameters planted with the calling sequence. This construction is dangerous since the division between code and data is not clear. Consequently use has not been made of this although if a mechanism for calling Fortran routines were added this would be used.

The sectored addressing system has been exploited by the local and global declaration system. One consequence of this is that procedures can easily be rearranged in core to suit particular requirements. No difficulties can arose since there is no mechanism for two procedures in the same sector to communicate except via sector 0. However, the user has to note the sector boundaries and pack his procedures appropriately. This difficulty could be overcome if the JST instruction set the local address base which was used to off-set the 'this sector' memory reference instructions. The addressing limit would therefore be one of 512 words on any subroutine. In some applications, the fact that links must be planted within the code is very inconvenient, since making re-entrant code is very difficult.

The fact that arithmetic is not possible in the index register has not proved as large a disadvantage as had first been thought. The vast majority of array accesses in high-level languages is with a simple subscript, so careful planning of the array scanning used together with IRS instructions usually gives acceptable results.

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A Hardware representation

(Omitted, the general form is an abbreviation of the bold text preceded by a full stop.)

B Failure numbers

(omitted)

C Limitations and restrictions

A number of fixed size arrays are used in the compiler which results in various restrictions. These are as follows:

1. ‘stack’ overflow. This results in failure number 452. 60 words is allocated for the stack which can be increased by altering the compile constant ‘stackheight’.

2. ‘lhsinst’ overflow. The number of simple variables + 3 * (number of subscripted variables on the left-hand side of an assignment statement) must be less than 30.

3. ‘cpool’ overflow. The number of memory reference instructions in one block of code to distinct literal constants (or compile constants) must be less than 30.

4. There is an overall restriction on the size of program determined by the amount or core-store available. Three or four words are required for each variable in the name list, plus space for the compiled code plus about 4,300 words for the compiler itself.