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SYMAP1 - AN EXPERIMENTAL SYMBOL MANIPULATION PROGRAM

by

George C. Francis

August 1970

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BALLISTIC RESEARCH LABORATORIES

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George C. Francis

Applied Mathematics Division

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BALLISTIC RESEARCH LABORATORIES

MEMORANDUM REPORT NO. 2060

GCFrancis/bj  
Aberdeen Proving Ground, Md.  
August 1970

SYMAP1 - AN EXPERIMENTAL SYMBOL MANIPULATION PROGRAM

ABSTRACT

SYMAP1 is a BRLESC computer program designed to carry out a variety of algebraic symbol manipulations including arithmetic operations, substitution, certain kinds of simplifications, and rudimentary differentiation. Main emphasis has been on polynomials in several variables (including truncated power series), but certain other mathematical forms can also be manipulated. Examples of certain applications to numerical analysis and theory of equations are included.

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## I. INTRODUCTION TO SYMAP1

In order to relieve a researcher of certain straightforward but tedious algebraic symbol manipulations, a BRLESC 1 computer program called SYMAP1 has been developed by the author. Sufficient capability has been demonstrated to permit announcing its availability. Additional features will be added as they are found useful, and more powerful techniques are being studied.

Major emphasis in the early stages has been on manipulation of polynomials in several variables (including truncated power series), but many features of SYMAP1 are not restricted to polynomials. Principal manipulations of expressions include the following (see also Figure 1):

| Manipulations:                                         | Symbolic Commands: |
|--------------------------------------------------------|--------------------|
| 1. Indicated sum of two expressions                    | ADD                |
| 2. Indicated difference                                | SUBTR              |
| 3. Indicated product                                   | MULT               |
| 4. Indicated quotient                                  | DIV                |
| 5. Indicated power                                     | EXPON              |
| 6. Certain substitutions in expressions                |                    |
| a. Name for name                                       | SUBSTN             |
| b. Name for expression                                 | SUBSTNE            |
| c. Expression for name                                 | SUBSTE             |
| d. Expression for expression                           | SUBSTEE            |
| 7. Display of any previously stored labeled expression | PRINT              |

In the above cases the expressions have few restrictions. In order that simplifications of the results may be virtually automatic, however, some limitations have to be imposed at present. Since the user may want to retain the unsimplified results for further use, simplification is considered a separate manipulation:

- |                              |         |
|------------------------------|---------|
| 8. Simplification (limited)  | SIMEXPR |
| 9. Differentiation (limited) | DIFF    |

At present differentiation is limited to polynomial - like expressions in the variable of differentiation (negative and decimal fraction exponents are allowed). Products and certain more general expressions can be handled by considering the parts separately and combining in several steps.

| Manipulations:     |           |          |     |     | Descriptions:                                                                    |
|--------------------|-----------|----------|-----|-----|----------------------------------------------------------------------------------|
| ADD<br>SIMEXPR     | PA<br>PC1 | PB<br>PC | PC1 |     | Add PA and PB to obtain PC1 and simplify as PC                                   |
| SUBTR<br>SIMEXPR   | PA<br>PD1 | PB<br>PD | PD1 |     | Subtract PB from PA to obtain PD1 and simplify as PD                             |
| MULT<br>SIMEXPR    | PT<br>PE1 | PA<br>PE | PE1 |     | Multiply PT times PA to obtain PE1 and simplify as PE                            |
| DIV<br>SIMEXPR     | PB<br>PF1 | PT<br>PF | PF1 |     | Divide PB by PT to obtain PF1 and simplify as PF                                 |
| EXPON<br>SIMEXPR   | PT<br>PG1 | PK<br>PG | PG1 |     | Exponentiate PT to PK to obtain PG1 and simplify as PG                           |
| SUBSTEE<br>SIMEXPR | PT<br>PH1 | X<br>PH  | PA  | PH1 | Substitute expression PT for expression X in PA to obtain PH1 and simplify as PH |
| SUBSTEE<br>SIMEXPR | PT<br>QB1 | Z<br>QB  | QA  | QB1 | Substitute expression PT for expression Z in QA to obtain QB1 and simplify as QB |
| DIFF               | R1        | X        | DR1 |     | Differentiate R1 w.r.t. X to obtain DR1                                          |

Figure 1. Sample Manipulations  
(Refer also to Figure 2)

Given:

|    |                                       |
|----|---------------------------------------|
| PA | $1.3*X^{**2}-.5*X^{**3}+.6*Y^{**1.7}$ |
| PB | $X^{**}-1.+1.3*X^{**2}-.7*Y^{**1.7}$  |
| PT | $2.*Y^{**3}.$                         |
| PK | $3.$                                  |
| X  | X                                     |
| Y  | Y                                     |
| Z  | Z1+Z2                                 |
| QA | $(Z1+Z2)^{**2}/Y+\cos(XI)+Z1+Z2$      |
| RI | $3.*X^{**2}.*Y+X^{**}-1./(Y+Z)$       |
| ,  | ,                                     |

Results (which can be manipulated further):

|     |                                                                            |
|-----|----------------------------------------------------------------------------|
| PC1 | $1.3*X^{**2}-.5*X^{**3}+.6*Y^{**1.7}+X^{**}-1.+1.3*X^{**2}-.7*Y^{**1.7}$   |
| PC  | $2.6*X^{**2}-.5*X^{**3}+X^{**}-1.+5.3*Y^{**1.7}$                           |
| PD1 | $1.3*X^{**2}-.5*X^{**3}+.6*Y^{**1.7}-(X^{**}-1.+1.3*X^{**2}-.7*Y^{**1.7})$ |
| PD  | $-.5*X^{**3}.-X^{**}-1.+6.7*Y^{**1.7}$                                     |
| PE1 | $2.*Y^{**3}.*(1.3*X^{**2}-.5*X^{**3}+.6*Y^{**1.7})$                        |
| PE  | $2.6*X^{**2}.*Y^{**3}.-X^{**3}.*Y^{**3}+.12.*Y^{**4.7}$                    |
| PF1 | $(X^{**}-1.+1.3*X^{**2}-.7*Y^{**1.7})/(2.*Y^{**3}.)$                       |
| PF  | $.5*X^{**}-1.*Y^{**}-3.+65*X^{**2}.*Y^{**}-3.-.35*Y^{**}-1.3$              |
| PG1 | $(2.*Y^{**3}.)^{**3}.$                                                     |
| PG  | $8.*Y^{**9}.$                                                              |
| PH1 | $1.3*(2.*Y^{**3}.)^{**2}-.5*(2.*Y^{**3}.)^{**3}+.6*Y^{**1.7}$              |
| PH  | $6.*Y^{**1.7}+5.2*Y^{**6}.-4.*Y^{**9}.$                                    |
| QB1 | $(2.*Y^{**3}.)^{**2}/Y+\cos(XI)+2.*Y^{**3}.$                               |
| QB  | $2.*Y^{**3}+.4.*Y^{**5}+\cos(XI)$                                          |
| DR1 | $6.*X*Y-X^{**}-2.*(Y+Z)^{**}-1.$                                           |

Figure 2. Sample Input and Results

(Refer also to Figure 1)

Certain difficulties are circumvented by doing some of the manipulations on algebraic forms expressed in a non-standard notation (called here canonical notation). Provision is made to translate (simple) expressions to and from this canonical notation and to manipulate expressions which are in canonical form:

|                                          |           |
|------------------------------------------|-----------|
| 10. Convert to canonical form            | CONVERT   |
| 11. Reconvert from canonical form        | RECONVERT |
| 12. Add in canonical form                | CADD      |
| 13. Subtract                             | CSUBT     |
| 14. Multiply                             | CMULT     |
| 15. Divide                               | CDIV      |
| 16. Exponentiate                         | CEXP      |
| 17. Simplify                             | CSIME     |
| 18. Differentiate                        | CDIFF     |
| 19. Substitute expression for expression | CSBEE     |
| 20. Print, one term per line             | SPREAD    |

The last (SPREAD), usable in either canonical or regular notation, is sometimes more convenient than PRINT when expressions involve many terms in several variables.

A realistic practical example will be considered next, using canonical forms largely.

## II. EXAMPLE FROM NUMERICAL ANALYSIS

In designing numerical approximations for partial derivatives for use in solving partial differential equations, the following expression can be considered in parabolic cases:

$$G(\xi, \eta) = (Ae^{-\xi} + B + Ce^{\xi})e^{\frac{1}{2}\eta} + (De^{-\xi} + E + Fe^{\xi})e^{-\frac{1}{2}\eta}$$

Here A, B, C, D, E, F are undetermined weight factors to apply to function values at points of a rectangular grid neighboring to the point at which the derivatives are evaluated.  $\xi$  and  $\eta$  are related to step-sizes in two orthogonal directions (grid distances).

It is often desirable to relate the step-sizes by setting

$$\eta = P\xi^2$$

where  $P$  is another undetermined constant.

Useful relations between the weights  $A, \dots, F$  can be obtained by expanding  $G(\xi, \eta)$  in powers of  $\xi$  and  $\eta$  and then replacing  $\eta$  or by expanding instead  $H(\xi) = G(\xi, P\xi^2)$  in powers of  $\xi$ , and setting the coefficient of each low power of  $\xi$  equal to zero.

The currently available program SYMAP1 can assist in this effort. If the exponentials are replaced by truncated power series,  $G(\xi, \eta)$  becomes an expression involving polynomials in  $\xi$  and  $\eta$ , and  $H(\xi)$  likewise in  $\xi$  alone. The multiplying, adding, substituting (in some cases), rearranging, and combining of like terms can be done by SYMAP1 on the computer BRLESC 1.

Figure 3 shows a possible sequence of SYMAP1 steps to achieve the result. Truncation of all series through a given power of  $\xi$  is arranged by specifying a parameter and setting a program option. Terms through power 8 can be handled in currently available memory. Note that  $G(\xi, \eta)$  would involve several dozen terms in this case, a situation in which hand computation might easily involve careless errors. It was to avoid such errors that SYMAP1 was originally proposed.

In Figure 3 the initial input (from cards) is a sequence of labeled expressions which are to be operated on. The end of this set of lines is indicated by a special sentinel card with commas in card columns 1 and 2. The labels are arbitrary (up to nine characters) but here are shown as rough mnemonics in some cases, such as EXI for  $e^\xi$ , EMHETA for  $e^{-\frac{1}{2}\eta}$ , EHETX for  $e^{\frac{1}{2}\eta}$  in terms of  $\xi$ , etc. The power series are truncated here after  $\xi^4$  or, equivalently,  $\eta^2$ .

Following the sentinel card are suitable SYMAP1 instructions, one per card. Many alternative sequences could have been used, but here the labeled expressions wanted are all converted into a convenient internal notation called canonical notation prior to any combining.

Input:

EXI  $1.+XI^{**1}+.0.5*XI^{**2}+.16666667*XI^{**3}+.04166667*XI^{**4}.$   
 EMXI  $1.-XI^{**1}+.0.5*XI^{**2}-.16666667*XI^{**3}+.04166667*XI^{**4}.$

EHETA  $1.+0.5*ETA^{**1}+.0.125*ETA^{**2}.$   
 EMHETA  $1.-0.5*ETA^{**1}+.0.125*ETA^{**2}.$

A  $A^{**1}.$   
 B  $B^{**1}.$   
 C  $C^{**1}.$   
 D  $D^{**1}.$   
 E  $E^{**1}.$   
 F  $F^{**1}.$

EHETX  $1.+0.5*P^{**1}*XI^{**2}+.0.125*P^{**2}*XI^{**4}.$   
 EMHETX  $1.-0.5*P^{**1}*XI^{**2}+.0.125*P^{**2}*XI^{**4}.$

,,

Steps:

|           |        |         |     |                                                       |
|-----------|--------|---------|-----|-------------------------------------------------------|
| CONVERT   | A      | CA      |     |                                                       |
| CONVERT   | B      | CB      |     |                                                       |
| CONVERT   | C      | CC      |     |                                                       |
| CONVERT   | D      | CD      |     |                                                       |
| CONVERT   | E      | CE      |     |                                                       |
| CONVERT   | F      | CF      |     |                                                       |
| CONVERT   | EXI    | CEXI    |     | $e^{\xi}$                                             |
| CONVERT   | EMXI   | CEMXI   |     | $e^{-\xi}$                                            |
| CONVERT   | EHETA  | CEHETA  | (*) | $e^{\frac{1}{2}\eta}$                                 |
| CONVERT   | EMHETA | CEMHETA | (*) | $e^{-\frac{1}{2}\eta}$                                |
| CONVERT   | EHETX  | CEH1    |     | $e^{\frac{1}{2}P\xi^2}$                               |
| CONVERT   | EMHETX | CEMH1   |     | $e^{-\frac{1}{2}P\xi^2}$                              |
| CMULT     | CA     | CEMXI   | T1  | $A.e^{-\xi}$                                          |
| CMULT     | CC     | CEXI    | T2  | $C.e^{\xi}$                                           |
| CADD      | T1     | CB      | T3  | $Ae^{-\xi} + B$                                       |
| CADD      | T3     | T2      | T4  | $Ae^{-\xi} + B + Ce^{\xi}$                            |
| CMULT     | T4     | CEHETA  | S1  | (*) $(Ae^{-\xi} + B + Ce^{\xi})e^{\frac{1}{2}\eta}$   |
| CMULT     | CD     | CEMXI   | T11 | $D.e^{-\xi}$                                          |
| CMULT     | CF     | CEXI    | T12 | $F.e^{\xi}$                                           |
| CADD      | T11    | CE      | T13 | $De^{-\xi} + E$                                       |
| CADD      | T13    | T12     | T14 | $De^{-\xi} + E + F.e^{\xi}$                           |
| CMULT     | T14    | CEMHETA | S2  | (*) $(De^{-\xi} + E + F.e^{\xi})e^{-\frac{1}{2}\eta}$ |
| CADD      | S1     | S2      | S3  | (*) $G(\xi, \eta)$                                    |
| RECONVERT | S3     | GFCN    |     | (*) $G(\xi, \eta)$                                    |
| SPREAD    | GFCN   |         |     | (*) $G(\xi, \eta)$                                    |
| CMULT     | T4     | CEH1    | S11 |                                                       |
| CMULT     | T14    | CEMH1   | S12 |                                                       |
| CADD      | S11    | S12     | S13 | $H(\xi) = G(\xi, P\xi^2)$                             |
| RECONVERT | S13    | HFCN    |     |                                                       |
| SPREAD    | HFCN   |         |     |                                                       |
| ,,        |        |         |     | (*) only if G itself is wanted                        |

Figure 3. Input and Manipulations for First Example

```

A
+B
+C
+D
+E
+F
-XI*A
+XI*C
-XI*D
+XI*F
+.5*XI**2.*P*A
+.5*XI**2.*P*B
+.5*XI**2.*P*C
-.5*XI**2.*P*D
-.5*XI**2.*P*E
-.5*XI**2.*P*F
+.5*XI**2.*A
+.5*XI**2.*C
+.5*XI**2.*D
+.5*XI**2.*F
-.5*XI**3.*P*A
+.5*XI**3.*P*C
+.5*XI**3.*P*D
-.5*XI**3.*P*F
-.1666667*XI**3.*A
+.1666667*XI**3.*C
-.1666667*XI**3.*D
+.1666667*XI**3.*F
+.25*XI**4.*P*A
+.25*XI**4.*P*C
-.25*XI**4.*P*D
-.25*XI**4.*P*F
+.125*XI**4.*P**2.*A
+.125*XI**4.*P**2.*B
+.125*XI**4.*P**2.*C
+.125*XI**4.*P**2.*D
+.125*XI**4.*P**2.*E
+.125*XI**4.*P**2.*F
+.0416667*XI**4.*A
+.0416667*XI**4.*C
+.0416667*XI**4.*D
+.0416667*XI**4.*F

```

Figure 4.  $H(\xi)$  in "Spread" Format

The comments at the right indicate the result obtained at each step. (CADD, CSUBT, and CMULT include some automatic simplification.) When a result of sufficient interest is obtained, such as  $H(\xi)$  near the end, it can be reconverted into a more readable form and if desired printed one term per line, i.e., "spread".

In this example the final result  $H(\xi)$  is displayed in ascending powers of  $\xi$ . Terms involving the same power of  $\xi$  are thus adjacent for the convenience of the reader. (See Figure 4.)

Well-known conclusions that can be drawn from this display are that for increasingly higher accuracy of numerical approximation, the parameters  $A, \dots, F, P$  should be selected to satisfy more and more (from the top) of the following relations, one for each power of  $\xi$ :

$$\begin{aligned} A + B + C + D + E + F &= 0 \\ -A + C - D + F &= 0 \\ P(A + B + C - D - E - F) + (A + C + D + F) &= 0 \\ 3*P*(-A + C + D - F) + (-A + C - D + F) &= 0 \\ 6*P*(A + C - D - F) + 3*P^2*(A + B + C + D + E + F) + (A + C + D + F) &= 0 \end{aligned}$$

Note that truncating after the fourth power of  $\xi$  still leads to 42 terms in the expression. This number would be much greater for 6th, 8th, etc. powers, with increasing chance of human error if done by hand. Expansions through power 8 have been run on BRLESC 1 for this problem.

In Figure 3 actual numerical coefficients (such as .125 and .16666667) were shown. After sufficient manipulation and combination such coefficients might become unrecognizable; so they could be treated as additional parameters and replaced at a later stage if desired. (See Figure 5.) This would make each term longer, however, and thus require some additional machine effort. (There is a limit on the number of factors per SYMAP1 term, currently seven in most cases, fourteen in special cases.) Figure 5 also further demonstrates that negative exponents of simple variables can be handled in SYMAP1. Decimal fractions in exponents are also allowed.

Given:

|         |                                                    |
|---------|----------------------------------------------------|
| EXI1    | 1.+XI**1.+TWO**-1.*XI**2.+TWO**-1.*TRE**-1.*XI**3. |
| EXI2    | TWO**-3.*TRE**-1.*XI**4.                           |
| EMXI1   | 1.-XI**1.+TWO**-1.*XI**2.-TWO**-1.*TRE**-1.*XI**3. |
| EMXI2   | TWO**-3.*TRE**-1.*XI**4.                           |
| EHETX1  | 1.+TWO**-1.*P**1.*XI**2.+TWO**-3.*P**2.*XI**4.     |
| EMHETX1 | 1.-TWO**-1.*P**1.*XI**2.+TWO**-3.*P**2.*XI**4.     |
| A       | A**1.                                              |
| B       | B**1.                                              |
| C       | C**1.                                              |
| D       | D**1.                                              |
| E       | E**1.                                              |
| F       | F**1.                                              |
| TWO     | 962                                                |
| TRE     | 963                                                |
| CTWO    | 2.\$                                               |
| CTRE    | 3.\$                                               |
| ,,      |                                                    |

Manipulations:

Results:

|         |         |      |
|---------|---------|------|
| CONVERT | A       | CA   |
| CONVERT | B       | CB   |
| CONVERT | C       | CC   |
| CONVERT | D       | CD   |
| CONVERT | E       | CE   |
| CONVERT | F       | CF   |
| CONVERT | EXI1    | CX1  |
| CONVERT | EXI2    | CX2  |
| CONVERT | EMXI1   | CMX1 |
| CONVERT | EMXI2   | CMX2 |
| CONVERT | EHETX1  | CH1  |
| CONVERT | EMHETX1 | CMH1 |

$$e^{\frac{1}{2}P\xi^2}$$

$$e^{-\frac{1}{2}P\xi^2}$$

Figure 5(a). Modified Version of First Example. Part 1

Manipulations:

Results:

|           |      |      |      |     |                              |
|-----------|------|------|------|-----|------------------------------|
| CADD      | CX1  | CX2  | CEX  |     | $e^{\xi}$                    |
| CADD      | CMX1 | CMX2 | CEMX |     | $e^{-\xi}$                   |
| CMULT     | CA   | CEMX | T21  |     | $Ae^{-\xi}$                  |
| CMULT     | CC   | CEX  | T22  |     | $Ce^{\xi}$                   |
| CADD      | T21  | CB   | T23  |     | $Ae^{-\xi} + B$              |
| CADD      | T23  | T22  | T24  |     | $Ae^{-\xi} + B + Ce^{\xi}$   |
| CMULT     | CD   | CEMX | T31  |     | $De^{-\xi}$                  |
| CMULT     | CF   | CEX  | T32  |     | $Fe^{\xi}$                   |
| CADD      | T31  | CE   | T33  |     | $De^{-\xi} + E$              |
| CADD      | T33  | T32  | T34  |     | $De^{-\xi} + E + Fe^{\xi}$   |
| CMULT     | T24  | CH1  | S21  |     |                              |
| CMULT     | T34  | CMH1 | S22  |     |                              |
| CADD      | S21  | S22  | S23  |     | $H(\xi)$                     |
| RECONVERT | S23  | HXI  |      |     | $H(\xi; TWO, TRE)$           |
| SPREAD    | HXI  |      |      |     |                              |
| CSBEE     | CTWO | TWO  | S23  | S31 | Replace TWO                  |
| CSIME     | S31  | S32  |      |     |                              |
| CSBEE     | CTRE | TRE  | S32  | S34 | Replace TRE                  |
| CSIME     | S34  | S35  |      |     |                              |
| RECONVERT | S35  | H1   |      |     | $H(\xi), \text{ simplified}$ |
| SPREAD    | H1   |      |      |     |                              |
| ,,        |      |      |      |     |                              |

Figure 5(b). Modified Version of First Example. Part 2

### III. INTERNAL NOTATION FOR CONSTANTS, VARIABLES, AND FUNCTION NAMES

Variables and parameters which occur in the manipulation of algebraic expressions are represented in the preferred internal notation of SYMAP1 by three digit integers: 100,101,...,999. Translations to and from this internal notation make use of several conversion tables, based on the length of the external symbol. Within the computer program Table 1AV contains single character names, such as A, B, X, Y and their three digit integer synonyms. Table 2AV likewise handles two-character names, such as XI, NU, Al, X', etc. Tables 3AV,4AV,...,9AV are provided for names of three or more characters.

The selection of the three digit integers is arbitrary but does affect the lexicographic sequencing of factors within terms and of terms within sums, etc. Thus, if some final result is wanted in ascending powers of Y, say, and in case of ties in ascending powers of X, then the integer for Y should be less than the integer for X and both should be less than the integers of other variables and parameters.

If for instance we represent Y by 501, X by 502, and A, B, C by 601, 602, 603 respectively, then internally Y becomes 501\*\*1.\$ and  $Y^2$  becomes 501\*\*2.\$, etc. The binary representation of the digits and characters within BRIESC 1 and the ordering rules of SYMAP1 then cause algebraic terms in Y, X, A, B, C to be sequenced as follows:

$$\begin{aligned} &Y, YX, YXA, YXB, \dots \\ &Y^2, Y^2X, Y^2XA, \dots, Y^2X^2, Y^2X^2A, \dots \\ &Y^3, Y^3X, Y^3XA, \dots, Y^3X^2, Y^3X^2A, \dots \\ &\dots \\ &X, XA, XAB, XB, \dots \\ &X^2, X^2A, \dots \\ &X^3, X^3A, \dots \\ &\dots \end{aligned}$$

Thus terms with like powers of Y are adjacent, and for a given power of Y those terms with like powers of X are adjacent, etc. Numerical coefficients do not affect this ordering. (Sufficiently high and

negative exponents do affect the ordering, but the adjacency within groups is maintained.) This adjacency property is useful in combining "like" terms after expansions.

If there is a preferred lexicographic order, this should be considered and the entries in Tables LAV, etc, specified appropriately.

Function names, similarly, are represented by integers of either 1 or 2 digits, using the same Tables LAV, etc. For sequencing, however, these integers are considered 10000 times larger at present, in order to keep functions at the right of any term in which they appear.

Since variables and function names are represented by integers, it is necessary that actual constants be distinguished with special marks. In SYMAP1 this is done by appending a dollar sign at the end of each constant. Also each constant is required to contain a decimal point. Thus unity is 1.\$ in canonical notation and zero is .0\$ internally. Decimal fractions at present are carried with up to eight digits if positive or up to seven digits if negative (an arbitrary decision but convenient in a computer with 10 characters per word).

Internally each factor has an explicit exponent, unity if nothing else, and each term has an explicit coefficient. A coefficient or exponent of unity is removed in the reconversion process, however, to keep most displayed expressions as near to normal notation as possible.

Let us consider another example in several variables.

#### IV. EXAMPLE FROM THE THEORY OF CUBIC EQUATIONS

As another example of symbol manipulation in SYMAP1 let us consider the nature of the roots of a cubic equation. Given the polynomial

$$p(x) = x^3 + bx^2 + cx + d ,$$

where b, c, d are real, let us characterize the region of bcd-space where p(x) has three real roots. It is well known that the requirement

for this condition is that the cubic discriminant defined by

$$\Delta(b,c,d) = 18bcd - 4b^3d + b^2c^2 - 4c^3 - 27d^2$$

be non-negative. Let us confirm this relation.

Of the three roots of any cubic with real coefficients, at least one root is real and the other two may be real and equal, real and unequal, or complex conjugates. Therefore, we can let the roots be  $r$ ,  $s+t$ , and  $s-t$  with  $r$  and  $s$  real and  $t$  zero, positive, or a pure imaginary for the three cases.

The real coefficients  $b$ ,  $c$ , and  $d$  are related to  $r$ ,  $s$ , and  $t$  as follows:

$$\begin{aligned} b &= -r - 2s \\ c &= 2rs + s^2 - t^2 \\ d &= -r(s^2 - t^2) \end{aligned}$$

If these last expressions are substituted for  $b$ ,  $c$ , and  $d$  in the discriminant formula, we obtain:

$$\Delta = \Delta_0 + \Delta_1 t^2 + \Delta_2 t^4 + \Delta_3 t^6$$

where the coefficients  $\Delta_j$  are polynomials in  $r$  and  $s$ .

If  $t=0$   $p(x)$  has at least a double root  $s$  and the properties of the discriminant state that  $\Delta$  vanishes. Hence we note that it must follow that the coefficient  $\Delta_0$  vanishes identically:

$$\Delta_0 = 0.$$

This fact can be verified using SYMAPL.

If indeed  $\Delta_0 = 0$ , then our problem of showing

$$\Delta(r,s,t) \geq 0$$

reduces to the equivalent problem of verifying that

$$\Delta/t^2 = \Delta_1 + \Delta_2 t^2 + \Delta_3 t^4,$$

a quadratic in  $t^2$ , is non-negative (when  $r$ ,  $s$ , and  $t$  are real).

Input:

```

B      -1.*R-2.*S
C      2.*R*S+S**2.-T**2.
D      -1.*R*S**2.+R*T**2.
TM2    T** -2.
TM4    T** -4.
IT2    801**2.$
IT4    801**4.$
IZERO  .0$
I4     4.$
I18    18.$
I27    27.$
,,

```

Steps:

Results:

|           |      |      |      |                                           |
|-----------|------|------|------|-------------------------------------------|
| CONVERT   | B    | IB   |      | b                                         |
| CONVERT   | C    | IC   |      | c                                         |
| CONVERT   | D    | ID   |      | d                                         |
| CMULT     | ID   | ID   | ID2  | $d^2$                                     |
| CMULT     | IC   | IC   | IC2  | $c^2$                                     |
| CMULT     | IB   | IB   | IB2  | $b^2$                                     |
| CMULT     | IC2  | IC   | IC3  | $c^3$                                     |
| CMULT     | IB2  | IB   | IB3  | $b^3$                                     |
| CMULT     | IB   | IC   | IBC  | bc                                        |
| CMULT     | IBC  | ID   | IBCD | bcd                                       |
| CMULT     | I18  | IBCD | T1   | $18bcd = \text{term 1}$                   |
| CMULT     | IB3  | ID   | IB3D | $b^3d$                                    |
| CMULT     | I4   | IB3D | T2   | $4b^3d = \text{term 2}$                   |
| CMULT     | IB2  | IC2  | T3   | $b^2c^2 = \text{term 3}$                  |
| CMULT     | I4   | IC3  | T4   | $4c^3 = \text{term 4}$                    |
| CMULT     | I27  | ID2  | T5   | $27d^2 = \text{term 5}$                   |
| CSUBT     | T1   | T2   | S2   |                                           |
| CADD      | S2   | T3   | S3   |                                           |
| CSUBT     | S3   | T4   | S4   |                                           |
| CSUBT     | S4   | T5   | S5   |                                           |
| RECONVERT | S5   | DISC |      | $\Delta$                                  |
| SPREAD    | DISC |      |      | (No term without t<br>so $\Delta_0 = 0$ ) |

Figure 6(a). Generating the Cubic Discriminant

SYMAP1 can be used to determine the literal form of the coefficients  $\Delta_1$ ,  $\Delta_2$ , and  $\Delta_3$  and then the form of the quadratic discriminant

$$E = (\Delta_2)^2 - 4\Delta_1\Delta_3 .$$

For all real  $r$  and  $s$  we would expect to find

$$\Delta_1 \geq 0 \quad \text{and} \quad E \leq 0 .$$

Let us verify these relations also using SYMAP1 as an aid.

Figure 6 indicates a possible set of SYMAP1 steps in support of such verifications. Input forms include  $b$ ,  $c$ ,  $d$  in terms of  $r$ ,  $s$ ,  $t$ , four useful powers of  $t$  (two of them in internal or canonical form), and four constants (also in canonical notation for convenience). The three digit integers 801, 802, and 803 were selected to represent  $t$ ,  $s$ , and  $r$  respectively. Any results are grouped by like powers of  $t$ .

Manipulations include converting  $b$ ,  $c$ , and  $d$  to canonical form, building up  $\Delta$  step by step, displaying  $\Delta$ , isolating the coefficients  $\Delta_1$ ,  $\Delta_2$ , and  $\Delta_3$ , and forming and displaying the quadratic discriminant  $E$ . The observer can draw his conclusions after some additional hand work including some factoring not within the capabilities of SYMAP1.

Figure 7 shows the literal forms of  $\Delta$ ,  $\Delta_1$ ,  $\Delta_2$ ,  $\Delta_3$ , and  $E$  in "spread" form. Note in particular that in  $\Delta$  no term is independent of  $t$ ; so  $\Delta_0 = 0$  as expected.  $\Delta_3$  is found to be the constant 4.  $\Delta_2$  can be factored by hand as  $\Delta_2 = -8(s-r)^2$ , real and non-positive. Similarly  $\Delta_1 = 4(s-r)^4$ , real and non-negative.  $E = \Delta_2^2 - 4\Delta_1\Delta_3 = 0$ , a fact which might not be expected without further analysis, but the desired conclusion  $E \leq 0$  is certainly verified.

Replacing  $\Delta_1$ ,  $\Delta_2$ ,  $\Delta_3$  in  $\Delta/t^2$  leads to:

$$\begin{aligned} \Delta/t^2 &= 4(s-r)^4 - 8(s-r)^2t^2 + 4t^4 \\ \Delta &= 4t^2[(s-r)^4 - 2(s-r)^2t^2 + t^4] \\ &= 4t^2[(s-r)^2 - t^2]^2 \geq 0 \end{aligned}$$

We have thus verified that the discriminant  $\Delta$  is non-negative if the cubic has three real roots. Furthermore,

|           |       |       |       |     |                                              |
|-----------|-------|-------|-------|-----|----------------------------------------------|
| CONVERT   | TM2   | ITM2  |       |     | $t^{-2}$                                     |
| CONVERT   | TM4   | ITM4  |       |     | $t^{-4}$                                     |
| CMULT     | ITM2  | S5    | S5A   |     | $\Delta \cdot t^{-2}$                        |
| RECONVERT | S5A   | RS5A  |       |     |                                              |
| SPREAD    | RS5A  |       |       |     | $\Delta_1 + \Delta_2 t^2 + \Delta_3 t^4$     |
| CSBEE     | IZERO | IT4   | S5A   | A2A | $\Delta_1 + \Delta_2 t^2 + \Delta_3 \cdot 0$ |
| CSIME     | A2A   | A2    |       |     | $\Delta_1 + \Delta_2 t^2$                    |
| CSUBT     | S5A   | A2    | A3    |     | $\Delta_3 t^4$                               |
| CMULT     | ITM4  | A3    | IDEL3 |     | $\Delta_3 t^4 \cdot t^{-4} = \Delta_3$       |
| CSBEE     | IZERO | IT2   | A2    | A4A | $\Delta_1 + \Delta_2 \cdot 0$                |
| CSIME     | A4A   | IDEL1 |       |     | $\Delta_1 = \Delta_1$                        |
| CSUBT     | A2    | IDEL1 | A5    |     | $\Delta_2 t^2$                               |
| CMULT     | ITM2  | A5    | IDEL2 |     | $\Delta_2 t^2 \cdot t^{-2} = \Delta_2$       |
| CMULT     | IDEL1 | IDEL3 | T11   |     | $\Delta_1 \Delta_3$                          |
| CMULT     | I4    | T11   | T12   |     | $4\Delta_1 \Delta_3$                         |
| CMULT     | IDEL2 | IDEL2 | T13   |     | $\Delta_2^2$                                 |
| CSUBT     | T13   | T11   | IE    |     | $\Delta_2^2 - 4\Delta_1 \Delta_3 = E$        |
| RECONVERT | IDEL1 | DEL1  |       |     |                                              |
| SPREAD    | DEL1  |       |       |     |                                              |
| RECONVERT | IDEL2 | DEL2  |       |     |                                              |
| SPREAD    | DEL2  |       |       |     |                                              |
| RECONVERT | IDEL3 | DEL3  |       |     |                                              |
| SPREAD    | DEL3  |       |       |     |                                              |
| RECONVERT | IE    | E     |       |     |                                              |
| SPREAD    | E     |       |       |     |                                              |
| ,,        |       |       |       |     |                                              |

Figure 6(b). Analyzing the Cubic Discriminant

|                        |                                      |
|------------------------|--------------------------------------|
| -16.*T**2.*S*R**3.     | $\Delta(R,S,T)$                      |
| +24.*T**2.*S**2.*R**2. |                                      |
| -16.*T**2.*S**3.*R     |                                      |
| +4.*T**2.*S**4.        |                                      |
| +4.*T**2.*R**4.        |                                      |
| +16.*T**4.*S*R         |                                      |
| -8.*T**4.*S**2.        |                                      |
| -8.*T**4.*R**2.        |                                      |
| +4.*T**6.              |                                      |
| -16.*S*R**3.           | $\Delta_1(R,S)$                      |
| +24.*S**2.*R**2.       |                                      |
| -16.*S**3.*R           |                                      |
| +4.*S**4.              |                                      |
| +4.*R**4.              |                                      |
| 16.*S*R                | $\Delta_2(R,S)$                      |
| -8.*S**2.              |                                      |
| -8.*R**2.              |                                      |
| 4.                     | $\Delta_3(R,S)$                      |
| .0                     | $E = \Delta_2^2 - 4\Delta_1\Delta_3$ |

Figure 7. Results of Second Example

$$\begin{aligned}\Delta &= 4t^2[s-r-t]^2[s-r+t]^2 \\ &= 4t^2[(s-t) - r]^2[(s+t) - r]^2 \geq 0 .\end{aligned}$$

In this last form it is quite clear that the cubic discriminant  $\Delta$  vanishes if  $t=0$  or if  $r = s+t$  or if  $r = s-t$ , exactly those cases when at least two roots are equal, and  $\Delta$  does not vanish in any other case.

In summary,

$\Delta \geq 0$  for any three real roots  
 $\Delta = 0$  for at least two equal roots (all real)  
 $\Delta > 0$  for three distinct real roots  
 and  $\Delta < 0$  in other cases, namely for one real root and two complex conjugate roots.

SYMAP1 could be used in a similar manner to help derive less well-known relations occurring in original investigations.

## V. SIMPLIFICATION OF FORMS

Several types of simplification occur automatically when SYMAP1 is used. Others can be achieved by appropriate combinations of steps, specified by the user. More flexibility is available when forms are retained in canonical notation; so use of this notation is encouraged.

In general the following simplifications occur, but there are exceptions, especially if complex combinations of steps are carried out without calling for intermediate simplifications. In the formulas below  $a, b, c, n, m, p, q, r$  are real decimal constants (not necessarily integers);  $x, y$  are primitives; and  $t, u, v, w$  are terms similar to the terms of a polynomial.

Within a term like factors are combined, and within a sum like terms are combined. Thus:

$$x^n x^m \rightarrow x^p \quad \text{where } p = n + m$$

$$ax^n y^m + bx^n y^m \rightarrow cx^n y^m \quad \text{where } c = a + b$$

Powers of simple products are expanded:

$$(ax^n y^m)^c \rightarrow bx^p y^q \quad \text{where } b = a^c, p = c \cdot n, q = c \cdot m$$

The distributive law is applied in one direction:

$$ax^c(b_1 x^n + b_2 x^m) \rightarrow r_1 x^p + r_2 x^q$$

but the reverse process (factoring) is not. Special cases of factoring can be done in several steps, however.

Parentheses are removed when possible in special cases, such as:

$$\begin{aligned} t + (u + v - w) &\rightarrow t + u + v - w \\ t - (u + v - w) &\rightarrow t - u - v + w \end{aligned}$$

Simple denominators are replaced:

$$\begin{aligned} u/a &\rightarrow b \cdot u \quad \text{where } b = a^{-1} \\ u/(ax^n) &\rightarrow b \cdot u \cdot x^{-n} \quad \text{where } b = a^{-1} \\ u/(ax^n + by^m) &\rightarrow u \cdot (ax^n + by^m)^{-1} \end{aligned}$$

Special cases of the above rules include:

$$\begin{aligned} x^n \cdot x^{-n} &\rightarrow 1 \\ ax^n - ax^n &\rightarrow 0 \end{aligned}$$

Indeterminate cases must be avoided by the user:

$$0^0 \quad 0/0 \quad 0 \cdot \infty \quad 0^\infty \quad \infty^0 \quad \infty/\infty \quad 1^\infty \quad \infty - \infty$$

Resequencing in some lexicographical order is standard to group similar factors and terms.

## VI. DETAILS OF SPECIFICATION OF MANIPULATIONS

The principal manipulation types were introduced earlier, and examples of their use were given. For those interested additional details are given here.

At present manipulations must be specified in advance on formatted punched cards. (When they become available, on-line keyboards, light

pens, etc. will make SYMAP even more responsive to user needs.) The manipulation type is specified at card column 1 and any additional parameters at columns 11, 21, 31, 41 as needed. The parameters are always names of previously specified forms or variables or of the form currently being generated. Up to 9 letters and digits may be used in names.

Arithmetic operations (add, subtract, multiply, divide, exponentiate) have three parameters: two operands and a result, in the usual order. PRINT and SPREAD require only one parameter, the name of the form to be displayed. CONVERT, RECONVERT, and the simplify types have two parameters each: the given form and a (new) name for the result. (Names cannot be reused with new meanings, even if the old form is not needed further.)

The substitution manipulations have four parameters in the order a, b, c, d, where a represents the form substituted, b the form substituted for, c the form substituted in, and d the result. Thus CSBEE CA CB CC CD means "substitute the form whose name is CA for the form whose name is CB wherever it occurs in the form whose name is CC and store the result with the label CD". Type CSBEE is the most commonly used substitution in SYMAP1. Type SUBSTEE is very similar but uses non-canonical forms.

SUBSTN is merely a renaming operation: "substitute the name a (not the form whose name is a) for the name b wherever b occurs in the form called c and label the result as d". SUBSTNE (name for expression) is similar except that b is the name of the form being substituted for. Finally SUBSTE (expression for name) says to substitute the expression whose name is a for the name b wherever b occurs in c and call the result d. All of these operate on non-canonical forms. Simplification of the results of these operations with SIMEXPR is not always successful, however; so use of canonical forms and CSBEE followed by CSIME is recommended.

The differentiation operations CDIFF and DIFF, for canonical and non-canonical forms, respectively, are currently limited to polynomial-like expressions in the variable of differentiation. Extensions are planned. CDIFF CA Y CB means "differentiate the form whose name is CA with respect to the primitive Y and call the result CB". Since CA is canonical, the variable Y does not appear in CA as such but rather as some previously assigned three digit number such as 101. SYMAP1 looks up the equivalent 101, and differentiates with respect to that symbol, giving a canonical result.

Manipulations are carried out in the order specified by the sequence of cards, and only input and previously completed results can be used in later manipulations. The final operation should be followed by a sentinel card (commas in columns 1 and 2) to terminate manipulations.

## VII. EVALUATION OF EXPRESSIONS

Although the power of SYMAP1 lies in its ability to manipulate polynomials and similar non-numerical expressions, there are occasions when an algebraic form must be evaluated for particular values of its variables. This capability is included in the substitution and simplification operations already described.

Given, say, a polynomial in X and Y where the values  $X = 4$  and  $Y = -3.25$  are to be assigned. The SYMAP1 steps needed include a substitution of 4 for X, a substitution of -3.25 for Y, and a simplification. The substitutions could be reversed if preferred, and simplification could be done after each substitution if display of intermediate results is desired. (See Figure 8.)

Substitution of constants for variables in trigonometric and similar expressions is possible, but simplification is not complete in such cases at present. Future extensions to SYMAP1 may provide for additional evaluations.

Given:

```

X          100
Y          101
PXY        3.*X**.5*Y+X*Y**2.
VX         4.$
VY         -3.25$
,,

```

Steps:

Results:

|           |     |     |     |     |            |
|-----------|-----|-----|-----|-----|------------|
| CONVERT   | PXY | CP  |     |     | P(X,Y)     |
| CSBEE     | VX  | X   | CP  | CP1 | P(4,Y)     |
| CSIME     | CP1 | CP2 |     |     |            |
| CSBEE     | VY  | Y   | CP2 | CP3 | P(4,-3.25) |
| CSIME     | CP3 | CP4 |     |     |            |
| RECONVERT | CP4 | RP  |     |     |            |
| ,,        |     |     |     |     |            |

Results in SYMAP1 notation:

|     |                                                   |
|-----|---------------------------------------------------|
| CP  | 3.\$100**.5\$,101**1.\$+1.\$100**1.\$,101**2.\$   |
| CP1 | 3.\$4.\$**.5\$,101**1.\$+1.\$4.\$**1.\$,101**2.\$ |
| CP2 | 6.\$101**1.\$+4.\$101**2.\$                       |
| CP3 | 6.\$(-3.25\$)**1.\$+4.\$(-3.25\$)**2.\$           |
| CP4 | 22.75\$                                           |
| RP  | 22.75                                             |

Figure 8. Evaluations

## VIII. VECTOR OPERATIONS

A limited number of operations on n-tuples of algebraic forms have been provided in SYMAP1. Others could be added. Currently available are VPRINT, VCONVERT, VRECONV, VADD, VSUBTR, and VSIME, which respectively print an n-tuple of consecutive forms, convert an n-tuple into canonical notation, reconvert from canonical form, add two n-tuples, subtract two n-tuples, and simplify two n-tuples.

In each case n, the order of the n-tuple, is specified at card column 41 as a one-digit positive integer. The other parameters (at columns 11, 21, 31 as needed) are those which would be needed for the first form of the n-tuple in non-vector operations.

Thus VPRINT X1 b b 7 would cause printing of the 7-tuple whose elements are the form X1 and its six successors, whatever their names. The various forms need not be similar with respect to length or any other feature. Similarly VCONVERT ETA IETA b 3 would cause ETA to be converted and labeled IETA and would then cause the next two forms after ETA, whatever their names, to be converted and given names much like IETA by adding unity for each in the 9th character of the name. VRECONV acts analogously, as does VSIME.

VADD and VSUBTR, because of their extra parameter, are very slightly different from the above. Thus VADD AB CD EF 4 would add the elements of the 4-tuple whose first element has the name AB to the corresponding elements starting at name CD and give the (unsimplified) results the names EF through EFbbbbbb3, respectively.

These vector operations merely save the user some repetitive card punching when very similar manipulations are needed on several sets of algebraic forms. The user must be careful to keep his sets adjacent, as it is the adjacency and not the similarity of names that matters in vector operations. Incidentally, elements of n-tuples may be manipulated as independent individuals if desired by using their individual names in the usual way. (See Figure 9.)

```

F1      X**2.+3.*X-5.
F2      X**2.-4.*X+2.
F3      X**2.+2.*X+4.
G1      2.*X-4.*Z
G2      3.*X+2.*Y
G3      X-Y+Z
H1      Y**2.-Y
H2      Y+2.*Z
H3      Y-Z
'',

VADD      F1      G1      J1      3
VSUBTR    J1      H1      K1      3
VSIME      K1      SK1     3
VCONVERT   SK1     CK1     3
CMULT      CK1     CK1     CK1A
CMULT      CK1bbbb1 CK1bbbb1 CK1B
CMULT      CK1bbbb2 CK1bbbb1 CK1C
VPRINT     CK1A      3
VRECONV    CK1A      L1      3
'',

```

Figure 9. Vector Operations

## IX. CONCLUSION

The present SYMAP1 has proven to be useful within its realm of application. With it manipulations can be carried out which would be extremely tedious if done manually, and the likelihood of simple errors of arithmetic is reduced. Various alternatives can be tried with little extra effort. Thus a researcher can be freed for more challenging investigations and more quickly be shown the effects of changes of attack on a given problem. Potential users of SYMAP1 are encouraged to try it.

Additional features will be added to the program as they are developed. Several of these are planned for the near future, and still others are currently being studied. Potential users of SYMAP1 on BRLESC 1 are encouraged to discuss their needs with the author.

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| 13. ABSTRACT<br>SYMAP1 is a BRLESC computer program designed to carry out a variety of algebraic symbol manipulations including arithmetic operations, substitution, certain kinds of simplifications, and rudimentary differentiation. Main emphasis has been on polynomials in several variables (including truncated power series), but certain other mathematical forms can also be manipulated. Examples of certain applications to numerical analysis and theory of equations are included. |                              |                                                                                    |

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| Symbol manipulation<br>Algebraic forms<br>Substitution in forms<br>Simplification of forms<br>Symbolic differentiation<br>Vector operations<br>BRLESC computer program<br>Numerical analysis example<br>Roots of cubics example |        |    |        |    |        |    |