Matrix Multiplication with theTMS32010 and TMS32020

APPLICATION REPORT: SPRA008

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TEXAS INSTRUMENTS

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Matrix Multiplication with theTMS32010 and TMS32020

Abstract

This report is on matrix multiplication with the TMS32010 and TMS32020. Matrix multiplication is useful in applications, such as graphics, numerical analysis, or high-speed control. Because of the high speed of the multiply/accumulate operations and fast data I/O, both processors can multiply in microseconds large matrices with their sizes only limited by the internal data memory. Programs are included in the report to illustrate matrix multiplication on both processors.

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INTRODUCTION

Matrix multiplication is useful in applications such as graphics, numerical analysis, or high-speed control. The purpose of this application report is to illustrate matrix multiplication on two digital signal processors, the TMS32010 and TMS32020.

Both the TMS32010 and TMS32020 can multiply any two matrices of size $M \times N$ and $N \times P$. The programs for the TMS32010 and TMS32020, included in the appendices, can multiply large matrices and are only limited by the amount of internal data RAM available. Assuming a 200-ns cycle time, the TMS32010 and TMS32020 can calculate $[1 \times 3] \times [3 \times 3]$ in 5.4 microseconds.

Before discussing the two versions of implementing a matrix multiplication algorithm, a brief review of matrix multiplication is presented along with three examples of graphics applications.

MATRIX MULTIPLICATION

The size of a matrix is defined by the number of rows and columns it contains. For example, the following is a 5×3 matrix since it contains five rows and three columns.

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \\ a_{41} & a_{42} & a_{43} \\ a_{51} & a_{52} & a_{53} \end{bmatrix}$$

Any two matrices can be multiplied together as long as the second matrix has the same number of rows as the first has of columns. This condition is called conformability. For example, if a matrix A is an $M \times N$ matix and a matrix B is an $N \times P$ matrix, then the two can be multiplied together with the resulting matrix being of size $M \times P$.

$$A = \begin{bmatrix} 3 & 4 \\ 2 & 7 \end{bmatrix} \qquad B = \begin{bmatrix} 4 \\ 6 \end{bmatrix} \qquad AB = \begin{bmatrix} 36 \\ 50 \end{bmatrix}$$

$$M \times N = 2 \times 2 \qquad N \times P = 2 \times 1 \qquad M \times P = 2 \times 1$$

Example: $(3)(4) + (4)(6) = 36$

Given the two conformable matrices A and B, the elements of $C = A \times B$ are given by:

$$C_{ij} = \sum_{k=1}^{N} a_{ik} \times b_{kj}$$

for $i = 1,\ldots,M$ and $j = 1,\ldots,P$

Q12 FORMAT

Applications often require multiplication of mixed numbers. Since the TMS32010 and TMS32020 implement fixed-point arithmetic, the programs in the appendices assume a Q12 format, i.e., 12 bits follow an assumed binary point. The bits to the right of the assumed binary point represent the fractional part of the number and the four bits to the left represent the integer part of the number. An example of Q12 format is as follows:

$$0\,0\,0\,1.1\,1\,0\,1\,1\,1\,1\,0\,0\,0\,0\,0 = 1.866$$

ASSUMED BINARY POINT

$$\begin{array}{rcl} & 0000.110111100000 & = 0.866 \text{ in Q12} \\ \times & 0000.100000000000 & = 0.5 \text{ in Q12} \\ \hline & 00000000.011011110000000000000000 & = 0.433 \text{ in Q24} \end{array}$$

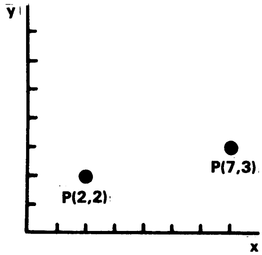
The result of a Q12 by Q12 multiplication is a number in a Q24 format that can easily be converted to Q12 by a logical left-shift of four. The first four bits will be lost as well as the last twelve, but these bits are insignificant for Q12. Note that the programs in the appendices provide no protection against overflow; therefore, the design engineer should implement a format that best fits the application.

GRAPHICS APPLICATIONS

Operations in graphics applications, such as translation, scaling, or rotation, require matrix manipulations to be performed in a limited amount of time. Therefore, the TMS32010 and TMS32020 processors are ideal for these applications. Graphics applications, such as scaling and rotation of points in a coordinate system, require multiplication of matrices. Translation is typically implemented by addition of two matrices. However, when points are represented in a homogeneous coordinate system, translation can be implemented by multiplication. In a homogeneous coordinate system, a point P(x,y) is represented as P(X,Y,1). This type of coordinate system is desirable since it relates translation with scaling and rotation.

Translation can be defined as the moving of a point or points in a coordinate system from one location to another without rotating. This is accomplished by adding a displacement value D_x to the X coordinate of a point and adding a displacement value D_y to the Y coordinate, thus moving the point from one location to another. Figure 1 shows both addition and multiplication methods of translation and an example of each.

Similar to translation, scaling can be implemented by matrix multiplication. Points can be scaled by multiplying



ADDITION METHOD

$[X_{NEW}\ Y_{NEW}] = [X_{OLD}\ Y_{OLD}] + [D_x\ D_y]$

where $D_x = 5$ and $D_y = 1$

MULTIPLICATION METHOD

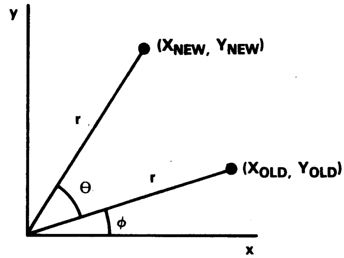
$$[X_{NEW}\ Y_{NEW}\ 1] = [X_{OLD}\ Y_{OLD}\ 1] \bullet \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ D_x & D_y & 1 \end{bmatrix}$$

where $D_x = 5$ and $D_y = 1$

Figure 1. Translation of Coordinates

each coordinate of a point (or points) by a scaling value S_x and S_y. Scaling an object is similar to stretching or shrinking an object. The coordinates of each point that makes up the object are multiplied by a scaling value which scales the object to a larger or smaller scale. Figure 2 shows the scaling of an object from one size to another.

Rotation of the coordinates of a point (or points) about an angle theta can also be accomplished by a matrix multiplication. The following set of equations results with the matrix multiplication required to rotate an object about any angle.



$$X_{OLD} = r\cos\phi$$
$$Y_{OLD} = r\sin\phi$$

$$X_{NEW} = r\cos(\Theta+\phi) = r\cos\phi\cos\Theta - r\sin\phi\sin\Theta$$
$$Y_{NEW} = r\sin(\Theta+\phi) = r\cos\phi\sin\Theta + r\sin\phi\cos\Theta$$

$$X_{NEW} = X_{OLD}\cos\Theta - Y_{OLD}\sin\Theta$$
$$Y_{NEW} = X_{OLD}\sin\Theta + Y_{OLD}\cos\Theta$$

OR

$$[X_{NEW}\ Y_{NEW}\ 1] = [X_{OLD}\ Y_{OLD}\ 1] \bullet \begin{bmatrix} \cos\Theta & \sin\Theta & 0 \\ -\sin\Theta & \cos\Theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

BEFORE SCALING **AFTER SCALING**

Let the scaling factors S_x and $S_y = 0.5$

$$[X_{NEW}\ Y_{NEW}\ 1] = [X_{OLD}\ Y_{OLD}\ 1] \bullet \begin{bmatrix} S_x & 0 & 0 \\ 0 & S_y & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

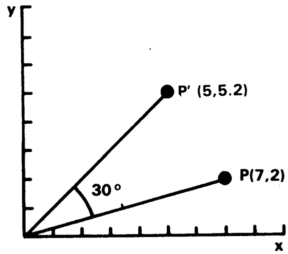
$$[X\ Y\ 1] = [4\ 4\ 1] \bullet \begin{bmatrix} 0.5 & 0 & 0 \\ 0 & 0.5 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$[X'\ Y'\ 1] = [2\ 2\ 1]$$

Figure 2. Scaling From One Size To Another

Figure 3 shows an implementation of these equations to rotate an object 30 degrees about the origin.

Figures 4 and 5 show a segment of straight-line TMS32010 and TMS32020 code, respectively. These programs calculate the coordinate rotation example using a Q12 format. Note that once the matrices are loaded into memory, the procssors can calculate the results in 5.4 microseconds. The segment of TMS32020 code in Figure 5 implements the MAC instruction. For small matrices, the MAC instruction in conjunction with the RPT instruction gains little due to the overhead timing of the MAC instruction. However, for larger matrices, this method is most efficient since the MAC instruction becomes single-cycle in the repeat mode. For applications that only require translation, scaling, or rotation of coordinates, straight-line code as in Figures 4 and 5 is more efficient than the larger programs in the appendices.



$$[X\ Y\ 1] = [7\ 2\ 1] \bullet \begin{bmatrix} 0.866 & 0.5 & 0 \\ -0.5 & 0.866 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$[X'\ Y'\ 1] = [5.0\ 5.2\ 1]$$

Figure 3. Implementation of Rotation Matrix

```
NO$IDT       32010 FAMILY MACRO ASSEMBLER   PC2.1 84.107    09:54:24  02-25-85
                                                                  PAGE 0001

                *************************************************************
                *                                                           *
                *      THIS ROUTINE ASSUMES THE INPUTS ARE IN Q12.          *
                *      THE FIRST NINE INPUTS SHOULD BE THE ROTATION         *
                *      MATRIX (HOMOGENEOUS COORDINATES), ENTERED BY         *
                *      COLUMNS. THE LAST THREE INPUTS SHOULD BE THE         *
                *      OLD X AND Y COORDINATES.                             *
                *                                                           *
                *************************************************************
0000 6E00       ROTATE LDPK   0
     000C       ANS    EQU    12
0001 6880              LARP   0
0002 7000              LARK   AR0,0   * POINT AT BEGINNING OF ROTATION MATRIX.
0003 7109              LARK   AR1,9   * POINT AT BEGINNING OF OLD COORDINATES.
0004 40A8              IN     *+,PA0  * INPUT ROTATION MATRIX AND OLD
0005 40A8              IN     *+,PA0  * COORDINATES.
0006 40A8              IN     *+,PA0
0007 40A8              IN     *+,PA0
0008 40A8              IN     *+,PA0
0009 40A8              IN     *+,PA0
000A 40A8              IN     *+,PA0
000B 40A8              IN     *+,PA0
000C 40A8              IN     *+,PA0
000D 40A8              IN     *+,PA0
000E 40A8              IN     *+,PA0
000F 40A8              IN     *+,PA0
0010 7F89              ZAC            * CLEAR ACCUMULATOR.
0011 7000              LARK   AR0,0
0012 6AA1              LT     *+,1    * CALCULATE NEW X COORDINATE.
0013 6DA0              MPY    *+,0
0014 6CA1              LTA    *+,1
0015 6DA0              MPY    *+,0
0016 6CA1              LTA    *+,1
0017 6DA0              MPY    *+,0
0018 7F8F              APAC
0019 5C0C              SACH   ANS,4   * CONVERT TO Q12 AND OUTPUT RESULT.
001A 480C              OUT    ANS,PA0
```

Figure 4. TMS32010 Code for Rotation

```
001B 7F89          ZAC
001C 7109          LARK    AR1,9     * CALCULATE NEW Y COORDINATES.
001D 6AA1          LT      *+,1
001E 6DA0          MPY     *+,0
001F 6CA1          LTA     *+,1
0020 6DA0          MPY     *+,0
0021 6CA1          LTA     *+,1
0022 6DA0          MPY     *+,0
0023 7F8F          APAC
0024 5C0C          SACH    ANS,4     * CONVERT TO Q12 AND OUTPUT RESULT.
0025 480C          OUT     ANS,PA0
0026 7F89          ZAC
0027 7109          LARK    AR1,9     * FINISH HOMOGENEOUS MATRIX.
0028 6AA1          LT      *+,1
0029 6DA0          MPY     *+,0
002A 6CA1          LTA     *+,1
002B 6DA0          MPY     *+,0
002C 6CA1          LTA     *+,1
002D 6DA0          MPY     *+,0
002E 7F8F          APAC
002F 5C0C          SACH    ANS,4
0030 480C          OUT     ANS,PA0
0031 7F8D          RET
NO ERRORS, NO WARNINGS
```

Figure 4. TMS32010 Code for Rotation (Concluded)

```
NO$IDT      32020 FAMILY MACRO ASSEMBLER   PC0.7 84.348    16:07:15  02-25-85
                                                                  PAGE 0001

               ***************************************************************
               *                                                             *
               *       THIS ROUTINE ASSUMES THE INPUTS ARE IN Q12.           *
               *       THE FIRST NINE INPUTS SHOULD BE THE ROTATION          *
               *       MATRIX (HOMOGENEOUS COORDINATES), ENTERED BY          *
               *       COLUMNS. THE LAST THREE INPUTS SHOULD BE THE          *
               *       OLD X AND Y COORDINATES.                              *
               *                                                             *
               ***************************************************************
0000 5589      ROTATE LARP     1           * USE AUXILIARY REGISTER 1.
     000C      ANS    EQU      12
0001 CA00             ZAC                  * INITIALIZE ACCUMULATOR.
0002 C806           - LDPK     6
0003 D100             LRLK     AR1,>300    * LOAD ROTATION MATRIX INTO B1.
0004 0300
0005 CB08             RPTK     8
0006 80A0             IN       *+,PA0
0007 D100             LRLK     AR1,>200    * LOAD COORDINATES INTO BLOCK B0.
0008 0200
0009 CB02             RPTK     2
000A 80A0             IN       *+,PA0
000B CE05             CNFP                 * CONFIGURE B0 AS PROGRAM MEMORY.
000C A000             MPYK     >0          * CLEAR P REGISTER.
000D D100             LRLK     AR1,>300
000E 0300
000F CB02             RPTK     2
0010 5DA0             MAC      >FF00,*+    * CALCULATE THE NEW X COORDINATE.
0011 FF00
0012 CE15             APAC
0013 6C0C             SACH     ANS,4
0014 E00C             OUT      ANS,PA0     * OUTPUT NEW X COORDINATE.
0015 A000             MPYK     >0          * CLEAR P REGISTER.
0016 CA00             ZAC
0017 CB02             RPTK     2
0018 5DA0             MAC      >FF00,*+    * CALCULATE NEW Y COORDINATE.
0019 FF00
001A CE15             APAC
001B 6C0C             SACH     ANS,4
001C E00C             OUT      ANS,PA0     * OUTPUT NEW Y COORDINATE.
001D A000             MPYK     >0          * CLEAR P REGISTER.
001E CA00             ZAC
001F CB02             RPTK     2
0020 5DA0             MAC      >FF00,*+    * FINISH HOMOGENEOUS MATRIX.
0021 FF00
0022 CE15             APAC
0023 6C0C             SACH     ANS,4
0024 E00C             OUT      ANS,PA0
0025 CE26             RET
NO ERRORS, NO WARNINGS
```

Figure 5. TMS32020 Code for Rotation

To combine translation, scaling, and rotation, a more general matrix can be implemented.

GENERAL MATRIX FOR TWO-DIMENSIONAL SYSTEMS

$$\begin{bmatrix} r_{11} & r_{12} & 0 \\ r_{21} & r_{22} & 0 \\ t_x & t_y & 1 \end{bmatrix}$$

The upper 2×2 matrix is a combination rotation matrix and scaling matrix. The t_x and t_y values are the translation values. A three-dimensional general matrix can be developed similar to the two-dimensional translation, scaling, and rotation matrix.

GENERAL MATRIX FOR THREE-DIMENSIONAL SYSTEMS

$$\begin{bmatrix} r_{11} & r_{12} & r_{13} & 0 \\ r_{21} & r_{22} & r_{23} & 0 \\ r_{31} & r_{32} & r_{33} & 0 \\ t_x & t_y & t_z & 1 \end{bmatrix}$$

IMPLEMENTATION OF THE MATRIX MULTIPLICATION ALGORITHM FOR THE TMS32010

The implementation of the algorithm for the TMS32010 shown in Figure 6 assumes that the two matrices to be multiplied together are of size $M \times N$ and $N \times P$. Three major

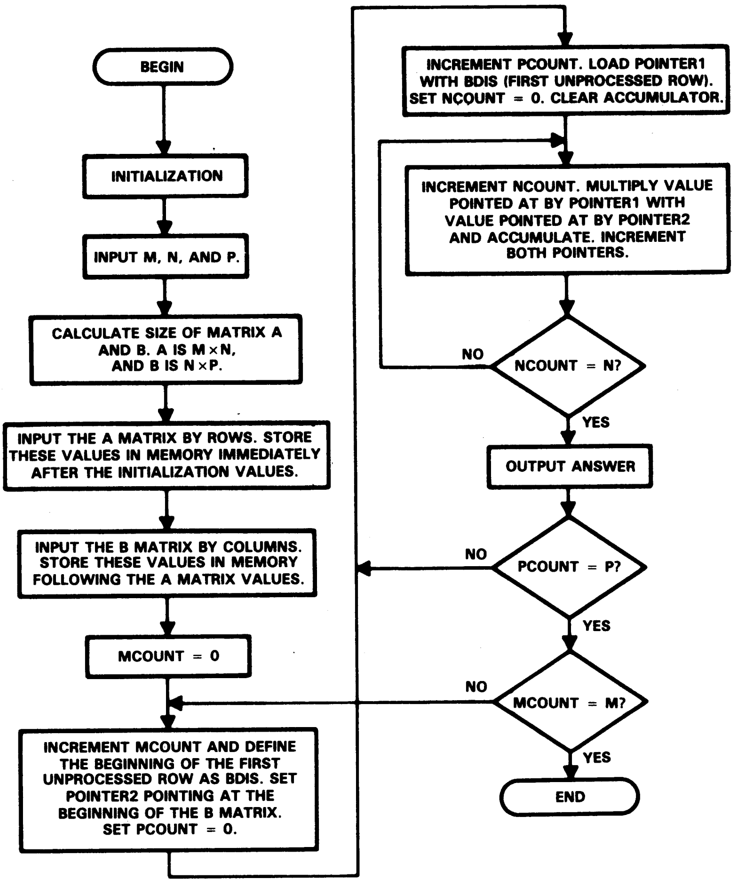


Figure 6. TMS32010 Flowchart

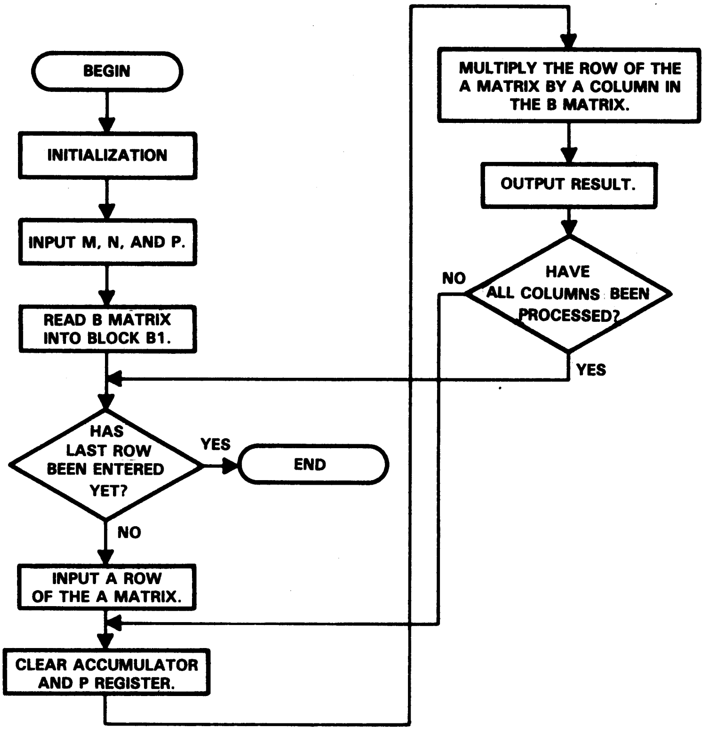


Figure 7. TMS32020 Flowchart

loops are included to multiply the two matrices. The outside loop control is labeled MCOUNT since it controls which row in the A matrix is being referenced during the multiplication. The secondary loop control is labeled PCOUNT because it counts how many columns in the B matrix have been processed. The inside loop control is labeled NCOUNT since it controls the multiplication of the values in the A matrix with the values in the B matrix.

IMPLEMENTATION OF THE MATRIX MULTIPLICATION ALGORITHM FOR THE TMS32020

The implementation of the algorithm for the TMS32020 is somewhat different since its advanced instruction set allows for a more efficient method of computing matrix multiplication. The TMS32020 version in Figure 7 also assumes that the two matrices to be multiplied are of size $M \times N$ and $N \times P$. This program takes a row of the A matrix, loads it into block B0 of data memory, and then multiplies this row by all columns in the B matrix. The TMS32020 continues this process until all the rows in the A matrix have been multiplied by all the columns in the B matrix. The TMS32020 version is similar to the TMS32010 in that the A matrix must be entered by rows and the B matrix by columns. This allows for a faster execution time. Figure 7 shows the basic implementation of the matrix multiplication algorithm that the TMS32020 uses to multiply two matrices.

Since the programs in the appendices treat the matrices differently, a memory map is included to help in understanding the two versions. Figure 8 shows how the matrices should look in memory after they have been entered. Note that for the TMS32020 version, the A matrix values reside in program memory since the CNFP (configure as program memory) instruction was implemented. Note also that only one row of the A matrix is in this block since the program enters one row at a time.

For the following matrices,

$$A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \quad B = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \end{bmatrix}$$

the memory would be configured in this manner for the TMS32010 and TMS32020.

TMS32010

DATA MEMORY

LOCATION (IN HEX)	VALUE
>00F	a_{11}
>010	a_{12}
>011	a_{21}
>012	a_{22}
>013	b_{11}
>014	b_{21}
>015	b_{12}
>016	b_{22}
>017	b_{13}
>018	b_{23}

TMS32020

DATA MEMORY

LOCATION (IN HEX)	VALUE
>308	b_{11}
>309	b_{21}
>30A	b_{12}
>30B	b_{22}
>30C	b_{13}
>30D	b_{23}

PROGRAM MEMORY

LOCATION (IN HEX)	VALUE
>FF00	a_{i1}
>FF01	a_{i2}

Figure 8. Memory Maps

SUMMARY

The TMS32010 and TMS32020 processors can be used to multiply large matrices efficiently. A brief review of matrix multiplication has been given to assist in the understanding of fundamental matrix multiplication. Three examples of graphics applications have been presented since these applications often require multiplication of matrices.

The TMS320 family has the power and flexibility to cost-effectively implement a wide range of high-speed graphics, numerical analysis, digital signal processing, and control applications. Since the TMS32010 and TMS32020 combine the flexibility of a high-speed controller with the numerical capability of an array processor, a new approach to applications such as graphics can now be considered.

REFERENCES

1. J.D. Foley and A. Van Dam, *Fundamentals of Interactive Commputer Graphics*, Addison-Wesley Publishing Company, Inc. (1982).
2. S.D. Conte and Carl de Boor, *Elementary Numerical Analysis*, McGraw-Hill, Inc. (1980).

Appendix A

```
NO$IDT      32010 FAMILY MACRO ASSEMBLER   PC2.1 84.107     10:03:42  02-25-85
                                                                   PAGE 0001

                   **************************************************
                   *   ALL INPUTS AND OUTPUTS FOR THIS PROGRAM SHOULD *
                   *   BE OR ARE IN Q12 FORMAT EXCEPT FOR THE M, N,   *
                   *   AND P INPUTS, WHICH SHOULD BE Q0.              *
                   **************************************************
0000                      AORG     0
          0000     M      EQU      >0
          0001     N      EQU      >1
          0002     P      EQU      >2
          0003     C1     EQU      >3
          0004     C2     EQU      >4
          0005     C3     EQU      >5
          0006     ANS    EQU      >6
          0007     ADIS   EQU      >7
          0008     BDIS   EQU      >8
          0009     CDIS   EQU      >9
          000A     TEMP   EQU      >A
          000B     COI    EQU      >B
          000C     COS    EQU      >C
          000D     T      EQU      >D
          000E     ONE    EQU      >E
                   *
                   * INITIALIZATION
                   *
0000 6E00                 LDPK     0
0001 6880                 LARP     0
0002 7E0F                 LACK     15
0003 500C                 SACL     COS
0004 500D                 SACL     T
0005 7E01                 LACK     1
0006 500E                 SACL     ONE
                   *
                   * MATRIX A IS M x N AND MATRIX B IS N x P.
                   * THESE STATEMENTS READ IN THE SIZES OF
                   * THE TWO MATRICES.
                   *
0007 4000                 IN       M,PA0
0008 4001                 IN       N,PA0
0009 4002                 IN       P,PA0
                   *
                   * CALCULATE THE LENGTH OF THE A MATRIX AND
                   * STORE THIS VALUE IN ADIS.
                   *
000A 6A00                 LT       M
000B 6D01                 MPY      N
000C 7F8E                 PAC
000D 5007                 SACL     ADIS
                   *
                   * CALCULATE THE LENGTH OF THE B MATRIX AND
                   * STORE THIS VALUE IN BDIS.
                   *
000E 6A01                 LT       N
000F 6D02                 MPY      P
0010 7F8E                 PAC
0011 5008                 SACL     BDIS
                   *
                   * POINT AT THE END OF THE INITIAL DATA.
                   *
0012 380C                 LAR AR0,COS
```

```
                *
                * READ THE A MATRIX VALUES INTO DATA RAM.
                * THIS MATRIX MUST BE ENTERED BY ROWS.
                * THE MATRIX VALUES WILL BE LOCATED IN
                * DATA RAM FOLLOWING THE INITIALIZATION
                * VALUES.
                *
0013 200B       FST     LAC     COI
0014 000E               ADD     ONE
0015 500B               SACL    COI
0016 4088               IN      *,PA0
0017 68A8               MAR     *+
0018 2007               LAC     ADIS
0019 100B               SUB     COI
001A FE00               BNZ     FST
001B 0013
                *
                * RESET COUNTER TO READ IN THE B MATRIX VALUES.
                *
001C 7F89               ZAC
001D 500B               SACL    COI
                *
                * READ THE B MATRIX VALUES INTO DATA RAM.
                * UNLIKE THE A MATRIX, THESE VALUES MUST BE
                * ENTERED BY COLUMNS.  THESE VALUES WILL BE
                * LOCATED IN DATA RAM FOLLOWING THE A MATRIX VALUES.
                *
                *
001E 200B       SND     LAC     COI
001F 000E               ADD     ONE
0020 500B               SACL    COI
0021 4088               IN      *,PA0
0022 68A8               MAR     *+
0023 2008               LAC     BDIS
0024 100B               SUB     COI
0025 FE00               BNZ     SND
0026 001E
                *
                * MORE INITIALIZATION
                *
0027 200D               LAC     T
0028 1001               SUB     N
0029 5003               SACL    C1
002A 200D               LAC     T
002B 0007               ADD     ADIS
002C 500D               SACL    T
002D 1001               SUB     N
002E 5007               SACL    ADIS
                *
                * CALCULATE A x B
                *
                *
                *
                *
                *                       N .
                *                     ______
                *                     \
                * OUTPUT(ij)    =      \  A(ik) x B(kj)
                *                      /
                *                     /
                *                     -----
                *                     k = 1
                *
002F 2003       FS      LAC     C1
0030 0001               ADD     N
```

```
0031 5003          SACL    C1
0032 6881          LARP    1
0033 390D          LAR     AR1,T
0034 6880          LARP    0
0035 7F89          ZAC
0036 5004          SACL    C2
0037 2004   SN     LAC     C2
0038 000E          ADD     ONE
0039 5004          SACL    C2
003A 3803          LAR     AR0,C1
003B 7F89          ZAC
003C 5006          SACL    ANS
003D 5005          SACL    C3
003E 2005   TH     LAC     C3
003F 000E          ADD     ONE
0040 5005          SACL    C3
0041 6506          ZALH    ANS
0042 6AA1          LT      *+,AR1
0043 6DA0          MPY     *+,AR0
0044 7F8F          APAC
0045 5806          SACH    ANS
0046 2005          LAC     C3
0047 1001          SUB     N
0048 FE00          BNZ     TH
0049 003E
            *
            * LOAD ACCUMULATOR WITH HIGH WORD OF Q24 RESULT.
            * LEFT-SHIFT FOUR TO CONVERT TO Q12.
            * NOTE THAT ONLY THE 12 MSB'S ARE SIGNIFICANT.
            *
004A 2406          LAC     ANS,4
004B 5006          SACL    ANS
004C 4806          OUT     ANS,PA0
004D 2004          LAC     C2
004E 1002          SUB     P
004F FE00          BNZ     SN
0050 0037
0051 2003          LAC     C1
0052 1007          SUB     ADIS
0053 FE00          BNZ     FS
0054 002F
0055 F900   QUIT   B       QUIT
0056 0055
NO ERRORS, NO WARNINGS
```

Appendix B

```
NO$IDT      32020 FAMILY MACRO ASSEMBLER   PC0.7 84.348    11:22:01  02-25-85
                                                                   PAGE 0001

                  *********************************************
                  *   ALL INPUTS AND OUTPUTS FOR THIS PROGRAM  *
                  *   SHOULD BE OR ARE IN Q12 FORMAT EXCEPT    *
                  *   FOR THE M, N, AND P, WHICH SHOULD BE Q0. *
                  *********************************************
0020                     AORG    32
          0000    M      EQU     >0
          0001    N      EQU     >1
          0002    P      EQU     >2
          0003    ANS    EQU     >3
          0004    BDM1   EQU     >4
          0005    ONE    EQU     >5
          0006    NM1    EQU     >6
          0007    PM1    EQU     >7
                  *
                  * INITIALIZATION
                  *
0020 C806                LDPK    6
0021 D100                LRLK    AR1,>300
0022 0300
0023 5589                LARP    1
0024 CA01                LACK    >1
0025 6005                SACL    ONE
                  *
                  * READ SIZES OF MATRICES.
                  *
0026 CB02                RPTK    2
0027 80A0                IN      *+,PA0
                  *
                  * MORE INITIALIZATION
                  *
0028 2001                LAC     M
0029 0005                ADD     ONE
002A 6001                SACL    M
002B 2000                LAC     N
002C 1005                SUB     ONE
002D 6006                SACL    NM1
002E 3C00                LT      N
002F 3802                MPY     P
0030 CE14                PAC
0031 1005                SUB     ONE
0032 6004                SACL    BDM1
0033 2002                LAC     P
0034 1005                SUB     ONE
0035 6007                SACL    PM1
                  *
                  * READ IN THE B MATRIX.
                  *
0036 D100                LRLK    AR1,>308
0037 0308
0038 4B04                RPT     BDM1
0039 80A0                IN      *+,PA0
003A 2001         CALLER LAC     M
003B 1005                SUB     ONE
003C 6001                SACL    M
003D F680                BZ      QT
003E 0052
                  *
                  * CALL ROUTINE TO READ IN A ROW
```

```
                   * OF THE A MATRIX.
                   *
     003F FE80            CALL    IO
     0040 0053
     0041 D100            LRLK    AR1,>308
     0042 0308
     0043 5589            LARP    1
     0044 3007            LAR     AR0,PM1
                   *
                   * CLEAR ACCUMULATOR AND P REGISTER.
                   *
     0045 A000     MUL    MPYK    0
     0046 CA00            ZAC
                   *
                   * MULTIPLY A ROW BY A COLUMN.
                   *
     0047 4B06            RPT     NM1
     0048 5DA0            MAC     >FF00,*+
     0049 FF00
     004A CE15            APAC
                   *
                   * OUTPUT RESULT.
                   *
     004B 6C03            SACH    ANS,4
     004C E003            OUT     ANS,PA0
     004D 5588            LARP    0
                   *
                   * CHECK TO SEE IF ALL COLUMNS HAVE BEEN PROCESSED.
                   *
     004E FB99            BANZ    MUL,*-,1
     004F 0045
                   *
                   *      GO GET NEXT ROW.
                   *
     0050 FF80            B       CALLER
     0051 003A
     0052 CE1F     QT     IDLE
     0053 CE04     IO     CNFD
     0054 5589            LARP    1
     0055 D100            LRLK    AR1,>200
     0056 0200
     0057 4B06            RPT     NM1
     0058 80A0            IN      *+,PA0
     0059 CE05            CNFP
     005A CE26            RET
NO ERRORS, NO WARNINGS
```