NPL Report DITC 109/88
February 1988

NATIONAL PHYSICAL LABORATORY

The Message Authenticator Algorithm (MAA) and its Implementation

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ISSN 0262-5369

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1 Introduction

A message authenticator algorithm (MAA) was developed by D.W. Davies and D.O. Clayden and published in 1983 [1]. The text of the original report is reproduced below, updated a little to reflect events since its first publication. Examples of programs for MAA are included in this report. The algorithm attracted the attention of the Committee of the London Clearing Banks and then Technical Committee 68 (Banking) of the International Standards Organisation, which adopted it as one of the approved algorithms for message authentication [2]. In the course of examining the algorithm a number of bodies tested its level of security. One potential attack was found, using a very large amount of chosen plain text in very long and artificial messages. It is questionable whether such an attack is realistic, since the ability of an adversary to subject an algorithm, with its secret key, to almost unlimited testing with chosen text would be a fatal weakness of an authenticated message scheme. Access to such a facility must be strictly controlled.

To avoid even this attack, the ISO standard 8731-2 contains a limitation of the total block of data to 1024 bytes and a 'mode of operation' in section 5 of the standard which chains these blocks together.

A long financial message can often be divided conveniently into segments which are no longer than 1024 bytes - for example into a series of separate payment messages. It is often preferable to provide each segment with its own authenticator, in the same way that error control is often segmented rather than covering a whole file. To detect insertion and deletion of segments, consecutive sequence numbering and checking can be used. Control totals, if authenticated, can prevent truncation at the end of the file. Another method is to send a group authenticator calculated from the sequence of segment authenticators. Groups of 256 segments can be authenticated in this way and if necessary a hierarchy of such authentication is possible, not limited to 1,000,000 blocks. This does not conflict with ISO 8731-2 and is, in effect, an alternative mode of operation.

In the reproduction of the 1983 report given below, the ISO 'mode of operation' has been inserted, and Table 4 is given in two versions 4(a) decimal and 4(b) hexadecimal, to help those testing main loop implementations. Table 5 of the original report contained an error in the first two columns of row S. Details appear in a note below the table. Unfortunately this error also occurs in the ISO version.

2 Purpose of the Algorithm

An 'authenticator' is a number which is sent with a message so that a check can be made by the receiver of the message that it has not been altered since it left the sender. For authenticators in general the sender and receiver share the knowledge of a key K which is otherwise secret. If M is the message, the authenticator is a function of K and M. It is calculated by the sender and again by the receiver. If the receiver's calculated value equals the authenticator value received with the message, the message is assumed to be correct. When a well designed authenticator is used, giving a 32 bit result, the probability that a message alteration will not be detected is 2^{-32} , which is small enough for most purposes.

3 Implementation Considerations

The algorithm was originally designed to be implemented on a main frame computer. In practice, implementations in high level languages have often proved slow in operation. The advent of low cost computers (PCs or similar) with larger word sizes increases the options for effective implementation of MAA.

There have been several requests for a version of the MAA, or a new algorithm, which could be implemented on a personal computer. The development of a new algorithm for this purpose would be likely to take a considerable time because of the amount of testing involved. Furthermore the MAA can now be implemented on a PC at a useful speed.

Many users prefer a version written in a high level language. For the highest speed the MAA needs to be written in assembly code, but the version in this report written in 'C' has achieved speeds of about one millisecond per message block of 32 bits on IBM compatible PCs of various types. This report also includes a version written in Basic, primarily as a description of the algorithm, and also to check results. It can be run on a BBC micro or on an IBM compatible PC using the MTEC BBCBasic(86) interpreter which uses 32 bit values for all arithmetic and bitwise boolean functions.

The MAA has several special requirements which influence the choice of language in which to write a program. In particular it needs:

1 Multiplication of two 32 bit unsigned numbers to produce a 64 bit unsigned product.

2 Addition of two unsigned 32 bit numbers to produce a 32 bit sum and a carry bit.

3 Boolean functions of 32 bit values.

4 Splitting 32 bit unsigned values into 8 bit bytes and concatenating back to 32 bit values.

The language 'C' copes with all of these requirements except (1) and the carry bit of (2). However it is capable of producing a 32 bit unsigned product from the multiplication of two 16 bit values, and the carry bit from addition can be derived from the most significant bits of the three values involved.

Pascal has the disadvantage that the 32nd bit is treated as a sign bit and a carry into the 33rd bit is reported as an overflow. Dealing with this can add a considerable time penalty. (A similar situation usually exists in Basic). We have not written an implementation in Pascal, but methods of dealing with these problems are illustrated in the Basic program. In particular, the function ADDU (unsigned addition) and the procedures MUL32 and MUL16 could be used as models for a Pascal version. Early Pascal compilers did not implement bitwise boolean functions, but these are now available in Prospero Pascal version 3.

A version of the MAA has been written by D.W. Davies in assembly code for the 6502. This takes about 6 milliseconds per message block using the BBC model B. A version written by D.O. Clayden in Turbo Basic (compiling) takes about 300 millisec per message block, about the same time as the Basic program herein when run with the MTEC BBCBasic(86) interpreter. The Turbo Basic program illustrates methods which are applicable in dialects which lack 32 bit boolean functions. This version and the 6502 version can be made available on request.

4 General Description

All numbers manipulated in this algorithm are regarded as 32 bit unsigned integers, unless otherwise stated. For such a number N, $0 \leq N < 2^{32}$. This algorithm can be implemented conveniently and efficiently in a computer with word length 32 bits or more.

The message can be a bit string of any length but for input to the algorithm we regard it as a sequence of 32 bit numbers M_1, M_2---M_n of which there are n, called 'message blocks'. The detail of how to pad out the last block M_n to 32 bits is not part of the algorithm but must be defined in any application. No weakness is introduced by choosing one of the simplest rules, such as extending to the right or left with zeros or ones.

During the process of testing and evaluation of this algorithm, it was found that its use for very long messages results in some reduction of the dependence of the authenticator on the early data in the message. To minimise this effect, ISO 8731-2 specifies that the algorithm shall not be used for messages with more than 1,000,000 blocks, i.e. n should not exceed 1,000,000. Note the 'mode of operation' which is applied to messages longer than 1024 bytes (n>256).

The key consists of two 32 bit numbers J and K and thus has a size of 64 bits.

The result of the algorithm is a 32 bit authenticator value denoted Z. The calculation can be performed on messages as short as one block (n=1).

The calculation, a flow diagram of which is shown on page 20, has three parts:

a   The 'Prelude' is a calculation made with the keys (J and K) alone and it generates six numbers X_0, Y_0, V_0, W, S and T which are used in the subsequent calculations. This part need not be repeated until a new key is installed.

b The 'Main loop' is a calculation which is repeated for each message block M_i, therefore for long messages it dominates the calculation.

c The 'Coda' consists of two operations of the main loop using as its 'message blocks' the two numbers S and T in turn, followed by a simple calculation of Z, the authenticator.

Therefore the processing load of the algorithm contains a part (the main loop and coda) proportional to n+2 where n is the message size, and a constant overhead each time the keys are changed.

5 Specification of the Functions Used in the Algorithm

A number of functions are used in the description of the algorithm. In the following, X and Y are 32 bit numbers and the result is a 32 bit number except where stated otherwise.

CYC(X)	is the result of a one-bit cyclic left shift of X
AND(X,Y)	is the result of the logical AND operation carried out on each of 32 bits.
OR(X,Y)	is the result of the logical OR operation carried out on each of 32 bits.
XOR(X,Y)	is the result of the XOR operation (modulo 2 addition) carried out on each of 32 bits.
ADD(X,Y)	is the result of adding X and Y discarding any carry from the 32nd bit, that is to say, addition modulo 2^{32}.
CAR(X,Y)	is the value of the carry from the 32nd bit when X is added to Y, it has the value 0 or 1.

MUL1(X,Y), MUL2(X,Y) and MUL2A(X,Y) are three different forms of multiplication, each with a 32 bit result.

To explain these multiplications, let the 64 bit product of X and Y be {U,L}. Here the curly brackets mean that the values enclosed are 'concatenated', U on left of L. Hence U is the upper (most significant) half of the product and L the lower half.

6 Definition of MUL1(X,Y)

Multiply X and Y to produce {U,L}. With S and C as local variables,

```
          S:= ADD(U,L);                (1)
          C:= CAR(U,L);                (2)
   MUL1(X,Y):= ADD(S,C)                (3)
```

That is to say, U is added to L with 'end around carry'.

Numerically the result is congruent to X*Y, the product of X and Y, modulo (2^{32}-1). This can be seen by the following argument. It is not necessarily the smallest residue because it may equal 2^{32}-1.

$$\begin{aligned} X*Y &= 2^{32}U + L \\ S &= U + L - 2^{32}C \qquad \text{from (1) and (2)} \\ \mathrm{MUL1}(X,Y) &= S + C \\ &= U + L - (2^{32} - 1)C \\ &= X*Y - (2^{32} - 1)(U + C) \end{aligned}$$

It is shown later that the addition (3) cannot produce a carry from the 32nd bit (see 'details of the multiplication functions').

7 Definition of MUL2(X,Y)

This form of multiplication is not used in the main loop, only in the prelude. With D, E, F, S and C as local variables,

```
          D:= ADD(U,U);                (4)
          E:= CAR(U,U);                (5)
          F:= ADD(D,2E);               (6)
          S:= ADD(F,L);                (7)
          C:= CAR(F,L);                (8)
   MUL2(X,Y):= ADD(S,2C)               (9)
```

Numerically the result is congruent to X*Y, the product of X and Y, modulo (2^{31}-2). This can be seen by the following argument. It is not necessarily the smallest residue because it may equal 2^{31}-2.

$$
\begin{aligned}
X*Y &= 2^{32}U + L & & \\
2U &= D + 2^{32}E & &\text{from (4) and (5)}\\
F &= D + 2E & &\text{from (6)}\\
F + L &= S + 2^{32}C & &\text{from (7) and (8)}\\
\mathrm{MUL2}(X,Y) &= S + 2C & &\text{from (9)}\\
&= F + L - (2^{32} - 2)C & &\\
&= D + 2E + L - (2^{32} - 2)C & &\\
&= 2U + L - (2^{32} - 2)(E + C) & &\\
&= X*Y - (2^{32} - 2)(U + E + C) & &
\end{aligned}
$$

It is shown later that additions (6) and (9) cannot produce a carry from the 32nd bit (see 'details of the multiplication functions').

8 Definition of MUL2A(X,Y)

This is a simplified form of MUL2(X,Y) used in the main loop, which yields the correct result only when at least one of the numbers X and Y has a zero in its most significant bit.

It is employed for economy in processing. D, S, C are local variables.

```
          D:= ADD(U,U);            (10)
          S:= ADD(D,L);            (11)
          C:= CAR(D,L);            (12)
 MUL2A(X,Y):= ADD(S,2C)            (13)
```

The result is congruent to X*Y modulo (2^{31}-2) under the conditions stated because, in the notation of MUL2(X,Y) above, the carry E = 0. This will be shown later (see 'details of the multiplication functions').

9 The Functions BYT{X,Y} and PAT{X,Y}

A procedure is used in the 'prelude' to condition both the keys and the results in order to prevent long strings of ones or zeros. It produces two results which are the conditioned values of X and Y and a number PAT{X,Y} which records the changes that have been made. PAT{X,Y} $\leq$ 255 so it is essentially an 8 bit number.

X and Y are regarded as strings of bytes. Using the notation {X,Y...} for concatenating,

$\{X,Y\} = \{B_0,B_1,B_2,B_3,B_4,B_5,B_6,B_7\}$

Thus bytes B_0 - B_3 are derived from X and B_4 - B_7 from Y.

The procedure is best described by a program where each byte B_i is regarded as an integer of length 8 bits:

```
P:= 0;
for i:= 0 to 7 do
     begin
     P:= 2 * P;
     if $B_i$ = 0 then
        begin
        P:= P + 1;
        $B'_i$:= P
        end
     else if $B_i$ = 255 then
        begin
        P:= P + 1;
        $B'_i$ = 255 - P
        end
     else
        $B'_i$:= $B_i$
     end;
```

The results are:

$\text{BYT}\{X,Y\} = \{B'_0,B'_1,B'_2,B'_3,B'_4,B'_5,B'_6,B'_7\}$
and $\text{PAT}\{X,Y\} = P$

Examples for checking an implementation of this function are given later.

10 The Prelude

```
{$J_1$,$K_1$}  := BYT{J,K};
      P  := PAT{J,K};                                  (14)
      Q  := (1+P)*(1+P)
```

First, a calculation using J_1 produces H_4, H_6 and H_8 from which X_0, V_0 and S are derived.

```
J1$_2$:= MUL1($J_1$,$J_1$);          J2$_2$:= MUL2($J_1$,$J_1$);
J1$_4$:= MUL1(J1$_2$,J1$_2$);        J2$_4$:= MUL2(J2$_2$,J2$_2$);
J1$_6$:= MUL1(J1$_2$,J1$_4$);        J2$_6$:= MUL2(J2$_2$,J2$_4$);      (15)
J1$_8$:= MUL1(J1$_2$,J1$_6$);        J2$_8$:= MUL2(J2$_2$,J2$_6$);

      $H_4$:= XOR(J1$_4$,J2$_4$);
      $H_6$:= XOR(J1$_6$,J2$_6$);                                (16)
      $H_8$:= XOR(J1$_8$,J2$_8$);
```

A similar calculation using K_1 produces H_5, H_7 and H_9, from which Y_0, W and T are derived.

```
K1$_2$:= MUL1($K_1$,$K_1$);          K2$_2$:= MUL2($K_1$,$K_1$);
K1$_4$:= MUL1(K1$_2$,K1$_2$);        K2$_4$:= MUL2(K2$_2$,K2$_2$);
K1$_5$:= MUL1($K_1$,K1$_4$);         K2$_5$:= MUL2($K_1$,K2$_4$);       (17)
K1$_7$:= MUL1(K1$_2$,K1$_5$);        K2$_7$:= MUL2(K2$_2$,K2$_5$);
K1$_9$:= MUL1(K1$_2$,K1$_7$);        K2$_9$:= MUL2(K2$_2$,K2$_7$);

      $H_0$:= XOR(K1$_5$,K2$_5$);
      $H_5$:= MUL2($H_0$,Q);
      $H_7$:= XOR(K1$_7$,K2$_7$);                                (19)
      $H_9$:= XOR(K1$_9$,K2$_9$);
```

Finally, the results are conditioned by the BYT function:

```
  {$X_0$,$Y_0$}  := BYT{$H_4$,$H_5$};
   {$V_0$,W}  := BYT{$H_6$,$H_7$};                              (20)
    {S,T}  := BYT{$H_8$,$H_9$}
```

Examples are given later for checking this part of the algorithm, except for lines (14).

11 The Main Loop

This loop is performed in turn for each of the message blocks M_i. In addition to M_i, the principal values employed are X and Y and the main results are the new values of X and Y. It also uses V and W and modifies V at each performance. Note that X, Y and V are initialised with the values provided by the Prelude. In order to use the same keys again, the initial values of X, Y and V must be preserved, therefore they are denoted X_0, Y_0 and V_0 and there is an initialising step X:= X_0, Y:= Y_0, V:= V_0, after which the main loop is entered for the first time. The 'coda', used after all message blocks have been processed by n cycles of the loop, is described in the next section.

The program is shown in columns to clarify its 'parallel' operation but it should be read in normal reading order, left to right on each line

```
           V:= CYC(V);                    (21)
           E:= XOR(V,W);                  (21)

X:= XOR(X,Mi);        Y:= XOR(Y,Mi);      (22)
F:= ADD(E,Y);         G:= ADD(E,X);       (23)
F:= OR(F,A);          G:= OR(G,B);        (23)
F:= AND(F,C);         G:= AND(G,D);       (23)
X:= MUL1(X,F);        Y:= MUL2A(Y,G)      (24)
```

The numbers A, B, C, D are constants which are, in hexadecimal notation:

Constant A:	0204 0801
Constant B:	0080 4021
Constant C:	BFEF 7FDF
Constant D:	7DFE FBFF

Lines (21) are common to both paths. Line (22) introduces the message block M_i. Lines (23) prepare the multipliers and line (24) generates new X and Y values. Only X, Y and V are modified for use in the next cycle. F and G are local variables. Since the constant D has its most significant digit zero, $G < 2^{31}$ and this ensures that MUL2A in line (24) will give the correct result, a multiplication modulo $2^{31} - 1$.

12 The Coda

After the last message block M_n has been processed, the main loop is performed with 'message block' S, then again with block T, i.e.

$M_{n+1} = S$, $M_{n+2} = T$.

After this, the authenticator is calculated as Z = XOR(X,Y) and the algorithm is complete. The values X_0, Y_0, V_0, W, S and T should be retained in order to calculate further authenticator values without repeating the prelude (key calculation) until the keys are changed.

13 Mode of operation

ISO 8731-2 contains this mode of operation for messages longer than 1024 bytes. The word 'segment' is used here to avoid confusion with the blocks B_i of 4 bytes.

> Messages longer than 1024 bytes shall be divided into segments of 1024 bytes and chained as follows:
>
> For the first segment of 1024 bytes the MAC (4 bytes) shall be formed. The MAC value shall be prefixed to (but not transmitted in) the second segment and the resultant 1028 bytes authenticated. This procedure shall continue, with the MAC of each segment prefixed to the next, until the last segment, which need not be of size 1024 bytes, and the final MAC shall be used as the transmitted MAC for the whole message.

14 Details of the Multiplication Functions

Recalling that X*Y produces the 64 bit product {U,L},

If $X,Y \le 2^{32}-1$, $X*Y \le 2^{64}-2^{33} + 1$
  Hence $U \le 2^{32}-2$
  and $L \le 2^{32}-1$, ie no restriction

1 In the calculation of MUL1(X,Y)
  $2^{32}C + S = U + L \le 2^{33}-3$ from (1) and (2)

If a carry occurs, $C = 1$ and $S \le 2^{32}-3$
  Hence $\text{MUL1}(X,Y) = S + C \le 2^{32}-2$ can produce no carry

2 In the calculation of MUL2(X,Y)

$2^{32}E + D = 2U \le 2^{33}-4$ from (4) and (5)

If a carry is produced, $E = 1$ and $D \le 2^{32}-4$

Hence $F = D + 2E \le 2^{32}-2$ can produce no carry

If no carry is produced $F = 2U$ is even and less than 2^{32}

Hence $F \le 2^{32}-2$ in either case

Also $2^{32}C + S = F + L \le 2^{33}-3$ from (7) and (8)

If a carry is produced, $C = 1$ and $S \le 2^{32}-3$

Hence $\mathrm{MUL2}(X,Y) = S + 2C \le 2^{32}-1$ can produce no carry

3 In the calculation of MUL2A(X,Y) where $X \le 2^{32}-1$, $Y \le 2^{31}-1$

$X*Y \le 2^{63}-2^{32}-2^{31} + 1$

Hence $U \le 2^{31}-1$, $2U \le 2^{32}-2$ can produce no carry

$2^{32}C + S = D + L = 2U + L \le 2^{33}-3$

If a carry is produced, $C = 1$ and $S \le 2^{32}-3$

Hence $\mathrm{MUL2A}(X,Y) = S + 2C \le 2^{32}-1$ can produce no carry

15 Test Examples For Parts of the Algorithm

For most parts of the algorithm, simple test examples are given. The data used are not always realistic, ie they are not values which could be produced by earlier parts of the algorithm, and artificial values of constants are used. This is done to keep the test cases so simple that they can be verified by a pencil and paper calculation and thus the verification of the algorithm's implementations does <u>not</u> consist of comparing one machine implementation with another. The parts thus tested are:

MUL1, MUL2, MUL2A

BYT{X,Y} and PAT{X,Y}

Prelude, except the initial BYT{J,K} operation

Main loop

The Coda is not tested separately because it uses only the main loop and one XOR function. For testing the whole algorithm, some results of test runs with the NPL implementation are given, but it would be difficult to test even the simplest case of the complete algorithm by pencil and paper calculation.

16 Test Examples for MUL1, MUL2, MUL2A

It is suggested that the multiplication operations should be tested with very small numbers and very large numbers. To represent a large number we use the ones complement. Thus if a is a small number (say less than 4096) we use the notation ~a to mean its ones complement, ie $2^{32} - 1 - a$. Examples for testing MUL1, MUL2 and MUL2A are given in Table 1.

For small numbers a and b, all three multiplication functions produce their true product a*b. When large numbers are used the functions can give different results. They should be tested both ways round, with MUL(x,y) and MUL(y,x) to verify that these are equal.

(1) Test cases for MUL1

In modulo $2^{32} - 1$ arithmetic ~a is effectively -a, therefore the results are very simple

```
      MUL1(~a,b) = MUL1(a,~b) = ~(a*b)
      MUL1(~a,~b) = a*b
```

(2) Test cases for MUL2

```
      MUL2(~a,b) = ~(a*b - b + 1)
      MUL2(a,~b) = ~(a*b - a + 1)
      MUL2(~a,~b) = a*b - a - b + 1
```

(3) Test cases for MUL2A

This will give the same result as MUL2 when tested with numbers within its range. For testing with large numbers, ~a and ~b - 2^{31} must be used.

```
      MUL2A(~a,b) = ~(a*b - b + 1)
      MUL2A(a,~b) = ~(a*b - a + 1)
```
MUL2A(~a,~b-2^{31}) = $2^{31}(1 - p) + a*b + p - b - 1$

where p is the parity of a; the value of its least significant bit.

That is, for even values of a the result is 2^{31} + a*b - b - 1
for odd values of a the result is a*b - b

	a	b	result
MUL1	0000 000F	0000 000E	0000 00D2
	FFFF FFF0	0000 000E	FFFF FF2D
	FFFF FFF0	FFFF FFF1	0000 00D2
MUL2	0000 000F	0000 000E	0000 00D2
	FFFF FFF0	0000 000E	FFFF FF3A
	FFFF FFF0	FFFF FFF1	0000 00B6
MUL2A	0000 000F	0000 000E	0000 00D2
	FFFF FFF0	0000 000E	FFFF FF3A
	7FFF FFF0	FFFF FFF1	8000 00C2
	FFFF FFF0	7FFF FFF1	0000 00C4

Table 1 Test cases for Multiplication Functions (hexadecimal)

17 Test Examples for BYT{X,Y} and PAT{X,Y}

Three cases for testing these functions are listed in Table 2

	X	Y
{X,Y}	00 00 00 00	00 00 00 00
BYT{X,Y}	01 03 07 0F	1F 3F 7F FF
PAT{X,Y}	FF	
{X,Y}	FF FF 00 FF	FF FF FF FF
BYT{X,Y}	FE FC 07 F0	E0 C0 80 00
PAT{X,Y}	FF	
{X,Y}	AB 00 FF CD	FF EF 00 01
BYT{X,Y}	AB 01 FC CD	F2 EF 35 01
PAT{X,Y}	6A	

Table 2 Test cases for the BYT and PAT Functions

18 Test Examples for the Prelude

An example is given in Table 3. The initial BYT{J,K} operation is not tested. We assume that the results from lines (14) are

J_1 = 0000 0100, K_1 = 0000 0080, P = 1,

$J1_2$	0001 0000	$J2_2$	0001 0000
$J1_4$	0000 0001	$J2_4$	0000 0002
$J1_6$	0001 0000	$J2_6$	0002 0000
$J1_8$	0000 0001	$J2_8$	0000 0004

H_4	0000 0003
H_6	0003 0000
H_8	0000 0005

$K1_2$	0000 4000	$K2_2$	0000 4000
$K1_4$	1000 0000	$K2_4$	1000 0000
$K1_5$	0000 0008	$K2_5$	0000 0010
$K1_7$	0002 0000	$K2_7$	0004 0000
$K1_9$	8000 0000	$K2_9$	0000 0002

H_0	0000 0018	
H_5	0000 0060	(Q = 4)
H_7	0006 0000	
H_9	8000 0002	

{X_0,Y_0}	0103 0703 1D3B 7760	PAT{X_0,Y_0}	EE
{V_0,W}	0103 050B 1706 5DBB	PAT{V_0,W}	BB
{S,T}	0103 0705 8039 7302	PAT{S,T}	E6

Table 3 Test cases for lines (15) - (20) of the Prelude

The PAT values obtained from conditioning the results of the prelude are quoted above for checking purposes but are not used in the algorithm.

19 Test Examples for the Main Loop

In Table 4, three examples of single block messages are given, using small and large numbers. There are two versions of Table 4, 4a in decimal and 4b in hexadecimal notation. In the decimal table there is a convention that ~a is 2^{32} - 1 - a. In the third example there are two cases of large numbers which must have zero in the 32nd bit, shown as ~2 - 2^{31} and ~3 - 2^{31} respectively. They could have been written 2^{31} - 2 and 2^{31} - 3 respectively. In order to keep the numbers small, artificial values of the constants A, B, C and D are used. Three single block examples are followed by a message of three blocks, in order to check that the implementation correctly retains the value of X, Y and W. The final S and T cycles of the coda are not included in this table.

	Single block messages			Three-block message			
A B	4 1	1 4	1 2	2 1	2 1	2 1	
C D	~8 ~4	~6 ~3	~1 ~2*	~4 ~4	~4 ~4	~4 ~4	
V W	3 3	3 3	7 7	1 1	2 1	4 1	
X_0 Y_0	2 3	~2 ~3	~2 ~3	1 2	3 2	20 9	
M	5	1	8	0	1	2	
V	6	6	14	2	4	8	CYC
E	5	5	9	3	5	9	XOR
X Y	7 6	~3 ~2	~10 ~11	1 2	2 3	22 11	XOR
F G	11 12	2 1	~2 ~1	5 4	8 7	20 31	ADD
F G	15 13	3 5	~2 ~1	7 5	10 7	22 31	OR
F G	7 9	1 4	~3 ~3*	3 1	10 3	18 27	AND
X Y	49 54	~3 ~5	30 30	3 2	20 9	396 297	MUL
Z	7	6	0	1	29	165	XOR

* - 2^{31}

Table 4a Test Cases for the Main Loop (decimal)

	Single block messages			Three-block message		
A	4	1	1	2	2	2
B	1	4	2	1	1	1
C	FFFFFFF7	FFFFFFF9	FFFFFFFE	FFFFFFFB	FFFFFFFB	FFFFFFFB
D	FFFFFFFB	FFFFFFFC	7FFFFFFD	FFFFFFFB	FFFFFFFB	FFFFFFFB
V	3	3	7	1	2	4
W	3	3	7	1	1	1
X_0	2	FFFFFFFD	FFFFFFFD	1	3	14
Y_0	3	FFFFFFFC	FFFFFFFC	2	2	9
M	5	1	8	0	1	2
V	6	6	E	2	4	8
E	5	5	9	3	5	9
X	7	FFFFFFFC	FFFFFFF5	1	2	16
Y	6	FFFFFFFD	FFFFFFF4	2	3	B
F	B	2	FFFFFFFD	5	8	14
G	C	1	FFFFFFFE	4	7	1F
F	F	3	FFFFFFFD	7	A	16
G	D	5	FFFFFFFE	5	7	1F
F	7	1	FFFFFFFC	3	A	12
G	9	4	7FFFFFFC	1	3	1B
X	31	FFFFFFFC	1E	3	14	18C
Y	36	FFFFFFFA	1E	2	9	129
Z	7	6	0	1	1D	A5

Table 4b Test Cases for the Main Loop (hexadecimal)

20 Test Examples for the Whole Algorithm

Using the NPL implementation of the algorithm, the four test examples with two block messages given in Table 5 were calculated. For ease of checking, intermediate results are tabulated: the results of the prelude and the X and Y values after each operation of the main loop, that is for M_1, M_2, S and T.

J	00FF 00FF	00FF 00FF	5555 5555	5555 5555
K	0000 0000	0000 0000	5A35 D667	5A35 D667
P	FF	FF	00	00
X_0	4A64 5A01	4A64 5A01	34AC F886	34AC F886
Y_0	50DE C930	50DE C930	7397 C9AE	7397 C9AE
V_0	5CCA 3239	5CCA 3239	7201 F4DC	7201 F4DC
W	FECC AA6E	FECC AA6E	2829 040B	2829 040B
M_1	5555 5555	AAAA AAAA	0000 0000	FFFF FFFF
X	48B2 04D6	6AEB ACF8	2FD7 6FFB	8DC8 BBDE
Y	5834 A585	9DB1 5CF6	550D 91CE	FE4E 5BDD
M_2	AAAA AAAA	5555 5555	FFFF FFFF	0000 0000
X	4F99 8E01	270E EDAF	A70F C148	CBC8 65BA
Y	BE9F 0917	B814 2629	1D10 D8D3	0297 AF6F
S	51ED E9C7	51ED E9C7	9E2E 7B36	9E2E 7B36
X	3449 25FC	2990 7CD8	B1CC 1CC5	3CF3 A7D2
Y	DB91 02B0	BA92 DB12	29C1 485F	160E E9B5
T	24B6 6FB5	24B6 6FB5	1364 7149	1364 7149
X	277B 4B25	28EA D8B3	288F C786	D048 2465
Y	D636 250D	81D1 0CA3	9115 A558	7050 EC5E
Z	F14D 6E28	A93B D410	B99A 62DE	A018 C83B

Table 5 Test Cases for the Whole Algorithm

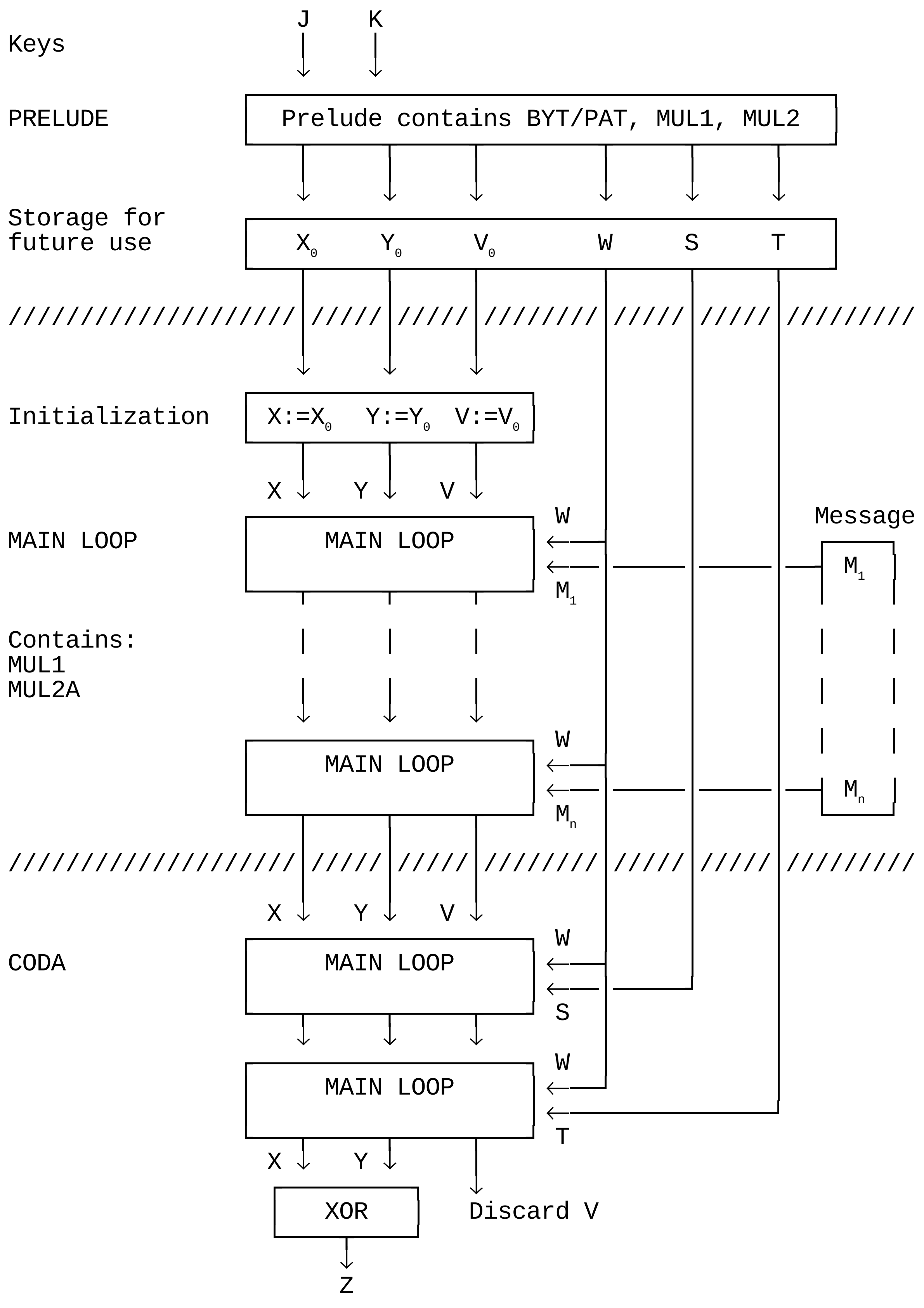
Note. Table 5 of the original report contained an error in the first two columns of row S. The values 51ED E967 (twice) should have been 51ED E9C7.

A further set of test cases for the whole algorithm is given in Table 6. The J and K values were chosen to give long strings of zeros after conditioning. The message consists of 20 blocks of zeros. Intermediate values of X and Y are listed as well as the final authenticator value Z.

J = 8001 8001, K = 8001 8000

block	X	Y	Z
1	303F F4AA	1277 A6D4	all message blocks are zeros
2	55DD 063F	4C49 AAE0	
3	51AF 3C1D	5BC0 2502	
4	A44A AAC0	63C7 0DBA	
5	4D53 901A	2E80 AC30	
6	5F38 EEF1	2A60 91AE	
7	F023 9DD5	3DD8 1AC6	
8	EB35 B97F	9372 CDC6	
9	4DA1 24A1	C6B1 317E	
10	7F83 9576	74B3 9176	
11	11A9 D254	D786 34BC	
12	D880 4CA5	FDC1 A8BA	
13	3F6F 7248	11AC 46B8	
14	ACBC 13DD	33D5 A466	
15	4CE9 33E1	C21A 1846	
16	C1ED 90DD	CD95 9B46	
17	3CD5 4DEB	613F 8E2A	
18	BBA5 7835	07C7 2EAA	
19	D784 3FDC	6AD6 E8A4	
20	5EBA 06C2	9189 6CFA	
S	1D9C 9655	98D1 CC75	
T	7BC1 80AB	A0B8 7B77	DB79 FBDC

Table 6 Test case for a 20 block message



21 Diagram showing data flow

22 Implementation in 'C'

The 'C' program is written in the form of a series of functions or procedures with a main program designed to run the tests described above. The larger functions described in the algorithm are implemented as functions or procedures, but the smaller ones, such as ADD, AND and CAR, are implemented in a single line of code. Two versions of the mainloop are provided called 'mainloop1' which outputs intermediate values for checking, and 'mainloop2' which is designed for maximum speed. The latter includes versions of mul1 and mul2a copied in full to avoid the time taken to call the functions.

'C' does not provide the carry bit from the addition of two unsigned values, but there are many ways of deriving it. The method used was selected after speed trials.

The function mul32 employs shifts of 16 bits. An alternative method is to employ a 'union' to access the halves of an unsigned long variable. However with the Turbo and Zorland compilers this takes longer than the method shown.

Those wishing to use the functions or procedures will need to write their own main program to cope with input and output.

A time measurement option has been included although time measurement is not part of standard 'C' and involves accessing the operating system. Inaccuracies of about a tenth of a second are likely, so measurements of short time intervals should be treated with reserve. The method 'guesstime' has been chosen as it is likely to be portable. It uses the one second clock in MS-DOS, and interpolates for fractions of a second.

The time measured for the main loop on IBM compatibles is approximately 1 millisec when compiled by the Turbo compiler and 1.1 millisec when compiled by the Zorland compiler.

Time measurement may need alternative methods when using compilers other than Turbo or Zorland, or operating systems other than MS-DOS.

```
/* MAA Message Authenticator Algorithm by D W Davies, NPL 1983.  */
/* Version in C by D O Clayden, NPL 1987.                        */
/* Copyright NPL 1987                                            */
/* Version MAA7C22 suitable for running all tests and timing.    */
/* Most printf statements are for test purposes only.            */
/* Mainloop time about 1 millisec excl input, on M24 and PC1512. */

#include <stdio.h>
#include <time.h>
#include <dos.h>

#define BIT31 0x80000000L
#define FFFF  0xFFFFL
unsigned long a,b,c,d,l,m,s,t,u,v,w,x,y,z,pat,sum,t4,t5,v0,x0,y0;

int menu1()
{
  int m;
  printf(" 1 Test small functions (Tables 1,2)\n");
  printf(" 2 Test prelude (Table 3)\n");
  printf(" 3 Test main (Table 4)\n");
  printf(" 4 Test prelude + main + coda (Table 5)\n");
  printf(" 5 Test and timing of repeated message blocks (Table 6)\n");
  printf(" 6 Quit to C \n");
  scanf("%d",&m);
  return(m);
} /* menu1 */

void mul32(a,b)
unsigned long a,b;
/* unsigned 64 bit product in u(upper) and l(lower) */
{
  unsigned long p1,p2,p3,sum;
  p1=(a&FFFF)*(b&FFFF);
  p2=(a&FFFF)*(b>>16);
  p3=(a>>16)*(b&FFFF);
  sum=(p1>>16)+(p2&FFFF)+(p3&FFFF);
  l=(p1&FFFF)+(sum<<16);
  u=(sum>>16)+(p2>>16)+(p3>>16)+((a>>16)*(b>>16));
} /* mul32 */
```

```
unsigned long mul1(a,b)
unsigned long a,b;
{
  unsigned long s,car;
  mul32(a,b);
  s=u+l;
  car=((u^l)&BIT31)? !(s&BIT31):(u&BIT31)!=0;
  return(s+car);
} /* mul1 */

unsigned long mul2(a,b)
unsigned long a,b;
{
  unsigned long d,f,s,car;
  mul32(a,b);
  d=u+u; car=(u&BIT31)!=0;
  f=d+car+car;
  s=f+l;
  car=((f^l)&BIT31)? !(s&BIT31):(f&BIT31)!=0;
  return(s+car+car);
} /* mul2 */

unsigned long mul2a(a,b)
unsigned long a,b;
{
  unsigned long d,s,car;
  mul32(a,b);
  d=u+u;
  s=d+l;
  car=((d^l)&BIT31)? !(s&BIT31):(d&BIT31)!=0;
  return(s+car+car);
} /* mul2a */

void byt(x,y)
unsigned long x,y;
{
  unsigned long p;
  int i,b[8];
  for (i=3; i>=0; i--) {
    b[i]=x&255; b[i+4]=y&255;
    x=x>>8; y=y>>8;
  }
  p=0;
  for (i=0; i<8; i++) {
    p=p+p;
    if (b[i]==O) {p+=1; b[i]=p;} else if (b[i]==255) {p+=1; b[i]=255-p;}
  }
  pat=p; x=0; y=0;
  for (i=0; i<4; i++) {
    x=(x<<8)+b[i]; y=(y<<8)+b[i+4];
  }
  u=x; l=y;
} /* byt */
```

```
void prelude(x,y,test)
unsigned long x,y;
int test;
{
  unsigned long j1[10],j2[10],k1[10],k2[10],h[10];
  unsigned long p,q;
  byt(x,y);
  j1[0]=u; k1[0]=l; p=pat;
  if (test>0) {
    j1[0]=x; k1[0]=y;
    printf("Enter P (2 hex): \n");
    scanf("%X",&p);
  }
  q=(p+1)*(p+1);
  j1[2]=mul1(j1[0],j1[0]); j2[2]=mul2(j1[0],j1[0]);
  j1[4]=mul1(j1[2],j1[2]); j2[4]=mul2(j2[2],j2[2]);
  j1[6]=mul1(j1[2],j1[4]); j2[6]=mul2(j2[2],j2[4]);
  j1[8]=mul1(j1[2],j1[6]); j2[8]=mul2(j2[2],j2[6]);
  h[4]=j1[4]^j2[4]; h[6]=j1[6]^j2[6]; h[8]=j1[8]^j2[8];
  printf("H4= %lX \n",h[4]);
  printf("H6= %lX \n",h[6]);
  printf("H8= %lX \n",h[8]);

  k1[2]=mul1(k1[0],k1[0]); k2[2]=mul2(k1[0],k1[0]);
  k1[4]=mul1(k1[2],k1[2]); k2[4]=mul2(k2[2],k2[2]);
  k1[5]=mul1(k1[0],k1[4]); k2[5]=mul2(k1[0],k2[4]);
  k1[7]=mul1(k1[2],k1[5]); k2[7]=mul2(k2[2],k2[5]);
  k1[9]=mul1(k1[2],k1[7]); k2[9]=mul2(k2[2],k2[7]);
  h[0]=k1[5]^k2[5]; h[5]=mul2(h[0],q); h[7]=k1[7]^k2[7]: h[9]=k1[9]^k2[9];
  printf("H0= %lX \n",h[0]);
  printf("H5= %lX \n",h[5]);
  printf("H7= %lX \n",h[7]);
  printf("H9= %lX \n",h[9]);

  byt(h[4],h[5]);
  x0=u; y0=l;
  printf("X0= %lX",x0);
  printf("  Y0= %lX",y0);
  printf("  PAT= %lX \n",pat);

  byt(h[6],h[7]);
  v0=u; w=l;
  printf("V0= %lX",v0);
  printf("  W= %lX",w);
  printf("  PAT= %lX \n",pat);

  byt(h[8],h[9]);
  s=u; t=l;
  printf("S= %lX",s);
  printf("  T= %lX",t);
  printf("  PAT= %lX \n",pat);
} /* prelude */
```

```
void abcd()
{
  a=0x2040801L;
  b=0x804021L;
  c=0xBFEF7FDFL;
  d=0x7DFEFBFFL;
  printf("A= %lX \n",a);
  printf("B= %lX \n",b);
  printf("C= %lX \n",c);
  printf("D= %1X \n",d);
} /* abcd */

void inmain()
{
  abcd();
  printf("Press 1 to enter A,B,C,D,V,W,X0,Y0,M ");
  printf("else <RET> for standard ABCD\n");
  if ((getch())=='1') {
    printf("Enter A (8 hex): \n"); scanf("%lX",&a);
    printf("Enter B (8 hex): \n"); scanf("%lX",&b);
    printf("~(8)=FFFFFFF7,~(4)=FFFFFFFB,~(6)=FFFFFFF9,~(3)=FFFFFFFC \n");
    printf("~(1)=FFFFFFFE,~(2*)=7FFFFFFD,~(2)=FFFFFFFD \n");
    printf("Enter C (8 hex): \n"); scanf("%lX",&c);
    printf("Enter D (8 hex): \n"); scanf("%lX",&d);
    printf("Enter V (8 hex): \n"); scanf("%lX",&v);
    printf("Enter W (8 hex): \n"); scanf("%lX",&w);
    printf("Enter X0 (8 hex): \n"); scanf("%lX",&x);
    printf("Enter Y0 (8 hex): \n"); scanf("%lX",&y);
    printf("Enter M (8 hex): \n"); scanf("%lX",&m);
} /* inmain */

void mainloop1(m)
unsigned long m;
{
  unsigned long e,f,g;
  printf("Results are in hexadecimal \n");
  v=(v&BIT31)? (v<<1)|1L:v<<1;                /* v=cyc(v); */
                 printf("V= %lX \n",v);
  e=v^w;         printf("E= %lX \n",e);
  x=x^m;         printf("X= %lX ",x);
  y=y^m;         printf("  Y= %lX \n",y);
  f=e+y;         printf("F= %lX ",f);
  g=e+x;         printf("  G= %lX \n",g);
  f=f|a;         printf("F= %lX ",f);
  g=g|b;         printf("  G= %lX \n",g);
  f=f&c;         printf("F= %lX ",f);
  g=g&d;         printf("  G= %lX \n",g);
  x=mul1(x,f);   printf("X= %lX ",x);
  y=mul2a(y,g);  printf("  Y= %lX \n",y);
} /* mainloop1 */
```

```
void mainloop2(m)
unsigned long m;
/* as mainloop1 without printf.  Mul1, mul2a copied to save time */
{
  unsigned long e,f,g,s;
  int car;
  v=(v&BIT31)? (v<<1)|1L:V<<1;          /* V=CYC(V); */
  e=v^w;
  x=x^m;   y=y^m;
  f=e+y;   g=e+x;
  f=f|a;   g=g|b;
  f=f&c;   g=g&d;

                                        /* x=mul1(x,f); */
  mul32(x,f);
  s=u+l;
  car=((u^l)&BIT31)? !(s&BIT31):(u&BIT31)!=0;
  x=(car) ? S+1L:S;

                                        /* y=mul2a(y,g); */
  mul32(y,g);
  g=u+u;
  s=g+l;
  car=((g^l)&BIT31)? !(s&BIT31):(g&BIT31)!=0;
  y=(car)? s+2L:s;
} /* mainloop2 */


/* NOTE. Time measurement is not standard C, hence may not be portable. */
/* Guesstime + fracsec uses the 1 second clock of MS-DOS.               */
/* Works with Turbo and Zorland compilers.                              */

signed long fracsec()
{
  unsigned long i;
  i=0; t5=time(NULL);
  do i++;           /* count while waiting for next second */
  while (time(NULL)==t5);
  return (i);
} /* fracsec */

float guesstime()
/* Uses fracsec and time (which counts whole seconds).           */
/* Probably most portable, may be least accurate if interrupted. */
/* OK for Turbo and Zorland versions 1 and 2.                    */
{
  unsigned long i,j,secs;
  t4=t5;
  i=fracsec(); secs=t5-t4-1; j=fracsec();
  if (i>j) i=j;
  return (secs+(j-i)/(float)j);
} /* guesstime */
```

```
main()
{
  unsigned long i,t1,t2;
  long ti;
  int nn,ii,choice,disp,car;
  float tf;
  t5=0;
  do {
    choice=menu1();
    printf("Note all results (except time) are in hexadecimal \n");
    switch(choice) {
      case 1:{
        printf(" Enter X (8 hex): \n"); scanf("%lX",&x);
        printf(" Enter Y (8 hex): \n"); scanf("%lX",&y);
        sum=x+y;
        printf("Sum= %lX",sum);
        car=((x^y)&BIT31) ? !(sum&BIT31):(x&BIT31)!=0;
        printf("  Carry= %X \n",car);
        sum=x+x;
        car=(x&BIT31)!=0;
        printf("2*X= %lX",sum);
        printf("  Carry= %X\n",car);
        printf("Product= %lX\n",x*y);
        mul32(x,y);
        printf("mul32 upper= %lX",u);
        printf("  mul32 lower= %lX \n",l);
        printf("cyc= %lX\n",((x<<1)|((x&BIT31)>>31)));
        printf("mul1=  %lX\n",mul1(x,y));
        printf("mul2=  %lX\n",mul2(x,y));
        printf("mul2a= %lX\n",mul2a(x,y));
        byt(x,y);
        printf("byt upper= %lX",u);
        printf("  byt lower= %lX\n",l);
        printf("pat= %X\n",pat);
      }; break;

      case 2:{
        printf(" Enter J1 (8 hex): \n"); scanf("%lX",&x);
        printf(" Enter K1 (8 hex): \n"); scanf("%lX",&y);
        prelude(x,y,1);
      }; break;

      case 3:{
        inmain();
        mainloop1(m);
        z=x^y; printf("Z= %lX\n",z);
      }; break;
      case 4:{
        printf(" Enter J (8 hex): \n"); scanf("%lX",&x);
        printf(" Enter K (8 hex): \n"); scanf("%lX",&y);
        prelude(x,y,0);
        x=x0; y=y0; v=v0; abcd();
        do {
          printf(" Enter M (8 hex): \n"); scanf("%lX",&m);
          mainloop2(m);
          printf("X= %lX",x); printf("  Y= %lX\n",y);
          printf("Press 1 for coda else <RET> for another message \n");
        } while ((getch())!='1');
        mainloop2(s);
        printf("X= %lX",x); printf("  Y= %lX\n",y);
        mainloop2(t);
        printf("X= %lX",x); printf("  Y= %lX\n",y);
        z=x^y; printf("Z= %lX\n",z);
      }; break;
      case 5:{
        printf(" Enter J (8 hex): \n"); scanf("%lX",&x);
        printf(" Enter K (8 hex): \n"); scanf("%lX",&y);
        prelude(x,y,0);
        x=x0; y=y0; v=v0; abcd();
        printf(" Enter M (8 hex): \n"); scanf("%lX",&m);
        printf(" Enter number of repeated message blocks: \n");
        scanf("%d",&nn);
        printf(" Press 1 to display X,Y values ");
        printf("else RET to measure time\n");
        disp=getch();
        if (disp=='1') {
          for (ii=1; ii<=nn; ii++) {
            mainloop2(m);
            printf("X= %lX",x); printf("  Y= %lX\n",y);
          }
          printf(" Press a key to proceed \n"); disp=getch();
        }
        else {
          i=fracsec();
          for (ii=1; ii<=nn; ii++) {mainloop2(m);}
          tf=guesstime();
          printf("Seconds in mainloop (guesstime)= %6.2f\n",tf); i=i;
          printf("Millisecs per message block= %6.2f\n",tf*1000.0/nn);
        }
        printf("X= %lX",x); printf("  Y= %lX\n",y);
        mainloop2(s);
        printf("X= %lX",x); printf("  Y= %lX\n",y);
        mainloop2(t);
        printf("X= %lX",x); printf("  Y= %lX\n",y);
        z=x^y; printf("Z= %1X \n",z);
      }; break;
    }
  } while (choice!=6);
} /* main */
```

23 Implementation in Basic

This version was originally developed on a BBC Model B micro, and also runs with the M-TEC BBCBASIC(86) interpreter [3] on IBM compatibles. Both of these interpreters provide 32 bit arithmetic and boolean functions.

The function ADDU executes unsigned addition and also leaves the value of the carry bit in the variable CAR%. It is designed to avoid causing overflow. There are many different ways of programming unsigned addition, the choice being between using conditional statements or complicated boolean expressions. The speed will depend upon the characteristics of the compiler or interpreter. The method shown was the fastest found using M-TEC Basic.

Multiplication is performed by the procedure MUL32 (which uses MUL16) to produce a 64 bit unsigned product in U% and L%.

In the Prelude, the J values, K values and H values are stored in individual variables although they could equally well be stored in arrays.

```
10 *KEY4SAVE"MAA7B05.BBC"|M
20 REM Message Authenticator Algorithm by D W Davies 1983
30 REM Version in 32 bit Basic for signed arithmetic by D O Clayden 1987
40 REM Copyright NPL 1987
50 REM Works correctly on BBC Model B
60 REM and in MTEC BBCBASIC(86) on IBM compatible PCs
70 :
80 DIM ABYT%(8)
90 VDU15
100 G4%=&40000000: G8%=&80000000: G3F%=&3FFFFFFF: REM GLOBAL CONSTANTS
110:
120 ON FNMENU1 GOTO140,320,360,400,530,680
130 :
140 PROCFETCH("X","Y",8)
150 SUM%=FNADDU(X%,Y%)
160 PRINT"SUM= ";~SUM%
170 PRINT"CARRY= ";CAR%
180 PROCMUL32(X%,Y%)
190 PRINT"MUL32 UPPER= ";~U%;" LOWER= ";~L%
200 PROD%=FNMUL1(X%,Y%)
210 PRINT"MUL1= ";~PROD%
220 PROD%=FNMUL2(X%,Y%)
230 PRINT"MUL2= ";~PROD%
240 PROD%=FNMUL2A(X%,Y%)
250 PRINT"MUL2A= ";~PROD%
260 PROCBYT(X%,Y%)
270 PRINT"BYT UPPER= ";~U%;" LOWER= ";~L%;;" PAT= ";~PAT%
280 PROD%=FNCYC(X%)
290 PRINT"CYC= ";~PROD%
300 GOTO120
310 :
320 PROCFETCH("J1","K1",8)
330 PROCPRELUDE(X%,Y%,1)
340 GOTO120
350 :
360 PROCINMAIN
370 PROCMAIN1(M%)
380 GOTO120
```

```
390 :
400 PROCFETCH("J","K",8)
410 PROCPRELUDE(X%,Y%,0)
420 X%=X0%: Y%=Y0%: V%=V0%
430 PROCABCD
440 INPUT"MESSAGE (8HEX)",T$:M%=EVAL("&"+T$)
450 PROCMAIN2(M%)
460 INPUT"Press 1 for Coda and exit else RET for more message",I%
470 IF I%=0 THEN 440
480 PROCMAIN2(S%)
490 PROCMAIN2(T%)
500 Z%=X%EORY%:PRINT"Z=";~Z%
510 GOTO120
520 :
530 PROCFETCH("J","K",8)
540 PROCPRELUDE(X%,Y%,0)
550 X%=X0%: Y%=Y0%: V%=V0%
560 PROCABCD
570 INPUT"MESSAGE (8HEX)",T$:M%=EVAL("&"+T$)
580 INPUT"Enter number of repeated message blocks",BLOCKS%
590 FOR NN%=1 TO BLOCKS%
600 PROCMAIN2(M%)
610 IF NN%MOD10=0 THEN INPUT"Press RET to continue":INPUTZ%
620 NEXT
630 PROCMAIN2(S%)
640 PROCMAIN2(T%)
650 Z%=X%EORY%:PRINT"Z=";~Z%
660 GOTO120
670 :
680 END
690 :
```

(continued overleaf)

```
690 :
700 DEF FNADDU(X%,Y%)
710 LOCALS%,T%
720 S%=(X%ANDG3F%)+(Y%ANDG3F%)
730 T%=X%EORY%
740 IF T%ANDG4% THEN CAR%=S%ANDG4%:S%=S%EORG4% ELSE CAR%=X%ANDG4%
750 IF CAR% THEN S%=S%EORG8%
760 IF T%ANDG8% THEN CAR%=S%ANDG8%:S%=S%EORG8% ELSE CAR%=X%ANDG8%
770 IF CAR% THEN CAR%=1
780 =S%
790 :
800 DEF FNMUL16(X%,Y%)
810 LOCAL P1%,P2%
820 IF (X%ANDY%AND&8000)=0 THEN =X%*Y%
830 P1%=X%*(Y%AND&7FFF)
840 P2%=(X%AND&7FFF)*&8000
850 P1%=FNADDU(P1%,P2%)
860 =FNADDU(P1%,&40000000)
870 :
880 DEF PROCMUL32(X%,Y%)
890 LOCAL XU%,XL%,YU%,YL%,P1%,P2%,H8%,H10%,HF%,H7F%
900 H8%=&8000: H10%=&10000: HF%=&FFFF: H7F%=&7FFF0000
910 XU%=(X%ANDH7F%)DIVH10%
920 IF X%<0 THEN XU%=XU%+H8%
930 XL%=X%ANDHF%
940 YU%=(Y%ANDH7F%)DIVH10%
950 IF Y%<0 THEN YU%=YU%+H8%
960 YL%=Y%ANDHF%
970 L%=FNMUL16(XL%,YL%)
980 P1%=FNMUL16(XL%,YU%)
990 P2%=FNMUL16(XU%,YL%)
1000 P1%=FNADDU(P1%,P2%)
1010 U%=(P1%ANDH7F%)DIVH10%
1020 IF P1%<0 THEN U%=U%+H8%
1030 U%=U%+CAR%*H10%
1040 P1%=(P1%ANDHF%)*H8%
1050 P1%=FNADDU(P1%,P1%)
1060 L%=FNADDU(L%,P1%)
1070 U%=U%+CAR%
1080 P1%=FNMUL16(XU%,YU%)
1090 U%=FNADDU(U%,P1%)
1100 ENDPROC
1110:
1120 DEF FNMENU1
1130 LOCAL N%
1140 PRINT'"Message Authenticator Menu"
1150 PRINT"1 Test small functions (Tables 1,2)"
1160 PRINT"2 Test Prelude (Table 3)"
1170 PRINT"3 Test Main (Table 4)"
1180 PRINT"4 Test Prelude+Main+Coda (Table 5)"
1190 PRINT"5 Test repeated message blocks (Table 6)"
1200 PRINT"6 Quit"
1210 INPUT"Select by number",N%
1220 IF (N%<1)OR(N%>6) THEN 1140
1230 =N%
```

```
1240 :
1250 DEF PROCFETCH(A$,B$,N%)
1260 LOCAL T$
1270 PRINTA$;" (";N%;"HEX)";:INPUTT$:X%=EVAL("&"+T$)
1280 PRINTB$;" (";N%;"HEX)";:INPUTT$:Y%=EVAL("&"+T$)
1290 ENDPROC
1300 :
1310 DEF FNMUL1(X%,Y%)
1320 LOCAL S%
1330 PROCMUL32(X%,Y%)
1340 S%=FNADDU(U%,L%)
1350 =FNADDU(S%,CAR%)
1360 :
1370 DEF FNMUL2(X%,Y%)
1380 LOCAL D%,F%,S%
1390 PROCMUL32(X%,Y%)
1400 D%=FNADDU(U%,U%)
1410 F%=FNADDU(D%,CAR%+CAR%)
1420 S%=FNADDU(F%,L%)
1430 =FNADDU(S%,CAR%+CAR%)
1440 :
1450 DEF FNMUL2A(X%,Y%)
1460 LOCAL D%,S%
1470 PROCMUL32(X%,Y%)
1480 D%=FNADDU(U%,U%)
1490 S%=FNADDU(D%,L%)
1500 =FNADDU(S%,CAR%+CAR%)
1510 :
1520 DEF FNCYC(X%)
1530 =FNADDU(X%,X%)+CAR%
1540 :
1550 DEF PROCBYT(X%,Y%)
1560 LOCAL I%,P%
1570 FOR I%=3 TO 0 STEP-1
1580  ABYT%(I%)=X%AND&FF:ABYT%(I%+4)=Y%AND&FF
1590  IF X%>=0 THEN X%=X%DIV&100 ELSE X%=(X%AND&7FFFFFFF)DIV&100+&800000
1600  IF Y%>=0 THEN Y%=Y%DIV&100 ELSE Y%=(Y%AND&7FFFFFFF)DIV&100+&800000
1610 NEXT
1620 P%=0
1630 FOR I%=0 TO 7
1640  P%=P%*2
1650  IF ABYT%(I%)=0 THEN P%=P%+1:ABYT%(I%)=P% ELSE
      IF ABYT%(I%)=&FF THEN P%=P%+1:ABYT%(I%)=&FF-P%
1660 NEXT
1670 PAT%=P%
1680 X%=0:Y%=0
1690 FOR I%=0 TO 3
1700  X%=X%*&80:X%=FNADDU(X%,X%)
1710  Y%=Y%*&80
1720  Y%=FNADDU(Y%,Y%)
1730  X%=X%+ABYT%(I%)
1740  Y%=Y%+ABYT%(I%+4)
1750 NEXT
1760 U%=X%:L%=Y%
1770 ENDPROC
```

```
1780 :
1790 DEF PROCPRELUDE(X%,Y%,TEST%)
1800 LOCAL P%,Q%,J1%,J12%,J22%,J14%,J24%,J16%,J26%,J18%,J28%
1810 LOCAL K1%,K12%,K22%,K14%,K24%,K15%,K25%,K17%,K27%,K19%,K29%
1820 LOCAL H0%,H4%,H5%,H6%,H7%,H8%,H9%
1830 PROCBYT(X%,Y%)
1840 J1%=U%: K1%=L%: P%=PAT%
1850 PRINT"P=";~P%
1860 IF TEST% THEN J1%=X%:K1%=Y%:INPUT"P",P%
1870 Q%=(1+P%)*(1+P%)
1880 J12%=FNMUL1(J1%,J1%)
1890 J22%=FNMUL2(J1%,J1%)
1900 J14%=FNMUL1(J12%,J12%)
1910 J24%=FNMUL2(J22%,J22%)
1920 J16%=FNMUL1(J12%,J14%)
1930 J26%=FNMUL2(J22%,J24%)
1940 J18%=FNMUL1(J12%,J16%)
1950 J28%=FNMUL2(J22%,J26%)
1960 H4%=J14%EORJ24%
1970 H6%=J16%EORJ26%
1980 H8%=J18%EORJ28%
1990 PRINT"H4=";~H4%
2000 PRINT"H6=";~H6%
2010 PRINT"H8=";~H8%
2020 K12%=FNMUL1(K1%,K1%)
2030 K22%=FNMUL2(K1%,K1%)
2040 K14%=FNMUL1(K12%,K12%)
2050 K24%=FNMUL2(K22%,K22%)
2060 K15%=FNMUL1(K1%,K14%)
2070 K25%=FNMUL2(K1%,K24%)
2080 K17%=FNMUL1(K12%,K15%)
2090 K27%=FNMUL2(K22%,K25%)
2100 K19%=FNMUL1(K12%,K17%)
2110 K29%=FNMUL2(K22%,K27%)
2120 H0%=K15%EORK25%
2130 H5%=FNMUL2(H0%,Q%)
2140 H7%=K17%EORK27%
2150 H9%=K19%EORK29%
2160 PRINT"H0=";~H0%
2170 PRINT"H5=";~H5%
2180 PRINT"H7=";~H7%
2190 PRINT"H9=";~H9%
2200 PROCBYT(H4%,H5%)
2210 X0%=U%:Y0%=L%
2220 PRINT"X0=";~X0%;" Y0=";~Y0%'"PAT=";~PAT%
2230 PROCBYT(H6%,H7%)
2240 V0%=U%: W%=L%
2250 PRINT"V0=";~V0%;" W=";~W%'"PAT=";~PAT%
2260 PROCBYT(H8%,H9%)
2270 S%=U%: T%=L%
2280 PRINT"S=";~S%;" T=";~T%'"PAT=";~PAT%
2290 PRINT"END OF PRELUDE"
2300 ENDPROC
```

```
2310 :
2320 DEF PROCINMAIN
2330 LOCAL T$
2340 INPUT"A (8HEX)",T$:A%=EVAL("&"+T$)
2350 INPUT"B (8HEX)",T$:B%=EVAL("&"+T$)
2360 INPUT"C (8HEX)",T$:C%=EVAL("&"+T$)
2370 INPUT"D (8HEX)",T$:D%=EVAL("&"+T$)
2380 INPUT"V (8HEX)",T$:V%=EVAL("&"+T$)
2390 INPUT"W (8HEX)",T$:W%=EVAL("&"+T$)
2400 INPUT"X (8HEX)",T$:X%=EVAL("&"+T$)
2410 INPUT"Y (8HEX)",T$:Y%=EVAL("&"+T$)
2420 INPUT"M (8HEX)",T$:M%=EVAL("&"+T$)
2430 ENDPROC
2440 :
2450 DEF PROCABCD
2460 A%=&02040801
2470 B%=&00804021
2480 C%=&BFEF7FDF
2490 D%=&7DFEFBFF
2500 ENDPROC
2510 :
2520 DEF PROCMAIN1(M%)
2530 LOCAL E%,F%,G%,T0
2540 T0=TIME
2550 V%=FNCYC(V%):PRINT"V=";~V%
2560 E%=V%EORW%:PRINT"E=";~E%
2570 X%=X%EORM%:PRINT"X=";~X%;
2580 Y%=Y%EORM%:PRINT" Y=";~Y%
2590 F%=FNADDU(E%,Y%):PRINT"F=";~F%;
2600 G%=FNADDU(E%,X%):PRINT" G=";~G%
2610 F%=F%ORA%:PRINT"F=";~F%;
2620 G%=G%ORB%:PRINT" G=";~G%
2630 F%=F%ANDC%:PRINT"F=";~F%;
2640 G%=G%ANDD%:PRINT" G=";~G%
2650 X%=FNMUL1(X%,F%)
2660 Y%=FNMUL2A(Y%,G%)
2670 PRINT"Seconds inside Main= ";(TIME-T0)/100
2680 PRINT"X=";~X%;" Y=";~Y%
2690 PRINT"X EOR Y=";~X%EORY%
2700 ENDPROC
2710 :
2720 DEF PROCMAIN2(M%)
2730 LOCAL E%,F%,G%,T0
2740 T0=TIME
2750 V%=FNCYC(V%)
2760 E%=V%EORW%
2770 X%=X%EORM%
2780 Y%=Y%EORM%
2790 F%=FNADDU(E%,Y%)
2800 G%=FNADDU(E%,X%)
2810 F%=F%ORA%
2820 G%=G%ORB%
2830 F%=F%ANDC%
2840 G%=G%ANDD%
2850 X%=FNMUL1(X%,F%)
2860 Y%=FNMUL2A(Y%,G%)
2870 PRINT"Seconds inside Main= ";(TIME-T0)/100
2880 PRINT"X=";~X%;" Y=";~Y%
2890 ENDPROC
```

24 References

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[3] BBCBASIC(86). An interpreter for BBC Basic which runs on IBM compatibles under MS-DOS. M-TEC Computer Services (UK), Ollands Road, Reepham, Norfolk NR10 4EL, UK.