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[54] CALCULATION UNIT  
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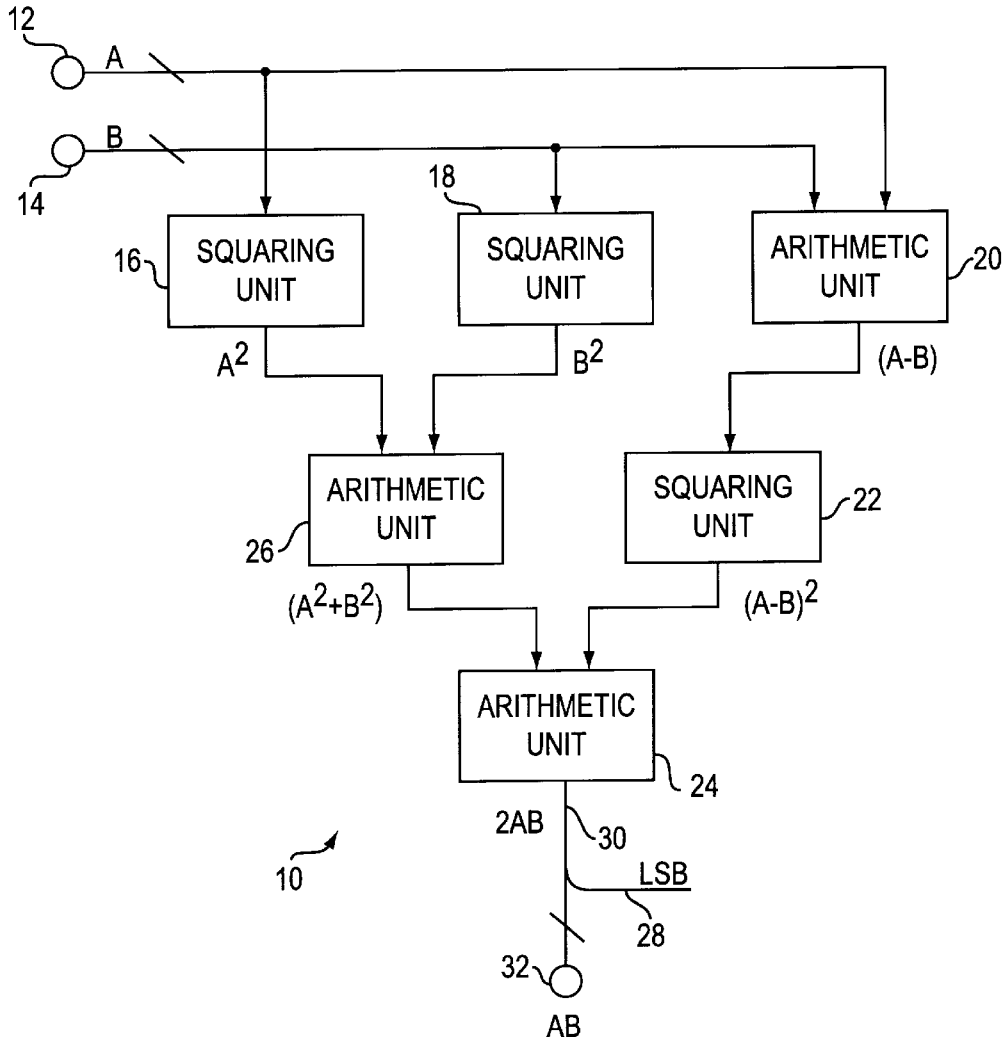
[51] Int. Cl.<sup>7</sup> ..... **G06F 7/52**  
[52] U.S. Cl. .... **708/620; 708/656**  
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364/757, 758, 761, 764; 708/620, 606,  
656

### [57] ABSTRACT

A multiplier uses squaring units to find the product of two binary numbers A and B by exploiting the algebraic expansion of  $(A-B)^2$  or  $(A+B)^2$ . The squaring units may be look-up memories. However, to multiply extremely large numbers, each squaring unit may itself have look-up memories and additional components. A divider may be formed by using the multiplier to multiply trial quotients by a divisor and by comparing the product with a dividend. The trial quotient is formed by shifting a one through a sequence of bit positions and latching the one at bit positions such that the trial quotient times the divisor does not exceed the dividend.

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17 Claims, 3 Drawing Sheets



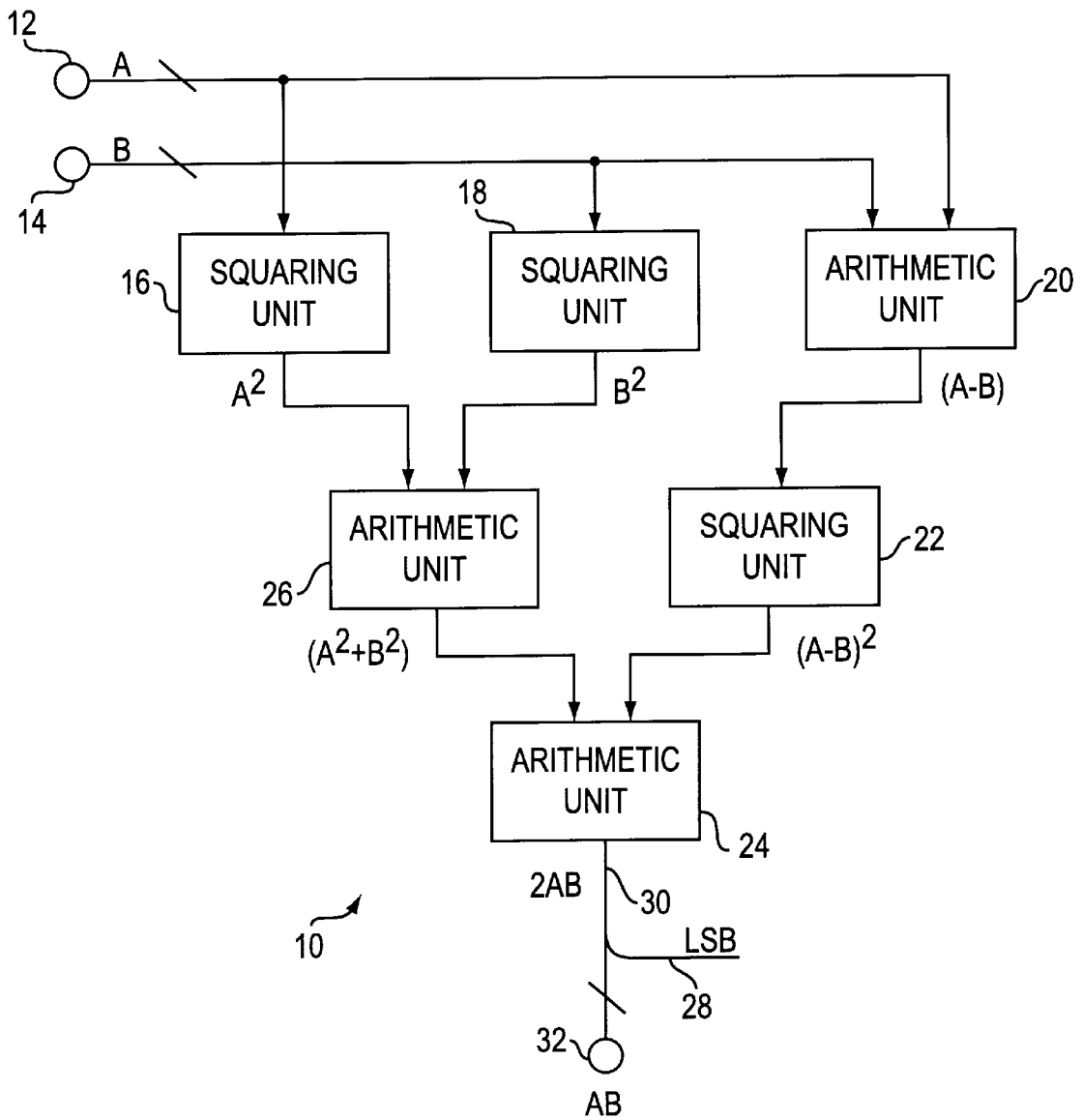


FIG. 1

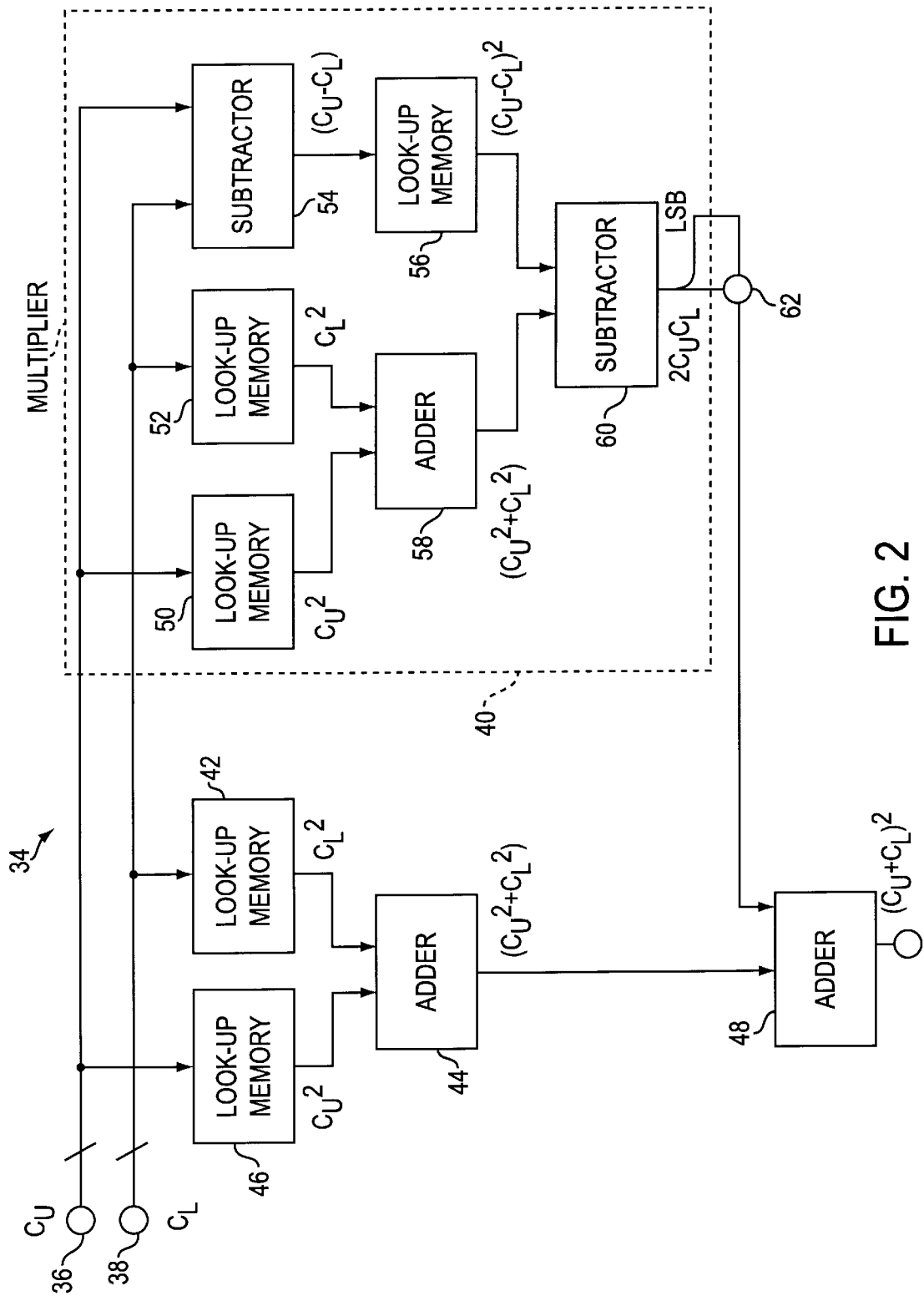


FIG. 2

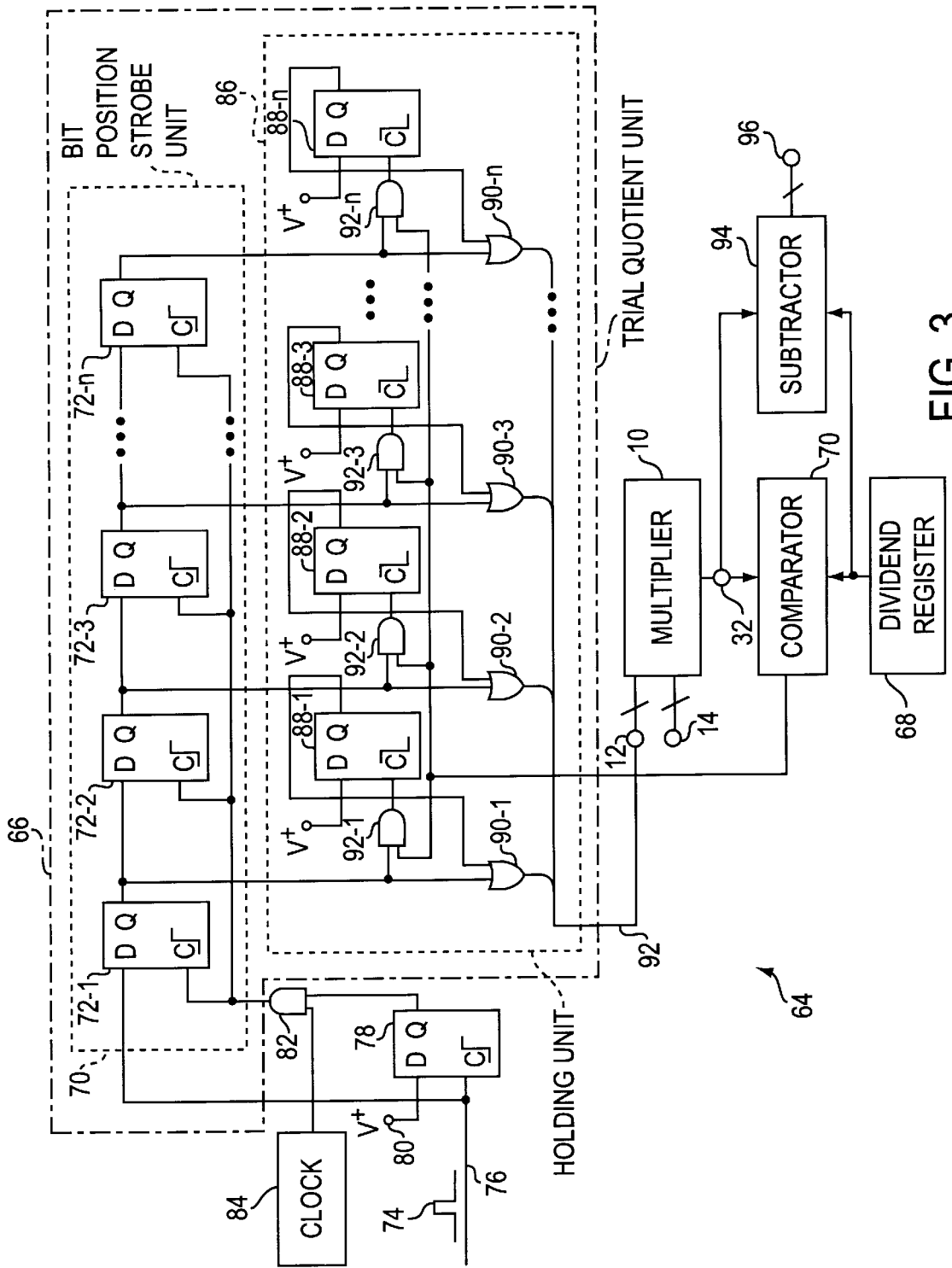


FIG. 3

## CALCULATION UNIT

## BACKGROUND OF THE INVENTION

The present invention is directed to a calculation unit, which may be configured as a multiplier or a divider for binary numbers.

Hardware adders are frequently encountered in digital circuitry. They can be fabricated using a reasonable number of gates. Hardware subtractors can also be found, frequently based on adders employing complement arithmetic. However, since hardware circuitry for binary multiplication would require an excessive number of gates, the multiplication function is usually implemented by multiple additions or by the shift-and-add method. Because both of these techniques are relatively slow, a hardware multiplier would be desirable in order to execute multiplications rapidly.

Multiplication tables are nearly as old as civilization itself. Indeed, archeologists have found multiplication tables inscribed on clay tablets while excavating ancient ruins in the Middle East. In more modern times, multiplication tables from 0x0 through 9x9, along with an algorithm for using these tables to multiply numbers of virtually any size, are taught to gradeschool students.

It would seem to be a relatively straightforward task to make a hardware multiplier by using a look-up memory which stores a multiplication table. For example, half of the address pins of a ROM could receive a first binary number A, and the remaining half of the address pins could receive a second binary number B, with each storage location in the ROM storing the product of a particular value for A times a particular value for B. There is, however, a serious flaw in this approach—the number of memory locations required would expand rapidly as the number of bits in the numbers A and B increases. In other words, the number of bits in A and B must be relatively small if a ROM having a practical number of addressable locations is to be used.

## SUMMARY OF THE INVENTION

An object of the invention is to provide a calculation unit for rapid multiplication and/or division.

Another object of the invention is to provide a calculation unit using look-up memories with relatively modest addresses spaces.

Another object of the invention is to provide a calculation unit which can operate on numbers with many bits.

Yet a further object of the invention is to provide a hardware multiplier and a hardware divider.

These and other objects of the invention, which will become apparent in the ensuing detailed description, can be attained by using look-up memories in a multiplier to store or otherwise encode a table of squares. Squares looked up by the memories can then be manipulated by adders and subtractors to find products. Such a multiplier can be used in a divider which additionally includes a trial quotient unit that supplies one of the input numbers to the multiplier, the other input number being the divisor, a dividend register which stores a dividend, and a comparator which compares the product found by the multiplier to the dividend in the dividend register.

In accordance with one aspect of the invention, a calculation unit comprises a first means for squaring a first number, a second means for squaring a second number, and a third means, which is connected to the first and second means, for finding the product of the first and second numbers.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram schematically illustrating a first embodiment of a calculation unit in accordance with the present invention, configured as a multiplier;

FIG. 2 is a block diagram schematically illustrating an embodiment of a squaring unit for use in the calculation unit of FIG. 1; and

FIG. 3 is a block diagram schematically illustrating a calculation unit in accordance with another embodiment, configured as a divider.

## DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 illustrates a calculation unit configured as a multiplier **10** for multiplying a binary number A which is applied to first input terminals **12** (only one of which is shown) by a second binary number B which is applied to second input terminals **14** (only one of which is shown). As will be discussed in more detail below, multiplier **10** exploits the algebraic expansion of the term  $(A-B)^2$ , which is equal to  $A^2-2AB+B^2$ . The binary number A is supplied to a squaring unit **16**, which generates the binary number  $A^2$  as its output. The squaring unit **16** may be a table look-up memory, such as a ROM (although an encoder which uses gates and/or switches to encode the number A into its square may be used instead of a ROM). The binary number B is supplied to a squaring unit **18**, which may also be a table look-up memory. The squaring unit **18** generates a binary number  $B^2$  as its output. The binary numbers A and B are both supplied to an arithmetic unit **20**, such as a subtractor (which, as used herein, includes an adder which adds one of the numbers to the two's complement of the other). Arithmetic unit **20** generates the binary value  $(A-B)$  as its output, which is supplied to a squaring unit **22**. The squaring unit **22**, which may be a look-up memory, supplies the binary value  $(A-B)^2$  to an arithmetic unit **24**, such as a subtractor.

The binary numbers  $A^2$  and  $B^2$  from squaring units **16** and **18** are supplied to an arithmetic unit **26**, here an adder, which supplies their sum  $(A^2+B^2)$  to the arithmetic unit **24**.

Since  $(A-B)^2$  is equal to  $A^2-2AB+B^2$ ,  $A^2+B^2-(A-B)^2$  is equal to  $2AB$ . The arithmetic unit **24** thus subtracts the binary number  $(A-B)^2$  from unit **22** from the binary number  $(A^2+B^2)$  from unit **26** to provide the binary value  $2AB$ . This is double the product of the input numbers A and B but, since we are dealing with binary numbers, we can divide by 2 simply by dropping the least significant bit on a line **28** of a bus **30**. The bus **30** thus conveys the product AB to output terminals **32** (only one of which is shown).

The advantage that multiplier **10** has over simply a single look-up memory (not illustrated) is that it can multiply much larger numbers. Suppose, for example, that the number A has 20 bits and that the number B also has 20 bits. If A and B were both supplied to the address input pins of a single look-up memory, the single memory would need to have about one thousand billion addressable storage locations. Such a memory is well beyond the capabilities of current technology. In contrast, the multiplier **10** could accommodate 20-bit input numbers using memories with about a million addressable storage locations for the squaring units. Thus, at the cost of using three memories and three arithmetic units, multiplier **10** is able to save huge numbers of storage locations that would otherwise be needed if a single look-up memory were employed.

It will be apparent that the multiplier **10**, as described above, could readily be modified to rely on the algebraic

expansion of  $(A+B)^2$  instead of  $(A-B)^2$ . Since  $(A+B)^2=A^2+2AB+B^2$ ,  $2AB=(A+B)^2-(A^2+B^2)$ . Thus, arithmetic unit **20** could be changed to an adder which produces the number  $(A+B)$ , which would be squared by the squaring unit **22**. Arithmetic unit **26** would then subtract  $(A^2+B^2)$  from  $(A+B)^2$ . Instead of using look-up memories for the squaring units **16**, **18**, and **22** in FIG. 1, one can use squaring units **34**, as shown in FIG. 2, in order to multiply really large numbers, ones that are larger than the number of addressable storage locations that are currently available in a single look-up memory. In FIG. 2, a large binary number

$$C=c_{2n-1}, \dots, c_n, c_{n-1}, \dots, c_1, c_0$$

is divided into upper and lower portions  $C_U$  and  $C_L$ . Here,  $C_L$  is the lowest n bits of C,

$$C_L=c_{n-1}, \dots, c_1, c_0$$

and  $C_U$  is the upper n bits, followed by n zeros.

$$C_U=c_{2n-1}, \dots, c_n, 0, 0, 0, \dots, 0.$$

In effect,  $C_U$  is what is left of C after the n lowest-order bits (which form  $C_L$ ) are removed and replaced by zeros. Dividing C into two portions in this way permits one to square it without needing a look-up memory having  $2^{2n}$  addressable storage locations, as will be discussed below.

In FIG. 2, the binary number  $C_U$  is received by first input terminals **36** (only one of which is shown) and the binary number  $C_L$  is received by second input terminals **38** (only one of which is shown).  $C_U$  and  $C_L$  are both supplied to a multiplier **40**. The number  $C_L$  is also supplied to a look-up memory **42**, which provides the number  $C_L^2$  to an adder **44**. The number  $C_U$  is supplied to a look-up memory **46**, which supplies  $C_U^2$  to adder **44**. The adder **44** supplies the sum  $(C_U^2+C_L^2)$  to an adder **48**, which also receives the product  $2C_U C_L$  from multiplier **40**. The output of adder **48** is  $(C_U+C_L)^2$ , or simply  $C^2$ .

Squaring unit **34** exploits the algebraic expansion of  $(A+B)^2$ , where A is replaced by  $C_U$  and D is replaced by  $C_L$ . Thus,

$$C^2=(C_U+C_L)^2=C_U^2+2C_U C_L+C_L^2.$$

The following example is provided to illustrate the operation of squaring unit **34**. Although the number of bits is small in this example, it will be apparent that the same rationale applies when the number of bits is large.

Suppose C has only four bits, so that  $C_L$  has two bits and  $C_U$  has two zeros preceded by what might be called two "active" bits. Since  $C_L$  has two bits in this example, memory **42** would need four memory locations, each storing the binary value shown in the following Table 1:

TABLE 1

Address	Decimal Equivalent	Decimal Equivalent Squared	Binary Value Stored
0 0	0	0	0000
0 1	1	1	0001
1 0	2	4	0100
1 1	3	9	1001

Since, in this example,  $C_u$  only has two active bits, followed by two zeros, the memory **46** also needs only four storage locations. However, the values they store reflect both

the two active bits and the two added zeros of  $C_U$ , as shown in the following Table 2:

TABLE 2

Address	Added Zeros	Decimal Equivalent	Decimal Equivalent Stored	Binary Value
0 0	0 0	0	0	00 000 000
0 1	0 0	4	16	00 010 000
1 0	0 0	8	64	01 000 000
1 1	0 0	12	144	10 010 000

As will be apparent from Table 2, what is stored in memory **46** in this example is the squares of the active bits of  $C_U$ , followed by four zeros. In the more general case, what would stored in memory **46** would be the squares of the active bits in  $C_U$ , followed by twice the number of low-order zeros in  $C_U$  (that is, followed by two zeros for each bit of  $C_U$ ). It will be apparent that, instead of actually storing the low-order zeroes in memory **46**, along with the squares of the active bits, the squares alone can be stored if their bit ranks are advanced in accordance with the number of low-order zeros when the squares are supplied to adder **44**.

Multiplier **40** includes a look-up memory **50** which squares  $C_U$ , a look-up memory **52** which squares  $C_L$ , and a subtractor **54** which finds their difference. A look-up memory **56** finds the square of their difference, and an adder **58** finds the sum of the squares. Finally, a subtractor **60** finds the product  $2C_U C_L$ . In conformity to FIG. 1, FIG. 2 shows the least significant bit as being removed before the rest of the product is supplied to output terminals **62** (only one of which is shown), but since the number  $2C_U C_L$  is needed by adder **48**, the drawing shows the least significant bit as being added back at terminal **62**. This has no practical significance, however, since the least significant bit will always be zero, and thus one can drop the least significant bit or not with impunity so long as the bit ranks of the remaining bits (that is, the proper powers of 2) are observed when the remaining bits are supplied to adder **48**.

In summary, in order to use the squaring unit of **34** to find the square of a large binary number for use in the multiplier in FIG. 1, one breaks the large binary number into upper and lower parts and then relies on the algebraic expansion of the sum of the parts to find the square of the large number. It will be apparent that this technique can be carried further. If the upper and lower parts are, themselves, large, they (that is, the upper and lower parts) can also be broken into their own upper and lower parts. That is, an enlarged squaring unit of the type shown in FIG. 2 could be based on FIG. 2, with the individual look-up memories being replaced by squaring units in accordance with FIG. 2.

FIG. 3 illustrates a calculation unit configured as a divider **64**. It includes a trial quotient unit **66** which supplies a binary trial quotient to the input terminals **12** of multiplier **10**. The multiplier **10** multiplies the trial quotient by a binary divisor that is supplied to input terminals **14**. The product of the trial quotient and the divisor appears at output terminals **32**. A dividend is stored in a dividend register **68**, and a comparator **70** compares the dividend with the product of the divisor and the trial quotient. The output of comparator **70** is digitally low if the product from multiplier **10** is larger than the dividend stored in register **68**. Conversely, if the dividend stored in register **68** is larger than the product from multiplier **10** or is equal to the product, the output of comparator **70** is digitally high.

The trial quotient unit **66** includes a bit position strobe unit **70** that is the same as the bucket-brigade circuit shown

on page 286 of Don Lancaster's book, *CMOS Cookbook*, 1st Ed., 1977. The bit position strobe unit **70** includes D-type flip-flops **72-1**, **72-2**, **72-3**, . . . , **72-n**, which are cleared to zero before operation begins. The D input of the first flip-flop **72-1** receives a start pulse **74** that is applied to a line **76**. The line **76** is connected to the clock input of a D-type flip-flop **78**, whose D input is connected to a terminal **80** which is maintained at a digitally high potential. Flip-flop **78** is clocked at the rising edge of the clock signal (here, the start pulse **74**), as is indicated by the forward-Z symbol shown adjacent the clock input in FIG. 3. Thus, at the rising edge of the start pulse **74**, the Q output of flip-flop **78** becomes high and stays high thereafter. The Q output of flip-flop **78** is connected to one input of an AND gate **82**. A clock signal supplied by a clock generator **84** is connected to the other input of AND gate **82**. Accordingly, the AND gate **82** passes the clock signal to the clock inputs of flip-flops **72** after the start pulse **74** has been supplied.

The start pulse **74** is long enough that the D input of flip-flop **72-1** remains high until the first time that the clock signal turns AND gate **82** ON. As a result, the Q output of flip-flop **72-1** becomes high. This is passed to the Q output of flip-flop **72-2** at the rising edge of the next clock pulse and, furthermore, the Q output of flip-flop **72-1** becomes low. In a similar manner, the digitally high value is passed from flip-flop to flip-flop, in bucket-brigade fashion, until the Q output of flip-flop **72-n** finally becomes high.

The trial quotient unit **66** also includes a holding unit **86**. It includes D-type flip-flops **88-1**, **88-2**, **88-3**, . . . , **88-n**, which are also cleared to zero before operation begins. The D inputs of flip-flops **88** are connected to terminals that are maintained at a digitally high potential. The Q outputs are connected to OR gates **90-1**, **90-2**, **90-3**, . . . , **90-n**. The outputs of AND gates **92-1**, **92-2**, **92-3**, . . . , **92-n** are connected to the clock inputs of flip-flops **88**. These flip-flops are clocked at the falling edge of the signal supplied to their clock inputs, as is indicated by the backward-Z symbols shown adjacent the clock inputs in FIG. 3. One input of each of the AND gates **92** is connected to the output of comparator **70**. The other input is connected to the Q output of the respective flip-flop **72**. Thus, when the Q output of flip-flop **72-1** becomes high, for example, the Q output of flip-flop **88-1** also becomes high, but only if the output of comparator **70** is simultaneously high. Subsequently, the Q output of flip-flop **88-2** becomes high if the Q output of flip-flop **72-2** is high and the output of comparator **70** is also high, and so forth for the remaining flip-flops **88**.

During operation, the divisor is applied to terminals **14**, the dividend is stored in register **68**, and the digital value supplied by trial quotient unit **66** to terminals **12** is zero before the start pulse **74**. The output of comparator **70** is thus low, and AND gates **92** are OFF. After the start pulse **74**, the Q output of flip-flop **72-1** becomes high, and this is passed by OR gate **90-1** to a bus **92** that is connected to the terminals **12**. The remaining OR gates **90** are OFF. The bus **92** thus carries to terminals **12** the trial quotient  $1\ 00\ .\ .\ .\ 0$ . Multiplier **10** multiplies the divisor by this trial quotient; the clock signal is slow enough that the product appears at terminals **32** while OR gate **90-1** is still ON. If the product at terminals **32** is larger than the dividend, comparator **70** outputs a low value and AND gate **92-1** remains OFF. Thereafter, the Q output of flip-flop **72-2** becomes high, and this is passed by OR gate **90-2** to bus **92**. The trial quotient is now  $010\ .\ .\ .\ 0$ . This is again multiplied by the divisor and compared with the dividend, and if the product of the trial quotient and the divisor is still larger than the dividend, then the output of comparator **70** remains low and AND gate **92-2**

remains OFF. The Q output of flip-flop **72-3** then becomes high, making the trial divisor  $001\ 0\ .\ .\ .\ 0$ . This process continues for subsequent pulses of the clock signal.

And now let us return to flip-flop **72-1**, and the trial quotient  $1\ 000\ .\ .\ .\ 0$ . If the product of this trial quotient and the divisor is less than the dividend or equal to the dividend, then the output of comparator **70** becomes high. This means that the AND gate **92-1** turns ON when the Q output of flip-flop **72-1** becomes high, and consequently flip-flop **88-1** keeps OR gate **90-1** ON, even after the Q output of flip-flop **72-1** becomes low. The trial divisor has thus acquired 1 as its most significant bit.

When the Q output of flip-flop **72-2** becomes high, the trial divisor is  $11\ 00\ .\ .\ .\ 0$ . If the dividend is smaller than the product of this trial quotient and the divisor, at the next clock pulse the trial quotient becomes  $10\ 1\ 0\ .\ .\ .\ 0$ . However, if the dividend is still greater than or equal to the product of the divisor and the trial quotient  $11\ 00\ .\ .\ .\ 0$ , flip-flop **88-2** turns on and the trial quotient thereby permanently acquires 1 in the second most significant bit position. When flip-flop **72-3** turns on as a result of the next clock pulse, the trial quotient thus becomes  $111\ 0\ .\ .\ .\ 0$ . This process continues for subsequent clock pulses.

What happens, then, is that the trial quotient begins at  $1\ 000\ .\ .\ .\ 0$ . It grows larger if the trial quotient times the divisor is less than the dividend and grows smaller if the trial quotient times the divisor is greater than the dividend. The reason for this is that, as a digital one is shifted through bit position strobe unit **70**, the holding unit **86** latches the digital one at bit positions such that the product determined by a multiplier **10** does not exceed the dividend. The comparator **70** may turn on and off numerous times during this procedure, but by the time the digital one shifts out of bit position strobe unit **70**, the trial quotient will have converged on the true quotient and, at most, will differ from the dividend by only a remainder.

Consequently, at the end of the process, the true quotient appears at terminals **12**. The remainder is found by a subtractor **94**, which subtracts the product of the quotient and the divisor from the dividend, and supplies the remainder bits to terminals **96** (only one of which is shown). The value appearing on terminals **96** represents the remainder only after a digital one has been shifted through all the positions of the bit position strobe unit **70**.

Although divider **64** employs multiplier **10**, a single look-up memory could be used instead if the numbers involved do not require the high capacity of multiplier **10**, or the multiplier **10** could be supplemented with squaring units **34** if even higher capacity is needed.

Although the multipliers and divider disclosed above have been discussed in terms of hardware, it will be apparent that they can also be implemented via software, in which case the squaring units will comprise random access memory.

It should be noted that divider **64** can be used to inspect the dividend loaded into register **68** for prime factors if a sequence of prime numbers, perhaps read out of a prime number memory (not shown), is supplied to terminals **14** as the dividend. A remainder of zero indicates that a prime factor has been found.

It should also be understood that the above description of the present invention is susceptible to various modifications, changes, and adaptations, and the same are intended to be comprehended within the meaning and range of equivalents of the appended claims.

What I claim is:

1. A calculation unit, comprising:  
first means for squaring a first number;

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second means for squaring a second number; and  
 third means, connected to the first and second means, for finding the product of the first and second numbers, the third means including  
 a first arithmetic unit which receives the first and second numbers and provides their difference as an output,  
 means receiving the output of the first arithmetic unit for squaring the difference between the first and second numbers,  
 a second arithmetic unit which receives the square of the first number and the square of the second number and provides their sum as an output, and  
 a third arithmetic unit which receives the sum of the squares of the first and second numbers and the square of the difference between the first and second numbers, the third arithmetic unit providing an output representing the product of the first and second numbers.

2. The calculation unit of claim 1, wherein the first means comprises a look-up memory.

3. The calculation unit of claim 1, wherein the first number is a binary number having an upper portion and a lower portion, and wherein the first means comprises fourth means for squaring the upper portion, fifth means for squaring the lower portion, and sixth means, connected to the fourth and fifth means, for finding the square of the first number.

4. The calculation unit of claim 3, wherein the sixth means comprises a multiplier which receives the upper and lower portions.

5. The calculation unit of claim 3, wherein the fourth means comprises a look-up memory.

6. The calculation unit of claim 1, wherein the first number is a divisor, and further comprising trial quotient means for generating a trial quotient, the trial quotient being the second number, and means for comparing the product of the first and second numbers with a dividend, the trial quotient means being connected to the means for comparing.

7. The calculation unit of claim 6, further comprising a subtractor to find the difference between the dividend and the product of the first and second numbers.

8. The calculation unit of claim 6, wherein the trial quotient means comprises bit position strobe means for passing a digital one through a plurality of bit positions, and holding unit means for selectively latching the digital one at different bit positions in response to a signal from the means for comparing.

9. A calculation unit, comprising:  
 a multiplier which receives a first number and a second number and which generates a product, the first number being a divisor;  
 means for storing a dividend;

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trial quotient means for generating a trial quotient, the trial quotient being supplied to the multiplier as the second number; and  
 means for comparing the product to the dividend,  
 wherein the trial quotient means comprises bit position strobe means for passing a digital one through a plurality of bit positions, and holding unit means for selectively latching the digital one at different bit positions in response to a signal from the means for comparing.

10. The calculation unit of claim 9, wherein the multiplier comprises:  
 first means for squaring the first number;  
 second means for squaring the second number; and  
 third means, connected to the first and second means, for finding the product.

11. The calculation unit of claim 10, wherein the first means comprises at least one look-up memory.

12. The calculation unit of claim 9, further comprising means for finding the difference between the product generated by the multiplier and the dividend stored by the means for storing.

13. A calculation unit, comprising:  
 a first squaring unit to square a first number;  
 a second squaring unit to square a second number;  
 a first arithmetic unit to find the difference between the first and second numbers;  
 a second arithmetic unit to find the sum of the square of the first number and the square of the second number;  
 a third squaring unit to square the difference between the first and second numbers; and  
 a third arithmetic unit which finds the product of the first and second numbers from the sum of the squares of the first and second numbers and the square of the difference between the first and second numbers.

14. The calculation unit of claim 13, wherein the first squaring unit comprises a look-up memory.

15. The calculation unit of claim 14, wherein the look-up memory comprises a ROM.

16. The calculation unit of claim 13, wherein the first number is a binary number having upper and lower portions, and wherein the first squaring unit comprises a look-up memory which receives the first portion and a look-up memory which receives the second portion.

17. The calculation unit of claim 13, wherein the first squaring unit comprises a first look-up ROM that stores a table of squares, the second squaring unit comprises a second look-up ROM that stores the table of squares, the third squaring unit comprises a third look-up ROM that stores the table of squares, and the first arithmetic unit comprises a subtractor.

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