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**MICROELECTRONIC: THE TECHNOLOGY
OF MAKING SMARTER, SMALLER AND
CHEAPER ELECTRONIC PRODUCTS.**

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BY

OLUWOLE ADEGBENRO



**UNIVERSITY OF LAGOS PRESS - 2004
INAUGURAL LECTURE SERIES**

MICROELECTRONIC: THE TECHNOLOGY OF MAKING SMARTER, SMALLER AND CHEAPER ELECTRONIC PRODUCTS.

An Inaugural Lecture Delivered at University of Lagos
Main Auditorium on Wednesday, 15th September, 2004.

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by

OLUWOLE ADEGBENRO

B.Sc. (Hons)(Lagos); M.Eng. (Alberta); D.Eng. (Tohoku)
FNSE, MIEICE, MIEEE

Professor of Electronics Engineering
Faculty of Engineering
University of Lagos

University of Lagos, 2004

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Published 2004

by

University of Lagos Press
Unilag P.O. Box 132
University of Lagos
Akoka, Yaba – Lagos
Nigeria

unilagpress@yahoo.com

ISSN 1119-4456

THE INAUGURAL LECTURE:

WHAT DOES IT MEAN TO ME?

It is generally believed that an inaugural lecture is debt a professor owes to the University community, which should be paid before disengagement from the system and that it has been a time-honored tradition adopted from the Western Universities. To me an inaugural lecture seems rather the payment of some form of debt the community owes the inaugural lecturer. Having been invited and having accepted the invitation, you are here with the belief that the exercise is going to be worthwhile which you may not know until it is over. Meanwhile you have invested your time and money in honoring the invitation. I greatly appreciate the effort you have made in this venture. I salute our ever-striving Vice-Chancellor, Professor Oye Ibidapo-Obe who as a matter of duty is present at every Inaugural Lecture during his tenure. To me nothing can be more demanding or onerous. I always wish him and his management team well and continue to wish his administration great success as he continues to steer the University in the right course.

In these days of information deluge in which we are surfeited with information, one may wonder whether this assembly is really necessary. The only justification I can find for it is that it is traditional and it serves as a means of show-casing an individual putting him or her in the lime-light if only for an hour or so; and thanks to Mass Communication it may perhaps be to a larger audience. As I respect tradition, I do not wish any departure from it rather I am here today to justify it, which I hope I will be able to do. At the end of the lecture it is my hope that both the lecturer and our esteemed audience would have paid each other back debts in a win-win situation.

Please bear with me!

What I have heard or seen (or learnt)

From many a scholar,

A pious hope it has been,

To render it crystal clear.

Bammera Pothanna's "Bhagavatham"

IN THE BEGINNING

If one wants to know about a complex thing, one starts with the simplest idea associated with it and if one wishes to build anything, one starts with its simplest building block – so it was with the ancient Greek about 2000 years ago when the word ‘atom’ meaning literally, “uncut-able” was given to a particle of a material that they supposed could not be divided further. This notion has persisted and it has acquired since that time a vast corpus that keeps on being constantly revised and reviewed since as far back as the 17th century when Isaac Newton postulated the corpuscular theory of light. John Dalton, a chemist suggested that each chemical element must be an aggregation of atoms. It is these postulate that succeeding chemists have used to build a quite impressive picture of how and what happens when elements combine. The question as to what is the internal structure of the atom – the atomic model is continually being asked. The question had been answered partly by Henri Becquerel in 1896. Marie and Pierre Curie in 1897 and later J.J. Thomson. Contributors who have tried to make the picture clearer are physicists namely Max Planck, Albert Einstein, Robert Milikan and Ernest Rutherford. The picture we have at the moment is that an atom is made up of electrons orbiting a nucleus almost like the planets orbit the sun in our solar system but the position of electrons unlike that of the planets are subject to the laws of probability and they could behave either as particles (or corpuscle) or as waves depending on the phenomenon that electrons are attributed to being responsible for. Contributors to the present atomic state of affairs are: James Chadwick, Enrico Fermi, Werner Heisenberg, Wolfgang Pauli, Erwin Schrödinger and Paul Dirac. We are told chiefly, that electron has a dual nature, and that there is uncertainty in knowing precisely both the position and the velocity of an electron simultaneously. (This has wider implications even in life – one cannot be part of a system from which one is gathering information without affecting the states of the systems but then one cannot gather accurate information without being part of the system. By being close to a system, one alters its natural state and the information gathered can no longer be a correct representation of the states of the system).

One would have hoped that by now the atomic picture would be getting clearer but alas it is becoming more and more confusing and the elementary picture of the atom we are told can no longer be used to explain some observable facts about the nature around us. The interesting thing about all this is that we have used a crude tool to obtain a better or finer tool – a situation that must continue ad infinitum.

What is now needed is a thoroughly new atomic model. It must be clearly understood that the role of science is not merely to help us to understand nature so that we can explain what it is but it is also to enable us to know what is achievable and so exploit it. By having precise knowledge of the behavior and structure of the atom, we shall know the limits and the scopes of our possibilities. We now understand that the three physical constants in the universe are energy, mass and the velocity of light, measurable in any defined units and are related by the Einstein's equation, $e = mc^2$. The discovery of this relationship was a turning point for scientific work on this planet. It is not quite a hundred years of this discovery for homo sapiens that have been in existence for several million years and the achievements of the last ten decades in my mind surpasses by far those of the millions of decades preceding it.

NEW MATERIALS AND TECHNOLOGY WANTED

Knowledge of materials is very essential to the progress of mankind. Mankind from its cradle had knowledge of the different kinds of materials provided by nature and what they could be used for. Appropriate materials were used for making tools and weapons and the knowledge and the characteristics of materials found in nature gradually became known as civilization progressed. In our present epoch of civilization, it is the availability and the knowledge of materials that make it possible to have the myriad of things that make our lives livable. Research into materials will make it ever possible to develop new products.

When electricity was discovered at the turn of the last century two broad classes of materials were known; metals, which are conductors, and non-metals, which are insulators. These two classes of materials

were all that were needed to harness the power of electricity at the early age of electrical engineering. This remained so till as early as the 1950s and the electronics of those days were based on vacuum tube devices. A vacuum tube device has its origin in the incandescent light bulb invented by Edison the form of which has not changed even till today. In vacuum tube devices, electrons emitted by a heated metal within a glass-enclosed vacuum are controlled. The world's first electronic components made from this principle are called thermionic valves and can be used in circuits for switching and amplification applications. The switching function of a vacuum tube device makes it possible to build an electronic computing machine. The world's first all-electronic machine, the ENIAC (Electronic Numerical Integrator and Calculator) took 30 months to build and was completed in February 1945. It used not less than 18,000 vacuum tubes, weighed several kilograms and covered several square meter of floor space. It required 5 operators to run and consumed prodigious amount of power both by its tubes and the ventilation apparatus for cooling them. This caliber of machine was truly a mammoth, (its computing capability is much less than that of today's low power personal computer) which by the well-known principle of evolution had to become extinct there being just no justification for its survival after the arrival of the solid-state devices.

However even though the incandescent light bulb is still in use, the latterly discovered solid-state devices have superseded vacuum tube devices in nearly every electronic circuit. Solid-state components and devices are made from materials that in their natural state at room temperature are in the solid form. (At room temperature these materials are neither in the gaseous nor liquid forms).

The invention of solid-state devices is shrouded in a lot of mystery. They were said to have been invented in the USA between the late 1940s and the early 1950s, but certain documentary evidence would have us believe that solid-state devices were products of reverse engineering from materials salvaged from a UFO (an extraterrestrial space ship) which had crash-landed in 1947 in the State of New Mexico near a town called Roswell in the USA. This should not seem as far-fetched as it sounds. Indeed there are many plausible arguments to

support it. First, ancient writings both secular and religious are replete with notions of alien intervention in the lives of Earth-bound men- giving us laws and guidance. These aliens being evidently so partial to their own favorites such as would not be expected of a Universal Creator! Secondly, early inventions directly credited to man were three-dimensional objects such as the wheel, weapons, time measuring devices, etc. For example, the notable invention that sparked off the industrial revolution, that of the steam engine by James Watt (1736-1819) was by direct *observation* of a steaming kettle. It is totally a different 'kettle of fish' when it comes to things on a microscopic scale such as the transistor, which cannot be directly visualised.

To my mind, to discover such an object such as a transistor, one must have an advantage of a readily available sample. Indeed many other electronic devices such as the Laser, and the integrated circuit as well as mechanical engineering innovations such as the stealth plane invincible to radar beams are said to be traceable to this UFO event. Individuals and Laboratories in the USA who were given direct access to the salvaged materials from the crash-landed UFO and who pioneered the efforts to make sense out of them were given the invention and patent rights of the developed products. This led to the discovery of a third class of electrical /electronic engineering material the semiconductor. A semiconductor material has electrical properties somewhere in between those of a conductor and an insulator. A manufacturing process can make a raw (intrinsic) semiconductor to behave like a conductor or like an insulator as may be desired. Examples of naturally occurring semiconductor materials are the chemical elements, silicon and germanium. Silicon for example is very abundant in nature as common sand and has the most excellent properties that make it very useful in building electronic components.

SOLID STATE COMPONENTS

The first semiconductor component invented was the diode. A diode behaves just like a water tap that allows water to flow in only one direction; of course the water it controls in this case is a stream of electrons, (which borrowing from water terminologies is called a current). Shortly after this a more powerful component called the

transistor was rolled out. A transistor can be looked at as consisting of two diodes connected back-to-back. Thus if the first diode allows current to flow, the second diode can be used to control the amount that get to the output. The conductivity (how well it conducts current) of a transistor can be determined during its manufacture by a process called doping. Doping consists of adding an accurately known quantity of another chemical element into a piece of intrinsic silicon. By the choice of the doping element the piece of intrinsic semiconductor may be made to have either a positive or a negative polarity. In electrical engineering, as in nature, the availability of both types of polarity spells a breakthrough. The transistor is made of semiconductors exhibiting both polarities and thus it is the ultimate electronic device. When you have the transistor you can do almost everything! The first transistors were discrete components; that is a single transistor on a piece of semiconductor individually packaged for use. The first laboratory-made transistor was rather crude.



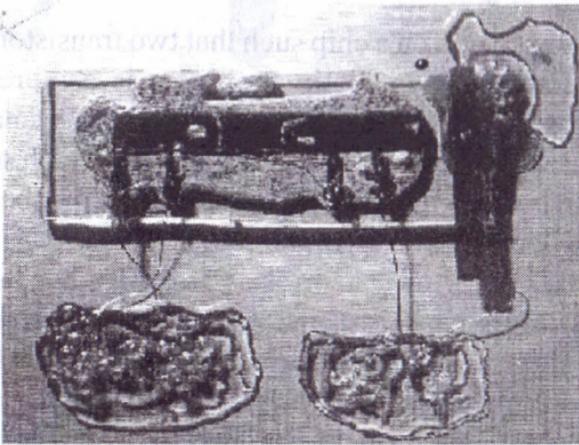
The first laboratory demonstration of transistor action

This came into being between 1952 and 1954. In making a transistor, some other types of materials must be deposited on the silicon substrate in precisely known amount and within a specified portion of the substrate

so as to form the structure that allows transistor action to take place. The processes involved in the fabrication of a transistor are called oxidation, photo masking, etching and diffusion. Each of these processes must be done as accurately as possible. The techniques and the technology of these processes are continually being refined so as to produce a transistor whose characteristics follow almost exactly those predicted by theory. To start with the silicon must be almost 100% pure without any traces of unwanted impurities and the processes mentioned must be carried out in an ultra-clean room. A class 10 clean room must have not more than 300 particles of a size of not more than 0.5micrometer per cubic meter of space. To achieve this is no small task and it is very expensive. A fabrication facility could cost as much as \$1.5B as of 1996.

CIRCUIT INTEGRATION

A transistor is a microscopic 3-dimensional device but because its third dimension, which is the depth in to the substrate, is even smaller than its length and breath, it is regarded as planar. The question now is how small an area can a transistor occupy, or how can we make a transistor as small as possible? Ever since the demonstration of the transistor in its crude form, efforts were made to fabricate a device comparable with the original sample especially as regards its size. This depended



The first demonstrated integrated circuit in 1958

very much on how the processes involved in its manufacture could be carried out as precisely and accurately as possible. Without precision and accuracy of the processes, the device would just not work! With much research effort and dedication, these processes were mastered. The credit for this achievement went to Jack Kilby, then working at Texas Instruments, a USA company, in July 1958. The first demonstrated integrated circuit in 1958 is shown. For this he was also awarded the Nobel Prize in Physics in 2000. The question of how to make a transistor as small as possible is partly being answered it depends on the degree of refinement of the manufacturing tools. For example a much finer process of X-ray lithography, which allows the printing of an object as small as 180nm, has replaced the photo-masking process.

MICROELECTRONICS

In microelectronics we deal in the infinitesimal, our dimensions are in the range of one-billionth of a meter. The size of silicon on which millions of transistors are built is a mere 75mm in diameter. The other question as to how small an area the smallest transistor would occupy to my mind depends on how accurately we know what an atom or even an electron is. Already a value of mass (9.1066×10^{-31} Kg) is assigned to an electron but can we know its volume or density? By the time we know this we may be in a position to know the smallest area to be taken by a transistor.

The smallest dimension on a chip such that two transistors are properly and well defined as two distinct objects is a mere 0.2×10^{-6} ^m (micrometer). (This is of the same order in size as a small bacteria or a large virus). The present size of a wafer on which transistors are built is 300mm in diameter. A rough estimate of the number of transistors that can be built on a wafer is 10,000,000.

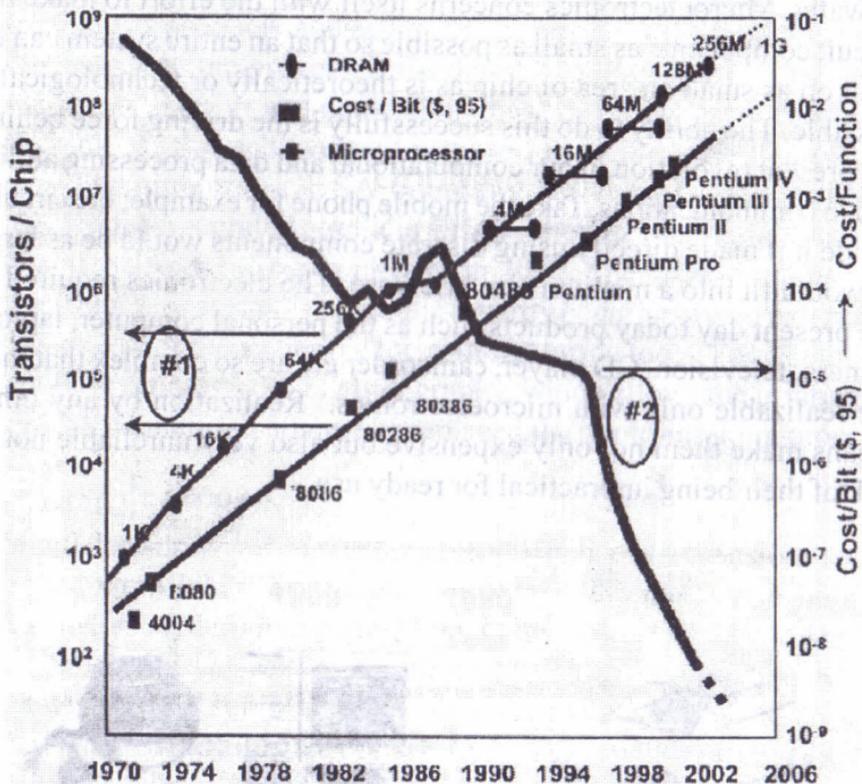
Transistors, resistors, capacitors and inductors are the main components used in building circuits that perform functions such as amplification, oscillation, filtering, switching, integration, differentiation etc. These functions are combined further to build systems and networks such as for computation, communication, control etc. An integrated circuit is one in which a function or even an entire system is built on a single chip

or wafer. Microelectronics concerns itself with the effort to make the circuit components as small as possible so that an entire system can be built on as small an area of chip as is theoretically or technologically possible. The ability to do this successfully is the driving force behind the present revolution in our computational and data processing ability and in communications. Take the mobile phone for example; the circuits inside it if made directly using discrete components would be as large as would fit into a medium size briefcase. The electronics required in the present day today products such as the personal computer, laptop, camera, television, CD player, camcorder etc are so complex that they are realizable only with microelectronics. Realization by any other means make them not only expensive but also very unreliable not to talk of their being impractical for ready use.



Electronic products where compactness is of great value

The beauty of microelectronic is that it not only gives us the advantage of compactness and improved performance but also makes the product cheaper. The trend in the performance indices of circuit integration since 1970 shows that things are forever looking rosy!



Trends in Transistor density on a chip and cost per function from 1970 -2006

The curves are forever moving in the right direction- the kind of curve a stockbroker or an investor would love to see. No wonder Bill Gates is one of the richest men in the world today thanks to microelectronics.

It is estimated that the electronics market served by microelectronic alone is worth some one trillion dollars.

MICROELECTRONICS AND THE DIGITAL WORLD

It is said that we now live in a digital world in which our appliances operate on digital electronic principle. The catch phrase of these days is that there is a digital divide between the developed and the developing worlds meaning that most of the electronic appliances we use here are still based on the older analog technology. This is a very recent development. Hitherto, electronics worldwide had been designed and

built on analog principle in which a signal to be amplified for example is taken to be continuous in time.

A continuous or an analog signal is believed to be what nature provides for; it is not accepted that nature has provided for any other form.

An example of man-made discretization is the way we write down spoken language using a finite number of symbols. This made speech storage on paper possible before electronic direct recording of sound was invented. The digital approach is very important because it offers enormous advantages in the following areas:

- Precision is always guaranteed and accuracy can be tailored to suit the need.
- Reliability is very high.
- Storage is very easily accomplished. Giving us the ability for more sophisticated processing such as made possible by having a memory.
- A digital circuit can always be built in an integrated form. It is therefore always compact and minimal in weight.
- It is amenable to microelectronic techniques and thus digital electronic products can be made to perform at very high performance levels because high performance enhancing ideas can be incorporated at little or no cost.

In a digital regime, samples of a continuous event are taken at regular intervals of time and the sampled value is quantized and coded in a binary weighted number system in which each binary digit is some power of 2. (In the decimal system, each digit position is some power of ten) In a binary or base-2 system, each digit of a number can be either a 0 or a 1. (In the decimal system each digit can take any of the values between 0 and 9) The binary system, is particularly useful from the point of view of a transistor because a transistor can transit between

two stable states- ON or OFF which can be used to represent the binary values 0 or 1. (It has recently become feasible to build a transistor that can transit between three and even four stable states. For the same amount of space, a base-3 system can carry more information than a base-2 system and a base-4 system is correspondingly more compact for expressing the same amount of information.) This is why the transistor is the basic building block of a digital circuit. Working in the binary number system is much the same as working in the decimal system except that it is by far simpler! The most complex arithmetic one has to be able to do is $1 + 1 = 0$ and a carry of 1 to the next higher digit.

In the binary system, mathematical manipulation relies on three basic operations: AND, OR and INVERT. Electronic circuits that perform these operations are called logic gates and they are built with transistors. In almost every aspect of our lives the things that we do are logical-ambiguity or fuzziness are generally not allowed one is allowed one of two possible options but not both at the same time. One is either telling the truth or not. It is an imperfect world that allows the admission of an illogical statement or equivocation by which some learned people making handsome living! Any logical expression involving any number of logical variables can be systematically analyzed and can be built using the three logic gates which themselves are built with transistors.

The *digital technique, circuit integration and microelectronic* are the trio sustaining the electronic revolution we are witnessing today. Microelectronics, by making a transistor smaller gives us the power to have more of them and circuit integration makes it possible to build an entire system on a chip. Now that we are this well endowed electronically, how best do we utilize our endowment? This is the problem that very large scale integration (VLSI) oriented system wants to tackle. We first of all wish to know the characteristics of systems that will benefit from VLSI.

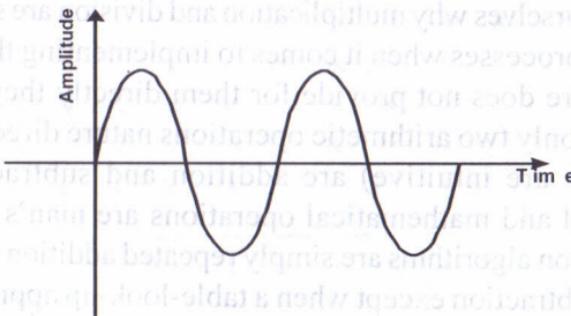
DIGITAL FILTERS

The basic internal architectural considerations that are desired of a system that is VLSI oriented are as follows:

- Clean functional partitioning in which parallel processing and pipelining will ensure a high throughput rate.
- Simple cellular building block to simplify logic design and testing.
- Minimum number of output pins.

There is a class of digital signal processing algorithm that is simple and offers tremendous opportunity for parallel processing and pipelining. An example of such algorithm is the digital processing of analog signal when it is desired to transform it. A particular form of transformation is filtering. An electronic filter is a circuit used in selecting or discriminating among several information carrying signals. For example in the mobile phone system filters make it possible for an individual to make and receive calls using the same airwave available to innumerable other users. Filtering is thus an important process in telecommunication and broadcasting, which makes radio and television transmission and reception possible. (The mechanical equivalent of an electronic filter is a sieve). The design of an electronic filter starts by considering how you want it to behave.

The understanding of the way a filter behaves is made possible by the research effort of a French man, Jacque Fourier, who proved mathematically that complex signals such as sound is a combination of the simplest form of signal. In nature the simplest signal is called a sine or a cosine wave.



The fundamental signal from which comple signals are made

A sine wave is distinguishable from another sine wave either by its different amplitude or its different frequency. (The frequency of a waveform states the number of times the waveform repeats itself in a second of time measurement.) Thus in order to transform a complex waveform by filtering we must know which of its frequency components we either wish to leave or remove as if by a sieve. In normal use a filter can either remove or leave a band of contiguous frequencies. Thus filters are described as band pass, band rejection, low pass, high pass, etc. The design of a filter is the mathematical processes of determining some numbers called the coefficient of the filter, which will make it behave like in any of the descriptions above. Filtering itself is the convolution of the filter coefficients and samples obtained from the analog signal. Convolution is represented mathematically as:

$$Y_n = \sum_{k=0}^{N-1} (H_k \cdot X_{n-k})$$

Y_n are the output samples, H_k are the filter coefficients and X_n are samples from the analog signal to be filtered. The determination of the number of coefficients, N , and the numerical values of the coefficient H , is a design problem solved through the specifications of the filter to be realised.

In a convolution, multiplication and addition are the only required arithmetic operations and multiplication constitutes the bottleneck of the entire process. If we can reduce the area of the chip required for the realization of a multiplier circuit and the time required to get it done, then the stricture of this bottleneck can be minimized. It may be pertinent to remind ourselves why multiplication and division are such problematic arithmetic processes when it comes to implementing them. The reason is that nature does not provide for them directly they are both man-made. The only two arithmetic operations nature directly provides for (and which are intuitive) are addition and subtraction all other arithmetical and mathematical operations are man's invention. All multiplication algorithms are simply repeated addition while division is repeated subtraction except when a table-look-up approach is adopted. (When we do mental multiplication of even two small numbers we are

One can therefore see why multiplication is such a time consuming operation. The time to finish the multiplication of any two numbers can be reduced if the process of adding two numbers can be speeded up. One method is to generate all the carries at each digit position ahead of the addition in each digit position if all the digits of the two numbers are known by the time the addition starts. In the weighted binary number system this is accomplished by a scheme called a 'carry-look-ahead' technique, since the logic of knowing when a carry occurs for any two bits is very simply predicted. Fortunately, *the problem of the 'carry' between digits can be totally circumvented if before performing addition we convert the two numbers into a non-weighted number system in which there is no inter-digit carry at all.*

THE RESIDUE NUMBER SYSTEM (RNS)

The residue number system owes its origin to what is now known as the Chinese Remainder Theorem that had been known for some 2000 years. The theorem shows how to compute an unknown value from the remainders or residues left, when known numbers called the modulus set divides the unknown value. Suppose an unknown value, x , gives the following residue (remainder) set $\{2,3,2\}$ with respect to the modulus set $\{3,5,7\}$. There is a unique solution for the unknown value, which can be obtained using the Chinese remainder theorem as, 23. The uniqueness of the solution makes it possible to represent x by its residue set. Any value between 0 and 104, which is the dynamic range (the product of 3, 5 and 7) made possible by this modulus set can be so uniquely represented. The only proviso is that no two numbers within the modulus set must be able to divide each other or have any common multiple. For example two even numbers cannot be within a modulus set. Selecting a modulus set wide and large enough can make up any desired dynamic range. Let me illustrate some properties of the RNS by some examples.

Decimal number	3	5	7
0	0	0	0
1	1	1	1
2	2	2	2
3	0	3	3
4	1	4	4
5	2	0	5
6	0	1	6
7	1	2	0
8	2	3	1
9	0	4	2
10	1	0	3
11	2	1	4
12	0	2	5
13	1	3	6
14	2	4	0
27	0	2	6
33	0	3	5
72	0	2	2
73	1	3	3
95	2	0	4
96	0	1	5
102	0	2	4
103	1	3	5
104	2	4	6
105	0	0	0

We see that each decimal value is represented by a unique set of residue. The ordering of the elements in the representation is immaterial provided an element corresponds to its modulus. For example, with respect to

the modulus set $\{5,7,3\}$, 104 will be represented as the set $\{4,6,2\}$. Let us now perform some simple arithmetic both in the decimal system and in its RNS representation:

Decimal	=	RNS
3	=	0 3 3
+8	=	<u>2 3 1</u>
<u>11</u>	=	<u>2 1 4</u>

$$8 \times 9 = 8+8+8+8+8+8+8+8+8 = 72$$

	2	3	1
x	<u>0</u>	<u>4</u>	<u>2</u>
	<u>0</u>	<u>2</u>	<u>2</u>

We see that the sum and product agree in the two examples. It is noted that in the two examples there is no carry from one digit to another; each addition or multiplication is confined to the digit concerned in the RNS case. It is always the desire of an electronic engineer to want to mechanize these operations, by building an electronic circuit that can perform the operation.

Multiplication when the value of the multiplier is fixed

Modulo- m arithmetic is a closed operation in the sense that for any two values in the set $Z_m = \{0,1,2,.. (m-1)\}$, called a Galois field, the result is also a member of the set. This fact enables multiplication or addition to be interpreted as a mere mapping between the members of the set. Consider the modulo-7 multiplication truth table shown; Z_m is the second

1	2	0	101
2	3	1	103
6	4	2	104
0	0	0	102

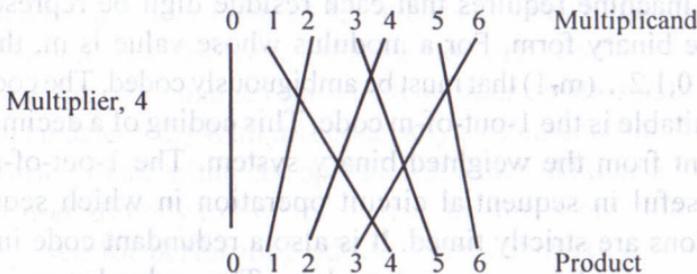
MULTIPLIER

		0	1	2	3	4	5	6
M U L T I P L I C A N D	0	0	0	0	0	0	0	0
	1	0	1	2	3	4	5	6
	2	0	2	4	6	1	3	5
	3	0	3	6	2	5	1	4
	4	0	4	1	5	2	6	3
	5	0	5	3	1	6	4	2
	6	0	6	5	4	3	2	1

Modulo-7 multiplication truth table

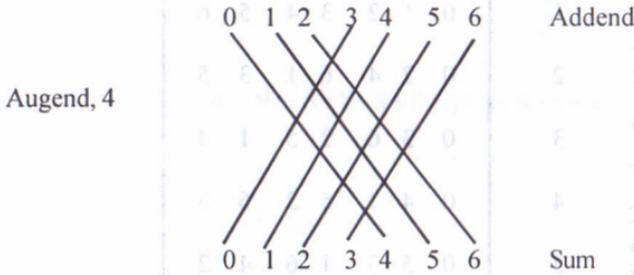
column (or the second row). Take the example of the situation when a multiplier say 4, is used to multiply any value of the multiplicand. The result is found as the fifth column (or the fifth row), which is the same as Z_m but with the elements rearranged.

This shows that in order to effect the multiplication of any value of the multiplicand by 4, all we need to do is some mapping as follows:



This mapping is true only if the multiplier is 4. The mapping will be different for any other value of multiplier.

Addition also follows a similar process. Suppose we wish to perform an addition in which the augend is 4 to any value of addend in modulo-7 arithmetic. The require mapping is as follows:



The mapping is correct only if the value of the augend is 4. The mapping will be different for any other value of the augend. Other values of moduli are similarly treated as in the examples just worked out.

The engineering problem of this is: How can we build an electronic machine that can perform the arithmetic directly given any two numbers in the RNS representation?

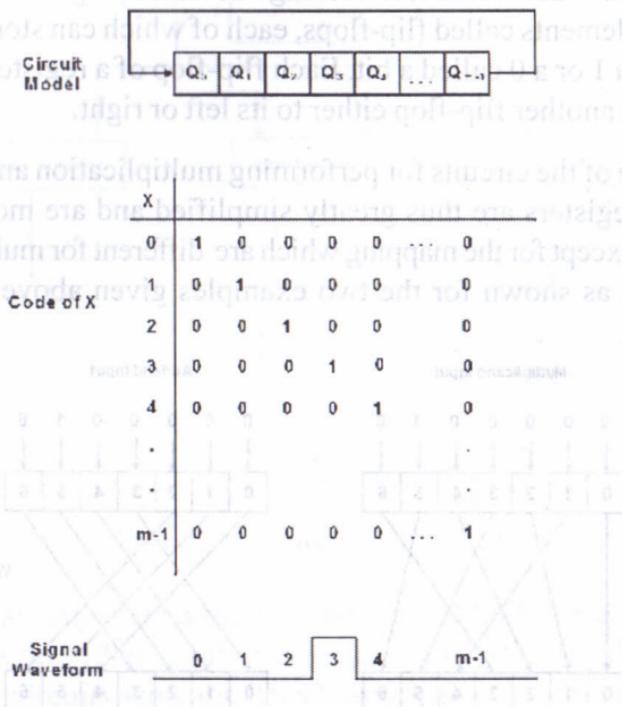
Since the RNS is non-conventional we need to look for a non-conventional approach to the solution of the engineering problem.

Coding of the residue digit

The hardware implementation of the residue arithmetic on a binary digital machine requires that each residue digit be represented in a suitable binary form. For a modulus whose value is m , there are m values, $0, 1, 2, \dots, (m-1)$ that must be ambiguously coded. The coding found very suitable is the 1-out-of- m code. This coding of a decimal value is different from the weighted binary system. The 1-out-of- m code is very useful in sequential circuit operation in which sequences of operations are strictly timed. It is also a redundant code in which m states are used to represent m bits. The redundancy is given as $R = m / (\log_2 m)$. It thus can detect R errors and the correction of $R/2$

errors. This is an advantage over the non-redundant weighted binary number coding.

Coding of a number in the adopted code is as shown:



Circuit model number coding and signal representation based on the 1-out-of-m code

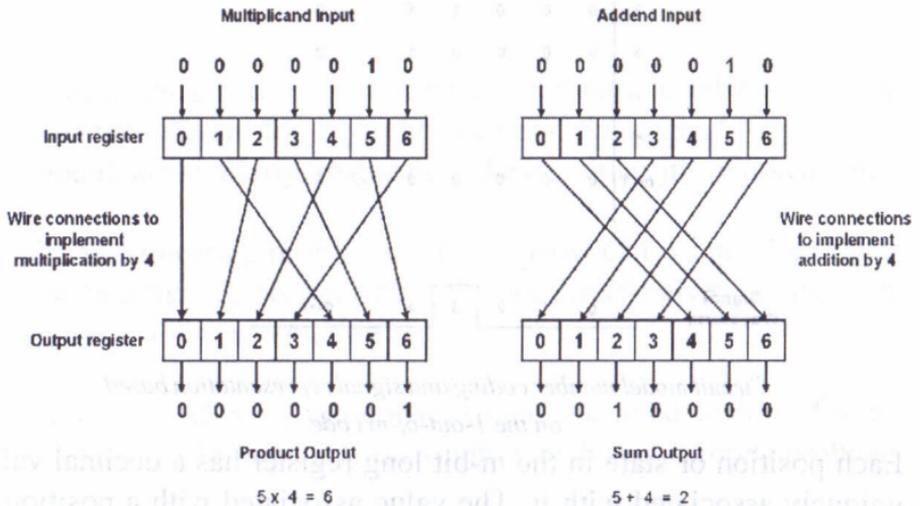
Each position or state in the m-bit long register has a decimal value uniquely associated with it. The value associated with a position is deemed to be present if and only if the state has a binary value of 1; all other bit positions must have a binary value of 0. If more than one bit position has a binary value of 1, it means an error has occurred, which is easily detected. (However, if a position that should correctly have a binary value of 1 changes state with another position, then such error cannot be detected.) With this code, any implementation that is used to perform any of the arithmetic operation of either addition or multiplication can be used directly to find its inverse. In other words the same circuit can be used for performing addition and subtraction while the same circuit can be used to perform both multiplication and division within a modulus as will be shown later.

The Schematic of the multiplier circuit

What is a Register?

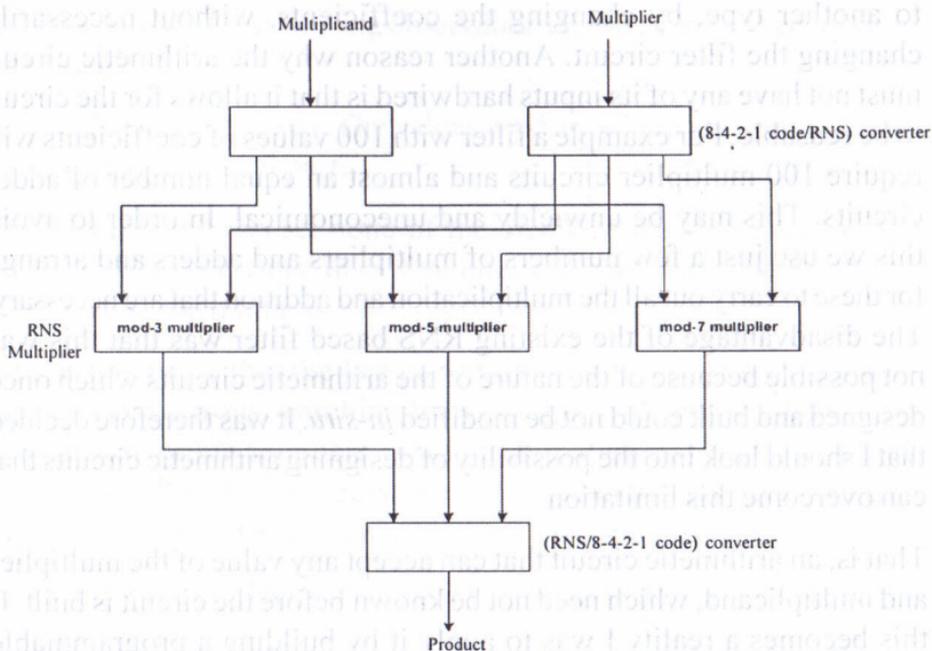
A state is the condition of a register, which either contains something or is empty; in other words it is a storage device. A register is made up of memory elements called flip-flops, each of which can store a binary state, either a 1 or a 0 called a bit. Each flip-flop of a register can shift its content to another flip-flop either to its left or right.

The structure of the circuits for performing multiplication and addition using shift registers are thus greatly simplified and are more or else very similar except for the mapping which are different for multiplication and addition as shown for the two examples given above when the modulus is 7.



Hardwire connections for effecting fixed value multiplication and addition in modulo-7 circuit

We see that when one of the values is given and the other value in the respective operation is fixed, the circuit implementation is fairly simple. All we need are two registers both of which can be parallel loaded simultaneously. The same consideration applies to all the other chosen modulus. Thus the times taken to perform both addition and multiplication are exactly the same in each modulus and in each of the other elements in the set of modulus. The structure of a multiplier or adder circuit based on the modulus set $\{3,5,7\}$ given that the numbers to be multiplied are in the weighted binary code is as shown:



Structure of a 3-moduli arithmetic circuit

With this arrangement a digital filter can be built for a given type of filter once the filter coefficients are known, (the fixed value in the arithmetic circuit) using the RNS based arithmetic circuits.

The advantages of this approach are essentially in the saving in the processing time, the relatively ease of implementation due to its modular nature (divide and conquer strategy) and the fact that the entire filter can be fabricated on a chip using a relatively smaller chip area.

That was the state of affairs I met at Tohoku University, Sendai, Japan in the Department of Electronic engineering under Professor Tatsuo Higuchi. The use of the RNS in a form that does not use a table-look-up technique in the filter itself was pioneered in this department and it was an ongoing research when I joined the department in April 1983.

MY OWN CONTRIBUTION

The fact is there are many other filtering requirements in which the type of filter need to be changed dynamically such as in adaptive filtering and the Kalman filters. In these cases the filter should be convertible

to another type, by changing the coefficients, without necessarily changing the filter circuit. Another reason why the arithmetic circuit must not have any of its inputs hardwired is that it allows for the circuit to be reusable. For example a filter with 100 values of coefficients will require 100 multiplier circuits and almost an equal number of adder circuits. This may be unwieldy and uneconomical. In order to avoid this we use just a few numbers of multipliers and adders and arrange for these to carry out all the multiplication and addition that are necessary. The disadvantage of the existing RNS based filter was that this was not possible because of the nature of the arithmetic circuits which once designed and built could not be modified *in-situ*. It was therefore decided that I should look into the possibility of designing arithmetic circuits that can overcome this limitation.

That is, an arithmetic circuit that can accept any value of the multiplier and multiplicand, which need not be known before the circuit is built. If this becomes a reality I was to apply it by building a programmable digital filter circuit based on the new residue number system arithmetic circuits.

Mathematics, the Queen of the Sciences

At this juncture, Mr. Vice Chancellor, sir, may I be permitted to remember the late Professor A.O Awojobi, one of the most brilliant professors of Mechanical engineering ever produced in this country? His research into mechanical resonance was groundbreaking at the Imperial College, University of London where he earned his PhD and later a DSc. through his published works alone. He used to begin his first year lecture in Engineering Mathematics by telling us, as would-be engineers, that we had to be very comfortable with studying and applying the knowledge of mathematics. If I remember correctly his first sentence at the first lecture was “Mathematics the Queen of the Sciences...” The fact is that there is no engineering discipline that does not require a heavy dosage of mathematics- more especially electrical and electronic engineering. The roles of mathematics in engineering are quite numerous. Most of the time engineers use the language of mathematics to explain themselves and quite often mathematics lead to the invention of new techniques. It may also be used to explain some observed phenomenon peculiar to engineering.

I wish to reiterate the following observations I made earlier in connection with the RNS:

1. It is integer based. The values used are whole numbers without any fractional part.
2. In a modulus set none of the elements may have a common multiple greater than 1 neither can any two moduli have a common multiple.

In order to ensure that the last condition holds it occurred to me that without any rigorous searching for a set of compatible numbers, a set made up of prime numbers would automatically satisfy it. Prime numbers are the set of numbers whose only common multiple is 1. This means that a modulus set can be selected from the following numbers:

2,3,5,7,11,13,17,19,23,29,31,37,41,43,47,53...

The set of prime numbers is actually endless of which the smallest member is 2 the only even prime number known as yet. It may be that the last prime number is even, if it exists at all! (Even if it exists it cannot be written down; there may not be paper large enough to contain it!) While it is relatively easy to identify the smaller prime numbers, there is not as yet any formula that can be used to generate a prime number. What then can be the usefulness of a set of numbers that cannot be generated by any formula. It is like the proverbial *orogbo* in *Yoruba* that has no lobes that can be shared and bitter when eaten.

The properties of prime numbers are studied under a topic in mathematics called Number Theory, which is relatively so obscure that it does not feature in the engineering mathematics curriculum. It might be assumed that it has very little engineering application. I will now explain how Number Theory helped me to solve the problem I have on hand. Let me use the example of modulo-7 arithmetic to illustrate the problem I had to solve. The elements in the set of modulo-7 arithmetic are 0,1,2,3,4,5,6. If I multiply any two numbers in the set I must be able to predict the result. For example, when I multiply 5 and 6 I must be able to get the answer, which is 2 another member of the same set. It then occurred to me that with the exception of the first element, 0, the

other members might be related in a simple way. Of course they form a sequence in which, starting from the left there is a difference of 1 as one proceeds to the right. While this knowledge could be useful for addition it does not work for multiplication. A study of Number Theory shows that indeed all the elements, with the exception of 0, are powers of 3, which is what is called the primitive root of the prime number, 7.

In modulo-7 arithmetic,

$$3 = 3^1 = 3$$

$$2 = 3^2 = 3 \times 3 = 9$$

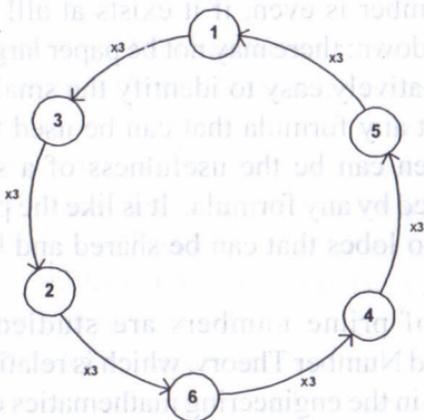
$$6 = 3^3 = 3 \times 3 \times 3 = 27$$

$$4 = 3^4 = 3 \times 3 \times 3 \times 3 = 81$$

$$5 = 3^5 = 3 \times 3 \times 3 \times 3 \times 3 = 243$$

$$1 = 3^6 = 3 \times 3 \times 3 \times 3 \times 3 \times 3 = 729$$

We thus see that as we move from one element to the other in the sequence 3,2,6,4,5,1 all we need to do is to multiply by 3 each time. A transition diagram, illustrating this and which can be used for performing multiplication, may be drawn as shown.



The transition table of a modulo-7 multiplier

The number in the small circle represents both the multiplicand and the product. Suppose I wish to do the multiplication $6 \times 4 = 6 \times 3^4 = 3$, I start the multiplication by entering the diagram at the value 6 and I move counter clockwise. Each time I move implies a multiplication by 3 and after doing this four times arrive at the answer, 3. As another example, $2 \times 5 = 2 \times 3^5 = 3$, I enter the diagram at the value 2 and move

round five times to arrive at the answer, 3. Still another example, $4 \times 5 = 5 \times 3^4 = 6$, I enter at 5, say, and I move round four times to reach the answer, 6.

It is now clear that to multiply any two modulo-7 numbers, we do not have to actually do any multiplication at all, simply because each movement from one state to the next implies a multiplication by 3 all the time.

Indeed every prime number has its own primitive root from which all the elements in its arithmetic set can be generated. Surprisingly, as the table below shows, the value of a primitive root is not unique to a prime number. For the first few prime numbers, the value 2 seems to be rather common as a primitive root.

Prime number	Primitive root
2	2
3	2
5	2
7	3
11	2
13	2
17	3
19	2
23	5

We see that the primitive roots are small numbers and an arrangement exactly similar to that in the case of 7 can be worked out.

For 11, the primitive root is 2 and

$$Z_m = \{0,1,2,3,4,5,6,7,8,9,10\}$$

$$2 = 2^1 = 2$$

$$4 = 2^2 = 2 \times 2 = 4$$

$$8 = 2^3 = 2 \times 2 \times 2 = 8$$

$$5 = 2^4 = 2 \times 2 \times 2 \times 2 = 16$$

$$10 = 2^5 = 2 \times 2 \times 2 \times 2 \times 2 = 32$$

$$9 = 2^6 = 2 \times 2 \times 2 \times 2 \times 2 \times 2 = 64$$

$$7 = 2^7 = 2 \times 2 \times 2 \times 2 \times 2 \times 2 \times 2 = 128$$

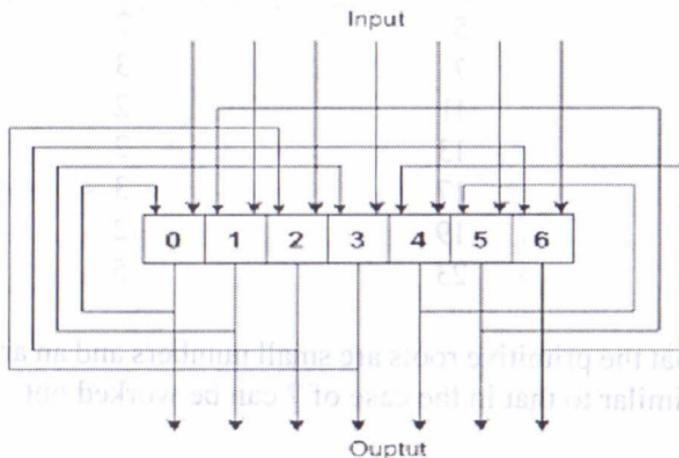
$$3 = 2^8 = 2 \times 2 = 256$$

$$6 = 2^9 = 2 \times 2 = 512$$

$$1 = 2^{10} = 2 \times 2 = 1024$$

Multiplication using shift register

If as before, we arrange 7 flip-flops so that each of them represent values as shown and connect them such that (with the exception of 0):



Connection of a register for implementing modulo-7 multiplication

The output of 1 is connected to the input of 3

The output of 3 is connected to the input of 2

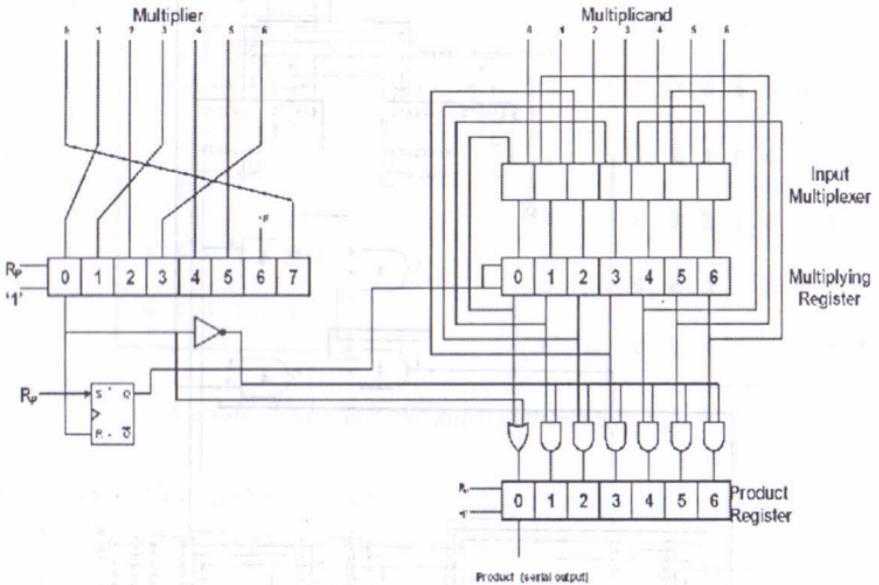
The output of 2 is connected to the input of 6

The output of 6 is connected to the input of 4

The output of 4 is connected to the input of 5

The output of 5 is connected to the input of 1

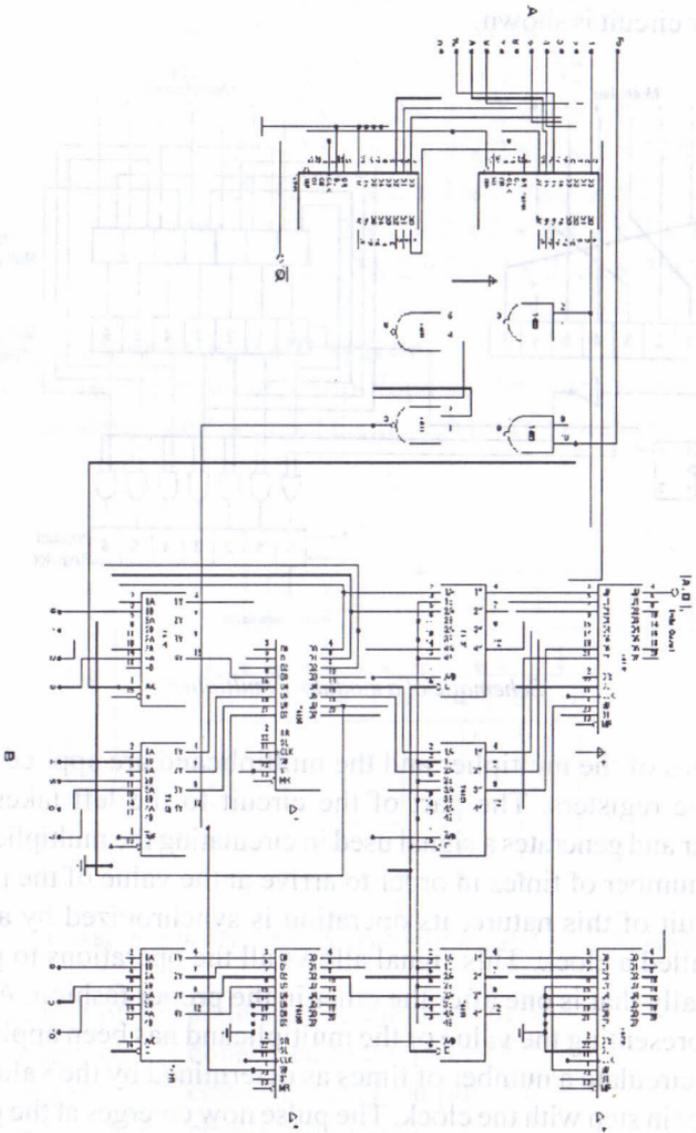
With this connection a pulse entering a flip-flop can be made to circulate for any number of times to get the value of the flip-flop representing the product. For example if a pulse enters the register at 2, denoting that the multiplicand is 2, and made to circulate 3 times, denoting a multiplier value of 6, it will emerge at 5, which is the product of 2 and 6 in modulo-7 multiplication. The schematic diagram of the modulo-7 multiplier circuit is shown.



Schematic of a modulo-7 multiplier

The values of the multiplier and the multiplicand are applied at their respective registers. The part of the circuit to the left takes in the multiplier and generates a signal used in circulating the multiplicand the desired number of times in order to arrive at the value of the product. In a circuit of this nature, its operation is synchronized by a timing signal called a clock. This signal allows all the operations to proceed sequentially that is one after the other in the proper fashion. After the pulse representing the value of the multiplicand has been applied, it is made to circulate a number of times as determined by the value of the multiplier in step with the clock. The pulse now emerges at the position representing the value of the product. R_p is a signal that initiates the beginning of the multiplying cycle. The operation is completed after 7

clock pulses. In general m clock pulses are required for a modulo- m multiplication. An actual circuit diagram for a modulo-11 multiplier using available off - the - shelf digital electronic LSI (large scale integration) circuit chips is shown.



Modulo-11 multiplier built using large scale integrated (LSI) chips

Principle of the adder/subtractor circuit

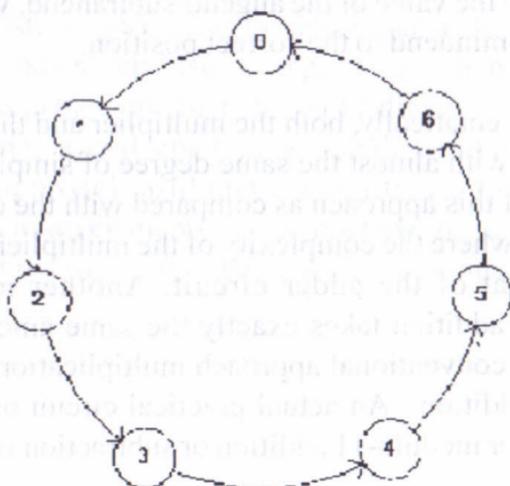
The modulo-7 addition and subtraction truth tables are shown

		AUGEND							
		+	0	1	2	3	4	5	6
A D D E N D	0	0	1	2	3	4	5	6	
	1	1	2	3	4	5	6	0	
	2	2	3	4	5	6	0	1	
	3	3	4	5	6	0	1	2	
	4	4	5	6	0	1	2	3	
	5	5	6	0	1	2	3	4	
	6	6	0	1	2	3	4	5	

		SUBTRAHEND							
		-	0	1	2	3	4	5	6
M I N U E N D	0	0	6	5	4	3	2	1	
	1	1	0	6	5	4	3	2	
	2	2	1	0	6	5	4	3	
	3	3	2	1	0	6	5	4	
	4	4	3	2	1	0	6	5	
	5	5	4	3	2	1	0	6	
	6	6	5	4	3	2	1	0	

Modulo-7 addition and subtraction truth-tables

It is observed that, unlike the entries in the multiplication truth table, the entries are linearly cyclic with a difference of 1 as one move either vertically or horizontally down or across the table. The state transition



The transition table of a modulo-7 Adder

diagram below constructed from these tables shows that for addition operation one moves counterclockwise along the circle and for subtraction one moves clockwise. The value within the small circle represents an input, the sum or the difference as the case may be. Consider the following examples:

$$5 + 6 = 4;$$

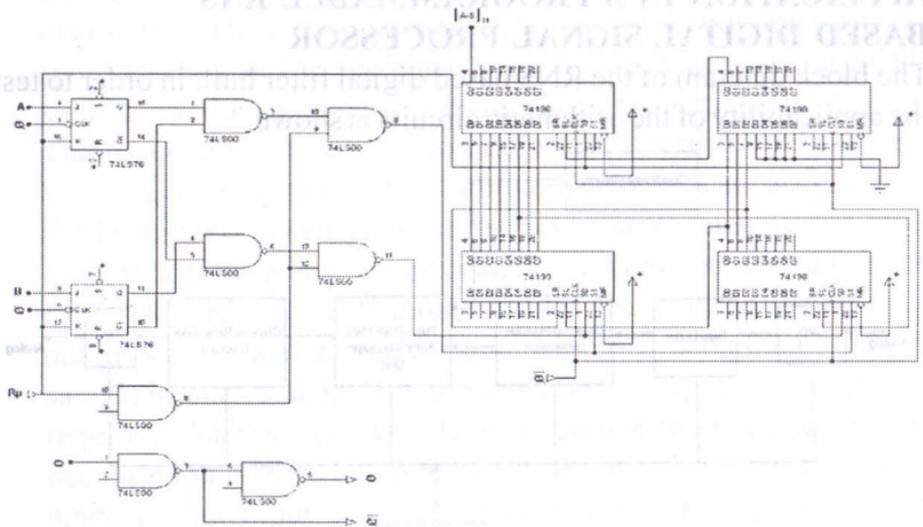
$$5 - 6 = -1 = 6$$

Using the state transition diagram, for the addition one starts with the addend, 5, and moves in the counterclockwise direction along the diagram 6 times (for the augend) to arrive at the value of the sum, 4. For the subtraction one starts with the value of the minuend, 5 and moves clockwise 6 times to arrive at the difference, 6. Thus addition and subtraction may be performed using the same structure.

Implementation using shift register

The implementation follows almost the same scheme as that in the multiplication except that that the connection of the output of a flip-flop is to the input of a flip-flop directly next in value. The output of flip-flop 0 is connected to the input of flip-flop 1; the output of the flip-flop 1 is connected to the input of flip-flop 2 and so on. As also in the multiplication scheme, the shift register at the left side of the diagram generates a signal derived from the value of the augend/subtrahend, which is used to shift the addend/minuend to the correct position.

It thus seen that schematically, both the multiplier and the adder have the same structure with almost the same degree of simplicity. This is one of the merits of this approach as compared with the conventional arithmetic circuits where the complexity of the multiplier circuit is by far larger than that of the adder circuit. Another merit is that multiplication and addition takes exactly the same amount of time; compared with the conventional approach multiplication takes much longer time than addition. An actual practical circuit using off-the-shelf components for modulo-11 addition or subtraction is shown.

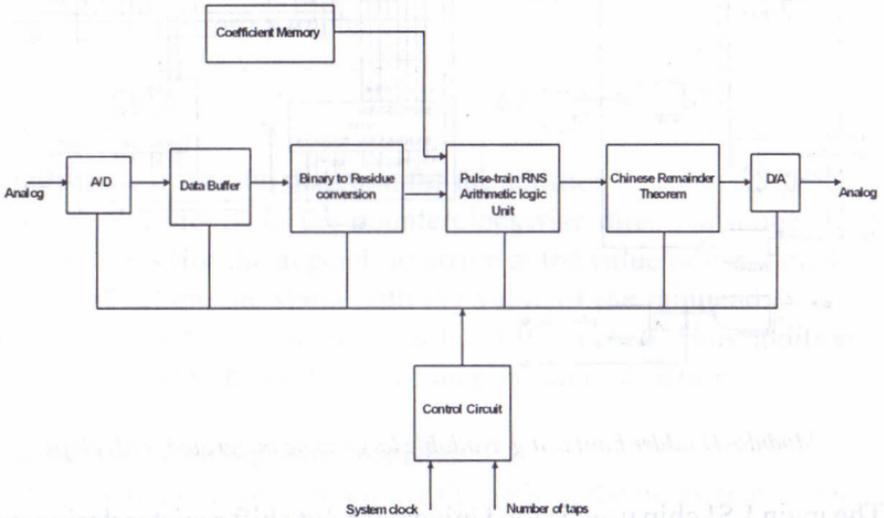


Modulo-11 adder built using available large scale integrated (LSI) chips

The main LSI chip used is the Universal 8-bit shift register designated by the manufacturer as 74198. This integrated circuit can perform four functions, namely, Parallel load, Shift left, Shift right and Hold. That is it can load all its eight flip-flops simultaneously with logical values applied at its input, shift the loaded value either left or right (as may be desired) and hold the value until a change of state is desired. The advantage of using a shift register to perform arithmetic is that it also performs storage functions. This has a very useful implication when these arithmetic circuits are used in the implementation of a digital filter because it will allow pipelining; a concept that we shall explain further. In the conventional approach arithmetic circuits are made with purely combinational circuit elements that do not have any memory capability and additional provision has to be made to store intermediate values.

APPLICATION IN A PROGRAMMABLE RNS BASED DIGITAL SIGNAL PROCESSOR

The block diagram of the RNS based digital filter built in order to test the applicability of the arithmetic circuits is shown.



The block diagram of the RNS based digital filter

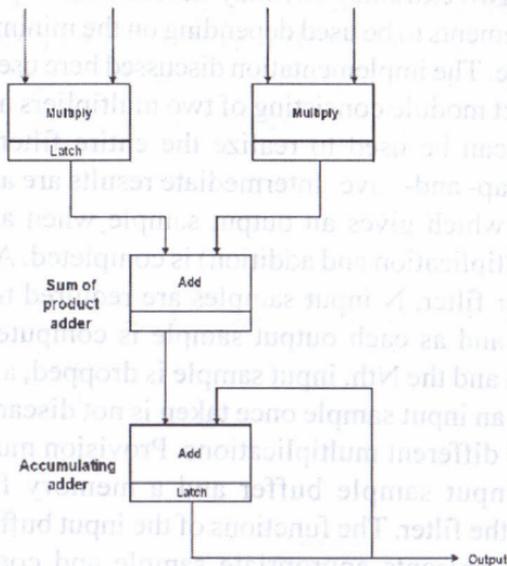
The analog input signal to be filtered is first converted to the digital form. The A/D gives a weighted binary number output. This output must be converted with respect to the chosen set of modulus to its residues.

The prime number modulus set adopted is $\{13, 17, 19, 23\}$. The product of these four numbers gives the dynamic range the difference between the smallest and the largest values that may occur during any arithmetic computation in this filter. A way of estimating the dynamic range of a filter *a priori* is well established in the literature.

Depending on the specification of a filter as many as 100 multiplications may need to be carried out in order to obtain just a single output sample. In order to get the output at the fastest rate possible for this filter, one will require 100 multipliers and 51 adders. This may turn out to be uneconomical and unwieldy due to the large amount of hardware needed. At the other extreme one may decide to implement this filter with just one multiplier and one adder at the least processing rate.

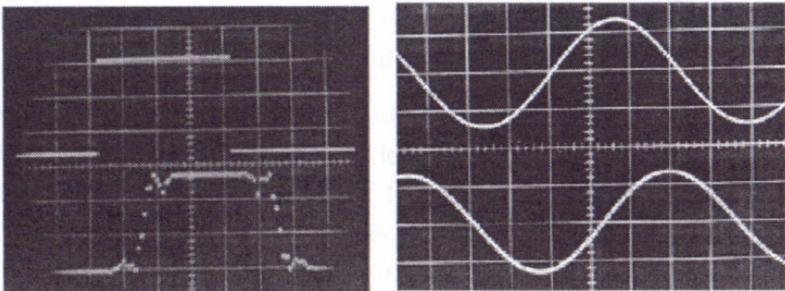
Between these two extremes one may decide on an optimum number of arithmetic elements to be used depending on the minimum processing speed acceptable. The implementation discussed here uses the minimum sum-of-product module consisting of two multipliers and two adders. This structure can be used to realize the entire filter by a strategy known as overlap- and- save. Intermediate results are accumulated by the last adder, which gives an output sample when all the required arithmetic (multiplication and addition) is completed. At any instance, for a Nth. order filter, N input samples are required to compute one output sample and as each output sample is computed a new input sample is taken and the Nth. input sample is dropped, as it is no longer required. Thus an input sample once taken is not discarded until it has been used in N different multiplications. Provision must therefore be made for an input sample buffer and a memory for storing the coefficients of the filter. The functions of the input buffer are to accept a new sample, presents appropriate sample and coefficient to the multipliers and to rearrange the samples such that the overlap-and-save strategy can be used. The new pulse train RNS arithmetic circuits just presented are used as the computing elements in the SOP module where the arithmetic of the filter is actually carried out. The pipelining of the operation in the SOP module means that a new multiplying process can start once the multiplier circuit has completed its latest operation even though the entire process of computing an output sample is still to be completed. Pipelining is an efficient way of processing that does not allow any processing equipment to be idle at any moment once operation has started.





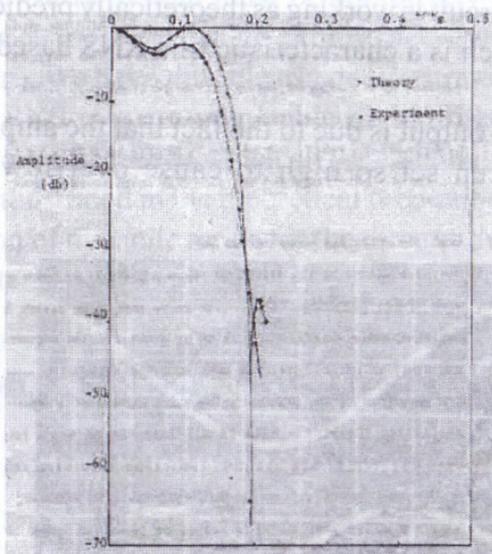
The sum-of-product (SOP) arithmetic module

The output of the RNS filter is converted to a conventional number representation using the CRT module so that a conventional D/A can be used to obtain a filtered analog output. The control circuit enables us to specify the order of the filter to be implemented so that the internal circuitry can be made ready to accommodate it. The constructed digital filter was used to experimentally verify the characteristics of two designed FIR filters namely: 23-order low-pass and 50-order band-pass. The responses of the low pass filter to a square wave and a sine wave are shown:

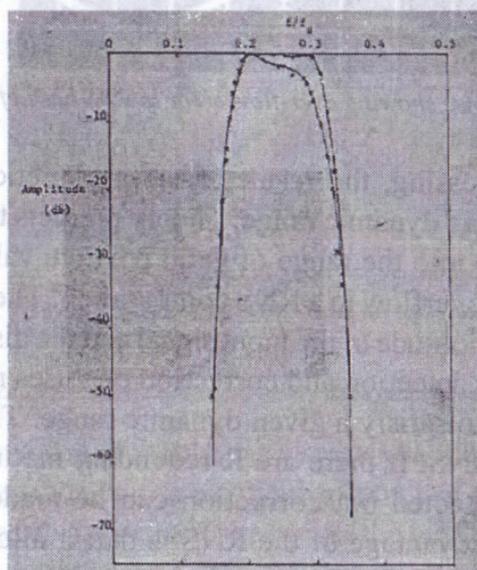


Response of the low pass filter to a square and line waves

The upper waveform is the input wave and the lower waveform is the output. For the square wave the output shows what happens after the high frequency components of the square wave has been filtered out by the low pass filter. The frequency of the sine wave is within the pass-band of the low-pass filter hence the output waveform is not attenuated. The amplitude/frequency characteristics of the low-pass filter and the band-pass filter are shown:



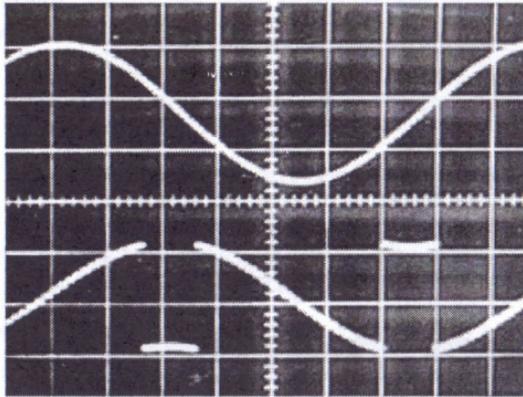
Experimentally obtained low pass digital filter characteristic



Experimentally obtained band pass digital filter characteristic

The experimentally obtained characteristics follow the theoretically predicted characteristics closely. This is the first time the same filter circuit has been used to realize different types of filter using the RNS approach. Any filter type of any order can be realized by merely reading in the filter coefficients already stored in a ROM (Read Only Memory). The input/output response of the filter to a sine wave of a frequency within the pass band is shown. This output waveform actually confirms that the RNS based circuit is working as theoretically predicted because of the distortion which is a characteristic of a RNS based system.

The distortion of the output is due to the fact that the amplitude of the input signal has been set so high to cause overflow during the computation.

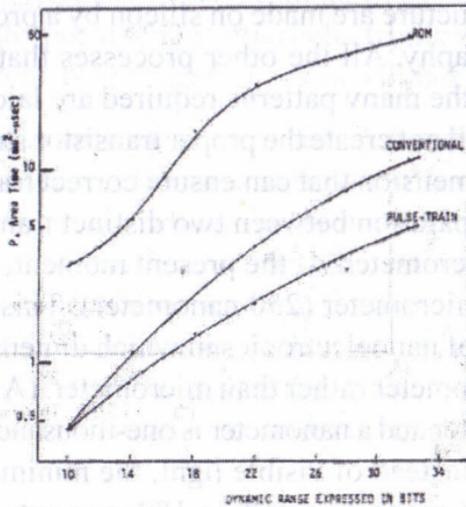


Filter response showing over-flow error in RNS based filter

That is, while processing, the result of the arithmetic calculations exceeded the designed dynamic range. Theory predicts that a negative overflow is mapped into the range of valid positive values and *vice-versa* for a positive overflow in a RNS computation. The solution is to simply reduce the amplitude of the input signal and the distortion would disappear. For error detection and correction one uses more modulus than are necessary to satisfy a given dynamic range. This is referred to as a redundant RNS. If there are R redundant moduli, error in R modulus can be detected but correction can be made in only $R/2$ modulus. Another advantage of the RNS is that it allows a graceful failure of a system in case there is error in any modulus. The particular

modulus is simply isolated and processing can continue but at a reduced dynamic range, which can be accommodated by reducing the amplitude of the input signal otherwise there would be overflow error. Thus by using the modular approach and because there is strict partitioning between the modulus, a bad module can be withdrawn from service without affecting the performance of the other modulus. (Whereas using the conventional weighted number system if there is error in just one bit, the entire system must be completely shut down in order to isolate the error because it cannot accommodate any graceful degradation). We have thus clearly demonstrated the feasibility of the use of the RNS in a programmable digital filter. Such a filter can be realized as a VLSI chip in which all the essential circuits are contained. This is demonstrated in the theoretical prediction of circuit complexity as a function of dynamic range for the three know methods of realizing a digital filter.

It shows very clearly the superiority of the RNS pulse train circuit for use at higher dynamic ranges.



Variation of hardware complexity as a function of dynamic range

Its chief drawback is that being a sequential circuit based system, its operation depends on the clock frequency and the largest modulus in the set of modulus adopted. The bigger the largest modulus, the slower the speed.

WHERE WE ARE HEADING

Nanoelectronics

If the goal of microelectronic is to make electronic devices as small as possible we can start by asking how we can make its simplest building block as small as possible. Alternatively we may ask; how small can we make a transistor? The answer to either question is very complex because it depends on the atomic model, and the crystal structure of the materials used in making the transistor. These will fix a theoretical limit to what is achievable. With the atomic model in vogue now, the tools available for use in making the transistor determines the limit to its size. The finer the tool, the smaller and better the product, especially for a product of the order in size, of a small bacteria or a big virus! (An analogous situation would be that of a neuro-surgeon operating with a scalpel the size and crudity of a kitchen knife!).

The most critical process in the manufacture of a transistor is lithography. Lithography determines the preciseness with which we can make a transistor and therefore defines its size. In lithography, patterns defining the transistor structure are made on silicon by a process similar to that used in photography. All the other processes that follow depend on how accurately the many patterns required are laid on one another. A misalignment will not create the proper transistor structure. Circa 1982, the minimum dimension that can ensure correct transistor structure or the minimum separation between two distinct transistors on a chip of silicon was 8 micrometer. At the present moment, this dimension has shrunk to 0.25 micrometer (250 nanometer). This means that we are at the threshold of nanoelectronics in which dimensions on silicon are measured in nanometer rather than micrometer. (A micrometer is one-millionth of a meter and a nanometer is one-thousandth of a micrometer) By using X-ray instead of visible light, the minimum dimension of a transistor can be made as small as 180nanometer. Further research will still make this dimension even smaller.

Single Electron Transistor

Transistor operation is explained in terms of the movement of a large number of electrons from one part of the structure to another in a controlled manner. As the size of the transistor becomes smaller, the

number of electrons will become so few and approach the limit of a single electron being responsible for transistor action. This has been demonstrated as possible at a temperature of minus 269 degrees centigrade- almost near what is referred to as absolute zero temperature, which is an extremely low temperature!

To make it a practical proposition, the operating temperature must be much higher than this. Success in this area depends on finding new materials that can exhibit the desired properties at higher temperatures. When this happens, the operating speed of electronic devices will be extremely fast.

Quantum Electronics

The driving force behind microelectronics seems to be the desire to build digital machines that are ever smarter, smaller and cheaper. Consumers ever want the superlatives in all these aspects and technology must satisfy these wants. With this in mind, research is striving to discover better materials and techniques of fabrication in order to improve the yield and better technique of using the large number of transistors made possible by microelectronic for a still better performance. It is a many-pronged attack in solving a problem.

Lately, the very fundamental idea of associating the action of a transistor with digital logic is receiving a revision. A transistor is a physical structure made up of several atoms, which forms the crystal structure of a material. Inside this material the electron plays its vital role of carrying electronic charges. The suggestion now is that instead of using a transistor as the basis of a logical operation, why not use an atom (or a collection of atoms) if it can be shown that an atom exhibits a logical behavior similar to that of a transistor under certain conditions.

In this case the smallest unit of information called a bit formerly associated with a transistor is now associated with an atom. However in order to be able to predict the behavior of the atom in this new role we will have to deviate from the well trodden path of Newtonian and Maxwellian theories that tend to look at a macroscopic rather than a microscopic picture. The behavior of an individual atom cannot be predicted from the known behavior of a material made from the same

collection of atoms when it forms a crystal. (Just as we cannot predict the behavior of a particular individual within a society from a study of the behavior of the entire society. By the same reasoning, one cannot, by studying the behavior of an individual, predict how a community made up of these individuals will behave. The concept of probability would have to be used in describing our observation of either the group or the individual within the group. Thus we can describe only the probable behavior of the group from the knowledge of the probable behavior of the individual...)

The new theory, known as Quantum Mechanics, which can be used to unravel this problem, was formulated in the first half of the 20th century. Erwin Schrödinger first formulated the equation that forms the backbone of this theory. The equation has the tendency to intimidate even the initiated by merely looking at it on paper because of its complexity, but it is essentially a multi-dimensional differential equation expressing the conservation of energy woven with threads of the wave notion of matter and cast in the language of probability.

This equation is meant to work along with what is known as the Uncertainty Principle due to Heisenberg. This principle expresses the fact that there are some pair of descriptive attributes of matter both of which cannot be known precisely simultaneously. Thus if we know exactly the location of an object such as an electron, we cannot with certainty know how fast it is moving. Without going into much further detail about these theories, there is much hope that they can be used to explain some of the apparently mystifying things about the universe we live in such as how a miracle, magic, juju, ESP, astral travel, etc appear to be done. Even now there appears to be a very thin dividing line between science and metaphysic they now seem to be leaning on each other! Observe the recent GSM/juju scare. Quantum mechanics tells us in probable terms, that such a possibility is within what is scientifically explainable. When quantum electronics become a reality what seems bizarre to us now will then be routinely done just as our present technology might appear as mere wizardry to our forebears.

CONCLUSIONS

Microelectronic, Education, National wealth and Quality of life

There is no doubt in my mind that Microelectronic is linked through Education to the creation of wealth and hence better quality of life. Nations whose citizens enjoy a high standard of living today export high technology and conversely nations that import high technology have a generally poor standard of living among the masses. Production and marketing of high technology is possible where a high premium is paid on education. Education is the only panacea for an ailing economy. All economic strictures are merely palliatives if education does not produce a competitive work force that can produce goods other nations want and if we cannot produce finished products of high quality from our raw resources we will remain poor. A country such as France, which turns fabrics into high fashion products, makes more money than the producers of the raw materials all put together. Thus a nation has a competitive edge if in the absence of raw resources she has the technology for processing the raw resources others have. We should also note that it is not in the economic interest of a developed economy to turn over to us the means by which she maintains its edge of having a higher standard of living, which most of us crave but which we seem unable to develop for ourselves. We must by ourselves develop the technology for processing our raw materials for at least local consumption and thus improve our standard of living. It seems to me that our national leaders tend to believe that this goal seem unachievable and hence not worth the effort and hence the lackadaisical attitude to education and research. There is no need, in order to drive home these points, to mention the economic miracles of the Far East Asian countries like Japan, South Korea, Taiwan and China. Japan is confident that she will maintain her leadership position because she believes she is leading in high technology research and the quality of her educational system is superior to those of her neighbors in the race for economic leadership. I certainly agree; myself being a product and a witness to these claims.

ACKNOWLEDGEMENTS

I believe that a human being is insignificant and almost helpless and without the contribution and support of numerous others cannot achieve anything. To me the only reason for any meaningful existence is to be of use to others or to serve others, and so my debt of gratitude is so immense that the whole of my being is full of gratitude to all those who contributed to making me the person I am.

One great fortune in my formative years was in attending the Government College Ibadan (1962-66) and in which the beginning of my academic leaning was formed. The discipline, love of fair play, integrity, conscientiousness both at work and play and whatsoever was of good report, which are the hallmark of a GCI student were somehow instilled in all who passed through its portals. After the A levels at the International School, University of Ibadan (1967-68), (where I enjoyed the scholastic comradeship of Omokayode Denloye (MD Unilag Consult) and David Oloowokere), I entered the University of Lagos to study Electrical engineering. Of all my lecturers in my undergraduate years, Dr Olusegun Ajayi, stood out for his love of teaching and dedication. He just was very interested in making sure that we did our work well especially in the Electrical machines, which was his specialty. In electronic it was the late Dr. T.A Kasim who made transistor circuits interesting and easy to learn. He was always looking for ways by which he could make students understand whatever he taught.

My special gratitude goes to Prof Tatsuo Higuchi and Prof Michitaka Kameyama of Tohoku University, Sendai, Japan under whom I obtained the Doctor of Engineering degree within the minimum time allotted for this degree through a Japanese Government Ministry of Education (Monbusho) Scholarship. (Imagine my anxiety when I was told right at the onset of my study by one of them in writing, which I still keep, that the doctor of engineering degree of a Japanese University “is the most difficult in the world”) Prof. Higuchi’s kindness and generosity, typical of all the Japanese I came across, cannot be imagined, one has to experience it to believe it. Throughout my almost three years stay as his student I lacked for nothing. This period was certainly the most fulfilling and most rewarding period in my life. I am very grateful to all those Japanese who made me feel at home while a very long way

from home. I remain grateful to Rev. & Mrs. William Draper, American missionaries, who had live in Japan for almost 40 years. They were wonderful in allaying my fears and anxiety about studying in a strange country such as Japan. Their support made it possible to complete my studies and they were a great comfort during some illness. To me they were a 'God-sent'.

Having spent my entire working life in the University of Lagos, I have had the opportunity of seeing its development since my undergraduate days. I have weathered at least seven different University administrations each one unique in its own way.

The leadership provided by Prof. Jelili Adebisi Omotola encouraged me as an individual by recognizing that I had something to offer in a capacity relevant to my experience and specialization. I am thankful to Prof. Omotola for his insight. Nearer home in my department I have enjoyed the support of all my senior and junior colleagues and I am always proud to say that there is none of them whom I am ashamed of working with. I am grateful to Profs R.I Salawu, Adekola, Ijaola, Awosope and Okoro all of whom I have known for more than 30 years. I thank Dr. A.I Mowete whom I respect for his assiduousness, and for being there to make me feel respected.

Outside the walls of the University, I have enjoyed a special relationship with the Onward Group of Companies and Epesok Paper Mills Ltd under the chairmanship of Chief S.O Obagun an industrialist of very high repute. Ever before the University recognized my worth as a practical engineer, Chief Obagun threw open the doors of his industries wide for me to practice my electrical/electronic know-how. His management staff of Prince Badejo (Former director of engineering), Mr. Hassan (former M.D)Chief Fasetire, MD, Mr. Olapoju, Finance Director, always bolster my confidence in the ability to solve some industrial practical problems to the mutual satisfaction of all parties and more to the benefit of my students who learn from real practical experience.

In the preparation of this inaugural lecture, I have had the assistance of Mr. Samuel Osafehinti, a recent graduate of my department. He is an embodiment of what an engineer is. His ability to use his brain and

hands to provide solution is highly rated. I thank him and wish him good luck as he embarks on his engineering career, I have no doubt he would get far. I also thank Mrs. Veronica Ijebusoma Ebodiwe for maintaining the office and for always being so mindful of making sure that I do not become overwhelmed by my numerous responsibilities.

I am very grateful to my late parents and my numerous relations who continue to support my aspirations and especially Mr. I.O. Oremodu who as a child recognised some academic promise in me and encouraged my parents to pay more attention to my education. I thank Chief I.O Akinyemi, (Baale of Idiaga, Ogun State) a retired Chief Engineer of the FRCN and one of the first sets of Nigerian engineers. He and his wife continue to show keen interest in me and I cherish the pride of place I have in their hearts. I thank very heartily my uncle Chief Amos Olatunde Ajayi, who since childhood has always lavished his attention on me, he more than any one else living expected me to go far academically.

I have enjoyed the comfort and support given by my very own, ever loving and lovely Modupeola, Aduke, dutiful and loyal wife and mother to our children, Oluyinka, Iyiola and Olumide. Oluyinka is characteristically so generous and kind and I certainly have not met anyone who is as self-sacrificing on my behalf as she is. Iyiola is so defensive of me that she is always ready to rise up to defend me against any attack. Olumide, ever so gentle and unassuming; he will never complain. To him everything is all right. With a family as wonderful as these, I have always had all that is needed to strive at achieving something. I think you will all agree with me that these children can be proud of how well they have brought up their daddy.

Now that the lecture is over, I must thank immensely the wonderful audience, who as I mentioned earlier took a gamble and risked their precious time to participate in this inaugural lecture. I took time to prepare this lecture just because I would not want to disappoint you and I was certain you would make it my day. I have had a wonderful evening and I hope I have been able to make this lecture a worthwhile experience.

Thank you very much for coming.

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University of Lagos Press