FEMTOTECH

Computing at the Femtometer Scale Using Quarks and Gluons

Prof. Dr. Hugo de Garis

profhugodegaris@yahoo.com
http://profhugodegaris.wordpress.com

Abstract

This essay shows how the properties of quarks and gluons can be used (in principle) to perform computation at the femtometer (i.e. 10^{-15} *meter) scale.*

1. Introduction

I've been thinking on and off for two decades about the possibility of a femtotech. Now that nanotech is well established, and well funded, I feel that the time is right to start thinking about the possibility of a femtotech.

You may ask, "What about picotech?" (i.e. technology at the picometer (10^{-12} m) scale). The simple answer to this question is that nature provides nothing at the picometer scale. An atom is about 10^{-10} m in size. The next smallest thing in nature is the nucleus which is about 100,000 times smaller, i.e. of 10^{-15} m in size, i.e. a femtometer, or a “fermi.” A nucleus is composed of protons and neutrons (i.e. “nucleons”), which we now know are composed of 3 quarks, which are bound (“glued”) together by massless (photon-like) particles called “gluons.”

Hence if one wanted to start thinking about a possible femtotech, one would probably need to start looking at how quarks and gluons behave, and see if these behaviors might be manipulated in such a way as to create a technology, i.e. computation and engineering (i.e. building stuff).

In this essay, I concentrate on the computation side, since my background is in computer science. Before I started ARCing (After Retirement Careering) I was a computer science professor who gave himself zero chance of getting a grant from conservative NSF or military funders in the US to speculate on the possibilities of a femtotech. But now that I’m no longer a “wager”, I’m free to do what I like, and can join the billion strong “army” of ARCers, to pursue my own passions.

So I started studying QCD (Quantum Chromo Dynamics), which is the mathematical physics theory of the strong force, or as it is known in more modern terms, the “color force”.

Since I have a computer science background, I knew what to look for when sniffing through QCD text books, to be able to map computer science concepts to QCD phenomena.

2. Bits and Logic Gates : the Heart of Computation

If you want to compute at the femto level, how do you do that? What would you need? To me, the essential ingredients of (digital) computing are bits and logic gates.

A bit is a two state system (e.g. voltage or no voltage, a closed or open switch, etc) that can be switched from one state to another. It is usual to represent one of these states as “1” and the other as “0”, i.e. as ***b***inary dig***its***. A logic gate is a device that can take bits as input and use their states (i.e. their 0 or 1 values) to calculate its output.

The three most famous gates, are the NOT gate, the OR gate, and the AND gate. The NOT gate switches a 1 to a 0, and a 0 to a 1. An OR gate outputs a 1 if one or more of its two inputs is a 1, else outputs a 0. An AND gate outputs a 1 only if the first AND second inputs are both 1, else outputs a 0.

There is a famous theorem in theoretical computer science, that says that the set of 3 logic gates {NOT, OR, AND} are “computationally universal”, i.e. using them, you can build any Boolean logic gate to detect any Boolean expression (e.g. (~X & Y) OR (W & Z)).

So if I can find a one to one mapping between these 3 logic gates and phenomena in QCD, I can compute anything in QCD. I would have a femtometer scale computation. That was the big prize I was after.

So, I set out to find phenomena in QCD that I could map bits and logic gates to. I was quickly rewarded. It was a case of “low hanging fruit.” I just happened to be the first person (as far as I know) wandering around the QCD orchard with a very specific type of cherry picking in mind.

3. The Color Charge on the Quarks and the Gluons

There are 4 types of force in the physical world, from weakest to strongest, they are – the gravitational force, the weak nuclear force, the electromagnetic force, and the strong nuclear force. (Actually, their relative strengths depend on the temperature at which these forces act. At extreme temperatures (energies) which occurred just after the big bang and now at the LHC (Large Hadron Collider) in Geneva, their strengths converge to the same value, a phenomenon called “grand unification.”)

In the 60s and 70s physicists became aware that the nucleons (the protons and the neutrons) consisted of 3 quarks, which have fractional electric charges (e.g. +/- 1/3 or 2/3 of the charge of an electron), and a new type of charge, called “color”. The electronic charge came in two types (positive and negative), which is something science has known about for several centuries. The color charge however comes in 3 types, “red” “blue” and “green.”

The electromagnetic force is “mediated” (conveyed) between two electrical charges via the photon (the particle of light). A photon is emitted by one of the charges and is absorbed by the other. This interaction creates the attractive or repulsive force between the electrical charges.

Something similar happens between quarks. The equivalent of the photon is called a gluon. A quark emits a gluon, which is then absorbed by another quark, and this creates the interaction between the two quarks.

There is an essential difference between a photon and a gluon. The photon has no charge of its own, whereas a gluon does have a color charge, in fact, each gluon has 2 such charges. It is bi-charged, or bi-colored. This means that gluons can interact with other gluons, forming complex “glueballs.” I will not be using glueballs in this essay, but they might play an important role in femtotech in the future?!

Strictly speaking, there are more than 3 color charges. In fact there are 6, namely red, blue, green, anti-red, anti-blue, and anti-green. A gluon (at least the type of gluon that I will use in this essay) has one of the first three, and one of the second three. So there are 6 such bi-colored gluons, a red, anti-blue; a red, anti-green; a blue, anti-red; a blue, anti-green; a green, anti-red; a green, anti-blue. In this essay I will use only the red, anti-blue and the blue, anti-red gluons, because (using Occam’s razor), they are all that I need.

4. Colors are Conserved in Quark-Gluon Reactions

How does a gluon interact with a quark? What happens? Remarkably, when a gluon and a quark interact, the gluon may change the quark's color, and in such a way, that the colors are conserved. For example, imagine a red, anti-blue gluon (which from now on will be abbreviated to Gr,~b) interacts with a blue colored quark (abbreviated from now on to Qb). The gluon will cause the quark to change its color from blue to red, i.e. in symbolic terms –

Gr,~b : Qb → Qr

In other words, the red, anti-blue gluon acts on the blue (color charged) quark, and converts it into a red (color charged) quark.

Note that before the interaction, there were 3 charges, a red, an anti-blue (both on the gluon), and a blue (on the quark). During the interaction, the anti-blue of the gluon and the blue of the quark, cancel, leaving only a red, which is now the color (charge) of the outgoing quark. The colors are conserved.

What would happen if a red, anti-blue gluon (Gr,~b) interacted with a red quark Qr? Nothing. Such an interaction is forbidden in nature, because the color charges in this case are not conserved (i.e. before the interaction, we have a red and an anti-blue charge on the gluon, and a red on the quark. If the quark absorbed the gluon and changed its color from red to blue, then the final charge would be just blue. But that doesn't match the "2 reds and 1 anti-blue charges" before the interaction. The colors are not conserved, so this interaction is QCD forbidden.

This color conservation operates with the *emission* of a gluon as well. For example, a red quark Qr could emit a red, anti-blue gluon (Gr,~b) and become a blue quark (Qb). This emission can be represented as

Qr → Qb + Gr,~b

Note that the colors are conserved. The blue and anti-blue cancel each other, leaving a red on both sides. Color conservation is one of the basic natural laws of QCD.

Now, a gluon that is emitted by one quark can be absorbed by another quark, rather like the way a photon can be emitted and absorbed by two electrically charged particles (which is the basis of the study of quantum electrodynamics, QED). By emitting and absorbing gluons, two quarks can interact with each other and influence each other. I will make heavy use of this phenomenon, as will soon become clear.

5. The "Aha Moment"

Probably some of you have already had an "aha moment" on how you might implement a femtotech based computing, based only on what I have said above.

Once I had read about the color charges and gluon emission and absorption, I had my “aha moment”. I felt I had found a way to compute at the femtometer scale, using quarks and gluons, at least in principle. For difficulties facing the practical engineering of these ideas, see towards the end of this essay.

The aha moment gave me the following basic ideas.

a) Represent a bit by the color of a quark. A red for 1, and a blue for 0. (I didn’t need to use green.)
b) To change the state (i.e. 1 to 0, or 0 to 1), change the color of the quark from red to blue, or vice versa.
c) To change the color of a quark, use an appropriately emitted gluon, i.e. one possessing the appropriate bi-coloring.
d) To implement logic gates (and this was the creative challenging part), use a sequence of gluon emission and absorption (of the same gluon).

6. Mapping the Gates to Quark-Gluon Interactions

Before I get into the specifics of the mappings, I need to introduce a fictional didactic device that I call a “quark chamber”, i.e. a region of space (perhaps as small as a nucleon), e.g. a sphere, in which a quark enters at one end, interacts (or fails to interact) and exits at the other end. Also entering or exiting the quark chamber is a gluon. In the case of gluon emission, the gluon exits the quark chamber. In the case of gluon absorption, the gluon enters the quark chamber and is absorbed within it.

NOT Gate

Fill the quark chamber with two gluons, i.e. a Gr,~b and a Gb,~r. If a red quark Qr enters the quark chamber, it will not interact with the Gr,~b gluon, but will be converted to a blue quark by absorption of a Gb,~r gluon, and will exit the quark chamber as a blue quark, according to the interaction

Gb,~r : Qr → Qb

An ipso facto interaction will occur for a blue quark entering the quark chamber, according to the interaction

Gr,~b : Qb → Qr

We thus have a NOT gate. A red quark is converted to a blue quark (1 to 0), and a blue quark is converted to a red quark (0 to 1). This is the definition of a NOT gate.

OR Gate

To implement an OR gate, is a bit more complicated. We need 2 quark chambers, A, B. Chamber A is a gluon generating chamber. If a red quark enters chamber A, a red, anti-blue gluon Gr,~b emission is caused in the chamber and the gluon then exits. (The resulting blue quark is ignored.)

If a blue quark enters chamber A, nothing happens. No gluon exits the chamber.

We now have 4 cases to consider –

a) ***red(1), red(2):*** (i.e. a red quark(1) enters chamber A, and a second red quark(2) enters chamber B). The red quark Qr(1) entering chamber A generates a Gr,~b gluon that enters chamber B. This gluon has no effect on the red Qr(2) entering chamber B at the same time. The red Qr(2) then passes out of chamber B unaffected. In other words, the output quark from chamber B is red. Hence if the inputs are red(1) and red(2) the output quark is red.

b) ***red(1), blue(2):*** The red quark Qr(1) entering chamber A generates a Gr,~b gluon that enters chamber B. The blue quark Qb(2) that enters chamber B is converted to a red quark Qr(2) that then exits chamber B. In other words, the output quark from chamber B is red. Hence if the inputs are red(1) and blue(2) the output quark is red.

c) ***blue(1), red(2):*** The blue quark Qb(1) entering chamber A generates NO gluon, so no gluon enters chamber B. The red quark Qr(2) that enters chamber B then exits unchanged. In other words, the output quark from chamber B is red. Hence if the inputs are blue(1) and red(2) the output quark is red.

d) ***blue(1), blue(2):*** The blue quark Qb(1) entering chamber A generates NO gluon, so no gluon enters chamber B. The blue quark Qb(2) that enters chamber B then exits chamber B unchanged. In other words, the output quark from chamber B is blue. Hence if the inputs are blue(1) and blue(2) the output quark is blue.

Thus the specifications of an OR gate are satisfied.

AND Gate

The AND gate is a bit more complicated still. It contains 3 chambers, A, B, C. Chambers A and B both output a red quark if the input is a red quark, and a blue, anti-red gluon Gb,~r if the input is a blue quark. This time, instead of dealing with single events, think in terms of a stream of input and output quarks. Chamber C has as input, the outputs of chambers A and B, as well as a fixed red quark Qr(3) input, for reasons that will soon become clear.

We again have 4 cases to consider –

a) red(1), red(2): (i.e. red quarks(1) enter chamber A, and red quarks(2) enter chamber B). The red quarks Qr(1) and Qr(2) pass unchanged into chamber C, along with the fixed red quarks Qr(3). There are only red quarks in chamber C, so only red quarks can exit chamber C. In other words, the output quarks from chamber C are red. Hence if the inputs are red(1) and red(2) the output quarks are red (now thinking in terms of streams of quarks).

b) red(1), blue(2): (i.e. red quarks(1) enter chamber A, and blue quarks(2) enter chamber B). The red quarks Qr(1) pass unchanged into chamber C, along with the fixed red quarks Qr(3). The blue quarks Qb(2) that enter chamber B generate blue, anti-red gluons Gb,~r which pass into chamber C. These gluons convert all the red quarks in chamber C to blue gluons, so that only blue quarks exit from chamber C. Hence if the inputs are red(1) and blue(2) the output quarks are blue.

c) blue(1), red(2): (i.e. blue quarks(1) enter chamber A, and red quarks(2) enter chamber B). The blue quarks Qb(1) that enter chamber A generate blue, anti-red gluons Gb,~r which pass into chamber C. The red quarks Qr(2) that enter chamber B pass unchanged into chamber C, along with the fixed red quarks Qr(3). These gluons convert all the red quarks in chamber C to blue gluons, so that only blue quarks exit from chamber C. Hence if the inputs are blue(1) and red(2) the output quarks are blue.

d) blue(1), blue(2): (i.e. blue quarks(1) enter chamber A, and blue quarks(2) enter chamber B). The blue quarks Qb(1) and Qb(2) both generate blue, anti-red gluons Gb,~r which pass into chamber C. These gluons convert the fixed red quarks entering chamber C to blue gluons, so that only blue quarks exit from chamber C. Hence if the inputs are blue(1) and blue(2) the output quarks are blue.

Thus the specifications of an AND gate are satisfied.

Now that all 3 gates have been mapped to quark-gluon interactions in QCD, one has an “in principle” recipe for femtometer scale computation.

7. Engineering Challenges

However the practical engineering problems remain, especially when considering something called “asymptotic freedom”, which says that quarks interact weakly when close together, but immensely strongly as they separate, rather like a tough rubber band being stretched. The more it is stretched, the greater the potential energy it has. Similarly with the 3 quarks inside a nucleon.

A nucleon is stable (in the nucleus) because it has 3 quarks, one is red, another blue, and the third green. These 3 colors “sum” to “white” (rather like a spinning color wheel of equally sized red, blue and green sectors), which is analogous to the way an atom, with its positively charged nucleus and its negatively charged electrons, sum to neutrality.

However, if one attempts to extract a quark from the nucleon, the gluons between the extracting quark and the other two quarks, behave in complex non linear ways, interacting with other gluons, to form a hugely powerful resistance, until the potential energy is so great that a quark, anti-quark pair can be formed, which combine to form a pion (pi meson). (Mesons consist of 2 quarks, i.e. a quark and its anti-quark.) Hence it seems impossible to isolate a quark (or a gluon). Experimentally, no quark or gluon has ever been isolated. Experimentalists have virtually given up trying.

Hence the implicit assumption in the above models, namely that isolated quarks and gluons are used, seems unphysical and unrealistic.

But, if the gluons and quarks are close together, the “stretching rubber band” phenomenon does not occur. There may be particles that contain more than 3 quarks, the so called “exotics”, which may have 3N quarks (i.e. a multiple of 3 to maintain color neutrality (“whiteness”) by summing an equal number of red, blue, and green color charges.)

There may also be “glueballs” that consist only of gluons that interact in highly non linear and hence complex ways.

Another possibility is to heat up the quark/gluon complex so much that one obtains a quark-gluon “plasma.” At a critical temperature, after cooling the plasma, quark-gluon “chains” may start forming, that may interact in ways similar to the way molecules interact within the cell, i.e. by complementary “lock and key” touching.

8. Conclusions

The above femtometer scale computation models are “in principle” only. To make them practical will probably require new thinking, to ensure that they are compatible with the severe constraints imposed by the principles of QCD, e.g. quark confinement and asymptotic freedom.

Hopefully, this essay will stimulate other researchers to enter this new research field of femtotech. Perhaps the “other side” of technology (i.e. the “building stuff” side, in contrast with the computational side) can be implemented with glueballs as well, or with quark/gluon “condensates.”

One thing is clear. If humanity does not make any progress along the lines of femtotech, sooner or later, human beings (or our artificially intelligent successors) will be scratching at the “nanotech walls” that confine us.

One final comment -- I’m thinking of trying to create an “attotech” (i.e. on the scale of 10^{-18} meters) by using the weak force particles (W and Z particles) that interact not only with quarks, but with the much lighter leptons (e.g. electrons, etc) as well.

Human technology has progressed from millitech, to microtech, to (recently) nanotech, and this essay attempts to start the thinking on femtotech (and attotech).

This downscaling trend provides a potential answer to the famous “Fermi paradox” (i.e. if intelligent life is so commonplace in the universe, “where are they?”). If intelligent creatures or machines can continue to “scale down” in their technologies, the answer to Fermi’s question would become “They are all around us, whole civilizations living inside elementary particles, too small for us to detect.”