Why color optical computing is efficient – especially for mobile computing – and how it is related to physics, to 7 ± 2 law, and to future of computing

Victor Timchenko[1], Yuriy P. Kondratenko[2],
Olga Kosheleva[3], and Vladik Kreinovich[3]
[1]Admiral Makarov National University of Shipbuilding, Ukraine,
vl.timchenko58@gmail.com
[2]Petro Mohyla Black Sea National University, Ukraine,
y_kondrat2002@yahoo.com
[3]University of Texas at El Paso, USA,
{olga,vladik}@utep.edu

Abstract

In several practical situations, it is effective to use color optical computing, where a signal is represented by a combination of basic colors. This technique does not require accurate maintenance of intensity and thus, require much fewer resources than other computational techniques. This makes it very appropriate for mobile devices, devices that need to operate with limited resources. However, it is somewhat surprising that this technique – that only uses a few features of the signal – is very empirically successful. In this paper, we provide a theoretical explanation for this empirical success, an explanation based on the general theoretical results about computational efficiency. This general explanation also helps to explain several difficult-to-explain features of human reasoning and of physics, such as seven plus minus two law and homogeneity of the Universe. The physics-related analysis bring us to back to color optical computing – namely, how its ideas can be used in computational devices of the distant future.

Keywords: Mobile devices, color optical computing, seven plus minus two law, homogeneity of the Universe, future of computing,

1 Problem: why is color optical computing efficient?

Empirical fact: color optical computing is efficient. One of the main ideas behind the technique known as *color optical computing* (see, e.g., [10, 11, 20, 21]) is representing data by colors, namely, by possible combinations of three basic colors: red, green, and blue. Somewhat surprisingly, this technique turned out to be very efficient in many applications.

Why is this success surprising? The success of color optical computing is surprising, since this technique looks very limited:

- it only used 3 colors and their combinations, and
- it is not using intensities at all, it only uses the presence or absence of the three basic colors in the corresponding color combination.

Limited-resources feature of color optical computing is especially important for mobile devices. Because of their limited nature, color optical computing requires much fewer resources – such as energy – than more traditional computational schemes. For example, for color optical computing, we do not need to accurate maintain the intensity level of a signal, no need to guarantee a certain intensity level of the transformed system when a transformation is needed, etc. This makes color optical computing very beneficial for mobile devices, since for them, resource limitations – such as power limitations – are crucial.

Resulting challenge: how can we explain the empirical success of color optical techniques? It is an empirical fact that, in spite of the limitations of the color optical computing technique, this technique is effective in many applications.

What we do in this paper. In this paper, we provide an explanation for the empirical success, an explanation based on the fundamental properties of computations. The idea behind ou explanation can also explain – at least on the qualitative level:

- difficult-to-explain psychological facts: e.g., that we perceive all colors as combinations of three basic colors, where the 7 plus minus two law comes from, etc.; and
- many difficult-to-explain physical facts: why protons and neurons consist of exactly three sub-particles (quarks), why most partiles have spin 1/2 or 1, why the Universe is homogeneous, etc.

2 General idea behind our explanations

Main idea. Most of our explanations are based on the known result by Donald Knuth (see, e.g., [9]) – that out of all base-n number systems, the base-3 number system is the most efficient, with the usual binary (base-2) number system the close second.

Comment. Strictly speaking, Knuth's result goes beyond the usual base-n number systems with integer n, it also deals witn number systems with non-integer n. In this case, the optimal number systems corresponds to $n = e = 1.71828\ldots$.

3 Our general idea explains why color computing is effective

Knuth's result explains why the color optical computing technique is effective: this techniques uses three basic colors and is, therefore, similar to using base-3 number system. It is, therefore more efficient than more traditional analog techniques that use continuum many basic states – corresponding to different colors and different intensity values – and thus, correspond to base-n number systems with large n.

4 Our general idea explains many difficult-to-explain psychological facts

From the biological viewpoint, we humans are close-to-optimal data processors. Our bodies and brains constantly process data:

- they process visual information from our eyes,
- they process audio information from our ears,
- they process tactile from touch,
- they process olfactory information coming from smells, etc.

We are also the result of billions of years of improving evolution, and most of these times our ancestors were processes this type of information – survival of the fittest would have eliminated all non-optimal data processing techniques. It is therefore reasonable to expect that the way we process this data is close to optimal.

Comment. While human ability to biologically process data may be close to optimal, our newer ability to process data – such as performing arithmetic operations and logical reasoning – is often far from optimal:

- it is well known – see, e.g., [7] – that humans systematically make logical mistakes in their reasoning;
- it is also known that the way we perform arithmetic operations is far from optimal: there are better ways to deal with negative numbersm better ways to multiply and divide numbers, better ways to sort data, better way to multiply matrices, etc.; see, e.g., [2] .

Knuth's result explains why we view colors as combinations of three basic colors. This result explains why instead of considering the 7 basis colors as the basis – which would correspond to base-7 number system – we perceive colors as combinations of three basis colors: read, green, and blue: this perception corresponds to the computationally most efficient base-3 number system.

Knuth's result explains the seven plus minus two law. It is an empirical fact that humans usually classify things into seven plus minus two groups; see, e.g., [15, 18]:

- Some people divide everything into $7 - 2 = 5$ groups.
- Some divide divide everything into $7 + 2 = 9$ groups.
- The largest number of people divide everything into exactly 7 groups.

If we use 2 digits of the base-3 system, we get exactly $3^2 = 9$ options. But, as we have mentioned, the most effective use of 2 digits is to use base-e systems, in which cases we have $e^2 \approx 7.4$ options. The closes integer to e^2 is 7, which explains why most people divide things into 7 categories.

Comment. The seven plus mins two law – that, as we have just shown, follows from Knuth's result – explains why in fuzzy techniques (see, e.g., [1, 8, 14, 16, 17, 22]), we usually divide the domain of each quantity into no more 7 subregions.

The fact that we usually use triangular membership functions that are described by three parameters is probably due directly to Knuth's result.

Why expert rules usually have no more than 3 conditions. Knuth's result also explains why rules formulated by experts usually have no more than three conditions; see, e.g., [6]. For example, an expert driver can say something like this:

- "If you are driving on a freeway at the speed of 100 km/h *and* the car in front of you is 10 meters ahead *and* it slows down to 95 km/h, then you should brake a little bit".

This rule is typical, and it has exactly 3 conditions.

However, experts very rarely describe their knowledge by using rules that have more than 3 conditions.

From human psychology to biology in general. Knuth's result also explains why organic molecules – molecules that form all living creatures – mostly contain three chemical element: carbon C, oxygen O, and hydrogen H.

5 The general idea explains many difficult-to-explain physical facts

How is all this related to physics? As we have mentioned, it makes sense to apply Knuth's results about optimal computations to biological data processing

– since billions of years of improving evolution has made such processing close to optimal. However, from a naive commonsense viewpoint, it is not clear how Knuth;s results can be applied to physics.

The possibility of such application comes from the fact – well known in physics – that laws of physics can be described in terms of optimization; see, e.g., [4, 19]. Namely, all physical laws – be it Newton's mechanics, Maxwell's equations describing electric and magnetic phenomena, Schrödinger's equations of quantum physics, Einstein's General Relativity Theory – can be described as minimizing the corresponding functional known as *action*.

To be more precise:

- In pre-quantum physics, the least action principle description was simply one of the possible alternative ways of representing a physical theory – another alternative was to use differential equations, as Newton, Maxwell, and others originally did.

- However, in quantum physics, action S is the main way to describe a general quantum theory. Namely, in its most universal *Feynman integral* formulation of quantum physics: the probability of getting from state A to state B is equal to the square of the absolute value $|\psi|^2$ of the amplitude ψ, and the amplitude is equal to the integral of the expression $\exp(\mathrm{i} \cdot S/\hbar)$ over all possible trajectories leading from A to B. (Here, $\mathrm{i} \stackrel{\text{def}}{=} \sqrt{-1}$, and $\hbar$ is Planck's constant – the fundamental constant of quantum physics.)

In the pre-quantum approximation, this means that the Universe selects the trajectory that minimizes the action S. This means that, in effect, the Universe kind of computes the minimum of action S.

In physics, the most efficient systems survive – so what we observe are systems that perform this minimization most efficiently. Since, as Knuth has shown, the most efficient computations are the ones that use base-3 representations, we thus expect to find base-3 structure in many observed physical phenomena – so that Knuth's optimality result can explain the appearance of 3 in these empirical phenomena.

Let us list some physical phenomena that can be thus explained – at least on the qualitative level.

Why most matter consists of three basic particles: n, p, and e$^-$. This may explain why most of the matter consists of three basic particles: proton p, neutron n, and electron e$^-$. Of these three, protons and electrons are absolutely stable, while neutrons can transforms, by themselves, into three particles: proton, electron, and an antineurtino:

$$\mathrm{n} \to \mathrm{p} + \mathrm{e}_i + \overline{\nu}.$$

Note that again, we have three components – three products of this reaction.

Why protons and neutrons consist of three quarks. The above general idea explains why each stable baryon – i.e., a proton or a neutron – consists of exactly 3 quarks. Actually, there are particles that consist of 4 quarks, but they are very unstable.

Why all stable particles have spin 1/2 or 1. In order to explain this empirical fact, let us recall what is a spin and what values it can take. Crudely speaking, the spin in the angular moment of a particle. According to quantum physics, particle's spin can only take certain values. Possible values depend on the quantum statistics describing the particle: some are *fermions*, while others are *bosons*.

- for fermions, the spin can only have non-negative half-integer values: 1/2, 3/2, 5/2, etc.
- for bosons, the spin can only have non-negative integer values: 0, 1, 2, etc.

For a partical with spin s, for each axis, the angular momentum corresponding to this axis can take one of the values

$$-s, -s+1, \ldots, s-1, s.$$

This means that bosons with spin s can have $2s+1$ different values of this angular momentum, while fermions with spin $n+1/2$ can have $2n+2$ different values.

Different values of the axis-related angular momentum correspond to different states of the particle. In line with our general reasoning, ideally, there should be 3 different states, i.e., three different values of the angular momentum. For bosons, this is possible when $2s+2=3$, i.e., when $s=1$. This explains the appearance of particles of spin 1.

For fermions, the number of different states is even, so it cannot be equal to 3. Thus, in line with Knuth's results, we should take the closest-to-optimal even value, which is 2. So, we should have $2n+2=2$, thus $n=0$, and the spin is equal to $s=n+1/2=1/2$. This explains the ubiquity of particles with spin 1/2.

Together with the results about bosons, it explains why we usually encounter only particles of spins 1/2 and 1, while theoretically, many other spins are possible – and some very unstable particles do have a different spin.

Maybe this explains why physical space is 3-dimensional. This may also explain why the physical space is 3-dimensional.

6 Physical implications beyond Knuth's idea

Some consequences of the idea that the Universe is optimally designed to perform complex computations go beyond Knuth's base-3 idea. Let us list some of these consequences.

Why equations of quantum physics are linear. This may not be a well known fact outside physics – and it may sound implausible to non-physicists who know how nonlinear our world is – but this is nevertheless true: the equations of quantum physics are linear. To be more precise, there are two types of changes of a quantum system:

- there are continuous changes described by Schrödinger's equation, the main equation of quantum physics – which is indeed linear – and
- there are discontinuous non-linear changes known as *measurements* (since actual measurements are particular case of such changes).

This sounds like one of the difficult-to-explain facts of life, but it can be easily explained from the computational viewpoint. Indeed, according to theoretical analysis (see, e.g., [12]), the fastest way to perform general computations is to use neural networks, i.e., in effect, to intertwine:

- linear transformations – that correspond to forming a linear combination

  $$x = w_1 \cdot x_1 + \ldots + w_n \cdot x_n + w_0$$

  of the inputs $x_1, \ldots, x_n$, and
- simple nonlinear transformations $y = s(x)$, where $s(x)$ is the so-called *activation function* (which is $s(x) = \max(0, x)$ for deep neural networks; see, e.g., [5]).

Why the Universe is homogeneous. The most efficient way to compute is, of course, to have many processors work in parallel. For a parallel computation to be the most efficient, it is important to make sure that all the processors are equally busy, that none of the computing areas is idle – in other words, to make sure that the tasks are distributed uniformly, and the resulting system is homogeneously busy. In application to the Universe, where computations are – kind of – performed by all the particles in parallel, this provides an additional explanation for a difficult-to-explain large-scale homogeneity of the Universe.

7 How is this related to future of computing?

We need faster computations. While modern computers are very fast, there are still many practical problems for which this computational speed is not sufficient. Let us give a few examples:

- Tornados bring a lot of destruction. It is difficult to predict their trajectory, so when a tornado appears, a warning is sent to a wide geographic area. In a tornado season, such warnings appear almost every day. People cannot follow all these warning, they need to work, to study etc, – so when a tornado hits an area, and people are not in shelters, people get hurt. At first glance, this should not be a problem, After all, tornados are atmospheric phenomena just like rains, winds, and hurricanes. We know the equations that describe these phenomena, and we are successfuly using these equations to reasonable accurately predict tomorrow's weather and the future path of a hurricane. It is indeed possible to use the same equation to predict the tornado's path, but since tornados change much faster than other atmospheric processes, these predictions take much longer – so much longer that on the best modern computers, the results become available only a few days after the tornado actually moved.

- With modern computers, it is, in principle, possible to predict how a virus will interact with a given chemical compound – and thus, decide whether this particular has a promise as a medicine against the viral infection. Ideally, we should be able to use this ability to test many possible compounds and thus find a possible cure for the corresponding viral disease. However, on current computers, within a reasonable time, we can only test a few compounds.

There are many such examples – examples explaining why computer engineers design more and more powerful supercomputers.

How can we make computations faster? There are, of course, engineering challenges that need to be overcome to make computers faster, For example, a big problem is heat: computers generate a lot of heat, and the need to cool them down prevents us from combining too many computational devices together. But already now, one of the main challenges is related to fundamental physics: namely, it is the fact thatl according to Special Relativity Theory, no physical process can be faster than the speed of light c. Let us explain how the speed-of-light restriction affects computation speed.

The linear size of a usual laptop is about 30 cm. The fastest we can send a signal from one side of the laptop to another is when we send the signal with the speed of light, which is 300 000 km/sec. If we divide 30 cm by the speed of light, we get 10^{-9} seconds – i.e., 1 nanosecond. During this time, a usual 4 Gigahertz laptop – that performs $4 \cdot 10^9$ operations per second – will have already performed 4 arithmetic operations. To make computations mush faster, we therefore need to make computational devices much smaller – which means all the memory cells, all the processing units must be made much smaller.

How can we shrink computational devices – all the way to the quark level. Already each cell contains only thousands of molecules. If we shrink them even more, we get:

- first to the level of individual molecules,
- then to the level of individual atoms, and
- then to the level of elementary particles.

Once we reach the level of protons and neutrons, the next step is to go to the level of their sub-particles – quarks. We have previously discussed that at the quark level, we will be able to use color optical computing ideas; see, e.g., [13].

But can we go beyond the quark level? But why stop at quarks – maybe there are sub-quark particles?

To analyze this question, we can use results from mathematical ecology, results that are in full accordance with Knuth's ideas – that only at most 3-4 level natural hierarchical systems are stable; see, e.g., [3].

In micro-physics, we already have molecule-atom-particle-quark hierarchy, with the 4th level already kind of unreal – in contrast to other levels of the hierarchy, quarks are not independent objects, they cannot be separated from each other.

This means that there are most probably no sub-quarks, so we need to concentrate of quark-based computing.

Comment. In effect, what we are saying in this section is that we need faster computations, and nature obligingly provides us with a potential to perform them. To a physicist reader, this conclusion may look similar to the so-called *anthropic principle*, according to which the Universe is favorable to us humans – all the physical constants are such that life becomes possible, while even small deviatons from these constants would have made it impossible. The conclusions are indeed similar, but the explanation for this perceived favoritism are different:

- The usual explanation of the anthropic principle is that actually there are many different universes with different values of the physical constants. In other universes, where the constants are different from ours, no life is possible. In a small number if universes – like ours – the randomly selected physical constants happen to be such that life becomes possible. After all, if we flip the coin many times, we will eventually see it falling head 10 or more times in a row. From this viewpoint, what looks like Universe's favor for us is actually natural – the fact that we exist means that are in such a universe where our existence is possible.

- Our explanation also does not imply any special favor from the Universe, but it is different from the anthropic one. Our explanation is based on the fact that, according to modern physics, physical laws are described in terms of minimizing a complex functional called *action*. From this viewpoint, all the dynamical changes in particles and fields, in effect, compute this minimum – and so the universe is designed in such a way that such a complex computation becomes possible. So, when we need to compute something, we can use the fact that the Universe is designed to be good for computing.

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