Reinventing Electronics with Cellular Automata

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This paper describes an exploration into what can be done with cellular automata to reinvent and re-engineer electronics in a new kind of physics implemented as a system of cellular automaton rules. An engineering approach is used, working forward to achieve a practical goal while introducing tools. The practical goal is to start from an electron level and obtain a working resistor-capacitor (RC) phase shift oscillator. This goal is achieved, and the oscillator is demonstrated. The paper tells the story of this adventure, including the experiences of failures, retries, work-arounds, and success.

1. Project Goals

The goal I set in this project is to explore the expressive power of cellular automata as an alternative basis for electrical engineering. This goal is primarily set as an intellectual challenge, although in the long term it may even have practical applications; for example, to design electrical and electronic equipment in cyberspaces such as Second Life. As an intellectual challenge the idea is to start from Wolfram's claims concerning fundamental physics. In his book *A New Kind of Science* (NKS), [1, p. 433], the findings of Chapter 9 are summarized by: "remarkably simple programs are often able to capture the essence of what is going on". Since traditional electrical engineering is clearly based on physics, it is worth a try to see whether the essence of what is going on in electrical engineering can be rediscovered in the behavior of simple programs.

Although electrical engineering and electronics are based on physics, many situations arise in which one need not go back to the level of fundamental physics. Instead of analyzing the flow of electrons, it suffices to calculate voltages and currents. Most often, one needs not use Maxwell's equations at all. Instead, by following the tradition of electrical network theory, one assumes a discrete spatial structure such that electricity flows through perfectly conducting wires, shielded by perfectly nonconducting isolators. In the end, Kirchhoff's laws, Ohm's law, the numbers printed on components such as resistors and capacitors, and the graphs and numbers provided by the manufacturers of transistors are all that remains. People at the intersection of science and engineering such as Ohm, Kirchhoff, Heaviside, Kennelly, Steinmetz, Tellegen, and others have created a kind of axiomatic basis. This basis enables one to perform technological design and verification work. This is the level of concepts I want to explore with cellular automata. Transistors work because of quantum mechanics, but I shall bypass the mathematical models of quantum mechanics, atom structure, tunnel effect, and Schrödinger's equation, and instead look for NKS-style phenomena from which I can make something worth being called a transistor. For an interesting discussion on the paradigm differences between engineering and science, I refer to the editorial by Brittain [2] and the presentation by Rauterberg [3].

The challenge I set is to be taken as an engineering challenge: the selected phenomena arising in the cellular automata have to be tamed and channeled in practical ways. I chose a specific well-known type of circuit, the resistor-capacitor (RC) phase shift oscillator, as a benchmark. I assume that if this can be done, other and more complex circuits are within reach too.

2. Electronics

Electronics is a branch of engineering that is distinguished from the more general field of electrical engineering by the inclusion of active components, such as electron tubes and transistors, and by the exclusion of mechanical devices, such as motors and relays. For many applications the partial differential equations of the electric fields and charges do not need to be considered. Instead, one models the system under consideration as a graph where the edges correspond to components and vertices correspond to the points where components are joined by wires. Kirchhoff's laws state that the sum of the currents flowing toward a junction is zero and that the sum of all voltages around a closed loop equals zero (taking certain sign conventions into account). Typical components are resistors and capacitors, described by linear equations. For resistors this linearity is known as Ohm's law, $I = V/R$. In the period 1886-1911 Heaviside, Kennelly, and Steinmetz found and taught the method of coping with capacitors in the same way as resistors, using complex numbers [4]. Circuit behavior is described using the terminology of voltages and currents, abstracting away from the electrons, the fields, and the material properties. The formal concepts are voltage with symbol V and current with symbol I. The units are volt (symbol V) and ampere (symbol A), respectively.

The theory also allows for three-poles, or n-poles, leading to the elegant network theory which found its completion in the work of Tellegen in the 1940s and 50s. In complete accordance with this, the most important tools found in every workshop are a voltmeter, an amperemeter, and an adjustable voltage source.

The active components can amplify voltages or currents. These components are three-poles (e.g., triodes, transistors, or field effect transistors), sometimes four- or five-poles (e.g., tetrodes, pentodes, or multigate field effect transistors). The free electron dynamical or quantum mechanical internal working is abstracted away into characteristics such as the slope

$$S = \frac{d\, I_{\text{plate}}}{d\, V_{\text{grid}}} \tag{1}$$

or the current gain

$$\beta = \frac{d\, I_{\text{collector}}}{d\, I_{\text{basis}}}. \tag{2}$$

In datasheets these numbers are complemented by graphs to capture the nonlinear aspects. As an example of a complete and useful circuit we present a phase shift oscillator in Figure 1. This is a practical implementation; see, for example, [5]. The amplifiers used here are 4049 complementary metal oxide semiconductor (CMOS) inverting buffers, but similar designs can be made using any active device, such as electron tubes, transistors, or field effect transistors. Each amplifier is a four-pole component.

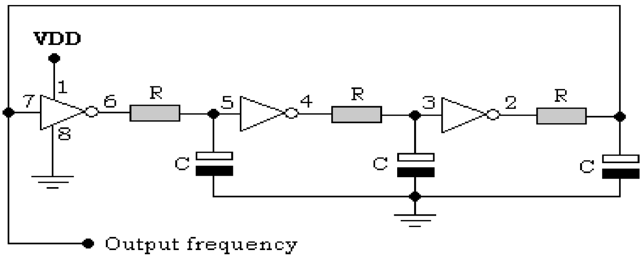


Figure 1. Phase shift oscillator. Each RC section gives a phase shift of 60°. It is the main goal of this paper to create such an oscillator in a new NKS-style of electronics.

The circuit of Figure 1 is analyzed as follows. Each RC section constitutes a voltage divider. Let Z_C be the impedance of each capacitor C, then each section has a transfer function $V_{\text{out}} / V_{\text{in}} = Z_C / (R + Z_C)$. Taking $Z_C = 1 / i\,\omega\, C$ and noting that there are three RC sections, the combined transfer function is $1 / (1 + i\,\omega\, R\, C)^3$. At one specific frequency this gives a phase shift of 180°. This frequency turns out to be

$$f = \frac{\sqrt{3}}{2\pi} \cdot \frac{1}{R\,C}. \tag{3}$$

If each amplifier causes a phase shift of 180°, this is the oscillation frequency. Oscillation occurs at this frequency if the total amplifier gain in the loop compensates for the amplitude loss by the RC sections (i.e., the Barkhausen criterion). The total gain is thus eight times, so each amplifier has to amplify two times or more.

This circuit is set as my goal, my benchmark for the exploration of cellular automata as an alternative basis for electrical engineering. Please note the absence of electrons, fields, and so forth in the analysis; this absence is not a weakness of the approach. From an engineering viewpoint, it is a strength. It allows an efficient way of working that did not come by itself, but only through the efforts of people such as Kirchhoff, Heaviside, Tellegen, and others to create a new level of abstraction. The industry completed the situation by developing standardized components and tools whose behavior can be understood at the same abstraction level.

3. Electronics in *A New Kind of Science*

The first challenge is to find a cellular automaton in which the idea of voltage (a kind of level) and the idea of current (a kind of flow) are present. After that, the second challenge is to apply an engineering approach (by which I mean constructing components and building tools, as well as assembling working circuits) which can be understood at the new abstraction level.

So I had to look for a suitable cellular automaton. Naturally, I began with a two-dimensional automaton on a regular grid, the color of each cell being updated according to its own value and the four neighbors left, right, above, and below. Occasionally I did the most fundamental experiments with one-dimensional versions of the same automaton. But it was clear to me from the very beginning that one dimension would not be enough to recreate the well-known circuits. Closed loops in circuits and junctions with more than two wires are essentially two-dimensional concepts. Two dimensions seem to fit well with the fact that circuits are usually represented by two-dimensional drawings (with some crossings). For the crossings, I relied on my personal observation that many interesting circuits are essentially planar, and those that have nonremovable crossings only have a few. Three dimensions were potentially useful, but I was afraid of the computational needs for running the automaton. So, balancing risks I chose two dimensions. Following Wolfram, cells are arranged circularly, which in two dimensions means a torus topology. This offers as a trick one crossing for free since things can be connected looping around the torus. It is fun to think of the torus as a Pacman game field; the Pacman can leave at the right edge and walk back in from the left, whereas at the same time an opponent ghost leaves at the top and walks back in from the bottom, yet the Pacman and the ghost do not meet.

The first approach using normal cellular automata was unsuccessful. Yet it is illustrative to show the difficulties encountered. Then I turned to block cellular automata, which work better. The next two sections are devoted to these approaches.

Note that I do not speak of simulations. If I wanted to simulate existing electronics, I would use existing tools such as computer-aided design (CAD) packages and symbolic calculations. This is about creating something new, so I use terms such as “running the automaton” or “putting a circuit into operation”.

3.1 Cellular Automaton Approach

The color of each cell is a nonnegative real number, representing a kind of voltage. Three specific numbers work as escape values: 0 for isolation, 0.5 for ground, and 9.5 for V_{cc}, the positive voltage of the power supply (in the real circuits made by me and my students, 9 V is an often-used value for batteries and power supplies). Charge is then represented by the sum of the voltages of the cells in a specified region. In order to preserve charge it is necessary to make sure that the voltage increase of one cell corresponds to the total decrease of voltages in its neighbors. In one dimension, an automaton is defined by an update function $f[e\_]$ which calculates the new color from an environment $e = \{b, c, d\}$ where b is the old value for the cell itself. An update rule that does this is the function that yields the update value $(b + d)/2$. Plotting the behavior soon reveals that this is more like a diffusion process, quite unlike normal electron behavior, but I pushed forward nevertheless. In two dimensions, assuming the environment e to be given as

$$e = \left[\begin{array}{ccc} & a & \\ b & c & d \\ & e & \end{array}\right], \tag{4}$$

the update value is $(a + b + d + e)/4$. This is not the only possibility; it is also possible to keep a larger part of the central cell’s own voltage c but then the exchange factor of $1/4$ becomes even less, making the diffusion process even slower. The function also has special clauses to intercept the escape values and treat them properly (e.g., if $c = \text{Gnd}$ then the cell stays grounded and similarly for V_{cc}). Isolation needs a change of the update function as follows: if N denotes the number of nonzero cells among a, b, d, and e, then the update value is $(a + b + N.c + d + e)/4$.

Circuit layouts are prepared as a monochrome bitmap (BMP) file using Mircosoft Paint. *Mathematica* 5.2 reads the file, adds a ground at a fixed position near the upper-left corner, and a V_{cc} near the lower-right corner, and runs the automaton. Figure 2 shows an example. It consists of three pictures: the gray scales of voltages from ground to V_{cc} in steps of 1 (Figure 2(b), top), an example circuit of 24×24 cells, with the ground, V_{cc}, and all other nonisolating cells initialized at 5 (Figure 2(a)). The circuit can be interpreted as two resistors in series. Figure 2(b) shows the result after 7000 steps. This result is satisfactory in the sense that the voltage divider formed by the two resistors seems to work, and the value at the junction is $(\text{Gnd} + V_{cc})/2$, as expected.

(a) (b)

Figure 2. Circuit layout, prepared as a monochrome BMP file using Mircosoft Paint. (a) A circuit of 24×24 cells, with ground and $V_{cc} = 9$. All other nonisolating cells are initialized at 5. The circuit can be interpreted as two resistors in series. (b) The result after 7000 steps. Above are the gray scales of voltages from ground to V_{cc} in steps of one.

Pleased with the result so far I turned to capacitors. A capacitor consists of two areas separated by isolation. A typical isolator would be a vertical line of isolation with a width of one cell. The first layer of cells to the left forms one plate, and the first layer of cells to the right forms the other plate.

The first idea is to make a rule in such a way that charge at one plate, the right plate say, sticks to the capacitor if there is a considerable voltage difference over the isolator, and moves away to the right otherwise. Consider an environment $\{b_3, b_2, b_1, c, d_1, d_2, d_3\}$ where b_3 is a cell inside the left plate, $b_2 = 0$ is an isolator cell, and b_1 is a cell in the right plate. Let c be the cell whose update is under consideration. Then a large Δvoltage would imply a small increase in c (and a corresponding decrease in b_1) whereas a small Δvoltage would imply a normal increase in c, for example, using the factor of $1/4$. Since similar phenomena could happen to the right of cell c, I assume that this approach leads to environments having a width of at least seven, and a height of at least seven (see Figure 3). These large environments seem inelegant and computationally unattractive.

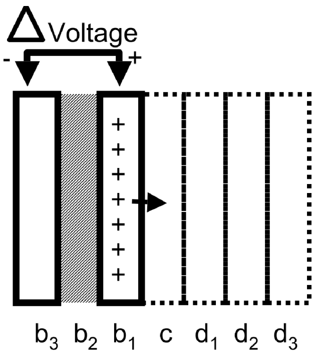


Figure 3. Tentative rule for a capacitor in one dimension. Cell c is under consideration for update. A large Δvoltage implies a small increase in c and a corresponding decrease in b_1. A small Δvoltage gives a normal increase in c, for example, using the factor of $1/4$. This type of rule is rejected because it leads to large environments.

At this point I gave up and searched for another idea to get a working capacitor. In a real capacitor with nonvacuum isolation, dielectric effects can happen in the isolator: dipoles in the material align with the effect of causing a charge shift. Energy is stored in the isolator material itself.

This inspired me for the next idea. Isolating cells get a nonpositive number, not just zero. This value is interpreted as a "dielectric effect". When the isolating cell is between a low voltage at its left and a high voltage at its right, the absolute value of this cell's dielectric effect is increased. Conversely, when between more or less equal voltages, it converts some of its dielectric effect into an increased voltage difference for the plates. One disadvantage is that the capacitors only work in one direction, but that is acceptable. After all, real capacitors are usually of the so-called electrolytic type, and their plates are thus tagged as "plus" and "minus" (when used wrongly, some of them even explode). The results are worse when running the automaton on my test circuits. In the following circuit, I would turn off the power supply after a while, so the capacitor would be discharged. Then I observed the discharging process via the resistor (the zigzag structure on the left in Figure 4).

Depending on the constants chosen, either there were no interesting discharging effects at all, or the system turned unstable. This is what happens once the capacitor is charged: the dielectric effect of the isolator provides extra voltage difference, which at its turn loads the capacitor's isolator with extra dielectric effect, and so on. It took me a while to find out and I had to go back to the one-dimensional case in order get a clear view. I gave up (again).

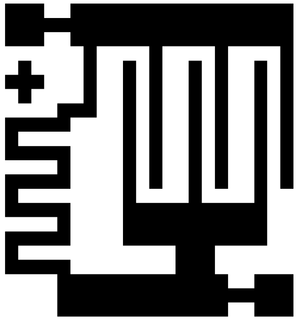


Figure 4. Experimental capacitor for the second attempt, based on dielectric-inspired rules. This type of rule is rejected because the behavior of the rule is not stable.

3.2 Block Cellular Automaton Approach

Preservation of electric charge is not the only preservation law in nature, so I figured out that Wolfram, when making his claims and even the hypothesis that there lies a very simple program from which all the known laws—and ultimately all the complexity we see in the universe—emerges, must have thought of this problem long before. Indeed, in [1] on page 458, he admits that most cellular automata are not fit for preserving quantities. But block cellular automata do this in a very natural way. Using BCAStep from [1], the initial one-dimensional experiment was promising; see Figure 5, which used the basic rule $\{\{0, 1\} \to \{1, 0\}, \{1, 0\} \to \{0, 1\}\}$.

The leftmost and rightmost positions (dark blue) are isolation (value 0.5). The example shows the red things (value 1) travel rightward while others travel leftward. Preservation is built in to the rules used, although nonpreserving rules can be written as well. At the isolation near the left and right edges, things bump back again.

The "things" made me think of electrons, protons, ions, or other electric charge carriers moving through empty space or through a conductor. Let us call them just "trons". It is up to me whether to use them as positive or negative carriers. For the two-dimensional version of BCAStep, one horizontal step applied to the entire field is followed by one vertical step, again for the entire field, just reusing the one-dimensional solution twice. It is amusing to see the trons run around in a playful circuit as in Figure 6. The light-blue areas are called "free space", or "conductor". The dark-blue areas are called "walls" or "isolation".

I adopted the following rule called "basic":

$$\begin{aligned} &\{0, 1\} \to \{1, 0\} \\ &\{1, 0\} \to \{0, 1\}. \end{aligned} \tag{5}$$

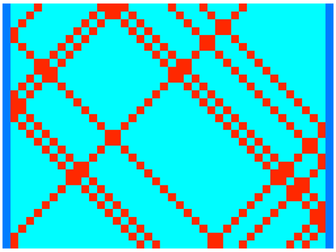


Figure 5. Development of a one-dimensional cellular automaton whose behavior is based on preservation. The conducting areas are light blue and isolating areas are dark blue.

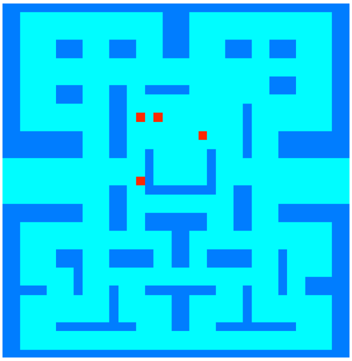


Figure 6. Trons (red) running in a playful circuit with conducting areas (light blue) and isolating areas (dark blue).

The trons are always on the move, each tron following a diagonal track with fixed speed (there are four such diagonal directions). They bump against the walls, apparently following the law that the angle of reflection is equal to the angle of incidence, and they disturb each other's trajectory when they meet. In the implementation, the basic rule is interleaved with another rule (to be explained later). The ratio is 1:6, so in every seven steps, one of them is a basic step. Usually the other rule hardly causes any movement, so the typical tron speed is $1/7$ cell per step (to the right, to the left, up, down, or in a diagonal direction). I write c for this constant, which makes me think of the speed of light. So $c = 1/7$.

4. Tools

4.1 Voltmeter

In this tron world it does not make sense to ask for the voltage at a given position, because this would be either zero or one, not a number from a continuous range as would be expected from a voltmeter.

Moreover, this one bit of information fluctuates at every step. Therefore the concept of voltage has to be developed as a statistical concept. But if we define a certain area of free space to be the area of interest, and moreover we define a certain area of time, we can calculate the average number of trons per cell. This is called voltage and, *par abus de language*, the unit volt means trons per cell.

Quite arbitrarily the color yellow is assigned the role of indicating the voltmeter area. The bitmap reader function in *Mathematica* is adapted such that it stores the area definition in a separate variable and after that turns all yellow positions into 0, that is, into free space. During execution, the voltmeter plays no role, but after execution, the evolved list of circuits is processed to find the averaged voltage as a function of time.

The example of Figure 7 shows how a simple 24×24 circuit is created in Microsoft Paint. The red space contains 100 trons. Then, when this is running in *Mathematica*, the block will fall apart and the trons run in all directions. After a while they divide evenly over the two main free spaces, but this takes a while because of the narrow conductor between the two spaces. During 3000 steps, the voltage in the voltmeter area increases. The voltmeter area is yellow (the right area). The voltage is as shown in the plot of Figure 8 (each dot is the average over 60 evolved circuits). The average voltage goes to 0.25 V (although there is "noise"). The 0.25 is not too far from the theoretical expectation of $100/320 = 0.31$, based on the fact that the total free space in this circuit is 320 cells.

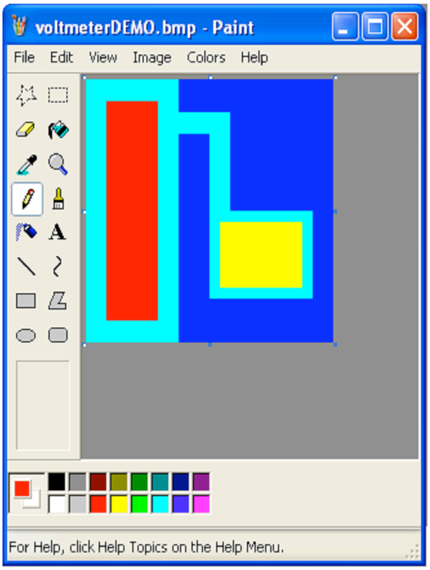


Figure 7. Circuit layout, prepared as a 16 color BMP file using Mircosoft Paint.

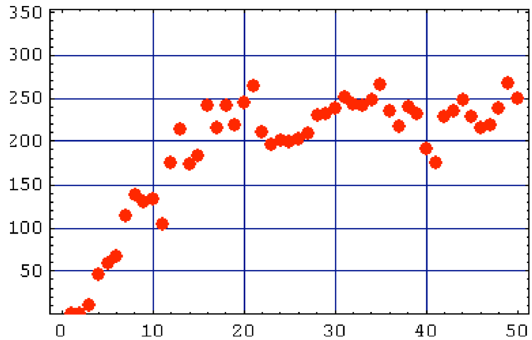


Figure 8. Using the voltmeter to see the voltage growth in the rightmost cavity of the circuit prepared in Figure 7 (the left cavity has 100 trons initially, the right cavity none). The average voltage goes to 0.25 V, although there is noise.

4.2 Amperemeter

Current is measured in trons per step, *par abus de language* called ampere. An amperemeter can be inserted as a rectangular brown segment in a pipe, by which I mean between two horizontal walls. It works like free space, but an instrumented version of BCAStep increments (decrements) a counter whenever a tron in a brown cell moves rightward (leftward). What currents can be expected in practice? If all cells in the amperemeter would contain a rightward moving tron, a conducting pipe of one cell height would convey one tron per c steps, that is, the current is $1/c$ A. In practice, the trons, while entering and being in the pipe, seem to hinder each other, effectively leading to one tron per four cells. So the maximal current is at most $1/(4\,c) = 35$ mA. In a wider pipe higher currents can occur.

4.3 Voltage Source

Two more colors are used to insert positive and ground voltage sources: a white cell will be refueled with trons on a regular basis, and a black cell will be emptied. This is done by a suitable modification of BCAStep. In Figure 9 an example input bitmap is shown with two resistor-like pipes put in series (recall that the right and left sides are connected). The white area acts as a 1 V source and the black area as a 0 V ground. Voltage is measured in the yellow area. The two smaller pictures show the circuit during its operational phase. Left is the initial state, right is a state after 3000 steps. At that time the voltage measured is 0.485 V (not too far from the 0.5 V expected for a volt age divider with two equal resistors). No tools are needed to know that the area around the source is at 1 V and the area around the ground is near 0 V.

Although I did no exhaustive set of experiments, a few tests showed that usually the current increases more or less monotonically with the voltage, and except at high voltages the relation seemed not too far off from linear.

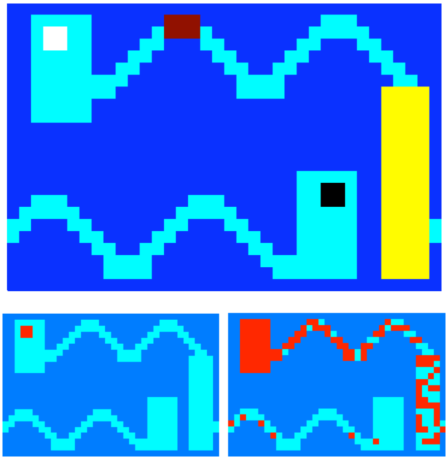


Figure 9. Using the voltage source to feed two resistor-like pipes put in series (recall that the right and left sides are connected). The white area acts as a 1 V source and the black area as a 0 V ground. Voltage is measured in the yellow area. The two smaller pictures below show the circuit during its operational phase. Left is the initial state; right is a state after 3000 steps.

5. Phase Shift Oscillator

First we need capacitors. A capacitor is a two-pole component modeled as $I = C\,dV/dt$. In words: the voltage increases by the current and the rate is determined by a constant factor, known as the capacity of the capacitor, expressed in Farad. In real physics this is achieved by having two conducting plates that are separated by an isolating wall. The electrons at one plate are attracted by the absence of negative charge carriers at the other plate (when there is a voltage difference) and repelled (otherwise).

Focusing on the behavior near a thin wall, and after a lot of experimentation, I added the following rule called "iso". Here two of the four clauses are shown; the other two are symmetric (x means isolation, 0.5):

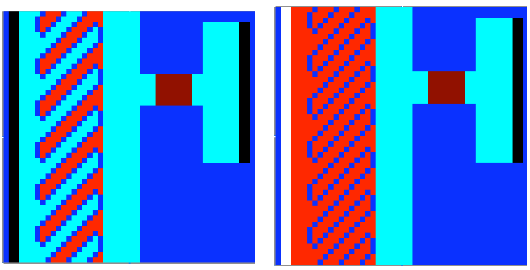
$$\begin{aligned} &\{1, x, 1, 0\} \to \{1, x, 0, 1\} \\ &\{0, x, 0, 1\} \to \{0, x, 1, 0\}. \end{aligned} \tag{6}$$

For the rule to have some noticeable effect, I found it necessary to give this rule high priority (otherwise the trons escape from the capacitor because the basic rule moves them outside reach of the iso rule). That is why basic runs at a lower frequency than iso. The factor of 7 is somewhat arbitrary (probably 5 works too). The rule basic is adapted for the new block size:

$$\begin{aligned}
&\{y, z, 0, 1\} \to \{y, z, 0, 1\}\\
&\{y, z, 1, 0\} \to \{y, z, 0, 1\}\\
&\{1, 0, y, z\} \to \{0, 1, y, z\}\\
&\{1, 0, y, z\} \to \{0, 1, y, z\}.
\end{aligned} \tag{7}$$

Although in real physics the Coulomb force also works at long distances, here the distance is limited by the block size four. For efficiency reasons I prefer not to extend the block size.

The two circuits in Figure 10 show the bitmaps for the same capacitor, but for two different initial states. In both states the right plate is at 1 V. The charge from the right plate can move through the amperemeter toward a grounded pole. The difference is that, in Figure 10(a), the left plate is at a fixed level of 0 V, whereas it is fixed at 1 V in Figure 10(b).



(a) (b)

Figure 10. Experimental capacitor in two different initial states. The charge from the right plate can move through the amperemeter toward a grounded pole. (a) The left plate is at a fixed level of 0 V, whereas in (b) it is fixed at 1 V.

The interesting question is what happens in each case. The capacitor in the first case will discharge somewhat, but even after many steps it keeps most of the charge on the right-hand side plate (lower plot in Figure 11, blue diamonds). For the capacitor in the second case, all trons will leave the right-hand side plate (middle plot, red squares). The total initial charge on the plate was 228 trons in both cases (horizontal plot, yellow triangles). Despite all the efforts, this is a miserable capacitor, but partly this is a consequence of the decision to work in two dimensions. In three dimensions, the area of the plates could grow quadratically when scaled, whereas the length of the feeding wires only grows linearly. In three dimensions, plates could really be stacked.

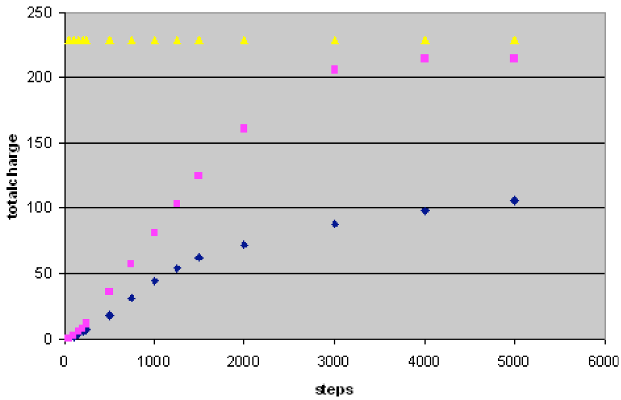


Figure 11. Charge dynamics of the capacitor of Figure 10. Lower plot, blue, diamonds: the capacitor in Figure 10(a). Middle plot, red, squares: the capacitor in Figure 10(b). Upper plot, yellow, triangles: initial charge level.

Another type of capacitor is easier, but it is not exactly a two-pole. It works like a capacitor with one plate connected to a common ground, the other plate being free. An example is given in the 28×16 circuit bitmap of Figure 12: The yellow area of $15 \times 5 = 75$ cells is the capacitor. The bitmap corresponds to the simple electric circuit of Figure 13. The voltage in the capacitor increases as shown in the plot of Figure 14, where the vertical axis is in millivolts (mV) and the horizontal axis in units of 100 steps (so total execution time is 5000 steps).

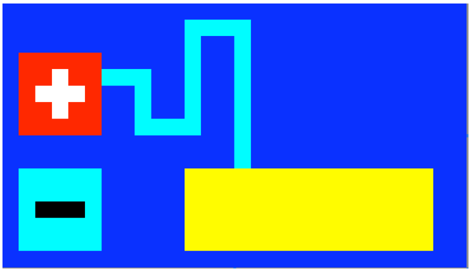


Figure 12. One-pole experimental capacitor formed by the right cavity. It is charged from the positive pole at the left (the white + sign). The cavity contains a voltmeter (color yellow).

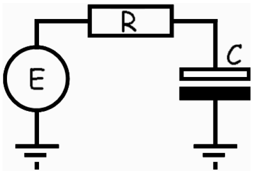


Figure 13. Electric diagram of the one-pole capacitor circuit of Figure 12.

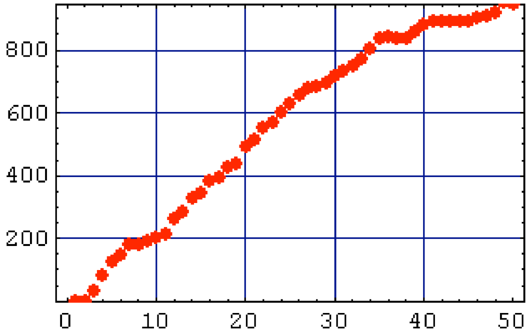


Figure 14. Charging the one-pole capacitor of Figure 12. The vertical level of 1000 mV means that 100% of the cells contain a tron.

Active components were not so easy to discover. The first triode was invented in 1906 by De Forest who called it an "audion", and the pentode by Tellegen in 1926 (see Figure 15 for an example of a classical tetrode vacuum tube). A wide variety of electron tubes exist: beam deflection tubes, velocity modulation tubes, klystrons, magnetrons, and many more. The transistor came in 1947 (Bardeen, Brattain, Shockly). Later it was followed by field effect transistors and integrated circuits.

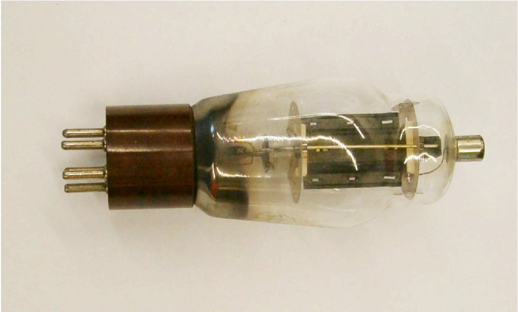


Figure 15. Classical vacuum tube.

So now it was time for me to invent an active component. My first attempts were inspired by the field effect transistor, but this did not work. Then I took inspiration from the beam deflection tube [6], and I got some amplification. The drawing of Figure 16 shows the essence of my beam deflection transistor (BDT, as I call it now).

A tron gun (1) sends trons (2) in the downward-rightward direction, so they descend along the gate isolator (3). At the other side of the gate (3) there may or may not be other trons (4), which, through the Coulomb effect (rule iso), influence the flow of trons (2). The deflected trons arrive at a drain (5) that is held at constant zero volt.

When not deflected, the trons (2) reach a so-called collector chamber, whose voltage thus depends on the presence of trons (4) near the gate (2). The resulting voltage can be wiretapped at junction (7).

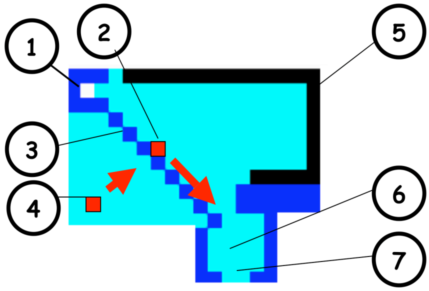


Figure 16. BDT. Tron gun (1) sends trons (2) descending along gate isolator (3). Gate (3), isolating trons (4), influencing flow of trons (2), which may arrive in collector chamber (6) and junction (7).

Using three RC phase shift sections and three BDTs, I made my first RC phase shift oscillator, see Figure 17. Running this for 50 000 steps shows a voltage that varies according to something close to a sine wave as shown in Figure 18.

In view of this success, I was delighted. I felt that all the essential problems were dealt with. My next task was to play and make lots of circuits and explore alternative oscillators.

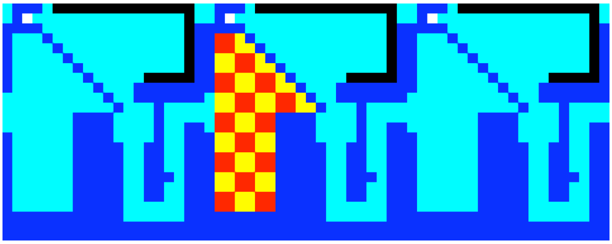


Figure 17. RC phase shift oscillator with three BDTs. The blocked area in the middle capacitor acts as the initial charge.

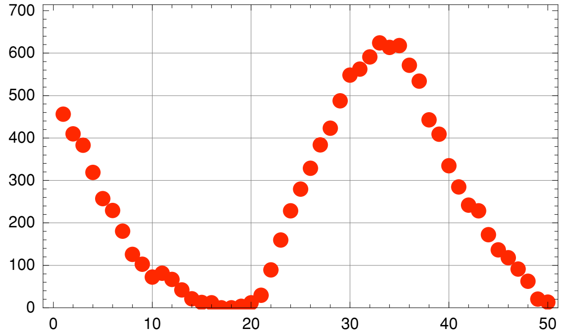


Figure 18. RC phase shift oscillator behavior obtained from the circuit of Figure 17. This wave form is taken as a proof that the oscillator works.

6. Componentization

In this section, to be further elaborated, I describe my disappointments and difficulties in getting reliable components. The phase shift oscillator circuit was a chaotic design in the sense that even the smallest, innocent-looking modification caused it to fail. During the following exploration I started to better understand how the trons behave. Again I took an engineering approach, trying to find guidelines, such that eventually I regained some predictive power.

After all, also in electronics, there are guidelines, "dos" and "don'ts". Only by observing these, sometimes implicit, rules of conduct, one can safely apply Kirchhoff's and Ohm's laws. For example, even the assumption that electricity flows through isolated wires of no resistance is not true for many reasons. Just to name the most important, the reasons are as follows.

- Internal resistance.
- Imperfect isolation.
- Skin effect.
- Parasitic capacitances.
- Thermic noise generation.
- Inductive couplings.

These are no less than *six* assumptions, all of which really can fail, although usually they are assumed (and taken care of) not to.

In the NKS physics explored here, the list of problems is equally long. But it is not the same list. I had to discover them one-by-one (e.g., delay time, grid alignment dependencies, standing waves, beams, etc.). And to do that I had to use additional tools such as the "bodyscan" tool that shows the flow of trons in a cumulative way. This is particularly useful for detecting beams and standing waves. The following example was taken from a test of the BDT. As can be seen in Figure 19, there is a standing wave in the left cavity, but in the gate cavity of the transistor the voltage is well averaged (except near the gate itself, where a capacity-effect happens, as expected). The siphon-like pipe (right) connects the collector to a negative voltage point (which remains invisible in this scan).

Figure 19. Bodyscan of the BDT.

Ideally there will be a catalog of components, documented by datasheets much in the same way as is the case in electronics. An example is shown in Appendix A.

7. Related Work

A related system called Wireworld had been developed by Brain Silverman in 1987 (see [7]). Each cell is in one of four states: empty, electron head, electron tail, or conductor. In the typical applications all wires are one cell wide. The circuits behave digitally; there is no such thing as Ohm's law. One electron occupies two cells, which means that an electron has an orientation: the direction in which it moves. When designing in Wireworld special attention must be paid to timing: gates work only when the input signals arrive simultaneously. Timing can be adjusted by adding extra delays (longer wires). Unlike my tron approach, Wireworld circuits can be simulated efficiently, since each electron can carry one bit of information. There exists a simulation of an entire digital computer. Figure 20 shows two diodes in Wireworld. The upper diode comes with two electrons, both moving to the right (green is head, red is tail). One electron has just passed the diode, the other is about to enter (and pass). There is one electron moving rightward toward the lower diode (where it will *not* pass). In this figure, adapted from Wikipedia Image: Wireworld two-diodes.gif, I have chosen dark blue as isolation and light blue as conductor (in Wireworld sometimes called “copper” and presented in a copper color). A red-green pair is an electron consisting of a tail and a head. It should be noted that there is no electron preservation principle built in to Wireworld. However, there is a kind of invariant: the electrons come and vanish in tail-head couples. In this sense Wireworld electrons are more like magnets with their pairs of inseparable poles.

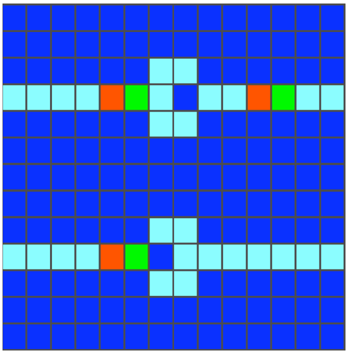


Figure 20. Wireworld circuit with two diodes.

8. Concluding Remarks

In my personal view, the explorations of this paper are useful and successful in the following sense.

1. The goal of creating a RC phase shift oscillator inside a cellular automaton has been achieved.
2. My assumption of the need for an engineering approach was confirmed by problems such as the alignment of the components.
3. The explorations helped me to think more about what is the essence of electrical engineering and to look up a variety of historic facts.

The results are not fully satisfying yet, and much still needs to be explored.

1. The present set of rules is somewhat messy and arbitrary. There are four sets of rules now, viz. for basic movement, isolation, power supply, and measurement, working in an interleaved manner. It is worthwhile to search for the simplest possible rules and get rid of the ad-hoc interleaving; it is an option for interesting future work.
2. The precise behavior of resistors and capacitors needs to be fully explored and documented, both at a fundamental level and at an empirical level. For example, now I use rules of thumb that a conducting pipe of diameter $d = 1$ has between $25\,\Omega$ and $30\,\Omega$ of resistance, a

pipe of $d = 2$ has about 11 Ω, and $d = 3$ has roughly 4 Ω. Sometimes the measurement seems to depend on specific alignment effects and in my view this hinders the reliable design of circuits.

3. In my experience, the appearing randomness of the tron movements inside pipes and cavities can be turned into an advantage in the sense that it helps to eliminate accidental special alignments and misalignments. It can undo effects of, for example, standing waves and instead allow using statistical tools.

Acknowledgments

I would like to thank Todd Rowland and Brian Silverman for bringing Wireworld to my attention. I thank the organizers of NKS2007 for the opportunity they offered me to present my work at the conference and the audience for their kind interest and for the useful discussions.

Appendix

A. 2NK0001 Datasheet Low-Power Beam Deflection Transistor

Features:

- Six dB gain.
- High-impedance input.
- Embedded power source.

Mechanical data:

- Dimensions: 18 × 15 cells.
- Alignment: (gun) vertical=even, horizontal=odd.

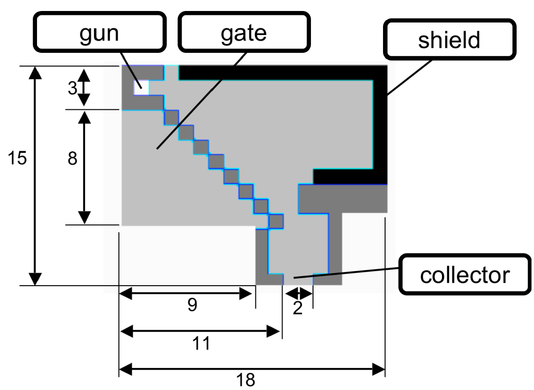


Figure A.1. Beam deflection transistor mechanical data.

Electric data:

- Working point: $V_{\text{gate}} = 0.1\,\text{V}$.
- Slope: $d\,V_c \big/ d\,V_g = 2$ at $V_g = 0.1$ and $R_c = 25\,\Omega$ (0 V).

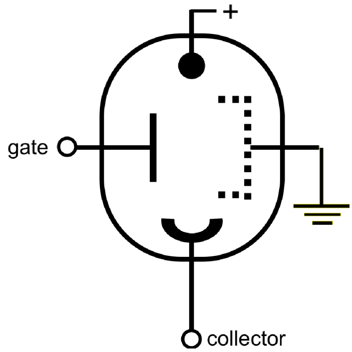


Figure A.2. Beam deflection transistor electrical diagram.

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