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CREATIVE EVOLUTION

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A single anecdote will serve to illuminate the life of maverick mathematician Nils Aall Barricelli, who was half Italian, half Norwegian, and 100 percent committed to his scientific research. But first, the official biography. "I was born in Rome 24 January 1912," he wrote in late 1951 on a Fulbright application that would eventually bring him to the United States. "In 1932 I passed the Italian Artium examination (classical line), and in 1936 the Italian graduation in Mathematical and physical sciences. In 1936 I settled in Norway where I have been working with scientific researches in theoretical statistics and stationary time series ... [and the] mathematical theory of evolution. ... Since 1947 I have been Assistant Professor at the University of Oslo."[1]

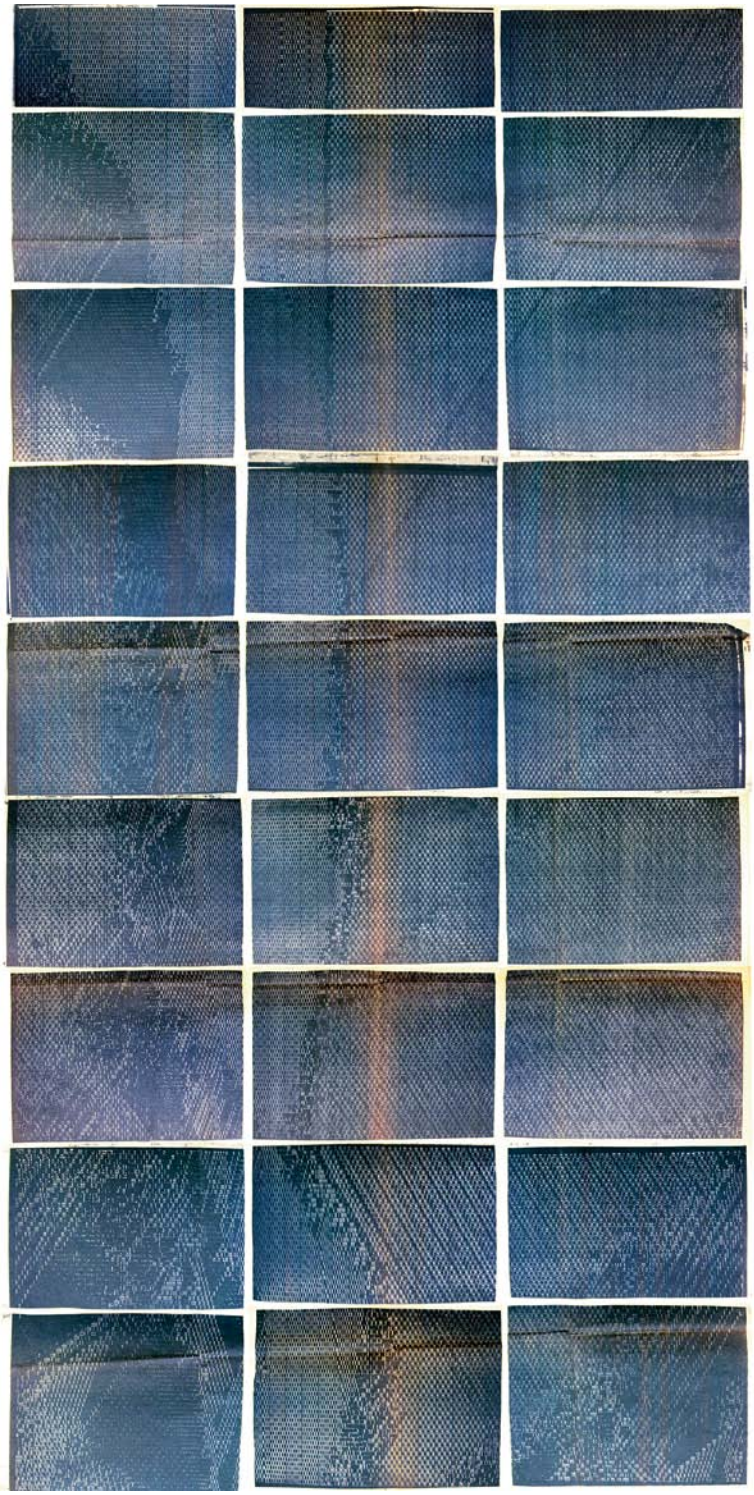
But there is a curious gap in his official biography, which is where the anecdote comes in. As a young student pursuing his doctorate, after finishing a body of research and after typing up his findings, he purportedly furnished to his doctoral committee a dissertation topping out at five hundred pages. A document this long was much too hefty for accepted standards of length in his field. His doctoral committee responded, sensibly, by mandating that Barricelli trim his dissertation to the acceptable length: fifty pages maximum.

No, was Barricelli's reply, five hundred pages or nothing. He finally chose nothing, forfeiting his doctoral degree in the home stretch.[2]

Barricelli gained a reputation for independence, fueled perhaps by his refusal to associate himself too closely to any specific research university for any amount of time, moving throughout his professional career from Rome to Oslo, Princeton, and Seattle, before ultimately returning to Norway and settling down as an unsalaried researcher at the University of Oslo for a period of twenty years near the end of his life. He was also keen to swim against the current: sometimes meeting with success as with his influential 1953 experiments on bionumeric evolution, sometimes belying a stubbornness that flew in the face of established scientific discourse as with his vain attempts later in life to upend Gödel's incompleteness theorems, and sometimes admitting a simple affection for anachronistic techniques as with his insistence on using computer punch cards long after his colleagues had abandoned them.

In the early 1950s, Barricelli succeeded in creating numeric organisms, based on principles gleaned from Darwin's theory of evolution. Barricelli's organisms and the universes they populated existed purely

Detail of illustration from a 1953 Barricelli experiment on bionumeric evolution showing both chaotic and stable gene clusters. The relatively chaotic center region depicts processes of mutation and disorganization; the texture fields on the right and left would be evidence of bionumeric organisms. Courtesy the Archives of the Institute for Advanced Study, Princeton.



Montage showing the full graphical output of one of Barricelli's 1953 experiments. Each small image tiles together to form a single mega-image. Several bionumeric organisms are clearly visible, as are their evolution over a few hundred reproductive cycles. Courtesy the Archives of the Institute for Advanced Study, Princeton.

as mathematical values. In his mind, however, they were true organisms, not simply mathematical models of life. Barricelli's universes are smooth, consisting of basic genetic entities able to rearrange themselves at the atomic level to form more complex symbiosis with other genetic entities. Inspired by the example of biological ecosystems, Barricelli sought to strike a balance in his artificial life experiments between two dangerous extremes, each threatening to block the development of living organisms: on the one hand, the eradication of heterogeneous forces brought on by the overreaching greediness of a single monoculture, and on the other, the suffocation of heterogeneous forces brought on by the collapse of organic structures into pure randomness and chaos. Life exists in the balance between unpredictable chaos and repetitive sameness, between pure randomness and absolute monoculture.

In 1951, Barricelli applied for a Fulbright to visit the Institute for Advanced Study in Princeton, New Jersey. His goal was to gain access to the Electronic Computer, which had been designed and built at the institute in the late 1940s by a team lead by John von Neumann. Already intrigued by his project, von Neumann had written a recommendation letter supporting Barricelli's Fulbright application, in which he stated that he was familiar with Barricelli's work on genetics, which struck him as highly original and interesting.[3]

Barricelli arrived in Princeton by early 1953. He was first accepted as a visitor and later granted "member" status in the School of Mathematics for his return in the spring of 1954. His membership letter was signed by nuclear scientist Robert Oppenheimer, the institute's director since 1947; with his membership, he received a grant-in-aid of $1,800.

Once arriving at the institute, von Neumann granted Barricelli access to some of the processing time offered by the Electronic Computer. During those years, the machine was busy chunking through ballistics numbers for use in national defense. But this happened primarily during daylight hours. Barricelli took over the night shift, spawning into the computer's memory scores of artificial organisms and then erasing them as dawn approached. His simulations first ran in the spring of 1953, research which he summarized in a paper written during that late spring and summer. During his return visits in 1954 and 1956, he modified and restaged his original experiments with the goal of achieving more successful results.

In order to create his artificial organisms, Barricelli started with a series of numbers, which he called "genes." Into this primitive ecosystem of genes Barricelli introduced mutation and reproduction rules, dubbed "norms," to govern how each gene could propagate over successive reproductive cycles. Iterating the reproductive cycle over hundreds and thousands of generations, Barricelli was able to reproduce phenomena roughly resembling Darwinian evolution. Over these many generations, genes coalesced into symbiotic groups of genes, which Barricelli called "organisms." These organisms, existing in a more or less stable fashion, could nevertheless butt up against a neighboring organism or a rogue infectious gene, thereby mutating the original organisms into new equilibriums of genes. With his genes, norms, and organisms, Barricelli created something akin to living systems, all within the strictly numerical simulation universe of the Electronic Computer.

How did it work? Barricelli established a "universe" consisting of a horizontal row of 512 genes. Genes were represented using integers from negative 18 to positive 18. According to "norms" he established governing mutation and reproduction, each number reproduced into the row below it. In this way, the norms translated rows of "parent" genes into subsequent rows of "child" genes, which in turn were reproduced again using the same norms into subsequent generations over and over. If and when gene-numbers reappeared in a sustained group, Barricelli would designate each group an "organism."

Proceeding in lines from top to bottom, Barricelli's algorithm produced a rectangular image consisting of a grid of genes appearing as individual pixels. When finished, the image yielded a snapshot of evolutionary time, with the oldest generations of organisms at the top and the youngest at the bottom.

The output of Barricelli's experiments was highly visual. He was essentially drawing directly in binary numbers, converting 1s and 0s into pixels in either on or off positions. Because he represented each gene as pixels, organisms were identified visually based on how the pixel patterns self-organized into texture fields, which were identified as shapes or zones within the image. Variations in texture delineated one organism from another, and the width and height of any given texture field indicated the lifespan of an organism.

It was important for Barricelli that norms have a *limited* scope. While norms might be applied globally to an entire universe, each norm was inherently local in that it governed the behavior of each individual gene based on variables derived from the gene's relative position. Macro rules—like transcendental identity or essential behavior—were eschewed in favor of small-scale, local ones, a principle consistent with how cellular automata systems operate more generally. Such systems tend to empower each small node with relative autonomy while limiting the scope of what the node can see or do.

Barricelli's universe was strictly its own organizational domain, supervening the vital: "Just because the special conditions prevailing on this earth seem to favor the forms of life which are based on organic compounds, this is no proof that it is not possible to build up other forms of life on an entirely different basis."[4] While admitting a connection back to Darwinian theory, he ultimately had no interest in merely simulating the realm of biology. His experiments were not models. Rather, he wished to open up an autonomous field of life that was exclusively bionumeric. Barricelli's numerical organisms were "alive" within a mathematical machine first and foremost. If they also revealed something about the biological realm, so be it.

The year 1953 was crucial for Barricelli. He had never achieved true evolution in his previous mathematical experiments. After that summer, he returned to Oslo and in October wrote a letter to von Neumann underscoring the profound leap forward that the Electronic Computer had afforded him. "No process of evolution had ever been observed prior to the Princeton experiments," he trumpeted.[5] Barricelli spent the late summer and fall of 1953 touring his results, presenting at the international congress on genetics in Bellagio on 30 August, and a few weeks later at the Institute for Telecommunications in Rome.

Yet the 1953 experiments were still inconclusive. He would have to return to Princeton in 1954 for more tests, this time refining his algorithms slightly to achieve more satisfying results. As he wrote, "It will be one of the most important aims of the next bionumerical experiments to find the way to start an unlimited evolution."[6] The 1953 experiments had been plagued by parasite genes. Yet more ominously, Barricelli had noticed that the experiments tended to result in standard, homogeneous patterns after a relatively short number of generations. Either pure uniformity or pure disorganization: either a single organism killed off all others, creating a monoculture, or no organisms gained a foothold, resulting in sustained randomness. His goal after returning in 1954 was to balance the experiments more carefully in the hopes of achieving an "unlimited evolution" between these two fatal extremes.

In order to achieve "durable evolution" and avoid the twin dangers of monoculture and chaos, Barricelli learned to deploy three or more norms in parallel. It was advantageous to have different norms bump up against each other like this. (He also eventually devised a system in which multiple universes were run simultaneously. He would copy entire sectors of genes from one universe to another in order to cross-fertilize them with "new blood.") Mixing two mathematical norms across such thresholds generated points of genetic friction, increasing the complexity of the gene pool and thereby increasing overall biodiversity. By introducing multiple norms into his reproductive cycle, Barricelli was able to achieve a continuous form of evolution from generation to generation. The evolution was judged to be successful if an equilibrium persisted between pure stasis and pure change. If, after a few thousand evolutionary cycles, the gene pool had disintegrated into randomness with no symbiotic organisms emerging, the experiment was a failure. Likewise if the gene pool was overrun by a single superorganism killing off all other living things, then too a failure. The goal was balance. Each kind of "feedback," whether it be assistive or disintegrating, was odious to life.

In this sense Barricelli is our first "biological Keynesian" in that he wished to mitigate the dangers lurking within his ecosystem by deliberately bridling the more unhealthy tendencies that when left unregulated would lead to systemic disaster. To sustain creative evolution, one must seek the equipoise of moderation through regulation.

By the 1960s, Barricelli had his sights set on new creative uses for his artificial organisms. His 1963 paper on "Numerical Testing of Evolution Theories" bears particular historical significance. In it, Barricelli proposes a "chemo-analogical computer" using DNA molecules as the computational substrate—a mere ten years after the discovery of DNA by Watson and Crick. According to Barricelli's conjectures, such a computer would consist of a normal "hardware" computer connected to a "wetware" environment made up of DNA molecules. Barricelli constructed a "DNA-norm" to govern the cellular phenomena of the base-pair interactions. Computations would first be transferred from hardware to wetware; the DNA molecules would perform the computations; and the results would be fed back into the computer. "Such a computer could essentially consist of an automatic, programmed chemical laboratory with read-in and read-out devices and other gadgets to perform the following operation: Interpret and transform information contained in IBM cards or magnetic tape into a specific arrangement of nucleotides and other molecules. Perform the

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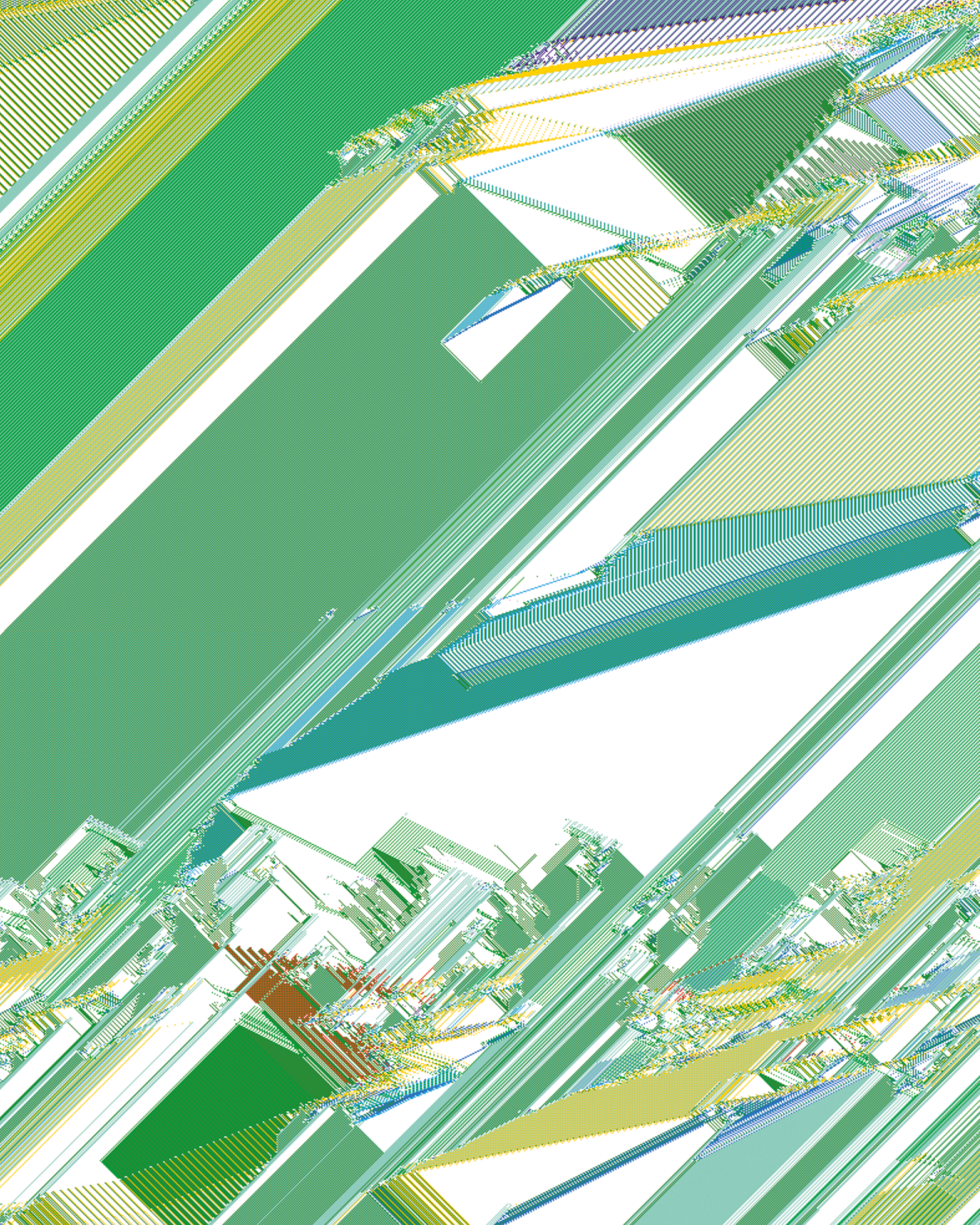
opposite: Digital image resulting from a 2010 restaging by the author of a Barricelli experiment. Barricelli's visualization technique has been altered—color has been added to show the gene groups more clearly, and the vertical axis has been compressed to increase the amount of evolutionary time that is visible. Each swatch of textured color within the image indicates a different organism. Borders between color fields mean that an organism has perished, been born, mutated, or otherwise evolved into something new.



chemical operations specified by the program (also contained in IBM cards or magnetic tape). Punch or read out the results into IBM cards or magnetic tape."[7] Today it would be called a DNA computer.

Barricelli also addresses games in the 1963 paper. Moving beyond simply modeling evolutionary behavior, he posed the question of "whether it would be possible to select symbioorganisms able to perform a specific task assigned to them."[8] Could his organisms be assigned a goal? Could they be tasked? Could they play and win games?

He selected a simple game called "Tac Tix," devised by the Dane Piet Hein who had adapted it from the ancient Chinese game nim. Barricelli read about nim and Tac Tix in the February 1958 issue of *Scientific American*, and devised a way to superimpose his cellular grids onto the grid of the game. Nim is binary in nature, as the article explained:

Since digital computers operate on the binary system, it is not difficult to program such a computer to play a perfect game of nim, or to build a special machine for this purpose. Edward U. Condon, the former director of the National Bureau of Standards who is now at Washington University of St. Louis, was a co-inventor of the first such machine. Patented in 1940 as the Nimatron, it was built by the Westinghouse Electric Corporation and exhibited in the Westinghouse building at the New York World's Fair. It played 100,000 games and won 90,000. Most of its defeats were administered by attendants demonstrating to skeptical spectators that the machine could be beaten.[9]

Barricelli ran his game tests on the IBM 704 computer at the A. E. C. Computing Center at New York University in the fall of 1959, and then again later at Brookhaven National Laboratory and Vanderbilt University. The result was a primitive form of "machine learning"—Barricelli is sometimes credited as the first to work in this domain—in which individual organisms would evolve in ways that were more suitable for game play, thereby becoming stronger opponents: "there is no doubt that ... the symbioorganisms are 'learning' the game by a sort of 'evolutionary learning process' based on mutation, crossing and selection."[10] Using what he learned from Tac Tix, Barricelli would eventually perfect a computerized chess game, which he sold to the Norwegian game publisher Damm.

Even if Barricelli is not well known, his legacy is imprinted across contemporary information science. The "Game of Life," a cellular automata system developed by British mathematician John Conway in 1970, is probably the most emblematic work from early artificial life research. In Conway's game, small organisms form and evolve across a two-dimensional environment. Like Barricelli's life forms, and von Neumann's cellular systems before them, Conway's organisms are animated by simple local rules, producing larger emergent behavior. Yet the most significant figure working in the shadow of von Neumann and Barricelli is Stephen Wolfram, author of *A New Kind of Science* and the most visible proselytizer of cellular automata today. Wolfram was not yet born when Barricelli completed his Princeton research, nevertheless his cellular automata systems, which aim to model any and all natural phenomena as computational processes, are the progeny of Barricelli and his numerical organisms.

Did Barricelli really create life? He went to great lengths to clarify whether he considered his bionumeric organisms "alive." By 1962, he even felt obligated to preface a scientific paper with a special "note by the author," reinforced a few pages later by a reiterative footnote, aimed at ameliorating potential anxieties. "Some of [my] conclusions may be surprising to the reader," he admitted. But anxious readers, wrote Barricelli, should cast aside their prejudicial emotions and act like mountain climbers who "hold on solid ground" in moments of peril: "Proven facts and rigorous deduction are the solid ground on which scientific knowledge can be based. Feelings and opinions and any form of instinctive resistance to new ideas are not."[11]

1 "Application for United States Government Travel Grant for Citizens of Norway," Barricelli member file, box 7, Institute for Advanced Study, Princeton, New Jersey (hereafter cited as IAS Archives).
2 The anecdote is from Tor Gulliksen's obituary of Barricelli, recounted during an interview the author conducted with Gulliksen in Oslo on 11 March 2009.
3 John von Neumann to Fulbright committee, letter, 5 February 1952. Barricelli member file, box 7, IAS Archives.
4 Nils Aall Barricelli, "Symbiogenetic Evolution Processes Realized by Artificial Methods," *Methodos*, vol. 9, nos. 35–36 (1957), p. 146.
5 Nils Aall Barricelli to John von Neumann, letter, 22 October 1953. Member file on Barricelli, IAS School of Mathematics, members, Ba–Bi, 1933–1977, IAS Archives.
6 Nils Aall Barricelli, "Experiments in Bionumeric Evolution Executed by the Electronic Computer at Princeton, N. J.," 12. Records of the Electronic Computer Project, box 4, folder 45 (with additional blueprints in map box 1), IAS Archives.
7 Nils Aall Barricelli, "Numerical Testing of Evolution Theories: Part II, Preliminary Tests of Performance Symbiogenesis and Terrestrial Life," *Acta Biotheoretica*, vol. 16, nos. 3–4 (1963), p. 121.
8 Ibid., p. 100.
9 Martin Gardner, "Mathematical Games: Concerning the Game of Nim and Its Mathematical Analysis," *Scientific American*, vol. 198, no. 2 (February 1958), pp. 104–111, p. 108.
10 Barricelli, "Numerical Testing of Evolution Theories: Part II," op. cit., p. 116.
11 For these quotations, see Nils Aall Barricelli, "Numerical Testing of Evolution Theories: Part I, Theoretical Introduction and Basic Tests," *Acta Biotheoretica*, vol. 16, nos. 1–2 (1962), pp. 69–70, and Barricelli, "Numerical Testing of Evolution Theories: Part II," op. cit., p. 7.