Library of Congress Cataloging-in-Publication Data

Kelly, Kevin, 1952–
Out of Control : the rise of neo-biological civilization / Kevin Kelly.
p. cm.
"A William Patrick book."
Includes bibliographical references and index.
ISBN 0-201-57793-3
1. Technological innovations—History. 2. Inventions—History.
3. Social networks—History. 4. Social groups—History. I. Title.
HC79. T4K44 1994
338'.064—dc20
94-2620
CIP

Jacket design by Jean Seal
Jacket illustration by Jamie Clay
Text design by Julia Runk Jones
Set in 10-pt ITC New Baskerville by Julia Runk Jones
Copyedited by Kyrill Schabert
Proofread by Vicki Hochstedler
Indexed by Ted Laux

1 2 3 4 5 6 7 8 9-MA-97969594
First printing, May 1994

OUT OF CONTROL

THE RISE OF NEO-BIOLOGICAL CIVILIZATION

KEVIN KELLY

A WILLIAM PATRICK BOOK

Addison-Wesley Publishing Company
Reading, Massachusetts Menlo Park, California New York Don Mills, Ontario Wokingham, England Amsterdam Bonn Sydney Singapore Tokyo Madrid San Juan Paris Seoul Milan Mexico City Taipei

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HIVE MIND

THE BEEHIVE beneath my office window quietly exhales legions of busybodies and then inhales them. On summer afternoons, when the sun seeps under the trees to backlight the hive, the approaching sunlit bees zoom into their tiny dark opening like curving tracer bullets. I watch them now as they haul in the last gleanings of nectar from the final manzanita blooms of the year. Soon the rains will come and the bees will hide. I will still gaze out the window as I write; they will still toil, but now in their dark home. Only on the balmiest day will I be blessed by the sight of their thousands in the sun.

Over years of beekeeping, I've tried my hand at relocating bee colonies out of buildings and trees as a quick and cheap way of starting new hives at home. One fall I gutted a bee tree that a neighbor felled. I took a chain saw and ripped into this toppled old tupelo. The poor tree was cancerous with bee comb. The further I cut into the belly of the tree, the more bees I found. The insects filled a cavity as large as I was. It was a gray, cool autumn day and all the bees were home, now agitated by the surgery. I finally plunged my hand into the mess of comb. Hot! Ninety-five degrees at least. Overcrowded with 100,000 cold-blooded bees, the hive had become a warm-blooded organism. The heated honey ran like thin, warm blood. My gut felt like I had reached my hand into a dying animal.

The idea of the collective hive as an animal was an idea late in coming. The Greeks and Romans were famous beekeepers who harvested respectable yields of honey from homemade hives, yet these ancients got almost every fact about bees wrong. Blame it on the lightless conspiracy of bee life, a secret guarded by ten thousand fanatically loyal, armed soldiers. Democritus thought bees spawned from the same source as maggots. Xenophon figured out the queen bee but erroneously assigned her supervisory responsibilities she doesn't have. Aristotle gets good marks for getting a lot right, including the semiaccurate observation that "ruler bees" put larva in the honeycomb cells. (They actually start out as eggs, but at least he corrects Democritus's misguided direction of maggot origins.) Not until the Renaissance was the female gender of the queen bee proved, or beeswax shown to be secreted from the undersides of bees. No one had a clue until modern genetics that a hive is a radical matriarchy and sisterhood: all bees, except the few good-for-nothing drones, are female and sisters. The hive was a mystery as unfathomable as an eclipse.

I've seen eclipses and I've seen bee swarms. Eclipses are spectacles I watch halfheartedly, mostly out of duty, I think, to their rarity and tradition, much as I might attend a Fourth of July parade. Bee swarms, on the other hand, evoke another sort of awe. I've seen more than a few hives throwing off a swarm, and never has one failed to transfix me utterly, or to dumbfound everyone else within sight of it.

A hive about to swarm is a hive possessed. It becomes visibly agitated around the mouth of its entrance. The colony whines in a centerless loud drone that vibrates the neighborhood. It begins to spit out masses of bees, as if it were emptying not only its guts but its soul. A poltergeist-like storm of tiny wills materializes over the hive box. It grows to be a small dark cloud of purpose, opaque with life. Boosted by a tremendous buzzing racket, the ghost slowly rises into the sky, leaving behind the empty box and quiet bafflement. The German theosophist Rudolf Steiner writes lucidly in his otherwise kooky *Nine Lectures on Bees:* "Just as the human soul takes leave of the body . . . one can truly see in the flying swarm an image of the departing human soul."

For many years Mark Thompson, a beekeeper local to my area, had the bizarre urge to build a Live-In Hive—an active bee home you could visit by inserting your head into it. He was working in a yard once when a beehive spewed a swarm of bees "like a flow of black lava, dissolving, then taking wing." The black cloud coalesced into a 20-foot-round black halo of 30,000 bees that hovered, UFO-like, six feet off the ground, exactly at eye level. The flickering insect halo began to drift slowly away, keeping a constant six feet above the earth. It was a Live-In Hive dream come true.

Mark didn't waver. Dropping his tools he slipped into the swarm, his bare head now in the eye of a bee hurricane. He trotted in sync across the yard as the swarm eased away. Wearing a bee halo, Mark hopped over one fence, then another. He was now running to keep up with the thundering animal in whose belly his head floated. They all crossed the road and hurried down an open field, and then he jumped another fence. He was tiring. The bees weren't; they picked up speed. The swarm-bearing man glided down a hill into a marsh. The two of them now resembled a superstitious swamp devil, humming, hovering, and plowing through the miasma. Mark churned wildly through the muck trying to keep up. Then, on some signal, the bees accelerated. They unhaloed Mark and left him standing there wet, "in panting, joyful amazement." Maintaining an eye-level altitude, the swarm floated across the landscape until it vanished, like a spirit unleashed, into a somber pine woods across the highway.

"Where is 'this spirit of the hive' . . . where does it reside?" asks the author Maurice Maeterlinck as early as 1901. "What is it that governs here, that issues orders, foresees the future…?" We are certain now it is not the queen bee. When a swarm pours itself out through the front slot of the hive, the queen bee can only follow. The queen's daughters manage the election of where and when the swarm should settle. A half-dozen anonymous workers scout ahead to check possible hive locations in hollow trees or wall cavities. They report back to the resting swarm by dancing on its contracting surface. During the report, the more theatrically a scout dances, the better the site she is championing. Deputy bees then check out the competing sites according to the intensity of the dances, and will concur with the scout by joining in the scout's twirling. That induces more followers to check out the lead prospects and join the ruckus when they return by leaping into the performance of their choice.

It's a rare bee, except for the scouts, who has inspected more than one site. The bees see a message, "Go there, it's a nice place." They go and return to dance/say, "Yeah, it's *really* nice." By compounding emphasis, the favorite sites get more visitors, thus increasing further visitors. As per the law of increasing returns, them that has get more votes, the have-nots get less. Gradually, one large, snowballing finale will dominate the dance-off. The biggest crowd wins.

It's an election hall of idiots, for idiots, and by idiots, and it works marvelously. This is the true nature of democracy and of all distributed governance. At the close of the curtain, by the choice of the citizens, the swarm takes the queen and thunders off in the direction indicated by mob vote. The queen who follows, does so humbly. If she could think, she would remember that she is but a mere peasant girl, blood sister of the very nurse bee instructed (by whom?) to select her larva, an ordinary larva, and raise it on a diet of royal jelly, transforming Cinderella into the queen. By what karma is the larva for a princess chosen? And who chooses the chooser?

"The hive chooses," is the disarming answer of William Morton Wheeler, a natural philosopher and entomologist of the old school, who founded the field of social insects. Writing in a bombshell of an essay in 1911 ("The Ant Colony as an Organism" in the *Journal of Morphology*), Wheeler claimed that an insect colony was not merely the analog of an organism, it is indeed an organism, in every important and scientific sense of the word. He wrote: "Like a cell or the person, it behaves as a unitary whole, maintaining its identity in space, resisting dissolution . . . neither a thing nor a concept, but a continual flux or process."

It was a mob of 20,000 united into oneness.

Wheeler, the ant pioneer, started calling the bustling cooperation of an insect colony a "superorganism" to clearly distinguish it from the metaphorical use of "organism." He was influenced by a philosophical strain at the turn of the century that saw holistic patterns overlaying the individual behavior of smaller parts. The enterprise of science was on its first steps of a headlong rush into the minute details of physics, biology, and all natural sciences. This pell-mell to reduce wholes to their constituents, seen as the most pragmatic path to understanding the wholes, would continue for the rest of the century and is still the dominant mode of scientific inquiry. Wheeler and colleges were an essential part of this reductionist perspective, as the 50 Wheeler monographs on specific esoteric ant behaviors testify. But at the same time, Wheeler saw "emergent properties" within the superorganism superseding the resident properties of the collective ants. Wheeler said the superorganism of the hive "emerges" from the mass of ordinary insect organisms. And he meant emergence as science—a technical, rational explanation—not mysticism or alchemy.

Wheeler held that this view of emergence was a way to reconcile the reduce-it-to-its parts approach with the see-it-as-a-whole approach. The duality of body/mind or whole/part simply evaporated when holistic behavior lawfully emerged from the limited behaviors of the parts. The specifics of how superstuff emerged from baser parts was very vague in everyone's mind. And still is.

What was clear to Wheeler's group was that emergence was a common natural phenomena. It was related to the ordinary kind of causation in everyday life, the kind where *A* causes *B* which causes *C*, or 2 + 2 = 4. Ordinary causality was invoked by chemists to cover the observation that sulfur atoms plus iron atoms equal iron sulfide molecules. According to fellow philosopher C. Lloyd Morgan, the concept of emergence signaled a different variety of causation. Here 2 + 2 does not equal 4; it does not even surprise with 5. In the logic of emergence, 2 + 2 = apples. "The emergent step, though it may seem more or less saltatory [a leap], is best regarded as a qualitative change of direction, or critical turning-point, in the course of events," writes Morgan in *Emergent Evolution,* a bold book in 1923. Morgan goes on to quote a verse of Browning poetry which confirms how music emerges from chords:

> And I know not if, save in this, such gift be allowed to man
> That out of three sounds he frame, not a fourth sound, but a star.

We would argue now that it is the complexity of our brains that extracts music from notes, since we presume oak trees can't hear Bach. Yet "Bachness"—all that invades us when we hear Bach—is an appropriately poetic image of how a meaningful pattern emerges from musical notes and generic information.

The organization of a tiny honeybee yields a pattern for its tinier one-tenth of a gram of wing cells, tissue, and chitin. The organism of a hive yields integration for its community of worker bees, drones, pollen and brood. The whole 50-pound hive organ emerges with its own identity from the tiny bee parts. The hive possesses much that none of its parts possesses. One speck of a honeybee brain operates with a memory of six days; the hive as a whole operates with a memory of three months, twice as long as the average bee lives.

Ants, too, have hive mind. A colony of ants on the move from one nest site to another exhibits the Kafkaesque underside of emergent control. As hordes of ants break camp and head west, hauling eggs, larva, pupae—the crown jewels—in their beaks, other ants of the same colony, patriotic workers, are hauling the trove east again just as fast, while still other workers, perhaps acknowledging conflicting messages, are running one direction and back again completely empty-handed. A typical day at the office. Yet, the ant colony moves. Without any visible decision making at a higher level, it chooses a new nest site, signals workers to begin building, and governs itself.

The marvel of "hive mind" is that no one is in control, and yet an invisible hand governs, a hand that emerges from very dumb members. The marvel is that more is different. To generate a colony organism from a bug organism requires only that the bugs be multiplied so that there are many, many more of them, and that they communicate with each other. At some stage the level of complexity reaches a point where new categories like "colony" can emerge from simple categories of "bug." Colony is inherent in bugness, implies this marvel. Thus, there is nothing to be found in a beehive that is not submerged in a bee. And yet you can search a bee forever with cyclotron and fluoroscope, and you will never find the hive.

This is a universal law of vivisystems: higher-level complexities cannot be inferred by lower-level existences. Nothing—no computer or mind, no means of mathematics, physics, or philosophy—can unravel the emergent pattern dissolved in the parts without actually playing it out. Only playing out a hive will tell you if a colony is immixed in a bee. The theorists put it this way: running a system is the quickest, shortest, and only sure method to discern emergent structures latent in it. There are no shortcuts to actually "expressing" a convoluted, nonlinear equation to discover what it does. Too much of its behavior is packed away.

That leads us to wonder what else is packed into the bee that we haven't seen yet? Or what else is packed into the hive that has not yet appeared because there haven't been enough honeybee hives in a row all at once? And for that matter, what is contained in a human that will not emerge until we are all interconnected by wires and politics? The most unexpected things will brew in this bionic hivelike supermind.

A SINK BRIMS with water. You pull the plug. The water stirs. A vortex materializes. It blooms into a tiny whirlpool, growing as if it were alive. In a minute the whirl extends from surface to drain, animating the whole basin. An ever changing cascade of water molecules swirls through the tornado, transmuting the whirlpool's being from moment to moment. Yet the whirlpool persists, essentially unchanged, dancing on the edge of collapse. "We are not stuff that abides, but patterns that perpetuate themselves," wrote Norbert Wiener.

As the sink empties, all of its water passes through the spiral. When finally the basin of water has sunk from the bowl to the cistern pipes, where does the form of the whirlpool go? For that matter, where did it come from?

The whirlpool appears reliably whenever we pull the plug. It is an emergent thing, like a flock, whose power and structure are not contained in the power and structure of a single water molecule. No matter how intimately you know the chemical character of H_2O, it does not prepare you for the character of a whirlpool. Like all emergent entities, the essence of a vortex emanates from a messy collection of other entities; in this case, a pool of water molecules. One drop of water is not enough for a whirlpool to appear in, just as one pinch of sand is not enough to hatch an avalanche. Emergence requires a population of entities, a multitude, a collective, a mob, more.

More is different. One grain of sand cannot avalanche, but pile up enough grains of sand and you get a dune that can trigger avalanches. Certain physical attributes such as temperature depend on collective behavior. A single molecule floating in space does not really have a temperature. Temperature is more correctly thought of as a group characteristic that a

population of molecules has. Though temperature is an emergent property, it can be measured precisely, confidently, and predictably. It is real.

It has long been appreciated by science that large numbers behave differently than small numbers. Mobs breed a requisite measure of complexity for emergent entities. The total number of possible interactions between two or more members accumulates exponentially as the number of members increases. At a high level of connectivity, and a high number of members, the dynamics of mobs takes hold. More *is* different.

THERE ARE TWO extreme ways to structure "moreness." At one extreme, you can construct a system as a long string of sequential operations, such as we do in a meandering factory assembly line. The internal logic of a clock as it measures off time by a complicated parade of movements is the archetype of a sequential system. Most mechanical systems follow the clock.

At the other far extreme, we find many systems ordered as a patchwork of parallel operations, very much as in the neural network of a brain or in a colony of ants. Action in these systems proceeds in a messy cascade of interdependent events. Instead of the discrete ticks of cause and effect that run a clock, a thousand clock springs try to simultaneously run a parallel system. Since there is no chain of command, the particular action of any single spring diffuses into the whole, making it easier for the sum of the whole to overwhelm the parts of the whole. What emerges from the collective is not a series of critical individual actions but a multitude of simultaneous actions whose collective pattern is far more important. This is the swarm model.

These two poles of the organization of moreness exist only in theory because all systems in real life are mixtures of these two extremes. Some large systems lean to the sequential model (the factory); others lean to the web model (the telephone system).

It seems that the things we find most interesting in the universe are all dwelling near the web end. We have the web of life, the tangle of the economy, the mob of societies, and the jungle of our own minds. As dynamic wholes, these all share certain characteristics: a certain liveliness, for one.

We know these parallel-operating wholes by different names. We know a swarm of bees, or a cloud of modems, or a network of brain neurons, or a food web of animals, or a collective of agents. The class of systems to which all of the above belong is variously called: networks, complex adaptive systems, swarm systems, vivisystems, or collective systems. I use all these terms in this book.

Organizationally, each of these is a collection of many (thousands) of autonomous members. "Autonomous" means that each member reacts individually according to internal rules and the state of its local environment. This is opposed to obeying orders from a center, or reacting in lock step to the overall environment.

These autonomous members are highly connected to each other, but not to a central hub. They thus form a peer network. Since there is no center of control, the management and heart of the system are said to be decentrally distributed within the system, as a hive is administered.

There are four distinct facets of distributed being that supply vivisystems their character:

- The absence of imposed centralized control
- The autonomous nature of subunits
- The high connectivity between the subunits
- The webby nonlinear causality of peers influencing peers.

The relative strengths and dominance of each factor have not yet been examined systematically.

One theme of this book is that distributed artificial vivisystems, such as parallel computing, silicon neural net chips, or the grand network of online networks commonly known as the Internet, provide people with some of the attractions of organic systems, but also, some of their drawbacks. I summarize the pros and cons of distributed systems here:

Benefits of Swarm Systems

- *Adaptable*—It is possible to build a clockwork system that can adjust to predetermined stimuli. But constructing a system that can adjust to new stimuli, or to change beyond a narrow range, requires a swarm—a hive mind. Only a whole containing many parts can allow a whole to persist while the parts die off or change to fit the new stimuli.

- *Evolvable*—Systems that can shift the locus of adaptation over time from one part of the system to another (from the body to the genes or from one individual to a population) must be swarm based. Noncollective systems cannot evolve (in the biological sense).

- *Resilient*—Because collective systems are built upon multitudes in parallel, there is redundancy. Individuals don't count. Small failures are lost in the hubbub. Big failures are held in check by becoming merely small failures at the next highest level on a hierarchy.

- *Boundless*—Plain old linear systems can sport positive feedback loops—the screeching disordered noise of PA microphone, for example. But in swarm systems, positive feedback can lead to increasing order. By incrementally extending new structure beyond the bounds of its initial state, a swarm can build its own scaffolding to build further structure. Spontaneous order helps create more order. Life begets more life, wealth creates more wealth, information breeds more information, all bursting the original cradle. And with no bounds in sight.

- *Novelty*—Swarm systems generate novelty for three reasons: (1) They are "sensitive to initial conditions"—a scientific shorthand for saying that the size of the effect is not proportional to the size of the cause—so they can make a surprising mountain out of a molehill. (2) They hide countless novel possibilities in the exponential combinations of many interlinked individuals. (3) They don't reckon individuals, so therefore individual variation and imperfection can be allowed. In swarm systems with heritability, individual variation and imperfection will lead to perpetual novelty, or what we call evolution.

Apparent Disadvantages of Swarm Systems

- *Nonoptimal*—Because they are redundant and have no central control, swarm systems are inefficient. Resources are allotted higgledy-piggledy, and duplication of effort is always rampant. What a waste for a frog to lay so many thousands of eggs for just a couple of juvenile offspring! Emergent controls such as prices in free-market economy—a swarm if there ever was one—tend to dampen inefficiency, but never eliminate it as a linear system can.

- *Noncontrollable*—There is no authority in charge. Guiding a swarm system can only be done as a shepherd would drive a herd: by applying force at crucial leverage points, and by subverting the natural tendencies of the system to new ends (use the sheep's fear of wolves to gather them with a dog that wants to chase sheep). An economy can't be controlled from the outside; it can only be slightly tweaked from within. A mind cannot be prevented from dreaming, it can only be plucked when it produces fruit. Wherever the word "emergent" appears, there disappears human control.

- *Nonpredictable*—The complexity of a swarm system bends it in unforeseeable ways. "The history of biology is about the unexpected," says Chris Langton, a researcher now developing mathematical swarm models. The word emergent has its dark side. Emergent novelty in a video game is tremendous fun; emegent novelty in our airplane traffic-control system would be a national emergency.

- *Nonunderstandable*—As far as we know, causality is like clockwork. Sequential clockwork systems we understand; nonlinear web systems are unadulterated mysteries. The latter drown in their self-made paradoxical logic. *A* causes *B*, *B* causes *A*. Swarm systems are oceans of intersecting logic: *A* indirectly causes everything else and everything else indirectly causes *A*. I call this lateral or horizontal causality. The credit for the true cause (or more precisely the true proportional mix of causes) will spread horizontally through the web until the trigger of a particular event is essentially unknowable. Stuff happens. We don't need to know exactly how a tomato cell works to be able to grow, eat, or even improve tomatoes. We don't need to know exactly how a massive computational collective system works to be able to build one, use it, and make it better. But whether we understand a system or not, we are responsible for it, so understanding would sure help.

• *Nonimmediate*—Light a fire, build up the steam, turn on a switch, and a linear system awakens. It's ready to serve you. If it stalls, restart it. Simple collective systems can be awakened simply. But complex swarm systems with rich hierarchies take time to boot up. The more complex, the longer it takes to warm up. Each hierarchical layer has to settle down; lateral causes have to slosh around and come to rest; a million autonomous agents have to acquaint themselves. I think this will be the hardest lesson for humans to learn: that organic complexity will entail organic time.

The tradeoff between the pros and cons of swarm logic is very similar to the cost/benefit decisions we would have to make about biological vivisystems, if we were ever asked to. But because we have grown up with biological systems and have had no alternatives, we have always accepted their costs without evaluation.

We can swap a slight tendency for weird glitches in a tool in exchange for supreme sustenance. In exchange for a swarm system of 17 million computer nodes on the Internet that won't go down (as a whole), we get a field that can sprout nasty computer worms, or erupt inexplicable local outages. But we gladly trade the wasteful inefficiencies of multiple routing in order to keep the Internet's remarkable flexibility. On the other hand, when we construct autonomous robots, I bet we give up some of their potential adaptability in exchange for preventing them from going off on their own beyond our full control.

As our inventions shift from the linear, predictable, causal attributes of the mechanical motor, to the crisscrossing, unpredictable, and fuzzy attributes of living systems, we need to shift our sense of what we expect from our machines. A simple rule of thumb may help:

- For jobs where supreme control is demanded, good old clockware is the way to go.
- Where supreme adaptability is required, out-of-control swarmware is what you want.

For each step we push our machines toward the collective, we move them toward life. And with each step away from the clock, our contraptions lose the cold, fast optimal efficiency of machines. Most tasks will balance some control for some adaptability, and so the apparatus that best does the job will be some cyborgian hybrid of part clock, part swarm. The more we can discover about the mathematical properties of generic swarm processing, the better our understanding will be of both artificial complexity and biological complexity.

Swarms highlight the complicated side of real things. They depart from the regular. The arithmetic of swarm computation is a continuation of Darwin's revolutionary study of the irregular populations of animals and plants undergoing irregular modification. Swarm logic tries to comprehend the out-of-kilter, to measure the erratic, and to time the unpredictable. It is an attempt, in the words of James Gleick, to map "the morphology of the amorphous"—to give a shape to that which seems to be inherently shapeless. Science has done all the easy tasks—the clean simple signals. Now all it can face is the noise; it must stare the messiness of life in the eye.

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AN OPEN UNIVERSE

A SWARM OF HONEYBEES absconds from the hive and then dangles in a cluster from a tree branch. If a nearby beekeeper is lucky, the swarm settles on a branch that is easy to reach. The bees, gorged with honey and no longer protecting their brood, are as docile as ladybugs.

I've found a swarm or two in my time hung no higher than my head, and I've moved them into an empty hive box for my own. The way you move 10,000 bees from a tree branch into a box is one of life's magic shows.

If there are neighbors watching you can impress them. You lay a white sheet or large piece of cardboard on the ground directly under the buzzing cluster of bees. You then slide the bottom entrance lip of an empty hive under one edge of the sheet so that the cloth or cardboard forms a gigantic ramp into the hive's opening. You pause dramatically, and then you give the branch a single vigorous shake.

The bees fall out of the tree in a single clump and spill onto the sheet like churning black molasses. Thousands of bees crawl over each other in a chaotic buzzing mass. Then slowly, you begin to notice something. The bees align themselves toward the hive opening and march into the entrance as if they were tiny robots under one command. And they are. If you bend down to the sheet and put your nose near the pool of crawling bees, you can smell a perfume like roses. You can see that the bees are hunched over and fanning their wings furiously as they walk. They are emitting the rose smell from a gland in their rear ends and fanning the scent back to the troops behind them. The scent says, "The queen is here. Follow me." The second follows the first and the third the second and five minutes later the sheet is almost empty as the last of the swarm sucks itself into the box.

The first life on Earth could not put on that show. It was not a matter of lacking the right variation. There simply was no room in all of the possibilities accorded by its initial genes for such a wild act. To use the smell of a rose

to coordinate 10,000 flying beings into a purposeful crawling beast was beyond early life's reach. Not only had early life not yet created the space—worker bee, queen relationship, honey from flowers, tree, hive, pheromones—in which to stage the show, it had not created the tools to make the space.

Nature dispenses breathtaking diversity because its charter is open ended. Life did not confine itself to producing its dazzling variety within the limited space of the few genes it first made. On the contrary, one of the first things life discovered was how to create new genes, more genes, variable genes, and a bigger genetic library.

A book in Borges's Library spans a million genes; a hi-resolution Hollywood movie frame, 30 million. Yet as immense as the libraries built out of these are, they are only a dust mote in the meta-library of all possible libraries.

It is one of the hallmarks of life that it continues to enlarge the space of its own being. Nature is an ever-expanding library of possibilities. It is an open universe. At the same time that life turns up the most improbable books from the Library shelves, it is adding new wings to the collection, making room for more of its improbable texts.

We don't know how life crossed the threshold from fixed gene space to variable gene space. Perhaps it was one particular gene's duty to determine the total number of genes in the chromosome. Then by mutating that one gene, the sum of genes in the string would increase or decrease. Or the size of the genome might have been indirectly determined by more than one gene. Or, more likely, genome size is determined by the structure of the genetic system itself.