SOME EVIDENCE FOR OMEGA

being Chapter Three of
A GENERAL THEORY OF VALUE

In a later work, *The Evolution of Complexity by Means of Natural Selection*, John T. Bonner more directly tackles the question of complexity growth in the realm of biology.[i] From a survey of statistical studies of species characteristics in relation to species age he draws several conclusions.

(1) The individual members of younger species tend to be larger in body weight and in size than older species, just as younger genera are larger than older ones.
(2) The typical population densities of a given species are inversely proportional to individual body mass.
(3) The number of different cell types involved in the "construction" of individuals of a given species decreases with evolutionary age. Or put another way: younger genera and species (such as mammals) are not only *larger* but are made up of a greater *variety* of cell-types than older genera and species (such as reptiles or arthropods).
(4) There has been an overall increase in the diversity and number of different species over evolutionary time (cf. our Figure 1.11).

In all, the picture Bonner discerns is one of increasing complexity, both potential and actual, at all scales, from individual cells to organisms to species to genera. There has been an increasing "division of labor" at all scales, Bonner finds, *and* an increase in the integration of these newly specialized functions into larger singular organisms, communities, and ecological systems. Greater differentiation of functions at any scale, together with larger agglomerations of similar functional units (cells, individuals) both represent an increase in C_{pot}. Both increase N in the formula $C_{pot} = \log N$, where N is the number of possible macrostates of a system comprising N possibly-interacting members. This growth in potential complexity is kept partially in check by the physical environment, partially by selection pressure, and partially by everyday mutual constraint on behavior. This is Bonner's "integration." Such constraints are represented by increase in organization, R, which is nothing more than actual complexity, C, growing but lagging behind C_{pot} by "just the right amount." Bonner does not report data that would allow us to compute Ω directly, or to check its optimality—its "right amountness"—with respect to C_{pot}, but his arguments everywhere make the case implicitly that such an optimum very likely exists.

Bonner takes up but does not press the issue of whether species-typical genome length, in terms of total number of DNA nucleotides or codons, is a suitable measure of complexity.

One would expect that total genome length would bear a strong correlation to species recency and complexity. It does not, however—for three related reasons. First, laboratory techniques for measuring the total genome length of a given species are delicate and give different results (the numbers published are estimates, averages);[ii] second, many genera have extremely wide ranges of genome length; and third, as we have learned, large swaths of the genome in all species appear to be "junk DNA"—DNA that is neither expressed in the organism's features nor involved in its growth and replication in any known way. This last factor especially renders "total genome length" a very broad index of organismic complexity at best. Indeed, we cannot even assume that the *ratio* of junk DNA to active DNA is the same from species to species.[iii]

With regard to Ω-optimality, several researchers have done statistical studies of DNA nucleotide sequences in order to estimate the (actual) complexity or to discern the degree of organization of DNA at different scales (read: "group lengths"). We began to look at this in Chapter One (p. 20 ff.). In 1994, R. N. Mantegna et. al. discovered greater natural-language-like statistical structure in non-coding regions of the genome than in coding regions, thus raising the question of whether junk DNA is really that junky. But the statistical similarity of junk DNA to 50,000-word long encyclopedia entries in English (which Mantegna used for comparison) might be more a coincidence than anything else—a curiosity. The same researchers also found that the redundancy of junk DNA is much higher (at group-lengths from 1 to 6 base-pairs) than that in coding regions, whose redundancy (or degree of organization, in our terms), they find, is close to zero.[iv] This is a conclusion we shall soon challenge.

Mark Ya Azbel in a 1995 study using autocorrelation functions agrees, concluding that DNA sequence structure at all scales is very close to white noise, i.e., random or supremely complex.[v] This, too, is a conclusion we shall challenge.

Wentian Lee, in a 1997 article reviewing progress to date on statistical studies of the complexity of DNA, finds few firm results to report except that DNA is either devilishly complex or statistically near random.[vi] This has partly to do with the youth of the field and partly to do with method, he concludes, which can charitably be described as "brute force:" using the computer to sift through millions of base-pair sequences and to look for correlations using statistical tests.

But curiously, all extant studies have overlooked a very interesting and well-known fact about DNA: to wit, that whereas there are 64 *possible* amino acids that codons (base-pair triplets) could specify, in nature we find only 20. Let us see where this leads.[vii]

Potential complexity, C_{pot}, presents no problem of measurement: C_{pot} is equal to $\log_2 4^3$, or 6 bits per codon. Actual complexity, C, is computable by looking at the frequency distribution of the codons that are used to specify the 20 amino acids plus 1 "stop" message.[viii] Luckily, so-called "codon usage tables" for many species are published.[ix] Using the formula for C given in Chapter One, we find a strong similarity across species for the magnitudes of C and R, and an even greater closeness yet between the empirically computed magnitude of Ω to the theoretical optimum magnitude of Ω as projected by our theory when C_{pot} = 6 bits. All points (from different species) lie along the contour of Ω equal to 4.24 bits. Note also that Ω/C_{pot} is approximately equal to $1/\sqrt{2}$, as it "should" be. The results are shown graphically in Figures 3.1a and 3.1b. The slight bias shown towards the more-*organized* side of the ridge of Ω may or may not turn out to be significant.

Figure 3.1, a and b The complexity, organization, and complexity-and-organization of a variety of species' DNA at the scale of codons.

The data used above was drawn from long DNA sequences of expressed genes, and not from non-coding or junk DNA. If we could assume that the ratio of coding to non-coding DNA were at least roughly the same across most species, we could multiply the magnitude of Ω per codon by the total number of expressed codons and arrive at a picture of total Ω of DNA (at codon scale) not unlike Figure 2.10, with humans located at the top right, viruses at the bottom left, and the rest of life's creatures arrayed with remarkable conformity to the Great Chain of

Being between them along the 45° diagonal of Ω-optimality—the ridge of the Ω-surface.

Man and beast, plant and mite, differ from each other not in the "quality" of their DNA, we realize, but in the *quantity* of DNA that instructs their biological growth and development. Indeed, because we share so many genes with all living things, we ought not be surprised when an information-theoretical analysis of our DNA shows there is little a difference in the quality of the weave. But DNA's Ω-optimality at the scale of codons and with respect to their function as amino-acid specifiers is more surprising. It is reported here, I believe, for the first time.[x]

Of the complexity-and-organization of a fully-grown creature living life at full tilt—all blood and bones and thought and action—we have no estimate. It must be orders of magnitude higher than even its total DNA Ω at the scale of codons, but one cannot help but imagine that it is at least *proportional* to that number. Some empirical clues to overall lifefulness, however, and its relationship to complexity-and-organization can be gleaned from the relatively new science of *artificial life*.[xi]

Artificial life seeks to simulate if not living systems themselves—cells, plants, animals—then conglomerations of simple models of these in interaction with each other *in silico*, i.e., in a computer.[xii] From the local interaction of many, many such "individuals"—each with no thought for the overall state of the system—larger-scale "social" organization often emerges of itself, and with it orderly change and long-term development or evolution.

The simplest kind of artificial life forms are called *cellular automata*, or CAs, a term invented by John von Neumann in 1966.[xiii] A basic CA is set up as an array or grid of *cells* ("automata") on a computer screen. The color (or "state") of each cell at any given time is made wholly dependent upon the colors (states) of all the cells around it a moment earlier (as well as, sometimes, its own previous state). When, under certain very simple and local rules, groups of such cells are set to changing states in this mutually dependent way, some rather complex and organized patterns of behavior emerges, this even though no rule for this larger order is anywhere written in the software. For example, in some CAs, groups of cells may coalesce and travel about like so many little machines or animals. Certain starting patterns proliferate like weedy wallpapers to take over the screen; others persist for only a few cycles, like fireflies, and wink out. These are analogies, of course, to natural life, but the spontaneous emergence of order and virtual motion is very real, and quite convincing as a picture of something fundamental about how systems can become *animate*—if not literally alive—when built from the "bottom up" out of large numbers of simple and local interactions. Certainly, none of this complexity could be predicted from an inspection of the algebra of the rule systems.

Some artificial life systems go further than basic CAs and try quite literally to model living creatures and their interaction with each other and with a physical environment. For example, researchers will introduce birth, self-reproduction, and death by violence, starvation, or old age. They might strew resources ("food" or "fuel") about the "landscape," or have rules of change-of-state that can change over an "organism's" history. These artificial life systems—perhaps the best-known of which is *Tierra* by Thomas Ray—are really models of ecosystems. As one might expect, when the rules are right, different "species" form and dominate and die off, "parasites" develop, "wars" occur, as do occasional ecological wipe-outs and recoveries...and all this can be witnessed on a computer screen over a matter of minutes or hours rather than the years it would take in nature.

One of the newest developments in artificial life studies is *artificial societies*, a term coined by Robert Axtell and Joshua Epstein. Here the attempt is made to model human social systems with such inter-cell processes as bilateral trade of "goods," communication with non-neighboring cells, each cell having changing and different "preferences," memory, and so forth.

Now, with these definitions behind us, let us look at a couple of these artificial life systems more closely.

Cellular automata and artificial life systems

Perhaps the best-known and simplest CA is one called *life*. *life* is a game (or research tool, depending on what you do with it) developed by John Conway in 1974 and today widely available in different versions online.[xiv] In *life*, each cell can be in one of two states, "on" or "off" (on the computer screen: black or white). To decide which of these states to be in next, each cell inspects the state of each of its eight immediate neighbors as well as its own current state and applies a certain decision rule, which we need not go into here.[xv]

The player/researcher creates a *starting pattern* of "on" and "off" cells on the screen, and the CA is allowed to run, updating the state of each cell at every step forward in time.[xvi] Most starting patterns quickly lead to a blank screen or to a sprinkling of frozen "on" cells. Many develop into boring wallpaper patterns that steadily fill the whole screen and then stop. But some starting patterns produce "life": configurations of cells that persist as they seem to travel about, that sometimes absorb each other and sometimes annihilate each other on collision, that spew and pulse and produce "progeny." There are "gliders," "glider guns," "eaters," "spaceships," "puffer trains," etc.

When we look at most of *life*'s viable patterns we notice that approximately one-fifth of the cells are usually "on," and four-fifths are "off." This means that the base probability of a randomly chosen cell in a lively pattern being found "on" is around 0.2, and the probability of a randomly chosen cell in a lively pattern being found "off" is around 0.8. Moreover, this pair of probabilities cannot change very much over time if the pattern is to replicate, travel, pulsate, breed, etc.

Now, a single cell can behave no more complexly than when its behavior appears to us to be random. Like a fair coin, its potential complexity, C_{pot} is 1 bit per update. But from the above observation about probabilities, we find that, as with a biased coin, actual complexity is 0.72 bits. This means that its degree of organization is 0.69 bits, and its complexity-and-organization is 0.71 bits.[xvii] *Life*'s rules and most successful patterns, it seems, exemplify those summation processes, parameter-settings, and cell configurations that generation after generation will deliver the optimum called for by our theory, namely Ω/C_{pot} approximately equal to $1/\sqrt{2}$, or 0.71, and C approximately equal to R. At the scale of a single cell responding to its immediate 8-cell neighborhood at least, *life*, like the rest of life, seems to prefer the ridge of Ω. To see how *life*'s rules actually pull this off, the reader is invited to study Appendix Four.

Conway's *life* was the first widely accessible instantiation of John von Neumann's theory of cellular automata. Thomas Ray's *Tierra* artificial life system goes much further in attempting to model evolutionary processes.[xviii] This *Tierra* does by replicating genetic self-reproduction *in silico*. With relatively simple local rules, *Tierra* is able to simulate the evolution of multicellular organisms from unicellular ones, population growth, increased genetic diversity, the evolution of parasite-host and predator-prey relations, and much else in one or several computers (read: ecologies) simultaneously. Although not without occasional reversals, the Rule is as it is in nature: speciation, greater length of genomic codes in new species, as well as more complex and more organized "social arrangements" emergent from less complex and less organized ones. *Tierra*'s algorithms are in principle amenable to further "Ω-analysis." Carrying out the analysis, however, remains a task for future research.

If *life* is the most simple, Robert Axtell and Joshua Epstein's *Sugarscape* is perhaps the most complex and ambitious attempt yet to extend cellular automata into the problem of modeling human societies. "Artificial societies" are what Axtell and Epstein want to create. With these in hand, they argue, social scientists might for the first time be able to test how different behavioral rules and incentives applied at the individual, local level, can create macroscopic social dynamics that go far beyond the easily foreseen and easily calculated aggregation of local effects. Artificial societies, they say, offer us a way to do "social science 'from the bottom up'."[xix]

Although far more elaborate than *life*, *Sugarscape* is concomitantly less abstract. For example, whereas in *life* all "creatures" and their motions across the screen *emerge* from inter-cell relationships like waves on the ocean, *Sugarscape* is programmed so that "agents" (which appear as red dots on the screen) are possessed of certain internal states that they *take with them* as they move rather literally (given that the whole thing is just software) from place to place in search of more "sugar." Each agent has a certain metabolic rate, a capacity to see a certain distance away from itself ("vision"), a capacity for storing excess sugar ("wealth"), and so forth. The prior distribution of sugar over the grid constitutes the landscape over which the agents roam like hungry ants, or like deer after forage. (The sugar in *Sugarscape* is able to grow back at a certain rate after it has been "consumed.")[xx]

For us, whether or not *Sugarscape* represents a plausible artificial society is less interesting than whether or not we can find *our* holy grail, Ω-optimality, in a system which clearly displays life-like behaviors (or doesn't) depending on local, CA-like rules and parameter-settings. The answer is: we can, but (so far) only for *Sugarscape* in its most basic form. The reader may or may not want to follow the technicalities in the notes.[xxi] We find that when an agent's neighborhood is 8 cells in size, which is "normal" in *Sugarscape*, then Ω is close to optimal in terms of our theory, and drops off slowly as the neighborhood gets larger. We see how the social sagas played out in *Sugarscape*—the migrations, the wars, the markets, the epidemics—are founded on rules that locate all agents and their "concerns" on or near the ridge of Ω.

We are not the first to look for some sort of complexity optimum that distinguishes living from non-living systems. Artificial-life pioneer Chris Langton sought to do the same for CAs with his "lambda parameter," λ. λ can vary between 0 and 1. When λ is less than 0.5, CAs tend to freeze or display simple repetitive behaviors; when λ is greater than 0.5, CAs tend to run to chaos, "snow" everywhere. When λ is roughly equal to 0.5, the system proliferates.[xxii]

Naturally, *our* question is: does Langton's empirical optimum value for λ bear any relationship to our theoretical optimum for Ω? The answer is yes. Again, readers interested in the technicalities should consult the notes.[xxiii] The bottom line is this: that over a large number of experiments, Langton reports that λ-approximately-equal-to-0.5 characterizes cellular automata that display complex-and-organized, life-like behaviors. Using Langton's own measures, we find that these CAs also lie on the ridge of Ω.

Studies in psychology

Early in the 20th Century, almost all empirical study of animal and human behavior was cast in the behavioralist theoretical framework created by J. B. Watson. Behaviorialists did not think it proper or productive to delve into an animal's thoughts, feelings, intentions, etc. in order to explain behavior. *That* was left to novelists, poets, and philosophers. Rather, like physicists and chemists, they were to pay attention only to the animal's unambiguous and overt responses to clear physical stimuli from the environment. Humans were to be studied the same way if the results were to be science.

Of special interest to behavioralists, then as now, was the question of *learning*. Under what conditions, they wanted to know, do animals discover or learn to cause rewarding experiences, and under what conditions do they learn to avoid punishing or unpleasant ones? It seems, for example, that all animals use this simple rule: repeat those behaviors that were rewarded in the past; do not repeat ones that were punishing or ineffective. Rewarded behaviors are "reinforced" while unrewarded or punished behaviors are "extinguished." Moreover, the memory processes involved in this *conditioning* process (as this kind of learning is called) need not be conscious. Worms can be conditioned to behave in certain ways, just as humans can be. The conceptual similarity to evolutionary processes should be clear: "good" behaviors get to be acted out another day; "bad" ones do not.

Over the years, an immense body of research using the behavioralists' deep and simple model has accumulated. A small part of that research has been interested in the extinction process per se, and one finding in particular has relevance to our quest to find Ω-maximization in nature. The finding is this: (new) behavior that is reinforced with complete reliability is more quickly learned than behavior that is intermittently reinforced, and much more quickly learned than behavior that is infrequently (or never) reinforced. Nothing unexpected here. But, when one looks at *extinction* rates, the always-reinforced-behavior disappears—is "unlearned"—very soon after reinforcement stops while *intermittently-reinforced behavior, once learned, persists for a much greater length of time after reinforcement stops*. This phenomenon is so reliable and universal that it has been given a name, to wit: the "partial reinforcement extinction effect."[xxiv]

The finding makes some intuitive sense: if one becomes accustomed to complete reliability in anything, departure from it is noticed immediately and gives one reason to become suspicious. If, on the other hand, one has become accustomed to less-than-perfect reliability, then change is less noticeable and, likely, less meaningful. So, what frequency of intermittent reinforcements, we wonder, produces the mildest extinction rates? Might it be one whose Ω is maximum? If so, then not only do we have another small piece of evidence supporting our theory, but also a new way to talk about what is going on with the partial reinforcement extinction effect.

The only study I found that produced the sort of data that could readily test our hypothesis was (luckily, I suppose) one that involved humans. The type of learning and extinction was of the "classical" conditioning type, i.e. involving the manipulation and training of partially involuntary behavior, in this case, the eye-blink response to a light flash associated or not with a puff of air to the cornea. The results of this study, by David Grant and Lowell Schipper in 1952, are summarized in Figure 3.2.[xxv]

Figure 3.2 Acquisition (learning) and extinction of the conditioned eye-blink response. Percentages in graph indicate relative frequency of reinforcement during acquisition period.

We see that when the light's turning on is associated with a puff of air 100% of the time during the acquisition period, conditioning holds for a few trials and then is rapidly lost in the extinction period (i.e. when the light is turned on *without* an accompanying puff of air). When the reinforcement is more erratic during acquisition, however, the strength of conditioning both jumps upward and stays relatively higher during extinction. This is especially the case for 75% reinforcement frequency. Doing the calculations of C_{pot}, C, and R and deriving from the value of Ω, we find that the 75% indeed has the highest Ω of the options they offered.[xxvi] Grant and Schipper only used the five reinforcement frequencies: 0, 25, 50, 75 and 100%. Had they used a 79% frequency in the experiment, which truly maximizes Ω, their subjects might have shown even greater retention of conditioning during the extinction phase.

But what could all this mean? What do flashing lights and puffs of air to the eye have to do with lifefulness, which is what I claim Ω-optimization represents? I would propose that *most living creatures are "wired" to be especially sensitive to the presence and behaviors of other living creatures, and thus to all life-like motions and behaviors, even if they issue, in fact, from* *mechanical processes*. Grant and Schipper's subjects, I suggest, were involuntarily responding to the quasi-random behavior of the experimental apparatus as they would to something alive, and the most "convincing" behavior—convincing neurologically of the unconscious hypothesis that the apparatus was intelligent, alive in some primitive way, or human-controlled—was the one that paired light-flashes with air-puffs with a probability distribution, a "reliability," that maximized Ω.[xxvii] If I am right, then coins whose bias was close to 80:20 would be thought more interesting, more fun to play with, and more memorable than either perfectly fair coins or coins that always came up heads. Remember how the cells in the most lively patterns of John Conway's *life* also maintained the Ω-maximizing probability distribution of around 0.2:0.8 for their *on:off* states? Game and toy manufacturers take note.[xxviii]

Spurred by the cybernetics movement that began after the Second World War, the 1950s and 1960s saw a surge of enthusiasm among experimental psychologists for studying the *information-processing* abilities of humans. Do people have an optimum performance level? Does this change with training or maturity or the complexity of the task? And how should one measure task- or stimulus-complexity—i.e. "information content"—as it appears to a human subject in the first place? Would the machinic formulae provided by Shannon and Weaver suffice?

Psychologists first into the breach were Fred Attneave and George A. Miller, followed by Daniel Berlyne whose synoptic 1960 book *Conflict, Arousal, and Curiosity* quickly became a touchstone in the field.[xxix] The research Berlyne reports upon, Berlyne's own work, and much research since, have all shown that there is not only an *upper* limit to the human ability to deal with complexity, but also a *most-preferred* level, with both "too much" and "too little" rejected.

Evidence of Ω? Let us see.

To start near the beginning: in his legendary paper, "The Magical Number Seven, Plus or Minus Two" in *Psychological Review* in 1956, George A. Miller experimentally sets human optimum information-processing capability at 7 items ("...plus or minus 2"), or between 2.3 and 3.2 bits, for any one task of absolute judgment upon, or immediate recall of, random stimuli that varied from each other on a single dimension (such as pitch, loudness, saltiness, size, weight, or position on a line).[xxx] Try to deal with more than 9 items at a time, and we start to make mistakes. These limits *can* be exceeded by increasing the dimensionality of the 9 items (for example, letting them each have color *and* size, position *and* length, and so on), but not by very much—to around 5 bits.

How, then, Miller asks, do we routinely accomplish feats that clearly require much greater spans of attention or memory, like driving a car or reciting a poem? His answer: "chunking." We group several items together and rename them as one thing, dealing with each *chunk* as a single item at a given time. The way we remember telephone numbers is illustrative: we do it by remembering little groups of numbers—in America, the three-digit area-code group, then the three-digit city- or neighborhood-wide group, and then the four digit household code usually broken into two. Each chunk is a ditty, and there is a rhythm to it all: dáh dah dah, dáh dah dah, dah dah, dah dah. Remember how you learned the alphabet? In general, says Miller, we are able to deal with large quantities of information (as measured at the smallest scale of elementary items) by grouping the items, grouping the groups of items, grouping the groups of groups, etc., in hierarchies of potential complexity of around 2.8 to 5 bits per scale level.

To the reader of this volume, Miller's "chunking" is a familiar idea. Both in this chapter and the last we talked about scaling and grouping, and Miller is pointing to the same phenomenon as occurs naturally in our mental processes. After all, if Nature can do it, why can't we? (Indeed, do we have any choice? Think of how your computer "desktop" is organized, or the contents page of a book.) But Miller also puts a number to the idea, and his data suggest that the "window of comprehension" of Figure 2.10 measures perhaps 5 bits on a side (though *through* this window *over time*, of course, flows a great deal more information).[xxxi]

Now Miller's "magic number seven" speaks less of an optimum than of an asymptotic maximum. The results he reports are summarized in Figure 3.3.

Figure 3.3 Limits of output complexities (information) for given input complexities in tasks involving absolute judgment of magnitudes, according to G. A. Miller.

What Miller did *not* do is force the input complexity even higher, or ask his subjects which level of input (or task) complexity they *preferred* dealing with. These questions were taken up by later researchers. In 1960, another Miller, James G. Miller, for example, reports several studies of mental and performance breakdown under information overload, an experience which was surely not very enjoyable for the subjects involved.[xxxii] I will report that work in a few pages. At this point we can say that it seems that animals, including human beings, are happiest when coping with an environment that is, for them, neither too boring nor too stimulating.

For Berlyne (also in 1960) this meant that animals seek to maintain an optimum level of *arousal* in brain and nervous system.[xxxiii] There exists, said Berlyne, an optimal complexity for objects and events in the animal's environment: *it is that level of (actual) complexity which, combined with the recent history, cognitive capacities, and current interests of the individual animal, places it at or near its optimal arousal level.*[xxxiv] But what is this "optimal arousal?" Well, arousal is independently measurable by galvanic skin response (GSR), "brain-waves" (EKG), heart rate, and other involuntary somatic signals, but it *feels* to us like healthful wide-awakeness. When we are optimally aroused we feel alert but at ease, relaxed but not dulled. It is a state of mind that corresponds to optimal brain function and optimal productivity of, and receptivity to, information. Not surprisingly, Berlyne and his colleagues found a preference for the "moderate psychological complexity" that usually delivers optimal arousal. And he found that events that move us closer to such moderate levels of complexity are preferred over those that take us away from them.

Now we, of course, have defined *value* as movement towards greater Ω, which is optimal at "moderate levels of complexity" too. The reader might compare Figure 3.4a with Figure 2.6. From this description it is easy to make the translation: optimal arousal is equivalent to the maximal (feeling of) lifefulness which happens when Ω is maximum for a given magnitude of C_{pot}.[xxxv]

Figure 3.4 a The basic relationship of perceived or psychological complexity to preference and , 3.4 b, over time (following Walker, 1973).

For Berlyne, the hill shape (or "inverted-U" as it is called) records an empirical fact, namely, that when it comes to dealing with complexity, people prefer things that are not too complex and not too simple but "just right"—like Goldilocks. For us, the hill shape is the Ω-surface cut across in some transverse section between rigidity and chaos...a profile, that is, cut by either by a contour of constant C_{pot} or a contour of constant $C + R$. Our theory has the advantage of being able to model non-constant potential complexities too, i.e. how "preference" interacts with experience, learning, and indeed, evolution, which are all processes that push back the frontier of C_{pot}.[xxxvi]

In 1973, Edward Walker supplemented Figure 3.4a with a diagram showing how, with learning or habituation, certain repeated once-overly-complex stimuli can come to seem "just right" and enjoyable. Figure 3.4b is a re-drawing of Walker's proposal.[xxxvii] Notice that while stimulus (event or task...) number 3 is the ultimate winner, at times before that numbers 1 and 2 were the winners (before going on to being boring). Walker cites several empirical studies that substantiate the theory embodied in Figure 3.4b. One such study looked at repeated playings of four piano compositions, rated independently at the outset as being very-simple, simple, complex, or very-complex. There were nineteen playings of each in all, in random orders, etc., etc. Subjects were asked to rate their "pleasingness" and "interest." Results? At first playing, the simpler compositions were preferred. By later playings, however, the "complex" composition was most pleasing. And there matters seemed to rest: the "very-complex" composition was rarely found most pleasing.[xxxviii]

Unfortunately, no quantitative analysis of the *a priori* actual complexity of the music was carried out or reported, and so we are unable to check whether Ω was maximum for the most-liked composition. What we *can* infer with some certainty, however, is this: that the subjects had established a ceiling value for C_{pot} which functioned as a reference for all of the compositions. (After all, each subject heard all four pieces several times and subjected them to mutual comparison.) Now, we know that holding C_{pot} constant, as a reference, and varying C gives us a hill or "inverted-U" curve, and so it seems that our theory offers a plausible explanation of what Heyduk's "pleasingness maximum" might have consisted in, namely: highest Ω for the reference C_{pot}.[xxxix] Walker comes to the same finding when he concludes that complexity, actually present in some ideal or non-ideal amount *in* the music and *for* the subjects, was the salient predictor of value (read: preference) in this experiment.

In an attempt to identify Ω more definitively in a comparable context, I performed a pilot study with experimental psychologist Dr. William Lee. Thirty-five subjects were asked to rate (for "enjoyment") a set of fifteen rhythm melodies, each using the 12 different notes between middle C and the B-flat nearly an octave higher, of equal temporal length, and without silences. Some sixteen million melodies were computer-generated using a random-number generator. From these, fifteen were selected and grouped into five groups of three, statistically-identical but different-sounding melodies. The five groups were chosen so that they were located at five equally-spaced positions along the $C_{pot} = \log_2 12 = 3.585$ bit contour, from rigid through chaotic. The experimental question was whether subjects would prefer melodies that were on the ridge of Ω over melodies that were further away from this presumed ideal.

The answer is Yes...almost. The most preferred group of melodies lay slightly to the right of the ridge of Ω, i.e. the more complex, less organized side.. The order thereafter followed theory. We concluded that either our formula for Ω needed parameterization to move the ridge clockwise a bit, or that our subjects were so bored with the experiment—it took an hour of listening to many repetitions of the stimuli in different pairings—that they preferred the more complex melodies. Had familiarity had made the melodies subjectively simpler over time in ways that our statistics could not measure? Perhaps. But we had another hypothesis that was easier to test: that the preference shown for slightly more complex and less organized melodies was in reaction to, or in compensation for, their rhythmic simplicity.

Figure 3.5a Preference for 60-note melodies (Benedikt and Lee; bold numbers represent preference order)

A second study was undertaken using more subjects (N = 25, 14 male), with better data analysis, and with the addition of *rhythmic* complexity-and-organization as a second independent variable. (The dependent variable remained "liking" or "preference.") This yielded the three-by-three matrix of stimuli shown in Figure 3.5b. Each of the nine cells in the matrix was represented by three randomly chosen computer-generated "songs" (which themselves used random generation processes filtered for the required statistics), each judged by all subjects on a seven-point rating scale from "dislike a lot" (-3) through "like a lot" (+3). There were thus twenty seven songs in all, which were played to subjects in three sets of nine, each randomly ordered. The number reported in each cell of Figure 3.5b represents the total score for each kind of song.

Figure 3.5b. Preference for 64-note "songs" (Benedikt and Burnham)

The winning song-group was the expected one: the group that was highest in Ω in both melody and rhythm. This supports our hypothesis nicely. Note, however, that overly-organized songs were strongly and consistently disliked, ameliorated slightly by optimal omega in melodic structure. Note too that when melodic complexity was high, more organization in rhythmic structure became somewhat ameliorative, possibly because it was a way of keeping *total* song complexity below some maximum level.[xl] (Cf. Figures 3.3 and 3.7)

Further studies would look at C and R not just at the scale of *one* note, as these two studies did, but at group-lengths of two, three, and four notes at time. This will measure C, R, and Ω at larger "scales" in the melody sequence, which is more like how real music is listened to (i.e. detecting little *patterns* of notes: chunking). A given melody would thus be represented by four points on the Ω surface, each on a larger arc of C_{pot} and another four representing rhythmic Ω, making eight points in all. Prediction: the more are the points that lie on the ridge of Ω, the more the "song" is liked…until some training-dependent, complexity-handling limit is reached.[xli]

One psychologist who has pursued the arousal/complexity model of human motivation and happiness farthest into the recent day is Mihaly Csikszentmihalyi. A major theme in most of his books, it stands out in several: *Beyond Boredom and Anxiety* (1975), *Optimal Experience* (1988, with Isabella Csikszentmihalyi), *Flow* (1990), *The Evolving Self* (1993), and *Finding Flow* (1997). As these titles suggest, Csikszentmihalyi extends Berlyne's concept of optimal arousal to the idea of *flow*. Like many thinkers, Csikszentmihalyi is critical of any needs-based, utilitarian view of man. He is interested in reminding us that some of the most rewarding and educative experiences a person can have come from autonomous action, from activities engaged in for their own sake and not for any social or economic or materially-productive purpose. Play and exploration are two prime examples of such activities. One does them because one enjoys *doing* them, because one feels on the one hand totally in control, and yet, on the other, without a bossy or conflicted *self* doing the controlling. Experience seems to "*flow*" in these situations; time flows, work flows...indeed, with flow, work is hardly "work". In a state of flow, we feel pleasure of a special sort: not the pleasure of consumption or ego-gratification but of being in tune with the world: active, competent, fully alive. Moreover, after experiencing states of flow, one feels drawn to taking on tasks that are a little more difficult, and a little more yet, and so on, as one's competence increases.

In *Beyond Boredom and Anxiety*, Csikszentmihalyi and his colleagues subjected rock climbers, chess players, dancers, and surgeons to a battery of surveys, experiments, and interviews. The dominant motivation they found among these individuals was not the achievement of some socially rewarded goal, or the making or spending of money, or the pleasures of affiliation with the like-minded, although all of these motivations played some part. The dominant motivation was to achieve a quasi-ecstatic state of mind Csikszentmihalyi called *flow*, and this at ever higher levels of complexity. Moreover, Csikszentmihalyi and his colleagues found, people deprived of flow experiences for long periods of time perform badly at tasks they would otherwise find easy. Frustration and ennui both, it seems, take their toll.

Here, and again in later books, he extends the ideal of flow to everyday life. The happiness of the flow experience is everywhere a potential—in every job, hobby, and engagement with the world.

Now, one diagram shows up frequently in Csikszentmihalyi's writing. It both encapsulates his theory of flow and shows how one might translate flow into the terms we have been using.

Figure 3.6 Csikszentmihalyi's model of flow, adapted from *Flow* (1990)

In Figure 3.6, the X-axis is "challenge" and the Y-axis is "skill."[xlii] Flow occurs when the magnitudes of the two are matched. The "flow channel" takes us to higher and higher levels of performance and to richer experiences.

The translation into our system of terms is easy: "challenge" corresponds to the complexity of the task as it actually is, *C*, but more importantly, as it is *to* the person undertaking the task. "Skill" corresponds to perceived organization, *R*, and the "flow channel" is our "ridge of Ω" by another name and at another scale of nature.

More carefully: It is perhaps easier to interpret challenge as actual, experienced complexity, *C*, than to interpret skill as experienced organization, *R*. But one needs to think about what "skill" really consists in, which is the ability to discern the order, the redundancy, that is inherent in the task and aligning one's behavior with it. The skilled chess player, for example, does not see an arbitrary arrangement of pieces. She sees a pattern and order. She also "sees" her opponent's plans. The unskilled chess player sees less: a simpler and less-complex order; and the one who cannot play chess at all sees only an inexplicable mingling and repositioning of carved wooden figures on a black and white grid. This front-end complexity, without organization, prevents him or her from seeing the greater complexity (and organization) that lies beyond.

The experienced climber looks at a rock face that to you and me would look quite intractable and sees in its "random" features clear opportunities for footholds and handholds. We say that he knows what to look for.

Similarly, the dancer's limbs, like the pianist's hands, are trained to remember and perform repeating patterns. What might look to *us* like an endless stream of surprising leaps and bends, what might sound to *us* like a never-ending torrent of half-familiar melodies and harmonies, to their performers look and sound quite different. For them the work is etched into blocks and repeats, into figures and chords all neatly named. Those names are located in a body of theory and convention, and the whole is clarified by practice and a great deal of passed-on wisdom. Indeed, performers can easily become bored with what they do even as new audiences remain enthralled, swept vicariously into the performer's original—now simulated—experience of flow.

With this reading, Figure 3.6 maps fairly neatly onto Figures 2.3, 2.4, and 2.7. Csikszentmihalyi's "zone of boredom," where skills exceed challenge by far, corresponds to our approaching the zone of rigidity, i.e. lifelessness due to too much structure, too much order, too little uncertainty and surprise. Csikszentmihalyi's "zone of anxiety," where challenge exceeds skill, corresponds approaching to our zone of chaos; where systems become life-diminished due to disorganization, insufficient structure, and loss of predictability. The match is not perfect, to be sure. Some translation is required to go back and forth between these two independently-arrived-at models, but the interpretive effort is modest.[xliii]

Unfortunately, none of the empirical data Csikszentmihalyi presents to readers is in a form that allows us to check for Ω-maximization directly, using our formulae. This is not surprising. Our rather strict formulation of Ω can be tested only by empirical studies in which the complexity of stimuli can be carefully and objectively measured, and Csikszentmihalyi is studying extremely complex human behaviors using verbal self-report as the chief measure. However, with his theory of flow, Csikszentmihalyi has gone further than any psychologist in bringing the laboratory insights of Berlyne and others together with the human potential movement in psychology (founded by Abraham Maslow, Carl Rogers, and others) to answer important questions about the nature of happiness and the quality of daily life.

Csikszentmihalyi's theory of flow, as portrayed by Figure 3.6, takes on some importance for us. It is a bridge not only from Csikszentmihalyi's lifelong work to the thesis of this chapter, but from the thesis of this chapter to the many questions that surround satisfaction, happiness, and pleasure as these terms are understood in economics, psychology, and moral philosophy. As I will suggest in Chapter Four, *satisfaction* is a measure of personal or life-world complexity-and-organization—Ω-as-achieved, Ω-as-felt—but modified by the proximity we feel between this level of Ω and a level we remember, or imagine, could be greater. *Happiness*, I will suggest, is what comes with the *increase* of our satisfaction: it is the mark and result of a "value experience," which happens when $\Delta\Omega$ is positive in sign.[xliv] And *pleasure*, I will suggest, corresponds to time rate-of-change of happiness; that is, pleasure is proportional to $\Delta\Omega / \Delta t$.

In later work, Csikszentmihalyi moves from a purely individualistic, purely psychological, point of view to a more political one. He begins to investigate the social values, conditions, roles, and institutions that are most productive of optimal experience, and those that are not. "We need institutions, families, schools, media, jobs, communities, environments," he writes in 1997, "that make the minds of the next generation more complex rather than more simple. We need more complex habits of life."[xlv]

In the chapters that follow—and without trading individual happiness for something nominally larger and more important (like "the good of society") as the proper site and measure of value—we will try our hand at describing in more detail how human intercourse produces and preserves not *complexity* exactly but, rather, complexity-and-organization, Ω, in both institutions and the minds that make them up. Csikszentmihalyi's work stands as a beacon and bridge to how this might be done.

People prefer complexity in their world in some "right amount": not too much, not too little. We go back to the 1960s, this time to the work done by another psychologist named Miller—not George A. Miller, who we looked at a few pages back—but James G. Miller.[xlvi] In a series of papers, J. G. Miller studied how people cope with information under- and overload by giving them tasks of increasing complexity, to be performed under increasing time pressure. Though his data were fairly noisy, Miller's experimental studies support a rather commonsense model: at less than, and more than, an optimum cognitive load, people's performance worsens. Figure 3.7 abstracts the results. We see that subjects' performance falls away from the 45° ideal-performance line at between 2.5 and 4.0 bits per second. With a 10 bit/sec input (or task) complexity, performance (or output complexity) peaked at around 5 bits per second.[xlvii]

Figure 3.7 Input Complexity, Output Complexity and Overload Stress (adapted from Meier, 1962, p. 81)

It would be hard not to notice the similarity between Figure 3.7 and Figure 2.6, which plots Ω against C for constant C_{pot}. The 5 bits/second information "dropped" by Miller's subjects might have been the degree of organization, R, they found in the task or that they "put there" by the coping mechanisms they used. No matter. Remember Paul and Quentin in Chapter One? Miller's subjects, it seems, found Csikszentmihalyi's *flow* at Ω-optimal task complexity.

Institutions, as systems, might prefer complexity in their world in some right amount too. Richard L Meier studied a large research library as it tried to cope with increasing demands on its services.[xlviii] Like Miller, Meier's compiled a list of coping strategies (he called his "policies") used when the information-processing load was too high. Meier's list is longer and clearer than

Miller's, but the two have many overlaps. I list them both below, and supplement each with an interpretation of what is going on using the terms developed in this chapter. The ordering of responses to overload, going from mild to dire, follows Meier.

INCREASING LOAD

Meier's "policies"	J. G. Miller's "coping strategies"	Complexity Interpretation
1. Queue inputs at peak periods	Queue inputs	Decrease N at any one time
2. Prioritize queue	Process errors (?)	Increase R
3. Destroy/ignore lowest priorities	Omission	Decrease N (i.e. C_{pot})
4. Adapt to repetition with active files	Filtering	Increase R, decrease N
5. Create branch facilities	Multiple channels	Divide N into smaller Ns
6. Encourage middle-men	as above	as above
7. Create a mobile reserve	as above	as above
8. Evolve minimum performance standards		Decrease C
9. Reduce these standards	Non-discrimination	as above
10. Search for a "magic formula"		as above
11. Let customers help themselves		Decrease N and R
12. Escape	Escape	Put $N = 0$
13. Work to (book) rule		Decrease C and R
14. Break up institution and salvage parts		Divide N into fewer, smaller sets

This tabulation of policies gives us only a hint of what was involved in the studies. One is struck, however, by the similarity between the responses of Miller's individuals and of Meier's institution to complexity-induced stress. Note that the fact that R is sometimes increased and sometimes decreased implies a search for workable, if not optimal, Ω—this as either C or C_{pot} (i.e. log$N$) retreat. It is remarkably easy, not to say amusing, to explore how Meier's list applies to a single, overworked person managing themselves, as it were.

Interesting too is a phenomenon which both Miller and Meier fail to note: the emergence of informal economies—traffic in favors, bribes, ingratiations, nepotism, etc.—when the formal structure of the firm is overloaded. Feeling underpaid, abused, overworked, people are beginning to "work to rule" on the surface but to work to another, more subtle set of rules in order actually to get things done. Whole countries can work this way. In the next chapter I will introduce the idea of *token economies*, and this is what we are talking about here.

What Miller and Meier's research confirms in the context of this chapter, though, is clear: the idea that the failure of any system to match the increased complexity of its environment can place severe stresses upon it. When there is no way to simplify the world, when there is no way to capitalize any further upon the environment's inherent organization and no way to escape to a less-complex environment, self-decomposition becomes the only option.

Happiest is the system that has found *rapprochement* between what it *can* do and what it *must* do, that can operate at its own best speed, not with no error, but with tolerable error.

Economic and social structures

Meier's research notwithstanding, the proposition that there might be an ideal level, or an ideal *kind*, of complexity in the social and economic arrangements people make, cannot be found in the literature. This is probably because the idea of complexity *per se* has not received much attention from either sociologists or economists. Economist Friedrich von Hayek was a notable exception, emphasizing as he did throughout his writings that modern economies are too complex to be centrally managed, or even effectively governed, by any one minister, committee, method, or theory. The miracle of economic coordination, argued von Hayek (following Adam Smith), is necessarily the product of thousands upon thousands of economic agents—individuals, companies—acting in self-interested ways with only limited, local, and time-sensitive information at hand, i.e., with the kind of information routinely supplied to transactors in marketplaces.[xlix]

The advent of the global "information economy" has caused a great number of popular books to be written on the subject of how telecommunications and computers are "changing everything" or, at the very least, how they are helping businesses manage the complexity these same technologies generate in connecting them to their customers and to each other more richly. Within *this* literature complexity is not a foreign idea. But neither is it taken as a quantifiable property of an evolving world—a driver, in some sense, of the very evolution we want, and therefore something to be sought after if it is complexity of the "right" kind.[l]

One of the first writers to shed light on the subject in economic terms was David Warsh in his 1984 study, *The Idea of Economic Complexity*.[li] Unfortunately (for us) Warsh does not show that there is an *optimal* quantity or quality of complexity in the economy, but he makes the convincing and empirically well-supported argument, first, that there has been a rapid increase in social and economic complexity over modern times, and second, that the characteristic *value*s of goods and services, insofar as they are measured by money prices, have increased over the same period in a way that is correlated to their increasing complexity.

Both product complexity and production-method complexity are deeply implicated in a product or service's value. More complex and specialized (read: organized) jobs are more highly remunerated too, both absolutely over time and relatively at a given epoch. This means that the overall increase in the number, variety, quality, and complexity of products and jobs in modern times is not something to be regretted, even though it has driven up prices and wages. Complexity-driven price (and wage) increase is altogether different from *inflation*, which is caused (primarily) by an excess in the money supply at the macro level. Unlike monetary inflation, says Warsh, complexity-driven "inflation" is essential to social and economic health; and always has been.

Now, item by item, little of what Warsh reported in 1984—such as the accelerating degree of specialization and integration of industry occurring at regional, national, and international levels, or the burgeoning volume, legal complexity, and number of people involved in directing capital flows between global marketplaces—would be news to anyone today. These trends continue apace. His detailed comparison between the variety of goods and jobs available today and the much smaller variety available a hundred years ago is striking, but no more striking than the comparison would have been a hundred years ago, relative to a hundred years before that, and so on, all the way back to the 1400s.[lii] With facts and figures such as these, though, Warsh turns our attention to the idea that complexity is a force its own right—and generally a force for the good. Without understanding complexity's deep relation to value, he argues, wealth is too easily thought of as being goods and money in *quantity*, rather than goods in variety and quality, about richness of experience. Without understanding complexity's deep relation to value also, the increasing complexity of economic life (and life-in-general) is apt to be seen as an evil: not a boon but a *bother*, a reason for complaint, something to be hacked at like bamboo or else escaped from. *Simplicity* becomes the watchword, the quality that can sell anything—from cars to computers to apartments to clothes to investment schemes to whole life-styles.

Whether in the form of nostalgia for "simpler times," or of a dream of technological utopia where everything is available at the click of a button, the appeal of simplicity is powerful. But if increasing product, job, and life complexity is essential to the production of value, as Warsh argues and we must agree, is the longing for simplicity *misguided*? Not entirely. Things *can* get too complicated, as we learned that from Berlyne and Miller and others, and when they do, lowering C helps. What could be better than discovering that something we value has become simpler to make or acquire? Moreover, our theory of value tells us, we can live closer to the ridge of Ω if, at the same time as we lower C, we increase R to compensate.

All this helps us realize that the simplicity we want is often not real simplicity. Quite to the contrary. What we want is a simple face or shell that screens us from the increasingly complex machinery (social or mechanical) that lies behind and within newly evolved things. In fact, we want performances and behaviors from our products that are highly sophisticated, we want levels of sensitivity to our needs and of reliability under stress that were impossible only a few years ago. This can come only through greater complexity and organization in the thing (or person). But very few people want to experience first hand what's under the hood of their new car, or inside the shell of their computer or camera—no more than want to see the inside of the human body in its full anatomical reality or who want to know everything another person knows. Hence the importance of designing simple computer graphic user interfaces (GUIs) and machine instrument panels. Hence, one might say, the importance of CEOs and politicians being able to "cut through" (or mask) the true complexity of the operations they run.[liii] Hence the value of tour guides. And so on.

Warsh captures some of these observations with what he calls *cost webs*. A cost web is a representation of all the independent institutions or businesses (and, at a smaller scale, individuals and machines) that presently work together to produce a given set of goods or services.[liv] Each business is a node in a graph, and between each node there passes information, money, and/or goods in some state of completion. The very size and complexity of a cost web, says Warsh, adds cost to the several products circulating through it. This is what one might expect on the grounds of the number of "middlemen" in the web, each taking his "cut." But webs also add value to the products circulating in them if, at each node, the complexity-and-organization of the product and/or its capacity to effect happiness is increased.[lv]

Take the cost web associated with the delivery of medical care. As one sees from Figure 3.8 (which still does not reach into very much detail), the number of agencies, suppliers, and professionals involved in delivering health care to patients has grown enormously. The price of health care has increased concomitantly. This would be greater cause for concern if the *quality* of modern health care were not so superior to that of the past. We need to realize that this "quality" is very much a function of the complexity-and-organization of the whole system.

The size and complexity of the average cost web is obscured to the final consumer, even deliberately screened, as I noted above. You don't know—and you don't *want* to know—what it took to put a plate of lobster salad in front of you at a restaurant. You just pay your waiter. In the case of medical care, however, it is not so obscured, as anyone who has questioned a hospital bill will agree.

Figure 3.8 Increasing size of the health care cost web, adapted from Warsh (1984). Arrows indicate flow of money. Links to rest of economy and taxes not shown.

Warsh's arguments might be summarized in this commonplace bit of wisdom: when it comes to quality, other things being equal, *you get what you pay for*. Although mass production and mechanization have lowered the real cost of many goods while increasing their quality, historically, the long-run pattern has been greater quantities of money flowing between a greater number of specialized entities, each more richly connected to others by communication and transportation links, and the output of which has consistently been products of increasing power, functionality, elaborateness...and absolute monetary cost. (Seen in this light, the fact that technological development can make certain goods cheaper *and* better, and not just one or the other, has to do with the fact that machines do not have rights and do not want to be free. It will be Chapter Ten before this claim is supported from within our theory of value, but I am not the first to note that, in general, the detachment of rights and freedoms from the agents of production is a mechanism that has long fueled economic growth, if not necessarily economic progress.)

The going price of a good or service is thus determined from two sides: from the production side by the complexity (we would say, the complexity-and-organization) of the process of making and marketing it, and on the consumption side by the increase it causes in the (average) consumer's state of satisfaction, which we identify with his lifefulness, Ω, which is also a state of complexity-and-organization. A market is where these two sets of complexities are matched. It will be Chapter Eight before we can look into how markets work in these terms more closely. Here I hope only to have outlined how, to use Warsh's terms, the complexity of the cost web of a good comes to increase the good's market price. If the increased price persists, we may take it also to be an approximation of its real value to people.[lvi,lvii]

Picking up where Warsh left off is Frederic L. Pryor. In his 1996 book, *Economic Evolution and Structure*, Pryor examines a wide array of more recent economic data sets looking for evidence of increasing complexity. One measure of complexity Pryor uses—he calls it "structural complexity"—is borrowed from Henry Theil, who in turn borrows the familiar-to-us measures of information and complexity developed by Claude Shannon and Warren Weaver.[lviii]

What does Pryor find in data covering the years 1950 to 1990?

First, a direct increase in the informational requirements of components of the economy. For example: an increase of information-processing skills in the workforce, a greater percentage of the labor pool engaged in the "creation, processing, and interpreting of information," an increase in the size of markets and the variety of products on sale in them, and an increase in the number of government regulations applying to business.

Second, greater interactivity within the system. For example: aided and abetted by the new communication technologies (wireless phone, internet, fax, email...), he finds that "interrelations between various sectors of the economy are becoming more extensive," that a larger share of the wealth is being created by government and by government institutions, and that financial arrangements between businesses, banks, investors, and governments, are becoming increasingly intricate as the ratio of financial to tangible assets everywhere rises.

Third, Pryor finds increasing heterogeneity—difference—among economic actors. For example: ethnic differences between people are becoming more important and more difficult to negotiate; differences in income and wealth are becoming greater, as are differences in the size between the largest and smallest firms.

All of these trends are aligned with "what we think of as increasing complexity," remarks Pryor. We would want to amend this, of course, to say that it is not complexity alone that is increasing, but also complexity-and-organization, Ω. Unfortunately, Pryor applies Theil's information-theoretical statistics to only a few of his analyses, and then only as a measure of heterogeneity in a population distribution (e.g. of income, age, or church membership). And so, although one can calculate Ω, *R*, and *C*/Ω for all of these distributions and find them located close to and to the right of the ridge of Ω, it is unclear why this result is significant. There seems to be no trend over these 40 years towards greater Ω in any of these distributions, just a local movement over a small and typical area on the Ω-surface.

By way of empirical support for our theory, then, the best we can take away from Pryor's work is confirmation of the fundamental evolutionary trend towards greater actual and potential complexity in the U.S. economic system. This growth in complexity cannot but be reflected in the minds and lives of ordinary people. From both Warsh and Pryor, we can also begin to appreciate that finding (or not finding) Ω-optimality in the social-economic system will require studies that are specifically designed to do so.[lix]

II. Some Corroborating Theories

Perhaps the earliest attempt to formalize aesthetic and moral value (as distinct from economic value or "utility") in terms of complexity was by the renowned mathematician George David Birkhoff in his 1933 book *Aesthetic Measure*. Ever since Pythagoras's discovery of the correspondence between the pitch of a plucked string and its length (for example, that halving the string's length raises the pitch a perfect octave), people have believed that perfect mathematical proportionality gives inherent, harmonious beauty to all things—from buildings, to paintings, to tools, to the human body. Certainly, much of aesthetic theory during the Renaissance was based on the idea of ideal geometrical proportions, and the idea was kept alive right through the 18th century. By then, of course, mathematics had established itself in all areas as that instrument most able to reveal "the music of the spheres." All that is harmonious and beautiful—on earth as well as in the starry cosmos—could be shown to be a play with numbers. Beyond simple "harmonic proportions" of the sort known to Pythagoras, Plato, Palladio, and Kepler, a million coincidences, symmetries, perfect divisibilities, integer relations between quantities, mysteriously reappearing constants, like π, and magical irrational numbers, like *e*, were seen to constitute not mathematics' beauty, but the world's—God's handiwork.

Birkhoff's specific contribution was to introduce *complexity* as such into this line of thinking.[lx] He proposed this formula: $M = O/C$ where M was an aesthetic value measure, O was a measure of "order," and C of complexity. The greater the degree of order of an object (or piece of music, or painting...) relative to its complexity, he said, the greater its aesthetic value. Aware of its limitations, Birkhoff proposed his formula with all due modesty. It was, he said, just a beginning.

The similarity to our theory is obvious. Can a translation be made?

I believe so, but not without offering some respectful amendments to Birkhoff's definitions of "order" and complexity. To wit, as we listen to Birkhoff explaining how he would measure C, it becomes apparent that his "C" is our C_{pot}: it increases directly with the number of sides of a polygon, it increases directly with the number of notes in a melody (these are his examples), and it contains no notion of the variable probabilities or expectations that would give us C instead. His definition of O, for "order," while it would seem linguistically to correspond to our R for "organization," is actually closer to our idea of Ω. This is because O, as Birkhoff explains it, can be positive for things harmonious, centered, and clear, or negative for things which display "ambiguity, undue repetition, and unnecessary imperfection." In our terms, "ambiguous" is too-much-C, "undue repetition" is too-much-R, and "unnecessary imperfection" too-little-R again, all of them conditions that would reduce the magnitude of Ω. His Story of O also permits of central optima and he wants O to be always positive for what he calls "somewhat less obvious" reasons, for example, when a picture or piece of music, for all its excursions into detail and various incident, returns always to a center or to the central tonic chord. This is to ask not just for order, O, as organization alone, but for complexity-*and*-organization, our Ω.

If I am right, then let us see what happens when we replace "$M = O/C$" with "$M = \Omega/C_{pot}$." Ω is at a maximum when $R = C$, and so is M a maximum when organization is equal to (actual) complexity. Holding Ω constant and varying C_{pot}, we find that M is at a maximum when $C_{pot} = \sqrt{2}(C) = \sqrt{2}(R)$. With this we can see that Birkhoff's aesthetic measure, M, is just a number that locates a work of art's distance from the ridge of Ω. What it cannot tell us is how high up the Ω-surface the work lies, i.e. how complex-and-organized it is in any absolute sense.

Birkhoff was also listening to one of the major philosophers of his time, Alfred North Whitehead. Or was it the other way round? In his magisterial 1939 work *Process and Reality*, Whitehead wrote:

> Order is not sufficient. What is required, is something much more complex. It is order entering upon novelty; so that the massiveness of order does not degenerate into mere repetition; and so that the novelty is always reflected back upon a background of a system. ...[T]he two elements must not...be disjoined. [They] belong to the goodness of the world... [lxi]

Perhaps the most influential attempt to link the quality of a work of art to ideas in information theory was Rudolph Arnheim's 1971 book-length essay *Entropy and Art*. After propounding to his readers what is surely the most confused explanation of entropy, information, structure, order, variety, evolution, etc., ever delivered with so much self-assurance, Arnheim's deep understanding of art at the formal-perceptual level finally guides him to a sustainable and appropriate conclusion.

Arnheim starts out alongside the many humanists of his time who applied themselves to unearthing a foundation for art in science. The function of art, and indeed of all purposeful human activity, they agreed, was to seek or create harmony and order against the "law of increasing entropy," i.e. the Second Law of Thermodynamics and the tides of chaos. Entropy, the universal solute, is the enemy. Perfect symmetry, regularity, clarity, crystalline form, material purity...were all rare in living nature, making their consistent production by man something of a triumph. But of course, this reductionist sort of argument—one that pits order (= good) and disorder (= entropy, bad) on a single dimension—cannot go very far. And so we are not surprised to find Arnheim by the end of *Entropy and Art* claiming that we have a "*need for complexity*" and then having to distinguish between "orderliness" (trivial, bad) and "order" (important, good). The degree of "order" can be greater or lesser as the work is more complex or less complex, he says, and now he begins to follow Birkhoff's usage. "Orderliness" is our R, "entropy" is C_{pot}, and "order" is Ω.

A good work of art, Arnheim concludes, "represents a state of...accomplished order and maximum relative entropy." Although an individual painting or piece of music is a limited thing, it "is not meant to stop the stream of life." It is meant, rather

> [to] concentrate...a view of the human condition;...mark[ing] the steps of [life's] progression, just as a man climbing the dark stairs of a medieval tower assures himself by the changing sights glimpsed through its narrow windows that he is getting somewhere at all.[lxii]

Arnheim arrives at a view of the value of art that is compatible with our own, namely, that art contributes to cultural evolution. How? Well, in many ways of course, depending on the context of the discussion. Using the terms of information theory, art contributes to cultural evolution by both proving and *im*proving people's capacity to see, hear, and create things of ever greater complexity-and-organization.

Written at around the same time as Arnheim's book, and focussing also on the arts, was

Morse Peckham's *Man's Rage for Chaos*. As the title suggests, Peckham was interested in emphasizing the complexity-increasing function of the arts than the organization-increasing, "ordering" function. "Why is order so wonderful?" he asks.

> Why must we praise it so? Why is it identifiable with all human value? Why do we see it when it is not even there? We have seen why: we praise order because it is an adaptational necessity for us that we experience order.[lxiii]

But this is not enough for Peckham. The unruly imagination must periodically triumph over canon, if only to establish a new and more complex canon with its new rules of order, itself to be challenged before too long. Dionysus beats Apollo, then Apollo beats Dionysus. The rage for order, being man's powerful desire to organize and dominate and codify, says Peckham, cannot be maintained without leading to totalitarianisms of all kinds. The rage for chaos, for disorder, provides the countervailing force. Play, humor, ambiguity, uncertainty, accident, and even certain sorts of destruction, provide the necessary freedom, and this in turn provides the variation-fodder upon which natural selection can operate, the grounds for artistic evolution. Rather than focus on compositional rules, Morse discusses techniques used by poets, composers, painters, and architects precisely to break the bonds of convention by allowing chance and entropy into their practices.

Let us step back for a moment. For it would seem that the oldest of *aesthetic* slogans, "unity in diversity" (we would say "organization 'in' complexity") with the implication that *more* unity and *more* diversity in a work is better than less, has not yet given up all its secrets. Is it a formula that goes beyond aesthetics, to ethics and economics? Certainly, with Ω, this has been my claim.[lxiv] Whitehead, cited earlier, certainly had more in mind by "goodness" than beauty in the realm of the arts only.

Birkhoff, Arnheim, and Peckham represent the tip of an iceberg of philosophical speculation about value in the arts—indeed, about the value *of* the arts as a whole. These speculations go back to Pythagoras and Plato, and none of the three have confined themselves, in explaining how beauty or art "works," to beauty or the arts. Today, on the other hand, sociologists, politicians, businessmen, clergy, and economists are apt to wonder why they should care one way or another about what "aestheticians" might conclude about value, even if they are right in their own domains. The arts, they would say, are nice to *have*, to be sure; but they are a recreation, a way of passing time, like sports. The arts are certainly not to be treated with the same seriousness as education, housing, health care, family relations, statecraft, or trade. Not *aesthetic* value but moral value, economic value, scientific value...*these* govern the day. Even if there were no "subjectivity" and experts could agree, with principled arguments, as to why certain paintings or pieces of music really *were* better than others, how could these arguments ever shed light on why, say, a higher tax on interstate trade is better than a lower tax, or whether increasing cash aid to the poor is a good or bad idea?

Answers tend to fall into two categories.

The first makes the case that the arts *are* important to the social and economic life of a nation, and are only *apparently* a luxury. One points to institutions like museums, theatres, dance companies, and so forth and argues for their "vital role" generating civic pride, downtown revitalization, urban investment and employment, quality of life, etc. Ditto handsome buildings. One points out the historic role of leisure in producing culture, or one highlights the size of the international trade in *objets d'art* and other things of beauty.[lxv] One might go so far as to condone the linking of government—which is definitely serious business—to sports and entertainment, both of which, like art, are ostensibly unnecessary and yet both of which have the power to (en)gross millions.

The second category of answers wants to link aesthetic value with value in general at a deeper, more abstract level. The explanations offered by Arnheim and Peckham belong to this second category, and, so far, so do ours. On this view, the reasons why product A prevails over product B in the marketplace are not unlike why painting A is held to be better than painting B in the pages of an art journal. On this view, value is value no matter what kind of object is under scrutiny, and no matter how "distorted" the amount of this value is by those who have a stake in it. Art historian and engineer, philosopher and businessman, have reason to speak to each other because at some level they are after the same thing. There is nothing "mere" about beauty or art, goes this argument, and why *this* is so goes back to old and powerful ideas of what the good life consists in, which in turn have to do with the conditions of human evolution, physical law, and the nature of "livingness" itself.

Still, to some, investigations into human nature, evolution, psychology, order, complexity, etc., just to explain aesthetic preference represents a clear case of intellectual overkill. Why not a shrug and a tolerant "well, there's no accounting for tastes"? Precisely because to make any sense of the matter at all, theorists of the aesthetic have found that they *must* tap into something far larger—not just into "social conditions," but nature and justice, language and desire, form and function. To explain *why* A is more pleasing-to-behold than B (rather than merely proclaim this to be the case) is to explain—well—everything: the goodness of goodness itself. And once *this* subject is opened to discussion and some progress made, all manifestations of value—moral, utilitarian, monetary, hedonic, ecological, literary, scientific...—stand exposed to a new and common light. Indeed, we are able to explain why, sometimes, just proclaiming that A is better than B makes it true that A *is* better than B. What is the role of *authority* in these matters, after all? We shall see in the next chapter.

Prominent among contemporary thinkers privileging the aesthetic—or rather, using aesthetics to see into the nature of all value in an evolutionary context—is the poet and essayist Frederick Turner. Three of his books are especially significant: *Natural Classicism: Essays in Literature and Science* (1985), *Beauty: the Value of Values* (1991), and *Tempest, Flute, & Oz: Essays on the Future* (also 1991).[lxvi]

For Turner, both complexity and its increase in the process of evolution are unalloyed goods, the source of all value. In man, complexity's chief agent of increase is *language*; language is the technology behind all technologies; it is our primary invention, the medium in which we communicate and think. Literature in particular, as a class of linguistic invention, acts as "the leading edge of universal evolution." It is the "mutating DNA...of cultural organisms of exquisite protean beauty."[lxvii] Turner is not blind to the value of science, music, and the other arts. Nor is he in the least bit disdainful of technology, utility, and economic life. But, man of letters that he is, the Word captures all.

One idea recurs in Turner's efforts to associate the creativity of nature with the creativity of man, and that is "reflexivity": the capacity that many evolving systems have for reading or referring to parts of themselves and producing from these readings something new and different. Just as DNA reads its own codons and makes the mistakes we can later call progress, so young writers look to the early work of masters of the canon and, in "failing" to imitate it, add something new—something good enough to be imitated...[lxviii] The same might be said of good jazz musicians, of good composers, of good actors, painters, sculptors, choreographers, and hopefully, someday soon again, architects. Reflexivity is this and more. For, moment-to-moment, the artist-at-work enters the future as into a succession of rooms—rooms of her own imagining. Surprised at what is unfolding by her own actions, welcoming some accidents and shutting out others, she watches what she does and she watches herself watching. "Given that what I have done is this," she asks, "what properly or naturally (or exactly-contrarily) follows?" And then: "Is this way of proceeding generative? Does this work that I am producing evoke, provoke, or protect life?" (Am I near the ridge of Ω? Is there more to be had?)

"Value can be created internally," Turner writes,

> ...by means of a complication, unification, and densifying of the information field to the point where it becomes reflexive, and therefore generative of original novelty. A very simple system, for instance one with only one element, cannot produce meaning because it cannot generate anything beyond itself. A somewhat more complex system, with orderly rules like a game of tic tac toe, may be capable of generating several states, but it is essentially deterministic—that is, its states can be counted and defined in advance by any calculator more complex than it is, and the order of their appearance can be predicted. It is therefore, not generative of any novelty. A system not bound by orderly rules is not a system, and can be reduced to an ensemble of independent and sterile simple systems. But if an orderly and rule-governed system is complex enough, it will cross a threshold beyond which no conceivable calculator could predict its future states, or at least predict them fast enough to outstrip their actual occurrence. At this point such a system is the most efficient predictor of its own future state and takes on the qualities of reflexivity, autonomy, original generativeness, meaning, and value.[lxix]

A specialist in complexity theory might quibble here with Turner as to whether non-predictability by a system simpler than itself is a sufficient criterion for distinguishing the salutary sort of complexity he is describing here from "plain old" complexity; and an evolutionist might want to add that "autonomy,..meaning, and value" come into the world not *purely* from inside a system and its own complexity but from a temporally extended relationship with an less-than-cooperative environment, etc., etc., all facts that Turner elsewhere shows he is perfectly in command of. But Turner is correct in the general thrust: a degree of self-reference, feedback, "reflexivity," is a potent catalyst to increasing a system's complexity, especially when not only some its own *complexity* is treated as though it were part of the environment, but some of its *organization* is gathered up too, i.e. its own "orderly rules." This is certainly the case with DNA, and how it reads itself.

The picture Turner wants to paint is much larger. He continues:

> This theoretical analysis of system types, interestingly enough, recapitulates the actual progress of evolution, from the almost sterile simplicity of the Big Bang through the largely deterministic systems of physical and chemical evolution, to the rich generativeness of life and the still richer creativity, autonomy, and meaning of human culture.[lxx]

Within the limits of the terms given by an earlier period in complexity theory, Turner can be read to be prefiguring our concept of Ω and its increase in evolution. (Indeed, this author read *Natural Classicism* soon after it came out, and the debt is here acknowledged.) Of particular interest is the idea of recapitulation. Our theory of value appeals to the same concept. Value consists in the increase of complexity-and-organization; evolution consists in the increase of the span between the lowest and highest degree of complexity-and-organization, which, if we assume that lowest bound is fixed (and equal to zero), is the same as saying: consists in the increase of complexity-and-organization. Value-events and value-experiences are microcosmic recapitulations of the grander trends of evolution. They are events and experiences which not only reflect the larger pattern but fall in line with it—in fact, constitute it.

For both Turner and ourselves, then, "value" and "evolution" are twinned phenomena, different only in timing and scale. Turner's purview is all of literature, drama, and poetry. But it is the language of complexity that allows him, and us, to recast what are actually ancient ideas about the place and perfectibility of humans in the "scale of nature" (*scala natura*) into a form we can hope to apply freshly to modern life.[lxxi]

Perhaps the most ambitious attempt in recent years to cast evolution—and specifically, the evolution of the kind of "good complexity" we have been calling Ω—as the basis of a rich and useful world-view, is *Nonzero: The Logic of Human Destiny* by Robert Wright.[lxxii]

The term "non-zero" is an abbreviation of "non-zero-sum," a term from game theory. In game theory there are two kinds of games: those in which the winner wins what the loser loses, and those in which both players win something (if not the same amount). The first kind of game is "zero sum," meaning that winnings plus losses equal zero; the second kind of game is non-zero-sum, meaning winnings plus losses are greater than zero.[lxxiii] Non-zero-sumness, says Wright, is characteristic of natural evolution. Surviving species, "winners," can and do co-exist when, instead of competing head to head, they specialize and get out of each other's way. This entails learning to exploit different environments or different features of the same environment; it entails developing better and cleverer ways to get things done; it entails cooperating with others, deliberately or not, with moral intention or not, but in ever more complex ways. We have described this process a number of times as enlarging the C_{pot} frontier, which in turn allows Ω to increase in absolute value.

Written colloquially and passionately, and without the ambition to produce a new theory, *Nonzero* nonetheless carries forward an argument based on a great deal of scientific and historical research. For Wright, the evidence is clear: evolution is a ladder, and elevation on that ladder is chiefly elevation in complexity. In this he takes issue with Stephen Jay Gould (as do I, if less strongly).[lxxiv] Where this chapter and the previous chapter of this book have spent only a page or two defending the idea that cultural evolution and biological evolution are sufficiently of-a-piece both to be called "evolution," Wright makes a stronger case, offering a two-hundred page narrative of human history. Where I have sketched the barest outlines of biological evolution, Wright provides a hundred pages of discussion. There *is* progress, concludes Wright, *real* progress in both biological and cultural evolution. And that progress is less a matter of chance and genetic drift than of responding to population density and avoiding the ensuing competition through specialization and cooperation. Implicit is the notion that all events, ideas, and things that contribute to such progress would be seen as having "value," if only retrospectively and by its beneficiaries.

Wright does not want to say that complexity-as-such is the purpose of life—the *telos* of evolution—or that there is some foreseeable arrival point. More-complexity is just a direction, and there is no end in sight. But he does ask us to take seriously Teilhard de Chardin's mid-20th century vision of the emergence (over the next few centuries, perhaps) of a globe-encircling superbrain called the *noösphere*—millions of brains (like neurons) linked by telecommunication links (like nerves) to create a single, higher-order consciousness. This idea, says Wright, although mystical "might not be crazy." Since neural numerosity and connectivity seems to have been the *sine qua non* of the emergence of consciousness in animals, it follows that social complexity, in the form of the sheer number of people communicating with each other, would at least set the stage for the emergence of a single super-consciousness located nowhere, in no one place, but, somehow, in the whole. The noösphere would be planet itself (or a thin coat on its surface, anyway)...*thinking*.[lxxv]

So grand is Teilhard's vision, even setting aside the dramatic Christian eschatology Teilhard propounded with it, that many Internet visionaries and "dot-com" CEOs are in thrall. Certainly, the concept of the noösphere (or the Net) works nicely as an overlay on the radical environmentalist idea of the earth as already a single super-organism, which is the Gaia Hypothesis made popular by James Lovelock.[lxxvi] No reader of *Wired* magazine in the 1990s would find these two ideas, or their association, strange.

Inspired by Teilhard, Wright closes his book with theological reflections of his own: if all good issues from God, does God exist outside of, in, over and above, or because of evolution? If evolution shepherds life-forms towards greater complexity, does this imply a moral direction too? Is more complexity (and again, we would say "is more complexity-and-organization...") a Good Thing, in an of itself? We say Yes. Wright says No.

For Wright, *consciousness* remains the stumbling block. Consciousness is the profound mystery that God accounts for. It is a gift, mysteriously super-added or slipped into a world that would otherwise contain people that looked and behaved just like us and animals that were indistinguishable from the ones we know and love and sometimes eat...*but who were all zombies, automatons*. Since the categories "good" and "bad" can only occur to, and in, conscious beings like ourselves, it follows that our choices and decisions about what is good and what is bad must also derive from God (if indirectly from His gift of consciousness) and not from our complexity as such, or our evolvedness.[lxxvii]

Wright tries to make sense of evolution, and he does so by trying, specifically, to find in it a moral purpose. Instead, he finds in it moral *opportunity*. Just as when we answer the question "If God is good, all-knowing, and all-powerful, why is there evil in the world?" with "Because He wanted us free to *choose* good over evil," so Wright suggests that our consciousness combined with our complexity puts us in a position to *choose* to align evolution—*our* continued evolution, that is—with the good. We can now evolve consciously, i.e. morally, with technologically-assisted communications and the globalization of cultures and economies to help us tilt the scales towards the good. Why do they help us tilt toward the good? Because they make it easier (and more profitable) for people to see others as *like* them, with the same desires and with interconnected fates, and because they intensify the contacts between consciousnesses in non-zero-sum ways that might—just might—lead to a single, integrated, global super-consciousness...

While I agree with Wright's overall views on complexity and evolution, the theological position taken in this book is slightly different. It suggests that consciousness is "simply" an emergent property of systems that succeed in sustaining their high levels of complexity-and-organization in environments that more or less demand it. Terrific, but no deep mystery. As argued in Chapter Two (p. 13), it follows that no zombie, no robot, no computer that was to all intents and purposes "just like us" would not also experience themselves as being alive, would not also have real feelings, would not also be capable of love, etc., just like us. Logically, God need not enter the picture for consciousness to exist or for goodness to reign. But factually, historically, "God" *has* entered the picture, and He remains "part of the equation." God is a beautiful idea had by us, nurtured by us, and in turn civilizing *of* us. Indeed, God is one of the most powerful memes yet evolved to protect and enhance life on earth. That wars and pogroms have been waged in His name prove only that there is more evolving to be done by Him, which is to say, by us too.

Little more will be heard about God in this book.[lxxviii] Our theory of value "worships" life only, and offers complexity-and-organization, Ω, as both a meme and a measure that can help us go about obtaining more life, and a better life, for all.

Although I hope to have been persuasive, the case for the theory of value presented in Chapter Two has not been completely made. Here, in Chapter Three, I have reported experiments that *could* have worked out otherwise (life's rules and DNA's codon complexity *could* have been other than Ω-optimal, students *could* have preferred low-Ω melodies, and so forth), and I have presented writer-philosophers who would agree with me as well as take issue. Much remains to be done, however, in order to confirm or disconfirm the larger claims of the theory with any real precision. And as much again remains to be done in order fully to engage the philosophers whose thinking underlies it.

In the next chapter we make a start on both projects by examining how complexity-and-organization enters the human psyche through the process of satisfying needs in a social context. Although evolution and complexity are still our watchwords, we leave pure biology behind. Psychology and economics enter. Cultural "forces" dominate. Our theory of value develops with new ideas, new data, and new opinions. We want to see if our so-far abstract theory *applies*. In reaching for application to recognizably human situations, it makes itself more complex, more organized, (hopefully) more plausible, and certainly more open to refutation by the evidence. •

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NOTES to Chapter Three: *Some Evidence for* Ω

i John Tyler Bonner, *The Evolution of Complexity by Means of Natural Selection* (Princeton, N.J., Princeton University Press, 1988).

ii Arthur Kornberg, *DNA Synthesis* (San Francisco: W. H. Freeman and Co., 1974), pp. 16 and 18.

iii For example, the length of the *Vacinnia* virus genome (one of the largest) is around 80,000 codons (recall that 1 codon = 3 nucleotide base-pairs in a row), the length of the *E. Coli* bacteria genome is around 1,300,000 codons, of yeast around 4,500,000 codons, of *Drosophila* (fruit fly) 55,000,000, of dogs 830,000,000, and of humans 1,000,000,000. So far so good for the theory: longer genome = bigger-and-smarter organism. But the South American lungfish has some 34,000,000,000 codons! Unless we are severely underestimating the sophistication of the average lungfish, or unless 99.9% of its DNA is junk, there goes our theory.

Why this relatively simple animal has so much DNA in its genome is, as far as I can tell, a mystery to biologists. Perhaps, as old a species as it is, the South American lungfish has particularly "sticky" DNA and/or a very specialized and long-stable environment. This combination might promote the collection and accumulation—rather than interpretation and use—of a great deal of genetic bric-a-brac. (Do not many "ancient" business firms and other human institutions tend to a similar pattern? Consider the acres of files in every government building basement. Consider the whole body of law, or the accumulation of "news." Old dictionaries. The deeper recesses of second hand bookstores...)

Genome length numbers from Kornberg, *DNA Synthesis*, 17, and from H.A. Sober, Gerald D. Fasman, eds., *Handbook of Biochemistry: Selected Data for Molecular Biology,* 3rd ed. (Cleveland: CRC Press, 1975-1977) Section H.

In February of 2001, Celera Genomics and the International Human Genome Sequencing Consortium suprised the scientific community by reporting that the total complement of genes in human DNA amounted to some 30,000 genes. This was still more than other creatures, but far less than the roughly 100,000 genes previously estimated. It would seem that small differences and additions at the fundamental "assembly-language" level represented by DNA can be tremendously consequential in functional and anatomical result. We had been understimating, it seems, the amount of information that can stored and transmitted by adding just a few new processing steps and a few new reading schemes to a relatively steady base of data. If DNA is a book that reads itself, it does so more eclectically—more "creatively"—than we previously thought.

iv R. N. Mantegna, S. V. Buldyrev, A. L. Goldberger, S. Havlin, C. -K. Peng, M. Simons, and H. E. Stanley, "Linguistic Features of Noncoding DNA Sequences," *Physical Review Letters*, 73, no. 23 (1994): 3169–3172.

"Redundancy" is defined thus: $R = 1 - (C_{pot} - C)/C_{pot}$. Note that $0 \leq R \leq 1$. It is a measure similar to our measure of organization, also denoted R, but which is not normalized and which is the square root of the difference of squares of C_{pot} and C.

As a test of similarity to natural languages, they use Zipf's Law, which states that if one plots word usage frequencies against a histogram of word rank-order of usage frequency on log-log paper, one gets a line of slope –1 for all natural languages. This would seem to indicate that all natural languages have a smooth hierarchical structure at the scale of words.

v Mark Ya Azbel, "Universality in DNA Statistical Structure," *Physical Review Letters*, 75, no. 1 (1995): 168–171. His abstract:

> The DNA correlation function is a slightly and slowly modulated autocorrelation function of a random sequence. Its coarse-grained root-mean-squared fluctuations are approximately homogenous and equal to those of a random sequence. A DNA molecule may be decomposed into a random sequence of white noise domains, which have different lengths and nucleotide concentrations but a universal length scale. No long range correlations are found in any of the studied DNA sequences.

vi See Wentian Li, "The Study of Correlation Structures of DNA Sequences: A Critical Review," *Computer and Chemistry,* June 1997, downloadable from *http://linkage.rockefeller.edu/wli/me/cc97.html.*

vii The reader will recall from Chapter One that DNA is made up long sequences of only four nucleotides, denoted A, C, T and G, grouped into triplets called codons, each specifying a protein-building amino acid. The maximum number of different amino acids that DNA *could* specify with one codon is thus 4^3, or 64. With only 20 found in nature, does this mean that 44 of the 64 possible three-letter permutations of A, C, T, and G are not used, never appear? Not at all. All possible permutations *are* used and all appear sooner or later in a representative length of DNA. Rather than omit permutations, nature has instead chosen to make many of these permutations—i.e. codons—*synonymous*. For example AGG, AGA, CGG, CGA, CGT, and CGC all specify the amino acid arginine, while ACG, ACA, ACT, and ACC all specify threonine. And the codons TGA, TAG, and TAA do not specify amino acids at all, but serve as *end* or *stop* instructions, each punctuating and breaking long sequences into functional groupings at a larger scale. This rather forgiving synonymity is what gives to DNA a certain robustness against error and noise in the system. Small mistakes are not often catastrophic when, say, a G in the third position of an arginine codon is replaced by an A...and we still get arginine.

[viii] Here is an analogy. Imagine being given a musical score using 64 (different) notes and a piano with 64 keys to play it on. Playing the score, however, you soon discover that the piano can *sound* only 20 notes and that a few keys are do not make any sound at all. With some experimentation you find that some notes are equivalently played by six keys, some by five, some by four, three, two, or one key. Here is the question: what best represents the degree of organization of the music: the score as written or the melody as heard? We have sided mainly with the second, the music as heard, taking the first, the score, to tell us only of the potential complexity.

Now, here is an argument *against* what I have done: Let's imagine that the 21-note melody (I am counting a keystroke of silence as one "note") is heard in an adjoining room. Seeing no score, the person just listening knows nothing of the 43 notes she is being "denied." She hears only a sequence of notes, with repeats and pauses. For her, the potential complexity of the melody is $M\log_2 21 = 4.39M$ bits where M is the total number of notes in the string, and not $M\log_2 64 = 6M$ bits. Assuming that her expectations *vis-à-vis* which note will sound next reflect each note's relative frequency given the one or two notes before it, we have a $C \leq C_{pot}$ for each note and for the whole sequence. That is to say, $R > 0$. But, with the very same sequence of notes, R for a person for whom C_{pot} is $6M$ bits is much greater than R for a person for whom C_{pot} is $4.39M$ bits. Who is right? The one who knows the score and hears the music, or the one who only hears the music? (We discussed a very similar situation in Chapter One, p. 10, where Paul and Quentin confront the same screen of changing colors but each is led to believe that a different number of colors is possible.) What *is* the degree of organization, R, of the music? More specifically, why have I not taken C_{pot} for the 20 amino acids (and one blank) to be 4.39 bits instead of 6 bits per codon?

The answer lies in seeing that a piano with 21 keys is not quite the same as a piano with 64 keys many of which are hooked up to play the same note. The smaller keyboard is more efficient to be sure, since it can play the same melodies as the bigger keyboard but with fewer keys, less material used, less space taken up, etc. *But the smaller, less-redundantly-configured keyboard is more prone to errors of fingering on the part of the player.* That is to say, the player of the larger, more-redundantly-configured keyboard can make more mistakes and get away with it.

This is precisely why evolution has given DNA the degree of organization that it has, and this sort of "move" by nature is precisely what this chapter has been aimed at identifying and appreciating. It is as though nature, rather than *writing* its self-reproducing code in a structured and symbol-efficient language, learned to use essentially random sequences of symbols as code by *reading* certain symbol-clusters as synonymous. A kind of color blindness.

[ix] Codon usage data is published by Genetics Computer Group, 575 Science Drive, Madison, WI 53711 USA and available online at *http://www.gcg.com/techsupport/data/codon_freq_tables.html*. Dog codon usage data compiled by Mellissa DeMille, is available at *http://mendel.berkeley.edu/dogs/dogcod.html*. Silk moth data provided by J. Michael Cherry the using GCG program CodonFrequency, is available at *http://magpie.bio.indiana.edu:70/Molecular-Biology/Molbio%20archive/codon/bmo.cod*. Codon usage for *C. elegans* is from M. Stenico, A. T. Lloyd, and P. M. Sharp, *Nucleic Acids Research* 22 (1994): 2437–2246. Virus codon usage tables can be found at *http://www.dna.affrc.go.jp/~nakamura/codon.html*. The author was not able to locate codon usage tables for the South American lungfish. The calculations that follow are mine.

[x] The following is an interesting mathematical fact that may or may not temper our interest in this result.

At any finite level of numerical precision, a *population* of probability distributions, each on N possibilities, $N < \infty$, randomly chosen from all possible probability distributions, would not be uniform in Ω. Very few would have $\Omega = 0$, and a large number of them would have Ω close to $(\log N)/\sqrt{2}$, which is Ω_{max} for N. (Cf. Note 13 of Chapter One) This fact can be visualized. Imagine an automated dice factory. At its core is a machine that produces a large number of randomly-biased dice. Each die is rolled a few hundred times and the sequences it produces measured for Ω. Both random-number-producing dice (i.e. fair ones where $p(i) \approx 1/N$, and $\Omega \approx 0$) and one-number-always-producing dice (i.e. dice where $p(i) \approx 1$ for one [and any] number between 1 and N, and $\Omega \approx 0$) will be very, very rare. Almost all of the dice will have biases that produce $\Omega > 0$ sequences, and a "disproportionate" number of them will produce sequences that are quite close to Ω_{max}.

What to make of this? It could seem to make our "discovery" of DNA's Ω-optimality at the scale of codons an artifact of the mathematics of random numbers and of the statistical measure upon them we call "Ω" rather than anything physically interesting—an artifact, that is, of the fact that the probability density of randomly-chosen probability distributions on the same number of possibilities, N, has an intrinsic shape that favors distributions that have high values of Ω.

On the other hand, that DNA (for example) *would* form itself in a way modelable by a wayward machine that randomly produces, not DNA sequences directly, but large numbers of the biased four-sided "dice" that then *produce* DNA sequences, is surely extraordinary. Fair dies, fair coins, fair roulette wheels, etc...are extraordinarily rare in nature, perhaps non-existent. So too are perfectly rigid structures (which would have to have zero degree Kelvin temperature).

It would seem that biological life is at once both highly improbable, just as conventional wisdom holds, *and* highly probable *once two or more randomness-producing mechanisms are hooked together in the "right," i.e. high-Ω-producing, way*. And what is this "right way"? This: one little randomness-engine producing dice-like devices that will control the relative frequency of subsequent events in the neighborhood. Presto: patterns that are neither totally random nor totally orderly dominate. Replicate. From now on, life and evolution are quite likely.

Should one predict that research will find a molecular-scale "dice factory" at work in the production of DNA? Perhaps. On the other hand, there is always the possibility that Ω-optimality has nothing to do with life, its actual generation, or our perception of it as a quality of the behavior of living—and what we judge to be life-like—things. So let me be clear, then, about what I am and am not proposing. As I said in Chapter Two, I am *not* proposing that high and optimal Ω in a system's behavior *ipso facto produces* life by some sort of statistical alchemy. High and optimal Ω is not a *sufficient* condition for life, as though anything that had optimal Ω would spring to its feet, like Pinnochio. Indeed, it may not even be a necessary condition, just a helpful one—one *conducive* to starting and maintaining life's electrochemical processes at the scale of cells and life's communication-coordination processes at the scale of society at large.

It is a small stretch, I believe, to hypothesize further that Ω-optimality might reappear as a common feature of artifacts, machines, and other non-living things that, in the life-*likeness* of their form and behavior, create an involuntary quickening of interest in them on the part of truly living things. Is there not more-life in the latter on account of the very seeing of the former, the quickening? "Art imitates Nature," said Plato; what we have arrived at is perhaps nothing more than another understanding of Plato's observation.

Einstein famously said, "The good Lord does not play dice." One wonders, though: did Einstein have in mind only perfectly *fair* dice?

[xi] For an overview, see Chris Langton, Ed., *Artificial Life* (1989), *Artificial Life II* (1992) and *Artificial Life III* (1994), all from Addison Wesley, Redwood City, CA. See also G. B. Ermentrout and L. Edelstein-Keshet, "Cellular Automata Approaches to Biological Modeling," *Journal of Theoretical Biology* 160 (1993): 97–113. See also this volume, Chapter Ten, pp. 53–55.

For more popular accounts, see Steve Grand, *Creation: Life and How to Make It* (London: Weidenfield and Nicolson, 2000), and Peter J. Bentley, *Digital Biology* (New York: Simon and Schuster, 2002).

[xii] Some would argue that computer simulations are not, properly speaking, empirical. It is hardly *nature* we are inquiring into, they would argue, except perhaps at the level of the nature of computation itself. However, since the very essence of computer simulations is the unpredictability of outcomes of simple rules applied *en masse*, which in that sense are able to produce dynamic macro results that are beyond ordinary mathematics to model, I would classify most CA, AL, and AS work as, if not fully empirical, then certainly fully experimental.

[xiii] In John Von Neumann, *Theory of Self-Reproducing Automata* (Urbana: University of Illinois Press, 1966) edited and completed by Arthur W. Burks. We came across CAs first in Chapter One. It should be noted that the grid used need not be rectangular. It can be triangular orhexaogonal—indeed, any tiling pattern would do—as well as threedimensional and polyhedral. In the literature, two dimensional rectangular grids dominate.

[xiv] I use *Lifelab*, a public domain program by Andrew Tevorrow. A strikingly beautiful version of life, by James Tindall, can be found at *www.singlecell.org/April/index.html*.

[xv] Unless you want to, that is. Here is the rule system obeyed by each cell:

(1) If exactly two neighboring cells are "on," stay in the present state (whatever that is, "on" or "off")
(2) If exactly three neighboring cells are "on," turn to "on" (no matter the present state, "on" or "off")
(3) Under all other circumstances, turn (or stay) "off."

These are called the "*2-3* rules." "*3-4*" rules also work, as do a very few other combinations of parameters. "Exploring Emergence", an "active essay" by Mitchel Resnick and Brian Silverman of the Epistemology and Learning Group at MIT's Media Laboratory uses life as a demonstration. It can be "read" online at *http://lcs.www.media.mit.edu/groups/el/projects/emergence/index.html*

[xvi] The updating is not actually simultaneous when the CA is working on a conventional computer. It is serial but programmed to give the same results as simultaneous updating.

[xvii] Here is the arithmetic: $C_{pot} = 1$ bit. $C = -[p(on)\log p(on) + p(off)\log p(off)] = -0.2\log(0.2) - 0.8\log(0.8) = 0.72$ bits. $R = (C_{pot}^2 - C^2)^{1/2} = (1^2 - 0.72^2)^{1/2} = 0.69$ bits. $\Omega = (0.72 \times 0.69)^{1/2} = 0.705$ bits.

[xviii] Kurt Thearling and Thomas Ray, "Evolving Multi-cellular Artificial Life," in R. Brooks and P. Maes, eds., *Proceedings of Artificial Life IV* (Cambridge: MIT Press, 1994), also available online at *http://www.santafe.edu/~kurt/text/alife4/alife4.shtml*. See also Thomas Ray, "Evolution, Complexity, Entropy and Artificial Reality," *Physica D*, 75 (1994): 239-263.

xix Robert Axtell and Joshua Epstein, *Growing Artificial Societies* (Cambridge: MIT Press, 1997). A CA/AL program halfway between *life* and *Sugarspace* is *StarLogo* by Mitchel Resnick et. al. at MIT Media Lab. The rules used by *StarLogo* were not available for analysis. In Chapter Four I will refer to the work of Robert Turknett, who constructed a CA that simulates a token-exchange economy, called *TokenTrade*. The reader may enjoy seeing this CA at work. Visit *http://www.ar.utexas.edu/cadlab/turknett/tokentrade.html*

xx This, at least, is the scenario with which Axtell and Epstein begin, and, of course, the scenario itself embodies an enormous amount of organization from the start—not unlike chess. Indeed, all of the more advanced capacities of agents in *Sugarscape* too (interbreeding, passing their wealth along to offspring, trading sugar for spice, etc.) have the character not of emergent features, but of impositions: agents are programmed to simulate these natural social and ecological relations as closely (but simply) as possible. *Sugarscape* is not social science from the *very* bottom up, then, but social science from a believed-minimum set of believed-necessary metabolic and interpersonal processes that have not themselves evolved from the life of their model.

xxi In Sugarscape, each cell can either have sugar in it in quantity 0, 1, 2, 3, or 4 units, or an agent on (or in) it. The agent's state has three substates: "vision" = number of neighboring cells seen 4, 8, 12, 16, 20, or 24; "metabolic rate" = sugar consumption of 1, 2, 3, or 4 units per unit time; and "wealth" = accumulated unconsumed sugar, from 0 to160 units. An agent surrounded by sugar cells has 5^x states to contemplate before deciding what to do, where x is the size of the neighborhood determined by the limits of its vision. (*Sugarscape* uses so-called von Neumann neighborhoods, meaning, only cells due north, south, east, and west of given cell, in a Greek-cross pattern.) The agent itself, however, can be in only one of 6x4x161 = 3864 different internal states. (I say "internal" because, unlike *life*, the agent/cell does not display most these states to the observer—i.e. us or other agents.) This means that the degree of *Sugarscape's* organization is given by the expression $R_1 = (C_{pot}^2 - C^2)^{1/2} = ([\log 5^x]^2 - [\log 3864]^2)^{1/2}$ bits. Here "C" is the R_1-delimited C_{pot} of the agent. At this same stage, we also have $\Omega_1 = [(11.92)(R_1)]^{1/2}$ bits. (Note: $\log_2 3864 = 11.92$.) We see that both R_1 and Ω_1 are a function of x, neighborhood size, which in *Sugarscape* is a variable parameter. Now let us look at the ratio Ω_1/C_{pot}, which is here equal to $[(11.92)(R_1)]^{1/2}/\log 5^x$. This ratio reaches its peak of $0.7071 = 1/\sqrt{2}$, a number we should find familiar, when $x = 7.26$. Not bad. The implication is that when an agent's neighborhood is 8 cells in size, which is "normal," then Ω_1/C_{pot} is 0.7 *and close to optimal in terms of our theory*, dropping off rapidly for values of $x < 8$ but gradually to 0.46 when $x = 24$.

A great deal has been left out even in this analysis; for example, the fact that the starting distribution of sugar is far from random—it is organized into two "hills," one centered in the northeast and one in the southwest quadrant of the field—and the fact that the number of agents at the start is also a very *life*-like ratio of 400 on a field of 2500 cells—making p(*agent*): p(*empty* or *sugar only*) = 0.16: 0.84, a ratio which is roughly maintained until progeny are introduced. A fuller analysis remains to be done.

xxii Christopher Langton, "Life at the Edge of Chaos," in C. G. Langton, C. Taylor, J. D. Farmer, and S. Rasmussen, eds., *Artificial Life II* (Redwood City, California: Addison Wesley, 1992), 41–91.

Langton defines lambda as follows: $\lambda = (K^N - n_q)/K^N$, where K is number of states permitted to each cell, N is the size of a single cell's neighborhood, and n_q is the number of transitions from K^N neighborhood-states at time t to one of K cell-states at time $(t + 1)$ that happens to be a "quiescent" state by the rules of the CA. (Note: there are K^{KN} possible transitions from a given neighborhood-state to *any* one of K cell-states.) This is Langton's empirical finding: that CA's are most interesting and "alive" when $\lambda \approx 0.5$. Langton reports that the $\lambda \approx 0.5$ optimum holds best for CAs whose $K \geq 4$ and $N \geq 5$. When all transitions are equally likely to lead to quiescence, $\lambda = 1 - 1/K$.

For a more technical and complete discussion of Langton's and others work in this area, see Stuart A. Kauffman's magisterial *The Origins of Order* (New York: Oxford University Press, 1993), especially Chapter Five, and, within this, pp. 218–221 and 232–235. For an early elucidation of the "phases" of CAs, from rigidity to chaos, see Steven Wolfram, "Universality and Complexity in Cellular Automata," *Physica D*, 1984, Vol. 10, pp. 1–35.

For more general intoductions to CAs and AL, see Steven Levy, *Artificial Life* (New York, Pantheon Books 1992), Claus Emmeche, *The Garden in the Machine* (Princeton University Press, 1994), and Gary Flake, *The Computational Beauty of Nature* (Cambridge, MIT Press, 1998).

xxiii Carrying on from the above footnote, we notice that "K^N" is Langton's correlate of our measure of potential complexity, which would be $\log K^{KN} = K^N \log K$. Similarly, Langton's expression $(K^N - n_q)$, being potential complexity minus organization (what could be more organizing than assigning a definite number of transitions to the "production" of quiescence?), can be taken as a correlate of our measure of *actual complexity*. It seems that λ is a measure that is at least similar to C/C_{pot}, a ratio that, as we know, yields greatest Ω when it is equal to $1/\sqrt{2} = \sqrt{0.5} = \sqrt{\lambda_{optimal}}$. This suggests that λ can be shown to behave like C^2/C_{pot}^2. Since $C^2 = C_{pot}^2 - R^2$ by definition, the numerator of Langton's λ formula would, in our terms, be $(K^N \log K)^2 - (\log n_q)^2$, and the denominator $(K^N \log K)^2$. Our theory says that λ should be 0.5 when $\log n_q = (K^N \log K)/\sqrt{2}$, that is, when $R = C_{pot}/\sqrt{2}$, and indeed, using Langton's formula for λ and the above substitutions, this is the case.

xxiv For a discussion thereof, see Michael Domjan, *The Essentials of Conditioning and Learning* (Pacific Grove: Brooks/Cole Publishing Co., 1995), 123 ff. There is also a literature of implicit learning, which argues that learning can take place without a person knowing it (see A. S. Reber,. "Implicit Learning and Tacit Knowledge," *Journal of Experimental Psychology: General* 1989, 118: 219-235) and considerable evidence that people are remarkably good at implicitly figuring out the probability distribution of events at several different scales and grouping lengths simultaneously (e.g. E. Servan-Schreiber, and J. R. Anderson. "Learning Artificial Grammars with Competitive Chunking," *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 1990, 16: 592-608).

[xxv] David A. Grant and Lowell M. Schipper, "The Acquisition and Extinction of Conditioned Eyelid Responses as a Function of the Percentage of Fixed-Ratio Random Reinforcement," *Journal of Experimental Psychology* 43 (1952), 313–320. This paper expands upon a pair of similar studies done by L. G. Humphreys in 1939, using only the 100% and 50% reinforcement schedules and finding the 50% schedule more resistant to extinction.

[xxvi] Better would have been 79%. Let the probability of reinforcement during the acquisition phase be p(r). The probability of no reinforcement during this phase, p(~r), is then [1 – p(r)]. There are the only two possibilities. Like a coin, $C_{pot} = \log_2(2) = 1$ bit. We know that Ω_{max} occurs when $C/C_{pot} = 1/\sqrt{2}$, i.e. when $C = C_{pot}/\sqrt{2}$, which in our case = $1/\sqrt{2} = 0.707$. Inspect Figure 1.1. For C_{pot} ("U_{before}" in Figure 1.1) equal to 0.707, p(r) = 0.79 and p(~r) = 0.21. Pretty close to 0.75 and 0.25.

[xxvii] For several less-startling explanations of the partial reinforcement extinction effect (PREE), also known as Humphreys' paradox, see Domjan, *Essentials,* 124–129.

[xxviii] As far as I know, no study has been made of the structural information in video games (or any games for that matter), where by "structural" I mean probability and time-spent (by-player) data mapped onto the "flow diagrams" of the game's logic and its alternative scenarios. It would be fascinating, for example, to analyze the Tamagotchi (which is a Japanese hand-held video game that simulates a pet that needs to be fed, cleaned, trained and taken care of) in these terms. How much of the Tamagotchi's addictiveness to pre-teenagers depends on the lifelikeness of scenario in the literary sense, one wonders, and how much of it depends on the underlying statistics of its behavior, i.e. its captivatingly balanced complexity and organization?

[xxix] George A. Miller, *Language and Communication* (New York: McGraw-Hill, 1951), Fred Attneave, *Applications of Information Theory to Psychology* (New York: Holt Rinehart and Winston, 1959), and Daniel Berlyne, *Conflict, Arousal, and Curiosity* (New York: McGraw Hill, 1960.) Two other landmark earlier studies were by W. N. Dember and R. W. Earle "Analysis of exploratory, manipulatory and curiosity behaviors," *Psychological Review* 64 (1957): 91–96, and Berlyne's own "The Influence of albedo and complexity of stimuli on visual fixation in the human infant," *British Journal of Psychology* 49 (1958): 315–318.

[xxx] *Psychological Review* 63, no. 2 (1956): 81–97.

[xxxi] See also Appendix Three in this volume, "On Omega at Different Scales."

[xxxii] J. G. Miller, "Information Input Overload and Psychopathology," *American Journal of Psychiatry* (February 1960): 695–704.

[xxxiii] Berlyne, *Conflict, Arousal, and Curiosity,* 163ff.

[xxxiv] How is the "arousal level" measured? By galvanic skin response (GSR), by changes in brain-wave (EEG) frequency and intensity, by muscular tension, pupil size, heart rate, blood pressure, and of course, self-report.

[xxxv] Over-aroused, we feel anxious and frantic, and we make mistakes or break down. Under-aroused, we feel dull, bored, paralyzed. Both states feel unpleasant. Although under- and over-arousal as brains states are mutually exclusive, there are life situations that make them all but simultaneous. For example, we find ourselves alternatingly under- and over-aroused when, on the one hand, we need to operate in a complex and demanding business environment (where, perhaps, we have too little control or experience), while on the other, at home, we find ourselves cocooned in the overly-familiar, deadening routines of home life and duty. Or perhaps the situation is reversed: stress and change at home, boredom at work. Few can manage these dichotomies for long or keep them apart. Better is a (waking) life that cleaves closer to ideal, i.e. moderate, levels of arousal most of the time.

"Nothing in excess," proclaims the temple of the Oracle at Delphi. "All things in moderation," echoes Aristotle in *Nicomachean Ethics*. Few people notice in Aristotle's prescription that *all* things are to be experienced in moderation—not just a few, certifiably-good, safe, and permitted things, but "*all*" things. Aristotle's reading of Delphic nostrum is, I would argue, less a plea for taking small bites than a subtle plea for inclusiveness, for a rich and diverse and open life, for curiosity and knowledge, sociality and privacy, stability and adventure. It is, in short, a plea for real complexity, better as there is more of it because it is complexity of the best sort, i.e. "moderated" complexity, which we now suspect means actual complexity evenly balanced with organization, which leads, of course, to optimal Ω. Not surprisingly, we learn that Aristotle was a "family man" and *bon-vivant*. He would have been delighted to learn that, halfway around the world, in China, Confucius had at the same time been advocating the same moderation principle as the Way of Heaven.

I go into this more fully in my paper "Complexity, Value, and the Psychological Postulates of Economics," *Critical Review* 10, no. 3 (Fall 1996): 551-594.

xxxvi Berlyne's theory and ours share not only similar interests but a similar mathematical structure also, to wit: $y = f(x)$ and the function is such that the maximum value of y (which is what we want more of) lies between "too much" and "too little" x. The outcome, anyway, is a classic "inverted-U" curve (or Wundt curve, as it is known in psychology). For Berlyne y is preference and x is information processing rate or arousal; for us y is complexity-and-organization, Ω, and x is actual complexity *or* organization.

xxxvii Edward Lewis Walker, "Complexity and Preference Theory," in D. E. Berlyne and K. B. Madsen, Eds., *Pleasure, Reward, Preference* (New York: Academic Press, 1973), 73.

xxxviii Walker, "Complexity..." page 80. Walker is here reporting the work of R. G. Heyduk, "Static and Dynamic Aspects of Rated and Exploratory Preference for Musical Compositions," being the latter's doctoral dissertation at the University of Michigan in 1972 and which appeared as "Rated preference of musical compositions as it relates to complexity and exposure frequency," in *Perception and Psychophysics* 17 (1975): 84–91.

Perhaps if Heyduk had carried on to 30 playings, the very complex composition would have "won", but then it seems evident that yet-more-complex composition could have been devised... Subjects rated "interestingness" linearly with actual complexity, but again, one feels sure that there is an upper limit to this too, after which the positive judgment would decline, as Walker remarks on p. 90, op. cit.

xxxix We might surmise that different subjects set C_{pot} at different absolute magnitudes due, say, to their differing intelligence or knowledge of music theory. No problem. A within-subject standard for C_{pot} is all we need. That is, we need only suppose that those subjects who underestimated the four pieces' potential complexity understimated their actual complexity too, and by a proportionate amount. In general, lack of sensitivity or intelligence can decrease both the potential and the actual complexity of an experience, lowering its Ω, just as heightened sensitivity and intelligence can do the opposite, increasing the Ω of an experience. These are different experiences *of the same thing*, true, but two observers, one dull and one bright, might still agree on how to rank order "pleasingness," "interestingness," or some other proxies for Ω and C over several pieces.

A toast, then, to education: probably the cheapest way (save the use of psychotropic drugs) to enrich world experience without having to enrich the world-experienced in any way.

xl This study was performed by the author and Prof. Clarke A. Burnham (Dept. of Psychology, University of Texas at Austin) with the assistance of Chad Wood, programmer, in the summer of 2002. The data showed weak statistical significance for variation in rythmic complexity-and-organization and strong statistical significance for melodic complexity-and-organization. The songs were presented in three sets of nine songs, randomly ordered within the nine but constrained to representing each of the cells once. On the whole, Set 3 was preferred to Set 2, which was in turn preferred to Set 1. This was due either to learning, or to increasing charitablility as subjects realized that the "songs"—all pretty lame as songs go—weren't going to get any better... As of this writing, experimentation continues.

xli For more on how to think about Ω at different scales in the same system, see Appendix Three, especially Figure A3.9, which is applicable to strings like melodies.

xlii Csikszentmihalyi presents this diagram with Skill along the X-axis and Challenge along the Y-axis. I have taken the liberty of switching their positions in order to make the comparison to our theory a little clearer.

xliii Csikszentmihalyi himself makes note of the connection between his model and complexity theory in a footnote to his book *The Evolving Self* (New York: HarperCollins, 1993), 318.

xliv Or more accurately when $\Delta(\Omega_{max} - \Omega_{actual}) = \Delta(S_{max} - S_{actual}) > 0$, where S stands for satisfaction. The identity between "a value experience" and (the momentary feeling of) happiness holds perfectly only when Ω_{max} (= S_{max}) remains constant between the two times of measurement in question.

xlv Mihaly Csikszentmihalyi, "Values and Socio-cultural Evolution," in Michael Benedikt, ed., *Center10: Value* (Austin: Center for American Architecture and Design/University of Texas Press, 1997), p. 51.

xlvi James G. Miller, "Information Input Overload and Psychopathology," 1960, and "Adjusting to Overloads of Information" in D. Rioch and E. Weinstein, Eds., *Disorders of Communication* (Baltimore: Williams and Wilkins, 1964).

xlvii The task was a laboratory experiment typical of the field, that involved watching flashing lights, identifying colors, pushing buttons, remembering logical instructions, etc. One suspects that performance figures would be higher with more natural tasks, but that the findings as a whole would hold. *Group* performances with the same sort of task were worse, peeling away from ideal at around 1 bit/sec and peaking at around 2.2 bits/sec. This last result suggests that committees are indeed slower than any one of their members, as I opined earlier.

[xlviii] Richard L. Meier, *A Communications Theory of Urban Growth* (Cambrdige: MIT Press, 1962), 74–79, which follows his "Social Change in Communications-Oriented Institutions," Report #10, *Mental Health Research Institute*, University of Michigan, 1961. Note: Miller and Meier had contact in these years: the former thanks the latter (and many others) in his above-mentioned paper.

[xlix] See for example "The Theory of Complex Phenomena," in his book *New Studies in Philosophy, Politics, Economics and the History of Ideas* (Chicago: University of Chicago Press, 1978).

The similarity here to the logic of cellular automata and artificial life sytems is not accidental. Von Hayek had read von Neumann, and vice versa. Both believed that the upper ranges of complexity-and-organization are accessible only to very large systems built from the "bottom up," i.e., systems that have a measure of autonomy at all scales of their operation, and that are coordinated not by a "central processor" in full communication with every little part, but by a complex message-passing system between micro-elements and subsystems only the "gist" of which is passed up to a central processor—should there be one at all. The self-regulation of myriad parts makes regulation of the whole a relatively simple matter, no more complex anyway than that required of any typical part. It also makes the inevitable occasional failure of a part non-catastrophic to the whole. Interconnected and free markets, argued Hayek, represent just this principle in the social realm, and their efficient functioning is all-but-self-evidently essential to the health of a nation.

[l] Three possible exceptions: Ernst Schumacher, *Small is Beautiful* (New York: Harper and Row, 1973), Kirkpatrick Sale, *Human Scale* (New York : Coward, McCann & Geoghegan, c1980.), and Jeremy Rifkin, *Entropy* (New York: Viking, 1980). None of these authors propose a way to quantify complexity. The economist Nicholas Georgescu-Roegen also made an assay into complexity theory with a book exploring the concept of entropy and the proposition that productive economic activity is what slows and even reverses the Second Law of Thermodynamics in our ecosystem. (See Georgescu-Roegen, *The Entropy Law and the Economic Process[*Cambridge, Mass., Harvard University Press, 1971]). His understanding of entropy and complexity however, left much to be desired.

[li] Some economists argue that a low rate of inflation is better than zero or negative inflation—first, because growth in the money supply needs to match growth in the population, at least roughly if every new economic player is to have a sufficient number of "chips" to play with, and second, because moderate inflation provides "cover" for quality increases and technical innovations that might, initially at least, cost more to put in place. In a low- or zero-inflation environment, when people do not *expect* prices and wages to rise, profits can be held on to or increased only through cost-cutting, through simplification of products, or through reduction of product variety. Kept up for too long, this pure efficiency-mindedness is anti-evolutionary.

There are other reasons, too, why a little inflation is better than none. Among them, as John Maynard Keynes pointed out, is the fact that wage earners *like* to feel a little richer each year, even if they know perfectly well that prices are going up at the same rate as their incomes. Most people believe that with canny shopping they can beat the system, i.e. avoid many of the price increases that the average Joe will suffer. This is a belief that many retailers are more than happy to indulge, of course, and it is not entirely unfounded. For when consumer-price-index-matching wage increases can be relied upon, the relative uncertainty as to *which* prices of *which* products and services will go up counts to the advantage of the wage earner. With more money definitely in his pocket and a shifting and competitive marketplace of sellers to face, he is likely, he knows, to have options. Money is freedom, and more of it is more. Period.

More about all this in Chapters Eight and Ten.

[lii] David Warsh, *The Idea of Economic Complexity* (New York: Viking Press, 1984) pp. 19, 20:

> No one who has lived through even a few decades of the twentieth century can doubt that complexity and economic interdependence have been growing at a remarkable rate. When the century began, people travelled by horse and rail and communicated by mail, a third of the population lived and worked on farms, and a specialist was a cavalry lieutenant or an organic chemist. Children were born at home and old people died there. A few industries were organized in great trusts—gunpowder, sugar, shoes, tobacco, oil, and some others—but compared with today's vertical integrations, these were simple operations, run out of their founders' vest pockets. The government in Washington D.C. employed a few thousand people organized in two dozen offices. As late as the 1920s, the senate met for only three months of the year.
>
> Today, soldiers operate nuclear missiles and submarines, businesses are managed by experts in long hierarchical chains, and even physicists work in teams. Three percent of the workforce does the farming; the rest engage in a bewildering array of manufacturing and services. The telephone...[and the Internet] have [all but] replaced the postal service and [TV, movies and home video] the Saturday night dance. Products have proliferated almost beyond the naming of them; indeed technical writers capable of clearly describing the differences between products and their functions are in great demand. There are plastics manufacturers, television producers,

nuclear weapons specialists, molecular biologists, strategic planners, fast-food hamburger cooks, astronauts, foreign currency traders, CAT-scan operators, Social Security actuaries, silicon chip designers [and computer programmers], corporate takeover specialists, Xerox repairmen, Occupational Health and Safety Inspectors, and historians of science—all of them specialists, none of whose jobs existed in any significant numbers before World War II.

liii There are exceptions to this rule, of course, usually in the arts and crafts where we enjoy seeing direct evidence of the artist's struggle or the history of the piece as it went from one process to another. Japanese *raku* pottery is one example.

An easy way for architects working in the modernist "hi-tech" style to increase the visual complexity of the spaces they create is to expose air-conditioning, plumbing, and electrical ductwork to view. So too is exposing structural and mechanical parts, little pieces and wires and nuts and bolts shown off in the name of "honesty." No fig leaves here.

There are other more rhetorical-political benefits to doing this, too. For, having exposed all the bits and pieces, what now stands forward is how well the architect has "brought them together." Not only can this "bringing together" metaphor be made to resonate beautifully with the "bringing together" of *people* (which is *always* a good thing) but it sets in motion an easy mode of aesthetic production: first "analyze" a thing into parts, then "articulate" the parts, then connect the parts together with lots of joints so it looks a machine designed to be taken apart again; then repeat at all scales.

liv At the beginning of the 19th century, political economist David Ricardo had much the same idea with his notion of "roundaboutness." Roundaboutness was proportional to the number of hands (and/or manufacturing steps and/or wholesale markets) a product had to pass through to be transformed from raw material to final product. Roundaboutness was given more formal treatment, and a revival, by Eugene von Bohm-Bawerk in his 1889 *The Positive Theory of Capital*. For a short history of the concept, see K. H. Hennings, "Roundabout methods of production," in John Eatwell et. al., eds., *The New Palgrave: Capital Theory* (New York: Macmillan Press, 1990), 232–236.

lv The concept of cost webs does not deal explicitly with the amount of knowledge or information applied at each node, which surely goes down with each new splitting of one job or business into two (i.e. at each new step in specialization). But the implication is that, over time, the amount of this information creeps back...until a new round of specialization and node break-up is called for.

lvi To help make his point Warsh cites economic historians Henry Phelps Brown and Sheila Hopkins who produced a chart showing changing prices of a simple market-basket of goods in England from 1250 until 1950. Plotted on a chart we see that periods of relative price stability alternate with periods of "inflation."

Figure 3.9 A seven-century price index for Southern England, adapted from Warsh (1984)

But, as Warsh points out, these long-lasting periods of price and wage increase had little or nothing to do with banking policies or the minting practices of kings, which account only for blips. Rather, they coincide with long periods of intense technological innovation, business specialization, financial invention, and/or expansion of trade—complexifying agents all. That more money had to be in circulation in order to finance and meter this growth in complexity does not imply that the extra money *caused* the inflation. (Indeed, the fifteenth century in England saw several currency debasements by the Royal mint, and as one can see from the Phelps Brown data over this period, price increases were very short term and reversible at this time.)

Warsh is not denying that inflation will ensue if more money is put into circulation than is needed by a nation to do its aggregate business. "Cost-push" and "demand-pull" explanations are closer to the mark, he thinks, but still miss the essential point. Prices and wages would not go up if only the dollar-volume-quantity-of-goods *size* of the economy increased. With productivity a constant and the ratio of money-in-circulation to total population held constant, too, there would be no pressure either way. But when not only the economy's size but the degree of its interconnectivity and specialization increases, then not only its potential complexity, C_{pot} (= $\log N$), increases, but its actual complexity, C , does too. More-money serves a decisional, informational function: it gives individual economic agents the greater freedom to make the greater number of choices they must make. Money is almost perfectly fungible: that is its unique property, and just the property needed for a society whose frequency of interactions with strangers is increasing not only directly, but indirectly with ever lengthening chains of association that make and bring goods to market.

In *Wealth of Nations*, Adam Smith had also associated the degree of division of labor with "the extent of the market." But "extent," as a number of writers have noticed, is an omnibus if not ambiguous term. It could mean: number of buyers and sellers, it could mean the volume of goods and money, it could mean the geographic far-flungedness of the origin of the goods traded, it could mean the variety of goods available, it could mean the number or variety of credit and payment arrangements available to buyers and sellers....it could mean all of these or any subset of these things. What Smith needed was modern complexity theory.

Another note: Official measures of the consumer price index (CPI) replace goods that are becoming more expensive with cheaper goods that satisfy the same needs (e.g. chicken for beef, etc.). These substitutions are intended to track the behavior of the average consumer. But they cancel out a large part of what Warsh (and we) are interested in, namely, the correlations between product variety, sophistication, price, and the complexity of the economic system as a whole. It is not true, anyway, that consumers do *not* always, or even most often, buy the cheaper of two goods that serve the same purpose. Firstly, people develop loyalties to certain brands as well as certain habits of consumption, secondly, the cheaper, substituted good is frequently not of the same quality as the one it replaces, and thirdly, new *kinds* of goods come onto the market, goods for which there was little desire or precedent (for example, the networked home computer, once unheard-of, now close to necessary). But even if it were largely true that the CPI reflects consumption behavior based on price-sensitive substitutions, this would not explain the general rise of the CPI over time, consumer-resistance and all. Ignoring quality- and complexity increase as a factor leaves only money-supply explanations of inflation combined with "demand-pull"/"cost-push" explanations that invoke competition among buyers for scarce goods at a time when organized labor has increased bargaining power, and neither of which appear to fit most of the facts of inflation (and deflation) in economic history.

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lvii Can it be a coincidence that, since the mid-1980's, growth in the money supply and the rate of inflation in the U.S. have essentially been decoupled? This was a period of massive computer-assisted complexification and coordination of market activity, as well as of finance itself, at a global scale. (See Silvia Nasar, "Unlearning the Lessons of Econ 101, "*The New York Times*, May 3, 1998, Section 4, 1.) The low inflation rate during the economic boom of the late 1990s in the U.S. was partially attributable to continuing computerization and globalization. But it was also supported by starkly rising wage and income inequality. Prices could not rise because *most* people could not afford them to, but were willing to work harder to get the same goods. What also absorbed inflationary pressure was rising household debt, the deteriorating and "overworked" physical environment of the lower-middle and working classes, and the increasing number of women entering the workforce in order to keep their households solvent.

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lviii Henry Theil, *Economics and Information Theory* (Chicago: Randy McNally, 1967).

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lix Cf. also Robert U. Ayres, *Information, Entropy and Progress* (New York: AIP Press 1994), parts of which were cited in Chapter One. For another element of empirical evidence for Ω, see Note 15 of Chapter Four, where I briefly report the work of Ronald Inglehart.

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lx Actually, he was following the statement of the eighteenth century Dutch philosopher Frans Hemsterhuis who defined Beauty, apparently famously, as "that which gives us the greatest number of ideas in the shortest period of time." (James R. Newman, *The World of Mathematics, Vol. 4,* [Redmond, Washington: Tempus Books-Microsoft Press, 1988 (1956)], 2158). Note Hemsterhuis's quite modern and psychological—not to say economic—point of view. The idea of information is now seeded.

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lxi Alfred North Whitehead, *Process and Reality* (New York: Macmillan,1978 [1929]), p. 339.

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lxii Rudolf Arnheim, *Entropy and Art* (Berkeley and Los Angeles: University of California Press, 1971), 56.

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lxiii Morse Peckham, *Man's Rage for Chaos: Biology, Behavior & the Arts* (New York: Schocken Books, 1967), 39.

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lxiv Besides, "unity in diversity" has a pleasingly modern and democratic political ring to it *E pluribus unum* (out of many, one) is inscribed on U.S. banknotes; but note, a fascist might be as comfortable with this slogan as we seem to be.

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lxv See for example, Joseph Pieper, *Leisure, the Basis of Culture* , trans. Alexander Dru,
Introd. by T.S. Eliot (London: Faber and Faber, 1952).

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lxvi *Natural Classicism: Essays in Literature and Science* (New York: Paragon House, 1985), *Beauty: the Value of Values* (Charlottesville/London: University Press of Virginia, 1991), and *Tempest, Flute, & Oz: Essays on the Future* (New York: Persea Books, 1991).

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lxvii "The Meaning of Value," in *Tempest, Flute, & Oz*, 41.

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lxviii See Harold Bloom, *The Anxiety of Influence: a theory of poetry* (New York: Oxford University Press, 1973.)

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lxix Turner 1991., p 40-41.

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lxx Ibid., p. 41. Note that Turner here follows the convention (which we have eschewed) of calling states of extremely high entropy "simple," a convention which can only be justified on the grounds that the system's entropy (read—correctly—its complexity) is so great that one can make only a few simple assertions about it that can hope to be correct. These assertions are perforce about its average and macroscopic state (such as its temperature, mass, or volume). Cf. Appendix Two on entropy.

lxxi See also Frederick Turner *The Religion of the Future: A Theological Fantasy* (in press, 2000)

lxxii Robert Wright, *Nonzero: the logic of human destiny* (New York: Pantheon Books, 2000). The title word Wright wanted to use but thought was too cumbersome, was "non-zero-sumness."

lxxiii Note that competitive sports where there a difference in final scores develops (like 112 -98 in basketball or 3-1 in soccer), and which would seem to imply that both sides won *something*, are still considered zero-sum games, because there is still only one winner who wins at the expense of the loser. Point spreads may tell us whether the game was close or not, or high-scoring or low-scoring, and so on; but the real score depends on who-had-more and who-had-less in the end, a binary choice. This is an unfortunate fact about *voting* too: 51:49 percent votes are not much different in the short run than 90:10 or 100:0 votes: the winning side gets its way entirely.

lxxiv See Notes 2 and 48 of Chapter Two.

lxxv See Pierre Teilhard de Chardin, *Christianity and Evolution*, trans. R. Hague (New York: Harcourt Brace Jovanovich 1974 [1971]), or *The Phenomenon of Man*, trans. B. Wall, with an Introduction by Julian Huxley (New York: Harper, 1959). The omega of Teilhard's Omega Point is not "our" omega except by a stretch of the imagination that I would not recommend to anyone planning to preserve their academic credentials.

lxxvi From Dr James Lovelock, *Gaia: A New Look at Life on Earth* (Oxford: Oxford University Press, 1995):

> The entire range of living matter on Earth from whales to viruses and from oaks to algae could be regarded as constituting a single living entity capable of maintaining the Earth's atmosphere to suit its overall needs and endowed with faculties and powers far beyond those of its constituent parts...[Gaia can be defined] as a complex entity involving the Earth's biosphere, atmosphere, oceans, and soil; the totality constituting a feedback of cybernetic systems which seeks an optimal physical and chemical environment for life on this planet.

lxxvii Though he quotes the Bible, Wright does not conceive of God in anything like His biblical form. His is more like a scientist's God, a universal principle of some sort, perhaps of Love... Like all "negative theologians," Wright is more sure of what God is *not* that of what He is. My own belief is that God and Man create each other, in an ongoing process.

lxxviii Of course, I fully recognize that the God referred to here is the One God of Jews, Christians, and Muslims. Many religions do not have one God but many; and several have no God at all but a sacred, universal Way.