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Welcome to the University of Chicago and to a shared adventure in education over the next four years. Because the accident of your birth dates has made you members of the class of 2000, you will be subjected to innumerable appeals during that time to change the world, to make the next millennium different from the present one. I hope you will do so, and I look forward to seeing how each and every one of you changes the world in wonderful and exciting ways. In the hour we have together today, I want to talk about predicting the future and the ways in which your education in the College of the University of Chicago will prepare you for that future.

In the words of the immortal Yogi Berra, “The future ain’t what it used to be.” That is a statement that rings very true today. Uncertainty is the hallmark of the late twentieth century: uncertainty about political stability in the world, uncertainty about job and economic prospects for yourselves and your contemporaries, uncertainty about the core values of a modern industrial society. I will argue that the sign of an educated man or woman is the ability to deal constructively and creatively with uncertainty and ambiguity. In good University of Chicago fashion, I will try to convince you first that ambiguity should be resisted and then, second, that it should be accepted. The aim of your education here is to learn to do each in its place.

You have been dealing with ambiguity throughout your education, of course. High school English classes debate the meaning of the whale symbol in *Moby Dick* and come up with many valuable answers, not a single simple one. On the other hand, I doubt that you spent much time in chemistry class debating whether sodium reacts with chlorine to produce sodium chloride (ordinary table salt): you can simply do the experiment and demonstrate that it does. So perhaps some of you are entering college with a somewhat parochial view of the continuum of the arts and sciences. On the one end are the humanities, in which any answer is correct as long as you argue forcefully enough. At the other extreme are the natural sciences, which deal with definite statements of fact and give yes-or-no answers to questions. In between are the social sciences, constantly aspiring to the exactitude of the natural sciences but sometimes falling back into the morass of ambiguity on the other side. (I speak as a natural scientist myself, and, of course, with tongue in cheek.)

I hope that the Common Core education that you are about to share here will, if it does nothing else, disabuse you of these clichés. From your humanities classes, you will see that the

Careful reading of original texts and the construction of well-reasoned arguments are processes that can become precise and focused with guidance and practice. From your natural sciences classes, you will learn that the most important questions about the world around us are ones that inevitably contain a degree of ambiguity, and the challenge is both to reduce that ambiguity as far as possible and to accept the underlying ambiguity that remains as an inherent property of nature. From your social sciences classes you will come to appreciate not the divisions between areas of knowledge but their fundamental unity, with quantitative and qualitative reasoning working together toward the same goals.

Let me talk some more about what natural scientists do and how that relates to this aim of education that I have identified as “learning to deal with ambiguity.” The goal of science is, of course, to understand the world, to work from the level of basic physical laws to account for the manifold complexities of the physical environment and of living species. Understanding in science (and especially in the physical sciences) is intimately tied up with prediction: we cannot truly say we understand something unless we can predict what will happen next in a given situation. This linkage between understanding and prediction is less true in the humanities and the social sciences. The deep insights gained by studying several works by a single artist do not allow us to predict the picture that artist will paint next, nor would such an exercise in prediction have any value. Although historians talk about learning lessons from history that will help us in the future, they would be very hesitant to predict the events that will reach the newspapers next year or in ten years from Bosnia or the Middle East.

How then are scientists able to make predictions? In my own field of physical chemistry, the key to successful prediction is to do carefully controlled experiments. That is what makes doing science so expensive: temperature must be held constant, air currents kept away, dust particles carefully excluded in order to obtain reproducible results. And so a physical chemist sets up a rigorously controlled, but also very artificial, environment, in which ambiguity is excluded to the greatest extent possible. Within this environment he or she can carefully manipulate one or several variables and measure the effect of each on the course of the chemical reaction. Only under these circumstances can reproducible results be found, reproducible not only within the lab but by another lab across the world where the same experimental conditions have been created. Any scientist knows, however, that even in the most carefully arranged experiment there will be outlier results that fall beyond the range of normal variability. Perhaps a heavy truck drove by and shook the apparatus at that moment, or a particular batch of chemical came from the supplier with an interfering impurity. The life of the experimental chemist is a constant struggle against the outside world in order to obtain reproducible, predictable results.

Of course, it occasionally happens that an outlier result leads to a new discovery. Recognizing the serendipitous surprise is the key to many real advances in science. When Alexander Fleming noticed a clear area in a bacterial culture dish where a tiny piece of mold had dropped, he did not simply throw that dish away and continue his experiment with the others; rather, he

isolated the mold and the antibiotic it produced, penicillin. When a surprise results from nature operating in ways we had not predicted, science advances; ninety-nine times out of a hundred, though, the surprise disappears when conditions are controlled more carefully. Particle physicists sort through millions of predictable results from high-energy particle collisions to locate the rare result that may signal a new physical process or a new particle; only after they obtain a sufficient number of such deviant events can they substantiate a claim of a new discovery.

So my first message to you is to resist ambiguity. Make your statements precise, and identify the conditions under which a particular outcome will be seen and when it will not. Explore surprises with tenacity until the surprise either disappears or becomes part of a new paradigm for understanding the world. Our progress out of the Stone Age has resulted from the human drive to subdue and eliminate ambiguity. Earthquakes, for example, are no longer seen as the random acts of a capricious god but as the natural result of plate tectonic motion, working through the laws of physics. This scientific explanation does not answer the question “Why an earthquake right here and now?” nor does it reduce the anguish of human suffering that such events cause. Obviously there are many questions yet to be answered about when earthquakes strike, what the mechanism is, and how the harmful effects can be lessened. One of the aims of education is to enable each of you to approach the real world in a rational fashion, analyzing events for cause and effect and resisting the temptation to give in to blind superstition. Our world needs more of this probing, rational, analytic approach to its problems.

I have twice just now used the word analysis to describe the process by which a problem or phenomenon is broken down into simpler component parts, each of which is more easily understood than the more complex whole. Analysis is a good chemical term: it refers to a long-standing tradition in chemistry by which materials are separated into substances, elements, and eventually individual atoms. The further the process of analysis is carried, the simpler are the resulting entities and the more predictable their behavior. (One must be careful here, though. At the microscopic level there are some deeply mysterious consequences of the laws of quantum mechanics.) One of the aims of your education is to enable you to break down complex concepts or processes into simpler pieces so you can understand them more clearly. Analysis reduces ambiguity and allows us to predict future results with confidence.

There is a complementary and equally important chemical tradition to analysis, namely, synthesis: making new and complex materials from simpler building blocks. Synthesis is the second aim of your education, and I would argue that if the outside world needs to fight irrationality and encourage analysis, perhaps the academy (the world inside the university) needs to place greater emphasis on synthesis and creating a whole. We are often better at tearing things to pieces than at putting them together. To achieve synthesis and deal with complexity in ourselves and the world requires us to accept a certain degree of ambiguity. This is the second aim of education I would like to examine.

What is the source of complexity? Why is it so difficult to control conditions of an experiment? What makes predictions further into the future more difficult and less precise? One explanation is referred to as the “Butterfly Effect”; in more mathematical terms it is called “exponential sensitivity to initial conditions” or even “flow on a manifold of negative curvature.” Let me describe the origins and implications of the first of these names, for those of you who are not familiar with chaos theory. The term comes from a talk given in 1979 by Edward Lorenz entitled “Predictability: Does the Flap of a Butterfly’s Wings in Brazil Set Off a Tornado in Texas?” Lorenz was one of the first mathematical meteorologists, a scientist who developed computer programs to calculate the behavior of the atmosphere and predict the weather. In such calculations, which have become far more sophisticated today with the advent of supercomputers, one starts with a set of equations for changes in atmospheric properties such as temperature and density through time and space. Then one chooses a set of initial conditions, in the real world obtained by sampling the atmosphere at weather stations distributed across the world. By solving the mathematical equations of the model, one then predicts the weather a day, week, or month later throughout the world.

Lorenz discovered that these equations for atmospheric dynamics are exquisitely sensitive to the initial conditions. A small change in the initial temperature or air velocity at one location affects only its immediate neighborhood for a short period of time. As time goes on, however, the effects on the atmosphere grow both in magnitude and in spatial extent, so that after a long enough period of calculation, the physical properties at each point in space are completely different. In other words, a small perturbation does not have small consequences; it entirely changes the resulting behavior. It is in this sense that a butterfly flapping its wings and setting up an air current in Brazil can, over a period of weeks or months, change the atmospheric dynamics far away over Texas to such an extent that a tornado appears when it would not have otherwise. What an image this is! On the one hand, the Butterfly Effect reminds us of how interconnected the world is: weather is a global phenomenon that connects us in surprising ways to events in Brazil and China. On the other hand, it demonstrates the futility of attempting precise predictions of future behavior based on knowledge of the present. The nonlinear processes that determine the weather eventually mix distance scales from the microscopic up to the global: small causes have huge effects.

Another way to think of this is as loss of information or of predictability with time. If we set up a carefully controlled experiment and try to predict the outcome, we will do fairly well for short times. As time passes, both the imprecision with which we were able to measure the initial conditions and the cumulative effect of tiny outside perturbations conspire to give results that no longer bear any relation to our predictions. In complex, nonlinear systems like the atmosphere (or, indeed, for any collection of molecules), there is a steady loss of information and predictive power with time. Chaos theory has become a fashionable subject in the last decade, explored by everyone from physiologists and population biologists to pure

mathematicians and computer hackers traveling through the bizarre geometry of the Mandelbrot set. An institute of nonlinear science is bankrolled largely by the financial industry, out of the hope that chaos theory will provide insight into the workings of the markets. The key discovery is that even the simplest models of three coupled nonlinear equations exhibit the full richness and complexity of much more complicated models.

The Italian novelist Italo Calvino has written a delightful set of stories called *Cosmicomics* in which he takes a very playful approach to the evolution of the universe. As a scientist, I find his literary explorations of scientific notions both thoughtprovoking and entertaining; I encourage you to read his book. One of the stories is entitled “How Much Shall We Bet?” (“Quanto Scommettiamo”) It portrays the relationship between the narrator, given the unpronounceable name of Qfwfq and the old Dean, (k)yK. The two of them are observers from before the beginning of the universe to the present, and they spend their time making bets about what will happen in the future. The Dean is described as a “fairly boring sort” who lacks imagination (like all Deans, I suppose), whereas Qfwfq has “much more imagination” and thus makes riskier bets.

Early in the history of the universe the bets made by the more daring Qfwfq are generally successful. He correctly predicts the condensing of gas clouds into protostars and protogalaxies, and builds up his winnings. As time goes on, he gets bolder and begins to make predictions further and further into the future, guessing for example that the Assyrians will invade Mesopotamia. The Dean keeps betting no, “simply because he refused to think there would ever be Assyrians and Mesopotamia and the Earth and the human race.” Qfwfq presses his luck still further and begins to predict the daily closing quotations on Wall Street and the results of sports contests: “Arsenal-Real Madrid, semifinals. Who wins?” As he projects further ahead into the future, in spite of the power of the computers with which he is working, he begins to get things wrong. The tables turn, and he loses all his earlier winnings to the Dean, who continues in his boring way to resist innovative predictions. The story ends with the Dean crowing, “What’s our score now, Qfwfq?”

Calvino’s parable illustrates how information and predictability are lost when systems become more complex. The way a billiard ball will bounce on a smooth billiard table can be predicted through a simple application of the laws of mechanics, but the shape adopted by a particular snowflake that grows as it falls through the atmosphere cannot. Information and predictability are also lost as time passes. Hit the same billiard ball hard and let it collide with the sides and other balls a dozen times; predicting where it will end up then becomes a much more challenging problem. It is far safer to bet with Calvino’s narrator on the motion of a star or galaxy than on the course of human history.

If we cannot predict the weather in Chicago this day next month, how can we make predictions even further into the future? Are they not completely invalidated? This becomes a critical

question as we think about possible global climate change resulting from human activity. Can we make any useful predictions about the year 2050, or does the Butterfly Effect render them all useless? Here some understanding of probability and statistics is essential. The first thing we can try to do is to make predictions not about instantaneous, local properties but about averages. We can predict, for example, that the eruption of a volcano will cause the average temperature in the Northern Hemisphere to decrease in the following year (averaging over a large spatial region), or we can predict that particular air circulation patterns over the Pacific will cause the average temperature this autumn in Chicago to be higher than it would be otherwise (averaging over a period of time). In neither case are we making predictions about what will happen on some particular day in the distant future, but our predictions are no less useful.

We may need even to go beyond averages and talk about probabilities. For example, we might argue that there is a 60 percent likelihood that next summer will be hotter than this summer. Such a prediction is not invalidated if it turns out that next summer is cooler; however, if such predictions are consistently wrong (i.e., if the probabilities assigned do not work out even on average), then we need to come up with a better predictive model. Scientists must deal with ambiguity as precisely as possible. Politicians tend to believe in global warming when the summer is hot in Washington, D.C., and disbelieve it when it is cold. What is needed instead is a long-term look at the predictive power of our atmospheric models, testing them against average behavior over extended periods of time.

One quality that scientists, politicians, and educated citizens alike need is the ability to make predictions about the future based on incomplete evidence. Such predictions should certainly be challenged and tested, but ultimately policy decisions will need to be made based on such incomplete evidence. In a tabletop chemistry experiment we can run the same test with the same initial conditions again and again until we have convinced ourselves and others that the answers are robust. There are two problems with trying to follow the same procedure for some of the complex issues on which we need to make scientifically sound decisions. The first is that we may not have time to wait; by the time everyone has been convinced by the evidence, the world may have changed in irreversible ways. The second is that we cannot do a controlled experiment on the global environment the way we might in a chemistry laboratory. In the lab we can start out two different runs on our apparatus at two different temperatures; in the universe we have only one earth on which to experiment, and the starting conditions cannot be freely adjusted. We are forced to make measurements and set out predictions in a continuously changing environment and then to decide policy based not on complete control and understanding but on the best current evidence, ambiguous as it may be. It is my personal conviction that humankind is currently trying a dangerous experiment with global change, whose outcome may only be known when it is too late to correct for the ill effects of that experiment.

So my second message to you is to accept ambiguity. Recognize that in complex systems detailed predictions are not possible but that useful forecasting of probable future behavior is still feasible, even based on incomplete evidence. Dealing realistically and, to whatever extent possible, quantitatively with such evidence is the mark of an educated citizen, and we desperately need more such citizens in the future. Make one of the aims of your education the ability to weigh evidence and assess likelihood, rejecting the false certainty of yes-no answers in complex situations. The skills you will be cultivating throughout your education will be ones of synthesis: the ability to put together many separate pieces to make rational judgments about difficult human- and global-scale problems.

In the remainder of this talk, I would like to relate my discussion of complexity and chaos both to the second law of thermodynamics and to the aims of education. This is also a good place to start your general education at the University of Chicago. The British novelist and scientist C. P. Snow, in his 1960 book *The Two Cultures and the Scientific Revolution*, bemoaned the lack of communication across the divide between the humanities and the sciences. He argued that every educated person should not only be familiar with the works of Shakespeare but also have a grasp of the fundamental meaning of the Second Law of Thermodynamics. I will leave Shakespeare to your Common Core Humanities classes, but will not let you go out from here today without learning something about the Second Law.

The Second Law states that, in any isolated system, the entropy (loosely speaking, the randomness or disorder) will increase with time. The reason is that disordered states of complex systems are overwhelmingly more probable than ordered states. Think of all the possible ways of placing a set of blocks around a room; in only a tiny fraction of them are the blocks carefully stacked in a pile or organized into a building. Is it then any wonder that after a group of small children has gone into the room the state of disorder has increased? When you leave a glass of water uncovered, is it a surprise that over time the water evaporates and moves into states of much greater disorder as water vapor throughout the room? The second law of thermodynamics gives rise to a directionality in time; it is a quantitative way of summarizing the observation that spontaneous processes make sense only in one direction and not the other. If you drop an egg, it splatters all over; the reverse process of the spontaneous reassembly of the same egg from its fragments would be deeply disturbing. Randomness and disorder increase in the universe.

Another more abstract form of the Second Law considers not the physical evolution of matter but the loss of information with time, in the sense I described earlier in connection with chaos theory. In information theory, information is referred to as negentropy (or “negative entropy”), because the two move in opposite directions: as information is lost with time, the entropy of the system increases. The Second Law prevents Calvino’s bettors from accurately predicting even the motion of inanimate objects far into the future. The existence of living beings with free will raises still deeper questions about the possibilities of predicting details of the future.

What does this discussion of the Second Law say about the aims of education? What, indeed, is the purpose of education in light of this inevitable degradation of order and information with time? Should we just sit back and let decay run its course? Before I answer this let me go back to thermodynamics and respond to some objections that I am sure many of you are raising in your own minds. What about the spontaneous appearance of order? Snowflakes form from water vapor in clouds, and beautiful ordered crystals grow from the amorphous disorder of solutions. How is this consistent with the Second Law? To answer this, note that in stating the Second Law I used a crucial word: in an isolated system the entropy increases. In a system in contact with its surroundings, however, the entropy can actually decrease. When ice crystallizes from liquid water or water vapor, heat is given off to the surroundings. This causes the entropy of the surroundings to increase at the same time the entropy of the system decreases. The Second Law is still satisfied: the total entropy of system plus surroundings, that is, the entropy of the universe, increases. The greater order of the ice crystals is bought at the cost of greater disorder in the surroundings. Though the latter is not always clearly visible (the surrounding molecules are simply flying around a little bit faster), it is critical for the process to occur.

In a system open to its environment, then, the entropy can go down if there is a corresponding increase in entropy of the surroundings by at least the same amount. This observation is critical to the existence of life on earth. Our sun, like all stars, is a producer of entropy. In the course of the nuclear reactions that convert hydrogen to helium at its center, entropy is constantly increasing. The sunlight that bathes the earth makes it an open system and drives processes on the earth in which entropy can go down. The growth of a plant from carbon dioxide and water certainly lowers the entropy and increases order, as the atoms of carbon, hydrogen, and oxygen are organized into sugars and cellulose polymers. This process is only made possible by the harvesting of the sun's light energy through photosynthesis. The coupling of the earth to the sun maintains the validity of the Second Law of Thermodynamics with the side benefit of allowing life to exist. Cut off the sun and isolate the earth, and the result would be a slow decay into disorder.

The Second Law provides a context for thinking about the nature of education. I would like to make a distinction here between information and knowledge. As all of you know, if you stuff your head full of information by cramming for a test the night before, you may retain that information for the next day if you are lucky, but within a few days or weeks most of the information will have disappeared. This loss of information with time is one manifestation of the Second Law, and it occurs on a microscopic level because the particular brain connections that store facts are changing all the time; if information is not used, it can no longer be retrieved after a while. My dictionary says that the term information implies "a random collection of material rather than orderly synthesis." Note the word synthesis again in this connection; it is characteristic not of raw information but of knowledge, which is defined as "familiarity, awareness, or understanding gained through experience or study." Knowledge

“includes material derived by inference or interpretation.” The aim of education is the synthesis of knowledge, and that requires not passive memorizing but organizing material into a coherent whole, formulating and testing hypotheses, and drawing conclusions about cause and effect. To gain knowledge is the aim of education.

We live in the Information Age in the late twentieth century. The choice of the word information in place of knowledge is a very apt one. The sources of information available to us have increased by orders of magnitude in just the last decade, but it would be difficult to argue that anything like that increase has occurred in our knowledge. The Internet and the World Wide Web enable us to access sources of information that reach far beyond the walls of our libraries. In preparing this talk, I spent an hour with a colleague in the Computer Science Department exploring the collective information available from the Web on the subject of the aims of education. We began with the pair of key words aims and education and came up with some 30,000 hits. After trying to limit the search in various ways, we ended up looking for occurrences of the actual phrase “Aims of Education.” The 187 times this appeared was manageable enough that we looked briefly at each one. There were uses of this phrase from all over the world: Singapore, Germany, Korea, Sweden, Australia. A number of the 187 uses pointed back to the University of Chicago, including a reference to a classic Aims of Education address by James Redfield in the 1970s. Some pointed to the original source of the term in the writings of Alfred North Whitehead. Some of the appearances of the phrase were quite amusing. I learned that the aims of education of a high school in Nagoya, Japan, were to develop students who (1) behave voluntarily, (2) demand virtue, and (3) are sound mentally and physically. The Web site also included a map in Japanese showing how to get to the school and a copy of the school song translated into English, which I will spare you.

Although this particular experiment at surfing the Web did not lead to new insights that I could incorporate into my talk, I can certainly imagine that for some projects it would prove quite useful. Assembling a vast amount of information, though, is not a substitute for synthesizing it into useful knowledge. Whether you work with file cards or with the newest Internet browser technology, the difficult step of organizing ideas and presenting them clearly still remains. If anything, this step becomes more difficult when there is such an overwhelming flood of raw information. It is the knowledge that you yourself develop that will remain with you, because it connects in deep and intricate ways with many different regions of your brain. The ability to think critically, to reason quantitatively, and to express yourself clearly are learning skills that you will take with you when you leave this College.

Let me return to the thermodynamic analogy that I was just discussing a few minutes ago. Don't think of yourself as a closed system, with a fixed amount of information stored up, because that information will inevitably decay away and disappear in accordance with the Second Law of Thermodynamics. Instead, picture yourself as an open system, receptive to the flow of new ideas in the same way that the earth's surface is bathed in energy from the sun. In

such an open system, the organization and synthesis of new knowledge are possible. Scientists have discovered beautiful and complex patterns that arise in open systems far from the point of equilibrium. Keep yourself balanced in that state which physicists refer to as “marginal stability,” a point that lies between the two extremes of boring equilibrium behavior (where little happens) and fully developed chaotic turbulence (where order has almost vanished). In this in-between state you will be most productive of new ideas and deep knowledge.

The education that you are looking forward to in the next four years is not a road map to be followed. Just as it is impossible to predict the weather on this date next month, so it is impossible to predict where each of you will end up four years from now, based on your current interests and skills. Be open to new possibilities: your life is not predetermined by what you bring in today but will be largely shaped by the interactions with others around you in the future. In fact, perhaps the only definite statement that one can make is, in the words of C. S. Lewis, that the future is “something which everyone reaches at the rate of sixty minutes an hour, whatever he does, whoever he is” (*The Screwtape Letters*, p. 25). On the other hand, remember also these words of Plato: “The direction in which education starts a man will determine his future life” (*Republic*, Book IV). Your education at the University of Chicago will determine your life not in the sense that its course will be predictable but rather in the sense that the openness to new knowledge that is encouraged within the academy will change the way in which you approach the future.

Think of your education here as a series of experiments in which you synthesize not a single final product identified as the target from the beginning but a set of interesting and complex intermediate materials. The course of these experiments will be directed by you, but will also be changed by the people and the world around you. Use your education to open yourself to the outside, not to close yourself off from it. To return to Calvino’s story, I hope that you will approach the future with the daring optimism of the narrator, Qfwfq, not the skeptical pessimism of the old Dean. Make bets that interesting things will happen in the future, and take steps to make sure that they do. You may be wrong on many of those bets, but the very act of thinking about the future in a creative way will change your life and the lives of those around you. As Martin Luther King, Jr., said, “I don’t know what the future holds, but I know who holds the future.”

One final word of advice from an old Dean: along with your millennial mission of saving the world, which I do hope you will take seriously, have some fun while you are here at the University. Take advantage of the opportunities that a great city like Chicago can offer: museums, architecture, neighborhoods to explore. On campus, get involved in activities: join or cheer on your athletic teams, take part in campus or national political life, share your special interests with others informally or in the dozens of clubs that exist here. As you build your education in the next four years, try to enjoy yourself along the way. The millennium will arrive sooner than you think.