Risk Within Reason

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Advances in low-level risk detection threaten to engulf us with information. Regulators typically respond to each newly highlighted risk, whether painstakingly uncovered through scientific investigation or divulged with fanfare by the media, on an ad hoc basis. This response makes it hard to relate disparate risks to the overall risk level and impedes intelligent risk reduction, which must consider the costs and benefits involved. Efficient risk management requires decisions not only about what to regulate and how stringently, but also about the appropriate division of labor among the agents influencing risks. These agents include individuals, whose potential contributions too often are overlooked, corporations, and government.

SOCIETY'S SYSTEM FOR MANAGING RISKS TO LIFE AND LIMB IS deeply flawed. We overreact to some risks and virtually ignore others. Often too much weight is placed on risks of low probability but high salience (such as those posed by trace carcinogens or terrorist action); risks of commission rather than omission; and risks, such as those associated with frontier technologies, whose magnitude is difficult to estimate. Too little effort is spent ameliorating voluntary risks, such as those involving automobiles and diet. When the bearers of risk do not share in the costs of reduction, moreover, extravagance is likely.

Part of the problem is that we rely on a mix of individual, corporate, and government decision to respond to risk. Our traditional coordinating mechanisms—markets and government action—are crippled by inadequate information, costly decision-making processes, and the need to accommodate citizens' misperceptions, sometimes arising from imbalances in media attention.

Risk can never be entirely eliminated from life, and reductions come at a price (in dollars, forgone pleasures, or both). Our current muddled approach makes it difficult to reach wise, well-informed decisions as to the preferred balance of risk and cost. Some large risks we ignore; some small ones we regulate stringently. Worse, our overreaction to very small risks impedes the kind of technological progress that has historically brought dramatic improvements in both health and material well-being. In addition, we are likely to misdirect our efforts, for example, by focusing on risks that command attention in the political process, such as newly identified carcinogens, rather than those where the greatest gains in well-being are available, such as individual life-style choices (*1*).

Our regulatory efforts focus too much on equipment and physical processes, too little on human error and venality. We may set stringent emission standards, which impose high costs per unit of environmental quality gained, yet ignore the haphazard operation of nuclear weapons plants.

Evidently willing to expend substantial resources to reduce risk, our society seems reluctant to look closely at the bargains it has struck. Unless we correct imbalances in the cost effectiveness of our risk management policies, we will continue to pay more than we should for health gains that are less than we could achieve.

The success of risk management policies should be judged in terms of their effect on expected utility, the only well-developed prescriptive framework for choice under uncertainty. This method assigns each potential outcome a value (utility) on a cardinal scale, weights these values by their probability of occurrence, and then adds them together to produce an expected utility, a summary measure of the attractiveness of an action (*2*). Although in practice the choices made by human beings under uncertainty frequently do not conform to the prescriptions of expected-utility theory, given time to reflect most people would accept the theory's axioms.

The formulation of risk policy should then begin by asking what outcomes would result from well-functioning market processes if individuals behaved so as to maximize their own expected utility. What level of adverse side effects from pharmaceuticals would be acceptable if we knew the risk and could take the time and effort to make sound decisions?

To provide the best possible basis for policy decisions, our hypothetical market should be open to future generations. If our great grandchildren could compensate the present generation for preserving resources and the environment, what environmental decisions would we make today? Such a thought experiment should guide our efforts to bequeath posterity an efficient mix of technological capabilities, environmental quality, and cultural attainments.

Human Fallibility in Responses to Risks

Decisions involving risks illustrate the limits of human rationality, as a substantial literature documents (*3–6*). Perhaps the most fundamental problem is that individuals have great difficulty comprehending extremely low-probability events, such as differentiating a risk of 10^{-7} from 10^{-5}, a risk 100 times as large. When assessing such risks, even scientists may not appreciate how much greater the payoff is that comes from addressing the larger probability.

The numerous decision-making problems that arise with respect to small probabilities are individually of little consequence. Expected welfare loss from any single error may well be negligible. Aggregated, however, low-probability events make up a large part of an individual's risk level. Even truly substantial risks, such as the chance of death from a stroke (roughly 1 in 2000 annually averaged over the population), are usually influenced by a myriad of decisions, each of which has only a small probabilistic impact on our longevity. Systematic errors in these decisions might have an enormous cumulative effect.

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Mistakes in estimation. Whereas people generally overestimate the likelihood of low-probability events (death by tornado), they underestimate higher risk levels (heart disease or stroke) (*5*). We are particularly likely to overestimate previously unrecognized risks in the aftermath of an unfavorable outcome (*6*). Such perceptional biases account for the emotional public response to such events as Three Mile Island or occasional incidents of deliberate poisoning of foodstuffs or medicines.

Risk perceptions may also be affected by the visibility of a risk, by fear associated with it, and by the extent to which individuals believe they can exercise control over it (*3, 5*). Consider the greenhouse effect, for example: although global warming is a prime concern of the Environmental Protection Agency (EPA), it ranks only 23rd among the U.S. public's environmental concerns (*7*). The high risk of automobile fatality—car accidents kill 1 in 5000 Americans each year (*8*)—might perhaps be reduced significantly if drivers, informed with a more realistic sense of what they can and cannot do to control the risk, drank less alcohol and wore seat belts more often.

Because experience tells us little about low-probability risks, we resort to correlated indicators that pose less serious problems. Record high temperatures of 1988, for example, may or may not have been signals of an impending greenhouse effect (*9*). Unfortunately, such signals are seldom as timely or clear-cut as canaries in the coal mine. Adverse events may occur without a warning; witness the San Francisco earthquake. When a warning does sound, moreover, it may bear little relation to the magnitude, likelihood, or nature of a problem. Proper forest management, for example, should not be contingent on a dramatic fire, such as the one in Yellowstone National Park.

Distortions in monetary valuation. Economic valuations are distorted by misweighting of risks. From an expected-utility perspective, for example, individuals generally place too high a value on preventing increases in a risk from its current level [the so-called "status quo bias" or "reference risk" effect (*10, 11*)]. Such biases are reflected in government policy. Products causing rare forms of cancer especially arouse public concern; new technologies are often regulated much more strictly than old technologies and familiar risks (*12*). Although man-made carcinogens are carefully controlled, policy often tolerates much higher levels of natural carcinogens. Because of this imbalance, we pay more dollars for our products and end up with greater risks to our lives.

Studies of consumers show that many individuals would be willing to pay a premium for the assured elimination of a risk (*11*), as the Russian roulette problem illustrates. Consider two alternative scenarios for a forced round of play. In the first, you have the option to purchase and remove one bullet from a gun that has three bullets in its six chambers. How much would you pay for this reduction in risk? (Assume you are unmarried, with no children.) In the second situation, the gun has only a single bullet. How much would you pay to buy back this bullet? From an economic standpoint, you should always be willing to pay at least as much and typically more in the first situation since there is some chance you will be killed by one of the remaining bullets, in which case money is worthless (or worth less) (*13*). However, experiments find respondents are typically willing to pay more when a single bullet is in the gun, because its removal will ensure survival (*11, 13, 14*).

The Chilean grape scare provides an example of a risk that does not lend itself to statistical estimation or scientific assessment. Neither the government nor consumers could estimate how much consumers' risk was increased by the discovery of traces of cyanide in two Chilean grapes in Philadelphia (*15*). When precise scientific judgments concerning probabilities are elusive, concerns about regret (*16*) are likely to be significant. If societal norms were flouted, regret would be greater still. (Few of us would leave a baby sleeping alone in a house while we drove off on a 10-minute errand, even though car-crash risks are much greater than home risks.) With hindsight, one is frequently able to identify why an individual or society should have known certain risk estimates were far too low, as we learned when riots followed Hurricane Hugo and a highway collapsed during the San Francisco earthquake. Regret is less of an issue when consequences cannot be tied back to a particular risk exposure or a particular decision maker.

The valuation of a risk is likely to depend on how the risk is generated. We tolerate voluntarily assumed risks more than those over which we have no control, such as environmental hazards. We regard acts of commission as much more serious than acts of omission. In pharmaceutical screening, for example, the Food and Drug Administration (FDA) worries more about introducing harmful new drugs than about missing opportunities for risk reduction offered by new pharmaceutical products (*17*).

Agency dilemmas. Problems of risk perception and valuation may become entangled with so-called agency problems. What rules apply when one individual or organization (the agent) makes risk decisions on behalf of another (the principal)? Should the agent replicate shortcomings in the principal's decision-making capabilities? Suppose there is 1 chance in 10,000 that a drug will have adverse consequences as severe as those of thalidomide. If the drug offers significant health benefits, it may be wise for society to permit even this high risk. Approving the drug, moreover, might generate information useful in revising the original risk assessment, so that the decision can later be reversed or amplified if appropriate. Yet in practice, the FDA (society's agent) would probably not make such a decision, because of its bias against accepting new risks (*17*).

Society's pattern of lopsided tradeoffs between errors of omission and commission persists for at least two reasons. First, apart from people's levels of risk, their consumption of information is relevant. When a federal agency demonstrates that it will not take chances with individual health, that reassurance alone enhances individual welfare. Conversely, a perception that the government tolerates risks to the public might be more damaging than the risks themselves. Second, it is easier to observe the costs of bad drugs that are approved than to assess the foregone benefits of good drugs that were not introduced. [However, potential beneficiaries, such as the users of saccharin and people with acquired immunodeficiency syndrome (AIDS), sometimes put substantial pressure on the FDA to compromise normally stringent procedures for approving food additives and drugs (*18, 19*)].

How should we proceed once we admit that individuals do not correctly react to many risks? We might ask the government to make many more decisions. It is not clear, however, that the government is well equipped to compute certain risks accurately or to make sensible decisions once that information is obtained. Alternatively, we could shift decision-making authority to those best qualified to make particular kinds of choices. Here, however, the problem arises that the preferences of those making a decision might not be the same as those affected by it. A third possibility would be to develop processes enabling both agents and principals to participate in risk-related decisions, but there is little evidence that such processes would produce convergence. Finally, we might try to improve individuals' decision-making skills by providing them, for example, with expert-certified information, much as accounting firms verify the accuracy of reported financial data.

The informational approach. Society's objective should be to foster informed consumer choice. With respect to cigarette smoking, for example, this may not be the same thing as seeking a smoke-free society. (Note that research linking aflatoxin and cancer risks (*20*) has not moved the Surgeon General to call for a peanut butter–free society.) Politically, of course, the passive smoking concern may be a trump card, so that the actual magnitude of the risk imposed on others becomes irrelevant.

Hazard warnings are often used to convey risk information. Congress has mandated labels for cigarettes, artificial sweeteners, and alcoholic beverages. Federal agencies impose labeling requirements for consumer products, workplace risks, and pesticides. Informational efforts work in conjunction with market forces rather than attempting to supersede them.

Individuals may have difficulty processing risk information, however (*6*). Overambitious information efforts may outstrip decision-making capabilities (for example, California Proposition 65 (*21*), which requires warnings for products that expose consumers to annual risks of cancer of 1 in 7 million). The dangers are underreaction, overreaction, and nonreaction—a complete dismissal of the risk information effort. Sound decisions are unlikely to result. Indeed, the supposition of informed consent is called into question.

More general human cognitive limitations also work against detailed informational efforts. If a warning label contains more than a handful of items, or if warnings proliferate, problems of information overload arise (*6*).

In a democratic society one should hesitate to override the legitimate preferences of segments of the population, taking care not to dismiss diversity of taste as mere nonrational choice (*22*). Where there is broad consensus on a rational course of action, however, and either the cost of providing information is high or individuals cannot process the information adequately, mandatory requirements may be preferable to risk information efforts. Laws requiring the use of seat belts are one possible example.

Individuals often fail to interpret risks or value their consequences accurately. Government efforts may escape some of these biases, but are often thrown off course by political pressures and agency losses. The consequence is that our risk portfolio enjoys no legitimacy and satisfies no one. The first step toward a remedy is to develop a broad-based understanding of the nature of risk.

Reason and Information About Risk

Information on risk is generated through several mechanisms. The most salient source is scientific research, but information can also be gained through experience, and knowledge of such information can be increased by distributing it more widely.

Risk, uncertainty, and ignorance. It is helpful to distinguish among risk, uncertainty, and ignorance. In the situation of risk, we know the states of the world that may prevail (a flipped coin will show one of two faces) and the precise probability of each state (heads and tails are equally likely). In the case of uncertainty, the precise probabilities are not known. With ignorance, we may not even be able to define what states of the world are possible.

The real world is rife with uncertainty. Even if we can make direct environmental measurements (for example, for atmospheric pollution), interpretation of our observations may be problematic (*9*). Does an unusually high temperature this year indicate an upward trend, or does it represent random variation around an unchanging mean?

As our technological capabilities grow and economic activity imposes further strains on the environment, we will increasingly find ourselves in situations of ignorance. As we enter apparently benign but uncharted territory, we cannot be confident that if there were threats, we would detect them. Many individual decisions, as well as scientific risk analyses, are afflicted by ignorance (*5*). California studies of transportation safety in the event of an earthquake, for example, failed to capture the full range of effects that may have led to the highway damage experienced in October 1989 (*23*). Under conditions of ignorance, the potential for bad societal decisions is particularly great. Conceivably, for example, environmental releases of genetically engineered organisms might alter the current ecological balance in ways we cannot anticipate (*24*).

Some observers insist that we simply cannot take such risks; others argue for weighing potential benefits the activity might bring against hypothetical disasters. In many areas, fundamental scientific research may shed light on what states of the world may prevail and with what probability. But while we wait, we must decide (if only negatively, by default) on the basis of our limited information whether to deploy experimental drugs that might save lives, innovative organisms that might preserve threatened ecosystems, and controversial technologies such as nuclear power, which reduces the environmental risks from reliance on fossil fuels but creates another class of hazards.

Learning about risks. Information can often be acquired by another party without destroying its productive value for those who already possess it. Small countries, for example, make use of the information generated by large countries, say in drug regulation. Since generating information is often a costly process, there can be a temptation to hold back from making the effort, in the hope of a free ride. Society has designed various mechanisms to promote the development of information: governments support research and development, and they issue patents to protect the private value of information. Information on risk levels, however, cannot be patented. Without government participation, too little will be produced.

Risk information may be generated through experience. An employee can observe the injuries suffered by his co-workers in various jobs. Since the annual odds that a typical worker will experience an injury leading to one lost day of work per year are 3 in 100, even an individual observer will find some basis for making inferences about risk. In many cases, unfortunately, society may never learn how risky a process is, because the process changes before we get enough experience. With an estimated 10^{-7} annual risk, it would take years of widespread observation even to learn whether the risk is an order of magnitude higher or lower than we initially believed. In addition, carcinogenic risks are often coupled with long time lags and multiple causal factors, so that precise inferences are not possible.

In such situations it is rarely feasible to await the outcome of direct observations. One strategy would be to look instead for symptoms of high levels of risk. Thus, to assess whether we have underestimated the probability of a nuclear meltdown, we might ascertain whether our component estimates of the probability of a pipe break or human error were substantially too low. Alternatively, we can look to parallel risk estimates to see whether they have been proven too high or too low, which would tell us about potential biases in risk-estimation technology.

Resolving discrepancies. Discrepancies in probabilistic beliefs provide an economic rationale for betting, and in many important instances, markets for such bets exist. Beliefs about economic prospects are exercised every day in markets for stocks and bonds, foreign exchange, and commodity futures (*25*). The scientific debate over cold fusion might have been resolved more rapidly if the participants had made similar bets, thus providing information to each other and to bystanders.

Other societal mechanisms are also used to resolve informational differences. Adversary processes such as those of the judicial system, or a science court with an expert on each side, can air opposing viewpoints, but unlike markets, they will not reveal the weight of opinion on the two sides.

Markets and their absence. Markets generate information used by the world at large, not just by those who trade. Assessments of risk may be adjusted through market processes, but only to the extent that they are reflected in prices. After a disaster in one chemical plant, for example, investors may hastily unload all chemical company stocks. If their implicit valuation of chemical company risk is too pessimistic, more realistic appraisers will find bargains and bid up share prices to an appropriate level. In a more mundane fashion, futures prices tell decision makers the expected future price of oil, and insurance premiums reveal information about assessed levels of risk.

For many important risk decisions, however, market mechanisms are not useful means of conveying risk information. Whereas a poorly operated business will lose its ability to produce for the market, no one will take over decision making for an adult who underinvests in his own health. Poaching on the poor decisions of others—a critical factor ensuring efficient production in economic markets—is simply not possible.

Many informational asymmetries are not resolved successfully through markets. Firms may have better notions of the risks posed by their products or employment than do the individuals who bear these risks, and individual purchasers of insurance policies may be better informed than the firm about the likely claims they will make under these policies. Ideally, everyone would have an incentive to convey information honestly and truthfully. In reality, however, a firm marketing a potentially hazardous good in a world with a capricious tort system may have too much to lose by informing consumers of the risky characteristics of its products.

Making the most of uncertainty. Information is valuable when it accurately represents the risks posed. For one-time-only decisions, from the standpoint of Bayesian decision making, the mean assessment of the probability of each outcome is all that matters, for that gives the likelihood with which the outcome will be received. For example, suppose that with option I there is a 10% chance that a 0.01 risk is imposed and a 90% chance that no risk is imposed; with option II, there is a 100% chance of a 0.002 risk. Option I should be preferred, since its mean risk ($0.1 \times 0.01 + 0.9 \times 0 = 0.001$) is lower than for option II (*26*).

In situations of learning and sequential decision, the precision of the estimate also matters. Paradoxically, imprecisely known probabilities are more favorable. Suppose you must choose between two alternative medical treatments. Therapy A is known to cure half the patients to whom it is applied. Therapy B is an experimental treatment that is equally likely to be either perfect or worthless. In each case, the probability of a cure is 0.5. In cases of single trial, the two options are equally attractive.

With two patients in sequential trials, however, the correct strategy is to pursue B. If the first patient recovers, give the second the same treatment; otherwise switch to A. With this strategy, on average 1.25 of two patients will recover, as opposed to only one out of two if the better known treatment A is chosen at the outset. [This is equivalent to the simplest version of the classic two-armed bandit problem (*27*).] In any choice between a certain and an uncertain risk of an adverse outcome, if the initial mean value for the probability is the same, the uncertain risk is preferable when learning and adaptive behavior after experience are possible.

Now suppose the experimental treatment is treatment C, which will turn out to be either a total failure or a 90% cure (with both possibilities equally likely). Trying C rather than A will be preferable [offering an expected 1.13 cures (*28*)], but now the first patient will face unfavorable odds with experimental treatment C (0.45 rather than 0.5 with A). If randomization is not possible, or if the first patient objects, perhaps even after a lottery is conducted, ethical norms would require offering him treatment A. This argument has been illogically extended to suggest that even if experimental treatment C looks better than established treatment A, we may find out it was worse, and we should therefore stick with A. In the medical context, patient interest provides an antidote to such misconceptions. Many experimental technologies are not blessed with such a counterweight.

Regulatory efforts and misplaced conservatism. Governmental efforts at developing risk information are not guided by the formal statistical properties of the risk but rather by administrative procedures incorporating various types of "conservatism." Although risk assessment biases may operate in both directions (*29*), most approved procedures tend to overstate the actual risk (*30*). In regulating toxic substances, for example, results from the most sensitive animal species are often used, and government agencies such as the EPA routinely focus on the upper end of the 95% confidence interval as the risk level, rather than use the mean of the distribution. A series of such conservative assumptions—for example, on exposure or focusing on the most sensitive humans—can overstate the mean probability of an unfavorable outcome by several orders of magnitude.

If lives are at stake, should we not be conservative when risk estimates are known to be uncertain? In fact, conservatism of this nature is undesirable for three reasons. First, these conservative biases often are not uniform across risks, so that comparative risk judgments may be in error. If we focus on reducing risks for which standard errors are large with respect to their level, then we will save fewer expected lives than if we were guided by the mean of our probability distribution on the risk level. In effect, society will be curtailing the wrong risks, ones that offer less expected health improvement than other available options, for the resources and benefits foregone. The bias that results will cut against new technologies and innovative products. Second, stringent regulation of uncertain risks destroys opportunities for learning, ignoring the lesson of the medical treatment example above. Third and most fundamental, tilting risk assessments in a conservative direction confuses the informational and decision aspects of research about risks (*30*). A conceptually sound form of conservatism would have the decision maker (not the risk estimator) adjust the weights on the consequences. Adjusting the probabilities amounts to lying to ourselves about what we expect.

Toward Reasonable Risk Policies

Restrictions on a risky activity, such as exposure limits or restrictions in use, should be based on the relative gains and losses of the activity as compared with its alternatives. In thinking about these tradeoffs, one should remember that improvements in mortality and morbidity have come primarily from technological progress and a higher standard of living, not from government regulation or private forbearance (*31*). A dramatic case in point is that of postwar Japan, where mortality rates have fallen for all age groups. Over the period 1955 to 1975, with a rapid rise in the standard of living, mortality rates for men aged 65 to 69 fell 32% and men aged 25 to 29 had a 64% drop (*32*). Sustained economic development also seems to be the principal factor in explaining mortality gains in the United States. In contrast, risk regulation policies often provide few major dividends (*33*).

It is useful to think about risk-averting policy in terms of the rates of tradeoff involved, such as the cost per expected life saved. Using this lives-saved standard of value highlights the most effective means of promoting our risk reduction objective (*34*). The cost-effectiveness of existing regulations ranges widely, from $200,000 per life saved for airplane cabin fire protection to as much as $132 million per life saved for the 1979 regulation of diethyl stilbestrol (DES) in cattlefeed (*35*). These wide discrepancies reflect differences among agencies in their risk-cost balancing as well as differences in the character of risk-reducing opportunities. The Federal Aviation Administration has traditionally undervalued lives, looking only at lost earnings, whereas food additive regulations and EPA ambient air quality standards are set without consideration of cost. Elimination of such interagency imbalances would foster better control of risks at less cost.

The fundamental policy question is how far to proceed with lifesaving expenditures. Economists are accused, sometimes with justification, of concluding too quickly that policy choice to promote the saving of lives is merely a question of setting an appropriate price. In contrast, society often is insensitive to the tradeoffs that must be made. Indeed, 80% of respondents polled 2 months after the Exxon *Valdez* oil spill indicated a willingness to pursue greater environmental protection "regardless of cost" (*36*). Ultimately, however, society must decide how much of a resource commitment it will make.

Learning from market outcomes. Market outcomes provide a natural starting point for obtaining information on how risk reduction policies are valued by their beneficiaries. Health risks are important components of goods and services sold on markets, providing an approach to valuation. Wage differentials for high-risk occupations imply a value of several million dollars for each expected death in the workplace (*37*).

Market data for many risk outcomes are not available, in part because government policies are largely directed at situations in which the market is believed not to function effectively, or at all. Thus, we have little price information to guide us when deciding, for example, whether society's resources would be better used to reduce rates of birth defects, to promote better nutrition, or to reduce oil spills from tankers.

The policies for which no market reference is possible are the very ones in which current practice may be farthest from the optimum. How much, for example, is it worth to prevent a low-level risk of genetic damage? Such valuation questions have received little careful consideration. When risks are received collectively, as when a sewage treatment plant or prison is placed in a community, little is learned about valuation, since compensation is rarely paid (*38*). The result has been severe inequity for the unfortunate few, and a democratic society that cannot find places to site essential though noxious facilities.

Finding appropriate roles. The government's responsibility in generating and using risk information involves structuring a decision process in which individuals and societal institutions work together. Policy choice in a democratic society is, however, complicated by discrepancies between lay and expert opinion. In some situations, the government must decide whether to intervene to overcome apparent limitations on individual choices. But it can be difficult to distinguish irrationality from legitimate citizen preferences. Are people who do not wear seat belts irrational? What about those who wolf down animal fats? Analogous questions arise with respect to policy emphasis. To what extent should the government focus on risks that are of particular concern to its citizens, who may be misinformed and subject to severe errors in perceptions and valuation of risk? Government agencies, subject to political pressures, may find it difficult to set their course in the direction indicated by dispassionate analysis of risks and overall benefits to society.

As science advances and our ability to detect risks improves, our opportunities for influencing risks have proliferated. To date we have proceeded haphazardly, responding to each risk in turn, whether it arises from a new technology, is revealed by scientific investigation, or is catapulted to prominence by media attention. This is not a sensible strategy for making balanced decisions across the entire spectrum of risks.

We need to acknowledge that risks to life and limb are inherent in modern society—indeed in life itself—and that systematic strategies for assessing and responding to risks are overdue. Such strategies will involve significant reassignment of decision-making responsibilities. Individuals should do more for themselves, paying greater attention, for example, to their diets and driving habits. Governments should focus less on microscopic contingencies, and more on human mistakes and misdeeds, the source of far greater risks.

REFERENCES AND NOTES

1. The role of life-style is discussed by V. Fuchs, *Who Shall Live? Health, Economics, and Social Choice* (Basic Books, New York, 1974), particularly pp. 52–54. He assesses the stark differences in mortality between high-living Nevada and sober Utah.
2. Under certainty, a mere ranking of outcomes is sufficient to determine the best choice. Choices under uncertainty require a more refined, cardinal metric to decide, for example: Is A preferred to a 50–50 chance of B or C? In most choice situations the probabilities are neither objectively defined nor easily estimated from data; subjectively estimated probabilities must guide action. L. J. Savage [in *The Foundations of Statistics* (Wiley, New York, 1954)] presents a careful axiomatic approach for combining the concepts of subjective probability and expected utility into a complete prescriptive basis for rational choice.
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10. W. Samuelson and R. Zeckhauser, *J. Risk Uncertainty* **1**, 7 (1988).
11. W. K. Viscusi, W. A. Magat, and J. Huber [*Rand J. Econ.* **18**, 465 (1987)] report an experiment involving household chemicals in which there is a reference risk effect and a premium for certain elimination of the risk.
12. P. Huber, *Regulation* 7, 23 (1983).
13. Let p be the initial probability of survival, q be the increased probability of survival, purchased at cost Z, $U(Y)$ be the utility of income if alive, where $U'(Y) > 0$, and $U(\text{Death}) = 0$, independent of income. Assuming expected utility maximization, by definition Z satisfies $pU(Y) + (1 - p)U(\text{Death}) = (p + q)U(Y - Z) + (1 - p - q)U(\text{Death})$, or setting $U(\text{Death}) = 0$, $pU(Y) = (p + q)U(Y - Z)$. Totally differentiating, one has

$$\frac{dZ}{dp} = \frac{U(Y - Z) - U(Y)}{(p + q)U'(Y - Z)} < 0.$$

14. D. Kahneman and A. Tversky explain a range of anomalies with prospect theory, including this problem, which they attribute to Zeckhauser. They find that where normative theory uses probabilities, humans use decision weights that are not linearly related to them [D. Kahneman and A. Tversky, *Econometrica* **47**, 263 (1979)].
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19. For example, the drug gancyclovir, used to treat a blindness-threatening eye infection suffered by one in four AIDS victims, was approved for use although it had not completed full clinical testing. In "Progress and placebos" [*Wall Street Journal* (29 June, 1989, p. A14)] it was observed that we had some difficulties counterbalancing the political-force approach to drug (and risk) regulation: "Should families of Alzheimer's patients follow the AIDS precedent, busing in about 1,000 of their demented parents to roam the agency's grounds outside of Washington for the benefit of television?"
20. B. N. Ames, R. Magaw, L. S. Gold, *Science* **236**, 271 (1987).
21. L. Roberts, *ibid.* **243**, 306 (1989).
22. The requirement that motorcyclists wear helmets, despite their known preferences, is justified because it copes with a significant financial externality (that is, high medical treatment costs and liability costs imposed on others). It also saves lives at reasonable cost.
23. T. Egan ["Building codes: Designs for last quake, not next," *New York Times*, 22 October 1989, p. 26] reported " 'The collapse came as a horrible surprise to us all,' said Robert J. Gore, assistant director of the California Department of Transportation . . . . The Bay Bridge lost a 250 ton section in the earthquake and Mr. Roberts (chief structural engineer for the State Transportation Department) said the standards for it had proved primitive. The collapse was due to 2 million pounds of force shearing off anchor bolts, he said. 'That's far in excess of what anyone would have calculated,' he said."
24. L. Roberts, *Science* **243**, 1134 (1989); *ibid.*, p. 1141.

25. A prominent theory—the so-called efficient markets hypothesis—holds that publicly available information about a firm will be transmitted rapidly into market outcomes as the stock price fully adjusts to reflect the influence of this information [E. Fama, L. Fisher, M. Jensen, R. Roll, *Int. Econ. Rev.* **10**, 1 (1969)]. K. J. Arrow [*Econ. Inquiry* **20**, 1 (1982)] cites empirical evidence on futures markets, indicating that the operation of these markets may be imperfect.
26. J. Pratt, H. Raiffa, R. Schlaifer, *Introduction to Statistical Decision Theory* (McGraw-Hill, New York, 1965).
27. D. A. Berry and B. Fristedt, *Bandit Problems: Sequential Allocation of Experiments* (Chapman and Hall, London, 1985).
28. When C is bad, 0.5 person is saved on average. When C is good, 90% of the trials succeed and 1.9 people are saved on average; 10% of the trials fail and after the switch to A, 0.5 person is saved on average. The expected value is 1.13.
29. L. Roberts, *Science* **243**, 1553 (1989); L. B. Lave, *ibid.* **236**, 291 (1987); L. Lave, Ed., *Quantitative Risk Assessment in Regulation* (Brookings Institution, Washington, DC, 1982).
30. A. Nichols and R. Zeckhauser, *Regulation* **10**, 13 (1986).
31. A. Wildavsky, *Searching for Safety* (Transaction Publishers, New Brunswick, NJ, 1988).
32. Data provided by Ministry of Health and Welfare, Japan.
33. The President's Council of Economic Advisers recently concluded that "In many cases, government control of risk is neither efficient nor effective." [*Economic Report of the President* (U.S. Government Printing Office, Washington, DC, 1987), p. 207.]
34. If very good information is available, one can use the more refined measure of cost per quality-adjusted life year (QALY) saved, thus taking into account both the number of person-years gained and their quality [R. J. Zeckhauser and D. S. Shepard, *Law Contemp. Probl.* **39**, 5 (1976)].
35. J. F. Morrall, *Regulation* **10**, 30 (1986).
36. A New York Times/CBS News Poll asked people if they agreed with the statement "Protecting the environment is so important that requirements and standards cannot be too high, and continuing environmental improvements must be made regardless of cost." Seventy-four percent of the public supported the statement in April 1989, shortly after the Exxon *Valdez* spill, while 80% agreed with it 2 months later. The *Times* concluded that "Public support for greater environmental efforts regardless of cost has soared since the Exxon *Valdez* oil spill in Alaska" ["Concern for environment," *New York Times*, 2 July 1989, p. 18].
37. W. K. Viscusi, *Risk by Choice* (Harvard Univ. Press, Cambridge, MA, 1983).
38. Little heed has been paid to innovative suggestions, such as the proposal of M. O'Hare, L. Bacow, and D. Sanderson [*Facility Siting and Public Opposition* (Van Nostrand Reinhold, New York, 1983)] that communities submit negative bids for accepting noxious facilities.
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The Formation of Sunlike Stars

CHARLES J. LADA AND FRANK H. SHU

Understanding how stars like the sun formed constitutes one of the principal challenges confronting modern astrophysics. In recent years, advances in observational technology, particularly at infrared and millimeter wavelengths, have produced an avalanche of critical data and unexpected discoveries about the process of star formation, which is blocked from external view at optical and shorter wavelengths by an obscuring blanket of interstellar dust. Fueled by this new knowledge, a comprehensive empirical picture of stellar genesis is beginning to emerge, laying the foundations for a coherent theory of the birth of sunlike stars.

THE ORIGIN OF STARS REPRESENTS ONE OF THE MOST fundamental unsolved problems of contemporary astrophysics. Stars are the basic objects of the universe. Indeed, the discovery of the nature of most stars as hydrogen-burning thermonuclear reactors and the subsequent development of the theory of stellar evolution rank among the greatest triumphs of 20th-century science. Deciphering stellar genesis, on the other hand, has proven to be a formidable challenge for astronomers. Until a quarter of a century ago, only a rudimentary understanding of the subject existed. This state of comparative ignorance prevailed because no substantive body of empirical data existed that could be used to critically test even the most basic hypotheses concerning stellar origins.

In our galaxy, stars form within the dust-enshrouded dense cores of molecular clouds [for example, (*1–3*)]. The obscuration provided by the solid grains that permeate the clouds renders newly forming stars (protostars) completely invisible at optical and shorter wavelengths. Moreover, the molecular gas that gives birth to young stars is itself extremely cold (10 to 20 K) and, with a few exceptions, can only be observed in emission in the submillimeter and millimeter regime, a spectral window opened by radio astronomers only in the 1970s. As a result, the classical tools of optical and radio astronomy do not effectively probe the regions where stars are born. Although the dust effectively absorbs visual and ultraviolet light emitted by buried young stellar objects (YSOs), this light heats the initially very cold dust and is eventually reradiated at mid- and far-infrared wavelengths.

During the last two decades, impressive advances in technology have provided astronomers with the ability to observe star-forming regions in considerable detail at infrared, millimeter, and submillimeter wavelengths. With this new instrumental capability, a direct assault on the star-formation problem became possible. Indeed, over the last few years, observations with filled-aperture telescopes and interferometric arrays have produced a series of remarkable, exciting, and unexpected discoveries that have begun to remove the veil of mystery that surrounds the star-formation process in our galaxy. As a result of these discoveries, we are beginning to understand the processes of star formation and early stellar evolution and are developing the foundation for a coherent theory of star formation.

Modern star-formation research has as an objective the elucidation of the physical process by which a giant molecular cloud transforms a small fraction of its mass into numerous self-gravitating balls of gas that have just the right range of masses—roughly, 10^{-1} to 10^{2} times the mass of the sun ($1\ M_{\odot} = 2 \times 10^{33}$ g)—to fuse the primary product of the Big Bang, hydrogen, into heavier elements by way of nuclear reactions. In this article, we review some of the remarkable progress recently made in the endeavor to achieve this objective.

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