Impact of Population Growth

Complacency concerning this component of man's predicament is unjustified and counterproductive.

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The interlocking crises in population, resources, and environment have been the focus of countless papers, dozens of prestigious symposia, and a growing avalanche of books. In this wealth of material, several questionable assertions have been appearing with increasing frequency. Perhaps the most serious of these is the notion that the size and growth rate of the U.S. population are only minor contributors to this country's adverse impact on local and global environments (*1, 2*). We propose to deal with this and several related misconceptions here, before persistent and unrebutted repetition entrenches them in the public mind—if not the scientific literature. Our discussion centers around five theorems which we believe are demonstrably true and which provide a framework for realistic analysis:

1) Population growth causes a *disproportionate* negative impact on the environment.

2) Problems of population size and growth, resource utilization and depletion, and environmental deterioration must be considered jointly and on a global basis. In this context, population control is obviously not a panacea—it is necessary but not alone sufficient to see us through the crisis.

3) Population density is a poor measure of population pressure, and redistributing population would be a dangerous pseudosolution to the population problem.

4) "Environment" must be broadly construed to include such things as the physical environment of urban ghettos, the human behavioral environment, and the epidemiological environment.

5) Theoretical solutions to our problems are often not operational and sometimes are not solutions.

We now examine these theorems in some detail.

Population Size and Per Capita Impact

In an agricultural or technological society, each human individual has a negative impact on his environment. He is responsible for some of the simplification (and resulting destabilization) of ecological systems which results from the practice of agriculture (*3*). He also participates in the utilization of renewable and nonrenewable resources. The total negative impact of such a society on the environment can be expressed, in the simplest terms, by the relation

$$I = P \cdot F$$

where P is the population, and F is a function which measures the per capita impact. A great deal of complexity is subsumed in this simple relation, however. For example, F increases with per capita consumption if technology is held constant, but may decrease in some cases if more benign technologies are introduced in the provision of a constant level of consumption. (We shall see in connection with theorem 5 that there are limits to the improvements one should anticipate from such "technological fixes.")

Pitfalls abound in the interpretation of manifest increases in the total impact I. For instance, it is easy to mistake changes in the composition of resource demand or environmental impact for absolute per capita increases, and thus to underestimate the role of the population multiplier. Moreover, it is often assumed that population size and per capita impact are independent variables, when in fact they are not. Consider, for example, the recent article by Coale (*1*), in which he disparages the role of U.S. population growth in environmental problems by noting that since 1940 "population has increased by 50 percent, but per capita use of electricity has been multiplied several times." This argument contains both the fallacies to which we have just referred.

First, a closer examination of very rapid increases in many kinds of consumption shows that these changes reflect a shift among alternatives within a larger (and much more slowly growing) category. Thus the 760 percent increase in electricity consumption from 1940 to 1969 (*4*) occurred in large part because the electrical *component* of the energy budget was (and is) increasing much faster than the budget itself. (Electricity comprised 12 percent of the U.S. energy consumption in 1940 versus 22 percent today.) The total energy use, a more important figure than its electrical component in terms of resources and the environment, increased much less dramatically—140 percent from 1940 to 1969. Under the simplest assumption (that is, that a given increase in population size accounts for an exactly proportional increase in consumption), this would mean that 38 percent of the increase in energy use during this period is explained by population growth (the actual population increase from 1940 to 1969 was 53 percent). Similar considerations reveal the imprudence of citing, say, aluminum consumption to show that population growth is an "unimportant" factor in resource use. Certainly, aluminum consumption has swelled by over 1400 percent since 1940, but much of the increase has been due to the substitution of aluminum for steel in many applications. Thus a fairer measure is combined consumption of aluminum and steel, which has risen only 117 percent since 1940. Again, under the simplest assumption, population growth accounts for 45 percent of the increase.

The "simplest assumption" is not valid, however, and this is the second flaw in Coale's example (and in his

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thesis). In short, he has failed to recognize that per capita consumption of energy and resources, and the associated per capita impact on the environment, are themselves functions of the population size. Our previous equation is more accurately written

$$I = P \cdot F(P)$$

displaying the fact that impact can increase faster than linearly with population. Of course, whether $F(P)$ is an increasing or decreasing function of P depends in part on whether diminishing returns or economies of scale are dominant in the activities of importance. In populous, industrial nations such as the United States, most economies of scale are already being exploited; we are on the diminishing returns part of most of the important curves.

As one example of diminishing returns, consider the problem of providing nonrenewable resources such as minerals and fossil fuels to a growing population, even at fixed levels of per capita consumption. As the richest supplies of these resources and those nearest to centers of use are consumed, we are obliged to use lower-grade ores, drill deeper, and extend our supply networks. All these activities increase our per capita use of energy and our per capita impact on the environment. In the case of partly renewable resources such as water (which is effectively nonrenewable when groundwater supplies are mined at rates far exceeding natural recharge), per capita costs and environmental impact escalate dramatically when the human population demands more than is locally available. Here the loss of free-flowing rivers and other economic, esthetic, and ecological costs of massive water-movement projects represent increased per capita diseconomies directly stimulated by population growth.

Diminishing returns are also operative in increasing food production to meet the needs of growing populations. Typically, attempts are made both to overproduce on land already farmed and to extend agriculture to marginal land. The former requires disproportionate energy use in obtaining and distributing water, fertilizer, and pesticides. The latter also increases per capita energy use, since the amount of energy invested per unit yield increases as less desirable land is cultivated. Similarly, as the richest fisheries stocks are depleted, the yield per unit effort drops, and more and more energy per capita is required to maintain the supply (*5*). Once a stock is depleted it may not recover—it may be nonrenewable.

Population size influences per capita impact in ways other than diminishing returns. As one example, consider the oversimplified but instructive situation in which each person in the population has links with every other person —roads, telephone lines, and so forth. These links involve energy and materials in their construction and use. Since the number of links increases much more rapidly than the number of people (*6*), so does the per capita consumption associated with the links.

Other factors may cause much steeper positive slopes in the per capita impact function, $F(P)$. One such phenomenon is the *threshold effect*. Below a certain level of pollution trees will survive in smog. But, at some point, when a small increment in population produces a small increment in smog, living trees become dead trees. Five hundred people may be able to live around a lake and dump their raw sewage into the lake, and the natural systems of the lake will be able to break down the sewage and keep the lake from undergoing rapid ecological change. Five hundred and five people may overload the system and result in a "polluted" or eutrophic lake. Another phenomenon capable of causing near-discontinuities is the *synergism*. For instance, as cities push out into farmland, air pollution increasingly becomes a mixture of agricultural chemicals with power plant and automobile effluents. Sulfur dioxide from the city paralyzes the cleaning mechanisms of the lungs, thus increasing the residence time of potential carcinogens in the agricultural chemicals. The joint effect may be much more than the sum of the individual effects. Investigation of synergistic effects is one of the most neglected areas of environmental evaluation.

Not only is there a connection between population size and per capita damage to the environment, but the cost of maintaining environmental quality at a given level escalates disproportionately as population size increases. This effect occurs in part because costs increase very rapidly as one tries to reduce contaminants per unit volume of effluent to lower and lower levels (diminishing returns again!). Consider municipal sewage, for example. The cost of removing 80 to 90 percent of the biochemical and chemical oxygen demand, 90 percent of the suspended solids, and 60 percent of the resistant organic material by means of secondary treatment is about 8 cents per 1000 gallons (3785 liters) in a large plant (*7*). But if the volume of sewage is such that its nutrient content creates a serious eutrophication problem (as is the case in the United States today), or if supply considerations dictate the reuse of sewage water for industry, agriculture, or groundwater recharge, advanced treatment is necessary. The cost ranges from two to four times as much as for secondary treatment (17 cents per 1000 gallons for carbon absorption; 34 cents per 1000 gallons for disinfection to yield a potable supply). This dramatic example of diminishing returns in pollution control could be repeated for stack gases, automobile exhausts, and so forth.

Now consider a situation in which the limited capacity of the environment to absorb abuse requires that we hold man's impact in some sector constant as population doubles. This means *per capita effectiveness* of pollution control in this sector must double (that is, effluent per person must be halved). In a typical situation, this would yield doubled per capita costs, or quadrupled total costs (and probably energy consumption) in this sector for a doubling of population. Of course, diminishing returns and threshold effects may be still more serious: we may easily have an eightfold increase in control costs for a doubling of population. Such arguments leave little ground for the assumption, popularized by Barry Commoner (*2*, *8*) and others, that a 1 percent rate of population growth spawns only 1 percent effects.

It is to be emphasized that the possible existence of "economies of scale" does not invalidate these arguments. Such savings, if available at all, would apply in the case of our sewage example to a change in the amount of effluent to be handled at an installation of a given type. For most technologies, the United States is already more than populous enough to achieve such economies and is doing so. They are accounted for in our example by citing figures for the largest treatment plants of each type. Population growth, on

the other hand, forces us into quantitative *and* qualitative changes in how we handle each unit volume of effluent—what fraction and what kinds of material we remove. Here economies of scale do not apply at all, and diminishing returns are the rule.

Global Context

We will not deal in detail with the best example of the global nature and interconnections of population resource and environmental problems—namely, the problems involved in feeding a world in which 10 to 20 million people starve to death annually (*9*), and in which the population is growing by some 70 million people per year. The ecological problems created by high-yield agriculture are awesome (*3, 10*) and are bound to have a negative feedback on food production. Indeed, the Food and Agriculture Organization of the United Nations has reported that in 1969 the world suffered its first absolute decline in fisheries yield since 1950. It seems likely that part of this decline is attributable to pollution originating in terrestrial agriculture.

A second source of the fisheries decline is, of course, overexploitation of fisheries by the developed countries. This problem, in turn, is illustrative of the situation in regard to many other resources, where similarly rapacious and shortsighted behavior by the developed nations is compromising the aspirations of the bulk of humanity to a decent existence. It is now becoming more widely comprehended that the United States alone accounts for perhaps 30 percent of the nonrenewable resources consumed in the world each year (for example, 37 percent of the energy, 25 percent of the steel, 28 percent of the tin, and 33 percent of the synthetic rubber) (*11*). This behavior is in large part inconsistent with American rhetoric about "developing" the countries of the Third World. *We* may be able to afford the technology to mine lower grade deposits when we have squandered the world's rich ores, but the underdeveloped countries, as their needs grow and their means remain meager, will not be able to do so. Some observers argue that the poor countries are today economically dependent on our use of their resources, and indeed that economists in these countries complain that world demand for their raw materials is too low (*1*). This proves only that their economists are as shortsighted as ours.

It is abundantly clear that the entire context in which we view the world resource pool and the relationships between developed and underdeveloped countries must be changed, if we are to have any hope of achieving a stable and prosperous existence for all human beings. It cannot be stated too forcefully that the developed countries (or, more accurately, the overdeveloped countries) are the principal culprits in the consumption and dispersion of the world's nonrenewable resources (*12*) as well as in appropriating much more than their share of the world's protein. Because of this consumption, and because of the enormous negative impact on the global environment accompanying it, the population growth in these countries must be regarded as the most serious in the world today.

In relation to theorem 2 we must emphasize that, even if population growth were halted, the present population of the world could easily destroy civilization as we know it. There is a wide choice of weapons—from unstable plant monocultures and agricultural hazes to DDT, mercury, and thermonuclear bombs. If population size were reduced and per capita consumption remained the same (or increased), we would still quickly run out of vital, high-grade resources or generate conflicts over diminishing supplies. Racism, economic exploitation, and war will not be eliminated by population control (of course, they are unlikely to be eliminated without it).

Population Density and Distribution

Theorem 3 deals with a problem related to the inequitable utilization of world resources. One of the commonest errors made by the uninitiated is to assume that population density (people per square mile) is the critical measure of overpopulation or underpopulation. For instance, Wattenberg states that the United States is not very crowded by "international standards" because Holland has 18 times the population density (*13*). We call this notion "the Netherlands fallacy." The Netherlands actually requires large chunks of the earth's resources and vast areas of land not within its borders to maintain itself. For example, it is the second largest per capita importer of protein in the world, and it imports 63 percent of its cereals, including 100 percent of its corn and rice. It also imports all of its cotton, 77 percent of its wool, and all of its iron ore, antimony, bauxite, chromium, copper, gold, lead, magnesite, manganese, mercury, molybdenum, nickel, silver, tin, tungsten, vanadium, zinc, phosphate rock (fertilizer), potash (fertilizer), asbestos, and diamonds. It produces energy equivalent to some 20 million metric tons of coal and consumes the equivalent of over 47 million metric tons (*14*).

A certain preoccupation with density as a useful measure of overpopulation is apparent in the article by Coale (*1*). He points to the existence of urban problems such as smog in Sydney, Australia, "even though the total population of Australia is about 12 million in an area 80 percent as big as the United States," as evidence that environmental problems are unrelated to population size. His argument would be more persuasive if problems of population *distribution* were the only ones with environmental consequences, and if population distribution were unrelated to resource distribution and population size. Actually, since the carrying capacity of the Australian continent is far below that of the United States, one would *expect* distribution problems—of which Sydney's smog is one symptom—to be encountered at a much lower total population there. Resources, such as water, are in very short supply, and people cluster where resources are available. (Evidently, it cannot be emphasized enough that carrying capacity includes the availability of a wide variety of resources in addition to space itself, and that population pressure is measured relative to the carrying capacity. One would expect water, soils, or the ability of the environment to absorb wastes to be the limiting resource in far more instances than land area.)

In addition, of course, many of the most serious environmental problems are essentially independent of the way in which population is distributed. These include the global problems of weather modification by carbon dioxide and particulate pollution, and the threats to the biosphere posed by man's massive inputs of pesticides, heavy metals, and oil (*15*). Similarly, the problems of resource depletion and ecosystem simplification by agriculture depend on how many people there are and their patterns of consumption, but

not in any major way on how they are distributed.

Naturally, we do not dispute that smog and most other familiar urban ills are serious problems, or that they are related to population distribution. Like many of the difficulties we face, these problems will not be cured simply by stopping population growth; direct and well-conceived assaults on the problems themselves will also be required. Such measures may occasionally include the redistribution of population, but the considerable difficulties and costs of this approach should not be underestimated. People live where they do not because of a perverse intention to add to the problems of their society but for reasons of economic necessity, convenience, and desire for agreeable surroundings. Areas that are uninhabited or sparsely populated today are presumably that way because they are deficient in some of the requisite factors. In many cases, the remedy for such deficiencies—for example, the provision of water and power to the wastelands of central Nevada—would be extraordinarily expensive in dollars, energy, and resources and would probably create environmental havoc. (Will we justify the rape of Canada's rivers to "colonize" more of our western deserts?)

Moving people to more "habitable" areas, such as the central valley of California or, indeed, most suburbs, exacerbates another serious problem—the paving-over of prime farmland. This is already so serious in California that, if current trends continue, about 50 percent of the best acreage in the nation's leading agricultural state will be destroyed by the year 2020 (*16*). Encouraging that trend hardly seems wise.

Whatever attempts may be made to solve distribution-related problems, they will be undermined if population growth continues, for two reasons. First, population growth and the aggravation of distribution problems are correlated—part of the increase will surely be absorbed in urban areas that can least afford the growth. Indeed, barring the unlikely prompt reversal of present trends, most of it will be absorbed there. Second, population growth puts a disproportionate drain on the very financial resources needed to combat its symptoms. Economist Joseph Spengler has estimated that 4 percent of national income goes to support our 1 percent per year rate of population growth in the United States (*17*). The 4 percent figure now amounts to about $30 billion per year. It seems safe to conclude that the faster we grow the less likely it is that we will find the funds either to alter population distribution patterns or to deal more comprehensively and realistically with our problems.

Meaning of Environment

Theorem 4 emphasizes the comprehensiveness of the environment crisis. All too many people think in terms of national parks and trout streams when they say "environment." For this reason many of the suppressed people of our nation consider ecology to be just one more "racist shuck" (*18*). They are apathetic or even hostile toward efforts to avert further environmental and sociological deterioration, because they have no reason to believe they will share the fruits of success (*19*). Slums, cockroaches, and rats are ecological problems, too. The correction of ghetto conditions in Detroit is neither more nor less important than saving the Great Lakes—both are imperative.

We must pay careful attention to sources of conflict both within the United States and between nations. Conflict within the United States blocks progress toward solving our problems; conflict among nations can easily "solve" them once and for all. Recent laboratory studies on human beings support the anecdotal evidence that crowding may increase aggressiveness in human males (*20*). These results underscore long-standing suspicions that population growth, translated through the inevitable uneven distribution into physical crowding, will tend to make the solution of all of our problems more difficult.

As a final example of the need to view "environment" broadly, note that human beings live in an epidemiological environment which deteriorates with crowding and malnutrition—both of which increase with population growth. The hazard posed by the prevalence of these conditions in the world today is compounded by man's unprecedented mobility: potential carriers of diseases of every description move routinely and in substantial numbers from continent to continent in a matter of hours. Nor is there any reason to believe that modern medicine has made widespread plague impossible (*21*). The Asian influenza epidemic of 1968 killed relatively few people only because the virus *happened* to be nonfatal to people in otherwise good health, not because of public health measures. Far deadlier viruses, which easily could be scourges without precedent in the population at large, have on more than one occasion been confined to research workers largely by good luck [for example, the Marburgvirus incident of 1967 (*22*) and the Lassa fever incident of 1970 (*21*, *23*)].

Solutions: Theoretical and Practical

Theorem 5 states that theoretical solutions to our problems are often not operational, and sometimes are not solutions. In terms of the problem of feeding the world, for example, technological fixes suffer from limitations in scale, lead time, and cost (*24*). Thus potentially attractive theoretical approaches—such as desalting seawater for agriculture, new irrigation systems, high-protein diet supplements—prove inadequate in practice. They are too little, too late, and too expensive, or they have sociological costs which hobble their effectiveness (*25*). Moreover, many aspects of our technological fixes, such as synthetic organic pesticides and inorganic nitrogen fertilizers, have created vast environmental problems which seem certain to erode global productivity and ecosystem stability (*26*). This is not to say that important gains have not been made through the application of technology to agriculture in the poor countries, or that further technological advances are not worth seeking. But it must be stressed that even the most enlightened technology cannot relieve the necessity of grappling forthrightly and promptly with population growth [as Norman Borlaug aptly observed on being notified of his Nobel Prize for development of the new wheats (*27*)].

Technological attempts to ameliorate the environmental impact of population growth and rising per capita affluence in the developed countries suffer from practical limitations similar to those just mentioned. Not only do such measures tend to be slow, costly, and insufficient in scale, but in addition they most often *shift* our impact rather than remove it. For example, our first generation of smog-control devices in-

creased emissions of oxides of nitrogen while reducing those of hydrocarbons and carbon monoxide. Our unhappiness about eutrophication has led to the replacement of phosphates in detergents with compounds like NTA—nitrilotriacetic acid—which has carcinogenic breakdown products and apparently enhances teratogenic effects of heavy metals (*28*). And our distaste for lung diseases apparently induced by sulfur dioxide inclines us to accept the hazards of radioactive waste disposal, fuel reprocessing, routine low-level emissions of radiation, and an apparently small but finite risk of catastrophic accidents associated with nuclear fission power plants. Similarly, electric automobiles would simply shift part of the environmental burden of personal transportation from the vicinity of highways to the vicinity of power plants.

We are not suggesting here that electric cars, or nuclear power plants, or substitutes for phosphates are inherently bad. We argue rather that they, too, pose environmental costs which must be weighed against those they eliminate. In many cases the choice is not obvious, and in *all* cases there will be some environmental impact. The residual per capita impact, after all the best choices have been made, must then be multiplied by the population engaging in the activity. If there are too many people, even the most wisely managed technology will not keep the environment from being overstressed.

In contending that a change in the way we use technology will invalidate these arguments, Commoner (*2, 8*) claims that our important environmental problems began in the 1940's with the introduction and rapid spread of certain "synthetic" technologies: pesticides and herbicides, inorganic fertilizers, plastics, nuclear energy, and high-compression gasoline engines. In so arguing, he appears to make two unfounded assumptions. The first is that man's pre-1940 environmental impact was innocuous and, without changes for the worse in technology, would have remained innocuous even at a much larger population size. The second assumption is that the advent of the new technologies was independent of the attempt to meet human needs and desires in a growing population. Actually, man's record as a simplifier of ecosystems and plunderer of resources can be traced from his probable role in the extinction of many Pleistocene mammals (*29*), through the destruction of the soils of Mesopotamia by salination and erosion, to the deforestation of Europe in the Middle Ages and the American dustbowls of the 1930's, to cite only some highlights. Man's contemporary arsenal of synthetic technological bludgeons indisputably magnifies the potential for disaster, but these were evolved in some measure to *cope* with population pressures, not independently of them. Moreover, it is worth noting that, of the four environmental threats viewed by the prestigious Williamstown study (*15*) as globally significant, three are associated with pre-1940 technologies which have simply increased in scale [heavy metals, oil in the seas, and carbon dioxide and particulates in the atmosphere, the latter probably due in considerable part to agriculture (*30*)]. Surely, then, we can anticipate that supplying food, fiber, and metals for a population even larger than today's will have a profound (and destabilizing) effect on the global ecosystem under *any* set of technological assumptions.

Conclusion

John Platt has aptly described man's present predicament as "a storm of crisis problems" (*31*). Complacency concerning any component of these problems—sociological, technological, economic, ecological—is unjustified and counterproductive. It is time to admit that there are no monolithic solutions to the problems we face. Indeed, population control, the redirection of technology, the transition from open to closed resource cycles, the equitable distribution of opportunity and the ingredients of prosperity must *all* be accomplished if there is to be a future worth having. Failure in any of these areas will surely sabotage the entire enterprise.

In connection with the five theorems elaborated here, we have dealt at length with the notion that population growth in industrial nations such as the United States is a minor factor, safely ignored. Those who so argue often add that, anyway, population control would be the slowest to take effect of all possible attacks on our various problems, since the inertia in attitudes and in the age structure of the population is so considerable. To conclude that this means population control should be assigned low priority strikes us as curious logic. Precisely because population is the most difficult and slowest to yield among the components of environmental deterioration, we must start on it at once. To ignore population today because the problem is a tough one is to commit ourselves to even gloomier prospects 20 years hence, when most of the "easy" means to reduce per capita impact on the environment will have been exhausted. The desperate and repressive measures for population control which might be contemplated then are reason in themselves to proceed with foresight, alacrity, and compassion today.

References and Notes

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2. B. Commoner, *Saturday Rev.* **53**, 50 (1970); *Humanist* **30**, 10 (1970).
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4. The figures used in this paragraph are all based on data in *Statistical Abstract of the United States 1970* (U.S. Department of Commerce) (Government Printing Office, Washington, D.C., 1970).
5. A dramatic example of this effect is given in R. Payne's analysis of the whale fisheries [*N.Y. Zool. Soc. Newsl.* (Nov. 1968)]. The graphs in Payne's paper are reproduced in Ehrlich and Ehrlich (*3*).
6. If N is the number of people, then the number of links is $N(N-1)/2$, and the number of links per capita is $(N-1)/2$.
7. These figures and the others in this paragraph are from *Cleaning Our Environment: The Chemical Basis for Action* (American Chemical Society, Washington, D.C., 1969), pp. 95–162.
8. In his unpublished testimony before the President's Commission on Population Growth and the American Future (17 Nov. 1970), Commoner acknowledged the operation of diminishing returns, threshold effects, and so on. Since such factors apparently do not account for *all* of the increase in per capita impact on the environment in recent decades, however, Commoner drew the unwarranted conclusion that they are negligible.
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10. L. Brown, *Sci. Amer.* **223**, 160 (1970); P. R. Ehrlich, *War on Hunger* **4**, 1 (1970).
11. These figures are based on data from the *United Nations Statistical Yearbook 1969* (United Nations, New York, 1969), with estimates added for the consumption by Mainland China when none were included.
12. The notion that dispersed resources, because they have not left the planet, are still available to us, and the hope that mineral supplies can be extended indefinitely by the application of vast amounts of energy to common rock have been the subject of lively debate elsewhere. See, for example, the articles by P. Cloud, T. Lovering, A. Weinberg, *Texas Quart.* **11**, 103, 127, 90 (Summer 1968); and *Resources and Man* (National Academy of Sciences) (Freeman, San Francisco, 1969). While the pessimists seem to have had the better of this argument, the entire matter is

academic in the context of the rate problem we face in the next 30 years. Over that time period, at least, cost, lead time, and logistics will see to it that industrial economies and dreams of development stand or fall with the availability of high-grade resources.
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Signal Detectability and Medical Decision-Making

Signal detectability studies help radiologists evaluate equipment systems and performance of assistants.

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Signal detection theory can be used to investigate two problems of interest to radiologists. First, the central concern in the study of radiographic image quality is to gain knowledge of the way in which physical image quality affects a diagnosis, not necessarily to design high fidelity imaging systems (*1*). Second, the increasing demand for diagnostic radiology examinations has stimulated studies to determine whether the effectiveness and efficiency of radiologists can be increased by the use of trained technical assistants.

Detection theory is a basis for treating discrimination experiments in psychophysics. In such experiments, one attempts to learn something about a sensory system by determining just how small a change in some aspect of the stimulus can be reliably detected. A central feature of this analysis is the distinction made between the criterion that the observer uses to decide whether a signal is present and his sensory capabilities as a signal detector. Receiver operating characteristic (ROC) curves can be used to separate the sensory and nonsensory variables. A large body of literature is available on signal detection theory in psychophysics (*2*) and the use of ROC curves (*3*).

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ROC Curve for Interpreting Chest Roentgenograms

In 1946 a group of radiologists and phthisiologists began an investigation to evaluate the effectiveness of various roentgenographic and photofluorographic techniques in detecting active pulmonary tuberculosis. Yerushalmy, who helped to initiate the study, has recently reviewed the results and the studies which followed (*4*). In the course of the investigation it was discovered that the variation in the interpretations of chest roentgenograms was of a disturbing magnitude: a physician would disagree with the diagnosis of a colleague on an average of one out of three times; on a second, independent reading of the same series of chest films, a physician would disagree with his own previous diagnosis on an average of one out of five times.

The results of the intensive studies of this phenomenon, which came to be known as observer error, are shown in an ROC graph in Fig. 1. The ROC curve is plotted on normal–normal coordinates (codex 41,453), according to the detection theory convention of false positive and true positive diagnoses on the x- and y-axes, respectively. Two parameters are abstracted from an ROC curve: the slope, and the sensitivity index d_e', where d_e' is defined as twice the normal deviates of the intersection of the ROC curve and the negative diagonal. The slope is interpreted as the ratio of the standard deviations of two distributions that, hypothetically, underlie the detection process. The measure d_e' is normalized by averaging the two variances of the underlying data-generating distributions. The more sensitively the observer performs as a signal detector, the larger the value of d_e'.

The ROC curve in Fig. 1 can explain the variation in roentgenogram interpretation. Suppose that the six points on the curve represent the diagnoses of six different physicians who have identical sensory capabilities for detecting the signals (film densities) of tuberculosis on the chest roentgenogram, but they have different criteria for what densities should actually be called tuberculosis. One assumes that they have the same sensory capabilities because the index of detectability, d_e', is the same for each physician.

The upper points on the curve represent individuals with more liberal decision criteria, whereas the lower