A Model for Medical Decision Making and Problem Solving
Mario Werner

Clinicians confront the classical problem of decision making under uncertainty, but a universal procedure by which they deal with this situation, both in diagnosis and therapy, can be defined. This consists in the choice of a specific course of action from available alternatives so as to reduce uncertainty. Formal analysis evidences that the expected value of this process depends on the a priori probabilities confronted, the discriminatory power of the action chosen, and the values and costs associated with possible outcomes. Clinical problem-solving represents the construction of a systematic strategy from multiple decisional building blocks. Depending on the level of uncertainty the physicians attach to their working hypothesis, they can choose among at least four prototype strategies: pattern recognition, the hypothetico-deductive process, arborization, and exhaustion. However, the resolution of real-life problems can involve a combination of these game plans. Formal analysis of each strategy permits definition of its appropriate a priori probabilities, action characteristics, and cost implications.

**Indexing Terms:** pattern recognition/hypothetico-deductive process/diagnosis by arborization/diagnosis by exhaustion

The vital importance of understanding how medical decisions are made arises from the startling inconsistencies in the way physicians perceive and manage seemingly identical circumstances (1, 2). The enormous implications of this diversity for individual patients, as much as its economic consequences, have made some standardization of medical decisions a central policy issue for third-party payers as well as the government. Recent federal legislation, therefore, has mandated the development of a body of normative medical guidelines, called practice parameters. Clearly, the creation and nationwide application of such directives demands some comprehension of how physicians solve problems.

In the 1960s the National Board of Medical Examiners commissioned a study to assess the competence of physicians in clinical training on the basis of their behavior in incidents judged by faculty observers to have a significant impact on outcome (3). Analysis of >3000 such critical incidents produced a catalog of behavioral components considered crucial, including the following: identifies initial pertinent hypotheses, tests all pertinent hypotheses, reevaluates hypotheses in the light of new findings, recognizes when sufficient data have been obtained and does not jump to conclusions, integrates data into one or more meaningful conclusions, and selects appropriate management and treatment plans. This action sequence provides a graphic roadmap of how physicians are expected to solve problems. Decision making is embedded in every aspect of clinical competence so defined. Indeed, the two are inseparable, because decision making underlies and is integral to all problem solving. Specifically, medical decisions deal with the type of history to be elicited, the focus of physical examination, the selection of paraclinical maneuvers such as laboratory tests, the interpretation of gathered data, the weighing of elements within a data set, the resolution of conflicting evidence, the choice and evaluation of diagnostic and therapeutic hypotheses, and the consideration of whether and how to act, investigate further, or simply allow the passage of time. These processes of diagnostic and therapeutic decision making should be viewed together because diagnosis is decision making for action selection, and diagnosis by itself is futile. Conversely, treatment response can be regarded as a diagnostic test that may modify the diagnosis, the subsequent therapy, or both (4).

Formal studies of medical decisions have been conducted in three ways, i.e., targeted to past, present, or future problem solving. The evaluative approach retrospectively audits clinical records and assesses medical performance according to such predetermined external criteria as the steps to be completed in the workup of a diagnostic hypothesis or the probability of achieving a therapeutic target regardless of process. The descriptive approach consists in observing and interrogating physicians as they tackle problems, through recording, transcribing, and subsequently analyzing the problem-solvers' remarks. The normative approach uses logic and quantitative analysis of risks and benefits associated with competing alternatives to define prescriptive strategies to guide future practice.

As they practice medicine, most physicians come to believe that diagnosis and treatment of illness are less taught than learned. Many patients implicitly agree that practical experience is a more crucial medical attribute than knowledge acquired in lecture halls, and, therefore, prefer a seasoned practitioner to a novice. Nonphysicians participating in healthcare delivery, on the other hand, frequently find it hard to enter into the intuitive cognitive processes of clinicians. Consequently, many of them believe that formal analysis of problem solving and frankly prescriptive strategies derived from such study can make physicians optimally deal with defined situations regardless of individual qualification.

The concatenated issues thus are: Can we understand medical decision making and problem solving;
can we model them; can we teach them; can we assess
them; and can we standardize them? I have analyzed
the latter three questions in a companion paper (5);
here, therefore, I will focus on the first two questions
exclusively.

The Process of Medical Decision Making and Problem
Solving

Behavioral scientists have long presumed that indi-
vidual differences in training and experience predict-
ably shape the process of solving problems. However,
more recent investigations of chess (6) as well as other
areas, including medicine (7), seem to conclude that
similarities between problem solvers outweigh differ-
ces. For instance, in one study medical students
employed the same thinking process as seasoned clin-
icians in the workup of the same patients. By contrast,
diagnostic and management outcomes were positively
related to education (8). According to such evidence,
experts would differ more from novices in their com-
mand of factual material than in their problem-solving
capacity, and both would simply apply the same ge-
neric methods to different data and with different goals
in mind.

The premise of my analysis, therefore, is that a
single universal pattern of medical decisions can be
described. Such a paradigm should apply not only to
the varied conditions in which medicine historically
has been practiced, but also to the multi-form diagnostic
and therapeutic choices physicians confront daily.
However, the paradigm need not apply to alternative
healing methods beyond the scope of traditional med-
icine. Thus, the paradigm should be a defining char-
acteristic of occidental medicine.

The eternal ingredients of medical problem solving
are medicine's current store of knowledge, the clues to
the patient's complaint gathered by the physician, and
the skill to apply the medical knowledge to the individ-
ual findings. Contemporary attempts at problem solv-
ing through the use of artificial intelligence well illus-
trate the fundamental role of these three elements in
the concept that linkage of disease models in memory
to patients' data produces the most reliable hypotheses
(9, 10). Of course, one could also generate new hypothe-
ses without recourse to additional data by simply
linking existing hypotheses (hypothesis-driven heuris-
tics), but in any experimental science this approach
must remain the exception.

The concept that this pattern of medical decisions
should have universal validity prompts some discom-
forting considerations as well, namely, that scientific
limitations have not impeded medical practice from
continuing to flourish nor has an irrelevant database
 disqualified the physician's counsel. Uroscopy, for in-
stance, long remained a lucrative branch of medieval
medicine. In fact, physicians have always had to select
definite action without knowing, on the one hand, all of
the possible actions and, on the other hand, the precise
consequences of each of the many courses open to them.
The postulate resulting from these aggregate consider-
ations then is that the content of medicine's book of
knowledge and the evidence collected from patients
change with time, but inevitably always remain incom-
plete. In the face of this, the medical decision problem
can be formally stated as follows: Given a sick person,
choose a treatment that maximizes the patient's ex-
pected benefit. To resolve this eternal problem, physi-
cians rely on an immutable process, i.e., the clinical
application of what is called the "scientific method."

In 1819 the French physician René Laennec asserted
in his treatise "De l'Auscultation Médicale" that chest dis-
ees could be more reliably diagnosed if physicians un-
derstood the significance of sounds produced by the or-
gans in that cavity, and if they monitored them with an
instrument he called stethoscope. After those revolu-
tionary innovations both general medical knowledge and
evidence obtainable from individual patients have soared
to ever higher rigor, but even the most exacting clinical
science remains tethered to the probabilistic bedrock of
vital processes. Osler summarized this in the aphorism,
"Medicine is a science of uncertainty and an art of
probability" (11). Varying and overlapping manifesta-
tions of health as well as disease render diagnostic
hypotheses ambiguous, just as incomplete information
regarding possible outcomes renders therapeutic deci-
sions uncertain. Relevant evidence can reduce uncer-
tainty. However, the purpose of collecting evidence can-
not be the unattainable goal to totally eliminate
uncertainty from medical decisions, but rather to bring it
to a level where more good than harm results.

The fact that thinking in biology and medicine is
stochastic and not deterministic crucially impacts on
clinical problem solving. Deterministic thinking pro-
cceeds from cause to effect and, hence, to analysis of
manifestations. Probabilistic thinking reverses that
order: Starting with the analysis of manifestations, it
seeks to uncover the causative effect and, hence, the
ultimate cause.

Medical problem solving in general follows a se-
quence of three basic steps that deal with, first, uncer-
tainty and the formulation of questions; second, some
deliberate action, say, the collection of clues by clinical
(history and physical) and paraclinical (biophysical and
laboratory) test systems; and, third, the weighing of
hypotheses as uncertainty is reduced. In any given
case, each of these steps represents a choice among
almost countless potential alternatives, facilitated by
probabilistic considerations. In practice, the process
typically begins with questions prompted by the symp-
toms that lead the patient to seek medical advice or
help. The usually small number of significant clues
restricts the options for the initial diagnostic or ther-
apeutic hypotheses. The physician then collects further
evidence to do one of two things, confirm (rule in) or
reject (rule out) candidate hypotheses. The sequence
can repeat itself, and the physician may again select
one action from several alternatives, in seeking a
conclusive decision from additional clues. In this way
the hypotheses generated by one round become the
questions to be answered by diagnostic tests or thera-

1216 CLINICAL CHEMISTRY, Vol. 41, No. 8(B), 1995
Some scientists, therefore, use diagnostic tests for clinical evaluation. The pretest probability reflects the discriminatory power of the test. Formally, the pretest probability is the probability that the patient has the disease given the presence of a test abnormality. It is represented by \( P(H) \), where \( H \) denotes the tested hypothesis being correct and \( \bar{H} \) denotes incorrect, \( T \) positive and \( \bar{T} \) negative test outcome, \( V \) values, and \( C \) costs. The \( P(\cdot|\cdot) \) terms represent the a priori (pretest) probabilities of the tested hypothesis being correct or incorrect, \( P(H) \) or \( P(\bar{H}) \). The \( P(y|x) \) quantities reflect the discriminatory power of the action system, i.e., the probabilities of true and false positives, \( P(T|H) \) and \( P(T|\bar{H}) \), as well as true and false negatives, \( P(\bar{T}|H) \) and \( P(\bar{T}|\bar{H}) \). Finally, for each of those four possibilities the third factor in each summand, \( V \) or \( C \), represents the associated outcome. Thus, (a) the pretest probability of a hypothesized diagnosis or outcome, (b) the discriminatory power of the action systems considered, and (c) the anticipated outcome values and costs become the crucial determinants of medical decisions. In the proposed model, therefore, medical problem solving skill would consist in the astute exploitation of these decisional parameters in the strategic construction of hypotheses. Let us next discuss these three determinants further.

Pretest Probability of Hypotheses

The know-how that experience confers is, in good part, conditioning to the likelihood of specified occurrences taught by repeated exposure. For disease incidence, age and sex are the most palpable determinants. Some conditions occur exclusively in one sex, in infancy or in old age, but even such findings as a moderately increased serum bilirubin value or an increased serum amylase activity have quite distinct differential diagnostic implications, say, in men under 40 years (most likely indicating hepatitis or chronic relapsing pancreatitis) as opposed to women older than that (most likely indicating cholelithiasis or acute relapsing pancreatitis). Yet the medical curriculum offers little formal instruction about the exploitation of these probabilities in linking the clues that patients present to hypotheses.

Pretest probabilities can further simplify choice because of the fact that, even though rare options may be many, frequent options necessarily always are few. For instance, a study of several thousand general medicine patients found that more than two in three cases presented one of just 10 leading symptoms (14). In each of these presentations, again, just a handful of diagnostic alternatives covered the large majority of patients. The same concentration on few diagnostic possibilities holds true for abnormal laboratory findings. For instance, numerous conditions cause hypercalcemia, but hyperparathyroidism and metastatic cancer account for about 9 in 10 cases. Therefore, a diagnostic strategy to consider just these two conditions initially, and to investigate other potential causes only if these two have been ruled out, has a high chance of success and is also cost effective (15).

In defining the analytical reliability demanded of laboratory assays, much has been made of the distinction between supposedly normal and abnormal findings at the limits of the normal range. However, more important clinical decisions hinge on the varying degree by which a result departs from the norm. These quantitative differences have qualitative implications, in that signal strength can establish a differential diagnostic framework defined by a priori probabilities. Fig. 1 illustrates how specific values of two enzymes used in the diagnosis of hepatic diseases delineate the scope of diagnostic options. For instance, a two-fold increase of aspartate transferase demands a consideration of quite disparate diseases, whereas a 100-fold increase exclusively allows the diagnosis of viral hepatitis. Analogous considerations apply in the case of alkaline phosphatase. Signal strength also affects therapeutic decisions. Hypercalcemia cases involving calcium concentrations of 110, 130, and 150 mg/L necessitate not only quantitatively but also qualitatively different management, as does hypernatremia or hyperglycemia in various severities. Finally, signal strength can define prognostic probabilities. An elegant study of Hodgkin disease showed that the severity of such simple indicators as localized pain or tumor, generalized fatigue, and weight loss differentiated 5-year survival better than did anatomic staging (16).

Discriminatory Power of Action Systems

At present, medicine essentially disposes of three different sources of diagnostic information: symptoms and signs observed in physical examination, biophysical findings such as electrocardiographic or radiological data, and laboratory findings. Symptoms and signs can be difficult to document objectively other than by verbal description and are difficult to quantify precisely. Biophysical findings are objectively documentable but typically difficult to quantify. Laboratory findings mostly are both objective and quantitative. Thus the latter represent the category of information perhaps best suited for studying not only the influence of the test system's discriminatory power on medical decisions, but also the adaptation that changing characteristics of evidence should induce in the process of decision making itself.
For instance, the crucial fact that the discriminatory power of a test system cannot be judged by either its sensitivity or its specificity viewed alone became appreciated fully only when objective, quantitative tests allowed analysis of the interdependence of these two quantities by such tools as the receiver-operator characteristic (ROC) curve (4). As a consequence, we now know that, depending on the test's purpose, sensitivity can always be traded for specificity, or vice versa. A second example is the formal assessment of the effect of the analytical uncertainty of a test on its capability to support therapeutic decision rules of various complexities. Thus, state-of-the-art assays of activated partial thromboplastin time were found to be capable of supporting two- and three-way algorithms for heparin dosage, but not the more complex patient classifications recommended by some (17).

Just as physicians should concentrate on the most probable options among the many possible diagnostic and therapeutic choices, they should also focus on but few tests among the almost infinite number available. In one study, 10 test orders (counting 6- and 12-test panels each as a single order) accounted for ~40% of all orders in hospitalized patients, ~60% of all orders in emergency room patients, and ~70% of all orders in clinic patients (18). Similarly, another study of >10,000 orders for the most common chemistry assays showed a biexponential distribution, in which <50 different orders or order combinations for these tests accounted for almost all of the requests. However, ~350 other rare orders also occurred in this sample, with about one-half of these being encountered only once over a 1-month period (19). One can reasonably ask whether such diversity is justifiable.

Anticipated Outcome Values and Costs

Decisions necessarily entail an evaluation of the various factors that are weighted in the process of arriving at them (20). Thus, decisions are value judgements, be they expressed directly and formally or only implicitly. To optimize the value of medical decisions in the broadest clinical context, not only the pretest probability of the working hypothesis and the discriminatory power of the considered action have to be estimated simultaneously, but also the costs and benefits associated with all possible decision outcomes. These latter values, whether tangible or intangible, unavoidably then must be weighed together when the decision is made (21).

Medical decisions always should affirm three intangible values, namely, to protect life, to hold health above sickness, and to treat individuals as persons, not simply as a means (22). George Bernard Shaw demonstrated in mordant fashion the potential contradictions in these commands in The Doctor's Dilemma. As the play opens, the protagonist has just been knighted for his discovery of a treatment for a previously incurable disease. He next receives two visits, one from a long-suffering colleague, Dr. Blenkinsop, who has devoted himself to ministering selflessly to the indigent but has now been diagnosed with the disease in question, and one from the alluring Mrs. Dubedat, who wishes to secure treatment of the same disease for her husband, a brilliant young painter but unrepentant rascal. However, the clinic's capacity permits enrolling only one additional patient. It is the play's biting irony to confound the doctor's decision further by his ardor for Mrs. Dubedat, more likely to be consummated were she...
widowed. With the perspicacity of genius Shaw has predicted our own dilemma to reconcile in a moral and ethical context our inevitably finite resources with seemingly infinitely expanding medical capabilities, including sundry organ replacements, in vitro fertilization, and the like.

The formal dilemma is that intangible and tangible valuations cannot be easily subsumed into a single denominator that can weigh them jointly, although such tools as the General Health Rating Index, the Quality of Well-Being Scale, and the Sickness Impact Profile attempt to do this (23). As an alternative, it has been proposed that valuation should cleanly separate two consecutive steps: first, the assessment of objective evidence anchored in science, and second, the assessment of desires and preferences of those affected by the outcome. Nevertheless, in certain situations, such as an acute threat to life, only one tangible benchmark, e.g., the likelihood of survival, need be taken into account (24).

Whatever the framework of values, action systems can produce only four outcomes, namely, a true positive or negative, and a false positive or negative. The main tangible benefit of a system resides in the diagnostic or therapeutic value of a true positive. However, a true negative also can provide tangible or intangible outcome value (25), say, by assisting multivariate diagnosis, by serving as a baseline against which values obtained after some therapeutic intervention can be gauged, or by offering reassurance. A false negative or a false positive represents costs associated with using the action system—a false sense of security as well as missed therapy in the first case and anxiety as well as superfluous, potentially harmful therapy in the second.

The fundamental medical principle regarding tangible values is primum nil nocere (do no harm). The cost of a decision can be minimized by using the mathematical derivative of the ROC curve derived from the total expected value (Eq. 1) representing an action system (26). The optimal decision threshold is derived from the value of the slope \( \alpha \) of the operating curve:

\[
\alpha = \frac{\Delta P (T|H)}{\Delta P (T|\overline{H})} = \frac{(V_{HT} + C_{HT}) P (\overline{H})}{(V_{HT} + C_{HT}) P (H)} \tag{2}
\]

If false treatment (false positive, \( \overline{HT} \)) has a low cost, but a missed diagnosis (false negative, \( HT \)) has a high cost, as in penicillin treatment of gonorrhea, \( C_{HT} / C_{HT} \) will be a small number, and the decision threshold will fall in the flat part of the ROC curve, favoring high sensitivity over specificity. Conversely, if false treatment has a high cost, but a missed diagnosis has a low cost, as in the chemotherapy of certain malignancies, \( C_{HT} / C_{HT} \) will be a large number, and the decision threshold will fall in the steep part of the curve, favoring high specificity over sensitivity.

### Strategies

Over the last three decades, considerable efforts have been undertaken to model the reasoned use of pretest probability, discriminatory power, and outcome in medical problem solving with the tools of decision analysis, artificial intelligence, and operations research (5). Although the rigor of such constructs may describe reasoning formally, they fail to fully capture the psychodynamics involved as physicians confront a probabilistic environment where complexity results not merely from the subject’s dimension but compounded by ethical and moral concerns. Clinical reality suggests at least four processes of mentation, namely, pattern recognition, the hypothetico-deductive process, arborization, and exhaustion. These prototypes meet the definition of a strategy (20) in that they form sequences of the decisional three-step process identified as the building block of medical problem solving. All four modes of problem solving are generic and thus equally applicable to diagnostic or therapeutic decisions.

The four strategies differ in the extent of uncertainty the decision maker believes he or she confronts at the outset (Table 1). The continuous spectrum of uncertainty ranges from decisions made under certainty through decisions made under various degrees of risk to decisions under total uncertainty. The extent of uncertainty determines whether action systems serve mainly to rule in or to rule out competing hypotheses. Decisions under risk are those of the greatest conceptual interest in medicine because they involve a judicious mix of ruling in and ruling out.

In a formal sense, risk implies that the competing hypotheses associated with a decision each have probabilities of occurrence, either known or obtainable from relevant indicators, that must be evaluated. For instance, if one has available both the a priori probabilities of the hypotheses considered and the data that permit their conversion to a posteriori probabilities, Bayes’ formula can be applied. However, given the impossibility of accounting simultaneously for all the factors that yield information potentially useful for predicting the likelihoods of various outcomes, medical decisions usually have to be made without fully assessing all available data. Thus, clinical problem solving also varies in its degree of tolerance for the uncertainty attached to a proposed solution once a diagnosis or therapy has been chosen (27).

**Pattern Recognition**

Pattern recognition relies on the instantaneous activation of a single highly probable hypothesis by the

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**Table 1. Four strategies for problem solving:**

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Confidence in hypothesis</th>
<th>Decisional problem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pattern recognition</td>
<td>Certain</td>
<td>Rule in</td>
</tr>
<tr>
<td>Hypothetico-deductive</td>
<td>Under risk</td>
<td>Rule in (rule out)</td>
</tr>
<tr>
<td>Arborization</td>
<td>Under risk or uncertain</td>
<td>Rule in and rule out</td>
</tr>
<tr>
<td>Exhaustion</td>
<td>Totally uncertain</td>
<td>Rule out</td>
</tr>
</tbody>
</table>

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**CLINICAL CHEMISTRY, Vol. 41, No. 8(B), 1995 1219**
earliest and often fragmentary clues harvested from the patient's history or physical examination. Favoring this process are the twin facts that most clinical cases are simple and straightforward and that most clinical signals of real value are striking. A single pathognomonic signal, whether visual, auditory, tactile, or otherwise, may trigger pattern recognition. Alternatively, a diagnostic signal constellation may prompt the single test that under the circumstances can confirm the pattern, e.g., an aspartate aminotransferase assay in a young drug addict with acute-onset jaundice who is suspected of having viral hepatitis. In pattern recognition, the decision makers act on the belief that they know most, if not all, of the decision parameters (i.e., decision under certainty). Accordingly, their principal decisional task is to rule in the working hypothesis.

Pattern recognition is the strategy most clearly favored by clinical experience, but attempts to validate this reflexive rather than reflective process by documentable clinical findings have yielded scant useful information. As is true for the ability to recognize a familiar face, we know little of where these hypotheses come from, and we cannot explain to others how we generate them. Accordingly, artificial intelligence has been unable to duplicate pattern recognition in pure form. However, the leverage afforded by evaluating multiple variables together rather than separately is well known. Indeed, relying on the fact that the whole is more than the sum of its parts, clinicians often will accept a hypothesis even if a given element of the set defining the pattern happens to be missing.

Telltale patterns combine otherwise mutually independent properties. For instance, combinations of markers for mammary adenocarcinoma discriminate malignant from benign lesions no better than any single component test assayed repeatedly, given that they all appear to derive from related cellular antigens (28). In contrast, rectal exam combined with assay of prostate-specific antigen detects more cases of prostatic cancer than either test used alone because the two tests have independent targets, i.e., related to anatomy and biochemistry (29). Indeed, it is more important that the variables of a pattern be independent than unadulterated or analytically specific. Thus, multivariate analysis discriminates certain diseases equally well, whether based on (e.g.) specific assays for individual serum proteins or on their electrophoretic fractionation, which resolves only chemically heterogeneous and overlapping fractions (30).

Hypothetico-Deductive Process

The hypothetico-deductive process can be characterized as follows: in clinical encounters physicians do not simply gather data until a solution becomes obvious, but form hypotheses early on. Indeed, they cannot be dissuaded from doing so (31). The hypotheses may be very specific or very general, but typically only about three working hypotheses—and perhaps the escape clause "or something else"—are considered simultaneously; any further information is gathered in that restricted context. In other words, the process consists in the conscious selection and logical testing of a short list of potential alternatives rather than of a single overwhelmingly probable hypothesis. On the other hand, in situations that offer multiple alternatives, the introduction of additional options can increase decision difficulty and, hence, increase the tendency to choose a distinctive option or to maintain the status quo (32). The choice of specific alternatives for consideration is governed by a weighing of three key characteristics: their likelihood, severity, and treatability. Thus, the hypothetico-deductive method represents decision making under risk, and the decisional tasks include both ruling in and ruling out hypotheses.

Schemes to solve medical problems by artificial intelligence frequently have attempted to duplicate the hypothetico-deductive process. Success with this strategy depends altogether on a mastery of directed but unbiased acquisition and interpretation of relevant data, the goal being to marshal the clinical and paraclinical maneuvers most likely to reduce the list of options to a single choice (33). Once this is achieved, however, the hypothetico-deductive process departs from the classical scientific method. Whereas the latter seeks to rule out competing hypotheses by crucial control experiments, clinicians mainly seek to rule in the lone remaining working hypothesis.

Arborization

Arborization sequentially analyzes data pertinent to a given presentation or problem in a systematic, preset process of step-by-step discrimination and elimination of options. Analysis is channeled along one of multiple available paths as the decision taken at any given branching point automatically determines the subsequent decision to be made before ultimately arriving at the correct hypothesis or action. Formal algorithms explicitly specify the patients that can be managed by them, the information that must be gathered, the conclusions to be drawn from findings, and the consequent diagnostic and therapeutic actions, but the complex reasoning that underlies the construction of flow charts is only implicitly expressed by its branching. Specifically, the valuations placed on each consequence (i.e., the particular outcome achieved through a specific course of action), without which logical decisions cannot be made, remain undisclosed and can at best be inferred. Thus, arborization is a more structured version of decision making under risk, where the decisional tasks include ruling in and ruling out hypotheses without preference for either.

In the late 1960s corpsmen assigned to a military dependents clinic first used this process to maintain the quality of care in the face of scant formal training (34). Subsequently, written algorithms have been used most commonly to train neophyte physicians, physicians' assistants, and nurse practitioners. The method's particular strength is believed to be in the triage of broad arrays of options, where diagnosis, not treatment, is the objective, or to resolve uncommon prob-
lems for any practitioner, not just those without an established role in medical decisions. However, operations research of different drug-related clinical situations suggests that problems in which therapeutic considerations outweigh diagnostic ones are more readily reduced to formal decision algorithms (5).

Together with the hypothetico-deductive process, arborization has been the main strategy in attempts to duplicate medical problem solving by artificial intelligence. However, the extent to which day-to-day medical practice relies on formal algorithms has not been documented. Particular weaknesses of the method are that previously evaluated information cannot be revisited for multifactorial evaluation in light of new data, and that the rigid sequencing makes it difficult, if not impossible, to accommodate multifaceted diagnostic problems such as comorbidity, or heterogeneous therapeutic problems such as potential side effects of drugs.

Exhaustion

Exhaustion accepts all possible alternatives, regardless of probability, for equal consideration to find the correct one by elimination of all incorrect ones. Conceptually, exhaustion can be seen as the individually applied counterpart of general population screening for disease, i.e., indiscriminate testing to detect a potential disease in a person who has no diagnostic manifestation of that condition. In this process the decision maker acts on the belief that no information as to the likelihood of any outcome is available (decision under total uncertainty); the decisional necessity, therefore, is to rule out all unwarranted hypotheses. Thus, the twin tasks of collecting and interpreting all medical facts conceivably relevant to the case replace the formulation of a working hypothesis.

The first electronic data-processing methods offering support in the interpretation of abnormal laboratory findings relied on exhaustion, while failing to exploit either signal strength or multivariate analysis. Some clinical teaching and medical texts at times seem also to favor exhaustion as a strategy, and novices may believe that it ensures against errors of omission. To the expert, however, exhaustion appears as a wasteful last resort, expedient only when a particularly rare or obscure situation prevents experience or knowledge from framing a working hypothesis.

Implications for Action Systems

By understanding the four prototypes of decision making, we can define for each the commensurate use of action systems and their appropriate characteristics (Table 2). Given the decisional certainty of pattern recognition, action is highly selective and confirmatory. Conversely, given the total decisional uncertainty of exhaustion, all available and affordable action (e.g., tests) may be ordered. The remaining two strategies represent decision making under risk, with the hypothetico-deductive strategy favoring selective and confirmatory action but also relying on sequential testing, and arborization relying on selective sequential action and testing.

In diagnosis, the following rules are applicable whether the test system is a single clue, a battery of indicators, or a logic sequence that represents the given strategy. Ruling in or confirming a hypothesis demands a high positive predictive value of the test system, as expressed in:

$$P(H|T) = \frac{HT}{HT + HT}$$ (3)

Hence, false positives (HT) must be minimized, and ruling in is most successful when the disease prevalence is high, i.e., large P(H), and when a wide normal range favors specificity. Conversely, ruling out or excluding a hypothesis demands a high negative predictive value of the system, as expressed in:

$$P(H|\bar{T}) = \frac{HT}{HT + HT}$$ (4)

Hence, false negatives (HT) must be minimized, and ruling out is most successful when disease prevalence is low, i.e., large P(\bar{H}), and when a narrow normal range favors sensitivity.

Although these formal conclusions pertaining to disease prevalence and to test characteristics appear also intuitively convincing, this is not equally true for analogous cost considerations based on expected value. Formal analysis implies that pattern recognition as a strategy is most appropriate where the cost of errors of omission is small compared with that of errors of commission. The opposite is true for exhaustion as a strategy. Finally, the hypothetico-deductive process

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Table 2. Four strategies for problem solving: associated choice of action systems, appropriate a priori probabilities, appropriate action characteristics, and appropriate cost implications.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Choice of action systems</th>
<th>Appropriate a priori probabilities</th>
<th>Appropriate action characteristics</th>
<th>Appropriate cost implications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pattern recognition</td>
<td>Selective, confirmatory</td>
<td>High</td>
<td>High specificity</td>
<td>High $C_{HF}/C_{T}$ ratio</td>
</tr>
<tr>
<td>Hypothetico-deductive</td>
<td>Selective, confirmatory (sequential)</td>
<td>High (neutral)</td>
<td>High specificity (high sensitivity)</td>
<td>High $C_{HF}/C_{T}$ ratio or neutral</td>
</tr>
<tr>
<td>Arborization</td>
<td>Selective, sequential</td>
<td>Neutral</td>
<td>High sensitivity and specificity</td>
<td>Neutral</td>
</tr>
<tr>
<td>Exhaustion</td>
<td>All available and affordable</td>
<td>Low</td>
<td>High sensitivity</td>
<td>Low $C_{HF}/C_{T}$ ratio</td>
</tr>
</tbody>
</table>

HT = false negative, HT = false positive.
and arborization balance to various degrees the costs of both error types.

**Conclusions**

Without understanding the process by which physicians arrive at decisions and solve problems, the current effort to develop normative guidelines for medical action cannot become systematic. My analysis distinguishes an universal decisional process and the strategies constructed from it. The former can be described and analyzed in a formal model, but the latter defy a similarly comprehensive and generic treatment, although their systematic classification appears possible.

Epigrammatically, pattern recognition can be characterized as the expert’s strategy, arborization as the delegate’s, exhaustion as the novice’s, and the hypothetico-deductive process as the strategy common to all. However, the four described processes of mentation are in fact used by virtually all clinicians virtually all of the time, for physicians cannot commit themselves exclusively and irreversibly to a single strategy when addressing a specific problem. For example, in the hypothetico-deductive process, a familiar pattern may emerge and be seized. Conversely, when pattern recognition falters, the hypothetico-deductive process may replace it, or when the latter reaches a dead end, only exhaustion may remain available.

**References**