USING DATA TYPES AND SCALES FOR ANALYSIS AND DECISION MAKING

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As the selection among alternatives and allocation of scarce resources is increasingly subjected to critical review and public second guessing, the popularity of quantitative prioritization schemes is increasing. Most models applied properly with reasonable assumptions are effective and defendable. In the past, prioritization models were used with empirical data where accuracy related to measurement precision, but today models are being used with data that reflect subjective assessments of relative values in abstract terms. The scales used to "quantify" these assessments frequently do not conform to the data requirements of the model with respect to fundamental rules of data manipulation. It is not unusual to discover a quantitative prioritization scheme has serious flaws in its data scale. Program managers, decision makers and analysts must recognize the four fundamental types of data and data scales, and understand the numerical manipulations that can be performed with each type.

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DECISION MAKING ENVIRONMENT

The defense acquisition climate is one of decreasing budgets and increasing demand for available funds. Efficiency dictates that managers prioritize programs so that each budget cut will not require a new evaluation of options. Additionally, managers are frequently being required to justify their decision in selecting among alternatives both within their organization and externally. The consequence is the increasing use of quantitative decision analysis. New techniques are constantly being introduced, some have reached the stage of popularity that results in their mention by sophisticated decision makers at cocktail parties (TQM, COEA, QFD, AHP, etc.),[1] and most have software available for easy application. Also, the increasing demand and fashionableness of quantitative decision analysis, and the availability of software models, have spurned a misuse of data that must be corrected less the proliferation of erroneous results discredit the real potential of decision analytical methods.

Abstract assessments are inherently subjective because the "true value" cannot be measured conventionally. A subjective assessment is a fundamental attempt to derive "numerical" measurement from personal value. Numerical data can be divided into four categories, differentiated by the scale used to separate the numerical values, and consequently, the mathematical manipulations (and therefore the type of assessments) that can be performed with each kind of data. In increasing level of flexibility and robustness (i.e., more can be done with the last type), the four types of data and scales are: nominal, ordinal, interval and ratio.

Understanding the different data and scale types can save analysts significant grief, keep decision makers from making erroneous choices, and may even keep some program managers out of court. An example is recent ruling by the General Service Administration Board of Contract Appeals which upheld procurement protest because the Navy violated fundamental rules of data analysis and decision making. The details are discussed in this article.

NOMINAL DATA AND NOMINAL SCALES

As implied by the title, this type of data has been given *names* or *labels* (nominal, from the french "*nom*" = name). Nominal data can be counted, but no superiority or preference can be implied from the numerical value of the labels, and no arithmetic manipulations can be performed on the labels themselves.

The convention within the United States is to designate highways that lead generally in a north-south direction with odd numbers, and those that lead generally east-west with even numbers. This labeling convention is useful for

1 Total Quality Management (TQM), Cost & Operational Effectiveness Analysis (COEA), Quality Funciton Deployment (QFD), Analytical Heirarchy Process (AHP).

quickly recognizing the general direction of a numbered highway and for easily counting the number of north-south highways going through a state by quickly counting the number of odd numbered routes. This is clearly nominal data. The data (number of north-south highways) can be counted, but no superiority is implied by the numerical designations (route 95 is not better than route 5 nor worse than 101), and no arithmetic can be performed with the labels (route 101 plus route 5 does not equal route 106). Nominal data has no scale in the conventional sense that a higher number is superior to a smaller number.

In developing a technology investment strategy to combat the supply of illegal drugs, an analyst decomposed the process into hierarchical schema. The illegal drug problem results from the production, wholesale, retail distribution, and resulting generation of capital. The production process further decomposes into growing, harvesting, and processing. Wholesaling depends on transportation (from the producing country to the United States) and entry into the United States. The act of retailing depends on distribution of the drugs to the street vendors and the actual sale to users. The capital generated can be banked, laundered, or reinvested to continue the drug cycle. This hierarchical decomposition is shown in Figure 1.

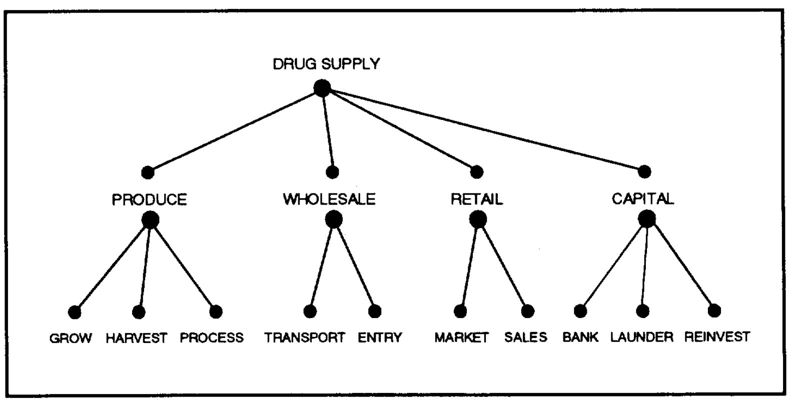

Figure 1. **Hierarchical Decomposition of Drug Supply**

For analytical accounting purposes each node was labeled to indicate its relative position and derivation within the decomposition. When numerically labeled, the decomposition took the form shown in Figure 2.

These numbers clearly are nominal. The number of factors relating to capital can be determined by counting the number of two digit labels beginning with the number four (the three factors under capital are 4.1, 4.2 and 4.3). No arithmetic can be performed with the data (labels) themselves,

Production 1			Wholesale 2		Retail 3		Capital 4		
Grow 1.1	Harvest 1.2	Process 1.3	Transport 2.1	Entry 2.2	Market 3.1	Sales 3.2	Bank 4.1	Launder 4.2	Reinvest 4.3

Figure 2. **Drug Process Accounting Scheme**

e.g. node 1.2 plus node 1.3 is meaningless, and no superiority is implied by the value of the number, e.g., node 4.1 is neither superior nor in any way more important than node 2.2. Obviously, the accounting methodology would be equally as useful if capital had been labeled as #1, wholesale as #3, production #2 and retail as #4 (with their subsets changed accordingly).

Nominal data can result from the categorization of variables. Dogs can be categorized by breed, cars by make or color, and people by religious preference or sex. If the categories are assigned numerical values, e.g., Female = 1, Male = 0 (or Female = 83, Male = 20), nominal data results. Again it does not make sense to do arithmetic with nominal data; it is meaningless to try to calculate the "average sex" from nominal data.

Nominal data, which is unique up to any one-to-one transformation, is the result of assigning labels (not necessarily numerical) to objects. An example of a one-to-one transformation, in the case of drug process accounting, is shown in Figure 3.

Production 1			Wholesale 2		Retail 3		Capital 4		
Grow 1.1	Harvest 1.2	Process 1.3	Transport 2.1	Entry 2.2	Market 3.1	Sales 3.2	Bank 4.1	Launder 4.2	Reinvest 4.3

⬇ One-To-One Transformation ⬇

Production A			Wholesale B		Retail C		Capital D		
Grow AA	Harvest AB	Process AC	Transport BA	Entry BB	Market CA	Sales CB	Bank DA	Launder DB	Reinvest DC

Figure 3. **Drug Process Accounting: One-To-One Transformation**

ORDINAL DATA AND ORDINAL SCALES

As the name implies "order" counts, and the size of the number indicates superiority and provides rank. *Webster's Dictionary* defines ordinal as "of a specified order or rank in a series" and an ordinal number as "a number designating the place (as first, second, or third) occupied by an item in a ordered sequence." The numerical value of ordinal data indicates its relative position or standing among the data set, however, the interval between the numbers (the scale) is arbitrary, need not be consisted, and is therefore meaningless. Consequently, ordinal data cannot be combined arithmetically.

The assignment of the numerical values of 3 = superior, 2 = good, and 1 = average, creates ordinal data. It is incorrect to assume that "good," with a numerical value of two, is twice as important or valuable as "average" which has been assigned the numerical value one. The scale, a one unit interval between values, is arbitrary and could just as well have been, Superior = 648, Good = 50, and Average = 46. Because the interval is arbitrary, the values cannot be combined arithmetically. In the first case, two "Goods" (2+2) would exceed one "Superior" but in the second case two "Goods" (50+50) would remain well below one superior. The result of such arithmetic clearly is nonsensical.

Ordinal data is useful because it clearly shows relative rank among data points. An ordinal scale is invariant under monotone increasing transformations. The numerical values that represent ordinal data indicate relative superiority and rank but an ordinal scale does *not* indicate by how much one factor is preferred over another. Ordinal data *cannot* be usefully combined arithmetically.

INTERVAL DATA AND INTERVAL SCALES

Interval data is associated with a consistent and meaningful scale. In addition to indicating order and rank, one can perform addition and subtraction (but not multiplication or division) with these numbers. Interval scales have no intrinsically meaningful origin. The zero point is selected for its convenience and does not indicate the absence of the characteristic being measured. Any interval size can be used to discriminate between successive values and create the scale as long as it is used consistently.

A critical sensing element in a high performance aircraft must be connected to the instrument panel with an optical fiber cable of precisely 200 millimeters (mm) in length. The quality control engineer at the production plant measures a sample of six cables as:

200.003	200.011
199.964	200.008
200.000	199.998

By convention and to make the data easier to work with, the engineer codes the data in thousandths of a millimeter above 200. The linear transformations is

$$y = (x - 200)(1,000)$$

and the data set becomes

03	11
-36	08
00	-02

This set of data is interval data relative to length. The zero point does not indicate an absence of length, however, the interval is consistent and meaningful.[3] The spread between the longest and shortest price of cable *(11 -(-36) = 47 thousandths of a mm)* is preserved *(200.011 - 199.964 = .047 mm)* because addition and subtraction of interval data is permissible. Since multiplication and division are not allowed the ratio of longest to shortest is meaningless, as shown below:

$$\frac{11}{-36} = -0.3056$$

and does not equal

$$\frac{200.011}{199.964} = 1.0002$$

Another good example of interval data and interval scales are the Fahrenheit and Celsius temperature scales. The freezing point of water was assigned the value 32° Fahrenheit and 0° Celsius. Note that the zero points (0°C and 0°F) do not indicate the absence of temperature. The boiling point of water was assigned the Fahrenheit value of 212°F and the Celsius value of 100°C. The scale spacing that indicates a one degree temperature change is 1/100 for the Celsius scale and 1/180 for the Fahrenheit scale (212°F - 32°F = 180°).

Since order counts, 60°F is hotter than 15°F and because the interval between each temperature is consistent additions and subtractions are possible, e.g., 40°C + 10°C = 50°C and 160°F is 20 degrees hotter than 140°F. Because the zero point does not indicate the absence of temperature these are interval data and cannot be multiplied or divided. It is incorrect to claim that 90°F is twice as hot as 45°F. The fallacy is easily understood by considering the equivalent temperatures in both Celsius and Fahrenheit scales and comparing the two ratios.:

$$90^{\circ} F = 32.2^{\circ} C \ \textit{and} \ 45^{\circ} F = 7.2^{\circ} C$$

$$\frac{90^{\circ} F}{45^{\circ} F} = 2.0 \qquad \frac{32.2^{\circ} F}{7.2^{\circ} F} = 4.5$$

Are the two temperatures twice as hot, or four and one-half times as hot? To multiply and divide temperature values "absolute" scales, as discussed

2 The zero point indicates an absence of error from the specified length.

under Ratio Data and Ratio Scales, must be used.

The data in interval scales are unique up to a positive linear transformation of the form $y = a + bx$ for $b > 0$. This property of interval data allows conversion between Fahrenheit and Celsius temperatures. Adding the constant, "a", shifts all values of "x" upward or downward by the same amount, and changes the origin (zero point) of the variable "y." Multiplying by the positive constant "b" changes the size of the unit of measure. The temperature transformation is:

$$C = (F - 32)\,\frac{5}{9}$$

or

$$y = -\frac{160}{9} + \frac{5}{9}x$$

RATIO DATA AND RATIO SCALES

Ratio data is the most robust form of data. With ratio data size indicates absolute position and importance, the interval between values (scale) is consistent, the zero point denotes the complete absence of the characteristic being measured, and all arithmetic operations can be meaningfully performed. The critical difference between the ratio scale and interval scale is that the ratio scale has an origin that is truly a point of reference where the characteristic being measured ceases to exist.

Examples of ratio data and ratio scales abound: distance, age, money, and volume. The zero point denotes a complete absence of the characteristic in each case, larger numbers rank higher than smaller numbers and ratios are meaningful, e.g., $45,000 is truly three times larger than $15,000.

As a second example, consider temperature scales again. To avoid the limited arithmetical manipulation that can be performed with Fahrenheit and Celsius data (interval data), engineers developed an "absolute temperature scale." Unlike the temperature scales based on the freezing point of water, the derivation of the absolute temperature scale is independent of the property of any particular substance. In the absolute temperature scale, zero degrees represents the lowest attainable temperature and the absence of molecular motion. Many engineering textbooks and reference manuals clearly state that, "The absolute temperature scale should be used for all calculations" (Lindeberg, 1992). In the English System (pounds and feet) the absolute temperature scale is the Rankine scale; in the SI System[3] (kilograms and meters) the absolute temperature scale is the Kelvin Scale.

3 The SI System is an outgrowth of the General Conference of Weights and Measures, an international treaty organization that established the System International d' Unites (International System of Units) in 1960.

The data in a ratio scale is invariant under positive linear transformations of the form $y = bx$ for $b > 0$. Notice that there is no constant term which can change the location of the origin (recall "a" in the transformation $y = a + bx$ for interval data). In this transform the origin, where $x = 0$, will remain a zero point origin regardless of the value of "b"; only the slope will change.

Another attribute of a ratio scale is that equal absolute variations correspond to equal proportional variations in the data. This attribute permits the use of semi-long graphs and charts.

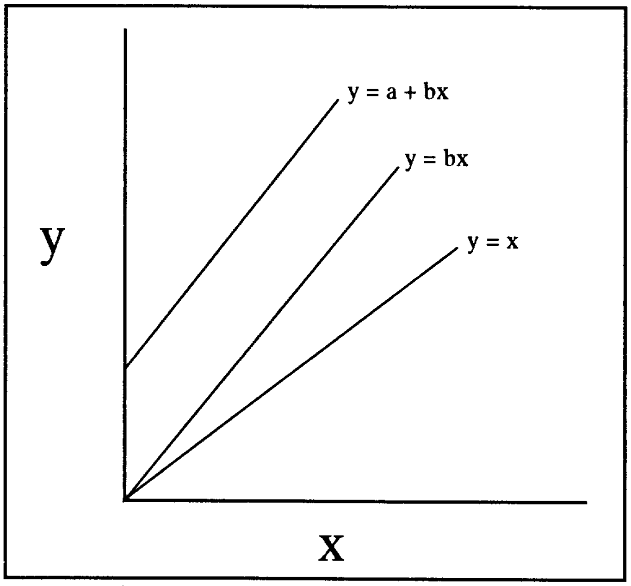

Figure 4. **Linear Data Transformations**

HOW DATA HAS BEEN MISUSED

Ship Design

A common misuse of data relates to the application of weighting factors to characteristics in an attempt to prioritize options. In the following example from a published technical paper, the subject has been changed to protect the guilty; however, all the numbers and calculations are exactly as originally published.

The objective was to select the best from among seven alternative ship designs. It was decided that the seven options (A, B, C, D, E, F, and G) should be evaluated relative to how well they responded to seventeen important design and performance criteria. The 17 important characteristics, in no particular order, were:

Acceptability (AC) - by the market place.
Admiralty Law (AL) - total compliance or waivers required.
Environment (EN) - adverse noise, overboard discharge, etc.
Cruising (CR) - in the open ocean unconstrained.
Maneuvering (MA) - in a channel, harbor entrance, etc.
Docking (DO) - mooring and anchoring.
Ocean Navigation (ON) - without a landmass or other visual reference.
Coastal Navigation (CN) - with a landmass and other visual references.
Manning Requirement (MR) - crew size and qualification requirements.
Efficiency (EF) - fuel usage per mile.
Administration (AD) - personnel record-keeping and status monitoring.
Safety (SA) - observation, from the bridge, of unsafe conditions on deck.
Recoverability (RE) - from collision, grounding, and other accidents.
Operating Flexibility (OF) - if electrical power to bridge is loss.
Loading/Unloading (LU) - time, flexibility, and equipment availability.
Delivery Capacity (DC) - cargo capacity (weight and volume).
Design Stability (DS) - roll, pitch, and yaw.

These 17 evaluation criteria were then weighted (assigned a value indicating relative importance) with what was called a criticality factor. The most important criterion (Docking) was assigned a 1 and the least important criterion (Administration) was assigned a 17. This is clearly ordinal data from an ordinal scale, although in descending order — lower numbers indicate increased characteristic importance relative to higher numbers. It is ordinal data because it ranks the criticality factors relative to each other but reveals nothing about how much more important one characteristic is considered relative to any other. The criticality factor rated 2 is considered more important than those rated 4 and 16 but it cannot be said to be twice as important and 8 times as important respectively. The data is not interval data, e.g., the sum of the two characteristics assigned criticality factors of 2 and 3 does not equal in importance the characteristic assigned a criticality factor of 5. The criticality factors are ordinal data representing relative rank only. They cannot be meaningfully summed, multiplied, or divided.

Next, the analyst assigned the seven options a number from 1 to 7 to indicate the degree to which they possess each characteristic being used as an evaluation criteria. Again lower numbers indicate "preference," a 1 indicates the most responsiveness and a 7 the least responsiveness. See Table 1. These data again are ordinal data. They provide relative rank but the interval is arbitrary, does not indicate how much better or worse each option responds to each criticality factor, and the "zero point" (a value of 7) does not imply an absence of response to a criticality factor.

No statistical or mathematical rule had been violated until the analyst proceeded to multiply the value of each criticality factor by the number indicating each option's responsiveness to that factor, and then summing these products for an overall evaluation of each option. The weighted summations, meant to indicate option ranking, are identified as "Totals" in Table 1 which is reproduced from the report.

CRITICALITY FACTORS			DESIGN OPTIONS						
			A	B	C	D	E	F	G
EVALUATION CHARACTERISTICS	AC	15	1	2	6	4	5	3	7
	AL	5	1	2	6	4	5	3	7
	EN	11	1	7	4	3	5	2	6
	CR	6	5	7	3	2	4	6	1
	MA	3	3	4	5	1	6	2	7
	DO	1	1	3	5	4	6	2	7
	ON	8	6	5	3	2	7	4	1
	CN	7	1	3	5	3	6	2	7
	MR	14	7	6	2	4	3	5	1
	EF	2	1	2	6	4	5	3	7
	AD	17	1	2	5	4	6	3	7
	SA	12	1	2	5	4	6	3	7
	RE	9	1	7	4	3	5	2	6
	OF	10	7	6	3	4	2	5	1
	LU	13	1	2	6	5	7	4	3
	DC	4	7	2	5	4	3	6	1
	DS	16	6	7	3	4	2	5	1
	TOTAL		471	642	658	568	727	559	651

Table 1. **Design Option Prioritization**

The report concluded that option A was the best because it had the lowest summation total; recall that the convention selected was to assign a 1 to the most important characteristic and most responsive option while assignments of 17 and 7 indicate the least important characteristics and least responsive option respectively. The analyst also noted in the report that not only was option A preferred but that it was significantly better than the next best option (option F) because it was 88 points lower (*559 - 471 = 88*).

To determine that the analysis is flawed, one need only look at the effect of the least important evaluation criteria, Administration (AD) that was assigned a criticality factor of 17. Suppose that the apparent winning design, designated Option A, has to slight the least important criteria, Administration, in order to achieve its high ranking in most of the more important criteria. If it subsequently received the lowest ranking (7) instead of the best (1) for Administration, the swing in total points is 102 (from $17 \times 1 = 17$ to $17 \times 7 = 119$), and Option A goes from most preferred to, at least, third place based only on a change in responsiveness to the least important factor. If Options C or G received the best rating for Administration — hypothetically relinquished by Option A — then Option A could move all the way down to fourth place.

As further demonstration of the consequences of multiplying ordinal data (treating it like ratio data, consider the following. As applied in the matrix the products are "penalty points" in that the smallest total value is the best option. The option that performed the *most important function* the worst (regardless of how badly it performs) was penalized only 7 points and is still nearly tied for first place. The option that performed the *least important function* the worst could lose everything even if it had been the best for nearly everything else, because it is penalized 119 points.

Proposal Evaluation

The following misuse of data is from a recent decision from the General Services Administration (GSA) Board of Contract Appeals, as reported in *Government Computer News* (Petrillo, 1993). In response to a procurement protest, the Board determined the Navy had made several evaluation errors. Several bidders argued that subfactor assessments should have been added to reach an overall proposal assessment; the Navy multiplied the subfactors. The Board concluded that the only reasonable approach was addition. [Was interval data treated like ratio data?]

The Board also determined that proposal evaluation errors had been made in the cost versus technical trade-off analysis. The first involved "probability analysis" where the proposal evaluators merely counted the number of tools in the offered software packages. Many of these tools had little or nothing to do with productivity and no attempt was made to determine which tools would help workers do their jobs. These productivity factors were then compared to a range of numerical weights assigned to price. This mapping of scales constituted the cost versus technical trade-off analysis. This misuse of data types and scales contributed to the Board's decision to overturn this procurement award.

KEYS TO CORRECT ANALYSIS

Each data type and associated scale have appropriate applications. It is inefficient to always generate ratio data. If you only desire to know which option is best, not how much better than other options, subjective assessment using an ordinal scale may be all that is necessary. If each option will be evaluated by adding independent assessments of several characteristics, an interval scale can be effectively used, still assuming that only rank ordering is desired.

Depending upon the application, relaxation in the presentation of results may be appropriate and improve acceptance by avoiding valid arguments about the accuracy of subjective assessments. Assume that you have been rigorous and consistent in creating a ratio scale for the use of experts in making assessments. Several adjacently ranked options may have very small numerical separation and invite argument over their individual assessments. If the purpose of the ranking is simply to segregate the "very good," the "average," and the "poor," the results may be grouped in such a manner for presentation — even to the point of listing options alphabetically within each group — despite the fact that ratio data allows specific ranking. Remember that even the best analysis becomes impotent if not implemented or somehow utilized by the decision maker.

When querying experts to gather assessments of preferences it is critical that the responders understand the strength of the numbers they are using in their evaluations. If an expert is told to evaluate two alternatives by selecting numbers between 1 and 10, and the expert perceives that one alternative is quite a bit better than the other, values of 8 and 2 may be assigned. If, however, you intend the scale from 1 to 10 to represent ratio data, and explain that as assignment of 8 and 2 indicates that the preferred option is considered to be four times better than the alternative, the expert's assessment may change to 6 and 3 indicating that one option is really considered only twice as good as the alternative. Such a change is significant.

Words Help, but be Careful

Words can be used to convey the meaning you intend numerical values to assume, but caution is called for because individuals interpret words differently. In soliciting probability assessments, the phrases "chances are slight," "highly unlikely," and "almost no chance" have been used to suggest a probability of occurrence in the 0 percent to 15 percent range. For probabilities in the 15 percent to 45 percent range, one frequently finds descriptors such as "probably not likely," "unlikely," "improbable," and "we doubt." Attempting to verbalize a probability between 55 percent and 85 percent one

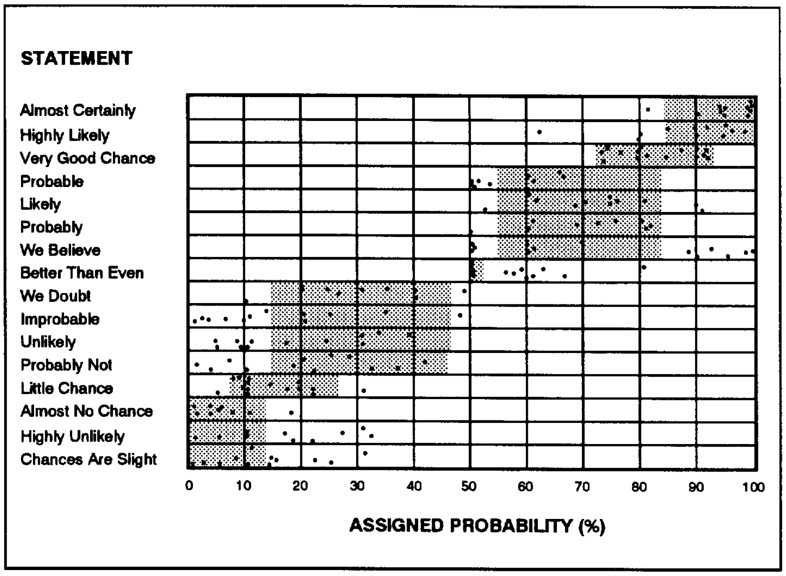

Figure 5. **Numerical Interpretation of Descriptors**

finds "we believe," "probably," "likely," and "probable." Finally, probabilities in the range of 85 to 100 percent are usually described as "highly likely," or "almost certain." When graduate students who had recently completed a course in statistics were asked to assign a probability to each of these descriptors, the results, shown in Figure 5, were not always as expected (Decision and Design, Inc., 1973).

Notice that two readers assigned probabilities as high as 30 percent to the descriptor "highly unlikely," the majority of readers interpreted "improbable" and "unlikely" as having a probability of between 0 percent and 15 percent rather than the intended 15 percent to 45 percent, and the probabilities assigned to the descriptor "we believe" ranged from just above 50 percent to over 95 percent.

The GSA Board of Contract Appeals decision discussed earlier also noted contract award discrepancies such as: "Although the solicitation described certain subfactors as being *of equal importance*, the most important of these had a maximum score more than four times greater than the least important." The Board ruled that this was too great a difference (Petrillo, 1993). Although the solicitation stated that one subfactor was "slightly more significant" than the other, the difference in weighting was 40 percent. The Board ruled that 40 percent was not "slightly more significant." The lesson to be learned is that verbal descriptors are useful, but they must be accompanied by explicit definitions or indications of the range of values they are intended to describe.

EXPECTED UTILITIES REQUIRE INTERVAL OR RATIO DATA

The product of a probability and a utility assessment, called expected utility, is an important frequently calculated decision criteria. Probabilities are ratio data over the scale 0.0 (the certainty of non-occurrence) to 1.0 (the certainty of occurrence). The utility assessments must be unique up to a linear transformation, either interval or ratio data, otherwise erroneous interpretations can be made.

As a demonstration of the problem that can occur if an ordinal scale is used for utility assessments, consider the choice of developing one of two competing systems, A and B, that have been evaluated by engineering experts as having the following probabilities of achieving discrete levels of capability:

	Superior	Good	Poor
System A	.40	.35	.25
System B	.30	.60	.10

In assessing the utility of achieving each level of capability assume one analyst chooses an ordinal scale from 1 to 10 and lets Superior = 10, Good = 6, and Poor = 2. His calculation of the expected utility for each system is thus,

$$E(A) = (.40)10 + (.35)6 + (.25)2 = 4.0 + 2.1 + 0.5 = 6.6$$
$$E(B) = (.30)10 + (.60)6 + (.10)2 = 3.0 + 3.6 + 0.2 = 6.8.$$

He would declare that System B is preferred.

If a second analyst selected an ordinal scale from 1 to 100 and assigned Superior = 95, Good = 70, and Poor = 60, he would calculate the expected utility of each system as,

$$E(A) = (.40)95 + (.35)70 + (.25)60 = 38.0 + 24.5 + 15.0 = 77.5$$
$$E(B) = (.30)95 + (.60)70 + (.10)60 = 28.5 + 42.0 + 6.0 = 76.5,$$

and declare that System A is preferred. This preference reversal problem can be avoided by using interval or ratio scales for assessing utility when expected values will be calculated.

HIGH NUMBERS SHOULD INDICATE PREFERENCE

Sometimes it is tempting to let the numerical value one (1) represent the most preferred option with higher numbers indicating lower preference. The appeal comes from the apparent consistency of the most preferred alternative (first priority or priority one) being assigned the numerical value of one. The problem occurs in generating ratio scales where the origin indicates the absence of a characteristic or attribute. Assuming that "some large value" represents this origin, it is intuitively unappealing. The preferred convention is for higher numbers to indicate increased preference.

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