EVALUATING EFFECTIVENESS OF DECISION SUPPORT SYSTEMS

UP 79-4

Submitted to:

Dr. Stanley Halpin, PERI-OS
Army Research Institute
5001 Eisenhower Avenue
Alexandria, Virginia 22333

May 1979

INTEGRATED SCIENCES CORPORATION
Santa Monica, California

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By:

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1640 Fifth Street
Santa Monica, California 90401

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1.0 INTRODUCTION

1.1 OBJECTIVES AND PROPOSAL ORGANIZATION

Many military decision support systems (DSS's) have been developed during the past decade but few studies have been undertaken to determine their worth. There has been virtually no work aimed at developing standardized measures of effectiveness and standardized types of experiments for comparing decisions made with and without DSS's. This is a proposal for a two-year program to develop tools for evaluating DSS's and to identify the types of military decisions that can benefit most from a DSS.

The specific objectives of the two-year program are:

1. Develop theoretical foundations for the quantitative evaluation of DSS's including the specification of verifiable hypotheses and the development of objective performance measures.

2. Develop generalizable experimental procedures for establishing the quantitative benefit of DSS's to decision makers in terms of (a) expected performance improvement over unaided decisions, (b) user time required to make good decisions, and (c) training and experience levels required to make good decisions using DSS's.

3. Develop a taxonomy of types of military decisions that can benefit most from application of DSS's and criteria for incorporation of DSS's into current military operational and training programs and systems.

The remainder of Section 1 of the proposal presents an overview of the program. Section 2 describes the technical approach in detail. Program schedules, a milestone chart, and a list of deliverables are presented in Section 3. Section 4 presents an overview of the management and qualifications of ISC to perform the prescribed tasks. References appear in Section 5. The Appendices include two papers describing research pertaining to the decision support system philosophy that is relevant to the proposed work.

1.2 BACKGROUND

The problem of subjecting decision-aiding techniques to operational tests, especially when value judgments are employed, has haunted the Decision-Analysis community since its formation and no satisfactory solution has yet been agreed upon. (Some of the basic difficulties in administering such tests are discussed in Appendices 1 and 2 which also contain conceptual solutions to this problem via a pragmatic interpretation of value judgments.) The decision support systems that are the object and focus of the proposed program are computerized aids that help a decision maker with two major functions: (1) problem structuring and (2) alternative evaluation and selection. Systems that only help organize, compute, and display data are "informational aids" in the sense that they provide the necessary background for a decision, but do not address directly the decision process itself. Further, the types of problems that decision support systems address are usually perceived by the user to consist of a complex network of relationships with variable and uncertain strengths. The final product is a recommendation for the selection of a particular course of action or a strategy plan, rather than a numerical output. Decision support systems are usually built to satisfy fuzzy or inexact criteria, which may even change during the decision process.

One of the primary features of the decision support system approach is the requirement for the decisionmaker to decompose his decision problem into component parts including consideration of:

- Relevant problem details
- Important related issues
- Possible side effects

This is called "problem structuring." It is usually assumed by decision analysts that the problem structuring process of forcing the decisionmaker to consider one aspect of the problem at a time and articulate his judgments regarding each aspect, leads to better overall decisions when these judgments are aggregated by mechanical means. In a DSS, the one-at-a-time judgments made

by the user are usually in the form of utilities and probabilities. The computer can quickly combine the local numerical judgments into a global recommendation.

One of the major areas of research and experimentation is based on this conjecture: better decisions are made from a series of local judgments that are mathematically aggregated than those obtained by letting the decisionmaker exercise global judgments. Leal (Reference 1) has shown that in cases of team decisionmaking, groups not only formulate a rich set of decision alternatives when using a structuring aid, but also tend to focus their attention on the more critical issues. Armstrong (Reference 2) has shown that estimates of factual quantities produced by decomposition were more valid in most cases than those obtained by direct assessments. However, Dalkey (Reference 3) has shown in experiments that, in certain cases, decisionmakers actually perform better when making global judgments than when considering problem details. Thus, there is no clear criterion for determining when a problem structuring function of a decision sypport system will help or actually hinder a decisionmaker.

1.3 OVERVIEW OF TECHNICAL APPROACH

The first step toward developing tools for evaluating the merit and beneficial application of DSS's is to construct the theoretical foundations for objective evaluation. This involves establishing:

1. Verifiable hypotheses of decision system merit.

2. Quantitative performance measures for comprehensive comparative evaluation of DSS and unaided decisionmaking.

The hypotheses link the problem structuring techniques with their effects on the performance of the decisionmaker. Once established, they form the basis for the experimental plan and the specification of criteria for deciding when DSS's are useful. The quantitative performance measures enable controlled experimentation to be directed toward the satisfaction of DSS evaluation objectives. Examples of numerical measures for judging the effectiveness of DSS's and unaided systems include:

- Decision Quality
- Judgment Consistency
- Judgment Validity
- Decision Time

These measures and others will form the basis for the methodology and guidelines for DSS evaluation and effectiveness criteria.

A simulated decision environment is necessary in order to generate experimental values of performance measures such as those mentioned above. One of the most important elements of the environment is the existence of a "correct" answer to a specific decision problem. In the absence of an agreed "correct" answer, DSS evaluations have so far been limited to experts' assessments of decision quality. Additional background and theoretical basis for the correct answer requirement are given in Subsection 2.5.

The major work in developing a DSS test bed will be construction of a "scenario generator." The scenario generator is computer software that sets up the experimentation environment in order to get the most information about the DSS performance measures of interest. By varying generator parameters, different environments can be simulated to obtain data on specified measures.

The scenario generator will enable a series of controlled experiments to be performed that will determine the relative merits of several decision systems as well as determine the kinds of applications where each type of decision system can be most beneficially used. Decision performance will be monitored and measured in situations involving decisionmaking with support and without support. Performance measures will be made all along the subject's learning curve from first acquaintance with the simulation environment to experienced usage gained from repeated trials. A candidate scenario generator based on ongoing work at ISC is described in Section 2.2.

The final results from experimental data analysis will, in addition to providing a comprehensive picture of the merit of decision support systems, form a basis for a general methodology for the evaluation and application of

future decision aids and support systems. This methodology can be applied to existing military operational aids as well as to training systems to allow objective judgments of their benefit and effectiveness.

2.0 TECHNICAL APPROACH

This section presents a description of the proposed technical approach to evaluating the effectiveness of military decision support systems. The major elements of the approach are (1) theoretical foundations, (2) scenario generator, (3) evaluation measures and data analysis, and (4) evaluation experiments.

2.1 THEORETICAL FOUNDATIONS

Before meaningful experimentation and methodology development can take place, a firm foundation for decision support system evaluation must be established. This foundation will consist of several basic verifiable hypotheses which are related to the benefits and applications of decision support systems. The hypotheses will serve to direct the construction of the simulated evaluation environment.

As an illustration of a typical verifiable hypothesis, one of the objectives of the program will be to test the hypothesis that "the most benefit from decision support systems is to be gained in the middle of the learning curve." Figure 1 shows two superimposed curves. The dotted line is the expected learning curve of a typical subject during the course of an experiment with a given task. Near the beginning, his progress is slow due to his unfamiliarity with the simulation environment. As his experience increases, he is able to progress at a faster rate because he has acquired means of classifying and interpreting new experiences. Finally, small improvements can still be made by "fine-tuning" the parameters of his developed conceptual framework.

The solid line in the figure represents what we believe to be the potential help that a decision support system can give the subject during his progress on a large class of decision tasks. Near the beginning of the interaction, the subject will be using most of his mental powers to become aware of the possible decision alternatives available to him and their impact on the environment and on the subject's perceived utility. A decision support structuring aid cannot be of much help since he has not yet formed a mental

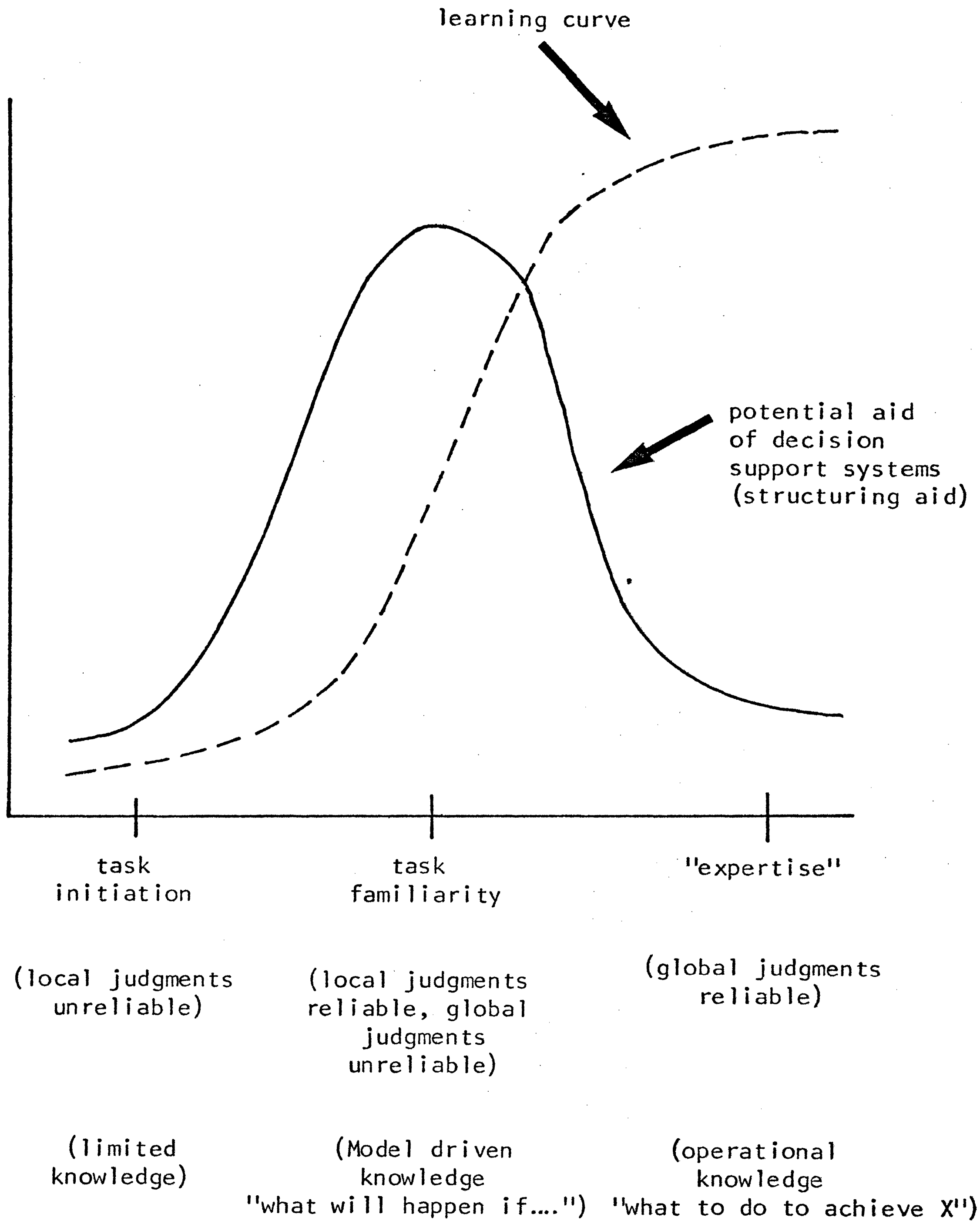

Figure 1. Potential Aid of Decision Support Systems.

picture of relevant relationships which govern the environment. Consequently, the local judgments he would be asked to issue are bound to be unreliable, resulting in error accumulation through the aggregation process and an inferior overall performance.

The peak of improvement with a decision support system should occur after enough task familiarity has been gained to produce reliable models of segments of the task domain. However, the subject does not yet have the wealth of experience which will allow him to make reliable global or operational judgments. Thus, a structuring aid that provides computational aggregation of local judgments will be of great benefit.

Near the end of the learning curve, the subject typically attains a level of "expertise" in the area and, drawing from his experience, is able to make reliable global judgments without the need to decompose the decision problem. We may picture the final phase of the skill acquisition process as a transformation (e.g., recompilation) of the user's knowledge representation (e.g., data structure). In intermediate phases his knowledge can be regarded as fragmented chunks of factual, declarative relationships, for example, "If action X, then usually effect Y." The format in the final phase is goal-driven and procedural. For example, "To achieve effect Y, do X' or, if Z is observable, do X." According to this model of format transformation, the benefit of a structuring aid should decrease at the final phases of skill acquisition. It may be the case that in such circumstances, an aid will actually hinder the decision maker in achieving a high level of performance. This hypothesis remains to be tested. It is through these and other verifiable hypotheses, that we hope to identify areas where decision support systems could be utilized effectively.

2.2 SCENARIO GENERATOR

An ideal environment for exercising the experiments proposed is a military simulation game. These games are driven by a model which contain a 'ground truth' defined by an optimal winning strategy. The rudimentary elements for creating such an environment exist within a simulation model that has been developed at ISC under Contract MDA903-78-C-2012. The ISC

simulation is called TOMM (Tactical On-Line Maneuver Modeling). The TOMM user interactively exercises the simulation by means of a function keyboard and trackball while sitting at a four-color, vector graphics display. The user sets up and plays out a division-level scenario. He is responsible for sketching terrain highlights of interest and defining opposing orders of battle. He specifies unit movements for both sides and, on request, the computer shows dynamic replays of these movements with likely sightings and engagements. The user can call for displays of detection and area of battlefield effectiveness contours for each unit type and size based on computer calculations. TOMM's displays assist the user in determining reasonable travel routes, travel speeds, and tactical outcomes of potential engagements. Thus the TOMM user can analyze alternative tactical situations thereby gaining reasonable answers to "what if?" questions.

The "scenario generator" will be a modified version of TOMM with the following capabilities:

- Controllable decision objectives and goals
- Controllable environment and initial conditions
- Situation description generator

By assigning values to a given set of parameters, the experimenter would determine the nature of the ~~mission objectives and the~~ constraints of the simulated environment. The assigned objective parameters would be translated into both a mathematical scoring function and a linguistic description (briefing) of the goals and their implications. Subjects will be given the time to study this description prior to commencing the game and, in addition, will be provided with performance feedback information at various stages during the game. The environmental constraint parameters would determine terrain-conditions, capability limitations, probabilistic cause-effect relationships, etc. Some of these constraints will be displayed to the user at the onset of the experiment (e.g., terrain conditions). Others would have to be <u>learned</u> by the user by repeated experiences (e.g., probability of being detected). A built-in situation description generator, which is model-driven, will present the user with graphic and textual information about the current situation, and will be updated as more information becomes available. The situation description generator

will be driven by a probabilistic "intelligence report simulator." The latter will receive as its input the actual environmental variables (weapon capabilities, troop movements, etc.) and translate those into a set of linguistic statements via a well controlled, noisy channel. This can be easily implemented by first passing the input variables through a conditional probability metrix to determine the type and likelihoods of observational data obtained. The transformed data is then described in linguistic terms. These descriptions can be controlled along a number of experimental dimensions:

- Amount of information presented
- Information accuracy (noise)
- Presentation format (probabilities, curves, maps, etc.)
- Timeliness of information (age)
- Level of detail of information

The scenario generator will have each of these dimensions formalized so that an experimenter can simply specify the values of key parameters to achieve certain global effects.

2.3 EVALUATION MEASURES AND DATA ANALYSIS

The selected evaluation measures must conform to the following requirements:

1. They must be quantitative with outcomes falling within a well-defined numerical scale. It is only through numerical comparisons that an objective measure of the effectiveness of decision support systems can be gained. "Expert Opinion" and "User Satisfaction," while valuable, can only give general indications of effectiveness and not the conclusive and reliable results that scientists usually require.

2. They must adhere to the general objectives of the evaluation plan. Evaluation measures, derived from established military evaluation objectives, will insure that meaningful guidelines and methodology can be generated for future evaluation applications.

3. They must be general enough to apply to a wide variation in circumstances, scenarios, and decision support systems.

The evaluation measures briefly described below are typical of those from which the selection will be made.

2.3.1 Decision Quality

Decision quality refers to the expected improvement in performance through use of a DSS. This improvement can be measured by comparing the performance score in similar experiments with and without the use of a DSS. This measurement, taken at key places along the learning curve will provide valuable information pertaining to the potential application points of DSS's.

2.3.2 Judgment Consistency

A disagreement between directly elicited judgments (both normative and factual) and those derivable from other judgments clearly indicates (a) a deficiency in mental manipulation and (b) areas of potential benefit for DSS applications. The formalization of a standard measure of consistency, across a large number of situations and judgments would be a valuable tool for assessing the quality of DSS methodologies. However, the elimination of inconsistencies (e.g., by ignoring a particular set of judgments in favor of another) would not, by itself, guarantee an increase in decision quality. The latter would be more directly measured by the concept of "validity."

2.3.3 Judgment Validity

Judgment validity measures the degree to which a pronounced judgment faithfully represents the subject's experience. For example, the validity of an estimate of a particular event probability is measured by the proximity of that estimate to the actual likelihood of that event as dictated by the physical or mathematical model which drives the (simulated) environment. Similarly, the validity of value judgments would be determined by how close these judgments are to the actual (maximal) expected score achievable within a given environment.

2.3.4 Decision Time

Structuring aids generally have a tendency to require a significant amount of time for use. It is possible to measure whether or not this time

expenditure is justified by the improvement in decision qulaity. We propose to derive a relation between the degree of structural details and the quality of resultant decisions. This relationship would enable us to formulate which level of detail would be most warranted for a given type of problem and expertise.

2.4 EVALUATION EXPERIMENTS

The essential principle underlying the evaluation method is that operational tests ought to be performed in an environment which is tightly controlled by and thoroughly known to the evaluator. The merit of any decision plan produced by the aided user could then be measured and compared with an objective measure (colloquially called the 'ground truth') of quality. To meet these requirements we envision the following test program: two computer programs would participate in the evaluation test, an environment simulator (scenario generator) and a decision support system.

The simulated environment program contains a well defined mathematical model of some stochastic, military problem domain. Any given choice of the parameters governing the mathematical model would result in a linguistic description of a scenario characterizing the behavior of the environment in the past, as well as its reaction to the user's decisions. The user would be given a reasonable length of time to interact with this simulated environment and to form a mental picture of the fabric of relations (heuristic model) which determines the environment's behavior. This mental picture need not have any similarity to the mathematical model which drives the simulated environment. However, any decision enacted by the user would result in a well defined (stochastic or deterministic) reaction of the environment to the decision. Part of the environmental model is a formula determining the user's score for any combination of factors which may prevail in the environment. (For example, user score might be expected military positional and/or material advantage at the end of a two-day peroid.) Consequently, any decision enacted by the user can be assigned a numerical value conditioned upon his most recent action and calculated on the basis of the known probabilistic parameters of the mathematical model. This objective value (utility) is occasionally displayed to the

user in the training phase, and is also the function which the user attempts to maximize using the mental picture formed so far.

The operational merit of a given decision-support system is measured with phased experiemtns. Once the user obtains a given level of familiarity with the environment (as indicated by the score for his unaided decisions), he will be offered the use of the aiding tools contained in the support system. His score with and without the aids will then be compared.

Note that this scheme, the measured quality of the aiding technique is made up of three distinct activities: (1) the ability of the user to form a faithful picture of the simulated environment, (2) the user's ability to articulate his perceived picture in the format provided by the aiding machine, and (3) the ability of the machine to manipulate the information provided by the user and come up with a reasonable recommendation. Note also that the user's ability to discover the underlying utility function imposed by the model is as importatn as his ability to decipher the factual cause-effect relationship within the environment (see Appendix B). All these elements are importatn components in any real-life decisionmaking situation, and ought, therefore, to be part of the evaluation program. Moreover, having a well-defined mathematical model would enable us to evaluate some of these components separately. Fro instance, a decision-aiding tool might be found useful in eliciting factual-knowledge but deficient in eliciting values.

3.0 PROGRAM IMPLEMENTATION

3.1 OVERVIEW

The general objectives of the proposed program were stated in Section 1. This section deals with the proposed program schedules, the program tasks, and the projected project deliverables.

3.2 PROGRAM PLAN

The proposed program plan is for a two-year phased effort involving theoretical research and development, test bed implementation, evaluation experiments, data evaluation, and evaluation methodology development. The following subsections describe these phases in detail.

3.2.1 First Year

The phases of the first-year effort are the following:

1. Develop theoretical foundations, establish verifiable hypotheses, and establish quantitative performance measures.

2. Select a suitable military application area and design the scenario generator for the simulated experimental environment.

3. Implement the scenario generator test bed at the ISC facilities using graphic display capabilities.

4. Establish criteria for decision support system application and a taxonomy of evaluatable military operational tasks.

3.2.2 Second Year

The phases of the second-year effort are the following:

1. Select or develop a suitable decision support system for evaluation and perform any necessary scenario generator integration tasks.

2. Design and conduct controlled evaluation experiments according to a prescribed experimental plan.

3. Analyze and evaluate the experimental data and provide conclusions about decision support system merit based on the experimental results.

4. Develop decision support system evaluation methodology for application to related military aiding systems.

3.3 MILESTONE CHART

Table 1 shows a milestone chart for the first year program phases and denotes the major deliverable dates beginning with the first month after date of contract (ADC).

3.4 DELIVERABLES

The following four deliverables are projected for the proposed first-year effort.

1. Theoretical Foundations Report - Describes all verifiable hypotheses, performance measures, and preliminary experimental plan.

2. Scenario Generator Design Report - Describes detailed design of scenario generator program and includes implementation plan and program specifications.

3. Progress Report on Scenario Generator Program Implementation - Describes three-months progress on program implementation.

4. Final Report - A summary of all work completed during the first year.

3,5 STAFFING

ISC has assembled a highly qualified team to perform the proposed work. The team will be directed by Dr. Antonio Leal. Dr. Leal will be responsible for liaison and for ensuring that the terms of the proposed contract are met. All technical products will be reviewed by him to ensure that they are technically sound and are responsive to customer requirements.

ISC will also use the consulting service of Dr. Judea Pearl, Professor of Engineering at UCLA. Dr. Pearl's expertise in decision analysis, pattern recognition, and computer methods of representing complex problems to decision-makers will be extremely valuable to the project.

1. Theoretical Foundations

2. Scenario Generator Design

3. Scenario Generator Implementation

4. Application Taxonomy And Criteria

Deliverables

1. Theoretical Concepts Report

2. Scenario Generator Design Report

3. Progress Report on Scenario Generator Program Implementation

4. Final Report

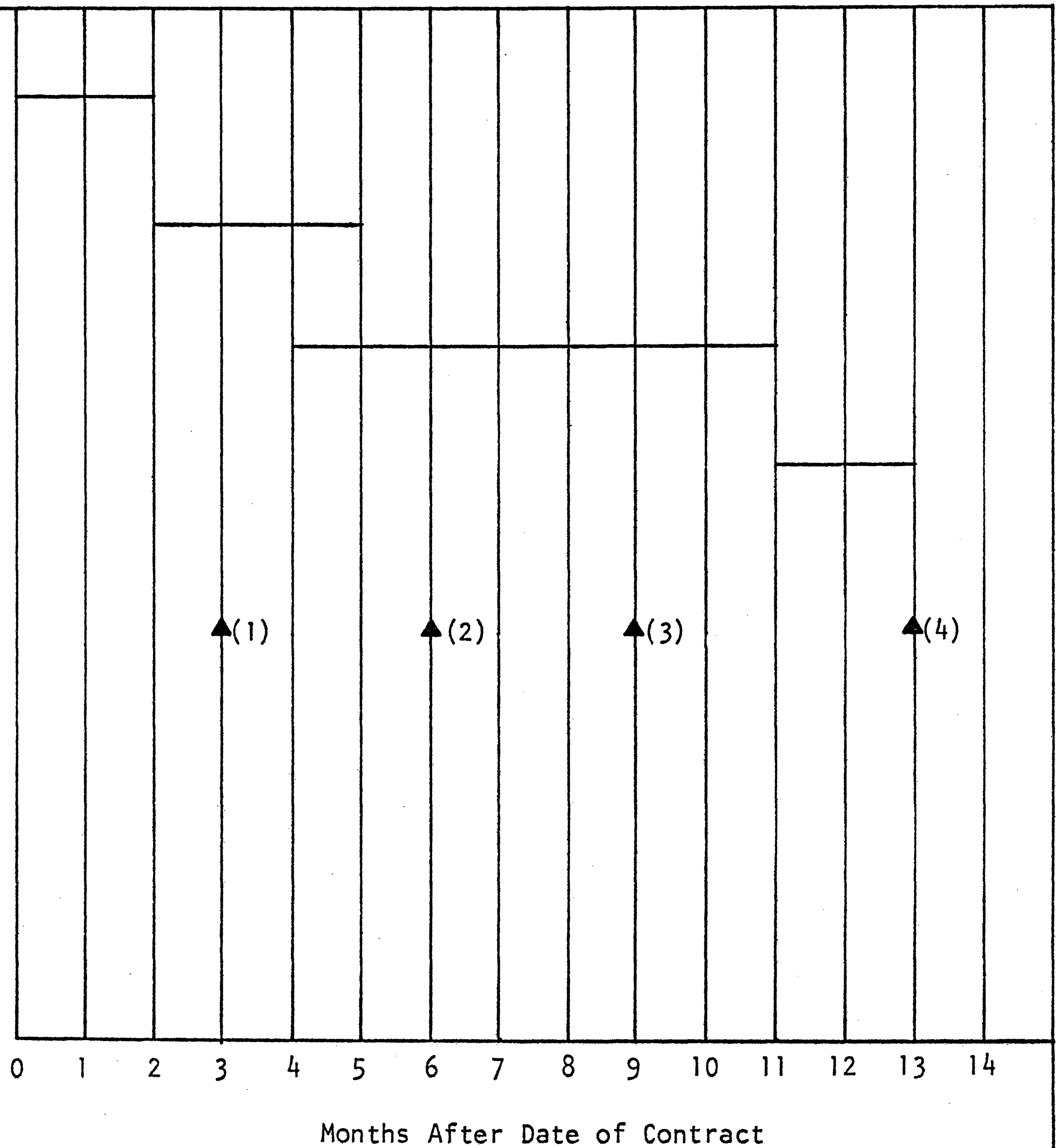

Table 1. Milestone Chart.

STAFF BIOGRAPHIES

ANTONIO LEAL (Chief Scientist) Security Clearance: SECRET

B.A. in Mathematics, University of Illinois
M.S. in Mathematics, University of Illinois
Ph.D., Computer-aided Decisionmaking

- Decision Analysis
- Pattern Recognition
- Artificial Intelligence
- Data Base Structuring
- Computer Language Design

Mr. Leal has twelve years of experience applying the principles of decision analysis and computer science to development of decision support systems and structuring of interactive data base systems. He has managed an Adaptive Information Systems group consisting of nine full-time professionals. Projects which he supervised include development of (1) interactive systems for group decision making, (2) adaptive decision-aiding for anti-submarine warfare, (3) applications of artificial intelligence and pattern recognition to ballistic missile defense, (4) applications of adaptive programming technology to military command group training and performance support, (5) knowledgeable opponent models for submarine tactics simulators, and (6) applications of adaptive systems technology to Marine battalion command functions. Systems developed during these projects have been implemented on the DEC PDP-11/45 under the UNIX operating system and on the IBM 5110 in APL. These were done for agencies of the Department of Defense including ARPA, ONR, ARI, NADC, NTEC, BMD/ATC and for JPL and NASA.

Dr. Leal has designed and developed a data base query language for logical access to relational data files. He developed and implemented methods to enhance programmer performance on large-scale APL systems. He has developed a hospital information processing system for the National Library of Medicine. Dr. Leal has devised and implemented a simulation of air defense warfare for the National Military Command System Support Center at the Pentagon.

Dr. Leal's research in artificial intelligence has focused on (1) natural language processing and data base question-answering systems,

(2) high-level computer Language design and interpreter implementation, (3) computer-aided planning systems with test and evaluation studies in cognitive processes and learning.

RELEVANT REPORTS AND PUBLICATIONS

Leal, A., Levin, S., Johnston, S., Agmon, M., Weltman, G. An Interactive Computer Aiding System for Group Decision Making. Report No. PQTR-1046-78-2, Perceptronics, Woodland Hills, California, February 1978.

Leal, A., Shaket, E., Gardiner, P., Freedy, A. Studies and Applications of Adaptive Decision Aiding in Anti-Submarine Warfare. Catalog of Selected Documents in Psychology, American Psychological Association, Vol. 7, Nov. 1977, p. 125.

Leal, A. and Pearl, J. "An Interactive Program for Conversational Elicitation of Decision Structures." IEEE Transactions on Systems, Man, and Cybernetics, Vol. SMC-7, No. 5, May 1977, pp. 368-376.

Leal, A. "Adaptive Decisions in Ballistic Missile Defense." IEEE Transactions on Systems, Man and Cybernetics, Vol. SMC-7, No. 5, May 1977, pp. 398-403.

Leal, A. An Interactive System for Conversational Elicitation of Decision Structures. School of Engineering and Applied Science, UCLA report UCLA-ENG-REP-7666 (Dissertation) June, 1976.

Burger, J. and Leal, A., "A Semantic-based Language Interface for Data Management Systems." Proceedings of the Eighth Hawaii International Conference on Science, January 1975.

BIOGRAPHY -- JUDEA PEARL

APRIL 1979

BIRTHDATE: 4 September 1936

DEGREES:	B.S.	(Electronics)	Technion, Israel	1960
	M.S.	(Electronics)	Newark College of Engineering Newark, New Jersey	1961
	M.S.	(Physics)	Rutgers University New Brunswick, New Jersey	1965
	Ph.D.	(Elec. Engr.)	Polytechnic Institute of Brooklyn Brooklyn, New York	1965

M.S. Thesis Title: "Electrical Conductivity of Blood in Motion"

Ph.D. Thesis Title: "Vortex Theory of Superconductive Memories"

PROFESSIONAL EXPERIENCE

New York University Medical School New York, New York	Research Engineer	1960-61
RCA Research Laboratories Princeton, New Jersey	Member of Technical Staff	1961-65
Electronic Memories, Inc. Hawthorne, California	Director, Advanced Memory Devices	1966-69

Consulting Activity

Data Industry, Hawthorne, California	11/69-12/69
Electronic Memories, Inc., Hawthorne, California	8/70-3/72
Rand Corporation, Santa Monica, California	4/73-Present
Jet Propulsion Laboratory, Pasadena, California	6/74-2/76
Integrated Sciences Corporation, Santa Monica, California	6/75-Present
Perceptronics, Inc., Woodland Hills, California	6/76-Present

TEACHING EXPERIENCE

Newark College of Engineering	Instructor	1961
University of California, Los Angeles		
Computer Science Department	Assistant Professor	7/69-6/70
Engineering Systems Department	Associate Professor	7/70-6/76
	Professor	7/76-Present

TEACHING EXPERIENCE (continued)

Courses Taught

Engr. M11	Patterns of Problem Solving
Engr. M12	Applied Patterns of Problem Solving
Engr. 100D	Information Processing Systems
Engr. 171A	Introduction to Feedback and Control Systems: Dynamic Systems Control I
Engr. 193A*	Engineering Probabilistics and Stochastics
Engr. 193B*	Engineering Statistics
Engr. 225D	Computer Memories and Memory Systems
Engr. 225M	Pattern Recognition
Engr. 271A	Dynamic Systems Optimal Control
Engr. 274A*	Problem Solving and Decision Making--P.S. I
Engr. 274B*	Problem Solving and Decision Making--P.S. II
Engr. 274C*	Computer Methods of Data-Analysis and Model-Formation

* Instructor-in-Charge

HONORS AND SPECIAL RECOGNITION RECEIVED

RCA Laboratories Achievement Award "for development of the Superconducting Parametric Amplifier"	1963
Performed the first experiment to prove the existence of the Magnus Force in superconductors, Electronic News, February 1966	1966
NATO Senior Fellowship in Science	1974
Pattern Recognition Society Award for an outstanding contribution to the Journal of Pattern Recognition (1976)	1978

FELLOWSHIPS AND RESEARCH GRANTS RECEIVED

Source	Amount	Purpose	Dates
ONR N00014-69-A-0200-4038	$ 30,000	Effectiveness of Orthogonal Transforms	10/1/71-9/30/73
NSF GJ 37329	$ 38,900	An Investigation of the Role of Representations in Problem Solving	3/1/73-8/31/74
NSF MCS 74-12208 A01 (formerly GJ 42732)	$ 78,000	An Investigation of the Role of Representations in Problem Solving	7/1/74-12/31/77
NAVY (N66001-75-C-0226)	$ 9,300	Adaptive Transforms in Signal Processing	6/1/75-12/1/75
NSF MCS 75-18734	$ 46,700	Investigating Computational Gains Using Partial Information	1/1/76-12/31/78
ONR N00014-78-C-0372	$ 72,014	A Goal-Directed Approach to Structuring Decision Problems	5/1/78-10/31/79
NSF MCS 78-07468	$156,705	An Investigation of the Role of Representations in Problem Solving	6/15/78-11/30/81
NSF MCS 78-18924	$ 68,751	Investigating Computational Gains Using Partial Information	2/15/79-1/31/82

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Pearl, J., "Distinctive Properties of Quantized Vortices in Superconducting Films," in Daunt, Edwards, Milford, and Yaqub (eds.), Low Temperature Physics-LT9, Plenum Press, New York, pp. 566-570, 1965.

Pearl, J., Andrews, H. C., and Pratt, W. K., "Performance Measures for Transform Data Coding," in H. C. Andrews (ed.), Tutorial and Selected Papers in Digital Image Processing, IEEE Computer Society, pp. 173-177, 1978.

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Liebman, F. M., Pearl, J., and Bagno, S., "The Electrical Conductance Properties of Blood in Motion," Physics in Medicine and Biology, Vol. 7, No. 2, pp. 177-194, October 1962.

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Pearl, J., "Electromagnetic Behavior of Thin-Film Structures," Journal of Applied Physics, Vol. 37, No. 8, pp. 2956-2963, July 1966.

Pearl, J., "Structure of Superconductive Vortices Near a Metal-Air Interface," Journal of Applied Physics, Vol. 37, No. 11, pp. 4139-4141, October 1966.

Pearl, J., "Field Distribution of Plated Wire Memory Elements and Its Effect on Memory Characteristics," IEEE Transactions on Magnetics, Vol. MAG-4, No. 3, p p. 366-371, September 1968.

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Pearl, J., "Application of Walsh Transform to Statistical Analysis," IEEE Transactions on Systems, Man and Cybernetics, Vol. SMC-1, No. 2, April 1971.

Pearl, J., "Walsh Processing of Random Signals," IEEE Transactions on Electromagnetic Compatibility, Vol. EMC-13, No. 3, August 1971.

Pearl, J., "Basis-Restricted Transformations and Performance Measures for Spectral Representations," IEEE Transactions on Information Theory, Vol. IT-17, No. 6, pp. 751-752, November 1971.

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Cryogenic Heat Pump Including a Magnetic Means for Moving a Normal Zone Along a Super-Conductive Rod	#3,393,526	July 23, 1968

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4.0 ISC QUALIFICATIONS

4.1 CORPORATE BACKGROUND

Integrated Sciences Corporation was established in 1967 by a group of experienced researchers to bring their diverse skills and backgrounds to bear on a wide range of governmental and industrial system problems. Company operations began with a staff of five professionals, on two government contracts. The company has grown steadily since that time, and over 170 contracts have been completed. The expertise of ISC personnel has been successfully applied to problems of military and civil systems, including energy, transportation and environmental planning. Research areas include work on:

- Mathematical Modeling and Simulation
- Computer Graphics and Display Engineering
- Man-Machine Interface Design
- Conceptual and Functional Design of Technological Systems
- Decision Support Systems
- Test/Experiment Design and Statistical Analysis of Data
- Econometric and Cost Effectiveness Analysis
- Program Planning and Monitoring
- Applications of Systems Analysis and Operations Research Techniques
- Analysis of Management Planning Decision Systems

Much of ISC's past work has resulted from referrals by satisfied customers. Clients whom we have served include the Naval Ocean Systems Center, Hawaii and San Diego Laboratories; the Office of Naval Research; the Army Research Institute; the Naval Underwater Systems Center; the Naval Material Command; the Naval Sea Systems Command; the Naval Ship Engineering Center; the Naval Underwater Systems Center; and the Naval Coastal Systems Center, Panama City.

ISC's full-time professional staff currently consists of engineers, scientists, mathematicians, computer programmers, and experimental psychologists. Work is currently in process on fifteen contracts for different government agencies. A sample of current and recent work performed by ISC is given below:

- Development and experimental evaluation of algorithms and man-machine interfaces that aid Naval task force commanders in selecting optimum tactics for penetrating enemy defenses.

- Development of interactive graphics software and man-machine interfaces used by an Army field commander to simulate hypothesized enemy tactics. This aid enables the user to test his hypotheses of enemy tactics against observed intelligence data.

- Applied research to investigate the benefits of color-coded displays and related fire control algorithms for a new submarine combat system. Includes simulation of the combat system on ISC's Simulation and Display Facility equipment and the running of a human factors experiment.

- Performance evaluation, through computer modeling and simulation, of several new, terminally guided, high rate, neutralizer concepts for countering ocean mines.

- Development and use of a computerized model that simulates swimmer attacks against assets defended by multiple sensors and weapons.

- Design of a display interface between an operator and a computer that processes data from elements of a complex defense system.

- Development of a proprietary new method for using standard sonar outputs to construct target images for deep ocean sonar systems. Includes simulation of the sonar's performance and the operation of the image construction and tracking algorithm.

- Development of an analytic method for using group subjective judgment data to prioritize exploratory development budgets. Included is the design of interactive graphics (computer) software enabling managers to use the stored subjective judgment data to explore the consequences of alternative funding allocation philosophies.

- Development and use of a computerized search/theoretical model to optimize the search strategy of a system seeking underwater targets.

- Economic and operations analysis of alternative concepts for growing kelp in the open ocean, harvesting and processing the kelp into natural gas and other products. Includes economic evaluations of subsystems, analysis of transportation trade-offs and system design.

- Preparation of a comprehensive plan for a twenty-million-dollar marine biological sciences program.

- Formulation and use of a method for obtaining and using subjective judgment data on multiple and diverse evaluation factors to select the best of alternative systems.

4.2 MANAGEMENT APPROACH

ISC management believes that definition of complex problems and development of approaches for their solution require the application of several scientific disciplines—an integration of sciences with their respective fields of knowledge and technology. Therein lies the premise for our name and the basis for our management philosophy. We utilize the systems approach to problems. Careful consideration is given to all aspects of the subject system, interfacing systems and the environments within which the system must operate to insure that meaningful and useful solutions are obtained. Also, we are quite sensitive to the need for practical approaches and designs that consider both material and time constraints and limitations of resources.

Accordingly, at the beginning of a proposal effort, ISC's President designates as project/contract manager a professional with an established reputation in the subject area, and the ability to communicate effectively with the customer and lead project personnel. The contract manager subdivides the work into task areas and, subject to the President's concurrence, selects senior staff members with the skills and experience needed to lead work in each task area. The contract manager and task leaders organize a team with all necessary disciplines appropriately represented, and assignments are made on the basis of expertise, past experience, capability and project requirements.

In the first week of the contract, responsibilities and time schedules are detailed to ensure proper interface with other research projects. Task leaders maintain close contact with researchers, holding project meetings with all team members and briefings for the project manager about once every week, or more frequently if required.

Periodic meetings are scheduled with staff personnel and consultants to ensure proper orientation of effort at each stage of the research. This enables us to evaluate research plans and accomplishments of each task and make appropriate changes where necessary to avoid costly duplication and maintain a close orientation toward project goals.

In our research projects we maintain close contact with the sponsor's contract monitor to keep him apprised of all research developments and resolve any problems that may arise. The ISC contract manager assumes the primary responsibility for proper liaison with the contract monitor.

4.3 SIMULATION AND DISPLAY FACILITY (SDF)

ISC's computer and display facility at its new offices was designed for command and control research from the computer floor up to the separately dimmed lighting fixtures. The facility has 550 square feet of space and ISC uses a Varian 73 minicomputer and an IDIIOM four-color, refresh, vector graphics display as vehicles for performing research. A block diagram of the system is shown in Figure 2. The system is highly expandable at low cost per unit of increased capability. For example, the present computer/display interface equipment can support four displays identical in capability to the one ISC has now; the Varian can be expanded to 256K of core, time sharing software, and multi-processing. Further, the Varian machine has already been interfaced with a sophisticated color raster display system (RAMTEK), thus this capability is easy to add if desired. The Varian and the IDIIOM display are described below.

1. Varian 73

The Varian 73 minicomputer processes 16-bit words with a full cycle time of 660 nanoseconds for the core memory. The CPU contains 16 general purpose registers. Input/Output between the computer and the peripherals (other than the IDIIOM/II) is handled via the Direct Memory Access (DMA). This minimizes the burden placed on the CPU by the peripherals. IDIIOM/II input/output is accomplished via a dedicated Priority Memory Access (PMA) channel. The PMA transfers data between the memory and the display at over

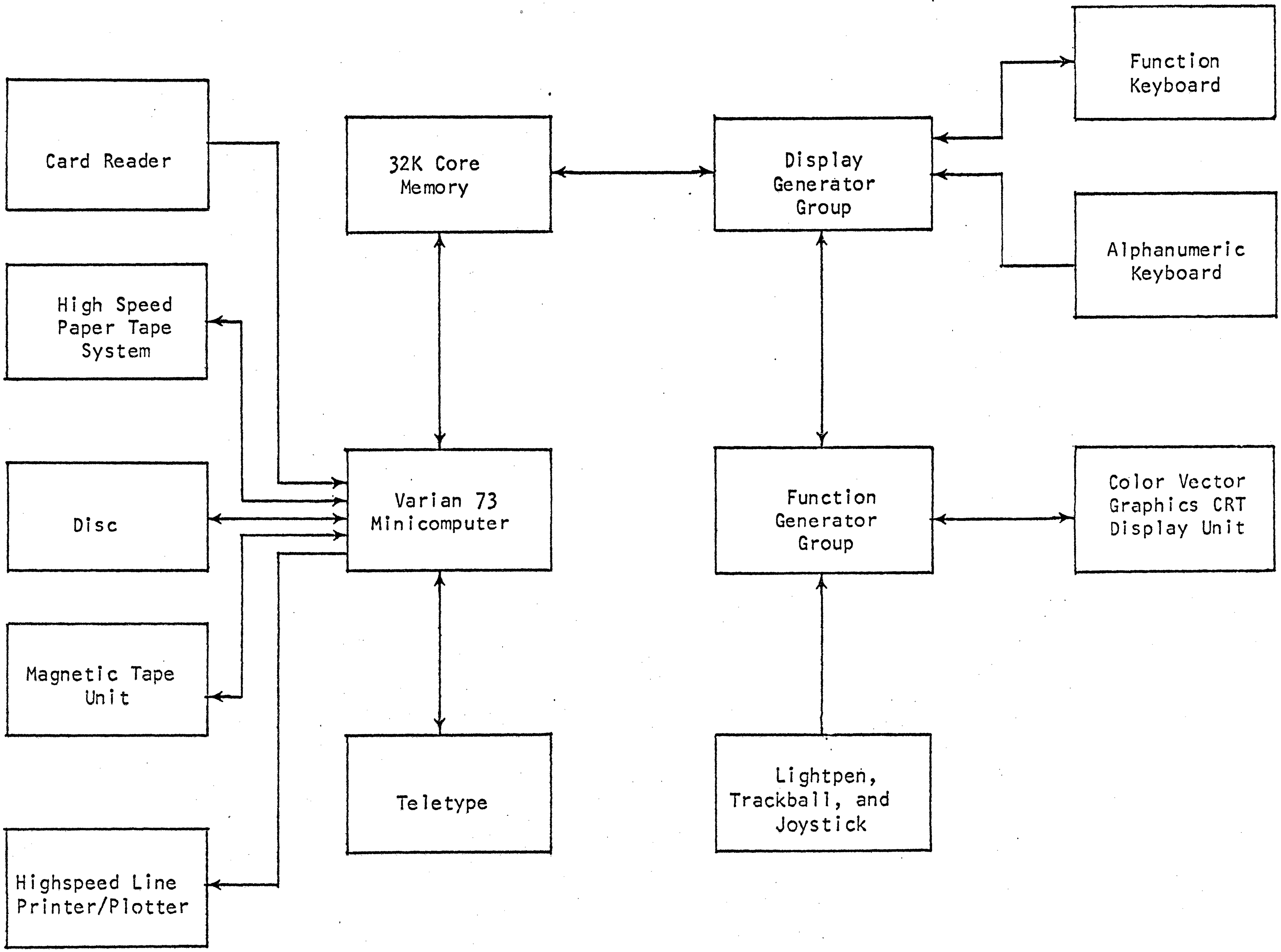

Figure 2. Hardware Configuration Diagram.

one million words/second. This precludes the data rate from interfering with display performance. The instruction set consists of 159 instructions, single and double word. The CPU features hardware multiply/divide and a real time clock. Eight levels of hardware priority interrupt are implemented (64 are possible).

2. Display Hardware

The IDIIOM/II display is a four-color, large-screen graphics system. The IDIIOM/II consists of a CRT along with its associated logic and control hardware. This system is driven by the Varian 73. The IDIIOM is highly interactive through the use of the light pen, trackball, joystick, function keyboard, and alphanumeric keyboard.

The IDIIOM/II uses a common core memory which can be independently and simultaneously accessed by two processors. One of these is the Central Processing Unit (CPU) of the minicomputer which acts as the Display Processor. The other processor is a special purpose Display Generator which is an integral part of the IDIIOM itself. The CRT is refreshed from this memory to provide a non-flickering display. About 6,600 characters, 5,500 short line segments, or 15,000 inches of long line segments can be displayed.

An additional capability is that of virtual display. This permits a display "universe" consisting of 4,096 "worlds" to be drawn. The display screen itself is one "world." The use of relative positioning allows the display window to be moved anywhere within these many "worlds."

Four intensity levels are also available under program control. Any graphic element can be blinked under program control. Four vector and circle line structures are available under program control: solid, dash, dot, and dash-dot. Also, characters can be rotated 90° counter-clockwise and plotted vertically under program control.

The CRT is a 21" diagonal penetron with a four color capability: red, orange, yellow, and green. The faceplate is HEA coated and etched for high contrast. The phosphor is P22. Average time to change color is fifteen µsec. Spot size is .015" to .025" depending upon intensity.

4.4 RELEVANT EXPERIENCE AND ON-GOING WORK

Integrated Sciences has specialized during the last five years in developing decision support systems that use:

- Interactive graphics software
- Simulation models, resource allocation algorithms, and weapon trajectory algorithms that are exercised interactively by decision makers at displays

ISC is on the cutting edge of the state-of-the-art in these areas. Despite ISC's modest size, several of its products in these areas are more sophisticated than similar products developed by the giants of the aerospace industry and the giants of the defense studies and analysis industry. We use our simulation and display facility (SDF) in the accomplishment of most of our work. Our SDF was established in 1974. It contains a Varian 73 minicomputer and a fully interactive, four-color, high speed IDIIOM II display system. The SDF was set up to support research and development for command and control systems.

This section summarizes major project experience relevant to the requirements of the RFP. Members of the proposed staff for the RADC work have directed or participated in each of the projects named. Subsections 3.1 through 3.8 are written so as to emphasize our experience in developing interactive graphics software, simulation models, resource allocation algorithms, and weapon trajectory algorithms. Function and task analysis of the kind required by the work statement were part of the work performed for each of these projects but function and task analysis were not the primary outputs of the work. Subsections 3.9 and 3.10 are summaries of projects for which function and task analysis were major products of our design work for complex systems.

4.4.1 Operational Decision Aids For Task Force Commanders

ISC has been working continuously for the Office of Naval Research under Contract N00014-75-C-0811 since March 1975 in the area of tactical decision aiding. The contract title is "Decision Aid Interface" and the value of the contract to date is $344,800. Under this contract ISC participates as

a member of the ONR Operational Decision Aids (ODA) team to investigate interactive computer graphics aids that a Naval task force commander can use in performing his functions in a real-time operational environment. The ONR contract monitor is Dr. Martin Tolcott (telephone: 202 - 696-4506).

ISC has already designed and experimentally evaluated three interactive graphics decision aids under this contract and is currently in the process of performing this same set of tasks for a fourth decision aid. In each case we have used UCLA students (mainly science and engineering students) as subjects in our simulation and display facility. One element of the work involved the implementation and experimental evaluation of an aid called "operator aided optimization" (OAO). This type of aid enables the user to make inputs to a machine which operates on the inputs and shows problem solutions derived from the inputs. The user and the machine work iteratively until the user is satisfied with the machine solution. Problems for which OAO is appropriate tend to have the following characteristics:

1. Solution space is of high dimensionality (e.g., ≥ 5);
2. Criterion function is nonlinear, and multi-modal, therefore the machine working alone may only find a local optimum instead of the global optimum.

The problem for which the ISC aids were constructed is the selection of (a) an air strike path through a field of ten enemy sensors and (b) aircraft speeds on each leg of the path. Utility of each candidate strike path was computed according to a predetermined utility function; the utility function was nonlinear and multi-modal. One of the ISC-designed aids uses a nonlinear programming (NP) algorithm; the other uses a dynamic programming (DP) algorithm. Figure 3 is a photograph of a typical CRT display format presented to the operator during the interactive solution process.

An experiment was designed by ISC to compare decision performance for both types of aids. Sixteen UCLA students solved problems with and without the aid and these data were compared. Subject data using the aids were also compared with the data resulting from using the algorithm in the automated mode. The principal findings from the experiment were:

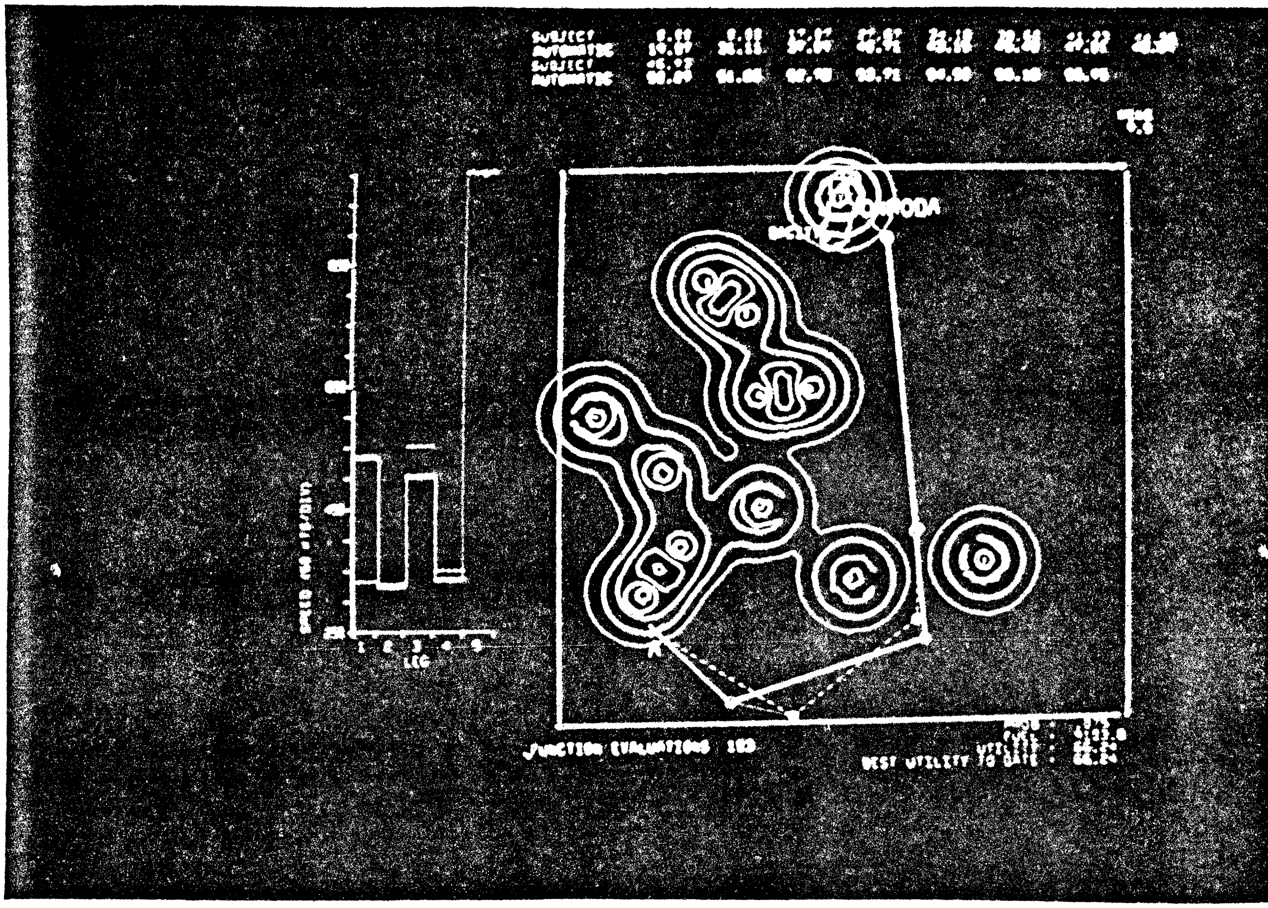

Figure 3. Typical Display Format Presented to Operator During the Interactive Solution Process for Defense Penetration Analysis for Carrier Air Strikes.

1. The operators using the NP aid did significantly better than without the aid. The average improvement across all subjects and trials was 29% with a range of 9% to 123%. Performance was significantly different across operators but this was solely for unaided operation. Thus the aid served as an "equalizer." It enabled operators having relatively low scores without the aid to do as well as those who had relatively high scores without the aid.
2. Operators using the DP aid did significantly better than without the aid. The average improvement across all subjects and trials was 12% with a range of 3.5% to 27%.
3. The lack of a technical education was apparently not an impediment to good performance with or without either aid. (Some of the operators did not have a technical education.)
4. The average time required to adequately train an operator to use either aid was about four hours.
5. A potential implication of the findings is that OAO is attractive to use when it is applicable because:

    a. The operator can see what is happening during the optimization. With pictorial problem representation, he can make adjustments to the optimization process or results to compensate for limitations in problem representation more easily than when there is no pictorial representation.
    b. The time required to train operators to use OAO with pictorial problem representation is apparently relatively short and does not require technical knowledge of the optimization algorithms.

4.4.2 Operator Aided Cruise Missile Trajectory Computation Technique

Under Contract N00140-78-C-6141 with the Naval Underwater Systems Center, Newport, Rhode Island, ISC performed research and analysis for developing new operator-aided cruise missile (CM) trajectory computation techniques for advanced underwater combat systems. The dollar amount of the contract was $55,000 and the contract monitor was Mr. Tony Bessacini, Code 3522 (telephone: 401 - 841-4576). The work was performed from December 1977 to December 1978.

The overwater control problem which is interactively solved by the aid we developed is stated as follows:

> Select a set of waypoints which will delineate a series of constant velocity cruise missile trajectory legs so that the cumulative probability of detection through a given field of sensors is minimized as the missile travels from its launch point to the landfall point.

The enemy sensor field which must be penetrated includes both stationary sensors and sensors whose locations are uncertain and therefore must be modeled by probability distributions. One important achievement of our work is that we were able to mathematically represent sensors with uncertain locations in a way that enabled the optimization algorithm to find the best penetration path in a computationally efficient way. (This is an exceptionally difficult problem which no one outside of ISC had solved up to the time that we did it.)

Our aid enables the operator to do the following using our interactive graphics display:

1. Enter a hypothetical track of future submarine movement and pick a potential future cruise missile launch point and a landfall point.
2. Sequentially use dynamic and nonlinear programming algorithms to find the best penetration trajectory from the chosen launch point. Our technique takes advantages of the strengths and avoids the weaknesses of each optimization type.

Figure 4 shows a field of seven stationary sensors, four of which are on a coastline and three of which are off the coastline. The rectangle represents a sensor whose position within the rectangle is uncertain. The four-segment path on the right side of the figure represents the submarine's potential future track. The hypothetical launch point is on the second leg of the submarine track, assuming that the ship is moving from south to north. The launch point is connected to the designated landfall point by an initial trial solution and the final optimum trajectory.

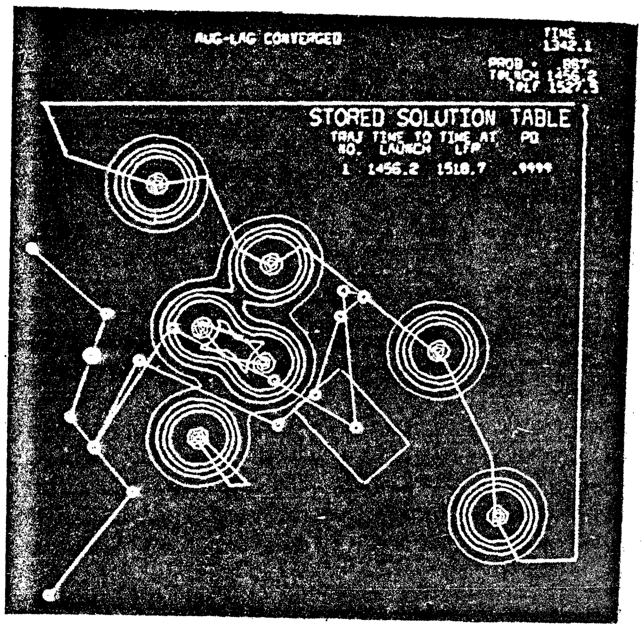

Figure 4. Scenario, Projected Own Ship Track, and Alternative Cruise Missile Trajectories to the Landfall Point.

4.4.3 Interactive Modeling of Army Battlefield Tactical Events (1977-1978 Contract)

ISC has been working for the Army Research Institute since April 1977 to develop interactive graphics aids for planning battlefield tactics. The work described in this subsection was done under Contract DAHC19-77-C-0022; contract value was $60,563 and the work was performed from April 1977 to February 1978. The contract monitor was Dr. Stanley Halpin (telephone: 202 - 274-9045).

We developed a modeling methodology, implemented it in software on our simulation and display facility, exercised the software, and carried out a preliminary evaluation of the methodology. The display software presented the operator/trainee with a geographical display of the battlefield area highlighting the relevant topographic and cultural features. In addition, the background software simulated the movement of actual enemy units as prescribed by a selected scenario containing a specific enemy order of battle. The actual enemy order of battle and movements were not shown to the operator. The operator/trainee selected the number, types, and routes of intelligence-gathering ground and air patrols. Then, as a function of the operator/trainee selected intelligence gathering tactics, a certain sequence of contact and observation reports was made available to him. From the sequence of reports generated by these patrols (which were determined by probabilistic detection and observation functions) the operator/trainee could interactively establish a hypothetical enemy order of battle and tactics scenario. In a real time context he could then evaluate his hypothetical solution so that it explained in the best way possible the continuing stream of intelligence reports input to him by the patrol units he deployed. This system is designed to evaluate the operator/trainee's ability to integrate a large amount of spatially and temporally varying data, and draw an accurate estimate of the enemy order of battle and disposition. Figure 5 presents a typical display shown to the operator/trainee during his analysis process. ISC has begun the second phase of this work for ARI; the new work is described in Subsection 4.4.4.

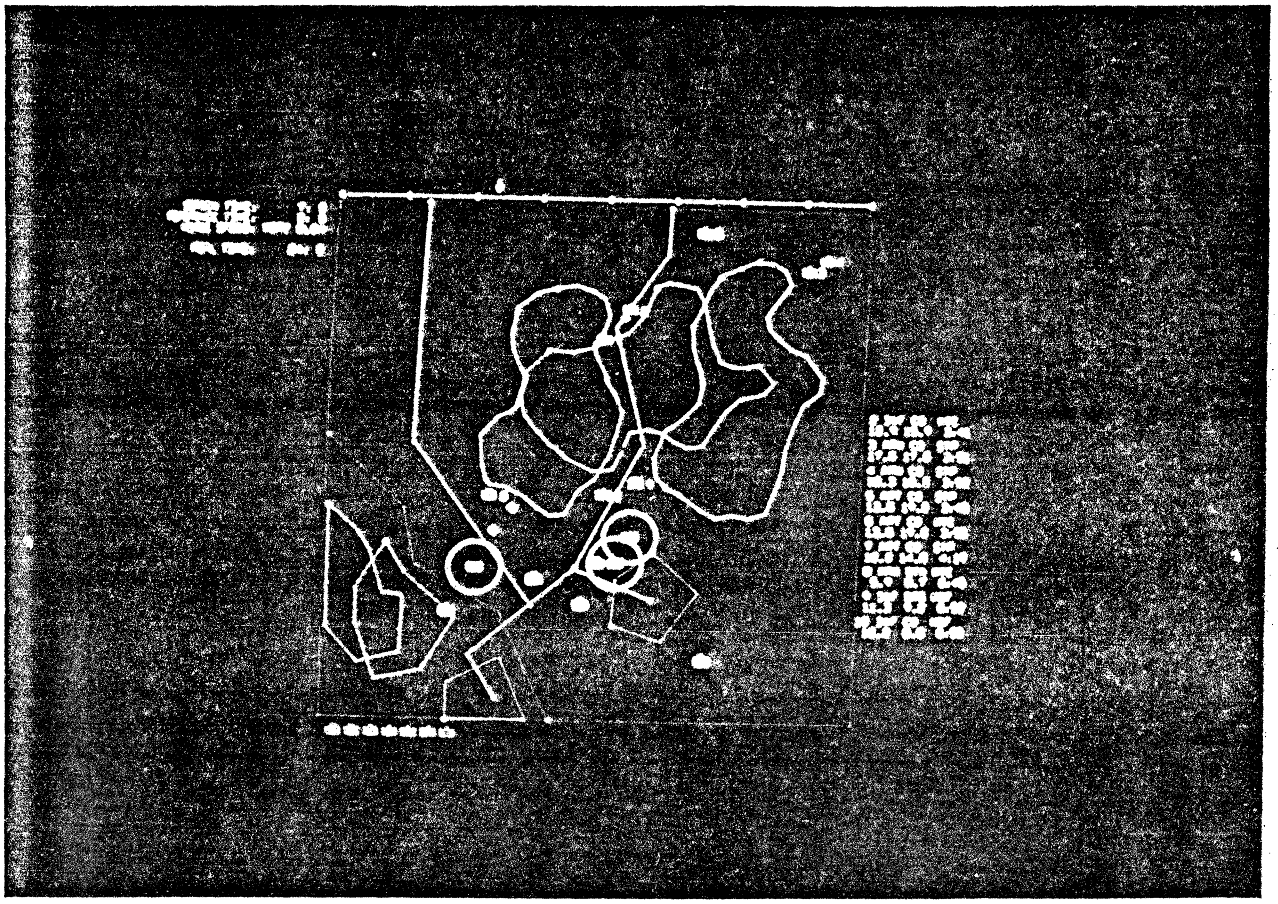

Figure 5. Typical CRT Display to Operator of Army Tactical Planning Aid.

4.4.4 Interactive Modeling of Army Battlefield Tactical Events (1978-1979 Contract)

The current Army Research Institute work is being done under contract MDA 903-78-C-2012; contract value is $66,984; contract term is July 1978 to July 1979. The contract monitor is Dr. Franklin Moses (telephone: 202 - 274-9045).

The system we are developing is called TOMM (Tactical On-Line Maneuver Modeling). Three elements of TOMM are being developed under the current contract. These are:

1. "Look-Ahead" Battlefield Model. This model enables the user to interactively define orders of battle for both sides, to designate a movement cluster of units and to move the cluster according to one of several predefined rules. The model also contains rules for detection and area of battlefield effectiveness (AOBE) of each unit type and size. The user can call routines to display detection and AOBE contours. The look-ahead model also simulates engagements and graphically displays engagement results. The model and man-machine interface are structured so that the user can rapidly analyze alternative tactical situations thereby obtaining reasonable answers to "what if?" questions.
2. Terrain Realism Model. The model allows the user to define forests, hills, cities, roads, lakes and rivers. Terrain mobility for each unit type is displayed in terms of GO, SLOW-GO, VERY SLOW-GO, and NO-GO regions as a function of the movement rate for the designated unit type.
3. Battlefield Representations. ISC is developing software that will display:

   (a) Static contours showing where units of given size/type can reach in future time when they start from a given place. Figure 6 indicates what this display will show.

   (b) Dynamic movement of a future-position contour.

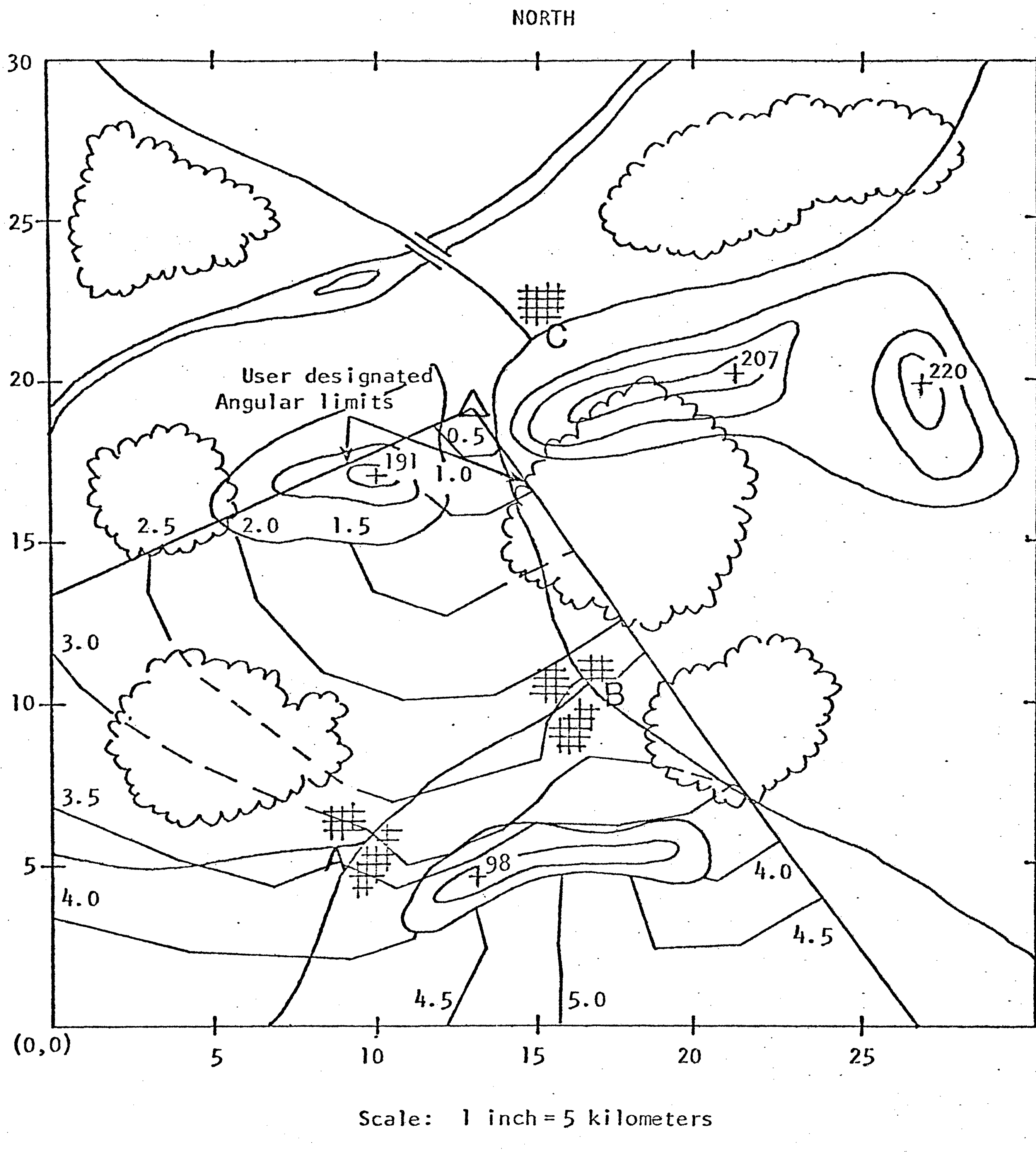

Figure 6. Display of Contours Showing a Designated Unit's Potential Future Positions.

4.4.5 Design and Test of An Interactive Computer Graphics System For Post-Launch Control of Submarine Launched Torpedoes

Under Contract N00140-76-C-6272 with the Naval Underwater Systems Center, Newport, Rhode Island, ISC designed, implemented and is now operating a complete Weapon Order Generator (WOG) console of a new submarine fire control system. The dollar value of the contract was $39,214; the work was done from December 1975 to January 1977. The contract monitor was Mr. Tony Bessacini, Code 3522 (telephone: 401 - 841-4576).

The WOG portion of the overall FCS is instrumented in the ISC Simulation and Display Facility and includes all the support software to simulate the FCS informational environment and on-line measurement performance data. The simulation calculates and continuously displays data in graphic and alphanumeric formats on the following target submarine and own-torpedo variables as they change during a problem: position, course and speed in three dimensions. The values of the displayed variables differ from the "true" values by errors that would be present in a real encounter.

An experiment was conducted. Each subject's task (there were seven subjects) was to control the torpedo in 72 trials in which the following were varied:

- Weapon control mode (2 levels, Corrected Intercept and Bearing Rider)
- Man-Machine interface design (2 levels, monochromatic and four-color)
- Target-to-torpedo geometries (3 levels).

A set of critical operator decisions and system parameters was automatically recorded by the computer as each trial progressed. A five-way analysis of variance was performed on the effects of weapon control mode, MMI design, target-to-torpedo geometries, subjects, and replications on system performance. One conclusion of the study is that use of color displays improves system performance in some situations and degrades performance in others. Therefore, system designers should not use color indiscriminately.

Figure 7 shows the display format during execution of interactive control of the simulated torpedo. The line emanating from the right center of the screen is the current estimated bearing to the target. The rectangle bisected by the bearing line represents $\pm 1\sigma$ estimated error in the Kalman filter solution for the submarine's location. The current estimated target location is at the center of the rectangle and estimated target course and speed is the vector emanating from this point. The ten most recent estimated target locations are the dots in and around the rectangle. The torpedo is shown as a triangle which represents the ensonification region of the torpedo's sonar. In the picture the torpedo is on an intercept course toward the target; the three most recently calculated intercept points are represented by "I's." The torpedo's ten most recent positions are shown as an almost-straight-line string of dots behind the torpedo. The alphanumeric information at the top and right side of the display is used by the operator to decide when to change torpedo course and when to turn on the torpedo's homing sonar.

4.4.6 System Interactive Performance Evaluator

A system interactive performance evaluator (SIPE) was developed to aid in the analysis and design of a new area defense system for the Naval Sea Systems Command (NAVSEA 03). This work was done under a series of contracts, namely:

- N61339-73-C-0123, $62,920, May 1973 to July 1974 for the Naval Coastal Systems Center (NCSC)
- N61339-74-C-0087, $71,178, March 1974 to March 1975 for NCSC
- N00024-75-C-4055, $112,526, November 1974 to July 1976 for NAVSEA

The program monitor for this work was Mr. Bill Welsh, Code 03424 (telephone: 202 - 692-1192).

Two versions of SIPE were developed. One version was primarily used in the development of a system to defend against combat swimmer attack. The second version was developed for a large scale coastal defense system whose threat spectrum included surface craft, cruise missiles, and submarines. Both versions allowed the input of detailed probability distributions which specified both the spatial and the temporal performances of individual system

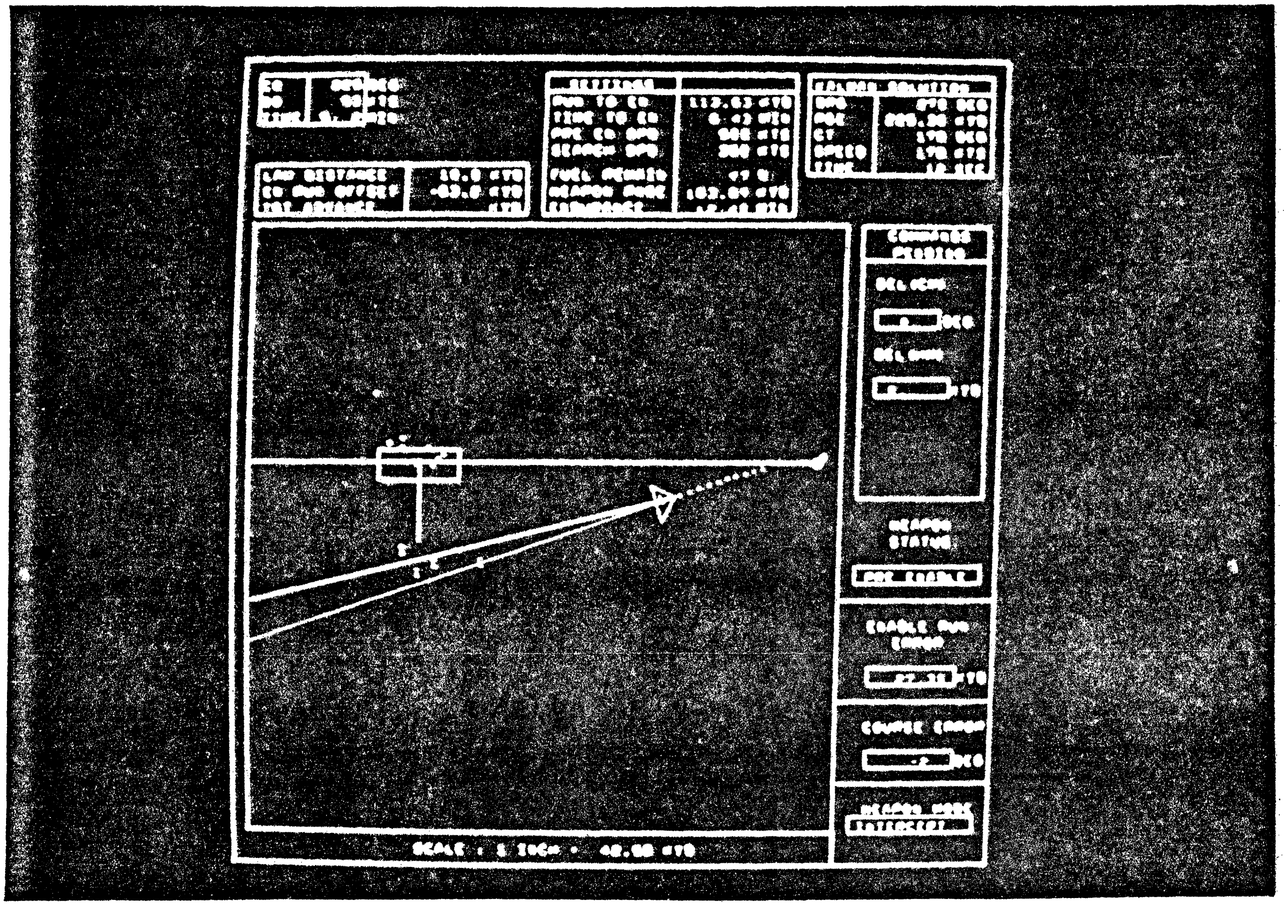

Figure 7. Display Format During Execution of Interactive Control of Simulated Torpedo.

elements (sensors, decision elements, and countermeasures/neutralization subsystems). Once deployed, the simulator would operate against targets which advanced along complex, input-specified trajectories. For instance, in the swimmer case, not only the horizon plane trajectory of the swimmer could be specified, but also the swimmer's vertical trajectory. This made the swimmer visible to various sensors with different degrees of detectability. SIPE also allows the modification of sensor performance as the advancing threat passes through regions of clutter or other areas where sensor performance would be degraded.

These versions of SIPE were used for three years to analyze area defense system designs. The SIPE simulation models conform basically to the Monte Carlo next-time-step and event-step configurations. The SIPE output consists of probability distributions which describe various critical events from the attack scenario, e.g., time and location of first detection, time and location of neutralization, relative frequency of threat penetration along given approach trajectory.

Figure 8 shows detection and neutralization results on the display after simulating an attack by three swimmers against the Trident Support Site at Bangor, Washington. The swimmer tracks are shown in red. The sector coverages of two sonars are shown in yellow. Sensor degradation regions are shown as dotted contours through which swimmer trajectories 2 and 3 pass.

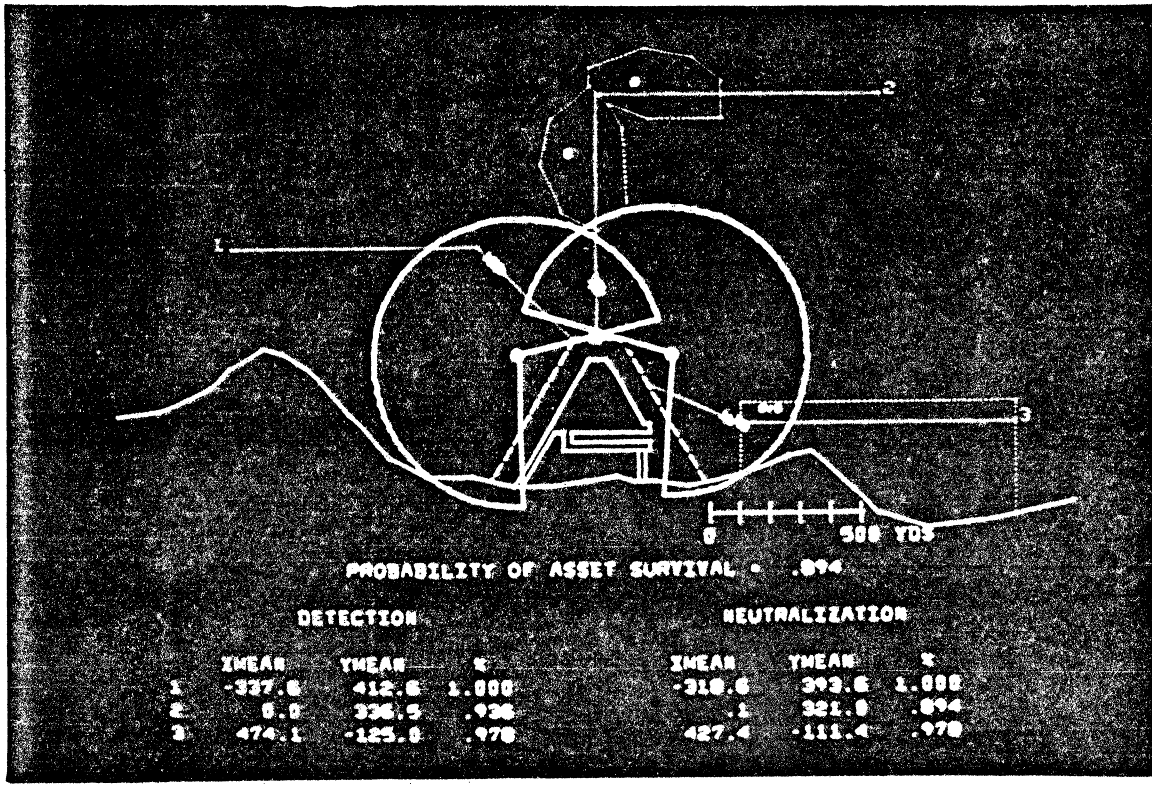

Figure 8. Results Shown on Display After Simulating a System Concept Against a Simultaneous Attack By All Three Trajectories.

5.0 COST PROPOSAL

5.1 COST SCHEDULE

All elements of our cost proposal are presented on a DD633-4 form. (See Exhibit 1.)

5.2 LABOR RATES

The proposed rates for all labor categories are weighted average expected rates, during the contract period, of personnel who will be assigned to the proposed study.

5.3 OVERHEAD RATE

Our overhead rate for 1978 was 111.8%. (See Exhibit 2.) We do not yet have an approved rate for 1978 because we have not yet been audited for 1978. We anticipate that our rate during the term of the proposed contract will be 101%. All elements of overhead expense considered are in accordance with Section XV of ASPR. Because of the homogeneous nature of our present and planned business, we have found it advantageous to use only a single composite overhead rate applied to direct labor. We have no separate overhead for general and administrative expense.

5.4 PER DIEM

Overnight travel will be required in order to perform the required work. We propose that per diem be the same as allowed civil service employees on travel.

5.5 CONTRACT TYPE

A cost - plus - fixed-fee contract is desired.

EXHIBIT 1.

DEPARTMENT OF DEFENSE
CONTRACT PRICING PROPOSAL
(RESEARCH AND DEVELOPMENT)

Form Approved
Budget Bureau No. 22-R100

This form is for use when *(i)* submission of cost or pricing data *(see ASPR 3-807.3)* is required and *(ii)* substitution for the DD Form 633 is authorized by the contracting officer.

PAGE NO. 1 | NO. OF PAGES 2

NAME OF OFFEROR: Integrated Sciences Corporation

HOME OFFICE ADDRESS *(Include ZIP Code)*: 1640 Fifth Street, Santa Monica, California 90401

SUPPLIES AND/OR SERVICES TO BE FURNISHED: Evaluating Effectiveness of Military Decision Support Systems

DIVISION(S) AND LOCATION(S) WHERE WORK IS TO BE PERFORMED: Address above

TOTAL AMOUNT OF PROPOSAL: $ 90,339.00

GOVT SOLICITATION NO.: N.A.

DETAIL DESCRIPTION OF COST ELEMENTS

1. DIRECT MATERIAL *(Itemize on Exhibit A)*			EST COST ($)	TOTAL EST COST[1]	REFERENCE[2]
a. PURCHASED PARTS Copying, report production			200.00		
b. SUBCONTRACTED ITEMS					
c. OTHER - (1) RAW MATERIAL					
(2) YOUR STANDARD COMMERCIAL ITEMS					
(3) INTERDIVISIONAL TRANSFERS *(At other than cost)*					
TOTAL DIRECT MATERIAL				200.00	
2. MATERIAL OVERHEAD[3] *(Rate % X $ base =)*					
3. DIRECT LABOR *(Specify)*	ESTIMATED HOURS	RATE/HOUR	EST COST ($)		
Chief Scientist	1350	19.23	25,960.50		
Staff Scientist	480	9.62	4,617.60		
Technical Assistant	200	6.42	1,284.00		
TOTAL DIRECT LABOR				31,862.10	
4. LABOR OVERHEAD *(Specify department or cost center)*[3]	O.H. RATE	X BASE =	EST COST ($)		
Calculated as a percentage of direct labor	101%	31,862.10	32,180.72		
TOTAL LABOR OVERHEAD				32,180.72	
5. SPECIAL TESTING *(Including field work at Government installations)*			EST COST ($)		
TOTAL SPECIAL TESTING					

6. SPECIAL EQUIPMENT *(If direct charge)* (

7. TRAVEL *(If direct charge)* (Give detai

a. TRANSPORTATION

b. PER DIEM OR SUBSISTENC

8. CONSULTANTS *(Identify*

Judea Pearl, Ph
measures, and
52 days

9. OTHER

10.

11.

TYPE David

NAME OF FIRM Integrated

DD FORM 633 1 APR 63

EXHIBIT 1,

EXHIBIT A - SUPPORTING SCHEDULE *(Specify. If more space is needed, use blank sheets)*		
COST EL NO.	ITEM DESCRIPTION *(See footnote 5)*	EST COST ($)
7a	2 trips to Washington, D.C. @ $424	848
7a	4 days auto rental @ $28	112
7a	Miscellaneous travel (trip insurance, parking, personal auto mileage	110
	Total Transportation	1,060

I. HAVE THE DEPARTMENT OF DEFENSE, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, OR THE ATOMIC ENERGY COMMISSION PERFORMED ANY REVIEW OF YOUR ACCOUNTS OR RECORDS IN CONNECTION WITH ANY OTHER GOVERNMENT PRIME CONTRACT OR SUBCONTRACT WITHIN THE PAST TWELVE MONTHS?

[XX] YES [ ] NO *If yes, identify below.*

NAME AND ADDRESS OF REVIEWING OFFICE *(Include ZIP Code)*: Defense Contract Audit Agency, 9920 S. LaCienega Blvd., Inglewood, CA 90301 Anthony J. Drexelius

TELEPHONE NUMBER/EXTENSION: (213) 643-2629

II. WILL YOU REQUIRE THE USE OF ANY GOVERNMENT PROPERTY IN THE PERFORMANCE OF THIS PROPOSED CONTRACT?

[ ] YES [XX] NO *If yes, identify on a separate page.*

III. DO YOU REQUIRE GOVERNMENT CONTRACT FINANCING TO PERFORM THIS PROPOSED CONTRACT?

[ ] YES [XX] NO *If yes, identify:* [ ] ADVANCE PAYMENTS [ ] PROGRESS PAYMENTS *OR* [ ] GUARANTEED LOANS

IV. DO YOU NOW HOLD ANY CONTRACT *(or, do you have any independently financed (IR & D) projects)* FOR THE SAME OR SIMILAR WORK CALLED FOR BY THIS PROPOSED CONTRACT?

[ ] YES [XX] NO *If yes, identify*

V. DOES THIS COST SUMMARY CONFORM WITH THE COST PRINCIPLES SET FORTH IN ASPR, SECTION XV *(See 3-807.2 (c) (2))*?

[XX] YES [ ] NO *If no, explain on a separate page.*

INSTRUCTIONS TO OFFERORS

1. The purpose of this form is to provide a standard format by which the offeror submits to the Government a summary of incurred and estimated cost (and attached supporting information) suitable for detailed review and analysis. Prior to the award of a contract resulting from this proposal the offeror shall, under the conditions stated in ASPR 3-807.3, be required to submit a Certificate of Current Cost or Pricing Data (see ASPR 3-807.3(e) and 3-807.4).

2. As part of the specific information required by this form, the offeror must submit with this form, and clearly identify as such, cost or pricing data (that is, data which is verifiable and factual and otherwise as defined in ASPR 3-807.3(e)). In addition, he must submit with this form any information reasonably required to explain the offeror's estimating process, including:
   a. the judgmental factors applied and the mathematical or other methods used in the estimate including those used in projecting from known da'
   b. the contingencies used by price.

3. When attachment of supporting cost or pricing data to this form is impracticable, the data will be specifically identified and described *(with schedules as appropriate)*, and made available to the contracting officer or his representative upon request.

4. The format for the "Cost Elements" is not intended as rigid requirements. These may be presented in different format with the prior approval of the contracting officer if required for more effective and efficient presentation. In all other respects this form will be completed and submitted without change.

5. By submission of this proposal, offeror, if selected for negotiation, grants to the contracting officer, or his authorized representative, the right to examine, for the purpose of verifying the cost or pricing data submitted, those books,

1 Enter in this co' which in the judg in the efficient costs in this letter contr supportin your pla trol, v orig pl crea etc.) in the p defective

EXHIBIT 2.

INTEGRATED SCIENCES CORPORATION

Overhead Expenses for 1978

	Dollars	Percent of Overhead
Rent	27,956.88	16.2
Office & Equipment Maintenance	513.86	.3
General Insurance	1,811.00	1.0
Office Supplies	4,089.19	2.4
Printing & Stationery	1,085.34	.6
Telephone	8,244.76	4.8
Postage	779.32	.4
Legal & Professional Expense	2,770.00	1.6
Equipment Rental	4,824.81	2.8
Depreciation	7,014.21	4.1
Library Expense	1,493.51	.9
Corporate Car	3,735.65	2.2
Marketing Travel & Misc. Expense	1,430.60	.8
Hiring Expense	503.00	.3
Secretarial Support	251.73	.1
Miscellaneous Expense	1,586.71	.9
Local Taxes & Fees	1,314.55	.8
Non Personnel	69,405.12	
Annual Leave & Holiday Pay	28,785.41	16.6
Employee Bonus Plan	2,106.20	1.2
Federal Payroll Taxes	11,174.58	6.5
State Payroll Taxes	2,585.47	1.5
Educational Benefits	618.50	.4
Employee Welfare	490.23	.3
Professional Development	2,782.12	1.6
Group Insurance	13,222.36	7.6
Personnel	61,764.87	
Indirect Labor	38,994.56	22.6
Marketing Labor	21,767.50	12.6
Subtotal	191,932.05	
Estimated State Tax	1,259.16	.7
Total Overhead	193,191.21	
Direct Labor	172,840.17	111.8

5.6 ISC PERSONNEL TO CONTACT ABOUT THE PROPOSAL

Proposal Area	Name	Company Position
Cost Proposal	David Walsh	Treasurer
Technical Content	Antonio Leal	Chief Scientist

Mr. Walsh has the authority to negotiate and enter into a contract for the company's services. The above personnel can be reached at (213) 393-0257.

5.7 FINANCIAL CAPABILITY

Financial requirements for carrying out the proposed work will be satisfied with current ISC financial resources and progress payments received from monthly billings during the term of the contract. A balance sheet, profit and loss statement, and notes to the financial statements are presented in Exhibits 3, 4, and 5.

5.8 RELATED CONTRACTS

ISC has recently performed research on several large projects requiring skills similar to those needed for the proposed work. Synopses of some of these contracts are given below.

a. Design of Man-Machine Interfaces for the Navy's Operational Decision Aiding Program (Contract N00012-75-C-0811) $344,800. This work is being done for the Office of Naval Research and includes the following:

- Simulation of Complex and Dynamic Systems on a Multi-Color Display
- Development of algorithms for solving the defense penetration problem for carrier-launched air strikes
- Design of Advanced Man-Machine Interfaces for use by Naval Commanders to solve the defense penetration problem for carrier-launched air strikes

EXHIBIT 3

INTEGRATED SCIENCES CORPORATION
STATEMENT OF INCOME AND RETAINED EARNINGS

December 31, 1973
through
December 31, 1978

1974	1975		1976		1977		1978	
84,417		$452,115		$666,466		$391,021		$427,925
.736		415,318		621,167		396,792		412,964
680		$ 36,797		$ 45,299		($ 5,771)		$ 14,961
	1749		771		1936		560	
500)	(5484)	(3,735)	(2364)	(1,593)	(1234)	702	(1004)	(444)
180		$ 33,062		$ 43,706		($ 5,069)		$ 14,517
	5184		5293		(1054)		2642	
500	3043	8,227	3934	9,227	200	(854)	1307	3,949
-		-0-		1,266		1,267		1,267
680		$ 24,835		$ 33,213		($ 5,482)		9,301
396		72,676		95,939		129,152		120,932
576		$ 97,511		$129,152		$123,670		$130,233
		1,572		-0-		2,738		1,356
576		$ 95,939		$129,152		$120,932		$128,877

EXHIBIT 4

INTEGRATED SCIENCES CORPORATION
BALANCE SHEET

December 31, 1973 through December 31, 1978

Current Asse
Cash
Market
Bill
Un

	1973	1974	1975	1976	1977	1978
	$ 19,578	$ 28,535	$ 34,383	$ 13,088	$ 9,775	$ 15,676
	-0-	30,983	-0-	32,082	23,696	8,222
	87,432	36,089	55,386	56,421	18,733	69,014
	[illegible]3,220	77,242	62,791	65,086	54,040	31,851
	[illegible]19	22	5,150	2,043	17,949	38,001
		-0-	-0-	-0-	4,843	-0-
		$172,871	$157,710	$168,720	$129,036	$162,764
		82,225	96,042	139,116	147,348	147,348
		(19,108)	(36,235)	(54,731)	(77,710)	(101,713)
		$ 63,117	$ 59,807	$ 84,385	$ 69,638	$ 45,635
		$ 1,454	$ 1,454	$ 4,698	$ 3,762	$ 3,762
		$237,442	$218,971	$257,803	$202,436	$212,161
		$ -0-	$ -0-	$ -0-	$ -0-	$ 8
		15,144	13,807	17,873	16,168	18,541
		18,444	19,871	17,015	-0-	-0-
		623	2,967	2,014	1,282	1,183
		16,014	33,189	19,560	7,619	3,785
		28,351	23,337	32,820	19,922	23,341
		-0-	-0-	5,939	3,083	2,996
		$ 78,576	$ 93,171	$ 95,221	$ 48,074	$ 49,854
		$ 58,031	$ -0-	$ -0-	$ -0-	$ -0-
		$136,607	$ 93,171	$ 95,221	$ 48,074	$ 49,854
		$ 18,068	$ 18,068	$ 18,068	$ 18,068	$ 18,068
		10,091	11,793	15,362	15,362	15,362
		72,676	95,939	129,152	120,932	128,877
		$100,835	$125,800	$162,582	$154,362	$162,307
		$237,442	$218,971	$257,803	$202,436	$212,161

EXHIBIT 5

INTEGRATED SCIENCES CORPORATION
NOTES TO FINANCIAL STATEMENTS

1. The company has a five-year lease on its office space at the rate of $3,530 per month. The lease expires in June 1981.

2. In February 1972, the Board of Directors of the Corporation approved a qualified stock option plan under which 2,000 shares of the Corporation's common stock are available for grant options to key employees to purchase stock at no less than market value at date of grant. There are currently no outstanding options to purchase shares.

- Design and Monitoring of Experiments
- Statistical Analysis of Experimental Results

b. Tactical On-Line Maneuver Modeling (Contract MDA903-78-C-2012) $66,984. This work is being done for the Army Research Institute and includes the following:

- Development of a "look ahead" battlefield model to take advantage of user oriented interactive graphic displays. The model provides straightforward user techniques for showing both friend and enemy unit types, unit levels, basic movement characteristics and engagement/firing actions on an automated display system.
- Calculation and display of battlefield mobility characteristics for different unit types.
- Calculation and display of contours representing the potential future locations of a unit.

c. Interactive Defense Penetration Analysis for Submarine-Launched Cruise Missiles (Contract N00140-78-C-6141) $55,000. This work was done for the Naval Underwater Systems Center, Newport, Rhode Island. It included the following:

- Definition of the overwater cruise missile control problem
- Generation of missile trajectory optimization models
- Development of interactive techniques for using computer graphics and the trajectory optimization models for solving the trajectory generation problem for a variety of launching conditions.

d. Interactive Modeling of Tactical Events (Contract DAHC19-77-C-0022) $60,563. This work was done for the Army Research Institute and includes the following:

- Design of a man-machine interface, including display formats and control mechanisms for entering and editing enemy tactical hypotheses. Development of operating interactive graphics software to implement the design.
- Development of simulation models of mobility, detection, classification, localization, and false alarm performance of intelligence gathering activities against the classes of enemy targets used in structuring tactical hypotheses.

- Design of the man-machine interface required for compressed time replay of enemy tactical hypotheses against simulation of intelligence gathering activities so that a decision maker can compare his hypotheses against the intelligence data and decide which hypothesis is most consistent with the data. Development of operating interactive graphics software to implement the design.

e. Scientific and Technical Services to Conduct a Baseline Study of Effects of Color on the Man-Machine Interface Performance of Underwater Fire Control Systems (Contract N00140-76-C-6272) $39,214. This work was performed for the Naval Underwater Systems Center, Newport, Rhode Island. The work includes the following:

- Design of alternative man-machine interfaces of a weapon order generator on a submarine fire control system
- Test and evaluation of interfaces designed

f. Systems Analysis and Human Factors Studies (Contract N00123-75-C-1202) $926,490. This work was performed for several programs at the Naval Undersea Center, San Diego. The work includes the following:

- Application of pattern recognition techniques to design of a bionic sonar
- Human engineering
- Design of an advanced deep ocean sonar system
- Requirements Analysis
- Cost Effectiveness Evaluations
- Operations Analysis
- Test and Evaluation Procedures for Research Studies
- Personnel Subsystem Development

g. Human Engineering Design Study to Support Defense Against Swimmer Attack (Contract N00123-73-C-0289) $84,533. This work was performed for the Naval Air Station, Point Mugu, California. The work included:

- Man-machine interface design of a console used by an operator of a swimmer defense system
- Test and evaluation of interfaces designed

6.0 REFERENCES

1. Leal, A., Levin, S., Johnston, S., Agmon, M., Weltman, G. An Interactive Computer Aiding System for Group Decision Making. Report No. PQTR-1046-78-2, Perceptronics, Woodland Hills, California, February 1978.

2. Armstrong, J. S., et al. "The Use of the Decomposition Principle in Making Judgments." Organizational Behavior and Human Performance, 1975, 14, pp. 257-263.

3. Dalkey, N. "An Experimental Study of Group Opinion: The Delphi Method." Futures, September 1969, Vol. 1, No. 5, pp. 408-426.

4. Pearl, J. On Demonstrating Effectiveness of Decision Analysis. Report No. 1272, UCLA Engineering Department, Los Angeles, September 1972.

5. Pearl, J. "A Framework for Processing Value Judgments." IEEE Transactions on Systems, Man, and Cybernetics, May 1977, SMC-7, No. 5, pp. 348-354.

APPENDIX A

SEPTEMBER 1972 UCLA ENGINEERING DEPARTMENT REPORT:

"ON DEMONSTRATING EFFECTIVENESS OF DECISION ANALYSIS"

UCLA PAPER ENG-1272
September 1972

ON DEMONSTRATING EFFECTIVENESS OF DECISION - ANALYSIS

J. Pearl

SCHOOL OF ENGINEERING AND APPLIED SCIENCE
UNIVERSITY OF CALIFORNIA
LOS ANGELES

ON DEMONSTRATING EFFECTIVENESS

OF DECISION – ANALYSIS

by

Judea Pearl

Associate Professor

School of Engineering and Applied Science

University of California, Los Angeles

September 1972

ABSTRACT

Decision Analysis is a methodology of selecting a course of action based on numerical encoding of an individual's value-system. The paper discusses the possibility of empirically demonstrating the merit of submitting to such methodology, as well as the feasibility of testing the fidelity of value-quantifying methods.

We dispute the notion that the aim of utility elicitation is to encode a subjective value-system which in itself escapes external control or examination. We argue that the very value-system that utility functions attempt to capture is an encoded version of some empirically observable experience. The merit of any value-elicitation technique should therefore be judged by its ability to closely reflect the essentials of this experience. Correspondingly, we propose to test the effectiveness of Decision Analysis procedures by their ability to improve the performance of laboratory trained subjects operating in a controlled simulated environment. The simulated environment presents decision situations with their associated rewards in accordance with some utility function, thus, guaranteeing consistency and uniformity. Score improvements recorded after subjects submit to Decision Analysis routines should be used to improve value elicitation techniques, identify areas where systematic errors are likely to occur, and to assess the cost-benefit tradeoffs of Decision Analysis practice.

I. INTRODUCTION

This paper was motivated by a discussion that took place in a recent workshop on "Subjective Optimality" conducted at the University of Michigan in July 1972. After hearing several reports on the application of Decision Analysis in various problem areas a question was raised whether there exist some means of measuning the benefit incurred by organizations who solicited the assistance of decision analysts in their specific problem areas. In the discussion that followed an argument was made that any meaningful claim for success should (at least in principle) be submitted to empirical test. Some Decision Analysis practitioners, on the other hand, claimd that their success does not lie with externally observable entities such as profitability or prosperity but rather with implementing decisions which are in conformity with the decision maker's subjective value judgment, and so escapes empirical scrutiny. The present paper aims at further analysis of this dilemma leading to a constructive method of validating some of the claims made by decision analysts.

The difficulty in submitting Decision Analysis (DA) to empirical test can best be presented after a distinction is made between DA's methodology, logical basis, and empirical claims. We shall start with a short description of the activity taking place when a decision analyst is called upon to aid in a decision-making process.[1]

Activity

1. Problem formulation — Identifying crucial variables, and separating them into control variables, state variables and consequences.
2. Elicitation of subjective probabilities connecting the states of nature and the consequences (outcomes).
3. Elicitation of the relative value (utility) of the outcomes to the decision maker.
4. Calculating that action which among all available alternatives maximizes the expected subjective utility.

Though many iterations of these sequences in various orders may sometimes by necessary, at any given time the decision analyst will be found involved with one of these four activities.

Direct vs. Indirect Benefits — It is not difficult to scan the list of activities above and reason how each may lead to beneficial results. Any moment of thought spent by the decision maker on analyzing cause-effect relations, listing alternatives, facing consequences, recounting past experiences, may sharpen his visibility and enhance his chances of making better decisions. These effects, however, we should call indirect benefits as they do not directly relate to the particular methods employed by DA but would accompany any arbitrary procedure which induces the decision maker to focus attention toward better understanding of his problem. Indirect effect of this sort will not be part of our considerations as even the most conservative decision analysts claim to offer greater service than merely serving as sounding boards to frustrated executives.

Another indirect effect not included in our evaluation is the benefit drawn from people's peculiar respect for written procedures. This effect was found to reduce tension among individuals as the final decision (usually submitted in the form of computer print out) seems detached from interpersonal conflicts. The written procedure was also shown to reduce anxiety among decision makers as it provides a potential scapegoat in case of blunders.

Our objective is to evaluate the direct benefits of the unique methods and procedures used by DA as opposed to some other rigid methodologies.

Logical Foundations of DA — The logical basis for DA methodology is provided by the celebrated axiomatic treatment of Van Neumann and Morgenstern (VNM).[2] The latter states that if an individual's preferences among lotteries obey a certain set of axioms then his preferences can be represented (or encoded) by a real function on the outcomes, called utility, in such a way that lottery A will be preferred to lottery B if and only if A results in a higher expected utility than B. When the decision problem contains uncertain events whose likelihood cannot be measured by relative frequency measurement then additional axioms must be supplied concerning the individual's way of reacting to uncertainties relative to his reactions toward repetitive events with well established probabilities.[3] When these axioms are added to VNM axioms it can then be shown that the individual's attitude toward uncertain events can be encoded by a "subjective" probability function and all his preferences can be determined by the "subjective" expected utility.

All this is well known and was presented here merely for contrasting the logical foundations of DA with its empirical claims. Decision analysts do not claim that individuals do behave in accordance with VNM axioms, for if they do they would not solicit analysts' assistance. They claim however that most individuals would like to (and therefore perhaps ought to) behave that way. This last statement is an announcement of an empirical fact which can be submitted to and has indeed been confirmed by empirical tests. The function which the decision analyst undertakes is to assist an individual decide "the way he really likes to act". To do that, the decision analyst exposes his subject to hypothetical decision situations and from his responses synthesizes two sets of functions: subjective probability, and utility.

The degree at which the decision analyst succeeds in eliciting these functions, and their relations to the entire preference system are the crucial elements in the problem of DA evaluation. While the elicitation of subjective probability can be (and has been) submitted to empirical tests,(7) the fidelity of encoding one's value judgment in the form of a utility function has defied measurements. In fact, some decision analysts argue that such a measurement is an impossibility.

The argument goes as follows: Testing the fidelity of our value elicitation method can only make sense if we find another means of measuring internal value systems. But internal value systems have only one form of external manifestation: through preference value judgments. Now, our method of value-elicitation is based on exactly this manifestation, therefore the utility

we come up with is, by definition, the subject's value system and no test in the world can refute or support this claim.

This argument may have settled the entire problem, was it not for an uneasy feeling that overcomes every empiricist hearing claims which defy empirical verification. Especially when he is asked to pay fat fees for implementing procedures based on such claims. His immediate response in a case like this would be either to dismiss the claims as metaphysical, or attempt and identify their meaningful and testable components. He may, for instance, ask himself: Would I be willing to pay a fee to a witch-doctor claiming to precisely measure the color of my intelligence? Here is an entity which is defined solely by the claimer's elicitation method; is our value-system of the same semantic level? I couldn't care less for the color of my intelligence but I sure would like to know my scale of values. It is exactly this difference that exposes the empirical basis underlying value-elicitation.

II. EMPIRICAL FOUNDATIONS OF VALUE ELICITATION

We would like to identify those empirical facts and claims which provide the necessary bridge between axiomatic decision theory (which in isolation remains purely tautological) and prescriptive decision theory as applied to real-life human decision making. For this purpose we first address ourselves to the question: What aspects of human behavior give rise to the notion that human decision making ought to be governed by a "value system"?

Let us consider the set C of all data of choice behavior produced by an individual over a long observation period in a certain decision-making environment. C may contain the individual's responses to a large number of

questions posed to him by a passive (non-advising) experimenter as well as choice preferences reflected by his actions. In general C will consist of a set P of preferences among specific choice alternatives and a set U of general principles about the structure of these preferences. Statements which belong to U are distinguished from those of P by the presence of universal or existential quantifiers. For example, the statement expressing the subject's acceptance of transitivity will belong to U as it expresses a universal principle compatible with all objects of choice, while the statement "I prefer lottery B" will belong to P.

The first empirical truth that we need to consider is: When allowed to operate without advice most individuals generate logically inconsistent C's.[4][5] This truth is substantiated by the very fact that decision analysts are often called upon to offer advice. Had C been free of contradictions the best advice the decision analyst can come up with would be to ask his client which alternative he prefers most and express his full support. That would amount to a sheer duplication of C.

The contradictions contained in C are of several types. They can be in a form of two or more incompatible preferences like 'A is preferred to B' and 'B is preferred to A', both appearing in C. There can be a conflict between a universal principle and a set of particular preferences, or even a conflict between two universal principles. We usually attribute these contradictions to limitations in human computational powers. The logical path between the universal principles in U and some of the decision situations in P may contain very long chains of deductive reasoning and arithmetical steps

of which we simply cannot keep track. One of the recognized merits of DA procedures is that this computational burden is substantially reduced via the employment of numerical codes which can be manipulated in a mechanical way.

But before one can employ numerical codes one must decide what he wants to code, especially when the object to be coded is imbedded in a logically inconsistent space. Since any numerical decision procedure is bound to be self-consistent we always expect to find deviations between some statements in C and the corresponding statements as derived from numerical procedures. Various decision procedures may differ, however, in the set of statements which they deviate from C. The latter depends on the particular choice of basis employed by the procedure.

A basis B is a subset of statements in C which is chosen for numerical encoding. Decision Analysis, for example, selects as a basis the set of universal principles from U known as the Von Newmann Morgenstern (VNM) axioms, and the set of particular preferences from P used by the analyst to elicit subjective probabilities and utilities. For the successful employment of this basis a second empirical fact must be true: Most individuals admit VNM axioms in their C records. This fact has indeed been supported experimentally.

Once encoded, the chosen basis can be used to generate a self-consistent set $C_a(B)$ (called the logical extension of B) of preferences and principles (theorems) which agrees with most, but disagrees with some statements in C. Adherence to a decision procedure implies that the decision

maker always takes the action recommended in C_a even when it conflicts with some statements he has made or may later admit in C.

But the choice of basis is quite arbitrary, any complete and self-consistent subset of C might serve as a basis for a numerical decision making procedure. What then are the aspects of C that make the basis chosen by DA better than any other choice? The following example will demonstrate the guidelines we ought to adopt for proper basis selection. Consider a set C which among many others also contains the following statements: (1) VNM axioms, (2) Indifference to a trip to the Bahamas or $1000 in cash, (3) Indifference to a trip to the Bahamas or $1200 in cash, (4) $1200 is preferred to $1000. Obviously C contains a contradiction, but one which we are very likely to make when asked to compare outcomes outside our field of familiarity. Consider now the ramifications of choosing two bases:

B_1 = (1), (2), (4) B_2 = (1), (2), (3)

Adherence to a procedure employing B_1 would mean that our subject should give up statement (3) and subscribe instead to: (3') "A trip to the Bahamas is inferior to $1200 in cash." On the other hand, a procedure employing B_2 would force him to give up (4) and replace it with (4') "Indifference to $1200 or $1000."

Intuitively we all feel that B_1 is more representative of the record C than B_2. Few of us will be willing to subscribe to (4') while the acceptance of (3') is quite harmless in view of the fact that we are usually not too proficient in assessing the fair market prices of vacation trips. It is not too hard to construct more elaborate examples of this sort to demonstrate how

improper choice of basis can cause many seemingly minor inconsistencies in C to be combined cumulatively and yield results which stand in complete contradiction to common sense (Plato's dialogues are classical examples of such technique). At the same time, there is nothing in C which dictates what constitutes a good basis. What then is the nature of the "value system" that decision analysts claim to capture while eliciting utilities?

As the previous example demonstrates, the ingredient missing from the raw data of choice behavior (C) is an indication of the individual's strength of conviction in each of the choice statements. In the example above statement (4) will invariably be expressed with more determination than either (2) or (3). The reason we tend to prefer B_1 over B_2 is that $C_a(B_2)$ is in conflict with a statement of high strength of conviction while $C_a(B_1)$ violates a statement we weren't too sure of to begin with.

If it were possible to obtain reliable measurements of the "strength of conviction", we could perhaps devise meaningful ways of evaluating decision analytical procedures. We would first define individual's value system V to be the set C of behavioral choice statements coupled with a set of real numbers (ranging, say, from 0 to 1) indicating the strength of conviction assigned to each of the statements in C, thus, $V \subseteq C \times Re$. A decision procedure resulting in choice system C_a will be evaluated by the degree of its conformity with the value systems of the subject. The degree of conformity should be some decreasing function of the sum of the statements in which C conflicts with C_a weighted by the strength of conviction of these statements.

The claim for success of decision analysts would then be phrased as follows:

> <u>We have found a method of selecting among the various members of C a subset B of statements which is both complete and consistent and whose logical extension $C_a(B)$ stands in close proximity to the value system V.</u>

The empirical verification of such claims would entail comparing $C_a(B)$ and V for a large number of individual subjects.

In essence several decision analysts have come very close to this formulation. They claim that through lengthy in depth discussions they are able to single out those variables and situations with which their clients feel most confortable and confident. Correspondingly, by way of verification they propose measuring clients satisfaction after implementing their decision procedures. Surely, a client could not stay satisfied for a long period of time if some of the decisions recommended to him on a computer print-out stood in direct conflict with his strongest convictions.

The drawback in relying on clients' satisfaction as a measure of success is twofold: first, some ramifications of a decision procedure may not be known for a long period of time until uncovered by a peculiar choice situation. For instance, in the example cited above we may be unaware that the procedure to which we subscribe implies indifference between \$1000 and \$1200. That fact might not reveal itself until we are actually faced with a choice situation involving sums of money in the range \$1000 to \$1200.

Second, and much more fundamental, satisfaction is a measure of conformity to one's value system after analysis. It provides no indication to the degree of value-bias induced by the very practice of the procedure under test. Indeed many decision analysts pride themselves on the fact that some of their clients undergo complete restructuring of their value-systems as a result of the analysis. The vague becomes clear, what seemed crucial before may become less important, and strong convictions may turn out to be sheer wishful thinking. What value systems were these analysts trying to capture? The one before or the one after analysis? If it is satisfaction that we are trying to create can't we do better by subjecting the decision maker to some sort of a self-hypnosis program (with the help of drugs perhaps) as a result of which he emerges satisfied with almost any decision he makes.

These questions lead to the realization that although satisfaction is a prerequisite for any successful decision procedure it cannot be regarded as a goal in its own right. We must define another observable manifestation of our value system aside from the collection of choices that brings about satisfaction. We can of course insist on taking the data $V \subseteq C \times Re$ before analysis to represent the decision-making true value-system. But our objective can be served more effectively if we bypass this tedious exercise and reexamine the reason we wish to consult our value system in the first place.

III. TESTING ELICITATION OF VALUES

We constantly struggle to make decisions which conform to our value system. To explain this phenomena from a pragmatic viewpoint, we must abandon the notion that value is an internal mental state isolated from our external

environment. The reason we consult our value system is that in it we hope to find a condensed version of our past experience to guide our future actions. The value system that we defined earlier as the set V is in itself a product of a mental encoding procedure whose objective is to capture the essentials of our environmental cultural and intellectual activities. If, for instance, we prefer to make decisions in accordance with the principle of transitivity it is not because we were born with an innate favor toward transitive relations but because we simply fail to recall from our experience any set of three pairs (A, B), (B, C) and (C, A) in which the first member in every pair produced more reward than the second. (A, B and C represent states of the world.) Preferences among specific situations and their associated strengths of conviction are similarly acquired via some process of averaging over one's past exposure to the situations and the reinforcements they carry, or with some aspects of those situations.

With such a behaviorist picture of value formation in mind we might ask: Why evaluate Decision Analysis on the basis of its fidelity in eliciting one's value system, why not measure its fidelity in coding the very experience which brought about that value system.

In laboratory conditions we can synthesize an artificial environment of choice-reward consistent with a well specified utility function. A group of subjects is then instructed to "learn to survive" in this environment, namely to make decisions which maximize their reward. After a certain training period, operating scores are taken and the group is placed under the supervision of a decision analyst who attempts to elicit their utility function (with

respect to said environment) and subsequently assists them in employing the utility function toward improving their decisions. The operating scores after analysis are then compared with those taken before analysis. In addition the utility elicited by the analyst is compared to the utility function underlying the environment and systematic errors are noted.

Two objections may be raised against using this test for measuring DA effectiveness: The first is based on the fact that the differences between the generating utility and the elicited utility reflect a sum of two errors; learning error and elicitation error. The former affects coding the environment into the subject's internal value-system and the latter accompanies coding their value-system into a numerical utility function. It is argued that Dicision Analysis should not be held responsible for subjects learning deficiencies but solely for elicitation errors and since the two are empirically inseparable the proposed test has no bearing on the effectiveness of Decision Analysis.

Our answer to this objection is that the two errors are at least partially separable. The systematic component of the learning error should be observable in the pre-analysis scoring records and so can be subtracted from the total systematic error. The non-systematic components may be washed out by averaging over a large non-interactive group.

The second objection refers to extraneous effects caused by the laboratory set up. In real life situations, the argument goes, the decision maker is free to expose his entire value system while in the proposed test he is asked to respond to a small subset of his system, that created by the laboratory environment. Since no one can completely divorce himself from past

values, experiences and aspirations we should expect much higher elicitation error in the laboratory than can actually be achieved in real life.

Our answer to this challenge is that in most decision situations of any importance we are not at all interested in eliciting the entirety of the decision maker's personal values. On the contrary, we are primarily interested in his value system with respect to a narrow cultural or organizational context.[6] A public official, for example, is expected to act not in accordance with his personal value system which he acquired over the years, but rather his assessment of the public value system at a particular time with respect to a specified issue. A corporate executive is expected to act in harmony with the risk policy of his corporation, even when it conflicts with his own temperament. We, therefore, are not interested in one's total experience but rather in one's ability to discriminate and select those experiences which are relevant to his duty. Accordingly, we should be interested in measuring the ability of DA to elicit one's evoked or learned values rather than one's intrinsic value-system. The set up in the proposed test is designed to match this objective; the subjects will not be asked to state their own personal preferences but rather the choices that they believe would result in a maximum return in the artificial environment which they studied.

The test procedure we described is similar in several respects to the tests we normally use to calibrate the elicitation of subjective probability.[7] In the latter case we record a set of personal preferences related to the occurrence of an uncertain event whose probability function we know exactly and from this record we construct a subjective probability curve. Having an

external calibration device allows the evaluation of various elicitation techniques. We can, for instance, measure the effect of various question phrasing, audio visual devices, group interaction, etc. on the accuracy of the elicited probability curves. The systematic errors found in such tests[8] may be used to compensate later results in cases where the probabilities are unknown or untestable. Our finding an external calibration for values equips the encoding of utility with identical possibilities.

In case our test reveals a marked systematic error in value encoding it stands to reason that appropriate compensations be affected before decisions are enacted. Such value-errors have long been recognized by moral philosophers. We are often warned against underrating virtues such as Health and Freedom whose "true value" can only be appreciated in their absence. We are also reminded of our tendency to overemphasize factors which play a role in our most recent experience at the expence of those experienced in the past. While the experiments proposed in this paper may lead the way toward quantifying these and similar effects they also present Decision Analysis with a tough social challenge; stating what the subject's utility ought to be strips VALUE from the sacred power it now possesses, a power whom all try to please and none dares question. Whereas people are generally willing to accept calibration of their subjective probabilities, how many of us are willing to submit to value calibration?

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APPENDIX B

MAY 1977 IEEE ARTICLE:

"A FRAMEWORK FOR PROCESSING VALUE JUDGMENTS"

A Framework for Processing Value Judgments

JUDEA PEARL, MEMBER, IEEE

Abstract—Traditional decision-analytic practice emphasizes the distinction between probability assessments and value (or utility) judgments. Whereas techniques for elicitation and integration of subjective probabilities often can be submitted to empirical tests of validity, the fidelity of encoding value judgments has so far defied measurements. A unified approach to the treatment of the two types of judgments is presented; value judgments are interpreted as conditional probability statements. Such formulation leads to rational methodologies and procedures for solving the following tasks: 1) empirical validation and refinement of value judgments and 2) aggregating value judgments obtained from a panel of experts.

I. Introduction

PHILOSOPHERS have long separated between two kinds of human knowledge, informative (or positive) knowledge and normative (or value) knowledge. In the first category philosophers grouped the physical and socio-economical sciences as well as our intuitive knowledge about objects, colors, geometrical shapes, etc. In the second category, which often enjoyed a more elevated status, we find the studies of ethics and religion.

Strangely, this philosophical tradition has retained its influence upon the thinking and practice governing the emerging technology of decision analysis (DA). From its early development in the 1940's until today, DA has prescribed separate interpretations and treatments to probabilistic and value judgments. Whereas the former is regarded as a formalization of experiential knowledge, the latter is treated as a subjective and capricious entity which aside from the requirement of satisfying transitivity may assume any structure whatsoever.

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The author is with the School of Engineering and Applied Science, University of California, Los Angeles, CA.

This distinction has resulted in a technological disparity between the methodologies available for processing probabilistic and value judgments. Whereas the former enjoys the benefits of Bayesian analysis, no parallel formulation is available for processing value judgments. The disparity is most clearly reflected in the absence of rational procedures for refining, updating, calibrating, and aggregating value judgments. While judgmental probabilities can be modified by experts, updated by empirical observations, and rectified by calibration, none of those techniques seems to apply to value judgments. Value preferences seem to remain immune from analytical or empirical scrutiny, a thing to uphold and not question, satisfy but not alter.

Consider, for example, the problem of calibration. Calibration procedures are used to bring probabilistic codings given by an individual closer to the truth frequencies of previous judgments [1], [2]. These procedures are used to remove systematic biases from both the individual's own perception of uncertainty and biases inherent in the elicitation method. Thus, if a probability assessor claims that his bread has fallen on the buttered side 90 percent of the time, we can use this overstatement to attempt to calibrate his prediction that his next car stands a 90 percent chance of being a lemon. However, if that same "expert" claims that he *prefers* arsenic to hot chocolate, we have no decision-analytic procedure of tempering this preference. It must be taken at face value and fed into an optimization procedure, which would produce an action conforming to almost any declaration depicting the expert's desires, however careless.

Next consider the problem of aggregation. When a panel of experts provides conflicting probability assessments, Bayesian techniques are available [3] for combining these assessments into a single probability structure reflecting the group overall knowledge. These techniques treat the experts

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as noisy information sources and incorporate the decision-maker's judgment of their reliability into the aggregation rule. No parallel techniques are available for aggregating value statements. It is strange that Bayesian methodology can resolve experts' disagreements on the failure probability of a nuclear reactor but could not handle disagreements concerning the social value of that reactor.

The purpose of this paper is to explore a paradigm of value semantics which may facilitate extensions of Bayesian decision-analytic techniques to the processing of value judgments and help rectify the imbalance now prevailing in our conception of the informative and normative modes of human knowledge.

II. A Paradigm for the Semantics of Value Judgments

The paradigm advanced in this paper asserts that *value judgments and probability statements are one and the same thing*. Both are numerical codes of experiential data, both are constructed by the same mental procedures, and both are utilized to guide future actions.

If probability quantifies a person's belief in the eventuality of a certain situation, then utility quantifies one's estimate of the benefit he might eventually draw from a certain situation. It is reasonable, therefore, to regard value judgments as conditional probability (or conditional expectation) statements. For example, the statement "I prefer outcome A to outcome B" may be interpreted to mean "I estimate tne probability of reaching a certain state of satisfaction conditioned upon A to be higher than that conditioned upon B," or "I estimate the total benefit achievable as a result of realizing A to be higher than that achievable after realizing B." In either interpretation the entity estimated by the value statement is the strength of causal connection between two eventualities; one being the outcome A or B, the second being a person's achieving a certain level of satisfaction. In the framework of Bayesian analysis, though, the quantification of causal relations among events is usually formulated through conditional probability (or conditional expectation) assertions. To remain consistent with this formulation it behooves us to regard each value statement as a parsimonious form of conditional probability assertions. It should therefore be treated as an empirical statement about "matters of fact" and should acquire a status equal to that of any probabilistic assertion which summarizes observational data.

To complete the unification of value judgments with probability statements we need to clarify the concept of "personal satisfaction" or "total benefit." In most people's eyes satisfaction may appear in a variety of shades and colors not all of which seem commensurable. For example, the satisfaction one receives from dining in a certain restaurant seems noncommensurable with that induced upon hearing encouraging political news, or with the fear of adding so many extra calories to one's diet. The unlike character of these kinds of satisfaction, however, seems to be derived from people's tendency to attribute to satisfaction the character of the anticipatory procedures invoked for estimating its future likelihood or future magnitude. The knowledge that added weight stands in causal connection to overeating, for example, serves an anticipatory function of estimating the degree of future discomfort resulting from a certain meal. The nature of the discomfort itself, though, is fairly commensurable with the nature of the gratification one receives during the meal. Both involve biological sensations of pleasure and pain.

Neurophysiology has found that many mammals' brains (including humans) contain a so-called "pleasure center," stimulation of which encourages that individual to seek further stimulation there. In rats, a conditioned reflex can be erected on this basis; in humans, the overt effect was that the patient asked the doctor to "Do that again, please." From this low level of neural sensation, therefore, it is reasonable to assume that only two parameters suffice to characterize the force which drives an organism's behavior: intensity and time duration. Formally we can express this assumption by stating that at any time an organism is attempting to maximize the expected value of a *satisfaction integral*:

$$S = \int_{t=t_0}^{\infty} s(t)\, dt \tag{1}$$

where $s(t)$ measures the intensity of the pleasure sensation at time t (a negative s should reflect painful sensations). Toda [4] used an identical formulation which he named an *adaptance* integral. S is a concept comparable to utility in the sense that, like utility, S is unidimensional and unique up to a linear transformation. However, unlike utility, S is not an attribute of a decision outcome, neither is it subjective in nature. It measures an actual neural activity of an organism undergoing a specific life history.

To connect S with the usual concept of utility, we assume that the organism configures its experiential knowledge in a form which permits him to calculate (or estimate) the function $E(S \mid \theta)$, where E stands for the expected value operation and θ is a description of a state of the world. We then say that the utility of the state θ is given by

$$V(\theta) = E(S \mid \theta). \tag{2}$$

Clearly, the mental calculation of $E(S \mid \theta)$ is subject to many biases and inconsistencies inherent in humans' computing machinery. The main deficiency lies in man's ability to organize past experience in a data structure that would permit him to calculate the probabilistic connection between S and θ (for all levels of S and all states θ). A second limitation lies in man's capacity to compute $E(S \mid \theta)$ on the basis of such probabilistic information. With these deficiencies in mind, our main assumptions at this point are 1) that an individual would attempt to harness his computational resources, however limited, to facilitate an approximate calculation of $E(S \mid \theta)$, and 2) that once a crude estimate of $E(S \mid \theta)$ is obtained, it is this estimate which governs individual choice behavior.

In our normal speech, the variable S does not appear explicitly as an argument of utility. We talk about utility of lotteries, outcomes or commodity bundles, tacitly implying

that the latter are only vehicles serving to achieve or estimate the total future benefit S to be experienced by our pleasure and pain centers.[1]

The reason that the role of the senses in affecting value judgments has almost completely disappeared from our everyday language is several fold. First, the argument S remains constant in all value judgments issued by an individual at time t_0, and so, it is redundant and may be dropped from a normal discourse. Second, the neural activity represented by S is so logically remote and perceptually uncertain that it rarely participates explicitly in the calculation of $E(S \mid \theta)$. Chess masters, for example, concern themselves primarily with heuristic concepts such as mobility, tempo, center-control, etc., rarely mentioning the ultimate goal of the game: checkmate. In much the same way our cognition system is equipped with heuristic concepts such as the pursuits of social virtues, economical wealth, or political power which serve to guide our choices toward an intermediate milestone. These concepts do not in themselves guarantee a realization of high S but where chosen by our culture as useful computational tools in the estimation of $E(S \mid \theta)$, by virtue of their tight correlation with future pleasure/pain balance.

Formal models for the evolution and utilization of such value concepts were developed in the literature on artificial intelligence [6], [7], and will be used later in Section III. The main point to notice here is that the usefulness of these heuristic concepts lies not in an extraphysical domain but rather depends on the degree to which they constitute a faithful code of experiential data. For example, a utility curve for money is only useful so long as it reflects one's experience regarding one's ability to convert certain sums of money to streams of neural gratification. The rationale for using this utility curve to govern future actions is based on inductive projection of this past experience onto an estimate of the individual's conversion abilities in the future (including sums of money not yet experienced), and should also be based on factual knowledge codified in probabilistic forms. Adherence to this paradigm of value should strip value judgments of their metaphysical, extrafactual status and reinstate them on equal footings with conditional probability statements, vulnerable to empirical scrutiny and manageable by Bayesian technology.

III. Potential Applications

In this section we shall explore some of the operational implications of the value paradigm developed in Section II. Two tasks are studied: validation and aggregation of value judgments.

[1] This idea, that human conception of value derives its structure from sensory information, goes back to John Locke. In his words, "And thus we see how Moral Being and Notions, are founded on, and terminated in these simple ideas, we have received from Sensation or Reflection, besides which, we have nothing at all in our Understanding, to employ our Thoughts about" [5, p. 195]. He further states, "So that whencesoever, we take the Rule of Moral Actions; or what standard soever we frame in our Minds the *ideas* of Virtues or Vices, they consist only, and are made up of Collections of simple *ideas* which we originally received from Sense or Reflection" [5, p. 196].

Validation

The problem of establishing an external means for demonstrating the effectiveness of decision-analytic methods is one of the most controversial issues in decision analysis [8]. The difficulty stems from the fact that by its very nature the idea of externally validating a value-processing procedure seems to imply a paradox: the proclaimed aim of such procedures is to remain as faithful as possible to the subjective preference structure of the value assessor. That structure, though, is only observable via the procedure under test, and so, value processing and decision-analytic procedures appears to be self-validated on *a priori* grounds.

Our interpretation of value judgments, however, offers a sound resolution of this dilemma. No longer is fidelity with internal value structure an end in itself. One's value structure is merely a code of empirical data, and so, fidelity with that data should provide the necessary validation test.

If one regards the individual value assessor as a transducer for empirical data, then the objectives of value processing procedure are two-fold: first, gaining a faithful access to the code of experience and second, rectifying distortions between that code and the original data. Identical objectives are assigned to probability-processing methods, coding distortions are handled by calibration, and elicitation distortions are minimized by the celebrated "divide and conquer" approach [9].

Let us begin by examining this last approach more closely. It is devised to rectify a mismatch between the format in which a problem (or inquiry) is presented to an individual and the format in which that individual coded his experiential data. A model of the latter contains a combination of specific facts or scenarios (e.g., it rained on my last birthday), generic relations (e.g., when it rains I am normally moody) and procedures for assessing and integrating the former to provide answers to queries [10]. By and large, the formats of the queries confronting an individual do not match the structure of his knowledge organization. For example, the query "Was I moody on my last birthday?" can be readily answered from the assumed stored knowledge. However, the query "Did it rain the last time I was moody?" requires further processing. This would be the case if my memory contains no explicit recollection of that last moody occasion, and if the memory file was not organized to be accessed by referring to my moods. An answer to such a query, though, can be reconstructed using knowledge fragments such as "When I have to write a paper I am almost always moody" and "Last season it hardly rained, and I had quite a few papers to write," etc. The reconstruction procedure may be formalized in terms of the Bayes rule which provides the basis for the methodology of probabilistic information processing [11]. The rationale for this methodology lies with the assumption that judgments *copied* from memory are more reliable than those *reconstructed* from memory, and so, the methodology provides mechanical aids to perform the reconstruction on the basis of probabilistic judgments explicitly stored in one's knowledge base. Note that not every division guarantees conquest, but only that which decomposes a query into a set of components which

are coded in explicit forms. Were I, for example, to decompose the query "Was I moody last time it rained?" (assumed to be coded explicitly) into a set of queries concerning the weather characteristics conditioned upon my state of mood (not coded explicitly), the reliability of the reconstructed answer would only be diminished.

Let us examine now if similar methodology could be applied to value elicitation. According to the paradigm proposed in Section II, value judgments require the mental calculation of $E(S \mid \theta)$, where θ is a description of a state of nature. It is clearly the case that no individual can expand the amount of memory necessary to store an explicit value of $E(S \mid \theta)$ for all conceivable θ. Rather, people seem to configure their experience in a form of probabilistic relations between S and various combinations of state attributes or aspects. For example, θ may represent the possession of a *specific* house, while our experience with the benefits of house dwelling is coded in terms of the benefit derived from certain combinations of aspects such as privacy, locality, number of rooms, etc. These entities which serve as primitives for our value code are called value *aspects*, (the name "attributes" or "dimensions" are also used) and will be designated by the vector $\boldsymbol{a} = (a_1, a_2, \cdots)$. In accordance with the "divide and conquer" principle, we should express the value $U(\theta)$ in terms of $\boldsymbol{a}$, which serves as a reference key to our code of knowledge. Thus we obtain

$$U(\theta) = E(S \mid \theta) = \sum_{\boldsymbol{a}} E(S \mid \boldsymbol{a},\theta)P(\boldsymbol{a} \mid \theta) \tag{3}$$

where $P(\boldsymbol{a} \mid \theta)$ represents the probability that aspect combination $\boldsymbol{a}$ would be attained assuming state θ is reached. Since the quantities $E(S \mid \boldsymbol{a},\theta)$ are never found in one's memory, we must replace them with $E(S \mid \boldsymbol{a})$:

$$U(\theta) = \sum_{\boldsymbol{a}} E(S \mid \boldsymbol{a})P(\boldsymbol{a} \mid \theta) \tag{4}$$

reflecting the fact that the value of any state θ can only be evaluated through its aspects, which in turn are defined by the language used in the organization of one's knowledge base.

If $P(\boldsymbol{a} \mid \theta)$ peaks sharply in the neighborhood of some aspect combination $\boldsymbol{a}(\theta)$, then (4) can be approximated by

$$U(\theta) \simeq E[S \mid \boldsymbol{a}(\theta)]. \tag{5}$$

For example, if a_3 represents the number of rooms in the example above, then $P(a_3 \mid \theta)$ is sharp since the number of rooms in a prospective house is usually known. Advanced knowledge of the degree of privacy (a_1) provided by a certain house, on the other hand, is generally less accurate and may require retaining the summation over $P(\boldsymbol{a} \mid \theta)$ in (4).

Among all techniques used in multiattribute utility analysis, the one most widely practiced and yet most hotly debated is the linear *decomposition* model [12], [13]. Here the analyst elicits the value (utility) of each attribute separately and the relative importance of these attributes and then combines these in a linear fashion to arrive at an overall utility evaluation. In terms of our model, the issue of whether the linear model is adequate reduces to the question of whether the conditional expectation $E(S \mid \boldsymbol{a})$ can be decomposed in a linear fashion to give:

$$E(S \mid \boldsymbol{a}) = f_1(a_1) + f_2(a_2) + \cdots. \tag{6}$$

Formally speaking, such a decomposition can be guaranteed only when the a's are both marginally and conditionally independent, a rare case for an arbitrarily chosen set of attributes. One should recall though that $\boldsymbol{a}$ is not arbitrary but represents that selected collection of descriptors used by an individual to organize his experiential knowledge. The selection of these a's has probably undergone a long process of perceptual and linguistic evolution aimed at economizing computations. A linear decomposition as in (6) would save a substantial amount of storage space and time in the calculation of $E(S \mid \boldsymbol{a})$. It stands to reason, therefore, that if a linear decomposition exists (using readily computable a's), it would be chosen by the race and utilized in knowledge organization.

All indications point to the fact that the attributes used by people to represent knowledge have evolved in such a way as to render the decomposition in (6) feasible. Anderson [14] has found that in a wide variety of judgmental situations (ranging from perceptual to linguistic experiments), human judgment of a unified "whole" can be modeled by very simple arithmetic combination (e.g., addition or multiplication) rules over the information components. Einhorn [15] and Dawes [16] reported that linear composities of attribute values elicited from individuals outperformed intuitive judgments obtained from the same individuals in such tasks as predicting a student's college success or the longevity of patients with Hodgkins disease. Samuel [7] has written one of the most successful checker-playing programs which evaluates game positions by a linear combination of attributes (e.g., material advantage, mobility) defined by a human player.

These experiments seem to support the notion that most human knowledge is organized in terms of linearly decomposable variables. Assuming now that value information is coded in a similar fashion, these experiments would constitute an external validation of the adequacy of the linear decomposition techniques. Indeed, it would be an extreme waste of computational resources for an organism to manage two different forms of knowledge representation, one for factual knowledge, the other for normative knowledge. (Would knowledge about shoes be organized differently than knowledge about socks?) The superior performance of linear decomposition techniques in predicting factual data [13] provides an external validation for the effectiveness of multiattribute utility elicitation, although the latter is not observable directly.

Value Aggregation

Bayesian techniques for aggregating probabilistic information obtained from several assessors are based on the concept that such assessments represent outcomes of a noisy experiment which are probabilistically related to the underlying state of the world [3]. Let $\boldsymbol{r} = (r_1, r_2, \cdots, r_n)$ constitute a vector of probabilistic reports obtained from

experts regarding the probability of a specific variable θ. A straightforward application of the Bayes rule yields

$$P(\theta \mid r) = kP(r \mid \theta)P(\theta). \quad (7)$$

The term $P(r \mid \theta)$ formalizes the decisionmaker's (or aggregator) knowledge regarding the manner in which the reports r are influenced by the underlying variable θ. It contains, for instance, his knowledge concerning the reputation of various experts insofar as issuing a faithful and accurate report. It also contains knowledge about the correlation expected among the experts (e.g., it protects against counting repetitive reports with equal weights).

The problem of integrating expert opinions is very similar to that of integrating knowledge received from various sections of one's memory. The internal clues or attributes used to predict an outcome serve the same function as external experts; the two represent a condensed code of past experience which is no longer available to the integrator. There is one difference, though, which makes the problem of expert aggregation harder than that of internal aggregation. A person is usually much more familiar with the nature of his internal procedures than with the nature of the experts he consults. For one thing, a person may have actively participated in the original design of his heuristic procedures (i.e., to render them linear decomposable) or may have observed their performance over a variety of inferential problems. In addition, tests on the operations of one's internal procedures can be readily conducted, as they involve only mental exercises. As a result, the articulation of the function $P(r \mid \theta)$ may, in general, be a much harder task than the characterization of $P(a \mid \theta)$ or $E(S \mid a)$ in (4).

Let us now imagine that a panel of experts provides a list of value judgments instead of a probabilistic report. For example, each of the n experts may issue a real number $V_i(\theta)$, $i = 1,\cdots,n$, reflecting his assessment of the social value of a certain project θ. Our guiding paradigm dictates that each of these assessments should be treated as a condensed code for the expert's personal experience with related events. It should be processed, therefore, as an outcome of a physical measurement on the underlying process relevant to the value of θ, in the same fashion as probabilistic reports.

Let us first examine the case of competitive experts. Assume that a leasing authority offers a certain parcel of undeveloped land for bid in the open market and that each bidder issues his personal judgment as to the value of the land. Such judgments are usually issued after a careful survey of the property and after assessing the manner in which the development project might fit into the bidder's frame of business. It represents, therefore, the quantity V_i which measures the expected benefit to the ith bidder, assuming he wins the contract. The leasing authority attempts to determine the real worth of the property $V(\theta)$ on the bases of its own study as well as the aggregate reports it receives from the bidders. That worth depends on both the total income stream the property can generate, and the ability of the decisionmaker to enjoy that income. (Unlike a neural activity stream $s(t)$, an income stream should be discounted to account for uncertainties in one's ability to consume the income [17] or convert it into neural satisfaction.) Assume, for the moment, that the decisionmaker's expected benefit $E(S \mid \Theta)$ could be calculated given a set of attributes $\Theta \doteq (\theta_1,\cdots,\theta_K)$ of the said property, (e.g., Θ could include the quantity of oil deposits, the depth of that oil, etc.). The value judgments $V_1,V_2,\cdots,V_n$ could be used to modify the decisionmaker's probability distribution on Θ, yielding an aggregate utility:

$$\begin{aligned} U &= E[S \mid V_1,V_2,\cdots,V_n] \\ &= \sum_{\Theta} E(S \mid \Theta)P(\Theta \mid V_1,V_2,\cdots,V_n) \\ &\cdot \sum_{\Theta} E(S \mid \Theta)\, \frac{P(V_1,V_2,\cdots,V_n \mid \Theta)P(\Theta)}{P(V_1,\cdots,V_n)}. \end{aligned} \quad (8)$$

The term $P(V_1,\cdots,V_n \mid \Theta)$ represents, like the terms $P(r \mid \Theta)$ in (7), the decisionmaker's model of the experts, especially the dependence of their reports $V_1,\cdots,V_n$ on the value-determining parameter Θ. It should reflect the professional reputation of their surveyors, a possible correlation among the latter, and even the possibility of a concerted attempt to underbid the agency. A Bayesian scheme identical to (8) was used by Kaplan [18] in analyzing off-shore oil bidding strategy. Its salient point is the exploitation of value judgments as means for sharpening the decisionmaker's estimation of a state parameter Θ, which affects his own personal utility.

Let us now return to a more cooperative situation and consider, for example, a public official polling his constituents regarding the value of a certain public policy. It is customary in problems of this sort to view the official as an echo to public wishes and to seek equitable entity called public utility, which should be obtained by some arithmetic aggregation rule applied to the individual values of the constituents [19]. Aside from the celebrated conceptual difficulties connected with the concept of group utility [20], [21], this model also suffers from a practical drawback: it is utterly unrealistic. Regardless of how benevolent the public official is, he is bound by the very nature of his neural system wiring to act in a way that would maximize his *own* expected gratification. Part of this gratification is derived from materially contributing to public welfare, part from enjoying the image and reputation of a good-doer, and part from power-derived personal benefits. In short, it contains all factors and forces which play a role in the normal political arena. The maximization of the gratification function S requires knowledge of certain parameters Θ which underly the sociopolitical scene. Θ could include, for example, the degree of public trust enjoyed by the official at any given time, his likelihood of retaining power, etc. A rational scheme of aggregating public values would therefore consist of utilizing the latter as information signals to update one's knowledge of Θ in a manner similar to that of (8). If, for example, a certain value-poll $V_1,\cdots,V_n$ strengthens the official's hypothesis that the wishes of a certain vocal section of the public are erratic or transitory and therefore could be ignored, it makes both ethical and

logical sense for him to incorporate this knowledge into his action scheme.

On this note we wish to argue that it is in the systemization of such knowledge-updating procedures, rather than the advocation of *ad hoc* value-aggregation rules that Bayes technology would provide a realistic assistance to the decision process.

IV. Summary

The basic paradigm expanded in this paper is that value judgments are to be interpreted as representations of factual information. The meaning of such judgments, therefore, lies solely in their connection to empirical data recorded by an individual or by a cultured society. Viewed in this light, the problem of processing value judgments becomes almost identical to that of processing other codes of experiential knowledge, i.e., probabilistic judgments. This view implies that, aside from the desire to satisfy one's value structure, other factors should also be considered, such as the faithfulness of the judgment and the appropriateness of the experience it represents to the facts surrounding the problems at hand. Bayes analysis, the formalism used for representing factual knowledge and probabilistic judgments, can also be used to capture such consideration of faithfulness and appropriateness of value judgments, and incorporate the latter in a unified representation of human knowledge.

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