CREATIVE DESIGN SKILLS
OF
ENGINEERING STUDENTS

by

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SUMMARY

An investigation has been carried out into the creative design skills of engineering students in the University of Melbourne. In order to tap students' creative abilities, open-ended design problems representative of those encountered by the professional engineer in practice were devised. Students' responses to the problems were then observed and analyzed.

The results showed that there were many interesting and apparently important aspects of the students' creative problem-solving behaviour which could be identified and measured, but which were not revealed by performance in conventional university examinations. These aspects of problem-solving appear to be important from the point of view of the students' later professional careers, but further work is needed to confirm this.
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CHAPTER 1

INTRODUCTION

1.1. GENERAL

As a result of the rapid growth of scientific knowledge since the Second World War, university courses in engineering have increasingly stressed scientific developments and the techniques of analysis they have made available to the engineer. However, in recent years, several leading engineers and educators have expressed fears that there is now too great an emphasis on the acquisition of scientific knowledge by engineering students. They have argued that the development of students' abilities to apply their knowledge constructively is being neglected. In his presidential address to The Institution of Mechanical Engineers in 1967, H.G. Conway said, "Today the great problem (in engineering education) is the trend towards the academic in our educational system. Few if any universities, bent on obtaining first class honours results, are giving rein to the creative powers of their students" (Conway, 1967).

Similar views have been expressed in the United States. In his introduction to the proceedings of a Conference on Education for Innovation, De Simone wrote "In the schools of engineering since the Second World War ... the stress has been an analysis rather than synthesis ... The art of creative engineering has been orphaned in the engineering schools ... The development of the inventive and innovative potential of engineering students should therefore be an active concern of government, industry and the Universities" (De Simone, 1968). One of the recommendations of this conference was that systematic studies should be carried
out into the identification of creative talent in engineering students.

However, professional engineers, whether practitioners or academics, have had great difficulty in coming to grips with the concept of creativity. In 1970, the Council of Engineering Institutions in the United Kingdom sponsored a Conference on Creativity in Engineering which "failed to agree on a definition of creativity, or a method of measuring creativity ... Better educational methods were thought to be the answer" (Whitfield, 1970). Design is an engineering activity in which creativity is generally thought to be a major ingredient. The Goals Report of the American Society for Engineering Education (Walker et al., 1968) states, "The importance of creative design throughout undergraduate and graduate programmes deserves the immediate attention of engineering educators. They must develop programmes which will give the student an opportunity to experience the thrills of invention, the excitement of original and imaginative thought in his chosen field." In view of this recommendation it is surprising to find that up to a year before the report was published there had been no experimental research into the use of open-ended design problems for testing or developing the creative abilities of engineering students (Craft, 1967). And in 1969 an A.S.E.E. Conference on Engineering Design deplored the lack of systematic research into the design process itself (Jenks, 1969).

The proceedings of the A.S.E.E. 1969 Conference suggest a number of ways of presenting creative design activities to undergraduates. The methods rely heavily on the use of group projects and case studies. In an earlier paper, Hayes and Tobias (1965) also discuss the use of group projects, confining their
attention to specialised topics in mechanical engineering. In neither case is there any indication as to how the performance of individual students is assessed, and there is very little information on the range and variety of students' responses to the exercises and projects described. There is almost a complete lack of quantitative data on the performance of engineering students in those undergraduate courses in which creativity appears to be an important element. For example, it is not known whether students who perform well in the creative aspects of engineering design are likely to have a record of successful academic achievement, or whether creative design exercises tap abilities not otherwise called on in their undergraduate courses.

1.2. AIMS

It is clear from the above discussion that there has been little research into creativity in engineering education. As a result there are many important questions to which it is impossible to give an authoritative answer. The starting point for the present investigation was acceptance of the basic premise that the problem-solving ability of engineering students should be developed by work on creative design exercises. This was in accord with the recommendation, quoted earlier, of the Goals Report of the American Society for Engineering Education and with the views of a number of prominent engineers. However, the educator who wishes to act on this premise in the development of an undergraduate course is faced with many unresolved questions concerning the nature of engineering design and the scope it provides for the exercise of creative skill. The aims of the research were therefore formulated as follows.
(1) To investigate creative design by university students of engineering. In particular,

(a) to establish a theory of the design process and the creative skills it calls into play, as a basis for the subsequent experimental programme;

(b) to devise tasks to elicit evidence of creative skills in engineering design;

(c) to observe the responses of engineering students to the tasks;

(d) to develop techniques for measuring the creative design skills displayed by students in response to the tasks.

(2) To investigate whether there were significant correlations between the different measures of students' creative skills developed in (1) and/or between these skills and other evidence of academic achievement such as examination marks.

(3) To develop methods for identifying those students most capable of creative engineering endeavour.

Achievement of these aims would lay the foundation for a long-term investigation into the role of creativity in engineering and the identification and measurement of the creative skills exercised by professional engineers. It was expected that elucidation of the role of creativity in engineering would help to clarify the objectives of engineering education, and that the knowledge so gained would in turn lead to improved teaching methods for developing the creative problem-solving skills of engineering students.
1.3. SCOPE OF THEESIS

1.3.1. Guidelines

Creativity offers a very broad and complex field of enquiry. It was therefore necessary to limit the scope of the investigation and the following guidelines were drawn up for the conduct of the research.

(1) Throughout, engineering design is considered as a form of problem-solving, i.e. a goal-directed human activity. It has been argued (e.g. by Vickers, 1965) that much human behaviour is not concerned with achieving goals but with regulating an on-going activity, for example, maintaining the set of relations between the different parts of a social system in accordance with accepted norms. Such regulatory behaviour is distinct from problem-solving and is not considered in the thesis.

(2) Design problems are open-ended, and typically have many possible solutions. For this reason analytical or mathematical problems having one correct answer are excluded from the discussion.

(3) The subjects taking part in the investigation are university engineering students, working individually on their own and not as members of groups.

(4) The design problems presented to them deal with the innovative design of engineering systems or products in order to give scope for the exercise of creative skills.

(5) Broadly speaking, the solution of design problems requires two types of activity: divergent and convergent. In the divergent phase of design, the problem is being formulated and ideas evolved as the designer searches for
acceptable solutions. In the convergent phase, the designer evaluates alternative proposals and makes decisions as he converges onto his final solution. In this thesis, the emphasis is on the divergent phase of design and the creative skills associated with it. The convergent phase is not the subject of study in its own right, but may be considered in conjunction with the divergent phase that preceded it as part of the overall design process.

(6) In practice a designer may find that important data are missing and he may then devise and conduct experiments to fill gaps in the information available. He may also carry out experiments to help predict the performance or behaviour of the system or product being designed. Special skills are required for devising and conducting experiments but they are outside the scope of the thesis which is essentially devoted to the study of the intellectual skills of the designer.

(7) The research is concerned with the cognitive behaviour of the engineering designer. Excluded from study are his personality, attitudes, values and motives. It is realised that the designer responds to a problem as a whole being, but many educationists have found the distinction between the cognitive and the affective domains a convenient one, for example, Bloom (1956) and Kratwohl et.al. (1964). In so far as the subjects in the present investigation are university students and in so far as current university courses heavily emphasise cognitive behaviour, it is reasonable to maintain this distinction - particularly as there are few or no precedents for this research and it is necessary to keep the scope of the work within acceptable limits.
1.3.2. Layout of Thesis

The thesis is arranged in the following order.

Chapter 2 establishes the general theoretical framework for the investigation and surveys the relevant literature on (a) engineering design and (b) the psychology of problem-solving and intelligence.

Chapter 3 reviews the relevant literature on creativity in engineering.

A series of experiments was then devised to elicit different aspects of creative effort in engineering design. Chapter 4 describes the planning of the experimental programme, which involved second and third year students in the University of Melbourne, and the methods used for processing and interpreting the results.

Chapter 5, 6, and 7 deal with the responses of students to the tasks presented to them, and the evidence concerning creative design skills is brought forward and critically examined.

During the course of the experiments, problems arose concerning the measurement of creative design skills. These are described in Chapter 8 and the implications for future research discussed.

In conclusion, Chapter 9 reviews the research and the results obtained, draws appropriate conclusions, and makes recommendations for future investigations.
2.1. INTRODUCTION

This chapter establishes the theoretical basis of the research. The aim is to provide a framework which will relate the experimental results to theories of problem-solving and intelligence and also to other investigations into the nature of engineering design and the work of the designer.

Firstly the different types of human problem-solving behaviour are considered, and design defined in this context as a form of problem-solving. There is, however, a great variety of engineering design problems. Ways of classifying these problems are next examined and a classification drawn up which places in perspective the experimental tasks used later in the research.

A design skill is defined as the ability to carry through successfully one step in the design process. The next section of the chapter therefore considers models of the design process proposed by different workers, the theoretical and experimental evidence in their favour and their applicability to the current investigation. As a result of this discussion an operational model is adopted to represent the divergent phase of engineering design. This model in turn leads to hypotheses concerning creative design skills. Supporting evidence for the hypothesised skills comes from psychological
research into the nature of human intelligence, and the chapter therefore concludes with an interpretation of creative design skills in terms of relevant psychological theory. This theory also offers guidance on methods of identifying and measuring these skills.

2.2. THE CONCEPT OF "PROBLEM"

The discussion is based on a cybernetic model of rational, human, goal-seeking behaviour, as proposed for example by Heywood (1970), Fig. 2.1.

Fig. 2.1. Model of Rational, Goal-Seeking Behaviour.

Problems do not exist in a vacuum, but arise when a human being - the problem-solver - perceives a goal but not the means of attaining it (Gagné, 1959; Merrifield et al., 1962; Krick, 1969).

The problem-solver therefore makes plans and acts in accordance with these plans in a way that he predicts will achieve the desired goal.
He observes the outcomes of his actions and if there is a difference between the outcomes and the desired goal he takes corrective action.

In attempting to achieve the goal and to maintain conditions at the desired level of performance, the problem-solver undertakes two major types of activity:

1. PLANNING actions to achieve the desired goal;
2. TROUBLE-SHOOTING, correcting deviations in performance from the desired standard.

These then are the two PRIMARY types of problem-solving activity.

This thesis is concerned with the planning activities characteristic of engineering design. It does not deal with trouble-shooting which is, however, extremely common in engineering operations and management where problems often arise because of deviations from accepted standards of performance (Kepner and Tregoe, 1965). In business administration, trouble-shooting is sometimes known as management by exception.

To support PRIMARY problem-solving there are three major types of SUBSIDIARY problems with which the problem-solver may have to deal in order to achieve his ultimate goal. They are:-

1. Problems of RESOURCE ALLOCATION, arising from difficulties experienced by the problem-solver in matching the resources required to solve the primary problem with the resources available.
2. Problems of INFORMATION ACQUISITION, arising from gaps between the information required by the problem-solver and the information available to him.
(3) Problems of VALUES, arising from difficulties experienced by the problem-solver in assigning values to the goals he hopes to achieve.

This thesis is concerned with primary problems and only considers subsidiary problems in passing.

The above discussion suggests a classification of problems based on the type of activity of the problem-solver. Following Hinton (1968), we may consider these activities as "processes" and describe the classification as one based on "process variables".

Alternatively, we can describe problems in terms of "task variables" independent of the problem-solver, as proposed by Ray (1955), Reitman (1964, 1965), Krick (1969).

In any problem there are :-

(a) an initial state of affairs or state of a system which may be represented by the components of a vector, \( A \), and

(b) a final state of affairs, \( B \).

The problem-solver is concerned with the means of transforming from \( A \) to \( B \), denoted \( \Rightarrow \).

Initially there will be some information about \( B \). According to the nature of the problem, \( B \) may be completely specified or only partially specified.

\( A \) may be completely specified, partially specified, or not specified at all.

The rules governing the transformation \( \Rightarrow \) may be well-defined (as in mathematical problems) or ill-defined or unknown.
The problem solver considers his problem isolated from an environment specified by a vector $E$ as indicated in Fig. 2.2, where $E$ may or may not change with time.

![Diagram of Problem Definition](image)

Fig. 2.2. Definition of Problem in terms of Task Variables.

While the above discussion has been kept as general as possible, there is one unusual problem-solving situation not covered by it. This arises when some device or process is given, and $B$ and $A$ have to be found. For example, an inventor creates a new device and asks, "What can I use this for?" or the manufacturer of a particular product wishing to broaden his market and increase sales asks "What other uses are there for this product besides the existing one?"

2.3. CLASSIFICATION OF DESIGN PROBLEMS

2.3.1. Design as a Form of Problem-Solving Behaviour

Fig. 2.3 classifies problems according to the nature of the process variables. This follows the discussion in Section 2.2 with the addition that planning problems are divided into two kinds depending on whether the planner

(a) solves problems in a static or quasi-static environment (DESIGN);
(b) solves problems in a dynamic or rapidly changing environment (GAME).

PROBLEMS IN GENERAL

<table>
<thead>
<tr>
<th>PRIMARY</th>
<th>SUBSIDIARY</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLANNING</td>
<td>TROUBLE-SHOOTING</td>
</tr>
</tbody>
</table>

DESIGN | GAME

Static or Dynamic Environment
Quasi-Static Environment ($E = \tilde{E}(t)$)
Environment ($E = \text{Constant}$)

Fig. 2.3. Classification of Problems - Classification Based on Process Variables.

Engineering design was first described as a sequential decision-making process by Rosenstein and English (1960, see Tribus, 1969, for a recent discussion), while von Neumann and Morgenstern (1947) in their classic discussion of game theory considered a game to consist of sequences of moves made in turn by a number of players, each move involving a choice or decision by a player. Thus both solving design problems and playing games are sequential, decision-making processes, the difference being that in the gaming situation there are significant changes in the
environment arising from the consequences of other players' moves, whereas this is not the case in design.

In passing it may be noted that certain types of problem classed as subsidiary from the point of view of this thesis are often important in practice. Some examples involving exploratory behaviour deserve mention.

The research scientist is concerned with exploring an existing environment rather than with planning for the future. He frequently has to formulate hypotheses to account for observed phenomena in terms of existing theories or perhaps to create a new theory. In many problems in scientific research, particularly in fundamental research, the final state $B$ is reasonably well-defined by a set of experimental data but the initial state $A$ and the transformation $\Rightarrow$ are essentially unknown. The scientist therefore, like the trouble-shooter of Section 2.2, has to evolve hypotheses, and his skill in so doing will presumably be allied to his skill in discerning patterns in or underlying connections between apparently disparate pieces of information.

Reitman (1965) refers to a very general class of problem which he calls "ill-defined problems", and suggests that there may be a continuum ranging from such well-defined formal problems as proving a mathematical theorem to such ill-defined problems as composing a piece of music. In ill-defined problems much exploratory effort may be devoted to acquiring information which helps to define the problem more precisely, i.e. to gaining information on $A$ and $B$ and on the boundary between the problem and its environment. As a result of his work on a research project on the objectives
of engineering education, Hill (1971) regards exploring ill-defined problems as an important type of human problem-solving activity.

2.3.2. Classifications of Design Problems Based on Task Variables.

(1) Classification Based on \( A \)

Problems in engineering design can be classified according to the nature of \( A \) into

(1) modifications to existing designs, for example modifying an existing production line to increase the output of finished components;

(2) new designs, where a new system or device is to be brought into being, for example designing a production line for a new automobile plant.

New designs may in turn be classified as

(1) innovative - where little or no information on \( A \) is given, for example design of a device for automatically sorting ripe from unripe fruit;

(2) evolutionary - where there is a good deal of information on the starting point \( A \) of the design from previous successful efforts, e.g. design of a steam turbine for a small power station;

(3) extrapolatory - where \( A \) consists of successful precedents physically smaller in size, or in the case of machinery, slower in operating speed. (Extrapolations may be along dimensions of either space or time.)

The type of system or product being designed is known, and this represents the starting point for the design. An example would be the design of a steam turbine for a large modern power station, say for an output of 1000 megawatts
when in existing practice turbines up to 500 megawatts have been successfully designed and operated.

The above discussion leads to the classification shown diagrammatically in Fig. 2.4.

ENGINEERING DESIGN

- Modifications to Existing Designs
- New Designs
  - Evolutionary Design
  - Extrapolatory Design
  - Innovative Design

Fig. 2.4. Classification of Problems in Engineering Design, Based on A.

(2) Classification Based on

It is also possible to classify problems in engineering design according to the nature of the means of transformation (⇒) from the starting point to the finishing point.

Different writers have proposed different classifications according to their own interests and to suit the purposes of their discussion. A review of the literature suggests the following distinctions are worthwhile.

(1) Policies
(2) Systems
(3) Products
(4) Parts
Policies

Vickers (1965) describes policy-making as "the setting of governing relations or norms" which regulate the activities of a society or social institution such as a local council or public company. He distinguishes between executive or practical problems, such as those dealt with by the engineer, and problems of policy which are the responsibility of the manager or administrator. However, the engineer may be called on in practice to play an administrative role and formulate policies. An example, from engineering education, is given by Converse (1969). Students in a design course in an American university were asked to study the problems involved in the management of a local river system and to formulate and justify some public policy they felt to be prudent.

Systems

Hall (1962) defines a system "as a set of objects with relationships between the objects and between their attributes", and the environment as "the set of all objects outside the system".

These definitions imply that it is possible (and useful) to separate a system from its environment in such a way that any interactions between the elements of the system and the environment are small, hopefully negligible. By correctly selecting the boundary between a system and its environment, the problem-solver hopes to mark off and define the universe containing all the factors of interest in a given problem.
Milner and Pengilley (1970) point out that it is necessary to distinguish between "static" systems where the behaviour of the system does not change with time (for example, a portal frame) and "dynamic" systems where the behaviour of the system does change with time (for example, a four bar chain). In turn a dynamic system may be uncontrolled (e.g. the solar system) or controlled (e.g. a motor car). In the latter case the dynamic system is partitioned into two sub-systems with which we associate, respectively, that part of the system which is controlled and that which controls. Fig. 2.5 illustrates this discussion.

![Classification of Systems](image)

**Fig. 2.5.** A Classification of Systems.

Jones (1966) distinguishes between "flow" systems and "associative" systems. As pointed out by Boulding (1967) and others, the flow characteristics are multi-dimensional and may involve the interchange of information, mass (including people as well as inanimate materials) and energy between the elements of the system. Examples of flow systems are thermal power stations, oil refineries, manufacturing plants.

In an associative system the primary relation between the elements is one of geometry and position, as for example in the motor car where
the engine, chassis, passenger compartment, suspension and controls
have to be arranged to form one compact package. Associative systems
have also been referred to as products, mechanical systems (Jones, 1966)
and machines (Gagné, 1962). Gagné uses the word "machine" in a general
sense to denote any physical means for extending man's capacity for
perceiving and manipulating the environment. He is concerned to
distinguish between the individual machine or product and the larger flow
system of which it is a part.

Crawford (1962) points out that it is useful to classify systems
along a continuum in terms of the relative amount of hardware present
critical to system function. The "man-ascendant" system characteristically
takes its physical form and spatial configuration from its human elements,
e.g. an infantry squad in an army. In a "machine-ascendant" system such
as a newspaper printing press, the machine itself defines the physical position
of and places obvious constraints on the performance of the men operating
it. A more detailed classification of man-machine systems would take
account of the fact that a human being can perform a number of different
roles in a system of which he is an element (Gregory, 1969), but this
extension of the argument is not warranted in the present introductory discussion.

Products

Much engineering design effort is devoted to the design of products.
Whereas the systems engineer is only concerned with the input-output behaviour
of a product as one element in his system, the product designer considers the
product as an entity in itself. Thus the designer of the motor car is
primarily concerned with one product, whereas the designer of transport
systems considers the motor car as just one of a number of elements he
has to deal with.

Various writers have identified particular classes of product in
the field of their interest. After a detailed analysis of many machines
(the word machine here being used in its conventional sense), Reuleaux
(1963) concluded that machines fall into two major categories -

(1) place-changing machines
(2) form-changing machines.

Watts (1966) considered another category, namely measuring
machines or instruments where the objective is to maintain functional
relationships between prescribed variables.

Some writers have considered "tools" as a separate category.
For example, Edel (1967) offered a confused classification based on a
mixture of task and process variables in which the tools and equipment required
for mass production systems formed a separate category. In a somewhat
similar way Eder (1966) considered powered manual equipment as a separate
class of design which extends man's manufacturing capabilities. Eder also
considered heavy engineering as a separate category.

To support his argument on possible future developments in the
British engineering industry, Davis (1964) devised a classification of
engineering products, once again based on a confused mixture of task and
process variables. When this mixture is unravelled the following dimensions
emerge:

1. Physical size (task variables)
2. Aesthetic content (task variables)
3. Quantity produced (task variables)
4. Innovational content (task variables)
5. Methods used by designer to predict performance of product (process variables)

A distinction made by economists and accepted by Davis in a revised classification (Davis, 1966) is that between consumer goods (produced in large quantities where aesthetic content is important) and capital goods. Other distinctions implicit in Davis' 1966 classification are based on complexity and scale, where the complexity of a product would presumably be measured by the number of parts of which it is composed and its scale by the number of levels in the design hierarchy.

All the distinctions drawn by Davis could of course be applied to systems as well as to products.

Parts

Parts are the individual pieces which have to be assembled together to form engineering products and systems.

Because of the large number of prior decisions already taken, the design of a part is usually subject to a large number of constraints. While there is scope for engineering judgment and attention to detail, there is little opportunity for the exercise of creative effort, and this thesis is therefore
entirely concerned with problems arising in the design of engineering products and systems.

(3) Classification Based on B

Several authors have discussed design problems from the point of view of the number of objectives to be met and the number of criteria used in assessing the alternative solutions proposed. Design problems may thus be classified according to the nature of the end condition B, and in particular according to

(1) the number of criteria by which performance of the design is judged;
(2) the number of dimensions on which this performance is measured;
(3) the types of scale used for measurement.

One of the simplest cases arises when there are two criteria and both can be measured objectively on the same scale. Field (1970) discussed a mechanical design problem of this type in which there were two conflicting requirements and each could be expressed on the same scale, namely cost in dollars. The problem concerned the design of a heat exchanger where increasing the velocity of cooling fluid led to a higher heat transfer rate and hence to a smaller heat exchanger of lower capital cost. At the same time the pressure drop experienced by the cooling fluid increased as did the pumping power required to circulate it. The compromise between the requirements for high rate of heat transfer and low pressure drop was made
in such a way that the total cost of the heat exchanger (capital cost plus running cost) was a minimum.

A more complex state of affairs exists in design problems having two conflicting criteria which are measured on different dimensions. For example, Gasparini and Chong (1969) investigated the design of motor car side pillars, where the requirement for structural integrity conflicts with that for minimum obstruction to the driver's vision of surrounding traffic. Another example is given by Whittle (1953). In the design of an early jet engine, he had to balance the susceptibility of the main shaft to vibration (as indicated by its critical speed) against the drop in engine output due to the complicated flow path of the air and gas stream through the engine.

In these two examples the performance of the design against the relevant criteria could be measured objectively on continuous scales. This need not always be the case: scales need not be continuous, comparisons may be made by subjective ratings. Wehrli (1968) examined an architectural problem - the design of a primary school - and set up 24 criteria based on considerations of aesthetics, the social psychology of teaching, circulation of traffic, and use of the site in relation to its environment. The designs proposed were ranked on a scale of 1 to 7 against each criterion by an expert judge.

Table 2.1 summarises the important characteristics of the examples discussed above; it sets out the design criteria and the dimensions and scales used with them.
<table>
<thead>
<tr>
<th>Example</th>
<th>Criteria</th>
<th>Dimensions</th>
<th>Scales</th>
<th>Nature of Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of Criteria</td>
<td>Nature of Criteria</td>
<td>Number of Dimensions</td>
<td>Nature of Dimensions</td>
</tr>
</tbody>
</table>
| Field (1970)            | 2            | (1) Heat transfer  
                          | 1            | Total cost    | Dollars | (1) Continuous |
|                         |              | (2) Pressure drop      |              |                |         | (2) Objective  |
| Gasparini and Chong     | 2            | (1) Structural integrity  
                          | 2            | (1) Force to break structure  
                          | lbf          | do.                |
| (1969)                  |              | (2) Driver vision  
                          |              | (2) Angle subtended at driver's eye 
                          | radian       | do.                |
|                         |              | by region of obfuscation |
| Whittle (1953)          | 2            | (1) Vibration of Shaft  
                          | 2            | (1) Difference between operating shaft speed and critical speed 
                          | rev/min      | do.                |
|                         |              | (2) Pressure drop in gas stream |
|                          |              | (2) Engine output  |
| Wehrli (1968)           | 24           | (1) Aesthetics  
                          | 24           | Subjective ranking  |
|                         |              | (2) Teaching  
                          |              | Interval scale, from 1 to 7 |
|                         |              | (3) Circulation of traffic 
                          |              | (1) Discontinuous |
|                         |              | (4) Site  
                          |              | (2) Subjective opinion of expert |
2.3.3. Classification of Design Problems Based on Interaction Between Designer and Task

During the course of a design project there are numerous opportunities for interactions to occur between task and process variables. Such interactions are most likely to arise in two phases of the design, namely

(1) problem definition

(2) decision-making.

Problem Definition

The discussion so far has implied the existence of one omniscient designer, but in a project of any size there will be a design team and a client who sets the problem in the first place.

The way a designer works and the results of his efforts may be significantly affected by social interactions with his client. This was clearly brought out in Mitroff's study (Mitroff 1966, 1968) of a mechanical engineer acting as a design consultant on pressure vessels to a group of physicists whose personalities and knowledge of engineering varied greatly. During the research reported in this thesis, the author in effect acted as client in setting problems to students who were called upon to offer engineering advice to the best of their knowledge and ability. The problems were stated in writing by the author as clearly and unambiguously as he could in order (a) to minimise the effects of the types of interaction described by Mitroff and (b) to maintain the interactions that did occur at a consistent level from problem to problem.
Decision-making

When the designer makes decisions the information available to him is usually incomplete. Moreover he is seldom able to predict the outcome of his decisions with absolute certainty. This leads to a classification of design problems according to whether decisions are made under conditions of

(a) certainty
(b) uncertainty
(c) risk.

This distinction is discussed in many text-books on decision-making and operations research, see for example Ackoff and Sasieni (1968).

2.3.4. Review

A survey has been made of the wide range of forms which design problems may take. The intention has been to keep the discussion at a general level in order to construct a framework against which the particular design problems to be examined in detail later in the thesis can be placed.

Table 2.2 summarises possible ways of classifying design problems based on factors external to and independent of the designer. Elements of the design situation internal to the designer and associated with his problem-solving methods will be considered in the next Section.

It may be noted that a classification such as that of Table 2.2 is a useful aid to the designer. If he can place a design problem in a certain category, then a range of sub-problems associated with that category will automatically be highlighted. For example, in systems design, there are
always sub-problems of ensuring compatibility between the different elements of the system and between these elements and the environment. In flow systems the designer has to consider the performance characteristics of interacting elements, thus in jet engines the output from the compressor always has to match the input to the turbine. In associative systems the physical dimensions of connecting parts must match satisfactorily and this leads immediately to questions of dimensional tolerancing.
<table>
<thead>
<tr>
<th>Item</th>
<th>Basis of Classification</th>
<th>Reference</th>
<th>Description of Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DESIGN - A</td>
<td>Innovational Content</td>
<td>Section 2.3.2 (1) Modification to existing design  (2) Evolution  (3) Extrapolation  (4) Innovation</td>
</tr>
<tr>
<td>2</td>
<td>DESIGN - ⇒</td>
<td>Type of Transformation</td>
<td>Section 2.3.2 (1) Policy (2) System  (3) Product  (4) Part</td>
</tr>
<tr>
<td>3</td>
<td>do.</td>
<td>Type of System</td>
<td>Milner and Pengilley (1970) (1) Static (2) Dynamic (a) Uncontrolled (b) Controlled</td>
</tr>
<tr>
<td>4</td>
<td>do.</td>
<td>Type of System</td>
<td>Boulding (1967) Jones (1966) (1) Flow system (a) Mass (b) Energy (c) Information (d) Combination of (a), (b), (c) (2) Associative system</td>
</tr>
<tr>
<td></td>
<td>2. Complexity</td>
<td>Section 2.3.2</td>
<td>Number of parts in system or product</td>
</tr>
<tr>
<td></td>
<td>3. Scale</td>
<td>Section 2.3.2</td>
<td>Number of levels in design Hierarchy</td>
</tr>
<tr>
<td>Item</td>
<td>Basis of Classification</td>
<td>Reference</td>
<td>Description of Classification</td>
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</tr>
<tr>
<td></td>
<td>Process or Task Variable</td>
<td>Classified according to</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>DESIGN - B</td>
<td>Criteria</td>
<td>Section 2.3.2 (1) Number of criteria (2) Number of dimensions on which performance against criteria is measured (3) Types of scale used for measurement</td>
</tr>
<tr>
<td>8</td>
<td>PRODUCTION</td>
<td>1. Total quantity made 2. Rate of production</td>
<td>Davis (1966) (1) Jobbing (2) Batch production (3) Mass production (4) Continuous production</td>
</tr>
<tr>
<td>9</td>
<td>USE</td>
<td>Economic factors</td>
<td>Davis (1966) (1) Consumer goods (2) Intermediate equipment (3) Capital goods</td>
</tr>
</tbody>
</table>
2.4. ENGINEERING DESIGN AS PROBLEM-SOLVING BEHAVIOUR

2.4.1. Introduction

As pointed out by Guilford (1967), model-building is an essential part of theory construction. As part of the theoretical framework for this investigation we now require a model of the design process. On the one hand, the model must be simple enough for it to be constructed and used, while on the other it must be complex enough to mirror adequately the complexities of the activities it endeavours to represent. In this thesis two models will be used, the first an operational model and the second a topological one. These models are intended to be theoretical descriptions or representations of the activities of engineering design; they are not manipulative models in the sense that engineers use mathematical and other models to simulate the performance of physical systems in order to predict and control their behaviour.

An operational model of engineering design (or of any other form of problem-solving for that matter) represents the actions of the engineering designer as a sequence or interconnected set of events with transmission of information between events.

A topological model represents the design process by means of a graph, for example a tree or network. This type of model is useful in research because it enables the efforts of different designers on complex problems to be compared. Topological models are thus an aid to investigation and also to the communication of results obtained. They will be discussed in Section 2.4.4.
Operational models of problem-solving have been suggested by many writers and thinkers. All are broadly similar as the following comparison between workers in the different fields of systems engineering (Hall, 1969) and psychology (Merrifield et al., 1962) shows.

Hall lists the steps in the general problem-solving procedure as follows:

1. Problem definition.
2. Design of value system - the development of objectives and criteria.
3. Synthesis - the collection and/or invention of alternative solutions.
4. Analysis - the prediction of consequences of alternative solutions.
5. Optimization of each alternative.
6. Decision-making - the application of value systems.
7. Implementation.

Merrifield et al. (1962) envisage the typical problem-solving process to consist of five phases, not necessarily clear-cut steps as there may be overlapping of particular events. The five phases are:-

1. Preparation
2. Analysis
3. Production
4. Verification
5. Re-application.
The first three items in this list correspond to the first three items in Hall, but whereas Merrifield et al. give the fourth step simply as "verification", Hall breaks this down into three separate steps. By "re-application", Merrifield et al. mean iterations and backtracking which may occur at any stage of the problem-solving process when progress appears unsatisfactory. This corresponds to Hall's comment that there will be feedbacks of information from later to earlier steps in his procedure and consequent iterations.

The next Section examines operational models of engineering design. These turn out to be similar to the general models outlined above, not a surprising result since design is an important form of problem-solving.

2.4.2. Operational Model of Engineering Design

Table 2.3 compares operational models of the design process put forward by a number of authors for engineering and allied fields of endeavour such as architecture and product design. All these authors support their arguments with case studies of actual designs from practice which fit the models proposed. While the terminology of different authors varies, it is interesting to observe that their proposals are very much alike.

Similar models have also been taken as the basis for discussion by a number of text-book writers and theorists who do not, however, quote specific examples. Included in this group are Alger and Hayes (1964), Edel (1967), Elmaghraby (1968), Jones (1967), Jones (1970), Roe et al. (1967), and Rosenstein and English (1960). Archer and Hall have also given expositions
<table>
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<tbody>
<tr>
<td><strong>Briefing</strong></td>
<td></td>
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<tr>
<td>Recognition of problem</td>
<td>Recognition of need</td>
<td>Recognition of problem</td>
<td></td>
<td>Confrontation</td>
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<tr>
<td><strong>Programming</strong></td>
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<tr>
<td>Definition of problem</td>
<td>Definition of goal (general)</td>
<td>Formulation of problem (general)</td>
<td>Analysis (collection and classification of all information relevant to design problem)</td>
<td>Formulation of problem</td>
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<tr>
<td>Data collection</td>
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<tr>
<td>Research (data collection)</td>
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<tr>
<td><strong>Analysis (planning strategy)</strong></td>
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<tr>
<td>Specification of task (detail)</td>
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<tr>
<td><strong>Synthesis</strong></td>
<td></td>
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<tr>
<td>Synthesis of solutions</td>
<td>Ideation</td>
<td>Search for alternative solutions</td>
<td>Synthesis (formulation of feasible alternatives)</td>
<td>Selection of design concepts</td>
<td>Elaboration of design concepts</td>
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<td></td>
<td>Conceptualization</td>
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<td><strong>Development</strong></td>
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<tr>
<td>Evaluation and decision</td>
<td>Analysis (decision based on theoretical predictions of performance)</td>
<td>Decision (Evaluation of alternative solutions and selection of the best)</td>
<td>Evaluation (judging of feasible solutions against criteria to find the most satisfactory)</td>
<td>Construction of models, theoretical and experimental analysis of models</td>
<td>Optimization decisions</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.3. Comparisons of Operational Models of the Design Process in Engineering and Allied Fields of Endeavour.
Table 2.3. (Continued)

<table>
<thead>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication</td>
<td>Implementation</td>
<td>Description of solution</td>
<td>Specification of solution</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Presentation</td>
<td></td>
<td>Supervision of construction</td>
</tr>
</tbody>
</table>
other than those summarized in Table 2.3 but in essentially the same terms (Archer, 1969, and Hall, 1962).

All authors point out that the solution of design problems is not a unidirectional, cut-and-dried procedure. One step in the process can overlap another so that it may not always be possible to consider a step in isolation from those preceding and following it. Feedback of information from later steps to earlier ones may lead to iterations which cannot often be predicted in advance, particularly in innovative problems.

The amount of detail included in their models by different authors varies. The most detailed account is presented by Archer (1965) in an extensive elaboration of the model summarized in Table 2.3 in which he establishes a P.E.R.T.-C.P.M. type of network consisting of 229 separate events. However, for the purposes of this investigation the author has preferred to use the relatively simple model set out in Table 2.4. As attention is being focussed on creative skills, the model is confined to the divergent phase of design, where the designer is continually diverging from his starting point, amassing new information, opening up and exploring new lines of attack on his problem. In the convergent phase of design, alternative proposals are evaluated and decisions made until the designer finally converges onto one final solution. This phase of the design process as explained earlier in Chapter 1 is outside the scope of the thesis.
Table 2.4. Operational Model of the Divergent Phase of Design.

1. Recognition of problem.
2. Definition of problem.
   2.1. Establishment of objectives, priorities, criteria.
   2.2. Identification of inputs to the design, resources available.
   2.3. Isolation of the design problem from its environment, establishment of the boundaries of the design.
   2.4. Identification of sub-problems likely to arise during the course of the design.
3. Collection of data.
4. Planning the strategy.
5. Creation of solutions to sub-problems.
6. Foreseeing implications of alternative solutions.

The amount of detail shown in Table 2.4 is a compromise between adequately representing the steps in the design of a complex product or system and those in the design of a simple product. Following Archer and Wehrli, "collection of data" and "planning the strategy" are retained as separate steps. They will almost certainly be present in complex designs but may be absent in simple ones. "Defining the problem" is too vague a description to stand on its own, and the detailed stages of problem definition have therefore been given in a form which follows the exposition of Section 2.2 and is similar to that of Rosenstein and English (1960) and Wehrli (1968). In the notation of
Section 2.2, the four stages listed correspond to:

(1) establishing the elements of B including its dimensions and the scales for measuring performance on each dimension, (2) identifying the elements of A, (3) distinguishing between the design problem and its environment E, and (4) recognising the structure of the design problem and possible gaps in the data available.

Evidence of design skills is provided by the successful execution of steps in the design process. In planning an experimental programme to elicit this evidence, it will be necessary to devise tasks corresponding to each step in the operational model of engineering design. This will be discussed further in Chapter 4.

2.4.3. Discussion of Operational Model

While the operational model set out in Table 2.4 follows closely previously published work, it is open to criticism on a number of grounds. Since the model occupies a central place in the investigation its possible shortcomings must be reviewed, namely (1) the formal nature of the model, (2) its static nature and (3) the amount of detail it contains. Each criticism is now considered in turn.

Firstly, then, there is the possibility that the model formalises processes of problem-solving which are usually informal, in that the designer may not be consciously aware of the steps through which he is working. Thus Donaldson (1959) comments that knowledge of structure is usually implicit in ordinary problem-solving. The model does not recognize informal or
intuitive problem-solving methods which may therefore be overlooked in a research programme based exclusively on it. To take account of this possibility and to give breadth to the investigation, a study of the role of informal methods in engineering design has been undertaken and the results are reported in due course in Chapter 7.

Allied to this criticism is that of Nadler (1967) and Jones (1970), who consider that operational models of design of the type discussed in Section 2.4 place too great an emphasis on breaking down problems into sub-problems. If these models are correct, the designer would lose sight of the forest because of his preoccupation with the trees, leading to what Jones describes as the "disintegration of design". Nadler argues that instead of trying to keep track of many uncoordinated bits and pieces of information, the engineer develops an overall unified design concept quite early in a project and this guides his later work. Nadler refers to this concept as an "ideal system", and the second step in his design method is "ideal system development". While provocative, his paper is inadequately documented, with only brief reference to the five cases he studied in order to construct his operational model. Only one of the five examples dealt with engineering; it considered the design of a power transformer, an evolutionary product where the designer had many precedents to guide his thinking initially. In the author's view, Nadler's criticism remains "not proven"; no evidence in its support was found in the research reported in this thesis.
The second major criticism is that the model is static and does not contain any reference to the dynamics of problem-solving behaviour. The designer may exercise intellectual skills of flexible thinking in the following ways which are not brought out by the model.

(1) Flexibility in changing goals and objectives if there appear to be insuperable difficulties to achieving them. As a result of their study of an innovative design problem, Frichsmuth and Allen (1969) concluded that an important way in which engineers could respond to difficult design problems was by modifying objectives and setting lower standards of performance rather than by spending a lot of time searching for acceptable solutions.

(2) Flexibility in relaxing constraints or in going outside the boundaries of the problem originally specified.

(3) Flexibility in changing strategies for solving design problems when the strategy chosen is unsuccessful or time-consuming.

Examples of flexibility in design will be given in Chapter 8. However, the evidence is anecdotal and unsystematic. There are in fact severe difficulties in the way of the experimenter who wishes to observe flexibility in design because it is spontaneous behaviour not under his direct control.

Typical of the third major criticism is Hykin's argument that operational models of the type discussed in Section 2.4 are too superficial and more insight is gained into the design process by recording the byways and dead-ends of the designer's thinking (Hykin, 1969). Evidence in support of this
view would presumably take the form of detailed verbal reports by designers on the progress of their work. However, there is little evidence of this sort available because very few engineering designers have recorded their efforts in sufficient detail. Of the few relevant case studies published, reports by Blanco (1962) and Covington (1967) should be noted, dealing respectively with the design of a stair-climbing wheelchair and a quick-disconnect fluid coupling. But it is not possible to generalize on the basis of this limited data.

Some workers such as Hill (1970) and Jones (1967) have subdivided the fifth step of the proposed operational model into two parts, the first being the creation of an idea or solution-in-principle and the second being the translation of that idea into physical form. There is some evidence to support this subdivision. Graham (1948) describes the innovative design of a mechanical variable-speed transmission, where it took twelve years and five design cycles after the principle of operation of the device had been conceived to arrive at its proper physical arrangement.

From the above discussion it will be seen that the operational model of the divergent phase of engineering design proposed in Table 2.4 may not be the most appropriate for all applications, and its possible shortcomings should be recognized. Nevertheless, many research workers have successfully used this model or one very like it and it will therefore be adopted.
2.4.4. Topological Models of Engineering Design

In this Section we are concerned with the use of topological models to represent design effort and thus enable comparisons to be made between the work of different designers. The use of topological models to aid the solution of complex multivariable design problems will be discussed later in Section 5.2.

As a result of his study of practical examples of innovative design, Marples (1961) concluded that engineering design consists of a sequence of critical decisions from the initial statement of the problem to the final specification of the hardware. Each critical decision involves the consideration of alternative proposals, predictions of the outcome of each with emphasis on the sub-problems raised, followed by evaluation of the outcomes against engineering criteria and the judged tractability of the unassessed portions of the design. Marples drew up a picture of the innovative engineering design process in which the progress of the design and the major decisions taken are represented in the form of a "decision tree".

A general case is illustrated in Fig. 2.6, where, following Marples, the vertical lines represent sub-problems arising at various points throughout the design and the sloping lines represent alternative solutions. $P_0$ is the original problem for which three alternative solutions are proposed, namely $a_1$, $a_2$ and $a_3$. Each of these in turn gives rise to sub-problems, for example the sub-problems associated with $a_2$ are $p_{21}$, $p_{22}$ and $p_{23}$ and so on down the tree. Thus the final solution is the combination of $a_{21211}$, $a_{22111}$, $a_{22211}$ and $a_{232}$.
As one moves down the tree, the level of abstraction decreases. At the top the problem and its solutions are described in relatively abstract terms. At the bottom one envisages detailed bits of hardware made from particular materials.

Fig. 2.7 shows the decision tree for an innovative mechanical design carried out under the author's supervision. The problem was to design a small experimental boiler for use in research into the applications of solar energy. As can be seen from the figure, the decision tree is a very convenient way of depicting the progress of the design.
PROBLEM: DESIGN OF SMALL SOLAR BOILER

Thermal Storage
- None
- External to boiler
- Integral with boiler

Number of Working Fluids
- One
- Several

Working Fluid
- H₂O
- SO₂
- Hg

Initial Conditions
- Atmos.
- Preheat temp.

Final Conditions
- Superheated
- Saturated

Relation to Critical Temperature
- Above
- Below

Degree of Superheat
- Low
- High

Pressure
- Maximum available
- \( \frac{1}{3} \) Max.

Final Temperature
- Near metallurgical limit
- Near instrumentation limit

Fig. 2.7. Decision Tree for Solar Boiler.
PROBLEM: Design of solar boiler with no thermal storage to generate steam at 700 lbf/in² gauge and 700°F from water at atmospheric temperature.

Fig. 2.7. (Continued)
As part of his celebrated study into the psychology of problem-solving, Duncker used an innovative design problem, namely to devise a means for destroying a tumour inside the human body by X-rays without at the same time destroying healthy tissue (Duncker, 1945). It is interesting to note that Duncker found he could classify the solutions proposed in a hierarchial way, using a tree to represent the efforts of the subjects in his experiments. To the original problem there were three different solutions-in-principle. How to work out the details of these solutions gave rise to a number of sub-solutions of which only one turned out to be feasible. The process is summarized in Fig. 2.8.

Fig. 2.8. Tree Representing Subjects' Efforts to Solve Duncker's X-ray Problem.
Another example of a decision tree to represent the full range of alternative courses of action open to a designer is given by Ball (1966); he discusses a novel application calling for a compact method of releasing a relatively large but controlled amount of energy in a short space of time.

To sum up, it is clear that decision trees are a useful way of representing the work of the designer on relatively complex innovative problems where there are series of sub-problems to be solved and decisions to be made. Examples will be presented and discussed in Chapter 8 to show how decision trees may be applied to help identify and measure design skills in such problems.

2.5. THEORIES OF INTELLIGENCE

2.5.1. Introduction

The activity of designing engineering systems and products is a form of intelligent behaviour. It is therefore appropriate to examine theories of intelligence to determine whether they can help to identify intellectual design skills.

One theory – Guilford's Structure of the Intellect (S.I.) model – is particularly relevant and will be discussed here because it provides a frame of reference which can be readily related to the operational model of problem-solving established in Section 2.4.
2.5.2. Guilford's Structure of the Intellect

The S.I. model is three-dimensional. If the human mind is viewed as a black box which transforms inputs of information into outputs, then the dimensions correspond to (i) informational input, (ii) the process or operation of transforming input to output and (iii) the output. Guilford calls these dimensions content, operation, and product, respectively.

Each dimension is sub-divided into a number of categories as explained in detail in Guilford's book (Guilford, 1967) and each category is identified by a letter of the alphabet in the following way.

<table>
<thead>
<tr>
<th>Operation - Cognition</th>
<th>(C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Memory</td>
<td>(M)</td>
</tr>
<tr>
<td>Divergent production</td>
<td>(D)</td>
</tr>
<tr>
<td>Convergent production</td>
<td>(N)</td>
</tr>
<tr>
<td>Evaluation</td>
<td>(E)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Content -</th>
<th>(F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figural</td>
<td></td>
</tr>
<tr>
<td>Symbolic</td>
<td>(S)</td>
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<tr>
<td>Semantic</td>
<td>(M)</td>
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<tr>
<td>Behavioural</td>
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<thead>
<tr>
<th>Product -</th>
<th>(U)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units</td>
<td></td>
</tr>
<tr>
<td>Classes</td>
<td>(C)</td>
</tr>
<tr>
<td>Relations</td>
<td>(R)</td>
</tr>
<tr>
<td>Systems</td>
<td>(S)</td>
</tr>
<tr>
<td>Transformations</td>
<td>(T)</td>
</tr>
<tr>
<td>Implications</td>
<td>(I)</td>
</tr>
</tbody>
</table>
The intersection of the 4 x 5 x 6 categories constitutes a threedimensional model with 120 cells. Each cell is considered to represent a specific intellectual ability and is denoted by a three-letter abbreviation. Thus CMI denotes cognition of semantic implications.

The S.I. model is relevant to the present discussion because its "operation" dimension closely corresponds to major steps in the operational model of problem-solving adopted in Section 2.4. Other theories of intelligence such as Vernon's well-known hierarchy of abilities (Vernon, 1950) cannot be directly related to models of problem-solving and consequently are not considered here. Guilford's definitions of the five categories of operation are now stated.

Cognition: awareness, immediate discovery or rediscovery, recognition of information in various forms; comprehension or understanding (Guilford, 1967, p. 203).

Memory: retention or storage, with some degree of availability, of information in the same form in which it was committed to storage and in connection with the same cues with which it was learned (Guilford, 1967, p. 211).

Divergent production: generation of information from given information, where the emphasis is upon variety and quantity of output from the same source (Guilford, 1967, p. 213).

Convergent production: generation of information from given information when the input is sufficient to determine a unique output (Guilford, 1967, p. 171).
Evaluation: the process of comparing a product of information with known information according to logical criteria, reaching a decision concerning criterion satisfaction (Guilford, 1967, p. 217).

On the basis of these definitions it would be reasonable to hypothesise that Guilford's "cognition abilities" enter into the early stages of problem-solving when the problem is recognized and defined, and that "memory" and "divergent production" abilities are required in the later stages of planning strategies and creating ideas. Occasionally a design problem may have only one strategy or solution in which case "convergent production" abilities would be important. "Evaluation" abilities would be expected to play a large part in the decision-making phase of design when the merits of alternative solutions are compared and the most acceptable one selected.

As a result of his study of the abilities of engineering students, Gluskinos (1968) concluded that it was reasonable to differentiate between Guilford's five operations and that this was a suitable method for classifying students' intellectual abilities. However, he found that the content of engineering problems consisted of semantic, numerical, figural and symbolic inputs all in close combination so that it made no sense to distinguish between them. The products of problem-solving would, he thought, also comprise several if not all of Guilford's categories.

Because its categories of input and output information appear inappropriate, it is doubtful whether the S.I. model can be applied in detail to help identify the abilities exercised in engineering problem-solving. Furthermore, as Gluskinos points out, the complete model with its 120 cells
is too cumbersome for applied educational research. Nevertheless it provides a convenient frame of reference and a heuristic tool for organising research into intellectual skills, in this instance, skills in engineering design.

2.5.3. Application of the S.I. Model to Creative Design Skills

The intellectual factors from the S.I. model which correspond most closely to the creative design skills hypothesised in Section 2.4 are set out in Table 2.5. In so far as many design problems in engineering are initially stated and defined verbally, the comparison is presented in terms of semantic information, although as pointed out above, all of the S.I. categories of informational input may well be present. Examples of the tasks devised by Guilford and his associates to identify and measure these factors are also listed.

This tabulation has been drawn up in order to interpret the hypothesised design skills in terms of a recognized psychological theory of intelligence. The aim is twofold. - to gain greater insight into the nature of these skills and to obtain some guidance on the sorts of tasks which might be used to identify and measure them.

At four places in Table 2.5 additional explanation is required and the following notes should be read in conjunction with it.

(1) In so far as the objectives of a design are to remedy some perceived defect in the environment, factor CMI may be associated with this phase of the design process. Guilford's tests do not include aesthetic or ethical
Table 2.5. Interpretation of Creative Design Skills in Terms of Intellectual Factors in Guilford's S.I. Model.

<table>
<thead>
<tr>
<th>Creative Design Skill (Table 2.4)</th>
<th>Intellectual Factors from S.I. Model (Guilford, 1967)</th>
<th>Examples of Tasks Used to identify Intellectual Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Guilford (p. 106) refers to the factor CMI as a general ability to see implications. It includes sensitivity to problems or cognizing things wrong in a particular situation or environment.</td>
<td></td>
</tr>
<tr>
<td>2. Definition of problem.</td>
<td>CMI ?</td>
<td>See Note (1)</td>
</tr>
<tr>
<td>2.1. Establishment of objectives, priorities, criteria.</td>
<td>See Note (2)</td>
<td></td>
</tr>
<tr>
<td>2.2. Identification of inputs to the design, resources available.</td>
<td>CMS ? CMT ?</td>
<td></td>
</tr>
<tr>
<td>2.3. Isolation of the design problem from its environment, establishment of the boundaries of the design.</td>
<td>CMS ? CMT ?</td>
<td>See Note (2)</td>
</tr>
</tbody>
</table>
Table 2.5. Continued.

<table>
<thead>
<tr>
<th>Creative Design Skill (Table 2.4.)</th>
<th>Intellectual Factors from S.I. Model (Guilford, 1967)</th>
<th>Examples of Tasks Used to identify Intellectual Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4. Identification of sub-problems likely to arise during the course of the design.</td>
<td>Cognition of systems. (CMS)</td>
<td>Guilford (p. 97) refers to CMS as comprehension of the structure of a problem which is stated verbally.</td>
</tr>
<tr>
<td>3. Collection of Data.</td>
<td>Convergent production of systems. (NMS)</td>
<td>Guilford (p. 178) suggests that the ability to organize hierarchies of information depends on the factor NMS.</td>
</tr>
<tr>
<td>4. Planning the Strategy.</td>
<td>Convergent production of systems. (NMS)</td>
<td>Guilford (p. 176) describes the factor NMS as the ability to plan a sequence of steps so as to complete a complex task.</td>
</tr>
<tr>
<td>5. Creation of solutions to sub-problems.</td>
<td>a. Divergent production of units, classes, systems, transformations, implications.</td>
<td>Guilford (p. 162) suggests that scientists and planners are concerned with semantic information, inventors with figural information. Presumably engineers are concerned with all four types of information.</td>
</tr>
</tbody>
</table>
Table 2.5. Continued.

<table>
<thead>
<tr>
<th>Creative Design Skill (Table 2.4.)</th>
<th>Intellectual Factors from S.I. Model (Guilford, 1967)</th>
<th>Examples of Tasks Used to identify Intellectual Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.</td>
<td>b. Convergent production of transformations. (NMT)</td>
<td>Gestalt Transformations. Subject to select one of five objects that could be used in whole or in part to accomplish some purpose for which none of the objects would normally be used.</td>
</tr>
<tr>
<td></td>
<td>Guilford (p. 181) suggests that factor NMT, the redefinition of the use or function of an object, could be an important ability in creative thinking.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>b. Divergent production of implications. (DMI)</td>
<td>As for 1 above.</td>
</tr>
<tr>
<td></td>
<td>As for 1 above.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>See Note (4).</td>
<td></td>
</tr>
</tbody>
</table>
criteria (Guilford, 1967, p. 185) and objectives based on aesthetics and ethics are outside the scope of his work.

(2) There is no S.I. factor which corresponds to steps 2.2 and 2.3 in a clear-cut manner. Cognition of systems and cognition of transformations seem to be the closest. Guilford defines a transformation as a change of existing or known information in its attributes, meaning, role, or use. An ability to recognize alternative meanings of the informational input may be important in arriving at the most appropriate definition of a design problem.

(3) The hypothesised design skill for which Guilford's model is least helpful is that of collecting data. For this reason the experiment to be reported on the information search phase of design is based on an alternative theoretical approach, the conceptual systems theory of Schroder et al. (1967). This is discussed in due course in Chapter 5.

(4) The divergent production abilities are identified and measured by Guilford in the following ways.

(a) Units - DMU - Ideational fluency, measured by number of items of information generated by a subject, e.g. the number of uses of a common brick.

(b) Classes - DMC - Ideational flexibility, measured by the number of classes or categories in a subject's response, e.g. to the Brick Uses Test.

(c) Relations - DMR - Associational fluency, measured by the number of different ways a subject completes an unfinished analogy.
(d) Systems - DMS - Expressional fluency, measured by responses to sentence construction tests. Guilford (1967, p. 152) suggests that DMS should be exercised in the divergent production of a wide range of semantic systems including scientific theories.

(e) Transformations - DMT - Originality, measured by the number of statistically rare responses to tests of divergent production, e.g. Unusual Uses, Remote Consequences or Remote Associations.

(f) Implications - DMI - Ability to elaborate, to think of detail in planning, e.g. a subject is given the outline of a plan and has to fill in the detailed steps to make it work.

2.6. CONCLUSION

Engineering design has been studied as a form of human problem-solving behaviour. An operational model of the divergent phase of the design process has been adopted and creative design skills defined in terms of the execution of the steps in the model. Furthermore, it has been shown that nearly all these skills can be directly related to psychological theories of intelligence, and this in turn suggests ways of identifying and measuring them.
CHAPTER 3

CREATIVE SKILLS IN ENGINEERING - A REVIEW

3.1. INTRODUCTION

The purpose of this chapter is to review the literature on creativity in engineering with particular reference to the identification and measurement of creative skills. Little research has been carried out in the specific field of engineering design, the subject of the thesis, and the review has therefore been extended to cover engineering generally.

Creativity in engineering is most readily associated with the work of outstanding inventors. For this reason some examples of highly creative effort in engineering will first be examined, examples drawn from the author's own discipline of mechanical engineering, namely

(1) James Watt
(2) Sir Frank Whittle
(3) Sir George Cayley

At this stage of our knowledge, invention is an unpredictable phenomenon which cannot be confined to the laboratory and made the subject of scientifically controlled experiments. The discussion therefore will be based as far as possible on the inventors' own writings.

Creative effort in more conventional engineering situations will then be studied. Ways of defining and measuring the creative output of both professional engineers and engineering students will be reviewed, together
with the results of investigations into the associated problems of predicting professional creativity and determining the relationship between creativity and intelligence.

3.2. EXAMPLES OF HIGHLY CREATIVE EFFORT

3.2.1. James Watt

As a young man of 27, James Watt invented the condenser for the Newcomen steam engine, and this together with other inventions of his opened the way for the general application of steam power. Watt became interested in improving the engine when he discovered, while repairing a model at the University of Glasgow, that its mode of operation was extremely inefficient.

In the Newcomen engine, power for each stroke was developed by first filling the cylinder with steam and then cooling it with a jet of water; this cooling action condensed the steam setting up a vacuum behind the piston, which was then forced to move by the pressure of the atmosphere. With every stroke of the piston the cylinder was alternately heated and cooled, and calculation showed Watt that this process was very wasteful of the heat supplied to the engine. He reasoned that if he could prevent this loss of heat, he would be able to reduce the engine's fuel consumption by 50 per cent, an accomplishment that was obviously worthwhile. Watt worked on this problem for two years but could find no solution to it. Then on a fine Sunday afternoon he went for a walk, and in his own words (quoted in Smiles, 1904) this is what happened.
"I had entered the Green by the gate at the foot of Charlotte Street, and had passed the old washing-house. I was thinking upon the engine at the time, and had gone as far as the Herd's house when the idea came into my mind that as steam was an elastic body it would rush into a vacuum, and if a communication were made between the cylinder and an exhausting vessel the steam would rush into this vessel and might there be condensed without cooling the cylinder ... I had not walked further than the golf-house when the whole thing was arranged in my mind."

Watt had then conceived his condensing steam engine and had laid the way for later developments of this type of prime mover during the period of the industrial revolution in England. The essential points in his experience from the standpoint of creative thinking are as follows. Watt had set up for himself a problem which, after two years of work and intensive thought, he had failed to solve. One day, while indulging in a reverie during the enforced idleness of a Scottish Sabbath, the solution of the problem came to him, unexpectedly and without effort.

3.2.2. Sir Frank Whittle

Sir Frank Whittle was born in 1907 and entered the R.A.F. as a youth of sixteen. In the years 1926-28 he was a flight cadet at the R.A.F. Station, Cranwell. Towards the end of the cadet training course he had to write a thesis and chose for his subject, "Future Developments in Aircraft Design". As he records in his autobiography (Whittle, 1953), it was at this time that he began thinking in terms of speeds of 500 miles per hour when the top speed
of R.A.F. fighters was 150 miles per hour. It seemed to him unlikely that the conventional combination of piston engine and propeller would meet the power plant requirements of the high-speed, high-altitude craft he had in mind; and in his thesis he discussed the possibilities of rocket propulsion and of gas turbines driving propellers. It did not occur to him then to use the gas turbine for jet propulsion.

During the eighteen months after he left Cranwell Whittle continued to consider this problem in his spare time from flying duties - the quest for a suitable power plant for a high-altitude, high-speed aeroplane. He gave much thought to a jet propulsion arrangement in which the propelling jet was generated by a low pressure fan driven by a piston engine, both the fan and its driving engine being situated within a hollow nacelle. His ideas included provision for extra heating of the air compressed by the fan by the burning of additional fuel before expulsion from the propelling nozzle. However, he eventually came to the conclusion that this offered no real advantage over the piston engine-propeller combination.

Towards the end of 1929 while he was attached to the Central Flying School at Wittering, the idea suddenly occurred to Whittle of substituting a turbine for a piston engine in this arrangement. He had returned to the idea of a gas turbine but this time of a type which produced a propelling jet instead of driving a propeller. Once this idea had taken shape it seemed odd to him that he had taken so long to arrive at a concept which seemed very obvious and of extraordinary simplicity. He patented his idea in January 1930, after it had been turned down by the British Air Ministry.
Whittle, like Watt, was faced with a difficult conceptual challenge where he was not readily able to find the desired solution. Also, like Watt, he was sufficiently well acquainted with his work to have already stored in his memory the bits of knowledge necessary for the final insight to occur. In both cases the individual's creative effort took place in four well-defined stages, identified by Wallas (1926) as preparation, incubation, illumination and verification. First, the existence of an important and worthwhile problem is recognized and there is an intensive attack on it in which the worker saturates himself in all its aspects without achieving satisfaction. In the next stage, that of incubation, the worker's interests become absorbed elsewhere and the problem ceases to occupy his conscious mind. Then, in some chance moment of reflection, his mind once more drifts back to the problem and an illuminating flash is received which leads to the solution. Finally, the solution is implemented and verified to be successful.

The foregoing account of the creative process has been widely accepted and many thinkers have attested to the benefits gained from a period of incubation when working on a difficult problem. Examples are discussed by Broadbent (1966) and Hadamard (1945), but the discussion remains largely anecdotal. Only a few experiments have been made on the role of incubation in problem-solving and these have been in fields remote from engineering (Patrick, 1938; Fulgosi and Guilford, 1968). It is difficult to accept the implication that incubation is the operation of the "unconscious mind". Woodworth (1954) put forward the hypothesis that in the period of incubation the problem is laid aside and the mind given a chance to rest and to get rid of
the false sets and false directions which block fruitful progress.

Many researchers have relied on an associative definition of creativity. For example, Mednick (1962), defined a "creation" as a new and useful combination of existing elements. It is interesting to note how Whittle's invention accords with this definition. He created a new aircraft power plant by the combination of two existing elements, the gas turbine and propulsion by the reaction of propelling jets. He had previously thought of combining a piston engine with a form of jet propulsion but had rejected this as impractical: it did not satisfy the criterion of usefulness. Creative engineering must yield results of value to others. Useful combinations are chosen while useless ones are avoided or discarded.

3.2.3. Sir George Cayley

A large and complicated engineering invention may well involve the solution of a multitude of sub-problems along the way. The aeroplane only became a practical possibility after several major sub-problems had been solved, namely

1. how to construct a power plant having a sufficiently high power to weight ratio;

2. how to maintain stable flight in the longitudinal, lateral and yaw directions;

3. how to control the flight path of the aeroplane.

All these problems were foreseen and, apart from (1), solved by Sir George Cayley in the first half of the nineteenth century, although his work
was not well publicised. At an early stage in his career, aged 26 or 27 (1799-1800), he took the decisive step in the history of aeroplane design of separating the device for producing thrust from the device for producing lift, thus inaugurating the concept of the powered fixed-wing aeroplane.

He wrote "The whole problem (of manned flight) is confined within these limits, viz. - to make a surface support a given weight by the application of power to the resistance of air" and "There can be no doubt that the inclined plane, with a horizontal propelling apparatus, is the true principle of aerial navigation by mechanical means" (quoted in Gibbs-Smith, 1962).

Cayley took the original problem of designing a device for manned flight and sub-divided it into two sub-problems dealing separately with

(1) the provision of lift

(2) the provision of thrust.

He then treated these sub-problems as independent and proposed independent solutions, namely

(1) lift from a fixed wing

(2) thrust from flappers or airscrews.

These separate solutions were then combined into the final design proposal. Cayley was not able to achieve his ambition of powered flight because of the lack of an engine of high power to weight ratio. Nevertheless he designed and flew gliders successfully.

One of the crucial steps taken by Cayley was the separation of the lift-producing device from the propelling device. In the flight of birds, the
only precedents known to him, these two functions were combined. We may therefore describe this creative act as a dissociative process, whereas Whittle's creation of the jet engine was an associative process. The two processes are conceptually similar, since any new and useful associations of elements must depend on those elements being first separated from their old and unproductive associations.

Watt's invention of the condenser can also be viewed as a dissociation in that he separated the function of condensing the steam from the function of transmitting motion to the piston.

It is interesting to observe in this context that Maier and his colleagues, working in the field of literary creativity and word usage, found that a subject's ability to break associative bonds between words often differed from his ability to reorganize these words into new combinations (Maier et al., 1967; Maier et al., 1968).

Following this examination of some of the characteristics and complexities of highly creative engineering endeavour, creativity at a more conventional level of problem-solving will now be reviewed.

3.3. ENGINEERING CREATIVITY - DEFINITION AND MEASUREMENT

3.3.1. Professional Engineers

The creativity of professional engineers has been assessed by different investigators in the following ways :-

(1) a specially devised composite criterion;

(2) supervisors' ratings;
(3) patents held.

Each of these is now considered in turn.

(1) Owen's Composite Criterion.

To date the most thorough-going investigation of creativity in engineering has been that of Owen's and his co-workers (Owens et al., 1957; Owens, 1969). They carried out a longitudinal study, starting in 1955 with 1,537 students of mechanical and related branches of engineering in 25 American universities who were administered a number of tests of mechanical creativity. In 1964 in a follow-up study, information was obtained on the professional careers of as many of these people who could be contacted, 61% of the original group.

One of the major purposes of the investigation was to determine the predictive validity of the 1955 tests (to be described in Section 3.4) against a composite criterion devised for assessing professional creativity in mechanical and related branches of engineering. The criterion contained ten elements covering (a) the type of work the professional engineer was engaged on, (b) the number of papers he had presented and published, and (c) the number of patents he held or had contributed to. The relative weighting of the elements varied as shown in Table 3.1 in accordance with their importance as judged by five members of the engineering faculty at Purdue University all of whom had had relevant academic and industrial experience. The criterion score of a given engineer was the sum of his weighted scores on the ten elements.

<table>
<thead>
<tr>
<th>Item</th>
<th>Weighting</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>(a) TYPE OF WORK</strong></td>
<td></td>
</tr>
<tr>
<td>1. Number of significant improvements to product and processes made in the last four years.</td>
<td>1</td>
</tr>
<tr>
<td>2. Number of significant contributions to the development of new products or processes made in the last four years.</td>
<td>1</td>
</tr>
<tr>
<td><strong>(b) TECHNICAL PAPERS</strong></td>
<td></td>
</tr>
<tr>
<td>3. Number of papers presented at professional meetings.</td>
<td>2</td>
</tr>
<tr>
<td>4. Number of Papers published in professional journals.</td>
<td>2</td>
</tr>
<tr>
<td><strong>(c) PATENTS</strong></td>
<td></td>
</tr>
<tr>
<td>(i) in the engineer's own name</td>
<td></td>
</tr>
<tr>
<td>5. Number of patents held</td>
<td>3</td>
</tr>
<tr>
<td>6. Number of patents pending</td>
<td>3</td>
</tr>
<tr>
<td>7. Number of patent disclosures</td>
<td>4</td>
</tr>
<tr>
<td>(ii) to which the engineer had contributed</td>
<td></td>
</tr>
<tr>
<td>8. Number of patents held</td>
<td>1</td>
</tr>
<tr>
<td>9. Number of patents pending</td>
<td>1</td>
</tr>
<tr>
<td>10. Number of patent disclosures</td>
<td>2</td>
</tr>
</tbody>
</table>

While this criterion is reasonably comprehensive, it is not all-embracing. In his detailed analysis of the data from the study, Van Slyke (1967) estimated that as much as 10% of the engineers' creative ability may not have been tapped by this criterion. Supporting examples cited by him of creative engineers with low scores included one who worked on
systems rather than products or processes and one who worked in a defence industry and who could not publish papers or take out patents for reasons of national security.

(2) Supervisors' Ratings

In their validation studies of tests devised for predicting the creative performance of professional engineers working in areas associated with machine design and product design and development, Harris (1955) and Owens et al. (1957) relied to a very large extent on supervisors' ratings. In nearly all cases a dichotomous classification was made, the supervisors being asked to rate the engineers working under them as either above average or below average in creativity. Usually the rating was carried out by one supervisor, occasionally by two.

However, the word "creativity" is very difficult to define with precision and it may carry a large penumbra of uncertainty. There is no guarantee that the definition used by an engineering supervisor would agree with that of a research worker in psychology. This point is brought out by Sprecher (1959). Using a carefully constructed questionnaire, he asked a group of professional engineers and engineering supervisors in a large industrial firm why they had ranked their colleagues and juniors as either high or low in creativity. Analysis of their answers showed that while novelty and worth of ideas were considered important they were not considered the most important. Many other factors were brought to light, the most frequently mentioned being that solutions to problems be comprehensive and generalizable. Also important were a group of work habit variables such
as the ability to proceed on one's own and the ability to organize and plan the details of a project, variables which emphasised a workmanlike approach to a new task. Sprecher concluded with a recommendation concerning the subjective assessment of the creativity of professional engineers by judges (such as supervisors) competent in engineering but with no training or experience in rating creativity. He said that at least three such judges were required in order to reach agreement on the rating to be given to an individual engineer.

After Sprecher published his results, research workers who used supervisor's ratings tried to make them more objective. McDermid (1965) and Datta (1964) used behavioural rating scales containing items such as "Has the subject tackled problems others avoided?" However, these rating scales had been developed from studies of research scientists and had not been validated for engineers. McDermid also used a peer rating scale on which each engineer was assessed by a colleague acquainted with his work. The correlation between the two sets of creativity ratings for a group of 58 engineers was only just significant at the 95% confidence level.

In his study of the cognitive style of creative engineers, scientists and artists, Babarik (1966) ranked the engineers in his groups in order of relative creativity on the basis of a paired comparisons procedure using two supervisors as judges.

(3) Patents

Counting the number of patents held by an engineer is an objective way of assessing professional creativity, even though as pointed out earlier
much creative engineering effort is not patentable.

Owens et al. (1957) in a subsidiary part of their research identified a group of creative engineers by the number of patents each held. Stuteville (1966) in his investigation into the life history of creative engineering inventors also used this criterion to obtain the subjects for his study.

In a similar manner, Harris (1955) in one of his validation studies used the number of suggestions submitted to a company's suggestion scheme to distinguish between creative and non-creative employees.

3.3.2. Engineering Students

The engineering student in a university does not have the same opportunity as the practising engineer for exercising his creative skills on a professional task. Some of the methods used for assessing the creativity of professional engineers cannot therefore be applied to students. For example, few if any students would have taken out patents and it would be pointless counting the number of patents they held.

It is possible, however, to present open-ended problems to students in a situation which is modelled on the professional environment but is not a direct replica of it, and then to observe and judge their performance. This is the approach used by Gluskinos (1968) in his work reviewed below.

Other research has relied on instructors' ratings of student creativity and on students' responses to specially devised tests.
The following methods have thus been used to assess the creativity of engineering students.

(1) Instructors' ratings.

(2) Responses to specially devised open-ended problems.

(3) Responses to specially devised tests:

(a) AC test of creative ability.

(b) Purdue creativity test.

(c) Guilford tests—tests devised by Guilford and his co-workers in accordance with his S.I. model.

(d) Barron-Welsh art scale.

Each of these is now considered in turn.

(1) Instructors' ratings.

In one of his validation studies, Harris (1955) used instructors' ratings of students' creative ability as revealed by their work on projects in machine design and product design. One instructor rated 37 students as high, average, or low in creative ability.

However, Mackinnon (1961) found that faculty ratings of the creativity of 40 senior engineering students had negligible correlation with ratings by his colleagues from the Institute for Personality Assessment and Research. He concluded that the engineering faculty's conception of creativity was quite different from that of the I.P.A.R. experts and was in fact indistinguishable from academic achievement in their undergraduate courses.

A similar conclusion was reached by Gluskinos (1968). He asked those members of the engineering faculty of the University of Utah who thought
their courses elicited creative behaviour from their students to rate the students on a 15-point creativity scale. He found that for the 178 students participating in the study there was a significant correlation between this rating and grade-point-average (GPA) but negligible correlation between it and scores derived from responses to the open-ended design problems described in part (2) below. Gluskinos concluded that in the eyes of the engineering faculty, GPA and creativity were very similar; he doubted whether the conventional engineering course elicited much creative behaviour anyway.

(2) Open-ended Design Problems

In a wide ranging study of the abilities of engineering students, Gluskinos (1968) asked his subjects to answer an open-ended design problem. A separate problem was used for each of the major branches of engineering - chemical engineering (15 students), civil engineering (81 students), electrical engineering (173 students), and mechanical engineering (60 students). A typical problem asked for as many methods as possible for supplying power to the motors of an electric car.

Student responses were scored independently by three raters, Gluskinos and two faculty members in the appropriate discipline. Four scores were obtained on the following dimensions:

(1) Fluency - the number of solutions offered, regardless of how acceptable they are.

(2) Flexibility - the number of categories or types of solutions.

(3) Novelty - Statistical rarity of the solutions offered.
Appropriateness - the extent to which the individual student had given thought to cost, reliability, maintainability, practicality, space and manufacturing requirements.

No significant results were obtained from the small group of chemical engineering students. However, for civil, electrical and mechanical engineering students, very high inter-rater reliabilities were found. On the first three dimensions: all correlations were statistically significant at the 99% confidence level and three quarters of them exceeded 0.60.

Results for the fourth dimension, appropriateness, were variable: all three inter-correlations for the electrical engineering students were significant at the 99% confidence level and two of the three correlations for the civil engineering students were significant at this level. However, in the case of the novel device considered by the mechanical engineering students, the concept of "appropriateness" was thought to be inapplicable and no ratings were obtained.

Apart from Gluskinos' work, there has been little experimental research on the performance of engineering students on open-ended design problems.

Specially Devised Tests

One of the objectives of Gluskinos' research was to determine whether student performance on open-ended design problems could be related to or predicted by their performance on standard intelligence and personality tests, also by specially devised creativity tests. He found that the AC test
of creative ability and the Purdue creativity test were reasonably successful in predicting performance on the design problems used. The Guilford tests were not very helpful: some correlated significantly with scores on the design problem but the majority did not.

Craft (1967) used the AC test to evaluate the effect of different methods of teaching descriptive geometry on the creativity of engineering students. Buhl (1958) also used this test to help identify creative engineering students.

Mackinnon (1961) regarded the Barron-Welsh art scale as a measure of creative talent and regretted that his group of 40 engineering students obtained low scores on it, lower than architects, creative writers, and creative research scientists. However, Stuteville (1966) in his study of the life history patterns of engineering inventors found that 9 of his 10 subjects had low to very low scores on this scale so that its value as an indicator of engineering creativity is very doubtful.

3.4. ENGINEERING CREATIVITY - PREDICTION

Special tests have been devised by a number of workers to predict engineering creativity, mainly in work associated with mechanical engineering. These tests are designed to help the selection and placement of professional engineers based on predictions of their future performance.

The AC Test was developed by Harris (1955) in conjunction with the AC Spark Plug Division of General Motors. The test consists of
five parts and is designed to give a measure of the quantity and uniqueness of the ideas an individual can produce in a given situation. In Part I the subject is asked to list all the possible consequences of five potentially dangerous or embarrassing situations. Part II contains five unusual and not necessarily true statements. For each statement the subject is asked to explain the statements supposing them to be true. Part III asks the subject to list as many faults as he can in five common domestic appliances. In Part IV the subject has to propose a solution to each of 5 novel open-ended problems, such as locating the position of a blockage in an underground pipeline. In Part V the subject has to list all the possible uses of five common objects.

Scoring of the test is based on a combination of

1. Quantity - the number of independent, relevant answers.
2. Uniqueness - statistical rarity of the answers.
3. Quality - the quality of the answers to Part IV as rated by a panel of four judges.

As reported above, parts of this test have been used with engineering students by Buhl (1958), Craft (1967) and Gluskinos (1968). Nevertheless the data on its reliability and validity are limited.

Another specially devised creativity test is the Purdue Test developed by Harris (1960). It has 20 items which are of three kinds. The first eight items are three-dimensional objects for which the instructions are: "List as many possible uses as you can for this object". In items 9 to 12 there are three-dimensional drawings of pairs of objects with the instructions:
"List as many possible uses as you can for these two objects when they are used together". For the last eight items the subject is presented with a line drawing accompanied by the question: "What is this? List as many possibilities as you can." Three scores are obtained from the test: a fluency score based on the number of unduplicated responses to each item, a flexibility score based on the number of classes of responses given to the first two kinds of items, and a combined score based on the flexibility score added to half the fluency score. In view of the limited data available on the validity of this test, Mayo (in Buros, 1965) did not recommend its use for the selection of creative engineers.

As a result of his longitudinal study, Owens (1969) found that of the battery of cognitive tests used in 1955 only one - the power source apparatus (PSA) test - had any success in predicting professional creativity as defined by the composite criterion quoted in Section 3.3.1. In this test the subject is given a power source and a prescribed sequence of motions and has to sketch as many intervening mechanisms as possible. There are 8 items and the score is the total number of workable solutions presented.

It is interesting to note that Owens found the PSA test to be a better predictor than tests containing less structured open-ended problems, e.g. tests which asked the subject to list all the possible uses for a given mechanism or to design as many appropriate mechanisms as possible to achieve a particular purpose. Owens interpreted this result in terms of theories of cognitive style (Schroder et al., 1967). He suggested that the individual who could accept numerous situational restrictions and still be
creative was able to integrate more inputs of information than the one who could not, so that the discriminating dimension was one of cognitive complexity.

Owens and his co-workers also administered two lengthy questionnaires to their subjects, one dealing with their life histories and the other with their job environments. Analysis of the answers showed that some non-cognitive and job environment measures were significant predictors of professional creativity according to the criterion used. With respect to job environment the most important factor which emerged was professional and research orientation of supervision. It seems probable that leadership by example from a person who has carried out successful creative work is a stimulus to do likewise. The personal non-cognitive characteristic found to relate to creative effort was that of favourable self-perception.

In this research the three best predictors of professional creativity were found to be (in order) -

1. professional and research orientation of supervision (a measure of the job environment);
2. score on PSA test (a cognitive measure);
3. favourable self-perception (a non-cognitive measure).

This combination of cognitive, non-cognitive, and environmental measures highlights the complex nature of professional creativity.

McDermid (1965) used a wide variety of non-cognitive measures - personality tests, check lists, and biographical data - in an attempt to predict the creativity of a group of professional engineers as this trait was rated by
their supervisors and peers. The results were inconclusive as nearly all the correlations obtained were low and not statistically significant.

Finally, Datta (1964) investigated the applicability of Mednick's Remote Associates Test to professional engineers. Mednick had developed this test on the basis of his associative theory of creativity (Mednick, 1962). It consists of questions in which the subject is asked to form unlikely or remote associations between given stimulus words. The test has the advantage of being quick and easy to administer, and presumably calls into play an ability similar to that displayed by Whittle in his creation of the jet engine, described in Section 3.2. However, the contents of the test are verbal and bear no relation to engineering. Moreover, it is doubtful whether the test taps the dissociative creative ability exhibited by Watt and Cayley, also described in Section 3.2. For these reasons it is not surprising that for a group of 21 engineers Datta found no correlation between test score and creativity as assessed by two supervisors.

3.5. CREATIVITY IN ENGINEERING AND INTELLIGENCE

To what extent should creativity be equated with intelligence? To what extent can creative effort in engineering be predicted from measures of known intellectual abilities?

Van Slyke (1967) reported zero correlation between intelligence as measured by ACE score and professional creativity as measured by the composite criterion given in Section 3.3.1.
Taylor et al. (1963) found that for a group of 239 research engineers, there was no relation between undergraduate grade point average and merit rating as a research worker. The industry in which the engineers were employed was not stated.

Gluskinos (1968) found that engineering students' performance on open-ended design problems did not correlate with grade point average, the intercorrelations being close to zero.

These results for professional engineers and engineering students agree with those from other fields where intercorrelations between measures of intelligence and creativity have been found to be negligible. In reviewing his own and others' work, Barron (1969) wrote "... for intrinsically creative activities a specifiable minimum I.Q. is probably necessary in order to engage in the activity at all, but beyond that minimum, which is often surprisingly low, creativity has little correlation with scores on I.Q. tests". Earlier he had suggested that beyond an I.Q. of about 120, measured intelligence is probably unimportant for creativity (Barron, 1961). As a result of the selection procedures used to control admission to universities it would be expected that university-trained engineers would have I.Q.'s greater than or equal to this figure.
3.6. CONCLUSION - IMPLICATIONS FOR RESEARCH

Engineering creativity has been reviewed from the point of view of the highly creative inventor, the professional engineer and the engineering student.

There is no universally agreed method of assessing creativity in engineering. In many investigations, creativity has been defined and measured by the number of solutions to open-ended problems and by the flexibility of thinking and originality revealed by these solutions.

In an investigation of the creative output of engineering students in response to novel design problems, one would expect the number of solutions brought forward to vary with the level of difficulty of the problem. It is of interest therefore to classify design problems according to the expected pattern of responses as (1) easy, (2) intermediate, (3) difficult.

(1) Easy Design Problems

It is hypothesised that easy problems elicit the distribution of responses shown in Fig. 3.1. In a typical case, a large number of problem-solvers are able to evolve a fair number of solutions with the distribution tapering off at either end. Only a few people are able to come up with a large number of solutions and only a few offer a small number of solutions.

(2) Intermediate Design Problems

Problems which elicit the distributions of responses shown in Fig. 3.2 are classified as being of an intermediate level of difficulty. According to the hypothesis on which this classification is based, the majority of problem-
solvers are able to generate only a small number of solutions while a few
are able to generate a large number of solutions.

(3) Difficult Design Problems

Only a very few people - presumably highly creative problem-solvers
or inventors - are able to generate even one or two solutions to difficult
novel design problems. A typical response characteristic is shown in
Fig. 3.3.

![Graph showing typical pattern of responses to an easy design problem.](image-url)
Fig. 3.2. Typical Patterns of Responses to Intermediate Design Problems.

Fig. 3.3. Typical Pattern of Responses to a Difficult Design Problem.
As pointed out in the Introduction to this chapter, it is extremely difficult if not impossible to study responses to difficult problems under controlled experimental conditions, if only because of the unpredictable length and unknown nature of the incubation period apparently required for their solution. The design problems used in the research programme explained in the next chapter are mostly of the "intermediate" type with some being "easy", and in no case is provision made for an extended incubation period.

Highly creative problem-solvers (whether engineers, scientists, or artists) do not wait for others to propose or identify problems, they are especially sensitive to the existence of unformulated problems themselves. For example, Galileo did not only solve the problem of determining the velocity of light, he formulated the problem itself. In the same way in the examples discussed in Section 3.2, Watt, Whittle and Cayley were led to formulate problems unrecognized by their contemporaries.

It should be noted therefore that in the research reported in this thesis, the starting points to the design problems had already been chosen. No evidence will be adduced relating to this aspect of highly creative endeavour.* However, "sensitivity to problems" has already been noted

* From time to time the author has invited engineering students to formulate their own design problems. Not all students have responded to the invitation and no systematic data are available.
as a factor in creative design skill in Chapter 2 and will be further investigated.

Moreover, the design problems are stated with few constraints. If Owens' interpretation is correct, the more creative engineer is able to integrate more inputs and can accept more constraints on his problem-solving than the less creative engineer. However, severe difficulties arise in attempting to distinguish between external constraints intrinsic to the problem and internal constraints imposed by the problem-solver on his own thinking irrespective of whether they are relevant to the problem or not. As a result the effect of constraints on engineering problem-solving has not been investigated in this thesis, although it could well be the subject of future research.
4.1. INTRODUCTION

The experimental programme was devised to investigate the intellectual skills of engineering students in the divergent phase of design, referred to collectively as creative design skills. With the exception of one experiment to be discussed later in Chapter 7, the subjects were second and third year students in the Faculty of Engineering, University of Melbourne and the tasks they were set in the experiments were part of their normal educational programme in engineering design.

The undergraduate course at Melbourne is of four years' duration and is described in the Faculty of Engineering Handbook published by the University. The role of design subjects has been discussed by the author elsewhere (Lewis, 1967). It is sufficient to note here that the first year of the course is essentially analytical in nature, and comprises four subjects - Engineering I, Engineering Mathematics I, Chemistry I and Physics I. Engineering I is a composite which includes elementary Statics, Descriptive Geometry and Engineering Drawing. The students meet design problems for the first time in the second year subject Engineering Design I.

The experimental tasks are described in Section 4.3 below. They cover the major steps in the operational model of the divergent design process in Table 2.4 with the exception of the second step, "definition of problem".
As can be seen from Table 2.4, this step consists of a number of different activities and because of its complexity might well be the subject of a separate investigation in its own right. Most of the tasks used in this research were well-defined. However, incidental information was obtained on how different subjects isolated a problem from its environment, and this will be reported in due course.

Intellectual skills in searching for and collecting information are examined in Chapter 5.

Chapter 6 deals with skills in recognising problems, creating solutions and foreseeing implications. The tasks are relatively simple and do not require planning of strategies.

The possibility exists that by formalising the engineering design process by means of an operational model, informal problem-solving skills may be overlooked. Chapter 7 is devoted to experiments on informal problem-solving where solutions are sought to novel or unusual design problems. These require creative effort, but the different steps in the operational model overlap and cannot be readily distinguished by the observer. The experiments were extended to include students from non-technical faculties to compare their performances with those from engineering.

When subjects attempt to solve complex design problems, a separate step may appear in their problem-solving procedure, that of planning the strategy. Two examples of this are reported in Chapter 8. While subjects' strategies are usually readily identifiable, devising ways of measuring their skills in strategic thinking is difficult. These and other problems arising
in the measurement of creative design skills are discussed in Chapter 8.

4.2. EXPERIMENTAL VARIABLES

4.2.1. Introduction

A large number of variables may affect the results of experiments on problem-solving, not all of them under the control of the experimenter. Of particular importance are the following four major types of variable.

1. The previous experience of the subjects.
2. The time allowed the subjects for performance of the tasks.
3. The environment in which the subjects work.
4. The instructions given to the subjects concerning performance of the tasks.

Each of these is now considered in turn.

4.2.2. Previous Experience

The performances on the experimental tasks of all engineering students enrolled for the relevant design subjects in the undergraduate course were available for analysis. Some results had to be discarded because the students concerned were unrepresentative in one way or another. Included in the final analyses were the results from all students who were male Australians, who were studying the relevant design subject for the first time, whose studies had not been affected by illness, and whose academic records in other parts of the undergraduate course were available for comparison with performances on creative design tasks.
While it was hoped to obtain reasonably homogenous groups of subjects in this way, no control could be exercised over the previous experience of the individual subjects.

Examples of the ways in which previous experience can facilitate problem-solving are given by Stimmel (1963) and Booker (1962) in the fields of operations research and engineering design respectively.

Stimmel investigated the performance of two groups of university students on a series of transportation problems, one group drawn from mathematics majors and the other from English majors. In a typical problem the subject was given the location of five supply points each containing two, three, or four units of supply. Each unit of supply had to be transported to one of fifteen destinations in such a way that the total distance over which the supplies were transported was to be a minimum. Stimmel found that although the problems could be stated in a way which required little knowledge of mathematics and although there was no known algorithm guaranteeing a minimum solution, subjects with a mathematical training performed better than those with training in English.

Booker (1962) discusses, inter alia, a problem concerned with the design of ductwork for large, gas-cooled, nuclear reactors. Expansion and contraction of the ducts themselves necessitates the use of bellows which have then to be supported or restrained to resist the large forces arising from internal gas pressure. Booker describes how one engineer arrived at a new design of bellows restraint unit - a frusto-conical design consisting of conical lattices of rods. The engineer's previous experience
included the development of gas turbines where on one occasion he had had to solve the problem of vibrating bearing housing of conical shape. In the process he had gained specialised knowledge of how conical surfaces deform, knowledge which few other engineers would have possessed. He was then able to make the connection between this precedent and the new problem of supporting a large bellows. Booker comments that the similarity between the bellows restraint design and its precedent was only apparent when viewed at a high level of abstraction.

Although the previous experience of the subjects participating in the experiments was an uncontrolled variable in the research to be reported here, the following steps were taken to mitigate its influence. In Chapter 5, the experimental task was set in an unfamiliar context which would have been equally strange to all subjects. In Chapter 6 it was decided to pay particular attention to subjects who performed consistently well on a number of different tasks of widely varying content. In Chapter 7, where the tasks involved the design and construction of simple structures, unfamiliar materials were used.

In any case, there is evidence to suggest that students entering the Faculty of Engineering at the University of Melbourne have little previous experience of engineering matters. In 1968 a survey was made of the knowledge of and attitudes towards engineering of senior students in several secondary schools in Melbourne (Lewis and Borg, 1969). It found that there was widespread ignorance about the profession of engineering among school students.
4.2.3. Time

Numerous authors have drawn attention to the incubation phase of creative problem-solving, but as pointed out in Section 3.2.2 this has been with respect to very difficult problems. In the present investigations the experimental tasks were not at that high level of difficulty where the available evidence suggests that an incubation phase is necessary; rather, they belonged to Categories (1) and (2) defined in Section 3.6.

As will be described in greater detail below, the tasks fell into two categories: short-term and long-term. The short-term tasks called for fluency and flexibility of ideation and were completed in periods of between 40 and 60 minutes. The longer tasks were based on more complex design problems where it was essential that the subjects take time either to plan their strategies or to elaborate their answers. The longer tasks were presented to students as "take-home" exercises with the injunction that each student was to work on his own and not seek advice. Because of the lack of experimental control of the subjects' working environment in the take-home exercises, it is possible for the results to be contaminated, perhaps because there was time for an incubation phase, or because some subjects sought outside help or discussed their work with other subjects, or because there were differences in their work habits and ability to organize time for the task amongst other engineering studies and extra-curricular activities.

Some results from take-home exercises will be presented in Chapters 6 and 7, and in assessing the significance of these results, the above criticisms have to be borne in mind. Nevertheless, in most cases the responses of the subjects were so varied and diverse that there could not have been any unwanted collaboration between them.
4.2.4. Environment

The physical environment in which the tasks were undertaken varied according to the nature of the experiment. Short-term tasks were completed at the University, either in drawing offices in the Faculty of Engineering or, if the tasks were part of a formal examination, in a university examination hall. In the longer tasks subjects were free to choose their own working environment whether at the university or at home.

In all cases subjects worked on their own and not as members of groups.

4.2.5. Instructions

Tasks were presented to the subject in writing as assignments or examination questions. A complete statement of the tasks (or design briefs) used in this research is given in Appendix I.

In the short-term, open-ended tasks devised to elicit fluent and flexible responses, the briefs contained instructions to the subject to list all the ideas he could think of in relation to the set task. Gluskinos used similar instructions in his open-ended design problems, for example, one instruction was "Devise as many methods as possible for supplying power to the motors of an electric automobile."

The aim of such instructions is to minimize the effects of self-censorship of ideas by subjects. Manske and Davis (1968) found that the quantity and quality of responses to an Unusual Uses Test varied with the type of instructions given. They concluded that in open-ended creativity
tests careful consideration had to be given not only to the formal instructions but also to the subject's own self-instructions which might inhibit him from writing down more remote ideas.

In one short-term task to be reported in Chapter 6, subjects were asked to foresee the implications of alternative solutions they had proposed to a design problem and to evaluate these solutions. Hyman (1961) demonstrated the adverse effect of a critical attitude to the production of creative solutions to a novel design problem. In view of Hyman's results, the subjects were instructed to keep the process of evaluation separate from the generation of ideas and to create as many ideas as they could before attempting any evaluation.

4.3. EXPERIMENTAL TASKS

4.3.1. Tasks

Table 4.1 sets out the experimental tasks used in this research and summarises relevant information about them. A complete statement of the tasks is given in Appendix I.

Task (1) was adapted from Karlins (1966). Task (2) was taken directly from a problem published in the journal, Engineering Materials and Design, in September, 1966. Tasks (2) and (3) were used early in an academic year as a pilot study to determine whether useful information could be obtained on students' skills in the creative stages of engineering design. Tasks (4), (5) and (6) and the methods for scoring them are similar in principle to tests developed by Guilford and his associates, but the tasks
have an engineering context. Tasks (7) and (8) were devised by the author as part of the educational programme in engineering design; they enable informal problem-solving skills to be studied. Tasks (9) and (10) were included in the investigation to extend its scope. The aim was to determine to what extent the simple procedures used to score responses to tasks (1) to (6) would be suitable for measuring performance on more elaborate innovative design problems.

While tasks (7) and (8) deal with purely technical products, the contents of the other tasks are man-machine systems or products of varying degrees of complexity, ranging from a hospital stand to the City of Melbourne. Most of the tasks are concerned with one-off situations. However, successful designs of page-turner could be expected to be manufactured in small quantities, hospital stands in large quantities, and car safety devices in very large quantities indeed. The contents of the tasks thus give a reasonable coverage of the classifications in Table 2.2.
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Creative Design Skill</th>
<th>Outline of Task</th>
<th>Proposed Scoring Procedure</th>
<th>Subjects</th>
<th>Task Environment</th>
<th>Time Allowed</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Collection of data.</td>
<td>(1) Construction of hospital on remote Pacific island. Subjects to state information required to undertake project successfully.</td>
<td>Number of items of information, number of categories of information. See Chapter 5.</td>
<td>2nd year engineering students (N=116)</td>
<td>University drawing office.</td>
<td>1 hour.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(2) Hospital stand. Subjects to redesign a hospital stand so that it can be easily adjusted by a person using one hand instead of two.</td>
<td>Quantity and quality of ideas.</td>
<td></td>
<td>Either university or home, at subject's discretion.</td>
<td>2 hours in the university timetable, but subjects had a week to think about the problem, if they wished.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(3) Drawing office. Subjects to design a new drawing office for use by engineering students.</td>
<td>Quantity and quality of ideas.</td>
<td>2nd year engineering students (N = 119)</td>
<td>Either university or home, at subject's discretion.</td>
<td>10 hours in the university timetable, 2 hours a week for 5 weeks.</td>
</tr>
<tr>
<td>6</td>
<td>Creation of solutions.</td>
<td>(4) Urban growth. Subjects to list all the problems they could foresee arising from the growth of population in the Greater Melbourne area in the next 25 years.</td>
<td>Number of problems foreseen. Number of categories of problems.</td>
<td>2nd year engineering students (N = 119)</td>
<td>University examination hall.</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1. Experimental Tasks.
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Creative Design Skill</th>
<th>Outline of Task</th>
<th>Proposed Scoring Procedure</th>
<th>Subjects</th>
<th>Task Environment</th>
<th>Time Allowed</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Creation of solutions.</td>
<td>(5) Transport system. Subjects to list all the ideas they could for transporting people to the central city area of Melbourne from a proposed underground car-park 1½ miles away.</td>
<td>Number of ideas.</td>
<td>2nd year engineering students (N=119)</td>
<td>University examination hall.</td>
<td>45 minutes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(6) Transport system. Subjects asked to list advantages and disadvantages of ideas put forward in response to task (5).</td>
<td>Number of criteria used in evaluation of ideas.</td>
<td>2nd year engineering students (N=119)</td>
<td>University examination hall.</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Informal creative problem-solving.</td>
<td>(7) Structure under static load. Subjects to design and build structures from sheet of polyurethane foam to conform to specified geometric constraints and sustain a vertical load.</td>
<td>Strength to weight ratio of structure.</td>
<td>3rd year mechanical engineering students (N=58). Also architecture students, and students from non-technical faculties.</td>
<td>See Chapter 7.</td>
<td></td>
</tr>
</tbody>
</table>

See Chapter 7.
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Creative Design Skill</th>
<th>Outline of Task</th>
<th>Proposed Scoring Procedure</th>
<th>Subjects</th>
<th>Task Environment</th>
<th>Time Allowed</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Informal creative problem-solving</td>
<td>(8) Structure under impact load. Subjects to design and build structures capable of landing an egg undamaged when dropped from a height of 45 feet onto asphalt.</td>
<td>Success or failure, according to whether egg undamaged or broken.</td>
<td>2nd year engineering students (N=116)</td>
<td>Either university or home, at subject's discretion.</td>
<td>2 hours in the university timetable, but subjects had a week to think about the problem, if they wished.</td>
</tr>
<tr>
<td>8</td>
<td>Planning the strategy and creating solutions to complex design problems</td>
<td>(9) Page-turner. Subjects to create as many ideas as they could for a device to turn the pages of books for hospital patients without arms.</td>
<td>See Chapter 8.</td>
<td>2nd year engineering students</td>
<td>University drawing office.</td>
<td>30 minutes.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(10) Car safety. Subjects to create as many ideas as they could for minimising the injuries to occupants of cars in accidents.</td>
<td>See Chapter 8.</td>
<td>3rd year mechanical engineering students</td>
<td>Either university or home, at subject's discretion.</td>
<td>12 hours in university timetable, 3 hours a week for 4 weeks.</td>
</tr>
</tbody>
</table>
4.3.2. Scheduling the Experimental Tasks in the Undergraduate Educational Programme

Apart from (4), (5) and (6), all tasks presented to engineering students were scheduled early in the academic year. At the University of Melbourne the academic year consists of 26 weeks of lectures and practical work interspersed by 2 three-week periods of private study and followed by 4 weeks of examinations.

The timing of the various tasks within this framework is shown in Table 4.2. Because of the long time required to analyse the results, the experiments were spread over four academic years, as noted in the table.

The introductory design subject for 2nd year students is called Engineering Design I and is compulsory for students of civil, electrical, and mechanical and related branches of engineering, but is not taken by students of chemical or metallurgical engineering. All third year mechanical engineering students take Engineering Design II.

The final mark gained by the student in Engineering Design I or Engineering Design II is a combination of his marks on design projects and assignments during the year and his mark in a formal examination at the end of the year. The relative weights given to examinations and project work are shown in Table 4.2, and students are informed of these weightings at the beginning of the academic year.
Table 4.2. Scheduling of Experimental Tasks in the Educational Programme in Engineering Design.

<table>
<thead>
<tr>
<th>Task</th>
<th>Academic year in which task was set</th>
<th>Timing - week or weeks in academic year</th>
<th>Name of design subject</th>
<th>Relative weighting of examinations and projects</th>
<th>Total time allocated to projects in design subject</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1970</td>
<td>5th week</td>
<td>Engineering Design I</td>
<td>60/40</td>
<td>26 two-hour sessions</td>
</tr>
<tr>
<td>2</td>
<td>1967</td>
<td>4th and 5th weeks</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>3</td>
<td>1967</td>
<td>6th to 10th weeks inclusive</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>4</td>
<td>1967</td>
<td>Formal examination at end of academic year</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>5</td>
<td>1967</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>6</td>
<td>1967</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>7</td>
<td>1970</td>
<td>1st and 2nd weeks</td>
<td>Engineering Design II</td>
<td>$3\frac{1}{3}/66\frac{2}{3}$</td>
<td>20 three-hour sessions</td>
</tr>
<tr>
<td>8</td>
<td>1970</td>
<td>6th and 7th weeks</td>
<td>Engineering Design I</td>
<td>60/40</td>
<td>26 two-hour sessions</td>
</tr>
<tr>
<td>9</td>
<td>1969</td>
<td>4th week</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>10</td>
<td>1969</td>
<td>1st to 4th weeks inclusive</td>
<td>Engineering Design II</td>
<td>50/50</td>
<td>20 three-hour sessions</td>
</tr>
</tbody>
</table>
4.4. ANALYSIS OF EXPERIMENTAL RESULTS

4.4.1. Scoring Procedures

In tasks (1) to (6) the results to be analysed consisted of written responses by the subjects. In the light of Gluskinos' research, consideration was given to scoring the responses on one or more of the three dimensions of fluency, flexibility, and quality of ideation.

In tasks (2) and (3), which were conducted as a pilot investigation, the responses were scored on the basis of the quantity and quality of ideas put forward. The scoring was carried out by other members of the university staff independent of the author but in accordance with written instructions provided by him. Copies of the instructions are included in Appendix I with the relevant design briefs.

In tasks (1) and (4) the concept of quality was irrelevant and scoring was based on the number of items of information to be searched for and the number of problems foreseen. Assessment of the quality of responses to tasks (5) and (6) was extremely difficult, and it was decided as far as possible to minimize the subjective element in the scoring procedure by counting numbers of ideas and numbers of criteria. There was still the possibility of individual items in responses being overlooked or wrongly interpreted. Two assessors working independently therefore scored the responses to each of these four tasks, one assessor being the author and the second a research assistant who had no direct contact with or knowledge of the subjects.
The research assistant for task (1) was a recent graduate in mechanical engineering. The research assistant for tasks (4), (5) and (6) was an engineering graduate who was employed as a teacher in a technical school at the time. He had had previous experience in scoring open-ended tests in an experiment to assess the creativity of school children in science. The use of two independent assessors was thought to be reasonable in view of the fact that subjective evaluations of quality were not being called for. The extent to which the independent assessors agreed and disagreed will be reported in due course in Chapters 5 and 6.

While the scoring of tasks (5) and (6) was based on quantity of ideas and not their quality, it should be borne in mind that there is evidence showing a strong positive correlation between the two. Gluskinos' results to this effect have already been noted in Section 3.3.2. Owens (1969) reported the highly significant correlation of 0.63 between two sets of scores obtained by 457 engineers on his Power Sources Apparatus Test. One set of scores consisted of the total number of ideas produced by each subject and the other set the number of workable ideas.

With respect to flexibility of ideation, when the experimental programme was planned, it was not clear in advance which tasks would generate responses that would fall into clearly defined categories, and thus yield scores for flexibility based on the number of categories covered. In the event, only the responses to tasks (1) and (4) fulfilled this condition. Further specialised scoring procedures were devised for task (1) and these are discussed in Chapter 5.
The responses of subjects to tasks (7) and (8) were physical structures, and it was possible to observe and measure the performance of these structures in an objective manner.

Scoring of responses to the complex tasks (9) and (10) introduced special problems, and these are discussed separately in Chapter 8.

4.4.2. Statistical Analysis

In accordance with the general aims of the research stated in Section 1.2, the results from the experimental programme were analysed in order to determine the following:

(1) Inter-correlations of scores on task (1).

(2) Inter-correlations of scores on tasks (2), (3), (4), (5) and (6).

(3) Correlations of scores on tasks (1) to (7) inclusive with academic effort as measured by marks gained in formal examinations.

(4) Comparison of the academic effort of successful and unsuccessful subjects in task (8).

Furthermore, detailed examination of the results showed that other interesting analyses could be made, and these are reported in subsequent chapters.

The t-test was used in the analysis in two ways: firstly, to check whether any of the observed correlations were statistically significant at 95% and 99% levels of confidence; secondly, when comparing distributions of scores obtained by different groups of subjects on the same task, to determine whether the observed differences between the means were likely
to have arisen by chance.

The distributions of scores on open-ended tests are usually skewed, as was the case, for example, in Owens' Power Sources Apparatus Test (Owens, 1969). While the t-test assumes normal distributions of data, it is robust to violation of assumptions, especially for sample sizes as large as in this research (McNemar, 1969, p.118 and p.156), and no errors are introduced into the analysis as a result.

4.5. CONCLUSION

In this chapter the overall programme of research has been presented. The following chapters describe in detail the experiments undertaken and the results obtained.
CHAPTER 5

SKILLS IN SEARCHING FOR
AND CLASSIFYING INFORMATION

5.1. INTRODUCTION

This chapter is concerned with the "information search" or "collection of data" step in the design process.

In any new and complex problem, the designer is either presented with or has to seek out a large quantity of information. He has to commit to memory a large number of items of information in such a way that they are readily available for recall. For this purpose he classifies related items of information into groups (or "chunks", Miller, 1956), and this classification reflects his understanding of the structure of the problem. Hopefully, the structure he imposes on the problem corresponds to its true structure, that is the intrinsic sets of relationships between its elements.

The structure of an evolutionary or extrapolatory design problem is usually well understood because there are precedents to guide the designer. By contrast, in innovative design there are few or no precedents to help the designer recognize the structure of a novel problem. Nevertheless, it is reasonable to suppose that the designer's appreciation of the structure of an innovative problem will influence the way he classifies the information he seeks and will in turn be influenced by it. The classification he adopts
as the basis for his work may therefore have a marked influence on later stages of the design and may well determine whether he reaches a successful solution.

The investigation to be reported in this chapter deals with a relatively complex, innovative design problem, where the search for information imposes a heavy cognitive load on the designer. Section 5.2 reviews evidence on human ability to process information when solving complex problems and discusses examples drawn from engineering design on the one hand and from cognitive psychology on the other. Section 5.3 examines the skills used in searching for and classifying information and suggests techniques of measuring them. These techniques are then applied in an experimental investigation.

The conduct of the experiment and the results obtained are presented in Section 5.4, while the final section of the chapter summarises the conclusions reached and makes recommendations for further research.

5.2 THE COGNITIVE LOAD ON THE DESIGNER

A number of research workers in the field of engineering design have discussed the designer's ability to solve problems under heavy cognitive load.

For example, in his book on engineering design, Matousek (1963) argues that designing is the "prolonged checking, pondering and compromising on requirements which are often quite contradictory until there appears - as the end product of numerous associations of ideas and of net-
works of ideas - the design".

Wilson (1969) analyses the design process with respect to one specialised mechanical product - powered artificial limbs. He gives several examples of the complicated nature of this process in which one decision by the designer can lead to a bewildering array of consequences. He concludes that this type of design problem consists of an extensive network of interacting sub-problems. In order to prevent the designer over-simplifying a network of interactions by ignoring or overlooking relevant linkages, Wilson favours the use of charts giving visual record of the networks of interactions linking different design decisions.

Morgan (1967) examines the design of evolutionary products - milling machines - where the designer can foresee that the problem can be broken down into a number of inter-related sub-problems. These he calls "decision areas" as each gives rise to alternative courses of action ("options") and decisions have to be made about which option to select. Morgan then discusses methods of eliminating incompatible options from related decision areas followed by a systematic survey of combinations of the remaining compatible options to find the best design. He makes extensive use of network diagrams to show the inter-relationships between decision areas.

Gott and Berridge (1966) are concerned with the complicated patterns of interactions which arise in the design of thermal power stations. The design of such large engineering systems is of course carried out by teams of designers, and the interactions between different parts of the design lead
to difficulties in co-ordinating the work of different teams. Gott and Berridge devote much of their paper to discussing the resulting problems of project management and control, but they present their argument verbally and make no use of interaction diagrams or networks.

Alexander (1964) considers the design of relatively complex, multivariable, quasi-static systems (quasi-static in the sense that design variables change only slowly with time). He argues that the unaided designer cannot consider simultaneously the large number of factors relevant to a particular decision. Decisions are therefore made on an oversimplified basis with most weight being given to those issues which happen, perhaps fortuitously, to catch the designer's attention.

All the design problems investigated by Alexander can be modelled by networks, in which the vertices represent design variables and the links between pairs of vertices represent interactions between the corresponding pairs of variables. He developed a set of computer programs called HIDECS (Alexander and Manheim, 1962, 1963) for decomposing a network in such a way that strongly interacting groups of variables, represented by groups of vertices in the network with many interconnecting links, were separated out. His aim was to break the design problem apart into clusters of variables that were as richly connected internally as possible. Examples of how this aids the designer's realization of the physical hardware are given by Alexander (1964) and Alexander and Manheim (1965), dealing respectively with an Indian village and a highway interchange.
The HIDECS programmes can be applied to any design problem capable of being modelled by a network, or its equivalent - a symmetric, binary matrix with zero diagonal. (See Harary, 1969, for a mathematical discussion of the equivalence of a labelled graph or network and its adjacency matrix.) Alexander was interested in evolutionary design problems where the relevant information had already been obtained. However, the HIDECS programmes could also be applied to the information search phase of a new design to help cluster related items of information together. This possibility is further explored in Section 5.3 below.

Cognitive psychologists have investigated the effects of information load on the performance of subjects in tasks relating to particular areas of research, a well-known example being the study of concept formation by Bruner et al. (1956). However, there is little evidence concerning the effects of increasing cognitive load on human performance in solving complex problems such as those typical of engineering design.

Schroder et al. (1967) describe one study which yielded results of interest to the present discussion, although their research was set in a competitive game-playing context. They observed the information-processing capabilities of groups of individuals in a tactical war game. Each group consisted of four subjects representing commanders of equal status on a naval fleet approaching an enemy-held island. The fleet contained ships of varying type and size, including aircraft carriers. The task was to find out what the situation was on the island and take appropriate action. To accomplish this task, the groups had to make hypotheses about
the strength and deployment of the enemy on the island, test these hypotheses, and make decisions for future action. A careful record was kept of the number and type of decisions made by the experimental groups.

It was found that different groups displayed differing abilities in keeping track of all the factors that arose during their experimental sessions and of the outcomes of past decisions they had made. Some groups – described as integratively complex in terms of Schroder's conceptual systems theory – performed well in this regard: they used more powerful strategies to process the information they received and they made more high-level decisions integrating larger amounts of informational input.

One could hypothesise that engineering designers would also vary in their ability to keep track of all the factors arising in the course of a long and complicated design problem, and that this would in turn depend on their skill in classifying the information they received according to the structure of the problem. The experimental investigation to be reported in Section 5.4 was undertaken in order to throw some light on this matter.

Karlin (1966) investigated the information seeking behaviour of 60 subjects, interpreting the results in terms of conceptual systems theory. The subjects of his experiments were given 57 categories of information by the experimenter so that they did not have to make any classifications themselves. Their task was to ask for items of information concerning
the people living on a remote Pacific island in order that a project for
building a hospital on the island could be successfully carried through.
Karlins measured the breadth of search of a subject by the number of
categories sampled and the depth of search by the number of items in
each category. He found that integratively more complex individuals
exhibited greater breadth of information search and their search was
more evenly distributed across the information domain provided.

As pointed out in the introduction, this chapter is concerned with
how the designer classifies the information he is seeking in a new
problem as well as with the breadth and depth of his search. In the
next section, possible ways of measuring his skills in these activities
are considered.

5.3. IDENTIFICATION AND MEASUREMENT OF SKILLS IN
SEARCHING FOR AND CLASSIFYING INFORMATION
IN COMPLEX DESIGN PROBLEMS

5.3.1. Hierarchy of Information

In a new and complex design problem there will be a large number
of items of information to be sought, quite possibly well over one hundred.
If these are classified into groups of related items there may still be too
many groups for the designer to keep track of, and the groups themselves
may be brought together as members of larger categories. In this way,
one can build up a picture of a hierarchy of information as illustrated in
Fig. 5.1, which also shows a system of numbering which could be used to
identify categories, sub-categories, and items of information.

Fig. 5.1. Hierarchy of information.

Experimental work was begun in the expectation that Fig. 5.1 would represent an adequate model for recording subjects' responses to an information search question. To explain the techniques used for scoring responses it is necessary to look ahead and anticipate some results of the enquiry. It was in fact found that the subjects elaborated on some items of information and not on others by giving specific examples. This gave rise to a fourth level in the information hierarchy and the general picture is then as shown in Fig. 5.2 where the letters a, b, c, represent elaborations.
5.3.2. Measurement of Skills

Procedures for measuring skills will now be discussed under two headings:

(1) Skill in information search

(2) Skill in classifying information.

For the purposes of this discussion it will be assumed that the hierarchy of information has already been established. The setting up of this hierarchy will be considered in Section 5.3.3.

Skill in Information Search

The information hierarchy provides measures of (a) breadth and (b) depth of search against which the performance of any one individual can be scored. These measures are similar to and extensions of those used by Karlins.
The breadth of the search for information by a subject S can be measured by the breadth of his coverage of information at each level in the hierarchy, that is by:

1. the number of categories covered (denoted $B_1$)
2. the number of sub-categories covered (denoted $B_2$)
3. the number of items given (denoted $B_3$)
4. the number of elaborations given (denoted $B_4$)

Various measures of depth of search might well be appropriate. They are listed here and their applicability to a particular experimental situation examined later.

The maximum depth (denoted MD) is the number of levels in the information hierarchy to which an individual penetrates, e.g. if he gives only categories and sub-categories then MD = 2, while MD = 3 if he goes as far as items of information and MD = 4 if he elaborates an item.

The maximum depth together with scores on breadth of coverage give a reasonably complete picture of an individual's search for information. However, additional data might be required. For example, given a person's performance at the $i^{th}$ level of the hierarchy with a score of $B_i$ elements at this level, what is the average depth of his search for information at the next level as measured by the proportion of the $B_i$ elements he has followed up at the $(i+1)^{th}$ level?

The average depth of search defined in this way (denoted AD) can be measured for penetrations from various levels in the hierarchy.
From the first level:

\[ AD_1 = \frac{\text{the number of categories for which } S \text{ gives at least one sub-category divided by the number of categories given by } S.} \]

From the second level:

\[ AD_2 = \frac{\text{the number of sub-categories for which } S \text{ gives at least one item divided by the number of sub-categories given by } S.} \]

From the third level:

\[ AD_3 = \frac{\text{the number of items for which } S \text{ gives at least one elaboration divided by the number of items given by } S.} \]

If \( AD_1 < 1 \), then the \((i+1)\)th level of the hierarchy will not have been penetrated by \( S \) as well as it might have been and presumably \( B_{i+1} \) will be lower.

In the foregoing, no attempt has been made to distinguish between elements at the same level of the hierarchy, e.g. all sub-categories are given equal weighting in arriving at \( B_2 \). To weight elements in the hierarchy would complicate the scoring procedure. Moreover, the weighting of an element would probably have to be based on a subjective evaluation of its relative importance. This was thought to be not only undesirable but unnecessary, as the aim was to develop a reasonably straightforward and objective scoring procedure which could be readily applied in a particular case.
Skill in Classifying Information

When searching for information an individual may work in a haphazard fashion, noting items of information more or less at random without any attempt at ordering or classifying them. Alternatively, he may structure his information search by explicitly classifying information and grouping related items into categories and sub-categories which correspond to the information hierarchy. If he does this he is acting in a way which reduces cognitive load and makes it easier for him to cover the information domain. We are therefore interested in the "level of structuring" an individual introduces into his search for information, as we would expect individuals using more highly structured approaches to give greater breadth of coverage and ultimately to generate more items of information.

Evidence on level of structuring will be presented in Section 5.4, evidence obtained from the written answers to an information search question by subjects participating in the experiment. In order to categorize answers according to the level of structure shown, the following criteria are proposed:

1. **No Structure**
   
   Answers show no evidence of structure and contain items of information written down in a disordered sequence, without any connecting links between adjacent items, apparently just as they occurred to the subject.
High Structure

Highly structured answers have the following characteristics:

(a) Headings, sub-headings, and paragraphing are used to group related items of information and identify the category to which they belong.

(b) Items within any one group are consistent in that they are all related to each other in a recognizable way. The group contains no stray or unrelated items.

Low Structure

Answers showing a low level of structure are intermediate between (1) and (2). In a typical case, a subject may have arranged his work into a number of paragraphs, but not all the items in each paragraph would be related. He shows some sense of structure but does not carry through his approach consistently.

It will be seen that the scale used for measuring level of structure has three intervals. At this stage of the research it was thought that the concept of level of structure was not sufficiently precise to permit the use of a scale with a larger number of intervals.

5.3.3. Establishing the Information Hierarchy

To establish the hierarchy relevant to an information search, subjects' answers are first analysed to determine all the items present. Since different subjects might express essentially the same idea in different
ways, there is an element of subjectivity in the interpretation of the answers. Not only the items of information listed in the answers but also the way the items are classified could be affected by interpretations placed on them by the investigator making the analysis.

It is clearly desirable for the analysis and the setting up of the information hierarchy to be carried out by more than one person. Then, if say two independent workers agree that the same hierarchy should apply to a particular information search, this can be taken as a good indication that the hierarchy provides an objective framework for measuring the performance of subjects in searching for information.

As an additional check that the hierarchy adopted is a reasonable one, the author proposes that Alexander's HIDECS 2 programme be used. Given a set of input items and a set of interactions between these items (all of which can be represented on a network by vertices and links respectively), HIDECS 2 performs a series of two-way partitions. The original set is partitioned into two subsets which are in turn divided making a total of four new subsets, and so on.

Each partition is carried out in such a way that, if all interactions are of equal significance, the information lost is a minimum. The resulting sets of strongly interacting items can then be examined to see whether they contain groupings overlooked by the experimenters in their formulation of the information hierarchy.
5.4. EXPERIMENTAL INVESTIGATION

5.4.1. Aims

In view of the importance of the information search phase to the solution of many complex design problems, it was decided to carry out an experiment to study human skills in this activity. Second year engineering students from the University of Melbourne participated as subjects. The aims were:

(1) To identify appropriate measures of information-seeking behaviour in complex design problems.

(2) To investigate the relation between the information-seeking behaviour and the academic effort of the subjects participating in the experiment. In the university examinations taken by the subjects, information is presented to them and they have no opportunity of demonstrating skills in searching for information. The following hypothesis is therefore advanced:

There will be no significant correlations between information-seeking behaviour as measured in (1) above and academic effort as measured by marks obtained in university examinations.

(3) To investigate the relation between the level of structuring of the subjects' answers to an information search question and their breadth of coverage of the information domain. The following hypothesis is advanced:

Subjects classed as "high structure" will score significantly better on measures of breadth of information search (i.e. $B_1$, $B_2$, $B_3$, $B_4$) than subjects classed as "low structure", who in turn will
score significantly better than subjects whose answers exhibit no structure.

(4) To investigate the relation between the level of structuring of the subjects' answers to an information search question and their performance in mathematics. It could be argued that a highly structured answer to an information search question indicates an ability to detect patterns and relationships in unfamiliar contexts, an ability that may also be exercised in solving abstract mathematical problems. The following hypothesis is therefore advanced with relation to "Engineering Mathematics", the name of the mathematics course studied by all engineering students at the University of Melbourne.

Subjects classed as "high structure" will gain significantly higher marks in Engineering Mathematics than subjects classed as "low structure", who will in turn gain significantly higher marks than subjects whose answers exhibit no structure.

(5) To investigate the relation between the level of structuring of the subjects' answers to an information search question and their academic effort as measured by marks gained in university examinations. In this instance no hypothesis is advanced regarding the possible nature of this relation.

(6) To investigate the applicability of the HIDECS 2 program to the classification of items of information search task.
5.4.2. Experiment

In this section the conduct of the experiment is described dealing firstly with the task to be performed and secondly with its presentation to the subjects.

Experimental Task

A suitable task for exercising skills in searching for information had to be devised which satisfied the following criteria: (a) the task had to be sufficiently complex to require a large amount of information to be searched for, and (b) it had to be set in a context which was unfamiliar to any of the subjects and outside their personal experience.

The question used by Karlins in his investigation (Karlins, 1966) fulfils these requirements. It was modified for this experiment to broaden its scope by asking for information concerning conditions on the island generally, not just for information concerning the people living there. Also, the subjects were not given any categories in which to search for information, as it was desired in this investigation to collect data on their capacity for structuring information in an unfamiliar context.

The task was presented to the subjects in the following form including an introductory preamble.

Frequently the designer has to spend time searching for relevant information to enable him to start work on a project. If the problem is novel or is vaguely defined, a lot of effort may be devoted to this activity in the initial phase of the design. This question deals with the collection of information for a new project.
Your answer should be as precise as possible indicating a clearly thought out appreciation of the problem, not vague waffle.

Imagine that you are the leader of a team of volunteers who have taken on the job of building a hospital for the indigenous community on a remote Pacific Island (the project being carried out under the aegis of the United Nations). An earlier attempt by missionaries to build such a hospital failed four years ago because of a hostile reaction from the local people.

What information would you require concerning the island and conditions on it in order to undertake the project successfully?

**Presentation of the Task**

The task was presented to second year engineering students in the University of Melbourne as a compulsory exercise in Engineering Design I. It was handed to students at the beginning of a two-hour design class following a lecture. Their answers were collected an hour later, after which time they began work on other exercises.

As one of the educational objectives of Engineering Design I is to develop a student's capacity for independent work, there was no close supervision over them by the five tutors in attendance. As far as the tutors could observe, the great majority of students were keen to work on their
own and develop their own individual approach to the question. Because the question was an open-ended one, the author expected that in any case careful comparison of their answers would show evidence of any unwanted collaboration. In fact subsequent analysis revealed three pairs of answers which were markedly similar and which were therefore discarded from the analysis.

The investigation included all male Australian students who were attempting Engineering Design I for the first time, who had passed the first year of their undergraduate engineering course at the University of Melbourne in the previous year and whose studies had not been affected by illness. When the three pairs of students who had collaborated were eliminated from consideration, there remained a total of 116 subjects whose performance was to be investigated. The average age of the subjects was 19 years 4 months, with a standard deviation of 8 months.

5.4.3. Analysis of Results

The methods used for analyzing the results obtained are now discussed under the following headings:

(1) Establishing the information hierarchy
(2) Scoring subjects' answers on measures of breadth and depth
(3) Classifying subjects' answers according to level of structure.

The analysis was carried out by the author (A) and a research assistant (B) who provided an independent check as described below. The experiment was carried out in the fourth week of the academic year when
the author had had little personal contact with the subjects and in any case had no knowledge of their previous academic record; B had no contact with the subjects at any stage.

Establishing the Information Hierarchy

The subjects' answers were first analysed by A who prepared an information hierarchy containing 6 categories, 28 sub-categories, 183 items of information and 32 elaborations. B then made an independent analysis and prepared a separate information hierarchy. A and B then consulted and found that there was a wide measure of agreement regarding categories and sub-categories, but differences concerning items and elaborations. After discussion a final information hierarchy was agreed on which contained the same major categories as the initial one prepared by A but had the following changes from it.

(a) The number of sub-categories was reduced from 28 to 27 by coalescing two related sub-categories of A into one.

(b) 16 items and 3 elaborations overlooked by A or incorrectly rejected by him as irrelevant were included. 2 items included by A were deleted because they duplicated other items in the hierarchy.

(c) 53 of the items listed by A were finally agreed to be elaborations of a smaller number of items, so that in the final hierarchy 53 of A's items were re-arranged as 16 items and 53 elaborations.
In the final information hierarchy, the numbers of items and elaborations were respectively:

\[ 183 + 16 - 2 - 53 + 16 = 160 \text{ items} \]

and \[ 32 + 3 + 53 = 88 \text{ elaborations.} \]

The final information hierarchy is summarised in Table 5.1 and set out in detail in Appendix II. The results from the HIDECS 2 programme are presented separately in Section 5.4.6 below. While the information structure given by this programme was not identical to Table 5.1 it was sufficiently similar to confirm Table 5.1 as a basis for analysis.

Scoring Subjects' Answers

A and B next analysed each answer independently and recorded its scores on the measures proposed in Section 5.3.2. They found that for 106 subjects their scores agreed; in the remaining 10 cases, there had been either one or two items overlooked by one of the analysts and picked up by the other.

Classifying Subjects' Answers According to Level of Structure

A and B independently read each answer and classified it as "high structure", "low structure", or "no structure" according to the criteria proposed in Section 5.3.2. After consultation, it was found that there was agreement in 106 of the 116 cases. The disagreements and how they were resolved after discussion between A and B are set out in Table 5.2.

The only other difficulty in classification arose with respect to a subject who concentrated on one category of information, namely category
Table 5.1. Summary of Information Hierarchy.

<table>
<thead>
<tr>
<th>Category</th>
<th>Sub-Category</th>
<th>Number of Items of Information</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>In Sub-Category</td>
</tr>
<tr>
<td>1. The Islanders</td>
<td>1.1 Population</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>1.2 Health</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>1.3 Economy</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>1.4 Education, skills</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>1.5 Religion</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>1.6 Indigenous culture</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>1.7 History</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1.8 Technology</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>1.9 Island society, politics and law</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>1.10 Character, temperament of islanders</td>
<td>6</td>
</tr>
<tr>
<td>2. Island</td>
<td>2.1 General</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>2.2 Food (excluding animals)</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>2.3 Animals</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>2.4 Construction materials</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>2.5 Factors affecting choice of construction materials</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>2.6 Water</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>2.7 Power</td>
<td>2</td>
</tr>
<tr>
<td>3. Choice of Site</td>
<td>3.1 Land available</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>3.2 Nature of site</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>3.3. Accessibility to patients</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3.4 Accessibility to supplies</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>3.5 Associated constructions</td>
<td>3</td>
</tr>
<tr>
<td>4. Climate</td>
<td>4.1 Weather</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>4.2 Natural disasters</td>
<td>6</td>
</tr>
<tr>
<td>5. Volunteers</td>
<td>5.1 Relevant information on island</td>
<td>5</td>
</tr>
<tr>
<td>6. Transport, communications between island and outside world</td>
<td>6.1 Communications</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>6.2 Transport</td>
<td>6</td>
</tr>
</tbody>
</table>
Table 5.2. Resolution of Disagreements Concerning Level of Structure.

<table>
<thead>
<tr>
<th>Number of Subjects</th>
<th>Initial Classification By A</th>
<th>By B</th>
<th>Final Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No structure</td>
<td>Low structure</td>
<td>No structure</td>
</tr>
<tr>
<td>6</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>2</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>1</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

(1) in Table 5.1 - the islanders. However, he clearly sub-divided his answer among a number of sub-categories and listed items in each sub-category in a consistent manner. Both A and B therefore independently classified his answer as "high structure".

5.4.4. Results

The results obtained are set out below in the following order:

(1) Appropriate measures of performance
(2) Correlations
(3) Level of structure

Appropriate Measures of Performance

Of the measures proposed in Section 5.3.2, $B_1$, $B_2$, $B_3$, $B_4$, and $AD_2$ were found to give useful information which is presented later in this Section. Frequency distributions of the scores obtained for $B_1$, $B_2$, $B_3$, and $B_4$ are shown later in Fig. 5.4. The distribution of the scores for $AD_2$ is shown in Fig. 5.3, below.
The proposed measures MD, AD₁ and AD₃ were found to be inappropriate. 108 of the 116 subjects elaborated items of information and gained a score on maximum depth of MD = 4. For the remaining 8 subjects, MD = 3. On AD₁, all but two subjects scored unity because they covered at least one sub-category of information in each major category. Thus MD and AD₁ were discarded because they did not yield scores which discriminated between the great majority of subjects.

With respect to AD₃, only 33 out of the total of 160 items were elaborated by the subjects who participated in the experiment. Because of

---

**Fig. 5.3.** Distribution of Scores on AD₂.
the uneven spread of elaborations across the information domain, AD3 could not be interpreted in a consistent manner across that domain. It was therefore dropped from the analysis.

Correlations

The subjects participating in the experiment were second year engineering students. At the end of this academic year, the following measures of academic effort were available for each subject.

(1) The average mark obtained in examinations held at the end of the first year of his course, denoted A1.

(2) The average mark obtained in examinations held at the end of the second year of his course, denoted A2.

(In calculating A2, marks for the subject Engineering Design I were excluded as this investigation was carried out in conjunction with the normal teaching programme in the subject.)

(3) The mark obtained in the engineering mathematics examination at the end of the first year, denoted M1.

(4) The mark obtained in the engineering mathematics examination at the end of the second year, denoted M2.

The correlation between academic effort and performance in the information search task is shown by the product-moment correlation coefficients in Table 5.3. Correlations significant at the 95% level of confidence are marked with an asterisk, while correlations significant at the 99% level or higher are marked with two asterisks. (Testing for
significant correlations has been discussed in Chapter 4. In this instance
$r_{.05} = 0.18$ and $r_{.01} = 0.24$.

Table 5.3. Correlations between Academic Effort and Performance on Information Search Task.

<table>
<thead>
<tr>
<th></th>
<th>$A_2$</th>
<th>$M_1$</th>
<th>$M_2$</th>
<th>$B_1$</th>
<th>$B_2$</th>
<th>$B_3$</th>
<th>$B_4$</th>
<th>$AD_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_1$</td>
<td>0.73**</td>
<td>0.80**</td>
<td>0.64**</td>
<td>-0.10</td>
<td>0.00</td>
<td>0.12</td>
<td>0.04</td>
<td>0.13</td>
</tr>
<tr>
<td>$A_2$</td>
<td>0.62**</td>
<td>0.83**</td>
<td>0.09</td>
<td>0.17</td>
<td>0.21*</td>
<td>0.06</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>$M_1$</td>
<td>0.65**</td>
<td>-0.03</td>
<td>0.01</td>
<td>0.22*</td>
<td>0.14</td>
<td>0.29**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_2$</td>
<td>0.06</td>
<td>0.08</td>
<td>0.20*</td>
<td>-0.05</td>
<td>0.20*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_1$</td>
<td></td>
<td>0.48*</td>
<td>0.30**</td>
<td>0.17</td>
<td></td>
<td>-0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_2$</td>
<td></td>
<td></td>
<td>0.61**</td>
<td>0.27**</td>
<td>-0.07</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_3$</td>
<td></td>
<td></td>
<td></td>
<td>0.54**</td>
<td>0.42**</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_4$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.22*</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Level of Structure

On the basis of their answers to the information search question, 39 subjects were classified as "high structure" (HS), 25 subjects as "low structure" (LS), and 52 subjects as "no structure" (NS). The performance of each of these groups was then compared on the following measures: $A_2, M_2, B_1, B_2, B_3, B_4$.

Comparisons were also made between the group of 64 subjects who provided structured answers and the group of 52 subjects who did not. $A_1$ and $M_1$ were initially included in the analysis, but as the results were
very similar to those for $A_2$ and $M_2$ and as the latter showed a greater
variation in performance of the 116 subjects, only $A_2$ and $M_2$ are
considered here.

Fig. 5.4 shows histograms of the distributions of the scores
obtained by each group of subjects. The means and standard deviations
of these distributions are set out in Table 5.4.

Table 5.4. Means and Standard Deviations of Scores obtained in University
Examinations and in the Information Search Task by "High
Structure", "Low Structure", and "No Structure" Groups of
Subjects.

<table>
<thead>
<tr>
<th>Measure of Performance</th>
<th>Group</th>
<th>Number of Subjects in Group</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_2$</td>
<td>HS</td>
<td>39</td>
<td>62.85</td>
<td>8.08</td>
</tr>
<tr>
<td></td>
<td>LS</td>
<td>25</td>
<td>63.80</td>
<td>11.17</td>
</tr>
<tr>
<td></td>
<td>NS</td>
<td>52</td>
<td>58.85</td>
<td>8.95</td>
</tr>
<tr>
<td></td>
<td>HS + LS</td>
<td>64</td>
<td>63.22</td>
<td>9.42</td>
</tr>
<tr>
<td>$M_2$</td>
<td>HS</td>
<td>39</td>
<td>61.79</td>
<td>12.46</td>
</tr>
<tr>
<td></td>
<td>LS</td>
<td>25</td>
<td>62.56</td>
<td>10.91</td>
</tr>
<tr>
<td></td>
<td>NS</td>
<td>52</td>
<td>57.98</td>
<td>11.16</td>
</tr>
<tr>
<td></td>
<td>HS + LS</td>
<td>64</td>
<td>62.09</td>
<td>11.89</td>
</tr>
<tr>
<td>$B_1$</td>
<td>HS</td>
<td>39</td>
<td>4.39</td>
<td>1.05</td>
</tr>
<tr>
<td></td>
<td>LS</td>
<td>25</td>
<td>4.48</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>NS</td>
<td>52</td>
<td>4.21</td>
<td>1.04</td>
</tr>
<tr>
<td></td>
<td>HS + LS</td>
<td>64</td>
<td>4.42</td>
<td>1.00</td>
</tr>
<tr>
<td>$B_2$</td>
<td>HS</td>
<td>39</td>
<td>11.56</td>
<td>2.56</td>
</tr>
<tr>
<td></td>
<td>LS</td>
<td>25</td>
<td>11.40</td>
<td>2.37</td>
</tr>
<tr>
<td></td>
<td>NS</td>
<td>52</td>
<td>9.40</td>
<td>2.98</td>
</tr>
<tr>
<td></td>
<td>HS + LS</td>
<td>64</td>
<td>11.50</td>
<td>2.49</td>
</tr>
<tr>
<td>$B_3$</td>
<td>HS</td>
<td>39</td>
<td>15.82</td>
<td>6.71</td>
</tr>
<tr>
<td></td>
<td>LS</td>
<td>25</td>
<td>11.72</td>
<td>4.55</td>
</tr>
<tr>
<td></td>
<td>NS</td>
<td>52</td>
<td>10.58</td>
<td>4.42</td>
</tr>
<tr>
<td></td>
<td>HS + LS</td>
<td>64</td>
<td>14.22</td>
<td>6.29</td>
</tr>
<tr>
<td>$B_4$</td>
<td>HS</td>
<td>39</td>
<td>3.39</td>
<td>2.40</td>
</tr>
<tr>
<td></td>
<td>LS</td>
<td>25</td>
<td>2.40</td>
<td>1.36</td>
</tr>
<tr>
<td></td>
<td>NS</td>
<td>52</td>
<td>2.27</td>
<td>1.69</td>
</tr>
<tr>
<td></td>
<td>HS + LS</td>
<td>64</td>
<td>3.00</td>
<td>2.11</td>
</tr>
</tbody>
</table>
Fig. 5.4. Distributions of Scores obtained in University Examinations and in the Information Search Task by "High Structure", "Low Structure", and "No Structure" Groups of Subjects.

Note: The figure at the top of each column in the histograms is the number of subjects whose scores lie in a particular range.
Fig. 5.4. (Continued)
Fig. 5.4. (Continued)
5.4.5. Discussion of Results

Correlations

Table 5.3. shows that the measures of academic effort are highly correlated, the values obtained being typical of those found in comparisons of the examination results of engineering students. For example, Christopherson in the United Kingdom found correlations in the range 0.60 to 0.81 between the results of examinations which were equivalent to the first and second year Australian University Examinations considered here (Christopherson, 1967).

With one exception all the correlations between measures of breadth of information search are highly significant (p < 0.01). The exception is the correlation between B₁ and B₄, hardly a surprising result as one would not expect the number of elaborations to depend strongly on the number of categories covered. Even in this case the correlation verges on significance, p < 0.08.

As was expected AD₂ and B₃ are highly correlated (p < 0.001), but no correlation was found between AD₂ and B₂. A subject who gains a high score on B₂ is likely to gain a high score on B₃, i.e. if he covers a large number of sub-categories he is likely to give a large number of items. However, he may or may not give items for a larger proportion of the sub-categories covered, no prediction can be made. Thus AD₂, the average depth of search, gives useful information about a subject's performance in addition to his scores on measures of breadth.
Comparison of the correlations between performance on the information search task and academic effort lend strong support to the first hypothesis advanced in Section 5.4.1, although it is not fully confirmed. Of the twenty correlations set out in Table 5.3, one is highly significant \((p < 0.01)\), four are significant \((p < 0.05)\), while in the other fifteen cases no significant correlation exists. Thus there are no significant correlations between \(B_1, B_2, \) and \(B_4\) and academic effort. \(B_3\) correlates with three measures of academic effort but not to a high level of significance. \(AD_2\) correlates with marks gained in mathematics, but how to interpret this result is not clear as there does not appear to be any underlying factor linking the two sets of performances.

Level of Structure

The second hypothesis advanced in Section 5.4.1 concerned the relationship between level of structure and breadth of information search. The results presented in Table 5.4 were analysed by using the t-test to compare the performance of the HS, LS, and NS groups of subjects on the four measures of breadth – \(B_1, B_2, B_3, B_4\). In each case the null hypothesis was proposed that the two sets of results being compared were drawn from identical populations. To test this hypothesis the t-test was applied to see whether the difference between the means could have arisen by chance.

As might be expected from inspection of Table 5.4, no significant differences were found between HS, LS and NS groups in their scores on \(B_1\). Results for \(B_2, B_3\) and \(B_4\) are set out in Table 5.5.
Table 5.5. Tests for Significant Differences in Performance on B₂, B₃ and B₄ by "High Structure", "Low Structure", and "No Structure" Students.

<table>
<thead>
<tr>
<th>Measure of Performance on Breadth of Information Search</th>
<th>Groups Compared</th>
<th>Difference between Means</th>
<th>Standard Error of Difference</th>
<th>t</th>
<th>Number of Degrees of Freedom</th>
<th>Null Hypothesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>B₂ (HS+LS) vs NS</td>
<td>2.10</td>
<td>0.51</td>
<td>4.09</td>
<td>114</td>
<td>Rejected, p &lt; 0.001</td>
<td>Confirmed</td>
</tr>
<tr>
<td>HS vs LS</td>
<td>0.16</td>
<td>0.65</td>
<td>0.25</td>
<td>62</td>
<td>Confirmed</td>
<td></td>
</tr>
<tr>
<td>HS vs NS</td>
<td>2.16</td>
<td>0.60</td>
<td>3.59</td>
<td>89</td>
<td>Rejected, p &lt; 0.001</td>
<td></td>
</tr>
<tr>
<td>LS vs NS</td>
<td>2.00</td>
<td>0.69</td>
<td>2.89</td>
<td>75</td>
<td>Rejected, p &lt; 0.01</td>
<td></td>
</tr>
<tr>
<td>B₃ (HS+LS) vs NS</td>
<td>3.64</td>
<td>1.04</td>
<td>3.50</td>
<td>114</td>
<td>Rejected, p &lt; 0.001</td>
<td></td>
</tr>
<tr>
<td>HS vs LS</td>
<td>4.10</td>
<td>1.55</td>
<td>2.64</td>
<td>62</td>
<td>Rejected, p &lt; 0.01</td>
<td></td>
</tr>
<tr>
<td>HS vs NS</td>
<td>5.24</td>
<td>1.18</td>
<td>4.43</td>
<td>89</td>
<td>Rejected, p &lt; 0.001</td>
<td></td>
</tr>
<tr>
<td>LS vs NS</td>
<td>1.14</td>
<td>1.10</td>
<td>1.04</td>
<td>75</td>
<td>Confirmed</td>
<td></td>
</tr>
<tr>
<td>B₄ (HS+LS) vs NS</td>
<td>0.73</td>
<td>0.29</td>
<td>2.48</td>
<td>114</td>
<td>Rejected, p &lt; 0.02</td>
<td></td>
</tr>
<tr>
<td>HS vs LS</td>
<td>0.99</td>
<td>0.54</td>
<td>1.84</td>
<td>62</td>
<td>Rejected, p &lt; 0.08</td>
<td></td>
</tr>
<tr>
<td>HS vs NS</td>
<td>1.12</td>
<td>0.43</td>
<td>2.57</td>
<td>89</td>
<td>Rejected, p &lt; 0.02</td>
<td></td>
</tr>
<tr>
<td>LS vs NS</td>
<td>0.13</td>
<td>0.39</td>
<td>0.33</td>
<td>75</td>
<td>Confirmed</td>
<td></td>
</tr>
</tbody>
</table>

The superior performance of the "high structure" subjects is evident. On each measure the HS group scored better than the NS group, giving a broader coverage of the information domain at the three lower levels of the hierarchy. The results are particularly significant in the case of B₂ and B₃ and moderately significant in the case of B₄. The HS group also scored significantly better on B₃ than the LS group. The most important part of the original hypothesis is thus confirmed.

The results of the LS group are inconsistent and that part of the hypothesis dealing with "low structure" subjects is not sustained. In the case of B₂, there is no significant difference between the HS and LS groups and both perform significantly better than the NS group. On the other hand, on B₃ and B₄ there is no significant difference between the LS and NS groups.
and both are out-scored by the HS group.

Also to be investigated was a possible relation between level of structure and performance in mathematics. To compare the two sets of results, the null hypothesis was adopted that both were drawn from identical populations, and the t-test then applied to determine whether the observed difference between their mean values could have arisen by chance. The results are shown in Table 5.6 together with the results of similar tests for investigating differences in academic effort.


<table>
<thead>
<tr>
<th>Measure of Academic Effort</th>
<th>Groups Compared</th>
<th>Difference between Means</th>
<th>Standard Error of Difference</th>
<th>t</th>
<th>Number of Degrees of Freedom</th>
<th>Null Hypothesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>A₂</td>
<td>(HS+LS) vs NS</td>
<td>4.37</td>
<td>1.74</td>
<td>2.52</td>
<td>114</td>
<td>Rejected, p &lt; 0.02</td>
</tr>
<tr>
<td></td>
<td>HS vs LS</td>
<td>0.95</td>
<td>2.45</td>
<td>0.38</td>
<td>62</td>
<td>Confirmed</td>
</tr>
<tr>
<td></td>
<td>HS vs NS</td>
<td>4.00</td>
<td>1.84</td>
<td>2.17</td>
<td>89</td>
<td>Rejected, p &lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>LS vs NS</td>
<td>4.95</td>
<td>2.39</td>
<td>2.07</td>
<td>75</td>
<td>Rejected, p &lt; 0.05</td>
</tr>
<tr>
<td>M₂</td>
<td>(HS+LS) vs NS</td>
<td>4.11</td>
<td>2.18</td>
<td>1.89</td>
<td>114</td>
<td>Rejected, p &lt; 0.07</td>
</tr>
<tr>
<td></td>
<td>HS vs LS</td>
<td>0.77</td>
<td>3.09</td>
<td>0.25</td>
<td>62</td>
<td>Confirmed</td>
</tr>
<tr>
<td></td>
<td>HS vs NS</td>
<td>3.81</td>
<td>2.52</td>
<td>1.51</td>
<td>89</td>
<td>Confirmed</td>
</tr>
<tr>
<td></td>
<td>LS vs NS</td>
<td>4.58</td>
<td>2.73</td>
<td>1.68</td>
<td>75</td>
<td>Rejected, p &lt; 0.10</td>
</tr>
</tbody>
</table>

The hypothesised relationship between level of structure and performance in mathematics was not found. While the LS group gained higher marks in mathematics than the NS group, the difference was barely significant. Moreover, the performance of the HS group was slightly poorer than that of the LS group - a result in direct contradiction to the proposed hypothesis.
A significant relationship did emerge when comparisons were made between level of structure and academic effort, \( A_2 \). As can be seen from Table 5.6, both the HS and LS groups gained significantly higher average marks in their university examinations than the NS group. While the evidence is far from conclusive, it does suggest that skill in structuring information helps performance in university examinations generally. In so far as the information search task presented to the subjects dealt with qualitative and not quantitative information (semantic information not symbolic, in Guilford's terms), the skill might be expected to aid performance in descriptive examinations rather than in mathematics.

The Boundaries of the Task

Analysis of their performances on the information search task yielded some evidence of the way subjects saw the boundaries of the task they had been set. Although this was not intended to be a major part of the investigation, the results are reported here because of their interest.

The sixth and last category in the information hierarchy in Table 5.1 is "Transport and Communications between the Island and the Outside World". Whether a subject included this category in his search for information could depend on how he saw the boundaries of the problem, whether he confined himself exclusively to conditions on the island or whether he extended his thinking to consider interactions between the island and its environment. More generally, some subjects may restrict their thinking to within boundaries which are clearly defined whereas others
are more ready to cross boundaries and look at tasks they have been set from a more inclusive viewpoint.

In this instance, 65 of the 116 subjects mentioned category No. 6, 56.0% of the total. There was no significant difference in performance between the group of subjects who mentioned category No. 6 and the group who did not with respect to academic effort as measured by $A_2$ and $M_2$. This is evident from Fig. 5.5 which shows the distributions of marks on $A_2$ and $M_2$ obtained by the two groups of subjects. Because questions in university examinations have clearly defined boundaries in order to delineate a small segment of knowledge on which the student is to be tested, one might expect performance in such examinations to be a poor predictor of whether or not a student mentions category No. 6. This in fact turns out to be the case.

Table 5.7 shows that there is no relationship, either positive or negative between subjects' coverage of category No. 6 and level of structure.

In this instance, whether subjects explore the boundaries of the task bears no relation to the level to which they structure the search for information.

Table 5.7. Percentages of Subjects of Different Levels of Structure who Mentioned Category No. 6.

<table>
<thead>
<tr>
<th>Level of Structure</th>
<th>Total Number of Subjects</th>
<th>Number of Subjects who Mentioned Category No. 6</th>
<th>Percentage of Subjects who Mentioned Category No. 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>HS</td>
<td>39</td>
<td>22</td>
<td>56.4</td>
</tr>
<tr>
<td>LS</td>
<td>25</td>
<td>15</td>
<td>60.0</td>
</tr>
<tr>
<td>NS</td>
<td>52</td>
<td>28</td>
<td>53.8</td>
</tr>
<tr>
<td>TOTAL</td>
<td>116</td>
<td>65</td>
<td>56.0</td>
</tr>
</tbody>
</table>
Fig. 5.5. Distributions of Marks in University Examinations for Subjects who Mentioned Category No. 6, and those who did not.
Fig. 5.5. (Continued)
5.4.6. Application of HIDECS 2 Programme

The application of the HIDECS 2 programme to form a hierarchy of groups of related items of information is now described under the following headings:

(1) Setting up the interaction matrix

(2) The hierarchy of information produced by HIDECS 2

(3) Discussion of results.

Setting up the Interaction Matrix

The interaction matrix is a symmetric, binary matrix with zero diagonal. Each cell in the matrix represents a possible interaction between pairs of items of information; 1 indicates that an interaction exists, 0 that it does not. In this case there are 160 items of information and the number of decisions whether or not an interaction exists is

\[
\frac{159 \times 160}{2} = 12,720
\]

The author (A) and research assistant (B) independently listed all the interactions they thought to be significant. They then consulted together and found that there were 246 discrepancies between their listings where one had identified an interaction but the other had not. These discrepancies were resolved after discussion and the final set of interactions agreed on. There were then 2,164 significant interactions, i.e. 17.0% of the total of 12,720. The percentage of discrepancies was \(\frac{246}{2,164} \times 100 = 11.4\%\).
The Information Hierarchy Produced by HIDECS 2

The interaction matrix was then punched on the data cards of the HIDECS 2 programme, and the programme run on the IBM 7044 computer at the University of Melbourne. (The original HIDECS 2 programme was written in FAP; Field (1970) describes its conversion to run on the 7044 computer.)

HIDECS 2 performs a series of two-way partitions on the input data. The results obtained from the first three stages of this process are summarised in Fig. 5.6 and set out in detail in Appendix II. In Fig. 5.6 major headings have been suggested for the groupings of items produced by HIDECS 2.

To arrive at Fig. 5.6 it has been necessary to make numerous simplifications to remove anomalies produced by the HIDECS technique of two-way partitioning. Results for only three such partitions are presented here because at lower levels in the HIDECS hierarchy the anomalies proliferate and useful sub-groupings of items of information were not obtained.

At the level of partitioning shown in Fig. 5.6 there are two defects in the HIDECS classification, as follows:

(1) A useful sub-division of the items in (1.1) is not obtained. This is probably because all these items interact strongly; the programme which is already long and complex is not equipped to deal with this situation.

(2) Items of information concerning the island's climate are split in an arbitrary way between the sub-groups under (2.1) in the hierarchy.
Fig. 5.6. Information Hierarchy Produced by HIDECS 2.
When the hierarchy of Fig. 5.6 is compared with that adopted previously in Table 5.1, the following differences are evident.

(1) The major category of "climate" does not appear.

(2) The major category of "volunteers" in Table 5.1 does not appear - items of information under this heading being distributed amongst other categories in the HIDECS set.

(3) "Construction materials" instead of being included under "natural resources" as in Table 5.1 becomes an important group in its own right in the HIDECS hierarchy.

(4) The sub-category "Islanders' technology" in Table 5.1 does not appear, the items it contains being distributed among the HIDECS hierarchy.

(a) "Military technology" is associated with "other information about the islanders".

(b) "Waste disposal" is associated with "population and health".

(c) "Communications and transport on the island" is associated with "communications and transport between the island and the outside world" to form one important grouping.

(d) "Building tools" and "methods of construction" are associated with "construction materials".

(e) "Use of existing buildings" is associated with "choice of hospital site".
After consideration of the above, the author derived the revised information hierarchy set out in Table 5.8. Table 5.8 incorporates the changes noted in (3) and (4) above but discards (1) and (2) on the grounds that "climate" and "volunteers" are major categories of information and should be retained.

Application of the revised hierarchy led to new sets of scores on breadth of information search at the levels of category and sub-category, denoted $B_1'$ and $B_2'$. Scores for $B_3$ and $B_4$ were unchanged.

The effect of a further revision to the first level of the information hierarchy was also investigated. In this revision the first category in Table 5.8 - the Islanders - was replaced by two major categories:

(a) Islanders' population and health, and
(b) Other information about the islanders.

This revision was suggested by the way HIDECS 2 partitioned information on the Islanders as shown in Fig. 5.6. It gave rise to a new set of scores for the number of categories covered by the subjects, denoted $B_1''$, $B_2''$, $B_3$ and $B_4$ were not affected.

Discussion of Results

The new set of correlations with $B_1'$, $B_1''$ and $B_2'$ are shown in Table 5.9.

Comparison with Table 5.3 shows that with one exception there is no change in the level of significance of the correlations obtained. For example, the correlations of $B_2'$ with $M_2$ and $B_3$ are respectively 0.08 and
Table 5.8. Summary of Revised Information Hierarchy.

<table>
<thead>
<tr>
<th>Category</th>
<th>Sub-Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The Islanders</td>
<td>1.1 Population</td>
</tr>
<tr>
<td></td>
<td>1.2 Health</td>
</tr>
<tr>
<td></td>
<td>1.3 Economy</td>
</tr>
<tr>
<td></td>
<td>1.4 Education, skills</td>
</tr>
<tr>
<td></td>
<td>1.5 Religion</td>
</tr>
<tr>
<td></td>
<td>1.6 Indigenous culture</td>
</tr>
<tr>
<td></td>
<td>1.7 History</td>
</tr>
<tr>
<td></td>
<td>1.8 Island society, politics, law</td>
</tr>
<tr>
<td></td>
<td>1.9 Character, temperament of islanders</td>
</tr>
<tr>
<td>2. Island Environment -</td>
<td>2.1 General</td>
</tr>
<tr>
<td>Natural Resources</td>
<td>2.2 Food (excluding animals)</td>
</tr>
<tr>
<td>(excluding Construction Materials)</td>
<td>2.3 Animals</td>
</tr>
<tr>
<td></td>
<td>2.4 Water</td>
</tr>
<tr>
<td></td>
<td>2.5 Power</td>
</tr>
<tr>
<td>3. Transport and Communications</td>
<td>3.1 Communications</td>
</tr>
<tr>
<td></td>
<td>3.2 Transport</td>
</tr>
<tr>
<td>4. Construction Materials</td>
<td>4.1 Materials</td>
</tr>
<tr>
<td></td>
<td>4.2 Factors affecting choice of materials</td>
</tr>
<tr>
<td>5. Choice of Site</td>
<td>5.1 Land available</td>
</tr>
<tr>
<td></td>
<td>5.2 Nature of site</td>
</tr>
<tr>
<td></td>
<td>5.3 Accessibility to patients</td>
</tr>
<tr>
<td></td>
<td>5.4 Accessibility to supplies</td>
</tr>
<tr>
<td></td>
<td>5.5 Associated constructions</td>
</tr>
<tr>
<td>6. Climate</td>
<td>6.1 Weather</td>
</tr>
<tr>
<td></td>
<td>6.2 Natural disasters</td>
</tr>
<tr>
<td>7. Volunteers</td>
<td>7.1 Relevant information on Island</td>
</tr>
</tbody>
</table>
Table 5.9. Correlations of Academic Effort and Performance in Information Search Task using Revised Information Hierarchies.

<table>
<thead>
<tr>
<th></th>
<th>$B_1'$</th>
<th>$B_1''$</th>
<th>$B_2'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_1''$</td>
<td>0.96</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_2'$</td>
<td>0.64</td>
<td>0.72</td>
<td></td>
</tr>
<tr>
<td>$A_1$</td>
<td>-0.11</td>
<td>-0.09</td>
<td>-0.01</td>
</tr>
<tr>
<td>$M_1$</td>
<td>-0.13</td>
<td>-0.09</td>
<td>0.01</td>
</tr>
<tr>
<td>$A_2$</td>
<td>0.14</td>
<td>0.16</td>
<td>0.17</td>
</tr>
<tr>
<td>$M_2$</td>
<td>0.04</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>$B_1$</td>
<td>0.89</td>
<td>0.84</td>
<td>0.49</td>
</tr>
<tr>
<td>$B_2$</td>
<td>0.62</td>
<td>0.71</td>
<td>0.99</td>
</tr>
<tr>
<td>$B_3$</td>
<td>0.35</td>
<td>0.44</td>
<td>0.62</td>
</tr>
<tr>
<td>$B_4$</td>
<td>0.11</td>
<td>0.13</td>
<td>0.28</td>
</tr>
<tr>
<td>$AD_2$</td>
<td>-0.19</td>
<td>-0.10</td>
<td>-0.03</td>
</tr>
</tbody>
</table>

0.62 compared with 0.08 and 0.61 for $B_2$. The one exception is the negative correlation between $AD_2$ and $B_1'$ which is now significant ($p < 0.05$) whereas that between $AD_2$ and $B_1$ was not.

With respect to level of structure, no significant differences were found between HS, LS and NS groups in performance on $B_1'$ and $B_1''$.

The result obtained for $B_1$ in the first information hierarchy is thus confirmed. Performance on $B_2'$ is shown in Table 5.10 for HS, LS and NS groups. As before the t-test was applied to confirm or reject the hypothesis that these sets of results were drawn from identical populations.

The results are summarised in Table 5.11.

<table>
<thead>
<tr>
<th>Group</th>
<th>Number of Subjects in Group</th>
<th>Means</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>HS</td>
<td>39</td>
<td>11.38</td>
<td>2.50</td>
</tr>
<tr>
<td>LS</td>
<td>25</td>
<td>11.32</td>
<td>2.43</td>
</tr>
<tr>
<td>NS</td>
<td>52</td>
<td>9.21</td>
<td>2.89</td>
</tr>
<tr>
<td>HS + LS</td>
<td>64</td>
<td>11.36</td>
<td>2.44</td>
</tr>
</tbody>
</table>

Table 5.11. Tests for Significant Differences in Performance on $B'_2$ by "High Structure", "Low Structure" and "No Structure" Subjects.

<table>
<thead>
<tr>
<th>Groups Compared</th>
<th>Difference Between Means</th>
<th>Standard Error of Difference</th>
<th>t</th>
<th>Number of Degrees of Freedom</th>
<th>Null Hypothesis of t</th>
</tr>
</thead>
<tbody>
<tr>
<td>(HS+LS) vs NS</td>
<td>2.15</td>
<td>0.50</td>
<td>4.31</td>
<td>114</td>
<td>Rejected, $p &lt; 0.001$</td>
</tr>
<tr>
<td>HS vs LS</td>
<td>0.07</td>
<td>0.64</td>
<td>0.10</td>
<td>62</td>
<td>Confirmed</td>
</tr>
<tr>
<td>HS vs NS</td>
<td>2.17</td>
<td>0.67</td>
<td>3.23</td>
<td>89</td>
<td>Rejected, $p &lt; 0.01$</td>
</tr>
<tr>
<td>LS vs NS</td>
<td>2.11</td>
<td>0.68</td>
<td>3.11</td>
<td>75</td>
<td>Rejected, $p &lt; 0.01$</td>
</tr>
</tbody>
</table>

The same differences in performance for the HS, LS and NS groups are observed for $B'_2$ as for $B_2$. In each case the "high structure" and "low structure" groups scored significantly better than the "no structure" group, while there is no significant difference between the "high structure" and "low structure" groups.

To sum up, application of the HIDECS 2 computer program to construct revised information hierarchies has led to essentially the same results as obtained with the original information hierarchy constructed by the author and a research assistant.
5.4.7. Conclusions and Recommendations

An experiment has been carried out to investigate the information-seeking behaviour of second-year engineering students in the University of Melbourne. The task set was based on a relatively complex, innovative problem. In it the student subjects had to specify the information they would require concerning a remote Pacific Island in order to plan and carry through a project for building a hospital on the island.

Analysis of the subjects' answers to the task led to the following conclusions:

(1) Appropriate scales can be developed to measure performance on relatively complex information search tasks. They enable the breadth and depth of search of different subjects to be compared.

(2) These scales are based on an information hierarchy. This raises the question - to what extent does establishment of the information hierarchy depend on the subjective opinions of the person making the analysis? In this experiment three similar hierarchies were constructed and used as a basis for scoring. The first was set up after independent analyses by the author and a research assistant; the second and third were set up after a computer analysis of the interactions between different items of information. There were slight changes in subjects' individual scores depending on which hierarchy the scores were based. However, the effect on comparisons made between the subjects' efforts in the information search task and their other academic performance was quite negligible. Thus while the subjective aspects of the measuring technique cannot be ignored, they had no influence on the results of the research reported here.
(3) With some minor exceptions, measures of breadth of information search were significantly correlated, but they did not correlate with academic effort as indicated by the results of university examinations.

(4) One measure of depth of information search was found to be useful, namely the proportion of sub-categories given by a subject for which items of information were enumerated. Not surprisingly, this measure correlated highly with a number of items produced, but not with the number of categories or sub-categories. The measure was also found to correlate significantly with marks in mathematics.

(5) Subjects who produced highly structured answers to the information search task gave significantly better coverage of all levels of the information domain except the highest. This result is in accordance with predictions from cognitive psychology based on an individual's limited capacity for processing complex information. To process large numbers of items of information successfully it is necessary to group related items together. Structuring information in this way is an important means of reducing what would otherwise be an excessive cognitive load.

(6) The performance of subjects who produced answers with only a small amount of structure present was intermediate between that of the "high structure" and "no structure" subjects. The "low structure" subjects covered significantly more sub-categories than the subjects whose answers exhibited no structure, but there was no significant difference between these
two groups in their production of items of information or elaborations.

It will be appreciated that the experiment reported here concerned one information search task and one group of subjects. The subjects who perform better on a complex information search task are presumably those with richer insight into the potentialities of an initially vague and amorphous situation. One might well expect the same subjects to be more sensitive to the implications of a new environment, to show greater sensitivity to remote or subtle problems not perceived by the majority of their peers. A final comment - during the course of the experiment there was an indication that some people are better able than others to explore the boundaries of problems and would therefore possess different skills in problem definition.

In the light of the above comments, it is recommended that further research be carried out:

(1) to confirm the results obtained in the present study with different information search tasks and different subjects;

(2) to investigate the relationship between performance in complex information search tasks and the intellectual factor referred to by Guilford as "sensitivity to problems";

(3) to investigate the intellectual skills associated with problem definition, in particular with respect to the setting of boundaries between a problem and its environment.
5.5. CONCLUSION

Searching for information is an important stage in solving a complex, innovative design problem.

In the study reported here using university students as subjects, the skills involved could be readily distinguished from those of more conventional academic endeavours.

Structuring the information was found to be an aid to breadth of search. However, it should perhaps be pointed out that there is a danger to the problem-solver of adopting an "over-structured" approach. If he relies too much on grouping items of information, he may lose sight of the interactions between items in different groups. While hopefully he constructs groups such that these interactions are small, they may not be entirely negligible. Putting this another way, the formation of groups of items may lead to some loss of information and this possibility should not be overlooked.

Finally, it should be realised that this chapter has treated the structuring of complex information as a static skill, whereas in practice it may also be a dynamic skill. The successful problem-solver may have to exhibit flexibility in his thinking i.e., be skilful in changing from one set of categories of information to another or in other words from one information hierarchy to another. Further research is required to explore this facet of problem-solving behaviour.
CHAPTER 6
SKILLS IN CREATING SOLUTIONS AND FORESEEING IMPLICATIONS

6.1. INTRODUCTION

The creativity of an engineering designer depends not only on his skill in creating solutions to problems, but also on his skill in recognising problems in the first place and then in foreseeing the implications or consequences of the alternative solutions he generates. A series of experiments was therefore devised with the general aim of tapping these different facets of creative behaviour. This chapter is devoted to a description of the experiments and to analysis and discussion of the results obtained.

Some of the material presented in this chapter has been published in a paper in the Bulletin of Mechanical Engineering Education, see Lewis (1968).
6.2. EXPERIMENTAL INVESTIGATION

6.2.1. General

The subjects in the experimental investigation were second year engineering students in the University of Melbourne. Included were all male, Australian students who were attempting Engineering Design I for the first time, who had passed the first year of the undergraduate course in the previous year and whose studies had not been affected by illness. The total number of subjects was 119. Their mean age at the time of the first experimental task was 19 years 7 months with a standard deviation of 8 months.

As part of the normal teaching programme during the academic year, the subjects were asked to perform five tasks which required distinctive creative effort. These experimental tasks, their timing during the academic year, and the subjects’ working environment have already been outlined in Chapter 4, and full details of the design briefs given to the subjects are set out in Appendix I.

In outline, the experimental tasks were as follows. (The tasks are identified by the same numbering scheme as in Table 4.1.)

Task (2): Hospital Stand.

Students were asked to redesign a hospital stand so that it could be adjusted by a person using one hand instead of two.
Task (3): Drawing Office.

Students were asked to design a new drawing office for use by first and second year engineering students. The office might be used for tutorials and other student activities besides formal drawing exercises.

Task (4): Urban Growth.

Students were asked to list all the problems they could foresee arising from the growth of population in the Greater Melbourne area in the next 25 years.


Students were asked to list as many ideas as they could for transporting people to the centre of the city of Melbourne from a proposed underground carpark 1½ miles away.


Students were asked to evaluate the ideas put forward in response to task (5) and to list their advantages and disadvantages.

It will be seen that tasks (2) and (5) are concerned with the creation of ideas. This is also true of task (3), but in this instance another factor is present as well, namely the subjects' sensitivity to problems not explicitly stated but implicit in the requirement that the drawing office be suitable for a wide variety of educational and social activities. Task (4) is concerned
wholly with sensitivity to problems while task (6) is based on skill in foreseeing implications and the outcomes of design proposals. The interpretation of creative design skills in terms of Guilford's intellectual factors in Section 2.5.3 suggests that performance on tasks (4) and (6) should be closely related.

The scheduling of the tasks in the academic year is shown in Table 4.2. Tasks (4), (5) and (6) formed the first question on an examination paper for which the subjects sat approximately six months after undertaking tasks (2) and (3). The subjects were given 10 minutes to study the question and then allowed 35 minutes for writing their answers, making 45 minutes in all.

Procedures for scoring subjects' written responses have been described in Chapter 4. Some additional explanation is required concerning the scoring of flexibility of response to task (4). As already noted, two sets of scores for fluency of response were obtained by the author and a research assistant working independently. To score flexibility, it was necessary to determine the categories into which individual responses could be grouped and then count the number of categories covered by each subject. For this purpose the two scorers constructed classifications independently of each other. Consultation then showed that the two classifications were very closely similar, and in fact gave rise to one set of scores for flexibility.

The results from the experiments consisted of the following sets of scores for each subject.
(1) Examination marks in the first year of the undergraduate course in Chemistry I, Engineering I, Engineering Mathematics I and Physics I, denoted \( M_1, M_2, M_3 \) and \( M_4 \) respectively. *

(2) Examination mark in the second year of the undergraduate course, the average for all sections of the syllabus except Engineering Design I. This is denoted \( M_5 \).

(3) Scores on experimental tasks, denoted \( M_6 \) to \( M_{11} \):
- \( M_6 \) and \( M_7 \) for tasks (2) and (3),
- \( M_8 \) for fluency of response to task (4),
- \( M_9 \) and \( M_{10} \) for tasks (5) and (6),
- \( M_{11} \) for flexibility of response to task (4).

6.2.2. Aims

The specific aims of this series of experiments were as follows:

(1) To investigate the correlations between the two sets of scores for \( M_8 \), \( M_9 \) and \( M_{10} \).

(2) To investigate the inter-correlations between the scores on the experimental tasks, \( M_6 \) to \( M_{11} \).

* At the University of Melbourne, an undergraduate has to pass each year of the engineering course before proceeding to the next year. In this instance, where a student had to repeat the first year of the course because he failed to pass at his first attempt, \( M_1 \) to \( M_4 \) are the marks he obtained at his first attempt.
To investigate the correlations between the scores on the experimental tasks and marks obtained in university examinations.

In each case the aim was to determine whether or not the observed correlations reached a statistically significant level, i.e. to at least the 95% level of confidence.

It was also intended to investigate the academic record and background of any subjects who performed consistently well in all five experimental tasks.

6.2.3. Results

The distributions of scores $M_1$ to $M_{11}$ obtained by the subjects are shown by the histograms in Fig. 6.1. Means and standard deviations are set out in Table 6.1. In this table and throughout the rest of this chapter, where two sets of figures are given for results involving $M_8$, $M_9$ and $M_{10}$, the author's results are given first and the research assistant's second.
Table 6.1. Means and Standard Deviations of Marks Obtained in University Examinations and Scores in Experimental Tasks.

<table>
<thead>
<tr>
<th>Score</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>M₁ - Chemistry I</td>
<td>62.50</td>
<td>13.22</td>
</tr>
<tr>
<td>M₂ - Engineering I</td>
<td>64.77</td>
<td>12.26</td>
</tr>
<tr>
<td>M₃ - Engineering Mathematics I</td>
<td>62.99</td>
<td>10.51</td>
</tr>
<tr>
<td>M₄ - Physics I</td>
<td>61.15</td>
<td>14.28</td>
</tr>
<tr>
<td>M₅ - Average Mark in 2nd Year</td>
<td>62.64</td>
<td>10.58</td>
</tr>
<tr>
<td>M₆ - Hospital Stand</td>
<td>10.03</td>
<td>4.43</td>
</tr>
<tr>
<td>M₇ - Drawing Office</td>
<td>1.88</td>
<td>1.01</td>
</tr>
<tr>
<td>M₈ - Urban Growth - Fluency</td>
<td>9.35, 10.01</td>
<td>3.22, 3.09</td>
</tr>
<tr>
<td>M₉ - Transport System - Ideation</td>
<td>6.61, 6.04</td>
<td>2.25, 1.86</td>
</tr>
<tr>
<td>M₁₀ - Transport System - Implications</td>
<td>9.07, 9.03</td>
<td>3.46, 3.51</td>
</tr>
<tr>
<td>M₁₁ - Urban Growth - Flexibility</td>
<td>4.91</td>
<td>1.46</td>
</tr>
</tbody>
</table>
Fig. 6.1. Distributions of Scores $M_1$ to $M_{11}$.

Note: The figure at the top of each column in the histograms is the number of subjects whose scores lie in a particular range.
Fig. 6.1. Continued.
Fig. 6.1. Continued.
Fig. 6.1. Continued.
Fig. 6.1. Continued.
Appendix II contains a complete list of the ideas put forward in response to tasks (2) and (5), the problems foreseen in task (4) and the categories into which these problems were classified, and the criteria used for evaluation in task (6).

The extent to which different sets of scores correlate with each other is shown by the product moment correlation coefficients in Table 6.2. Significant correlations are identified with asterisks, one asterisk for 95% confidence level and two asterisks for 99% confidence level. Results involving $M_8$, $M_9$ and $M_{10}$ have only been noted in this way if both observed correlations reach the same level of significance. Correlations between the two sets of scores for $M_8$, $M_9$ and $M_{10}$ are shown separately in Table 6.3.

<table>
<thead>
<tr>
<th>Task (4) : Urban Growth</th>
<th>Score</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_8$</td>
<td>0.89</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Task (5) : Transport System - Ideation</th>
<th>Score</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_9$</td>
<td>0.86</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Task (6) : Transport System - Implications</th>
<th>Score</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{10}$</td>
<td>0.91</td>
<td></td>
</tr>
</tbody>
</table>
Table 6.2. Correlations between Scores Obtained in Experimental Tasks and in University Examinations.

<table>
<thead>
<tr>
<th></th>
<th>M₂</th>
<th>M₃</th>
<th>M₄</th>
<th>M₅</th>
<th>M₆</th>
<th>M₇</th>
<th>M₈</th>
<th>M₉</th>
<th>M₁₀</th>
<th>M₁₁</th>
</tr>
</thead>
<tbody>
<tr>
<td>M¹</td>
<td>0.43*</td>
<td>0.71**</td>
<td>0.72**</td>
<td>0.62**</td>
<td>-0.08</td>
<td>-0.06</td>
<td>-0.05</td>
<td>-0.15</td>
<td>0.08</td>
<td>-0.04</td>
</tr>
<tr>
<td>M₂</td>
<td></td>
<td>0.44**</td>
<td>0.54**</td>
<td>0.39**</td>
<td>0.14</td>
<td>0.22*</td>
<td>0.07</td>
<td>0.00</td>
<td>0.15</td>
<td>0.06</td>
</tr>
<tr>
<td>M₃</td>
<td></td>
<td></td>
<td>0.68**</td>
<td>0.51**</td>
<td>-0.14</td>
<td>-0.05</td>
<td>-0.08</td>
<td>-0.20</td>
<td>-0.09</td>
<td>-0.08</td>
</tr>
<tr>
<td>M₄</td>
<td></td>
<td></td>
<td></td>
<td>0.60**</td>
<td>-0.08</td>
<td>0.00</td>
<td>-0.09</td>
<td>-0.18</td>
<td>-0.06</td>
<td>-0.06</td>
</tr>
<tr>
<td>M₅</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.16</td>
<td>0.21*</td>
<td>0.03</td>
<td>-0.01</td>
<td>0.12</td>
<td>0.01</td>
</tr>
<tr>
<td>M₆</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.53**</td>
<td>0.22</td>
<td>0.26</td>
<td>0.22</td>
<td>0.28**</td>
</tr>
<tr>
<td>M₇</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.24</td>
<td>0.31</td>
<td>0.24</td>
<td>0.28**</td>
</tr>
<tr>
<td>M₈</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.31</td>
<td>0.42</td>
<td>0.81</td>
</tr>
<tr>
<td>M₉</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.49</td>
<td>0.29</td>
</tr>
<tr>
<td>M¹₀</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.43</td>
</tr>
<tr>
<td>M¹₁</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.40**</td>
</tr>
</tbody>
</table>
6.2.4. Discussion of Results

The results will be discussed under the following headings,

(1) Objectivity of scoring
(2) Distributions
(3) Correlations.

Objectivity of Scoring

Table 6.3 shows extremely significant correlations between the two sets of scores for M₈, M₉ and M₁₀, indicating close agreement between the two independent assessments. Furthermore, Table 6.2 shows that correlations of other scores with M₈, M₉ and M₁₀ based on the author's assessments are in good agreement with correlations based on the research assistant's assessments. For example, the two correlations of M₇ with M₉ are 0.31 and 0.29, both highly significant (p < 0.01). Thus any comments made on the scores M₈, M₉ and M₁₀ and any conclusions drawn from them do not depend on whether the assessments were made by the author or by the research assistant.

Distributions

When the distributions of scores on the five experimental tasks are compared, it is seen that for M₇ (design of drawing office) is the most highly skewed towards the lower end of the range, with a relatively high percentage of the subjects receiving low scores. The subjects found
this to be the most difficult of the five tasks, perhaps because of familiarity with the existing drawing office they had used during first year studies. It may have been difficult for them to free their thinking from existing associations and preconceptions of what form a drawing office should take.

The distributions for M₈ (problems of urban growth) and M₁₀ (evaluation of transport system) peak at relatively higher scores in their respective ranges than M₆, M₇ and M₉. This is illustrated by the ratios of mean to maximum scores in Table 6.4. It appears that in this series of tasks many subjects found it more difficult to create ideas than they did to recognize the problems and defects associated with existing or proposed designs.

Table 6.4. Ratios of Mean to Maximum Scores for M₆ to M₁₀ Inclusive.

<table>
<thead>
<tr>
<th>Score</th>
<th>Ratio of Mean to Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>M₆</td>
<td>0.40</td>
</tr>
<tr>
<td>M₇</td>
<td>0.38</td>
</tr>
<tr>
<td>M₈</td>
<td>0.52, 0.59</td>
</tr>
<tr>
<td>M₉</td>
<td>0.44, 0.43</td>
</tr>
<tr>
<td>M₁₀</td>
<td>0.50, 0.48</td>
</tr>
</tbody>
</table>
Correlations

Scores on all the experimental tasks correlate with each other to a significant degree, 95% confidence level or better. The subjects' performance on tasks (4), (5) and (6) correlates reasonably well with their work on tasks (2) and (3) in the more informal and relaxed environment of first term, six of the eight correlations being significant at the 99% confidence level. The highest correlation between scores on experimental tasks is that between $M_8$ and $M_{11}$ for fluency and flexibility of response to problems of urban growth. A high correlation is also observed between $M_8$ and $M_{10}$, bearing out the prediction in Section 6.2.1 that performance on tasks (4) and (6) should be closely related.

All marks in university examinations correlate with each other to a very significant degree, 99% confidence level or better.

On the other hand, of the 30 correlations between examination marks and scores on experimental tasks, only 2 are significant. Most of the other 28 correlations are low, and none of them reach the 95% level of significance. In general it would not have been possible to predict the subjects' performance on the experimental tasks from their results in university examinations.

It may be noted in passing that the significant correlation between $M_7$ (design of drawing office) and $M_2$ (mark in Engineering I) is not unexpected, since the subjects' previous educational experience of drawing offices had been obtained in Engineering I.
6.2.5. Outstanding Performances

A subject who scored well in one experimental task may have been affected by circumstances peculiar to that task. For example, it may have dealt with a topic in which he was already interested so that he had many pieces of information available in his memory to form new combinations. On the other hand, if a subject were found to score consistently well on all tasks, then he might be regarded as a creative individual, a person capable of applying his creative skills to a diverse range of problems.

The following procedure was used to determine which subjects had consistently good performance. Scores M₆ to M₁₀ were converted to percentages, each score being expressed as a percentage of the maximum obtained on a particular task. In so far as one score was required to represent a subject's effort on each of the five tasks, M₈ was preferred to M₁₁ in the case of task (4) because it was similar in nature to the other scores which emphasised fluency rather than flexibility of ideation. To determine subjects whose performance was consistently good the following criterion was applied: Their average score on the five tasks exceeded 70% and the average of their three best scores also exceeded 70%. Five subjects were found to satisfy this criterion, designated Group I.

To determine to what extent the selection of outstanding subjects depended on choice of criterion, the figure of 70% was relaxed to 60% with the other conditions unaltered. Four additional subjects were found whose
performances satisfied the second criterion but not the first. They are designated Group II.

Table 6.5 sets out the scores obtained by the nine outstanding subjects on the experimental tasks, $M_6$ to $M_{10}$ being expressed as percentages as already explained. Other relevant information on their age, schooling, and academic record is given in Table 6.6. With one exception - subject G in Group II - it did not matter whether the author's or the research assistant's scores were used for $M_8$, $M_9$ and $M_{10}$ in applying the criteria. As can be seen from Table 6.5, G only just fails the second criterion if the research assistant's scores are used.

Table 6.5. Outstanding Performances in Experimental Tasks.

<table>
<thead>
<tr>
<th>Subject</th>
<th>$M_6$</th>
<th>$M_7$</th>
<th>$M_8$</th>
<th>$M_9$</th>
<th>$M_{10}$</th>
<th>Total $M_6$ to $M_{10}$</th>
<th>$M_{11}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>96</td>
<td>80</td>
<td>89</td>
<td>100</td>
<td>100</td>
<td>465</td>
<td>7</td>
</tr>
<tr>
<td>B</td>
<td>72</td>
<td>80</td>
<td>83</td>
<td>80</td>
<td>50</td>
<td>365</td>
<td>7</td>
</tr>
<tr>
<td>C</td>
<td>64</td>
<td>100</td>
<td>61</td>
<td>60</td>
<td>78</td>
<td>363</td>
<td>8</td>
</tr>
<tr>
<td>D</td>
<td>100</td>
<td>100</td>
<td>78</td>
<td>80</td>
<td>67</td>
<td>425</td>
<td>7</td>
</tr>
<tr>
<td>E</td>
<td>52</td>
<td>100</td>
<td>78</td>
<td>73</td>
<td>72</td>
<td>375</td>
<td>7</td>
</tr>
<tr>
<td>Group II</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>84</td>
<td>80</td>
<td>72</td>
<td>33</td>
<td>56</td>
<td>325</td>
<td>5</td>
</tr>
<tr>
<td>G</td>
<td>52</td>
<td>60</td>
<td>82</td>
<td>53</td>
<td>61</td>
<td>315</td>
<td>7</td>
</tr>
<tr>
<td>H</td>
<td>80</td>
<td>80</td>
<td>65</td>
<td>29</td>
<td>47</td>
<td>301</td>
<td>6</td>
</tr>
<tr>
<td>J</td>
<td>60</td>
<td>60</td>
<td>67</td>
<td>47</td>
<td>83</td>
<td>317</td>
<td>6</td>
</tr>
</tbody>
</table>


Table 6.6. Age, Schooling, and Academic Record of Subjects with Consistently Good Performance in Experimental Tasks.

Note: $H_1$, $H_2$, $H_3$ denote level of academic performance in terms of first, second and third class honours respectively.

<table>
<thead>
<tr>
<th>Age - Relative to Mean for all 119 subjects</th>
<th>Type of Secondary School Attended</th>
<th>Academic Record</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1st Year</td>
</tr>
<tr>
<td>A 7 months older</td>
<td>High school in Melbourne</td>
<td>Took two years to pass 1st year</td>
</tr>
<tr>
<td>B 13 months older</td>
<td>Independent Presbyterian School in Melbourne</td>
<td>Took two years to pass 1st year</td>
</tr>
<tr>
<td>C 4 months younger</td>
<td>High school in Melbourne</td>
<td>Pass</td>
</tr>
<tr>
<td>D 10 months younger</td>
<td>High school in Melbourne</td>
<td>$H_2$</td>
</tr>
<tr>
<td>E 6 months older</td>
<td>Roman Catholic school in country town</td>
<td>Took two years to pass 1st year</td>
</tr>
<tr>
<td>F 2 months younger</td>
<td>High school in Melbourne</td>
<td>$H_2$</td>
</tr>
<tr>
<td>G 5 months older</td>
<td>High school in country town</td>
<td>Pass</td>
</tr>
<tr>
<td>H 17 months older</td>
<td>Roman Catholic School in country town</td>
<td>Took two years to pass 1st year</td>
</tr>
<tr>
<td>J 1 month younger</td>
<td>High school in Melbourne</td>
<td>$H_1$</td>
</tr>
</tbody>
</table>
Table 6.6 shows that the academic record of these subjects varied greatly, from the uniform excellence of J to C who dropped out of the course in his final year after scraping passes in the three previous years. A, B, E and H took two years to pass 1st Year. Subsequently A and B passed their examinations quite satisfactorily. E and H experienced trouble in 3rd Year mathematics, E scraping a pass and H failing at his first attempt. Apart from C, the other eight subjects did well in the 4th Year of their courses. At this stage of the undergraduate engineering course at the University of Melbourne, there is more project work and students are encouraged to undertake independent investigations. The subjects may have responded to this change in educational emphasis.

The average age of the subjects A to J was slightly higher than that of the whole group, but the difference is not significant. Their education prior to university was undertaken at nine different schools, representing the major types of secondary education available to local students. A, C, E, D, G, J attended State secondary schools (known in Australia as high schools), G in a country town and the others in Melbourne. E and H attended Roman Catholic schools in country towns while B attended a private school founded and supported by the Presbyterian Church. There is thus no common factor in the age or schooling of the nine outstanding subjects which may have contributed to the development of their creative skills.
6.3. CONCLUDING COMMENTS

A series of experiments was carried out to investigate the creative design skills of second year engineering students in the University of Melbourne. Five experimental tasks were devised to elicit evidence on the exercise of these skills. The following comments can be made on the results obtained from the group of 119 students who participated as subjects in the experiments.

(1) The performance of the subjects on all the creative design tasks correlated reasonably well, but there was virtually no correlation between performance on these tasks and contemporary performance in university examinations. It would not have been possible to predict performance on the creative design tasks from a knowledge of the subjects' previous academic record.

(2) A few subjects showed consistently high creative effort on all five tasks. Application of a stringent criterion for defining consistently high performance yielded five subjects, while an additional four subjects satisfied a less stringent criterion. The academic record of these subjects varied from high honours to failure, but most of them did well when they reached the final year of their course. A possible reason for this is the change in emphasis to more independent project work in the later stages of their undergraduate engineering programmes.
CHAPTER 7

INFORMAL PROBLEM-SOLVING SKILLS
IN ENGINEERING DESIGN

7.1. INTRODUCTION

In Chapter 2, a formal operational model of the design process was presented which provided the framework for the subsequent discussion of design skills. It was pointed out then that one of the dangers of formalising the design process in this way was that informal methods or procedures might be overlooked. The purpose of this chapter is therefore to investigate informal problem-solving in engineering design.

Discussions of informal design methods have frequently introduced the notion of "intuition" (Alexander, 1964; Wehrli, 1968), and the chapter will be largely devoted to examining the nature of intuition and its usefulness in engineering design. To this end, the literature on both the psychology of intuition and the role of intuition in engineering will be reviewed. A working definition of intuition in engineering design will then be proposed and the results of an experimental study examined in the light of this definition.

The results of a second experiment on the relationship between informal design skill and skill in formal design methods will also be presented and discussed.
7.2. THE NATURE OF INTUITION

7.2.1. Intuition from the Viewpoint of the Psychologist

Bruner (1960) defined intuition as the intellectual technique for arriving at plausible but tentative formulations without going through the analytic steps by which such formulations would be found to be valid or invalid conclusions.

This definition implies that it is possible, at least in theory, to work through the analytic steps logically necessary to reach the conclusion. But often in practice, the engineer and the scientist have to make judgments on the basis of insufficient evidence, and the word "intuition" is used to describe their success at this sort of task. For example, Bartlett (1958) discusses one important way intuition can operate in scientific research, namely in the forecasting of fruitful lines of enquiry. Some scientists, he says, have the intuitive ability to identify, ahead of anybody else, lines of experimental development which are likely to be fruitful, even though the same scientists cannot say anything about the evidence they use to reach their conclusion. They are not consciously aware of what informational cues they use.

Pikas (1966) and Westcott (1968) discuss psychological experiments in concept formation in which the individual is required to learn a principle and put it to work in making decisions without any conscious verbal statement of the principle or awareness of the basis of the decisions. Pikas calls this intuitive decision-making and equates "intuitive" with "non-verbal".
Berne (1949-1962) in a series of six papers has developed a psychodynamic view of the operation of intuition. His starting point was his own experience in clinical diagnosis where he found he was able to predict the occupation of many patients after a minimum of verbal communication. Generalizing from this, Berne suggested that in diagnosis a great variety of cues can be, and commonly are, used for reaching judgments, without the individual who is making the judgment having any idea what the cues are or even that a judgment has been made.

Berne further hypothesized that a methodical and systematic approach to problems can stifle potential intuitions. In his view, engineers being highly educated, often have the greatest resistance to intuitive cognition. On the other hand, a British philosopher has written - "The more we have studied a subject and thought rationally about it, using our powers of inference, the more likely we are to be in a state of mind in which we shall intuit rightly" (Ewing, 1941).

In his book on intuition, Westcott (1968) concluded that there was little empirical evidence to support either of these views. The exhaustive use of reasoning and the logical acquisition of knowledge may precede an intuition but this is not necessarily so.

Westcott is one of the few psychologists to have studied intuition in laboratory experiments (Westcott, 1961, 1964, 1966, 1968; Westcott and Ranzoni 1963). He defined intuition as the process of reaching a conclusion on the basis of little information when that conclusion would be
normally reached on the basis of significantly more information.

A total of 243 university students participated as subjects in the first experiments in which Westcott administered 20 problems to each subject. The problems were stated in terms of alphanumeric symbols so that no specialised knowledge was called upon. Each problem consisted of a series of items of information, the series being constructed by Westcott in accordance with a specific rule. Examples of the sort of problem he used are:-

(1) What is the next letter in the series A, C, E, ... ?

(2) What is the next member of the series 4:2, 9:3, 25:5, ... ?

In effect, the subjects had to recognise the rule, and then apply it to determine the next member of the series. An important feature of the experiment was that although the subjects were free to take as many examples of items in a series as they wished before giving an answer, they were encouraged to solve the problems using as little information as possible.

Westcott found that his subjects behaved with a high degree of consistency in all problems; in fact it was possible to classify them into four groups, depending on how much information they asked for and whether they got the right answer or not.

(1) Those who demanded much information and reached correct conclusions, characterised by Westcott as steady logical thinkers.
(2) Those who demanded much information and reached incorrect conclusions, poor problem solvers.

(3) Those who demanded little information and reached incorrect conclusions, wild guessers.

(4) Those who demanded little information and reached correct conclusions, successful intuitive thinkers in Westcott's view – about 10% of his subjects.

There was no correlation between successful intuitive thinking and academic success.

In a follow-up study, Westcott found that the characteristics of these four groups with respect to information demand and problem-solving success remained stable over a period of three years. His experiments provide evidence for asserting the existence of intuition.

7.2.2. Intuition from the Viewpoint of the Engineer

According to a life-long friend and colleague, Sir Charles Parsons was a brilliant intuitive engineer (Stoney, 1937). Although possessing high mathematical ability, he rarely if ever made use of formal mathematical reasoning in the solution of any problem. "He was able to arrive, apparently in some sub-conscious way, at conclusions which were almost invariably correct." Stoney further records that "Parsons had an extraordinary intuition on all matters connected with design. No matter how difficult or novel the problem he seemed to know intuitively how to solve it." For example, he successfully designed the blading for his multi-stage,
axial-flow steam turbines at a time when the science of aerodynamics was in its infancy and there were no theoretical or experimental data on the behaviour of aerofoils. Another example given by Stoney: the proportions of Parsons' first turbo-dynamo designed when electrical knowledge was rudimentary could hardly have been improved upon fifty years later. We may conclude that in Parsons' case intuition is the ability to make successful decisions regarding the size, shape, and spatial arrangement of components in innovative design problems, i.e. in problems where there are no precedents and no body of established theoretical knowledge to guide the designer as he translates his concepts into hardware. (Refer to Section 2.3.2 for classification of design problems as innovative, extrapolatory, or evolutionary).

To Freund (1969), intuition is the ability to make successful decisions in extrapolatory design problems, where existing precedents are smaller in size or slower in speed and there is little or no information on the consequences of increasing scale. He cites as an example the design of 40,000 h.p. clutches for a gas-turbine powered cargo ship when the designer's previous experience only extended to 8,000 h.p. clutches.

Reverting to Parsons for a moment, Stoney also commented on his great ability as an experimenter which enabled him to obtain very useful results from quite crude apparatus. These comments by Stoney together with those of Freund can be related to a more recent example. Gasiunas (1970) describes an extrapolatory design problem where a successful solution was reached partly as a result of information gained from a few simple experiments.
and partly as a result of intuition. The problem concerned the design of advanced, single-stage boiler-feed pumps for heads of 1,500 to 2,000 lbf/in$^2$, where it is essential to prevent destruction of the rotor by erosion of material from around its periphery due to large, high-frequency, pressure fluctuations in the region between the rotor and stator. The relevant theory due to Copley (1963) and others only provides a much over-simplified mathematical model of a very complex physical phenomenon, so that the designer cannot rely on formal, analytic methods. An earlier unpublished paper by Gasiunas on the design of supercavitating axial-flow pumps also reveals the ability to combine simple but informative experiments with hunches to arrive at a successful design. Gasiunas may be regarded therefore as a contemporary example of an intuitive engineering designer.

It is reasonable to hypothesise that intuition can also play a constructive role in evolutionary design problems. An example would be in deciding how to distribute metal to best advantage in castings of complicated shape which are subject to complicated load patterns, as in the crank case or cylinder head of an internal combustion engine. In such cases there is no readily available model to enable the designer to predict how a structure will behave in practice. Mathematical models for predicting stress and strain can only be constructed for structural components having relatively simple geometries. (In this sort of situation the engineer may be content to rely on his intuitive judgment, or he may decide to obtain more information from an experimental programme using physical models or analogues.)
On the other hand, there may well be severe limitations on the effective use of intuition in solving some design problems, as has been pointed out by Alexander (1964). He observed that even in comparatively simple design problems; the number of factors to be considered by the designer is enormous. Alexander argues that if he is just content to rely on intuition, the designer is likely to be overwhelmed by the burden of decision-making. Some systematic method of relieving this cognitive load is necessary, hence Alexander's book. The limitations of intuition in engineering are also pointed out by Wymore (1967). The engineer is being called upon to solve problems of greater and greater complexity; most problems in systems engineering involve a dimensionality greater than three. In so far as intuitions are derived from unconscious observations or cues from the external world of three dimensions they may prove inadequate. He writes "Most aspects of systems theory seem so to transcend intuition that it is only through mathematical rigour that any confidence can be placed in the results of systems theory."

A few writers have referred to intuitive methods in design, contrasting them with formal or explicit methods and procedures. Volmer (1969) discusses mechanism design by what he calls the method of synthesis through iterative analysis using iterative feedback loops of information to make adjustments to the design and improve it until the optimum is obtained. He then goes on to comment that the method he has applied explicitly is already used by good designers intuitively. In his experiments on architectural design, Wehrli (1968) found that the technique of giving novel names
to objects was used intuitively by some of his subjects. They used the technique of "novel-naming" to aid their design without being consciously aware of the fact. For example, an object which is part of the design of a primary school is given the new name of "multi-media centre" instead of the old name of "library". The new label frees the designer from associations linked to the old conventional classifications and allows him to think afresh on new and changing activities and the new and changing environments appropriate to them.

What Volmer and Wehrli refer to as intuitive methods are respectively methods for organising a sequence of quantitative design decisions and for generating new ideas. The common factor in their use of the word "intuitive" is that the method is applied by the designer without his being consciously aware of it. The description of such informal problem-solving methods as "intuition" may therefore be regarded as legitimate, but it is not common in the engineering literature. "Intuition" will not be used in this very general way in the present discussion, but to denote informal methods of predicting the performance of a new design in accordance with the definition given below.

7.2.3. The View of Intuition Adopted in this Thesis

The examples cited of intuition in engineering design have all dealt with machine-ascendant systems (Crawford,1962; refer also to the discussion in Section 2.3.2 ). It appears that the role of intuition is most readily identified in such systems and attention will be largely confined to them in what follows.
These examples were all concerned with that stage of the design process when the designer was translating his ideas into hardware, and was making decisions on the size, shape, and spatial arrangement of components. However, the information available for making the decisions was incomplete in that the designer was not able to use one of the recognised, formal, modelling techniques to predict the performance of his new design. (The formal modelling techniques used by engineers are described by Krick, 1969, Chapter 5.) The designer was thus forced to rely on informal techniques of prediction for reasons which varied according to the nature of the problem, whether it was innovative, extrapolatory, or evolutionary. These reasons are set out in Table 7.1.

Table 7.1. The Role of Intuition in Engineering Design.

<table>
<thead>
<tr>
<th>Type of Design Problem</th>
<th>Reasons for Designer's Inability to Predict Performance by Formal Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Innovative</td>
<td>No established body of theoretical knowledge. No precedents in the form of previously successful systems or components.</td>
</tr>
<tr>
<td>Extrapolatory</td>
<td>No information available on &quot;scale effects&quot;; existing precedents are smaller or slower.</td>
</tr>
<tr>
<td>Evolutionary</td>
<td>A mathematical or other type of model for predicting performance is either excessively complicated or cannot be constructed on the basis of existing theoretical knowledge.</td>
</tr>
</tbody>
</table>

We are therefore led to suggest that in the design of machine-ascendant systems intuition is the ability to make successful decisions

(a) at that stage of the design when ideas are being translated into hardware, and
when the information available to the designer is incomplete and he has to rely on informal methods of predicting performance. The designer himself may be unaware of the informal methods he uses.

The criterion of success is that the solution to the design problem works (innovative or extrapolatory design) or that its performance is superior to previous solutions (evolutionary design).

The foregoing definition of intuition will be used throughout the remainder of this chapter.

It is intriguing to speculate how an intuitive ability may develop in a person. Perhaps it is the result of informal learning experiences accumulated through day-to-day living, outside the formal educational process. In the case of engineers, it may well be associated with their hobbies or recreational activities.

Is the development of an intuitive ability a legitimate objective in engineering education? Most writers ignore this question or answer no, presumably on the grounds that something so informal cannot be incorporated into the formal educational process. The opposite view is taken by Hill (in Jenks, 1969) in his paper on encouraging an engineering sixth sense in university students. He writes "To possess a sixth sense is to have a power like one of the five senses, but not one of them. It is often referred to as an intuitive power, the ability to be right about things based on quick or even snap judgments." Hill states clearly and unambiguously that one of the objectives of his undergraduate design programme at Tufts University is to develop this sixth sense.
7.3 AN EXPERIMENTAL STUDY OF
INTUITION IN ENGINEERING DESIGN

7.3.1. Aims

In the light of the differing views expressed regarding the role of intuition in engineering design and its importance in engineering education, an experiment was carried out to try and throw some light on the matter. Male students from technical and non-technical faculties in the University of Melbourne participated as subjects.

The aims were:

(1) To investigate the role of intuition in the solution of an engineering design problem.

(2) To compare the relative effectiveness of intuitive and formal methods in the solution of an engineering design problem.

There was also a third, less important aim:

(3) To obtain information about the characteristics and background of intuitive designers.

7.3.2. Method

It was decided that the experiment should be in the field of structural design, because if intuition were to be used then it would be most appropriate to the design of some three-dimensional object.

The design problem should be simple and not time-consuming, and should be such as to allow either analytical design methods or an informal, intuitive approach.
A problem was selected to suit these requirements. A model structure was to be designed for maximum strength to weight ratio when supporting a compressive load and conforming to specified geometrical constraints. Each student taking part in the experiment was given an 18" x 12" sheet of polyurethane foam of uniform thickness of 3/4" from which to construct his model. This he did by cutting out material which he did not think contributed strength proportionate to its weight. Full details of the briefs given to the student designers are in Appendix I.

In the form of foam sheeting, polyurethane is composed of a multitude of small cells clearly visible to the naked eye. When a load is applied to a structure made from this material, each cell is a potential source of stress concentration and hence of structural weakness. This means that the strength of the structure, measured by the load at which it fractures, will not be greatly affected by quality of workmanship. A student who cut out his structure roughly might leave some unintentionally sharp corners giving rise to local concentrations of stress. However, as the structure would already be riddled with stress concentrations due to the cellular nature of the material, any additional stress concentrations would have to be moderately severe to affect the load at which the structure failed.

This was one of the reasons why polyurethane foam was used in the experiment. Others were that it is easily worked requiring a minimum of manual skill, and that it is never used in practice in load-bearing structures so that none of the students participating would have had previous experience
of it in this sort of application.

The models submitted by the students were weighed on an accurate balance and then loaded to failure on a simple testing rig in which the load was applied via a calibrated spring balance as shown in Fig. 7.1.

![Schematic Layout of Loading Rig](image)

**Fig. 7.1. Schematic Layout of Loading Rig.**

Weights of models were determined to an accuracy of $\pm 0.5\%$.

Loads at failure were determined to within $\pm 2.5\%$.

Thus the strength to weight ratios to be reported later are accurate to within $\pm 3\%$.

Three groups of students took part in the experiment.

1. **Group I** - all third year mechanical engineering students for which the exercise was a required part of the undergraduate course ($N=58$). The mean age of the group was 20 years 10 months with a standard deviation of 11 months.
Group II - "naive" students from non-technical faculties recruited by advertising through the University's Appointments Board (N=44). Students from the following faculties participated: Arts, Commerce, Education, Law, Medicine. The mean age of the group was 19 years 9 months with a standard deviation of 1 year 10 months.

Group III - some third year architecture students who volunteered to take part (N=16). The mean age of the group was 21 years 1 month with a standard deviation of 1 year 1 month.

Details of the design problem as given to (1) engineering students and (2) naive and architecture students are shown in Appendix I. It will be noted that the engineering students received their design brief one Thursday afternoon and handed in their completed models one week later. While no direct control was exercised to ensure that the students worked on their own, the wide variety of models submitted made it clear that they did so. The naive and architecture students had one afternoon to work on the problem. Although three hours were allowed, none of these students took longer than two hours to design and build their models. They worked in individual cubicles and could not observe each other's progress. The engineering students were given more time to work on the problem because it was intended that they should use a formal, analytic approach which is inherently more time-consuming.
For the engineering students the exercise was part of their undergraduate course and the results obtained counted toward their final mark in the subject, Engineering Design II. The naive and architecture students were paid $4 each for their afternoon's work. In addition, prizes of $10 and $5 were offered for the two models having the highest strength to weight ratio in both the naive group and the architecture group.

From the design brief it will be seen that each engineering student had to prepare a written report and attend a seminar prepared to explain and justify his design. Thus the engineering students had to verbalize their approach to the design and were strongly encouraged to adopt formal, analytical methods. Previously in their course, they had studied simple structural theory which might be expected to assist them in the design. However, this theory deals with isotropic materials whereas polyurethane foam is anisotropic. Never in their previous undergraduate work had a structure they had designed themselves been built, much less tested to destruction. Nevertheless there is a strong emphasis on logic and rational thinking throughout the undergraduate engineering course and the work of this group of students could be expected to reflect this.

The naive students, it was hoped, would adopt an intuitive approach to the design, putting material where they thought intuitively it would do the most good. These students had very little acquaintance with mathematics and none at all with structural theory, even at an elementary level.

The architecture students form a group intermediate between the other two in previous experience and training. They volunteered to take
part when they heard that some comparative experiment was being undertaken. Their results are presented separately in due course.

In accordance with the aims of the experiment it was intended:

(1) to compare the results from Groups I and II to see whether there were any statistically significant differences;

(2) to examine the most successful designs from Groups I and II and compare the design methods used;

(3) determine whether any members of Group II could be classed as successful intuitive designers, and if so to investigate their backgrounds.

To qualify as a successful intuitive designer, it was decided (arbitrarily) that a member of Group II had to have designed and built a model which gave a strength to weight ratio exceeding the mean value for Group I by at least one standard deviation.

7.3.3. Results

The results are presented under the following headings:

(1) Material properties

(2) Performance of groups

(3) Leading members of Groups I and II

(4) Methods used by leading designers.
Material Properties

To check the consistency of the polyurethane supplied for the experiment, samples 4" x 4" x 3/4" in size were cut at random from 8 of the 118 sheets used and tested for crushing strength by applying a compressive load perpendicular to the surface of the sheet. The results obtained were:

29.6, 29.9, 29.9, 30.1, 30.2, 30.2, 30.2, 30.3, 30.5 lbf/in², the mean crushing strength being 30.1 lbf/in².

Crushing strength was used as an index of the mechanical properties of the polyurethane. The observed variations were small, and it was concluded that a material having consistent properties was used.

Performance of Groups

Histograms of results for Groups I, II, and III are shown in Fig. 7.2, the means and standard deviations in Table 7.2.

Table 7.2. Mean Values and Standard Deviations of Observed Strength to Weight Ratios

<table>
<thead>
<tr>
<th>GROUP</th>
<th>MEAN VALUE</th>
<th>STANDARD DEVIATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group I - engineering students</td>
<td>372</td>
<td>97.1</td>
</tr>
<tr>
<td>Group II - naive students</td>
<td>239</td>
<td>99.7</td>
</tr>
<tr>
<td>Group III - architecture students</td>
<td>283</td>
<td>66.1</td>
</tr>
</tbody>
</table>
Fig. 7.2.  Distributions of Strength to Weight Ratios of Model Structures.
The t-test is applied to determine whether there are significant differences between the observed distributions of results for the three groups. To compare two of the groups, the null hypothesis is first adopted that both sets of results are drawn from identical populations. However, as can be seen from Table 7.3, when Groups I and II and Groups I and III are compared, the observed differences between the means are most unlikely to have arisen by chance and the null hypothesis can be confidently rejected in each case.

Table 7.3. Comparison of Performance of Groups I, II and III in Experiment on Structural Design.

<table>
<thead>
<tr>
<th>Groups Compared</th>
<th>Difference between Means</th>
<th>Standard Error of Difference</th>
<th>t</th>
<th>Number of Degrees of Freedom</th>
<th>Null Hypothesis is</th>
</tr>
</thead>
<tbody>
<tr>
<td>I &amp; II</td>
<td>133</td>
<td>19.8</td>
<td>6.72</td>
<td>100</td>
<td>Rejected, p &lt; 0.001</td>
</tr>
<tr>
<td>I &amp; III</td>
<td>89</td>
<td>26.1</td>
<td>3.42</td>
<td>72</td>
<td>Rejected, p &lt; 0.001</td>
</tr>
</tbody>
</table>

For Group I, the third year mechanical engineering students, an investigation was made to determine whether there was a significant correlation between performance in this experiment and academic effort. The observed strength to weight ratios of the structures were found to correlate 0.09 with the average mark gained in the annual university examinations. As there was thus no significant relationship between the two sets of student performances, this line of investigation was not pursued further.
Leading Members of Groups I and II

According to the criterion adopted, a successful intuitive designer must achieve a strength to weight ratio of at least $372 + 97 = 469$. The leading two members of Group II obtained measured strength to weight ratio of 470 and 460 and therefore meet this standard within the limits of experimental error. The third best result was a strength to weight of 430, which does not meet the standard.

The highest strength to weight ratio in Group I was 565.

The best structure from Group I and the best from Group II are drawn to scale in Fig. 7.3. The profiles shown were obtained by tracing the outlines of the models submitted by the designers.

(a) Leading Design from Group I.

Fig. 7.3. Leading Designs from Groups I and II.
Design Methods

The methods used by the leading designers are now described.

The leading designer in Group I, Mr. M., aged 20 years 6 months, submitted a written report explaining his approach to the problem and subsequently made available a rough work sheet on which he had made notes of important features of the design. The following account of his work is based on these records.
There were two major alternative types of structure which would fit into the space available and carry the applied load successfully (Mr. M. argued):

(a) ring - structures consisting of a ring or annulus of material.

(b) framework - consisting of triangular sections top and bottom with straight vertical members on each side.

Simple, order-of-magnitude calculations showed (b) to be stronger than (a) for the same amount of material because parts of type (a) structures may be subject to comparatively large bending moments. Therefore type (b) adopted.

The specified void space which the structure had to surround (ABCD in Fig. 7.4) was not central, but nearer the bottom than the top.
The potentially weakest part of the structure was the bottom section between AB and the loading pad. It would be pointless making the upper part stronger than this by having a design which intruded into CDEF. Therefore, the void space which the structure had to surround was extended to be equidistant from both upper and lower loading pads. Thus Mr. M. decided to make the structure symmetrical about a horizontal line midway between the loading pads.

(3) The thickness of material in the horizontal members next to the loading pads was reduced because Mr. M. estimated that only small compressive forces were acting in this part of the structure. These members were bowed slightly so that contact with the loading pads would be near the corners (marked G in Fig. 7.4) and thus closer to the vertical side members so that the eccentricity of the loading of these members would be as small as possible.

(4) The proportions of the different parts of the structure were then determined by eye. Mr. M. later verbally reported that these proportions had been determined "by intuition" (this without any prompting by the interviewer or knowledge of the use to which his comments were being put). Upon further questioning, he elaborated on what he understood by intuition in the following words - "Intuition, a process which does not involve logical thought, reaching a conclusion when there is insufficient grounds for making a rational judgment".

It should be noted that Mr. M. was twenty years of age, that his hobby was sailing, and that he had built a 20-foot yacht doing a lot of the
structural design of auxiliary fittings himself "by intuition" (another unsolicited comment).

The most successful designers in Group II were:

(1) Mr. W. a first year commerce student, seventeen years old, and

(2) Mr. K. a second year medical student, nineteen years old.

The following information about their background and approach to the design problem was obtained by personal interview.

Mr. W. was educated at a Melbourne high school and had not studied any subjects with a technical bias. His father was a chartered accountant, and he did not have any hobbies which involved constructive work with materials. His main thought while making his model was "to distribute the load as uniformly as possible".

Mr. K. was also educated at a Melbourne high school and had studied Pure and Applied Mathematics up to Matriculation level. This included analysis of forces in pin-jointed frameworks but he said that he could not remember much of it and felt that nothing from these studies had been applied in his design. Mr. K. said that he approached the problem by firstly cutting out a structure containing the maximum amount of material allowed by the geometrical constraints, and then cutting out material from this basic shape where he felt it was warranted.

In an effort to obtain more information about the range of abilities of Messrs. W. and K., they were administered a Mechanical Comprehension
Test (Bennett and Fry, 1941). Mr. W.'s score corresponded to the 12 percentile level for engineering freshmen, and Mr. K.'s score to the 36 percentile level, according to norms given by the American originators of the test. The test consists of 60 questions of which 21 deal specifically with forces on structures. Mr. W. answered 10 of these questions correctly while Mr. K. answered 14 correctly.

7.3.4. Discussion of Results

As a group, the engineering students performed significantly better than the architecture students and better again than the naive students. While this result might have been expected in view of their experience and training, what was not expected was the wide dispersion of the engineers' results, almost as wide as that of the naive students.

The architecture students were a small group of volunteers. Consequently their results will not be discussed further except to note one feature of their work, namely that the average weight of their models was lower than for the other two groups. Apparently, the requirement of light weight was to them the over-riding factor in the design.

The most successful design was that of an engineering student whose part-time interests included building yachts and designing fittings for yachts, and his written report plus follow-up interview showed an interesting combination of formal reasoning and intuition in his approach to the design problem. Major decisions regarding the form of the structure were taken as a result of an analytic discussion; once the general shape had
been determined proportions of individual parts were established by intuition.

Two naive students from non-technical faculties achieved designs which were superior to 80% of engineering students. Their method of approach insofar as they could verbalize it was "to distribute the load as evenly as possible" and "to remove material from sections where it did not contribute to the strength of the structure". Attempts to probe the backgrounds of these students yielded no information which could help explain their success. In particular, their responses to questions on structures in a Mechanical Comprehension Test were of poor or mediocre quality.

No evidence was obtained from the naive students to support the hypothesis stated in Section 7.2.3 that intuition in design is the result of accumulated informal learning experiences. On the other hand, the example of the leading engineering student, Mr. M. does lend some support to this hypothesis.

Many of the designs produced by the naive group were unusual or bizarre structures (at least to the observer trained in engineering), which showed little or no appreciation of structural behaviour and which were impossible to classify. However, the engineers' designs readily fell into three classifications:-

(1) triangulated frames similar in principle to the winning design;
(2) ring type structures;
structures intermediate between (1) and (2).

The results are summarized in Table 7.4.

Table 7.4. Classification of Designs of Engineering Students.

<table>
<thead>
<tr>
<th>Type of Structure</th>
<th>Number of Designs</th>
<th>Strength to Weight Ratios</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Range</td>
<td>Mean</td>
<td></td>
</tr>
<tr>
<td>Triangulated Frame</td>
<td>9</td>
<td>385-565</td>
<td>478</td>
<td></td>
</tr>
<tr>
<td>Intermediate</td>
<td>16</td>
<td>285-545</td>
<td>410</td>
<td></td>
</tr>
<tr>
<td>Ring</td>
<td>33</td>
<td>200-500</td>
<td>330</td>
<td></td>
</tr>
</tbody>
</table>

The majority decided on ring-type structures without considering the possibility that superior alternatives might exist. A possible reason for this was that the basic theory of the structural behaviour of rings had been covered in lectures in the second year of their course, so that this was a simple structural form they were familiar with. Still it was disappointing that the engineering students did not show greater flexibility in their thinking and explore alternative designs more adequately.

7.3.5. Conclusions and Recommendations

From a survey of the relevant literature on the psychology of intuition and from a study of the operation of intuition in engineering, a definition has been developed applicable to engineering design.

Examples of the successful use of intuition in engineering design are given in Table 7.5. All the examples deal with the design of three-
dimensional components of machine-ascendant systems. In each case
the design concept had already been chosen, and the role of intuition was
to help the designer translate his concept into engineering hardware
by establishing appropriate sizes, shapes and spatial relationships of
individual parts of the design. The designer relied on intuition because
he could not predict performance on the basis of recognized modelling
techniques, such as the use of mathematical models: either there was
no relevant scientific theory available to construct the model or, if
there were, the model was too cumbersome to be used.

In the experimental study of structural design, the most successful
result was obtained by judicious combination of formal reasoning and
intuition. Good but not exceptional results were obtained by two designers
who relied solely on intuition. In a group of 44, this represents a
success rate of about 5% compared to the figure of 10% found by Westcott
(1968) in his quest for successful intuitive thinkers.

While one would hesitate to generalize on the basis of one experiment,
it seems reasonable to draw the following conclusions.

(1) Intuition can play a useful role in structural design, and
more generally in the design of three-dimensional products.

(2) The role of intuition in engineering design is to help make
decisions about the dimensions of engineering hardware
when either no theory is available to predict the behaviour
of a proposed design, or the existing theory is too cumber-
some to be used, or there are unpredictable scale effects.
<table>
<thead>
<tr>
<th>Type of Design Problem</th>
<th>Designer</th>
<th>Design Concept</th>
<th>Application of Intuition</th>
<th>Role of Intuition in the Example Cited</th>
</tr>
</thead>
<tbody>
<tr>
<td>Innovative</td>
<td>Sir Charles Parsons</td>
<td>Multi-stage, axial-flow, steam turbine</td>
<td>Shape and dimensions of turbine blading</td>
<td>Designer could not construct a mathematical model because there was no relevant theory and no data on aerofoils and cascades.</td>
</tr>
<tr>
<td>Innovative</td>
<td>Mr. W. and Mr. K., two naive students (Section 7.3)</td>
<td>Model Structure</td>
<td>Shape and dimensions of structure</td>
<td>Designers had no knowledge of scientific theories of structural behaviour.</td>
</tr>
<tr>
<td>Extrapolatory</td>
<td>A. Gasiunas (Section 7.2)</td>
<td>Single-stage, centrifugal, boiler-feed pump</td>
<td>Shape and dimensions of rotor and stator</td>
<td>Designer could not predict scale effects because he could not construct a usable mathematical model of a complicated physical situation. However, he recognized the relevant factors and obtained useful information from relatively simple experiments.</td>
</tr>
<tr>
<td>Evolutionary</td>
<td>Mr. M., an engineering student (Section 7.3)</td>
<td>Model Structure</td>
<td>Dimensions of parts of structure</td>
<td>Established theory helped the designer determine the shape of the structure; dimensions of individual parts determined by intuition.</td>
</tr>
</tbody>
</table>
All the examples discussed have dealt with the design of three-dimensional physical products. Insofar as the engineer is increasingly concerned with multi-dimensional systems at a high level of abstraction, the role of intuition may be expected to become less important or even non-existent.

Whether or not the successful use of intuition can be promoted by some formal educational programme is not known, although one engineering educator has deliberately set out to achieve this aim. Hill (in Jenks, 1969). The example of Mr. M. in the experiment on structural design provides some evidence to support the hypothesis that intuition is acquired as a result of informal learning experiences. However, further research is necessary

(1) to identify the useful role, if any, of intuition in the design of multi-dimensional engineering systems;

(2) to determine whether intuitive ability in engineering design can be developed by a formal educational programme.
7.4. AN EXPERIMENTAL STUDY OF FORMAL AND INFORMAL SKILLS IN ENGINEERING DESIGN

7.4.1. Aims

We have seen in Section 7.2.1 that Berne (1962) speculated that a methodical and systematic approach to problems could stifle potential intuitions. Pursuing this line of thought, we might propose the hypothesis that people who are skilled in developing a systematic approach to problems will perform poorly in informal or unstructured problem-solving.

This hypothesis was investigated in an experiment in which a group of 116 male, Australian, second-year engineering students participated as subjects, as part of their normal undergraduate programme in the subject Engineering Design I. This was the same group as that of Chapter 5. Information about their systematic approach to problems was already available from the level of structuring displayed in their answers to the question on searching for information in order to construct a hospital on a remote Pacific island.

The same students were also set an exercise in informal problem-solving. Would students who gave highly structured answers to the hospital problem do relatively poorly in the informal problem? And would students whose answers to the hospital problem revealed little or no structure do well in the informal problem? These were the questions the experiment was designed to answer. If the answer to both questions was yes, this would provide evidence to support the hypothesis.
7.4.2. Method

The performance of a group of 116 second-year engineering students in two different problem-solving situations was compared.

The first problem and the responses of the students to it have been described in Chapter 5. It yielded data on the level of structuring the students adopted in their approach to a new and complex problem.

In the second problem, each student had to design and build a structure capable of supporting a fresh egg, so that when dropped from the level of the window sill of the second year drawing office it struck the asphalt footpath 45 feet below and the egg was not broken. The structure had to be self-contained, its size was not to exceed 18 inches by 18 inches by 18 inches, and only a limited number of materials were allowed – newspaper, aluminium foil, paper clips, rubber bands, string, and transparent adhesive tape. A prize was offered for the lightest successful structure. Full details of the brief given to the students are set out in Appendix I.

The students were given the brief one Monday afternoon and the structures were tested the following Monday. While no direct control was exercised to ensure that they worked on their own, the wide variety of structures submitted made it clear that they did so.

While the subject Engineering Design I lays some stress on formal methods, this exercise was undertaken in the sixth and seventh weeks of the first term of the academic year. The students could be expected to rely on their own informal methods for solving the problem. Moreover, they were
not asked to submit written or oral reports nor to justify the design verbally. Whether a structure succeeded or failed would therefore be regarded as an indication of informal problem-solving skill.

In order to test the hypothesis stated in Section 7.4.1, it was intended to determine:

1. whether students who succeeded in the egg-drop problem (that is, whose structures preserved the egg intact) had a significantly lower level of structuring in their answers to the hospital problem;

2. whether students who failed in the egg-drop problem had a significantly higher level of structuring in their answers to the hospital problem.

7.4.3. Results

A wide variety of structures was designed and built by the students. 61 of the structures were successful; some examples are shown in Fig. 7.5.

7.5. The successful designs fell into five major categories:

1. Large bundles of shredded paper with the egg contained in the centre.

2. Frameworks - usually tetra-hedrons or cubes with sides formed from tightly rolled cylinders of paper and the egg supported in a central cocoon by rubber bands.
Fig. 7.5. Examples of Successful Structures in Egg-Drop Problem.
Fig. 7.5.  (Continued)
Fig. 7.5. (Continued)

A comparison was also made between the academic performance of the two groups of students, those who passed and those who failed, the egg-drop problem. Fig. 7.6 shows this comparison in the form of histograms of the distributions of the average marks obtained in the first year of their undergraduate course by the two groups of students.
(3) Parachutes - successful designs of parachute had holes cut in the canopy to ensure more or less vertical descent.

(4) Cones - narrow cones formed from rolled sheets of newspaper, the egg being supported a few inches above the nose which crumpled and absorbed energy on impact.

(5) Autogyros - constructed with paper propeller blades to give a slow rate of descent and land the egg safely.

The results of the comparison of student performance in the hospital and egg-drop problems are shown in Table 7.6.

Table 7.6. Comparison of Student Performance in Hospital and Egg-Drop Problems.

<table>
<thead>
<tr>
<th>Level of Structuring in Hospital Problem</th>
<th>Egg-Drop Problem</th>
<th>Number of Students who Succeeded</th>
<th>Number of Students who Failed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium to High</td>
<td></td>
<td>21</td>
<td>17</td>
</tr>
<tr>
<td>Marginal to Low</td>
<td></td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Nil</td>
<td></td>
<td>27</td>
<td>25</td>
</tr>
</tbody>
</table>

A comparison was also made between the academic performance of the two groups of students, those who passed and those who failed, on the egg-drop problem. Fig. 7.6 shows this comparison in the form of histograms of the distributions of the average marks obtained in the first year of their undergraduate course by the two groups of students. Means
and standard deviations of the two distributions are given in Table 7.7 together with the range of marks covered in each case.

Note: The figure at the top of each column in the histograms denotes the number of students whose scores lie in a particular range.

Fig. 7.6. Distributions of Average Mark in First Year of Students Passing and Failing the Egg-Drop Problem.
Table 7.7. Mean Values, Standard Deviations, and Ranges of Students' Average Mark in First Year.

<table>
<thead>
<tr>
<th></th>
<th>Mean Value</th>
<th>Standard Deviation</th>
<th>Range of Marks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Succeeded in Egg-Drop Problem</td>
<td>64.2</td>
<td>8.9</td>
<td>47 to 89</td>
</tr>
<tr>
<td>Failed in Egg-Drop Problem</td>
<td>64.0</td>
<td>10.0</td>
<td>50 to 89</td>
</tr>
</tbody>
</table>

7.4.4. Discussion of Results

The egg-drop problem evoked a wide range of student designs of which just over half were successful; 61 out 116 = 52.5%. The performance of the two groups of students - those who succeeded in the egg-drop problem and those who failed - was then analyzed.

The results presented in Table 7.6 show that there was no significant difference between the two groups in the level of structuring displayed in their answers to the hospital problem.

Fig. 7.6 and Table 7.7 show that there was no significant difference in the academic performance of the two groups as measured by their average mark gained in first-year examinations.

7.4.5. Conclusion

In the experiment reported here, no evidence was obtained to support the hypothesis that subjects who adopt methodical approaches to complex problems are likely to perform poorly in problems which are of an informal, unstructured nature.
Whether subjects gave structured or unstructured answers to the hospital problem was independent of their success in the egg-drop problem. This is perhaps not surprising when it is remembered that responses to the hospital problem were verbal whereas responses to the egg-drop problem were figural.

There was no relationship between success or failure in the egg-drop problem and academic performance of the students participating in the experiment. This result is in accordance with Westcott's observation (Westcott, 1963) that successful intuitive thinking in his experiments bore no correlation with academic success.

7.5. CONCLUSION

Investigations into engineering design have usually been based on a formal operational model of the design process of the type presented in Chapter 2. In using such a model, it is assumed that the designer is aware of the nature of his activity and where it fits into the operational model, for example, whether he is defining the problem, creating ideas, making decisions, and so on.

In some cases these individual steps may coalesce or overlap and the designer is probably not consciously aware of the nature of the activity on which he is engaged nor of the methods he is using. Such situations have been described as "informal problem-solving". As the creative part of the design is not then consciously separated from other design activities, it was decided to study informal methods of solving design problems as part of the programme of research reported in this thesis.
Firstly, the role of intuition was examined. In the context of the design of machine-ascendant, engineering systems, intuition was found to be the ability to make successful decisions when the recognised formal methods for predicting the consequences of such decisions were not available.

This is not to imply that intuition may not be important in other ways in engineering. The design of man-machine systems may be assisted by intuitions regarding the behaviour of people in such systems, and this could be the subject of further research. The accent here is on "may" because the proportion of successful intuitive thinkers has been found to be small, around 5% in the experiment on structural design reported in Section 7, 3 and 10% in the experiments by Westcott (Westcott, 1963).

Intuition may also be important in another type of problem-solving in engineering, namely trouble-shooting. It seems likely that it could assist the diagnosis of faults in engineering systems, just as it may help medical diagnosis (Berne, 1949).

In the field of design, some research workers have described as intuitive any method used by a designer of which he is not consciously aware. The author has avoided extending the meaning of intuition in this way, preferring instead to refer to informal design methods.

An experiment has been described in which the performance of subjects in an informal problem-solving exercise was studied. The subjects were university engineering students, and the problem was to design and build a structure to support a fresh egg and prevent it from breaking when
dropped from a height of 45 feet. In this instance there was found to be no relationship, either positive or negative, between students' success at solving the problem and (a) their academic performance and (b) their ability to structure or classify an amorphous body of verbal information.

Once again it has been demonstrated that engineering students have interesting and potentially important abilities not related to conventional academic success. Furthermore, in his professional career the engineer may be called upon

(1) to organize solutions to complex, multi-variable problems where there are large quantities of verbal information, for example, in written specifications and contract documents;

(2) to design novel pieces of hardware for unusual applications where existing modelling techniques cannot be used.

Unless his education prepares him for such professional problem-solving he is unlikely to succeed in both situations, perhaps not even in one of them. After all, 26 students (22.5% of the total of 116) failed the egg-drop project and did not structure their answers to the hospital problem at all.
CHAPTER 8

PROBLEMS OF MEASURING CREATIVE SKILLS
IN ENGINEERING DESIGN

8.1. INTRODUCTION

The tasks used to study creative design skills in the previous three chapters have been relatively straightforward. Scoring subjects' responses has also been straightforward. The question therefore arises whether the scoring procedures used so far can be applied to measurement of the skills exercised in the divergent phase of solving complex design problems. Section 8.2 considers the responses of two different groups of engineering students to two complex design tasks, tasks (9) and (10) in the experimental programme. Ways of representing and scoring performance of subjects on these tasks are discussed.

The subjects were allowed only a short time to respond to task (9), whereas task (10) was a take-home exercise with sufficient time for each subject to plan his approach. According to the operational model adopted in Chapter 2, planning strategies is an important step in the solution of complex design problems. Some evidence on skill in planning strategies was obtained from the responses to task (10) but difficulties of measurement arose. These are also discussed in Section 8.2.

So long as the measurement of skills is based on a formal, operational model of the design process, the quality of the results obtained
will depend on the adequacy of the model. Does the model adopted in this thesis have sufficient detail, or is it too superficial so that underlying abilities responsible for the observed creative skills are overlooked? Some research workers have emphasised the importance to successful creative thinking of the use of analogies. Others have emphasised flexibility in setting the boundaries of a problem and of generalizing. Still others have drawn attention to visual thinking in contrast to verbalization. Whether or not a person possesses one or other of these hypothesised intellectual abilities has not been the object of study in this research. However, some informal evidence relating to these issues has been obtained, and is presented and discussed in Section 8.3.

An aspect of creative effort not explicitly brought out in the responses to the ten experimental tasks is elegance of problem solving. This refers to skill in weaving together different strands of thought in a complex problem. Section 8.4 discusses the concept of elegance and the difficulties it introduces into procedures for measuring creative design skills.
8.2. COMPLEX DESIGN TASKS

8.2.1. Introduction

Task (9) was presented to second year engineering students in Engineering Design I early in the 1969 academic year. It was one of a group of three short exercises each lasting half an hour which they worked through one afternoon. The exercises were presented to the students with the general aim of stimulating their thinking on unfamiliar problems.

The task called for ideas for the design of a device for turning the pages of books for hospital patients who had lost the use of their arms but were otherwise healthy. The design brief (reproduced in full in Appendix 1) also asked for assessment of these ideas, and the students were instructed to keep their evaluations quite separate from the initial phase of ideation. Responses from 140 male, Australian, students who were attempting Engineering Design I for the first time were available for analysis.

Task (10) was presented to thirty third year students of mechanical engineering as their first project in Engineering Design II in the 1969 academic year. It was a take-home exercise spread over four weeks and was in two parts. The first part which is of interest here dealt with ways of minimizing injuries to the occupants of motor cars in accidents. The design brief (reproduced in Appendix 1) called for as many ideas as the students could think of on this matter. The second part of the project considered the elaboration of one solution to the problem, namely a
collapsible steering column, and was not part of the research programme reported here.

Both tasks (9) and (10) deal with relatively complex innovative design problems. As shown by Marples (1961) and as noted by the author in the example shown in Fig. 2.7, design trees can often be used to represent the structure of the design process in such problems. Accordingly, the aims of this part of the experimental programme were:

1. To investigate the use of topological models to represent the structure of two tasks typical of complex, innovative engineering design.
2. To investigate possible methods of scoring responses to these tasks.

The point should be made that subjects’ responses were analysed not to obtain scores to measure individual performances, but to determine what scoring procedures were feasible. In the light of this, the analyses reported below were carried out by the author, and no research assistant was employed to check the results obtained.

3.2.2. Device for Turning Pages of Books

The design tree for the page-turning device depends on

1. the source of power;
2. the operating cycle.

The source of power for the device is the first critical decision to be made by the designer. The responses to task (9) covered three
alternatives: (a) an external source of power independent of the patient, (b) the patient himself as the source of power, and (c) a combination of (a) and (b). There were thus three main categories of design to be considered, designated I, II and III, respectively.

In category I designs where an external source of power is used to drive the device, the operating cycle consists of six events as follows:

1. Actuate, start cycle.
2. Separate \( X \) from \( X + 1 \) (where \( X \) is the page to be turned).
3. Hold \( X + 1 \) flat.
4. Turn \( X \).
5. Hold \( X \) flat.
6. Reset for next cycle.

If the patient is the source of power for separating and turning the pages (category II designs), the operating cycle consists of events (2) to (5). In category III designs, events (1) to (5) have to be catered for, but event (6) may or may not be relevant.

The second major decision to be made concerns the method of operation of the device. This in turn requires consideration of the alternative solutions to the sub-problems of how to accomplish each event in the operating cycle.

As well as operating the page-turner there is also the problem of mounting it over or near the hospital bed. This requires a support whose main features can be established independently of the operation of the device.
The foregoing argument leads to the design tree in Fig. 8.1, which shows the structure of the design up to the point where the sub-problems to be solved are how to accomplish the individual events in the operating cycle. Note that Fig. 8.1 follows Marples' scheme in which, as we move down the design tree, we are considering alternatively sub-problems and solutions proposed to these sub-problems. It will be understood that many solutions are proposed during the course of a design, and the word "solution" is used as a convenient shorthand way of denoting a tentative proposal put forward by a designer for further investigation.

**PROBLEM: DESIGN OF PAGE-TURNING DEVICE**

![Diagram of design tree for page-turning device]

Fig. 8.1. Design Tree for Page-Turning Device.
Analysis of the responses to task (9) showed that except for one matter they all conformed to the structure shown in Fig. 8.1. The exception arose from the fact that a few subjects took a more general view of the task; their work is discussed in Section 8.3.3 below. 64 subjects considered category I designs only, 19 subjects considered category II designs only, 55 subjects considered both categories I and II, while 2 subjects proposed category III designs.

Further analysis of the responses led to the construction of a master design tree, representing all the sub-problems and solutions considered by all the subjects. The master diagram is given in Appendix II, and because of the complexity and difficulty of the task is a complicated and lengthy document. To illustrate this point, one small section of the master diagram is reproduced in Fig. 8.2, that following on from the sub-problem of accomplishing event (1) in the operating cycle of category I designs. Fig. 8.2 also illustrates a possible notation for identifying solutions and sub-problems which are in turn listed in Tables 8.1 and 8.2. The question "How?" which appears at an intermediate level in the figure corresponds to the sub-problem of determining what physical embodiment should be given to an abstract idea or principle of solution.

140 design trees representing the responses of individual subjects could be constructed and a comparative picture of each subject's effort obtained by overlaying his tree on the master diagram. However, this would be a lengthy and time-consuming procedure.
Section of Master Design Tree Concerning Event (1) in Category I Designs.
Table 8.1. Solutions Proposed in Fig. 8.2.

<table>
<thead>
<tr>
<th>Solutions</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a1</td>
<td>Electronic signal from brain wave.</td>
</tr>
<tr>
<td>2a2</td>
<td>Patient to move part of his body to operate switch or press button.</td>
</tr>
<tr>
<td>2a3</td>
<td>Detector operated by movement of patient's eye.</td>
</tr>
<tr>
<td>2a4</td>
<td>Patient's saliva to complete electric circuit.</td>
</tr>
<tr>
<td>2a5</td>
<td>Acoustic device sensitive to patient's voice.</td>
</tr>
<tr>
<td>2a6</td>
<td>Pneumatic actuator operated by patient's breath.</td>
</tr>
<tr>
<td>3a1</td>
<td>Patient to move head or foot to interrupt electromagnetic beam to photocell, or light on patient's head shines on photo-electric actuator.</td>
</tr>
<tr>
<td>3a2</td>
<td>Automatic timer.</td>
</tr>
<tr>
<td></td>
<td>Automatic eye which recognizes page numbers.</td>
</tr>
</tbody>
</table>

Table 8.2. Sub-problems Noted in Fig. 8.2.

<table>
<thead>
<tr>
<th>Sub-problems</th>
<th>Description</th>
<th>Solution Giving Rise to Sub-problem</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Accidental pressing of wrong button.</td>
<td>2a1</td>
</tr>
<tr>
<td>2</td>
<td>Foot or other part of body may be covered by blankets.</td>
<td>2a1</td>
</tr>
<tr>
<td>3</td>
<td>Mouth operation unhygienic.</td>
<td>2a1, 2a5</td>
</tr>
<tr>
<td>4</td>
<td>Patient's view obscured by book.</td>
<td>2a1</td>
</tr>
<tr>
<td>5</td>
<td>Saliva dries up in exciting parts of book.</td>
<td>2a3</td>
</tr>
<tr>
<td>6</td>
<td>Shielding of acoustic device from noise.</td>
<td>2a4</td>
</tr>
<tr>
<td>7</td>
<td>Long wait at end of chapter.</td>
<td>3a1</td>
</tr>
<tr>
<td>8</td>
<td>Sleepy patient.</td>
<td>3a1</td>
</tr>
</tbody>
</table>
8.2.3. Prevention of Injury in Car Accidents.

The responses to task (10) are discussed under two headings:-

(1) Breadth and depth of ideation.
(2) Planning the strategy.

Breadth and Depth of Ideation

A design tree for the divergent phase of this problem was constructed by the author by considering the types of accident in which motor cars are involved and the sources of injury to the occupants.

The argument is briefly summarized here.

Types of accident are:-

(1) Single car running off the road and into a stationary obstacle such as a tree or pole.
(2) Single car rolling over.
(3) Single car running under the back of a parked truck.
(4) Car colliding with other vehicle
   (a) head-on
   (b) obliquely
   (c) side-on
   (d) head-to-tail.
(5) Car colliding with cyclist or pedestrian.

Sources of injury to the occupants of a car in an accident are:-

(1) Gross deformation of passenger compartment due to
   (a) crushing of frame
(b) intrusion of engine or steering column
(c) intrusion of external object such as the tray of a truck.
(2) Contact of unrestrained occupants with car interior.
(3) Ejection of occupants from car.
(4) Inadequate passenger support; for example, whiplash injuries.
(5) Fire.
(6) Asphyxiation by exhaust gases of engine.
(7) Scalding by hot water from radiator.
(8) Burns from battery acid.

This suggests an initial structuring of the design in which the original problem is broken down into eight sub-problems, namely the prevention of injuries arising from each of the eight sources above. Further consideration shows, however, that items (2) and (4) lead directly to the subject of passenger support and restraint. Item (3) is also closely related. It is reasonable therefore to treat passenger support and restraint as a sub-problem in its own right. The original problem is then broken down into the following eight sub-problems, denoted $P_1$ to $P_8$, and for the early part of the design they are considered to be independent so that they can be tackled in parallel. Later in the design and more particularly in the convergent phase, interactions would have to be considered.
P_1 - Prevention of injury due to gross deformation of passenger compartment.

P_2 - Prevention of injury due to contact of unrestrained occupants with car interior.

P_3 - Passenger support and restraint.

P_4 - Prevention of injury due to ejection of occupants.

P_5 - Prevention of injury due to fire.

P_6 - Prevention of injury due to asphyxiation.

P_7 - Prevention of injury due to scalding.

P_8 - Prevention of injury due to acid burns.

P_1 can be further subdivided as follows according to the type of accident producing the gross deformation of the passenger compartment.

P_1^1 - deformation due to head-on collision.

P_1^2 - deformation due to oblique collision.

P_1^3 - deformation due to head-to-tail collision.

P_1^4 - deformation due to side-on collision.

P_1^5 - deformation due to roll-over.

P_1^6 - deformation due to car running under tray of truck.

P_2 can also be subdivided according to whether the occupants come into contact with glass or with other interior surfaces.

Further elaboration of this argument leads to the initial form of the design tree shown in Fig. 8.3. The master diagram representing the combined efforts of all the subjects is given in Appendix II.
Fig. 8.3. Construction of Design Tree for Task (10).

While the master diagram is fairly complicated, it is not as complicated as that for the page-turning device. By examining the design tree for each subject it is possible to extract scores which measure interesting aspects of his work without excessive expenditure of time and effort. To demonstrate this it is first necessary to consider the form of the master design tree. A typical master diagram is shown in Fig. 8.4; one of the features of such diagrams is the uneven length of the different strands of the design. In this context a "strand" is defined as any unfinished branch of the tree. Thus in Fig. 8.4, there are 17 strands, 5 under sub-problem $P_1$, 9 under sub-problem $P_2$, and
3 under sub-problem $P_3$. One strand ends at the depth marked $D_1$, 7 strands at depth $D_2$, and 9 strands at depth $D_3$.

Fig. 8.4. A typical Design Tree.

Despite the uneven length of the tree, it is possible to derive measures of subjects' breadth and depth of performance in a manner similar to that for the information hierarchy in Chapter 5. Possible ways of scoring a subject's response to task (10) which are relatively simple and quick to apply are :-
(1) Breadth, measured by
(a) the number of strands in a subject’s response,
and
(b) the ratio of this number to the total number of strands in the master design tree.

(2) Maximum depth, measured by the maximum level on the master design tree to which a subject penetrates. (Each row of sub-problems counts as one level as does each row of solutions.)

(3) Depth, measured by the proportion of a subject’s strands which are carried to the maximum limit on the master diagram.

(4) Average depth, measured by
\[ \frac{1}{n} \sum_{i=1}^{n} \left( \frac{D_i}{D} \right) \]
where \( D_i \) is the depth of a subject’s \( i \)th strand, \( D \) is the depth of this strand on the master diagram, and there are \( n \) strands in the subject’s response.

To demonstrate the feasibility of this procedure, the performance of two subjects was analysed, the subjects chosen being by inspection close to the best and worst in the group. The results are shown in Table 8.3.
Table 8.3. Performance of Two Subjects on Task (10).

<table>
<thead>
<tr>
<th>Measure of Performance</th>
<th>First Subject</th>
<th>Second Subject</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Breadth  - (a)</td>
<td>52</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>0.46</td>
<td>0.14</td>
</tr>
<tr>
<td>2. Maximum depth</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>3. Proportion of strands carried to maximum depth</td>
<td>0.91</td>
<td>0.50</td>
</tr>
<tr>
<td>4. Average depth</td>
<td>0.86</td>
<td>0.59</td>
</tr>
</tbody>
</table>

Planning the Strategy

The responses to task (10) were examined to find evidence on the strategies used. From their written replies it was clear that ten subjects had planned their work in the same way as the author, that is as described above with reference to the construction of the master design tree. Another ten subjects had adopted a different strategy based on consideration in turn of different sections of the car - the front, the rear, the sides, and the interior of the passenger compartment.

The remaining ten subjects did not use any recognizable strategy. Their proposals were not set out in any clear-cut order and their discussion was characterized by numerous back-tracks from later parts of the design to other associated parts which had been discussed earlier. There may be several reasons for this lack of planning. One possibility is that it reflects the fact that the subjects are not accustomed to planning strategies in ordinary problem solving in everyday affairs.
If this is correct and if it is accepted that planning the strategy is an essential step in the solution of even moderately complex engineering problems, then to develop skill in this phase of problem solving becomes an important educational objective.

Measurement of skill in planning strategies is complicated by the fact that often, as in this case, it may be possible to adopt alternative strategies. It is necessary firstly to compare the merits of alternative strategies against a criterion and secondly, given that a certain strategy is adopted, to observe how consistently that strategy is applied by the designer.

A suitable criterion for comparing alternative strategies would be the time and effort expended by the designer in reaching a successful solution. As pointed out by Bruner (in Bruner et al., 1966), a good strategy is one which reduces the cognitive strain on the individual. This in turn cannot be directly observed, but one could presumably rely on subjective assessments made by experienced designers to rank alternative strategies in order of merit.

The consistency with which a designer implements his chosen strategy can be observed by the number of back-tracks and cross-references in his work. In a manner similar to "level of structure" in Chapter 5, one would expect that a scale with a small number of intervals could be set up to measure a person's performance in this regard, probably a three-interval scale would be appropriate as in Chapter 5.
8.2.4. Comments

The responses of the subjects to tasks (9) and (10) have brought to light difficulties of measurement not present in the other more straight-forward tasks. In some cases, the way to overcome these difficulties is clear, in others further research is indicated.

It was found that the responses to task (10) could be represented pictorially by design trees. While this representation was moderately complicated it did allow numerical scores to be calculated to measure the breadth and depth of the divergent design effort of each subject. Sets of these scores have been obtained from different groups of students and professional engineers, and are being evaluated in a separate research programme outside the scope of this thesis.

Analysis of the responses to task (10) also showed that subjects used two different strategies in their approach to the problem. It was concluded that skill in planning strategies consists of

1. skill in selecting a good strategy which leads to a successful solution with relatively small expenditure of time and effort by the designer, and

2. skill in applying the selected strategy consistently.

It was hypothesised that measurement of the first skill could be made by the ranking of alternative strategies in order of merit by experienced designers, while the experience of Chapter 5 suggests that the second skill could be rated on a three-interval scale using two independent assessors.
Design trees could be used to represent both the individual responses to task (9) and the combined response of all subjects. In this instance, the task and the corresponding topological model were too complicated for any simple numerical scores to be extracted. To arrive at the scores of breadth and depth proposed for task (10) would have required in this case about 10 man hours per subject, and if an independent check were to be made this figure would have been doubled.

Another problem also emerged in task (9), arising out of the inherent difficulty of the task. This was the tendency for some subjects to produce "way-out" ideas of extremely doubtful feasibility, for example, the suggestion of actuating the page-turning device by a brain wave, as noted in Fig. 8.2 and Table 8.1. Should such "pseudo-solutions" be counted in scoring a subject's breadth of ideation or should they be ignored? Perhaps the simplest way to cut the gordian knot of scoring responses to task (9) would be to rely on overall assessments of creative effort by experienced raters, possibly using a scale of 1 to 5 as for task (3).
8.3. OPERATIONAL MODEL

8.3.1. Introduction

We now turn attention to the operational model of the divergent phase of engineering design adopted in Chapter 2 and its adequacy as an instrument for measuring creative design skills.

The written responses of some subjects to the experimental tasks showed evidence of two creative abilities at a more fundamental level than that of the model. These were: (a) the ability to use analogies and (b) flexibility of approach to an unfamiliar problem, the capacity to view it in a more general or all-inclusive way. The evidence, obtained incidentally in the course of the investigation, is now presented and discussed.

Some research workers and educators have emphasised skills of visual thinking in creative engineering design. Because of its importance this topic is also reviewed.

8.3.2. Use of Analogies

The person who can recognize similarities between apparently dissimilar situations is more likely to be an effective problem solver than one who cannot. The perception of analogies presumably enlarges the mental resources of the problem solver by enabling him to consider a richer variety of ideas as possible solutions to his problem. It is not
surprising that several authors have drawn attention to the importance of thinking by analogy when attempting to solve difficult innovative problems.

Dreistadt (1968) discusses the role of analogies in major scientific discoveries. He explains the insights leading to these discoveries as occurring when the problem solver finds a stimulus pattern (the analogy) in which part of the pattern structure is like part of the structure of the problem, and the rest of the structure of this stimulus pattern indicates how to organize the unintegrated elements of the problem, or how to re-organize the problem by putting elements that are out of place into their correct place. He gives examples of great scientific discoveries from Archimedes to Einstein which fit his theoretical exposition. An oft-quoted example is Kekulé's discovery of the benzene ring. Prior to this discovery Kekulé had taken a leading part in formulating the molecular structure of hydrocarbon molecules, all of which had been built up from chains of carbon atoms. After fruitless investigation into the structure of benzene, he was dozing by the fire one night and had a dream in which there occurred the vivid image of a snake swallowing its tail. The image persisted when he awoke and, by analogy, he was led to the idea of the benzene molecule consisting of a circular array or ring of carbon atoms. In his analysis of Kekulé's work, Cackowski (1969) points out that the scientist probably had a mental disposition or set towards chainlike structures as a result of his previous research, but that he had the ability to break the set when given an appropriate cue.
Cackowski traces the history of the cue - the image of the snake swallowing its tail - back several years to an incident when Kekulé appeared as a witness in a murder trial in which the murder was accompanied by a theft of jewellery including a ring that consisted of two intertwined metal snakes biting their own tails.

In similar vein, Gagné (1965) writes that the major scientific discovery in contrast to the common or garden variety involves a major effort of generalization, a combining of ideas that come from widely separated knowledge systems, a bold use of analogy that transcends what is usually meant by generalizing within a class of problem situations. He instances the kinetic theory of gases as an example of this sort of generalisation.

Gordon (1961) argues that reasoning by analogy is essential to creative problem solving both in science and in art. He writes, "The creative mind realizes a higher order of relevance which lends meaning to what we would normally or logically regard as a collection of irrelevant detail". His book on "Synectics" describes techniques whereby analogical reasoning can hopefully be fostered to help solve difficult problems.

An analogy can be defined as a similarity of relations between concepts or objects, and a metaphor as an analogy expressed verbally. Schon (1967) sees the metaphor as a pervasive influence in language and fundamental to the creation of solutions to difficult open-ended problems: a person's experience gives him a storehouse of potential
metaphors. Some of the examples discussed by Schon are drawn from the working of problem solving groups in the field of product development. One group of chemists was faced with the problem of nylon paint brushes which delivered paint in fits and starts instead of as a smooth, continuous flow. Metaphors were freely used by members of the group to describe the behaviour of the paint on the brush. Notions of channels, pipes and pumping provided a metaphor in terms of which the behaviour of the brush could be understood and the problem solved, although the nylon fibres were not pipes or channels as usually defined.

Turning now to task (9). In the written responses to this task, 12 subjects (8.6% of the total of 140) made explicit use of metaphors to arrive at ideas for ways of gripping and turning pages of books. Quotations from their responses are given below.

(1) An air suction device could be used "as is done with many types of duplicating machines today."

(2) "A small suction cup similar to that used in printing machinery."

(3) Pages could be lifted by a "suction device like a vacuum cleaner" or by "a device like a tram conductor's thumb guard".

(4) Friction device for gripping pages "similar to a tram conductor's thumb removing tickets".

(5) Friction pad - "I visualize some kind of rubber surface similar to the thumb stalls of tram conductors".
(6) Stick "with postman's rubber on the end" for separating pages.

(7) "An arm with a rubber end would push the corner of the book (much the same as a finger does) to lift the page slightly".

(8) Rod with rubber pad for turning pages "in the manner of a moist finger".

(9) To help grip the pages "indent them like an encyclopaedia index".

(10) Attach tabs to pages of book "in a pattern like a telephone index".

(11) Lever for turning pages to have "windscreen wiper" action.

(12) Have a nurse standing by to turn pages of book "like a concert pianist's assistant".

The last analogy in this list is interesting because it shows that the subject (Mr. H.) was prepared to go outside the stated boundaries of the task which called for a "device", that is a piece of inanimate hardware rather than a human page-turner. Another example of the use of analogy by Mr. H. was in response to a design exercise similar to task (8), the egg-drop project. He designed a device "arranged on the principle of the shuttlecock" which worked very successfully.

Another example of the use of analogy is given by Mr. D., a second year engineering student, who as his first exercise in Engineering Design I had to build a structure from two sheets of newspaper to satisfy
certain geometrical constraints and to support as many drawing boards as possible. He had to consider the behaviour of structural members in compression at a comparatively early stage of his course before any relevant engineering theory on columns had been presented. In his report, Mr. D. wrote, "The hollow cylinder is used in nature most effectively in reed stalks, bamboo shoots, and animal bones, and is approximately as strong under compressive load as a solid cylinder of comparable diameter."

The tentative conclusion one draws from the above examples is that the use of analogies can aid the design of engineering products. However, Dreistadt and Schon go further than this and suggest that analogies can be helpful at higher levels of abstraction in the design of engineering systems and the development of scientific theories.

8.3.3. Flexibility of Approach

In Section 2.4.3 of Chapter 2 the possibility was raised that a designer might exhibit flexibility in his thinking by going outside the boundaries of the problem as specified in the design brief given to him. There was some evidence of this behaviour in responses to tasks (9) and (10).

The design brief for task (9) specified a device for turning the pages of a book. A number of subjects saw this as part of a more general problem, namely the transfer of information to the hospital patient.

13 subjects (9.3% of the total of 140) considered audio methods of transferring
information to the patient, for example by playing records on tapes or by having somebody read to him; one of the 13 was one of the analogical thinkers mentioned in Section 8.3.2, the other 12 were not. 21 subjects (15.0% of the total) considered other visual methods of communicating with the patient using films, slides or a specially designed book in the form of a continuous scroll. Eleven of the 21 subjects also proposed audio methods, one of the eleven being one of the analogical thinkers mentioned in Section 8.3.2; one of the remaining ten subjects was also a user of analogy.

An implied constraint on responses to task (10) was that the crash protection devices were to suit cars of conventional design. In this instance six subjects (20% of the total) proposed solutions which bypassed or ignored this constraint. The bypass solutions covered alternative methods of propulsion by electric batteries or fuel cells, alternative methods of steering using joysticks or side hand-wheels, and alternative methods of suspension.

Just how important is the ability to relax constraints, either explicit or implicit in engineering design? There is perhaps no general answer to this question; it depends on the nature of the problem and whether it deals with innovative or evolutionary design. Nevertheless it may be noted that engineering students reveal differing abilities in this regard.
8.3.4. Visualization

Visualization can refer to two different but related abilities.

In the first place it may denote spatial ability, commonly referred to as the ability to think and visualize objects in three dimensions. Many tests have been devised to measure this ability, see for example the summary by Michael et al. (1957).

Harris (1960) hypothesised that spatial ability defined in this way would be an important factor in the creative design of three-dimensional products. He constructed a test for creativity in which eight of a total of twenty items presented the subject with a simple two-dimensional drawing and asked him to list as many three-dimensional interpretations possible. However, when Owens et al. (1957) included tests of spatial ability in their test battery to study creativity in machine design, they found them of no use: the spatial ability tests did not discriminate creative from non-creative subjects. The subjects were design engineers in industry rated as either creative or non-creative by their supervisors in accordance with criteria provided by Owens and his co-workers.

The second and broader meaning of visualization is that of visual imagery, of thinking non-verbally by means of visual images. Mednick (1962) in developing his associative theory of creativity speculated that there may be different cognitive styles, for example visualizers and verbalizers, and that one or the other might be the more effective depending on the type of problem to be solved. Katona (1949) found that few subjects who successfully solved his matchstick problems could afterwards describe
the methods by which they reached their solutions. The ability to solve these problems could be acquired without verbal formulation of what had been learned and successfully performed.

Adult problem solving behaviour is the outcome of cognitive growth during childhood. Bruner et al. (1966) discuss the ways in which growing human beings represent their experience of the world and how they organize for future use what they have encountered. At first, Bruner suggests, the child's world is known to him principally by the habitual actions he uses for coping with it. Then in time there is added a technique of representation through imagery, "iconic representation", in which the child pictures the world to himself by an image or spatial schema that is relatively independent of action. Gradually as the child grows up there is added the third "symbolic" phase, in which is developed a new and powerful method of translating action and image into language. Bruner hypothesises that either the habit of using imagery is suppressed as language is learned, or it is retained during language acquisition and is adapted to the requirements of complex problem-solving.

In the field of engineering invention, Walkup (1965) argues that successful creating depends on the vividness of mental images and the skill with which the individual manipulates them. He records informal discussions with inventors in mechanical and chemical engineering who reported thinking visually about complex mechanisms and organic molecules.
McKim (1968) discusses the role of language in solving design problems, and classifies the different languages available to the designer according to their level of abstraction, the languages higher in his list being the more abstract. His list is as follows:

1. Verbal and mathematical symbols.
2. Abstract visual analogues such as networks, Venn diagrams.
3. Charts, diagrams, and schematics.
4. Engineering drawings in orthographic projection.
5. Perspective drawings and sketches.
6. Three-dimensional mock-ups and models.

According to McKim the creative designer of engineering products should be fluent in all languages.

Neither Walkup nor McKim provide evidence from controlled experiments to support their arguments. Much of their theorizing concerns unobservable mental behaviour, and while superficially plausible it must remain speculative, incapable of verification. Nevertheless, the criticism that emerges from their discussions should be borne in mind. Many of the tasks used in the experimental programme reported in this thesis have relied on written answers in which the subjects verbalized their responses to the tasks presented to them. In tasks (2), (3), (9) and (10) the subject could develop his ideas and communicate them by means of sketches as well as by words. No verbal statements were required from the subjects in task (8). The remaining five tasks called for purely verbal responses.
Because so many of the tasks and the responses to them were couched in verbal terms, the creative skills of subjects who were visualizers rather than verbalizers may have been overlooked. The finding of Owens et al. (1957) that spatial ability is not a component of creativity in machine design argues against this. That so much of the subjects' previous education had depended on verbal communication may also make the possibility unlikely.

8.4. ELEGANCE IN SOLVING DESIGN PROBLEMS

Elegance of creative effort in engineering design can be interpreted in terms of the design trees representing the divergent phase of design.

One can imagine a situation where the designer evolves a solution which satisfies more than one sub-problem simultaneously, and thereby "kills two birds with one stone". A truly elegant solution does not in turn give rise to difficult sub-problems, and the design tree converges to a node as shown in Fig. 8.5 for a typical case.

Fig. 8.5. Elegance of Creative Effort Illustrated on a Design Tree.
An example may help to clarify the concept of elegance. In the case of the page-turning device a designer might submit a proposal for combining the operations of separating and turning the pages, perhaps by interleaving the pages with a set of wires which are moved across the book periodically one after the other. But such a proposal introduces difficult sub-problems concerning the preparation of the book in the first place and the size of the wires, and so does not qualify as an elegant solution.

No especially elegant solutions were in fact observed in the responses to tasks (9) and (10). However, it seems reasonable to suppose that such solutions to the sub-problems occurring in a complex design can be recognized by experienced observers and represented by converging lines on a design tree. There appears no obvious way of measuring elegance of creative effort in engineering design. Presumably one would have to rely on subjective ratings by experienced designers.

This along with other matters raised in this chapter could well be the subject of further research.

8.5. CONCLUSION

This chapter has reviewed difficulties in the measurement of creative design skills which arose during the experimental programme or which could be foreseen as likely to arise in future research. In some cases clear-cut lines of research emerged from the discussion while in others the way forward is uncertain. In particular, whether the distinction drawn by
Walkup, McKim and others between visual and verbal thinking can be usefully pursued is far from sure. However, on the basis of the experimental results reported in this chapter further research is required into the following matters.

(1) Development of scoring procedures for creative effort in complex design problems, procedures which are not excessively time-consuming or long-winded.

(2) Use of analogies in creative effort and the measurement of abilities in this regard. It would appear not too difficult to devise a special problem solving course to train people in the use of analogies. The effectiveness of such training could be gauged by the performance of graduates from the course on criterion tasks compared with the performance of a control group who had not received the special training but were of the same age and intelligence and who initially possessed the same ability to make use of analogies.

(3) Relaxation of constraints in the solution of engineering design problems and the measurement of abilities in this regard.
CHAPTER 9
CONCLUSION

9.1. INTRODUCTION

The purpose of this chapter is to review the results obtained in relation to the original aims stated in Chapter 1, to discuss their significance for engineering education, and to make recommendations for further research.

The investigation has been concerned with the responses of second and third year engineering students in the University of Melbourne to a variety of open-ended tasks. The tasks were devised to obtain evidence of their creative design skills and the responses took the form of written answers to questions and the construction of some simple structures. In order to keep the scope of the investigation within reasonable bounds, certain guidelines were adopted. The responses of individual students were elicited and analysed; they did not work as members of groups. Attention was confined to their cognitive behaviour, experimental skills were excluded from consideration. Since university students are well above average in intelligence, the research is concerned with a select group of people. The results obtained and the conclusions drawn would not be expected to hold for the general population.

Important findings are reviewed in Section 9.2 under sub-headings corresponding to the original aims of the investigation stated in Chapter 1, and the significance of these findings for engineering education is discussed. Recommendations for further research are then made in Section 9.3.
9.2. FINDINGS

9.2.1. Theory - Aim (1a)

The theoretical background to the research was established in Chapters 2 and 3 after a review of the literature on engineering design and that on creativity in engineering. Further theoretical discussion was given in the introductory sections of Chapters 5 and 7 as a prelude to the particular topics investigated in those chapters.

A significant part of the theoretical studies was the establishment of the operational model of the divergent phase of the design process in Chapter 2. It was noted in Section 2.5.2 that major steps in this model corresponded to operations in Guilford's structure of the intellect. A link between engineering design and the psychology of intelligence was thus established, a link which had not previously been recognised in the literature of either field of study.

This operational model has provided a convenient theoretical framework for the construction of the experimental tasks used in Chapters 5 and 6 and for the analysis of students' responses to the tasks. It has in turn led to interesting comparisons between the level of skill displayed by different students. The successful use of the model in this way suggests that it could well be the theoretical basis for further research into the creative design skills of engineering students and for that matter of professional engineers as well.

It was argued in Section 2.4 that a formal, operational model of the design process is an important tool for planning and executing research into creative design skills. However, the responses to the tasks described in Chapter 7 showed that data on creative design skill could be obtained without the explicit use of such
a model. It was also pointed out in Chapter 2 that the model adopted may be
too superficial and may overlook fundamental abilities in creative design.
Some evidence to support this view was brought forward in Section 8.3 where
it was noted that students differ in their ability to use analogies and to think
flexibly when solving design problems. It was also noted that some engineering
educators consider the ability to visualise and form mental images of importance
to creative design.

To sum up, the operational model established in Chapter 2 has helped
to lay the foundation for the measurement of a number of creative design skills
and for the analysis of the engineering design process. Within the scope of
the present research programme, it has not been possible to resolve doubts
that the model may be too detailed for some applications or perhaps not detailed
enough for others. Further research is necessary to identify the types of design
problem whose solution can be described in terms of the model and for which
it is therefore a useful technique of analysis.

9.2.2. Creative Design Tasks and Responses to Them - Aims (lb) and (lc)

A series of open-ended tasks has been devised to tap the creative design
skills of engineering students in the University of Melbourne. Chapters 5 to 8
and Appendix II contain detailed information on the responses of the students to
the tasks. Histograms of distributions and means and standard deviations have
been given wherever possible. Quantitative data on student response to open-
ended tasks is now available to engineering educators, in most cases for the
first time. The data should be of value to educators who wish to use the same
or similar tasks because they now have standards for assessing the performance of their students in comparison with those at a typical Australian university.

9.2.3. Measurement of Creative Design Skills - Aim (1d)

The techniques developed in Chapters 5 and 6 for measuring creative skills in engineering design and summarised in Table 9.1, together with the techniques suggested in Chapter 8 for measuring skill in planning strategies. The evidence on informal problem-solving skills presented in Chapter 7 is not susceptible to the type of formal analysis shown in Table 9.1, and is therefore discussed separately in Section 9.2.4 below.

Table 9.1. Measurement of Creative Skills in Engineering Design.

<table>
<thead>
<tr>
<th>Creative Design Skill</th>
<th>Step in Operational Model (Table 2.4)</th>
<th>Description</th>
<th>Scale of Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>b. Number of classes of problems recognised.</td>
</tr>
<tr>
<td>3. Collection of data.</td>
<td>3. Collection of data.</td>
<td>Breadth of information search.</td>
<td>Number of categories sub-categories, items, and elaborations of information.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Depth of information search.</td>
<td>Number of sub-categories containing at least one item divided by total number of sub-categories.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Level of structure.</td>
<td>Three-interval scale according to whether level of structure is high, low, or non-existent.</td>
</tr>
<tr>
<td>4. Planning the strategy</td>
<td>4. Planning the strategy</td>
<td>Selection of strategy.</td>
<td>Rank ordering by experts.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Consistency in application.</td>
<td>Three-interval scale similar to that for level of structure.</td>
</tr>
</tbody>
</table>
Table 9.1. (Continued)

<table>
<thead>
<tr>
<th>Step in Operational Model (Table 2.4)</th>
<th>Description</th>
<th>Scale of Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>6. Foreseeing implications.</td>
<td>Foresight.</td>
<td>Number of criteria used to evaluate alternative solutions.</td>
</tr>
</tbody>
</table>

Table 9.1 shows that techniques are now available for measuring many creative skills in engineering design. However, two important issues arise in the application of these techniques, namely the objectivity of the measurements and the lack of an absolute scale of measurement. These are now discussed.

Objectivity of Measurement

In Chapter 7, the subjects' performance was measured objectively by the observed strength to weight ratios of structures and by success or failure on the egg-drop project. On the other hand, in Chapters 5 and 6 there was an element of subjectivity in the measurement of subjects' performance. Items in their written responses were sometimes expressed ambiguously and thus open to differing interpretations. This ambiguity of expression could have affected scores based on numbers of ideas or numbers of items of information in the responses. Analyses of subjects' written responses were therefore made by two people, the author and a research assistant, the latter an engineering graduate having no personal contact with the subjects nor knowledge of their academic records. In each experiment the difference between the two sets of
scores obtained in this way was small, enabling reliable comparisons to be made between different aspects of the subjects' performances.

The content of the tasks in Chapters 5 and 6 was such that in all but two cases it was not possible to make a comparison of the quality of the items put forward. Variations in scores due to variations in the analysts' subjective evaluations of quality therefore did not arise. The two cases where some assessment of quality was included in the score were discussed in Section 4.4.1 - the design of a hospital stand and the design of a drawing office. As already noted, quality and quantity of ideas have usually been found to correlate highly, for example by Owens (1969) for 457 research and development engineers in industry and by Gluskinos (1968) for a group of 173 electrical engineering students.

Relativity of Measurement

One of the features of the measuring techniques used was that they enabled the relative performance of the subjects on various tasks to be studied. To measure each subject's performance on an absolute scale would require analyses of responses from very large numbers of subjects and normalisation of the results, as for I.Q. It is questionable whether this procedure would be worth the effort involved because of the difficulty in devising tasks whose contents are not affected by changing social issues or the climate of opinion prevailing in society. For example, responses to the tasks set in Chapters 5 and 6 could depend on the publicity given to problems of underdeveloped countries or remote communities. Responses to the tasks in Chapter 6 which concerned urban
problems and innovative transport methods would certainly be affected by social issues and local progress in urban development.

Creative skills are exercised on innovative problems of which the majority of people may not be aware. The creative person is very often ahead of the rest of society in recognising problems, but in time the rest of society catches up, solutions are worked out and the element of creativity disappears. For this reason it is highly unlikely that universal standards can be set up for measuring creative skills in engineering design. However, correlational techniques enable comparisons to be made between the performance of groups of subjects on different tasks. It is also possible to identify subjects whose performance is superior and to examine their efforts in detail. These two approaches have been adopted in the present study.

9.2.4. Correlations - Aim (2)

Table 9.2 sets out the results of experiments where significant positive correlations were found between performances on different tasks. Possible interpretations of these results are also summarised.
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Significant Positive Correlation between</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Level of structure and breadth of information search.</td>
<td>Structuring information reduces cognitive load on subject.</td>
</tr>
<tr>
<td></td>
<td>Level of structure and academic effort in examinations.</td>
<td>Structuring information reduces cognitive load on examinee.</td>
</tr>
<tr>
<td></td>
<td>Average depth of information search and performance in mathematics.</td>
<td>No interpretation offered.</td>
</tr>
<tr>
<td>6</td>
<td>Sensitivity to problems, fluency of ideation, flexibility of ideation, and foreseeing implications.</td>
<td>These skills may be regarded as components of a more all-embracing creative skill.</td>
</tr>
</tbody>
</table>

No relation, either positive or negative, was found between level of structure in the information search task and examination marks in mathematics. A positive relation had been hypothesised on the grounds that both performances depended on an underlying skill of recognition of pattern or structure. This hypothesis was not supported, perhaps because of the different categories of information - verbal and symbolic - used in the two performances.

No relation, either positive or negative, was found between subjects' level of structure in the information search task and their success in the egg-drop experiment. The hypothesis had been proposed that people who bring carefully organised and structured thinking to bear on new problems will perform poorly in informal problem-solving. If this is correct, the sought-for relation should be negative. However, no evidence was found to support the hypothesis, perhaps because here again the responses to the experimental tasks made use of two different categories of information - verbal and figural respectively.
In many of the tasks, subjects' performances were found to have no correlation with academic achievement in university examinations or to be independent of their academic record. These results are summarised in Table 9.3.

Table 9.3. Summary of Performance Found to be Independent of Academic Record in University Examinations.

<table>
<thead>
<tr>
<th>Item</th>
<th>Performance</th>
<th>Chapter</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Breadth of information search</td>
<td>5</td>
<td>2nd year engineering students</td>
</tr>
<tr>
<td>2</td>
<td>Exploration of problem boundaries</td>
<td>5</td>
<td>As item (1)</td>
</tr>
<tr>
<td>3</td>
<td>Creation of ideas</td>
<td>6</td>
<td>2nd year engineering students different from Item(1)</td>
</tr>
<tr>
<td>4</td>
<td>Creation of ideas</td>
<td>6</td>
<td>As item (3)</td>
</tr>
<tr>
<td>5</td>
<td>Creation of ideas</td>
<td>6</td>
<td>As item (3)</td>
</tr>
<tr>
<td>6</td>
<td>Sensitivity to problems</td>
<td>6</td>
<td>As item (3)</td>
</tr>
<tr>
<td>7</td>
<td>Foreseeing implications</td>
<td>6</td>
<td>As item (3)</td>
</tr>
<tr>
<td>8</td>
<td>Optimum design of structure for static load</td>
<td>7</td>
<td>3rd year mechanical engineering students</td>
</tr>
<tr>
<td>9</td>
<td>Design of structure for impact load</td>
<td>7</td>
<td>As item (1)</td>
</tr>
</tbody>
</table>
In view of the evidence in Table 9.3 it is not surprising to find that the performance on the job of the professional engineers who took part in Taylor et al.'s study was not related to their undergraduate academic record (Taylor et al., 1963).

Table 9.3 shows that engineering students are capable of a wide range of interesting problem-solving behaviour, which is potentially important to their future careers but which is not revealed by the usual scores of academic performance. While techniques of assessing students' performance vary from university to university, the great majority rely heavily on formal examinations. The research reported in this thesis suggests that the picture of student ability so obtained is at the very least unbalanced and may in fact be grossly misleading.

9.2.5 Identification of Creative Talent in Engineering Students - Aim (3)

The results presented in Chapter 6 show that some engineering students perform consistently well in their responses to a variety of open-ended tasks. It is reasonable to conclude that these are the students most capable of creative engineering endeavour. If this is correct, then considerable progress has been made towards identifying students of high creative talent in engineering. This result is of importance to engineering education because such students will require encouragement to make full use of their abilities in their undergraduate courses, particularly if the courses are biased towards analytical methods.

Furthermore, if creative students are made aware of the special skills they possess, they will be encouraged to make their careers in professional
work which emphasises initiative and innovation rather than routine problem-solving. If this happens, there is then a much greater chance that their potential for making a significant contribution to engineering will be realised.

9.2.6. Long-term Research Aims

Some progress has been made towards satisfying the long-term research aims outlined at the end of Section 1.2. Tasks and scoring techniques similar to those developed for use with engineering students could be applied to professional engineers in order to measure their creative design skills. Better knowledge of the skills possessed by professional engineers would lead to more precise definition of the objectives of engineering education and the goals to which engineering educators should direct their efforts.

The creative design skills displayed by engineering students in the present investigation were largely independent of their formal academic performance. If, in accordance with the recommendation of the A.S.E.E. Goals Report quoted in Section 1.1, it is decided to develop these skills during university education, then special teaching methods will be required with emphasis on synthesis rather than analysis. The experimental tasks devised for this research could well provide the basis for such methods.

9.3. FURTHER WORK

Comparison of the work reported in this thesis with the survey of previous work in Chapter 3 shows that there are few precedents. As a result much of the research undertaken has been exploratory and further work is required to
yield definitive results. It is recommended that further investigations into
creative skills in engineering design should be undertaken as follows.*

(1) Investigations to determine the types of design problem in
which the divergent phase of the process of solution can be
described in terms of the operational model established in
Section 2.4.; modification of the model if necessary to extend
its range of application.

(2) Experiments to confirm or disconfirm the results obtained,
with different groups of engineering students working on
the same or different tasks requiring the exercise of creative
design skills. Also to be studied are the effects of varying
environments and varying task instructions.

(3) Experiments to explore and define the nature of skills in
problem definition.

(4) Experiments to investigate the scope of engineering creativity.
For example, are there significant correlations between other
creative design skills besides those correlations reported in
Chapter 6?

(5) Experiments to identify and measure the creative design skills
exercised in complex problems such as those discussed in Chapter 8.

* The author advises that he has carried out some experiments under items
(1), (2), (3), (4), (5) and (7) in this list. It is planned to carry out experiments
under items (6) and (8) in the near future. Because of the very time-consuming
nature of the data analysis, it will be some time before the results are ready
for publication.
(6) Experiments to investigate creative design skills in tasks where there are many constraints and/or conflicting requirements. Is the ability to integrate informational inputs under these conditions an important factor as suggested by Owens (1969)?

(7) Experiments to identify and measure the creative design skills of professional engineers.

(8) Experiments in teaching methods to determine the best way of developing the creative design skills of engineering students.

9.4. CONCLUSION

An investigation has been carried out into the creative design skills of engineering students in the University of Melbourne. In order to tap students' creative abilities, open-ended tasks representative of those encountered by the professional engineer in practice were devised. Students' responses to the tasks were then observed and analysed.

The results showed that there were many interesting and apparently important aspects of the students' creative problem-solving behaviour which could be identified and measured, but which were not revealed by performance in conventional university examinations. These aspects of problem-solving appear to be important from the point of view of the students' later professional careers, but further work is needed to confirm this.
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APPENDIX I

EXPERIMENTAL TASKS

The design briefs given to the subjects are set out below for tasks (1) to (10). Details of the instructions given to other assessors by the author for scoring of responses to tasks (2) to (6) inclusive are also included.

Task (1)

Frequently the designer has to spend time searching for relevant information to enable him to start work on a project. If the problem is novel or is vaguely defined, a lot of effort may be devoted to this activity in the initial phase of the design. This question deals with the collection of information for a new project. Your answer should be as precise as possible indicating a clearly thought out appreciation of the problem, not vague waffle.

Imagine that you are the leader of a team of volunteers who have taken on the job of building a hospital for the indigenous community on a remote Pacific island (the project being undertaken under the aegis of the United Nations). An earlier attempt by missionaries to build such a hospital failed four years ago because of a hostile reaction from the local people.

What information would you require concerning the island and conditions on it in order to undertake the project successfully?
Task (2)

In a piece of hospital equipment a tubular stand with a sliding tubular adjustable element is used to support a weight of about 10 pounds. Fig. I.1 shows the kind of stand in use at present.

It will be seen that two hands are necessary to make the height adjustment. One hand must grasp the upper tubular part while the other is used to clamp and unclamp it. Means must be found to make the adjustment with one hand, presumably by securing the clamping handle to the sliding tube so that it can not only perform the weight supporting function but also the clamping one as well. The upper sliding tubular element is of $1\frac{1}{2}$ inches diameter mild steel and it has a vertical height adjustment of 18 inches.

Think up as many ways as you can of solving the problem, and give your answer in the form of sketches with brief explanatory notes.

Fig. I.1. Hospital Stand.
Task (3)

Future additions to the Chemical Engineering Building will include one floor to be devoted to a drawing office for first and second year engineering students. Preliminary layout drawings showing the space to be occupied by the new office are available for your inspection.

Design the drawing office.

Your work on this assignment will fall into three parts.

(1) An initial appreciation of the design problem, to be handed in on the first Monday afternoon. You will have to decide just what activities will go on in the new office. Besides drawing and other graphical exercises there may be tutorials in mathematics and other subjects. There will be various types of communication between lecturers, tutors, and students. The social activities of students may also have to be considered. You should summarize this initial appreciation by listing the objectives which your design should fulfil and rating the importance of the objectives, e.g. whether they are essential, highly desirable, desirable, or marginal.

(b) Design and layout of the Drawing Office, including typical fittings such as benches, desks, blackboards, seats, stools, etc. You will have to consider the individual work space of the student as well as factors such as lighting, acoustics, and noise.

(c) Conclusions reached and recommendations made as a result of your design study. If possible include an assessment of how successful you think your design is, how well it has met the objectives listed in (a).
Discuss any particular difficulties that have arisen and any major compromises that have had to be made in the course of the design. Students whose work on this assignment is of a high standard may be asked to prepare a special report for submission to the Faculty of Engineering.

Task (4)

The designer must be sensitive to problems implied in his work but not explicitly stated. This question is to test your ability to perceive such problems. In your answer list as many problems as you can think of and give sufficient brief explanation about each problem in your list to ensure that it is clearly defined. Students who give a reasonable number of significant problems in their answers will score a pass on this question. Students who perceive a large number of significant problems will be awarded bonus marks.

The question is:

What problems do you foresee arising from the growth of population in the Greater Melbourne area in the next 25 years?

Task (5)

Imagine that in five years' time it is proposed to build a large underground car-park below the Domain near the corner of St. Kilda Road and Domain Road, i.e. about one-and-a-half miles south of the centre of the city. The design problem is to devise some means of transport for the
people who park their cars in this car-park and wish to travel to the city.

Create as many ways as you can for transporting people from the proposed car-park to the city. In your answer list the alternatives with sufficient brief explanation to ensure that your proposals can be readily understood.

At this stage let your ideas run freely without any constraint or attempt at evaluation. Students who produce a reasonable number of worthwhile ideas will score a pass on this question. Students who produce a large number of worthwhile ideas will be awarded bonus marks.

Task (6)

List the advantages and disadvantages of each alternative method of transport that you have proposed in answer to the previous question. State clearly what factors you think should be taken into account when making a comparison of alternative designs.

Task (7) - Design Brief Given to Third Year Students in Mechanical Engineering

INTRODUCTION

This is a short project comprising the design and construction of a simple structure. The objective is to obtain maximum strength to weight ratio. Competing structures will be submitted by professional designers.
SPECIFICATIONS

The position of the applied load and the space constraints on the design are shown on the diagram provided. Note that the thickness of the structure is not to exceed 3/4 inch. The structure is to rest on a 2 inch wide base and is to support a central vertical load. As constructed, it is not to touch or cross the cross-hatched profile shown in the diagram.

INSTRUCTIONS

The structure is to be made from the sheet of polyurethane foam supplied. No other materials (solid or liquid) may be used.

Each designer is to submit a brief written report in support of his work, and should be prepared to explain and justify his design before a jury of staff and colleagues. In the report the reasoning behind the design should be clearly and concisely explained, and the place where the structure is expected to fail and the mode of failure indicated. The discussion should be qualitative, occupying about one foolscap page, with a sketch or drawing of the design on a second page. No calculations are required.

The report is to be submitted before testing of the structure. Following testing, an appendix is to be submitted commenting on the results and suggesting possible improvements to the design.

TESTING

Each structure will be weighed, tested to failure, and its strength to weight ratio calculated. Tests will be carried out in the Stress Analysis
Laboratory and you should make yourselves familiar with the test arrangements.

TIMETABLE

Thursday 12th March - Assignment sheets handed out.
Thursday 19th March - Models submitted by 5.00 p.m.
Thursday 26th March - 2.00 p.m. Design Seminar.

- Reports submitted.
- 2.30 p.m. Models tested.
- Comments on test results submitted by 3.30 p.m.

MARKING SCHEDULE

(1) Report 12

Argument and discussion.

(2) Test

(a) Strength to weight ratio 7
(b) Place and mode of failure -
closeness of test to prediction 2

(3) Hindsight 4

Comments on test results and suggested improvements to the design.

TOTAL 25

Bonus marks will be awarded for meritorious work, in particular for
(a) contributions to the design seminar

(b) high strength to weight ratio.

Fig. I.2. Design of Structure for Static Load. Diagram Provided with Design Brief for Task (7).
Task (7) – Design Brief Given to Third Year Architecture Students and Naive Subjects from Non-Technical Faculties

The objective of this exercise is to construct a simple model in such a way as to maximize its "strength to weight" ratio. Its strength is equal to the maximum force the model is able to withstand before breaking and the weight is the weight of the model before testing. So to maximize "strength to weight" ratio, you must construct a model with the greatest possible strength while attempting to satisfy the conflicting requirement of low weight.

The structure is to be made from the polyurethane foam sheet provided. No other materials, solid or liquid, may be used.

The position of the applied load and the space constraints on the design are shown on the diagram provided. The thickness of the structure is not to exceed 3/4 inch. The structure is to rest on a 2 inch wide base and is to support a central vertical load. As constructed, it is not to touch or cross the cross-hatched profile shown in the diagram.

(Note: a diagram similar to that shown in Fig. I.2. was supplied to each subject with this design brief.)

Task (8)

INTRODUCTION

This assignment emphasises the conceptual phase of design where the engineer is chiefly concerned with generating new ideas. It deals with physical hardware for a clearly defined application. Each student is to work
individually on the assignment. No report is required.

ASSIGNMENT

Design and build a structure capable of supporting a fresh egg so that when dropped from the level of a window sill in Drawing Office B, it strikes the asphalt at ground level and the egg does not break (shell not cracked). The vertical height of the drop is 45 feet.

Conditions to be satisfied:

(1) The size of the structure is not to exceed 18 inches x 18 inches x 18 inches.

(2) The structure is to be self-contained.

(3) The structure is to be built from one or more of the following materials:

(a) sheets of newspaper
(b) paper clips
(c) rubber bands
(d) transparent adhesive tape, "Durex" or equivalent
(e) string
(f) aluminium foil.

(4) If the first launch lands the structure on grass or the structure hits the side of the building or other obstruction, two further launches are allowed. A structure which does not successfully land an egg on the asphalt after three attempts is deemed to have failed.
INTRODUCTION

The designer has to

(1) define the problems he faces and be aware of their implications;
(2) create possible alternative solutions;
(3) compare and evaluate these alternatives in order to decide which one to adopt.

ASSIGNMENT

You are a consulting engineer and a doctor has approached you with the request that you design a device for turning over the pages of books being read by hospital patients who have no arms or who have lost the use of their arms from disease. The patients spend most of their time lying on their backs, and have full use of their mental faculties. They can be propped in a semi-upright position by nurses placing pillows behind their backs. The doctor points to a typical case and says, "Here is a patient lying in bed; here are the books he wants to read. The rest is up to you."

(a) Make an initial appreciation of the design of a suitable page-turning device to be operated by the patient (preferably in not more than 150 words). A major part of your appreciation should deal with the objectives to be satisfied by the design and their relative importance, whether you rate them as essential, desirable, or marginal.
(b) Create as many ideas as you can for solving the design problem, i.e. for devising a suitable page-turner. List your ideas with sufficient brief explanation and/or sketches to ensure that your proposals can be readily understood. In this part of the assignment let your ideas run as freely as possible without any constraint or attempt at evaluation.

(c) List the advantages and disadvantages of each idea in (b). Hence classify your proposed solutions as promising and probably worth further investigation or as unpromising and probably not worth further investigation.

Task (10)

INTRODUCTION

This project deals with the preliminary design of a collapsible steering column for a Morris 1100 car. You are also asked to consider the wider problem of crash protection devices.

PROJECT

(1) Make a survey of crash protection devices for motor-cars. The point of view we are taking here is that since nearly all drivers have at least one serious accident in their lives we wish to investigate ways in which injuries to drivers and passengers can be minimised.

Your survey should list all the ideas you can think of for minimising injuries in car accidents, plus a brief statement (preferably one sentence) assessing the value of each idea, whether it has any important advantages or disadvantages.
(2) Carry out the preliminary design of a collapsible steering column for a Morris 1100 car.

INSTRUCTIONS

Your work on the collapsible steering column falls into three parts:

(1) Definition of the problem, specification of the task to be performed in engineering terms.

(2) Creation of ideas for solving the problem. Initially let your ideas run freely and come up with as many solutions as you can. You are advised to try to generate your ideas but if you find these are slow in coming group discussions will be held to help get things moving.

(3) Analysis and evaluation of the alternative proposals.

Remember that only a preliminary design is required at this stage. It is your job to identify and suggest solutions for the sub-problems thrown up during the course of the design. Do not become enmeshed in detail; the most promising ideas will be analysed in detail later in the year.

A Morris 1100 car is available for inspection.

A formal report is not required, but make sure that your work is arranged in a logical order with important results clearly shown. Give the reasoning behind all important decisions, and make liberal use of sketches to illustrate your ideas.
INSTRUCTIONS FOR SCORING RESPONSES
TO TASKS (2) TO (6) INCLUSIVE

Task (2)

To help maintain a consistent standard of scoring on this task the author gave the assessors the following written instructions. He also checked a random sample of their scores. The assessments were made by five of the author's colleagues, members of staff in the Department of Mechanical Engineering, University of Melbourne.

"Each distinct design idea should receive a maximum of 5 marks according to how you rate its practicability and simplicity on the scale: 5 - excellent, 4 - good, 3 - fair, 2 - poor, 1 - very poor. Some students may put forward ideas which are essentially different variations on the one theme. Each variation should be awarded some marks (less than 5, of course), the closer the variation to the original theme the few marks it should receive. In arriving at your marks, try as far as possible to exclude any assessment of students' sketching ability or skill in communication."

Task (3)

This task was scored by the same six people as task (2), and in this instance the author checked all the assessments. To help maintain a consistent standard of scoring the author gave the following written instructions to the assessors.
"The creative effort of each student should be rated according
to the following scale:-

5 - student has many original ideas of high value;
4 - very marked creative effort by student;
3 - significant creative effort by student;
2 - some creative effort by student;
1 - little or no creative effort by student.

Creativity as the word is ordinarily used includes the ability to perceive problems unrecognised by conventional minds. In this exercise only the more creative students would be aware of one rather subtle problem, namely the adverse emotional effect produced by a monotonous array of desks. Students who recognize this problem should score 3 out of 5 and if they do something about it 4 or 5 out of 5. Students who have one mildly creative idea such as storing drawings boards vertically instead of horizontally as at present should score 1 out of 5, and if they have a second idea of the same calibre should score 2 out of 5."

Tasks (4), (5) and (6)

The research assistant who made the independent assessments of responses to tasks (4), (5) and (6) had had previous experience in scoring open-ended tests in an experiment on the creativity of school children in science. He was instructed to make an objective count of the number of problems foreseen in task (4), of the number of ideas for the proposed transport system in task (5), and of the number of factors used to make
comparisons of alternative proposals in task (6). He was also instructed in task (4) to classify related problems into categories for the purpose of determining the flexibility shown in the subjects' responses.
APPENDIX II

EXPERIMENTAL RESULTS

Details of experimental results on tasks (1), (2), (4), (5), (6), (9) and (10) are given below, supplementary to the information given in Chapters 5, 6 and 8.

Task (1)

The final information hierarchy agreed to by the author and research assistant was as follows. Items of information are numbered from 1 to 160, and elaborations of items are denoted (a), (b), (c), etc.

1. The Islanders.
   1.1. Population.
       1. Total population.
       2. Distribution of population according to age.
       3. Distribution of population according to sex.
       4. Geographical distribution of population on island.
       5. Sizes of families.
       6. Physique, stature.
       7. Rate of increase of population.
          a. At present.
          b. After the hospital is built.
       8. Number of white people living on island.
       9. Tourist traffic.
10. Migration from neighbouring islands.

1.2. Health.

11. Diseases existing on island.

12. Contagious or infectious diseases requiring isolation.
   a. Plague.
   b. Tuberculosis.
   c. Leprosy.

13. Length of time diseases affect patients.


15. Diseases requiring X-rays.


17. Number of people affected per disease.

18. Variation of (17) with time, epidemics.

19. Dental health.

20. Personal injuries.
   a. Shark attacks.
   b. Diver's bends.
   c. Fights.

   a. Birth rate.
   b. Infant mortality.

22. Old age, geriatrics.


24. Personal hygiene.
25. Existing medical service on island.

1.3. Economy.

26. Rural activities, farming.

27. Industry.

28. Maritime activities, fishing.

29. Trade.

30. Standard of living.


32. Cost of labour.

33. Cost of land.

34. Payment for medical care.

35. Future economic developments.
   a. Tourism.

1.4. Education, Skills.

36. Knowledge of outside world.

37. Literacy.

38. Schools.


40. Existing skills relevant to hospital project.
   a. Woodcraft.

41. Number of people having various skills.

42. Latent skills capable of development by training.

1.5. Religion.

43. Organisation of religion, priesthood.
44. Religious beliefs.
45. Sacred sites.
46. Witchdoctors.
47. Taboos.

1.6. Culture.

48. Race.
49. Language.
50. Architectural aesthetics.
51. Social customs.
52. Folklore.
53. Clothing.
54. The family as a unit of society.
   a. Would relatives accompany patients to hospital, camp in grounds?
   b. Would relatives cook food for patients?
55. Dominant sex.
56. Cannibalism.

1.7. History.

57. Previous contact with civilization.
   a. Traders.
   b. Colonists.
   c. Missionaries.
   d. Soldiers in World War II.
58. Previous behaviour of outsiders to islanders.
   a. Respect for religious beliefs.
   b. Respect for sacred objects.
   c. Respect for women.
   d. Respect for natural resources.

1.8. Technology.

59. Weapons.

60. Waste disposal, sewerage.

61. Existing means of disseminating information on the island.
   a. Word of mouth.
   b. Writing.
   c. Radio.

62. Existing forms of transport on the island.
   a. Barges on rivers.
   b. Vehicles on roads.
   c. Effect of rain on existing transport.

63. Existing methods of construction used on the island.
   a. Weatherproofing.
   b. Beds.

64. Existing tools and equipment for building.

65. Existing buildings, potential use as hospital.

1.9. Island Society, Politics, and Law.

66. Social stratification, tribes.

67. Laws.
68. Land ownership.

69. Form of government.
   a. Colony.
   b. Democracy.
   c. Monarchy.
   d. Council of elders.

70. Attitude of islanders to their government.

71. Leaders of island society.
   a. Character.
   b. Friendliness.

72. Community organizations who might help to construct hospital.

1.10. Character and Temperament of the Islanders.

73. General character.
   a. Warlike or meek?
   b. Self-reliant.
   c. Lazy or hard-working?

74. Small groups of agitators.

75. Attitude of islanders to intimate doctor-patient relationship.

76. Motivation towards hospital project.
   a. Do islanders themselves want the hospital?
   b. Are islanders willing to help build the hospital?

77. Attitude of islanders to outsiders.
   a. Attitude towards other races.
b. Attitude towards other cultures, ways of life.

c. Attitude towards future medical staff of hospital.

e. Attitude towards the United Nations.

78. Attitude of islanders to modern technology.

a. Attitude towards machines.

b. Attitude towards modern medical techniques.

2. Island Environment.

2.1. General.

79. Area.

80. Topography.

a. Contours.

b. Mountains and Hills.

c. Valleys.

81. Bays and reefs.

82. Surface condition of ground.

a. Bogs.

b. Swamps.

83. Geology.

84. Vegetation.

2.2. Food (excluding animals).

85. Quantity of food available on island.

86. Types of food available on island.

87. Regions of island where food available.
88. New cultivation.
89. Deterioration with age.

2.3. Animals.

90. Animals for food.
91. Beasts of Burden.
92. Animals dangerous to man.
   a. Insects.
   b. Vermin.
93. Quantity of animals on island.
94. Types of animals on island.
95. Regions of island where animals found.

2.4. Construction Materials.

96. Quantity of timber available.
97. Types of timber available.
98. Clay.
100. Sand.
101. Materials left behind by missionaries.
102. Materials available from nearby islands.

2.5. Factors affecting Choice of Construction Materials.

103. Proposed use in building.
   a. Roofing.
   b. Walls.
   c. Foundations.
104. Cost.
   a. Ease of processing.
   b. Cost of transport.

105. Use of construction materials in island buildings.

106. Cleanliness.


108. Soil erosion due to exploitation of island's resources.

109. Damage to island's ecology.

110. Aesthetics.

2.6. Water.

111. Quality.

112. Quantity.

113. Sources.
   a. Rain.
   b. Rivers.
   c. Lakes.

2.7. Power.

114. Hydroelectric.

115. Fuels occurring naturally on island.

3. Choice of Site.

3.1. Land Available.

116. Existing use of land on island for villages, houses.

117. Land available for storing supplies.
118. Existence of site already cleared.

119. Islanders' wishes with respect to site of hospital.

3.2. Nature of Site.

120. Elevation above sea level.

121. Slope.

122. Vegetation cover.

123. Soil.
   a. Foundations.
   b. Swamps.
   c. Drainage.
   d. Rocks.
   e. Blasting.

3.3. Accessibility of Site to Patients.

124. Distance to potential patients.

125. Distance to patients' transport.

126. Time and effort of transporting patients to hospital.

3.4. Accessibility of Site to Supplies.

127. Distance to port or airport.

128. Distance to water supply.

129. Distance to natural power supply.

130. Distance to possible construction materials.

131. Time and effort of transporting supplies to hospital.

3.5. Feasibility of Associated Constructions.

132. New roads.
133. New ports or airports.
134. New dams and aqueducts.

4. Climate.

4.1. Weather.

135. Temperature.
136. Humidity.
137. Rain.
   a. Monsoons.
138. Wind.
139. Daylight, sunshine.
140. Storms.
   a. Cyclones.
   b. Typhoons.
   c. Hurricanes.
   d. Tornadoes.
141. Variation of weather with time.
142. Variation of weather in space.

4.2. Natural Disasters.

143. Earthquakes.
144. Fires.
145. Floods.
146. Tidal waves.
147. Volcanoes.
148. Landslides.
5. Volunteers.

5.1. Relevant Information on Island.

149. Accommodation during construction of hospital.
   a. Distance of accommodation from site.

150. Food.

151. Recreation.

152. Health.
   a. Local diseases.
   b. Climate.


6. Transport, Communications between Island and Outside world.


154. Existing means of communication.

6.2. Transport.

155. Existing means of transport.
   a. Ship.
   b. Aircraft.

156. Frequency of existing transport.

157. Accessibility of island.
   a. Distance from major port or centre of population.
   b. Nationality of nearest port.
   c. Time for journey from nearest port.

158. Emergency transport facilities.
a. Facilities for transporting seriously ill patients from island.

b. Facilities for bringing emergency supplies onto island.

159. Airstrips and heliports.

160. Ports,
   a. Area.
   b. Depth of Water.
   c. Distance from villages.
   d. Loading and unloading facilities.
   e. Development of trade with outside world.

The first three stages of the information hierarchy produced by the HIDECS 2 program are shown in Fig. II,1. Items of information are identified by the same numbers as in the above list.
Fig. II.1. Information Hierarchy produced by HIDECS 2.
Task (2)

The subjects' responses to task (2) covered the following methods for raising and lowering the hospital stand.


(2) Rack and pinion.

(3) Nut turning on screw thread similar to piano stool.

(4) Mechanism similar to that for raising and lowering domestic clothes hoists.

(5) Pawl and ratchet.

(6) Friction grip with special release attachment.

(7) Hydraulic pressure.

(8) Pneumatic pressure.

Task (4)

Listed below are the problems foreseen by the subjects in response to task (4) on Melbourne's urban growth. There were thirty-seven problems in all, and they have been classified into the ten categories agreed upon by the author and the research assistant. No subject mentioned more than one of the problems in the tenth category, "Miscellaneous".

(1) Essential Services.

1. Water supply.

2. Gas supply.
3. Electricity supply.
4. Sewerage.
5. Garbage, refuse disposal.

(2) Emergency Services.
6. Fire.
7. Police.
8. Ambulance.

(3) Schools and Hospitals.
9. Schools and universities.

(4) Transport.
13. Public transport.
14. Private transport, roads and highways.
15. Parking.
16. Docks and shipping facilities.
17. Airports.

(5) Communications.
18. Telephones.
19. Postal services.

(6) Distribution of Goods.

(7) Housing.
22. Urban sprawl.
23. Slum reclamation, resettlement.

(8) Government.
24. City plan, zoning.
25. Administration and co-ordination of city development.

(9) Urban Environment, Quality of Living.
26. Air pollution.
27. Noise.
29. Recreation areas and parks.
30. Psychological stress, delinquency.
31. Decay of city centre.

(10) Miscellaneous.
32. Unemployment.
33. Civil defence.
34. Increase in land values.
35. Location of quarries.
36. Assimilation of migrants.
37. Loss of market gardens.
Task (5)

The ideas put forward by the subjects in response to task (5) are summarized below. The summary is based on lists compiled independently by the author and the research assistant for their assessments. The task dealt with a new transport system from a proposed underground carpark to the centre of Melbourne. There were forty-three ideas in all and they are listed in the following order:– aerial, transport, transport elevated from the ground, surface transport, and below-surface transport.

Aerial Transport:
1. Aircraft.
2. Helicopters.
3. Hovercraft.
4. Rockets.

Elevated Transport:
5. Monorail.
7. Buses on elevated roadway.
8. Elevated tramway.
9. Cable cars.
10. Minicars on elevated roadway.
11. Chairlift.
12. Tube with pneumatically propelled capsules.

Surface Transport:

15. Trams - development of existing system.
16. Buses - development of existing system.
17. Trams - new design.
18. Buses - new design.
19. Trains.
20. Trolley buses.
21. Ferries on new canal.
22. Minicars - chauffeur driven or self-drive.
23. Minicars - automatically guided.
24. Cable cars.
25. Taxis.
27. Bicycles.
29. Roller Skates and tow rope.
30. Car conveyor.
32. Conveyor belt - people sitting.
33. Pedestrian walkway.

Below-Surface Transport:

34. Underground railway - conventional design.
35. Underground railway - unconventional design.
36. Underground cable cars.
37. Underground buses.
38. Minicars.
39. Taxis.
40. Pneumatic capsules.
41. Underground chairlift.
42. Conveyor belt.
43. Pedestrian walkway.

Task (6)

All the criteria used by the subjects in response to task (6) are summarised below. The summary is based on lists compiled independently by the author and the research assistant for their assessments. Some criteria are applicable to all transport systems, others are specific to one class of transport. General criteria are listed first. The class of transport to which a specific criterion applies is given in brackets after that criterion.

1. Capital cost.
2. Operating cost.
3. Cost of developing new methods.
4. Passenger-carrying capacity.
5. Time for journey.
6. Flexibility in handling peak and off-peak traffic.
7. Capacity for depositing travellers at several places in the city.
10. Ease of maintenance.
11. Cleanliness.
13. Air pollution.
15. Matching of proposal with existing systems.
16. Use of ground at surface level.
17. Capacity for handling travellers with physical disabilities.
18. Potential for attracting tourists.
19. Psychological attraction of new development, the "with-it" image.
20. Capacity for handling travellers' luggage and parcels.
22. Number of skilled people required to operate system.
23. Resistance to damage by vandals.
24. Time to bring transport system into operation.
25. Embarking and disembarking travellers (chairlifts, conveyors, elevated transport).
27. Interruptions and difficulties at existing road intersections in the city (surface transport).
28. Protection of travellers and vehicles from weather (surface and above-surface transport).
29. Ventilation (below-surface transport).
30. Delays due to breakdowns (transport guided on tracks).
31. Turning vehicles round at ends of journey (transport guided on tracks).
33. Crossing Yarra river (below-surface transport).
34. Soil conditions for tunnelling (below-surface transport).
35. Avoidance of existing underground services in tunnelling (below-surface transport).
36. Interference with existing tram and telegraph wires (elevated transport).
37. Provision of special city terminal (above-surface transport).
38. Administration of transport system, working out time-tables (systems for handling people in large batches).
39. Provision of high voltage cables (electrically operated transport).
40. Creation of vacuum (pneumatic capsules).
41. Claustrophobia (people in confined space).
42. Jerk of cable (cable cars).
43. Special skills required by travellers (motorcycles, bicycles).
Task (9)

The main structure of the problem of designing a page-turning device has been shown schematically in Figs. 8.1 and 8.2 in Chapter 8. Set out on the following pages are the design trees representing the response to the task of the group of subjects in the experiment. The responses fall into three major categories according to the source of power adopted.

Category I - Source of power external to patient.
Category II - Patient as the source of power.
Category III - Combination of external source of power and power supplied by patient.

The structure of the design shown in Fig. 8.1 is based on a cycle consisting of six operations.

1. Actuate - start cycle.
2. Separate X from X + 1 (where X = page to be turned).
3. Hold X + 1 flat.
4. Turn X.
5. Hold X flat.
6. Reset for next cycle.

All six operations are relevant for designs in Category I, while Category II designs make use of operations (2) to (5). Only two subjects submitted designs in Category III and both considered operations (1) to (5) but not operation (6).
Task (9) :- Page-Turning Device

Design Trees for Category I -

Source of Power External to Patient
**SOLUTIONS:**

- $a_1^1$: Electronic signal from brain wave
- $a_2^1$: Patient to move part of his body to operate switch or press button
- $a_3^1$: Detector operated by movement of patient's eye
- $a_4^1$: Patient's saliva to complete electric circuit
- $a_5^1$: Acoustic device sensitive to patient's voice
- $a_6^1$: Pneumatic actuator operated by patient's breath
- $a_7^1$: Patient to move part of his body to interrupt electromagnetic beam to photocell, or light attached to patient's head to shine on photo-electric actuator
- $a_8^1$: Automatic timer
- $a_9^1$: Automatic eye which recognizes page numbers

**SUBPROBLEMS:**

1. Accidental pressing of wrong button
2. Foot may be covered by blankets
3. Mouth operation unhygienic
4. Patient's view of his body obscured by book
5. Saliva dries up in exciting parts of book
6. Shielding of acoustic device from noise
7. Long wait at end of chapter
8. Sleepy patient
**PROBLEM**

**Solutions**

**Subproblems**

**Solutions**

**Subproblems**

**Solutions**

---

**EVENT (2): SEPARATE X FROM X+1**

- **Electrostatic**
- **Magnetic**
- **Mechanical**
- **Air pressure**
- **Elasticity of paper**
- **Friction**
- **Adhesion**
- **Gravity**

---

**SOLUTIONS:**

- $d_1^1$: Repulsion between pages of similar charge
- $d_1^2$: Attraction of page to object of opposite charge
- $d_1^3$: Attraction of magnet and magnetic clips or tabs attached to each page
- $d_1^4$: Attraction of magnet and magnetic paint on page corners
- $d_1^5$: Attraction of magnet and magnetic printing ink
- $d_1^6$: Pages preseparated by objects which engage page-turner: metal strips or tabs, strands of cotton
- $d_1^7$: Small pin or hook or wire inserted between pages
- $d_1^8$: Wedge or plate inserted between pages
- $d_1^9$: Mechanical jaw, clamps or tweezers
- $d_1^{10}$: Vacuum or suction pad
- $d_1^{11}$: Overpressure from blower
- $d_1^{12}$: Expansion of membrane previously inserted between pages
- $d_1^{13}$: Rough surface moved over page: rubber, serrated metal
- $d_1^{14}$: Roller moved over page
- $d_1^{15}$: Application to page of bar with glue-tip or damp sponge
- $d_1^{16}$: Flexible tapes with ends adhering to page
- $d_1^{17}$: Book upside down, retaining strips moved away
- $d_1^{18}$: Move retaining strips on edge of page $X$: Sideways, parallel to spine of book
EVENT (2): SEPARATE X FROM X+1

**SUBPROBLEMS:**

1. Preparatory effort required
2. How to select only one page at a time
3. Possible damage to page
4. Operation on humid days
5. Possible electrocution of patient
6. How to release page X
7. Excessive thickness of magnetic tabs
8. Difficult to reverse
9. Excessive thickness of interleaving strips
10. Large amount of auxiliary equipment
11. Large number of membranes scattered about
12. How to renew or apply adhesive

**SOLUTIONS:**

<table>
<thead>
<tr>
<th>Subproblem</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subproblem giving rise to a proposed solution</td>
<td>Release electric field (a1 - 6)</td>
</tr>
<tr>
<td>Subproblem</td>
<td>Release magnetic field (a2 - 6)</td>
</tr>
<tr>
<td>3. Control strength of magnetic field</td>
<td>Stagger magnetic tabs from page to page (a3 - 2)</td>
</tr>
<tr>
<td>4. Stragger magnetic tabs from page to page</td>
<td>Interleave non-magnetic separators (a4 - 2)</td>
</tr>
<tr>
<td>5. Interleave non-magnetic separators</td>
<td>Have magnets on both sides of page (a5 - 2)</td>
</tr>
<tr>
<td>6. Have magnets on both sides of page</td>
<td>Series of tapered pre-separators (a6 - 2)</td>
</tr>
<tr>
<td>7. Series of tapered pre-separators</td>
<td>Adjust depth of insert to take just one page (a7 - 2)</td>
</tr>
<tr>
<td>8. Adjust depth of insert to take just one page</td>
<td>Auxiliary air jet at end of insert (a8 - 2)</td>
</tr>
<tr>
<td>9. Auxiliary air jet at end of insert</td>
<td>Nurse to adjust vacuum (a9 - 2)</td>
</tr>
<tr>
<td>10. Nurse to adjust vacuum</td>
<td>Auxiliary suction pad to unstick pages (a10 - 2)</td>
</tr>
<tr>
<td>11. Auxiliary suction pad to unstick pages</td>
<td>Auxiliary air jet to lift pages initially (a11 - 2)</td>
</tr>
<tr>
<td>12. Auxiliary air jet to lift pages initially</td>
<td>Large number of small suction holes (a12 - 3)</td>
</tr>
<tr>
<td>13. Large number of small suction holes</td>
<td>Release vacuum (a13 - 2)</td>
</tr>
<tr>
<td>14. Release vacuum</td>
<td>Adjustable contact pressure, spring-loaded roller (a14 - 2)</td>
</tr>
<tr>
<td>15. Adjustable contact pressure, spring-loaded roller</td>
<td>Two gripping arms (a15 - 2)</td>
</tr>
<tr>
<td>16. Two gripping arms</td>
<td>Indent pages so that movement of strip releases only one page (a16 - 2, a17 - 2)</td>
</tr>
</tbody>
</table>

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**PROBLEM**

**SOLUTIONS**

**Subproblems**

**Solutions**

**EVENT (3): HOLD X+1 FLAT**

**SOLUTIONS:**

- \( a_1 \) - Retractable clamps, arms (rigid)
- \( a_2 \) - Retractable lines, rubber strips (flexible)
- \( a_3 \) - Indented pages with movable strip - Combines with Event (2)
- \( a_4 \) - Side channels with suction holes - Combines with Event (2)
- \( a_5 \) - Wire or belt with pad sliding horizontally - Combines with Event (4)
- \( a_6 \) - Transparent cover - Combines with Event (5)
- \( a_7 \) - Excess air pressure
- \( a_8 \) - Application of magnetic field

**SUBPROBLEMS:**

1 - Dealing with books of different thicknesses
2 - Timing and actuation of retractable clamps
3 - Obscuration of print by clamps
4 - Lifting of flexible strips

**SOLUTIONS:**

Subproblem giving rise to a proposed solution is in brackets after that solution

1 - Cams in retracting linkage - \( a_1 = 1 \)
2 - Length adjustment in linkage, turnbuckle - \( a_1 = 1 \)
3 - Mechanical trip on page-turner - \( a_2 = 2 \)
4 - Rod with hook - \( a_2 = 4 \)
SOLUTIONS:

$P_1 = a_1$
- Mains A.C.
- Battery
- Compressed spring
- Elasticity of paper
- Book upside down

$P_2 = a_1$
- Mechanical arrangement of levers and links
- Wind cords attached to pages onto drum
- Expanding insert
- Rotating arm, axis of arm parallel to spine of book
- Rotating arms, pads on arms, axis above page
- Horizontal slider with pad rigidly attached
- Horizontal moving belt with pad attached, belt at right angles to spine of book
- Horizontal wire parallel to spine, moving at right angles to spine
- Excess air pressure from blower
- Book upside down
- Elasticity of paper

Combines with Event (2) - $a' a^2 a^3 a^4 a^5 a_6$

(2) - $a_6$

(2) - $a_3$

(2) - $a_1$

(2) - $a_6 a_5 a_6$

(2) - $a_6 a_5 a_6$

(2) - $a_6$

(2) - $a_7$
EVENT (4): TURN X

SUBPROBLEMS:
1 - Page-Turner inoperative when power fails
2 - How to reverse
3 - How to deal with different thicknesses of books
4 - How to deal with different size books
5 - How to turn one page only

SOLUTIONS:
Subproblem giving rise to a proposed solution is in brackets after that solution

1 - Two rotating arms, one forward one reverse (P_2 - a_4 - 2)
2 - Two horizontal sliders, one forward and one reverse (P_3 - a_6 - 2)
3 - Slipping clutch in transmission (P_4 - a_1 - 3)
4 - Spring-loaded arm with spring adjustment (P_2 - a_1 - 3)
5 - Telescopic arm in linkage (P_2 - a_1 - 4)
PROBLEM

Solutions

Subproblem

Solutions

Subproblems

Solutions

EVENT (5): HOLD X FLAT

Mechanical

Magnetic

Pneumatic

SOLUTIONS:

$\alpha_1^1$ - Retractable clamps or arms, rigid
$\alpha_1^2$ - Retractable lines, rubber strips, flexible
$\alpha_3^1$ - Side channels
$\alpha_4^1$ - Wire or belt sliding horizontally
$\alpha_5^1$ - Transparent cover
$\alpha_6^1$ - Excess air pressure
$\alpha_7^1$ - Application of magnetic field

SUBPROBLEMS:

1 - How to deal with books of different thickness
2 - Timing and actuation of retractable clamps
3 - Obscuration of print by clamps
4 - Lifting of flexible strips

SOLUTIONS:

1 - Cams in retracting linkage
   Subproblem giving
   rise to a proposed solution is in brackets
   after that solution
   $\alpha_1^1$- 1

2 - Length adjustment in linkage, turnbuckle
   $\alpha_1^1$- 1

3 - Mechanical trip on page-turner
   $\alpha_1^1$- 2

4 - Rod with hook
   $\alpha_4^1$- 4
SOLUTIONS:  

- \( a_1 \): Rotating arm moves through 360°  
- \( a_2 \): Combines with Event (4) - \( P_2 - a_4 \)  
- \( a_3 \): Guides to return slider or pad to initial position  
- \( a_4 \): Special reciprocating or return linkage  
- \( a_5 \): Spring return  
- \( a_6 \): Tension weights
Task (9) :- Page-Turning Device

Design Trees for Category II -

Patient as Source of Power
SOLUTIONS:

- \( a_1 \) - Attraction of page to object of opposite charge
- \( a_2 \) - Attraction of magnet to magnetic clips or tabs on page
- \( a_3 \) - Pages preseparated by solid objects which engage turner
- \( a_4 \) - Small pin or wire inserted between pages
- \( a_5 \) - Suction
- \( a_6 \) - Blowing
- \( a_7 \) - Rough surface moved over page
- \( a_8 \) - Glue, paste on tip of rod
- \( a_9 \) - Mouth
- \( a_{10} \) - Nose
- \( a_{11} \) - Toes
EVENT (2): SEPARATE $X$ FROM $X+1$

**SUBPROBLEMS:**

1. How to select only one page at a time
2. Possible damage to page
3. Possible electrocution of patient
4. Preparatory effort required
5. Excessive thickness of interleaving strips
6. How to release $X$
7. Dexterity required of patient

**SOLUTION:**

1. Large number of small suction holes \((a_1^4 - 2)\)

Subproblem giving rise to proposed solution is in brackets after solution.
PROBLEM  EVENT (3): HOLD X+1 FLAT

Solution  Mechanical

Subproblem  How?

Solution  Flexible Strips

PROBLEM  EVENT (5): HOLD X FLAT

Solution  Mechanical

Subproblem  How?

Solution  Flexible Strips
PROBLEM

EVENT (4): TURN X

SOLUTIONS:

\begin{align*}
a_1 &= \text{Rod in mouth} \\
a_2 &= \text{Rod attached to head} \\
a_3 &= \text{Mouth or nose, direct} \\
a_4 &= \text{Toes, direct}
\end{align*}

SUBPROBLEMS:

1. Tiring to patient
2. Patient cannot pick up rod he drops
3. Patient with rod in mouth cannot talk
4. Rod may carry germs
5. Dexterity required of patient
6. How to move book from reading position to head and back again
7. Feet may be covered by blanket
8. How to move book from reading position to toes and back again

\begin{align*}
\text{SOLUTIONS:} & \\
\text{Subproblem giving rise to proposed solution is in brackets after that solution} &
\end{align*}

\begin{align*}
\text{Solutions:} & \\
\text{Special support for rod (a_1-1)} & \\
\text{Rod made of hygienic material (a_1-4)} & \\
\text{Rod sterilized periodically by nurse (a_1-4)} & \\
\text{Clips on page to help patient (a_5-5)} & \\
\text{Pedal drive to mobile stand (a_3-6, a_4-8)} & \\
\text{View book at end of bed through special optical system (a_4-8)} &
\end{align*}
Task (9) : - Page-Turning Device

Design Trees for Category III -

Combination of External Source of Power

and Power Supplied by Patient
PROBLEM:
EXECUTION
OF EVENTS IN
OPERATING
CYCLE

1. ACTIVATE EXTERNAL SOURCE
OF POWER

2. SEPARATE X FROM X+1 FLAT

3. HOLD X+1 FLAT

4. TURN X

5. HOLD X FLAT

Solutions

Subproblem

How?

Patient
Physical
Press
Button

Flexible
Strips

Bed
in
Position

Flexible
Strips

Patient
Physical
Press
Button

Gravity

Flexible
Strips

Retractable
Strip

Retractable
Strip

Support
for Rod

Tiring to
Patient

How to
grip X

How?

How?

How?

How?

How?

How?

How?

How?

How?

How?

How?

How to
separate
pages

How to
turn
one page only

Solutions

Subproblems

How?
Task (10)

In this task the subjects were asked to design ways of minimising injuries to the occupants of motor cars in accidents. As discussed in Chapter 8 the problem can be considered to consist of eight major subproblems, denoted $P_1$ to $P_8$ as follows.

$P_1$ - Prevention of injury due to deformation of passenger compartment leading to high contact pressures on the human body.

$P_2$ - Prevention of injury due to contact of unrestrained occupants with interior of car.

$P_3$ - Passenger support and restraint.

$P_4$ - Prevention of injury due to ejection of occupants from car.

$P_5$ - Prevention of injury due to fire.

$P_6$ - Prevention of injury due to asphyxiation by exhaust gases from engine.

$P_7$ - Prevention of injury due to scalding by radiator water.

$P_8$ - Prevention of injury due to burns by battery acid.

The design trees representing the responses of the group of subjects in the experiment are set out on the following pages in these eight categories. In the case of $P_1$, a further sub-division is made based on the type of accident leading to deformation of the car structure, namely

(1) head-on collision of one vehicle with another vehicle or stationary object;
(2) oblique collision of one vehicle with another vehicle or stationary object;
(3) head-to-tail collision of two vehicles;
(4) side-on collision of one vehicle with another;
(5) roll-over of vehicle;
(6) car running under tray of truck.
**PROBLEM**

**Subproblems**

**Solutions**

**Subproblems**

**Solutions**

**Subproblems**

**Solutions**

**SUBPROBLEMS:**

- $P_1^1$ - Prevention of injury due to deformation of car structure in head-on collision
- $P_1^2$ - Prevention of injury due to deformation of car structure in oblique collision
- $P_1^3$ - Prevention of injury due to deformation of car structure in head-to-tail collision
- $P_1^4$ - Prevention of injury due to deformation of car structure in side-on collision
- $P_1^5$ - Prevention of injury due to deformation of car structure in roll-over
- $P_1^6$ - Prevention of injury due to deformation of car structure - car under tray of truck

**SOLUTIONS:**

- $a_1^1$ - Engine slides under passenger compartment
- $a_2^1$ - Energy-absorbing steering wheel and column
- $a_3^1$ - Strong front section of passenger compartment
- $a_4^1$ - Energy-absorbing front section of car body
- $a_5^1$ - As for head-on collision
- $a_2^2$ - Swinging bumpers
- $a_3^2$ - Rounded front of car, rounded bumpers
- $a_4^2$ - Strong rear section of passenger compartment
- $a_5^2$ - Energy-absorbing rear section of car
- $a_4^3$ - Strong side of passenger compartment
SOLUTIONS:  
(Continued)  
$a_4^2$ - Energy-absorbing side structure of car  
$a_3^4$ - Passengers seated above bumpers  
$a_7^5$ - Strong roof of car  
$a_6^6$ - Strong supports for roof of car  

SUBPROBLEMS:  
$p_1^{1,21}$ - Steering column: reduction of contact force between driver and steering wheel  
$p_1^{1,22}$ - Steering wheel: reduction of contact pressure on driver's chest  
$p_1^{1,3}$ - Instability of car  

SOLUTIONS:  
$a_1^1$ - Engine supported on shear bolts  
$a_2^1$ - Engine and mounting dropped to ground  
$a_3^1$ - Strong front wall of passenger compartment  
$a_4^1$ - Steering column to have small deflection  
$a_5^1$ - Energy-absorbing steering column  
$a_6^2$ - Steering wheel with padded hub  
$a_7^2$ - Rim and spokes of steering wheel made from flexible material  
$a_8^2$ - Special bumpers  
$a_9^2$ - Deformation of existing body structure  
$a_{10}^2$ - Energy-absorbing elements added to existing structure  
$a_{11}^2$ - Linkage  
$a_{12}^1$ - Special bumpers as $a_{14}^2$  
$a_{13}^1$ - Longeron  
$a_{14}^2$ - Honeycomb  
$a_{15}^3$ - Catching device to lock cars on impact  
$a_{16}^3$ - Car frame with roll bars  

SUBPROBLEMS:  
1 - How? Physical embodiment of idea  
2 - Material properties required  
3 - Padding interferes with driver's view of instrument panel  
4 - Height of bumpers on some cars different to height of longerons on others  

SOLUTIONS:  
1 - Steering box in remote position  
2 - Pivoted steering column  
3 - Pneumatic, using compressed air  
4 - Hydraulic, using kinetic energy of water jets  
5 - Elastic, using spring to store energy  
6 - Standard height of bumpers
PROBLEM

Subproblems

Solutions

Subproblems

SUBPROBLEMS:
P\textsubscript{2\textprime} - Prevention of injury due to contact with inside of car, excluding glass surfaces
P\textsubscript{2\textquoteright\textprime} - Prevention of injury due to contact with glass surfaces
P\textsubscript{2\textquoteright\textquoteright\textprime} - Prevention of injury due to contact with windscreen
P\textsubscript{2\textquoteright\textquoteright\textquoteright\textprime} - Prevention of injury due to contact with windows

SOLUTIONS:
\begin{align*}
\alpha\textsuperscript{1} & \{ \alpha\textsuperscript{1\prime} & \}
\alpha\textsuperscript{2} & \{ \alpha\textsuperscript{2\prime} & \}
\end{align*}
P\textsubscript{2} and P\textsubscript{2\textprime} have a common solution - protective clothing for occupants of car

\begin{align*}
\alpha\textsuperscript{1\prime} & - \text{Special glass} \\
\alpha\textsuperscript{2\prime} & - \text{Pop-out windscreen} \\
\alpha\textsuperscript{1\prime\prime} & - \text{Special glass} \\
\alpha\textsuperscript{2\prime\prime} & - \text{Pop-out windows} \\
\end{align*}

SUBPROBLEMS:

1 - Discomfort of occupants
2 - Laziness of occupants
3 - Ineffectiveness at high contact pressures
4 - Technical Feasibility
5 - Ejection of occupants
SUBPROBLEMS:

Prevention of injury due to contact of occupants with

- $P_2^1$: Dashboard
- $P_2^2$: Parcel tray, glove box
- $P_2^3$: Control knobs, switches, ashtray on dashboard
- $P_2^4$: Radio
- $P_2^5$: Seat belt mountings, coat hooks, front window locks
- $P_2^6$: Door linings, door pillars, roof, rear of front seat
- $P_2^7$: Door handles, window winders, arm rests
- $P_2^8$: Gear lever or selector, hand brake
- $P_2^9$: Sun visors
- $P_2^{10}$: Rear vision mirror

SOLUTIONS:

- $d_2^1$: Recess in front of passenger
- $d_2^2$: Collapsible, energy-absorbing construction
- $d_2^3$: Rounded corners, no sharp edges
- $d_2^4$: Padding
- $d_2^5$: Omit or relocate
- $d_2^6$: Collapsible, energy-absorbing construction
- $d_2^7$: Rounded corners
- $d_2^8$: Padding
SOLUTIONS:
(Continued)

a\textsuperscript{13} - Omit or relocate.
a\textsuperscript{13} - Padded recess.
a\textsuperscript{13} - Rounded edges.
a\textsuperscript{13} - Construction in flexible material which bends on impact.
a\textsuperscript{13} - Snap off on impact.
a\textsuperscript{13} - Rounded corners, no sharp edges.
a\textsuperscript{13} - Padded recess.
a\textsuperscript{13} - Rounded corners, no sharp edges.
a\textsuperscript{13} - Construction in flexible material.
a\textsuperscript{13} - Rounded corners, no sharp edges.
a\textsuperscript{13} - Padding.
a\textsuperscript{13} - Redesign using padded recesses.
a\textsuperscript{13} - Rounded edges.
a\textsuperscript{13} - Construction in flexible material.
a\textsuperscript{13} - Snap off on impact.
a\textsuperscript{13} - Snap off on impact leaving no jagged edges.
a\textsuperscript{13} - Locate in non-critical area.
a\textsuperscript{13} - Rounded corners, no sharp edges.
a\textsuperscript{13} - Padding.
a\textsuperscript{13} - Rounded edges.
a\textsuperscript{13} - Padding around around corners.
a\textsuperscript{13} - Snap off on impact.
a\textsuperscript{13} - Mounting constructed of flexible material.
a\textsuperscript{13} - Special glass.

SUBPROBLEMS:

1 - How to place sufficient energy-absorbing material in limited space.
2 - Properties of energy-absorbing material, possible deterioration.
SOLUTIONS:

- $a_{11}$ - Padded cocoon
- $a_{21}$ - Bucket seats
- $a_{12}$ - Strong anchorage
- $a_{13}$ - Head rests
- $a_{14}$ - Tilting seats
- $a_{22}$ - Linkage with actuator
- $a_{15}$ - Legal sanction
- $a_{23}$ - Belt fastener connected to ignition
- $a_{24}$ - Harness
- $a_{25}$ - Lap belt
- $a_{34}$ - Lap and sash belt
- $a_{16}$ - Strong anchorage
- $a_{26}$ - Buckle on hip
- $a_{35}$ - Inertia reel to limit contact pressure on body
- $a_{61}$ - TV aids

SUBPROBLEMS:

1. Wide range of human dimensions to be accommodated
2. Restrictions on movements of occupants
3. Driver's vision restricted
4. Wide range of human dimensions
5. Accessibility of controls
6. Ease of escaping from car after crash
SOLUTIONS:  

- $d_1^{1.1}$ - Fusible link wiring
- $d_2^{1.1}$ - Device to disconnect battery
- $d_1^{2.1}$ - Strong petrol tank
- $d_2^{2.1}$ - Petrol tank located in remote position
- $d_3^{2.1}$ - Petrol tank in or of fireproof material
- $d_4^{2.1}$ - Petrol tank in or of absorbent material
- $d_5^{2.1}$ - Strong inlet to petrol tank
- $d_6^{1.1}$ - Inlet designed not to spill petrol when car over turns
- $d_5^{1.2.2}$ - Strong outlet from petrol tank
- $d_6^{1.2.2}$ - Carburettor designed not to leak when car over turns
- $d_3^3$ - Fire wall on passenger compartment
- $d_3^4$ - Fire extinguisher

SOLUTIONS TO SUBPROBLEMS:  

1 - Construction in plastic foam material
2 - Bracket on inlet pipe designed to break before pipe
3 - Flexible section in line to engine
**PROBLEM**

**Solutions**

**Subproblems**

**Solutions**

**Subproblems**

**SOLUTIONS:**

- $a_1$ - Solutions to subproblem $P_3$ are applicable, see p.362
- $a_2$ - Burst-proof locks
- $a_3$ - Sliding doors
- $a_4$ - Strong door hinges at front of car

**SUBPROBLEMS:**

1. Escape of occupants after car crash
2. Escape of occupants before impending crash
3. Ability to withstand different types of crash

**PROBLEM**

**Solutions**

**Subproblems**

**Solutions**

**Subproblems**

**SOLUTIONS:**

- $P_6 - a_1$ Absorb noxious gases from engine exhaust
- $P_6 - a_2$ Isolate passenger compartment from noxious gases
- $P_7 - a_1$ Strong radiator hose connections
- $P_8 - a_1$ Strong battery mounting
Creative design skills of engineering students


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