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PROBLEM SOLVING IN ARCHITECTURAL DESIGN

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PROBLEM SOLVING IN ARCHITECTURAL DESIGN

Men have become like gods. Isn't it about time that we understood our divinity? Science offers us total mastery over our environment and over our destiny, yet instead of rejoicing we feel deeply afraid. Why should this be? How might these fears be resolved?

Edmund Leach
(1967 Reith Lectures)

SUMMARY

This thesis is presented in two parts. The first part is an attempt to set out a framework of factors influencing the problem solving stage of the architectural design process. The discussion covers the nature of architectural problems and some of the main ways in which they differ from other types of design problems. The structure of constraints that both the problem and the architect impose upon solutions are seen as of great importance in defining the type of design problem solving situation. The problem solver, or architect, is then studied. The literature of the psychology of thinking is surveyed for relevant work. All of the traditional schools of psychology are found wanting in terms of providing a comprehensive theory of thinking. Various types of thinking are examined, particularly structural and productive thought, for their relevance to design problem solving. Finally some reported common traits of architects are briefly reviewed.

The second section is a report of two main experiments which model some aspects of architectural design problem solving. The first experiment examines the way in which architects come to understand the structure of their problems. The performances of first and final year architectural students are compared with those of postgraduate science students and sixth form pupils. On the whole these groups show significantly different results and also different cognitive strategies. The second experiment poses design problems which involve both subjective and objective criteria, and examines the way in which

final year architectural students are able to relate the different types of constraint produced.

In the final section the significance of all the results is suggested. Some educational and methodological implications are discussed and some further experiments and investigations are proposed.

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1. ARCHITECTURAL DESIGN

Since all architecture rests on false principles, the architecture of antiquity was an error. Truth alone is beautiful. In architecture truth is product of the calculations made to satisfy known needs with known means.

Tony Garnier (1938)

I seek through comprehensive anticipatory design science and its reduction to physical practices to reform the environment instead of trying to reform men.

Buckminster Fuller (1967)

1. ARCHITECTURAL DESIGN

1.1 Introduction

1.2 Intuitive design

1.3 Design method

1.4 Systems design

1.5 The architect's design education

1.1 Introduction

Constructing and maintaining man's built environment is now a vast and complex task. Current estimates of population growth, and the drift towards urban areas indicate that buildings and cities will have to be capable of rapid expansion and modification to keep pace with the demands of their inhabitants. It has been predicted that we will build as much again before the year 2,000 as has already been built. (The United States will require at least 350 new cities of 100,000 population each - Von Eckardt, 1965.)

The central figure in this rapidly expanding design field is still the architect, although he is surrounded by more and more specialist designers and consultants. Macro-environmental design decisions are now made by politicians, regional and urban planners; while decisions at the micro end of the scale are made by interior and industrial designers and ergonomists. In addition the architect is advised by a growing range of technological specialists, and he is increasingly influenced by human factors specialists in such areas as psychology, sociology and ethology.

What now is the role of the architect? What decisions does he, and should he, be making, and in what order? Could he be doing his job better and educating the next generation more efficiently? These questions and other similar ones are currently uppermost in the minds of the British architectural profession as it undergoes

a painful, critical self examination.

While seeking to preserve the atmosphere of artistic licence which allowed the great architects of the past to produce their many masterpieces, architects of today are confronted with the complexity and increased responsibility of shaping the lives of their fellow men. Progressive writers have for some years, been advocating that the once sacrosanct workings of a designer's mind should be probed.

"The act of making an architectural decision can perhaps be stripped of its mystique, while some far more viable set of operations is seen to add up to something - not a style, not even a discipline, but some indefinable aggregate of operations which have been intelligent and appropriate and have given a situation its fourth dimension." Peter Cook (1967)

It is towards this goal of understanding more accurately what an architect does when he designs that this work is directed. The architectural design process will be seen as a series of cognitive tasks open to examination by psychological experimentation and observation, the results of which will be reported for only one stage of the process. The implications of these findings for the on-going systematisation of design and for the teaching of design will be explored.

Before getting involved in the details of the architect's task it is necessary to see more clearly how his role has developed, and how and why, it is changing now, and also to see how architects

have been, and are being, educated. The rest of this section will deal briefly with these topics.

1.2 Intuitive Design

Until quite recently architects believed almost exclusively in the Intuitive Design method. It was widely held that design ability is innate and unteachable. Furthermore it was said that introspection about his methods would render a student self-conscious and unable to design freely. A more extreme variant of this attitude held that the design process is mystical and lives completely outside the scope of scientific enquiry. Wehrli (1968) includes a fairly full discussion of the Beaux Art attitude towards intuitive design and illustrates the impossibility of making any scientific progress with design research inside this school of thought. He points out that thinking and intuiting are both important for the architect in his dual role of half scientist, half artist.

The manipulation of logic involved in rationalism has never been a popular mode of thought with architects even though it can adequately solve many of their problems. Similarly, empirical methods have hitherto been neglected, although the value of experimental findings and observation is now increasingly recognised. Students are now actively encouraged to seek for and use empirical data in the solution of their college problems. With the growth of the fund of knowledge from the human sciences now applicable to architectural design it is not surprising that some architects wish to become exclusively empirical in their methods. These are the design methodologists who seek an overall decision framework

supported by a library of design techniques to strengthen the designer's own intuitive ability. Although there are now these two opposing factors in the design world, most discussion is not well informed, and the majority of designers would seem not to have thought seriously about their own philosophy of design. For most architects, design is still what architects do and what students must learn.

This concentration on the intuitive method of design has contributed to the current confusion on the difference between designers and artists. Some 'artist-architects' have exploited the Beaux Arts movement to justify their own personal expressionism, often indulged in at the cost of more serious necessities. Extremists of this complexion will typically retire behind words such as 'aesthetics' which they refuse to define carefully enough for meaningful discussion. A reactionary swing has given rise to a group solidly resisting the use of these undefined words, and who consequently do not admit the existence of the concepts for which they stand. Only recently have such movements as architectural psychology given rise to attempts to understand subjective notions in scientific terms.

The architect in the twentieth century must be seen primarily as a designer rather than an artist. That is to say his task is to identify and solve real world problems. The artist by contrast is free to express his own ideas about problems, often of his own making, without the need to solve them. He is also free to shift

his aims as work proceeds and feedback is obtained from its physical reality. Frequently the problems that face the architect are so serious, both economically and environmentally that he must accurately set and attain his goals at any necessary cost to the expression of his personal emotions. This absolute necessity to solve problems in a limited time even in the absence of sufficient data distinguishes the architect from both scientists and artists.

The designer then must first solve the problems set for him, although obviously the sensitive architect would wish to explore these problems in order to discover the regions in which he has the freedom to exercise his own 'artistic' judgement.

1.3 Design Method

Throughout this work the phrase 'design method' will refer to the overall decision framework and method of attack used by a designer. This framework may allow or suggest the use of particular design techniques throughout its various stages. 'Techniques' are prepared packages for use in specified situations. They may be directed towards data collection or analysis, problem description or solution, and simulation or evaluation. The methodology may be governed by a theory of design or general design philosophy.

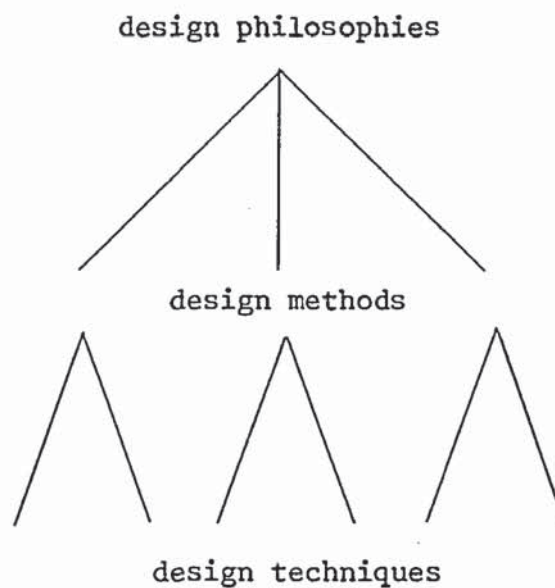


diagram 1.3.1

Thus it can be seen that the Beaux Arts design philosophy mainly used intuitive design method and relied almost entirely upon visual graphic techniques at all stages.

In the last ten years there has been a movement towards the systematisation of design method. A number of conferences have been held and many papers written. Some meetings attracted designers of differing background as at the Conference on Design Methods reported by Jones and Thornley (1963), which was really a conference on design techniques. The papers are almost exclusively devoted to design tools developed for use in limited situations. Several different types of technique are represented and some, particularly Alexander's, have become classics. A similarly interdisciplinary symposium on design method was held at the University of Aston in Birmingham in 1965. In its time this was a very comprehensive conference and the edited papers (Gregory, 1966) are still worthy of careful reading. Design method was clearly seen in relation to human nature, design techniques and the management processes. In addition a few papers looked at some elements of the design process in more individual detail.

The following year architectural educationalists gathered at the Hochschule fur Gestaltung at Ulm in Germany for a conference-course on the teaching of design and design method in architecture. This meeting largely discussed existing school courses and programmes and was perceived by architects as an important communication channel rather than breaking new ground. The 1967 Conference on Design Methods in Architecture at Portsmouth concentrated mainly on design techniques most of which had been strongly influenced by the work of Alexander reported in the 1963

conference. However, in most of the papers given by architects there were discrepancies between their techniques and overall methodologies. Perhaps only Bruce Archer, not an architect, was able to demonstrate techniques sensibly related in a consistent methodology.

A more complete and developed methodology was reported by Singleton (1967) at the conference on 'The Human Operator in Complex Systems', again at the University of Aston in Birmingham. This methodology allows for the design of hardware and for the selection and training of its human operators, and stresses the importance of carefully designing man/machine interfaces. Although not originally intended for architects, it is easy to see how this sort of functional, more abstract, and human oriented approach could lead to an effective overall decision framework for the environmental design team.

Nearly all of these design method conferences have been devoted to the search for idealistic, almost Utopian, design methods. The contributors have concentrated on how they think we should design rather than how we do design. Few, if any, of the design tools developed have lived up to the expectations of our early enthusiasm. Often a loosely connected group of techniques has been wrongly held up as a model method which will infallibly produce better results quicker. To some extent disillusionment has now set in, and a reactionary swing away from systematic method is noticeable amongst architectural students.

1.4 Systems Design

Along with the increase in urbanisation referred to in section 1.1 comes the growing interdependence of people and organisations. As a result the stand alone, or isolated building is no longer appropriate to our needs. Instead, each new edifice has to be related to the total urban environment, as well as being internally ordered. Indeed some designers have proposed that future cities may be built as one vast structure with throw-away units plugged into the main service systems (Peter Cook, 1967).

Not only is the concept of the stand alone building now outdated but so is that of the stand alone architect. The politician, the regional and urban planner, the transport and communications engineer, all interact with the architect in designing the complex of buildings that we call a city. At the same time the design service offered to his client by the architect is growing more comprehensive, and he finds it necessary to call in many specialist consultants such as interior, furniture, and graphic designers. Also the development of building technology has progressed so far beyond the architect's range of comprehension that he frequently has to consult technical advisors such as structural, heating, ventilating and soil engineers. Other environmental specialists now exist in areas such as acoustics to help designers of particular building types.

The architect now often calls in outside help with work which

previously was very much his own. The research and data analysis stages of large projects are frequently carried out by firms of consultants in the United States, while in this country large architectural practices may employ computer programmers and systems analysts. At the other end of the job the presentation of design decisions to the client may be partly carried out by specialists such as modelmakers and graphic and perspective artists.

All of this points to the increasing need for effective and efficient communications systems between all the members of the environmental design team. The design work has to be divided up between architects and others, and data and decisions have to be passed from one to another. This in turn accentuates the need for a systematic framework to the design process, so that decisions are made in a meaningful sequence, and all workers are continuously sufficiently informed.

This interdisciplinary situation, along with the technological explosion, has given rise to a 'system' approach to environmental design. The central tenet of this new philosophy is, that buildings are only the means to an end. The architect is seen as part of a team dedicated to designing a human system, and his particular contribution is the building which contains and shapes the system. Moreover, the architect is inevitably getting more involved at the systems level rather than at the technological level.

Boguslaw (1965) calls these environmental systems designers the new Utopians when he notes that although they plan the whole urban environment as did the creators of Utopia, they see it as a dynamic system rather than a static ideal. The same author summarises the basic notions of systems theory simply and in a way that is easily related to environmental design.

- (a) Connective notion: a system is made up of elements which are connected in some way.
- (b) Control notion: systems may be classified as either open-loop or closed-loop. In the closed-loop system some or all of the outputs of the system are fed back and used for self regulating control.
- (c) Interdisciplinary notion: by studying the function of a system, experts in many different fields can find a common language.
- (d) Picture notion:
- (i) each element is seen as part of a complete whole, and it cannot be varied independently of the rest of the system.
 - (ii) elements are members of systems which are in turn subsystems of

larger systems, etc.

(e) Organism notion: systems are like living bodies in that they can grow, adapt and be modified.

(f) Purpose: systems can be non-goal or goal oriented. Solar systems are examples of the former and urban transport systems of the latter.

This simple and fundamental set of ideas seems innocuous enough but when compared to the old renaissance school of thought, they are as different as is the theory of relativity to Newtonian physics, and the environmental design world is still undergoing the upheaval that this implies.

The present day designer is freed from most of the technological constraints which formed the basis of the architectural styles of history. In the past, the designer of large spaces was heavily restricted by the available structural technology. Now cathedral or opera house architects can construct almost any space that they care to design! However, this newly found freedom has temporarily confounded many architects, leaving them without any clearly defined style. This was anticipated by the 'functionalist' school of the 1920's with their slogan "form follows function". But the function which the form followed was usually either

structural or technological rather than human, and with the contemporary scorn for ornamentation, architecture often became distinctly inhuman.

Handler (1970) notes that 'functionalism' was an extremely varied beast.

"To some The Functional was equated with The Utilitarian, to some with Constructivism, to some with The Expressive; to others it was identified with The Geometric, to still others with The Organic or The Efficacious."

Perhaps the essence of functionalism was not a style but rather a new way of looking at architectural problems. It was thinking and feeling about buildings in terms of the way they work. "What we have, in effect, is performance as the touchstone in designing and evaluating buildings"(Handler, 1970). The functionalists were, however, still groping towards an understanding of total building performance and it is perhaps not surprising that they concentrated their effort in limited areas.

The systems approach to architecture attempts to encompass all the various ways in which a building is said to perform. Not just as a piece of engineering, a large scale sculpture, a collection of components, or a water-proof shelter, but also as an integrated part of the urban whole and most of all as an environment sympathetic to human activities.

1.5 The Architect's Design Education

Our social systems are to some extent influenced by the architecture which contains them, and in turn architecture is formed by designers who have been shaped by their education. Although this chain appears to be a long one, it is easy to see the parallels between education and the physical results throughout the history of architecture, and so the study of architectural education can be seen to be relevant to this work.

Architectural education has always been very practical in its outlook, concentrating more on the product of design rather than the process. In this country the practising architect must be a member of a professional institute which governs very closely what he may or may not do. The educational system is largely dictated by the profession and is geared to satisfying the requirements of entry to the profession. A student must show his ability not only at design but also in all the building technologies, in legal and management responsibilities, and at all the techniques of his trades such as drawing and surveying.

Architectural education is only now beginning to emerge from the grip of the Beaux Arts school, which first opened in Paris in 1807. Under this system students were issued with schemes or projects which they took back to their studios to work on, and only seriously contacted their tutors when they had completed the final drawings, which were then criticised by juries. The schemes increased in complexity as the student satisfied his tutors. He was expected to start on the

'analytique' which was usually a small section of a building such as a porch or a lobby, and from this he graduated to small houses and on to multiple function complexes such as college buildings or hotels. In addition from time to time he had to produce measured drawings to develop his drafting and surveying techniques, and 'esquisses' or sketch designs which had to be produced rapidly. In principle the student was expected to learn by experience and practice. He was not taught or shown but rather criticised after he had tried. Students were expected to, and probably did, learn more from their fellows than from their tutors.

Primitive as this training obviously is, it has for a long time been the means of educating architectural designers. Only in the last five years has the measured drawing left the scene, while the sketch design and graded sequence of schemes are still the vehicles of most design education. Gradually the Beaux Arts doctrine became diluted with the introduction of more technologies and environmental sciences into architectural courses. The result is the formidably wide range of subjects in which the student now presents himself for examination. In 1964 the RIBA issued "Diversification", a report to the Board of Architectural Education recommending student specialisation in schools of architecture. The specialisation envisaged was in terms of product rather than problem type as the following passage illustrates:-

"Despite the obvious importance of the study of human and social sciences in architecture today, the working group was doubtful about including the subject in their list of separate major specialisations." (and did not do so!)

More recently (1969) the RIBA Board of Education issued a paper for discussion entitled, 'Extending the meaning of the word architect', in which the difference between problems and solutions is highlighted.

"In practical terms, this means that the schools (of architecture) must produce, and the RIBA must welcome those whose excellence is towards 'problem understanding' as well as those whose excellence is towards the design of solutions. These two types are not divided by a sharp line, but have tendencies towards either end of a spectrum. Both have a great deal in common, and both to some extent can do the other job."

This is a recognition, albeit a cautious one, that architectural design might be composed of more than one type of task, and consequently that different types of ability might be required at the successive stages irrespective of the type of product reached. It is towards constructively developing this same argument that this work is dedicated.

2. THE DIMENSIONS OF THE DESIGN SITUATION

Design is a continuous problem solving process.

Herbert (1968)

2. THE DIMENSIONS OF THE DESIGN SITUATION

2.1 Introduction

2.2 The design process

2.3 The problem solving stages of design

2.4 The dimensions of the design situation

2.1 Introduction

Design has become one of those words which have such a wide range of applicability that two situations which they describe may appear to share almost nothing in common. Why should an engineer be said to design a concrete beam, while a theatre designer is also said to design a set? Surely very different activities? The former process appears precise, predetermined and mathematical, while the latter seems nebulous, spontaneous and creative. What makes this particular study so difficult is that both these kinds of activity can be identified in architectural design, although it will be argued later that the central task lies somewhere between the two extremes. We lack a comprehensive taxonomy of design situations, other than that provided by solution types, which hardly helps in the description of process. Such a taxonomy could prove invaluable in promoting the smooth functioning of the increasingly familiar interdisciplinary teams designing our urban structures.

This section is an attempt to establish the major variables of the situation which exists when a designer is said to have designed. This is of course necessary before research can be carried out into design problem solving, otherwise there is a real danger that the results of experiments may be clouded by any variation of the conditions along unrecognised dimensions.

2.2 The Design Process

As has been previously pointed out (Lawson, 1970) more attention has been directed towards producing idealistic models of how we might design rather than finding out how we do actually design or what distinguishes good designers from bad ones. The following commonly observed points must all be considered when attempting to describe the human design activity.

1. One designer can be regularly better than another.
2. Some designers get better with experience and education.
3. Some designers seem naturally good.
4. An individual designer can go through good and bad phases.

This would suggest that there are both innate hereditary factors and also educational developmental factors contributing to architectural design ability. Investigations of these factors and their interaction should lead to information valuable in the selection and training of future generations of architects. This investigation would seem most easily begun with an examination of the tasks that an architect must complete between being briefed about a problem and handing over to his client the final working solution.

Preparation

Analysis

Synthesis

Evaluation

Communication

The names of these basic tasks have been in our vocabulary for so long that they are now seldom questioned as representing real activities. What is still very much under debate is the precise sequence and amount of overlap that occurs in practice. Since most architects do not work in a self-analytical mode it is difficult to answer these questions from practice or controlled observations and experimentation becomes necessary.

Observation has led some designers to produce simple models of the design process, while others have considered the process at a more philosophical level. Asimow (1962) declared that "Engineering design is a purposeful activity directed towards the goal of fulfilling human needs". He laid down the principles of design as he saw it and carefully defined all his terms. Bruce Archer (1965) and his team have developed, and worked to, a complete decision framework for the design process held together by a critical path network. Several limited projects such as the well known one on the hospital bed have been completed and reported upon. However, no data as to the nature of the designer's performance is as yet available and Archer's model can only be tested by the quality of his products. Eastman (1968) in a limited experiment observed graduate students designing a residential bathroom, but the experimental design does not enable any generalisation from the results.

Rosenstein, Rathbone and Schneerer (1964) have proposed the following anatomy of the design process:

Identification of the needs

Information collecting and organisation

Identification, modelling and statement of system variables

Criteria development for optimum design

Synthesis

Test evaluation and prediction of performance

Decision steps

Optimisation

Iteration

Communication, Implementation, Presentation

Wehrli (1968) formulated what he called a behavioural model of the design process which he investigated in a series of reported experiments.

Stage I : Orient

- A. Undertake problem to solve
- B. Organise resources to solve problem

Stage II : Programme

- A. Collect data
- B. State the problem
- C. Set abstract criteria
- D. Set concrete criteria

Stage III : Analyse

- A. Reduce to simple elements
- B. Classify
- C. Standardise

Stage IV : Hypothesise

Get a concept or concepts

Stage V : Approach or Strategy

- A. Trial and error
- B. Linear search
- C. Rough to precise
- D. Comparative schemes
- E. Progressively add detail

Stage VI : Synthesise

Articulate, or group, physical elements

Stage VII : Evaluate predictively

- A. Evaluate solution against abstract criteria
- B. Evaluate solution against concrete criteria
- C. Project self into scheme
- D. Project drawings, models, etc. into full scale and topological connectiveness, and imagine functions and behaviours

Other writers have concentrated on the iterative nature of most designers' behaviour. Herbert (1968) hypothesised a hierarchical looping model for both the analysis and synthesis activities. The designer works down a decision hierarchy working from the general to the particular, analysing his problem and breaking it down into ever smaller units, then synthesising solutions and assembling these

into larger more general purpose solutions.

Lawson (1968) pointed out that design models must take account of the apparent reversal of procedure as the designer moves from solving primary problems, (What function is required?) to secondary problems (How is it to function?). That is, in the case of most architectural schemes, moving from questions of human activities, and their system of organisation to questions of building technology. Considering only primary problems, Lawson (1968) suggested that the design process can be seen as one of breaking the problem down into the smallest analyseable (by the designer) units, 'isolates', grouping these into meaningful 'sets' and establishing the 'relations' between these sets.

Thus, to return to Herbert's (1968) hierarchy, the process can be seen as two consecutive tasks of working down an analysis hierarchy and then up a synthesis hierarchy.

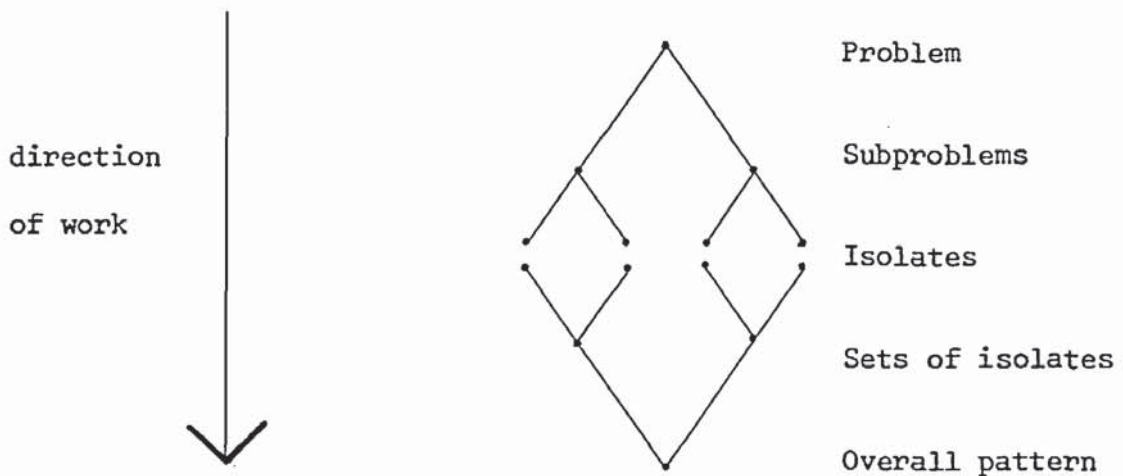


diagram 2.2.1

Secondary problems seem to cause the designer to work back towards the micro end of the scheme again as he 'details' his building, according to the performance specifications laid down by the systems design decisions. This model is closely analogous to that put forward by Miller, Galanter and Pribram (1960) who were considering cognitive performance in a more general context. (see section 4.2.3)

Markus (1969) has listed four basic sources of information available to a designer faced with a complex problem.

- A. His own experience
- B. Others experience
- C. Existing research work
- D. New research work

It is, perhaps, the inevitable mixing of these four strategies that contributes towards the appearance of random behaviour that the designer often portrays. At the one extreme his own experience may be so thorough that his performance seems intuitive, while at the other his organisation of the search for data is much more self conscious. Thus he may appear to almost skip over some of the activities or stages hypothesised by design models.

2.3 The Problem Solving Stages of Design

The range of different tasks that make up the design process have been discussed briefly in the previous section where it was noted that the exact sequence of these tasks is still open for debate. However, we can fix some parts of the sequence quite readily. Data must be collected before it can be analysed and resources must be organised before data is collected. The first three of Wehrli's stages are then fixed in order.

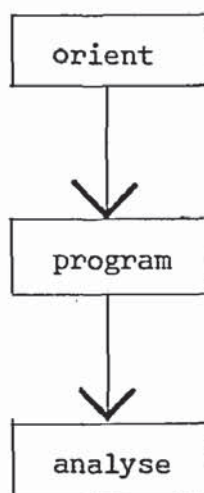


diagram 2.3.1

The next stage (IV) according to Wehrli's model is "Hypothesise" where the designer gets ideas as to how to structure his solution. In stage V he then selects his problem solving strategies and goes on to "Synthesise" in stage VI. Here we cannot regard the sequence of the model as reliable, as most designers will admit that these three stages all influence each other and get jumbled together.

Visual concepts can get changed, and strategies shift as the problem solving activity proceeds. In addition new ways of analysing the data may be suggested.

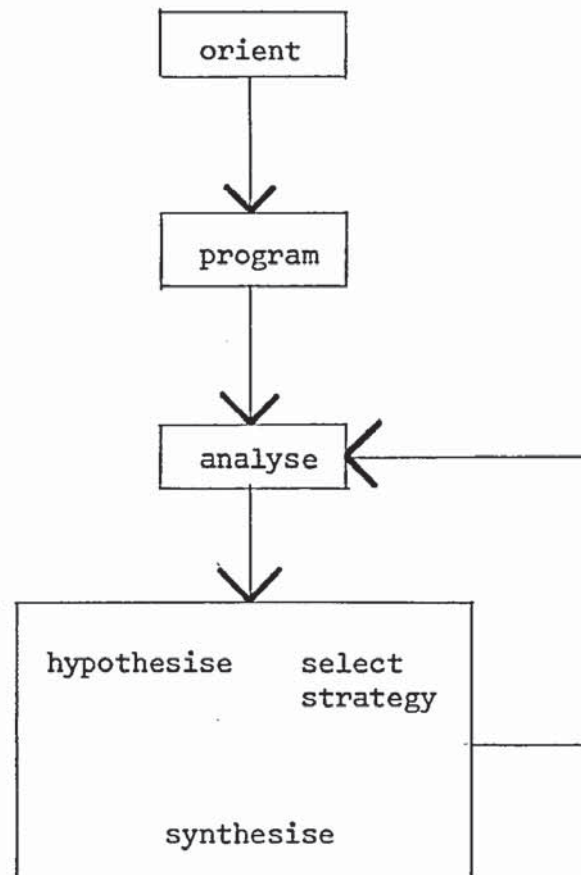


diagram 2.3.2

Once out of this central problem solving stage the sequence becomes simple again, for solutions cannot be 'evaluated' until they have been synthesised. But it is important to allow our designer the option of generating new solutions after his evaluation. Finally, we can add the Rosenstein et al. (1964) 'Communication' and 'Implementation' stages.

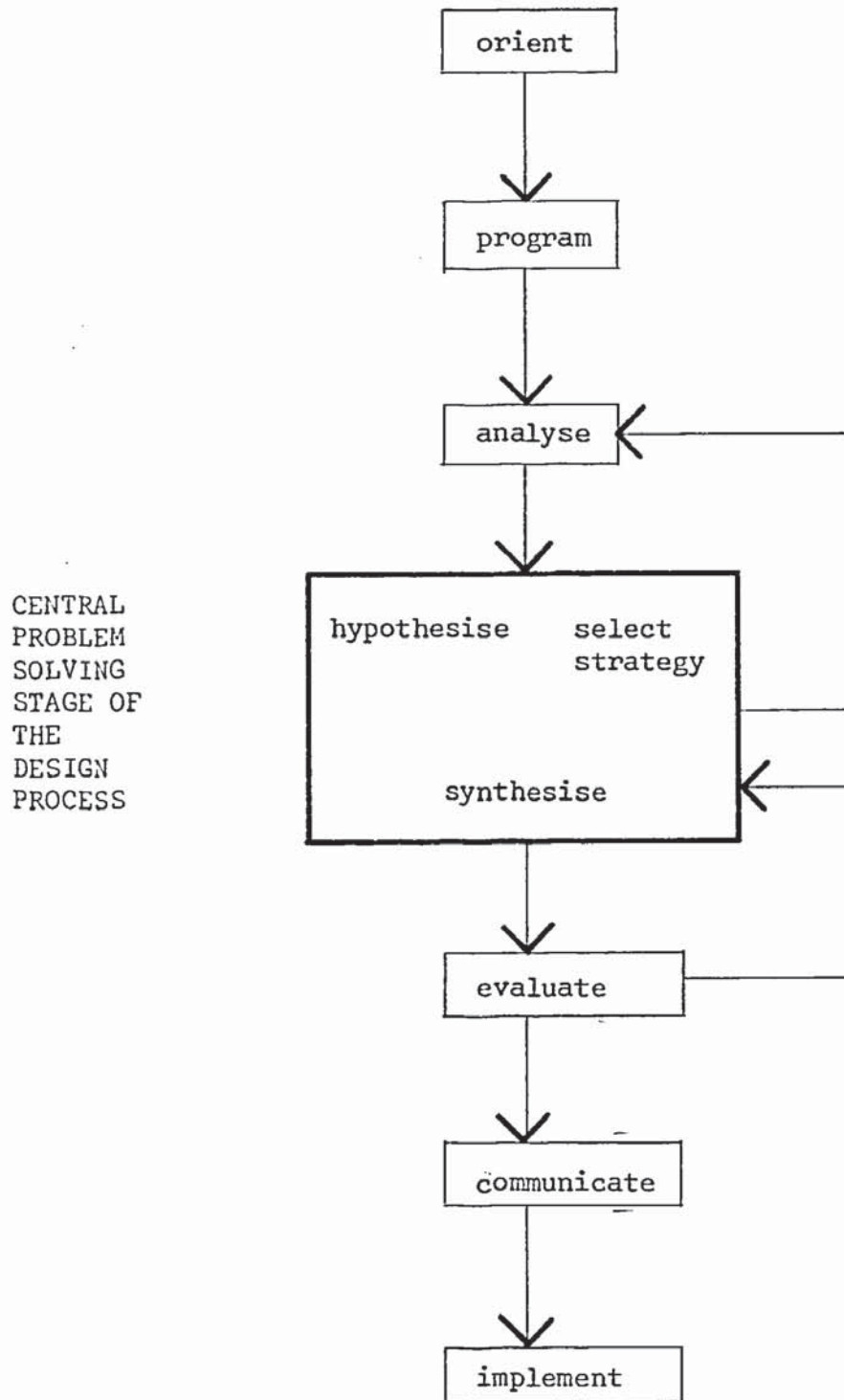


diagram 2.3.3

It is this central problem solving stage of design that the rest of this work will investigate.

2.4 The Dimensions of the Design Situation

As indicated in Section 1 the Beaux Arts school considered the most important set of factors contributing to the nature of the design situation to be those associated with the final solution. Students were trained on a series of schemes graded for complexity of solution, and indeed the scheme was described more as a task of producing a solution than one of solving a problem. A student would be asked to design a porch or a church, not to solve the environmental problems of entering or worshipping. This thinking still has an influence on current architectural practice where designers can be seen to 'specialise' in solution types such as schools or libraries.

However, classifying the design situation by its end product would seem to be rather putting the cart before the horse, for the solution is something which is formed by the design process and has not existed in advance of it. Design is defined by Wehrli (1968) as "the man-machine problem solving process which results in a scheme or schemes". At this very general level we can represent design by a simple diagram.

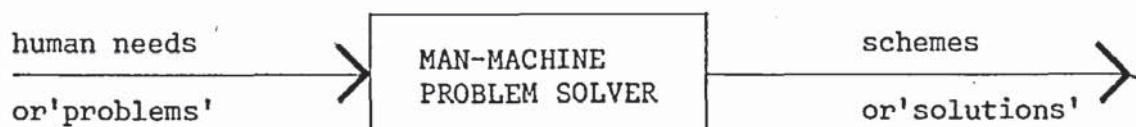


diagram 2.4.1

Clearly then, the nature of the solutions is a function of the nature of the problems and their solvers.

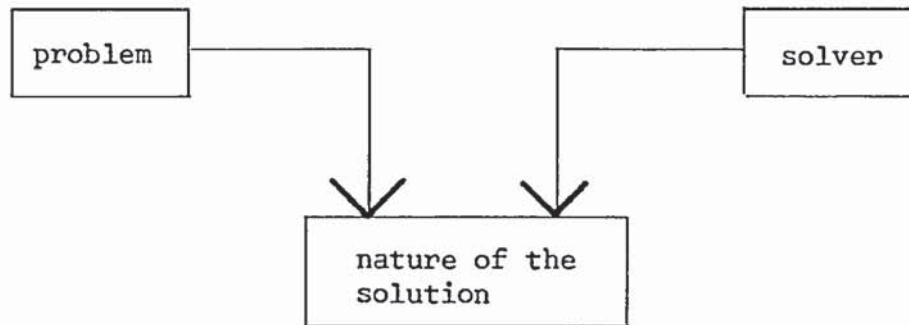


diagram 2.4.2

The design situation can be altered by varying any of these three boxes. For example the real world problem caused recently by fires in multistorey hospital buildings might well be solved differently by an architect and by a psychologist. The architect might suggest a scheme of fire doors and escape stairs, while the psychologist might suggest a better fire drill training for the staff. Thus although the solution to some extent describes the design situation, it is really only half the story, and a fuller description may be obtained from the problem and its solver. These will be studied in sections 3 and 4 respectively.

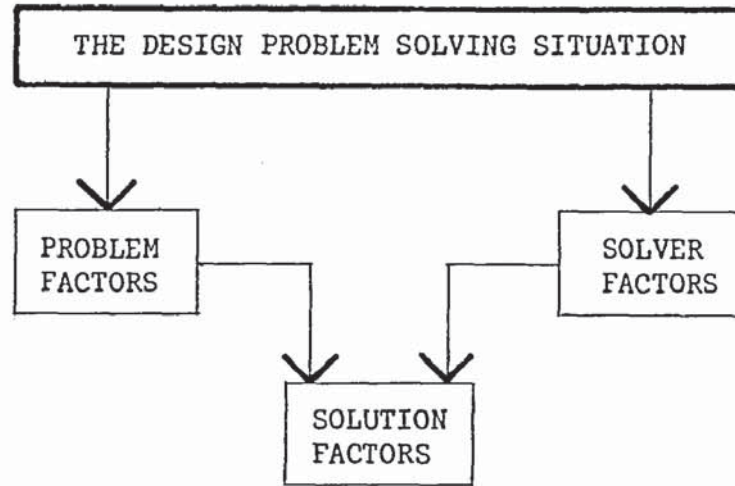


diagram 2.4.3

This diagram makes it possible to relate different types of design situation. Confusion has arisen in the past because each kind of designer has tended to use the word design to relate only to the situations that he encounters. Thus an architect finds it difficult to accept that an engineer 'designs' a beam, and an engineer fails to appreciate most of the activities involved in architectural design. With the increasing popularity of the interdisciplinary systems approach (see section 1.1, 1.2) a better understanding of the nature and relationship of different types of design is vital.

Finally, it should be recognised that the diagram is as yet incomplete. It is common-sense to suppose that certain types of problem ideally call for certain solver characteristics, and in reverse that particular solvers may generate specific kinds of sub-problem. These cross influences will be discussed in the subsequent sections.

3. PROBLEM FACTORS

A problem which different from one solved in the past, but which has the same principle involved in the solution, cannot have its solution explained by similarity because there is no similarity until both solutions are known.

Maier (1931)

3. PROBLEM FACTORS

3.1 What is a problem?

3.2 Problems and subproblems

3.3 Attributes of design problems

3.4 Problem size

3.5 The structure of architectural problems

3.6 The effect of structure on the problem solving task

3.1 What is a Problem?

At this point it is necessary to be sure just what is meant by the word 'problem' in this context. It is used here in the sense given by Duncker (1945).

"A problem arises when a living creature has a goal but does not know how this goal is to be reached. Whenever one cannot go from the given situation simply by action there has to be recourse to thinking."

Vinacke (1952) adds a few other details:

"In a problem solving situation, the individual is confronted by external conditions in which an obstacle or difficulty must be overcome to reach a goal."

The situations used by psychologists investigating our problem solving processes seem to fall into four main kinds:

1. Puzzles

Mechanical	require manipulation of physical components to change the state of the whole.
Constructional	require components to be assembled in a particular way.

2. Structural Problems

Plane geometry	certain relations have to be shown by deduction.
Anagrams	meaningful relation of letters to be achieved out of a jumble.

3. Application of Principles

Series completion	a series of numbers, letters or shapes
-------------------	----------------------------------------

has to be continued along the same structural lines as already exist.

Practical techniques application of basic physical concepts such as gravity, density and friction, etc., to achieve a specified end.

4. Generation of Principles

Concept formation a general rule has to be generated to explain a series of individual events.

It can be seen that these types of problem differ in the way the goal and the obstacle are presented to the subject. The obstacle in the mechanical puzzle is physical, real and very obvious, but where and what is the obstacle in the concept formation task? This theme will be taken up again later in this section.

Wehrli (1968) starts his study of 'open ended problem solving design' with a proposed classification of problem types which is mainly based on the number of solutions available;

"I submit that problems may be called pseudo problems when they have a unique solution, selection problems when the solution is selected from a set of alternatives (and open ended) problems have an infinite number of possible solutions."

Wehrli further proposes that both open ended problems and selection problems can be of the "prototypical" or "mapping" variety.

"For a mapping problem the general nature of the solution is known in advance but the means for achieving it is not."

'How to tie a bowline knot' and 'How to make a moon landing'* are

*The author was writing before a moon landing had actually been made!

selection and open ended variants respectively.

"Prototypical problems are those for which a prototype is available for use as a model to be adopted or copied in part or in whole."

'Which car should I buy' and 'The design of a school' are the corresponding selection and open ended examples. Finally, Wehrli identifies "double open ended problems" as those in which neither the nature of a solution nor the means of achieving it are known. This is illustrated by 'The education of children in the ghettos', which concerns not only possible schools but educational methods and social problems. Wehrli's 'puzzle' classification as, all problems with a unique solution, would normally include both 'puzzles' and 'structural problems' as in the first list, since anagrams have usually only one meaningful answer. The real distinction between puzzles and structural problems is that a unique solution to the latter can be achieved in a variety of ways and not just one as with genuine puzzles.

An architectural designer must generate principles which govern the form of his solution, and apply those principles. The solution must achieve certain desired structural relations between its elements. Thus although puzzles and Wehrli's pseudo-problems do not seem relevant to a study of design, structural problems and the generation and application of principles do.

TABLE 1 from Wehrli (1968)

Characteristics of Problem Types

Problem Type	Variant	Example	No. of Possible Solutions	No. of Solutions Sought	Expected Success of Solution
Pseudo-problem		How should we deal with poltergeists?	Infinite	None	-
Puzzle		How many beans in the jar?	One	One	Absolute
Selection Problem	Mapping Problem	How to tie a bowline knot	Equal to the number of alternatives	One	Relative
Open-Ended Problem	Prototypical Problem	Which car should I buy?	Equal to the number of alternatives	One	Relative
	Mapping Problem	How to make a moon landing	Infinite	One	Relative
Double open-Ended Problem	Prototypical Problem	The design of a school	Infinite	One (a)	Relative
	Mapping Problem	How to educate children in the ghettos	Infinite	Multiple Solution	Relative

(a) Sometimes multiple solutions are used for design problems. In an apartment building, for example, not just one apartment type (solution) but several types (solutions) may be provided.

3.2 Problems and Subproblems

Design is a goal oriented continuous problem solving process. It is continuous because the architect goes on breaking down his original problem into progressively smaller and more detailed subproblems (see the hierarchical model in section 1.7). There is no finite end point to the design problem solving process, the architect stops when he personally decides to. This decision is usually based on the amount of time available. There can never be a design which could not benefit from a further more detailed examination of its sub-problems. The real skill of the designer in this context lies in detecting the point after which the benefits of extra effort do not justify the work involved. This may well not be at the same level in every case. For example, the means of opening cupboard doors in a small boat or caravan is quite critical to the efficient functioning of the whole interior. This is clearly not so in the ordinary domestic environment, where a designer may not be at all interested in the relative advantages of sliding, hinged or pivoted doors.

At the other end of the process, the hierarchy of problems has no finite apex, for all problems can be seen as sub-problems of larger problems. (For a more full and useful exploration of the essential hierarchical structure of things see Koestler, 1967).

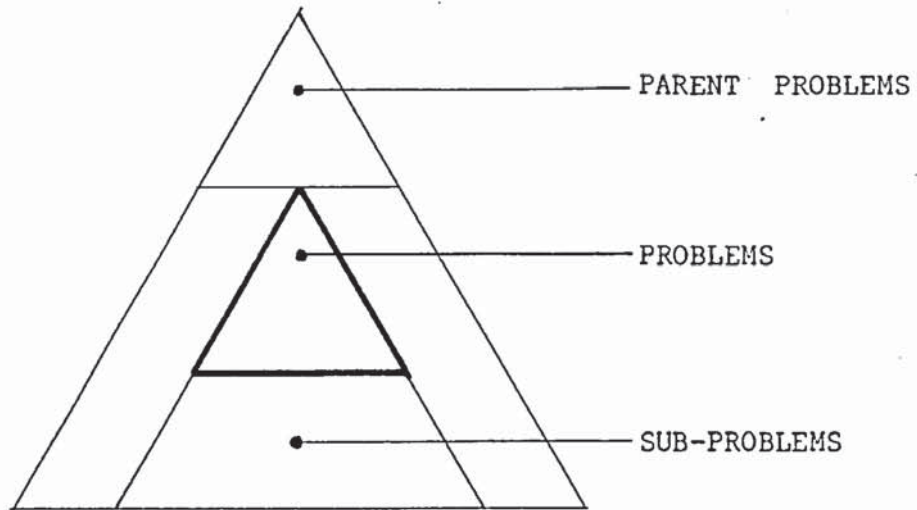


diagram 3.2.1

The designer has to be careful to see his original problem in its right context, but it is easy to go on climbing back up the hierarchy and to lose sight of the real problem.

In summary, the design situation must not be seen as one problem, but rather a whole series of related problems.

3.3 Attributes of design problems

Obviously a designer will not find all the problems that he encounters equally difficult. Moreover different designers may perform better at different sorts of problem. 'Difficulty' is a complex subjective concept made up of many interacting elements. If the human variables involved in 'problem difficulty' can be eliminated, then it should be possible to examine those remaining variables which constitute the nature of the problem.

The most obvious attribute of a problem is its size. A large problem involving many variables is likely to be more difficult to solve than one involving only a few variables. This is still not a full picture because some very simple puzzles can prove extremely difficult to solve. Typically this sort of problem appears ridiculously simple in retrospect, and the knack of solving it lies more in selecting the correct approach than in carrying out a deep analysis.

Problems then, can obviously vary both in size and kind. These two main factors will be explored in the next sections.

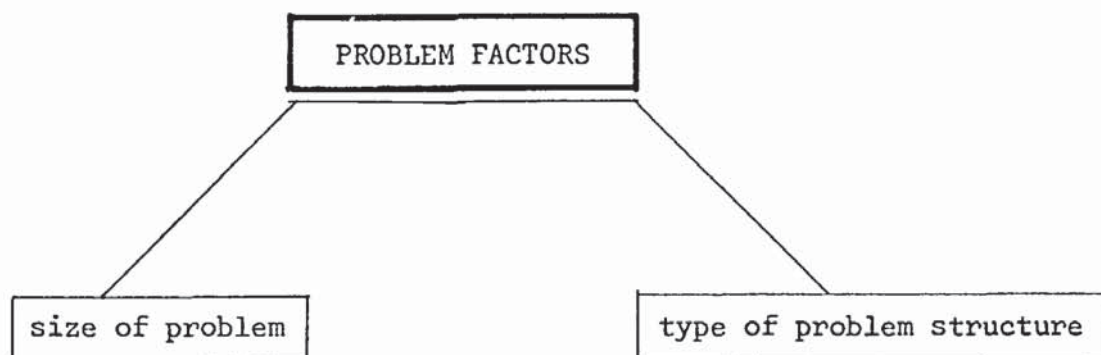


diagram 3.3.1

3.4 Problem size

At first glance a large scale problem may seem more complex than a smaller scale one. This is not really so, as all problems can be seen as sub-problems in the 'Universal Hierarchy' and there is no reason to suppose that problems get more complex further up the hierarchy. (See section 3.2 and Koestler, 1967). A town planning problem is only larger than an architectural problem if they are both studied down to the same amount of detail. Producing an urban redevelopment scheme is not necessarily more complex than designing any one of its buildings.

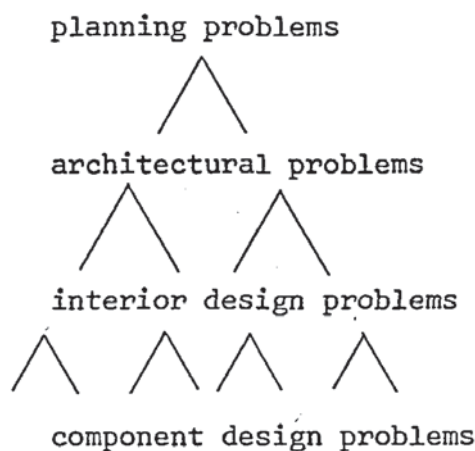


diagram 3.4.1 An environmental design problem tree

Thus the 'depth' down the problem hierarchy that the designer is expected to penetrate, rather than the point at which he begins is the important factor.

Design problems vary in terms of the number and nature of their

constituent elements, thus making them more or less complex.

Consider the design of a simple product which can be made of two alternative materials and in three alternative shapes.

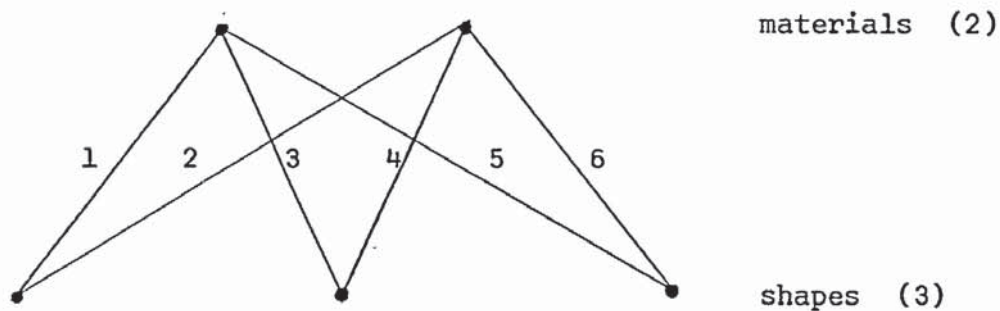
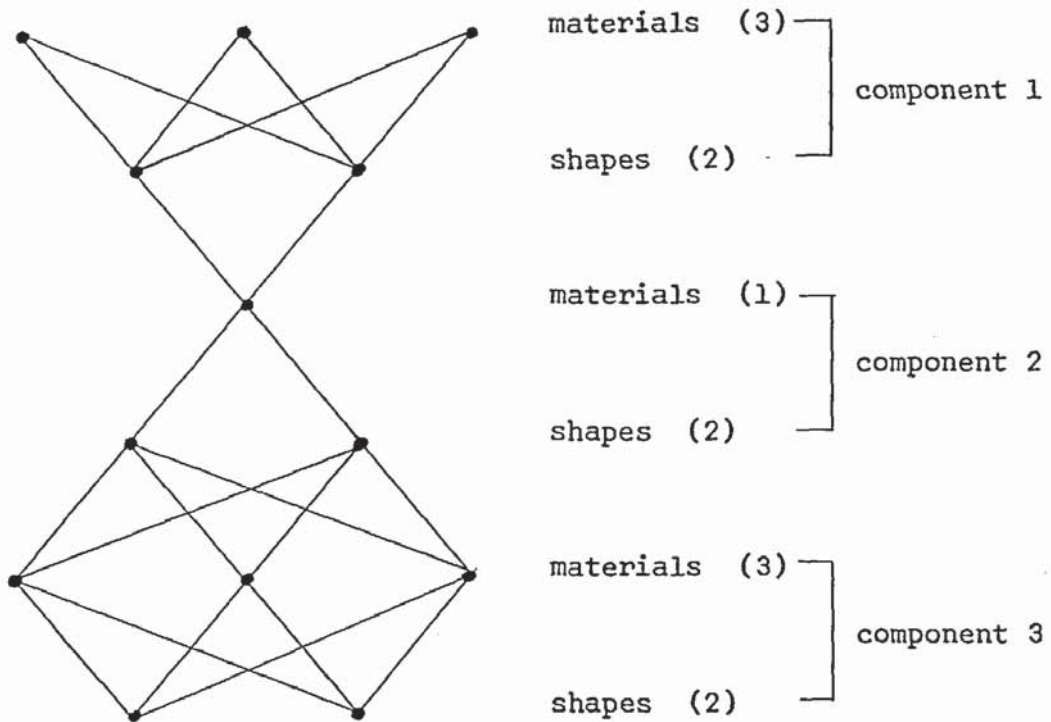


diagram 3.4.2

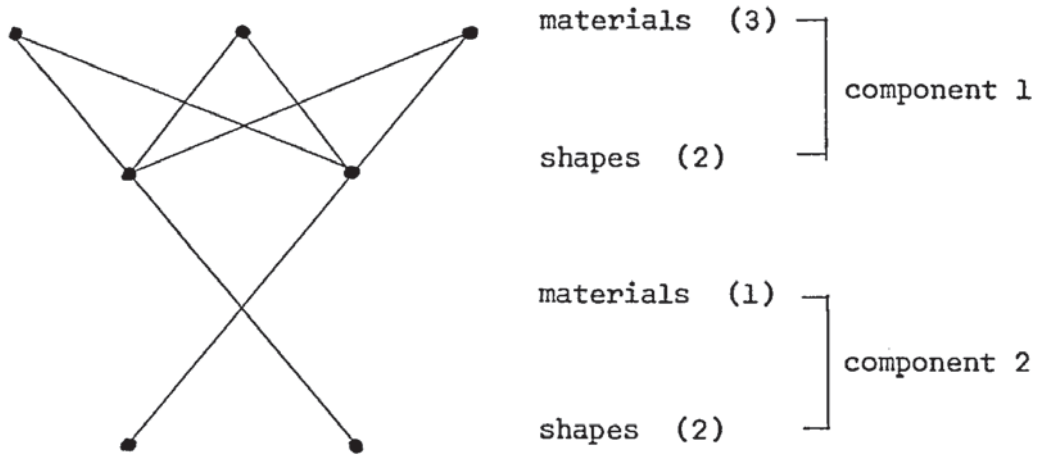
There are six possible ways of designing the product as indicated by the connecting lines in diagram 3.4.2. Diagram 3.4.3 represents a larger design problem having three components each of which can be made of a number of materials and in a number of shapes.



There are 72 ways of designing the product ($3 \times 2 \times 1 \times 2 \times 3 \times 2 = 72$)

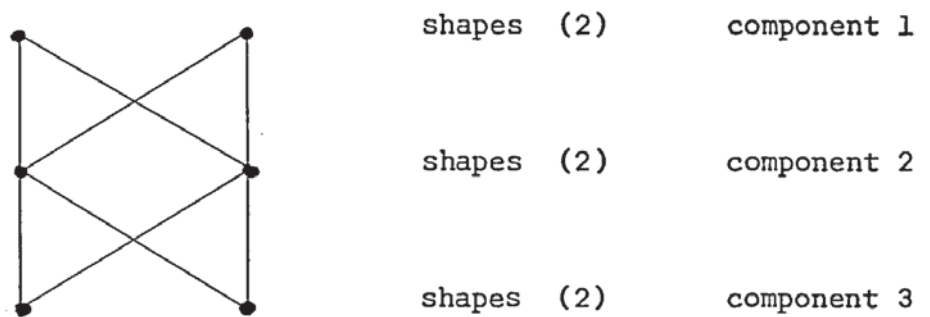
diagram 3.4.3

The task of finding an optimal solution to this problem is clearly greater than in the previous example. This complexity is a function of the number of components, the number of dimensions along which they can vary, and the number of steps to each dimension. Reducing any of these three factors results in simpler design problems, as in diagrams 3.4.4/5/6.



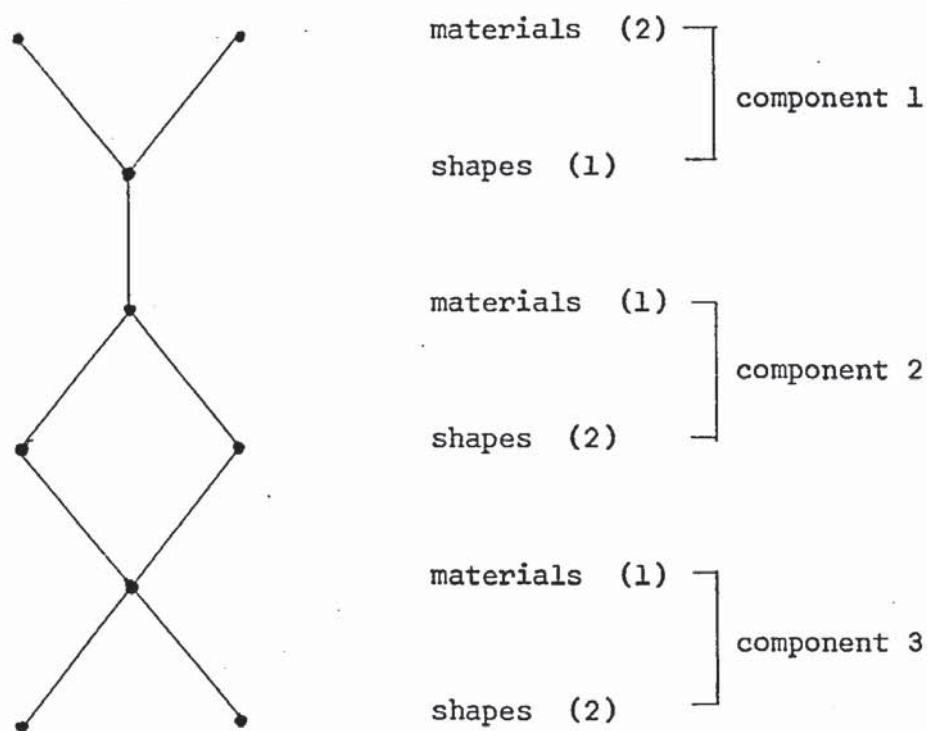
There are 12 ways of designing the product $(3 \times 2 \times 1 \times 2 = 12)$

diagram 3.4.4 FEWER COMPONENTS



There are 8 ways of designing the product $(2 \times 2 \times 2 = 8)$

diagram 3.4.5 FEWER DIMENSIONS



There are 8 ways of designing the product ($2 \times 1 \times 1 \times 2 \times 1 \times 2 = 8$)

diagram 3.4.6 FEWER DIMENSION STEPS

In summary, problem size can be seen as a function of the depth, and of the number of its constituent elements, and the nature of their variation.

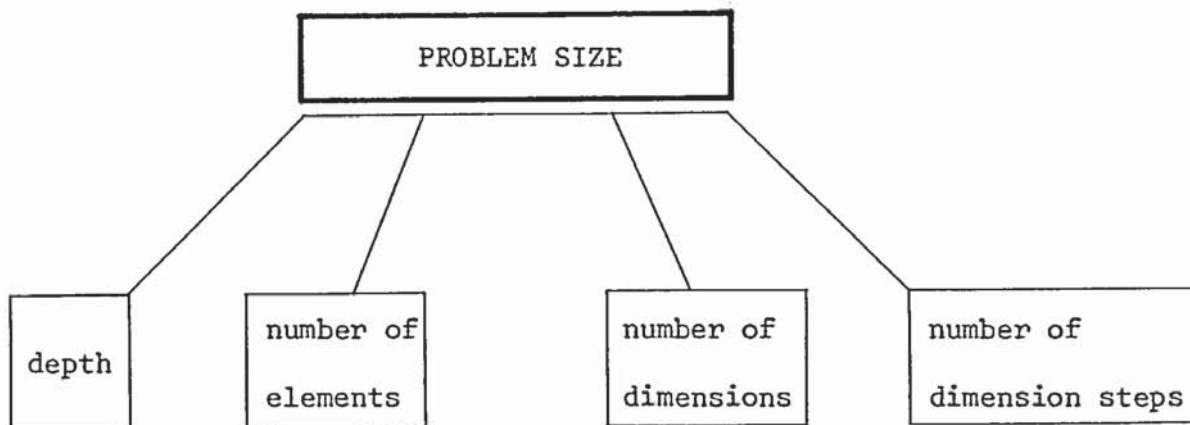


diagram 3.4.7

3.5 The Structure of Architectural Problems

Traditionally architectural problems have been defined by the goal rather than the obstacle. The goal, or solution, must be a building, that is why one goes to an architect. It is perhaps because of the obvious differences between the solutions of the various environmental design problems that they have been classified this way. A planner produces towns, an architect buildings, an interior designer interiors and so on. However, it is not just that their goals, or solutions, are different, but also the obstacles that they meet are different. They do in fact perform quite different jobs, as is quite apparent from even a superficial knowledge of them. This section is an attempt to show just why they are different, and what makes architectural problems as they are.

Any architectural problem involves countless sub-problems. As mentioned in section 3.4 they tend to be organised hierarchically from planning to component design. The architect's main concern is, however, not with grand plans or furniture details, but with the organisation of forms and spaces and the activities contained by them.

Spaces vary in plan, section, shape and size, and in their geographical relation to other spaces. They may be connected in many different ways in a building - by human movement, by service cables, pipes, ducts and roads, acoustically, visually, and any combination of these types of connection is possible.

Principally then, the architect's problems are multivariate, although from time to time he may abstract sections for study which are puzzles (see section 3.1). (For example, a study might be made during a complex design task of how to configure four spaces so that each is connected to every other, and to include a general access point).

The central problem of all architectural design is the translation of functions (human activities) into three dimensional forms (buildings).

"Form follows function is the catchphrase that spells modern architecture to most laymen."

(Peter Blake, 1963, Encyclopaedia of Modern Architecture)

"Every problem has a structure of its own. Good design depends upon the designer's ability to act according to this structure and not to run arbitrarily counter to it."

(Alexander and Chermayeff, 1963)

Having abandoned systems of visual rules for generating his forms, the architect now seeks visual pattern or structure in the complex interaction of functions that are to be housed in his building.

Alexander and Chermayeff (1963) succinctly identify the main difficulty here.

"Too many designers miss the fact that the new issues which legitimately demand new forms are there, if the pattern of the problem could only be seen as it is and not as the bromide image conveniently at hand in the catalogue or magazine around the corner."

First then, the architect must be able to perceive the structure or pattern of his problem directly rather than reflected in the form of an already designed building of similar function. This latter leads to the transmission of errors, irrelevant pre-conceptions and inaccurate extrapolations, with a possible tendency to establish new traditions of form. Quite how this structure could be presented to the architect, and the likely results will be discussed later; here I shall concentrate on the nature of the structure.

This structure is composed of three main sets of relations between the variables of the problem. Each of the three sets of relations puts a constraint on the designer's freedom of action, and thus provides the 'obstacle' to reaching the 'goal'. I shall call the three constraints, the internal constraint, the external constraint and the designer's constraint.

The internal constraint is composed of the various interactions between the variables of the architectural system being designed. An interaction is said to exist between two variables if they are not completely independent. Thus, if the architect alters the state of one variable and consequently finds he must change another variable, then these two variables are not independent. There is an interaction between them, and this interaction constrains the architect's freedom. For example, he may find that a space he is designing could be a variety of lengths, widths and heights. The volume, however, may be rather more carefully specified, and this relatively fixed volume relates the other variables and restricts the total number of design

possibilities.

As often as not the variables may interact in more than one way. In the above example there may be critical combinations of height and area which produce acceptable acoustics, yet these same two variables may interact so that certain other combinations produce the best visual solution. To simultaneously satisfy these acoustic and visual criteria there may only be a small overlap to meet this condition.

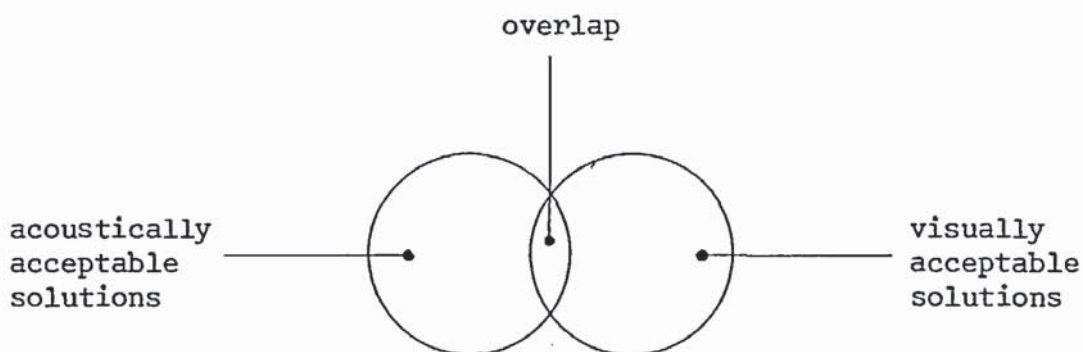


diagram 3.5.1

If there is not overlap, and both acoustic and visual standards cannot be met in one solution, the architect must compromise and make a value judgement on the relative importance of the two criteria. In either case he obviously needs accurate and easily understood information about the relationships of the variables, the criteria and the way they influence one another.

In addition to internal constraint there is a second constraint on design - external constraint. This constraint is supplied not by

the architectural system alone, but by the interaction of the environment at large with the architectural system. This constraint is different from internal constraint because the interaction is between the internal variables and fixed external factors. The architect has control over the internal variables, but he cannot, of course, exercise any control over the external variables. To return to the earlier example again, the shape of the site may prohibit certain combinations of width and length for our space. The sources of external constraint are legion, they may range from the direction of the prevailing wind and aspect of the site, through considerations of surrounding buildings, roads and pedestrian access, to planning and building legislation. As with the internal constraint, the architect needs to be able to perceive the range of acceptable options that is defined by these external constraints.

The third set of constraints, the designers' constraints, are produced entirely by the architect himself while he is actually working on a design and they generally take the shape of implicit rules about the form of the building. For example, the architect may feel it inappropriate to produce a large scale effect on an elevation of his building which is adjacent to an existing small scale edifice. This 'external' constraint may force him to move large spaces away from this elevation, or reduce their height. He may generate 'internal' constraints which fix spaces in relation to each other for a variety of reasons, perhaps simply so that people could easily conceptualise their way around a large building, i.e. he generates an internal structure which the user can perceive in meaningful terms as a user

of the space - the structure gives geographical significance and meaning to the building.

Rand (1970) discussing commercial graphic design has generated a taxonomy of constraints that shows a considerable similarity with this one.

"The designer (graphics) is primarily confronted with three classes of material; a) the given material: product, copy, slogan, logotype, format, media, production process; b) the formal material: space, contrast, proportion, harmony, rhythm, repetition, line, mass, shape, color, weight, volume, value, texture; c) the psychological material: visual perception and optical problems, the spectators instincts, intuitions and emotions, as well as the designers own needs."

Rand's 'given materials' are clearly external constraints. They are invariable in that they are given to the designer, and not determined by him. The formal materials are internal to the problem, varied and controlled by the designer. Finally Rand's reference to the designer's own needs under 'psychological materials' indicates that he has designer imposed constraints in mind.

It would seem quite reasonable to generalise this taxonomy of internal, external and designer constraints to all forms of design, but it is not the intention to pursue this argument further here. The nature of architectural problems, at least, is very obviously created by the balance of the three sets of constraints. The effects of this structural variety are discussed in the next section.

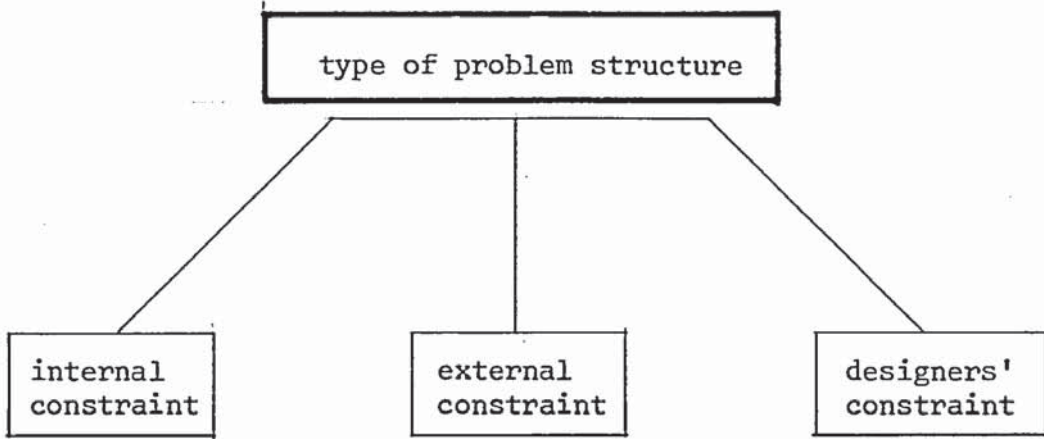


diagram 3.5.2

3.6 The Effect of Structure on the Problem Solving Task

As the amount of structure, or constraint, in a problem is increased then the range of freedom of the designer decreases and the nature of the solution becomes more prescribed. Eventually there is little or no room for manoeuvre and the form of the final product is inevitable. At this point the designer himself is totally redundant and his job, such as it is, would be better done by a computer.

There is no risk of this happening in architecture. There is a long tradition of respect for the 'designer's constraint' over which he is allowed almost unlimited control. Apart from this, the sheer size of architectural problems and the nature of the variables is such that a designer has many potential ways out of any difficulty. This is not so in all environmental design. Compared with the architect, the civil engineer has few variables and few possible solutions to any problem. The result is much more a foregone conclusion. His choice is so limited that he can often count the basic alternatives on one hand. For example, the main variable of bridge design is the structural system employed; it must be an arch, beam, cantilever or catenary, and the external constraints may rule several of those out. This sort of restriction is inconceivable in architecture. At the other extreme, theatre design is relatively unconstrained. Apart from the external constraints of the stage and the script there is little to restrict the designer and he has an almost unlimited set of alternatives.

Architecture clearly lies near the middle of this spectrum since all its three sets of constraints are generally considered important, and are given roughly equal balance. At different times, the architect may have to deal with either heavily constrained or lightly constrained problems. Wehrli (1968) introduced the notion of 'open endedness' of architectural problems, but he implicitly assumed that open and closed ended problems are discrete categories. Lawson (1970) has suggested that architectural problems can be seen as varying in the degree of open endedness which they exhibit.

"The more open ended problem is typically rather unconstrained with respect to the number and variety of its solutions. It is also frequently not easy to see just what the obstacle to its solution is."

Basically the architect always starts with a very open ended problem; no-one would dare predict what the outcome will be. However, as he works and some decisions are made a structure grows and the architect encounters more closed ended problems. Lawson (1970) has also pointed out, as did Wehrli (1968), that the typically open ended problem presents the architect with a substantially different sort of task to that presented by the typically closed ended problem. The former needing a creative, imaginative kind of thought to generate alternatives, and the latter calling for a clear examination of the problem structure so as to develop a sufficient understanding to pinpoint the optimal solution.

These points are more appropriately developed in the next section, which examines the problem solver himself.

4. PROBLEM SOLVER FACTORS

The truth is that in everyday thinking any person enters the circumstances which set his mind at work already predisposed in favour of certain argument sequences and against others.

Bartlett (1958)

4. PROBLEM SOLVER FACTORS

4.1 Introduction

4.1.1 General

4.1.2 Thinking

4.2 Theories of thinking

4.2.1 Associationist theories of thinking

4.2.2 Gestalt theories of thinking

4.2.3 Information processing theories of thinking

4.2.4 Thinking as part of cognitive psychology

4.3 Types of thinking

4.3.1 Productive thinking and architectural design

4.3.2 Structural thinking and architectural design

4.4 Structural thinking

4.4.1 The effects of different types of structure

4.4.2 The formation of hypotheses

4.4.3 The rejection of hypotheses

4.4.4 The use of positive and negative instances

4.5 Architects as a special cognitive group

4.5.1 The architectural student's choice of career

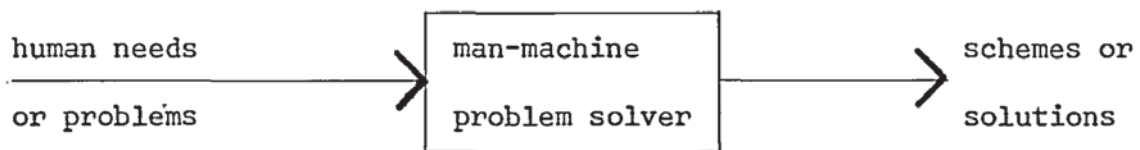
4.5.2 The influence of the school of architecture

4.5.3 Personality studies

4.1 Introduction

4.1.1 General

Let us briefly return to the 'black box' diagram in section 2.4.



It is the function of this section to explore the nature of the problem solver box as it exists, or could exist, in architectural design.

Traditionally the architect himself is at the centre of the problem solving activity. However, he has never resembled Rodin's 'Thinker' who sits in solitary meditation, but has, in contrast, always externalised his thoughts, not only as an end-product, but as an integral part of the thinking process itself. The whole purpose of outputting his thoughts in this way is so that they can be input again, manipulated and evaluated.

Until recent times the architect has worked almost exclusively with two dimensional graphic techniques. These drawings may have been to visually represent some projected design in either all three dimensions (perspective, isometric) or only two (plan, section), or to represent relationships (flow diagram, etc.). Now architects are

turning to other means of externalising their thought processes. Often non-graphical, these new techniques are sometimes verbal, such as Brainstorming or synectics, or mathematical, such as various operations research procedures.

Whether he writes, draws, or speaks the architect's thinking processes must be to some extent channelled by the grammar of this externalisation technique. It is well known that when drawing flow diagrams the architect tends to come to think of the arrangement of spaces represented as a proper plan.

'The problem solver box' consists of human thinker, machines and techniques, and if we are to understand its nature we must consider all three. Machines and techniques are largely under our control, while our own cognitive machinery is much less so. Machines and software techniques can be more suitably integrated into the design situation if we more fully understand the thinking processes of the designer himself.

4.1.2 Thinking

The term 'thinking' is the first stumbling block to be encountered in a study of the human thought processes. Like many other words in psychology, 'thinking' has been lifted from common usage and given special meaning, thus causing confusion. We all 'think', and we all recognise that 'thinking' goes on, but where does it begin and end? Frequently when the word 'thinking' occurs in common usage we could substitute another word for it and still retain our meaning.

"You are not thinking about what you are doing!"

"I did not think about it at the time."

"I think that my football team will win the cup."

"I think that will be alright."

Here we could substitute "attending to", "remember", "believe" and

"I am not really sure". This gives us virtually no clue to what thinking really is. Dictionary definitions are not much more informative:

'Think - to exercise the mind; to resolve ideas in the mind.'

(Chambers 20th Century Dictionary)

Now we must search for the meaning of 'mind':

'Mind - that which thinks.' (Chambers 20th Century Dictionary)

Descartes distinguished mind from matter as 'that which thinks', so we have not progressed greatly in three centuries. Psychologists' definitions are generally more precise but still offer a considerable variety of interpretation.

'Thinking - any course or train of ideas: in the narrower and stricter sense; a course of ideas initiated by a problem.' (Drever, A Dictionary of Psychology)

Bartlett (1958) suggests that we should "regard thinking as an extension of evidence in line with the evidence and in such a manner as to fill up gaps in the evidence". Bartlett also comments "It seems reasonable to try to begin by treating thinking provisionally as a complex and high-level kind of skill". A cautious suggestion indeed! But Thomson (1959) uses Ryle's phraseology to support this notion "thought is very much a matter of drills and skills".

Vinacke (1952) takes a definition from English (1934) as a starting point for determining what thinking is not. According to Vinacke

"thinking is cognitive but not perceptual, and involves at least some processes and components which are not derived from, or do not deal with, objects present in the immediate environment."

Vinacke says also that thinking can not be divorced from other behavioural processes.

"We shall find continually not only that perceiving and thinking are interrelated processes, but also that emotion, motivation, learning and other aspects of behaviour enter into thinking."

Lastly Vinacke stresses the role of past experience in thinking,

"Thinking involves the apprehension and manipulation of objects, the application of properties of objects and situations, but not solely in terms of perceptions at the present moment."

Many psychologists have felt that one of the key attributes of thinking is direction. Bartlett (1958) in likening thinking to bodily skills points out that,

"it is, in fact, impossible to continue very far in any realistic study of bodily skill without introducing the function of a guiding and controlling direction".

Maier in many studies was interested in the effect that context has upon the direction taken from the starting point in a thinking task.

"Thinking does not take place in a vacuum, but in the midst of a complex pattern of nervous activity".

(Vinacke, 1952)

"Context has a profound influence upon the way in which the thought process will develop".

(Werthermer, 1959)

This context is made up of current and immediately recent environmental events, and of the vast variety of past experiences of the thinker.

A major obstacle in applying the methods of experimental psychology to thinking is the difficulty of observing it. Thinking can, and often does go on in a completely internal world. The thought process need not be started by, nor concerned with current events in the environment, and moreover it need not conclude with any communication to the outside world. The would be experimenter must present stimuli to, and enforce response from, his subject if he is to observe the thought process.

4.2 Theories of Thinking

4.2.1 Associationist theories of thinking

Thinking has been studied by both the associationist and gestaltist schools of psychology, each school attending to only some aspects of the phenomenon. More recently human thinking has been examined in the light of advanced machine intelligence, but these studies too have their limitations. Modern 'cognitive' theorists aim to take a more comprehensive view. In this section the particular contribution of the associationist school will be considered.

Thorndike believed that human intelligence comprises only one basic process, the formation of associations. Since then many broadly behaviouristically minded psychologists have attempted to explain thinking in terms of direct associative links between stimuli and responses. The first, and probably most dogmatic, exponent of this approach was Watson who originally argued that thinking is only subvocal speech. "What the psychologists have hitherto called thought is in short nothing but talking to ourselves"..... Watson thus expected to find slight activity in the vocal muscles during thinking. Jacobson and Marx found evidence of peripheral muscular activity during thinking, but of course, failed to show that this was the thinking itself. Hull modified the idea suggesting such a small muscular response that it would have no effect except for feedback information to guide its successor.

Osgood (1952) introduced the notion of purely "Cortical responses"

without any necessary resultant activity of effector systems. This idea was accompanied by other suggestions of intermediate mediating mechanisms and was developed by Berlyne (1965) who produced quite extensive diagrams of complete trains of thought, linking a variety of stimuli to a variety of responses. The total picture portrayed is one of a sequence triggered by an external stimulus, flowing through a succession of choice points, the path being decided by the relative associative strengths of the various S-R links.

These associationist models of thinking seem quite inapplicable to goal oriented or directed thinking, such as we might expect a designer to engage in during his problem solving process. What Vinacke (1952) calls "autistic thinking" or daydreaming, loosely translated into lay terminology, is more easily explained by the associationist model. The associationists have tended to explain goal directed thinking as successive trial and error loops. Simply, the solution is found because it is tried out and changes the problem situation into the goal attained situation, removing the obstacle. Thorndike's cats escaped from their puzzle boxes in this manner. However, thinking, unlike escaping from a puzzle box, does not necessarily involve motor activity. Instead each solution must be imagined and mentally assessed. If unsuccessful then it suggests the next solution to be tried. Furneaux (1960) attempts to explain all problem solving along these lines using the two basic mechanisms of sampling and evaluating. The sampling mechanism selects a possible solution in a quasi-random fashion and the evaluating mechanism assesses it.

Berlyne's ingenious S-R explanation of directed thinking is also worthy of our attention. For Berlyne, and Osgood, a stimulus is associated with a whole hierarchy of responses, not just a single response. Berlyne suggests that in a multi-stimulus problem solving situation the same response may occur in a number of hierarchies and all its relative associative strengths may be summed, making it more likely than any other response. However, this results in the possibility of the response, which occurs when two stimuli are present, being unlikely to occur when either stimuli are presented individually. Brown (1967) shows how a concept of relevance must be added to Berlyne's convergence idea to make any sense.

It seems likely that among the associations to "continent" will be found the word "country"; and that "country" will also be an associate of "France". Convergence would make "country" a likely response to the question, "In which continent does one find France?" Yet, in practice, it is a most unlikely response.

Serious attempts to produce complete models of thinking processes using only associative links are now out of fashion.

"Today stimulus response theorists themselves are inventing hypothetical mechanisms with vigor and enthusiasm and only faint twinges of conscience." (Neisser, 1967)

4.2.2 Gestalt theories of thinking

Gestalt theories of thinking concentrate on processes and organisation rather than mechanisms. The gestaltist's ideas tend to complement the largely behaviouristic notions of the associationists by more naturally

relating to directed rather than undirected thinking.

Wertheimer (1945) considered thinking to be a dynamic process developing within the context of the situation. He has established an overall view of problem solving based on a series of experiments, mainly on children. Problem solving, for Wertheimer, consists of grasping the structural relationships of the situation and reorganising them until a way to the solution is perceived. This reorganisation is achieved by applying various modes of attack, redescribing the problem, and using analogous situations. Such a process is not just the sum of several steps, not an aggregate of several operations, but the growth of one line of thinking out of the gaps in the situation.

Gestaltists stressed the importance of the thinkers' experience, and the context of the situation in which he finds himself. Not surprisingly, considering their original work, the early gestaltists saw thought as inexorably bound up with perception. De Groot (1965) used Köhler's "experimental adventures with anthropoids" to illustrate this point.

"We humans are struck by the inability of these otherwise quite intelligent animals to take a ring off a nail; a possibility that we immediately see. Due to our experience with nails and rings and their usage, we see the situation in a totally different way than the ape does. Similar examples can be given touching upon the relation between adults and children."

De Groot went on to show how the experienced chess player 'reads' a situation rather than 'reasons it out'. He claimed that a master is

a master purely because of experience, which produces a 'schooled and highly specific way of 'perceiving' and 'a system of reproductively available methods in memory'.

Bartlett in his experiments on remembering (1932) and thinking (1958) paid particular attention to our internal representation of the external world. Heavily influenced by the work of Head he developed the notion of an internalised symbolic cognitive map or image which he called "schema".

"'Schema' refers to an active organisation of past reactions, or of past experiences, which must always be supposed to be operating in any well-adapted organic response. That is, whenever there is any order or regularity of behaviour, a particular response is possible only because it is related to other similar responses which have been serially organised, yet which operate, not simply as individual members coming one after another, but as a unitary mass. Determination by schemata is the most fundamental of all ways in which we can be influenced by reactions and experiences which occurred some time in the past. All in-coming impulses of a certain kind, or mode, go together to build up an active, organised setting; visual, auditory, various types of cutaneous impulses and the like, at a relatively low level; all the experiences connected by a common interest: in sport, in literature, history, art, science, philosophy, and so on, on a higher level"

Bartlett (1932)

Bartlett showed how we use our schemata to structure, and therefore modify, incoming data by requiring subjects to remember complex visual or verbal stimuli for periods of weeks and then reproduce them. Other psychologists such as Bruner and Piaget have shown how the human thought processes develop in parallel with the ontogenetic acquisition of basic schemata. These experiments have revealed the child's problem solving abilities to develop in a predictable sequence.

Selz () described problem solving in terms of 'processes' or 'operations'. These operations are organised 'strategically' so that the result of each operation determines the next operation. Processes are thus strung together in a chain to form a complete problem solving sequence. The stringing is achieved by reference to a 'strategy', unlike the direct S-R linking of an associationist model which ensures that the sequence is always goal directed. Two types of successive stringing were listed by Selz, 'cumulative' and 'subsidiary'. In cumulative stringing the following operation builds upon its immediate predecessor. In subsidiary stringing the preceding operation was unsuccessful and the following step is a fresh attempt. A problem takes the form of a "schematic anticipation" which fully specifies the method toward solving the problem. Problem solving is seen as involving two basic activities, 'finding means of solution' and 'applying them'.

Duncker (1945) in a famous study "on problem solving", applied Wertheimer's earlier ideas (Wertheimer's book was published post-humously) to explain the behaviour of subjects faced with a particular kind of problem. Duncker's problems typically appear very difficult until the correct means of solution is found. The application of this correct 'means of solution' is immediately obvious, the problem becomes simple, and the subject never finds it difficult again. Duncker related this phenomenon to that observed by Kohler, who perhaps rather dubiously claimed that his apes showed "insight" when finally removing the ring from the nail and doing so readily at future encounters.

These problems of Duncker's show remarkable similarity to those currently posed in popular form by de Bono (1968), who introduces the concept of 'lateral thinking'. This area is more appropriately developed in a later section devoted to problem solving.

4.2.3 Information processing theories of thinking

The advent of information processing machines, and the development of their supporting software has stimulated new interest in our own thinking processes. This has resulted in a new movement which cannot be fairly categorised as solely associationist or solely gestaltist. Associationist theories share a common commitment to reducing thinking to a series of elementary, mechanistic neural events. In contrast, this newer approach postulates an information processing system with large storage capacity. Mechanisms do have an important role in information processing theories but are linked together by complex strategies which are held in storage and can be dynamically modified. Like the gestaltist approach, these information processing notions more readily explain directed thinking than undirected thinking.

Posner, in various writings (1962, 1965) developed Bartlett's view of thinking as a skill quantitatively, using the new information metric. He suggested that thinking tasks require a subject to transform the input stimuli into responses, and that the extent of those transformations could be measured using Shannon's theory (Shannon and Weaver, 1949). This work is part of a broader application of information theory to cognitive psychology generally advanced by Garner (1962), who reports experiments in short term memory, discrimination, pattern

perception, language and concept formations. This approach has shown a rather more limited success than was at first expected, although its full potential is almost certainly not yet evident.

Other psychologists have not attempted to measure behaviour directly in terms of information content, but have instead looked at the way information is used to control complex processes. This approach springs from the work by Weiner (1948) on cybernetics and his and other later attempts to use it to understand human motor activity control.

Newell, Simon and Shaw (1958) put forward a theory of human problem solving based upon analogy to a computer program model. They considered the organism to be a system consisting of effectors, receptors, and a control system. It is with the control system that they concerned themselves in studying thinking processes. Their control system is comprised of memory, information processes, and programs. The memories contain symbolised information, and are interconnected by various ordering relations. The information processes are extremely elementary and perfectly definite operations which operate on information stored in the memories under control of the programs. Newell, Simon and Shaw produced various computer programs which model human problem solving in specific situations. The computer when programmed in this way exhibits behaviour resembling such hitherto peculiarly human characteristics as 'purpose', 'set' and 'insight'. This at least shatters the mystery and mystique surrounding work on thought processes by showing how sequences of elementary information processes could

account for the successful solution of complex problems. Whether such simple processes exist in the human brain, and if they do whether they resemble those used by the computer is still open to considerable doubt. Newell, Simon and Shaw sum up the value of their work

"The invention of the digital computer has acquainted the world with a device, obviously a mechanism, whose response to stimuli is clearly more complex and 'active' than the response of more traditional switching networks."

Reitman (1965) has pointed out a number of difficulties inherent in using computer simulations of cognitive process. However, Reitman seems to confuse the computer with its program. He claims that computers tend to be purposive when humans need not be and may get bored. Programs can be written which are random, interruptable and distractable, with possibilities of switching between a variety of routines. Thus it is not the computer that is, or is not purposive, but the program, which is written by a human! Reitman also considers the program to be identical with the theory, when in fact it can only be a model of that theory. A more useful point made by Reitman concerns the utility of computer program models.

"At what point does the complexity of a theory (by which he means program) become so great as to render it useless as a scientific tool?"

This remark is provoked by the enormous size of Newell, Simon and Shaw's GPS (General Problem Solver) program. This program is so large and complex that it is doubtful if anyone other than its creators could understand its functioning in any detail.

Miller, Galanter and Pribram (1960) in a brilliantly speculative book explored the notion of control in cognitive processes. Rather than using the computer directly as did Newell and his colleagues their work uses it only by implication. These authors develop their arguments in terms of flow diagrams such as might be drawn before writing a program. The way in which control is passed from one box in the diagram to another defines the characteristics of the performance of the overall system under consideration. Miller, Galanter and Pribram used two basic concepts, the "plan" and the "image", best understood by the sentence:- "one imagines what ones day is going to be like and makes plans to cope with it."

The "plan" is defined as any hierarchical process in the organism that can control the order in which a sequence of operations is to be performed. The "image" is all the accumulated, organised knowledge that the organism has about itself and its world. Execution of plans can be overt or not, and the organism can alternate between many plans.

The fundamental nature of these concepts enabled the authors to relate various kinds of human behaviour from motor skill to concept attainment in terms of functional (rather than physical) processes. This approach is very similar to that of Koestler (1960) in another speculative book. Koestler concentrates on organisation, and particularly the theoretical advantages of hierarchical organisations over other forms. Koestler too, is able to consider a wide variety of behaviour, from the way we form administrative systems to language generation models.

It is interesting to note that this functionalist systems approach, which is stimulating so much growth in cognitive psychology is another branch of the same movement causing the recent advances in architectural design method. (see section 1.4)

4.2.4 Thinking as part of cognitive psychology

Cognitive psychology is the study of all the mental operations involved in the reception, storage and processing of information.

"Such terms as sensation, perception, imagery, retention, recall, problem solving and thinking, among many others refer to hypothetical stages or aspects of cognition."

(Neisser, 1967)

Such an all embracing definition of cognition leaves one wondering what it does not include. Indeed it is immediately apparent that cognition, so defined, must be involved in everything human beings do.

Recently 'cognitive psychology' has become associated with an approach to human behaviour from a particular point of view. This is summarised by Neisser (1967) as "asking how a man's actions and experiences result from what he saw, remembered or believed". The new cognitive psychology deals with process and operational function rather than physical mechanisms, and in this sense seems to have grown from gestalt psychology rather than behaviourism. Such notable writers as Miller et al. (1960) and Neisser (1967) state quite explicitly that the reason for their studying cognitive processes is because they are there. Neisser claims, with justification, that even stimulusresponse theorists are now "inventing hypothetical mechanisms with vigour and enthusiasm and only faint twinges of conscience". In tracing the fate of the sensory

input through the cognitive systems much use has been made of the metrics developed by the information sciences. The cognitive psychologists follow the first flush of enthusiasm shown by psychologists for applying information theory to human beings, and are perhaps less fanatical about its potential.

"The bit was developed to describe the performance of rather unselective systems; a telephone cannot decide which portions of the incoming message are important. We shall see that human beings behave very differently, and are by no means neutral or passive toward the incoming information. Instead, they select some parts for attention at the expense of others, recoding and reformulating them in complex ways."

(Neisser, 1967)

In their study of process, the cognitive psychologists have made use of the analogy between machines and men. Here too they are more cautious than some of their predecessors.

"Unlike men, artificially intelligent programmes tend to be single minded, undistractable, and unemotional."

(Neisser, 1967)

"The computer procedure cannot be called intelligent. Unless one is willing, with carefree operationalism, to define mental processes by their external output or unless one's notion of intelligence functions is so mechanistic that the behaviour of the computer does in fact meet the description."

(Arnheim, 1970)

Like the gestaltists, the cognitive psychologists regard cognitive process as constructive and organisational. Adaptive variation of sensory input or recalled information is the rule rather than accurate reproduction. One does not recall stimuli or responses directly from

'traces' existing in memory, but by an elaborate process of reconstruction. This has been expressed in a more extreme form by popular writers such as de Bono (1970).

"The function of mind is mistake; the efficiency of the brain is due to its being a bad memory surface."

An important feature of the cognitive psychology approach is the consideration of the problem of the 'executive'. The recognition of active organisation and reconstruction in perception and memory, rather than passive recording and recall, implies the existence of some executive process in control. In the past this existence has always been denied.

"The notion of a separate processor, or executive, is rejected not only by classical association theory but by behaviourism, by the 'trace theory' of Rock and Cerasso(1964) and by Gestalt psychology."

(Neisser, 1967)

Miller, Galanter and Pribram (1960) are quite explicit about the control exercised by their hypothetical executive:

"A plan is any hierarchical process in the organism that can control the order in which a sequence of operations is performed."

This is a natural development of the work of such writers as Bartlett, Bruner and Piaget who have all concentrated on the inherent organising and structuring characteristics of the cognitive processes without actually affirming the existence of an executive process.

The main notions and premises of the cognitive psychology approach are succinctly set out by Neisser (1967), and they form an apt summary

to this section.

1. Stored information consists of traces of previous constructive mental (or overt) actions.
2. The primary process is a multiple activity, analogous to parallel processing in computers, which constructs crudely formed "thoughts" or ideas on the basis of stored information. Its functions are similar to those of the pre-attentive processes in vision and hearing. Its products are only fleetingly conscious, unless they undergo elaboration by secondary process.
3. The secondary processes of directed thought and deliberate recall are like focal attention in vision. They are serial in character, and construct ideas and images which are determined partly by stored information, partly by wishes and expectations.
4. The executive control of thinking in the secondary process is carried out by a system analogous to the executive routine of a computer program.
5. The secondary processes themselves are mostly acquired through experience, in the same way as all other memories - which also represent early processes - are acquired.
6. Failures to recall information which is actually in storage are like failures to notice something in the visual field, or failures to hear something that has been said. The executive processes of recall may be directed elsewhere, either deliberately or because of a misguided strategy of search; they may also lack the necessary constructive abilities altogether.

4.3 Types of Thinking

Ryle (1949) notes that the term 'thinking' is a polymorphous concept, like the term 'farming'. Thinking, he suggests, consists of many different kinds of activity which may have little in common with each other, indeed two persons engaged in two kinds of thinking may not share any common activities. In the past psychologists have attempted to study thinking by dividing it up into sub-divisions which could be examined separately. For this reason the sub-divisions are often more convenient than meaningful. Perhaps the most well used categories are those of 'reasoning' and 'imagining'. (Vinacke, 1952)

In 'reasoning' the individual is said to carry out mental operations within some coherent symbolic system. Reasoning is considered purposive and directed towards a particular conclusion. This category is usually held to include logic, problem-solving and concept formation. When imagining the individual is said to draw from his own experience, combining material in a relatively unstructured way. Artistic, creative and autistic thought are normally considered 'imaginative'.

This kind of simplistic taxonomy is perhaps as misleading as it is helpful. If 'reasoning' and 'imagining' really were independent categories of thought one should not be able to sensibly speak of 'creative problem-solving', or a 'logical artistic development', which are both meaningful concepts. Some kinds of problems, even in such apparently logical disciplines as engineering, can be solved creatively. Certainly art can be logical and have well developed

structure. (Mueller, 1967). The fact is that rarely can one find an instance in the world outside the experimental psychologist's laboratory when one kind of thought is employed in isolation. The mode of thinking adopted in any particular situation is dependent on many factors. However, most writers seem to concentrate on two main related factors, the thinkers relation to the external world, and the nature of the directional control he exercises over his thought processes.

Murphy (1947) suggests that mental processes are bipolar, being influenced both by the external world and by inner needs. In his study of personality Murphy is particularly interested in the individual's susceptibility to these influences, and the resultant predominance of certain kinds of thinking observed in the individual. The normal person is rarely entirely preoccupied by either one of these influences for any amount of time, but rather alternates between the two. It is, however, possible to identify conditions under which one would expect the normal person to attend more to one influence than the other.

When problem-solving the normal person is attending more to the demands of the external world than to his inner needs; in imaginative thinking the individual is satisfying inner needs through cognitive activity that may be quite unrelated to the real world. This is precisely the distinction between design and art as cognitive tasks. Design is directed towards solving a real world problem while art is self motivated and centres on the expression of inner thoughts. (see section

1.2) This does not mean that imaginative thought should be excluded from the design process, but that its products must always be evaluated by rational thought, in order that the designers work should be relevant to his real world problem.

Guilford (1956) in a review of factorial research into intelligence concluded that intellectual factors could be sub-divided into two major groups - thinking and memory factors. The thinking factors are composed of cognition (discovery) factors, production factors and evaluation factors. Further to this Guilford found two types of production - convergent and divergent production.

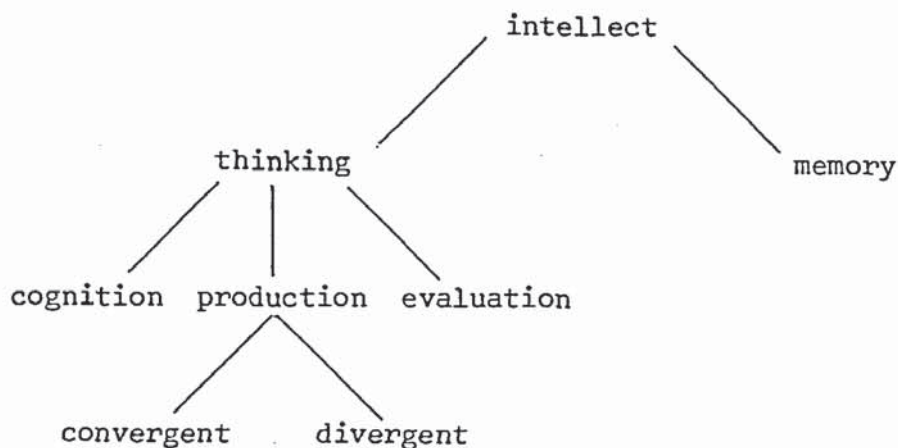


diagram 4.3.1

"The cognition factors have to do with becoming aware of mental items or constructs of one kind or another."

These factors reflect the individual's ability to recognise classes

of objects or ideas. Guilford maintains that recognition of a class may depend upon "figural", "structural" or conceptual content of its elements. One might recognise a class by perceiving its members, and relating their figural properties. One might recognise a rule or class by some structural relations between its members (as in the 'complete the series of symbols' type of IQ test question). Finally one might recognise a class conceptually, such as the class of all men with degrees in psychology. The cognition (discovery) of conceptual factors Guilford says is "an ability to define or structure problems". Guilford notes that this category includes the ability to recognise the existence of a problem. Guilford continues:

"Whether we shall ever find parallel factors for seeing problems of deficiencies of figural and structural types (as opposed to conceptual) remains to be seen. Problems of a figural type are faced in such aesthetic pursuits as painting and architecture."

Guilford specifically refers to architecture again when discussing what he refers to as perceptual foresight ability (as measured by maze tests).

"This ability may be important for the architect, the engineer, and the industrial layout planner."

Guilford's second group of thinking factors is concerned with the production of some end result. "Having understood a problem we must take further steps to solve it." As with cognition (discovery) factors Guilford lists three types of content, figural, structural and conceptual. That which is produced has value primarily at the perceptual level, or because of the relations between elements, or because it has meaning. However, Guilford does not pursue the analogy between the two groups of factors to any great extent.

Guilford expected that subjects would show both an ability to perceive order and an ability to generate it. The first ability would come under cognition (discovery) factors and the second under production factors.

"In the investigation of planning abilities it was hypothesised that there would be an ability to see or to appreciate order or lack of it, as a feature of preparation for planning. It was also hypothesised that there would be an ability to produce order among objects, ideas or events, in the production of a plan. A single ordering factor was found."

Thus Guilford found not two abilities to handle structure, or order, but one which seemed to belong amongst the production factors rather than the cognition factors. Guilford separates his production factors into two sub-groups which he calls divergent and convergent production. Since this taxonomy shows marked similarities to the notions of several other writers it will be dealt with in a separate section devoted entirely to types of productive thinking.

Guilford calls his final group of thinking factors 'evaluation factors'. These are abilities to make "decisions concerning the goodness, suitability, or effectiveness of the results of thinking." This calls for judgement either between several items, or by reference to absolute criteria. Guilford lists two groups of evaluation factors; perceptual and conceptual. The judgement is being made either on the figural qualities of the items or on their conceptual properties.

A study of the nature of architectural problems (see section 3)

reveals that the central task of the architect is to discover the inherent structure of his problem and produce a three dimensional expression of that structure. It would seem that what Guilford calls 'production factors' will play a large part in his thinking processes. The ability to recognise and produce order or structure both at the perceptual and structural levels will be all important. Both 'structural thinking' and 'productive thinking' deserve and receive more detailed attention in the next sections.

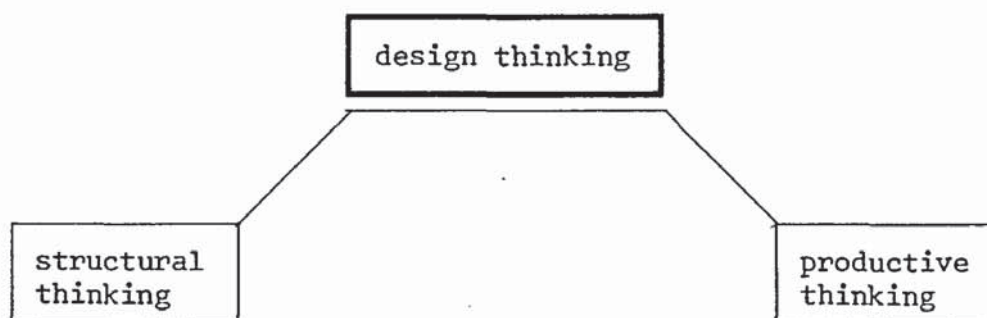


diagram 4.3.2

4.3.1 Productive thinking and architectural design

Wertheimer (1945) introduced the notion of 'productive thinking'. He was concerned with the directional quality of thought; "what happens when, now and then, thinking forges ahead?" He showed with a whole series of small experiments how, when in a problem situation, thinking

can be productive if it follows an appropriate direction. There are at least two fundamental questions the experimental psychologist can ask here. Is the thinker trying to control the direction of his thinking and if so is the direction productive or not?

It is clear that mental processes are bipolar in their directional quality just as in their relation to the external world. The thinker can wilfully control the direction of his thought, or he can allow it to wander aimlessly. The normal person does not engage solely in either one kind of thought, but varies the degree of directional control he exercises. Here is another distinction between design and art. The designer must consciously direct his thought processes towards a particular end, although he may deliberately use undirected thought at times. The artist, however, is quite able to follow the natural direction of his mind, or to control and change the direction of his thinking.

Bartlett's (1958) classification could be used to support this argument distinguishing as it does between the artist's thinking and that of the designer.

"There is thinking which uncovers laws of finished structure or of relations among facts of observation and experiment. There is thinking which follows conventions of society or of the single person, and there is other thinking still which seeks and expresses standards."

Clearly the search for, and expression of standards is pure artistic thought. The designer must primarily indulge in Bartlett's first kind of thinking in order that he can appreciate the relationships of the elements of his problem. The amount of purely expressionistic thinking he can do is a function of the amount of designer's constraint allowed

in his problem (see section 3.5).

Guilford (1950, 1956) has identified two modes of productive thinking which he calls convergent and divergent production.

"In convergent thinking, there is usually one conclusion or answer that is regarded as unique, and thinking is channelled or controlled in the direction of that answer."

This rather curious phraseology is later explained more fully. What Guilford seems to mean is that there is a uniquely correct answer to a problem requiring convergent thinking.

"In divergent thinking, on the other hand, there is much searching or going off in various directions."

Guilford goes on to state that divergent thinking is most clearly seen when there is no unique conclusion.

Guilford treats convergent and divergent thinking as separate and independent dimensions of ability which, he says, can occur in any proportions in an individual. Guilford maintains that, even though few real world tasks require exclusively convergent or divergent thought, the distinction is still valid and useful.

"The distribution is not so clear in some problem-solving tests, in which there must be, and usually is, some divergent thinking or search as well as ultimate convergence towards the solution. But the processes are logically and operationally separable, even in such activities."

This realistic attitude towards problem-solving makes Guilford's work

ideally suited for use in the study of design.

Several other later workers have used Guilford's notions of convergence and divergence to study personality differences. Notable amongst these are Getzels and Jackson (1952) and Hudson (1967, 1970) both of whom studied school children. Getzels and Jackson (1962) distinguished individuals of high IQ from those with high creative abilities.

Two groups of subjects were used for a variety of tests and observations. One group was high in IQ or convergent abilities but low in creative talent. The second group exhibited considerable creativity, or divergent abilities, but had low IQ. Getzels and Jackson noted that Guilford's "convergent thinking" and "divergent thinking" are similar to Rogers' "defensiveness" and "openness" and Maslow's "safety" and "growth".

Both Getzels and Jackson and Hudson found significantly different archetypal personalities associated with individuals high in convergent or divergent production abilities. Most interesting of the findings in this context is the tendency for convergers to be attracted to arts courses and divergers to science courses. Since architectural design is neither entirely open or closed end it is inevitable that both divergent and convergent thought will be needed. Consequently both kinds of ability are required in architects. The debate as to whether this balance of abilities can or should be found within each individual seems now a permanent feature of architectural discussions.

Bartlett (1958) suggests that there are two main modes of thinking both of which can be 'productive' in Wertheimer's sense of the word. These two modes of thinking he calls "thinking in closed systems" and "adventurous thinking". Bartlett defines a closed system as possessing a limited number of units which may be arranged in a variety of orders or relations. Formal logic is such a closed system as are arithmetic, algebra and geometry. Bartlett identifies two processes in closed system thinking, interpolation and extrapolation. Here again we see the concept of the directionality of the thinking processes being used to distinguish between them.

"Genuine thinking is always a process possessing direction. In interpolation the terminal point and at least some evidence about the way there are given, and all that has to be found is the rest of the way. In extrapolation what is provided is some evidence about the way; the rest of the way and the terminal point have to be discovered or constructed. So it is in extrapolation that directional characters or properties are likely to become most prominent."

These two processes of Bartlett's closed system thinking, interpolation and extrapolation are most attractive concepts, and it is easy to think of many exemplars of them. Indeed Bartlett was able to go further and examine the characteristics of people thinking in these ways with simple laboratory tasks. However, when we consider real world design conditions, the situation loses some of its clarity. Rarely in design does one know or not know the terminal point, but rather one has some information about it. Indeed it is a matter of degree rather than absolute extremes. In some kinds of design one knows almost exactly where one will end up, in other kinds one has very little idea. Architectural design seems to be near the middle of this spectrum being neither entirely open or closed ended. (see section 3.6)

Bartlett's other mode of productive thought, adventurous thinking is less clearly defined than thinking in closed systems. The repertoire of elements which can be considered is not prescribed in this mode of thought. Indeed it often depends for its success upon elements normally thought of as in different ensembles being considered together, hence its adventurous nature. Adventurous thinking is usually at its most productive when this kind of juxtaposition leads to a genuinely new direction.

The difference between adventurous thinking, and thinking in closed systems seems to be basically that of directional control. In most of Bartlett's discussion he seems to assume that the thinker is consciously and deliberately dealing with the needs of the external world. He does not consider for example, the kind of autistic thought that goes on when we daydream, and in this his writings seem to relate easily to the design activity. However, Lawson (1970) pointed out that when considering design, the distinction between Bartlett's 'adventurous thinking', and 'thinking' in closed systems' becomes as blurred as the distinction between interpolation and extrapolation.

One can easily find closed systems, as defined by Bartlett, in architectural problems if one looks for them. The problem of arranging tables and chairs in a restaurant certainly requires 'thinking in closed systems'. Such examples, however, do not bear too close an examination. Most sensible architects would try to design a restaurant from the inside out. The architect is not given a 'kit' of parts. If a particular arrangement will not fit, the architect may try

different sizes or shapes of tables or he may alter the shape of the restaurant. The ensemble of elements that the architect works with is neither entirely closed nor entirely open. He often needs to combine adventurous thinking with thinking in closed systems to deal adequately with his problems. Posner (1962) has developed a taxonomy of human information processing which corresponds well with Bartlett's modes of thinking. Working from quite different starting points the two classification systems identify the same basic divisions of productive thought. Posner considers that thinking in relation to external factors can be studied by comparing inputs with outputs thus discovering the informational transform carried out in the brain. Three basic types of transform are listed; information conservation, information reduction, and information creation. Conservation tasks include such well observed experimental situations as reaction time and memory span. The subject is expected to preserve all of the input information in his response. Reduction tasks such as addition, classification, and selection require the subject to produce only a specified subset of the input information. Posner's third set of tasks, information creation, require the subject to produce more information than is in the input.

Posner himself (1965) has observed the similarities of his information creation category to Bartlett's 'adventurous thinking'. Bartlett describes translation tasks in closed system thinking in which there is one to one correspondence between two codes, and the subject is required to translate from one to the other. This is quite clearly an information conservation task in Posner's taxonomy. Bartlett

describes other closed system tasks in which the response is in some way implicit in the stimulus or input. The required response here is obviously a reduction of the information contained in the stimulus.

By taking this informational approach to thinking Posner (1962) suggests that Bartlett's qualitative distinctions may become quantitative differences. There seems hope here too that not only different modes of thinking can be related but also other cognitive processes such as memory and discrimination. Thus while many would maintain that Posner's ideas are behaviouristic, because of his dependence on the mechanistic informational metric, he associates himself with a gestalt based psychologist such as Bartlett and one begins to doubt the value of the distinction, in this field at least.

Other, perhaps slightly less serious writers, have popularised the notion of different types of productive thought. De Bono (1967) introduced the notion of "lateral thinking" which he contrasted with the more normal "vertical thinking". De Bono suggests that "lateral thinking" ability can be consciously acquired and developed. "Lateral thinking" is in many ways similar to Gordon's (1961) "synectics" which is an artificially contrived mode of thinking likely to be useful in open ended situations. These approaches are based upon encouraging the individual to deliberately distort his problem and look at it in a new way. Gordon instructs the thinker to make the familiar, unfamiliar, and the unfamiliar, familiar. This kind of work is not so much an attempt to discover the nature of our thought processes, but rather to encourage particular patterns of thinking in certain

problem-solving and designing situations.

In conclusion, it seems that there are at least two kinds of productive thought. The one, convergent production, tends towards conservation, interpolation and reduction, and often proceeds in regular systematic logical steps. The other, divergent production, tends towards change, exploration, and expansion, and is often unpredictable, uncontrollable and proceeds irregularly. Clearly architectural design requires both kinds of thought (see section 3), and it is this that makes such a challenging and satisfying area both in practice and research.

4.3.2 Structural thinking and architectural design

To think sensibly about a large system, one must consider both its constituent parts and their relationships. It is the recognition that relations are at least as important as parts that characterises the modern systems approach to architectural design, and it is with the cognition of relations that this section is concerned. Just how do we perceive order and structure in a system external to ourselves which we are studying?

When an architect reaches the central problem-solving stage of design (see diagram 2.3.3) he has identified the constituent parts of the system he is working with. Next he must develop an understanding of the way in which these parts are inter-related and also relate to the macro-system (internal and external constraints, see section 3.5). Traditionally this task has been embedded in the complementary one of

building up a three-dimensional structure incorporating the parts in suitable relations. The architect seems to be learning about the structure of his system while he is attempting to design it. This phenomena is perhaps not very surprising in the light of Guilford's finding that there seems to be only one ability covering the recognition and production of order. Few psychologists seem to have considered both the recognition and production of order at the same time, and if one is to learn from other work in this field one must first turn to studies of man's recognition of structure.

In their now classical 'study of thinking' Bruner, Goodnow and Austin (1956) attempted to discover how we recognise structure in multi-dimensional stimuli. The experiments reported in this study usually come under the category of concept attainment. The work is based on the premise that we use the presence or absence of certain combinations of attributes to define for ourselves categories. Bruner et al. refer to these categories as concepts, and show how they are built up and modified as more information becomes available. Bruner in his developmental work on concept formation has shown how a child may develop accurate concepts from inaccurate ones. For example, a young child may recognise 'cows' by the presence of four legs. It is perhaps not until he calls a horse 'cow' in the presence of a parent that he learns that both four legs and horns must be present for an animal to be called 'cow'.

The work of Bruner et al. is often quoted in association with the various writings of Piaget on the child's development of a conceptual

structure. Piaget's theory describes a sequential development process that has a serially determined order. At each stage he identifies certain cognitive abilities which develop. In the final stage of 'formal operations' Piaget notes that our ability to carry out logical operations on abstract symbols appears. Whereas Bruner et al. concentrate on concepts being a category structure dependent upon the relations of attributes, Piaget is more interested in abstract concepts. The development of the child's concept of number or of conservation of matter, seems a more generally acceptable use of 'concept', than Bruner et al.'s category system. Piaget is primarily interested in the first appearance of a concept in the individual mind, concept formation, whereas Bruner et al. study adults 'attaining concepts'. The latter is not so much a matter of intellectual advance as simply detecting some structure in a closed system.

This distinction between the works of Bruner and Piaget is, I believe, an important one. Although I have not seen it made elsewhere, it would seem to follow quite reasonably from Guilford's (1956) model of the intellect. Guilford's model provides for three kinds of content in cognitive operations; figural, structural and conceptual. (The 1967 model includes four types of content; figural, symbolic, semantic and behavioural. This more elaborate structure does not help the present discussion and seems in some ways to confuse the issue.) It can be seen that Bruner et al.'s 'concepts' are concerned with the figural or 'structural' relations of parts of the whole, but Piaget's concepts are concerned with conceptual content. Thus, although Bruner et al. call their book 'A study of thinking' and call their categories

'concepts', it seems that they are really discussing that rather more limited area which I have called structural thinking.

The experiments reported in Bruner et al. (1956) are concerned with the structural relations of attributes of multi-dimensional stimuli. Subjects were presented with an array of cards showing simple symbols having from four to six attributes varying over two or three values each. The attributes were quantities, or simple qualities such as shape, colour and pattern. Thus one card might show four, red, squares and another two, green circles. Either the subject or the experimenter (in different experiments) selected one card at a time, and the subject was told whether or not the card exemplified a particular concept that the experimenter had predetermined. The subject then had to use this information to discover the concept chosen by the experimenter.

The 'concepts' used by Bruner et al. were structural relations between the attributes of the symbols. Thus one 'concept' might be 'all cards with red squares,' and another might be 'all cards that either have circles or are green.'

This kind of experiment was first used in relation to the design process by Lewis (1963) who examined the communication within design teams by substituting a group for the single subject in the Bruner et al. experiment. More recently the idea was developed by Lawson (1969) to examine the way individual subjects looked for and processed information about a multi-dimensional structure. Several groups of findings relevant to this study are growing out of these and other

experiments in structural thinking, and they are reported in the next section.

4.4 Structural Thinking

4.4.1 The effects of different types of structure

A lot of attention has been given to subjects' performance in perceiving different kinds of structural relations in concept attainment type experiments. A discussion of most of the structural relations employed is to be found in Haygood and Bourne (1965). These authors follow the practice of listing relations in a hierarchy according to the number of logical 'and'/'or' symbols to specify them. Logical 'and' (.) relating two attributes indicates their joint presence, where-as logical 'or' (U) indicates the presence of either or both of them. In addition an attribute may be specified as present or absent independently of any other attributes. Let us consider a four dimensional two value matrix with dimensions A, B, C, D.

		A1		A2	
		B1	B2	B1	B2
C1	D1				
	D2				
C2	D1				
	D2				

diagram 4.4.1

The simple structural relations have been named, and these names will be used in future discussion. The simple presence of one attribute

(A1) is known as the 'affirmation', and its absence ($\overline{A1}$) as the 'negation'. At the next level of complexity two attributes related by logical 'and' ($A1 \cdot B1$) gives a 'conjunction', and when related by logical 'or' ($A1 \cup B1$) gives a 'disjunction'. Other more complex levels still are to be found in the literature (see Haygood and Bourne, 1965).

It seems reasonable to suppose that the more attributes that are linked by these two basic operations (and,or) in any one 'concept' the more difficulty the subject will have in attaining it. This has been shown to be true by Neisser and Weene (1962), who generated a hierarchy of complexity similar to that used by Haygood and Bourne. Neisser and Weene used a three level hierarchy (see diagram 4.4.2) while Hunt and Kreuter (1962), who also reached the same conclusions, used rather fewer concept types.

Rather more attention has been directed towards the apparent intra-level differences in subjects ability to attain concepts. Many authors have suggested that subjects find disjunctive concepts more difficult to attain than conjunctive concepts at the same level in the hierarchy. However, these various findings are not directly comparable since the experimental conditions differ.

Bruner et al. (1956) suggested that their subjects experienced more difficulty in handling disjunctive concepts than conjunctive concepts.

..

"What is peculiarly difficult about attaining a disjunctive category is that two of its members, each uniform in terms of an ultimate

Conceptual Rules Describing Partitions of a Population with Two Focal Attributes (from Haygood and Bourne, 1965)

^a symbolic descriptions using only the three basic operators, ., U, and negation, are given in brackets. . = logical and
^b There is no special symbol for exclusion in general use.

Level	Basic rule			Parti- tion	Complementary rule		
	Parti- tion	Name	Symbolic description		Verbal description	Name	Symbolic description ^a
I	E	Affirmation	R	H	Negation	R	All patterns which are not red are examples of the concept
II	K	Conjunction	R·S	D	Alternative denial	$\frac{R \bar{S}}{R\bar{S}}$	All patterns which are either not red or not square are examples
A		Inclusive disjunction	RUS	N	Joint denial	$\frac{R \bar{S}}{R\cdot\bar{S}}$	All patterns which are neither red nor square are examples
C		Conditional	$\frac{R\rightarrow S}{R\bar{S}}$	L	Exclusion ^b	R· \bar{S}	All patterns which are red and not square are examples
III	F	Biconditional	$\frac{R\leftrightarrow S}{(R\cdot S)U(\bar{R}\cdot\bar{S})}$	J	Exclusive disjunction	$\frac{R\bar{S}}{(R\cdot\bar{S})U(\bar{R}\cdot S)}$	All patterns which are red or square but not both are examples

criterion may have no defining attributes in common."

The authors go on to show how in their opinion we strive to avoid disjunctive categories in everyday life.

"At the outset, before stringent control is imposed, the defining attributes of the class 'clinical psychologist' tend to be disjunctive. (either experienced or had academic training) Social control has a regularizing effect rendering the definition of the class conjunctive. A board of examiners is created and examinations are set."

Although the subsequent argument seems introspectively reasonable the authors fail to prove it conclusively with their data. Disjunctive and conjunctive concepts were used in two separate sets of experiments. In each case the subjects knew what the concept type was, and their only task was to identify the relevant attributes. Several conditions were used under which either the experimenter or the subject would select the instances with different sizes of array. In no case, however, was the same sized array used under the same conditions for both conjunctive and disjunctive concepts.

Lawson (1969) discussed the difficulty of comparing conjunctive and disjunctive concepts in the same experiment.

"When should a disjunctive problem be considered as objectively difficult as a conjunctive one? One possible answer is, when it has the same number of members (positive instances). However, it is impossible to create this situation unless the two problems come from different sizes of total array, in which case are they really comparable?"

Several information theory models of problem difficulty were examined.

One promising model revealed that only sets containing a disjunctive relation exhibit contingent uncertainty between their dimensions. This might explain subjects extra difficulties with disjunctive concepts. However, this model also predicted increasing difficulty with conjunctive concepts as they get larger (i.e. higher levels in the hierarchy) which is contradicted by the findings of all writers on the subject.

Conant and Trabasso (1964) compared the performance of subjects attempting to attain conjunctive and disjunctive concepts under equal information conditions. Four attributes each had two values to give a sixteen cell matrix which was laid out in front of the subject. The subject was instructed whether the concept would be conjunctive or disjunctive, and was allowed to select instances until he could verbalise the concept. A four binary variable array can be partitioned such that it leaves a disjunction and its complementary conjunction. This makes the minimum number of selections required to define either a disjunction or a conjunction equal. Subjects required more instances to attain the disjunctive concepts than the conjunctive concepts.

Lawson (1969) carried out a similar experiment using a four binary variable matrix, but with conjunctive and disjunctive problems mixed randomly in each session. Subjects did not therefore know in advance what kind of concept they were dealing with. Lawson found that subjects required significantly more selections to arrive at the disjunctive concepts than the conjunctive concepts at the same hierarchical level.

In addition many more disjunctive problems remained unsolved after the maximum allowable sixteen instances. In this experiment the subjects attended for four experimental sessions, and considerable learning effects were observed. However, the differences between disjunctive and conjunctive concept attainment were still significant on the fourth day. Jeeves (1971) reports a longer experiment which also showed significant results on the final session.

It seems reasonable to conclude from these findings that disjunctive concepts are more difficult to attain than conjunctive concepts, although the reason why this should be so is not yet obvious. Three related factors have been suspected of causing this phenomenon by several writers; the way in which subjects form hypotheses about the concepts, the way in which they attempt to test these hypotheses and the use of positive and negative information.

4.4.2 The formation of hypotheses

In their experiments on concept attainment Bruner et al. made a detailed a posteriori analysis of subjects information search and interpretation strategies. These strategies operate upon the last piece of information received by the subject and tell him which instance he should select next, and what to make of the information gained. Bruner et al. identified two main groups of strategies which they called 'scanning' and 'focussing'.

When using a 'simultaneous scanning strategy' the subject considers all possible concepts simultaneously, and, as information becomes

available, he dismisses those which are logically impossible. This strategy is almost certainly optimal in its utilisation of information. However, the problem of computing which instance to select next is a large one and the interpretation of information requires the storage of vast amounts of previously received information.

A cognitively more simple strategy called 'successive scanning' depends upon the subject considering only one concept at a time. He tests the concept by selecting an instance, and if proved wrong selects a new concept and tests that. This approach obviously tends to result in a great deal of redundancy in the selected attribute combinations, and can be a lengthy procedure.

Scanning strategies are characterised by the subject concentrating on concepts. The second group of strategies identified by Bruner et al., focussing strategies, are characterised by the subject concentrating on the variables or attributes of the array.

In 'conservative focussing' the subject first finds a positive instance and focusses on its attributes, varying one at a time for each selection. If the new selection is positive, then the attribute altered is considered irrelevant, if negative then the attribute is critical. This is a cognitively simple and popular technique, but it gives rise to confusion when the concept is disjunctive (two positive instances of a disjunctive set need not share any common attributes).

The last of Bruner et al.'s strategies is called 'focus gambling'.

This strategy resembles conservative focussing except that the subject changes more than one attribute each time. This means taking a gamble; it could be a lot quicker if the new instance is still positive, but little information is gained if it is negative.

Lawson (1969) pointed out that no one of these strategies could work alone in the design situation.

"The designer's task is far too vast for scanning techniques, and he never knows in advance that the structure is solely conjunctive. In fact, as Bruner et al. note, the focussing strategy leads subjects into chaos when applied to disjunctive problems. Neither focussing or scanning alone are sufficient to meet the designer's needs."

Lewis (1963) in his experiments on design group problem solving, which used the Bruner et al. material, did not find his subjects adhering to these strategies. Even so it would seem that Bruner et al. have identified several major variables in search strategies. Bruner et al. also described information reception strategies, used by the subject in experiments where the experimenter selected the instances. These fall into two categories analogous to the search scanning and focussing types. The complete lack of freedom and control given to the subject renders these experiments irrelevant to a study of design problem solving.

Of all the strategies identified by Bruner et al. 'simultaneous scanning' makes the greatest use of the available information. Neisser and Weene (1962) wrote a program to enable a computer (IBM 709) to operate this simultaneous scanning strategy. The machine started

by considering all possible concepts, and rejected logically impossible ones as information came in. Unfortunately the computer was not allowed to make its own selections in this experiment, although various different sequences of instances could be presented for the same concept. It was found that the simple (level 1) concepts such as affirmations or negations took longer to solve than conjunctions or disjunctions. Neisser and Weene found the reverse true for their human subjects who seemed to consider the possible concepts in a hierarchical order. This hierarchy followed the hierarchy of structural complexity referred to in the previous section. Thus subjects tended to hypothesise structurally simple concepts before hypothesising more complex ones.

Hunt and Hovland (1960) examined subjects' preference for hypothesising with conjunctive, relational and disjunctive concepts. Subjects were shown stimulus cards with variously coloured shapes and stripes. A relational concept might be "the same number of stripes and shapes", while conjunctive and disjunctive concepts had the same structure as previously described. A series of cards labelled either 'alpha' or 'not alpha' were presented to the subject who was asked to define 'alpha'. In each case it was logically possible to describe any of the three types of concept. Hunt and Hovland found that their subjects tended to hypothesise conjunctive and relational concepts significantly more often than disjunctive concepts.

Lawson (1969) in an experiment which mixed affirmations, conjunctions and disjunctions in one session, allowed subjects to select their own

instances. The results of this experiment tended to confirm the findings of both Neisser and Weene, and Hunt and Hovland. After each selection the subject was requested to hypothesise the concept, and to continue selecting instances until he was certain he was correct. Lawson analysed the protocols of subjects solving 56 problems each. He found that the protocols followed a hierarchical order showing preference to the conjunctions rather than the disjunctions at each level.

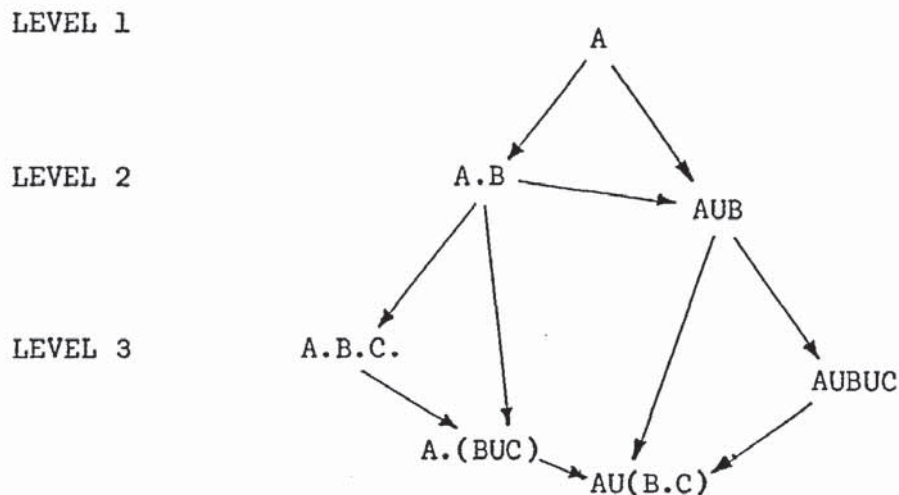


diagram 4.4.3

Lawson found that when a hypothesis was refuted the next hypothesis to be formed was either at the hierarchy level below or a disjunctive hypothesis at the same level. This was found to be true for 89% of the 616 protocols analysed.

It would seem from all of these results that subjects show a

significant preference for hypothesising structurally simple concepts or conjunctive concepts rather than complex or disjunctive concepts.

4.4.3 The rejection of hypotheses

Our subject having formed a hypothesis about a concept, we must assume that he will use the next instance to test that hypothesis. Of most interest in this connection are those experiments which allow the subject to select his own instances. The subject may choose an instance which would be positive if his hypothesis should prove correct, or one that would be negative. More importantly, the subject may either be attempting to confirm his hypothesis or to refute it.

Wason (1960) carried out an open ended concept attainment experiment to investigate subjects ability to reject old hypotheses. Subjects were told that a series of three numbers conformed to a certain relational rule. They were asked to find the rule by generating new series and asking if they fitted the rule too. They were then to hypothesise what the rule was and continue. The series Wason presented was deliberately highly redundant (12, 24, 36) while the rule was very basic (any increasing series). He found that subjects tended to concoct more highly constrained hypotheses than necessary (e.g. increasing in 12's), and then seek confirmation with the next series they proposed (e.g. 48, 60, 72). After generating several such series the subject would announce that he was sure he was correct. Even when told they were wrong some subjects remained so attached to their hypothesis that they merely rephrased it, or further constrained it, (the difference between the first and third number is 24 and the second

number is the first plus half the difference).

Wason has been criticised over this experiment (Wetherick, 1962) on the grounds that 'the subjects' task is misleading', mainly because of the redundancy of the series initially presented to the subject. This criticism, however, seems to rise from a complete misunderstanding of the nature and purpose of the experiment. Wason himself (1968) has replied to this criticism.

"Unlike most concept attainment tasks the point was not to see whether subjects discovered the rule - the point was to see how they behaved when their hypotheses had been corroborated by confirming evidence."

One is forced to agree with Wason in his conclusion that subjects show an alarming tendency to seek confirmation rather than refutation of their hypotheses. On a much grander scale this point has been elaborately developed by Popper (1962) who Wason quotes,

"It is easy to obtain confirmations or verifications for nearly every theory - if we look for confirmations."

Bruner et al. in their experiments, found a tendency for subjects to seek confirmations for conjunctive hypotheses inside disjunctive rules. A subject may for example get the impression from the instances he has seen that the attributes 'red' and 'circle' are important in the concept. He then hypothesises 'red and circle' and selects an instance containing both attributes. If the concept is really 'red or circle' the instance will be positive. Thus the subject finds his erroneous hypothesis

confirmed. The findings of Hunt and Howland (1960) that subjects preferred conjunctive to disjunctive hypotheses suggest that it is quite easy for a subject to start down the trail of confirmed conjunctions as identified by Bruner et al.

Lawson (1969) noted large individual differences, apparent in his results, in subjects' capacity for self criticism.

"KM arrives at a conjunctive hypothesis with a disjunctive problem. There are four possible confirming instances, and all are tried. In a similar situation CP immediately seeks rejection by varying one (not both) of the critical attributes, and makes a saving of several selections over KM."

The four sessions used in Lawson's (1969) experiment are insufficient to come to general conclusions about learning. However, a trend is apparent showing subjects becoming more critical of their hypotheses in later sessions.

4.4.4 The use of positive and negative instances

In a game of twenty questions the participants may only ask the chairman questions to which he can sensibly reply either 'yes' or 'no'.

Depending upon the way the question is phrased one answer will often be more useful than the other. For example, if the team have identified that the answer is an item of clothing they may ask, "is it a hat?". The answer 'yes' would obviously be more useful than the answer 'no'. If the team were to ask, "is it worn above the belt?" either answer is probably as useful. In a limited universe of events, where the number of questions that can be asked is finite, it is often possible

to ask questions to which the answer 'no' is more useful than the answer 'yes'. If an item has not got some attributes, it is relatively simple to infer which attributes it may still have. Huttenlocker (1966) has shown that this simple inference from negative instance to positive conclusions is problematic, at least for young children.

Huttenlocker presented children between the ages of six and twelve with two switches and a light bulb. The child is asked to tell the experimenter, on the basis of throwing only one switch, what turns the light on. There are four possible situations. The light may initially be on or off, and the throwing of the switch may change it or not. The four conditions; off-on, on-off, on-on, off-off, require increasing numbers of inferences to arrive at the required answer. Huttenlocker found that the six year old can perform almost as well as the twelve year old in the easiest (on-off) situation. However, the more inferences he must make the poorer his performance. In contrast the twelve year old child continues to perform almost as well in all the other conditions.

Whitfield (1951) compared the value of positive and negative information given to subjects in a matching experiment. The subject was given 8 different objects and a sorting board. The sorting board was divided into 8, 4, or 2 cells in the three different conditions of the experiment. Each object was allocated a cell by the experimenter before the experiment commenced. The subject then placed the items, one in each of the 8 cells (1st condition), or two in each of the 4 cells (2nd condition) or four in each of the 2 cells (3rd condition).

The experimenter told the subject which cells, if any, were correctly occupied and then removed all the objects. The subject had to get the completely correct placing of all 8 objects with as few trials as possible. In the first condition (8 cells) the information that an object is correctly placed is more valuable than the information that it is not. However, in the third condition (2 cells) these two types of information are exactly equal. In the 4 and 2 cell conditions, Whitfield sometimes told his subjects how many objects were correctly placed. In the 2 cell condition the information that one object is correct is equivalent to the information that three objects are incorrect. Whitfield observed that the mean number of further trials to success was significantly greater when following the latter, negative kind of information, than when following the former, positive kind of information.

Donaldson (1959) carried out a matching experiment similar to Whitfield's, but specifically designed to compare the value of positive and negative information. In this experiment subjects were able to choose whether to use positive or negative information, but were penalised more heavily for choosing positive information. Donaldson found that subjects were both unwilling and unable to work with negative information as opposed to positive information.

In a concept attainment experiment each instance that the subject encounters will either be an exemplar of the concept or not. Most writers refer to the instance as being either positive or negative. In an experiment which requires the subject to hypothesise the concept,

the instance will also either confirm or refute the subject's current hypothesis. If the subject's hypothesis is refuted, logically he must change it; if confirmed he may maintain it. This applies whether the instance is positive or negative, and can be represented by the decision matrix below.

instance	positive	negative
confirming	maintain hypothesis	
refuting	change hypothesis	

diagram 4.4.4

Bruner et al. found more departures from this decision matrix for refuting instances than for confirming instances. In addition some of the changed hypotheses, which were correct responses to a refuting instance, were logically untenable. More surprisingly more departures were also found in the negative column than in the positive column of the matrix. Some subjects were even reported to change their hypotheses under the negative-confirming condition.

Smoke (1932) reported that subjects showed extremely poor results when attempting to learn concepts from negative instances. When presented entirely with positive instances, he claimed subjects learn concepts considerably faster and more reliably. Smoke did not, however, use a defined universe of attributes and dimensions for his subjects to

work with. Hovland and Weiss (1953) have pointed out that in this rather unstructured situation, it is not possible to compare the potential information content of positive and negative instances.

Hovland and Weiss (1953) report a series of experiments specifically designed to correct this deficiency in Smoke's much earlier work. In the first experiment subjects were presented with a series of positive instances sufficient to define the concept. This was then followed by a similar series of negative instances. The information content of the two series was calculated and equated by a method developed by one of the authors (Hovland, 1952). In the second experiment a complete series of positive or negative instances was presented simultaneously instead of successively. In the third experiment concepts were selected so that they required an identical number of positive, negative or mixed instances to define them exactly. Hovland and Weiss concluded from their results that:

- "a. The correct concept is attained by a higher percentage of subjects when transmitted by all-positive instances than by all-negative instances.
- b. Mixed positive and negative instances are intermediate between all-positive and all-negative series in difficulty of learning.
- c. When the negative instances are displayed simultaneously, the accuracy of concept attainment is higher than when they are presented successively."

Thus the general conclusion from these results is that negative instances are less valuable than positive instances, but more valuable than Smoke estimates.

Lawson (1969) measured the time taken for subjects to arrive at their next hypothesis after receiving the information from an instance, which they selected themselves. The results were cast into four separate time distributions representing the four possible contingencies (positive and negative, confirming and refuting). The reported findings of Whitfield, Huttenlocker, Hovland and Weiss, Bruner et al. and Smoke suggest that negative instances are found more difficult to process than positive instances and refuting instances more difficult than confirming instances. It would seem reasonable to expect this to be reflected in Lawson's time distributions. However, Lawson found that subjects took significantly longer to process positive refuting instances than negative refuting instances. (see graph p53) Since the reverse was true for confirming rather than refuting instances, it seems likely that Lawson's subjects were not extracting as much information from negative refuting instances as they might.

Lawson observed from his informational analysis that positive instances are not only more numerous in disjunctions, but also contain more irrelevant information than in conjunctions.

"Theoretically it is easier to specify a disjunction by what it is not, than by what it is. However, this cannot be done without attending to the negative instances."

This seems to suggest that subjects' preferences for conjunctive concepts and for positive instances are inexorably bound together.

4.5 Architects as a Special Cognitive Group

4.5.1 The architectural student's choice of career

When enquiring into the ways in which students select architecture as a career one soon encounters the concept of vocation. It is popularly held that the majority of architects are called to their profession rather than rationally selecting it. Architecture is not taught at school, nor does it follow on naturally from any school subjects. It is rare to find students who were given more than superficial and doubtful descriptions of the architect's task by their school career advisory service. Typically it seems that art masters show the best understanding of the design careers, and students with aptitude for design in their school artwork may be advised to study architecture. It is rare to find a student who has been recommended to study architecture by a school master because he is strong in other subjects such as mathematics or physics. Perhaps this is due to a natural tendency for teachers to suggest that their own subject should be read at university.

Lawson (1972) found that 91% of students at the Birmingham School of Architecture said that they had first thought of becoming an architect themselves rather than had it suggested to them. Of the remaining 9% most had been recommended by a relative, often an architect, to follow the career. Only one student in the school had received professional vocational advice to become an architect. Lawson found that the decision to become an architect was typically taken at 15.33 years, which seems a normal time for career choice (although a small number

of students claimed to have chosen their career before the age of ten). This does not suggest a profound and early calling to an inevitable vocation. It seems likely that many students now select architecture because they do not have an obvious first subject, which they could read at university, but rather they have broad but undistinguished abilities often including art. Although this hypothesis is as yet untested it is supported subjectively by many responsible for the entrance of students to schools of architecture. Headmasters' reports often recommend students to schools of architecture on the basis that they are generally competent, without any outstanding abilities but fairly good at art.

When a student has chosen his career he must then subject himself to the selection procedures of a school of architecture. Usually a student is asked to attend for an interview with samples of his work. GCE results are usually treated as necessary but are relatively unimportant in selection. Most schools administer some 'aptitude' tests which are usually angled to detect spatial ability, but again a minimum level of attainment is all that is required. The school usually bases its final decision on the interview and student's work. If the student has particularly good examination results or has performed well at an aptitude test this is taken as extra evidence.

4.5.2 The influence of the school of architecture

Students of architecture attend college full time for a period of up to five years. The vast majority of students come directly from school, although there is also a small proportion of older students

who have typically been employed in architects' offices for some years. The vast majority of students attend schools of architecture between the ages of 17/18 and 22/23. It seems reasonable to suppose that many lasting attitudes, habits and interests will form in these years and that the intellectual environment of a school of architecture will have some influence on them. As outlined in section 1, architectural education depends largely upon a succession of exercises of increasing difficulty and complexity.

The final year architectural student then, has been solving similar problems in a fairly intensive manner for nearly five years. It seems reasonable to hypothesise that he will have developed some strategies and tactics which he employs more or less consciously when problem-solving. The whole language of communication used by architects is visual. Problems are expressed visually as much as possible, and solutions always are. This spatial language may well reinforce some cognitive strategies and discourage others. This seems especially likely in the case of the typical student who comes to the school with an apparent preference for tasks calling for high spatial ability.

Both observational and armchair psychological investigations suggest that architectural students will not show a representative cross-section of what may be loosely called cognitive style. Evidence that this is so will be examined in the next section.

4.5.3 Personality studies

Architects seem to have fascinated those psychologists who search for the personality correlates of creative talent. MacKinnon (1962) tells us that,

"it is in architects, of all our samples, that we can expect to find what is generally most characteristic of creative persons in what other profession can one expect better to observe the multifarious expressions of creativity?"

MacKinnon studied architects who had been judged by their peers to be highly creative, along with other groups of architects, whom he had no reason to believe had exceptional creative talent. MacKinnon has found that highly creative persons tend to exhibit certain common personality traits. Over simply stated, his architects generally showed these traits and in a more pronounced manner in the 'highly creative' group. More than this, MacKinnon claims that the typical creative architect can be distinguished in some ways from creative individuals in other occupations such as science, mathematics or art.

MacKinnon summarises the creative architect as aggressive, dominant, self confident and not especially sociable. He is self centred, persuasive, relatively uninhibited, and independent. MacKinnon also found that creative architects were not interested in "striving for achievement in settings where conforming behaviour is expected or required". With reference to their college work it was found that "In work and courses which caught their interest they could turn in an A performance, but in courses that failed to strike their imagination they were quite willing to do no work at all."

This rings very true to those familiar with architectural education.

It is nearly always the less distinguished students who have the broad and comprehensive grasp of their subject. The more creative students reinforce their natural spatial abilities, and often turn in quite inadequate performances in the other more technical aspects of the subject.

Perhaps one of MacKinnon's most disturbing findings is that it was the less creative architects who described themselves as showing a "sympathetic concern for others". In contrast the more creative architects felt that they showed high individuality and determination. It would perhaps be more appropriate to show sympathetic concern than individuality in the design of environments for other people!

MacKinnon's studies do not tell us anything about the actual modes or levels of performance shown by creative architects, but rather reveal those personality traits which they most commonly exhibit. For this reason, this sort of study cannot tell us anything directly about architects' problem solving behaviour. However, such general personality factors may help us to better understand the results of problem solving experiments and it is for this reason that the work has been briefly surveyed here.

5. PROBLEM SOLVING IN ARCHITECTURAL DESIGN

A bee puts to shame many an architect in the construction of her cells. But what distinguishes the worst of architects from the best of bees is this, that the architect raises his structure in imagination before he erects it in reality. At the end of every labour process we get a result that already existed in the imagination of the labourer at its beginning.

Karl Marx
(Das Capital)

5. Problem Solving in Architectural Design

This section is intended as a short summary of the preceding discussion and arguments. It is recognised that design is a very varied activity, and that different design situations seem to share few common attributes. Even within architectural design much variation is possible. There has been much debate as to the constituent activities of design and their sequence. After stripping away the initial preparatory and final communication stages we are left with a complex problem solving stage.

The traditional classifications of design by solution types is seen as largely irrelevant to a study of design problem solving. It would seem more profitable to investigate the differences in types of problem and types of solver. The discussion of section 3 reveals two important attributes of design problems, size and structure (see diagram 5.1).

A description of the problem is not a comprehensive picture of a design situation. Different designers will produce different solutions to the same problem. Section 4, discussing architectural design and thinking, comes to the usual psychological conclusion that as designers we share much in common but also exhibit individual differences. It seems reasonable to summarise the lengthy discussion on design thinking by the two related activities of Problem Structure Discovery and Solution Structure Production (see diagram 5.2).

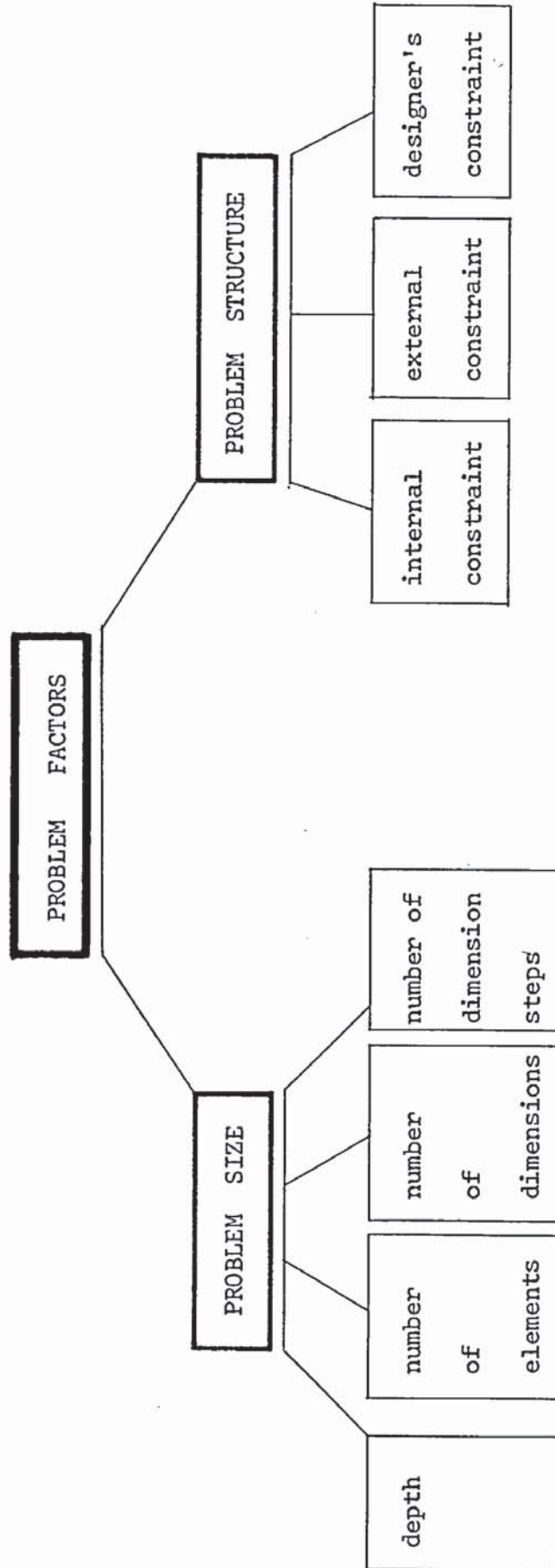


diagram 5.1

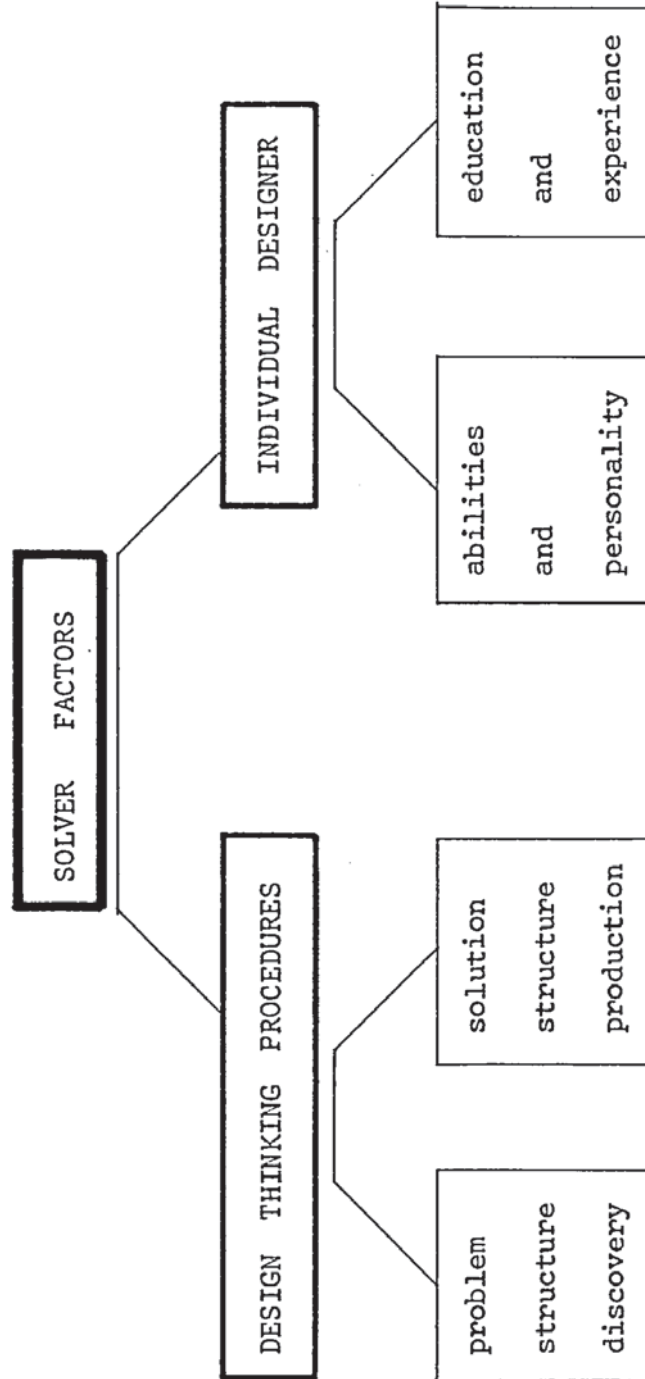


diagram 5.2

This model provides a series of factors apparently important in forming a design situation. If this model is accurate and comprehensive it should be possible to generate a description of any design situation by varying these factors. It is tempting and entertaining to look for the various traditional design categories in this model by describing the types of problem and designer usually associated with them. However, this seems a little like Freud using case histories to prove the accuracy of his conceptual model. Rather than accepting the model it must be challenged and investigated.

It is the relationship between problem factors and solver factors that most needs examination. The psychologist cannot remain interested for long in a problem factor, which when varied does not result in changes in the designer's behaviour. Such problem factors do not help in the description of different design situations. The ultimate objective in arriving at such a description must be to ensure that the right designers are solving the right problems in the best possible way. Hopefully the all important solutions will then look after themselves.

6. THE BLOCKS EXPERIMENT

How do we sort out the apparent chaos of our environment into anything like order? Experimentally speaking, we may assume that the order is our own fabrication and then the problem of finding how we fabricate these regularities becomes a problem in experimental psychology, and not in philosophy.

Dienes and Jeeves (1965)

6. THE BLOCKS EXPERIMENT

6.1 The experimental situation

6.1.1 The purpose of the experiment

6.1.2 Design of the BLOCKS experiment

6.1.3 The BLOCKS experiment as a design problem

6.2 The pilot experiment

6.2.1 Design and procedure

6.2.2 Results

6.2.2.1 The validity of the experimental task as a model of architectural design problem solving

6.2.2.2 The effects of different kinds of structure on the subjects' performance at the experimental task

6.2.2.3 Evidence of different cognitive strategies

6.2.2.4 Evidence of designer generated constraints

6.2.3 Conclusions on the success of the pilot experiment

6.3 The main experiment

6.3.1 Design and procedure

6.3.2 Subjects

6.3.3 Results of the first phase

6.3.4 The 'set blocks' experiment

6.3.5 Strategy analysis

6.3.6 The second phase of the experiment

6.4 Conclusions

6.4.1 The results

6.4.2 The experiment

6.1 The Experimental Situation

6.1.1 The purpose of the experiment

The first part of this work has been devoted to a discussion of problem-solving in architectural design. The nature of both the problems and the problem-solvers has been discussed, and a model built up of the major variables identified. This second section is an attempt to discover more about the cognitive processes involved in architectural design problem-solving. There were two main aims for carrying out this work. Firstly to produce information likely to be helpful in the selection and training of architects. Secondly to produce guidelines for the successful integration of computer aids for architects into the design problem-solving process.

Whenever a group of architects come together to discuss the nature of architecture and design there is bound to be considerable disagreement. It is difficult to find a consensus definition of architecture except at a very general level. One fact is quite clear; that it is relatively easy to find two practising architects in situations which apparently share almost no common attributes. If an experimental study such as this, is to make progress, we must retreat to the generalised and relatively abstract level of agreement. The architect's primary and central task is to produce a three dimensional structure of space and form to accommodate an abstract structure of related human activities. The purpose of the experiments to be described is to understand how architects perceive the relations between variables in multidimensional design problems, and how they produce desired relations between the

elements of their solutions.

These experiments were designed to give answers to five main questions.

1. Do some kinds of structure cause architects more trouble than others, as might be indicated by the results of various structural thinking experiments (see section 4.4)?
2. What range of variation in problem-solving strategies is to be found amongst architects?
3. Do architects' problem-solving strategies consistently differ from those of other groups?
4. If so, are these effects a function of selection or education?
5. What are the relative advantages and disadvantages of the various strategies employed by architects and other groups.

6.1.2 Design of the 'BLOCKS' experiment

To be capable of giving answers to the questions listed in the previous section the experiment has to be carefully designed. If the results of this experiment are to be extrapolated to give conclusions about the real design situation, then it must model that aspect of the process with which it is concerned as accurately as possible. Most importantly the subject must produce a unique spatial configuration of elements so as to satisfy some abstract structure. The universe of possible alternative solutions must be so large as to make successive trial and error an uneconomic strategy, but bounded so that any solution the subject can produce may be predicted. Many experiments and tests require subjects to produce spatial configurations of elements, but they are not models of a true design process because they lack hidden

structural rules.

The solution that our subject is to produce must be constrained by structural rules, which he must discover for himself. The task of discovering structural rules has been investigated by many experiments (as described in section 4). Here the discovery of the structure is the end, and not a means to an end as in a true design situation. In our experiment then, the discovery of the structure and production of the solution must be integrated and the subject must not be instructed to perceive them as separate tasks.

If architects are to be compared with other groups then neither the discovery of the structure or the production of solutions must require the subject to have specialist knowledge. Problems must not be posed that are likely to be differentially familiar to the various groups of subjects.

In summary there are three main conditions to be satisfied in the design of this experiment:-

1. It must present a task which involves the production of a spatial configuration of elements respecting an abstract structure.
2. The structure-discovery and solution-production tasks must be integrated.
3. The task must be sufficiently non-technical so as to allow designers and non-designers an equal chance.

The 'BLOCKS' experiment has been designed to satisfy these requirements.

The experimental material consists of four pairs of coloured blocks, and a rectangular plan mounted on a turntable. The two members of each pair of blocks are identically shaped but different to all other blocks. The top and bottom surfaces of one block in a pair are white, while those of the other are black. All remaining surfaces are either red or blue. The two blocks of a pair show different patterns of red and blue surfaces. The blocks are numbered one to eight for identification purposes. The rectangular plan consists of a grid of three by four bays, each bay being $1\frac{1}{2}$ inches square. The blocks are also based on this dimensional module (see appendix 9.1).

In the experiment, the subject is asked to arrange four of the blocks, one from each pair, on the plan so as to cover all twelve squares and with no blocks projecting. The blocks must be laid with the black or white surfaces uppermost, and the subject is asked to maximise the amount of either blue or red showing around the external vertical face. The subject is told that not all possible combinations of blocks will be allowed each time, and a rule requiring certain blocks to be present will be fixed before each problem. The subject is not told what the rule is, but he is allowed to ask if a combination of blocks that he has assembled is acceptable or not. The subject is asked to reach the best solution that he thinks is possible by asking as few questions as he can.

The subject is not instructed to discover the rule, but rather to produce a solution, as in a real design situation. The subject may produce a solution either as a result of discovering the rule or in

complete ignorance of the rule.

6.1.3 The Blocks experiment as a design problem

The Blocks experiment is intended as a model of the structural aspects of design problem solving situations. In this section, the experimental blocks situation is examined in terms of the diagram of problem factors developed in section 3.

Problem size

The Blocks experiment requires four components in a complete solution (four different shaped blocks). There are two alternatives for each component, making a total number of sixteen different combinations. The components may be arranged in twelve topologically different ways, and there are thirtytwo possible adjustments of individual blocks. This makes a total of 6,144 possible solutions to the problem. This number is sufficiently large to render trial and error an unprofitable strategy.

Problem structure

The external constraint is supplied by the experimental material. The four by three bay rectangular plan must always be respected, and the shape and colour distribution of the blocks are fixed. This constraint is constant for every problem.

The internal constraint is supplied by the structural rule imposed for each problem. This means that only certain relationships between some blocks produce acceptable solutions.

This constraint varies from problem to problem, and defines the range of acceptable solutions in each case. Although many types of rule are possible, only three have been used. They are:

- Affirmation - one block must be present (A)
- Conjunction - two blocks must both be present (A and B)
- Disjunction - either or both of two blocks must be present (A or B)

The subject knows that each rule will be in one of these three formats. The letters 'A' and 'B' can mean any of the eight blocks, except that A and B cannot belong to the same pair of blocks. There are therefore 8 possible affirmations and 24 possible conjunctions or disjunctions, making a total of 56 possible sets of internal constraint.

It can be seen from the diagram (6.1.1) that there are 8 acceptable combinations of blocks when the rule is an affirmation, 4 when a

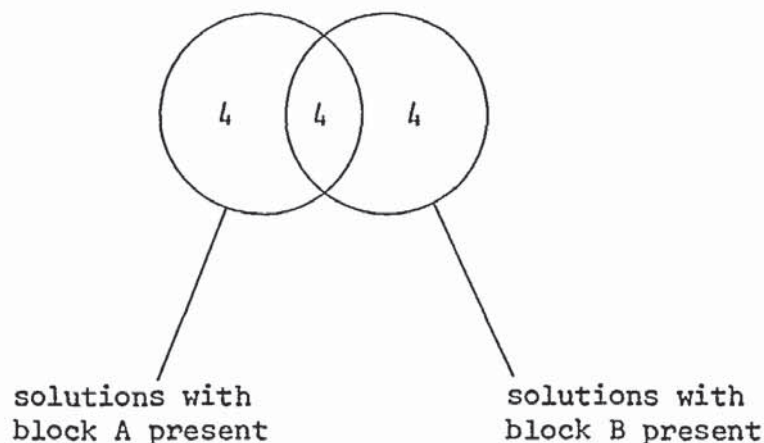


diagram 6.1.1

conjunction and 12 when a disjunction. (Each combination permits 384 arrangements of blocks.) This is summarised in table 6.1.1

table 6.1.1 Types of problems used in BLOCKS experiment

rule name	symbol	no. of possible rules	no. of acceptable combinations	total no. of solutions
affirmation	A	8	8	3072
conjunction	A.B	24	4	1536
disjunction	AUB	24	12	4608
no constraint	-	-	16	6144

Apart from the added variable of the arrangements of blocks, this structure is exactly analogous to that used by Lawson (1969) (see 4.4.1) in his concept attainment experiment. This parallel will be taken up further in a later section.

The designer's constraint is artificially contrived so as to remain constant between subjects and problems. This constraint is provided by the requirement to maximise the amount of either red or blue showing around the vertical face of the solution. That is, not only does our designer (the subject) have to produce a solution which entirely

respects the external and internal constraints of the problem, but he also wants a 'blue/red solution'. This designer's constraint is imposed independently of the internal and external constraints.

6.2 The Pilot experiment

6.2.1 Design and procedure

The study of design problem-solving situations in the first part of this work resulted in a hypothetical diagram of their major variable factors (section 5). The blocks experiment has been designed with reference to problem factors section of this diagram. Thus we may hypothesise that, even though the experimental situation is abstract, architects will find that it contains the essential characteristics of real design problem-solving. This should enable an investigation of the problem-solver himself, hopefully providing answers to the questions listed in section 6.1. The main reason for carrying out this pilot study was to determine whether or not the experiment was likely to provide these answers.

The experiment was conducted in a small well lighted room about three metres square. The experimental materials were placed on a table, about one metre square in the centre of the room. The subject and the experimenter sat on opposite sides of the table, and a trolley containing data recording equipment was situated along side the experimenter.

The experimenter recorded the subjects questions and solutions on prepared forms. The experimenter answered the subjects questions with a verbal 'YES' or 'NO', and if the subject asked other than protocol questions the experimenter replied 'I CANNOT ANSWER THAT KIND OF QUESTION.' Both the experimenter and subject wore neck microphones,

and their voices were recorded on one channel of a stereo tape-recorder. A pre-recorded tape announcing the time lapsed every fifteen seconds was simultaneously and silently played into the other channel.

When the subject finally submitted his solution the experimenter told him what the rule had been and what the maximum colour score was. The subject was then asked in an informal way what he had thought the rule was, or whether he had not known at all.

Six male final year students from the Birmingham School of Architecture acted as subjects. The subjects attended for four sessions at approximately the same time on consecutive days. The first session was used solely for training and familiarisation, and no data was recorded. The subjects attended in two groups of three for the training session, and individually for the three experimental sessions.

At the training session, the subjects were handed a copy of the instructions (see appendix 9.3) and these were read out aloud by the experimenter. After asking the subjects if they understood the instructions the experimenter explained that the session was for training purposes only, and that the data would not be used. The subjects were then supplied with neck microphones and encouraged to think aloud and make any comments however ridiculous they might seem. Each of the three subjects then solved one problem with the other two observing silently. Three more problems were then solved by the whole group. The subjects were then told that they would have to solve six different problems in each of the remaining three sessions.

Two examples of each type of rule (affirmation, conjunction, disjunction) made up the six problems in each session. Three of the problems involved maximising 'red' and three 'blue'. Three different such groups of six problems were used, one for each session. The problems were presented in three different random sequences. This is best explained by tables 6.2.1/2

table 6.2.1 Groups of problems used in BLOCKS experiment
(letters R/B refer to colour to be maximised)

Problems		Groups					
type	no.	1		2		3	
conjunction	1	1.5	B	3.6	R	5.8	B
conjunction	2	1.8	R	4.7	B	2.7	R
affirmation	3	4	B	5	B	5	R
affirmation	4	3	R	2	R	7	B
disjunction	5	3u8	B	6u8	R	2u8	B
disjunction	6	2u3	R	1u5	B	3u6	R

table 6.2.2 Sequences of presentation of problems

Presentation sequence	Problem numbers						
A	6	3	2	5	1	4	
B	1	2	5	4	3	6	
C	4	5	2	6	1	3	

Each of the six subjects received a different combination of sequence of problem presentation and order of groups for the three experimental sessions (table 6.2.3).

table 6.2.3 Order of problem groups (numbers) and problem sequences (letters) for each subject

Subject number	Experimental sessions		
	First	Second	Third
1	1A	2B	3C
2	2C	3A	1B
3	3B	1C	2A
4	2B	1A	3C
5	3A	2C	1B
6	1C	3B	2A

6.2.2 Results

Since there were only six architectural students acting as subjects for this pilot experiment, its results are necessarily limited. Out of the five questions posed in section 6.1, three involve comparisons between architects and others. These obviously cannot be answered here. The first two questions are concerned with the effects of different structure and the range of problem-solving strategies used. To a limited extent these questions can be answered, but primarily this pilot study must be seen as a test of the experimental situation itself. Thus although the results will be discussed with respect to

structure and strategy, conclusions about these factors are deferred until after the main experiment has been reported.

6.2.2.1 The validity of the experimental task as a model of architectural design problem-solving

Five out of the six subjects made several unprompted references to the similarity they perceived between the experimental task, and architectural design. The sixth subject, having made no unprompted remarks on this subject, was asked if he did perceive any similarities. He replied: "Yes, I had assumed that was what the experiment was about". It seems reasonable to discount this response in the interests of conservatism, since the subject was asked a leading question.

The subjects' comments seem to fall into two groups. In the first group the subject is noting the similarity of the experimental problem to design problems.

"You know this is just like designing"

Most of the remarks in this group were further elaborated with references to specific design situations.

"I can see this as a problem of getting daylight to parts of certain spaces, and still planning those spaces properly."

"This certainly is a tight planning problem this time. One always goes through phases of tight planning like this in designing buildings."

The second group of comments refer to a similarity that the subject has noticed between his behaviour in the experiment and his behaviour in the design studio.

"I can work all day on a problem like this at the drawing board and then solve it at night in bed."

"You often design something and work for three days and find the first

thing was right. That's just what is happening here."

"I want to try and cut out this guesswork somehow. I guess too much when I'm designing, it confuses me in the end, and I'm getting confused here."

The subjects did not know until after the experiment that the experimenter was an architect/psychologist, and all assumed him to be a psychologist. It therefore seems reasonable to take the opinions of the five unprompted subjects as an indication of some degree of similarity between the experimental task and architectural design problem-solving.

6.2.2.2 The effects of different kinds of structure on subjects' performance at the experimental task

The simplest measure of performance that can be made in the BLOCKS experiment is that of colour score. The subject has been asked to show as much of one of the colours (red/blue) as he can on the external vertical face of his solution. This vertical face is divided into fourteen modular bays, with the eight blocks coloured as in the experiment the maximum possible scores are 14 blue or 13 red, with no restricting structural rules. Each rule has its own maximum possible score varying between 11 and 14 for blue, and 10 and 13 for red. Table 6.2.4 shows these scores for the three sessions for subject 1.

table 6.2.4 Colour scores for subject 1

Session	problem	colour to be max.	subjects score (S)	maximum score possible (M)	M - S
1	2u3	R	13	13	0
	4	B	14	14	0
	1.8	R	13	13	0
	3u8	B	13	14	1
	1.5	B	12	12	0
	3	R	11	12	1
2	3.6	R	9	10	1
	4.7	B	14	14	0
	6u8	R	11	13	2
	2	R	13	13	0
	5	B	12	13	1
	1u5	B	13	14	1
3	7	B	14	14	0
	2u8	B	14	14	0
	2.7	R	13	13	0
	3u6	R	10	12	2
	5.8	B	11	11	0
	5	R	13	13	0
Totals	-	-	223	232	9

The total differences between the maximum possible colour scores and those actually achieved by each subject ($M - S$) can be plotted against each of the three types of structure (see table 6.2.5).

table 6.2.5 Total colour score error ($M - S$) for each subject over three sessions

Subject	Problem type		
	conjunction	affirmation	disjunction
1	1	2	6
2	1	2	6
3	2	1	1
4	1	1	4
5	0	0	4
6	2	1	0
Totals	7	7	21
Means	1.17	1.17	3.49

It can be seen from table 6.2.5 that the total colour score error for disjunctive problems is three times that for conjunctive problems. Probably because of the small sample size, this is still not a large enough difference to yield a significant result with any of the suitable

non-parametric tests or even the two tailed t-test. In spite of this lack of statistical significance, these results indicate very strongly that the disjunction is causing subjects considerably more trouble than the conjunction or affirmation.

This seems slightly paradoxical when reference to diagram 6.1.1 and table 6.1.1 show that the disjunctive rule permits three times more solutions than the conjunction. These results are more understandable when interpreted in the light of Lawson's (1969) findings (reported in section 4.4). These results showed that under equal information conditions, with an array identical to that used in this experiment, subjects took longer and were more inaccurate when recognising disjunctive structure rather than conjunctive structure. Strategy analysis revealed that subjects were preferring to look for conjunctive structure before, if at all, going on to look for disjunctive structure.

It seems reasonable to hypothesise that subjects in this pilot study were falsely identifying a conjunctive structure when in fact the rule was of the much less restricting disjunctive type. It can be seen from diagram 6.2.1 that the set of all solutions using block A or block B or both (disjunction $A \cup B$) contains the sets of solutions using block A (affirmation), block B (affirmation), and blocks A and B (conjunction $A \cdot B$).

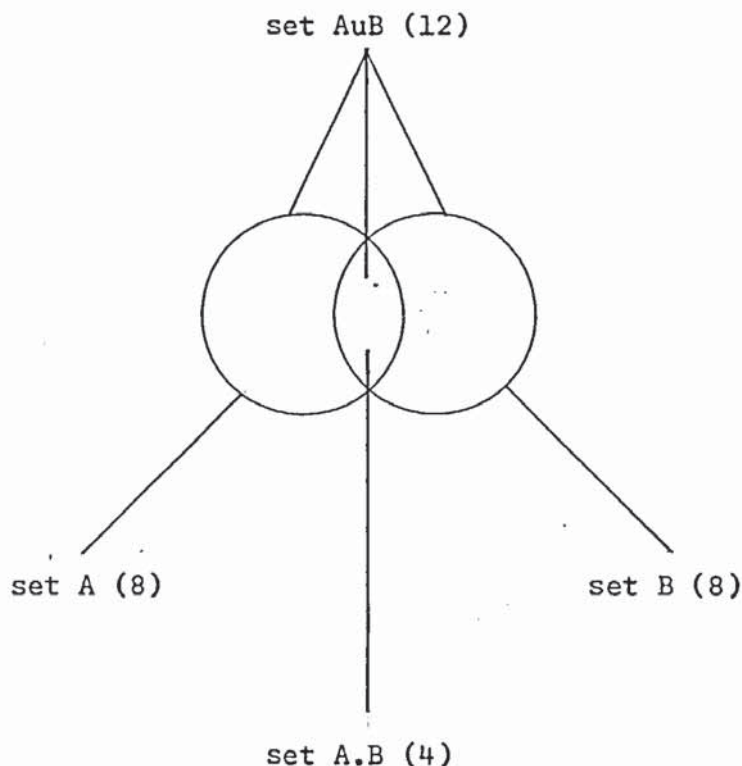


diagram 6.2.1 (figures show set sizes)

A larger colour score error ($M - S$) for disjunctive problems could be explained by subjects failing to perceive the disjunction but rather perceiving the conjunction or one of the affirmations. This has the result of unnecessarily restricting the number of combinations of blocks available. This hypothesis is supported by the subjects' responses when asked what they had discovered about the structure at the end of each problem. Very few disjunctions were correctly identified, but rather seen as conjunctions or affirmations. Also, slightly surprisingly, more affirmations were perceived as conjunctions than were recognised correctly (table 6.2.6).

table 6.2.6 Actual rule types as perceived by subjects

Perceived rule type	Actual rule type			Totals as perceived
	conjunction	affirmation	disjunction	
conjunction	29	20	5	54
affirmation	4	12	20	36
disjunction	-	-	3	3
undiscovered	3	4	8	15
actual totals	36	36	36	108

The hypothesis that subjects tended to perceive the structure as more restricting than it was is further supported by their observed comments and behaviour. After a run of unacceptable solutions a subject discovers an acceptable solution by changing one block from the last attempt. He all too easily comes to the apparently reasonable conclusion that the presence of that block is vital, and so perceives an affirmation, when in fact the rule is disjunctive. This pattern was observed several times with five out of the six subjects.

6.2.2.3 Evidence of different cognitive strategies

In the blocks experiment the subject is asked to produce a solution to a problem which has some constraints which are unknown to him.

Obviously any information about the structure of the constraints is likely to be of value in this situation. In fact the problem can be seen as consisting of two separate tasks. Firstly identification of the constraints and secondly production of the optimum solution permitted by those constraints. The array of variables, and types of structural rules used in the experiment are identical to those reported in Lawson (1969), and similar to those by other workers reported in section 4.4. The discussion of information search and interpretation strategies identified in those experiments is entirely relevant to this experiment.

In actual practice the task of structure identification is not separate from that of solution production, but rather part of it. In reality subjects did not fully discover the constraints before producing their solutions, as is evidenced by the errors shown in table 6.2.6. The question being asked here, however, is not what the subjects achieved, but what they set out to achieve.

The most frequently recognisable opening gambit was to select the block with the larger area of the colour to be maximised out of each pair. These four blocks would then be arranged so as to give as high a colour score as the subject could achieve. The first question would then be asked. If the combination proved acceptable the subject could then assume he had the best possible solution and stop. If, however, the combination proved unacceptable the subject had gathered some information about the constraint and had to proceed to the next stage of his strategy. The most common continuation at this point would be to change the block which had least effect on the colour score

obtainable. This process would then continue until an acceptable solution was found when the subject would assume that he must have automatically achieved the highest possible colour score.

In this strategy the subject is focussing on his solution, changes are made only with reference to achieving high colour scores and not to obtain information. This strategy was identified to some extent in an a posteriori inspection of the protocols of five out of the six subjects. Supporting evidence for the existence of this strategy comes from some of the subjects' comments.

"I shall start by choosing all blocks with more red, this is the key to the problem."

"I'll pick the ones with all the most red on first no you've just got to be satisfied with less reds."

"What I'm doing here is to change the least offensive block if I get a NO."

"NO's are no help, its not until I get a YES that I can do something, then it just clicks."

"That's the first YES I've had, and it must be the best colour score I can get, because I've maximised all along."

Only one subject out of the six consistently showed signs of following a fundamentally different strategy. This subject did not select the most suitably coloured blocks first, but chose either all the white blocks or all the black blocks. Whatever the result of his inquiry about the first combination of blocks this subject would then immediately change all four blocks. Next he would choose two from each of these sets and combine them, and so on. This subject had intuitively, rather than from theoretical study, learnt to operate the classical information search strategy of 'split halving'. The choice of blocks used in his

questions was based entirely upon their potential information content, and not their ability to give high colour scores. This subject commented less than the others, but he seemed to know very well what he was doing.

"Identification of the critical blocks is the most pressing thing at first."

This subject had also managed to devise a simple technique for relieving cognitive effort.

"I like to start with all white or all black, its easier to remember then."

However, this strategy although beautifully designed for information gathering, did have its disadvantages.

"Now then (after asking four questions), I'm maximising blue aren't I? (Experimenter, "No red") "Oh red, really!?"

Thus in this pilot study it was possible to recognise at least two quite different well formed strategies. These strategies will be referred to as 'solution focussing' and 'problem focussing', in all further discussion. Both strategies seem to be effective in enabling the subject to cut out an inspection of large numbers of solutions and quickly arrive at a solution that seems to him to be optimal. It is noticeable that the mean number of solutions inspected, by asking the experimenter if they are acceptable, is only 4.9. This is out of a total of 16 possible questions each time.

6.2.2.4 Evidence of designer generated constraints

Several of the subjects surprisingly tried to add their own constraints to the problem. Some subjects became quite obsessed with the pattern of white and black on the top surface of their own solution. On several occasions a perfectly satisfactory solution was rejected on the grounds that the black/white pattern seemed visually uncomfortable to the subject. The following comments were made by one subject.

"Black and white on top worries me a bit; an unhappy relationship."
(changes blocks)

"Quite happy with that one, there's two of each (black and white), a pity that isn't the rule."

The same subject was also frequently sidetracked by the pattern of red and blue bays on the vertical surfaces of less than maximum solutions.

"It seems important to get the proportions of red and blue right on the vertical surfaces."

"I would like to get that one red bay in the middle of the side instead of at the end, that would be a much neater solution."

This subject was considered to be one of the most creative members of his year by both his tutors and peers, and went on to achieve an upper second class degree. The same subject commented later;

"A computer would come in useful here. When you are trying to maximise something absolutely you might as well use a computer."

For this subject at least, design must involve the generation of 'designer constraints'. Otherwise, he feels, the process is not satisfying and would be better carried out by a computer.

6.2.3 Conclusions on the success of the pilot experiment

A small extra pilot study was carried out with three social science students acting as subjects. They completed a training session and two

experimental sessions. The overall level of performance of these subjects was similar to that achieved by the architects. The data is insufficient to comment on in further detail.

The BLOCKS experiment has been demonstrated to be of value by this pilot study. Both architects and non-architects can solve its problems. The problems are difficult enough to reveal different levels of performance. Different types of problem structure can be used and compared, and subjects' cognitive strategies can be detected.

6.3 The Main Experiment

6.3.1 Design and procedure

The experimental material, problems and the sequence of problem presentation remained identical to those used in the pilot experiment. The main changes involved the removal of both the experimenter and tape recorder from the laboratory. The experimenter was replaced by a Digital Equipment Corporation PDP 9 computer used on-line. No record was made of subjects' comments.

The use of an on-line computer connected to the laboratory by a remote teletype terminal left the subject alone to work less self-consciously and in his own time. The computer input the problems from prepared paper tapes and output instructions, questions and information on the subjects' teletype. In return the subject was able to input questions and information through the teletype keyboard. The computer provided instantaneous and infallible responses to the subjects' questions, unlike the experimenter in the pilot study, for whom the whole procedure seemed like a vigilance task! Because of the availability of computer time only two or three subjects could be run each week. The subjects attended together for the training session on the first day, and then individually on the three successive days. The same instructions were read out to the subjects as had been used in the pilot study. These were then followed by instructions on the use of the teletype terminal for communication with the computer. These instructions were displayed in front of the subject throughout the experiment (see appendix 9.3).

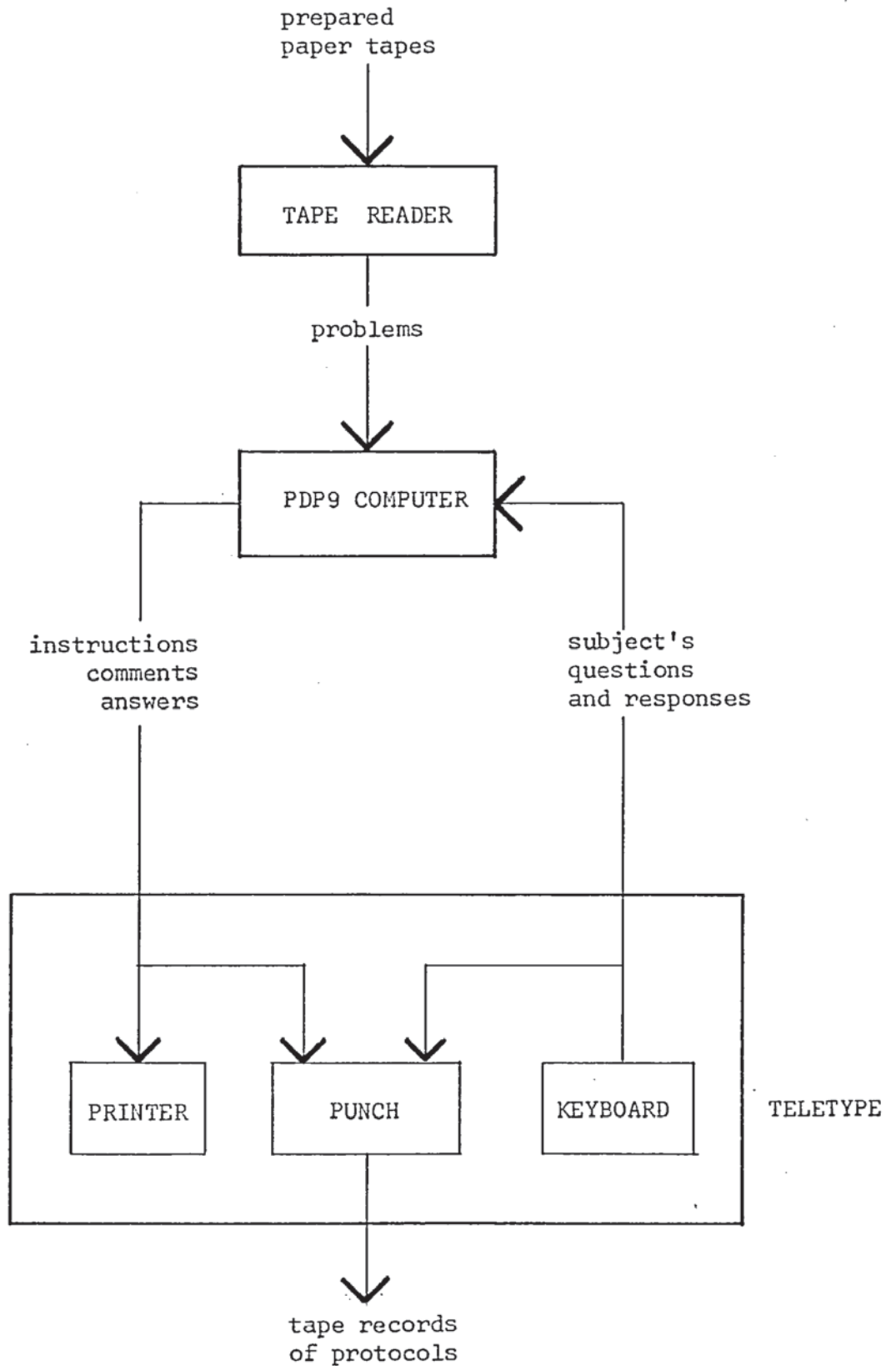


diagram 6.3.1 Blocks system diagram

The experimental session was controlled by a Macro 9 program called BLOCXT, which provided largely self explanatory output text strings and required the subject to input only digits, 'space' and 'carriage return'. (see appendix 9.4). The Keyboard of the teletype was masked so as to reveal only these keys (and 'rubout'). The hard copy output of the teletype was masked so as to reveal only the immediately preceding output. This would then disappear as soon as the teletype was used again. The teletype punch provided a complete paper tape record of the session (see diagram 6.3.1).

It is difficult to be certain of the motivational effects, or lack of them, produced by the computer rather than the presence of the experimenter. Most subjects soon adjusted to the use of the teletype, and if anything seemed more relaxed than when directly observed by the experimenter. The BLOCXT program output the comment, "YOU ASKED A LOT OF QUESTIONS" if the subject asked seven or more questions. Without this facility it was thought that subjects might gradually increase their concept of a reasonable number of questions.

6.3.2 Subjects

Subjects were run in multiples of six, replicating the experimental design shown in table 6.2.3. In the first phase of the experiment two different groups of subject were run under identical conditions. The first group (A5) were all fifth year students in the Birmingham School of Architecture. The second group (S5) were all science graduates reading for higher degrees in the faculties of science and social science in the University of Aston. The School of Architecture

is an affiliated department of the University and is situated on the same campus. Both groups of subjects were studying in this same environment, and were of similar ages. Intelligence tests were not used to select subjects, since there was no evidence to show that test IQ scores would be meaningfully correlated with cognitive strategies on the blocks experiment. However, both groups of students would have been of at least university level intelligence. The subjects were paid for their attendance and all of them seemed to enjoy the experimental sessions.

6.3.3 Results of the first phase

The performance of the two groups of subjects, fifth year architects (A5) and scientists (S5) at each of the three types of problem, conjunction, affirmation and disjunction is shown in tables 6.3.1 and 6.3.2. Diagram 6.3.2 compares the mean scores for each of the groups. The results of the pilot study appear to be a reasonably accurate reflection of the performance of the larger group of architects used in the main study. The scientists' performance is apparently quite different being poor on conjunctive and good on disjunctive. It is interesting to note, however, that the grand mean score over all subjects and problems is almost identical for the two groups.

The difference between the subjects' performance at the conjunctive and disjunctive problems was examined separately for each group. In the case of the architects a two-tailed t-test for related samples showed a value of student's t ($df, 17$) which has a chance probability of less than 0.05. (The relative difference between the two problems

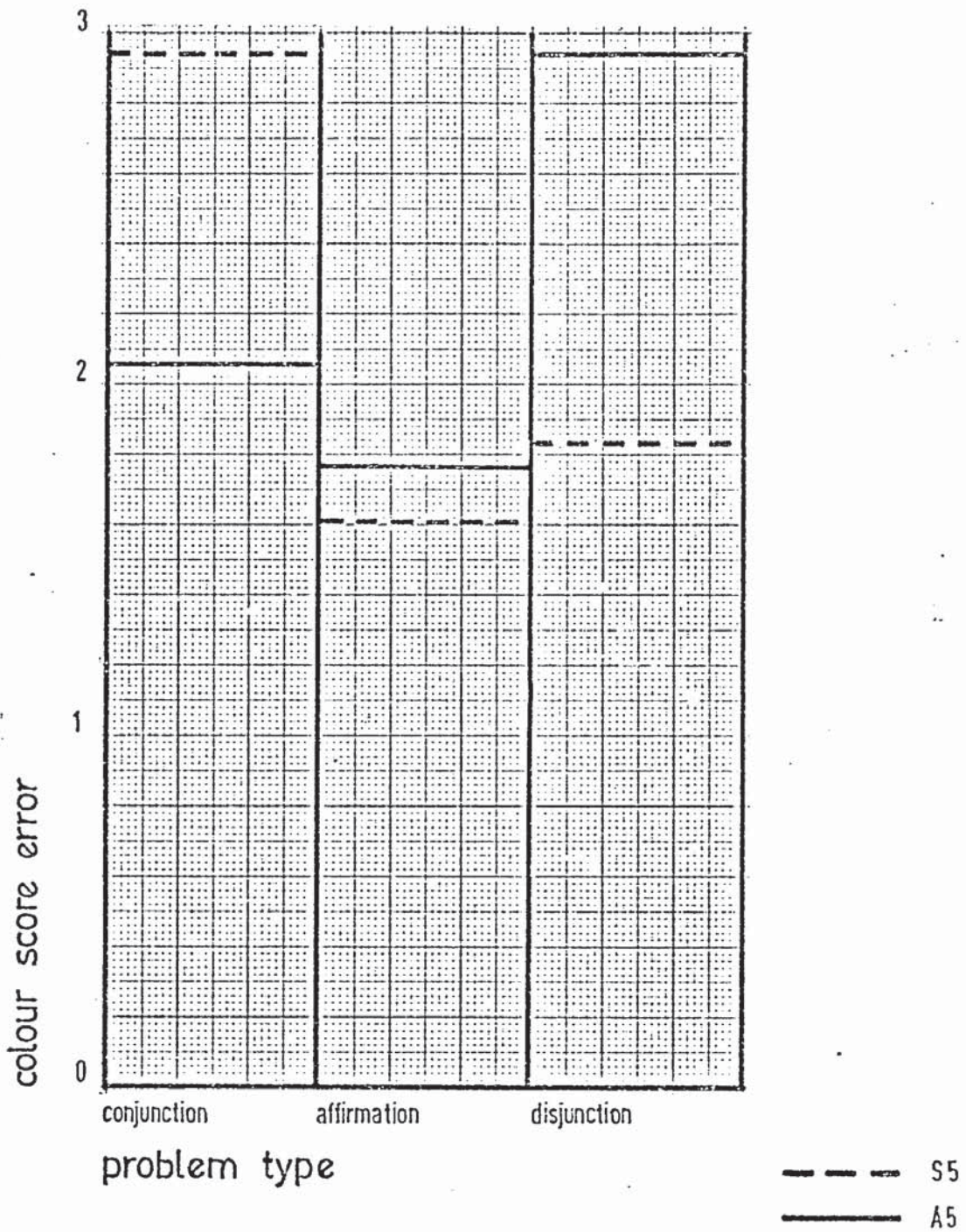
table 6.3.1 Colour score error (M - S) for fifth year architects (A5)
for each problem type

Subject number*	Problem type			Total
	conjunction	affirmation	disjunction	
2/1	3	3	5	11
2/2	3	3	4	10
2/3	1	0	3	4
2/4	3	1	2	6
2/5	5	2	4	11
2/6	1	3	4	8
3/1	0	2	2	4
3/2	2	2	5	9
3/3	3	1	4	8
3/4	4	2	1	7
3/5	1	3	3	7
3/6	3	0	1	4
4/1	0	0	0	0
4/2	2	0	4	6
4/3	0	2	1	3
4/4	1	4	4	9
4/5	4	3	4	11
4/6	1	1	2	4
Total	37	32	53	122
Mean	2.055	1.777	2.944	6.777

*N.B. the architects are numbered from 2/1 to avoid confusion with the pilot group numbered 1/1 - 1/6

table 6.3.2 Colour score error (M - S) for fifth year scientists (S5) for each problem type

Subject number	Problem type			Total
	conjunction	affirmation	disjunction	
1/1	10	2	2	14
1/2	0	2	2	4
1/3	1	1	2	4
1/4	1	1	3	5
1/5	4	1	4	9
1/6	8	3	3	14
2/1	1	1	2	4
2/2	4	2	1	7
2/3	2	2	4	8
2/4	1	1	1	3
2/5	1	0	1	2
2/6	0	2	1	3
3/1	0	1	1	2
3/2	6	2	2	10
3/3	3	2	0	5
3/4	4	0	2	6
3/5	2	4	1	7
3/6	5	2	1	8
Total	53	29	33	115
Mean	2.944	1.611	1.833	6.388



diag. 6.3.2 OVERALL PERFORMANCE -phase 1

is slightly less than that found in the pilot study.) The t-test just failed to show a significant difference between the two problem types for the science students. However, it must be recognised that the two results were in opposite directions.

A full analysis of variance was carried out on the results of the two main groups of subjects. All effects were considered fixed, since only these two groups of subjects performing on the three problem types used were of interest. Table 6.3.3 shows a summary of the results. Neither of the factors, problem type or subject group were found to have a significant effect when considered separately. The interaction between them, however, was found to be highly significant even at the 0.001 level. This result could be easily predicted by merely examining the various totals. Summed over both groups the problem types show similar scores, and summed over all problems the subject groups show similar scores. It therefore seems reasonable to conclude that the two groups of subjects differed significantly in their abilities to solve the three problem types although achieving a similar overall level of performance. Again reference to the totals shows that the two groups performed equally well on the problems with an affirmation rule. This leaves nearly all the variation to be accounted for in the groups' comparative handling of problems with conjunctive and disjunctive rules. This is just what is indicated by the significant interaction factor found from analysis of variance.

table 6.3.3 Summary table for analysis of variance for (A5) and (S5) subjects colour scores at three problem types

	S.S.	df.	M.S.	F(MS/MSerror)	p
groups	0.56	1	0.56	1	>0.05
problems	13.72	2	6.86	2.44	>0.05
interaction	119.79	2	59.89	21.29	<0.001 (df 2,102)
error	286.73	102	2.81	-	-
Totals	520.80	-	-	-	-

Why should subjects produce lower colour scores than the maximum, and why should these scores vary between subjects and problem types? It is possible to make two quite different kinds of error in the blocks experiment. A subject may fail to correctly identify the structural rule constraining him to use only certain combinations of blocks. However, to have produced an acceptable solution he must have unwittingly respected the constraint. In this case, as shown by the results of the pilot study, the probability is that the subject was perceiving a more constraining rule, which is a subset of the actual rule. For example, a conjunction or affirmation may be incorrectly identified when the rule is in fact disjunctive. There is a second, more obvious reason for a subject achieving less than the maximum colour score. Having correctly identified the structural rule a subject may quite simply fail to arrange the blocks available to him in an optimal configuration.

In the pilot study subjects were asked at the end of each problem what they had thought the rule was. This practice was not continued in the main experiment for two reasons. Firstly it was thought that it attracted too much attention to the perception of structure and might tend to suggest a way of working that the subject might not otherwise have followed. Secondly the experimenter was not present in the laboratory and a more formal procedure for recording this information would almost certainly have affected the subject's attitude to the problems.

It is possible to distinguish these two error types in a fairly reliable way from the subject's protocol and final solution recorded on paper tape during the session. Reference to the appendix (9.4) shows that the program (BLOCXT) controlling the experiment is capable of solving the problems and, if required, can output details of all the optimal solutions. All the eighteen problems used were solved by BLOCXT and a list of all possible optimal solutions was compiled. This list shows the four blocks used in each solution and their topological configuration.

All solutions in which the subject had achieved a less than maximum colour score were examined to see whether the blocks used could have been rearranged to give the maximum score. This would indicate a planning error (PE), the remaining errors being due to the wrong blocks being used. These structural errors (SE) consist of solutions in which some block or blocks must be changed before a maximum colour score is possible. The use of one or more unfavourably coloured blocks indicates

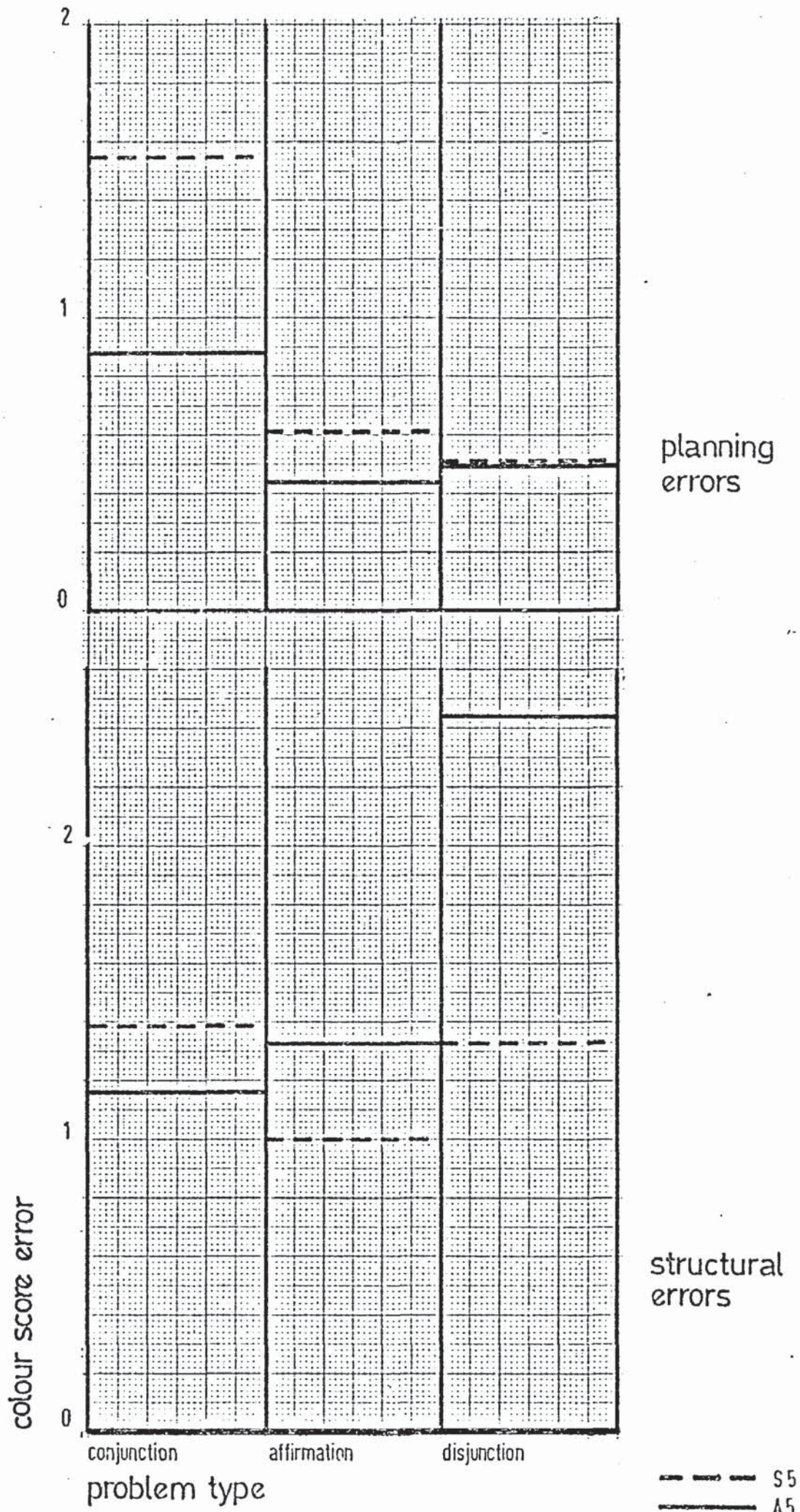
table 6.3.4 Types of colour score error for fifth year architects (A5) for each problem type

Subject number	Problem type							
	conjunction		affirmation		disjunction		Total	
	*PE	SE	PE	SE	PE	SE	PE	SE
2/1	1	2	0	3	2	3	3	8
2/2	0	3	0	3	0	4	0	10
2/3	0	1	0	0	0	3	0	4
2/4	1	2	0	1	0	2	1	5
2/5	1	4	1	1	3	1	5	6
2/6	1	0	2	1	0	4	3	5
3/1	0	0	1	1	0	2	1	3
3/2	2	0	2	0	1	4	5	4
3/3	2	1	0	1	0	4	2	6
3/4	2	2	0	2	0	1	2	5
3/5	0	1	0	3	0	3	6	7
3/6	3	0	0	0	1	0	4	0
4/1	0	0	0	0	0	0	0	0
4/2	2	0	0	0	2	2	4	2
4/3	0	0	0	2	0	1	0	3
4/4	0	1	2	2	0	4	2	7
4/5	1	3	6	3	0	4	1	10
4/6	0	1	0	1	0	2	0	4
Total	16	21	8	24	9	44	33	89
Mean	0.888	1.166	0.444	1.333	0.500	2.444	1.833	4.944

*N.B. PE = planning error; SE = structural error, see text

table 6.3.5 Types of colour score error for fifth year scientists (S5) for each problem type

Subject number	Problem type							
	conjunction		affirmation		disjunction		Total	
	PE	SE	PE	SE	PE	SE	PE	SE
1/1	1	9	0	2	0	2	1	13
1/2	0	0	1	1	0	2	1	3
1/3	1	0	1	0	0	2	2	2
1/4	1	0	0	1	1	2	2	3
1/5	1	3	1	0	1	3	3	6
1/6	2	6	1	2	1	2	4	10
2/1	1	0	0	1	0	2	1	3
2/2	1	3	1	1	0	1	2	5
2/3	1	1	1	1	1	3	3	5
2/4	0	1	0	1	1	0	1	2
2/5	0	1	0	0	1	0	2	0
2/6	0	0	2	0	0	1	2	1
3/1	0	0	0	1	0	1	0	2
3/2	5	1	1	1	1	1	7	3
3/3	3	0	0	2	0	0	3	2
3/4	4	0	0	0	1	1	5	1
3/5	2	0	1	3	1	0	4	3
3/6	5	0	1	1	0	1	6	2
Total	28	25	11	18	9	24	48	67
Mean	1.555	1.388	0.611	1.000	0.500	1.333	2.666	3.722



diag. 6.3.3 TYPES OF ERROR - phase 1

a lack of understanding by the subject of the actual constraints of the problem.

It seems quite reasonable to hypothesise that the more spatially able architects would make relatively fewer planning errors than the scientists. The results confirm this hypothesis, but what is perhaps more interesting is that the two types of error seem also to be related to problem type (see tables 6.3.4/5). Diagram 6.3.3 shows that the two largest differences between the groups are those for Structural Errors(SE) on disjunctive problems, and those for Planning Errors (PE) on conjunctive problems. A t-test was carried out on each of these two sets of scores in the same manner as previously described on the overall error scores. The result showed that the architects had a significantly ($p < 0.01$) higher structural error score than the scientists in the case of disjunctive problems. The scientists higher planning error score in the case of conjunctive problems was not found to be significant. Finally the two types of errors were summed for each subject over all three types of problem to discover if there was a significant difference between the two groups' planning and structural errors. Neither differences were found to be significant with any test.

6.3.4 The set blocks experiment

The results so far posed some fascinating questions. Considerable differences had been identified between the two groups of subjects. These differences had still to be explained. However the most easily predicted difference of all had not materialised. The architects did

not show a statistically significant lower overall planning error score than the scientists. The 'set blocks' experiment was a small follow up study to test whether or not the architects' spatial planning ability really was higher than that of the scientists. Rather than use spatial ability tests of perhaps doubtful relevance to the main experimental task, the same apparatus was used.

The subject was asked to plan specified, or 'set', combinations of four blocks to show as much of one of the two colours (red or blue) as possible on the vertical face of the periphery. The same blocks and rectangular plan were used. Each subject was asked to take each of the sixteen possible combinations of the four pairs of blocks and maximise both the two colours in each case. The problems were presented in a random sequence on punched paper tape fed through the reader of a teletype. After each problem the subject typed out his score on the keyboard before going on to the next problem. Thus a paper tape copy of the whole session was produced for analysis. Each of the eighteen subjects in both groups returned for this experiment which consisted of one session lasting for about an hour. The subject was instructed to work as quickly as he could without making mistakes.

This experimental task can be seen as similar to that in the main experiment, except that the structure is made explicit, and allows only one combination of blocks for each problem. Again the problems were solved by BLOCXT and the subjects' solutions scored according to the number of faces showing the wrong colour over and above the minimum possible number. These error scores are presented for each group in

table 6.3.6 Total colour score errors for fifth year architects (A5) and scientists (S5) on 'set blocks' experiment

Scientists. (S5)		Architects (A5)	
subject number	error score	subject number	error score
1/1	5	2/1	6
1/2	8	2/2	2
1/3	6	2/3	5
1/4	4	2/4	4
1/5	6	2/5	1
1/6	11	2/6	9
2/1	18	3/1	2
2/2	7	3/2	3
2/3	2	3/3	6
2/4	7	3/4	1
2/5	8	3/5	7
2/6	5	3/6	5
3/1	9	4/1	4
3/2	10	4/2	3
3/3	8	4/3	5
3/4	7	4/4	3
3/5	6	4/5	4
3/6	8	4/6	3
Total	135		73

table 6.3.6. Since all subjects solved the problems in the same random sequence there is no special pairing of subjects as in the main experiment. In the interests of conservatism and simplicity the Mann-Whitney U test was carried out on the two sets of scores. The value of U obtained was 27 which has a probability of less than 0.001 even for a two tailed test. It is therefore safe to conclude that the architects group were indeed better at the spatial planning of blocks than the scientists. Thus the lower overall planning error score for architects in the main experiment can reasonably be considered meaningful even though not significantly lower than that of the scientists.

6.3.5 Strategy analysis

Diagram 6.3.3 shows that as the structure of the problems becomes less constraining the architects make more structural errors whereas the scientists do not. As the structure becomes less constraining the scientists make more planning errors whereas the architects do not (significantly). These consistent differences could be reflections of different strategies adopted by the two groups. The protocol tapes of each session show the sequence of combinations of blocks which the subjects tried out. If there were indeed different strategies then it should be possible to detect them in these sequences. PICAPS (Protocol Information Content And Potential colour Scores) is a program which accepts the protocol tapes and carries out three types of profile analysis (see appendix 9.4). The results of the pilot study suggested that there may be two types of strategy based on either solution or problem focussing. It can be hypothesised that PICAPS would generate

different profiles for these two strategies.

The first set of statistics produced by PICAPS is the number of blocks in any question not found in the previous question. The second statistic is a cumulative informational content score. For each question PICAPS calculates the number of single blocks or pairs of blocks not present in any previous question of the protocol. Since there are always four blocks present in each question the first question must have a score of ten (4 single blocks + 6 pairs of blocks). Since the structural rules only concern a single block (affirmation), or pairs of blocks (conjunction, disjunction), there is no score for the trigrams and tetragrams present in each question. The third statistic produced by PICAPS is the maximum colour score obtainable with the particular combination of blocks in each question.

A problem focussing strategy should give rise to a steeply rising information content score since the blocks are being chosen to give maximal information. A solution focussing strategy should give rise to high colour scores and erratic information content scores. In this case the subject is choosing his blocks on the basis of which will most readily plan so as to give a good red or blue solution. Details including sample outputs of PICAPS are included in the appendix. The two groups of subjects were compared on all three PICAPS statistics.

Changed blocks statistics

A grand mean number of blocks changed from the previous question was first computed for each subject. (The first question of each problem

was of course not counted). These means tended to approach unity. It is most unlikely that a subject could score less than unity since this could only come about if over half of his questions were asked about exactly the same four blocks as their predecessors. This artificial lower limit makes the assumption of normality in the data unreasonable. Non-parametric tests have therefore been used for comparisons between the two groups. It seemed reasonable at first to use related samples tests, since the sequence of problem presentation had been identical for a pair of subjects one, from each group. However, since the sequence of problems was replicated three times in each sample of eighteen subjects, there is no absolutely correct pairing. In fact there are $6 \times 6 = 36$ possible pairings. A matched pairs test would have to be carried out 36 times and another test made on the distribution of probability achieved; a tedious process.

However, it does not seem entirely reasonable to use independent samples tests, since the samples are not entirely independent. A compromise was reached by using the Wilcoxon signed ranks matched pairs test (once) and the Mann-Whitney test for independent samples. The former proved significant at the 0.01 level and the latter at the 0.05 level (two-tailed). In the interests of conservatism the Mann-Whitney result was accepted.

The conclusion to be drawn from this result is that the scientists changed significantly ($p < 0.05$) more blocks between questions than did the architects.

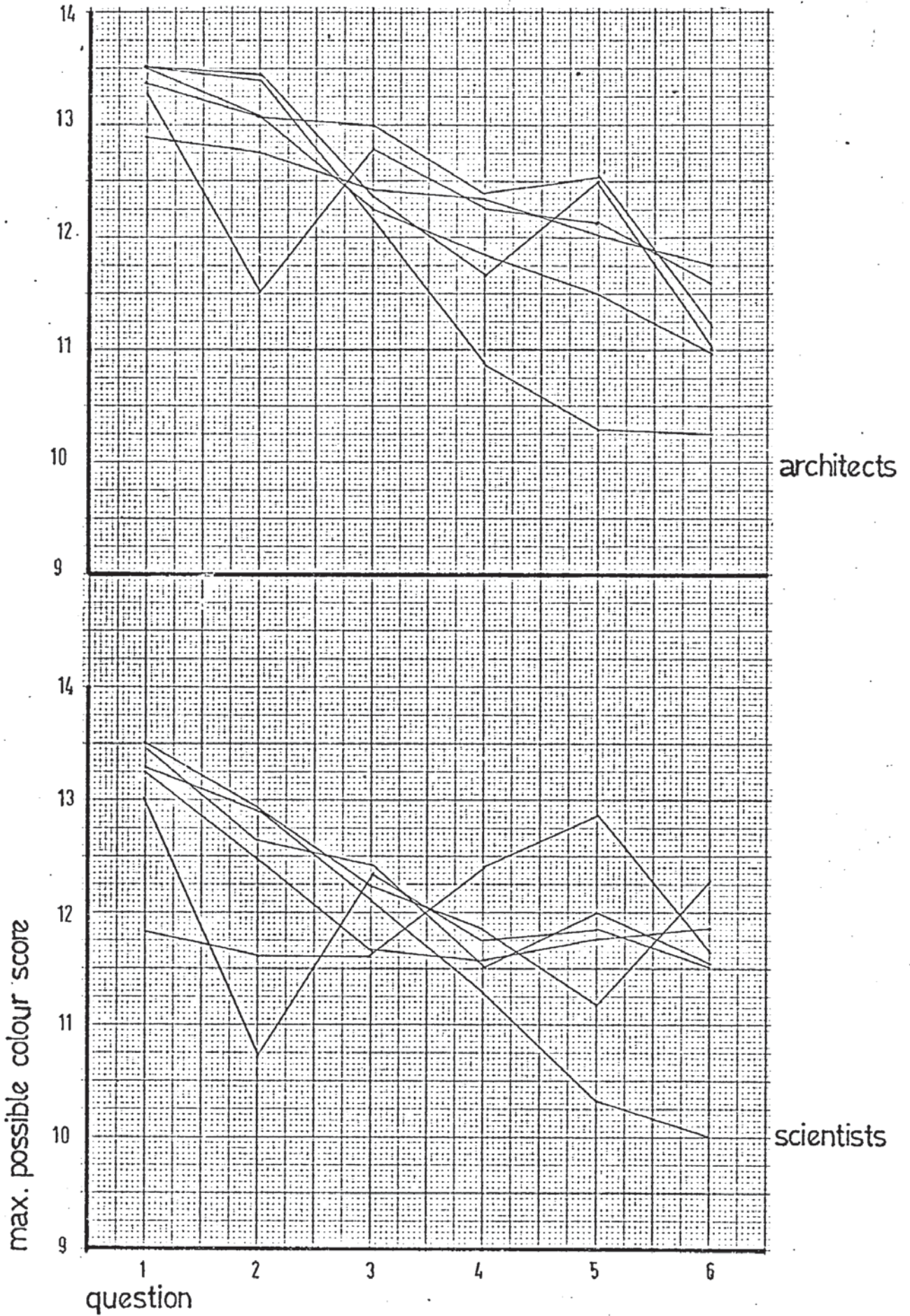
The information content statistic

This statistic was unable to show significant differences between the two groups with any tests.

The colour score statistic

The colour score statistic gave rise to two interesting comparisons between the groups. The mean colour score was computed for each subject for each of the first six questions asked over all eighteen problems solved. Since most problems were solved in under six questions, the statistic becomes most unreliable after the sixth question. The two graphs in diagram 6.3.4 show these means plotted against questions for the two groups. Since it is not possible to show all eighteen curves without loss of clarity only six typical subjects are represented from each group. Examination of these and the remaining curves shows a tendency for the architects' scores to start off high and drop more slowly and consistently than those of the scientists. The difference between the groups seems most noticeable for the first four questions.

This was investigated statistically by computing a grand colour score mean for each subject over the first four questions of all problems. The variances of these means were also computed. These means are of course computed from different sample sizes for each subject so a non-parametric test had to be used for comparison between the groups. As with the blocks changed statistic the Mann-Whitney U test was chosen. This revealed that for two-tailed tests the architects mean colour scores were significantly ($p < 0.002$) higher and the associated variances significantly ($p < 0.05$) lower than the scientists. These



diag. 6.3.4 COLOUR SCORE STATISTIC

table 6.3.7 Strategy analysis for fifth year architects (A5) and scientists (S5)

mean number of blocks changed		first four questions colour score (Q4)			
		mean		variance	
A5	S5	A5	S5	A5	S5
1.96	2.08	11.58	12.20	3.24	2.74
1.14	1.12	13.14	12.79	0.71	1.57
1.25	1.27	12.80	12.74	1.10	1.37
1.73	2.20	12.98	12.00	1.04	1.29
1.23	1.56	13.02	12.36	0.90	2.07
1.60	1.86	12.76	12.76	1.45	1.01
1.24	1.44	13.02	13.21	0.86	0.66
1.26	1.90	12.83	11.96	1.42	2.74
2.04	1.68	12.64	12.47	1.52	1.07
1.45	1.47	12.65	12.75	1.49	1.17
1.71	1.47	13.13	12.96	0.69	0.81
1.58	1.62	12.79	12.26	2.00	0.86
1.65	1.83	12.85	12.66	1.00	2.15
1.18	2.21	13.07	11.68	1.08	1.96
1.02	1.42	13.02	11.82	0.95	2.80
1.37	1.58	12.77	12.28	1.36	2.35
1.55	1.76	12.90	12.09	0.69	3.27
1.76	2.14	13.00	11.54	0.79	2.62

statistics and those from the changed blocks measure are summarised in table 6.3.7.

Conclusions

The rather disappointing performance of the information content statistic is perhaps not too surprising. This score represents the information score available to the subject, and as such is not necessarily a good indication of the information actually used. Lack of memory and focussing of attention conspire against the full use of all the information available. The number of blocks changed, however, gives a statistic which directly reflects some action or search after information on the subject's part.

These results seem to show a tendency towards solution focussing by the architects (high consistent colour scores, low number of blocks changed) and a tendency towards problem focussing by the scientists (low erratic colour scores, high number of blocks changed).

6.3.6 The second phase of the experiment

A group of fifth year architectural students had shown significantly different performance on the experimental task to a group of science students also in their post-graduate years at Aston University. This second phase of the experiment was necessary to place these differences in perspective. So far it cannot be determined whether the differences are due to natural predispositions, educational experience, or a combination of the two. It is also possible that the differences detected are due to a peculiarity in the cognitive behaviour of

scientists, and that the architects are quite representative of the rest of the intelligent problem solving population. Two further groups of subjects underwent this second phase of the experiment, which was in all other respects identical to the first. The two groups were sixth form pupils, and first year entry architectural students.

The sixth form pupils had all just completed their 'A' level GCE examinations and were awaiting their results. They proposed entering a variety of jobs or university courses. The first year architects were tested in their first and second terms before gaining any experience of actual design. As usual they had taken a wide variety of 'A' level subjects.

The performances of the two groups of subjects at the three types of problem; conjunction, affirmation and disjunction are shown in tables 6.3.8/9 (comparable with tables 6.3.1/2). An inspection of the column totals in these tables shows the performances to be insignificantly different between groups. However, unlike the other subjects in the first phase of the experiment, neither group showed a preference for either conjunctive or disjunctive problems. Both sixth form and first year architects showed an equally poor performance at both these problem types compared to the simpler affirmation. This is summarised by diagram 6.3.5 which can be compared with diagram 6.3.2 for first phase subjects.

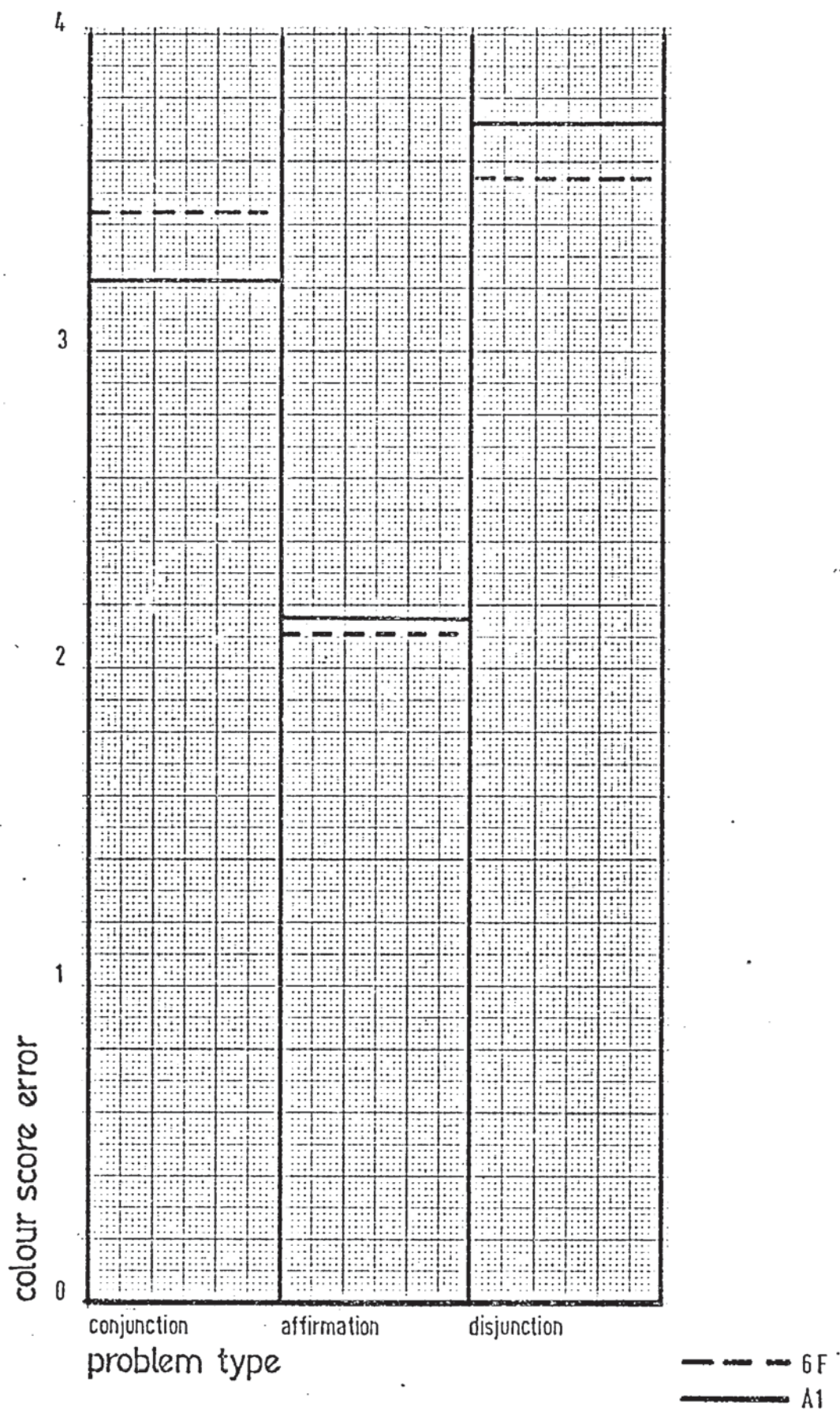
It is noticeable that both second phase groups showed higher overall colour score error scores than the first phase groups. However, a

table 6.3.8 Colour score error (M - S) for sixth form students (6F)
for each problem type

Subject number	Problem type			Total
	conjunction	affirmation	disjunction	
1/1	2	0	1	3
1/2	6	4	6	16
1/3	4	1	3	8
1/4	5	7	8	20
1/5	3	0	4	7
1/6	0	3	0	3
2/1	3	4	2	9
2/2	7	1	6	14
2/3	4	7	6	17
2/4	0	1	3	4
2/5	3	2	4	9
2/6	3	1	3	7
3/1	5	1	3	9
3/2	0	0	4	4
3/3	6	3	4	13
3/4	7	1	5	13
3/5	1	2	1	4
3/6	3	0	1	4
Total	62	38	64	164
Mean	3.444	2.111	3.555	

table 6.3.9 Colour score error (M - S) for first year architects (A1)
for each problem type

Subject number	Problem type			Total
	conjunction	affirmation	disjunction	
1/1	4	1	7	12
1/2	2	2	2	6
1/3	6	2	4	12
1/4	4	3	3	10
1/5	7	4	7	18
1/6	2	2	3	7
2/1	2	2	3	7
2/2	4	2	2	8
2/3	4	4	2	10
2/4	6	4	9	19
2/5	1	2	2	5
2/6	5	2	3	10
3/1	3	4	6	13
3/2	1	1	4	6
3/3	2	0	4	6
3/4	1	2	2	5
3/5	3	0	3	6
3/6	1	2	1	4
Total	58	39	67	164
Mean	3.222	2.166	3.722	



diag. 6.3.5 OVERALL PERFORMANCE - phase 2

Kruskal-Wallis analysis of variance on these grand totals just fails to give a significant chi-squared value for differences between the four groups. (It seems possible that the large number of ties weakens this test here.)

Tables 6.3.10/11 and diagram 6.3.6 show the types of errors made by the two groups of subjects in the second experimental phase. It can be seen that for each problem type the first year architects made fewer planning errors and more structural errors than the sixth form subjects, although none of these differences were found to be significant by the Mann-Whitney U test. Diagram 6.3.7 shows the error types for all four groups. This graph readily shows the lack of structural errors made by the fifth year scientists at disjunctive problems, and the lack of planning errors made by the fifth year scientists at conjunctive problems. A Kruskal-Wallis analysis of variance was carried out on the four groups for each of the six combinations of problem type and error type. Only the structural errors for disjunctive problems were found to be significantly different between groups ($p < 0.05$). In the case of conjunctive problems a Mann-Whitney U test showed that the fifth year architects made significantly fewer planning errors than sixth form students ($p < 0.02$ two-tailed).

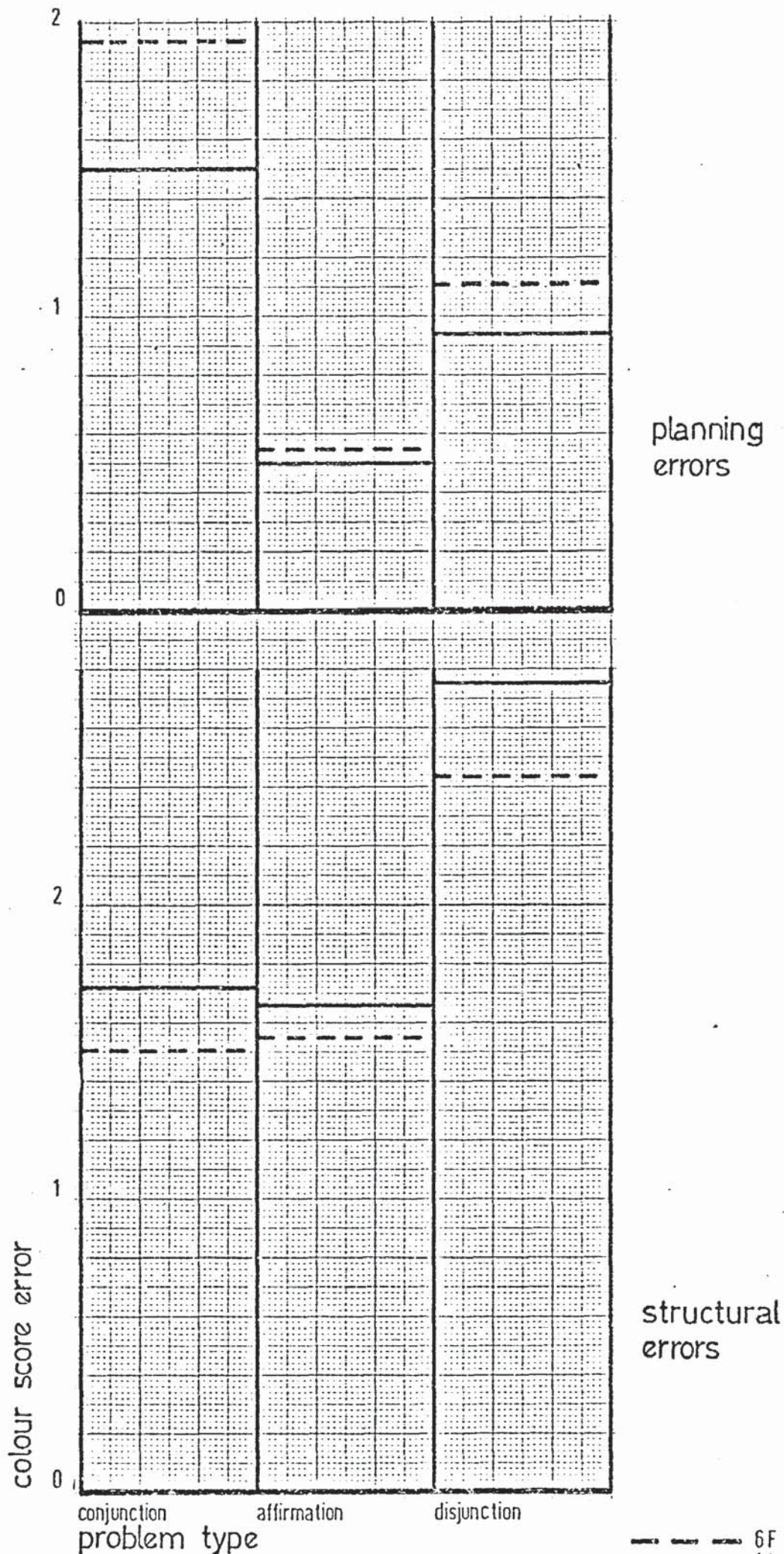
The strategy analysis was carried out exactly as in the first phase, but the results are only presented here in a summarised form so that direct comparison can be made between the four experimental groups. Diagram 6.3.8. shows the mean colour score statistic plotted for each group over the first four questions. The associated standard deviation

table 6.3.10 Types of colour score error for sixth form (6F) students for each problem type

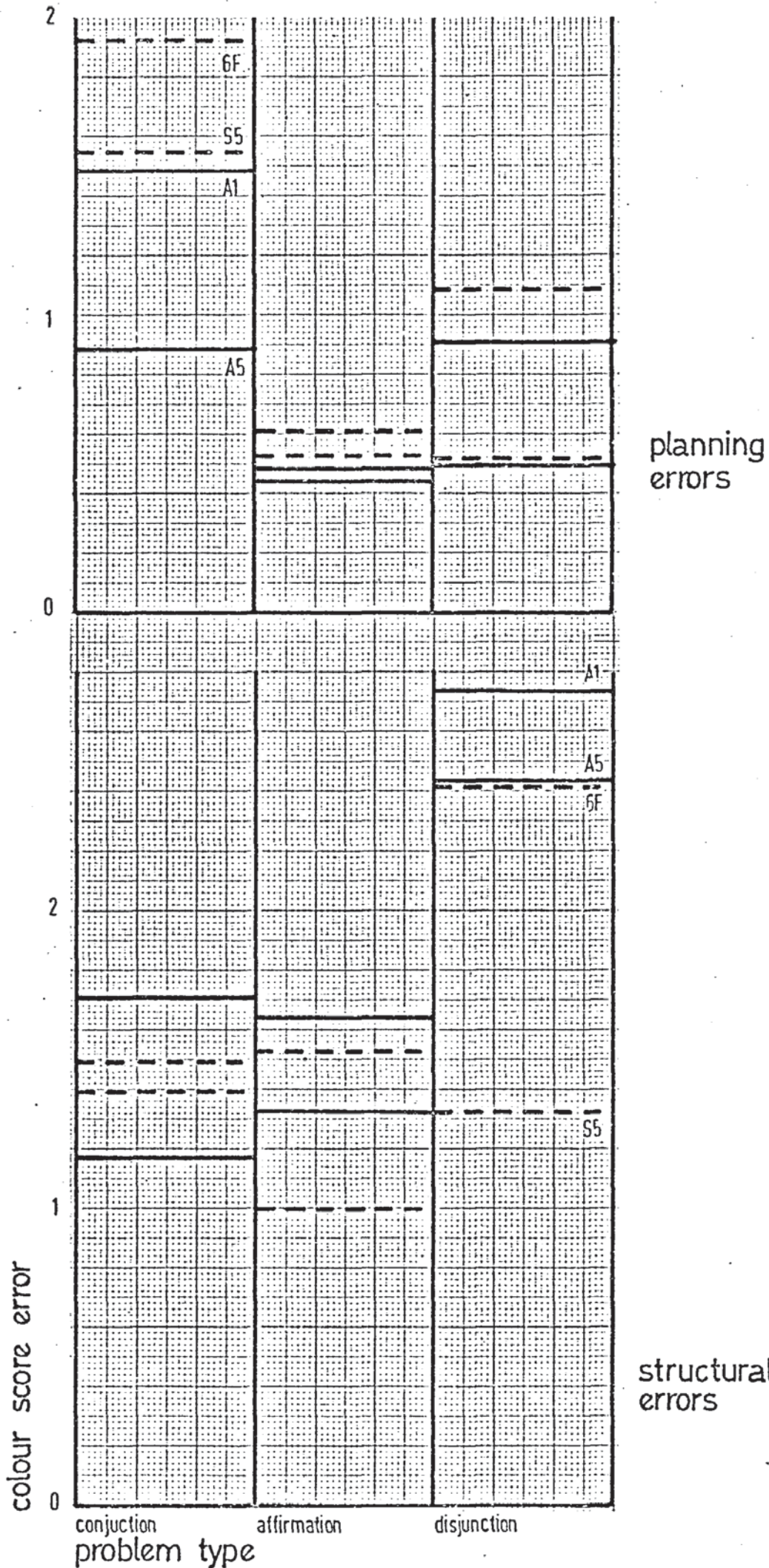
Subject number	Problem type							
	conjunction		affirmation		disjunction		Total	
	PE	SE	PE	SE	PE	SE	PE	SE
1/1	2	0	0	0	0	1	2	1
1/2	6	0	1	3	0	6	7	9
1/3	1	3	0	1	1	2	2	6
1/4	1	4	2	5	3	5	6	14
1/5	3	0	0	0	2	2	5	2
1/6	0	0	0	3	0	0	0	3
2/1	1	2	2	2	0	2	3	6
2/2	4	3	0	1	4	2	8	6
2/3	1	3	0	7	1	5	2	15
2/4	0	0	0	1	0	3	0	4
2/5	3	0	1	1	2	2	6	3
2/6	3	0	1	0	0	3	4	3
3/1	1	4	0	1	2	1	3	6
3/2	0	0	0	0	2	2	2	2
3/3	4	2	2	1	2	2	8	5
3/4	3	4	0	1	1	4	4	9
3/5	1	0	1	1	0	1	1	3
3/6	1	2	0	0	0	1	1	3
Total	35	27	10	28	20	44	65	99
Mean	1.944	1.500	0.555	1.555	1.111	2.444		

table 6.3.11 Types of colour score error for first year architects (A1) for each problem type

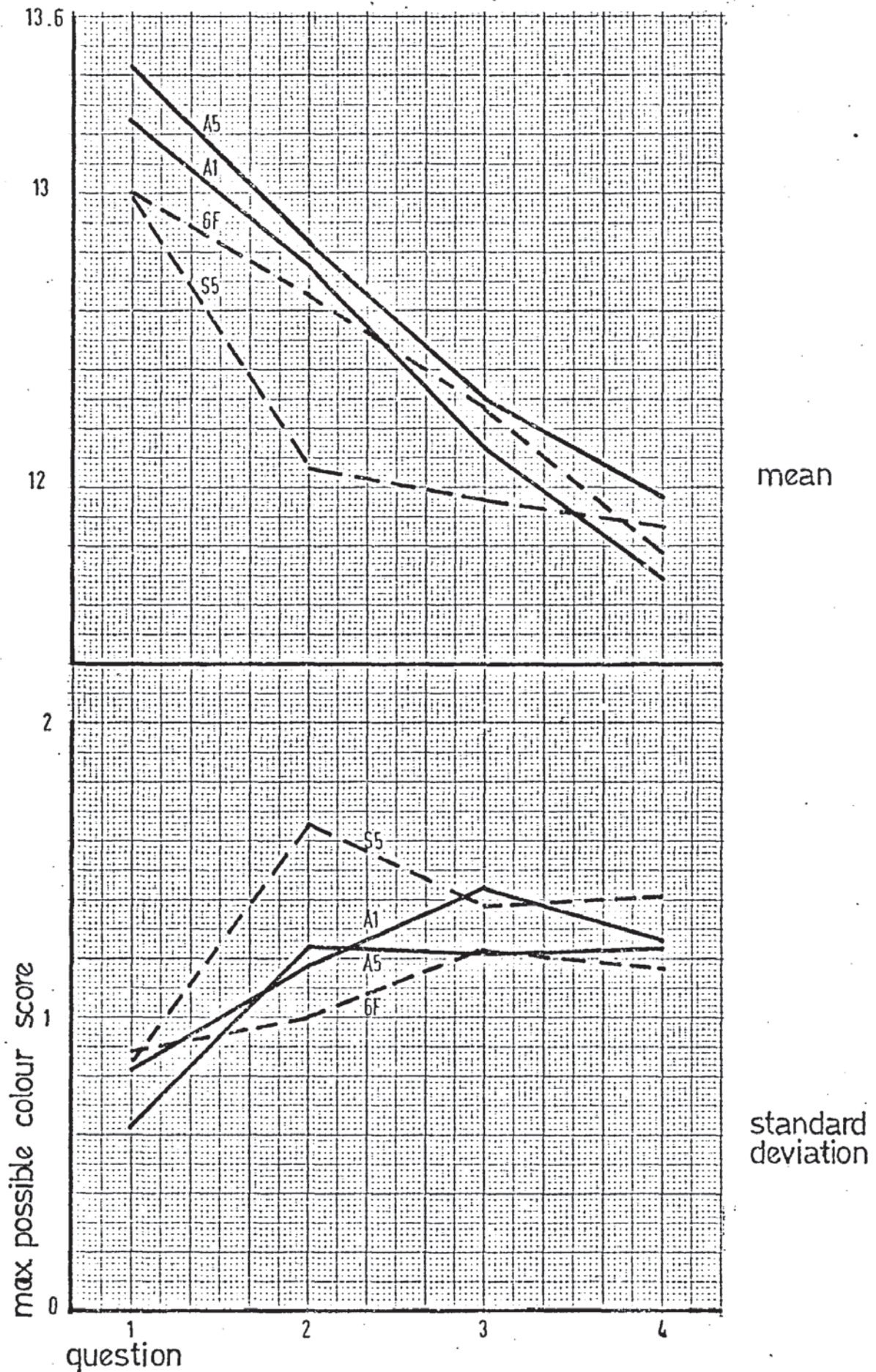
Subject number	Problem type							
	conjunction		affirmation		disjunction		Total	
	PE	SE	PE	SE	PE	SE	PE	SE
1/1	2	2	0	1	0	7	2	10
1/2	1	1	0	2	0	2	1	5
1/3	2	4	0	2	0	4	2	10
1/4	4	0	0	3	0	3	4	6
1/5	2	5	3	1	2	5	7	11
1/6	1	1	1	1	3	0	5	2
2/1	1	1	0	2	1	2	2	5
2/2	3	1	2	0	0	2	5	3
2/3	3	1	1	3	0	2	4	6
2/4	2	4	0	4	0	9	2	17
2/5	0	1	0	2	0	2	0	5
2/6	1	4	0	2	0	3	1	9
3/1	0	3	1	3	3	3	4	9
3/2	1	0	0	1	3	1	4	2
3/3	1	1	0	0	2	2	3	3
3/4	1	0	1	1	1	1	3	2
3/5	2	1	0	0	2	1	4	2
3/6	0	1	0	2	0	1	0	4
Total	27	31	9	30	17	50	53	111
Mean	1.500	1.722	0.500	1.666	0.944	2.777		



diag. 6.3.6 TYPES OF ERROR - phase 2



diag. 6.3.7 TYPES OF ERROR



diag. 6.3.8 STRATEGY PROFILES

of this statistic is also plotted. The low values and high variability of the fifth year scientists profile is particularly noticeable compared with the other three groups. The second phase subjects' profiles are mainly intermediate to the fifth year scientists and architects. A Kruskal-Wallis analysis of variance showed significant differences ($p < 0.05$) between the groups both in terms of means and standard deviations. It is perhaps dangerous to infer too much from these results. All the profiles are fairly similar in shape and value, and are plotted from different numbers of readings.

The changed blocks statistic for both second phase groups was also intermediate to the fifth year architects and scientists, but no statistically significant differences were found. The information content statistic was not computed.

6.4 Conclusions

6.4.1 The results

The various results obtained from the blocks experiment seem to point to several general conclusions.

Fifth year scientists and architects showed well developed but different cognitive strategies when faced with the blocks experimental task. The scientists showed a problem oriented strategy in which attention is focussed on acquiring an understanding of the structure of the problem. The architects on the other hand operated a solution oriented strategy in which attention is focussed on the production of a solution. Neither of these strategies were so obviously or consistently present in either the sixth form or first year architect groups. This suggests that both scientists and architects had acquired their strategies during their five years of higher education.

It could be argued that the strategies of these two fifth year university groups reflected the educational methods that they had undergone. An architect is taught mainly by example and practice. He is judged by the solutions he produces rather than the methods that he uses to arrive at them. Not so the scientist who is taught by a succession of concepts and is only exercised by examples in order to demonstrate that he can apply those principles.

However, this is perhaps too simple an explanation. The set blocks experiment showed that the fifth year architects were better solution

planners than the scientists. Also, both architect groups made fewer planning errors than the other two groups. Conversely the fifth year scientists and sixth form students tended to make fewer structural errors than the architects. Thus although there were not detectably significant strategy differences between the first year architects and sixth formers, the architects already showed greater ability in the production of solutions and less ability in the recognition of problem structure than the sixth form sample. It could then, be argued that the two sets of educational methods merely re-inforced an already existent difference in approach between those who choose science and architecture careers.

There seems to be a very strong connection between strategy and performance which can be seen by reference to the performance diagrams 6.3.2/5. The fifth year scientists gain over the other groups by making fewer errors at disjunctive problems. We have seen that this is due to a tendency to make fewer structural errors which would reasonably follow from a problem structure focussing strategy. The fifth year architects gain by making fewer errors at conjunctive problems due to a tendency to make fewer planning errors. This would reasonably follow from a solution planning oriented strategy. This seems to fit very nicely with previous findings and common sense. Concept attainment experiments show that disjunctive structure is more difficult to understand than conjunctive structure. Conjunctive problems must give rise to tighter planning situations than disjunctions due to the lower number of alternative configurations. Thus both the scientists and architects show enhanced performance on

just those problems in which one would expect their respective strategies to pay off.

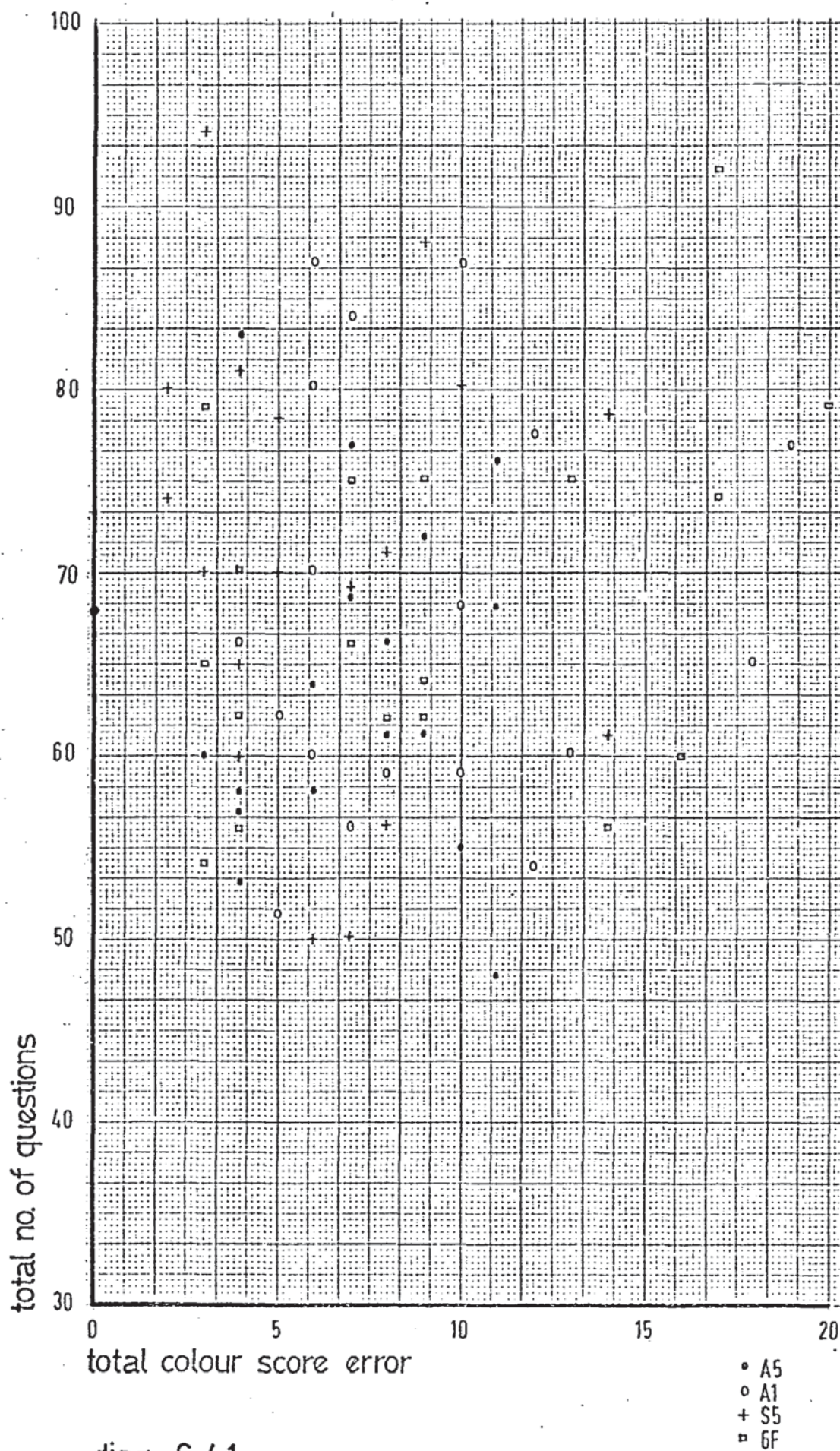
6.4.2 The experiment

So far no reference has been made to the total number of questions asked by subjects, or the time taken over each session. Diagram 6.4.1 shows all subjects plotted by their total colour score error and number of questions asked. It can easily be seen from this scatter-plot that there is no relationship whatever between these variables. That is, the successful subject did not simply achieve low colour score error by asking a lot of questions. Similarly groups of subjects cannot be distinguished by the total number of questions they asked.

Although no accurate record was kept of session times, it was obvious during the experiment that times did not vary significantly from subject to subject. Most subjects spent about 45 minutes on their first session and just under 30 minutes on their last.

It seems fair to conclude that on the whole subjects were trying hard to perform well at the experimental task by thinking about the problem and developing a strategy rather than by simply asking a large number of questions and taking their time. This is what had been hoped for and in respect the experiment seems to have been successful.

It has become apparent, after computing the statistical analysis of results, that the group sizes of 18 were too small. In most cases



the results of the second phase groups were intermediate to those of the two first phase groups. This tended to cause difficulties in the use of non-parametric analysis of variance techniques which are weakened by the presence of ties.

Unfortunately the experiment is not quickly administered and is dependent upon an on-line computer. The availability of computer time and the reliability of the computer therefore imposed serious constraints on the number of subjects that could be run in a specified time. The sixth form group had to be run entirely in the summer vacation, and the other groups were all run between October and February. A longer period would have called into question the homogeneity of these groups especially the first year architects who started to get experience of architectural design in the following March.

After the first phase of the experiment had been completed it became apparent that it had a serious limitation as a model of the design situation. This suggested the development of another experiment which is described in the next section.

7. THE CHEQUERBOARD EXPERIMENT

In architecture, creative products are both an expression of the architect and thus a very personal product, and at the same time an impersonal meeting of the demands of an external problem.

Mackinnon (1962b)

7. THE CHEQUERBOARD EXPERIMENT

7.1 The first experimental situation

7.1.1 Purpose of the experiment

7.1.2 Design of the experiment

7.1.3 The experiment as a model of a design situation

7.2 Results

7.2.1 Agreement in simplicity ratings

7.2.2 Differences between problem types

7.2.3 Different strategies

7.3 Conclusions from the first experiment

7.4 The second experimental situation

7.4.1 Purpose of the experiment

7.4.2 Design of the experiment

7.5 Results

7.5.1 Simplicity ratings

7.5.2 Economy scores

7.5.3 Differences between problem types

7.5.4 Perception of structural rules

7.5.5 Strategy analysis

7.6 Conclusions from the second experiment

7.7 Some parallel observational evidence of design strategies

7.1 The Experimental Situation

7.1.1 Purpose of the experiment

A major criticism can be levelled at the blocks experiment in as much as it fails to provide the subject with any real scope for developing his own 'designer constraint'. It had been thought that the artificially provided designer constraint (of maximum colour on the vertical face of the design) would be sufficient. This constraint was independent from both the discovery of structure and the production of the overall form of the solution (internal and external constraints). The structural rules never involved colour and the distribution of colour was identical within each pair of blocks. Even so in the pilot study several subjects added further constraints of their own invention, usually about the pattern of black and white on the top surface of the blocks. Discussion with subjects from the main experiment revealed that this was by no means untypical.

Since the original argument of the first part of this thesis was developed and the blocks experiment designed there has been much time and opportunity for further observation of architects actually designing. This observation has generated some hypotheses about the nature of designer's constraint. Many architects and interior designers have responded favourably to the model of the three sets of constraints. In the ensuing discussions several designers have expressed a need for a minimum content of self-produced constraint in their problems. Unless there is such an opportunity it seems that many designers would be uninterested in the problem. Observing such designers at work shows

that this self-produced constraint is rarely superficial or ornamental but fairly fundamental. Indeed it is often used to generate the overall form of the building itself. Thus it can usually only be expressed in qualitative and not quantitative terms. This raises serious doubts as to whether such designers are really in control of their own constraints or not. What happens when the internal constraints become very severe? How flexible are these designer constraints?

The format of the blocks experiment is too rigid and structured to allow these ideas to be investigated. The chequerboard experiment is an attempt to observe such unpredictable and open ended behaviour in relatively controlled conditions.

7.1.2 Design of the experiment

An experimental design situation is required opposite to that achieved in the blocks experiment. The balance here is not one of discovery of internal structure but rather of the generation of the designers' own structure. For that reason in this experiment the internal constraint is made explicit and is kept to simple topological relations between elements. Conversely the designer's constraint is a vital part of the problem. The subject knows that unless he produces his own rules his solution will fail.

The experimental material consists of six different modular rectilinear shapes of card, and a rectangular plan grid of 11 bays by 7 bays using the same module. The shapes are coloured red and blue differently on opposite faces. The pattern of colouring follows the modular grid. In addition to these shapes the subject was

provided with twenty-five single module squares red on one surface and blue on the other (see appendix 9.2). The experimental task is most easily explained by the standard subjects' instructions.

"You will see in front of you various differently shaped blue and red coloured cards. You are asked to place them together on the grid so as to produce a pattern. You must use all the six large cards and any number of the small square cards. The cards are differently coloured on opposite faces and may be laid either way up. The cards must be placed within the structure of the grid and the square cards only may lie on top of other cards so as to change their colour.

The pattern you produce will be assessed against two sets of criteria, those of simplicity and economy.

The pattern should be simple as if to be easily remembered and reconstructed. Two factors should be considered. The simplicity of the overall form, and the simplicity of the distribution of colour and its sympathy with the form.

The pattern should be economical both in overall perimeter length and in total area, (square cards count as increased area even if laid over other cards).

In some problems you will be required to have certain specified cards adjacent. To be adjacent the two cards must share a minimum of one bay common boundary. You will have fifteen minutes maximum for each problem and there will be three problems in the session. I shall warn you when there is only one minute left, and you should check that you have all the required relations between cards before finishing.

The patterns produced will be assessed by all other subjects for their simplicity at the end of the experiment."

These instructions were read out to the subject at the start of the first of two sessions. The two sessions each contained three problems, and were held on successive days at the same time. The three problems represented three different levels of imposed internal structure. As explained in the instructions this structure was produced by requiring certain cards to be adjacent. In the first session, the first level of structure (U) had no required adjacencies, the second (L) required

three and the third (H) six. The second session had three problems in reverse order but with different adjacencies. In the case of the last (U2) condition the subject was told not to produce the same design as he had used in his first problem (U1) in the first session. In each problem the adjacencies were drawn out on a card which was left in front of the subject while he worked (see appendix 9.2). Also in front of the subject was a card reminding him of the criteria against which his designs would be assessed.

The subject sat at a large workbench with the experimenter to one side and about a metre and a half away. At the end of each problem the experimenter recorded the design in every detail on a blank grid. At the end of the session the patterns were reconstructed and photographed with 35mm colour film. The colour accuracy proved very good (using Ektachrome X), enabling these slides to be used for evaluation in the second half of the experiment. In addition to recording subjects' solutions the experimenter made notes on the manner in which the various shapes were manipulated by the subject. There was no pre-determined format for this, although, as the results later reveal, one soon developed.

The subjects were 14 of the fifth year architectural students group from the previous experiment. After all of these subjects had completed their two sessions each subject was recalled for a further session to evaluate the simplicity achieved in each of the 84 designs. The slides were projected onto a vertical screen to the same size as the original. The subject was first told that he should rate each slide out of 7 for

its simplicity, against the same criteria of shape and colour used in the designing sessions. A scale of seven points was laid in front of the subject and he was shown a random sequence of all the slides in quick succession. Having seen all the slides the subject was then told to try and use each of the seven scale points equally frequently. He was shown the slides again and verbally responded to each slide in his own time.

The problem solving phase of the experiment was piloted with four non-architectural subjects. Their performance was not analysed but the experimental task proved readily understandable. After this first phase had been completed and slides made of all the solutions these same four subjects showed no difficulty in the simplicity assessment task.

7.1.3 The experiment as a model of a design situation

The Chequerboard experiment presents a rather more open ended task than does the Blocks experiment. The subject himself decides the overall form of the solution, and the internal relationships between parts of it are mapped out for him. The subject is faced with the typical design problem of equating subjective qualitative criteria and objective quantitative criteria. He must make a 'value judgement' and decide how much economy he is prepared to sacrifice in the interests of simplicity. Having made this judgement which will of course vary between individuals, he must hold this value constant under varying degrees of structural complexity.

The difficulty of maintaining this consistency through the three levels of structural complexity cannot be overestimated. The third level (H) was selected to be exceedingly difficult to handle and was therefore likely to disturb the balance. With so many internal relations to achieve the subject would do very well to be able to concentrate equally on both sets of criteria. The interesting question was, what strategies would subjects adopt, to relate the internal constraints, the economic or external constraints, and their own designer generated visual form constraints?

7.2 Results

7.2.1 Agreement in simplicity ratings

At the end of the experiment, each of the 84 patterns produced had been assessed for their simplicity on a seven point scale by all fourteen subjects. Before reducing these fourteen scores to a mean score some test of consistency had to be applied. If the judges were not using similar concepts of visual simplicity then their average ratings would be meaningless statistics.

Since the object of the exercise was to determine for which problem each subject had produced his simplest patterns the subjects were dealt with separately. Fourteen rankings were made up from the judges' scores for the six patterns produced by a subject. Kendall's coefficient of concordance was then calculated to discover the degree of agreement between these fourteen rankings, and a grand mean ranking produced. This analysis was carried out by a program (KENDALLW, see appendix) which also converted the coefficient to the chi-squared distribution. Table 7.2.1 shows the chi-squared values obtained and their significance levels.

In every case the test shows that the agreement between the judges is so high that the probability of such a result occurring by chance with non-agreeing judges is only 0.001. It would seem that we can be confident that the subjects had a common notion of visual simplicity when judging the patterns.

table 7.2.1 Agreement between judges' simplicity scores for each subject

Subject number	Kendall's W	Chi-Squared
1	0.88	61.48
2	0.84	58.94
3	0.86	60.06
4	0.86	60.51
5	0.67	46.97
6	0.75	52.29
7	0.90	63.04
8	0.85	59.27
9	0.81	56.57
10	0.68	47.33
11	0.83	57.81
12	0.85	59.84
13	0.74	51.47
14	0.80	55.78

with 5 degrees of freedom a chi-squared value of 20.52 or more is significant at the 0.001 level

Since the judges agree so well and were also the producers of the patterns themselves it seems reasonable to take the mean assessment of each pattern as an indicator of its success in terms of its designer's objectives.

7.2.2 Differences between problem types

Tables 7.2.2 and 7.2.3 show the simplicity and economy scores for each of the fourteen subjects for each of the three problem types. The tables show the scores achieved in the first and second sessions and a total for each problem type. Since the problem types occurred in reverse order in the second session the use of the totals should prevent learning effects from showing up between problem types.

The simplicity scores in table 7.2.2 are simply the mean simplicity rating given to each pattern by all fourteen judges. The scale runs from very simple (1) to complex (7). The economy scores were arrived at by counting the number of perimeter bays by which a pattern exceeded the minimum possible and adding the number of extra tiles used. Further discussion of these results will be about the totals for each problem type, solved in both sessions.

A preliminary examination of the two sets of column totals reveals an interesting result. The two constrained problems have caused considerable loss of simplicity over the unconstrained problem. However, only the more highly constrained problem causes any loss of economy. A Friedman two way analysis of variance shows the simplicity scores to be significantly different (p less than 0.05), while the economy scores just fail to show a significant difference.

table 7.2.2 Mean simplicity scores allocated by 14 judges for each pattern

Subject number	Problem type Unconstrained			Low constraint			High constraint		
	1	2	Total	1	2	Total	1	2	Total
1	1.86	2.64	4.50	4.86	5.36	10.22	2.93	6.36	9.29
2	4.78	1.78	6.56	5.36	1.86	7.22	5.07	6.14	11.21
3	1.93	3.07	5.00	4.93	2.50	7.43	4.86	6.21	11.07
4	1.14	2.64	3.78	4.28	4.21	8.49	2.07	5.71	7.78
5	1.86	3.78	5.64	3.43	1.86	5.29	1.14	3.43	4.57
6	1.93	5.21	7.14	5.43	2.43	7.86	2.57	2.43	5.00
7	1.28	1.36	2.64	3.21	1.28	4.49	1.64	3.36	5.00
8	1.36	2.71	4.07	2.28	4.67	6.35	1.28	6.50	7.78
9	1.21	3.28	4.49	2.50	1.21	3.71	4.07	2.43	6.50
10	3.14	3.86	7.00	4.78	4.50	9.28	3.64	6.07	9.71
11	1.78	2.93	4.71	5.07	3.50	8.57	1.36	1.64	3.00
12	2.99	1.78	4.77	6.71	1.64	8.35	2.93	3.28	6.21
13	2.71	1.14	3.85	5.14	4.71	9.85	5.57	3.78	9.35
14	5.71	3.36	9.07	6.07	5.64	11.71	6.28	2.57	8.85
Totals	33.68	39.54	73.22	64.05	45.37	109.42	45.41	59.91	105.32

Each cell represents the mean score out of 7 awarded by 14 judges to each pattern produced for each problem type in the first (1) and second sessions (2).

table 7.2.3 Mean economy scores for each pattern

Subject number	Problem type								
	Unconstrained			Low constraint			High constraint		
	1	2	Total	1	2	Total	1	2	Total
1	3	6	9	0	3	3	10	5	15
2	2	3	5	3	3	6	3	2	5
3	3	2	5	1	2	3	4	0	4
4	4	2	6	2	7	9	3	10	13
5	3	3	6	4	3	7	4	2	6
6	3	2	5	2	4	6	3	6	9
7	11	5	16	8	5	13	6	9	15
8	5	7	12	4	7	11	7	6	13
9	3	3	6	4	2	6	19	3	22
10	3	2	5	3	3	6	3	2	5
11	2	2	4	3	2	5	5	9	14
12	4	2	6	4	8	12	2	12	14
13	3	5	8	3	3	6	0	2	2
14	1	4	5	2	2	4	3	3	6
Totals	50	48	98	43	54	97	72	71	143

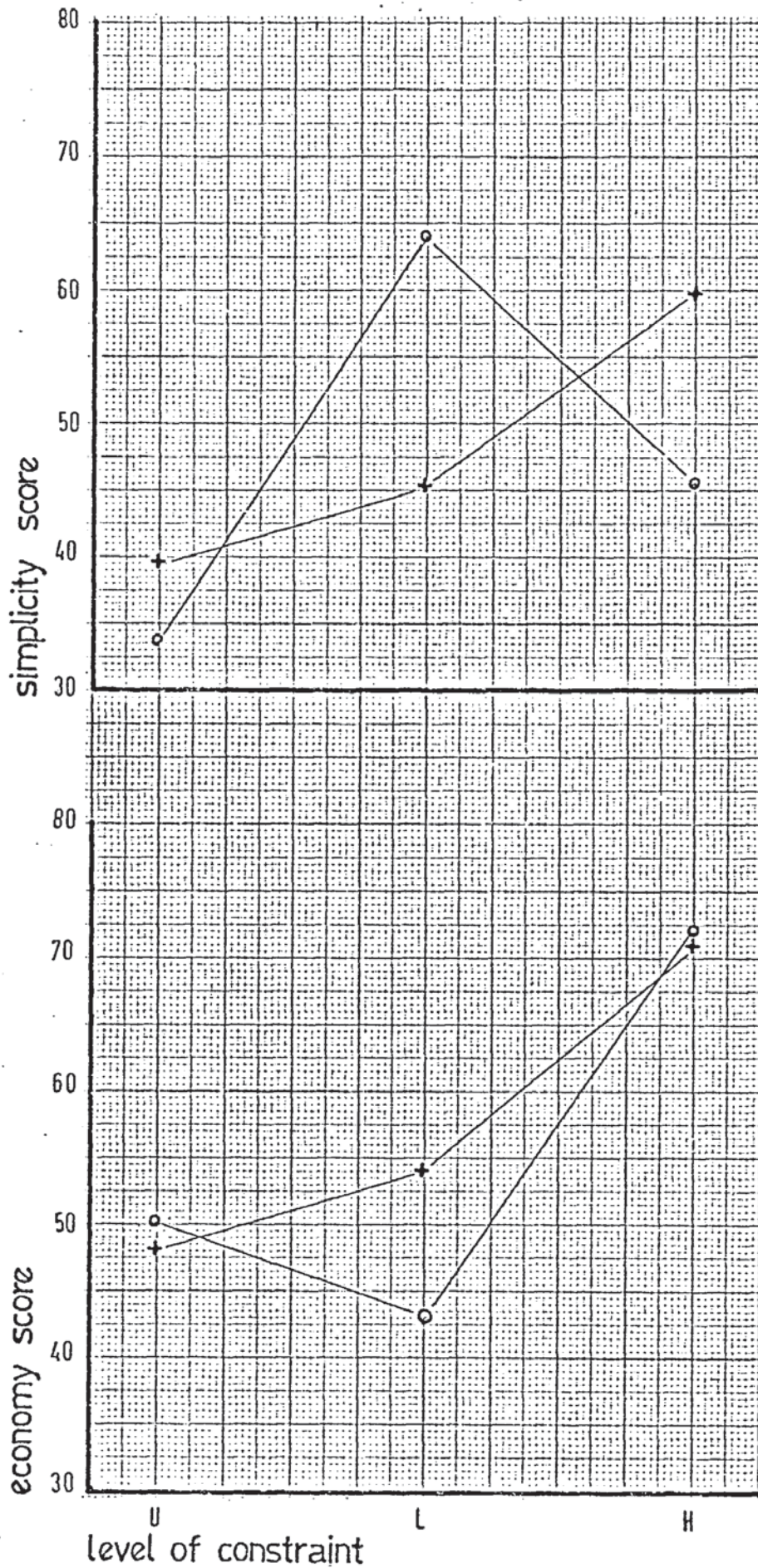
Each cell represents the economy score associated with the patterns produced for each problem type in the first (1) and second (2) sessions. (see text for derivation of economy scores)

On the whole the subjects have achieved the required balance between economy and simplicity, both being lost with the increase in constraint. However, this apparently impressive performance does not bear examination in the individual case. Only five subjects managed to achieve their highest simplicity score for the unconstrained problem and their lowest for the highly constrained problem. Similarly only four subjects produced their most economical solutions for the unconstrained problem and their most uneconomical for the highly constrained problem. Not a single subject achieved both these expected profiles. Indeed six of the fourteen subjects had their worst economy scores associated with their simplest patterns. The indications are that most subjects have in fact concentrated on maintaining their standards of either simplicity or economy and not both simultaneously.

A further interesting result is that plotted in diagram 7.2.1, which shows the grand total simplicity and economy scores for all subjects. In each case the problem which rendered the simpler solutions also rendered less economical solutions than the other problem of the same level. However, only in one case (Low constraint) does this inversion appear significant, and indeed it is difficult to see how one could define the statistical significance of these results. However, they do lend support to the argument that subjects tended to concentrate on only one of the criteria in any one problem. In fact the indication is that, perhaps in some way, the problem itself has suggested which criterion to choose.

7.2.3 Different strategies

As previously mentioned, the experimenter made notes on the way subjects



session 1 ○
2 +

diag. 7.21 OVERALL PERFORMANCE

manipulated the experimental pieces. In addition some insight was gained from the many comments subjects made, either to themselves or the experimenter. From these observations three distinct strategies became apparent and conversations with subjects after their experimental sessions confirmed their existence. I shall call these three strategies, Solution Focussing, Structure Focussing and Element Focussing.

The solution focussing strategy is perhaps the simplest of all, although it is by no means the most helpful. Here the subject decides in an arbitrary manner what form the solution will take. Perhaps a blue square with a red border, or a cross. He then proceeds to push the pieces around until both his constraint and the set structural constraints are respected. Some actual subjects comments illustrate this.

"I think you've got to try and imagine a pattern before you start, but it doesn't always work out so you modify it as you go along."

Since with this strategy the form of the solution is conceived without reference to the problem structure it is often inappropriate. Some subjects are able to learn about the problem as they work and modify their objective. Others are less flexible and become frustrated.

"I seem to have reached impasse here. I set my mind on something that does not work".

The second strategy, structure focussing, is quite different. Here the subject assembles the pieces in their required relationship immediately and shuffles them around until some shape or form begins to appear.

"Right, well the first thing to do is to get all these shapes next to each other, and see what we get."

The final strategy, element focussing was not predicted before it was observed. In this case the subject fits together groups of pieces that he finds difficult to accommodate otherwise. Thus the two L-shaped pieces were often used together. Several subjects always started by placing the larger pieces first and fitted the smaller ones around them later. Frequently two or three pieces are fitted together early on and remain throughout the rest of the designing process. This sub-pattern, often very simple in itself, can be extremely difficult to integrate with other pieces.

"I can see the same old faults again, hanging on to small section of a pattern that I want and trying to fit everything else to it. Its happening at the moment in my studio work."

With one notable exception all the subjects could usually be seen to be working one of these three strategies. Only one subject's movements regularly defied classification. This subject apparently lacked purpose and would handle all the pieces in turn several times. Quite reasonable patterns were lost by a succession of alterations to different pieces, and this subject was unable to recreate them without considerable effort. Most subjects seemed to use only one strategy most of the time, and solution focussing was certainly the most popular. Three subjects preferred element focussing and two structure focussing. Only one subject demonstrated a conscious effort to modify his strategy to suit the problem. This subject solution focussed on the unconstrained problems and structure focussed on the constrained problems. He also used element focussing to arrange the L-shaped pieces into a simple

pattern, but this was readily abandoned if the other strategies required it. It is interesting to note that this subject (5) scored almost identically for the three problem types both for economy and simplicity. Whether this is due to his intelligent adaptive use of strategy cannot be discovered from these results.

Subjects seemed to fall into two quite easily recognisable groups in terms of their attitude towards the design criteria. The first group were those who found the criteria in conflict and made comments about compromise between simplicity and economy. The second much smaller group of five subjects (including S.5) appeared to cluster the two sets of criteria under another integrating factor, thus resolving the conflict. One such subject referred repeatedly to 'visual economy' and another commented that a pattern for him was not simple if it used a lot of pieces. Not surprisingly this group of subjects appeared more confident in their work. Unlike many other subjects they rarely scattered the pieces and 'started again' but rather worked steadily towards a solution. They also seemed to get more satisfaction out of the experiment, although this is obviously a highly subjective observation.

7.3 Conclusions

This experiment being much smaller, more loosely structured and, perhaps, less well planned than the first, was unlikely to yield hard convincing conclusions. Those conclusions which can be slightly speculatively drawn from the results will be more appropriately discussed in the next section. However, two factors about the experiment itself emerged quite clearly.

Firstly it is possible to conduct an experiment with a restricted ensemble of elements making up a design problem that will tax the ingenuity of the subject while still allowing scope for his personal creativity. Subjective criteria for successful designs can be used and measurements made using the subjects themselves as judges. The considerable agreement between the subjects as to the visual simplicity of the patterns renders it unnecessary to define that criterion more precisely. Clearly the subjects knew what was meant by it and worked to achieve it.

Secondly the presence of the experimenter himself in the laboratory can be of enormous value. Automatic recording apparatus will only monitor those variables which the experimenter must select in advance. Even an assistant is unlikely to obtain the insight gained by this experimenter unless extremely well trained and motivated. Many of these insights gained in the laboratory seem very important at this point in time and suggest many more hypotheses which might profitably be tested. This will be discussed further in the next, final section.

7.4 The Second Experiment

7.4.1 Purpose of the experiment

The blocks experiment is an attempt to investigate the way in which a designer comes to understand the pattern of internal constraints in his problem. The first chequerboard experiment serves as a pilot demonstration of how subjective 'designer constraints' can be introduced into an experimental design situation. The second chequerboard experiment requires the subject to discover the internal constraints of the problem while at the same time working towards a subjective 'designer constraint' and determining the form of the solution himself. The question to be answered here is what will happen to the problem, solution and element focussing strategies identified in section 7.2 under these far more realistic conditions. Will these strategies still appear or were they, perhaps like Bruner et al's strategies, the products of a limited experimental situation? If the strategies do still appear what effects do each of them have on the form of the solution they generate?

7.4.2 Design of the experiment

The experimental material consists of four pairs of coloured modular rectilinear cardboard shapes, and a rectangular plan grid of 11 bays by 7 bays as used in the chequerboard experiment. The two members of each pair of cards are identically shaped but different to all other cards. The cards are coloured red and blue in a modular fashion being the same on both faces. The edges of one card in each pair are white

while those of the other are black. In addition to these cards the subject is also provided with twelve single module squares red on one surface and blue on the other (see Appendix 9.2). The subject is instructed as follows:

"You will see in front of you 8 coloured cards. There are four pairs of differently shaped cards; each pair having one white edged and one black edged card. In addition there is a plan grid based on the same module and some single module cards. You are asked to arrange four of the larger cards, one from each pair (that is either the white or black tile but not both) on the plan grid to make a pattern. The cards must not overlap each other and must respect the modular grid. You may use the single module cards to lie on top of the other cards to change their colour and to lie alongside them to complete a pattern.

The pattern you produce will be assessed against two sets of criteria, those of simplicity and economy. The pattern should be simple as if to be easily remembered and reconstructed. Two factors should be considered. The simplicity of the overall form, and the simplicity of the distribution of colour and its sympathy with the form. You must achieve your simple pattern being as economical as you can with the additional one module cards.

For each trial there will be a rule governing 'allowed' and 'not allowed' combinations of cards. The rules can be of the following kinds:-

The black edged square must be present

The black edged square and the white straight.....

The black edged square or the white straight.....

You will not be told what the rule is. You may arrange four cards on the plan and ask if the combination is allowed. The rule always relates to combinations and not plan arrangements of cards.

You are asked to arrive at the simplest and most economical pattern of a permitted combination of cards by asking as few questions as possible. You should always take time to think. The patterns will be assessed by all other subjects for their simplicity at the end of the experiment."

These instructions were read out to the subjects who attended in pairs for the training session. Each subject then solved one problem and the pair solved a third together. Each subject then attended for two more sessions on successive days at the same time. The subjects

solved three problems in each session made up of one of each of the three problem types. The sequence of problem types in the second session was in reverse order to that in the first. This is summarised in table 7.4.1

table 7.4.1 Sequences of presentation of problems

subject number			session one			session two		
1	7	13	A	C	D	D	C	A
2	8	14	A	D	C	C	D	A
3	9	15	C	A	D	D	A	C
4	10	11	C	D	A	A	D	C
5	11	17	D	A	C	C	A	D
6	12	18	D	C	A	A	C	D

key A = affirmation

C = conjunction

D = disjunction

Thus subjects solved conjunctions, affirmations and disjunctions with an array (2 x 4) identical to that used in the blocks experiment, but using solution criteria as developed in the first chequerboard experiment.

Each subject then completed one more session in which he was asked to solve all six problems again but with prior knowledge of the structural rules.

The subjects were 18 fifth year students from the Birmingham School of Architecture who had no experience of the previous experiments. After all the subjects had completed their three sessions, each subject then returned for one further session to evaluate the simplicity of the designs produced. The procedure here was exactly as developed in the chequerboard experiment.

Since this experiment is an elaboration of the previous two it required little piloting and only three subjects were used. This simply served to train the experimenter in his task. During each session the experimenter sat with prepared data forms (Appendix 9.2) and recorded the subject's progress. For each question asked the experimenter observed the subject's behaviour and assessed whether the subject had solution, problem or element focussed. The subject was not told the correct rule after each problem and his knowledge of it was gained from informal conversation.

7.5 Results of the Second Experiment

7.5.1 Simplicity ratings

The procedure adopted here was that developed in the first chequerboard experiment. The subjects first awarded every pattern a mark out of seven for simplicity. (1 simple - 7 complex). Eighteen rankings were made up from these assessments for the six patterns produced by each subject. Kendall's coefficient of concordance was then calculated to discover the degree of agreement between these rankings. The computer program KENDALW lists the coefficient and converts it to a value of chi-squared. Table 7.5.1 shows these values and their significance levels. As with the previous experiment all the results are significant at the 0.001 level. Only one subject (12) showed a consistent tendency to judge out of step with the others, and it is also noticeable that his own simplicity scores are extremely poor. It seems fair to conclude that, subject 12 excepted, the judges held a common notion of simplicity throughout all the phases of the experiment. Kendall's W was not computed for the simplicity ratings on the patterns produced under the second condition of prior knowledge of problem structure.

table 7.5.1 Agreement between judges' simplicity scores for each subject

Subject number	Kendall's W	Chi-Squared
1	0.57	51.3
2	0.85	76.5
3	0.72	64.8
4	0.73	65.7
5	0.81	72.9
6	0.30	27.0
7	0.68	61.2
8	0.65	58.5
9	0.71	63.9
10	0.67	60.3
11	0.64	57.6
12	0.28	25.2
13	0.43	38.2
14	0.37	33.3
15	0.53	47.7
16	0.72	64.8
17	0.66	59.4
18	0.68	61.2

with 5 degrees of freedom a chi-squared value of 20.52 or more is

significant at the 0.001 level. The Kendall's W shows the extent to which the judges agreed on the relative simplicity of the patterns produced by the subject referred to in the first column. In fact most subjects produced patterns either very similar to or identical with patterns already generated in the first phase of the experiment. Thus in many cases these patterns had already been assessed and the judges agreement tested.

7.5.2 Economy scores

The economy scores of all the subjects through all three problem types and both experimental conditions were very consistent. There seem to be two main reasons for this. Firstly the four compulsory tiles had a total area of thirteen square bays, which means that a simple rectangle can be produced by the addition of one (2×7) or two (3×5) extra tiles. By far the majority of solutions had one of these rectangular forms. Subjects tended to use one shape for most of their solutions, and nearly all subjects accepted the cost of one or two tiles to achieve this simple outline. Several resourceful subjects managed a 3×5 rectangle with the centre tile missing to reduce the cost by one tile. The next simple forms after the 3×5 rectangle would be a 3×6 (18 square bays) or 4×5 (20 square bays) which would require an extra 5 or 7 tiles. There is no reason to think these rectangles any simpler than the much cheaper 3×5 or 2×7 , and indeed they were not used.

The second reason for the consistently low cost solutions seems to be a general feeling amongst the subjects that laying tiles over others

was rather 'a cheat'. It seemed to be too easy a way out. However, subjects would allow themselves one overlaid tile if it completed a simple pattern such as a chessboard. No subject overlaid more than one tile in any problem. This point is referred to again in the conclusions.

The result of these influences was to ensure that almost all patterns required one or two tiles to produce or exceptionally none or three. No subject used more than three tiles. Statistical tests have failed to reveal any difference in the use of extra tiles either between the three problem types or the two experimental conditions.

7.5.3 Differences between problem types

A mean simplicity score for each pattern was compiled from the eighteen seven point ratings awarded to it. These statistics are shown in table 7.5.2 together with a mean score for the two problems of each type for each subject. The grand mean score for each of the three problem types just shows the familiar picture of relatively poor performance at conjunctive and disjunctive problems and better performance with affirmations. However, this is not yet the full picture as it is unlikely that it was physically possible to produce equally simple solutions to all six problems. Indeed it could be argued that disjunctive problems should be capable of simpler solution than affirmations since they offer a greater variety of combinations of pieces. Similarly affirmations should prove simpler than conjunctions.

Table 7.5.3 shows the mean simplicity scores for the patterns produced

table 7.5.2 Mean simplicity scores for problems solved under the first condition (no prior knowledge of problem structure).

Subject number	Conjunction			Affirmation			Disjunction		
	1	2	mean	1	2	mean	1	2	mean
1	3.7	2.6	3.1	4.7	5.2	4.9	5.1	2.2	3.6
2	3.8	5.3	4.6	5.2	1.4	3.3	5.7	2.6	4.1
3	3.0	2.7	2.8	2.1	1.2	1.6	2.3	2.9	2.6
4	2.6	2.6	2.6	1.9	3.1	2.5	3.1	1.3	2.2
5	4.8	2.6	3.7	6.0	4.4	5.2	6.5	3.8	5.2
6	3.1	2.6	2.8	3.4	4.3	3.8	3.1	6.3	4.7
7	5.4	5.0	5.2	6.6	2.5	4.5	4.3	2.4	3.4
8	3.0	4.3	3.6	6.3	3.0	4.7	4.4	4.7	4.5
9	2.7	6.3	4.5	5.3	3.3	4.3	6.2	4.5	5.3
10	2.5	3.2	2.8	2.2	1.2	1.7	5.2	2.7	3.9
11	6.3	4.6	5.3	3.4	2.8	3.1	3.0	2.6	2.8
12	6.6	6.6	6.6	6.8	6.9	6.9	6.6	4.7	5.6
13	4.2	5.2	4.7	3.2	4.8	4.0	3.0	6.6	3.3
14	4.3	4.7	4.5	4.1	4.3	4.2	2.8	3.0	2.9
15	2.9	4.1	3.5	2.8	3.4	3.1	4.1	6.1	5.1
16	3.8	4.6	4.2	2.1	2.9	2.5	4.5	5.3	4.9
17	3.1	3.5	3.3	2.1	3.1	2.6	3.5	4.1	3.8
18	3.5	4.1	3.8	2.7	3.3	3.0	3.6	5.6	4.7
Total			4.0			3.6			4.0

Each cell represents the mean score out of 7 awarded by 18 judges to each pattern produced by the subject for each problem type in the first (1) and second (2) sessions.

table 7.5.3 Mean simplicity scores for problems solved under the second condition (full knowledge of problem structure)

Subject number	Conjunction			Affirmation			Disjunction		
	1	2	mean	1	2	mean	1	2	mean
1	2.4	2.2	2.3	3.0	3.4	3.2	1.6	1.2	1.4
2	2.0	2.4	2.2	2.0	1.4	1.7	1.8	1.4	1.6
3	2.1	2.1	2.1	1.3	1.1	1.2	1.8	1.0	1.4
4	1.8	2.2	2.0	1.4	1.0	1.2	2.0	1.2	1.6
5	2.4	2.4	2.4	4.6	3.4	4.0	1.0	1.8	1.4
6	2.6	2.4	2.5	1.7	1.9	1.8	1.0	1.4	1.2
7	3.8	4.2	4.0	1.1	1.3	1.2	1.5	1.5	1.5
8	2.5	2.1	2.3	1.3	2.1	1.7	1.8	1.8	1.8
9	2.0	4.0	3.1	1.2	1.4	1.3	2.0	2.4	2.2
10	2.5	2.5	2.5	1.6	1.2	1.4	1.6	2.4	2.0
11	4.0	4.0	4.0	1.8	1.0	1.4	1.2	1.8	1.5
12	4.0	2.2	3.1	3.4	3.0	3.2	1.6	1.2	1.4
13	4.2	4.0	4.1	2.1	1.3	1.7	1.4	1.4	1.4
14	2.2	2.4	2.3	1.6	1.0	1.3	2.0	1.4	1.7
15	2.0	1.8	1.9	2.1	1.5	1.8	2.0	1.6	1.8
16	2.8	2.0	2.4	1.9	1.5	1.7	1.6	1.2	1.4
17	1.8	1.8	1.8	1.4	1.2	1.3	1.2	1.2	1.2
18	1.8	2.4	2.1	1.8	1.4	1.6	2.6	1.0	1.8
Total			2.7			1.9			1.6

table 7.5.4 Mean simplicity score differences between the two conditions (table 7.5.2 - table 7.5.3) ie no prior knowledge of rule - full knowledge of rule

Subject number	Conjunction			Affirmation			Disjunction		
	1	2	mean	1	2	mean	1	2	mean
1	1.3	0.4*	0.8	1.7	1.8	1.7	3.5	1.0	2.2
2	1.8	2.9*	2.4	3.2*	0.0*	1.6	3.9	1.2	2.5
3	0.9*	0.6*	0.7	0.8	0.1*	0.4	0.5	1.9	1.2
4	0.8	0.4	0.6	0.5*	2.1	1.3	1.1	0.1	0.6
5	2.4	0.2	1.3	1.4	1.0	1.2	5.5	2.0	3.8
6	0.5	0.2*	0.3	1.7	2.4*	2.0	1.1	4.9	3.5
7	1.6*	0.8	1.2	5.5	1.2*	3.3	2.8	0.9	1.9
8	0.5*	2.2*	1.3	5.0	0.9*	3.0	2.6	2.9	2.7
9	0.7	2.3*	1.4	4.1*	1.9	3.0	4.2	2.1	3.1
10	0.0*	0.7*	0.3	0.6*	0.0*	0.3	3.6	0.3*	1.9
11	2.3	0.6*	1.3	1.6	1.8*	1.7	1.8	0.8	1.3
12	2.6	4.6	3.4	3.4	3.9	3.7	5.0	3.5	4.2
13	0.0*	1.2*	0.6	1.1*	3.5*	2.3	1.6	2.2	1.9
14	2.1*	2.3*	2.2	2.5*	3.3	2.9	0.8	1.6*	1.2
15	0.9	2.3	1.6	0.7	1.9*	1.3	2.1	4.5	3.3
16	1.0	2.6*	1.8	0.2*	1.4*	0.8	2.9	4.1	3.5
17	1.3*	1.7	1.5	0.7*	1.9*	1.3	2.3	2.9	2.6
18	1.7*	1.7	1.7	0.9*	1.9*	1.4	1.0	4.6	2.9
Total			1.4			1.7			2.5

*problem type recognised by subject

under the second experimental condition of prior knowledge of the structural rule. The grand mean scores for each problem type reveal that the disjunctions and affirmations were capable of simpler solutions than the conjunctions. Table 7.5.4 completes the picture by removing this bias, being the difference between table 7.5.2 and 7.5.3. A Friedman two way analysis of variance shows the three sets of differences in table 7.5.4 to be significantly different at the 0.02 level. As in the Blocks experiment, performance on the disjunctive problems seems comparatively poor. In the Blocks experiment analysis of the error types seemed to indicate that subjects were not accurately perceiving the disjunctive rule. Evidence from the pilot blocks experiment supported this and suggested that subjects were in fact erroneously identifying the rather more constraining affirmations or conjunctions.

7.5.4 Perception of structural rules

The presence of the experimenter in the laboratory in this experiment made possible a more detailed study of the actual perception of problem type. Informal conversations at the end of each problem easily extracted from the subject his knowledge of the rule involved. Table 7.5.5 shows the numbers of each type of problem perceived either correctly or incorrectly or completely undiscovered. (This table is analogous to table 6.2.6)

table 7.5.5 Actual rule types as perceived by subjects

Perceived rule type	Actual rule type			Totals as perceived
	conjunction	affirmation	disjunction	
conjunction	19	2	3	24
affirmation	8	21	16	45
disjunction	0	0	2	2
undiscovered	9	13	15	37
actual totals	36	36	36	108
actual rule completely correctly identified	5	12	0	-

It can be seen that out of 108 problems a total of 42 were identified by subjects as the correct type and in only 17 cases was the subject sure that he actually knew the rule. A two way chi-square test on table 7.5.5 gives a value of 33.41 for chi-square with 6 degrees of freedom, which is significant at the 0.001 level. This confirms that conjunctions and affirmations are significantly more likely to be perceived correctly than disjunctions.

The 42 problems in which the subject had correctly identified the rule type are marked with an asterisk in table 7.5.4. It is possible to

test the difference between the simplicity score differences obtained for these problems as against the 66 others using the Kolmogorov-Smirnov test for two unequal sized independent samples. This is found to be just significant at the 0.01 level.

These results quite clearly demonstrate that subjects tend to perceive disjunctions as more constraining problems than in reality and consequently produce designs inferior to those they are capable of producing with full knowledge of the structure of the problem they are solving.

7.5.5 Strategy analysis

The Chequer-board format of experiment allows the experimenter to closely observe and discuss with the subject his strategy and understanding of the problem. However, unlike the Blocks format it does not allow the on-line computerised recording of protocols. However, the sequence of pieces used by subjects in their questions was recorded by hand. The only strategy analysis statistic computable from this data is the number of pieces changed between questions. This is analogous to the blocks changed statistic in the Blocks experiment. This average value for subjects varied between 1.2 and 2.1 but no overall pattern was discernable.

As the subject worked the experimenter attempted to interpret the strategic elements of his actions. If the experimenter recognised a strategy as problem, solution or element focussing he made a note on his data recording sheet. This data is obviously not entirely objective, since it was only the experimenter's interpretation that was recorded.

The experimenter had, however, already gained considerable experience of recognising strategies during the earlier experiments without which this would not have been possible. The experimenter's opinion was often supported by the subjects' uninvited comments during the session and by discussion after the sessions had been completed. The experimenter soon came to recognise three quite distinct forms of behaviour associated with the three strategies.

A problem focussing strategy can be identified often from the very beginning of the task by the manner in which the subject lays out the pieces. Typically subjects laid out the pieces in a two by four matrix, with white edged pieces and black edged pieces in separate rows; the columns consisting of the four different shapes. Pieces would then be selected from this matrix and returned to their positions after use. Subjects would often select pieces from the matrix in an orderly, even geometrical, fashion. Thus the matrix itself was used as a form of aid to memory (what pieces have already been used), and as a plan of campaign (which pieces to try next). Almost all the subject needs to remember is a rule for generating the spatial sequences of pieces and the sequence of answers given by the experimenter.

In the case of a solution focussing strategy by contrast the action took place in the working board itself. The pieces were not laid out in a systematic fashion, except perhaps arranged in pairs of same shaped cards. The subject worked at producing an effect or pattern and frequently changed pieces several times between questions. This procedure often resulted in illegal combinations with one or more

shapes not represented in the solution. After receiving a negative reply to a question subjects would completely clear the board and apparently start all over again, sometimes even arriving back at the same combination of pieces.

The element focussing strategy was very popular as an opening gambit. In this case the subject would arrange the pieces not in a two by four matrix but rather in families of similarly coloured cards. A frequent distinction was made between pieces with large areas of colour and pieces which looked more like parts of a chessboard. Solutions would then be built up with pieces which as far as possible came from the same family. In some cases this strategy also resulted in illegal combinations. Several subjects spent some time exploring different topological arrangements of two or three shapes, particularly the two 'L' shaped pieces.

Most subjects tended to keep to the same pattern of working throughout the six problems. In fact there seemed to be a tendency for the procedures to become reinforced by practice, but the experiment was really too short to be sure about this. By far the most popular strategy was that of solution focussing, although many subjects mixed this with an opening gambit of element focussing. Some subjects had less clearly defined strategies than the others. Notable was subject 12 who seemed to proceed almost entirely without strategic thinking but merely tactically in response to the developing situation. This subject got very poor simplicity scores and also judged simplicity rather out of step with his peers. He was one of only two subjects to

fail to identify the problem type in all six cases.

Four subjects (2, 10, 11, 14) regularly employed a problem focussing strategy. Subjects 10 and 14 were extremely methodical and were the only two subjects to correctly identify a disjunctive rule. As a group these four subjects had a mean score of 3.5 out of 6 for correctly identifying problem structure. This is as against 2.3 out of 6 for the other subjects. The problem focussing subjects did not produce either simpler or more complex designs overall, but their score on disjunctive problems of 1.7 is considerably better than the 2.5 of the whole group. Unfortunately the number of problem focussing subjects is so small that it does not seem worthwhile or meaningful to test these results statistically.

It had been hoped that the 18 subjects would contain about 50% problem focussers. Three members of staff at the Birmingham School of Architecture had categorised all the final year students as having a tendency toward either problem or solution focussing in their normal work. All three staff had been correct about subjects 2, 10, 11, 14 and two staff identified two more subjects who did use problem focussing, though not predominantly.

7.6 Conclusions from the Second Experiment

The results of this second chequerboard experiment seem to support the conclusions drawn from the earlier blocks experiment. (see section 6.4.1) However, this experiment, being closer to the real design task, is a much more convincing demonstration of the effects of problem solver's strategy on his final design solution. As in the blocks experiment we see final year architectural students have tended to acquire a solution focussing strategy. This is frequently combined with some element focussing, as seen in the first chequerboard experiment. Subjects seemed much more interested in their solutions than the problem itself. Many were quite unbothered by their ignorance of the rule type while completely fascinated by the task of assembling the pieces into a design.

However, we must be careful not to condemn this approach. Although the solution focussing strategy does not seem to lead to a very good understanding of the problem structure it certainly enables the designer to develop a very comprehensive grasp of the range of solutions. It seems that these subjects were just far more interested in putting things together than analysing relationships. However, the second phase of the experiment demonstrates quite clearly that the same subjects are able to put these same pieces together in more satisfactory ways when the relationships are understood.

A most interesting and not entirely expected phenomenon is that of the reluctance of subjects to use extra pieces in their designs. There is

quite a strong feeling that this is untidy and even cheating. Design it seems, ceases to be challenging and rewarding unless one has to work with a limited ensemble of components. Almost every subject made quite unprompted comments to this effect and some even criticised the experimenter for allowing the use of extra pieces in the experiment. This they thought would encourage others to take the easy way out. It seems that they underestimated the amount of encouragement needed!

All the subjects enjoyed the experiment and saw parallels with real world design situations. This indicated a most important characteristic of designing and designers not built into the model of the design process in section 5. The whole business of designing is absorbing, fascinating and extremely rewarding to some people, and those people do it because they find it rewarding. Any experimental situation which is not fascinating and rewarding is likely to receive only half-hearted attention from designers; a fact which most design educationalists are only too well aware!

7.7 Some Parallel Observational Evidence of Design Strategies

During the year in which the second chequerboard experiment took place the subjects were engaged upon the design of a large and complex office building for Northamptonshire County Council. The brief specified that the main working areas should be designed on an open plan and landscaped basis. The experimenter acted as a consultant on the human factors problems of this proposal and thus was able to keep a close watch on the students design procedure. It should perhaps be realised this project presented the student with a very considerable range of problems. The offices were to contain the local government departments, the council chambers and the county library. The site was well out of the town centre and the new structure plan caused problems of both public and private transportation. Finally apart from the obvious human problem, the open plan office causes structural and servicing problems in order to achieve large uninterrupted spaces with full internal environmental control. About halfway through the project the students, some of whom worked in groups, presented their outline proposals and method of working. We shall briefly consider several of these submissions.

The first student, who worked alone, started his presentation with a description of the Northampton structure plan and the topographical characteristics of the site. The structure plan laid down major radial public transport routes one passing each side of the site. These were to be connected by orbital pedestrian ways one of which crossed the site. This suggested to our first student that the whole building

complex should sit astride this major public pedestrian way. The slope of the site suggested further that the office accommodation could lie on two levels to the south of this pedestrian concourse and overlook the parkland, with staff recreational spaces around the glazed perimeter of the office block. The public library and council chambers would then lie to the north of the concourse and be carefully integrated with it. This student had thus defined the location and form of his building in terms of the external constraints of transportation and site. His final solution embodied all these principles.

The second submission came from a group of three students. They did not yet have a building form or any real idea of its ultimate siting. They showed how they had studied the requirements of an office worker at a desk in the open plan spaces. They had defined the equipment needed, its layout and sizes and the method of environmental control. They had arrived at a solution for a 20m square office bay with services integrated with structure in the ceiling and floor location points for furniture and screens. They were now studying the way these modular bays would be assembled together into a complete building. This group had concentrated almost exclusively on the internal constraints of the office itself. It is interesting that their final solution was criticised for the design of the library, which it was said looked tacked on as an afterthought.

The third group presented sketch perspectives of a sequence of spaces as seen when entering their building. This group were concerned that such a large edifice would cause visitors to lose their way. They

had designed a series of office spaces clustered around service cores in turn clustered around a central entrance and reception space. There was no information as to how the building would sit on the site or as to the detail functioning of the office spaces. This group had a reputation for being strong imagers and spatial creators and had set out to design by posing their own problems. An even more startling example of designer constraint working was given by an individual student. He was convinced of the need to provide complete car parking for the office staff. His solution had already taken shape and consisted of three huge double interlocked helical ramps. One ramp was office space and the other, locked into the first like a French staircase, provided service access and car parking space. He spent many happy weeks solving the considerable technical problems of structural support and external skin design caused by this layout.

Thus it can be seen that each of the three sets of constraints - internal, external and designer, can provide a point of departure in complex problems. That the point of departure had a very strong effect on the final solution can be seen very readily in the examples quoted above; that a point of departure is necessary can hardly be disputed. With his limited span of attention and comprehension the human designer must start not with the whole problem but only a part of it.

The public at large and technologists in particular, frequently criticise the approach of the typical solution focussing architect. Many would think that the second group in the examples above have a more sensible

approach much more likely to result in a solution satisfying the needs of its users. An interesting example of the value of solution focussing and of adherence to designer constraints can be seen in just this case.

The external envelope is a great problem in open plan offices. In order to produce acoustical privacy the space has to act as if it were really an open air space with no reflecting surfaces. Such a large space must be air conditioned and stable temperature and humidity levels maintained. Glass is an excellent acoustical reflector, and transmitter of heat. Heat loss in the winter is not a great problem, but large areas of glass can cause solar gain and glare problems in the summer. All of this seems to suggest that the external skin should be solid and with a rough and absorptive inner surface. This was the solution used by the second group of students. However, the solution focussing students had resolved that this was not acceptable to them, and that people deserved a view out of the building. They discovered that by using tinted glass at an angle of 15° to the vertical with the top edge leaning out of the building the problems could be solved. At this angle the glass was able to reflect solar radiation externally and to reflect internal noises up to the ceiling where they could be absorbed. Thus the solution focussing strategy can have the effect of overcoming difficulties rather than simply looking for a logical pattern which itself suggests a solution.

8. CONCLUSIONS

"Now for the evidence," said the King, "and then the sentence."
"No!" said the Queen, "first the sentence, and then the evidence!"
"Nonsense!" cried Alice, so loudly that everybody jumped, "the
idea of having the sentence first!"

Lewis Carroll
(Alice through the looking glass)

8. CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

8.1 Structural thinking

8.2 Structural thinking in design

8.2.1 The structure of problems and solutions

8.2.2 Cognitive strategies in design

8.3 Implications for architectural design

8.3.1 Some implications for computer-aided architectural design

8.3.2 Some implications for architectural education

8.1 Structural Thinking

Although these experiments were devised in order to examine problem solving specifically in a design context the results do suggest some conclusions on structural thinking in general. As shown in section 4.4 many researchers have concluded from their experiments that we are better at handling conjunctive concepts than disjunctive concepts. The experiments reported here can offer some slight chance of refuting this general hypothesis.

In the blocks experiment three out of the four groups produced more structural errors for disjunctive problems rather than the conjunctive problems. In the second chequerboard experiment final year architects produced more complex than necessary patterns for their disjunctive problems, and the results indicate that this was due to their relative inability to accurately recognise disjunctive structure. However, it must be remembered that fifth year science students performed equally well on disjunctive and conjunctive problems in the blocks experiment.

Strategy analysis in all the experiments reported here has demonstrated that the problem solving strategy employed has a strong influence on the subject's performance on different types of problem. In more general phraseology cognitive style influences results. In order that we more fully understand structural thinking perhaps we should attempt more studies in which subjects with potentially different approaches are set to solve a variety of problems. One cannot help but wonder just how many cognitive psychology experiments have been carried out

on psychology undergraduates. Surely a very special sub-group of the population in terms of thinking styles!

Longitudinal studies seem very necessary in the light of the results of the blocks experiment. Although first year architects did not perform significantly differently to sixth form pupils, fifth year science and architecture students did. This suggests that education may well influence cognitive style in a fairly general way. Dienes and Jeeves (1965) cleverly designed an experiment in which they could compare the structural thinking characteristics of children and adults, but alas the adults were represented by first year psychology students!

Many experiments on structural thinking have concentrated on the sequence of hypotheses adopted by subjects. Bruner et al. (1956), Hunt and Hovland (1960), Neisser and Weene (1962) and Lawson (1969) have all reported sequences of hypotheses held in concept attainment experiments, and Wason (1960) reports an experiment specifically designed to investigate the sequence of hypotheses, and the subjects unwillingness to change his last hypothesis. One can easily understand the reasons for the popularity of such studies. There are few meaningful outward physical signs of thought, and the experimenter who wishes to observe its process must force the thinker to externalise in some way. However, there is a danger that the required externalisations come to govern the process, as can be seen here. Lawson (1969) did not encounter a subject who failed to hold a hypothesis, whereas the second chequerboard experiment shows that in about a third of all cases (37 out of 108) subjects had no idea what sort of problem they had solved even after they had produced their solution. Admittedly emphasis was not laid on

the discovery of problem structure in this experiment, but equally the forced externalisation of hypotheses could be held to emphasise this too much, and to suggest an unnatural way of thinking.

This is the standard danger of all psychological experiments. The danger that the subjects' response may be a function of the experimental situation rather than the real world of which it is a model. This seems particularly true when it comes to cognitive strategy. The human mind is quite adaptable enough to take advantage of any distortion in the experimental model and generate a strategy accordingly. In the classical concept attainment experiment the array of all possible events is systematically laid out in matrix form for the subject to see. Surely any quick witted subject would utilise this in forming his information search strategy. This is confirmed by Bruner et al's study of 'on the board' versus 'in the head' experiments. When the matrix was removed some strategies were no longer effective. "Four out of the five scanners came to ruin when they had to do problems in their head." It would therefore seem dangerous to generalise from this specific strategy to some theory about real world concept attainment as do Bruner et al. Similarly with the experiments reported here. They were intended as a model of the design situation, in which problem discovery is integrated with solution production, and not as a general model of concept attainment. Even so the experimental format, particularly in its earlier blocks version, does seem to have interest for cognitive psychologists and to suggest to them further but rather more generally applicable investigations.

It seems that the essential attribute of these experiments which is so interesting is, almost paradoxically, that the structure identification task is hidden. The subject is asked to take some action and produce a set of relations and in order to do this it is desirable to identify some existing relations. This is possibly a better model of most everyday thinking situations than the rather more self conscious conventional concept attainment experiment. Rarely, other than perhaps in science, does one want to identify a set of relationships simply for the sake of it. More usually one is motivated by the need to take some future action. This is rather nicely demonstrated by the example used early in Bruner et al's work.

"Consider the chain of events leading up to the learning of a concept, and we purposely choose an example from everyday life. Our hypothetical subject is a foreigner who has arrived in town and is being introduced around by an old resident who is a trusted friend of his. The people to whom he is being introduced are the instances. After each encounter with a new person his friend remarks either, 'He's an influential person' or 'He's a nice fellow but not very influential.'"

We are given to believe that - the classic concept attainment experiment is an excellent model of this situation, but not so. Unless Bruner et al's foreigner is a sociologist studying the concept of community he is not just passively observing a situation, but is himself involved and can act upon that situation. That is, he can not only study the attributes of influential people, but also try out various forms of behaviour himself to see what response this elicits. Indeed, parallelling the architectural subjects reported here, he may come to be influential before discovering the relationship of attributes

separating influential from non-influential people. As Wertheimer (1959) said "context has a profound influence upon the way in which the thoughtprocess will develop". Concept attainment in a context of the need for action as encountered in every day life may be a different process to that found in the traditional laboratory experiment. The blocks and chequerboard experiments both provide that context of action but specifically a design action. It is possible that other variants of the basic form could be developed possibly requiring verbal rather than spatial relationships to be formed.

One important question has to be answered before the value of this approach can be ascertained. That is, what is the effect of shortening the timescale. In real life we are developing and attaining many concepts simultaneously and over extended periods. In the experimental condition the subject purposely sets out to solve one problem at once and in a limited period of time. While this may be a reasonable representation of design problem solving, it is obviously not an accurate model of much structure identification. The subject is obviously able to utilise his short term memory and it is reasonable to suppose that this may cause him to adopt a different strategy to that employed in everyday life where we can store and restore information in our long term memory. This suggests that some experiments should be conducted over a longer time span to discover the influences of short and long term memory on cognitive strategies.

Finally this section must end with an admission of defeat. A problem

which appeared at the beginning of this study still remains unsolved. That is how to study relational and conditional concepts in the same experiment as conjunctive and disjunctive concepts. Clearly this cannot be done meaningfully until one has some objective measure of the information required to attain these concepts and can create equal conditions in which to compare the subjects' performance. Lawson (1969) demonstrated that in a four binary variable array conjunctive and disjunctive concepts required equal information for identification (reported in section 4.4.1) and this array has been used throughout all these experiments. Unfortunately it can be shown using simple boolean logic that in any binary variable array a conditional relationship simplifies to and is identical with a disjunctive rule and a biconditional rule reduces to a double conjunction. In an array using variables with more than two steps this can be avoided, but disjunctions and conjunctions are no longer complementary, and as yet there is no theoretical scale of difficulty on which to measure all these concepts. Without such measurement it seems pointless to compare subjects performance in attaining the various concepts.

8.2 Structural Thinking in Design

8.2.1 The structure of problems and solutions

The last section included a reminder that design involves both recognition of the structure of problems and production of the structure of solutions. This cannot be repeated too often since this is surely the fascination that the design activity holds for us. It would perhaps, seem quite natural to most enquiring minds that the activities should occur in that sequence; recognition and then production. This seems so logical a progression that many writers have suggested that designers should consciously adopt such a methodology. However, the plain fact of the matter is that designers do not work in what may seem on paper to be a nice neat logical manner.

In both the blocks and chequerboard experiments fifth year architectural students appeared to show more interest in the production of solutions than in the recognition of problem structure. More importantly, they integrated these two activities more than their scientific peers. The fifth year science students worked more logically through phases of problem structure investigation and then solution structure generation. In design, solutions take on a visual form, while problems have form only in the abstract. Since designers are on the whole selected and trained for visual awareness, it is not surprising that they are more interested in visual solutions than abstract problems. It was mentioned in section 4.3 that in his experiments Guilford found only one ordering factor. That is, one ability to either recognise or produce structure. The results of this (blocks) experiment might be taken to suggest that

this is untrue. The scientists appear to show high recognition ability but low production ability in comparison with the architects. However, Guilford's model itself provides a possible explanation here. It was the architects' failing to recognise structural order and the scientists' inability to produce figural order which distinguished the two groups. Thus it is not only a matter of the recognition or production of order but also of its figural or structural content.

This 1956 model of Guilford's is extremely helpful for gaining insight into structural thinking in design. The architect has to produce figural order in his solutions from the structural order of his problems. Not so the artist who usually produces his figural order from a conceptual or meaningful structure, although much modern art is concerned purely with figural order for its own sake. When the architectural designer introduces his own constraints then he may be thinking like the artist in either figural or conceptual terms. That is he may desire form or proportion for its own sake or to give some external expressive meaning to his architecture. At this point it is interesting to note the parallels not only between Guilford's (1956) model and the model of design constraints suggested in section 3, but also that of Garner (1962) who also examined "structure as a psychological concept."

Garner points out that "meaning" has connotations both of structure and significance.

"A particular word may be meaningful in the sense of signification, but the entire language becomes meaningful only if some structure is perceived in the total set of symbols."

Garner shows how meaning as significance cannot be quantified but how meaning as structure can. He also shows how this structure can be divided into internal and external constraint, and he develops the mathematical relations which exist between them. In his commentary Garner points out that language systems, because they must have external reference to communicate, must have a high degree of external constraint.

He goes on:

"On the other hand, the arts have not been bound by the need for an amount of communication, and thus have been much freer to use higher degrees of internal constraint. Modern visual art, for example has tended more and more to keep external structure to a minimum in favour of internal meaning."

McLuhan (1964) is following the same line of argument when he points out that communication media become art forms as they are superceded by new media with greater information carrying capacity.

This sort of discussion is followed up more fully by Mueller (1967) and Moles (1968) in their studies of communication theory and art, but as yet no one has discussed these concepts with direct reference to architectural design. This can perhaps be more easily done with reference to Guilford's model and the design constraint model presented here.

If one examines the high style periods of classical and renaissance architecture one can easily perceive the attention paid by the architects to designer generated internal constraints in the figural content of their solutions. (In more old fashioned language: a highly developed visual grammar) By contrast the modern dictum of form follows function

implies a greater interest in problem generated internal constraints of a structural nature. However, as was pointed out in section 1.4, the modern architectural movement also has its roots in functionalist expressionism. Not only does the form follow from the function but it also expresses that function. The modern building is required to signify how it works and what it does. Clearly the role of the modern architect is a very difficult and complex one. The model of design constraints (diagram 3.5.2) now appears far too simple. There would seem to be at least eight ways of generating constraints to be imposed upon an architectural solution. Using these constraints the architect must make his building function at all the levels expected of a piece of twentieth century architecture.

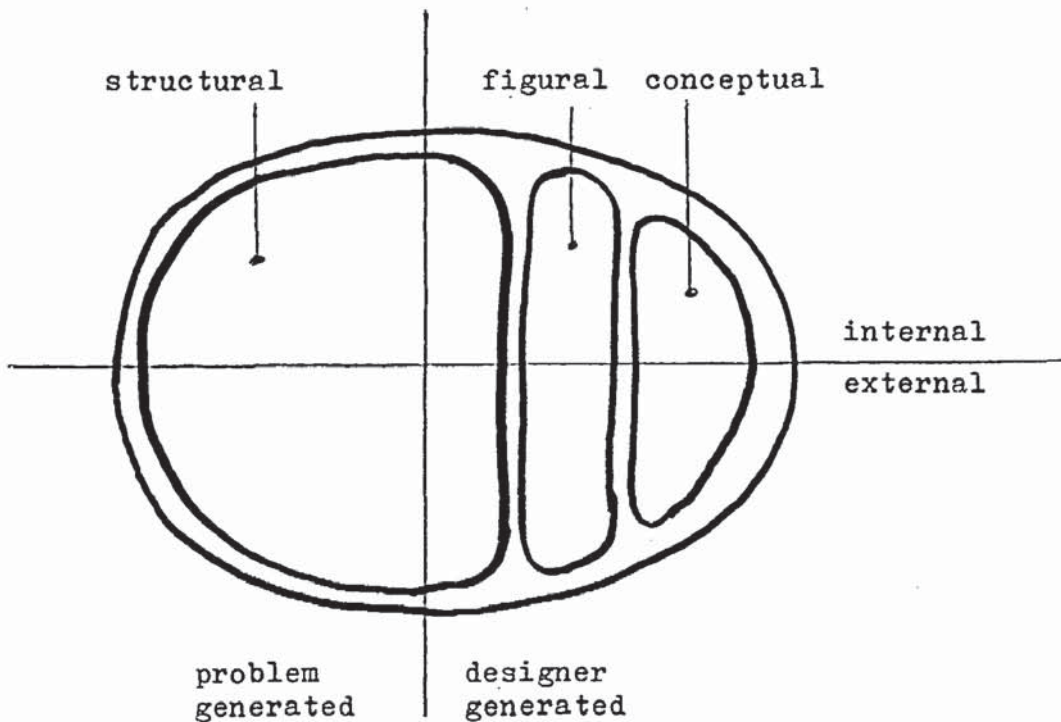


diagram 8.1.1 Design constraints

8.2.2 Cognitive strategies in design

Observations from the blocks and chequerboard experiments have suggested that at least three cognitive strategies can be operated in the central problem solving stage of design. They are problem structure focussing, solution focussing and element focussing, and they have already been described in previous sections. These three strategies do seem quite fundamental and distinct. However, only two sets of experiments have been carried out and it is quite possible that other experiments and experimenters may identify many other strategies. That possibility cannot be discussed here, but questions can be asked about the three strategies so far identified.

Cognitive strategies are necessary when problems are large and complex. They help the designer to organise the search for, and interpretation of information, thus enabling him to grasp the critical aspects of the problem. In both the experiments we have seen that each strategy works better for some problems than for others. In the blocks experiment the solution focussing strategy enabled the spatially able architects to produce optimal solutions in the heavily constrained conjunctive problems. However, as Bruner et al (1956) pointed out in a parallel experiment such a strategy is dangerous when there are disjunctions about. Indeed the architects, operating a solution focussing strategy did very badly at disjunctive problems. Conversely the scientists were let down by their problem structure focussing strategy in the case of conjunctions because it failed to help them produce the correct spatial solution structure. In the chequerboard experiments, solution focussing was useful in generating designer

constraints for the low constraint conditions but proved to be an extra hardship in the high constraint conditions. Element focussing is a strategy which seems to show a degree of design sophistication. The problem solver is here anticipating difficulties in the production of his solution because of the inherent nature of the elements themselves not the relations between them. An inspection of the tapes and protocols from the blocks pilot study showed that those subjects also seemed at times to operate an element focussing strategy. It is impossible to tell whether or not subjects used this strategy in the main blocks experiment due to the rather rigid data monitoring procedure.

So far we have not uncovered anything of much value to the designer. It is of little use to know that a particular strategy is best suited to solving particular types of problems unless one knows in advance what type of problem one is faced with. Designers at either end of the open-closed ended problem spectrum have little difficulty here. A fashion designer knows in advance of starting a project that most of the constraints must be generated by him. He can therefore safely adopt a solution focussing strategy. He thinks of a 'visual concept' and defines it more and more carefully by producing a succession of solutions until he is satisfied that behind his final creation there lies a coherent grammar of visual form governing colour, texture, shape and pattern. At the closed end of the spectrum the chemical engineer knows that the process that he is trying to accommodate is complex enough and he cannot afford to introduce any extra designer constraints until he fully understands it. He can therefore safely adopt a problem structure focussing strategy. He may use a mathematical

programming technique to optimise his layout and understand the tradeoffs between various solutions.

Life is not so simple for the architect who is caught near the centre of the open-closed ended problem spectrum. Only very occasionally does an architect find that he can design in an entirely solution focussing or problem focussing way. In most instances he must be able to treat different parts of a project in different ways. He must always respect the internal and external constraints of his problem but at the same time be ready to take advantage of any opportunity to impose designer constraints. In other words, the architectural designer must continually be sensitive to the changing nature of the problem if he is to apply the most suitable strategy at each stage. This sounds a great deal simpler than it in fact is, and the considerable educational and methodological implications will be briefly discussed in the next section.

8.3 Implications for Architectural Design

8.3.1 Some implications for computer-aided architectural design

The results of the blocks experiment suggest that architects' strategies may be better suited for the generation of solutions than the recognition of problem structure. This is by no means a catastrophic failing since the error that results tends to be conservative. The architect is working to a structure more constraining than exists in reality. However, this may cause unnecessary compromises to be made where the constraints give rise to conflicts. This aggravates the design methodologists who quite reasonably feel that better buildings could be designed more quickly and cheaply if only the design process was more accurate. Almost invariably this implies the use of computerised techniques.

One of the most notable of these is the program of Whitehead and Eldars (1964) which can design single storey buildings from projected inter space flow figures. However, such programs can only optimise quantities and not qualities. Lawson (1971) has pointed out that for the architect much of the structure of a design problem consists of value relations between factors which cannot be reduced to a common metric. Whitehead and Eldars program relies upon costing the movement time of building users. Often, however, the kind of movement is as important as the distance moved. Many human circulation problems are very subtle and delicate. A manager's room must often only be accessed by visitors through his secretary's room, but he must be able to leave without being seen by those waiting for him, and to reach the board

room without encountering any other members of the committee. This sort of factor cannot be meaningfully costed, and the architect must consider it separately from many other similar factors.

The human problem solver in the form of the architect remains the better decision maker in the face of all this complexity of information. However, he cannot make sensible decisions until he has fully grasped the structure of the problem. In his now classical work Alexander (1964) proposed a problem structuring aid to design. This was perhaps the first genuine attempt at computer aided architectural design. Here the computer does not generate solutions but rather presents the designer with the problem structured in a particularly visual way. Alexander's technique suffered from many restrictions and potential inaccuracies. The designer was only allowed to input binary codes which indicated whether he considered that two elements interacted or not. The program then factor analysed the data and output the results in the form of a cluster diagram. All interactions were treated as if they were identical in strength and kind, and the architect could never tell what distortions had been caused by this gross over simplification. Even with these weaknesses, however, Alexander's technique showed how man and computer could work together in the design situation.

A number of workers are now busy developing the extensive software necessary for computer aided architectural design systems. Unlike Alexander's earlier work most efforts are now concentrated on generating interactive systems in which the architect and computer exchange

information throughout the process. Negroponte (1970) has reviewed many of the more spectacular ideas which often utilise computer graphics and seem more directed towards assisting the architect understand his solutions than his problems. Davis and Kennedy (1970) report their efforts to develop 'EPS', a program for the evaluation of problem structure. However, apart from some work by Cross little effort is being expended to determine how beneficial computer aids actually are to the designer. Lawson (1971) has suggested that such research is vital, and that problem structuring aids should be investigated first.

"Just what roles should be allocated to man and computer in architectural design? Clearly we must not just allocate a role to the computer based on what it can already do in rather more deterministic design areas. Controlled experimental usage of interactive computer design systems is necessary before we can be sure of their effectiveness. However, research already carried out into the problem solving strategies of architects begins to suggest the form that these experimental systems might take.

Human circulation patterns might be studied by the architect developing a link diagram aided by computer generated tables, matrices and cluster diagrams. The link diagram might be assembled interactively on a graphics terminal with the computer suggesting which link should be included next. The architect could continuously manipulate the diagram to achieve a better pattern, which could be stored if required. At any time the architect could refer back to the interaction chart and change his weightings on different user groups, getting immediate feedback by observing the resultant distortions to his link diagrams. This sort of system would allow the architect to develop an understanding of this section of the problem enabling him to integrate it with other aspects in a meaningful way.

This raises another question, how much of this integration is done by the computer? We can easily imagine a system in which the computer interrupts the designer every time an external constraint is violated. For example, as the architect re-organises a staircase to achieve a better relationship between two spaces, the computer interrupts by informing him that fire regulations have been contravened. Will the architect respond gratefully to all such interrupts, should he be able to turn them off? As yet this sort of question remains largely unanswered."

8.3.2 Some implications for architectural education

Like any group of architectural students, the subjects in the experiments reported here had come to their studies from a wide range of backgrounds. All the science students had read their science and at least one other at 'A' level. There was no such uniformity amongst the architects, some had read sciences, some arts, and some a combination of the two. Even so the groups of fifth year architectural students showed no less uniformity than the scientists in their choice of strategy. Their five years of study would seem to have influenced their thinking procedures quite considerably. Is it possible that some of those architectural students would have become better 'problem understanders' had they received a different education, and would they possibly have been more value to their profession? Certainly many of the rather more analytically minded students show severe difficulties in their first two years at a school of architecture. It is worth remembering the words of the 1964 RIBA board of education paper quoted more fully in section 1.5

"..... the schools of architecture must produce, the RIBA must welcome those whose excellence is towards 'problem understanding' as well as those whose excellence is towards the design of solutions."

How this might be done in terms of selection and curricula it is not easy to see. However, perhaps the results of this experimental programme suggest some avenues which might usefully be explored.

In those critical developmental student years architects should be encouraged to examine their design problem solving with their tutors. Surely many designers would have benefitted from knowing that there were other approaches before they had fully developed their own one

strategy. If students are to be encouraged to be openly critical of their methods then the educational environment must change. It is no good asking a student to experiment with process if he knows that it is his solution that will be assessed by his examiners.

Interestingly many of the subjects commented in discussion after these experiments that it was easy to discuss method objectively since the solution to the laboratory problem was never held up for examination. It is often thought in architectural education that communication between staff and students is at all times best mediated by a studio design project. Perhaps the seminar room would be more suitable here. A more self conscious and even quasi-gaming situation may be far more suitable for discussing the students most tender weakness, his lack of methodology. The last wave of design method teaching, now past, took place in the lecture room. Method was taught and not discussed. The inevitable rebellion against such dogmatism lead to the present unfortunate position where methodology is inadequately discussed. The blocks experiment reveals a most obvious but often ignored phenomenon; that beginners at design do not work in a manner similar to the more experienced and sophisticated practitioners who teach them. Both the blocks and chequerboard experiments indicate that design students acquire a strong tendency to focus their attention on solutions rather than problems. The generation of solutions and the study of problems are often quite separate activities in architectural courses, and it is usually the former which is emphasised. After all designing buildings is what architects do! In order to understand his problems the student needs and receives much tuition in a wide variety of science and technology subjects. Each of these subjects must be

taught in a sensible progression. The student also needs very considerable amounts of practice at designing and this he gets in the form of studio projects. These projects must be small and simple to begin with and progressively extend the students ability to handle size and complexity. This inevitably means that unless all science and technology can be taught before any practice is given that the students understanding of the practice problems that he meets early in his course is superficial and simplistic. Such a rigidly divided course would certainly be indigestible to most design students, for paradoxically the design student is seldom interested in learning science unless he can already see its relevance to architectural problems.

Perhaps then, we should not be surprised that architectural students acquire a solution focussing strategy during their five years of education. Such a strategy would work well in the early years, but increasingly make for difficulties in the later years when the student is expected to understand his problems on a broader and deeper basis.

As an attempt to counter this, and growing directly out of the work reported in this thesis, the Birmingham School of Architecture has recently embarked upon a 'Design Education Research Programme'. The main aims of this programme are twofold. First to study the processes by which architectural students come to form, handle and relate their concepts, and develop their design strategies. Secondly to develop teaching programmes to optimise these learning processes. This work has already suggested several such teaching programmes and two prototypes are already being developed.

The first of these teaching programmes is a group working situation in which students find themselves role playing in simulations of real world design decision making. Each member of the group has to communicate information and decisions and call for information and decisions from others. Various situational parameters are fed into the simulation and the effects of these and the behaviour of the other members on the strategy of each member is noted and discussed. Thus alternative strategies, their strengths and weaknesses, are discussed without assessment of the students performance.

In the second experimental teaching programme the student interacts not with other students but with a computer. He tries to solve a problem in which several variables are important and their interaction critical. This utilises the format of the experiments reported here except that in perceiving the problem structure the student is also educating himself. For example a student may be asked to provide a particular pattern of daylighting for a given space, with as little thermal loss as possible. The computer program would allow him to input different fenestration patterns giving instant feedback on the thermal and illumination performance. Thus by trying a succession of solutions the student would come to appreciate the interaction and trade-off between daylighting, solar gain and thermal loss. This situation has all the three major design constraints (internal, external and designer generated) present and may well prove a more interesting and effective way of teaching principles of physical science than the rather more passive (for the student) lecture or demonstration.

Obviously such experimental teaching programmes may produce little progress unless they are monitored and evaluated. The results of these experiments seem to indicate that the existing five year course not only communicates techniques and concepts to the student but also helps to form his basic cognitive strategies. It is therefore hoped to carry out longitudinal studies using the experimental format developed here to observe the timing and nature of these changes in relation to both existing and new courses. From this we may be able to assess the long term influence of design courses upon the students' range and depth of design strategies, and consequently his ability to perform in a variety of circumstances.

9. APPENDICES

9.1 Blocks experimental equipment

9.2 Chequerboard experimental equipment

9.3 Blocks subject instruction

9.4 On-line computer programs

9.4.1 BLOCXT
flow diagram
sample printout
program listing

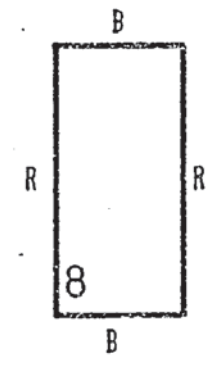
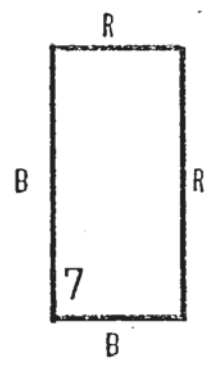
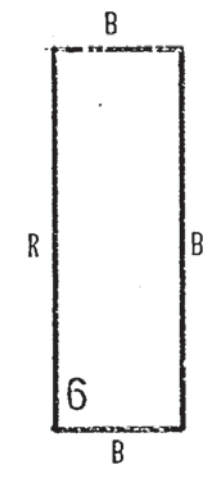
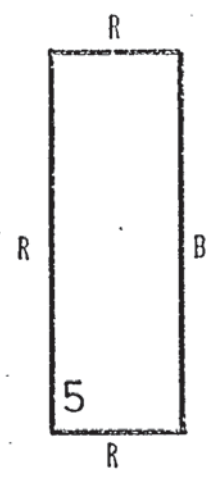
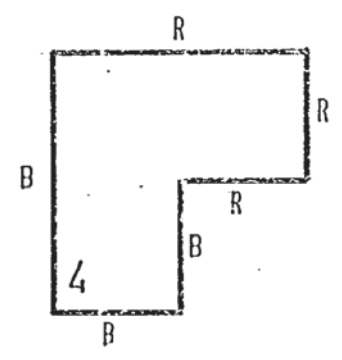
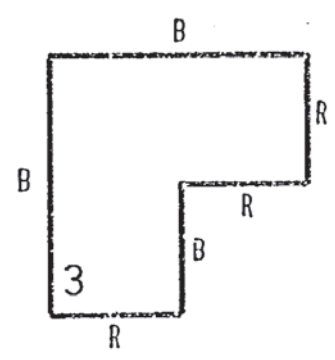
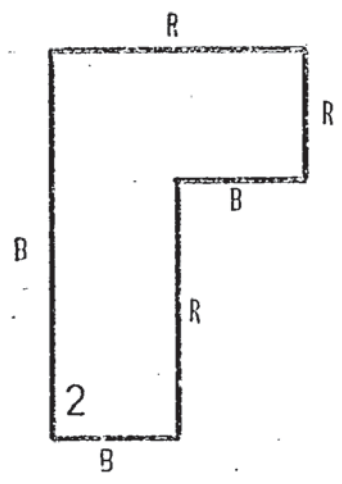
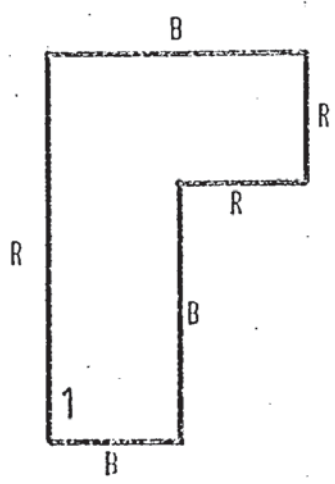
9.4.2 PICAPS
flow diagram
sample printout
program listing

9.5 Analysis programs
REALPARA
FRIEDMAN
KRUSKAL
KENDALLW

9.6 References

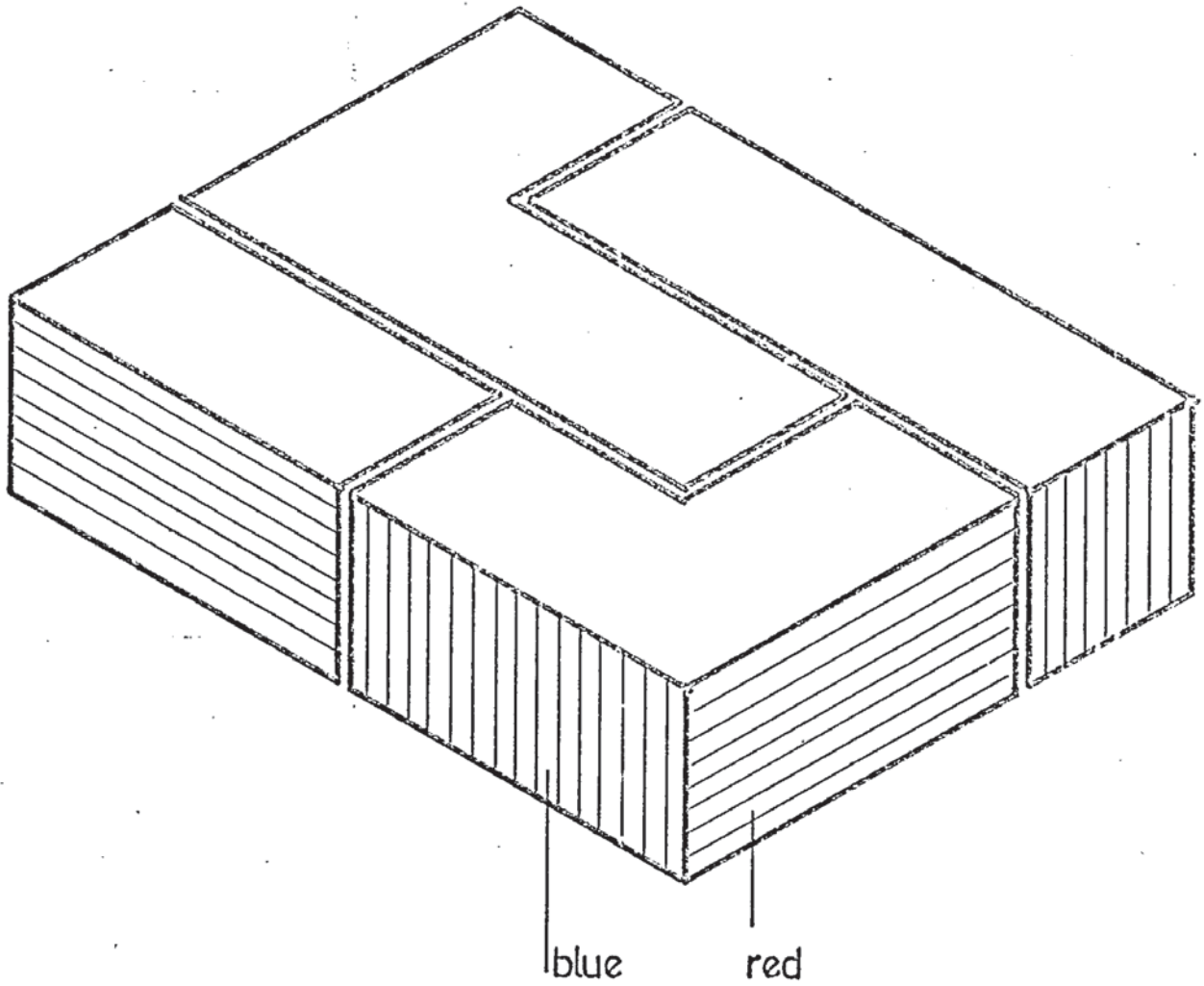
white

black

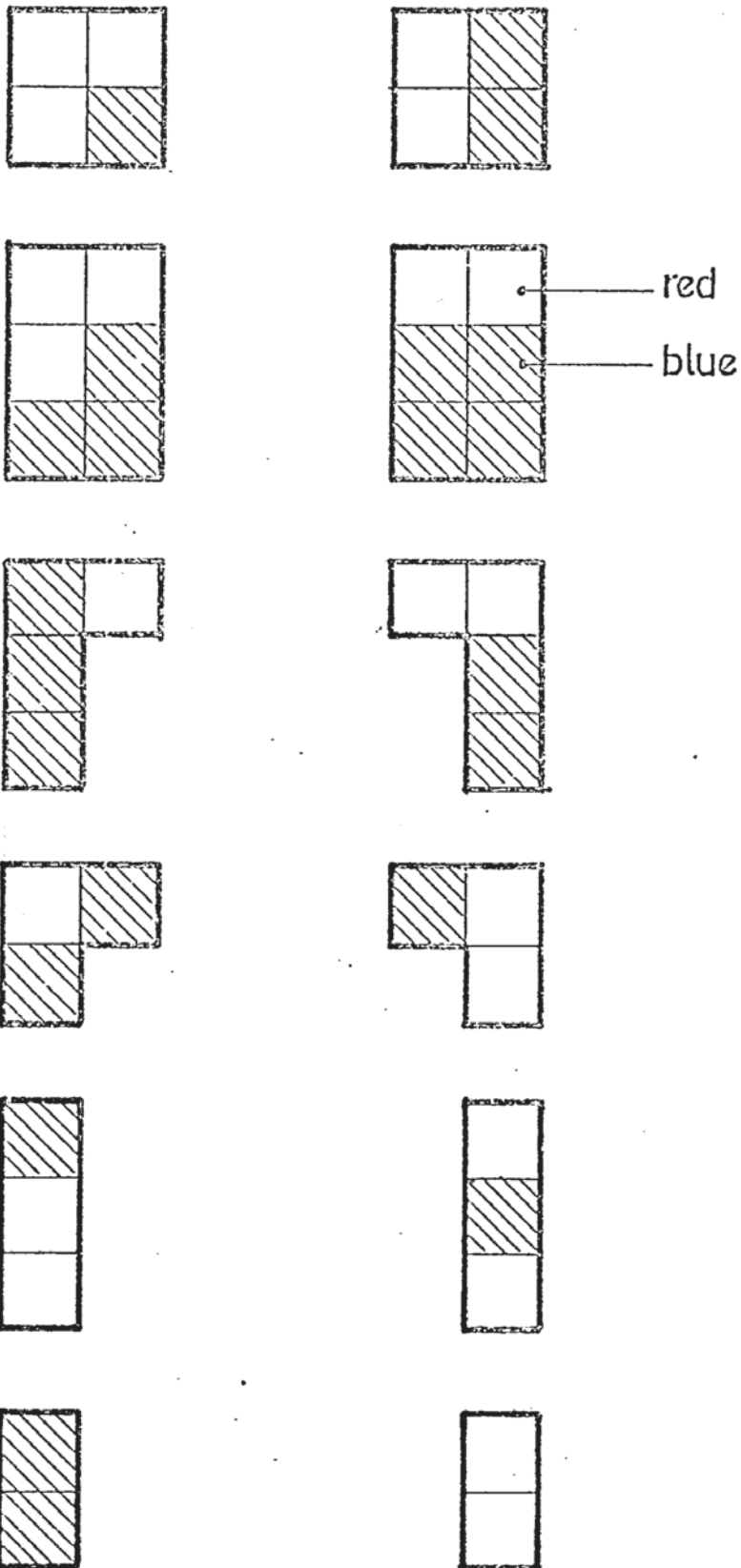


R = red
B = blue

9.1 PLAN VIEW OF BLOCKS

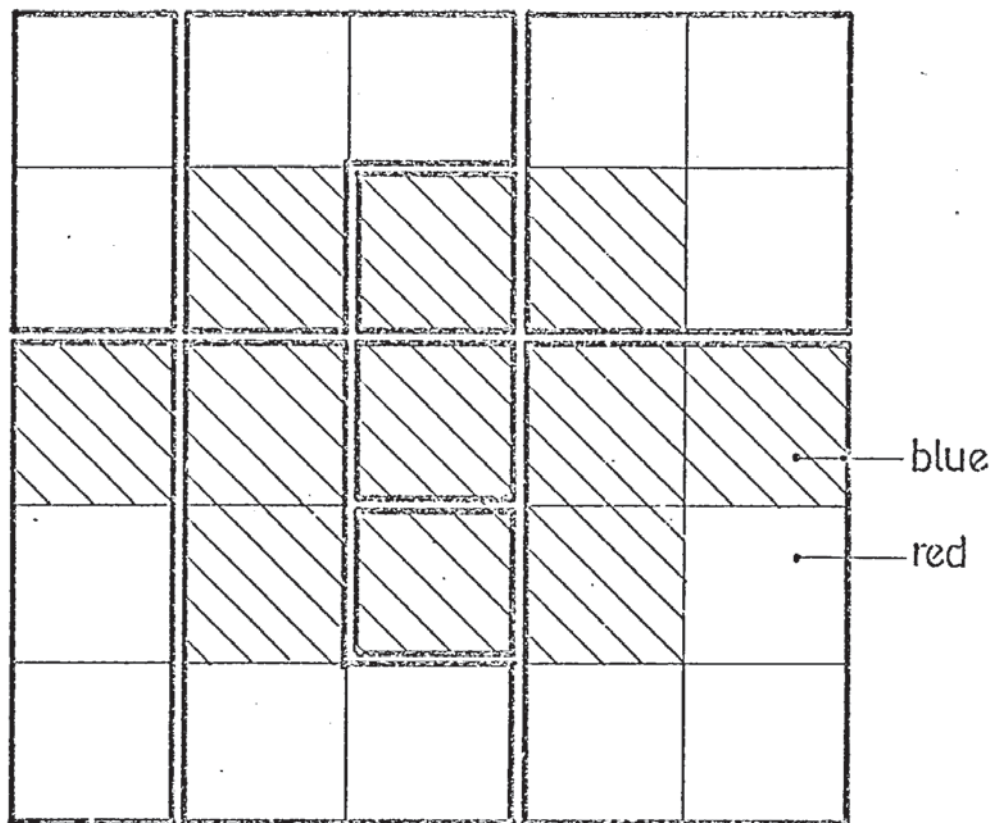


9.1 TYPICAL ARRANGEMENT OF BLOCKS PIECES

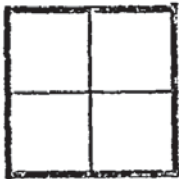
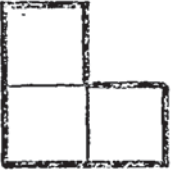


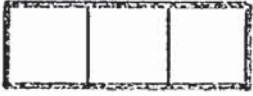
n.b. figure shows the two faces of each piece

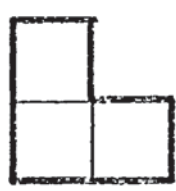
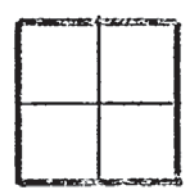
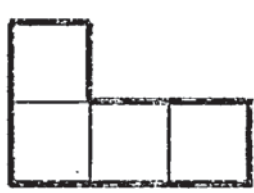
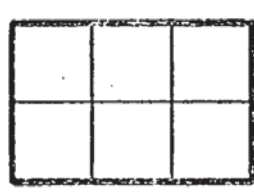
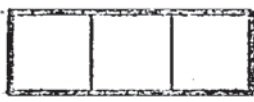
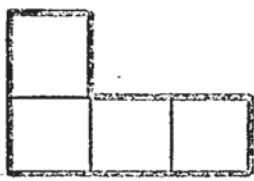
9.2 CHEQUERBOARD PIECES

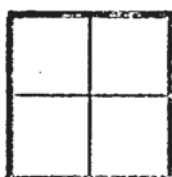


9.2 TYPICAL ARRANGEMENT OF CHEQUERBOARD
PIECES



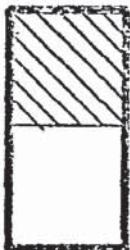
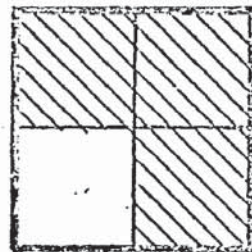
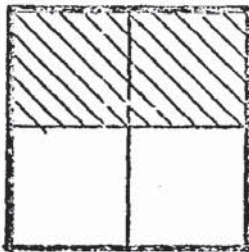
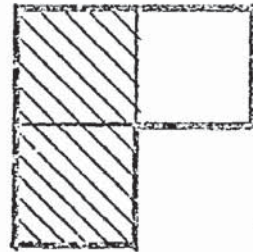
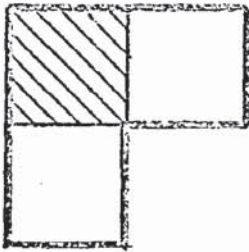
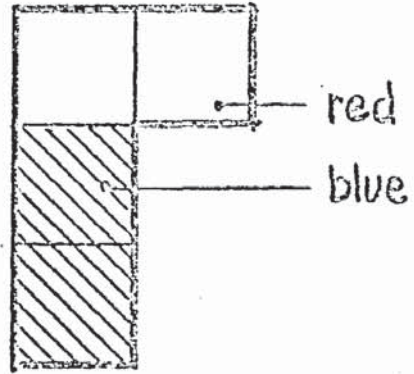
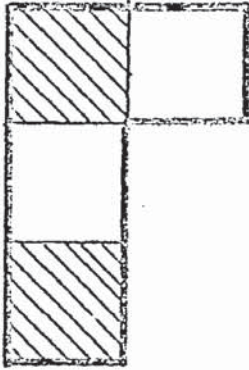






white

black



9.2 PIECES FOR THE SECOND CHEQUERBOARD EXPERIMENT

INSTRUCTIONS TO SUBJECTS

You will see in front of you 8 coloured blocks. There are 4 pairs of differently shaped block; one white and one black block making up each pair. In addition there is a plan grid of 3 x 4 bays on a turntable. You are asked to arrange 4 of the blocks, 1 from each pair (that is either the white or the black block, but not both) on the plan so as to cover all 12 squares and with no blocks projecting.

The blocks must be laid with the black or white surfaces uppermost, and each time you will be asked to maximise the amount of blue or red showing around the external wall. It may or may not be possible to get all 14 squares showing the appropriate colour.

For each trial there will be a rule governing 'allowed' and 'not allowed' combinations of blocks. The rules can be of the following kinds;- The long black block must be present.

The long black block and the short white block.....

The long black block or the short white block.....

You will not be told what the rule is. You may arrange 4 blocks on the plan and ask if the combination is allowed. The rule always relates to combinations and not plan arrangements of blocks.

You are asked to arrive at the best arrangement of a permitted combination of blocks with as few questions as possible. You should always take time to think, and try to ask the most useful question and extract the most information from the answers.

The computer will control the experiment by giving you appropriate instructions and information. It will begin by telling you which colour to maximise (red or blue), and will then wait for questions.

PLEASE MAXIMISE RED FOR PROBLEM 1

You should ask a question by typing the numbers of the four blocks used, and then pressing 'carriage return'. The computer will reply YES, NO, or ILEGAL COMBINATION (in the case of your using two blocks from one pair).

1357

YES

When you have formulated your final solution you should type four zeros and 'carriage return'.

0000

The computer will reply;

TYPE 4 BLOCKS USED IN PROBLEM 1

You should type them exactly as if it were another question. The computer will again reply;

HOW MANY BAYS ARE THE WRONG COLOUR 1

This should be typed followed by 'carriage return'.

1

The computer will now tell you the maximum possible score for your own interest. You should clear away the blocks and press the space bar (at the bottom of the keyboard) for the next problem. From time to time the computer may make comments about your performance which you should heed.

If you make an error it can be erased by pressing the 'rubout' key before pressing 'carriage return'. 'Rubout' erases one character at a time, so two presses will erase the two previous characters.

9.4.1 BLOCXT

BLOCXT is a Macro 9 program with some Fortran IV input/output routines written for use on an 8K DEC PDP9 computer. The program calls for problems to be input on paper tape, and communicates with the subject by means of a Teletype. Data is recorded on the teletype punch in a format suitable for direct input to the PICAPS analysis program. A second version of this program, BLOCXR, is capable of setting problems randomly, rather than requiring prepared paper tape input.

BLOCXT provides a completely self sufficient environment for running a six problem session of the 'Blocks' experiment. Instructions, comments and answers are printed out for the subject on the Teletype requiring him to respond with the digits, carriage return and space keys only. The subject is informed at each stage how he should next respond, and the program remains in input phase as long as he requires.

PROGRAM LABEL

OPERATION

START

the program is to run for 6 cycles

request, input and store operating mode code

RECYCL

wait for recycle instruction

recycle from end

GOAGIN

6 cycles done?

YES

THAT IS ALL THANK YOU

NO

PAPER

input problem from paper tape

finish

which type is it?

A

A OR B

A AND B

PAPER

input block no.

input two block nos.

is rule possible?

NO

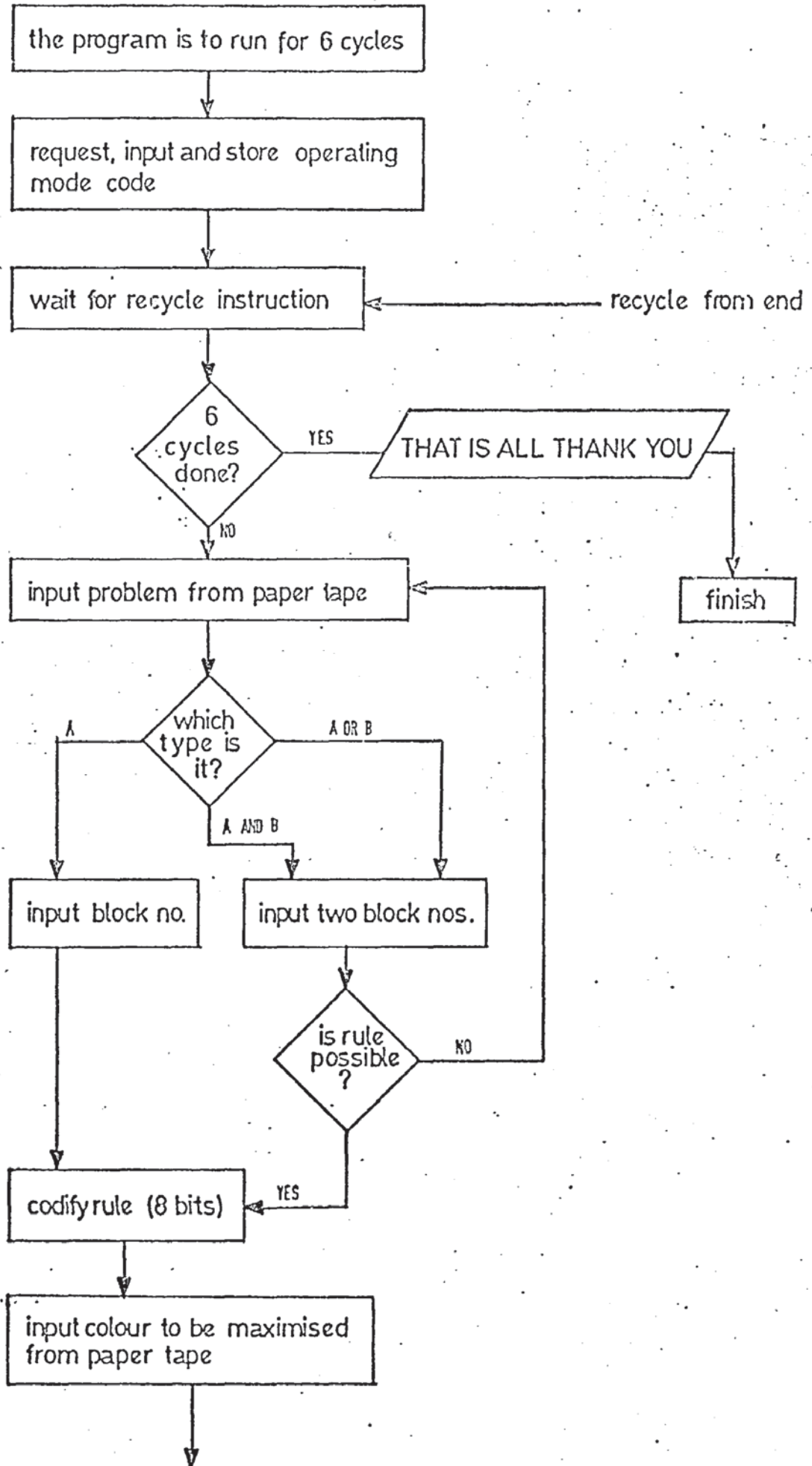
CODIFY

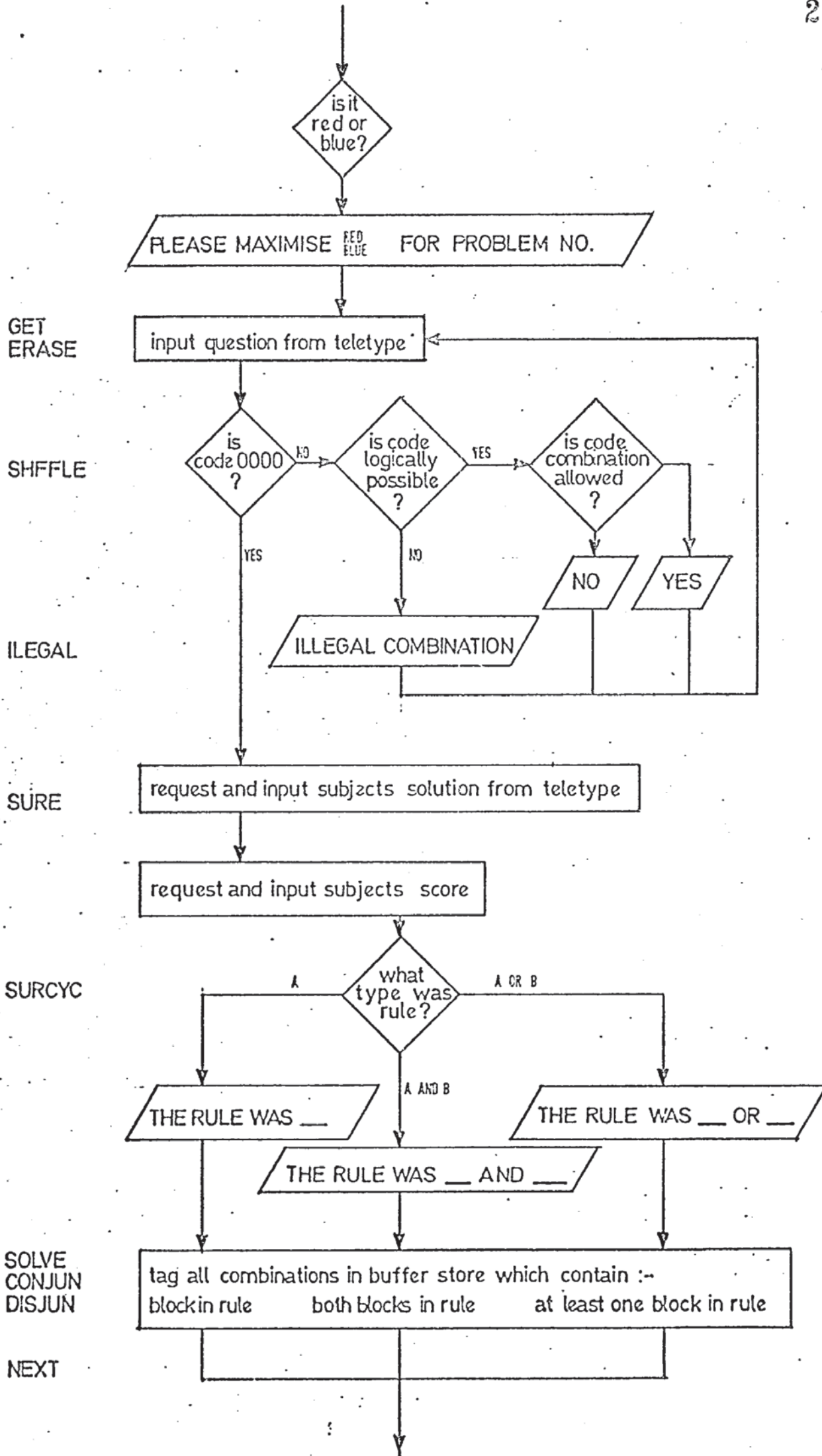
codifyrule (8 bits)

YES

GETCOL PAPER

input colour to be maximised from paper tape

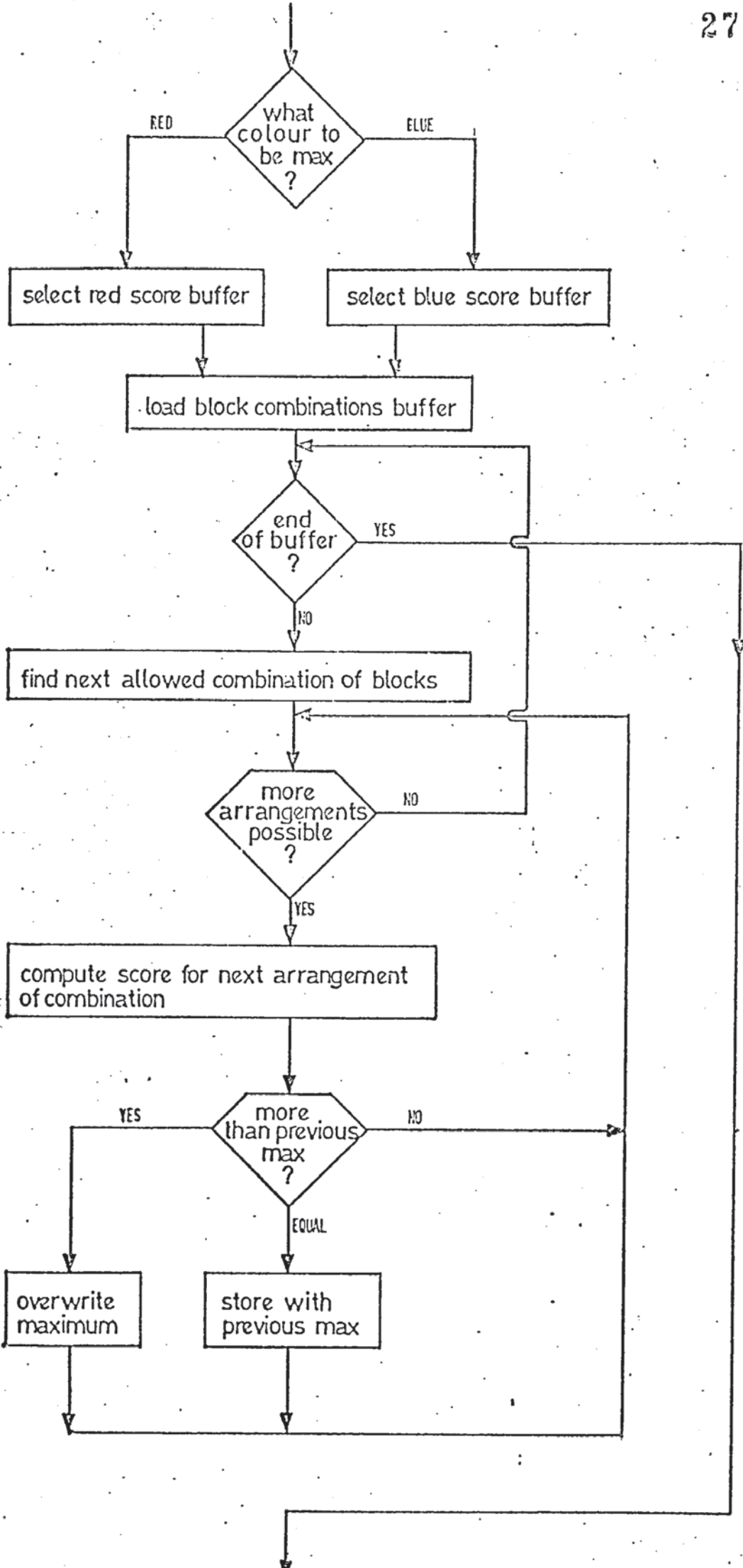


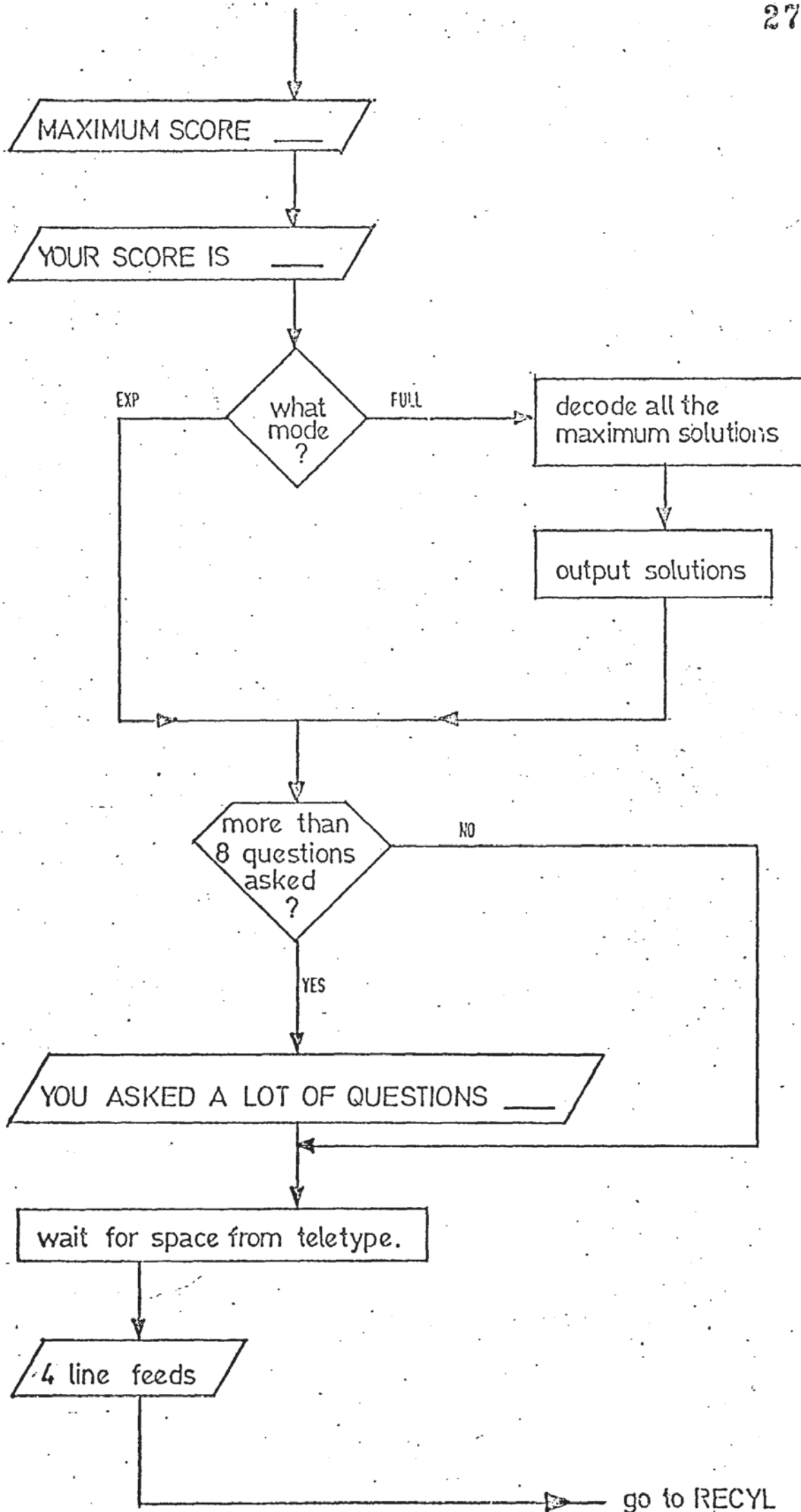


NEXT LOOP

CONTIN

UNPACK





.TITLE BLOCKT

/TO CONTROL BLOCKS EXPERIMENT FROM PAPER
 /TAPE
 /AND SET PROBLEMS FOR 'BLOCKS' FROM PAPER
 /TAPE INPUT
 /BRL MAY 70

.IODEV 4
 .GLOBL .FP,.FW,.FE,.FR,.FF

TSF=700401
 TLS=700406
 KSF=700301
 KRB=700312
 RSA=700104
 RSF=700101
 RRB=700112

/THIS SEGMENT INITIALISES PROGRAM

START DZM PROBNO#
 LAC (-7
 DAC SESION#
 JMS* .FP /REQUESTS OPERATING MODE
 JMS* .FW /2=FULL STN,1=RULE,0=EXP MODE
 .DSA (4
 .DSA FRMT20
 JMS* .FE
 .DSA DUMMY
 JMS* .FF
 JMS* .FR /READS OPERATING MODE CODE AND STORES
 .DSA (4
 .DSA FRMT17
 JMS* .FE
 .DSA MODE#
 JMS* .FF
 JMP RECYCL /HOLDS PROGRAM RUN FOR 0

/THIS SEGMENT READS PROBLEM FROM PAPER TAPE

GOAGIN ISZ PROBNO
 ISZ SESION /IS SESSION COMPLETE?
 JMP .+2
 JMP FINISH /YES SHUT DOWN PROGRAM
 JMS PAPER /NO CONTINUE
 SAD (215 /WAITS FOR CR
 JMS PAPER
 SAD (212 /WAITS FOR LF
 JMP .+2
 JMP .-5
 JMS PAPER /GETS RULE TYPE,1=A,2=AANDB,3=AORB
 AND (3 /MASKS
 DAC DISCON
 DAC SWITCH
 SAD (1
 JMP A

A	JMP	AANDB	
	JMS	PAPER	/FOR BLOCK NUMBER
	TAD	(-260	
	DAC	RULE#	
	JMS	CODIFY	
	LAC	NCODE	
	DAC	CODE#	
	DZM	DISCON#	
	JMP	GETCOL	
AANDB	JMS	PAPER	/FOR 1ST BLOCK IN RULE
	TAD	(-260	
	DAC	FIRST#	
	DAC	ILGAL1	
	AND	(1	/MASKS
	SNA		/LOOKS FOR BIT1 SET (ODD)
	JMP	EVEN	
ODD	LAC	FIRST	
	TAD	(1	
	DAC	ILGAL2	
	JMP	•+4	
EVEN	LAC	FIRST	
	TAD	(-1	
	DAC	ILGAL2#	
	JMS	PAPER	/FOR 2ND BLOCK IN RULE
	TAD	(-260	
	SAD	ILGAL1#	/CHECKS FOR 2 BLOCKS THE SAME
	JMP	•-4	
	SAD	ILGAL2	/CHECKS FOR 2 IN THE SAME PAIR OF /BLOCKS
	JMP	•-6	
	DAC	SECOND#	
	LAC	FIRST	
	DAC	RULE	
	JMS	CODIFY	/CODIFIES 1ST BLOCK
	LAC	NCODE	
	DAC	CODE	
	LAC	SECOND	
	DAC	RULE	
	JMS	CODIFY	/CODIFIES 2ND BLOCK
	LAC	NCODE	
	TAD	CODE	
	DAC	CODE	
	LAC	DISCON	
	SAD	(2	/TESTS FOR CONJ OR DISJ. RULE
	JMP	CONJ	
DISJ	LAW	1	
	DAC	DISCON	
	JMP	GETCOL	
CONJ	DZM	DISCON	
GETCOL	JMS	PAPER	/GETS COLOUR CODE
	TAD	(-260	
	DAC	REDBLU#	
	LAC	REDBLU	
	SAD	(1	
	JMP	•+11	
	JMS*	•FP	/PRINTS MAXIMISE REQUEST IF RED


```

JMS*      .FW
.DSA      (4
.DSA      FRMT7
JMS*      .FE
.DSA      PROBNO
JMS*      .FF
JMP       .+10
JMS*      .FP      /PRINTS MAXIMISE REQUEST IF BLUE
JMS*      .FW
.DSA      (4
.DSA      FRMT18
JMS*      .FE
.DSA      PROBNO
JMS*      .FF
DZM       QUSTN#
JMP       ANSWER
    
```

/THIS SEGMENT READS IN SUBJECT'S QUESTIONS

```

ANSWER    ISZ      QUSTN      /COUNTS NO. OF QUESTIONS ASKED
          LAC      (-4        /SET UP QUESTION INPUT BUFFER
          DAC      INC#
          LAC      (INSTOR
          DAC      PTSTOR#
          DZM      ZEROS
GET        JMS      READ1      /GETS QUESTIONS FROM TELETYPE
          LAC      NUMBER#
          SAD      (215      /WAIT FOR C.R.
          JMP      GET
          SAD      (212      /WAIT FOR L.F.
          JMP      GET
          SAD      (377      /IS CHARACTER ERASED BY SUBJECT?
          JMP      ERASE     /YES- DELETE IT
          LAC      (260      /NO- PROCESS IT
          CMA
          TAD      (1
          TAD      NUMBER
          DAC*     PTSTOR     /STORE CHARACTER
          TAD      ZEROS#     /ADD TO CUMULATIVE TOTAL
          DAC      ZEROS
          ISZ      PTSTOR     /INC BUFFER POINTDRS
          ISZ      INC
          JMP      GET        /GET NEXT CHARACTER
          JMS      READ1
          SAD      (215
          JMP      SHFFLE     /ALL FOUR CHARACTERS HAVE BEEN
                               /INPUT
          SAD      (377
          JMP      ERASE     /DELETE ERASED CHARACTER
          JMP      .-5
ERASE     LAC      (INSTOR   /RUBS OUT PREVIOUS CHARACTER
          CMA
          TAD      (1
          TAD      PTSTOR     /CHECKS AT LEAST ONE TO ERASE
          SNA
    
```

	JMP	GET	
	LAC	(-1	
	TAD	INC	
	DAC	INC	
	LAC	(-1	
	TAD	PTSTOR	
	DAC	PTSTOR	
	DZM	ZEROS	/RESETS FOR SWITCH TO SURE ROUTINE
	LAC	(334	/OUTPUTS BACKSLASH ON TELETYPE
	TLS		
	JMP	GET	
SHFFLE	LAC	ZEROS	/TURNS QUESTION INTO 8 BIT CODE
	SNA		
	JMP	SURE	
	LAC	(-3	
	DAC	COUNT	
	LAC	(INSTOR	
	DAC	PTSTOR	
ILEGAL	LAC*	PTSTOR	/TESTS FOR ILEGAL COMBINATIONS
	AND	(1	/MASK
	SZA		/TESTS FOR ODD OR EVEN NO. BLOCK
	JMP	+.5	
	LAC*	PTSTOR	
	TAD	(-1	
	DAC	ILGAL1	
	JMP	+.4	
	LAC*	PTSTOR	
	TAD	(1	
	DAC	ILGAL1	
	LAC	ILGAL1	
	SAD	INSTOR+1	
	JMP	WRONG	/TWO BLOCKS FROM THE SAME PAIR
	SAD	INSTOR+2	
	JMP	WRONG	/TWO BLOCKS FROM THE SAME PAIR
	SAD	INSTOR+3	
	JMP	WRONG	/TWO BLOCKS FROM THE SAME PAIR
	ISZ	PTSTOR	
	ISZ	COUNT	
	JMP	ILEGAL	
	DZM	EIGHT#	
	LAC	(INSTOR	/RESET BUFFER POINTERS
	DAC	PTSTOR	
	LAC	(-4	
	DAC	INC	
	LAC*	PTSTOR	
	DAC	RULE	
	JMS	CODIFY	
	LAC	NCODE	
	TAD	EIGHT	
	DAC	EIGHT	
	ISZ	PTSTOR	
	ISZ	INC	
	JMP	.-10	

```

/THIS SEGMENT ANSWERS SUBJECTS QUESTIONS
      LAC      DISCON      /WHAT KIND IS RULE?
      SZA
      JMP      DISANS      /0 CONJUNCTIVE
CONANS  LAC      EIGHT#    /1 DISJUNCTIVE
      AND      CODE
      SAD      CODE
      JMP      YES
      JMP      NO
DISANS  LAC      EIGHT      /IF DISJUNCTIVE
      AND      CODE
      SZA
      JMP      YES
      JMP      NO
YES     JMS*     .FP        /OUTPUTS ANSWER, COLOUR, NO. QUESTIONS
      LAC      REDBLU
      SAD      (1
      JMP      .+10
      JMS*     .FW
      .DSA     (4
      .DSA     FRMT50
      JMS*     .FE
      .DSA     QUSTN
      JMS*     .FF
      JMP      ANSWER
      JMS*     .FW        /WRITE 'YES'
      .DSA     (4
      .DSA     FRMT51
      JMS*     .FE
      .DSA     QUSTN
      JMS*     .FF
NO      JMP      ANSWER
      JMS*     .FP        /OUTPUTS ANSWER, COLOUR, NO. QUESTIONS
      LAC      REDBLU
      SAD      (1
      JMP      .+10
      JMS*     .FW
      .DSA     (4
      .DSA     FRMT52
      JMS*     .FE
      .DSA     QUSTN
      JMS*     .FF
      JMP      ANSWER
      JMS*     .FW        /WRITE 'NO'
      .DSA     (4
      .DSA     FRMT53
      JMS*     .FE
      .DSA     QUSTN
      JMS*     .FF
WRONG  JMP      ANSWER
      JMS*     .FP        /OUTPUTS INSTRUCTION IF QUESTION
                                /ILEGAL
      JMS*     .FW
      .DSA     (4
      .DSA     FRMT26
      JMS*     .FE

```

.DSA QUSTN
 JMS* .FF
 JMP ANSWER

```

/THIS SEGMENT INPUTS PROBLEM SOLUTION
SURE JMS* .FP /REQUEST BLOCKS USED IN SOLUTION
      JMS* .FW
      .DSA (4
      .DSA FRMT14
      JMS* .FE
      .DSA PROBNO
      JMS* .FF
      JMS* .FR /INPUTS BLOCKS
      .DSA (4
      .DSA FRMT15
      JMS* .FE
      .DSA FOUR#
      JMS* .FF
      JMS* .FP /REQUESTS SCORE
      JMS* .FW
      .DSA (4
      .DSA FRMT16
      JMS* .FE
      .DSA PROBNO
      JMS* .FF
      JMS* .FR /INPUTS SCORE
      .DSA (4
      .DSA FRMT17
      JMS* .FE
      .DSA SUBSCO#
      JMS* .FF
      LAC SUBSCO
      CMA /CALCULATES SUBJECTS SCORE OUT OF 14
      TAD (1
      TAD FRTEEN
      DAC SUBSCO
      LAC (DECOD1
      DAC POINT#
      LAW -10
      DAC COUNT#
      LAC CODE
      DAC PACKER#
      JMP SURCYC
    
```

```

/THIS SEGMENT OUTPUTS PROBLEM RULE IF REQUIRED
SURCYC LAC PACKER
        AND (1 /MASK
        SNA /LOOK FOR BIT SET (BLOCK USED)
        JMP .+6
        LAC COUNT
        CMA /MAKE POSITIVE AGAIN
        TAD (1
    
```


	DAC*	POINT	
	ISZ	POINT	
	LAC	PACKER	
	RAR		/ROTATE CODE FOR UNPACKING
	DAC	PACKER	
	ISZ	COUNT	
	JMP	SURCYC	
	LAC	MODE	/IS RULE WANTED ON OUTPUT ?
	SNA		/YES, WHAT TYPE OF RULE ?
	JMP	SOLVE	/NOT WANTED
	LAC	SWITCH#	/TO DETERMINE RULE TYPE, 1=AOT, /2=ANDOT, 3=OROT
	SAD	(1	
	JMP	AOT	
	SAD	(2	
	JMP	ANDOT	
	JMP	OROT	
AOT	JMS*	.FP	
	JMS*	.FW	/OUTPUTS RULE
	.DSA	(4	
	.DSA	FRMT4	
	JMS*	.FE	
	.DSA	DECOD1	
	JMS*	.FF	
	JMP	SOLVE	
ANDOT	JMS*	.FP	
	JMS*	.FW	/OUTPUTS RULE
	.DSA	(4	
	.DSA	FRMT5	
	JMS*	.FE	
	.DSA	DECOD2	
	JMS*	.FE	
	.DSA	DECOD1	
	JMS*	.FF	
	JMP	SOLVE	
OROT	JMS*	.FP	
	JMS*	.FW	/OUTPUTS RULE
	.DSA	(4	
	.DSA	FRMT6	
	JMS*	.FE	
	.DSA	DECOD2	
	JMS*	.FE	
	.DSA	DECOD1	
	JMS*	.FF	
	JMP	SOLVE	
CODIFY	XX		/CODIFIES BLOCK NUMBERS
	LAC	RULE	
	CMA		
	TAD	(1	/NEGATES
	DAC	RULE	
	LAC	(400	/BIT SET IN POSITION 1
	DAC	NCODE#	
	LAC	NCODE	
	RCR		/ROTATE TO THE RIGHT TO THE
	DAC	NCODE	/VALUE OF RULE
	ISZ	RULE	

```

PAPER      JMP      .-4
           JMP*    CODIFY
           XX      /GET FROM PAPER TAPE
           IOF
           RSA
           RSF
           JMP      .-1
           RRB
           JMP*    PAPER
READ       XX      /GENERAL READ SUBROT
           IOF
           KSF
           JMP      .-1
           KRB
           SAD     (215   /C.R.
           JMP      .-4
           SAD     (212   /LINE FEED
           JMP      .-6
           AND     (7     /MASK
READ1      JMP*    READ
           XX
           IOF
           KSF
           JMP      .-1
           KRB
           DAC     NUMBER
           JMP*    READ1
RECYCL    JMS     READ   /HOLDS RECYCLE UNTIL ALL 8 BITS 0
           SZA
           JMP      .-2
           LAC     (-4
           DAC     INC
           IOF
           CLA
           TLS
           LAC     (212   /OUTPUTS LINE FEEDS BETWEEN PROBLEMS
           TSF
           JMP      .-1
           TLS
           ISZ     INC
           JMP      .-5
           JMP     GOAGIN
FINISH    JMS*    .FP
           JMS*    .FW
           .DSA   (4
           .DSA   FRMT25
           JMS*    .FE
           .DSA   DUMMY
           JMS*    .FF
           LAS     /0= BACK TO MONITOR,1=BACK TO START
           SZA
           JMP     START
           .EXIT   /SHUT DOWN PROGRAM
DECOD1    .BLOCK  1
DECOD2    .BLOCK  1
DUMMY     0
    
```

```

FRMT1 .ASCII '(31H PRIME RANDOM NUMBER GENERATOR ,11)'
FRMT2 .ASCII '(15)'
FRMT3 .ASCII '(12H 12345678 ,12)'
FRMT4 .ASCII '(13H THE RULE IS ,11)'
FRMT5 .ASCII '(13H THE RULE IS ,11,5H AND ,11)'
FRMT6 .ASCII '(13H THE RULE IS ,11,4H OR ,11)'
FRMT7 .ASCII '(33H PLEASE MAXIMISE RED FOR PROBLEM ,12)'
FRMT18 .ASCII '(34H PLEASE MAXIMISE BLUE FOR PROBLEM ,12)'
FRMT50 .ASCII '(14H YES (RED) ,12)'
FRMT51 .ASCII '(14H YES (BLUE) ,12)'
FRMT52 .ASCII '(14H NO (RED) ,12)'
FRMT53 .ASCII '(14H NO (BLUE) ,12)'
FRMT26 .ASCII '(20H ILEGAL COMBINATION ,12)'
FRMT14 .ASCII '(31H TYPE 4 BLOCKS USED IN PROBLEM ,12)'
FRMT15 .ASCII '(14)'
FRMT16 .ASCII '(36H HOW MANY BAYS ARE THE WRONG COLOUR ,12)'
FRMT17 .ASCII '(11)'
FRMT25 .ASCII '(25H THAT IS ALL THANK YOU ,11)'
FRMT20 .ASCII '(29H SLTNS+RULE 2, RULE 1, SCORE ,11)'
FRTEEN 16
INSTOR .BLOCK 4

```

/THIS SEGMENT TAGS ALL ALLOWABLE COMBINATIONS OF BLOCKS

```

SOLVE LAC (CODES-1
      DAC 11
      LAC (TAGS-1
      DAC 12
      LAW -20
      DAC COUNT
      DZM MAXISC
      LAC DISCON /TO GET RULE TYPE
      SZA
      JMP DISJUN
      JMP CONJUN
DISJUN LAC* 11 /TAGS ALLOWED COMBINATIONS OF BLOCKS IF
      /DISJ.
      AND CODE
      SZA
      JMP .+4
      LAC (1
      DAC* 12
      JMP .+2
      DZM* 12
      ISZ COUNT
      JMP DISJUN
      JMP NEXT
CONJUN LAC* 11 /TAGS ALLOWED COMBINATIONS OF BLOCKS IF
      /CONJ.
      AND CODE
      SAD CODE
      JMP .+4
      LAC (1
      DAC* 12
      JMP .+2

```

```

DZM*      12
ISZ       COUNT
JMP       CONJUN
NEXT      LAC      (CODES-1
DAC       11
LAC       (TAGS-1
DAC       12
LAW       -20
DAC       COUNT
LOOP      LAC      REDBLU    /LOADS COLOUR SCORE BUFFER
SAD       (1          /IS COLOUR TO BE MAXIMISED RED OR BLUE?
JMP       .+3
JMS       BLUE      /BLUE
JMP       CONTIN
JMS       RED       /RED
JMP       CONTIN
RED       XX
LAC       (SHAPER   /SET POINTERS TO RED SCORE BUFFER
DAC       POINT#
JMP*      RED
BLUE      XX
LAC       (SHAPEB   /SET POINTERS TO BLUE SCORE BUFFER
DAC       POINT
JMP*      BLUE
/
/
/
/THIS SEGMENT LOOKS FOR MAXIMUM SCORES AMONGST ALLOWED COMBINATIONS
CONTIN   LAC*      12
SZ       /LOOK FOR TAG
JMP      .+5      /FIND TAG
JMS      UNPACK   /NO TAG SET
ISZ      COUNT
JMP      LOOP
JMP      REPACK
LAC*     11
ISZ      COUNT
JMP      LOOP
JMP      REPACK
UNPACK   XX          /UNPACKS ALLOWED COMBINATION CODE
LAW      -15
DAC      CYCLE#
LAC*     11
DAC      TEMP#
ROWS     ISZ      CYCLE
JMP      .+2
JMP*     UNPACK
DZM      SCORE     /ZERO MAXIMUM SCORE BUFFER
LAC      TEMP
AND      (100      /WHICH BLOCK IN 1ST PAIR ?
JMS      PAIR
LAC      TEMP
AND      (20      /WHICH BLOCK IN 2ND PAIR ?
JMS      PAIR
LAC      TEMP
AND      (4        /WHICH BLOCK IN 3RD PAIR ?

```


	JMS	PAIR	
	LAC	TEMP	
	AND	(1	/WHICH BLOCK IN 4TH PAIR ?
	JMS	PAIR	
	JMP	COMPAR	
PAIR	XX		/THIS SUBROUTINE FINDS MAX SCORE FOR /EACH BLOCK
	SZA		
	JMP	RIGHT	
	LAC*	POINT	
	TAD	SCORE#	/CUMULATIVE TOTAL FOR ALL FOUR /BLOCKS
	DAC	SCORE	
	ISZ	POINT	
	ISZ	POINT	
	JMP*	PAIR	
RIGHT	ISZ	POINT	
	LAC*	POINT	
	TAD	SCORE	
	DAC	SCORE	
	ISZ	POINT	
	JMP*	PAIR	
COMPAR	LAC	SCORE	/COMPARES MAX SCORE WITH PREVIOUS /MAX.
	CMA		
	TAD	(1	/NEGATE
	TAD	(16	/NUMBER OF DESIRED COLOUR
	DAC	SCORE	
	LAC	MAXISC#	
	CMA		
	TAD	(1	
	TAD	SCORE	/SUBTRACT PREVIOUS MAXIMUM
	SPA		
	JMP	ROWS	
	SNA		
	JMP	EQUAL	
BETTER	DZM	NOSOLS#	/TESTS FOR MORE OPTIMAL SLTN
	LAC	(MAXICO	
	DAC	CODIND#	
	LAC	(TYPE	
	DAC	TYPIND#	
	JMP	.+3	
EQUAL	ISZ	TYPIND	/TESTS FOR EQUALLY OPTIMAL SLTN
	ISZ	CODIND	
	LAC	TEMP	
	DAC*	CODIND	
	LAC	SCORE	
	DAC	MAXISC	
	LAC	CYCLE	
	TAD	(15	
	DAC*	TYPIND	
	ISZ	NOSOLS	
	JMP	ROWS	
	JMP	REPACK	

```

/THIS SEGMENT OUTPUTS SOLUTIONS AND SCORES
REPACK  JMS*      .FW      /OUTPUTS MAX.SCORE
        .DSA      (4
        .DSA      FRMT11
        JMS*      .FE
        .DSA      MAXISC
        JMS*      .FF
        JMS*      .FW      /OUTPUTS SUBJECTS SCORE
        .DSA      (4
        .DSA      FRMT21
        JMS*      .FE
        .DSA      SUBSCO
        JMS*      .FF
        LAC      MODE
        SAD      (2      /OMITS FULL SLTN OUTPUT IN EXP MODE
        JMP      .+2
        JMP      OVERQU
        JMS*      .FW      /OUTPUTS NUMBER OF MAX. SOLUTIONS
        .DSA      (4
        .DSA      FRMT13
        JMS*      .FE
        .DSA      NOSOLS
        JMS*      .FF
        LAC      (MAXICO
        DAC      CODIND
        LAC      (TYPE
        DAC      TYPIND
        LAC      NOSOLS
        CMA
        TAD      (1
        DAC      COUNT
OUTPUT  LAC*      CODIND  /REPACKS SOLUTIONS FOR OUTPUT
        AND      (100    /FORMAT
        SZA
        JMP      LBA
LWA     LAC      (1
        DAC      ELEM1#
        JMP      SET2
LBA     LAC      (2
        DAC      ELEM1
SET2    LAC*      CODIND
        AND      (20    /MASK
        SZA
        JMP      SBA
SWA     LAC      (3
        DAC      ELEM2#
        JMP      SET3
SBA     LAC      (4
        DAC      ELEM2
SET3    LAC*      CODIND
        AND      (4      /MASK
        SZA
        JMP      LBS
LWS     LAC      (5
    
```

```

DAC          ELEM3#
LBS          JMP          SET4
LBS          LAC          C6
DAC          ELEM3
SET4         LAC*        CODIND
AND          C1          /MASK
SZA
SWS          JMP          SBS
LBS          LAC          C7
DAC          ELEM4#
SBS          JMP          WRITE
LBS          LAC          C10
DAC          ELEM4
WRITE        JMP          WRITE
WRITE        JMS*        .FP          /OUTPUTS SLTNS AND SCORE
WRITE        JMS*        .FW
WRITE        .DSA        C4
WRITE        .DSA        FRMT10
WRITE        JMS*        .FE
WRITE        .DSA        TYPIND+400000
WRITE        JMS*        .FF
WRITE        JMS*        .FW
WRITE        .DSA        C4
WRITE        .DSA        FRMT12
WRITE        JMS*        .FE
WRITE        .DSA        ELEM1
WRITE        JMS*        .FE
WRITE        .DSA        ELEM2
WRITE        JMS*        .FE
WRITE        .DSA        ELEM3
WRITE        JMS*        .FE
WRITE        .DSA        ELEM4
WRITE        JMS*        .FF
WRITE        ISZ        CODIND
WRITE        ISZ        TYPIND
WRITE        ISZ        COUNT
OVERQU      JMP          OUTPUT
OVERQU      LAC          QUSTN          /END OF DATA BYE-PASS IN EXP MODE
OVERQU      CMA
OVERQU      TAD          C10          /LOOKS FOR TOO MANY QUESTIONS ASKED
OVERQU      SMA
OVERQU      JMP          RECYCL
OVERQU      LAC          QUSTN
OVERQU      TAD          C-1
OVERQU      DAC          QUSTN
OVERQU      JMS*        .FW          /OUTPUTS COMMENT ON QUSTN NO.
OVERQU      .DSA        C4
OVERQU      .DSA        FRMT19
OVERQU      JMS*        .FE
OVERQU      .DSA        QUSTN
OVERQU      JMS*        .FF
OVERQU      JMP          RECYCL
FRMT19     .ASCII '(30H YOU ASKED A LOT OF QUESTIONS ,12)'
FRMT10     .ASCII '(24H SOLUTION CONFIGURATION ,12)'
FRMT11     .ASCII '(15H MAXIMUM SCORE ,12)'
FRMT12     .ASCII '(8H BLOCKS ,12,12,12,12)'

```

FRMT13 .ASCII '(30H NO. OF ALTERNATIVE SOLUTIONS ,12)'
 FRMT21 .ASCII '(15H YOUR SCORE IS ,12)'
 MAXICO .BLOCK 20
 TYPE .BLOCK 20
 TAGS .BLOCK 20

/

/

/

/THIS IS A BUFFER OF COLOUR SCORES
 SHAPEB

3
 4
 0
 0
 0
 2
 0
 0
 3
 4
 2
 0
 0
 2
 0
 1
 3
 4
 0
 0
 0
 1
 0
 1
 3
 4
 4
 2
 0
 1
 0
 0
 0
 3
 1
 2
 0
 0
 2
 0
 1
 3
 1
 2
 0
 0
 2
 0

1
2
3
2
0
0
2
0
1
2
3
0
0
0
2
0
1
1
4
2
0
0
2
0
1
1
4
2
0
0
2
0
0
1
4
2
0
0
1
0
1
2
0
4
2
0
1
0
1
3
2
1
0
2
0
0

SHAPER

2
3
0
0
0
2
0
0
2
3
0
1
0
2
0
0
2
3
0
1
0
1
0
0
2
1
3
0
2
1
0
0
2

/

/THIS IS A BUFFER OF ALL 16 COMBINATIONS OF BLOCKS IN 8BIT CODES
CODES

252
152
232
246
251
132
146
151
126
131
125
145
226
231
245
225

•END

START

BLOCXT - sample output in full solution mode

MONITOR V4E

\$G 1

+S

SLTNS+RULE 2, RULE 1, SCORE 0

2

PLEASE MAXIMISE BLUE FOR PROBLEM 1

0000

TYPE 4 BLOCKS USED IN PROBLEM 1

2367

HOW MANY BAYS ARE THE WRONG COLOUR 1

0

THE RULE IS 7

MAXIMUM SCORE 14

YOUR SCORE IS 14

NO. OF ALTERNATIVE SOLUTIONS 6

SOLUTION CONFIGURATION 9

BLOCKS 2 3 6 7

SOLUTION CONFIGURATION 9

BLOCKS 2 4 6 7

SOLUTION CONFIGURATION 10

BLOCKS 2 4 6 7

SOLUTION CONFIGURATION 11

BLOCKS 2 4 6 7

SOLUTION CONFIGURATION 5

BLOCKS 1 4 6 7

SOLUTION CONFIGURATION 6

BLOCKS 1 4 6 7

BLOCXT - sample experimental output.

G 1
 †S
 SLTNS+RULE 2, RULE 1, SCORE 0
 0

PLEASE MAXIMISE RED FOR PROBLEM 1
 1458

NO (RED) 1

1457

NO (RED) 2

1358

NO (RED) 3

1468

NO (RED) 4

2458

NO (RED) 5

2358

NO (RED) 6

2357

NO (RED) 7

2457

NO (RED) 8

2367

YES (RED) 9

2357

NO (RED) 10

0000

TYPE 4 BLOCKS USED IN PROBLEM 1

2367

HOW MANY BAYS ARE THE WRONG COLOUR 1

5

MAXIMUM SCORE 10

YOUR SCORE IS 9

YOU ASKED A LOT OF QUESTIONS 10

LOAD programme

request for operating mode

experimental mode

computer sets problem

subject asks questions

computer replies

subject finishes problem

computer requests solution

subjects! solution

computer requests score

subjects! score

computer gives result

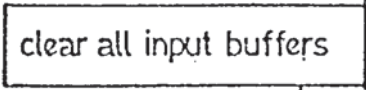
9.4.2 PICAPS

(Potential Information Content And Potential colour Scores)

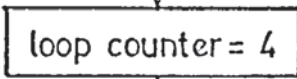
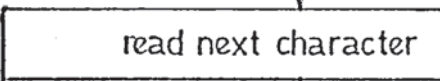
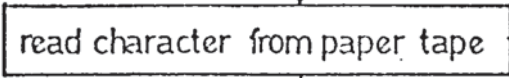
Like BLOCXT, PICAPS is a Macro 9 program with Fortran IV output routines for use on an 8K DEC PDP9 computer. The program calls for the paper tape output of BLOCXT to be input, and outputs a hard copy on a teletype.

PICAPS analyses the protocols for each 'Blocks' problem and outputs digital strategy profiles. For each question asked PICAPS calculates the number of individual blocks and pairs of blocks not present in any previous question of that problem. PICAPS also calculates how many blocks have changed since the last question. Finally PICAPS computes the highest possible colour score with that combination of four blocks. The profile is then output in a tabular form on the Teletype and PICAPS reads the next problem. On reaching the end of the session PICAPS calls for the next tape and waits.

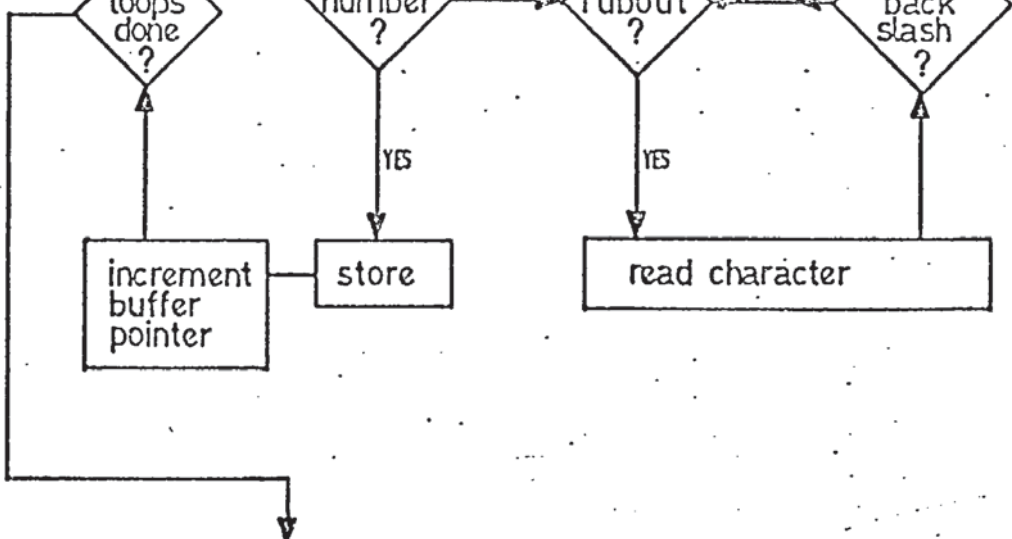
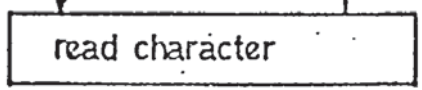
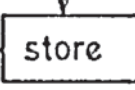
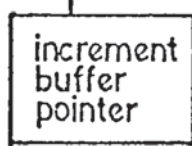
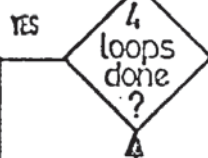
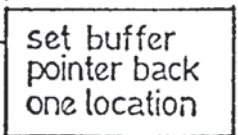
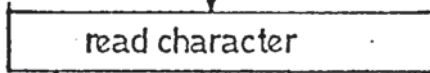
START



AGAIN



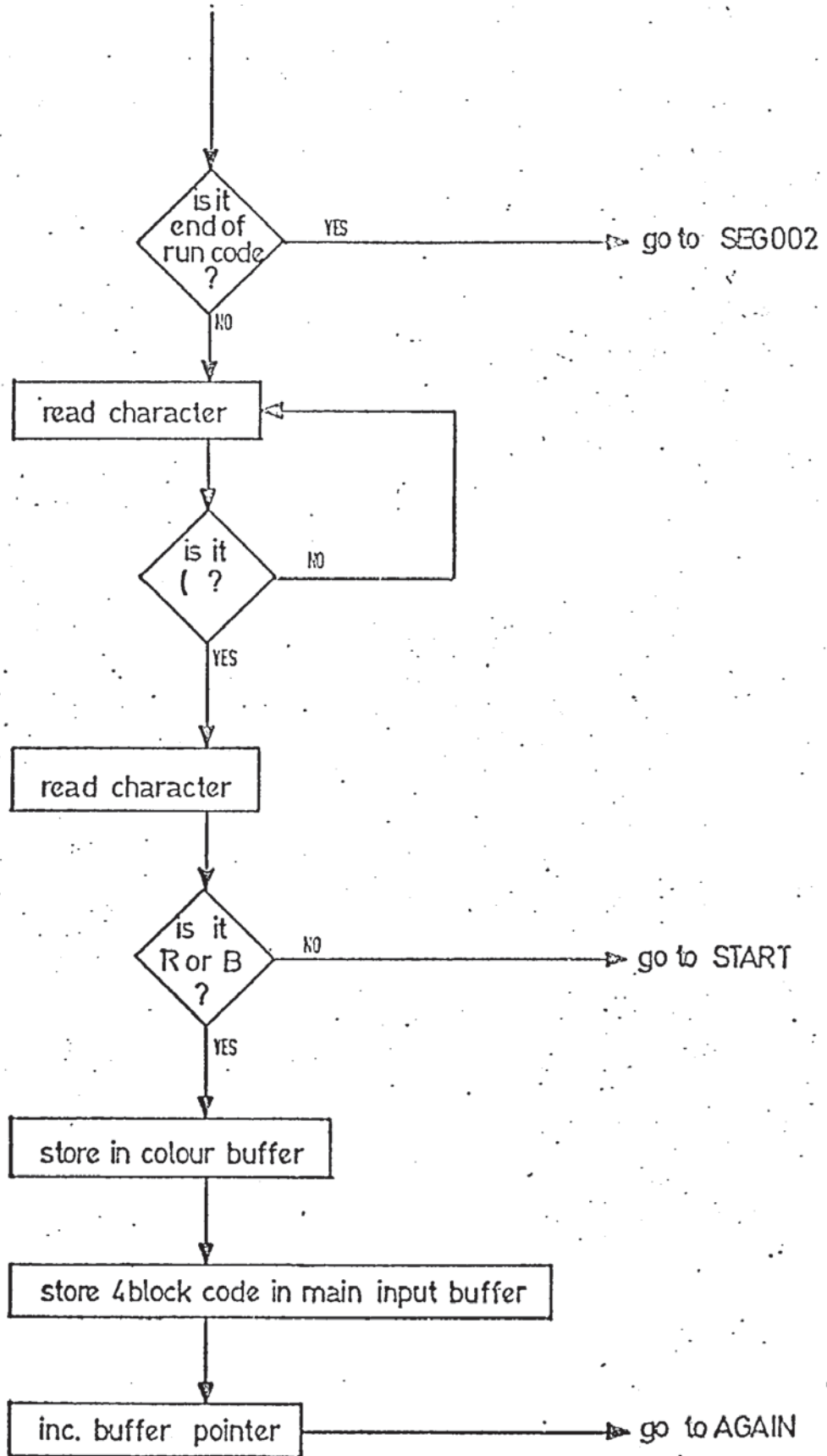
GETCOD RUBOUT



COLOUR

R
B

LOOPST



SEG002

reset main buffer pointers

loop counter = no. of codes read in

REENTRY
ENCODE

unpack next 4 block code to give 8 bit code

LOOP
COMPAR

compute and store max colour score
for 8 bit / 4 block code

SEG003

count number of blocks different to
previous code and store

RELOOK

count and store no. of new unigrams and
digrams not previously used in problem

SEEN

all codes
analysed
?

NO

YES

SEG004

table headings

LOOPOT

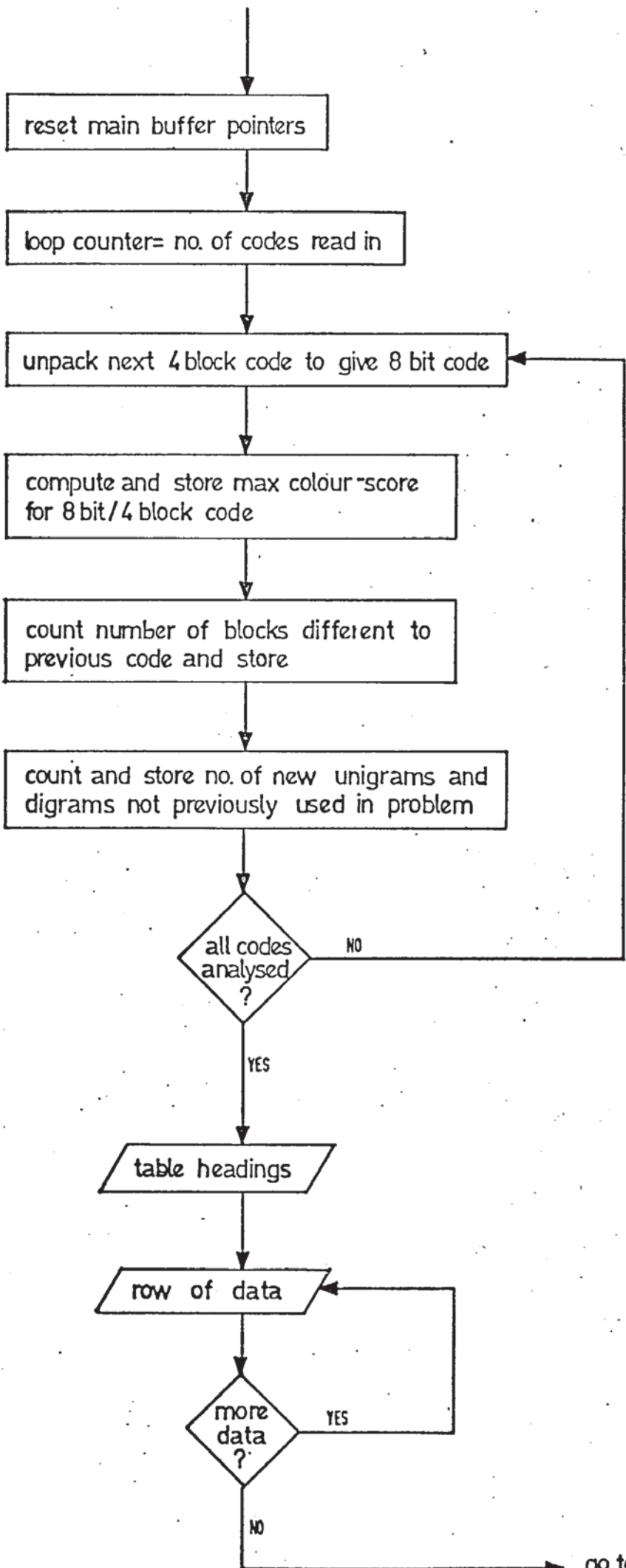
row of data

more
data
?

YES

NO

go to START



PICAPS - sample output of one session analysed

	CS	IC	TI	BC
1	BLUE			
1	14	10	10	0
2	14	4	14	1
3	12	4	18	1
4	12	4	22	1
5	10	4	26	1
6	13	1	27	2
7	11	1	28	1
8	11	1	29	2
2	RED			
1	13	10	10	0
3	BLUE			
1	14	10	10	0
4	BLUE			
1	13	10	10	0
2	14	4	14	1
5	RED			
1	13	10	10	0
2	13	4	14	1
6	RED			
1	13	10	10	0
2	13	4	14	1
3	13	4	18	1
4	11	4	22	1
5	12	1	23	1
6	12	0	23	0

LOAD TAPE AND CONTINUE 0

see below

problem 1 (max. blue)
question 1

program requests next session
paper tape for analysis

CS = colour score
IC = information content
TI = total information
BC = no. blocks changed from
last question

•TITLE PICAPS

/PROTOCOL INFORMATION CONTENT AND
 /POTENTIAL SCORES
 /PROGRAM TO ANALYSE BLOCKS DATA TAPES
 /BRL NOV. 70

•GLOBL •FP, •FW, •FE, •FF
 •IODEV 4

RSA=700104
 RSF=700101
 RRB=700112

/THIS SEGMENT INITIALISES PROGRAM

```

START  LAC      (INSTOR
        DAC      BLCKPT#  /SET MAIN BUFFER POINTER
        DZM      NCODES#  /COUNTER FOR NO OF CODES INPUT
        DZM      MAXISC
        LAC      (MAXIMA
        DAC      PTMAX#
        LAC      (SCORES
        DAC      PTSCOR#
        LAC      (CHNGBL
        DAC      PTCHNG#
        LAC      (SNTAGS  /CLEAR TAGS BUFFER
        DAC      PTTAGS
        LAW      -40
        DAC      FOURTY
        DZM*     PTTAGS
        ISZ      PTTAGS
        ISZ      FOURTY
        JMP      •-3
AGAIN  JMS      TAPE      /GET CHAR.
        SAD      (15      /WAIT FOR PDP9 CR
        SKP
        JMP      AGAIN    /RESTART SEARCH
        JMS      TAPE
        SAD      (212    /WAIT FOR LF
        SKP
        JMP      AGAIN    /RESTART SEARCH
        LAC      (BLOCK
        DAC      PTBLCK  /SET BUFFER POINTER
        LAW      -4
        DAC      COUNT#  /SET COUNTER
GETCOD JMS      TAPE      /GET CHAR.
        DAC      TEMP#   /TEMP STORE
        AND      (260
        SAD      (260    /IS IT NO. OR RUBOUT?
        SKP      /YES
        JMP      AGAIN    /NO RRSTART SEARCH
        LAC      TEMP
        SAD      (377    /IS IT RUBOUT?
        JMP      RUBOUT  /YES
        DAC*     PTBLCK# /NO, IT IS A NUMBER
        ISZ      PTBLCK  /INC BUFFER POINTER
        ISZ      COUNT   /INC COUNTER, 4 CYCLES COMPLETE?
    
```

	JMP	GETCOD	/NO
	JMS	TAPE	/YES
	SAD	(215	/ISIT CR?
	JMP	COLOUR	/YES
	SAD	(377	/IS IT RUBOUT?
	JMP	RUBOUT	/YES
RUBOUT	JMP	AGAIN	/NO, ILEGAL CHAR. RESTART SEARCH
	JMS	TAPE	/HANDLES SUBJECT ERASED CHARACTERS
	SAD	(334	/IS IT ECHOED BACKSLASH?
	SKP		/YES
	JMP	AGAIN	/NO RESTART SEARCH
	LAC	COUNT	
	SAD	(-4	
	SKP		/HAVE ANY CHARACTERS BEEN INPUT TO
			/ERASE?
	JMP	AGAIN	/NO RESART SEARCH
	LAC	COUNT	/YES
	TAD	(-1	/SET COUNTER BACK ONE
	DAC	COUNT	
	LAC	PTBLCK	
	TAD	(-1	
	DAC	PTBLCK	/SET BUFFER POINTER BACK ONE
	JMP	GETCOD	/GET REPLACED CHAR.
TAPE	XX		/READS CHAR FROM PAPER TAPE
	IOF		
GD0001	IORS		
	AND	(1000	
	SZA		/IS THERE ANY TAPE IN READER
	JMP	NOTAPE	/NO
	NOP		/YES
GD0002	RSA		
	RSF		
	JMP	.-1	
	RRB		/READ
	SZA		/SKP BLANK TAPE
	JMP*	TAPE	/EXIT WITH CHAR. IN AC.
	JMP	GD0002	
NOTAPE	JMS*	.FP	/IF NO TAPE IN READER
	JMS*	.FW	
	.DSA	(4	
	.DSA	FRMTAP	/INSTRUCTION
	JMS*	.FE	
	.DSA	DUMMY	
	JMS*	.FF	
	DZM	RUNS#	/ZEROS RUNS COUNTER FOR NEW SESSION
	IOF		
	HLT		/CONTINUE
	NOP		
	RSA		
	RSF		
	JMP	.-1	
	JMP	GD0002	
COLOUR	LAC	BLOCK	
	SAD	(260	/IS IT END OF RUN?
	JMP	SEG002	/YES
	JMS	TAPE	/NO LOOK FOR COLOUR


```

SAD      (40      /WAIT FOR SPACE
SKP
JMP      .-3
JMS      TAPE
SAD      (40      /LOOK FOR SECOND SPACE
SKP      /SPACE
JMP      GETCOD   /NOT SPACE S ENTERED ILEGAL
                        /COMBINATION

JMS      TAPE
SAD      (50      /WAIT FOR BRACKET
SKP
JMP      .-3
JMS      TAPE     /GET COLOUR CHAR
SAD      (102     /BLUE
JMP      B
SAD      (122     /RED
JMP      R
JMP      AGAIN    /ABORT ,ILEGAL CHAR.
R        DZM      REDBLU# /SET TO RED
B        JMP      ALLIN
ALLIN    LAC      (1
DAC      REDBLU   /SET TO BLUE
ALLIN    LAC      (BLOCK /SET POINTERS
DAC      PTBLCK
LAW      -4
DAC      COUNT
LOOPST   LAC*     PTBLCK  /STORE BLOCK NOS IN MAIN BUFFER
DAC*     BLCKPT
ISZ      PTBLCK
ISZ      BLCKPT
ISZ      COUNT
JMP      LOOPST
ISZ      NCODES
JMP      AGAIN

FRMTAP   .ASCII '(25H LOAD TAPE AND CONTINUE ,ii)'
DUMMY    0
BLOCK    .BLOCK   4
INSTOR   .BLOCK   200
/
/
/
/

/THIS SEGMENT ANALYSES POTENTIAL COLOUR SCORES
SEG002   LAC      (INSTOR-1 /SET MAIN BUFFER POINTER
DAC      BLCKPT#
LAC      NCODES
CMA
TAD      (1
DAC      CODCNT#  /NEGATE NCODES AS COUNTER
LAC      (777     /TO GET NO BLOCKS CHANGED ON 1ST
                        /SELTN

RENTRY   DAC      LSTCOD#
DZM      CODE#
LAW      -4
DAC      COUNT#
ENCODE   ISZ      BLCKPT
    
```

	LAC*	BLCKPT
	TAD	(-260
	CMA	
	TAD	(1 /NEGATE BLOCK NUMBER
	DAC	CODING# /STORE
	LAC	(400 /SET BIT 9
	DAC	CODED# /STORE
	LAC	CODED
	RCR	/ROTATE RIGHT
	DAC	CODED /STOR
	ISZ	CODING /INCREMENT NEGATED BLOCK NO.
	JMP	.-4 /ROTATE AGAIN IF NOT ZERO
	LAC	CODED
	TAD	CODE /ADD CODES OF PREVIOUS BLOCKS
	DAC	CODE /STORE
	ISZ	COUNT
	JMP	ENCODE /GET NEXT BLOCKS NUMBER
	DZM	MAXISC#
	JMS	INIT
ALLWED	JMP	ALLWED
	LAC*	11
	AND	CODE
	SAD	CODE
	JMP	+.4
	LAC	(1
	DAC*	12
	JMP	+.2
	DZM*	12
	ISZ	COUNT#
	JMP	ALLWED
	JMS	INIT
INIT	JMP	LOOP
	XX	
	LAC	(CODES-1
	DAC	11
	LAC	(TAGS-1
	DAC	12
	LAW	-20
	DAC	COUNT
LOOP	JMP*	INIT
	LAC	REDBLU
	SZA	
	JMP	+.3
	JMS	BLUE
	JMP	CONTIN
	JMS	RED
RED	JMP	CONTIN
	XX	
	LAC	(SHAPER
	DAC	POINT#
BLUE	JMP*	RED
	XX	
	LAC	(SHAPEB
	DAC	POINT
CONTIN	JMP*	BLUE
	LAC*	12

	SZA		/LOOK FOR TAG
	JMP	+5	/FIND TAG
	JMS	UNPACK	/NO TAG SET
	ISZ	COUNT	
	JMP	LOOP	
	JMP	SCRSTR	
	LAC*	11	
	ISZ	COUNT	
	JMP	LOOP	
	JMP	SCRSTR	
UNPACK	XX		
	LAW	-15	
	DAC	CYCLE#	
	LAC*	11	
	DAC	TEMP#	
ROWS	ISZ	CYCLE	
	JMP	+2	
	JMP*	UNPACK	
	DZM	SCORE	
	LAC	TEMP	
	AND	(100	/MASK
	JMS	PAIR	
	LAC	TEMP	
	AND	(20	
	JMS	PAIR	
	LAC	TEMP	
	AND	(4	
	JMS	PAIR	
	LAC	TEMP	
	AND	(1	
	JMS	PAIR	
	JMP	COMPAR	
PAIR	XX		
	SZA		
	JMP	RIGHT	
	LAC*	POINT	
	TAD	SCORE#	
	DAC	SCORE	
	ISZ	POINT	
	ISZ	POINT	
	JMP*	PAIR	
RIGHT	ISZ	POINT	
	LAC*	POINT	
	TAD	SCORE	
	DAC	SCORE	
	ISZ	POINT	
	JMP*	PAIR	
COMPAR	LAC	SCORE	
	CMA		
	TAD	(1	/NEGATE
	TAD	(16	/NUMBER OF DESIRED COLOUR
	DAC	SCORE	
	LAC	MAXISC	
	CMA		
	TAD	(1	
	TAD	SCORE	/SUBTRACT PREVIOUS MAXIMUM

```

SPA
JMP      ROWS
LAC      SCORE
DAC      MAXISC
JMP      ROWS
SCRSTR   LAC      MAXISC      /STORE SCORE IN MAIN BUFFER
          DAC*    PTMAX
          ISZ     PTMAX      /INC POINTER
          JMP     SEG003
MAXIMA   •BLOCK  40
TAGS     •BLOCK  20

```

/

/

/

/

/THIS IS A BUFFER OF COLOUR SCORES
SHAPEB

3
4
0
0
0
2
0
0
0
3
4
2
0
0
2
0
1
3
4
4
0
0
0
1
0
1
3
4
4
2
0
1
0
0
3
1
2
0
0
2
0
1

3
1
2
0
0
2
0
1
2
3
2
0
0
2
0
1
2
3
0
0
0
2
0
1
1
4
2
0
0
2
0
1
1
4
2
0
0
2
0
0
1
4
2
0
0
1
0
1
2
0
4
2
0
1
0
1

SHAPER

3
2
1
0
2
0
0
2
3
2
0
0
2
0
0
0
3
2
1
0
1
0
0
2
3
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2
1
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2
1
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2
3
2
1
0
2
0
0
0

3
2
1
0
2
0
0
2
3
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0
0
2
0
0
2
3
0
1
0
2
0
0
2
3
0
1
0
1
0
0
2
1
3
0
2
1
0
0
2

CODES

252
152
232
246
251
132
146
151
126
131
125
145
226
231
245
225

/ / / /
 /THIS SEGMENT ANALYSES INFORMATION CONTENT OF SELECTIONS

```

SEG003  NOP
NXTCOD  LAW      -40      /SET POINTERS
        DAC      FOURTY#   /AND COUNTERS
        LAC      (SNTAGS
        DAC      PTTAGS#
        LAC      (CMBTNS
        DAC      PTCMBS#
        DZM      INFO#     /CLEAR TEMP STORE
    
```

/ /
 /THIS SUB-SEGMENT COMPUTES NUMBER OF BLOCKS CHANGED FROM LAST CODE

```

        LAC      CODE
        AND      LSTCOD    /TO GET COMMON BLOCKS
        DAC      CHANGE#   /TEMP STORE FOR ROTATION
        LAW      -10
        DAC      COUNT#    /SET ROTATION COUNTER TO 8
        DZM      DIFF#     /ZERO COMMON BLOCK STORE
        LAC      CHANGE
        AND      (1        /LOOK FOR BLOCKS THE SAME
        SZA      /ARE THEY THE SAME?
        ISZ      DIFF      /YES
        LAC      CHANGE    /NO
        RCR      /ROTATE RIGHT
        DAC      CHANGE
        ISZ      COUNT     /8 LOOPS COMPLETE?
        JMP      .-10      /NO
        LAC      DIFF      /YES
        CMA
        TAD      (1        /NEGATE NUMBER THE SAME
        TAD      (4        /TO GET NUMBER DIFFERENT
        DAC*     PTCHNG    /STORE IN MAIN BUFFER
        ISZ      PTCHNG    /INC POINTER
        LAC      CODE
        DAC      LSTCOD    /REPLACE OLD LAST CODE WITH PRESENT
        /CODE
RELOOK  LAC*     PTTAGS    /LOOKS THRO BUFFERS
        SZA      /ALREADY SEEN?
        JMP      SEEN      /YES
        LAC*     PTCMBS    /NO
        AND      CODE
        SAD*     PTCMBS    /DOES CODE CONTAIN COMBINATION?
        SKP      /YES
        JMP      SEEN      /NO
        ISZ*     PTTAGS    /TAG IT AS SEEN
        ISZ      INFO      /SCORE IT AS SEEN
SEEN    ISZ      PTTAGS    /INC POINTERS
        ISZ      PTCMBS
        ISZ      FOURTY    /32 LOOPS DONE?
        JMP      RELOOK    /NO
        LAC      INFO      /YES STORE IN MAIN BUFFER
        DAC*     PTSCOR
    
```


	ISZ	PTSCOR	/INC POINTER
	ISZ	CODCNT	/ALL CODES ANALYSED?
	JMP	RENTRY	/NO RENTER SEG002 TO ANALYSE NEXT
	JMP	SEG004	/YES GO TO OUPUT SEGMENT
SNTAGS	.BLOCK	40	
SCORES	.BLOCK	40	
CHNGBL	.BLOCK	40	

/

/

/

/THIS IS A BUFFER OF ALL BLOCKS AND PAIRS OF BLOCKS

CMBTNS	200	/SINGLE BLOCKS
--------	-----	----------------

100

40

20

10

4

2

1

/1 AND

240

220

210

204

202

201

140

/2 AND

120

110

104

102

101

50

/3 AND

44

42

41

30

/4 AND

24

22

21

12

/5 AND

11

6

/6 AND

5

/

/

/

/THIS SEGMENT OUTPUTS ALL THE SCORES

SEG004	ISZ	RUNS	/INC RUNS COUNTER
	LAC	REDBLU	/WAS IT RED OR BLUE RUN?
	SZA		
	JMP	OUTB	/BLUE
OUTR	JMS*	.FP	/RED
	JMS*	.FW	
	.DSA	(4	
	.DSA	FRMTR	
	JMS*	.FE	

```

      .DSA      RUNS
      JMS*      .FF
      JMP       .+10
OUTB   JMS*      .FP
      JMS*      .FW
      .DSA      (4
      .DSA      FRMTB
      JMS*      .FE
      .DSA      RUNS
      JMS*      .FF
      LAC       (SCORES /SET BUFFER POINTERS
      DAC       PTSCOR
      LAC       (MAXIMA
      DAC       PTMAX
      LAC       (CHNGBL
      DAC       PTCHNG
      LAC       NCODES
      CMA
      TAD       (1
      DAC       CODCNT /SET OUTPUT LOOP COUNTER
      DZM       CUMTOT# /ZERO CUMULATIVE SCORE TOTAL
      DZM       NUMBER# /ZERO INDEX NUMBER
LOOPOT ISZ       NUMBER /OUTPUT LOOP
      LAC*      PTSCOR
      DAC       INFO
      TAD       CUMTOT
      DAC       CUMTOT /CUMULATE TOTAL
      LAC*      PTMAX
      DAC       MAXISC
      LAC*      PTCHNG
      DAC       CHANGE
      JMS*      .FW /COMMENCE OUTPUT STRING
      .DSA      (4
      .DSA      FRMT1
      JMS*      .FE
      .DSA      NUMBER
      JMS*      .FE
      .DSA      MAXISC
      JMS*      .FE
      .DSA      INFO
      JMS*      .FE
      .DSA      CUMTOT
      JMS*      .FE
      .DSA      CHANGE
      JMS*      .FF /COMPLETE OUTPUT STRING
      ISZ       PTSCOR /INC ALL BUFFER POINTERS
      ISZ       PTMAX
      ISZ       PTCHNG
      ISZ       CODCNT /ALL SCORES OUTPUT?
      JMP       LOOPOT /NO
      JMP       START /YES
FRMT1  .ASCII '(I3,4X,I3,4X,I3,2X,I3,2X,I3)'
FRMTR  .ASCII '(I3,8H RED)'
FRMTB  .ASCII '(I3,9H BLUE)'
      .END      START
    
```

9.5 Analysis Programs

Strategy analysis is a largely a-posteriori matter, and many statistics must often be calculated before strategies can be identified. These statistics are often non-parametric, and the results of tests are required quickly if the work is to proceed smoothly. This suite of programs was used extensively in the analysis of both experiments. They are all written in Algol for an ICL 1905.

REALPARA calculates the major parameters of a set of real or integer numbers. Means, variances, standard deviation, maximum, minimum, log mean, skew and kurtosis are all calculated.

FRIEDMAN computes Friedman's two way analysis of variance on an array of real numbers. Output includes the array ranked by rows and the value and degrees of freedom of Chi-Squared.

KRUSKAL computes the Kruskal-Wallis one way analysis of variance. Output includes the array ranked overall and Chi-Squared. Correction is made for tied ranks.

KENDALLW computes Kendall's coefficient of concordance between a series of rankings. Output includes the grand ranking order and the value of Chi-Squared.

```

JOB REALPARA,ARSTHU76,LAWSON,STREAM 1
ALGOL
****
DOC SOURCE
'BEGIN'COMMENT'(ARSTHU76:REALPARA BPL OCT71
PROGRAM CALCULATES THE PRINCIPAL STATISTICAL
PARAMETERS OF A SET OF REAL VARIABLES OF UP TO
3 DIGITS BEFORE AND AFTER THE DECIMAL POINT,
DATA ENTRY; N=NUMBER IN SAMPLE, DESCRIPTIVE TEXT
TERMINATED BY XXX, MAIN DATA, REPEAT, 0=END OF RUN );
REAL SUMX,SUMSQ,MAX,MIN,MEAN,VAR,SDEV,X,SUM3,SUM4,SUMLOG;
INTEGER N,COUNT;
SELECT OUTPUT(0);
WRITETEXT('(%N%XXXXXMEAN%XXXXXVARIANCE%STD,DEV%XXMAXIMUM%
MINIMUM%XXSKF%XXKURTOSIS%LOGHFAN%)');
NEWLINE(4);
MORE: N:=READ;
IF N=0 THEN GOTO FINISH;
SUMX:=SUMSQ:=SUM3:=SUM4:=MAX:=SUMLOG:=0; MIN:=10000;
COPYTEXT('XXX'); COMMENT'(INPUT DATA TAG AND XXX);
NEWLINE(1);
FOR COUNT:=1 STEP 1 UNTIL N DO
BEGIN X:=READ;
SUMSQ:=SUMSQ+X*X;
SUM3:=SUM3+X^3;
SUM4:=SUM4+X^4;
SUMLOG:=SUMLOG+LN(X);
SUMX:=SUMX+X;
IF X>MAX THEN MAX:=X;
IF X<MIN THEN MIN:=X;
END;
MEAN:=SUMX/N;
VAR:=SUMSQ/N-MEAN*MEAN;
SDEV:=SORT(VAR);
PRINT(N,3,0);
PRINT(MEAN,3,3);
PRINT(VAR,3,3);
PRINT(SDEV,2,3);
PRINT(MAX,3,3);
PRINT(MIN,3,3);
PRINT((((SUM3/N)-(MEAN^3))^2)/(VAR^3),2,3);
PRINT((((SUM4/N)-(MEAN^4))/(VAR^2)),2,3);
PRINT((EXP(SUMLOG/N)),3,3); NEWLINE(2);
GOTO MORE;
FINISH:
END;
****

```


JOB FRIEDMAN, ARSTH076, LAWSON, STREAM 1
 ALGOL

DOC SOURCE

```
'BEGIN' 'COMMENT' ('ARSTH076, FREIDMAN, BRL OCT71
PROGRAM INPUTS REAL ARRAY OF NUMBERS UP TO 3 DIGITS
BEFORE AND AFTER THE DECIMAL POINT, EACH ROW OF THE
ARRAY IS RANKED AND THE RANKED ARRAY IS STORED AND
OUTPUT, FREIDMAN'S TWO WAY ANALYSIS OF VARIANCE
IS CARRIED OUT, GIVING THE VALUE OF CHI-SQUARED
AND ITS DEGREES OF FREEDOM,
DATA ENTRY, N=NUMBER OF ROWS, K=NUMBER OF COLUMNS,
DESCRIPTIVE TEXT TERMINATED BY XXX, MAIN DATA BY
ROWS, REPEAT FACILITY, 0=END OF RUN ,);
  INTEGER N,K,COUNT,INDEX,SAME,CYCLE;
  REAL RANKNO,LARGEST,RSQ,R;
MORE: N:=READ;
  IF N=0 THEN 'GOTO' FINISH;
  K:=READ;
  COPYIFXT('('XXX')'); NEWLINE(2);
  'BEGIN' 'ARRAY' RAWSC[1:K],RANK[1:N,1:K];
  'FOR' INDEX:=1 'STEP' 1 'UNTIL' N 'DO'
  'BEGIN' 'FOR' COUNT:=1 'STEP' 1 'UNTIL' K 'DO'
    RAWSC[COUNT]:=READ;
    RANKNO:=0;
    AGAIN: COUNT:=SAME:=1;
    LARGEST:=0;
    LOOP: 'IF' RAWSC[COUNT]>LARGEST 'THEN' 'GOTO' BIGGER
      'ELSE' 'IF' RAWSC[COUNT]=LARGEST 'THEN' 'GOTO' EQUAL
      'ELSE' 'GOTO' INC;
    BIGGER: LARGEST:=RAWSC[COUNT];
      SAME:=1;
      'GOTO' INC;
    EQUAL: SAME:=SAME+1;
    INC: 'IF' COUNT=K 'THEN' 'GOTO' DONE;
      COUNT:=COUNT+1;
      'GOTO' LOOP;
    DONE: RANKNO:=RANKNO+(SAME/2)+(1/2);
      'IF' LARGEST=0 'THEN' 'GOTO' ROWDON;
      'FOR' COUNT:=1 'STEP' 1 'UNTIL' K 'DO'
      'BEGIN' 'IF' RAWSC[COUNT] NE LARGEST 'THEN' 'GOTO' DUMMY;
        RAWSC[COUNT]:=0;
        RANK[INDEX,COUNT]:=RANKNO;
      DUMMY:
      'END' ALL RANK NUMBERS PLACED FOR ROW;
        RANKNO:=(RANKNO+(SAME/2)+(1/2))-1;
        'GOTO' AGAIN;
      ROWDON:
    'END' GET ANOTHER ROW OF DATA;
    'COMMENT' (OUTPUT REGIM'S HERE);
    WRITETEXT('('N&ISX')'); PRINT (N,2,0); NEWLINE(1);
    WRITETEXT('('K&ISX')'); PRINT (K,2,0); NEWLINE(2);
    WRITETEXT('('ARRAY RANKED BY ROWS')'); NEWLINE(1);
    'FOR' INDEX:=1 'STEP' 1 'UNTIL' N 'DO'
    'BEGIN' NEWLINE(1);
      'FOR' COUNT:=1 'STEP' 1 'UNTIL' K 'DO'
      PRINT (RANK[INDEX,COUNT],2,2);
    'END' OF OUTPUT OF ONE ROW OF RANKS;
  'COMMENT' (END OF OUTPUT OF ALL ROWS OF RANKS);
  RSQ:=0;
  'FOR' COUNT:=1 'STEP' 1 'UNTIL' K 'DO'
  'BEGIN' R:=0;
    'FOR' INDEX:=1 'STEP' 1 'UNTIL' N 'DO'
    R:=R+RANK[INDEX,COUNT];
    RSQ:=RSQ+(R*R);
  'END' OF COMPUTING SUM OF SQUARED COLUMN TOTALS;
  NEWLINE(2);
  WRITETEXT('('CHISQUARED&IS')');
  PRINT(((12/(N+K+(K+1)))*RSQ)-(3+N*(K+1)),3,4);
  WRITETEXT('('WITH')');
  PRINT(K-1,3,0);
  WRITETEXT('('DEGRFESXOF&FREEDOM')'); PAPERTHROW;
  'GOTO' MORE; 'COMMENT' (TO REPEAT IF NECESSARY);
'END';
FINISH;
'END' OF PROGRAM;
  'FOR' CYCLE:=1 'STEP' 1 'UNTIL' K DO
  'BEGIN' RANKNO:=0;
  'END';
```

```

JOB KRUSKAL, ARSTH076, LAWSON, STREAM 1
ALGOL
****
DOC SOURCE
'BEGIN' 'COMMENT' (ARSTH076, KRUSKAL, DRL NOV 71
PROGRAM INPUTS REAL ARRAY OF NUMBERS UP TO 3 DIGITS
BEFORE AND AFTER THE DECIMAL POINT, THERE NEED NOT BE
EQUAL NUMBERS IN EACH COLUMN, BUT THE FIRST COLUMN MUST
BE THE LARGEST, KRUSKAL-WALLIS ONE WAY ANALYSIS OF
VARIANCE IS COMPUTED ON THE RANKED ARRAY, CHI-SQUARED
AND ITS DEGREES OF FREEDOM ARE GIVEN,
DATA ENTRY, K=NUMBER OF COLUMNS, N1, N2, NK=NUMBER OF
ROWS IN EACH COLUMN, DESCRIPTIVE TEXT TERMINATED BY XXX
MAIN DATA BY ROWS, REPEAT FACILITY, 0=END OF RUN, NO
WHERE COLUMN SIZES ARE DIFFERENT 0 MUST BE ENTERED FOR
NON EXISTANT DATA,);
INTEGRAL K, COL, N, ROW, SAME;
REAL RANKNO, LARGEST, TIES, RSQ, R, SIZE, W;
MORE: K:=READ;
IF K=0 THEN GOTO FINISH;
TIES:=0;
'BEGIN' 'ARRAY' NO(1:K);
FOR COL:=1 STEP 1 UNTIL K DO
NO[COL]:=READ;
N:=NO[1];
COPYTEXT('XXX'): NEWLINE(2);
'BEGIN' 'ARRAY' DATA, RANK(1:N, 1:K);
FOR ROW:=1 STEP 1 UNTIL N DO
'BEGIN' FOR COL:=1 STEP 1 UNTIL K DO
DATA[ROW, COL]:=READ;
END OF DATA INPUT;
RANKNO:=0;
AGAIN: LARGEST:=0; SAME:=1;
FOR ROW:=1 STEP 1 UNTIL N DO
'BEGIN' FOR COL:=1 STEP 1 UNTIL K DO
'BEGIN' IF DATA[ROW, COL] > LARGEST THEN GOTO BIGGER
ELSE IF DATA[ROW, COL] = LARGEST THEN GOTO EQUAL
ELSE GOTO INC;
BIGGER: LARGEST:=DATA[ROW, COL];
SAME:=1;
GOTO INC;
EQUAL: SAME:=SAME+1;
INC:
END OF SEARCH ACROSS ROW;
END AND ALL ROWS FOR NEXT LARGEST;
IF LARGEST=0 THEN GOTO ALLFOUND;
RANKNO:=RANKNO+(SAME/2)+(1/2);
TIES:=TIES+(SAME-1);
FOR ROW:=1 STEP 1 UNTIL N DO
'BEGIN' FOR COL:=1 STEP 1 UNTIL K DO
'BEGIN' IF DATA[ROW, COL] NE LARGEST THEN GOTO DUMMY;
DATA[ROW, COL]:=0;
RANK[ROW, COL]:=RANKNO;
DUMMY:
END OF SEARCH ACROSS ROW;
END AND ALL ROWS, RANK PLACED;
RANKNO:=RANKNO+(SAME/2)+(1/2)-1;
GOTO AGAIN;
ALLFOUND: WRITETEXT('RANKED ARRAY'); NEWLINE(1);
FOR ROW:=1 STEP 1 UNTIL N DO
'BEGIN' FOR COL:=1 STEP 1 UNTIL K DO
'BEGIN' PRINT (RANK[ROW, COL], 3, 1);
END OF ONE ROW OF OUTPUT; NEWLINE(1);
END OF ALL ROWS OUTPUT;
RSQ:=0;
FOR COL:=1 STEP 1 UNTIL K DO
'BEGIN' R:=0;
FOR ROW:=1 STEP 1 UNTIL N DO
R:=R+RANK[ROW, COL];
RSQ:=RSQ+(R*R)/NO[COL];
END OF COMPUTING COL TOT32OVER COL SIZE;
NEWLINE(2);
WRITETEXT('CHISQUARED IS');
SIZE:=0;
FOR COL:=1 STEP 1 UNTIL K DO
SIZE:=SIZE+NO[COL];
W:= ((12/(SIZE*(SIZE+1)))*RSQ)-(3*(SIZE+1));
PRINT (W, 3, 4);
NEWLINE(1); WRITETEXT('OR');
PRINT (W/(1-(TIES/(SIZE-1)))) , 3, 4);
WRITETEXT('CORRECTED FOR TIES'); NEWLINE(1);
WRITETEXT('WITH');
PRINT (K-1, 3, 0);
WRITETEXT('DEGREES OF FREEDOM'); PAPER THROW;
GOTO MORE;
END OF BLOCK ENCLOSING DYNAMIC ARRAYS;
END BEFORE EXIT LOOP;
FINISH;
END OF PROGRAM;
****

```

KRU 100
KRU 200
KPU 300
KRU 400
KRU 500
KRU 600
KRU 700
KRU 800
KRU 900
KRU 1000
KRU 1100
KPU 1200
KRU 1300
KRU 1400
KPU 1500
KRU 1600
KRU 1650
KPU 1700
KRU 1800
KRU 1900
KRU 2000
KPU 2100
KPU 2200
KPU 2300
KRU 2400
KPU 2500
KPU 2550
KPU 2600
KRU 2700
KPU 2800
KPU 2900
KPU 3000
KRU 3100
KPU 3200
KRU 3300
KPU 3400
KPU 3500
KPU 3600
KPU 3700
KPU 3800
KPU 3900
KRU 4000
KRU 4100
KPU 4200
KRU 4300
KRU 4400
KPU 4500
KRU 4600
KPU 4700
KPU 4800
KRU 4900
KPU 5000
KRU 5100
KPU 5200
KPU 5300
KRU 5400
KRU 5500
KPU 6000
KRU 6100
KRU 6200
KRU 6300
KPU 6400
KRU 6500
KPU 6600
KRU 6700
KRU 6800
KRU 6900
KRU 7000
KRU 7100
KEN 7150
KRU 7200
KEN 7300
KRU 7500
KRU 7600
KRU 7700
KRU 7800
KRU 7900
KRU 8000
KRU 8100
KPU 8200
KRU 8300

DOC SOURCE

```

'BEGIN' COMMENT ('ARSTH076, KENDALLW, APRIL JAN72
PROGRAM INPUTS A PRAY OF N RANKINGS OF K ITEMS AND
COMPUTES KENDALL'S COEFFICIENT OF CONCORDANCE, CHI
SQUARED AND ITS DEGREES OF FREEDOM ARE GIVEN, A GRAND
COLUMN TOTAL AND RANKING IS ALSO OUTPUT,
DATA EMPTY, K= NUMBER OF ITEMS, N= NUMBER OF JUDGES,
DESCRIPTIVE TEXT TERMINATED BY XXX, DATA BY ROWS,
REPEAT FACILITY, 0= END OF RUN.);
'INTEGER' SAME, TIES, K, N, COUNT, ROW, COL;
'REAL' DEV, S, T, LARGEST, DUMMY, MEAN, W, RANKNO;
MORE: K:=READ;
'IF' K=0 THEN 'GOTO' FINISH;
N:=READ;
COPYTEXT ('(XXX)'); NEWLINE (?);
'BEGIN' REAL 'ARRAY' RANKS[1:N, 1:K], TOTALS[1:K], RANKTOT[1:K];
S:=MEAN:=0;
'FOR' COL:=1 'STEP' 1 'UNTIL' K 'DO'
TOTALS[COL]:=0;
'FOR' ROW:=1 'STEP' 1 'UNTIL' N 'DO'
'BEGIN' 'FOR' COL:=1 'STEP' 1 'UNTIL' K 'DO'
'BEGIN' RANKS[ROW, COL]:=READ;
TOTALS[COL]:=TOTALS[COL]+RANKS[ROW, COL];
MEAN:=MEAN+RANKS[ROW, COL];
'END' OF INPUTTING A ROW;
'END' OF INPUTTING ALL ROWS, COLUMNS TOTALLED;
MEAN:=MEAN/K;
'FOR' COL:=1 'STEP' 1 'UNTIL' K 'DO'
'BEGIN' DUMMY:=TOTALS[COL]-MEAN;
DEV:=DUMMY*DUMMY;
S:=S+ DEV;
'END' OF COMPUTING SUM OF SQUARES OF MEAN DEVIANCES(S);
WRITE TEXT ('(COLUMN NUMBER)');
'FOR' COL:=1 'STEP' 1 'UNTIL' K 'DO'
PRINT(COL, S, 0);
NEWLINE(1);
WRITE TEXT ('(COLUMN TOTALS)');
'FOR' COL:=1 'STEP' 1 'UNTIL' K 'DO'
PRINT(TOTALS[COL], 3, 1);
NEWLINE(1);
RANKNO:=K+1;
RANKING: COL:=SAME:=1; LARGEST:=0;
LOOP: 'IF' TOTALS[COL]>LARGEST THEN 'GOTO' BIGGER
'ELSE' 'IF' TOTALS[COL]=LARGEST THEN 'GOTO' EQUAL
'ELSE' 'GOTO' INC;
BIGGER: LARGEST:=TOTALS[COL];
SAME:=1;
'GOTO' INC;
EQUAL: SAME:=SAME+1;
INC: 'IF' COL=K THEN 'GOTO' DONE;
COL:=COL+1;
'GOTO' LOOP;
DONE: RANKNO:=RANKNO-((SAME/2)+(1/2));
'IF' LARGEST=0 THEN 'GOTO' ROWDON;
'FOR' COL:=1 'STEP' 1 'UNTIL' K 'DO'
'BEGIN' 'IF' TOTALS[COL] NE LARGEST THEN 'GOTO' JUMP;
TOTALS[COL]:=0;
RANKTOT[COL]:=RANKNO;
JUMP:
'END' OF PLACING NEXT COLUMN TOTAL RANKING;
RANKNO:=RANKNO-((SAME/2)+(1/2)-1);
'GOTO' RANKING;
ROWDON:
WRITE TEXT ('(GRAND RANKING)');
'FOR' COL:=1 'STEP' 1 'UNTIL' K 'DO'
PRINT(RANKTOT[COL], 3, 1);
NEWLINE(3);
T:=0;
'FOR' ROW:=1 'STEP' 1 'UNTIL' N 'DO'
'BEGIN' TIES:=0;
'FOR' COL:=1 'STEP' 1 'UNTIL' K 'DO'
'BEGIN' COMMENT ('LOOKING FOR TIES');
DUMMY:=RANKS[ROW, COL];
RANKS[ROW, COL]:=0;
SAME:=1;
'FOR' COUNT:=1 'STEP' 1 'UNTIL' K 'DO'
'IF' DUMMY=RANKS[ROW, COUNT] THEN SAME:=SAME+1;
'IF' SAME>1 THEN 'GOTO' ADD 'ELSE' 'GOTO' SKIP;
ADD: TIES:=TIES+(SAME+3-SAME);
SKIP:
'END' OF COMPUTING NUMBER OF TIED RANKS IN ONE ROW;
T:=T+(TIES/12);
'END' OF COMPUTING SUMS OF T;
WRITE TEXT ('(KENDALL W X Y Z CHI SQUARED X D, F, )'); NEWLINE(1);
W:=S/((N*N*(K+3-K))/12);
PRINT(W, 1, 4); SPACE(4);
PRINT((N*W*(K-1)), 3, 4); SPACE(2);
PRINT(K-1, 2, 0); NEWLINE(1);
W:=S/(((N+4*(K+3-K))/12)-N*T);
PRINT(W, 1, 4); SPACE(4);
PRINT((N*W*(K-1)), 3, 4); SPACE(2);
PRINT(K-1, 2, 0); NEWLINE(1);
WRITE TEXT ('(THE LOWER VALUES ARE CORRECTED FOR TIES)');
NEWLINE(5);
'GOTO' MORE;
'END' OF ARRAY BLOCK;
FINISH:
'END' OF PROGRAM;
****

```

KFN 100
KFN 200
KFN 400
KFN 500
KFN 600
KFN 700
KFN 800
KFN 900
KFN 1000
KFN 1100
KFN 1200
KFN 1300
KFN 1400
KFN 1450
KFN 1500
KFN 1600
KFN 1700
KFN 1800
KFN 1900
KFN 2000
KFN 2100
KFN 2200
KFN 2300
KFN 2400
KFN 2500
KFN 2600
KFN 2700
KFN 2800
KFN 2900
KFN 3000
KFN 3100
KFN 3200
KFN 3300
KFN 3400
KFN 3500
KFN 3600
KFN 3700
KFN 3800
KFN 3900
KFN 4000
KFN 4100
KFN 4200
KFN 4300
KFN 4400
KFN 4500
KFN 4600
KFN 4700
KFN 4800
KFN 4900
KFN 5000
KFN 5100
KFN 5200
KFN 5300
KFN 5400
KFN 5500
KFN 5600
KFN 5700
KFN 5800
KFN 5900
KFN 6000
KFN 6100
KFN 6200
KFN 6300
KFN 6400
KFN 6500
KFN 6600
KFN 6700
KFN 6800
KFN 6900
KFN 7000
KFN 7100
KFN 7200
KFN 7300
KFN 7400
KFN 7500
KFN 7600
KFN 7700
KFN 7800
KFN 7900
KFN 8000
KFN 8100
KFN 8200
KFN 8300
KFN 8400
KFN 8410
KFN 8420
KFN 8430
KFN 8440
KFN 8450
KFN 8460
KFN 8470
KFN 8480
KFN 8500
KFN 8600
KFN 8990
KFN 9000
KFN 9100
KFN 9200

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