Paper presented to the Personal Construct Network Conference, Cincinnati, June 22-24 1984.

APPLICATIONS OF PERSONAL CONSTRUCT THEORY TO EXPERT SYSTEMS

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ABSTRACT

The term **expert system** has come to be applied to interactive systems which provide one person with interactive access to another person's skills encoded in a computer in some way. However, what has been termed **knowledge engineering**, the reduction of a large body of knowledge to a precise set of facts and rules, has already become a major bottleneck impeding the application of expert systems in new domains. This paper suggests that Personal Construct Psychology provides both the theoretical framework and practical tools for knowledge engineering in expert systems. In particular, interactive computer repertory grid techniques may be used to bridge the communication gap between system analyst and expert and aid the knowledge engineer in developing the expert's vocabulary. Some experiments are described which validate the use of the program in this way by re-constructing the basic distinctions used in the Business Information Analysis and Integration Technique (BIAIT) used to determine the accounting needs of a company.

EXPERT SYSTEMS

The computer simulation of people in the roles of experts on some topic has become an important application of interactive computer systems. It has generated a new industry based on creating **expert systems** to make the practical working knowledge of a human expert in a specific subject area such as medicine or geology widely available to those without direct access to the original expert. Programs now exist that have made practical achievements in medical diagnosis, interpretation of mass spectroscopy results, analysis of geological survey data, and other problems where one would normally go to a human expert for advice.

Figure 1 shows part of a dialog between MYCIN, developed by Edward Shortliffe at Stanford University (Shortliffe 1976), and a clinician responsible for testing and treating a patient. MYCIN is designed to make a diagnosis and suggest therapy for patients with microbial infections. The expertise embedded in MYCIN is encoded as a set of rules of the form:

RULE 50

If 1) the infection is primary-bacteremia, and
2) the site of the culture is one of the sterile sites, and
3) the suspected portal of entry of the organism is the gastro-intenstinal tract,

Then there is suggestive evidence (.7) that the identity of the organism is bacteroides.

These rules are obtained from specialists in microbial infections and their application to particular data is fairly simple data processing. The rules are validated through their application to many cases and revised when they fail to give the correct diagnosis.

Figure 2 shows a brief summary of some well-known expert systems, and figure 3 shows a brief summary of the areas of application and numbers in use (Gevarter 1983). These figures are probably a severe underestimate of both the numbers and domains, as many industrial expert systems are not known in the public domain.

KNOWLEDGE ENGINEERING

The initial success of expert system developments (Michie 1979) and the development of a number of reasonably domain-independent software support systems for the encoding and application of knowledge (Hayes-Roth et al 1983) has opened up the possibility of widespread usage of expert systems. In particular, the Japanese Fifth Generation Computing development program (Moto-oka 1982) assumes this will happen and is targeted on knowledge processing rather than information processing. However, what Feigenbaum (1980) terms **knowledge engineering**, the reduction of a large body of knowledge to a precise set of facts and rules, has already become a major bottleneck impeding the application of expert systems in new domains. We need to

understand more about the nature of expertise in itself (Hawkins 1983) and to able to apply this knowledge to the elicitation of expertise in specific domains.

The underlying problem for knowledge engineering is well stated by Hayes-Roth et al:

> "Knowledge acquisition is a bottleneck in the construction of expert systems. The knowledge engineer's job is to act as a go-between to help an expert build a system. Since the knowledge engineer has far less knowledge of the domain than the expert, however, communication problems impede the process of transferring expertise into a program. The vocabulary initially used by the expert to talk about the domain with a novice is often inadequate for problem-solving; thus the knowledge engineer and expert must work together to extend and refine it. One of the most difficult aspects of the knowledge engineer's task is helping the expert to structure the domain knowledge, to identify and formalize the domain concepts." (Hayes-Roth et al 1983).

The problem of knowledge elicitation from a skilled person is well-known in the literature of psychology. Bainbridge (1979) has reviewed the difficulties of verbal debriefing and notes that there is no necessary correlation between verbal reports and mental behavior, and that many psychologists feel strongly that verbal data are useless. However, this remark must be taken in the context of experimental psychologists working within a positivist, behavioral paradigm. Other schools of psychology have developed techniques for making use of verbal interaction, for example through interviewing techniques that attempt to by-pass cognitive defenses, including those resulting from automization of skilled behavior. Welbank (1983) has reviewed many of these techniques in the context of knowledge engineering.

This paper is concerned with interactive computer aids to the knowledge engineer based on Kelly's (1955, Shaw 1980) **Personal Construct Psychology** (PCP) which uses a model of the person that has strong systemic and psychological foundations (Mancuso & Adams-Webber 1982). PCP provides a model of human knowledge representation, acquisition and processing, that has been made operational through computer programs for interactive knowledge elicitation (Shaw 1980). These may be used in developing the expert's vocabulary and in encoding aspects of his reasoning for a rule-based system. The expert interacts with a program, PEGASUS (Shaw & Gaines 1981b,1984) that encourages him to make clear the distinctions he uses in applying his expertise. This helps him to structure his knowledge and identify and formalize his concepts. The program may also be used in a teaching mode in order to enable others to come to use the expert's vocabulary in the same way as he does. Some experiments are described to validate the use of PEGASUS in this way by reconstructing the basic distinctions used in the Business Information Analysis and Integration Technique (BIAIT) used to determine the accounting needs of a company (Carlson 1979, Sowa 1984).

PERSONAL CONSTRUCT PSYCHOLOGY

Kelly developed a systemic theory of human cognition based on the single primitive of a **construct**, or dichotomous distinction. For a person, constructs are:

> "transparent templets which he creates and then attempts to fit over the realities of which the world is composed."

He proposes that all of human activity can be seen as a process of anticipating the future by construing the replication of events:

> "Constructs are used for predictions of things to come, and the world keeps rolling on and revealing these predictions to be either correct or misleading. This fact provides a basis for the revision of constructs and, eventually, of whole construct systems." (Kelly 1955)

Hence his psychological model of man is strongly epistemological and concerned with the way in which man models his experience and uses this model to anticipate the future. The anticipation may be passive, as in prediction, or active, as in action.

Kelly developed his theory in the context of clinical psychology and hence was concerned to have techniques which used it to by-pass cognitive defenses and elicit the construct systems underlying behavior. This is precisely the problem of knowledge engineering noted above. His **repertory grid** (Shaw 1980) is a way of representing personal constructs as a set of distinctions made about elements relevant to the problem domain. In clinical psychology this domain will often be personal relationships and the elements may be family members and friends. In the development of expert systems the elements will be key entities in the problem domain such as oil-well sites or business transactions. Repertory grids have been widely used: in clinical psychology (Shepherd & Watson 1982); to study processes of knowledge acquisition in education (Pope & Keen 1981); and to study decision making by individuals and groups in management (Shaw 1980). We have developed an integrated range of programs, PLANET (Shaw 1982), which operationalizes Kelly's work and may be used for the interactive elicitation and analysis of repertory grids. These programs have been widely used internationally in clinical psychology, education and management studies (Shaw 1981), and the present paper describes their application to knowledge engineering for expert systems.

Kelly's PCP is important because it develops a complete psychology of both the normal and abnormal, which has strong systemic foundations (Gaines & Shaw 1981a). In the long term these may be more important to knowledge engineering than the techniques currently based on them. The next section briefly reviews the systems analysis aspects of these foundations.

PLANET: A KNOWLEDGE ENGINEERING SYSTEM

The program system that we have developed and are using for knowledge engineering is called **PLANET** (Personal Learning, Analysis, Negotiation & Elicitation Techniques) (Shaw 1982,

Gaines & Shaw 1984). It runs as a menu-driven suite of interactive programs on a variety of computers and, while preliminary versions were developed on the PDP10, there proved to be no difficulty in issuing PLANET for the Apple II enabling its widespread use in field studies. The programs are all concerned with repertory grid elicitation and analysis, and divide naturally into four groups:

Construct elicitation. **PEGASUS** is a highly interactive program that elicits constructs through a conversational dialog with an expert, generated by feedback of its ongoing analysis of his construct system. PEGASUS offers many options, one of which is to receive feedback from a stored bank of expert constructs, thus enabling a student to learn to use an expert's construct system. **ARGUS** is a variant of PEGASUS that puts one individual in the position of several others and elicits his view of their viewpoints as well as his own.

Single construct system analysis. **FOCUS** provides a hierarchical clustering of an expert's construct system that preserves the data elicited from him so that the sources of the analysis are evident and can be discussed. **PRINGRID** is a non-hierarchical cluster analysis based on principal components that can be used to gauge the major dimensions along which distinctions are being made. **ENTAIL** is a logical analysis of the construct system taking the expert's distinctions to be fuzzy predicates. The entailment structure it generates can be used as a decision tree expressing the relationship between an expert's data and his conclusions, both personally expressed.

Multiple construct system analysis. **MINUS** compares two grids based on the same elements and constructs to highlight the differences between them. **CORE** provides an interactive comparison of such grids to determine where there are differences and extract invariancies, e.g. over time or over a group of people. **SOCIOGRIDS** analyses the total construct structure generated by a number of people construing the same elements from their individual viewpoints. It produces **socionets** showing the relationships between individual construct systems within the group and a **mode grid** reflecting the constructs shared across the group.

Database administration. **DATA, INPUT, OUTPUT** and other programs within PLANET provide the facilities needed to manage the large databases of construct data generated from field studies of expertise.

PLANET provides a set of tools for the knowledge engineer. PEGASUS enables the construct systems of all those involved in the application of expertise to be elicited, SOCIOGRIDS enables the consensual structure to be derived from these, and ENTAIL enables this to be turned into a decision tree when appropriate.

The next section is concerned with validating the methodology described applied to knowledge engineering.

BIAIT: A TEST CASE FOR VALIDATION

One of the problems of evaluating any methodology for knowledge engineering is to have some clear-cut test cases where the conceptual framework of experts has been both elicited and validated. Sowa (1984) describes one such case where the record keeping needs of a business can be prescribed through the BIAIT analysis technique (Carlson 1979) based on seven features:

1. Does the supplier bill the customer, or does the customer pay cash?
2. Does the supplier deliver the product at some time in the future, or does the customer take the order with him?
3. Does the supplier keep a profile of the customer, or is every transaction a surprise?
4. Is the price negotiated or fixed?
5. Is the product rented or purchased?
6. Does the supplier keep track of the product after it is sold or not?
7. Is the product made to order or provided from stock?

Sowa notes that these features:

> "seem almost obvious once they are presented, but finding the right features and categories may take months or years of analysis. The proper set of categories provides a structural framework that helps us organize the detailed facts and general principles of a system. Without them, nothing seems to fit, and the resulting system is far too complex or unwieldy." (Sowa 1984)

The BIAIT features are examples of constructs applied to orders placed between a customer and supplier. They provide a useful test case with which to evaluate the personal construct elicitation methodology provided in PLANET. An empirical study is being carried out to determine whether PEGASUS can be used to elicit the BIAIT distinctions from those with some accounting or business knowledge. It is particularly interesting to determine how open such a study may be: can the knowledge engineer operate in a completely unstructured way or does he have to "seed" the solution by selection of a set of elements. We usually assume that even if we cannot comprehend the expertise we can recognize an expert, and hence a key strategy for knowledge engineering is the selection of experts with whom to collaborate. This has strong prima facie validity but it would also be interesting to demonstrate it empirically. To do so through the PLANET analysis would itself be an indication of the validity of the methodology.

Hence, the initial experiments have been based on taking a spectrum of those with assumed expertise in business record keeping, from businessmen and accountants, to accounting students at various stages of their education, and using PEGASUS to elicit their constructs relating to business transactions. Again, in the interests of an initial open-ended approach, the construing has not been tightly constrained to relate to the record-keeping aspects of the transactions. It has been interesting to determine what distinctions are made that do not relate to record-keeping, or relate to it in ways different from BIAIT.

PEGASUS IN ACTION

PEGASUS commences its interaction by asking for the purpose of the elicitation and then for a set of elements relevant to this purpose. In the dialog the computer output is shown in normal face and the human input in **bold**:

Type in your purpose for doing this grid?**examining business record keeping**

You must choose a set of six elements keeping in mind why you want to do this grid. They could be people, events, pieces of music, pictures, books, or what you want but whatever you choose they must be of the same type and each must be well known to you. Try to choose specific things. Now type each one after each question mark.

Element 1?**selling newspapers from a stand**
Element 2?**selling antiques in a market**
Element 3?**selling custom drapes**
Element 4?**selling large appliances**
Element 5?**hiring out a car to a customer**
Element 6?**providing TV rental services**
Element 7?**selling car insurance**
Element 8?**providing electricity for home**
Element 9?**providing dental services**
Element 10?**being agent for home purchase**

One technique used by PEGASUS to elicit constructs is that of triadic comparison:

Triad for elicitation of construct 1
1 selling newspapers from a stand
2 selling antiques in a market
3 selling custom drapes

Can you choose two of this triad of elements which are in some way alike and different from the other one.
What is the number of the one which is different?1

Now I want you to think about what you have in mind when you separate the pair from the other one. How can you describe the two ends or poles of the scale which discriminate selling antiques in a market and selling custom drapes on the left pole from selling newspapers from a stand on the right pole?
Just type one or two words for each pole to remind you what you are thinking or feeling when you use this construct.

left pole rated 1 --?**no. of different objects**
right pole rated 5 --?**same object in quantity**

Now assume that selling antiques in a market and selling custom drapes are assigned the value 1 and selling newspapers from a stand is assigned the value 5 according to

how you feel about them please assign to each of the other elements in turn a provisional value from 1 to 5

```
 2 selling antiques in a market      1
 3 selling custom drapes             1
 1 selling newspapers from a stand   5
 4 selling large appliances         ?3
 5 hiring out a car to a customer   ?1
 6 providing TV rertal services     ?2
 7 selling car insurance            ?4
 8 providing electricity for home   ?5
 9 providing dental services        ?2
10 being agent for home purchase    ?3
```

Another technique is that of matching the ratings given to elements and asking for a construct that differentiates between two highly matched elements:

The two elements 1 selling newspapers from a stand and 8 providing electricity for home are matched at the 87 percent level. This means that so far you have not distinguished between selling newspapers from a stand and providing electricity for home.
Do you want to split these?**Y**

Think of a construct which separates these two elements, with selling newspapers from a stand on the left pole and providing electricity for home on the right pole.

left pole rated 1 --?**supplied one at a time**
right pole rated 5 --?**direct delivery**

According to how you feel about them please assign to each of the other elements in turn a provisional value from 1 to 5

```
 1 selling newspapers from a stand   1
 8 providing electricity for home    5
 2 selling antiques in a market     ?1
 3 selling custom drapes            ?2
 4 selling large appliances         ?1
 5 hiring out a car to a customer   ?1
 6 providing TV rental services     ?4
 7 selling car insurance            ?3
 9 providing dental services        ?1
10 being agent for home purchase    ?1
```

A technique that allows PEGASUS to elicit additional elements is to match constructs across elements and ask for a new element that differentiates between two highly matched constructs:

The two constructs you called
5 direct delivery -- supplied one at a time
9 'hands-on' delivery -- nonpersonal delivery
are matched at the 75 percent level

This means that most of the time you are saying direct delivery you are also saying 'hands-on' delivery and most of the time you are saying supplied one at a time you are also saying nonpersonal delivery. Think of another element which is either direct delivery and nonpersonal delivery or 'hands-on' delivery and supplied one at a time. If you really cannot do this then just press RETURN after the first question mark but please try.

Then you must give this element a rating value on each construct in turn. After each question mark type a value from 1 to 5

What is your element?

Through a combination of triadic comparison, element matching, and construct matching, a PEGASUS interaction draws out from the user his conceptual framework relating to the purpose of the elicitation.

SOCIOGRIDS IN ACTION

The construct elicitation described in the previous section is being carried out with a number of subjects from those experienced in business record-keeping to students with some knowledge of accounting. It is clearly possible to analyse for each subject whether the BIAIT constructs are among those elicited, how closely they are mimiced, and which ones are missing, and this analysis is being done. However, as noted earlier, one can also attempt to validate the methodology by seeing whether it is possible to reconstruct the ranking in expertise of the subjects through a SOCIOGRIDS analysis. For example, in an earlier study (Shaw 1980) of quality control for a garment company the SOCIOGRIDS analysis re-constructed the management hierarchy of the firm from the construct systems of staff involved in construing garment faults.

The operation of SOCIOGRIDS is based on Kelly's (1955) commonality corollary that: to the extent that one person employs a construction of experience that subsumes that of another in a given domain, that person can understand the cognitive processes of the other person in that domain. Thus, an expert system for a domain can be defined as one which subsumes the relevant constructions of experience of experts in that domain.

SOCIOGRIDS derives linkages between people (socionets) by comparing grids in pairs and calculating the average over all constructs in grid A of the similarity of the best match for each construct in grid B. This measures to what extent the system of construction modeled in grid B subsumes that modeled in grid A. These subsumption averages are ordered and used to produce socionets showing the degree to which one person's construction system subsumes that of another. SOCIOGRIDS derives a consensual construction system (mode grid) by comparing each construct in

turn with those in every grid and calculating the average over all grids of the best match for the construct in each grid. This measures to what extent a given construct is represented in the construction system of every person, and hence is consensual.

Link 1 in Fig.4 shows the most highly matched pair which is BIAIT and a businessman; link 2 shows another matched pair which is an economics student and a visual arts student. As the links are formed these initial pairs are joined into one group at link 4. A new subgroup is formed at link 6, then gradually the other participants are brought in and joined into one group. The nodes forming the central part of the network are BIAIT, the two businessmen, an economics student and the visual arts student. This can be seen at link 14 which is shown more completely in Fig. 5.

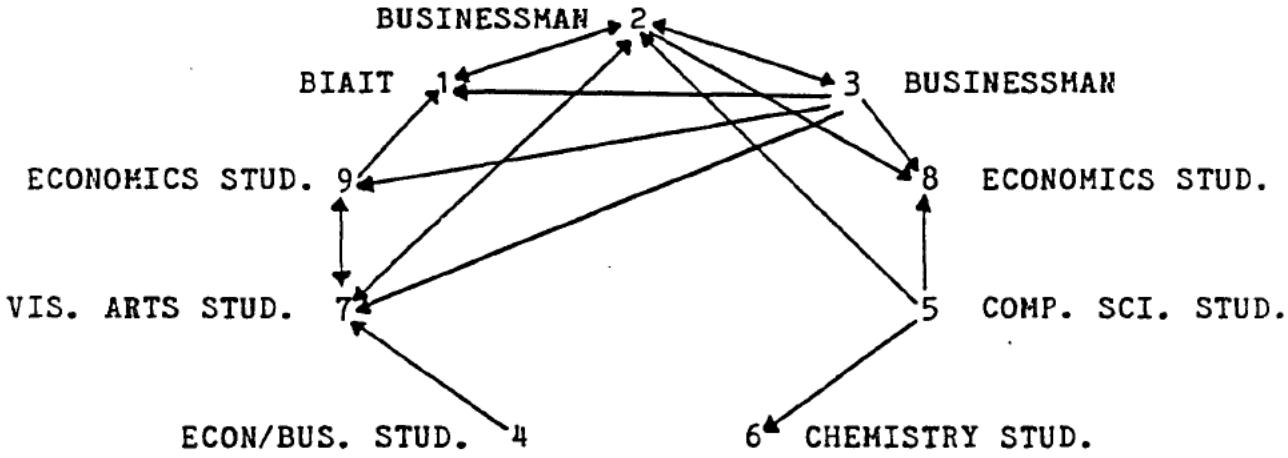

Fig. 5 Socionet produced by SOCIOGRIDS

This is mainly what one would expect, with the businessmen and the economics students closely related to BIAIT. The only disconcerting result is the position of the visual arts student who is clearly a central part of the cluster. On enquiring into the background of this student, it transpired that she had only recently become a student, having spent the previous 25 years as an administrative secretary in an insurance organization.

OTHER DEVELOPMENTS

ENTAIL (Gaines & Shaw 1981, Shaw & Gaines 1982) gives a dependency analysis of the grid by listing logical entailments not falsified by the data and it was expected that this would aid removal of unnecessary constructs. However, this is only partially successful because the grid as elicited contains mixed cases which show up as non-extreme ratings (2,3,or 4). For example, some customers of Hertz pay cash and others by credit card. When these customers are rated on other constructs this information is lost. The interaction is being extended to query the rating of elements that are not at extremes. The user will be given the opportunity to describe the elements in more detail as short case histories (i.e. instantiated case frames) and to

as short case histories (i.e. instantiated case frames) and to add qualifications to these as he construes them in relation to new constructs.

The dependency analysis is also being extended to be interactive so that it may lead to the elicitation of further elements if the system suggests dependencies with which the expert disagrees, or to the modification of ratings if the expert suggests dependencies which are not possible according to the data he has entered. The overall objective is to allow the expert to explore the dimensions of his conceptual structure, testing it against specific cases, and discussing its implications, until he is comfortable that the representation elicited reasonably represents his knowledge.

The system we have described is concerned primarily with the expert's conceptual structure for describing problems. It can also be applied to his conceptual structure for describing solutions or actions, in this case the different forms of record keeping appropriate to different types of business. Rule elicitation then consists of determining the relationship between these two conceptual spaces. This enables the techniques described in this paper to be used to construct complete systems using decision trees or other means to reproduce expertise.

SUMMARY AND CONCLUSIONS

PLANET, an interactive computer aid to expedite the initial stages of knowledge engineering has been described and illustrated through an example. It is based on the personal contruct model of human knowledge acquisition and reasoning that has deep systemic and psychological foundations. PLANET contains a number of sub-programs to do this: PEGASUS elicits from an expert the fundamental distinctions, or constructs, he is using in applying his expertise; SOCIOGRIDS analyses the relationships between members of a group through their differing construct systems and determines consensual constructs; ENTAIL analyses the logical dependencies between constructs and can present these as rules.

A basis for validating the methodology by eliciting knowledge in an area where an optimum structure has already been developed has been presented. An ongoing empirical trial of the techniques in a test case based on the BIAIT analysis of the record-keeping requirements of business enterprises has been described. The initial results show that the spectrum of expertise in the group of subjects used is being re-constructed in the analysis and hence that the methodology shows promise of being valid.

ACKNOWLEDGEMENTS

Financial assistance for this work has been made available by the National Sciences and Engineering Research Council of Canada.

```
--------PATIENT-1--------
(1) Patient's name: (first-last)
**FRED SMITH
(2) Sex:
**MALE
(3) Age:
**55
(4) Have you been able to obtain positive cultures from a site at which
    Fred Smith has an infection?
**YES
  --------INFECTION-1--------
  (5) What is the infection?
  **PRIMARY-BACTEREMIA
  (6) Please give the date and approximate time when signs or symptoms
      of the primary-bacteremia (INFECTION-1) first appeared. (mo/da/yr)
  **MAY 5, 1975
  The most recent culture associated with the primary-bacteremia
  (INFECTION-1) will be referred to as:
    --------CULTURE-1--------
    (7) From what site was the specimen for CULTURE-1 taken?
    **BLOOD
    (8) Please give the date and time when this blood culture (CULTURE-1)
        was obtained. (mo/da/yr)
    **MAY 9, 1975
    The first significant organism from this blood culture (CULTURE-1)
    will be referred to as:
      --------ORGANISM-1--------
      (9) Enter the identity of ORGANISM-1:
      **UNKNOWN
      (10) Is ORGANISM-1 a rod or coccus (etc.):
      **ROD
      (11) The gram stain of ORGANISM-1:
      **GRAMNEG
      (12) Have there been POSITIVE cultures from sites which are NOT
           associated with infections about which you are seeking advice?
      **NO
      (13) Did ORGANISM-1 grow aerobically?
      **YES (8)
      (14) Did ORGANISM-1 grow anaerobically?
      **YES
      (15) What is the suspected portal of entry of ORGANISM-1
           into the sterile site?
      **GI (6)
```

Fig. 1 Some interaction with MYCIN

DENDRAL	structure of chemical compounds from mass-spectral data and knowledge of mass spectrometry
META-DENDRAL	inferring rules of mass spectrometry
MYCIN	diagnosis of blood infections and recommendations for treatment
TEIRESIAS	knowledge acquisition and debugging
EMYCIN	empty (essential) MYCIN expert system shell
PUFF	EMYCIN with knowledge base for pulmonary function disorders
MOLGEN	scientist's assistant for planning experiments in molecular genetics
PROSPECTOR	assisting evaluation of geological prospects
CASNET	diagnosis of glaucoma (eye disease)
XCON	(was called R1) system for configuring VAXs
INTERNIST	advisors for general internal medicine (can deal with symptoms and diagnose 500 diseases)
AM	automated mathematician discovers interesting conjectures in mathematics
CRYSALIS	infers protein structure from electron density maps

Fig. 2 Some well-known expert systems

FUNCTION	NUMBER	DOMAINS
Diagnosis	9	medicine, computer faults, nuclear reactor accidents
Data analysis	8	geology, chemistry, protein crystallography, medicine, oil-well logs
Analysis	5	electrical circuits, naval threat, mechanics, digital circuits, earthquake damage assessment
Design	3	computer system configuration, circuit, chemical synthesis
Planning	10	chemical synthesis, robotics, molecular genetics, medical diagnosis, scheduling
Learning	2	chemistry, heuristics
Concept formation	1	mathematics
Monitoring	1	patient respiration
Computer-aided instruction	9	electronics, mathematics, medical diagnosis, coaching, plant operation
Knowledge acquisition	2	medical diagnosis, geology
Expert system construction	10	medical diagnosis/consultation, electronic diagnosis
Intelligent assistant	7	weapons assignment, medicine, radiology, computer sales, nuclear plant configuration
Management	2	project, automated factory
Automatic programming	7	modelling of oil-well logs
Image understanding	2	understanding images

Fig. 3 Applications of expert systems

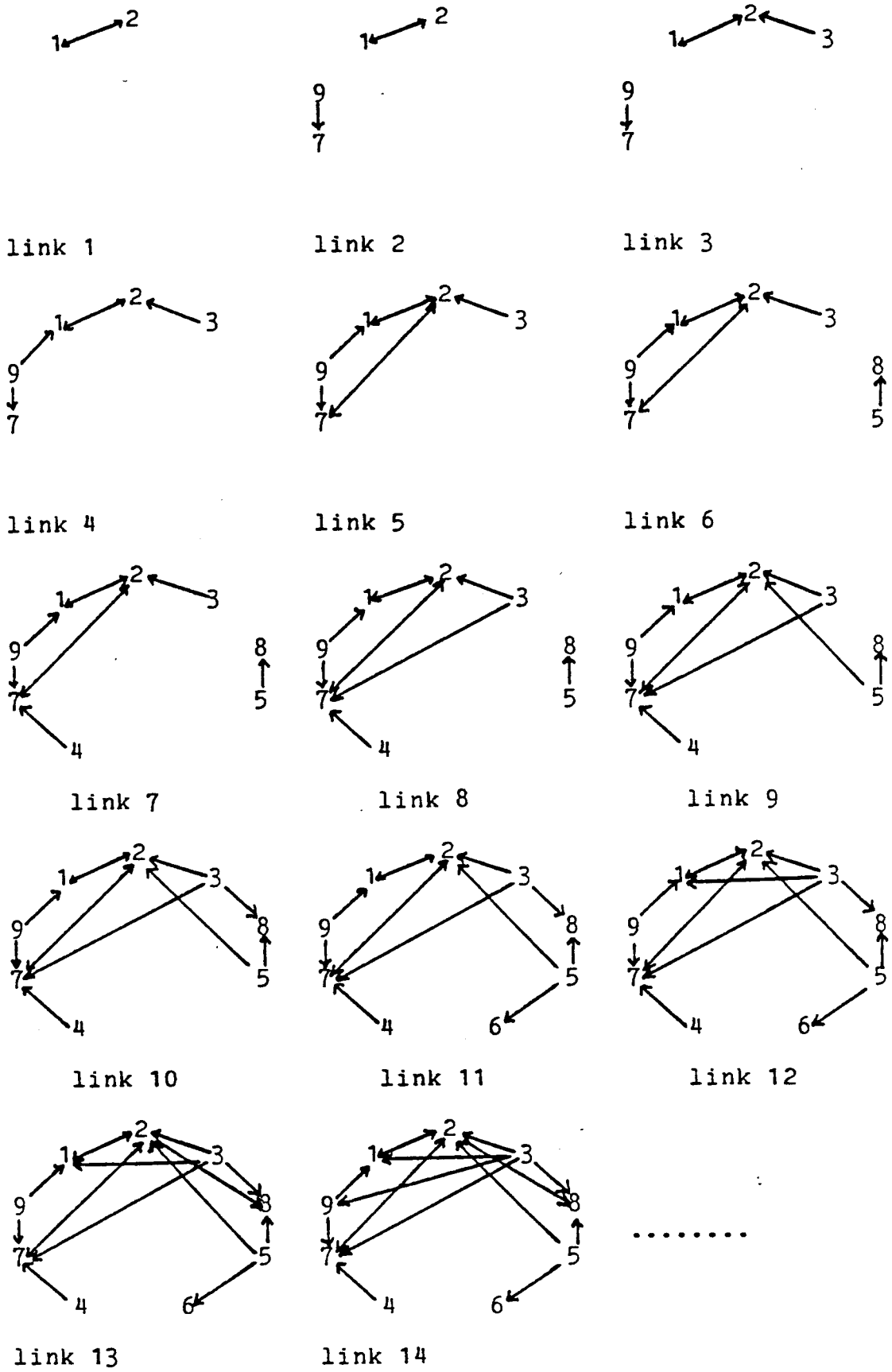

Fig. 4 Series of socionets produced by SOCIOGRIDS

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