ENGINEERING KNOWLEDGE-BASED SYSTEMS: THE TRANSFER OF EXPERTISE

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The problems of knowledge engineering for expert systems, the transfer of expertise from a person to a computer, are discussed. A methodology for automatic, computer-based knowledge elicitation is described in which the system interacts with an expert to enable him to express the constructs underlying his knowledge. Automatic construct elicitation and analysis may be used to pump-prime an expert system shell with initial rules that are derived from an expert. The system can then be further developed using the techniques of the shell itself. The techniques described are useful for eliciting the expert vocabulary and aiding the expert in coming to structure the knowledge domain.

Knowledge Engineering

The initial success of expert system (ES) developments [7,11] and the development of a number of reasonably domain-independent software support systems for the encoding and application of knowledge has opened up the possibility of widespread usage of ESs. In particular, the Fifth Generation Computing System development program [3,10] assumes this will happen and is targeted on knowledge processing rather than information processing. However, **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 ESs.

The problems of knowledge engineering are:

"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." [8]

This paper is concerned with interactive computer aids to the knowledge engineer based on Kelly's [9] **Personal Construct Psychology** (PCP) which uses a model of the person that has strong systemic and psychological foundations [4,15]. PCP provides a model of human knowledge representation, acquisition and processing that has been made operational through computer programs for interactive knowledge elicitation [12,14]. 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 [5,12] 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 have been described [17] to validate the use of PEGASUS 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 [19].

Personal Construct Psychology

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

"transparent templets which he creates and then attempts to fit over the realities of which the world is composed." [9]

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." [9]

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** [12] 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 ESs 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 [18]; to study processes of knowledge acquisition in education [13]; and to study decision making by individuals and groups in management [12]. PLANET [14] is an integrated suite of programs that 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 [13], and the present paper describes their application to knowledge engineering for ESs.

PLANET: A Knowledge Engineering System

PLANET (Personal Learning, Analysis, Negotiation & Elicitation Techniques) is a suite of interactive computer programs for knowledge engineering [14]. 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 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

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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. It can also provide rules for input to an ES shell [1,6].

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. **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.

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 as shown. Note that in the dialog the computer output is shown in normal face and the human input in **bold:**

What is your purpose for this grid?**staff appraisal**

Name six elements.

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?**S1**
Element 2?**S2**
Element 3?**S3**
Element 4?**S4**
Element 5?**S5**
Element 6?**S6**

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

Triad for elicitation of construct 1
1 S1
2 S2
3 S3

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?**3**

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 S1 and S2 on the left pole from S3 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 --?**intelligent**
right pole rated 5 --?**dim**

Now assume that S1 and S2 are assigned the value 1 and S3 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

1 S1 1
2 S2 1
3 S3 5
4 S4 ?**5**
5 S5 ?**3**
6 S6 ?**3**
7 S7 ?**5**
8 S8 ?**2**
9 S9 ?**3**

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

The two elements 5 S5 and 6 S6 are matched at the 90 percent level. This means that so far you have not distinguished between S5 and S6

Do you want to split these?**y**

Think of a construct which separates these two elements, with S5 on the left pole and S6 on the right pole.

left pole rated 1 --?**self starters**
right pole rated 5 --?**need a push**

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

5 S5 1
6 S6 5
1 S1 ?**2**
2 S2 ?**1**
3 S3 ?**5**
4 S4 ?**5**
7 S7 ?**5**
8 S8 ?**3**
9 S9 ?**4**
10 S10 ?**5**

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
1 intelligent -- dim
4 little supervision reqd -- need supervision
are matched at the 66 percent level

This means that most of the time you are saying intelligent you are also saying little supervision reqd and most of the time you are saying dim you are also saying need supervision. Think of another element which is either intelligent and need supervision or little supervision reqd and dim. 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

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value from 1 to 5

What is your element?S10

Type in the ratings for this element on each construct.
Left pole rated 1, right pole rated 5.

   intelligent -- dim?5
   willing -- unwilling?2
   new boy -- old sweats?3
   little supervision reqd -- need supervision?3
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Through a combination of triadic comparison, element matching, and construct matching a PEGASUS interaction elicits from the user his system of constructs relating to the topic being studied. Figure 1 is the final grid of the manager.

ENTAIL in Action

ENTAIL [5,6,16] gives a dependency analysis of the grid by listing logical entailments consistent with the data. 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.

		1	2	3	4	5	6	7	8	9	10		
intelligent	1	1	1	4	5	3	3	5	2	3	5	1	dim
willing	2	1	2	4	5	1	1	4	3	1	2	2	unwilling
new boy	3	1	2	3	5	4	4	4	1	4	3	3	old sweats
little supervision reqd	4	3	1	4	5	2	1	5	2	2	3	4	need supervision
motivated	5	1	1	4	5	2	2	5	3	3	2	5	less motivated
reliable	6	3	2	2	5	1	1	5	1	2	3	6	not so reliable
mild	7	3	4	5	2	2	3	1	5	4	5	7	abrasive
ideas men	8	1	1	5	4	2	3	1	3	4	4	8	staid
self starters	9	2	1	5	5	1	3	5	3	4	5	9	need a push
creative	10	1	1	5	5	2	3	4	3	4	5	10	non-creative
helpful	11	4	3	4	2	3	5	1	4	5	5	11	unhelpful
professional	12	1	2	3	3	2	1	5	2	4	4	12	less professional
overall rating high	13	2	1	3	4	1	2	5	2	3	4	13	overall rating low
messers	14	2	2	5	4	3	5	1	5	3	1	14	tidy
		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10		

Fig. 1 PEGASUS repertory grid elicited on staff appraisal

Figure 2 shows the ENTAIL analyis of the grid of Figure 1. The entailments are shown with three values, the first a truth value from 0 to 100 (e.g. L 9 > L 13 truth 100), the second the probability of the hypothesis being true, and the third number is the uncertainty reduction generated by asserting this entailment. All three are in the range from 0 to 100. The uncertainty reduction measures the information carried by the assertion and is used to ensure that trivial entailments consistent with the data are pruned [6].

We quantify the notion of a hypothesis being true "usually" by ascribing a probability to the hypothesis measured by the relative frequency with which it is true. For example, using the data of L9 and L13, L9>L13 has truth value 1 with probability 1; it is always absolutely true. However, L13>L9 is more interesting because it has truth value 0.5 with probability 1, truth value 0.75 with probability 0.9 (fails in one case out of ten), and truth value 1.0 with probability 0.4 (fails in six cases out of ten).

ENTAIL checks for equivalence separately from the check for one-way entailment. This is because the uncertainty reduction from the hypothesis of equivalence, x≡y, cannot be inferred from the separate uncertainty reductions of the logically equivalent pair of hypotheses, x>y and y>x, although it will be at least the sum of these. In order to rank-order the hypotheses the uncertainty reduction for one-sided entailment is doubled for comparison with that of two-sided equivalence.

The entailments derived by ENTAIL can be converted directly to rules that may be loaded into a standard EF shell as Boose [1] has shown. The truth value of the rule codes into the truth value representation used by the shell. The rules may be checked by the expert for their content but their prior evaluation for uncertainty reduction makes it unlikely that spurious rules will be generated. The rules form a decision tree expressing the relationship between an expert's data and his conclusions, both personally expressed. For example, the data of Figure 1 may be regarded as that of an expert on staff appraisal concerned with deriving his "overall rating" (construct 13) from behavioral assessments such as "intelligent" and "creative". The ENTAIL analysis of Figure 11 shows that L1, L4, L6, L8, L10 and L12 imply L13, that intelligent, creative, reliable and professional self-starters requiring little supervision receive a high overall rating, whereas L2, L4, L5, L6, L9 and L12 imply L13, that being unwilling, less motivated, not so reliable, less professional, needing supervision and needing a push leads to a low overall rating.

Entail	Truth	Prob.	Information (Cutoff 35)
L 9 > L13	100	100	59 self starters > overall rating high
L 1 > L 9	75	100	58 intelligent > self starters
L10 > L 8	100	100	57 creative > ideas men
R 9 > R 1	75	100	56 need a push > dim
L 1 > L10	75	100	52 intelligent > creative
R 8 > R10	100	100	52 staid > non-creative
R13 > R 6	75	100	52 overall rating low > not so reliable
L10 > L 9	75	100	51 creative > self starters
R10 > R 1	75	100	49 non-creative > dim
L 9 > L10	75	100	47 self starters > creative
L10 ≡ L 1	75	100	47 creative ≡ intelligent
R 1 ≡ R10	75	100	47 dim ≡ non-creative
R 9 ≡ R10	75	100	47 need a push ≡ non-creative
R13 > R 9	100	100	46 overall rating low > need a push
R 4 > R13	75	100	44 need supervision > overall rating low
R 5 > R 4	75	100	44 less motivated > need supervision
R 5 > R13	75	100	44 less motivated > overall rating low
L 1 > L 3	75	100	42 intelligent > new boy
L 6 > L13	75	100	42 reliable > overall rating high
L 4 ≡ L13	75	100	39 little supervision reqd ≡ overall rating high
L13 ≡ L 6	75	100	39 overall rating high ≡ reliable
R 1 > R 6	50	100	39 dim > not so reliable
R 6 ≡ R13	75	100	39 not so reliable ≡ overall rating low
R13 ≡ R 4	75	100	39 overall rating low ≡ need supervision
R12 > R13	75	100	38 less professional > overall rating low
R13 > R12	75	100	38 overall rating low > less professional
L 8 ≡ L10	100	70	37 ideas men ≡ creative
R 9 > R 4	50	100	37 need a push > need supervision
R 9 > R12	50	100	37 need a push > less professional
R 9 > R13	50	100	37 need a push > overall rating low
R10 ≡ R 8	100	70	37 non-creative ≡ staid
L 4 > L 5	75	100	36 little supervision reqd > motivated
L 4 > L 9	50	100	36 little supervision reqd > self starters
L12 > L 9	50	100	36 professional > self starters
L12 ≡ L13	75	100	36 professional ≡ overall rating high
L13 > L 5	75	100	36 overall rating high > motivated
L13 > L 9	50	100	36 overall rating high > self starters
R 2 > R 4	75	100	35 unwilling > need supervision
R 2 > R 5	75	100	35 unwilling > less motivated
R 2 > R13	75	100	35 unwilling > overall rating low
R 3 > R 1	75	100	35 old sweats > dim

Fig. 2 Entailment Analysis of Repertory Grid on Staff Appraisal

Summary

PLANET is an interactive computer aid to expedite the initial stages of knowledge engineering. PLANET is based on the personal contruct model of human knowledge acquisition and reasoning that has deep systemic and psychological foundations. Kelly's personal construct psychology identifies the system of construction being used by an expert as fundamental to his thought processes. Within PLANET, PEGASUS elicits from an expert the fundamental distinctions, or constructs, he is using in applying his expertise. ENTAIL analyses the logical dependencies between constructs and can be used to develop rules for an ES shell. SOCIOGRIDS analyses the relations between experts and can be used to develop consensual construct systems. The programs and methodology have been widely used since 1978 not only for expert system development but also for a wide variety of knowledge elicitation studies in management. Boose has implemented a related system, **ETS**, on a LISP machine and produced over two hundred expert in an industrial environment [1]. In situations where it is applicable the methodology can save at least two months of project calendar time, and decision support systems can be prototyped in a few hours.

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