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A Brief Account of Work on Adaptive Teaching and Measuring Systems

GORDON PASK

Teaching contains both an information part and control part. The efficient control of human learning can be obtained only by using an adaptive system which is able to change the course and the level of teaching according to the successes of learning subjects.

1. INTRODUCTORY COMMENTS

The work on adaptive teaching systems carried out at our laboratory started in 1954 and has continued with only minor interruptions until the present. Within this interval a fairly large number of different adaptive teaching and training devices have been fabricated, most of them with industrial training applications. The bias attached to our activity has gradually changed, in the first place to favour investigations of the general character of the learning and teaching process, and next, to emphasise the general form of adaptively controlled man/machine interaction (of which "teaching" is an important but particular case). Consequently, most of the work in progress at the moment involves "laboratory" skills which are superficially divorced from real life situations (but which satisfy the usual requirements for effective experimentation, for example, the requirement that a student can become proficient at performing the job within the few hours allocated to a single experimental test).

It is no accident that most of our data stems from laboratory situations. In the laboratory, a skill can be isolated and learned to an arbitrary criterion of proficiency, an individual subject can be identified and continually observed and it is easy to compare laboratory situations that differ in respect to only one, or only a few important properties. In industry, on the other hand, all of these observations are difficult in one way or another. Further, it must be recognised that an adaptive teaching system is only one component that requires integrating into the entire industrial teaching or training programme. The method of integration is undoubtedly important but it seems impossible either to discuss it or to account for its effects upon group measurements until more is known about the isolated adaptive teaching system.

Different designs of adaptive teaching device are simulated by programmes for the special purpose computor shown in Fig. 1. This device can be connected to display facilities and response facilities pertinent to the skill concerned.

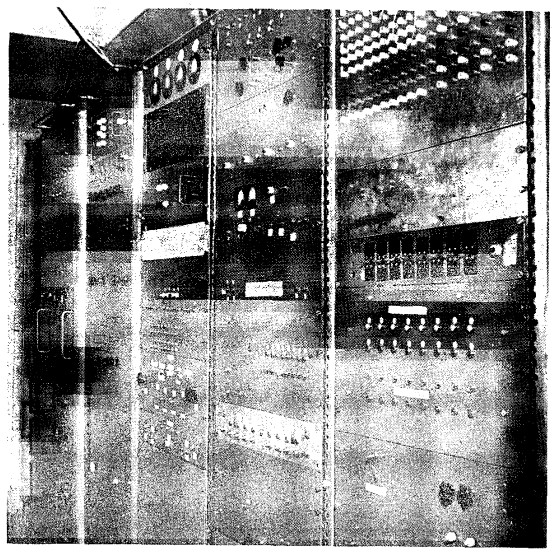

Fig. 1.

2. CYBERNETIC APPROACH

From a Cybernetic point of view, teaching is a form of control, namely, control of a learning process. So far as we are immediately concerned the learning process will take place in a human being (rather than an animal or a machine).

If we enquire "What sort of interaction typically acts upon and modifies human learning" (or "what is a suitable exemplar or paradigm case") the reply is surely a *conversation,* possibly the rather specialised conversation known as a *tutorial.* Hence, if we intend to build a control mechanism that is able to teach, or, what amounts to the same thing, if we aim to specify a control algorithm for teaching, then we must, in the first place, establish conditions in which conversation with a man can occur. Later, as a specialisation of these conditions, it may be possible to build up a tutorial relationship with reference to the student.

These comments are intended in a literal sense, not as a collection of convenient metaphors. They express the conviction that the logical principles that constrain the interaction between a student and an instructor are the principles of a conversation (which allow for the evolution of systems and the development of concepts) rather than those of "communication" (at any rate, in the technical sence of "communication").

3. THE DISCOURSE

The conversation between a student and an instructor need not be verbal. Spoken words can be replaced by symbols that are more readily detected by mechanical devices. Thus the teaching machine can select visual symbols, such as collections of signal lamps, and the student can respond by selecting one out of several possible response buttons. The change of modality, from verbal discourse to sign displaying and button pressing discourse, is unimportant. However, it is important that whatever modality is chosen should possess the same capabilities as a natural language at any rate with reference to whatever universe of discourse is entailed by the relevant skill.

In particular, the stimuli produced by the real life or mechanical instructor must denote *problems* which may or may not be *simplified* or partially solved, the responses must denote *solutions* (to problems or simplified problems) and a form of acceptable solution or goal must be specified. These requirements seem trite and possibly trivial since everybody pays lip service to similar conditions. In view of this I would like to stress that *unless* these requirements are taken seriously (and this may lead to all manner of difficulties), it is not even possible to embark upon the construction of a logically respectable model for teaching. To show the cogency of this pronouncement it is possible to rephrase the problem and solution requirement as a stipulation that the student is presented with situations in which he can act as a control system aiming to achieve the goal of providing acceptable solutions. Another feature of natural language that must be preserved in the chosen modality of discourse is the possibility of designating the level of discourse. In everyday discussion we achieve level designation by using statements like "I mean A to be interpreted as an instruction" or "I mean B to be interpreted as a problem" where A and B are phrases in the everyday language.

Now it may be very difficult to embody this open endedness in a formal language (such as the language of stimuli denoting problems and response selections denoting solutions to problems). In particular, if (as later) we are using the system for measurement as well as instruction, it may be undesirable to admit level designation within the formal language of the experiment or teaching situation, since the existence of level designation can be shown to introduce a form of ambiguity which is harmless, indeed is beneficial, in discourse but which cannot be admitted in a system of measurement. If so, the flexibility of a natural language and the level designating facility of a natural language, must be replaced by a more elaborate structure of formal languages in which each level of discourse is represented by one member from an hierarchy of formal languages. In such a system an *instruction* is kept distinct from a problem denoting *stimulus* because instructions are selected from the alphabet of a higher order formal language and stimuli are selected from the distinct alphabet of a lower order formal language. In the experimental or teaching situation these alphabets correspond, physically, to distinct display and response arrangements.

4. STUDENT MODEL

In order to design a mechanism (or to specify an algorithm) for maintaining conversation with a man we need some model for man. One model, (which we have used often and which is compatible with the conversational role of the student) represents a man as a system that needs to learn. To be more exact, we pose the hypothesis that man is a self-organising system, in the sense of von Foerster, given certain restrictions that are outlined in previous theoretical papers. Once again this stipulation is intended in its literal sense. It implies, in the first place, that man is so constructed that he must maintain a certain rate of *adaptation*. If this is to be relevant and goal directed adaptation (which is presumably desirable if we aim to teach the man) then our machine or algorithm must provide sufficient novelty for the man to learn *about*. It is not difficult to argue that this condition can be satisfied if and only if the student is presented with problems that are intelligible but sufficiently "difficult" to occupy his interest and attention (the term "difficult" is to be understood as "unsimplified" in the sense that "simplified" was used a moment ago). Since the required level of difficulty or unsimplification changes as goal directed adaptation takes place it is necessary to measure the student's proficiency and to modulate the difficulty of the problems that are posed as a function of this measurement.

The next implication of our postulate that a man needs to learn is that, over and above maintaining a certain rate of adaptation, he forms concepts that represent classes of lower level organisations (if he did not form an hierarchy of concepts we need only say "man adapts" rather than "man learns"). This image of learning is common enough in the literature although it receives different names from different authors (development of a higher signalling system – Pavlov; development of a TOTE hierarchy – Miller, Gallanter and Pribram; the development of levels of grouping – Piaget; the development of a semantic structure – Vygotsky; the development of schemata - Bartlett and Hebb) to cite only a few of them. It is manifest as an organisation of perceptual motor groupings into more elaborate selective structures in such manual skills as typewriting and as an organisation of analogy relations in the domain of intellectual skills. For the present discussion, we need only comment that in order to act upon or modify a given level of concept in the student we must have access to expressions in the corresponding level of discourse, or, if levels of discourse are represented by an hierarchy of formal languages, access to the corresponding level in this hierarchy of formal languages.

5. ADAPTIVE SYSTEM

Now it is not too difficult to show that if we accept this model of man as a self-organising system, then the least elaborate machine able to control the learning

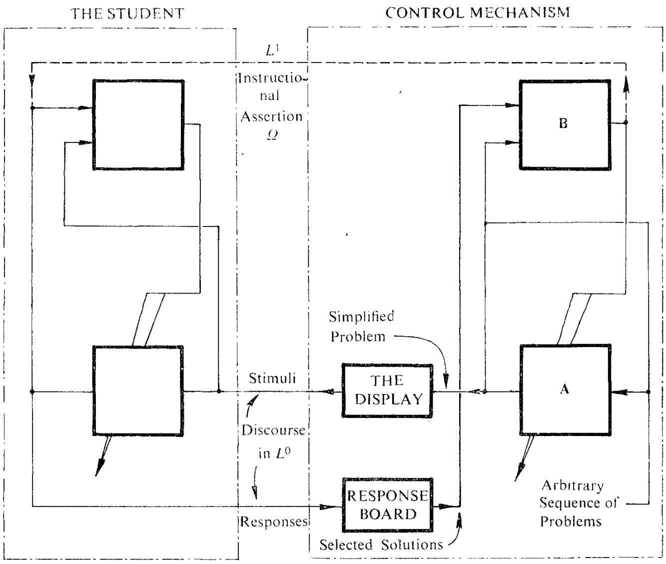

Fig. 2.

process in man (to the extent of maintaining conversational interaction) is an hierarchically organised adaptive control mechanism in the theoretical sense of Mesarovic or Tarjan. If the discourse involves a skill that is reducible (by the TOTE procedure, where applicable, or by one of the procedures cited, for example, in our theoretical publications) to an m-th level conceptual structure, then the minimal hierarchically organised adaptive control mechanism will have $m + 1$ levels.

The lowest order other than trivial system is the first order adaptive control system shown in Fig. 2 where the learning process in the student is also imaged as an hierarchically organised adaptive control system. In Fig. 2 the experimental control mechanism consits, apart from the display and response board, of boxes labelled A and B. Of these A receives an arbitrary and pre-determined sequence of problems of a given class and simplifies these (to form simplified problems) to a degree, μ, determined by the box A. The possibly simplified problems are represented by the stimuli that denote them in the display. This control mechanism also receives response selections from the subject, through the response board. These denote solutions to problems and are compared in B with the immediately presented problem according to a correct solution rule Ω that specifies the goal or objective of the skill (to achieve solutions of a class that are acceptable given Ω). The box B computes an average measure of correct response rate, say a measure ϱ and it is informed of the present value of μ. It determines the next value of μ according to a strategy like

> Minimise μ given that the rate of change of ϱ
> is not negative and that if there is no decrease
> in μ the rate of change of ϱ is positive

Strategies of this type can be shown to maintain conversational interaction in the sense of the present discussion and they also have the property of minimising the degree of co-operative assistance given to the student by simplifying or partically solving the problems he is required to solve contingent upon a positive rate of learning. Insofar as we deem a student who is able to solve more difficult problems a more proficient student, these strategies can be held to maximise the rate of learning in a first order system (and thus to be adequate teaching procedures for a first order system).

The discourse in a first order system takes place in L^0 (the lowest level of discourse denoting stimuli and responses or problems and solutions to these problems).

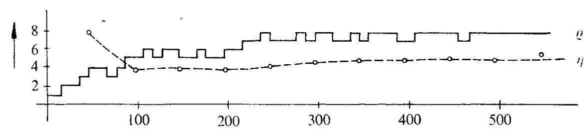

Fig. 3. ($\eta = \mu_{max} - \mu$)

However, even here, there is an initial statement of the goal, Ω, which is an assertion at a higher level of discourse L^1 and there may be knowledge of results data which is also a statement in L^1. The important point is that the L^1 statements in a simple adaptive teaching system of this sort are made by the machine and there are no L^1 replies from the student.

A typical learning curve for a first order adaptively stabilised teaching system is shown in Fig. 3. The data in Fig. 3 is gleaned from a perceptual motor skill and the difficulty function $\eta = \mu_{max} - \mu$ is represented, in place of μ, for convenience.

The construction of higher order teaching systems entails the iteration of the arguments we have already outlined and yields structures of the sort shown in Fig. 4

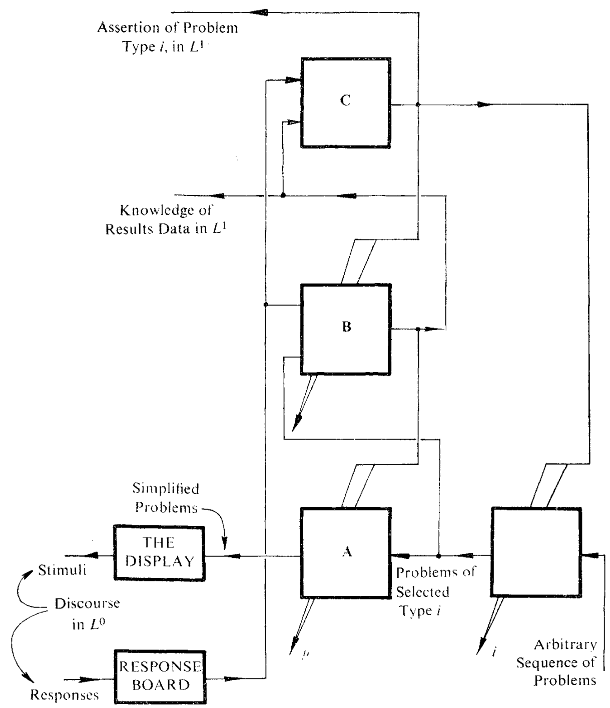

Fig. 4.

(the subject model is omitted). Boxes A and B perform the functions we have already discribed. Box C computes some property of the first order system and selects a type of problem or a subskill of the skill for rehearsal (the definition of a problem type rests upon the class of algorithmic processes allowed in solving the problem. But if we changed the rule Ω_i for different values of $i = 1, 2, \ldots, n$ we should certainly change the problem type). Suppose, in this case, that $i = 1$ or 2 and that there are consequently a pair of rules Ω_1 and Ω_2 that the subject may be asked to apply to the problems that he is posed. Box C may compute the product of η_1 and η_2 (or the product of $\mu_{max} - \mu_1$ and $\mu_{max} - \mu_2$) and adjust the length of trial blocks in which the application of Ω_1 and Ω_2 is rehearsed to maximise this product (this strategy involves rehearsing most often the subskill for which the value of η_i is lowest).

7. SOME DATA

The data in Table 1 shows some comparative results, in terms of number of trials, T, needed to reach a criterion performance, for the skill of speed reading. The adaptive condition in Table 1 is achieved by instructing the student with an adaptive control mechanism of the sort shown in Fig. 4, the level of difficulty η_i being interpreted as the rate of scanning of the scanning aperture that exposes the material and i being interpreted as the type of data to which the student is asked to attend before each block of exposures of reading material (in the arrangement used in these experiments the student is automatically, tested on his appreciation of i = "numerical data" or of i = "sequential data" after any block).

The relative efficiency of an adaptive teaching system is exhibited, in terms of T, in Table 2. The data in Table 2 stems from a perceptual motor skill involving the application of one or another of transformation rules Ω_1 or Ω_2 to groups of illuminated lamps (the subject indicates his response by pressing groups of response buttons within an interval of $\Delta t = 4$ secs after the presentation of a stimulus).

In condition A the student is instructed by the adaptive control mechanism in Fig. 4. In condition B the device of Fig. 4 is degraded or decomposed by replacing Box B with a chance mechanism that selects $i = 1$ or $i = 2$ with equal likelihood and independently of the behaviour of the student. In the same way the data for Condition C is obtained from a system in which the adaptive control mechanism is further degraded or decomposed by replacing Box B by an arbitrary incrementing procedure that is independent of (the immediate) behaviour of the student.

8. PARTICIPANT INTERACTION

Consider a simple first order teaching system of the sort we have discussed. Although, for most subjects, the interaction is *stable* (in the sense that the first order adaptive control mechanism can compensate for any change in ϱ by a corresponding change in η or in μ) there are a few subjects for whom this is *not* the case. An oscillatory or fluctuating η value replaces the steadily increasing η of any stabilised system.

If data from these few aberrent subjects is more carefully examined, the instability can (so far always) be accounted for in terms of a misuse or an illegal usage of L^0. According to legal usage, response selections in L^0 denote solutions to problems.

Table 1.

Comparison of Conditions for Speed Reading Skill

Experimental Series 1 Total Correct Responses per Session		Experimental Series 2 Mean Terminal Reading Time	
(Adaptive) Condition A	(Non-adaptive) Condition B	(Adaptive) Condition C	(Non-adaptive) Condition D
21	17	29	28
23	18	29	32
27	18	31	34
28	19	32	34
30	22	33	35
30	22	34	37
31	24	34	39
32	26	34	39
33	26	35	39
24	27	36	40
34	27	36	41
34	27	36	41
36	29	36	43
37	32	38	43
38	35	38	44
39	35	39	45
41	37	40	47
41	38	40	47
42	38	43	49
44	41	45	49
$\bar{x} = 33{\cdot}75$	27·90	35·90	40·30
For the above data, student's $t = 2{\cdot}6$. With 38 d.f. this value exceeds the 2% level of significance ($p < 0{\cdot}02$)		For the above data, student's $t = 2{\cdot}7$. With 38 d.f. this value exceeds the 1% level of significance ($p < 0{\cdot}01$)	

Conditions A (*Adaptive*): Reading time increased or decreased according to score on previous comprehension tests.

Conditions B (*Non-adaptive*): Reading time systematically reduced by 2 seconds per trial to a terminal allowance, after 16 trials, of 36 seconds (36 seconds being the mean terminal allowance achieved in Condition A).

Condition C (*Adaptive*): Two types of material (for training subjects to comprehend numerical and non-numerical data) presented in anorder determined by subject's success on comprehension tests.

Condition D (*Non-Adaptive*): Two types of material presented in alternate blocks of four, irrespective of subject's performance score.

Table 2.

Values of T obtained in Conditions A, B, & C

T_A	T_B	T_C
150	180	130
170	210	140
190	220	150
190	230	190
220	250	240
220	270	290
250	310	320
260	330	320
260	350	360
270	350	390
290	370	430
290	370	450
300	390	470
310	410	490
310	420	500
330	440	510
360	460	510
380	460	530
440	470	570
Sums 5480	6860	7420
Mean 274	343	371

Jonckhere's Trend test has been applied to these data to test the hypothesis that $T_C > T_B > T_A$. If, in the ranked comparison entailed by this test, "tied" values are counted as $\frac{1}{2}$, the "Ties $\frac{1}{2}$" figure applies. If ties are "broken" in favour of the null hypothesis of no trend, the "broken" figure applies.

For $T_C > T_B > T_A$ the test variables $S/\sigma = 2{\cdot}73$ (ties $\frac{1}{2}$)
$= 2{\cdot}62$ (broken).

In each case the null hypothesis of no trend can be rejected at the 0·5% level since these values each exceed 2·57.

The instability in systems involving aberrant subjects is due to sequences of mistakes that appear to be *deliberate* and (since these mistake sequences are correlated with subsequent changes in η or μ) that appear to be introduced in order to change the mode of instruction. Thus they do not denote mistaken solutions. They are not, in fact, *mistakes.* They are an attempt to "talk to" the adaptive control mechanism in a fashion that is not allowed by L^0 legality.

This impression is confirmed by introspective comments. The subjects say that they "become involved" with the adaptive device. Further, we should predict that this mode of *participant* interaction would be inhibited by any modification of the system that reduced the possibility of correlating sequences of actions with a sub-

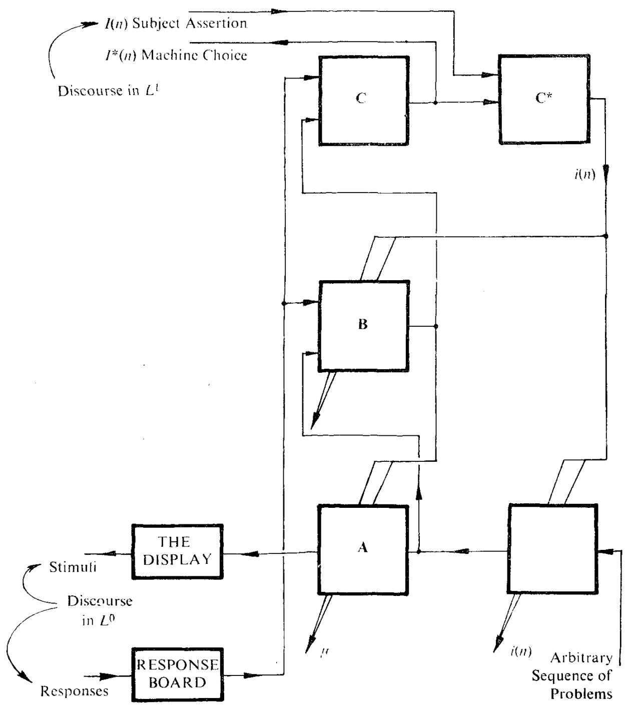

Fig. 5.

sequent change in the value of η or of μ (and it has been found that participant interaction *can* be inhibited either by interpolating a chance event into the feedback loop or by interpolating a delay into the feedback loop).

Participant interaction is more often evident in higher order system (for some skills, about 30% of the subjects may indulge in this mode of interaction). However, it can be inhibited by either of the expedients mentioned a moment ago.

Unfortunately, when participant interaction is inhibited in a higher order system, the system often becomes crassly instable for a variety of other reasons, all of which indicate the inadequacy of the simple strategies we have so far examined. Consequently we are led to consider the possibility of adaptive systems called "Metasystems" in which the L^0 illegal statements of participant interaction are definitely encouraged by the provision of an L^1 response facility in which these statements are L^1 legal. The least elaborate metasystem is illustrated in Fig. 5. In contrast to the previously described arrangements the subject can respond or *reply* in L^1 to the extent of asserting his preference for one mode of instruction or another. The component C* in Fig. 5 computes an indication $\Theta(n)$ of success at the n-th trial of the form

$$\Theta(n) = \frac{1}{\tau} \sum_{n,n-\tau} \sum_{i} \eta_i(n) \cdot \varrho_i(n)$$

satisfying the conditions

$$1 \geqq \Theta(n) \geqq 0 \,, \quad \Theta(0) = 0 \,, \quad \Theta(T) = 1$$

and, if the subject prefers $i(n) = I(n)$ at the n-th trial and component C selects $i(n) = I^*(n)$ then the value of $i(n) = I(n)$ in chosen with a weight (or for some systems with a probability) of $\Theta(n)$ and the converse value selections of $i(n) = I^*(n)$ is chosen with a weight or probability $1 - \Theta(n)$. Thus the student is allowed to control the manner of instruction at the n-th trial to a degree that depends upon his success at this n-th trial (initially, as a novice and at $n = 0$, he is allowed no control and when, at $n = T$ he is proficient, he is allowed complete control). Recent data indicates that adaptive metasystems provide more *effective* instruction than simple adaptive teaching systems and they certainly induce more *rapid* learning for a number of skills.

10. OTHER APPLICATIONS

In conclusion we comment that the technique of adaptively stabilising the experimental conditions is not restricted to teaching (although, as we have argued, certain stabilising strategies are also teaching strategies). We have used adaptively stabilised systems in order to make approximately stationary state measurements of various parameters of the subject (on the principle that a stationary state measuring condition is approximated insofar as the adaptive control mechanism *compensates* for changes that are due to learning on the part of the subject).

Indeed, with some restrictions, this stabilisation maintains a constancy of *relation* between the subject and the experimenter. This constancy is the essential pre-requisite for measurement in psychology and conventional techniques often fail to achieve it.

Hence, with due attention to the rather restricted set of situations in which adaptive stabilisation can be used, it is not unreasonable to suppose that it constitues a novel experimental method.

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VÝTAH

Stručné sdělení o systému adaptivní výuky a jejím měření

GORDON PASK

Vyučování lze chápat jako zvláštní interakci mezi vyučujícím a učícím se jedincem, jejíž podstatu tvoří výuková konverzace. Nemusí být verbální. Mluvené slovo v ní může být nahrazeno jazykem symbolů, signálů a jednoduchých operací. Funkci stimulu v ní přejímá problém, funkci odpovědi má řešení tohoto problému. Výuková konverzace, jako každá jiná, může začít pouze tehdy, jsou-li na ní obě strany stejně zainteresovány. Zkušenost však ukazuje, že člověk není vždy soustava, která má potřebu učit se. Většinou je nutno tuto potřebu vyvolat. Dosahuje se toho tím, že se učení změní ve zcela osobní, částečně konkurenční a částečně kooperativní hru mezi učitelem a žákem. Tedy v jakousi hru o vědomosti a dovednosti s pevně stanovenými pravidly soutěže a spolupráce a s pevně stanoveným cílem naučit. Funkce učitele v ní spočívá v tom, že musí se žákem soutěžit tím, že mu dává různě těžké úkoly. Zároveň však musí sledovat jeho počínání a v případě žákova neúspěchu změnit soutěž ve spolupráci a pomoc. Úloha žáka spočívá v tom, že řeší předložené úlohy. Přitom však rovněž sleduje svého spoluhráče – učitele s cílem, postihnout jeho požadavky a co tyto požadavky uspokojuje. Učitel a žák tvoří tedy složitý adaptivní systém, jejž lze modelovat na kybernetickém zařízení. Jde o složité vyučovací stroje, schopné zachytit pravděpodobnostní charakteristiky žákova výkonu a podle nich zvolit strategii učení, odpovídající žákovým možnostem a předpokladům. Podle hladiny výukové konverzace, již umožňují, že dělí na systémy prvního až i-tého řádu. Za nejefektivnější z hlediska pedagogických cílů lze považovat adaptivní metasystémy, umožňující podle ukazatelů úspěšnosti přecházet z jedné hladiny konverzace do druhé. Tyto systémy tedy nejen učí, ale zároveň poskytují subjektu učení také možnosti ovlivňovat úspěšností svého počínání způsob a postup učení.

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