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The nature and role of hypotheses in school science investigations

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Investigations form an integral and significant part of school science activities. The creation of hypotheses is an essential part of any scientific investigation, but no coherent concept of hypothesis can be derived from the current literature of science education. By focusing on the role of hypotheses as tentative solutions to problems, a basic concept of hypothesis is proposed. This is developed and differentiated in relation to the different kinds of knowledge which science education seeks to promote. It is argued that recognizing different kinds of hypothesis in this way can help to clarify both the aims and the methods of scientific investigation in schools.

Introduction

Practical work carried out by pupils at first hand has a long history as part of science education (see Layton 1973). Within the whole spectrum of practical work in school science, a number of different groups of activities can usefully be identified. A recent inservice resource package (NCC 1991), for example, identified four such groups: basic skills, observations, illustrative work and investigative work. First-hand investigations as part of the educative process give pupils the opportunity to use both creativity and critical thought, often together with practical and observational skills, to solve a problem or find an answer to a question.

The essential feature of effective investigation is not that pupils work only on problems or questions raised by themselves, since it may at times be much more effective for the teacher to suggest the focus for an investigation, but rather that they develop and validate their own solutions. As Driver (1983: 81) points out, the

> ...case for including opportunities for pupils to undertake their own investigations [is] not in order to establish an important principle, but to gain some experience of planning an experiment using their own initiative.... These experimental exercises offer an opportunity to encourage individual initiative and imagination.

One activity of central importance in any scientific investigation, which always requires individual initiative and imagination, is the making of hypotheses. The National Curriculum in Science, established in England and Wales in 1988, as revised in 1991 (DES 1991, p. 3) requires that

> ...pupils should develop the intellectual and practical skills that allow them to explore the world of science and to develop a fuller understanding...of the procedures of scientific exploration.... This work should take place in the context of activities that...encourage the ability to... hypothesise and predict.

This requirement that pupils should develop the ability to hypothesize and predict has a direct effect on science teaching only in England and Wales, but focuses

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attention on a general problem which has been in the background of science education for many years: there is no effective and generally accepted concept of hypothesis in relation to the investigative work which pupils undertake in schools.

To play an effective part in the development of science education, any concept of hypothesis must satisfy three criteria. First, it must make clear the nature of hypotheses and their role in scientific investigation. Second, it must enable teachers to recognize hypotheses and the opportunities for making and using them. Third, it must help teachers to develop an understanding of hypotheses in relation to the whole range of investigative work which is undertaken as part of school science.

Concepts of hypothesis currently used in science education

In recent literature of science education, concepts of 'hypothesis' fall into three groups, corresponding to the kind of hypothetical statement being considered, whether explanatory, predictive or descriptive.

The concept of hypothesis most widely used in recent writing on science education is that of *hypothesis-as-explanation*, by which a cause is proposed for an observed effect. 'Hypothesis' is written of in this sense not only by philosophers of science (for example, Hempel 1966, p. 5, Popper 1972, p. 46) but also by many writers on science in school (Ennever and Harlen 1972, p. 5, UNESCO 1980, p. 30, Driver 1983, p. 63, Harlen 1985, p. 31, Millar and Driver 1987, p. 44, Millar 1989, p. 56, Jarvis 1991, pp. 46, 62, 137). This concept of hypothesis has been simply summarized for teachers, in the context of the Standard Attainment Tests carried out by all seven-year-old children in England and Wales in 1991 (SEAC 1990, p. 25), as 'a reasoned explanation of why they think something has happened or will happen... an "I think... because" statement'. In the same set of criteria, 'hypothesis' is clearly distinguished from 'prediction', which is characterized as 'a simple "What I think will happen" statement'.

Gilbert and Matthews (1986, p. 9), however, base their primary science work programme on a different concept of hypothesis, which contradicts the SEAC criteria. They refer to 'suggesting explanations and making predictions (hypotheses)', taking the view that predictions are hypotheses, whereas suggested explanations are not. The concept of *hypothesis-as-prediction* is also to be found in UNESCO (1980, p. 30), which gives 'Birds will not eat chenille worms' as an example, and in the National Curriculum for England and Wales (DES 1989, p. 3) where the *only* example of hypothesis given is 'This ball will bounce higher that that one'. The latter is significant as an example of the ambiguity currently surrounding the term 'hypothesis' in education, since, if the assessment criteria of the relevant national tests were followed (SEAC 1990, p. 25), it would not be regarded as a hypothesis but as a prediction.

A third kind of hypothesis also appears in the UNESCO *Handbook* (UNESCO 1980, p. 30). This takes the form of a simple statement of what is supposed to be the case; the example being 'Fertilizer X is good for growing gungo peas', which neither explains nor, in this form, directly predicts anything. This is what Westaway (1931, p. 241) terms a *descriptive hypothesis*. Hypotheses of this kind may be called for in school-based investigations, for example 'Woodlice prefer damp, dark conditions' (Monger and Tilstone 1974, p. 11), and 'Salamanders return each year to their native stream' (Mayer 1978, p. 183). They are also quoted in educational material as examples of the development of science and its interaction with society, for example by Monger and Tilstone (1974, p. 186) who discuss, as an example of a hypothesis, Jenner's conjecture that infection with cow-pox confers immunity from smallpox.

Descriptive hypotheses also appear in the proposed revision of science in the National Curriculum for England and Wales (DES 1991, p. 3). The proposed new attainment targets relating to hypothesizing in levels 1 to 5 are as follows:

> Level 2: Ask questions and suggest ideas of the 'how', 'why' and 'what will happen if' variety.
>
> Level 3: Suggest testable ideas based on everyday experience, for example, *all metals are attracted by magnets.*
>
> Level 4: Suggest testable ideas based on some prior knowledge and understanding, for example, *all objects fall, heavy objects fall fastest.*
>
> Level 5: Formulate hypotheses involving causal links, based on some piece of scientific knowledge or theory, for example, *more sugar will dissolve in hot water than in the same volume of cold water because temperature increases solubility.*

There appears to be a requirement here that the term 'hypothesis' should be used only for statements proposing 'causal links'. The 'testable ideas' looked for at levels 3 and 4, however, would clearly *function* as hypotheses within an investigation, even though both are no more than simple descriptions of what is thought to be the case. Either might be true (though, curiously for examples in a proposed National Curriculum, neither is) and both suggest ways in which their truth might be tested.

This brief survey of recent literature makes no claim to be comprehensive, but it does demonstrate that the term 'hypothesis' as currently used in science education (usually without qualification) can refer to an explanation, a prediction, or to a straightforward description of what is thought to be the case. In only one of the references cited (UNESCO 1980, p. 30) is any acknowledgement made that hypotheses may vary in character, while among publications related to the National Curriculum for England and Wales (DES 1989, 1991, SEAC 1990) there is ambiguity and even contradiction. Given the growing emphasis on school science as an active, investigative undertaking, this uncertainty over a concept central to scientific enquiry is clearly unsatisfactory.

Failure to develop a coherent concept of hypothesis within science education has come about because each author or working group has concentrated on one particular kind of hypothetical statement, but has referred to it as if it were representative of hypotheses in general. This has been accompanied by a corresponding disregard for what all scientific hypotheses have in common: their role as tentative solutions to scientific problems. As a result, the concepts of hypothesis which emerge from the literature of science education are narrow, exclusive and often contradictory, rather than being broad, inclusive and representative of the rich variety which characterizes scientific investigation in practice. One particularly serious consequence of this is the almost complete disregard for hypotheses which are not in the form of statements. Some examples of these, such as experimental devices and methods of measurement, are discussed below.

The overall role of hypothesis in scientific investigation

In order to develop a unified concept it is necessary, in the first instance at least, to identify and concentrate on the properties which individual cases or examples have in common. What all hypotheses have in common is their overall role within the investigations of which they form a part. As Cohen and Nagel (1934, p. 200) point out, 'We cannot take a single step forward in an enquiry unless we begin with a *suggested* explanation or solution of the difficulty which originated it'. Hypothesis is the name usually given to such a suggested explanation or solution. Without at least a tentative solution to the problem in mind, there is nothing to direct attention: it is impossible to determine what action is required or what evidence is likely to be relevant. Only after one has a hypothesis is it possible to decide what is to be observed (as well as how, when and where) or which variables are likely to be significant. As Hempel (1966, p. 12) observes,

> ... what particular sorts of data it is reasonable to collect is not determined by the problem under study, but by a tentative answer to it that the investigator entertains in the forms of a conjecture or hypothesis... which gives direction to a scientific investigation.

There seems to be broad, if tacit, agreement among science educators that the role of the hypothesis is to act as a tentative answer or solution to a question or problem. There has, however, been no attempt to use this as the basis for a concept of hypothesis which could be useful in developing and discussing the very wide range of investigations undertaken in school science as a whole.

Hypotheses in relation to learning in school science

Only when it has been firmly established that *any tentative solution capable of giving direction to an investigation is a hypothesis, whatever form it may take*, does it become possible to recognize and understand different kinds of hypothesis in relation to the investigations of which they form a part. These, in turn, reflect the different kinds of knowledge and understanding which science education seeks to promote. Wellington (1989, p. 11) argues that there are three broad categories:

1. Knowledge that – facts, 'happenings', phenomena;
2. Knowledge how (to) – skills, processes, abilities;
3. Knowledge why – explanations, models, analogies, frameworks, theories...

adding that 'a "Better Science" education will not focus on any one of these three categories at the expense of others'.

Investigations have an essential role in promoting learning in all three of these categories of knowledge; but *each category requires hypotheses which are different in character*. In the following sections, three different kinds of hypothesis will be considered:

(i) descriptive or predictive hypotheses which relate to knowledge that;
(ii) causal or explanatory hypotheses which relate to knowledge why;
(iii) procedural or technological hypotheses which relate to knowledge how to.

There are other kinds of hypothesis, most notably those of law (Westaway 1931, p. 242) and pattern, which propose relationships such as the Law of Refraction, or patterns such as the early versions of the Periodic Table, but do not seek to explain them. Such hypotheses are similar in character to descriptive hypotheses, but are more abstract and usually more complex. They are likely to be important in investigations at secondary level and above, but are not considered further in this paper.

Descriptive and predictive hypotheses

A hypothesis in this category can take two forms. In its descriptive form it is a statement which asserts, as a matter of fact, something whose truth is at the time unconfirmed. Examples which children might use in school science are:

> The plastic cup keeps coffee hotter than the china one does.
> All metals are attracted by my magnet.
> These balls bounce higher on the hard floor than they do on the soft carpet.

All these statements can be hypotheses, but only if they involve those who think them up in going beyond what is known and speculating on what *might be* the case. All of them are testable and each could act as the starting point of an investigation, giving a clear indication of the information which would be required in order to ascertain whether or not it were true.

Descriptive hypotheses such as those quoted have an alternative form, which gives rise directly to the concept of hypothesis-as-prediction referred to earlier. Any simple descriptive hypothesis can be restated as a prediction with no change in substantive meaning. By stating what is supposed to be the case, it predicts what, under certain conditions, will be found to be the case, for example 'Coffee *will stay* hotter in the plastic cup than in the china one'.

Descriptive and predictive hypotheses are often simple, and many of them can be regarded as more or less informed guesses or answers to questions asked in a scientific context. Perhaps because of this, there has been in science education a tendency to underplay their importance by concentrating on hypothesis-as-explanation. Descriptive hypotheses, however, are far from being trivial, either in science education or science as a whole. For example, Avogadro's Hypothesis, on which a great deal of physical chemistry depends, is simply a statement of what is thought to be the case, while the hypothetical model of DNA proposed by Watson and Crick is even more obviously descriptive.

In teaching and learning science, simple descriptive–predictive hypotheses are likely to be of particular importance in the early years. There are several reasons for this. Such hypotheses often arise very simply and naturally from children's spontaneous predictive guessing (Jarvis 1991, p. 7), and from what Harlen (1985, p. 35) terms 'testable questions'. If early science investigations are approached as guessing-games ('What do you think will happen if you . . . ?'), most children not only predict freely but also begin to devise ways in which their predictions can be tested. They may also have the opportunity to learn early in their science education that an incorrect prediction is not a 'wrong answer' but rather something from which they can learn (Jarvis 1991, pp. 7, 20, 21).

Simple descriptive hypotheses are also important in education, first, because they yield predictions very readily (as in the examples already quoted), which very often also indicate ways in which their truth can be tested. Second, such simple guesses can lead on to more generalized and complex testing and learning. For example, if a group of children has tested the hypothesis that balls bounce higher on hard surfaces than on soft ones, they could be encouraged to find out if the hypothesis holds good for all the surfaces they can test. Such investigations also reinforce the point that scientific understanding, the ability to explain why things are as they are, seems rarely to arrive all at once, but rather develops piece by piece from earlier and often simpler experiences. Simply finding out for oneself that something is the case can therefore be a significant learning experience, upon which conceptual learning and explanatory models may later be built (see Harlen 1985, Chs 3 and 4, Harlen and Jelly 1989, pp. 54–55).

Explanatory–causal hypotheses

As the examples quoted show, descriptive–predictive hypotheses are important both in scientific research and education; but scientists are rarely if ever content with knowing simply that something is the case. There is always a wish to understand, to be able to explain, to know why. Sometimes this wish has to go unfulfilled – there are, for example, no generally accepted explanations of either magnetism or gravity – but much of the power, influence and fascination of science come from its ability to explain the world in ways that lead to further and unexpected knowledge.

A tentative explanation of an observation is different in character from a descriptive–predictive hypothesis. In making a descriptive hypothesis one speculates about matters of fact; about what is thought to be the case. Jenner, for example, hypothesized that inoculation with cow-pox would have a definite effect, i.e., that it would confer immunity from smallpox. There was no question, then or later, of his hypothesis proposing a cause for this effect (Beveridge 1950, pp. 38–40). In making an explanatory or causal hypothesis, on the other hand, the facts (i.e., observed effects) are not the focus of the enquiry. What one speculates about is what caused things to be as they are. For example, Semmelweis's hypothesis that puerperal fever in the Vienna General Hospital was caused by 'cadaveric matter' on the hands of doctors and students was put forward, in 1847, only after he had established the facts about the incidence of the disease in great detail (Hempel 1966, pp. 3–5).

In terms of logical structure an explanatory–causal hypothesis is more complex than a descriptive–predictive one, because instead of asserting a hypothetical fact it proposes a possible relationship between a known effect and a hypothetical cause. This does not mean, however, that explanatory–causal hypotheses are always complex in terms of content or difficult to understand. Some, of course, are both, but others are among the simplest of everyday speculations. Every time we say 'I think it might be because...' we are making a hypothesis of this kind. In the context of science education, the character of explanatory–causal hypotheses is seen most readily when the effects they seek to explain are simple, easily perceived and not in doubt. Pupils are more likely to produce relevant, plausible and testable hypotheses when they are trying to find causes for things or events they have experienced at first hand, a point which is of particular importance in the early years. If they watch seedlings growing towards a window, for example, or see woodlice disappearing from view into damp leaf-litter, even young children are likely to be able to think up interesting and testable explanations.

In principle, testing explanatory hypotheses is similar to testing descriptive ones. The hypothesis acts as the basis for one or more predictions, which are tested by controlled experiments or observations. There is, however, an important difference. Explanatory hypotheses cannot be transformed directly into predictions in the way that simple descriptive ones can. Predictions have to be derived from them by (deductive) reasoning. To be valid and useful, a prediction must state that an event (or set of events) will (or will not) be observed under certain conditions. In addition, the predicted outcome must be one which would be expected if, and only if, the hypothesis were true. Arriving at such predictions is often much more a matter of common sense than such a formal statement may make it appear. If, for example, young children hypothesize that woodlice burrow into damp leaves because they don't like light, they will probably be capable of predicting that the animals will, if given a choice, shun bright light and remain in the dark.

In some circumstances, however, considerable knowledge and understanding may be required if predictions capable of falsifying an explanatory hypothesis are to be produced, and it is unwise to assume that they will always be readily forthcoming. To adapt an example quoted earlier: the fact that hot liquid in a plastic cup cools slowly could be explained by hypothesizing that the plastic 'keeps the heat in', i.e., is a poor thermal conductor. To make a prediction which could test this hypothesis is, however, much less straightforward. One testable prediction is that if hot drinks in a plastic cup and a ceramic cup used as a control are kept at the same temperature, the outside of the ceramic cup will become hotter. To make such a testable prediction requires not only an understanding of conductivity and its consequences, but also significant ability in deductive reasoning.

The role of explanatory hypotheses in science education is potentially a very important one, since explanation and the understanding of cause and effect are major aims of science as a whole. In addition, as Driver (1983, pp. 24–30, 41–49) points out, the making, criticism and testing of explanations has an important part to play, not only in the growth of understanding of science as an investigative activity, but also in the resolution of conflicts between the alternative conceptual frameworks which pupils bring to science education and a more mature scientific knowledge and understanding.

Procedural or technological hypotheses

Procedural and technological hypotheses contribute to the third kind of knowledge identified by Wellington (1989, p. 11): the technical knowledge of how to carry out experiments, controlled observations, measurements and other practical procedures. The conventional view, that such activities inevitably have an auxiliary rather than a principal role in a scientific investigation, has been strongly challenged by Hacking, who refers (1983, p. 150) to 'the class or caste difference between the theorizer and the experimenter. It has little to do with philosophy. We find prejudices in favour of theory, as far back as there is institutional science'. These prejudices are perhaps the reason why the practical problems of observation and experimentation, and the hypotheses to which they give rise, have received little attention, either from philosophers or educators in science. The solving of practical problems in science is important in itself, but it also forms a strong methodological link between science and some branches of technology (see Johnsey 1986). For example, if children are asked to make a parachute which will carry a 10 g weight to the ground as slowly as possible, they will probably produce a variety of parachutes, some of which will be modified and improved as a result of testing. In such a situation there is a problem to be solved which has equal relevance to both science and technology. Simply creating hypotheses in the form of verbal statements is of very limited use in attempting to solve this kind of problem because words will convey only a small part of what actually needs to be done. This is shown by the way in which children, though they may verbalize part of their solution ('A bigger parachute will fall more slowly'), very often go far beyond what they have expressed or could express in words, through what they actually construct and test. The real hypotheses, which express the ideas thought up as tentative solutions to the problem, are the devices themselves, which have to be designed, made, tested and then modified in order to improve them. Technological hypotheses of this kind are a prominent feature of children's work in the common ground between science and technology (Johnsey 1986), but far less attention has been paid to their role in other areas of science, although this is no less important.

Any scientific testing of a prediction requires pupils to have some understanding of a 'fair test' (i.e., the control and manipulation of variables) and the recording of results in the context of the particular investigation. Given such an understanding, some scientific testing is likely to be straightforward, for example finding out whether raising the end of a ramp always makes a ball rolled down the ramp go further along the floor. In many other situations, however, pupils may be required, or at least given the opportunity, to invent methods of testing or measurement for themselves. For example, in order to test the (descriptive) hypothesis that the weight of a person affects how easily a shoe slips on the floor, pupils need to invent a method of testing. Here again verbal hypothesizing is not enough, though language and social interaction are likely to be important in producing and criticizing possible solutions. It is the tentative methods of testing, which must themselves be tested and validated, which are the trial solutions to the problem. Such procedural hypothesizing is very similar to technological hypothesizing, but in principle at least it is more complex, because the solution not only has to work, but also has to satisfy the requirements of 'fair testing'.

Even in situations which appear very simple, the need to invent valid and consistent methods of testing and measurement can give rise to quite difficult problems. In finding out whether balls bounce higher on a hard floor than on a soft carpet, for example, how can the height of bounce be measured accurately? Investigating the strength of materials, for example the tearing strength of paper, similarly offers the opportunity for pupils to invent a method of testing. Although it has not been customary to regard them as such, trial solutions to problems of this kind are no less hypotheses, and no less scientific, than the descriptive or explanatory hypotheses to the testing of which they contribute. Even though they are concerned with procedural or technological problems rather than with factual knowledge or understanding, they are, like verbal statements, the expression of ideas which give direction to a scientific investigation (see Hempel 1966, p. 12) and without which the investigation cannot proceed. They function in relation to scientific knowledge *how* (to) in exactly the same way that descriptive and explanatory hypotheses do in relation to knowledge *that* and knowledge *why*. They are, in addition, hypotheses which are testable in the most direct way possible: do they satisfy the requirements of 'fair testing' and do they work?

Examples of investigations which involve pupils in devising and testing procedural and technological hypotheses are common in school science (see, for example, NCC 1991, p. 23). It is noticeable, however, that in the context of 'pure' science such hypothesizing is not explicitly discussed in the way that is usual in 'applied' or 'technological' science (see Johnsey 1986). As I have pointed out elsewhere (Wenham, in press), the view that practical problem solving in science is somehow less than truly 'scientific' is arbitrary and unhelpful, especially in the context of education. Such a view is supported by ideas taking shape within the broader context of science as a whole. Hacking (1983, pp. 131, 146), for example, believes that our understanding of science has been blurred and distorted by 'a single-minded obsession with representation and thinking and theory, at the expense of intervention and action and experiment.... Reality has to do with causation and our notions of reality are formed from our abilities to change the world'. If, as Wellington (1989, p. 11) suggests, science educators should regard 'knowledge how to' as an equal partner with 'knowledge that' and 'knowledge why', the inventiveness and ingenuity of pupils in devising, making, modifying and refining methods of testing and measurement should be regarded no less highly than other parts of the investigations of which they form an integral part. As Hacking (1983, p. 167) points out, 'Often... the test of ingenuity or even greatness, is less to observe and report, than to get some bit of equipment to exhibit phenomena in a reliable way'.

A basic concept of hypothesis

Millar and Driver (1987, p. 44) point out that 'hypothesising is something humans do all the time.... What is of interest for science education is not the development of some general ability to hypothesize, but of some insight into *scientific* hypothesizing'. Such an insight cannot be gained without an effective basic concept of hypothesis. As I have shown, an effective and generally acceptable concept of hypothesis does not emerge from the literature of science education. It cannot be gained simply by way of examples, nor by concentrating on particular kinds of hypothetical statements, because hypotheses vary as widely as the investigations of which they form a part and the knowledge and understanding they aim to produce. Even at school level, the range of knowledge and the variety of investigations in science are both very wide. The full range of hypotheses likely to be needed in an active and investigative school science programme can be recognized and understood only if one has a basic concept to which all individual examples can be referred.

Recognizing the variety of hypotheses and linking them to different kinds of knowledge and enquiry can help teachers and pupils clarify both the aims and the methods of scientific investigation in schools. It may also enable teachers to exploit more effectively opportunities for sequences of investigation, both planned and unexpected. A common sequence of hypothesizing and testing begins with play, observation and experimentation, which give rise to questions and *descriptive* hypotheses. (For example, 'If you raise the end of the ramp, the ball will roll further along the floor'.) Such hypotheses are tested and either upheld or, as in this example, refuted and modified. ('There is a best slope for rolling the ball. If the slope is steeper, it doesn't go as far.') After testing, an *explanatory* hypothesis may then be sought. (For example, 'With a very steep slope the ball doesn't go as far, because it bounces as it hits the floor and this makes it slow down'.) Testing this tentative explanation is likely to require the creation and testing of *procedural* hypotheses, for example modifying the bottom of the ramp so that the ball does not bounce, or trying to assess impact by rolling small balls of modelling clay down the ramp and varying the steepness of the slope.

The simple, basic concept of hypothesis put forward here, i.e., that hypotheses are tentative solutions to problems, which give direction to human enquiries, has two outstanding advantages as a starting point. Both have particular relevance to non-specialist, elementary school teachers and to teacher educators responsible for their training, because it is in this sector, where the confidence of individual teachers in their ability to teach science is likely to be low, that ambiguity and contradiction over the concept of hypothesis have recently been most evident. First, the basic concept not only provides a common reference point for thinking and communication, but also allows individual teachers to develop and differentiate their concept of hypothesis according to the needs of their pupils and the range of scientific investigations in which they engage. Second, it emphasizes the point made by Millar and Driver (1987, p. 4) that hypothesizing is a universal and constant human activity.

Scientific hypothesizing is simply one aspect of the general human tendency to speculate, conjecture and guess, developed and extended in the context of systematic investigations using scientific knowledge and concepts. Science in schools grows out of the exploratory behaviour and interpretations of the world which pupils bring with them, coupled with the knowledge, understanding and experience of the teacher. But it is only when teachers understand the nature and role of hypotheses in relation to pupils' conceptual frameworks and first-hand experience that investigations can make their full contribution to science education. It suggested that the simple, functional and unified concept of hypothesis put forward here is a practical basis for such an understanding.

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