# *Experimenting on (and with) Hidden Entities: The Inextricability of Representation and Intervention*

*Theodore Arabatzis*

## *1. Why use the term "hidden entities"?* [1]

Let me start with a comment on my choice of terms. I have chosen the term "hidden entities" instead of other more familiar terms, such as "unobservable entities" or "theoretical entities", for the following reasons. First, I wanted to avoid the thorny issues surrounding the observable-unobservable distinction. This distinction immediately invites questions about the boundary between the observable and the unobservable and about its epistemic significance. Forty five years ago Grover Maxwell argued that it is not possible to draw a sharp dividing line between the observable and the unobservable realms and that, therefore, the distinction in question lacked any epistemological and ontological significance (Maxwell 1962). This issue has been debated by philosophers of science ever since, especially after Van Fraassen reinstated the distinction and placed it at the centre of his constructive empiricist epistemology.

Second, I also avoided the term "theoretical entities" because it conveys the misleading impression that hidden entities do not transcend the theoretical framework in which they are embedded. In fact, these entities are trans-theoretical objects, which cut across different theories or even entire disciplines. Several philosophers of science have stressed their trans-theoretical character. On the one hand, philosophers such as Nancy Cartrwright and Ian Hacking have emphasized the synchronic dimension of the trans-theoretical character of hidden entities. Witness Cartwright's remark concerning "the electron, about which we have a large number of incomplete and sometimes conflicting theories" (Cartwright 1983, 92). On the other hand, philosophers such as Dudley Shapere and Hillary Putnam have pointed out the diachronic dimension of the trans-theoretical character of hidden entities, that is, the fact that these entities are usually the objects of consecutive scientific theories. Furthermore, the term "theoretical entities" undervalues completely the fact that many of the entities in question become experimental objects that are investigated in the laboratory, often without any guidance from a systematic theory about their nature.

Of course, I could also use other terms, such as "inferred entities" or "hypothetical entities". For the period in which my work has focused so far (the late 19$^{th}$ and early 20$^{th}$ centuries) the terms "hidden" or "invisible" entities have the additional advantage that they denote an actors' category. Heinrich Hertz, for instance, in his posthumously published *Principles of Mechanics* (1894) remarked that "the form of the atoms, their connection, their motion in most cases – all these are entirely hidden from us" (Hertz 1956, 18). And the French experimental physicist Jean Perrin described the aim of science in these colourful terms:

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[1] I have borrowed this term from the title of an international laboratory for the history of science organized by the Dibner Institute in June 1998.

> In studying a machine, we do not confine ourselves only to the consideration of its visible parts … We certainly observe these visible pieces as closely as we can, but at the same time we seek to divine the *hidden* gears and parts that explain its apparent motions.
> To divine in this way the existence and properties of objects that still lie outside our ken, *to explain the complications of the visible in terms of invisible simplicity*, is the function of the intuitive intelligence which, thanks to men such as Dalton and Boltzmann, has given us the doctrine of Atoms. (Perrin 1916, vii.)

In our constructivist age, the term "hidden" may have some objectionable overtones, suggesting a pre-existing reality waiting to be disclosed.[2] I think, however, that one may adopt a distinction between a hidden and an apparent realm, while remaining neutral in metaphysical disputes concerning the nature of reality.

## *2. A glance at the role of hidden entities in the history of the physical sciences*

The explanation of phenomena by postulating hidden entities has been a significant aspect of the sciences, at least since the 17th century. Think, for instance, of the central tenet of the mechanical philosophy, namely that the fundamental constituents of the world are imperceptible material particles in constant motion. Those particles (e.g. Descartes' corpuscles) were introduced for explanatory purposes, to accommodate various phenomena within a mechanical framework. In the following centuries we witness a multiplication of novel entities, most of which were introduced for similar reasons, that is, to accommodate within a mechanical framework phenomena that were not easily susceptible to mechanical explanation. For example, the 18th century subtle fluids were posited to make mechanical sense of phenomena, such as electricity and magnetism, which seemed to involve action at a distance. Similarly the 19th century luminiferous ether was put forward to incorporate light within a mechanical framework. Thus, many of the hidden objects of 18th and 19th century natural philosophy were introduced in response to a conceptual difficulty faced by the mechanical tradition, which could not tolerate the obscure phenomenon of action at a distance.

In the 19th century, other hidden entities, such as the atom, were invoked to systematize and explain empirical regularities (e.g., the laws of definite and multiple proportions). Many scientists, however, thought of "atoms" as dispensable fictions and the question of their ontological status remained open throughout the century. And, finally, in the 20th century we witness a real explosion in the number of the hidden entities that populate the world, ranging from elementary particles to genes.

## *3. The problem of underdetermination*

This brief and impressionistic historical sketch, indicates that hidden entities have often (always?) been introduced for explanatory purposes. Some of them (e.g., the subtle fluids) were subjected to experimental investigation, whereas others (e.g., the ether) were resistant to experimental detection. The proliferation of hidden entities made more acute the problem of underdetermination, namely that there are more than one hypotheses or theories that are

2 This was pointed out to me by Ursula Klein and Hans-Jörg Rheinberger.

compatible with the phenomena. Strictly speaking, there are infinitely many. This problem had been discussed since antiquity. The introduction of hidden entities, however, made it more intractable. Any inductive generalization faces "horizontal" underdetermination, but with the hypothetical postulation of entities "underneath" the phenomena one has to worry also about "vertical" underdetermination.[3] That was evident to Descartes, who wrote in the *Principles of Philosophy* (1644): "With regard to the things that cannot be perceived by the senses, it is enough to explain their possible nature, even though their actual nature may be different" (Descartes 1984, 289).

## *4. Bypassing underdetermination: Cartwright and Hacking on entity realism*

There have been various attempts to come to terms with the problem of underdetermination. The one I will discuss here was put forward by Ian Hacking, who tried to bypass this problem by focusing on experimental practice and the specific mode of causal reasoning that is employed in that practice. A similar view has been adopted and further developed by Nancy Cartwright. Instrumentation and experimentation, in Hacking's and Cartwright's view, can provide, under certain circumstances, unmediated (largely theory-free) access to the hidden reality behind the appearances:

> many of the things that are realities for physics are not things to be seen. They are non-visual features – the spin of the electron, the stress between the gas surface, the rigidity of the rod. Observation – seeing with the naked eye – is not the test of existence here. Experiment is. Experiments are made to isolate true causes and to eliminate false starts (Cartwright 1983, p. 8).

Hacking has argued that the manipulation of hidden entities in the laboratory compels us to be realists about them. The uses of hidden entities as investigative probes and as engineering tools leave little room for doubting their existence. Hidden entities cease to be hypothetical when we succeed in manipulating them. For instance, the reality of electrons is beyond reasonable doubt, since we have devices with which we can spray them. In Hacking's seductive words, "if you can spray them, then they are real" (see Hacking 1983, 22ff.). Of course, it may turn out that our theoretical representations of electrons and their properties are mistaken, but it is highly unlikely that electrons will turn out to be fictitious. Cartwright concurs:

> I agree with Hacking that when we can manipulate our theoretical entities in fine and detailed ways to intervene in other processes, then we have the best evidence possible for our claims about what they can and cannot do; and theoretical entities that have been warranted by well-tested causal claims like that are seldom discarded in the progress of science. (Cartwright 1983, p. 98)

This version of realism, as several commentators have pointed out, faces several difficulties.[4]

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[3] I borrow these terms from Worrall 2000.
[4] See, for instance, Arabatzis 2001, Elsamahi 1994, Gross 1990, Morrison 1990, Reiner and Pierson 1995, Resnik 1994.

## 5. Problems of entity realism

**5a**. Perhaps the main difficulty is that the premise of Hacking's argument, namely that we can spray electrons, begs the question by assuming "what is under dispute" (van Fraassen 1985, 298). "Manipulation" is a success term – we cannot manipulate something that does not exist (cf. Nola 2002, 5). Perhaps that is why Hacking calls his "conclusion … obvious, even trifling" (Hacking 1983, 146). The very description of an act of laboratory manipulation as "spraying of electrons" presupposes the existence of electrons. To put it another way, our confidence in the existence of electrons must precede our claim that we successfully manipulate electrons (cf. Seager 1995, 467-468). Actually, it would be pertinent to invert Hacking's slogan as follows: "If they are real, then you spray them."[5]

Furthermore, it is always possible to describe an experimental situation, purportedly involving a hidden entity, in phenomenological terms. We can describe the objects we manipulate at the "apparent" level (cf. Arabatzis 2001, S535; Boon 2004, 226; and Clarke 2001, 713-714). This is the point of the following passage from Whitehead's *The Principle of Relativity with applications to Physical Science*:

> When Sir Ernest Rutherford at Cambridge knocks a molecule to pieces, he does not see a molecule or an electron. What he observes is a flash of light. There is at most a parallelism between his observation and the conjectural molecular catastrophe (Whitehead 1922, 61).

Since our manipulations always take place "in the realm of the sensible" (Seager 1995, 472) they can also be described at that level. Therefore, their re-description as manipulations of a hidden entity does not imply but rather presupposes its existence.

Furthermore, even if the expression "spraying of electrons" were the best available description of a given experimental situation, we would not have to commit ourselves to believing in the existence of electrons. An immersion in the theoretical and experimental practices of science is compatible with maintaining a critical distance from their ontological implications. There is a striking passage from van Fraassen's *The Scientific Image*, which is worth quoting here:

> It may be the case that I have no adequate way to describe this box, and the role it plays in my world, except as a VHF receiver. From this it does not follow that I believe that the concept of very high frequency electromagnetic waves corresponds to an individually identifiable element of reality. Concepts involve theories and are inconceivable without them, to paraphrase Sellars. But immersion in the theoretical world-picture does not preclude 'bracketing' its ontological implications (van Fraassen 1980a, 81).

van Fraassen's point concerned the "theoretical world-picture", but it also holds at the level of experimental practice.

**5b**. A related difficulty is what I will call the "manipulation of what" problem: before we invoke manipulability as a demonstrative principle, we need to identify the entity that we manipulate. In many experimental situations we manipulate *something* without knowing *what kind of thing* we

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5 This was suggested to me, in conversation, by Bas van Fraassen.

manipulate. For instance, in the last quarter of the 19th century several physicists manipulated cathode rays, experimental objects that were produced in the discharge of electricity through gases at very low pressure. The identification of cathode rays with electrons at the end of the 19th century revealed that the earlier manipulations of cathode rays had been, in fact, manipulations of electrons. Prior to that identification, however, the physicists who manipulated cathode rays did not know what kind of thing they manipulated. Hacking has claimed that "from the very beginning people were less testing the existence of electrons than interacting with them" (Hacking 1983, 262). Actually, people were interacting with electrons well before they even suspected their existence. Thus, manipulability, by itself, cannot establish the existence of, say, electrons, as opposed to cathode rays or an "I know-not-what" something (cf. Achinstein 2001, 412; and Boon 2004, 229).

To put it another way, the "material realization"[6] of an experiment can be compatible with a plurality of descriptions (and theoretical interpretations) of what is going on in the experiment. Since the material realization of an experiment underdetermines its theoretical interpretation, the question "What entity is being manipulated in the experiment in question?" cannot be answered merely on the basis of the experimental operations performed by the experimenter. The epistemic gap from our manipulations of "apparent" entities to the existence of hidden entities can only be bridged by our representations of the hidden world.

**5c**. And this brings me back to the problem of underdetermination. One would expect that theoretical explanations as well as entity-based explanations of phenomena face equally this problem. Nancy Cartwright, however, has argued that there is an asymmetry in these two kinds of explanation. Only entity-based explanations are exempt from underdetermination:

> We can infer the truth of an explanation only if there are no alternatives that account in an equally satisfactory way for the phenomena. In physics nowadays, I shall argue, an acceptable causal story is supposed to satisfy this requirement. But exactly the opposite is the case with the specific equations and models that make up our theoretical explanations. There is redundancy of theoretical treatment, but not of causal account (Cartwright 1983, p. 76).

The problem here, as I see it, is that Cartwright assumes that the current absence of alternatives implies the absence of alternatives period. One could very well conceive of the existence of two or more empirically adequate causal accounts of the same phenomena, based on the existence of altogether different entities. After all, in the history of the sciences there have been such cases – for instance, a phlogiston-based and an oxygen-based account of combustion (Arabatzis 2001, S534; Carrier 1993, 401-403). I don't see how this possibility could be excluded (cf. Clarke 2001, 719 and Gelfert 2003, 248). Of course, "if God tells you … that the ionization produced by the negative charge explains the track in the cloud chamber, then you do have reason, conclusive reason, to believe … that there is an electron in the chamber." (1983, 93) If God provided that crucial piece of information, we would not have to worry about underdetermination. In the absence of a divine tip, however, we have to figure out by ourselves that an electron is the cause of the track in the

[6] The term is from Radder 1995, 69.

cloud chamber. And how could we ever be certain that no other entity fills that causal role or that the track in the cloud chamber is not just a brute fact without a cause?

**5d.** I have argued, so far, that the putative manipulation of a hidden entity is not a sufficient criterion for establishing its existence. Is it a necessary one? In response to his critics, Hacking has recognized the variety of standards of proof, in addition to manipulability, that are brought to bear, *within* scientific practice, on the existence of hidden entities.

> But perhaps I could be saying that our ability to interfere with and use an entity is the only sound argument for its existence? Not at all. … I said that engineering, not theorizing is the *best* proof of scientific realism about entities. … I never said engineering or anything else was the *only* evidence or the *only* proof (Hacking 1995/96, 538).
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> My experimental argument for entity realism may imply a sufficient (epistemological) condition for holding that an entity exists. But it does not imply a necessary condition. There may be many kinds of evidence that an entity exists. I hold only that manipulationability is the best evidence (*ibid.*, 540).

Thus, manipulability should not be interpreted as a necessary condition for belief in the existence of a hidden entity. A difficulty remains, however: within scientific practice manipulability is sometimes (often?) not considered the "best proof" or the "best evidence" in favour of an entity (Gelfert 2003, Massimi 2004, Morrison 1990). So if we applied Hacking's criterion we would, sometimes, end up accepting entities that are contentious among the relevant experts or even admitted to be fictitious. In other words, the criterion may recommend ontological commitment even in cases where the scientific community has not unambiguously decided in favour of the existence of an entity.

Cartwright's exclusive emphasis on causal inference faces the same problem. Consider her account of

> the radiometer, invented by William Crookes in 1853. It is a little windmill whose vanes, black on one side, white on the other, are enclosed in an evacuated glass bowl. When light falls on the radiometer, the vanes rotate. At first it was assumed that light pressure causes the vanes to go round. Soon it was realized that the pressure of light would not be nearly great enough. It was then agreed that the rotation is due to the action of the gas molecules left inside the evacuated bowl. … in 1879 James Clerk Maxwell, using the kinetic theory of gases, argued that the forces in the gas would be the same in all directions, and so could not push the vanes. Instead differential heating in the gas produces tangential stresses, which cause slippage of the gas over the surface. As the gas flows around the edge, it pulls the vanes with it.
> …
> The molecules in Crookes's radiometer are invisible, and the tangential stresses are not the kinds of things one would have expected to see in the first place. Yet, … I believe in both. I believe in them because I accept Maxwell's causal account of why the vanes move around (Cartwright 1983, 5-6).

As with Hacking's manipulability criterion, the problem here is the anticipation of the verdict of the scientific community. Molecules remained controversial entities till the beginning of the 20$^{th}$

century. Apparently, many physicists and chemists were not (and, I think, should not have been) swayed by Maxwell's causal account of the radiometer's function to believe in molecules. The moral of this case is that we should avoid anticipating (or even replacing) the judgements of the scientific community by relying exclusively on epistemological criteria whose application has not carried the day among the scientists themselves.

**5e**. So far I have argued for two inter-related theses. First, the manipulability of a hidden entity is neither necessary nor sufficient for demonstrating its existence. Rather than focusing on a single epistemological criterion at the expense of everything else, historians and philosophers of science should attend to the multitude of theoretical and experimental practices that are brought to bear on the existence of hidden entities. Second, in experimentation on (and with) hidden entities representation and intervention are intertwined (cf. Putnam 1995, 58-59; and Gelfert 2003, 247).[7] Our knowledge of hidden entities is never, in Bertrand Russell's terms, "knowledge by acquaintance", but always "knowledge by description". And the descriptions in question are formulated within a, more or less developed, theoretical framework. As I will suggest below, however, some aspects of those descriptions derive from experimentation and remain stable across theoretical frameworks.

## *6. The historiographical virtues of agnosticism*

Given that manipulability cannot get around the hypothetical status of hidden entities, I think that it is preferable to adopt an agnostic attitude towards those entities when we attempt to write the history of their representations. And this is for two reasons: First, because the long-standing philosophical debate over the reality of "theoretical" entities has reached a stalemate, notwithstanding a consensus among contemporary philosophers of science, realists and anti-realists alike, that those entities are essential for scientific practice. Second, and more important, because we have to do justice to the historical fact that important scientists believed passionately (and, I think, for good reasons) in entities that turned out to be fictitious. We have to understand, in epistemic terms, how it was possible, or even reasonable, for a physicist of J. J. Thomson's caliber to claim in 1909 that "The ether is not a fantastic creation of the speculative philosopher; it is as essential to us as the air we breathe" (J. J. Thomson 1909, 267). By immersing ourselves in the theoretical, instrumental, and experimental practices of past scientists, in their "virtual reality" (Seager 1995), it becomes possible to understand how the scientists in question developed an, often strong, conviction in the reality of their objects of study. At the same time, however, the fact that some of those objects have perished motivates us to distance ourselves from the ontological commitments of the historical actors.

A passage from Arthur Eddington's *The Philosophy of Physical Science* captures the crux of this historiographical stance:

> [T]he physical universe [and the physical objects which constitute it] is defined as the theme of a specified body of knowledge, just as Mr. Pickwick might be defined as the hero of a

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7 Strangely enough, Hacking admits the inextricability of representation and intervention: "We represent in order to intervene, and we intervene in the light of representations" (Hacking 1983, 31).

> specified novel. A great advantage of this definition is that it does not prejudge the question whether the physical universe – or Mr. Pickwick – really exists. That is left open for discussion if we can agree on a definition of "really exists" (Eddington 1958, 3).

In a similar manner a hidden entity might be defined as the object of a body of knowledge and of a set of practices. As I have argued elsewhere, we can make sense of those entities and their role in scientific practice, without necessarily assuming their existence (Arabatzis 2006).

## *7. Sidestepping the problem of realism*

So, I am proposing to sidestep the normative aspects of the problem of entity-realism and focus on issues which, though related to it, have a descriptive and interpretative character. Here I will touch upon four of those issues:

**7a.** To begin with, there is a descriptive counterpart to the normative philosophical problem. How do the scientists themselves become convinced that a hidden entity is real? Although I would hesitate to give a simple answer to such a huge question, I would stress two factors that are important in this respect: The first factor has to do with theory. The empirical adequacy and explanatory power of the theory positing a hidden entity are usually considered among the most important reasons for believing in its existence. The second factor is related to experiment. The over-determination of a hidden entity's properties in different experimental settings is often an important reason in favour of its existence. For example, in the late $19^{th}$ and the early $20^{th}$ centuries the charge to mass ratio of the electron was determined by different methods and in different kinds of experiments: on cathode rays, on ß-rays, on thermionic emission, and in spectroscopy. The approximate agreement of the results obtained convinced many physicists that electrons were real entities.

**7b.** The second issue concerns the role of experimentation on hidden entities in the construction of their representations. How do scientists infer the characteristics of such entities by experimenting on them? Here I will draw on two philosophers: Pierre Duhem and Norwood Russell Hanson. As Duhem argued, a hidden entity is associated with a constellation of effects: an electric current, for instance, "may manifest itself not only in mechanical effects but in effects that are chemical, thermal, luminous, etc" (Duhem 1954, 151). What we need to understand in specific cases is how these different effects are held together as manifestations of a single entity.[8]

Furthermore, we need to understand how specific characteristics are attributed to those entities. Hanson's remark that "The idea of … atomic particles is a conceptual construction 'backwards' from what we observe in the large" is particularly helpful in this respect (Hanson 1963, p. 47). When an experimentally produced phenomenon is attributed to a hidden entity, the characteristics of the phenomenon that are of interest to the scientist(s) must be linked with the putative properties and behaviour of the entity in question. As Cartwright has put it, echoing Hanson's idea,

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8 For a preliminary attempt to answer this question, see Arabatzis 2006.

> Given our general knowledge about what kinds of conditions and happenings are possible in the circumstances, we reason backwards from the detailed structure of the effects to exactly what characteristics the causes must have in order to bring them about (Cartwright 1983, 6).

For instance, in late 19th century spectroscopy the phenomena observed in the laboratory had three salient characteristics: the frequency, intensity, and polarization of spectral lines. Once spectral lines were attributed to a hidden entity, the electron within the atom, their characteristics had to be linked with the properties and behaviour of that entity. The frequency, intensity, and polarization of spectral lines were correlated with the frequency, amplitude, and direction of vibration of the electron within the atom. In that way, experimentally obtained information guided the articulation of the representation of the electron.

A related question concerns the *measurement* of hidden entities. Since the late nineteenth century various properties of hidden entities have been measured, the mass and charge of elementary particles being among the most prominent. How is it possible to measure something that is hidden? The process of measurement in this case is very similar to Newton's "deduction from the phenomena". Given the hypothesis that an entity exists and that it is subject to certain laws, it is possible to use experimental results to fill in the blanks in the description of the entity. Thus, the measurement of hidden entities can be represented as "the continuation of theory construction by other means" (van Fraassen 1980b, 673).

**7c.** We should grant, I think, that theory is crucial for the experimental investigation of hidden entities. We should still ask, however, whether these entities qua experimental objects have any independence from their theoretical representations. In other words, do they have a life of their own? I think that they do, and this is an insight of lasting value in Hacking's and Cartwright's "experimentalism". A considerable part of our knowledge of hidden entities derives from experiment and, in an important sense, is partly independent from theory. First, it is often the case that scientists are involved in exploratory experimentation on hidden entities, without being guided by a full-fledged theoretical account of their nature (Clarke 2001, 711; Steinle 1997, 2002). That was the case, for example, in experimentation on cathode rays during the last quarter of the 19th century (Hiebert 1995). Furthermore, experimentally determined properties of hidden entities are often incorporated into very different theoretical representations of them. Scientists who may disagree about the ultimate nature of those entities may come to agree about their experimentally determined properties. Those properties may, in turn, become essential for identifying their carriers in different experimental settings. For instance, J. J. Thomson in England, Walter Kaufmann in Germany, and Paul Villard in France had very different ideas about the ultimate nature of cathode rays. Thomson identified them with subatomic particles; Kaufmann represented them as ether waves; and Villard believed that they were charged hydrogen particles. All of them, however, agreed on the value of their mass to charge ratio.[9]

**7d.** A final issue: How do hidden entities function as epistemic objects? What role do they play in the creation of new scientific knowledge? Here I will be even more epigrammatic than I have been so far: First, they play a heuristic role in experimentation – they generate new questions that guide

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[9] See Arabatzis 2004 and Lelong 2001.

experimental research. Second, they are recalcitrant objects that give rise to surprises – experimentation may endow them with novel (and sometimes unexpected) properties.[10] The case of cathode rays is, once more, instructive. Questions about their constitution played a significant role in the experimental investigation of the discharge of electricity through gases. Furthermore, the experimental probing of their properties led to surprising results, most notably the unexpectedly small ratio $m/e$.

To conclude, I hope I have said enough to indicate that our understanding of hidden entities and their role in experimental practice can be enhanced by adopting an integrated historical-cum-philosophical approach. On the one hand, philosophical reflection on the problem of entity realism has a lot to gain by examining historically how those entities were introduced and investigated. On the other hand, the historical analysis of the careers of those entities *qua* experimental objects may profit from the philosophical debates concerning their existence. But I should leave a detailed analysis of this fruitful interaction for a future occasion.

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[10] Hans-Jörg Rheinberger has discussed in detail these two aspects of epistemic objects. See, for instance, Rheinberger 1997.

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