THE DEMATERIALIZATION OF MATTER*

NORWOOD RUSSELL HANSON**

Indiana University

1. The philosophical version of the primary-secondary distinction concerns (a) the 'real' properties of matter, (b) the epistemology of sensation, and (*c*) a contrast challenged by Berkely as illusory.

The scientific version of the primary-secondary distinction concerns (a') the physical properties of matter, (b') a contrast essential within the history of atomism, and (c') a contrast challenged by 20th century microphysics as *de facto* untenable.

2. The primary-secondary distinction within physics can be interpreted in two ways:

a. it can refer to content; e.g. 'Matter *has* the properties of mass, shape, density... etc. — it only appears to have the properties of warmth, fragrance, etc.' Or,
b. it can refer to form; e.g. 'Whatever properties our best theories accord to primary matter, e.g., electrons, these are by definition *primary*. All other properties of, e.g., macromatter, are derivative.'

Concerning 2.a., this interpretation is simply false when 17th, 18th, or 19th century values for the property-variables are introduced. Concerning 2.b., this either uninformative or misleading. It is uninformative when it constitutes no more than a decision to use the word 'primary' as an umbrella-word for all the properties contemporary micro-physics accords to fundamental material particles, *whatever these may be*. It is misleading when it turns on an implicit contrast between certain properties particles may be said to have when 'harnessed' to a detector, and certain other properties these particles have when free and unharnessed to any detector. This contrast does not exist. Quantum-theoretic information is always about particles-and-their-detectors-in-combination. Dissolve this combination and you destroy any possible knowledge of the particle. Hence the notion of 'completely objectifiable properties of particles' is in principle unsound. (Cf. Hanson, *American Journal of Physics*, 27 January, 1959).

I

William Whewell wrote in 1834:

> "...If we in our thoughts attempt to divest matter of its powers of resisting and moving, it ceases to be matter, according to our conceptions, and we can no longer reason upon it with any distinctness. And yet... the properties of matter... do not obtain by any absolute necessity..."[1]

Within the subsequent century the matter-concept underwent radical changes. Let us explore these changes and note how they relate to the distinction between primary and secondary properties.

Determining the essence of the matter-concept was a problem already familiar to Democritus:

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[1] W. Whewell, *Astronomy and General Physics* (London, 1834), pp. 211-12.

> "A thing merely appears to have color; it merely appears to be sweet or bitter. Only atoms and empty space have a real existence."[2]

Compare Plato:

> "Properties such as hard, warm, and whatever their names may be, are nothing in themselves..."[3]

Galileo joined this chorus:

> "White or red, bitter or sweet, noisy or silent, fragrant or malodorous, are names for certain effects upon the sense organs."[4]

Locke gives the distinction its classic shape:

> "The qualities then that are in bodies, rightly considered, are...: First, the bulk, figure, number, situation, and motion or rest of their solid parts. Those are in them, whether we perceive them or not; and when they are of that size that we can discover them, we have by these an idea of the thing as it is in itself; as is plain in artificial things. These I call *primary qualities*. Secondly, the power that is in any body, by reason of its insensible primary qualities, to operate after a peculiar manner any of our senses, and thereby produce in *us* the different ideas of several colors, sounds, smells, tastes, etc. These are usually called *sensible qualities*... The first of these... may be properly called real, original, or primary qualities; because they are in the things themselves, whether they are perceived or not: and upon their different modifications it is that the secondary qualities depend."[5]

Thus on the one hand there are the properties matter *really has*; these are geometrical, statical, and dynamical. Shape, mass, motion and impact — these are a body's primary properties. However, its apparent color in ultraviolet light — or daylight — its taste, its tone, its fragrance; these are the body's secondary properties. Our appreciation of these latter varies with the state of our senses; secondary properties result from interaction between percipient and perceived. The primary qualities, however, seem "in the bodies themselves". Hence, they are the very properties of matter itself.

As historians know, the primary-secondary distinction dissolved in George Berkeley's inkwell. Knowing a body's shape seemed to the Bishop as much the result of interaction as any secondary property. (18th-century psychologists knew that a given mass could generate variable perceptions in subjects differently conditioned.) Berkeley's epistemology, therefore, erased any distinction in principle between primary and secondary properties. Either the two were equally weak, or equally strong — depending on how one interprets Berkeley. Either secondary properties are just as basic to matter as the primaries, or the primaries give no more indication of matter 'as it really is' than the secondaries. The latter seems more like Berkeley; hence I adopt it here.

Berkeley's analyses, however, seemed *merely* philosophical. Distinctions between primaries and secondaries may indeed fail under strict analysis. But

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[2] Diels, *Fragmente der Vorsokratiker* (A49, A1, section 45).

[3] *Theaetetus*, 156e.

[4] *Opere*, vol, IV, pp. 333 ff.

[5] *Essay* (London, 1726), Book II, chapter 8, section 23.

Berkeley's scientific contemporaries still treated the distinction as fundamental, philosophers notwithstanding. Scientists were concerned with the physical properties of objects, not their 'real' properties. We shall return to this distinction.

Consider now Heisenberg's insight into the history of atomism and the manner in which it reflects the primary-secondary contrast:

> "It is impossible to explain ... qualities of matter except by tracing these back to the behavior of entities which themselves no longer possess these qualities. If atoms are really to explain the origin of color and smell of visible material bodies, then they cannot possess properties like color and smell ... Atomic theory consistently denies the atom any such perceptible qualities."[6]

Boyle is making a similar point:

> "Matter being in its own nature but one, the diversity we see in bodies must necessarily arise from somewhat else than the matter they consist of."[7]

Lucretius' atoms were colorless; an aggregate's color depended on the size, shape, and interrelations of its constituent atoms.[8] His atoms were without heat, sound, taste, or smell.[9]

And Bacon wrote:

> "Bodies entirely even in the particles which affect vision are transparent, bodies simply uneven are white, bodies uneven and in a compound yet regular texture are all colors except black; while bodies uneven and in a compound, irregular, and confused texture are black."[10]

Birch writes of Newton:

> "The atoms ... were themselves, he thought, transparent; opacity was caused by 'the multitude of reflections caused in their internal parts'."[11]

Thus the atomic hypothesis, and its intricate history, would crumble unless the ancient distinction between primary and secondary qualities braced it. No classical atomist thought atoms to be colored, fragrant, hot, or tasteable; the basic function of atoms was to explain away such properties as but the molar manifestations of the atom's primary properties and geometrical configurations.

Not every atomist stressed the same atomic primary, although all agreed that, whatever they were, the atom's properties were necessarily primary, an argument to which we shall return. The atom's primaries usually included things like position, shape, motions, etc.

Position was paramount for Democritus, but it was *shape* for Epicurus and Lucretius. Newton fixed on the *motions* of atoms. Gassendi remarked their

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[6] Heisenberg, *Die Antike*, vol. VIII.

[7] Boyle, *Works* (London, 1744), vol. III, p. 15.

[8] Lucretius, *On the Nature of Things* (Oxford), Book II, p. 98, lines 703 ff.

[9] *Op. cit.* Book II, pp. 94 ff., lines 842 ff.

[10] Bacon, *Works* (London, 1824), Aphorism xxiii, vol. VIII, p. 222.

[11] Birch, *History of the Royal Society* (London, 1756-7), vol. III, pp. 247 ff.

combinatory properties; this already constitutes an extension of the Lockean notion. But doubtless combinatory capacity would have been accepted by all as a primary property, although not every atomist would have stressed it *à la* Gassendi. Henceforth, the term 'primary' will be used in this extended way. Atomic *irresolvability* attracted Boyle, but this is virtually tautological, since *atomos* means just this. For Lavoisier, Richter, and Dalton, *mass* was basic. Berzelius stressed their *binding force* (again this falls within our extended class of primaries). Further properties were stressed by Faraday, Weber, Maxwell, Boltzmann, Clausius, Mayer, Loschmidt, and Hittorf. But, by all, the atoms were characterized by some cluster of primary properties, on a selected one of which further theoretical constructions were founded. The exception is Stumpf, who could not imagine atoms as spatial bodies lacking color.[12] But he is the exception proving the rule — by which is meant 'probing the rule': we know what is generally true when we note how a counterinstance deviates.

The predominant sentiment of the Scientific Revolution was expressed by Newton:

> "I ... suspect that [the phenomena of nature] may all depend upon certain forces by which the particles of bodies ... are either mutually impelled towards one another and cohere in regular figures, or are repelled and recede from one another."[13]

Here is a yet wider extension of Locke's use of 'primary'. But forces which impel and repel would surely be on the primary side of the ancient fence.

The degree to which the primary-secondary distinction remained scientifically fundamental, despite Berkeley's leveling analysis, is illustrated by Euler:

> "The whole of natural science consists in showing in what state the bodies were when this or that change took place, and that ... just that change had to take place which actually occurred."[14]

Helmholtz is as direct:

> "The task of physical science is to reduce all phenomena of nature to forces of attraction and repulsion the intensity of which is dependent only upon the mutual distance of material bodies. Only if this problem is solved are we sure that nature is conceivable."[15]

These sentiments reflect a spectrum of related attitudes: the mechanical philosophy, theoretical determinism, the reduction of all science to physics. These are generable only from an implicit atomism. Historically, this devolves into something resembling the classical distinction between primary and secondary properties.

'Resembling' is an operative word. Berkeley speculated about the *real* properties of matter. He felt the classical primary-secondary distinction to be

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[12] Stumpf, *Uber den Psychologischen Urstrung der Raumvorstellung* (Leipzig, 1873) p. 22.

[13] Newton, *Principia*, p. xviii.

[14] Euler, *Anleitung zur Naturlehre* (in *Opere Posthuma*, II, Leipzig and Berlin, 1911), vol. VI, section 50.

[15] Helmholtz, *Über die Erhaltung der Kraft*.

unsound. These properties were on the same epistemic level so far as knowing 'reality' was concerned. One of the Bishop's scientific contemporaries could grant this, however, and yet preserve the same distinction at a different level — that concerned not with matter's *real* properties (a philosopher's inquiry at most), but with its *physical* properties. This latter is a scientist's inquiry at least.

Berkeley's 'Thou shalt not speak of primary properties as philosophically real' is hence distinguishable from a prohibition heard in this century. 'Thou shalt not speak of primary properties as physically real'. In the 18th century a scientist could have accepted the first and rejected the second. Now he may very well accept the second, whatever may be his attitude towards the first.

Hence, so far as one is concerned with distinguishing primary properties (which were real and in matter itself) from secondary properties (which were merely produced in us) — Berkeley's epistemic criticism was devastating. Still, the distinction remained viable in natural philosophy, the province not of philosophically real, but of physically real properties. Physically real properties contrast with mere appearances (intersubjectively understood). That a submerged stick is really straight contrasts with its bent appearance. And that the solidified CO_2 is really cold contrasts with our impression of it as blistering hot. But concern with the philosophically real undercuts these scientific inquiries altogether. The latter concern stable, permanent properties of objects as contrasted with those which are evanescent, contextually dependent, and accrue to them *via* special conditions of observation, e.g. ultraviolet illumination, intoxicated observers. Berkeley's inquiry is concerned with the philosophical extension of this scientific contrast, as signalled by the question: 'And which of these kinds of properties does matter *really have*?' The scientist's use of the primary-secondary distinction is restricted to delineating the contrast 'observed under all conditions' vs. 'observed only under special conditions'. The philosopher asks the more pervasive question, which Berkeley answers by a denial: to wit, there are no better grounds for supposing matter really has properties we regularly observe it to have, than there are for thinking its properties are those we irregularly observe.

Within the class of physically real properties scientists did distinguish primaries from secondaries. They had to do so to sustain an intelligible atomism. But Berkeley's objectives were not scientific; he dismissed the distinction as philosophically untenable. Physical science is only now undergoing its Berkeleyan self-criticism. When Whewell wrote, it had not. He spoke of conceptual constraints against tinkering with our ideas of the primary physical properties of matter. These constraints are no longer as binding as in the 19th century. Indeed, our understanding of elementary matter, of electrons, cannot proceed within a classical conception of primary physical properties.

For a theory of electrons to succeed now, the electron-idea must be divested of its classical conceptions of resisting and moving. This is what Whewell claimed we could not do:

> "Divest matter of its powers of resisting and moving ... and we can no longer reason upon it with any distinctness." (*Op. cit. loc. cit.*)

But electrons can be reasoned upon with distinctness, although, it may be granted, they remain unfamiliar material objects.

II

Consider the representative answers to "classical" questions about the electron, that most fundamental of particles.

What is the "diameter" of an electron? The usual theoretical answer is that it is of the order of 6×10^{-13} centimeters. Experimentally this is not determinable. Such a magnitude would be very difficult to detect because of pion and nucleon pair-creation phenomena at the required energies (80 BEV). The concept of electronic diameter is based on the formula $d = 2a - 2e^2/m_0c^2 \approx 5.7 \times 10^{-13}$ cm; or, $r \cong e^2/m_0c^2 \approx 2.81785 \times 10^{-13}$ cm. No evidence contradicts this, but the fine determination is beyond current laboratory technique. Of course, some theoreticians put the diameter at 0, arguing that this is compatible with electron-proton scattering experiments at 1 BEV. Indeed, the quantum electrodynamics of small distances is already at stake in this question.

If theory allows the electron to have a diameter, it ought also to have a shape. What shape? Is it spherical? Punctiform? There is no experimental information enabling one now to form any consistent geometrical model of the electron. Of course, the electron's charge is assumed to have spherical distribution, as with its magnetic moment. Nonetheless, experimentalists are often prone to treat electrons as points. Again, this issue, like the 'diametral' one above, awaits such tests as the very high energy electron-electron scattering experiments now planned at Stanford.

What about the electron's "solidity"? Again, neither theory nor experiments help. Some theoreticians feel the concept to be meaningless. Others remark that the deeper electron penetration proceeds the more difficult a decision becomes because of the myriad new particles created by the probing particle and the target-electron. Still others think the particle may have a 'solid' central core where some current theories break down (10^{-13} cm.). If this is not the case, then the electron can only be described as a cloud of virtual particles plus a central bare point charge.

Other magnitudes within electron physics are readily determinable. Collisions are understood: there are sound theories within quantum electrodynamics and myriad experiments on electron scattering properties. The electron's rest mass (after 'renormalization') is determinable: $m_0 = 9.1083 \times 10^{-28}$ grams, a quantity confirmed in many divergent types of experiment. But again, the relation between electronic mass and charge is troublesome. (Attempts to understand mass in self-energy terms have been unsuccessful.) The spin-angular-momentum of the electron is always 1/2, again well-established by the Zeeman effect, and other experiments. And quantal transformations of the electron (as theoretically represented in the Lorentz group) require just this spin. The rest energy of the electron is m_0c^2, as disclosed in electron-positron pair production. This energy value determines the development of the electron's state in time. There are no *de facto* negative energies encountered in electron physics. However, negative frequencies make theoretical sense.

All this must be appreciated lest it seem that science's total knowledge of the electron is too slight to permit generalizations about today's matter-concept. A great deal is known about the particle. What is known, however, seems incompatible with classical ideas about matter. Thus, while one can always speak of the state of a classical particle, i.e., its simultaneous position and velocity, nothing like this can even be articulated in quantum theory, wherein the position and momentum operators are managed according to the rule: $PM - MP \cong (h/2\pi i)\,\psi$. This has implications. Is it that physics is just not yet in a position to determine electron states? No. Quantum mechanics is the only theory through which electrons can now be understood at all; that theory excludes the very possibility of forming a consistent concept of an electronic particle's state. Either we speak precisely of its position, or of its momentum. But one cannot speak precisely of both at once. Similarly, we can speak of a person then as a bachelor, and now as married. But we cannot speak of him as being at once married and a bachelor; the reason is analogous to that within microphysics. Conceptual tension results in either case. This is not to say that the tension in both cases is identical: it is not.

This has macrophysical consequences. It is often mooted that the conceptual pain of indeterminacy is restricted to the physics of very tiny and very brief phenomena. Not true. A Geiger counter intercepting β particles from an unstable isotopic source will click in a wholly unpredictable way. Once a particle has been emitted, the counter's click is determined classically. But it remains conceptually untenable to predict when a particle *will* be emitted, and hence when the counter will next click. This is a logical feature of the only available means for understanding intra-atomic phenomena. Indeed, a Geiger counter so arranged constitutes the perfect randomizer. Its macrophysical clicks must be *in principle* unpredictable.

Still further classical properties of matter are jolted in electron theory. Electron solidity is a concept for which there is no relevant quantum theory or experiment. "Being in contact with an electron" has the same null status, although some theoreticians feel sympathetic to the possibility, especially when interpreted in field-theoretic terms. A spectacular departure from classical theory is the process of particle first described in the early 1930's. That particles could "materialize" out of radiation is an idea for which 20th-century physics had no preparation. Joliot and Curie, Millikan and Anderson, Blackett and Occhialini, Fermi and Uhlenbeck, noted oppositely curving cloud-chamber tracks of identical range emanating from a common point within a radiative source. This was a new phenomenon. The mass-energy equivalence had long been known; still, it remained implicit in molar physics that matter could be transformed from this shape to that, or from one state to another — but never could it become other than matter. Nor could it be created from other than matter. This discovery of the positron crushed this assumption. So matter (e.g., electrons) can be created out of energy alone. Yet, when electrons are created, one cannot speak of their states, shapes, or solidity in the familiar molar ways. Furthermore, the theoretical reason for supposing two electrons could not simultaneously occupy the same place is not overpoweringly strong, even though the Pauli exclusion principle has never been experimentally violated. And when an orbital electron is excited in the H-atom, it jumps out to a wider orbit; yet one has no way of speaking of it as having ever been between the orbits. There is no workable concept of an electron's age — (unless it be taken as ∞) — nor any intelligible conception of its density. Again, this is not ignorance comparable to science's limitations concerning Venus. In the latter case, we lack facts; but we know what it would be like to have them. Within electron theory, the limitations referred to are built into the conceptual structure of the theory itself. We do not know now what it would be like to manage electrons as we do, save in terms of the theories and concepts we have actually got. Change the concepts and you change our current theories. But *until* the theories are changed, we must do as they now instruct us to do, namely, abandon earlier notions of the properties of material particles.

All of these points are elaborated in more detail in the Appendix to this paper.

Matter has been dematerialized, not just as a concept of the philosophically real, but now as an idea of modern physics. Matter can be analyzed down to the level of fundamental particles. But at that depth the direction of the analysis changes, and this constitutes a major conceptual surprise in the history of science. The things which for Newton typified matter — e.g., an exactly determinable state, a point shape, absolute solidity — these are now the properties electrons do not, because theoretically they cannot, have.

Matter has been dematerialized, but now more radically than with Berkeley. He showed that, despite ancient epistemic dogmas, primary and secondary properties were in the same conceptual boat. One of his scientific contemporaries could have inferred from the Bishop's analyses that therefore primary properties were just as weak as were the secondaries as indicators of the real properties of matter. He could have concluded this and still continued to do consistent physics. For Berkeley's criticism was abstractly philosophical. It concerned our knowledge of the 'real' properties of matter, as opposed to its physical properties. It left Newtonian mechanics intact and unscathed. Similarly, perplexities of contemporary epistemology have no effect on today's mechanical engineers.

The dematerialization of matter encountered in this century, however, has rocket mechanics at its foundations. As an intra-physical revolution in ideas, this compares with the intra-mathematical revolution initiated by Gödel. Some scientists still think of electrons as point-masses with most of the properties of minute billiard balls — just as some mathematicians still have Formalist (i.e. Hilbertian) hankerings. But how unclear such physicists can be when questioned about the nature of things like β-beam interference patterns.

Either they say nothing at all, or nothing at all intelligible (usually capped with some remark like 'I am an empiricist'). Int he 18th century one could have accepted Berkeley's demonstration of the inadequacy of primary properties as indicators of 'real' matter, and still do consistent physics; much as today a psychologist can grant there are philosophical problems about other minds, and still rely on the verbal responses of his subjects. But the 20th century's dematerialization of matter has made it conceptually impossible to accept a Newtonian picture of the properties of matter and still do consistent physics.

Some will assent to much I have said here, and yet will qualify my conclusion. They may grant that the ancient distinction between primary and secondary properties, like philosophy itself, branched into the natural philosophy of the 17th century, and the pure philosophy of the 18th century — the latter as typified in Berkeley. And an intimate historical connection between the successful growth of atomism in science and the correlative dependence of scientists on some version of the primary-secondary distinction might also be granted. Perhaps it will even be conceded that Berkeley's challenge to this distinction affected only the epistemological branch of the conceptual tree, not its scientific branch. The latter has been affected only by *contemporary* matter theory, wherein any correspondence between the properties matter (e.g. electrons) is now known to have, and the classical 'primary' properties, is at best analogical, and at worst non-existent.

These are my theses thus far. From them, however, some will not conclude, as I do, that modern physics has destroyed our intra-scientific version of the primary-secondary distinction just as Berkeley destroyed its intra-philosophical version. At least one critic will torment the body of my argument by hacking off its tail as follows :

> "Granted, the properties electrons are now known to have, α, β, γ, δ, ... may be different from the properties classically termed 'primary'. *This* does not destroy the primary-secondary distinction. Quite the contrary. For if the electron *has* α, β, γ, δ, ... then, however dissimilar from the classical primaries of philosophy and natural philosophy, then α, β, γ, δ, ... *are* (along with the properties of other particles) the primary properties of matter, whatever they may be. And these primary electronic, (protonic, neutronic) properties contrast with other manifestations of elementary particles and their aggregates, which disclose themselves only *via* interactions between observers and things observed, e.g. manifestations like the colors, tastes and odors of macrophysical objects (which are, after all, but constellations of fundamental particles). Granted, physics has changed the values appropriate for the property-variables α, β, γ, δ, ... still, the primary-secondary distinction remains viable so long as there are good reasons for claiming that fundamental particles *do* have α, β, γ, δ, ... etc. This remains true so long as some properties of aggregates and some properties of components-of-aggregates are distinguishable in that the former result from observer-interaction whereas the latter, however unfamiliar, are such that we have good theoretical reasons for thinking them observer-independent.

> A theory of the electron is a theory about the properties electrons *have*, not a theory describing what bubbles up out of electron-observer interactions. The primary-secondary distinction of classical physics has now become a contrast between the objectifiable and the non-objectifiable properties of microparticles."

This specific criticism gets airborne only *via* a runway of concessions to my general thesis, to establish the plausibility of which has been my only objective here. I disagree with the entire spirit of this criticism and its tendency towards complete objectifiability within quantum theory. (I would indicate why, were there space.) But since there is in this criticism no challenge to the historical point that *our* ideas about the primary properties of particles are different from those of the tradition concerned with primary properties (despite Whewell's contention that no such change could occur), nor any challenge to the further point that Berkeley's attack on the primary-secondary distinction left physicists free to exploit the distinction in their atomistic theories of the 18th and 19th centuries, whereas they are no longer free to do this in the old way — since these main points are unaffected by the contention that the objectifiability-non-objectifiability contrast *is* the same as primary-secondary contrast (with the property-values left unspecified). I will back off with only the grumble that even this contention could be demonstrated as indefensible. But the demonstration must await another occasion.

APPENDIX

The important feature of our electron-positron theory is that it is a quantum-field theory. This means that the fields $\psi(x)$ are operators, rather than functions representing the state of the electron. E.g., $\psi(x)$ creates a positron or destroys an electron and $\psi^{+}(x)$ does the reverse. It is not feasible to describe this theory in detail, but the important physical fact is that in this theory electrons and positrons may be created and destroyed. A high energy γ-ray ($E > 2mc^2$) passing through the Coulomb field of a nucleus can create an electron-positron pair. Such a situation cannot be described by an ordinary wave function; rather it is described by a state vector in an abstract (non-separable) Hilbert space in which the basic states have different numbers of particles. Since the Hamiltonian of the system has matrix elements between these states of different particle number, transitions such as $\gamma \rightarrow e^{+} + e^{-}$ are possible.

A few words about the non-relativistic limit where particle number is conserved and the ordinary wave function is a useful, though approximate, concept:

If the energies involved in a given physical situation are small compared to an electron's rest energy, one encounters this limit. This is the realm of most of atomic physics and chemistry (aside from small relativistic corrections which show up in fine structure, the Lamb shift, etc.). This is ordinary wave mechanics with wave-functions which obey the Pauli exclusion principle — odd under interchange of particle variables. In this realm, certain classical 'primary' questions are simply answered: the electron is intrinsically a point particle with spin one-half and a definite mass. Here "point" means that it is described by a wave function u $(\vec{x},t)$ in which there is no variable for internal structure (other than spin). Intrinsically the electron's charge is located at a point where it has an infinite density (δ-function). Age of an electron has no meaning; solidity has no meaning (can a point be compressed ?); shape has no meaning (does a point have a shape ?). Of course u$(\vec{x}, t)$ gives a probability distribution for such quantities as position, momentum energy. This is ordinary wave mechanics and is well confirmed by experiment (within its proper domain of applicability).

Perhaps an illustration will be helpful.

$P(\vec{x},t) = u\ (\vec{x},t)^2$ is probability distribution for x.

$\rho(\vec{x},t)$ is observable charge distribution

The theory says:

$$\rho(\vec{x},t) = e \qquad P(\vec{x},t) = e \iiint \delta(\vec{x} - \vec{x}') \qquad P(\vec{x}',t)\ d^3x'$$

The $\delta(\vec{x} - \vec{x})$ represents the intrinsic point charge nature of the electron. Conceivably, a different connection could exist between ρ and P, with $\delta(\overline{x - \vec{x}'})$ replaced by $f(\overline{x - \vec{x}'})$, for example, with f a "spread-out" δ-function. Such an f would represent the intrinsic (or, if you like, internal) charge distribution of the electron. The remarkable agreement of atomic spectra with theoretical predictions of wave mechanics indicates that f is a δ-function, or at least has a very small spatial extension. (The Lamb shift, can, in some sense, be interpreted as due to a finite size of the electron).

Let us turn to the more complete theory. It should be emphasized that the word 'electron' is ambiguous; that is, the precise definition of what we mean by 'an electron' or 'a positron' cannot be given without taking into account the interactions of the particle with other fields, such as the electromagnetic field. To illustrate, we might try to write

$$\psi'' \ \psi_{ce+} + \psi_{de-}$$

where ψ_{ce+} creates positrons and ψ_{de-} destroys electrons. It is easy to verify that this separation is not independent of the interaction. For instance, if there is no interaction, one obtains a separation $\psi'_{ce++} + \psi'_{de-}$, (free representation). But if one has a Coulomb potential there is a different separation $\psi''_{ce+} + \psi''_{de-}$, (bound representation). If we try to express the state of a bound electron (say the lowest state) in terms of the free representation, we find that it is a superposition of states of a free electron and various numbers of electron-positron pairs. However, in that case we would adopt the point of view that the bound representation is the proper one and gives the appropriate definition of an electron.

The situation is more complicated when we consider more realistic interactions such as that with the electromagnetic field, which is itself quantized (photons can be created and destroyed). Then we distinguish between "bare" electrons and "physical" electrons. The bare electrons correspond to the free representation in which interactions are neglected. These states form the starting point in perturbation treatments of the interaction. The physical electron state is supposed to contain all the effects of the interaction, and in some sense *is* the state which is produced from the bare electron state when the interactions are "turned on." It has definite mass and spin, but presumably has an intrinsic structure due to the interactions. This structure consists of a cloud of virtual bare photons and bare electron-positron pairs with one extra bare electron (this statement is more a characterization of the mathematical formalism than a meaningful physical statement). In space this structure is supposed to extend a distance of about $\hbar/mc$, and in time about $\hbar/mc^2$. A physical electron has physical dimensions and other properties such as shape, charge density, and distribution of charge (the last three really mean about the same thing). The "age" of an electron plays no great role in the theory: i.e., the behavior of an electron is independent of its age.

This structure of the physical electron due to its interactions has been verified experimentally in many ways: Lamb shift, anomalous moment of electron, effect on hyperfine splitting, and effect on electron scattering from a Coulomb field. This structure comes from a theory in which the fields are local: that is, the intrinsic bare fields are points and the interactions take place at a point. Calculations using this theory give remarkably accurate predictions of the four types of experiments just mentioned — i.e., the internal structure produced by the interactions is well understood. It is conceivable that in addition to this the bare particles could themselves have an intrinsic non-point structure. There is at the moment no evidence for this. However, an important high-energy electron-electron scattering experiment is in progress at Stanford University. With the present theory, the results of that experiment have been predicted in advance. If the experiment agrees with these predictions, it will mean that the electron has no internal structure other than that produced by interactions (I must emphasize that the physical electron has a known structure of dimensions $\sim 10^{-10}$ cm. which can be allowed for in the experiment); of course this statement would have been verified only for distances greater than $\sim 10^{-14}$ cm. Disagreement would mean that the laws of physics at distances less than 10^{-13} or 10^{-14} cm. may be different from our present conceptions. Future experiments will investigate this possible "breakdown of quantum electrodynamics" in even smaller regions of space-time.

To summarize:

(i) Intrinsically the non-interacting electron appears to have no structure at distances greater than 10^{-13} cm. The Stanford experiment will check whether this is true at smaller distances.

(ii) However, the interactions with the quantized electromagnetic field which lead to electron scattering, pair creation, etc. also give the physical electron an internal structure. This structure can (in principle) be computed accurately, and extends to distances of order $\hbar/mc$.

(iii) On a larger scale one may find the uncertainties associated with the manner of formation of the electron's wave packet. The present point of view is that these do not represent the internal structure of the electron.