

Response to M. S. de Bianchi and M. Nauenberg

Art Hobson

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NOTES AND DISCUSSIONS

Quantum fields are not fields; comment on “There are no particles, there are only fields,” by Art Hobson [Am. J. Phys. 81(3), 211–223 (2013)]

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In a recent article,¹ Hobson defends the superiority of the field concept in quantum physics in comparison to the particle concept. His view is that if we acknowledge that the fundamental constituents of physical reality are fields, and not particles, then much of the interpretational difficulties of quantum physics would disappear. However, as will be explained more fully in this comment, quantum fields are no more fields than quantum particles are particles, so the replacement of a particle ontology (or particle and field ontology) by an all field ontology will not solve the typical quantum interpretational problems.

Let us start by considering the main reason why a quantum entity cannot be considered a particle; we will then show that the same argument applies, *mutatis mutandis*, to the field concept. A particle (or corpuscle) is, by definition, a system that is localized in space. This means that if a physical entity is a particle, then, in every moment, it must be characterizable by a specific position (for instance its center-of-mass) in our three-dimensional Euclidean space. Let us call this fundamental attribute *spatiality*.

But if microscopic entities are assumed to obey Heisenberg’s uncertainty principle (HUP), as we know they do, one is forced to admit that the concept of a “microscopic particle” is a self-contradictory one. This is because if an entity obeys HUP, one cannot simultaneously determine its position and momentum and, therefore, one cannot determine—even in principle—how the position of the entity will vary in time. Consequently, one cannot predict with certainty its future locations.

Now, according to the reality criterion formulated by Einstein, Podolsky, and Rosen,² and further refined by Piron and Aerts,^{3–5} the notion of *actual existence* is intimately related to the notion of predictability. That is, a property can be said to be *actual* for a given physical entity if and only if should one decide to observe it, the success of the observation would in principle be predictable in advance with certainty.

According to this general reality (or existence) criterion, one must conclude that a microscopic entity obeying HUP cannot actually possess the property of being always present somewhere in space, as there are no means to predict its spatial localizations with certainty, not even in principle. Therefore, whatever its true nature, a microscopic entity is a *non-spatial* entity, and if only for this reason it cannot be considered a particle.⁵ But then, if quantum entities are not particles, as they are intrinsically non-spatial, what can we say about their nature? Can we affirm, as suggested by Hobson, that these entities are mere fields, that the wave

function ψ_t must be interpreted as a real, space-filling extended field?

The main point of this comment is to show that the wave function cannot describe an actual spatial field. Indeed, although classical fields, contrary to classical particles, are spatially extended entities spread out over space, they are still *spatial* entities. A field is an entity defined throughout space, possessing specific, *actual* properties (for instance, force vectors) at every point. Therefore, a field is as much a spatial entity as a particle. The only difference is that a particle is imagined to possess, at any moment of time, a specific, almost point-like location, whereas a field is imagined to be spread out in space.

Thus, even the classical notion of a field is unable to describe the non-spatial nature of a quantum entity. This becomes even more evident if one considers the situation of several quantum entities. Because of entanglement, the so-called fields of several quantum entities are certainly not fields that can be defined in a three-dimensional space, but only in a higher-dimensional configuration space.

Another way of showing that the wave function ψ_t cannot describe an actual spatial field is to study the notion of *quantum sojourn time*.^{6,7} Indeed, apart from the special case of bound states, one can show that the overall time potentially spent, on average, by a quantum entity in a given volume of space (say a ball of radius r)—defined by $\int_{-\infty}^{\infty} dt \|P_r \psi_t\|^2$, where P_r is the projection operator onto the set of states localized in the ball—is finite for all values of $r < \infty$. This is in contradiction with the hypothesis that ψ_t should describe a space-filling, extended field permanently present in space because if this were the case then such an average total time should be infinite.⁶

It is worth emphasizing that the possibility of understanding quantum non-spatiality is intimately related to the possibility of solving the measurement problem, at least at a conceptual level. Hobson rightly observes that the replacement of the concept of particle by the concept of field cannot solve such a problem, but he fails to consider that both the particle and the field concepts are inadequate because of the measurement issue.

A quantum “field” can certainly be understood in the abstract sense of a “field of potentialities,”—a field of potential properties that can possibly be actualized (in our three-dimensional space) through measurement processes (interactions with measuring apparatuses). This transition from a “potential” mode of being to an “actual” mode of being, where each time only one among countless different possibilities is selected, is at the heart of a quantum measurement

and certainly needs to be considered if one wants to clarify the true nature of quantum entities. In the final analysis, what quantum mechanics teaches us is that not all of physical reality is contained within space as we know it, and that we need to drop the preconception that so-called microscopic “particles” and quantum “fields” would necessarily be spatial entities.^{5,6,8–10}

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¹A. Hobson, “There are no particles, there are only fields,” *Am. J. Phys.* **81**(3), 211–223 (2013).

²A. Einstein, B. Podolsky and N. Rosen, “Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?,” *Phys. Rev.* **47**, 777–780 (1935): “If, without in any way disturbing a system, we can predict with certainty [...] the value of a physical quantity, then there exist an element of physical reality corresponding to this physical quantity.”

³C. Piron, *Foundations of Quantum Physics* (W. A. Benjamin Inc., Massachusetts, 1976).

⁴D. Aerts, “Description of many physical entities without the paradoxes encountered in quantum mechanics,” *Found. Phys.* **12**, 1131–1170 (1982).

⁵M. Sassoli de Bianchi, “Ephemeral properties and the illusion of microscopic particles,” *Found. Sci.* **16**(4), 393–409 (2011).

⁶M. Sassoli de Bianchi, “From permanence to total availability: A quantum conceptual upgrade,” *Found. Sci.* **17**(3), 223–244 (2012).

⁷M. Sassoli de Bianchi, “Time-delay of classical and quantum scattering processes: a conceptual overview and a general definition,” *Cent. Eur. J. Phys.* **10**(2), 282–319 (2012).

⁸D. Aerts, “The stuff the world is made of: Physics and reality,” in *The White Book of ‘Einstein Meets Magritte’*, edited by Diederik Aerts, Jan Broekaert and Ernest Mathijs (Kluwer Academic Publishers, Dordrecht, 1999), pp. 129–183.

⁹D. Aerts, “The entity and modern physics: the creation-discovery view of reality,” in *Interpreting Bodies: Classical and Quantum Objects in Modern Physics*, edited by Elena Castellani (Princeton U.P., Princeton, 1998), pp. 223–257.

¹⁰M. Sassoli de Bianchi, “The δ -quantum machine, the k -model, and the non-ordinary spatiality of quantum entities,” *Found. Sci.* **18**(1), 11–41 (2013).

Comment on “There are no particles, there are only fields,” by Art Hobson [*Am. J. Phys.* **81**, 211–223 (2013)]

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In his recent AJP article,¹ Art Hobson writes that “there are overwhelming grounds to conclude that all the fundamental constituents of quantum physics are fields rather than particles. Rigorous analysis shows that, even under a broad definition of ‘particle,’ particles are inconsistent with the combined principles of relativity and quantum physics... We conclude that ‘particles’ cannot ever be localized. To call a thing a ‘particle’ when it cannot ever be localized in any finite region is surely a gross misuse of that word.”

To most physicist, however, it will come as a big surprise to learn that the fundamental entities that we call elementary particles cannot be localized. For example, it is well known that in the ground state of the hydrogen atom, the probability of finding the electron in an interval $(r, r + dr)$, where r is the relative distance between the electron and the proton, falls off exponentially, and becomes negligible after r is a few Bohr radii in magnitude. But this probability density is never *identically* equal to zero because the exponential function remains finite for $r < \infty$.

It turns out that a similar mathematical condition is Hobson’s rationale for his claim that particles cannot be localized, based on an unphysical definition of localization: “a presumed particle is said to be ‘localized’ at t_0 if it is prepared in such a way as to ensure that it will upon measurement be found, with probability 1, to be within some arbitrarily large but finite region V_0 at t_0 .”¹ Such a restriction, however, does not apply to physical states associated with

elementary particles, which must be represented by continuous and differentiable wave functions.² Also, contrary to his assertion, free particles, even when moving at relativistic speeds, can be very well confined by wave-packets consisting of a coherent superposition of unbounded plane waves that conform with Heisenberg’s uncertainty relation. There have been innumerable experiments measuring accurately the velocity of elementary particles by determining the time elapsed between signals at two detectors separated at a fixed distance. But such measurements would be impossible if particles could not be accurately localized.³ In passing, Hobson admits, without comment, that atoms in a solid are localized,⁴ without recognizing that atoms are composite particles. Moreover, macroscopic particles are also governed by the laws of quantum mechanics, and even the motion of astronomically large objects, like planets and stars, can also be described by Schrödinger’s equation.⁵

Concerning the proverbial two slit experiment—the classic signature of wave particle duality—which has now been carried out with carbon-60 molecules, each having a diameter (~ 1 nm) about 350 times the mean wavelength in the experiment.^{6,7} Hobson asks: “How does one quantum get information as to how many slits are open? If a quantum is a field that is extended over both slits, there’s no problem. But could a particle coming through just one slit obtain this information by detecting physical forces from the other relatively distant, slit?” It is meaningless, however, to pose

questions in terms of *forces*, because such questions make sense only when the motion is governed by Newton's classical laws. In quantum mechanics, on the other hand, the motion of a particle is described by a wave function ψ , and the front of this function must spread over both slits in order for the outcome to exhibit the characteristic interference pattern that builds up when numerous identically prepared particles impact *locally* on a screen behind the slits (see Hobson's Fig. 1). Before a particle reaches the screen, it is somewhere in a macroscopic volume containing the source, the slits, and the screen. But it remains localized inside this volume, and it is detected in a point like region on the screen due to a macroscopic amplification of its interaction with a localized atom on the screen. In quantum mechanics this phenomenon is described by the interaction of a well localized particle with the atom.

Hobson then proceeds to discuss "nonlocality as arguably the characteristic quantum phenomenon." He quotes Einstein who noted, during the 1927 Solvay Conference, that "a peculiar action-at-a-distance must be assumed to take place" when the Schrödinger field for a single quantum passes through a single slit, diffracts in a spherical wave, and strikes a detection screen. Since the interaction of the quantum with the screen is localized, Einstein worried that the entire wave instantly collapses over the rest of the screen, contradicting his postulate of special relativity. But Einstein's concern was unjustified because the Schrödinger wave function is a mathematical abstraction, and not a physical field in the manner originally envisioned by Louis de Broigle and later also by David Bohm.⁸ Of course, a physical field like the classical electromagnetic field cannot collapse instantaneously, because in this case any change in the electric or magnetic field at one point in space-time induces changes in these fields at nearby points that propagate with the speed of light, in accordance with Maxwell's equations. In contrast, however, after the interaction of a particle with an atom in the detector, leading to an irreversible macroscopic amplification, an abstract wave function ψ that neglects these effects ceases to be relevant (like any probability function after one of the possible outcomes has occurred), i.e. nothing physical, or material, "collapses."

Hobson also asserts that Einstein's EPR paper "anticipated nonlocality of two entangled quanta." but he does not discuss what is meant by nonlocality in this context. The meaning is attributed to John Bell, who proved with his now famous inequality that a *local* "hidden variable" theory of two-particle entanglement cannot reproduce the predictions of quantum

mechanics, but that this is still possible with a *nonlocal* classical theory.⁹ It does not follow, however, as Hobson claims, that quantum correlations, which are based on fundamental *local* interactions, lead to nonlocality as a characteristic quantum phenomenon. Instead, it means that some of our cherished notions from classical physics, e.g., that *unobserved* particles occupy definite positions and/or have definite polarizations in space-time, and conclusions based on classical correlations, have to be abandoned.

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¹A. Hobson, "There are no particles, there are only fields," *Am. J. Phys.* **81**, 211–223 (2013).

²For example, in non-relativistic quantum mechanics it is well known that momentum is represented by a differential operator $-i\hbar\partial/\partial x$, but this is meaningless at any point where a wave-function is discontinuous. In Sec. V of Ref. 1, Hobson refers to two rigorous "no-go theorems" purporting to demonstrate that the existence of localized particles leads to a contradiction between special relativity and quantum mechanics. While such proofs may be mathematically correct, the premises about localization, as we have indicated here, are unphysical.

³The most recent and highly publicized experiments were the measurements of the speed of neutrinos produced at a target in CERN, and detected 730km away at Gran Sasso. The width of the neutrino wave packet was approximately 10 cm (localization length), as determined by the width of the pulse of protons that produced the neutrinos at CERN. Initial experiments appeared to indicate that the neutrino speed was faster than the speed of light, but these results turned out to be incorrect; see, M. Anonello *et al.*, "Measurement of the neutrino velocity with the ICARUS detector at the CNGS beam," *Phys. Lett.* **13**, 17–22 (2012).

⁴In Sec. IV A or Ref. 1, Hobson writes: "This shows that a quantum can interact locally with atoms, but it doesn't show that quanta are point particles. A large object (a big balloon, say) can interact quite locally with another object (a tiny needle, say). The localization seen in the two figures is characteristic of the detector, which is made of localized atoms, rather than of the detected quanta. The detection, however, localizes ("collapses"—Secs. IV B and IV C) the quantum."

⁵M. Nauenberg, "Quantum wavepackets on Kepler elliptic orbits," *Phys. Rev. A* **40**, 1133–1136 (1989); "Wave packets: Past and Present" in *The Physics and Chemistry of Wave Packets*, edited by T. Uzer and J. Yeazell (Wiley, New York, 2000), pp. 1–29.

⁶M. Arndt, O. Nairz, J. Vos-Andreae, C. Keller, G. van der Zouw, and A. Zeilinger, "Wave-particle duality of C₆₀ molecules," *Nature* **401**, 680–682 (1999).

⁷O. Nairz, M. Arndt, and A. Zeilinger, "Quantum interference experiments with large molecules," *Am. J. Phys.* **71**, 319–325 (2003).

⁸D. Bohm, "A suggested interpretation of the quantum theory in terms of 'hidden' variables I," *Phys. Rev.* **85**, 166–179 (1952); "A suggested interpretation of the quantum theory in terms of 'hidden' variables II," *Phys. Rev.* **85**, 180–193 (1952).

⁹J. Bell, "On the Einstein-Podolsky-Rosen Paradox," *Physics* **1**, 195–200 (1964). Reproduced in *Speakable and Unsayable in Quantum Mechanics* (Cambridge U.P., 1987), pp. 14–21.

Response to M. S. de Bianchi and M. Nauenberg

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I thank M. S. de Bianchi and M. Nauenberg for their comments. Each makes four points. Each of the following paragraphs responds to one of those points.

de Bianchi's paragraphs 2–6 comprise his first point. He states (paragraph 5) that, "A microscopic entity obeying HUP cannot actually possess the property of being always

present somewhere in space,” and “Whatever its true nature, a microscopic entity is a *non-spatial* entity.” It is clear from de Bianchi’s letter, from his Ref. 5, and also from the work of D. Aerts referenced therein, that he defines a “non-spatial entity” as an entity that always exists but that does not exist in space-time except when it is momentarily “pulled” into space-time by interacting with a macroscopic detection apparatus. This notion that electrons and photons, not to mention other quanta such as molecules, spend most of their existence residing somewhere outside of space-time is unusual, to say the least. Do molecules reside in space and time only when they are observed? In claiming that electrons and photons do not always reside in space-time, de Bianchi makes one of those extraordinary claims that, as Carl Sagan put it, requires extraordinary evidence. de Bianchi’s only evidence is EPR’s reality criterion. However, this criterion for “reality” is not the only one possible. In fact, the EPR paper (de Bianchi’s Ref. 2) states quite sensibly that “this criterion, while far from exhausting all possible ways of recognizing a physical reality, at least provides us with one such way.” Furthermore, de Bianchi claims the EPR criterion to be both a necessary and sufficient (“if and only if,” paragraph 4) condition for a property to be real, while EPR and common sense recognize it as only a sufficient condition. It is not, as de Bianchi claims, a necessary condition. In other words, a property’s reality does not necessarily imply that the property is predictable. For example, the decay of a nucleus is surely a real event, but it is not predictable. Thus, we cannot conclude, on the basis of the uncertainty principle and EPR’s reality criterion, that quanta reside outside of space-time.

In his fourth paragraph from the end, de Bianchi argues that an N -body quantum system requires a $3N$ -dimensional configuration-space description, and that this again implies quantum entities cannot be fields in 3-dimensional space. The higher-dimensional description is the mathematical reflection of entanglement, according to which a 2-quantum (“2-particle”) wavefunction cannot necessarily be written as the product of two 1-quantum wavefunctions. But entanglement does not mean that quantum physics occurs somewhere beyond normal space-time, any more than the $6N$ -dimensional phase-space distribution functions of classical statistical mechanics mean that these systems lie beyond normal space-time. Like most of mathematical physics, the configuration-space representation is abstract, but it represents events happening in real space-time, not somewhere beyond space and time.

Regarding the “sojourn time” argument (third paragraph from the end), de Bianchi’s comment does not provide enough detail to evaluate his claim. Turning to his Ref. 6, it turns out that the quantity $\|P_r \psi\|^2 \equiv f(r,t)$ is the probability for an N -quantum system to be found, at time t , within a $3N$ -dimensional ball in configuration space that is centered at the origin and has $3N$ -dimensional radius r . Reference 6 claims the following: (1) The integral of $f(r,t)$ over all time is the overall average time that the quantum system spends within the ball, (2) this time is finite for all $r < \infty$, and (3) this contradicts the notion that ψ describes a space-filling field because the average total time should be infinite for any space-filling field. I see no reason for any of these 3 claims. In fact, it is easy to disprove claim (2). Suppose that ψ is such that, for some particular value of r , $f(r,t) = b$ for all time, where b is a fixed number with $0 \leq b \leq 1$ (because $f(r,t)$ is a probability). Such wave functions are not hard to find.

But for such a wave function the integral of $f(r,t)$ over all time is infinite.

In his final two paragraphs, de Bianchi argues that “both the particle and field concepts are inadequate because of the measurement issue.” But he fails to give any specific reason why this is so. I will grant that measurement is a serious problem for quantum physics, but I do not see why it delegitimizes the field concept.

Regarding Nauenberg’s response, Hegerfeldt’s theorem says that the absolute localization of a single quantum such as an electron is impossible because it would contradict Einstein causality: the electron could be found arbitrarily far from the original localization region at any arbitrarily short time following the time at which it was inside that region. Nauenberg argues that such *absolute* localization (zero probability of finding the electron outside some finite region) is “unphysical” and “does not apply to physical states associated with elementary particles.” But this is just my point: absolute localization is inconsistent with the states of elementary quanta. Hegerfeldt’s theorem establishes this as a fundamental matter of principle. The infinitely long exponential tails that Nauenberg is willing to ignore because their probability “becomes negligible” are important matters of principle. Such tails, whether exponential or not, must exist. Thus I return to my original point: it is unwise and unreasonable to call a thing a “particle” when, as a matter of fundamental principle, it must always spread over an infinite spatial region.

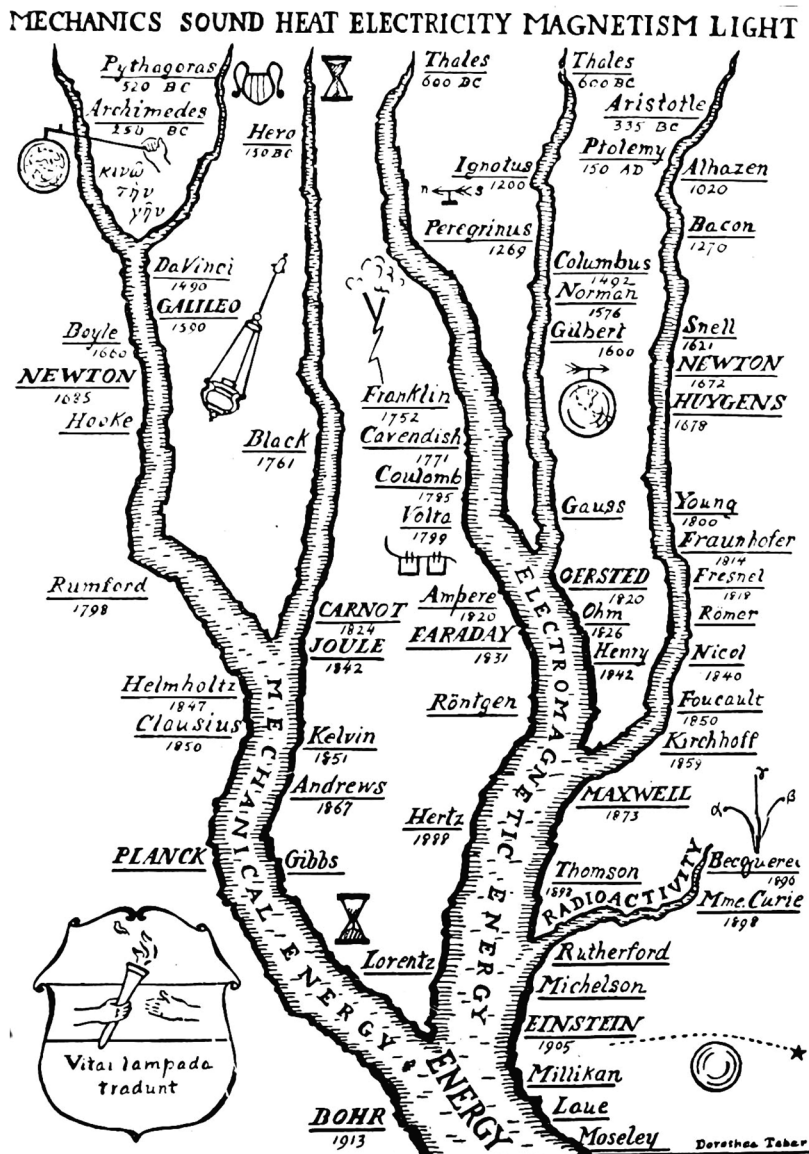
Nauenberg argues that it is meaningless to pose questions in terms of forces because forces make sense only in the context of Newton’s laws. But surely we can speak of Coulomb forces and other forces when analyzing the motion of electrons and other quanta. Granted, the “particle” (the quantum) is always described by a wave function, rather than by a specific classical position. This is the point of my article: each individual quantum is a wave as described by its wave function. My argument about the two-slit experiment is: each individual quantum responds to the fact that both slits are open; this cannot be due to any long-distance force (or call it an “interaction” or a “potential” if you don’t like the word “force”) that extends over the distance from one slit to the other. Thus each quantum must come through both slits.

I of course disagree with Nauenberg’s contention that “Einstein’s concern [about nonlocal connections] was unjustified, because the ... wave function is a mathematical abstraction, and not a physical field.” A central point of my paper is that the wave function is a physical field (note that Einstein calls it the “Schrodinger field,” a far better term than “wave function”)—e.g., the wave function of an electron *is* the electron. In fact my paper’s sub-section titled “Single-quantum nonlocality” shows that Einstein’s concern was justified. Something real and nonlocal does occur when a single-quantum wave packet collapses. However, it turns out that, as discussed in my paper, nonlocality delicately manages to avoid contradicting special relativity, resolving the problem that was of concern to Einstein.

Regarding Nauenberg’s final paragraph, entangled states of two-quantum systems imply non-local correlations between the systems, and these correlations violate Bell’s inequality. This violation means that the correlations are too tightly dependent on the non-local phase relationship (a relationship that can be instantly changed at either system) between the two systems to be explainable by purely local means. So such correlations do, contrary to Nauenberg’s

assertion, lead to nonlocality as a characteristic quantum phenomenon. It is true, as Nauenberg says in his final sentence, that some of our cherished notions from classical

physics, e.g., that unobserved particles occupy definite positions, must be abandoned. This is because the so-called "particles" are actually infinitely extended fields.



Map of Physics

This map of the land of physics was drawn by the artist Dorothea Taber (b. 1887). The physicists are arranged chronologically and end with Bohr (1913), Laue and Moseley. Look for Galileo's pendulum, Franklin's cloud and kite, Gilbert's magnetic model of the earth, Einstein's deflection of star light, Archimedes' lever (to move the earth), and the deflection of alpha, beta and gamma rays in magnetic fields, (Notes and photograph by Thomas B. Greenslade, Jr., Kenyon College)