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A CASE OF ENTITY REALISTS USING ABDUCTIVE CONFIRMATION

(Un caso de realistas de entidades que recurren a la confirmación abductiva)

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Keywords

Abduction
Action potential
Confirmation
Entity realism
Hacking
Hodgkin
Huxley

ABSTRACT: The paper has three objectives. First, it argues that Hodgkin, Huxley, and Katz were entity realists who confirmed the existence of specific entities by abduction. Second, it outlines a theory of this abductive reasoning. Third, it shows how the case is a counterexample to Hacking's contention that experimentalists do not accept abductive evidence. The paper is not a "mere counterexample" paper, as it outlines a positive account of how to understand Hodgkin, Huxley, and Katz's abductive reasoning and their entity realism. This single case invites the question of how many more such cases are to be found.

Palabras clave

Abducción
Potencial de acción
Confirmación
Realismo de entidades
Hacking
Hodgkin
Huxley

RESUMEN: Este artículo tiene tres objetivos. Primero, argumenta que Hodgkin, Huxley y Katz fueron realistas de entidades que confirmaron la existencia de entidades específicas mediante la abducción. Segundo, esboza una teoría de este razonamiento abductivo. Tercero, muestra cómo este caso constituye un contraejemplo a la afirmación de Hacking de que los experimentalistas no aceptan la evidencia abductiva. El artículo no es un mero contraejemplo, ya que presenta una explicación positiva de cómo comprender el razonamiento abductivo de Hodgkin, Huxley y Katz y su realismo de entidades. Este caso particular invita a preguntarse cuántos casos similares existen.

Gako-hitzak

Abdukzioa
Ekintza-potentziala
Berrespena
Entitate-errealismoa
Hacking
Hodgkin
Huxley

LABURPENA: Artikulu honek hiru helburu ditu. Lehenik eta behin, argudiatzen du Hodgkin, Huxley eta Katz entitate-errealistak zirela eta entitate jakin batzuen existentzia abdukzio bidez berretsi zutela. Bigarrenik, abdukzio bidezko arrazoibide horren teoria bat laburbiltzen du. Hirugarrenik, erakusten du kasu hau kontradibide bat dela Hacking-en harako baieztapen hartarako, alegia, esperimentalistek ez dutela abdukzio bidezko ebidentziarik onartzen. Artikulua ez da «kontradibide soil» bat; izan ere, Hodgkin, Huxley eta Katzen abdukzio bidezko arrazoibidea eta haien entitate-errealismoa ulertzeko moduari buruzko azalpen positibo bat ematen du. Kasu zehatz honek galdera egitera garamatza antzeko beste zenbat kasu aurki litezkeen.

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Around the middle of the twentieth century, Alan Hodgkin, Andrew Huxley, and Bernard Katz came to believe that action potentials are associated with specific entities, namely, changes in axonal membrane permeability and ion fluxes through that membrane. They were realists about these entities. Through their experimental work, they supported these beliefs even though, given the technology of their day, they could not observe the changes in the membrane or the movements of sodium ions. Instead, they supported these beliefs using abductive reasons. They believed in changes in membrane permeability and ion fluxes, because those unobserved changes and fluxes explained the changes in the electrical potential across the axonal membrane. In brief, Hodgkin, Huxley, and Katz were entity realists who used abductive confirmation.

The primary objective of this paper is to draw attention to this case. Many recent discussions of entity realism do not consider such cases.[1] Further, the existence of one case raises the question of whether there are others. A secondary objective is to outline more explicit theories of Hodgkin, Huxley, and Katz's thinking. These physiologists obviously do not explicitly claim that they are entity realists who have confirmed the existence of unobserved entities using abduction. Historians and philosophers of science must, therefore, draw attention to features of Hodgkin, Huxley, and Katz's experiments, their reasoning, and their commentary on their work, to show that they were implicitly entity realists who used abductive confirmation. A tertiary objective is to draw attention to the implications of this case for Ian Hacking's views regarding entity realism and confirmation. Hacking suggests that scientists do not confirm the existence of unobservable entities using abductive reasons. Instead, they confirm them by manipulating them to reason about other entities.

This paper is organized according to the foregoing three objectives. Section 1 will briefly review some of Hodgkin, Huxley, and Katz's experimental work from 1939 to 1949, making the case that they believed in specific unobserved entities for abductive reasons. Section 2 will outline a theory of abduction and entity realism that characterizes what is implicit in Hodgkin, Huxley, and Katz's work. This means that Hodgkin, Huxley, and Katz's work will serve as more than a "mere counterexample" to theses by Hacking. Their work motivates a theory of scientific ontology and methodology. Finally, section 3 will relate the Hodgkin-Huxley-Katz case to Hacking's views on entity realism and confirmation.[2]

1. Hodgkin, Huxley, and Katz on the Action Potential

The work discussed here is Hodgkin, Huxley, and Katz's research on the biophysical basis of the neuronal action potential published between 1939 and 1949. Section 1.1 will review an experiment by Hodgkin and Huxley, which they took to support the conclusion that there is an "overshoot" in the action potential, thereby challenging Julius Bernstein's "membrane hypothesis". Section 1.2 will review an experiment by Hodgkin and Katz, which they took to support the conclusion that sodium influx is responsible for the initial inward current of the action potential. These two experiments form part of the backdrop to the series of five papers by Hodgkin, Huxley, and Katz published in 1952. These latter papers led to Hodgkin and Huxley sharing the 1963 Nobel Prize in Medicine or Physiology with John Eccles.

1.1. Hodgkin and Huxley 1939-1945

In 1939, the accepted view of the neuronal action potential was due to Bernstein. On his view, at rest, the interior of the axon is more negative than the exterior. There is, Bernstein proposed, an imbalance of ions across the membrane.

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1 See Eronen (2019), Khalili (2023, 2024), Khalili & Kazemi (2025), Nanay (2019, 2022), and Patton (2025).

2 Aizawa & Headley (2022, 2025) broaches the thesis that Hodgkin and Huxley used abductive reasoning. Aizawa (2025) adds to this a more elaborate theory of how Hodgkin and Huxley connected abduction and confirmation. Aizawa (forthcoming) shows how the theory of abduction applies to Jacobus van 't Hoff's theory that carbon atoms have a tetrahedral structure. The present work indicates how this earlier work bears on entity realism and Hacking's views on the confirmation of unobserved entities, a topic not discussed in earlier work.

With a sufficiently large depolarization of the axon, however, he further proposed that there is a temporary breakdown in the axonal membrane's resistance to the flow of ions. As a result, ions flow through the membrane down their concentration gradients and approach an equilibrium. In other words, one of the physical consequences of this proposal was that careful measurements of the action potential would yield a curve like that shown in the left half of Figure 1, wherein the action potential would "peak" near zero.

In 1939, Hodgkin and Huxley managed to insert microelectrodes into the recently discovered squid giant axons and obtain more precise measurements of the action potential.[3] These measurements revealed a dramatic "overshoot" of the action potential, as shown in the right half of Figure 1. Note that another common way of describing this result was to say that the action potential exceeded the resting potential. Still another way of describing the result was to note that the potential reverses from the resting state, in which the axon is more negative on the inside than on the outside, to an active state in which the axon is more positive on the inside than on the outside. It is important to note these alternative descriptions since Hodgkin, Huxley, and Katz used them in quotes provided below. Although Hodgkin and Huxley did not comment upon it in 1939, they appreciated that this experimental result challenged the membrane hypothesis.[4]

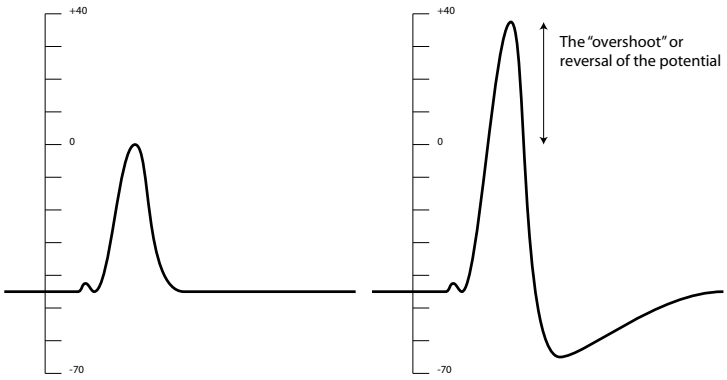


Figure 1

Action potential expected on Bernstein's hypothesis (left)
and action potential as measured in Hodgkin & Huxley, 1939 (right)

In 1945, following the interruption of World War II, Hodgkin and Huxley returned to measuring the action potential, further confirming its overshoot. In the introduction to their paper, Hodgkin and Huxley comment,

> A method of inserting microelectrodes into squid axons was developed, and direct measurements of action and resting potentials were obtained in the summer of 1939 (Hodgkin & Huxley, 1939). At about the same time, Curtis & Cole (1940) evolved a rather different technique for performing the same experiment, and in a subsequent paper (Curtis & Cole, 1942) concluded that the action potential exceeds the resting potential by a large amount. The present paper provides an independent confirmation of this conclusion and extends it to crustacean nerve fibres. (Hodgkin & Huxley, 1945, p. 176)

Note Hodgkin and Huxley's claim to be providing confirmation. In performing further experiments, Hodgkin and Huxley concluded that "The difference between action and resting potentials is too large to be explained by a liquid

[3] See Hodgkin & Huxley (1939).
[4] See Hodgkin (1994).

junction potential between the axoplasm and the microelectrode. It must be due to a genuine reversal of potential at the surface membrane of an active section of nerve" (Hodgkin & Huxley, 1945, p. 194).[5] Note here the invocation of explanation in connection with disconfirmation of the hypothesis that the difference is due to a liquid junction potential.

1.2. Hodgkin and Katz, 1946-1949

In the fall of 1946, Katz told Hodgkin about a forthcoming paper of his reporting that crab axons were inexcitable in sodium-free media. This inspired Hodgkin and Katz to examine the role of extracellular sodium in squid giant axons during the summer of 1947. The results of this work were published in (Hodgkin & Katz, 1949) and presented the first formulation of the Hodgkin-Huxley-Katz theory of the action potential.

The theory in (Hodgkin & Katz, 1949), in outline, proposed that an action potential has two phases. See Figure 2. In the first phase, lasting about a millisecond, the stimulation of the axon quickly increases the sodium permeability of the membrane, allowing excess extracellular sodium to enter the axon. This drives the initial "upward" shift and overshoot/reversal of the action potential. In the second phase, the sodium permeability decreases and the potassium permeability increases. With the increase in potassium permeability, potassium flows down its concentration gradient, exiting the cell. This drives the later "downward" shift of the action potential. As Hodgkin and Katz observed, "A simple consequence of the hypothesis is that the magnitude of the action potential should be greatly influenced by the concentration of sodium in the external fluid" (Hodgkin & Katz, 1949, p. 38). This is what they proposed to investigate. The following discussion will, therefore, largely set aside the role of potassium efflux and the change in potassium membrane permeability.

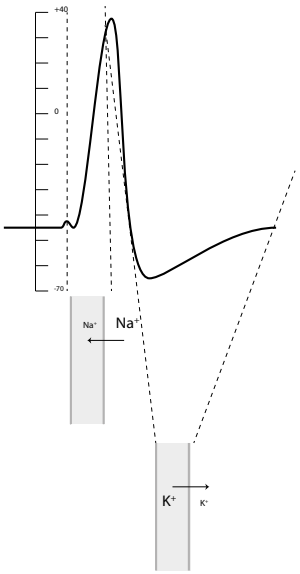


Figure 2

The 1949 Hodgkin-Huxley-Katz theory of the basis of the action potential.
NB, the scale here follows the convention used in (Hodgkin & Katz, 1949), rather than contemporary conventions

[5] A liquid junction potential is a potential difference that arises at the interface of two solutions of different ionic compositions. In the case at hand, there was one solution in the axoplasm and another in the microelectrode. Although Hodgkin and Huxley did not know the exact constituents of the axoplasm and hence did not know the precise value of the junction potential, they claimed that their estimates were smaller than could be used to explain the measured reversal potential.

(Hodgkin & Katz, 1949) reports on several experiments; however, for present purposes, it will suffice to review their second one. In this experiment, Hodgkin and Katz depolarized an axon in three different conditions: 1) the standard seawater solution (containing sodium), 2) a reduced sodium solution (33% sea water, 67% isotonic dextrose), and then again 3) the standard seawater solution (containing sodium). For ease of reference, call this the "three-curve experiment". This experiment is representative of the other experiments in (Hodgkin & Katz, 1949) insofar as it examines action potentials in different media over time.[6]

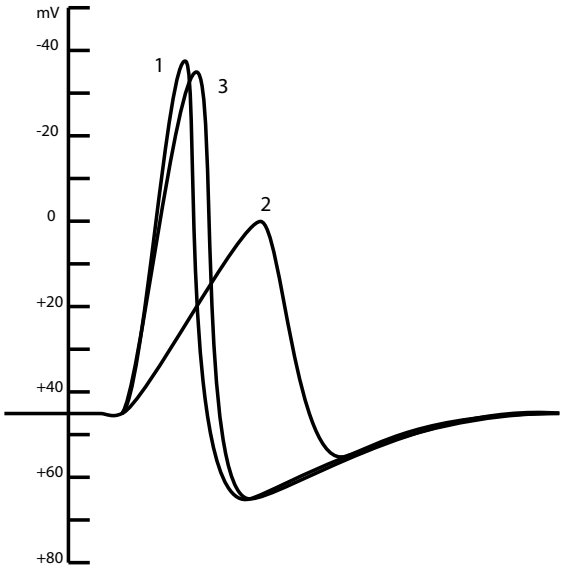


Figure 3

Action of sodium-deficient solutions on the resting and action potential. 1, response in seawater; 2, after 16 min. in 33% seawater, 67% isotonic dextrose; 3, 13 min. after reapplication of sea water. (Redrawn from (Hodgkin & Katz, 1949, p. 48, Figure 4.1a)).

For present purposes, the principal observations from this experiment are 1) that, in the reduced-sodium medium, the action potential has a lower peak (i.e., the peak is at 0 mV rather than near -40mV) and 2) that the time to reach this lower peak is delayed (i.e., the peak is shifted to the right). To appreciate Hodgkin and Katz's thinking about their experimental work, consider some of the commentary they offered on it. In the second paragraph of their paper, they write, "According to the membrane theory excitation leads to a loss of the normal selectively permeable character of the membrane, with the result that the resting potential falls towards zero during activity. This aspect of the theory is at variance with modern observations and must be rejected" (Hodgkin & Katz, 1949, p. 38). This is the conclusion based on the Hodgkin-Huxley work from 1939-1945, namely, that Bernstein's membrane theory is incorrect. It is not based on the three-curve experiment described in the preceding paragraph. Next, they comment: "However, a large reversal of membrane potential can be obtained if it is assumed that the active membrane does not lose its selective permeability, but reverses the resting conditions by becoming highly and specifically permeable to sodium. ... The essential point in the hypothesis is that the permeability to sodium must rise to a value which is much higher than that to potassium and chloride" (Hodgkin & Katz, 1949, p. 38). The "reversal of membrane potential" refers to the overshoot reported in (Hodgkin & Huxley, 1939), shown in the right half of Figure 1. The comment points to the existence of a change in

[6] Because of space limitations, it is left to the reader to verify that the three-curve experiment is representative of the other experiments in Hodgkin & Katz (1949), that the three-curve experiment is not cherry-picked.

membrane permeability. This is reinforced by the following: "The hypothesis ... presupposes the existence of a special mechanism which allows sodium ions to traverse the active membrane" (Hodgkin & Katz, 1949, p. 38). Finally, in the summary of their paper, Hodgkin and Katz write,

> The reversal of membrane potential during the action potential can be explained if it is assumed that the permeability conditions of the membrane in the active state are the reverse of those in the resting state. The resting membrane is taken to be more permeable to potassium than sodium, and the active membrane more permeable to sodium than to potassium. A reversed membrane potential can arise in a system of this kind if the concentration of sodium in the external solution is greater than that in the axoplasm.
>
> This hypothesis is supported by the following observations made with a microelectrode in squid giant axons:
>
> 1. The action potential is abolished by sodium-free solutions, but returns to its former value when sea water is replaced.
>
> 2. Dilution of sea water with isotonic dextrose produces a slight increase in resting potential, but a large and reversible decrease in the height of the action potential. (Hodgkin & Katz, 1949, p. 73)

Note, in the first sentence, that Hodgkin and Huxley take themselves to have an explanation of the reversal potential. In this text, 1. refers to Hodgkin and Huxley's first experiment (which has not been discussed here), whereas 2. refers to the three-curve experiment. (The present discussion does not address the slight increase in resting potential.)

This commentary indicates that, based on the experiments reported in 1939 and 1945, Hodgkin and Huxley drew three principal conclusions. First, Bernstein's theory of the action potential was not correct. Second, there exists an action potential (which was never seriously in doubt at that time) with an overshoot/reversal in potential (which they take to have been established by 1945). Third, there exists a change in membrane permeability to sodium and the movements of sodium ions into the cell during the initial phase of the action potential.

2. Hodgkin, Huxley, and Katz's Abduction and Entity Realism

The preceding discussion of Hodgkin, Huxley, and Katz's experimental work was meant to present the science in terms that are relatively neutral with respect to the philosophical theories to be presented in this section. This section presents theories of abduction and entity realism that are meant to accurately describe Hodgkin, Huxley, and Katz's experimental work. Section 2.1 will introduce the theory of abductive confirmation and disconfirmation whereas Section 2.2 will introduce the theory of entity realism. As noted in the introduction, this combination of scientific views has not been discussed in the literature on entity realism.

2.1. Hodgkin, Huxley, and Katz's Abduction

To start, consider some general features of how the term "abduction" is understood here. The proposal is that abduction is inferring some hypothesis H because H explains some evidence E. This interpretation does not embrace some of the more common interpretations of "abduction".

First, one should distinguish between what is here meant by "abduction" and what Gilbert Harman meant by "inference to the best explanation" (IBE).[7] For Harman, inference to the best explanation is *warranted* abduction, and ab-

[7] There are, of course, other versions of IBE, such as those in Lipton (2004), Bird (2022), and Davey (forthcoming), to name but a few. Present space limitations prevent an examination of them.

ductive inferences are warranted when one is able to reject all the rival hypotheses.[8] Moreover, for Harman, there is an open-ended list of considerations that one might use to reject rival hypotheses. These considerations include simplicity, plausibility, breadth, and so forth. To put matters in another way, Harman's IBE is meant to answer two questions. Question 1: What reason is there to believe H? Answer 1: H explains E.[9] Question 2: Why think that H is the correct explanation, rather than H'? Answer 2: There could be many reasons, such as H is simpler than H', H has a broader scope than H', and so forth. By contrast, and consistent with Harman's view, what is here meant by "abduction" is merely part of this story. "Abduction", as used here, just implicates H's explaining E. To put this matter another way, abduction, as understood here, does not compare rival hypotheses in the way that IBE does.[10]

Second, "abduction" is not meant to be the same as "Peircean abduction"; it is not meant to be used as Peirce is commonly taken to have used it.[11] According to a common reading of Peirce, scientists use abduction to introduce (pursuit-worthy) new hypotheses that are subsequently confirmed using hypothetico-deductive methods.[12] The proposal in this paper is that Hodgkin, Huxley, and Katz use abduction to confirm hypotheses in the sense that abduction gives a reason to believe some hypothesis, even when those reasons may not amount to *compelling reasons*. They are reasons that, to critics, may not justify belief in hypothesis H. Indeed, even a scientist who proposes that H explains E may not take that reason to be strong enough to justify belief.

Third, and perhaps most germane for the present discussion, "abduction" is not used as Hacking uses it in (Hacking, 1983). Although Hacking has very little to say about abduction, he does say this: "The idea of 'inference to the best explanation' is quite old. C.S. Peirce (1839–1914) called it the method of hypothesis, or abduction. The idea is that if, confronted by some phenomenon, you find one explanation (perhaps with some initial plausibility) that makes sense of what is otherwise inexplicable, then you should conclude that the explanation is probably right" (Hacking, 1983, p. 52). So, Hacking identifies abduction and IBE, whereas that is not the proposal here. Further, Hacking expresses this as a normative claim (presumably for scientists, and not just philosophers) about what one should conclude. In this paper, abduction is not understood that way. The concept of "abduction" is intended here to describe some instances of scientific reasoning without any normative commitment. It is used for sociology of science.

Hodgkin and Katz's reasoning was not just any old type of abductive reasoning. It was not like thinking that a deer walked through the snow here, because that explains the marks in the snow. That would be causal abduction, because the deer walking through the snow provides a causal explanation of the marks in the snow. Instead, Hodgkin and Katz's reasoning was compositional: the change in membrane potential during the course of the action potential was compositionally explained by the change in the number of charges inside and outside of the axon. The potential was composed, or made up of, the balance of internal and external charges.[13] A theory of abduction involves a theory of explanation. So, a theory of causal abduction involves a theory of causal explanation, and a theory of compositional abduction involves a theory of compositional explanation.[14]

The theory of compositional explanation proposes that, in the explanations Hodgkin, Huxley, and Katz invoked, the explanans entities ontologically determine the explanandum entities.[15] Thus, for Hodgkin and Katz, the explanation of the action potential by the movements of ions across the membrane presupposes that the movements of ions across the

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8 N.B., Harman does not explain what he means by "warrant".

9 In many formulations of IBE, the proposal is that H potentially explains E. That refinement does not change the principal point here.

10 See Dellsén (2024).

11 Hacking (1989) takes abduction to introduce pursuit-worthy hypotheses.

12 Cabrera (2023) provides an overview of this line of thought, along with multiple references.

13 Some New Mechanists might count this as an instance of mechanistic constitutive explanation. See Craver (2007).

14 For a precursor to this taxonomy, see Psillos (2002), Schurz (2008), and Schupbach (2017).

15 This idea borrows from Jaegwon Kim's "realist" conception of explanation, according to which an explanation is a representation of an ontological dependence relation. See Kim (1994).

membrane ontologically determines the action potential. Apply this idea to the three-curve experiment. The proposal is that Hodgkin and Katz believed that

> For curve 1, x_1 φ_1-ing, x_2 φ_2-ing, ..., x_n φ_n-ing compositionally explain S ψ-ing
> For curve 2, x_1 φ_1-ing, x_2 φ_2-ing, ..., x_m φ_m-ing compositionally explain S ψ^*-ing
> For curve 3, x_1 φ_1-ing, x_2 φ_2-ing, ..., x_l φ_l-ing compositionally explain S ψ^{**}-ing,

and this means that Hodgkin and Katz were also committed to the view that

> For curve 1, x_1 φ_1-ing, x_2 φ_2-ing, ..., x_n φ_n-ing ontologically determine S ψ-ing
> For curve 2, x_1 φ_1-ing, x_2 φ_2-ing, ..., x_m φ_m-ing ontologically determine S ψ^*-ing
> For curve 3, x_1 φ_1-ing, x_2 φ_2-ing, ..., x_l φ_l-ing ontologically determine S ψ^{**}-ing.

Notice that, in the experiments under examination, the action potentials in these curves—these explananda—are spatio-temporal particulars. The images on the oscilloscope (redrawn in Figure 3) were taken by Hodgkin, Huxley, and Katz to indicate action potentials at specific times and places. Further, in the experiments under examination, the ions moving across the membrane—the explanantia—are also spatio-temporal particulars. The focus on the explanation of spatio-temporal particulars by other spatio-temporal particulars means that Hodgkin, Huxley, and Katz's explanations are *singular* compositional explanations. These singular compositional explanations are the basis for singular compositional abductive inferences in just the way that the (singular) causal explanation of the marks in the snow is the basis for a (singular) causal abductive inference.

The foregoing account of explanation and abduction helps articulate the rationale in the theory of confirmation that Hodgkin, Huxley, and Katz had in mind. Hodgkin and Katz believed that the early influx of sodium ions compositionally explains the experimentally measured initial rise of the action potential. But that means that they took the early influx of the sodium to ontologically determine the initial rise of the action potential. They also had the further thought that an influx of sodium could not explain the initial rise—it could not ontologically determine the initial rise—if it did not exist. Hodgkin and Katz's presupposition is that the compositional explanation that they offered presupposes the existence of the entities referred to in the sentences stating the explanans. Their explanation, thus, presupposed the existence of the entities in the explanans. It presupposes that there is an influx of sodium. Philosophers of science need not hold that all explanations work like this one. Instead, one need merely suppose that Hodgkin and Katz's explanation worked this way.[16]

The foregoing introduces a theory of confirmation, but there is also a theory of disconfirmation. In thinking about Bernstein's membrane theory, Hodgkin and Huxley supposed that, if Bernstein's theory were correct, there would be no overshoot. There was an overshoot, so there is reason to think Bernstein's theory is not correct. Consider the point more abstractly. In thinking about Bernstein's membrane theory, Hodgkin and Huxley supposed that if Bernstein's theory were correct, then some entities x_1 φ_1-ing, x_2 φ_2-ing, ..., x_n φ_n-ing ontologically determine S ψ-ing. But, when they performed an experiment to measure S ψ-ing, they did not find S ψ-ing. Instead, they found S ψ^*-ing. But, if x_1 φ_1-ing, x_2 φ_2-ing, ..., x_n φ_n-ing ontologically determine S ψ-ing, rather than S ψ^*-ing, then x_1 φ_1-ing, x_2 φ_2-ing, ..., x_n φ_n-ing must not be in place. In other words, there is reason to believe that the configuration of entities that Bernstein supposed to be in play in the action potential were not in play in the action potential.

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[16] The existence of a change in membrane permeability is brought into the picture, since Hodgkin and Katz must postulate this as a cause of the influx of sodium ions. The change in membrane permeability to sodium, along with the sodium concentration gradient across the membrane, cause the influx of sodium ions. If there were no change in membrane permeability to sodium ions, the sodium ions would not enter the axon.

Section 1 reviewed an example of Hodgkin, Huxley, and Katz providing reasons against one theory of the action potential and reasons in favor of another. Section 2.1 has now sketched an abductive theory of confirmation and disconfirmation that attempts to characterize these reasons. It attempts to characterize the theory of confirmation and disconfirmation that Hodgkin, Huxley, and Katz had in mind. Section 2.2 will now articulate the entity realism that is implicit in their work.

2.2. Hodgkin, Huxley, and Katz's Entity Realism

In the Hodgkin, Huxley, and Katz experiments, the explanantia entities—the things singular compositional abductive confirmation is meant to confirm—are spatiotemporal individuals, rather than (natural) kinds. Thus, for Hodgkin, Huxley, and Katz to say that sodium ion influxes exist or are real is for them to say that there are individual sodium ion influxes that exist at specific times and places. This is Hodgkin, Huxley, and Katz's entity realism. This is to say nothing about natural kinds, assuming, of course, that a natural kind is something more than just the spatio-temporally particular individuals themselves. The rationale for Hodgkin, Huxley, and Katz's limited ontological commitment is that abductive inferences from experimental work might confirm the existence of individual sodium ion fluxes at specific places and times, but that further generalizations from those spatiotemporal particulars will likely be needed in order to justify the existence of kinds. Moreover, one would want a philosophical theory of what a kind is.

Further fleshing out this entity realism, "entities" will not be limited to spatio-temporally localized individuals, such as electrons, axonal membranes, or sodium ions. "Entities" will include activity instances, such as changes in membrane permeability, and property instances, such as the charges of individual sodium ions. Entities in these distinct ontological categories are needed to describe Hodgkin, Huxley, and Katz's work accurately. Hodgkin, Huxley, and Katz believed that individuals with property instances engage in activity instances. Their interpretation of the experiment presupposes that individual, positively charged sodium ions move from the extracellular space into the axoplasm.

This ontological framework forestalls an objection Alan Musgrave directed at Hacking's entity realism many years ago: "To believe in an entity, while believing nothing further about that entity, is to believe nothing, I tell you that I believe in hobgoblins (believe that the term 'hobgoblin' is a referring term). So, you reply, you think there are little people who creep into houses at night and do the housework. Oh no, say I, I do not believe that hobgoblins do that. Actually, I have no beliefs at all about what hobgoblins do or what they are like. I just believe in them" (Musgrave, 1996, p. 20). The entity realism here ascribed to Hodgkin, Huxley, and Katz is not the bare "property-free"/"activity free" entity realism Musgrave criticizes. Hodgkin, Huxley, and Katz did not merely believe in the existence of sodium ions. They also believed that each ion has a unit positive charge (a property instance) and that each passes through the axonal membrane (an activity instance).

Consider, now, a contrast between theory realism and entity realism. A theory realist aims to have a true theory of the world. An entity realist, however, aims to refer to things (spatio-temporal particulars) in the world. This formulation is at least similar to many formulations in the philosophical literature. It is not, however, exactly the one Hacking develops, but it faces the same challenge his formulation does: How is it that entity realism and theory realism do not collapse into each other? As Hacking makes the point, "The two realisms may seem identical. If you believe a theory, do you not believe in the existence of the entities it speaks about? If you believe in some entities, must you not describe them in some theoretical way that you accept? This seeming identity is illusory. The vast majority of experimental physicists are realists about entities but not about theories" (Hacking, 1982, p. 72). Unfortunately, neither Hacking's reply in the last sentence nor his later comments specify how one is to avoid entity realism and theory realism collapsing into each other.

A more positive approach to this question should specify something about what one means by a "theory". Years ago, for example, Musgrave proposed that "any collection of beliefs about X's counts as an X-theory" (Musgrave, 1996, p. 21). Insofar as this is a stipulative use of "theory", then a commitment to the sort of entity realism just described will bring

with it a commitment to theory realism. Nevertheless, one might still defend a distinction between entity realism and theory realism by proposing a use of "theory" that respects more common features of actual scientific and philosophical usage. If one is interested in capturing a more common usage for "theory", one will likely reject the set of beliefs,

> An electron weighs less than a ton.
>
> An electron is not a banana.
>
> John loves electrons.

as a theory of electrons. This would count as a "Musgrave theory", but presumably one wants a more restrictive account of what a theory is.

One quite minimal feature of more common uses of "theory" is that scientific theories, at the very least, aim to state general features of the world. They sometimes express or entail generalizations about the world.[17] Thus, the historian and philosopher of science can distinguish ontological commitments to spatiotemporal particulars, as found in the proposed formulation of entity realism, and ontological commitments made by general statements, empirical generalizations (or laws), and hence theories. This is, obviously, not a philosophical theory of what a theory is. Instead, it is merely a means to distinguish between scientists trying to develop a true theory and scientists trying to embrace referring expressions. There may be other, better ways to distinguish between entity realism and theory realism, but this one meshes well with the theory of confirmation attributed to Hodgkin, Huxley, and Katz.

Consider now how the historian and philosopher of science may ascertain what scientists are trying to refer to. The proposal is that some scientists do this by trying to confirm hypotheses with terms that refer. Hodgkin, Huxley, and Katz did this when trying to confirm that movements of sodium and potassium ions generate action potentials. In other words, in attempting to confirm the hypothesis that there are changes in membrane permeability during an action potential, Hodgkin, Huxley, and Katz were referring to changes in membrane permeability. This is not to assume, in general, that whenever a scientist tries to confirm some hypothesis H containing a term T, the scientist must presuppose that T refers. That would be a hasty generalization from a single case. The weaker assumption is that when Hodgkin, Huxley, and Katz tried to confirm the influx of sodium during the action potential, they were trying to refer to an influx of sodium.

3. Hacking on Experimentation and Scientific Realism

Having presented some of Hodgkin, Huxley, and Katz's experimental work (Section 1) and some of their ontological and methodological presuppositions (Section 2), this section will draw attention to some implications for Hacking's views regarding entity realism and confirmation. At the top of the list of the implications is that, contrary to Hacking's contention, some scientists do use abductive reasoning to confirm the existence of unobserved entities.

To begin, consider the scope and ambitions of Hacking's account. Consider, first, the proposed scope of Hacking's entity realism. Sometimes he appears to describe the whole of science. At other times, he seems to limit his proposal to physics or experimental physics. So, for example, he writes, "Different sciences at different times exhibit different relationships between 'theory' and 'experiment'. One chief role of experiment is the creation of phenomena. Experimenters bring into being phenomena that do not naturally exist in a pure state. These phenomena are the touchstones of physics, the keys to nature, and the source of much modern technology" (Hacking, 1982, pp. 71-72). Cf. Hacking (1984, p. 155). Later, he claims that "The vast majority of experimental physicists are realists about entities but not about the-

[17] This view is a weaker version of the assumption that a theory is a set of laws or a set of law statements. It is in keeping with Nancy Cartwright's idea of theory as organizing scientific knowledge. See Cartwright (1983).

ories. Some are, no doubt, realists about theories too, but that is less central to their concerns. Experimenters are often realists about the entities that they investigate, but they do not have to be so" (Hacking, 1982, p. 72). Cf. Hacking (1984, p. 155, italics in original). For present purposes, the assumption is that Hacking's theory is meant to cover the case of mid-twentieth-century experimental physiology. After all, what non-ad hoc reason is there to limit the scope of Hacking's theory to experimental physics?

An important component of Hacking's discussion of experimentation and entity realism is the treatment of scientific work on parity and weak neutral currents. Thus, *prima facie*, Hacking shares with the present work the goal of characterizing scientific practice. Importantly, although Hacking evidently intends to describe scientific practice—although he sees himself as providing a bit of sociology of science—he also has larger aspirations. For example, he writes,

> Do I describe a merely sociological fact about experimentalists? It is not surprising, it will be said, that these good practical people are realists. They need that for their own self-esteem. But the self-vindicating realism of experimenters shows nothing about what actually exists in the world. In reply I repeat the distinction between realism about entities and realism about theories and models. (Hacking, 1982, p. 73)

Prima facie, in the final sentence, Hacking indicates that he does not intend to make a mere sociological observation about experimentalists. He, instead, believes scientific practice has some epistemological or metaphysical implications for entity realism. Then, later, he writes,

> Even if experimenters are realists about entities, it does not follow that they are right. Perhaps it is a matter of psychology: the very skills that make for a great experimenter go with a certain cast of mind that objectifies whatever it thinks about. Yet this will not do. The experimenter cheerfully regards neutral bosons as merely hypothetical entities, while electrons are real. (Hacking, 1982, p. 76)

Hacking also comments that,

> Bain was surely right a century ago, when assumptions about the minute structure of matter could not be proved. The only proof could be indirect, namely, that hypotheses seemed to provide some explanation and helped make good predictions. Such inferences, however, need never produce conviction in the philosopher inclined to instrumentalism or some other brand of idealism. (Hacking, 1982, p. 85). Cf. Hacking (1984, p. 169)[18]

In the final sentence, Hacking suggests that he is concerned to address instrumentalists or idealists. The work in this paper does not address the extent to which scientific practice warrants an epistemological or metaphysical conclusion. That requires further argumentation. Instead, this paper aspires to a more detailed and accurate account of scientific practice that is true to the case of Hodgkin, Huxley, and Katz. Getting an accurate historical accounting is the project here.

3.1. Hacking and the Ontology of Entity Realism

Turn, now, to Hacking's formulation of the distinction between entity realism and theory realism:

> I turn to the purely philosophical issue of scientific realism. Simply call it "realism" for short. There are two basic kinds: realism about entities and realism about theories. There is no agreement on the precise definition of either. Realism about theories says that we try to form true

[18] Hacking (1982) and Hacking (1984) overlap extensively, even having the same title. Moreover, there are extensive overlaps with Hacking (1983). This paper will not attempt to sort through the variations in Hacking's presentations.

> theories about the world, about the inner constitution of matter and about the outer reaches of space. ... Realism about entities—and I include processes, states, waves, currents, interactions, fields, black holes, and the like among entities—asserts the existence of at least some of the entities that are the stock in trade of physics. (Hacking, 1984, p. 155)[19]

In principle, Hacking might have provided parallel formulations of entity realism and theory realism of the sort introduced in Section 2.2. There is, in theory, that much agreement between the entity realism developed here and Hacking's entity realism.

That said, the account in Section 2 is not meant to embrace some of Hacking's views on the relative importance of theory realism versus entity realism. Recall Hacking's comment, quoted above, that, "The vast majority of experimental physicists are realists about entities but not about theories. Some are, no doubt, realists about theories too, but that is less central to their concerns" (Hacking, 1982, p. 72). Perhaps experimentalists are committed to both entity realism and theory realism; however, the present account does not weigh in on the centrality of these distinct concerns.

It is important to note that Hacking also makes some strong modal claims that have not been explored here. Hacking proposes that "Discussions about scientific realism or antirealism usually talk about theories, explanation, and prediction. Debates at that level are necessarily inconclusive. Only at the level of experimental practice is scientific realism unavoidable—but this realism is not about theories and truth" (Hacking, 1984, p. 154). This paper does not defend the idea that debates over scientific theoretical realism are inconclusive. Much less does it defend the idea that these debates are necessarily inconclusive. Nor does the paper claim that at the level of experimental practice scientific realism is unavoidable. This paper sets aside all these strong modal claims in favor of weaker non-modal descriptive claims: Hodgkin, Huxley, and Katz were entity realists who supported their realism with abductive reasoning.

3.2. Hacking on the Confirmation of Entities

Turn now to confirmation. For the historian and philosopher of science seeking to understand experimental practice, it is worthwhile distinguishing between the idea that experimentation generates evidence (for some entity X) and the idea that experimentation generates knowledge (of some entity X). The distinction is worthwhile insofar as scientists sometimes interpret an experiment as providing some evidence for some hypothesis, even when that evidence is not sufficient for knowledge. In general, scientists may agree that a single experiment generates evidence but differ over whether the available evidence generates knowledge of the hypothesis. The discussion that follows is to be interpreted in terms of the weaker concept of evidence, rather than the stronger concept of *compelling* evidence sufficient for generating knowledge.

Hacking appears to commit to three theses regarding the confirmation of entities:

> (A) Experimentalists do not take experimentation on entities to provide evidence for the reality of entities.
>
> (B) Experimentalists do not take abductively inferring entities to provide evidence of the reality of entities.
>
> (C) Experimentalists take the manipulation of the entities to provide evidence for the reality of entities.[20]

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[19] Hacking often uses "we" to refer to both philosophers and scientists. The intent of this paper is to characterize scientific reasoning without assuming that it is the same as philosophical reasoning. Thus, "we" is not used like this in the paper.

[20] One might interpret Hacking to be making stronger claims, not about what constitutes evidence for the reality of entities, but what constitutes knowledge of the reality of entities. Given that the more important aim of the present paper is to understand Hodgkin, Huxley, and Katz's work, rather than exhaustively survey Hacking's options, this interpretation is not pursued here. One might also interpret Hacking

These are the conclusions Hacking would have us draw from his case study of the electron and neutral bosons. These theses indicate what experimentalists take and do not take to be evidence for the reality of entities. Unfortunately, Hacking's exposition is not always as clear and univocal as these theses suggest.

Hacking claims that "Experimenting on an entity does not commit you to believing that it exists. Only manipulating an entity, in order to experiment on something else, need do that" (Hacking, 1983, p. 263).[21] The scientific review in Section 1 indicates that Hacking has overgeneralized. Contrary to thesis (A), Hodgkin and Huxley used the results of their experiments in 1939 and 1945 to support the existence of an overshoot/reversal of the action potential. Contrary to thesis (B), Hodgkin and Katz reasoned abductively about the results of their three-curve experiment to establish the existence of an inward flux of sodium ions during an action potential.[22] Finally, contrary to thesis (C), Hodgkin and Huxley believed in the action potential and its overshoot before Hodgkin and Katz used them in their 1949 interpretation of the action potential. One of the upshots of Hodgkin and Huxley's 1945 paper was that the overshoot was not an artifact. Moreover, if Hodgkin and Katz had not accepted the action potential and its overshoot as real, rather than an artifact, they would not have used it as a basis for their three-curve experiment in 1949.

The interpretation of Hacking's comment that "Experimenting on an entity does not commit you to believing that it exist" is not absolutely unassailable. Maybe by "commit" Hacking means to imply some sort of compulsion to believe in an entity that is not found in the Hodgkin, Huxley, and Katz case. But what is this compulsion? And maybe the "you" is meant only to philosophers reading the paper, but not experimental physiologists. But why would the attitude of philosophers matter to how one is to understand Hodgkin, Huxley, and Katz's reasoning? These are not questions pursued here, since the primary concern is with understanding Hodgkin, Huxley, and Katz's entity realism and their experimental reasoning, rather than an exhaustive critique of Hacking's entity realism.

When it comes to thesis (B), Hacking is at times decidedly equivocal.[23] Much of his reasoning is framed in terms of the importance of an explanation. In an early chapter in *Representing and Intervening*, Hacking claims that,

> There are times when we feel a great gain in understanding by the organization of new explanatory hypotheses. But that feeling is not a ground for supposing that the hypothesis is true. Van Fraassen and Cartwright urge that being an explanation is never a ground for belief. I am less stringent than they: it seems to me like Peirce to be merely a feeble ground. In 1905 Einstein explained the photoelectric effect with a theory of photons. He thereby made attractive the notion of quantized bundles of light. But the ground for believing the theory is its predictive success, and so forth, not its explanatory power. Feeling the key turn in the lock makes you feel that you have an exciting new idea to work with. It is not a ground for the truth of the idea: that comes later. (Hacking, 1983, p. 53)

In the first two sentences, one might think that Hacking's view is that explanation is not evidence in favor of a hypothesis. But then again, he could be read as maintaining that an explanation generates both evidence and a feeling, but that it is not the *feeling* that provides the evidence. This allows an explanation to be evidence in favor a hypothesis. This second interpretation is consistent with what Hacking says next: unlike van Fraassen and Cartwright, but like Peirce, he

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as making normative claims, such as that experimentalists should not take experimentation on entities to provide evidence for the reality of entities. These normative claims go beyond the present concern with getting an accurate historical accounting of Hodgkin, Huxley, and Katz's work.

21 Hacking also claims that "The experimentalist does not believe in electrons because, ... they 'save the phenomena.' [Thesis (B)] On the contrary, we believe in them because we use them to create new phenomena, such as the phenomenon of parity violation in weak neutral current interactions." [Thesis (C)]

22 Further, as noted above in footnote 12, they also performed another abductive inference to the conclusion that action potentials involve the existence of a change in membrane permeability.

23 See also footnote 16.

believes that an explanation can provide a weak ground.[24] Now the view appears to be that explanation does provide evidence; but only weak evidence. But then, following the comments about Einstein, Hacking explicitly denies that explanatory power provides ground, that is, evidence. Instead, it is predictive success that provides confirmation. Then, he returns to the idea that the feeling of understanding that comes with explanation does not provide confirmation, again leaving open the possibility that there is something about explanation *other than the feeling of understanding* that does provide confirmation. But, then shortly after, he comments that "Even if, contrary to what I have said, explanation were a ground for belief ..." (Hacking, 1983, p. 54). As noted, Hacking is thoroughly equivocal here.

In a later paper, Hacking is less equivocal but less direct in presenting his view. He writes,

> Inference to the best explanation is often traced back to C. S. Peirce and what he called the method of hypothesis (and also retroduction, abduction). In maturity Peirce did not think that the method of hypothesis gave ground for belief, but only for further investigation, testing, and induction. (Hacking, 1989, p. 568)

It is true that inference to the best explanation is often traced back to Peirce. Harman, for example, claimed that "'The inference to the best explanation' corresponds approximately to what others have called 'abduction'" (Harman, 1965, p. 88), and this is widely understood to be an implicit reference to Peirce. This is not, however, to say that IBE and abduction are the same. As noted above, Harman believed that IBE is *warranted* abduction, so for Harman at least, there is a difference. Moreover, the difference is supposed to be that IBE is supposed to provide warrant, so *prima facie* it is supposed to provide evidence. By contrast, judging from his subsequent comments, Hacking means to identify IBE and abduction, and then understand both, as Peirce did, as *not* providing ground/ evidence/ confirmation/ warrant.[25]

Given that Hodgkin, Huxley, and Katz's experimental work conflicts with the foregoing reading of Hacking's view, one might wonder if Hacking does, in fact, really deny that scientists use abduction for confirmation. Indeed, one might think that all Hacking really wants to say is that the evidence from manipulation is better than evidence from abduction. This is, after all, what he claims: "The best kinds of evidence for the reality of a postulated or inferred entity is that we can begin to measure it or otherwise understand its causal powers. The best evidence, in turn, that we have this kind of understanding is that we can set out, from scratch, to build machines that will work fairly reliably, taking advantage of this or that causal nexus" (Hacking, 1983, p. 274).

If Hacking were to retreat to the weaker view that manipulation creates better evidence than abduction, that would be a major concession.[26] It would concede the main point of this paper. If he were to allow that abductive reasoning provides confirmation (that is weaker than confirmation by manipulation), he would thereby risk opening the floodgates to many more unobservable entities, not just the relatively fewer unobservable entities that can be manipulated for further experimental ends. Bear in mind that he supports an anti-realism in astrophysics, where he takes manipulation for experimentation to be impossible.[27]

The upshot here is that—admitting the various ambiguities in Hacking's writing—Hodgkin, Huxley, and Katz's work challenges all three of Hacking's descriptive methodological theses. These mid-twentieth-century experimental physiologists used experiments on action potentials to confirm the existence of the overshoot. Further, they used abductive

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[24] Note that many Peirce scholars believe that Peirce thought that abduction serves merely to introduce some hypothesis, rather than to confirm it. See Cabrera (2023) for discussion and references.

[25] Note, as well, that even if in maturity Peirce did not think that the method of hypothesis gave ground for belief, that leaves open the issue about whether Peirce was right. One of the morals of Sections 1 and 2 is that Hodgkin, Huxley, and Katz, at least, believed that abductive reasoning provides evidence.

[26] Were Hacking to retreat to this view, it should invite closer questioning of the reasons he has for it.

[27] See Hacking (1989).

reasoning to confirm the existence of an early sodium influx during an action potential.[28] Hodgkin, Huxley, and Katz were, thus, entity realists who confirmed the existence of certain entities using abduction.

5. Conclusion

The examination of a portion of Hodgkin, Huxley, and Katz's work from 1939 to 1949 reveals that they embraced entity realism about action potentials, changes in membrane permeability, and ion fluxes. They also believed in some of these entities for abductive reasons. This conclusion is at odds with Hacking's combination of entity realism with a rejection of abductive reasoning. Moreover, this conclusion is not on the philosophical radar in current work on entity realism.

There are, of course, any number of further issues to be explored. For one thing, we have reviewed only one instance of entity realists embracing abduction. How many more are there, if any? What normative conclusions might one draw from the cases? Presumably, the more instances of highly respected scientific work, such as Hodgkin, Huxley, and Katz's work on the action potential, the stronger the case for thinking that philosophers of science should take seriously the view that abductive reasoning can support entity realism. Finally, there are many details of Hacking's philosophy of experiment that one might wish to pursue. Why think that manipulationist evidence is stronger than abductive evidence? Why think that theory realism is necessarily inconclusive?

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[28] They also used abductive reasoning to confirm the existence of a change in membrane permeability to sodium.

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