Understanding as Explanatory Knowledge: The Case of Bjorken Scaling

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Introduction

Recently, the concept of understanding has garnered increasing attention among philosophers of science[1]. Yet, there has been little consensus on what understanding actually *is*. In this paper, we argue that understanding is knowledge of a phenomenon plus knowledge of an explanation achieved through reliable explanatory evaluation (Section 1). We then use a brief episode in the recent history of particle physics to showcase various features of our account (Sections 2 and 3). Finally, we argue that our view fares better than two alternatives ably developed by Robert Batterman and Henk de Regt (Section 4).

1. Understanding as explanatory knowledge

In this section, we present our account of understanding (1.1), and then present our strategy for illustrating its plausibility (1.2). The remainder of the paper then executes that strategy.

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[1] See (Batterman 2000, 2002; De Regt and Dieks 2005; De Regt, Leonelli, and Eigner 2009; Grimm 2006; Trout 2002).

1.1. The Explanatory Knowledge Model of Understanding

According to our account of understanding:

(EK) *S* understands why *p* if and only if:

(a) *S* knows that *p*; and

(b) For some *q*, *S's* true belief that *q correctly explains p* is produced/maintained by reliable explanatory evaluation.

Since it is widely (though not universally) held that knowledge is reliably formed true belief, understanding why *p* is thus knowledge that *p* plus knowledge that *q correctly explains p*[2]. For this reason we call this the Explanatory Knowledge (EK) model of understanding.

Such a view has a venerable history in the philosophy of science. Grimm (2006) cites Achinstein, Kitcher, Lipton, Salmon, and Woodward as endorsing the view that understanding is a species of knowledge. However, these views focus on the concept of explanation, while paying relatively little attention to the concept of knowledge. By contrast, the EK Model says little about explanation, but is clearer about the epistemology of understanding.

Our choice for focusing less on the concept of explanation is deliberate. We accept a plurality of explanatory relations. Thus, we will not subscribe to an exclusively causal model, an exclusively unificationist model, etc. Instead, these—and others—are appropriate in different contexts.

Before proceeding, two additional points are in order. First, in condition (b), we use the phrase "correctly explains" to sidestep debates about scientific realism. Given that

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[2] Knowledge requires an additional, "anti-Gettier condition." Khalifa (2013c) argues that reliable explanatory evaluation satisfies this condition.

realists take approximate truth to be necessary for correct explanation, while their critics frequently think that correct explanations may fall short of approximate truth, we simply use this terminology to indicate the standard of explanatory propriety that comes out victorious when the final arguments for and against realism are tallied. Thus, even if antirealists turn out to have the more defensible view of explanation, we would still hold that understanding entails the true belief that *q correctly explains p*; we would only add that the concept of *correctly explains* should be glossed antirealistically[3].

Second, while the EK Model remains agnostic as to how understanders come to have knowledge of the explanandum (item a above), it places further constraints on their knowledge of explanatory propositions (item b). Specifically, it requires such beliefs to be formed via *reliable explanatory evaluation*. Recall the motivation for the EK Model: many philosophers of science take understanding to be explanatory knowledge, but have mostly black-boxed the kind of knowledge that is relevant to understanding. To open this black box, we start with the popular epistemological idea that knowledge (roughly stated) is true belief produced/maintained by a reliable cognitive process (Goldman 2011). We use the phrase 'reliable explanatory evaluation' to refer to the paradigmatic way to acquire beliefs about correct explanations. Roughly stated, we take explanatory evaluation to consist of three stages[4]:

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[3] For the purposes of illustration, suppose that Van Fraassen's (1980) account of explanation turns out victorious in the final analysis. Then, very roughly stated, the EK Model would hold that *S* understands why *p* only if *S* believes that *q correctly explains p*, *q* and *p* are part of an empirically adequate theory, and *q* stands in some context-relative relevance relation to *p*—the latter two clauses (roughly) indicating van Fraassen's truth-conditions for *q correct explains p*. We stress that we are *not* taking a stance on the realism issue.

[4] Our view resembles Lipton's (2004, 61) account of Inference to the Best Explanation, wherein "the explanation that would, if true, provide the deepest understanding is the

1. Generation of plausible potential explanations of the phenomenon of concern;
2. Comparative assessments of these potential explanations; and
3. Forming doxastic attitudes about the correctness of these potential explanations on the basis of these comparative assessments.

While we will not analyze these abilities any further, we will briefly describe some salient features of each. Regarding the first stage, a potential explanation *q* of *p* is an explanation that, if true, would correctly explain *p*. However, some potential explanations are implausible, e.g., explaining Newton's death by appeal to alien laser guns. While we offer no precise account of plausibility, typical considerations include fit with accepted background theories and simplicity. Of course, given our earlier caveat about correct explanation, we should also stress that some plausible explanations are incorrect. For realists, such explanations will be ones that fail to be approximately true; for antirealists, such explanations fail to satisfy a more modest requirement, e.g. empirical adequacy.

Turning to the second stage, comparative assessments of two explanations q_i and q_j of *p* basically amount to judgments that q_i *better explains p than does* q_j. Such judgments are based on additional empirical information (e.g. if some additional evidence *e* favors q_i over q_j as a correct explanation of *p*) and various theoretical or explanatory virtues (e.g. simplicity, scope, mechanism, conservatism, analogy, testability, unification, fruitfulness).

In the third stage, these comparative assessments prescribe and proscribe doxastic attitudes as to which of these explanations, if any, is correct. Paradigmatically, one comes

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explanation that is likeliest to be true." However, our earlier discussion dictates that we replace Lipton's two references to "true" with "correct," and bracket the issue as to whether or not such an explanation is likeliest to be true.

to believe that only one explanation is correct because it outshines the other explanations in the second stage. However, we use the phrase 'doxastic attitude' so as to allow for, e.g. cases in which one suspends belief about any explanation being correct. An explanatory evaluator is reliable with respect to a given explanandum *p* if she could not easily have arrived at an incorrect doxastic attitude regarding the correctness of plausible potential explanations of *p* when the manner and information whereby she generated those explanations, as well as the manner, evidence, and theoretical virtues whereby she comparatively assessed those explanations, are held fixed[5].

With explanatory evaluation sufficiently (albeit programmatically) elaborated, we now state our reasons for requiring it of understanding. Some have argued that certain kinds of explanatory knowledge—say learning an explanation by rote memorization or by unreflective acceptance of testimony—do not amount to understanding (De Regt 2009). These counterexamples cite the subject's lack of skill or ability as a reason to withhold understanding. Reliable explanatory evaluation of the sort just described involves substantial cognitive ability: subjects must be able to generate plausible potential explanations, gather and use evidence to make comparative assessments, employ the theoretical virtues to make comparative assessments, and form the appropriate doxastic attitudes on the basis of these assessments[6]. Hence we not only blunt this objection, we specify more precisely the abilities needed for understanding.

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[5] This can be further elaborated using "safety-based" epistemologies, where *S* knows that *p* only if *S's* true belief that *p* could not easily have been false. This, in turn, can be analyzed further using possible worlds semantics (Pritchard 2009). See (Khalifa 2013c) for a safety-based epistemology of understanding that appeals to reliable explanatory evaluation.

[6] Or, because understanding admits of degrees, we might say that learning by rote yields modest understanding while highly reliable explanatory evaluation yields robust

1.2. Strategy to be pursued

In the balance of the paper, we will illustrate the EK Model's plausibility by examining the history of Bjorken scaling. In the late 1960s, James "BJ" Bjorken made a novel prediction about a certain kind of scaling. Bjorken used rather abstract theoretical tools that were largely opaque to a majority of physicists—even the experimental physicists who performed the experiment that confirmed Bjorken's prediction. Shortly thereafter, Richard Feynman explained scaling in terms of 'partons,' giving Bjorken's complex mathematical model and the scaling phenomenon a physical interpretation that was intelligible to a much wider range of physicists. Feynman's parton model allowed experimental physicists to run further experiments that ruled out other potential explanations of scaling throughout the early 1970s. We will show that, by the end of this period of development, all of the EK Model's requirements were satisfied.

We have chosen this example for several reasons. First, as an enterprise, particle physics provides exemplary understanding. Second, in this particular case, a period of confusion (i.e. lack of understanding) arose and was subsequently resolved. Studying this transition illustrates how the EK Model accounts for the conversion from a well-confirmed but opaque phenomenon into an object of understanding. We will conclude our discussion by highlighting several advantages that the EK Model has over Batterman and De Regt's accounts of understanding.

Before proceeding, we stress that our appeal to history is best seen as complementing more theoretical arguments that understanding is explanatory knowledge,

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understanding (ceteris paribus), with many intermediate stages of understanding graded according to how well they approximate the latter.

(e.g. Grimm 2006). We hope that our historically informed discussion illustrates that these theoretical ideas are not merely idle speculations.

2. Bjorken's asymptotic explanation

In this section, we: (2.1) describe Bjorken's prediction, (2.2) show that, even before Feynman's interpretation, the EK Model's requirement of known explananda (item a, above) is satisfied, and (2.3) discuss Bjorken's explanation of the phenomenon he predicted. At the beginning of the next section, we highlight the aspects whereby Bjorken's explanation failed to provide understanding.

2.1. Early history of Bjorken scaling

In the latter half of 1967, a team of researchers from the Stanford Linear Accelerator (SLAC) group and the Massachusetts Institute of Technology (MIT) measured the "scatter" that results from firing a beam of electrons at a proton target. More precisely, they measured the *cross-section* σ, the likelihood of an interaction between particles.

These experiments were designed to discover basic properties of subatomic particles. In classifying these particles, the *hadron-lepton* distinction is very important. Hadrons are subatomic particles that are affected by nuclear or "strong" forces, while leptons are immune to such forces. Thus, neutrons and protons (as well as, e.g., kaons and pions) are hadrons, and electrons (as well as muons and neutrinos) are leptons.

Physicists represent scattering experiments as BT → X, where B refers to the beam particle, T to the target particle, and X to the particles that result from their interaction. The most important SLAC-MIT experiments of this time can be represented as ep → X, where e refers to electrons, and p to protons. The research team examined two kinds of scattering phenomena. The first, *elastic* scattering, involves interactions in which beam and target particles—in this case, electrons and protons, respectively—retain their identities. Thus, elastic scattering experiments can be represented as ep → ep. The second, *inelastic* scattering, involves interactions in which the proton need not retain its identity, i.e. ep → eX, for all X. The team did not attempt to identify the various particles comprising X in these inelastic scattering experiments.

Prior to the SLAC-MIT experiments, it was assumed that cross-sections for both elastic and inelastic scattering would fall off sharply when electron beams were fired at higher energy levels and scatter was measured at larger angles. Quantum electrodynamics (QED), the dominant theory of the time, assumed that electrons interacted as hard, point-like entities[7], while protons had a diffuse, soft structure extended over a finite volume of space. If QED were correct, then there would be very little scatter at high energies and large angles, as soft protons would only permit electrons to strike glancing blows. Elastic scattering experiments performed prior to 1967 were consonant with this result, as cross-sections for electron-proton scattering were much smaller at larger angles than cross-sections for electron-electron scattering.

The SLAC-MIT team fired the electron beam at higher energies than their predecessors. All of their results were consistent with prior theory and experiment, *except* for the surprising discovery that the cross-sections for electron-proton and electron-electron interactions are roughly the *same* at *inelastic* scattering at high energies and large angles—what is called the "deep inelastic" region. In other words, the electron-proton interactions have much higher cross-sections than was previously expected for

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[7] Strictly speaking, QED only assumes this in first-order approximation. We omit this detail.

deep inelastic scattering. *Contra* QED, this suggests that the proton is composed of hard point-like entities.

Bjorken, working at the SLAC theory group, was one of the few physicists unsurprised by this result, as in 1966 he had already predicted it using a then-esoteric mathematical framework in quantum field theory called current algebra[8]. More precisely, Bjorken predicted that the absolute energy of an experiment does not determine the cross-section of electron-proton scattering, which is consistent with the SLAC-MIT team's surprising result that these cross-sections do not decrease at higher energy levels.

According to Bjorken, the cross-section of deep inelastic scattering—hereafter σ_{DIS}—is determined instead by the ratio of the energy loss of the scattering electrons v to the momentum transfer between the electron and the proton q. This point is intimately related to *Bjorken scaling,* which we discuss in more detail below. Bjorken suspected that a more direct consequence of scaling could be gleaned from the experimenters' results, so in April 1968, he urged them to plot two well known functions that represent the proton's structure (W_1 and W_2) against what would later be known as the *Bjorken scaling variable*[9] $\omega = -q^2/Mv$. Here, M is the proton's mass. As Bjorken predicted, the results fell on unique curves—now called *scaling curves*.

2.2. Knowledge of explananda

The EK Model requires knowledge of an explanandum. After discussing which explananda are in play in this example, we discuss some of the ways in which the experimenters came to know these explananda.

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[8] First published in (Bjorken 1967).

[9] This is Bjorken's original notation. Subsequently, the scaling variable was defined as $x = q^2/2Mv$.

There are two principal explananda in this little slice of particle physics. The first explanandum is the scattering phenomenon, i.e.

Why is $\sigma_{DIS}/\sigma_{MOTT} \approx 1$ (rather than < 1)?

Here σ_{MOTT} is the cross-section of electron-electron scattering, and the parenthetical contrast indicates the result predicted by QED. Since it was known that electrons were hard, but QED assumed that protons are soft, the experiments suggest that electron-proton scattering more closely resembles electron-electron scattering than QED predicts.

A second explanandum, concerning scaling, requires a bit more exposition. At the most general level, a scaling law (Bjorken's or otherwise) is a function f such that $f(cx) \propto f(x)$, where c is a constant. Thus, changing the size or scale of the function's argument preserves the shape of the function. A simple example of scaling is the equation that expresses a square's area A as a function of the square of the length l of one of its sides, i.e. $A(l) = l^2$. Regardless of the length of l—i.e. regardless of the scale of the square—this relationship holds. In this case, we say that area *scales like* length squared.

In Bjorken scaling, the principle is the same, but the relationships and quantities are a bit more involved. Specifically, the Bjorken scaling laws are:

$W_1 = F_1(\omega)$; *and*

$\nu W_2 = F_2(\omega)$

Just as area scales like length squared, W_1 scales like $F_1(\omega)$, and W_2 scales like $F_2(\omega)$. These scaling laws serve as our second explanandum. In short, inquirers were interested in understanding why these scaling relations hold.

Other explananda figure in subsequent parts of this story. Below, we will argue that these are best seen as part of the scientists' evaluation of the parton explanation. For now, we turn to whether the scientists had *knowledge* of the following:

(E1) $\sigma_{\mathrm{DIS}}/\sigma_{\mathrm{MOTT}} \approx 1$ (rather than < 1);

(E2) $W_1 = F_1(\omega)$ *and* $\nu W_2 = F_2(\omega)$

Minimally, it would appear that the scientists believed that these two phenomena were not mere artifacts. Moreover, by the lights of our best current science, these beliefs are true and were delivered by reliable methods. Thus, quite plausibly, the scientists knew these two explananda.

For instance, one might think that the surprising results about deep inelastic scattering would have provided sufficient reason for members of the SLAC-MIT team to reject QED's assumption about a soft proton. However, members of the team debated whether the large number of electrons that had lost their energy in the deep inelastic scattering experiments was the result of their colliding with the hard, point-like constituents of the proton or the result of the electrons radiating photons during the collision (a well-known phenomenon). In order to rule out the latter possibility, members of the SLAC team used a computer-driven, time-intensive process to make "radiative corrections" in order to disambiguate the data. In the spring of 1968—nearly a year after the experiment was performed—the radiative corrections were complete, revealing that the high number of low-energy electrons could not be explained away by photon radiation. These precautions are precisely the kinds of things that distinguish knowledge from a fortuitously true belief. Since the same data were used to plot the scaling curves, parallel points apply to this explanandum.

2.3. Bjorken's explanation

Of course, simply *knowing that* (E1) and (E2) are true does not amount to *understanding why* they are true. According to the EK Model, what is also needed is a correct explanation of these two phenomena. Bjorken's account of scaling is an example of *asymptotic explanation*, which has received its most lucid philosophical exposition from Robert Batterman (2002).

To explain universal phenomena asymptotically involves identifying and eliminating details that are irrelevant to the behavior in question. To this end, one employs sophisticated mathematical techniques to examine the asymptotic behavior of the appropriate governing functions. Give or take a few niceties, the general schema for (one kind of) asymptotic explanation is:

Asymptotic Explanation Schema[10]

Explanation Target:

Why does the same **pattern of behavior** emerge in diverse physical **systems**?

Explanatory Pattern:

The **pattern of behavior** can be expressed as a mathematical **function**.

Various **details** about these **systems** are constant in the **asymptotic limit** of this **function**.

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[10] We borrow the use of explanation schemas (though not asymptotic ones) from Thagard (1999). In broad outline, this schema replicates Batterman's (2002, 44) three criteria of asymptotic explanations:

- "…the explanation involves some kind of asymptotic analysis
- The universality is the result of the stability under perturbation of the underlying microscopic details [i.e., the behavior of a system tends to remain the same even when basic features of the system are changed].
- The stability under perturbation (or 'structural stability') is explained by the underlying microscopic physics of the systems being investigated."

> Given the **underlying microphysics** of the **system**, differences in these **details** are irrelevant to the **pattern of behavior**.

Here, the boldface phrases are variables that are filled in according to the explanandum of interest. We will fill in this schema below.

Certain variables in this explanation schema deserve further clarification. By **details**, we simply mean parameters that are used to describe the system. For example, in the example discussed below, these details include beam energy and scattering angles of electrons. By **underlying microphysics**, we mean the interactions on the microscopic level of the various details of the systems.

The technical variable in this explanation schema, the **asymptotic limit**, also warrants clarification. In particular, we stress its use in identifying explanatorily irrelevant parameters. Taking a function to an asymptotic limit simply means identifying how the function behaves when one or more of its arguments approaches either zero or infinity. For instance, consider the function $f(x) = x^2 + 9$. Clearly:

$$\lim_{x \to 0} f(x) = 9$$

Asymptotic limits are theoretically beneficial because they provide a hypothetical set of 'extreme conditions'. These extreme conditions help abstract away the many explanatorily irrelevant factors that are present in normal conditions. If a certain explanatory factor can be found even in these extreme conditions, it's liable to be present (to one degree or another) in all other systems of interest. Consequently, its relevance to the explanandum is warranted.

Many of Batterman's (2002, 16) examples of asymptotic reasoning utilize *dimensional analysis.* In this context, dimensional analysis involves examination and manipulation of the various dimensions involved in a given problem, with the goal of creating dimensionless parameters. By taking one or more of these dimensionless parameters to be either very small or very large and implementing the appropriate limit, one can replace one of the parameters with a constant, thereby yielding equations more tractable than the original. Often, these equations exhibit self-similarity, or scaling behavior. Importantly, self-similarity indicates a type of stability has been achieved independently of details regarding initial and boundary conditions. Even in the frequent cases where such limits don't exist, more complex mathematics can be implemented and self-similarity can emerge[11].

Bjorken offered an asymptotic explanation of (E2) using dimensional analysis. In his account of inelastic scattering, Bjorken initially relied on effective mass, which is a dimensional constant. As noted above, dimensionless quantities are quite useful in cases where asymptotics are to be used. Accordingly, Bjorken created the dimensionless *Bjorken scaling variable,* $\omega = -q^2 / Mv$. With this tool in hand, he introduced a limit that would eventually be known as the "Bjorken limit": v (the energy lost by the electron in collision) and q^2 (the square of the momentum transfer between the electron and the proton) are both taken to infinity, but the ratio $\omega = v/q^2$ is held constant.

Thus, the limits in question were:

$$\lim_{q^2 \to \infty, \frac{v}{q^2} \text{ fixed}} vW_2(q^2, v) = F_2(-q^2/Mv) = F_2(\omega)$$

and

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[11] See Batterman (2000, 254; 2002, 16) for further details.

$$\lim_{q^2 \to \infty, \frac{v}{q^2} \text{ fixed}} MW_1(q^2, v) = F_1(-q^2/Mv) = F_1(\omega)$$

This states that at very high energies (implied by the $q^2 \rightarrow \infty$ limit), the proton's structure (represented by the structure functions W_1 and W_2) becomes a function of the ratio (ω) between the square of the momentum transfer between the electron and the proton (q^2) and the electrons' energy loss (v)[12].

With these ideas in hand, we can see how Bjorken instantiated the asymptotic explanatory pattern in his explanation of scaling:

<u>*Explanation Target*</u>:

Why does $W_1 = F_1(\omega)$ and $vW_2 = F_2(\omega)$ in diverse lepton-hadron scattering experiments ?

<u>*Application of Explanatory Pattern*</u>:

W_1 and W_2 can be expressed as mathematical functions of q^2 and v.

E and θ are constant in the Bjorken limit in W_1 and W_2.

Given the **underlying microphysics** of the lepton-hadron scattering experiments, differences in E and θ are irrelevant to W_1's equaling $F_1(\omega)$ and vW_2's equaling $F_2(\omega)$ in the lepton-hadron scattering experiments[13].

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[12] For the mathematically disinclined, we can steal a glimpse at Bjorken's central theoretical insight by observing the punctuation in the argument of the Bjorken functions *F*. The division sign signals that, initial appearances notwithstanding, q^2 and *v depend on each other* in determining the values of the structure functions—a point that can be observed only when they're approaching "extreme conditions" (i.e. when both approach ∞).

[13] Importantly, it's debatable if Bjorken provided the **underlying microphysics**. We address this in Section 3.1.

Here *E* refers to the beam energy of the electrons and *θ* refers to the scattering angle of an outgoing electron. Importantly, others previously thought that *E* and *θ* are or could be explanatorily relevant to the structure functions.

Because W_1 and W_2 determine σ_{DIS}, there is an intimate link between the scaling phenomena (E2) and the other explanandum (E1), the unexpected scattering results. More precisely, it was well known prior to the scattering experiments that:

$$\sigma_{DIS} \approx \sigma_{MOTT}\left[W_2 + 2W_1 \tan^2\left(\frac{\theta}{2}\right)\right]$$

Here θ refers to the scattering angle of an outgoing electron. Effectively, Bjorken's scaling laws imply that the expression $W_2 + 2W_1 \tan^2\left(\frac{\theta}{2}\right)$ approaches 1 as we increase the energy level of the scattering experiment. Thus, Bjorken could easily explain the deep inelastic scattering results (E1) as a consequence of his explanation of scaling.

3. A lack of understanding

When the Bjorken scaling curves were first discovered, experimenters did not understand why (E1) and (E2) were true. Indeed, as the SLAC-MIT group's paper reporting of the scaling phenomenon was being written for publication, one of Bjorken's postdocs, Emmanuel Paschos, was quoted as saying, "The experimenters have this puzzling graph of the structure function BJ asked them to make…He claims the data should 'scale' and it does, but nobody seems to *understand* what this ‘scaling’ means” (Riordan 1987, 150; emphasis added)[14].

Why did such a gap in understanding exist? Two reasons suggest themselves. First, it’s debatable if Bjorken filled in one variable in this explanation schema—namely the **underlying microphysics** of the scattering experiments. Thus, arguably it was an incorrect (because incomplete) explanation (3.1). Second, Bjorken did not satisfy other conditions of the EK Model. According to the EK Model (item b, above), it is not enough to *have* an explanation; one must *know* it, and moreover, this knowledge must be the result of reliable explanatory evaluation (3.2). The reception of and response to Bjorken’s asymptotic explanation suggest that physicists did not think that these other conditions were satisfied.

Before turning to this history, we stress that Bjorken’s shortcomings shouldn’t be overstated. Certainly, he recognized that the scaling and scattering results implied (*pace* QED) that hadrons were not diffusely structured, but instead were hard and behaved more like point-like entities, such as electrons. However, his commitments beyond this were quite weak. For instance, by the time he first made the scaling prediction, he had entertained the possibility that hadrons were composed of quarks, but was not particularly enamored with the idea, later describing it as “the most trivial, simple representation of local current algebra that you could think of.”[15]

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[14] (Cao 2010, 96, 98; Pickering 1984, 132) also argue that Bjorken’s account was not well understood by other physicists.

[15] As reported in (Riordan 1987, 153). Similarly, Cao (2010, 89) reports that “Bjorken was not particularly fascinated by the constituent quark model for various reasons [which] made it easier for him to move away from the constituent quark model as an underpinning picture in his further explorations.”

3.1. Incomplete explanation

This disclaimer notwithstanding, we examine the first factor that prevented experimental physicists from understanding the scaling phenomena: the incompleteness of Bjorken's explanation. Paschos' exasperation about the opacity of Bjorken's explanation fell upon the ears of Richard Feynman, who explained the experimental results in terms of the 'parton' model in August 1968. Although it was formally quite similar to Bjorken's current-algebraic account of scaling, the parton model was a mechanical model that experimenters found easier to understand than Bjorken's abstruse mathematics. One MIT experimenter remarked that with the advent of the parton model, "Experimenters could finally talk to theorists in a language both *understood*" (Riordan 1987, 152 emphasis added).

Before proceeding, let us elaborate the sense in which Bjorken's explanation was incomplete. First, "incompleteness" should not be understood here to entail some failure to meet requirements of an ideal explanation. Rather, it is a failure to provide values for all of the variables involved in an accepted or acceptable explanation schema, as is the case with Bjorken's failure to fill in the Asymptotic Explanation Schema described above. Second, the explanation is incomplete because **underlying microphysics** is a variable in the Asymptotic Explanation Schema, but it would be a hasty to infer from this single historical example that all understanding-conferring explanations must be microphysical, reductive, or mechanistic in character. Indeed, the requirement for an underlying microphysics comes from Batterman (see note 10), who explicitly denies that asymptotic explanations are mechanistic (Batterman 2002, 9-13).

Feynman's parton explanation was valuable precisely because it provided a mechanical model that filled in the lacuna in Bjorken's explanation. Feynman achieved this by deploying two strategies previously used while theorizing about high-energy proton-proton interactions. These ideas then readily applied to both scaling and deep inelastic electron-proton scattering.

The first strategy is called "working in the infinite momentum frame." Feynman imagined that, because of their high relative velocity, each proton would 'see' the other as relativistically contracted along its direction of motion—roughly as a 'pancake.' Because the strong interactions between protons are of short range, each proton would also see the other as a frozen snapshot of its constituent particles. At this stage of research, Feynman was agnostic as to whether these particles were quarks or other hadrons, so he simply used the term "partons" as a placeholder. Using the second strategy—impulse approximation—he further assumed that within a single pancake (i.e. proton), partons did not interact with each other. Consequently, in strong interactions, each parton acts as an independent, quasi-free entity.

This picture of the proton enabled Feynman to explain both of our explananda. First, in deep inelastic scattering, the incoming electron emits a photon, which then interacts with a single free parton. Much like electrons, Feynman assumes that partons are structureless and point-like. Consequently, the cross section of protons in the deep inelastic region is similar to the cross section of electrons in this region, i.e. $\sigma_{DIS}/\sigma_{MOTT} \approx 1$.

Second, Feynman explained scaling as follows: W_1 and W_2 measure the distribution of the partons' momentum within the proton. In an interaction between an electron and a proton, the partons' momentum would be determined entirely by the momentum transfer between the electron and the proton (*q*) and the electron's energy loss (*v*). Consequently, W_1 and W_2 scale with functions of ω.

Thus, Feynman's mechanical parton model filled in much of the **underlying microphysics** that Bjorken's explanation lacked. If one likes, this functions as a "module" in the Asymptotic Explanation Schema:

Mechanical Model Schema

Explanation Target:

How do the **underlying microphysics** affect a **pattern of behavior** in a **system**?

Explanation Pattern:

The **system** is made up of **parts**.

The **parts** have **properties** and **interact** with each other.

According to the **underlying microphysics, interacting** objects with these **properties** are subject to certain **laws**.

The **pattern of behavior** is a **product** of these **law-**governed **interactions**.

Feynman filled in the schema as follows:

Explanation Target:

Why does $W_1 = F_1(\omega)$ and $vW_2 = F_2(\omega)$ in electron-proton interaction?

Application of Explanation Pattern:

The electron-proton interaction is made up of electrons and partons.

The electrons and partons are hard and point-like and collide with each other.

Per the infinite momentum frame and impulse approximation, when hard and point-like objects collide, their momentum transfer is a function of ω.

W_1 and W_2 are momentum distributions of the partons in these collisions. Moreover, Bjorken and Feynman's collective explanation is correct—which is a requirement of the EK Model. By the standards of current science, partons are the theoretical precursors to quarks. Historically, it's worth noting that the quark idea was alive and well by 1964—several years before the SLAC-MIT experiments. However, the lack of any empirical evidence of any freestanding, fractionally charged quarks made them unpopular with many particle physicists throughout the early 1970s. Undoubtedly, this partly motivated Bjorken and Feynman to adopt a more ontologically modest stance that, e.g. leptons' colliding with *something point-like* in a hadron correctly explains the deep inelastic scattering and scaling phenomena.

3.2. No reliable explanatory evaluation

Thus far, we have argued that Bjorken's explanation did not provide understanding to other physicists because it was incomplete (hence incorrect), and this was remedied by Feynman's mechanical parton model. The EK Model also suggests that merely *possessing* a correct explanation falls short of understanding—the explanation must be *known*, to wit by means of *reliable explanatory evaluation*. As we shall now argue, after Feynman's interpretation, the experimental physicists engaged in reliable explanatory evaluation, primarily by running additional experiments designed to rule out competing (i.e. other plausible potential) explanations of the deep inelastic scattering and scaling phenomena.

Recall the three stages of explanatory evaluation: the generation of plausible potential explanations, comparative assessment of those explanations, and formation of doxastic attitudes on the basis of those assessments. The particle physicists in question evaluated explanations in roughly this way. QED offered one potential explanation of the scattering experiments. If it were correct, then σ_{DIS} would have been low. But the experimental evidence indicated the opposite. Similarly, if the high σ_{DIS} were a result of photon radiation, then σ_{DIS} would have been low after the radiative corrections. However, this also turned out to be false. So Bjorken's current-algebraic model gained traction.

However, the extent to which Bjorken's explanation was produced via *reliable* explanatory evaluation is limited, and, importantly, was also unclear to his contemporaries. This is supported by the fact that further explanations were generated and compared to the parton model.

Specifically, two other models offered potential explanations of these phenomena. As we'll now argue, each of these explanations was rejected using the same process of explanatory evaluation just described. Importantly, the experimental physicists designed and conceived of experiments that ruled out these explanations only after learning of Feynman's addenda. Hence, per the EK Model, Feynman's amendments to Bjorken's explanation contributed to understanding by facilitating reliable explanatory evaluation.

First, in August 1969, the SLAC group, this time led by Richard Taylor, designed another series of experiments intended to adjudicate between a parton model and Sakurai's vector meson dominance model, which held that partons were unnecessary explanatory posits. Instead, Sakurai held that proton-electron interactions were mediated by a "vector meson," which explained the scaling phenomenon. According to Sakurai, $R = \sigma_L/\sigma_T$, the ratio of the proton's tendencies to absorb virtual photons longitudinally to its tendencies to absorb those photons transversely, should be quite large (in between 1 and 10). By contrast, parton models held that it should be quite small (in between 0 and 1).

The experiments strongly indicated the latter, and Taylor's presentation of their results at the Electron-Photon Symposium held in Liverpool during September 1969 is widely regarded as the death-knell of vector meson dominance theories, which provided the most popular explanation of scattering behavior in the high-energy physics community for most of the sixties.

Similarly, in 1971-1972, experimenters at the European Center for Particle Physics (CERN) conducted experiments highlighting advantages of the parton model over Arbanel et al.'s Regge exchange explanation of scaling. According to the Regge exchange model, scaling was the result of a whole series of hadrons being exchanged during the electron-proton collision. The Regge exchange model posited a soft hadron. Thus, it predicted that collisions between hadrons would produce few particles at larger angles. However, when CERN ran proton-proton collisions, it found a far larger number of particles at these large angles than the Regge exchange model could account for. In contrast, the parton model explained this phenomenon with relative ease: protons are composed of small structures that go ricocheting off of one another during such collisions.

In evaluating these explanations and designing these experiments, the physicists introduced further explananda, e.g.

(E3) R is below (rather than above) 1.

(E4) Many (rather than fewer) particles were found at large angles in the proton-proton scattering experiments at CERN.

Moreover, as with (E1) and (E2), the experimenters took measures to guarantee that these phenomena were not mere artifacts. Thus the physicists had *knowledge* of these explananda.

Thus, the physicists were clearly evaluating explanations reliably. Hence, their belief that the parton model correctly explained the deep inelastic scattering and scaling phenomena could not easily have been false. Consequently, the requisite cognitive processes produce their true beliefs reliably. So, they possessed the kind of explanatory knowledge that the EK Model equates with understanding.

4. EK versus rival accounts

Thus, we have shown that by the time the parton model was accepted as providing understanding of (E1) and (E2), physicists had true beliefs about the correct explanations of these two phenomena, and these beliefs were supported by reliable explanatory evaluation. In other words, the EK Model provides a plausible interpretation of the physicists' norms of understanding. However, perhaps there are other plausible interpretations of these norms. To conclude our discussion, we look at two of the most plausible contenders: (4.1) Batterman's account of understanding, and (4.2) De Regt's account of understanding. In comparing the EK Model to these two accounts, we will argue that the former captures a wider range of scientific understanding, and also sheds light on aspects of understanding untouched by the latter.

4.1. Batterman on understanding

As we have already seen, Batterman's account of asymptotic explanation provides a productive framework for interpreting Bjorken's reasoning. Using this framework, Batterman has explicitly avowed an account of scientific understanding:

> The explanations I have been discussing involve, essentially, methods for extracting structurally stable features of the equations that purportedly model or govern the phenomenon of interest. These features are often emergent in appropriate asymptotic domains, and their perspicuous mathematical representation constitutes an essential component of our understanding of the world (Batterman 2002, 59).

The EK Model differs from this account of understanding in being pluralistic about explanation, and in making the epistemic requirements of understanding more explicit. While Batterman does not explicitly disavow either of these points, we shall now argue that, if he did, his account of understanding would quickly be found wanting. Hence, Batterman's account of understanding is best seen as a limiting case of the EK Model.

First, Batterman's account of understanding puts special emphasis on asymptotic explanations. If taken as a requirement for all understanding, then this is surely too strong, for it would imply that scientific understanding is necessarily mathematical, and moreover must always involve asymptotic limits. By contrast, the EK Model allows for non-mathematical understanding in the sciences. Consider, for instance, Semmelweis' oft-discussed discovery of the causes of childbed fever, e.g. (Lipton 2004). Semmelweis accepted a (broadly) correct yet qualitative explanation of childbed fever via the aforementioned process of explanatory evaluation. Indeed, even Feynman's contribution above suggests that non-mathematical explanations frequently complement asymptotic ones. Thus, not only asymptotic explanations provide understanding, as the EK Model suggests.

The EK Model also clarifies a lacuna in Batterman's account of understanding. Batterman does not specify the cognitive relationship whereby an asymptotic explanation provides understanding to a scientist. Simply "having" an asymptotic explanation does not guarantee that it provides understanding. For instance, the experimental physicists clearly "had" Bjorken's asymptotic explanation prior to Feynman's amendments in some sense, yet the quotations above indicate that this explanation afforded them little understanding. Rather, they understood the phenomena only when they could reliably evaluate the explanation of those phenomena (as described in the abstract in Section 1.1, and in the particular case of Bjorken scaling in Section 3.2), just as the EK Model requires.

4.2. De Regt on understanding

De Regt provides another prominent view of understanding[16]. After presenting his view, we argue that the EK Model has several advantages over it. De Regt's two core commitments are a Criterion for Understanding Phenomena:

(CUP) A phenomenon *P* is understood scientifically if a theory *T* of *P* exists that is intelligible (and the explanation of *P* by *T* meets accepted logical and empirical requirements).

and a Criterion for the Intelligibility of Theories:

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[16] We use (De Regt 2009), though we note that (De Regt and Dieks 2005) echo similar ideas.

(CIT) A scientific theory *T* (in one or more of its representations) is intelligible for scientists (in context *C*) if they can recognize qualitatively characteristic consequences of *T* without performing exact calculations (De Regt 2009: 32-33).

Combined, these entail a Principle of Understanding:

(PU) A phenomenon P is understood scientifically if a theory *T* of *P* exists such that:

(1) Scientists (in some context *C*) can recognize qualitatively characteristic consequences of *T* without performing exact calculations; and

(2) The explanation of *P* by *T* meets accepted logical and empirical requirements

To its credit, PU nicely captures how Feynman's parton model provides understanding. Furthermore, De Regt's view is sufficiently rich that we cannot subsume it under the EK Model, as we did with Batterman's view. Nevertheless, we now offer three reasons why the EK Model is superior to De Regt's.

1. *Not all plausible cases of scientific understanding that satisfy the EK Model are also instances of PU*. Clearly, it is possible to satisfy the EK Model by drawing consequences of a theory through exact calculation. For instance, in the Asymptotic Reasoning Schema, the **asymptotic limit** variable is typically determined through exact calculation. Not only does this account for Bjorken's contribution to our understanding of the phenomena described above, it is representative of a much broader point: sometimes scientists come to understand things by gaining greater technical proficiency through the

use of quantitative and formal vocabularies. This seems altogether plausible, yet PU does not account for it.

Admittedly, since De Regt does not specify necessary conditions for understanding, he need not deny that scientists can gain understanding in this way. Perhaps there is some other way to understand a phenomenon with exact calculations that is not captured by PU. However, he has not offered an explicit account of this kind of understanding. By contrast, the EK Model provides a unified account of both qualitative and quantitative understanding.

2. *The EK Model provides a clearer rationale for the value of understanding*. Intuitively, understanding is both worth having and an aim of science. The EK Model suggests the point of understanding is to believe correct explanations (however 'correct explanations' are glossed in the final analysis), which sits well with the shopworn claim that explanation is an important scientific activity[17]. Reliable explanatory evaluation is thereby instrumentally valuable, i.e. an effective means to believing only correct explanations.

Like us, De Regt (2009, 26) grants that "Having an appropriate explanation…is … an essential epistemic aim of science." However, unlike us, he then argues that this requires the kind of understanding described by PU. Yet, our first point against PU implies that understanding is not limited to qualitative reasoning in the absence of exact

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[17] Note that even if something like Van Fraassen's account is right, then explanations can still be epistemically valuable, albeit indirectly: "the *epistemic* merits a theory may have or must have to figure in good explanations are not *sui generis*; they are just the merits it had in being empirically adequate, of significant empirical strength, and so forth" (van Fraassen 1980, 88).

calculation. Consequently, if understanding is valuable, it's not always because of the features showcased in PU.

To that end, the EK Model identifies the conditions wherein qualitative reasoning in the absence of exact calculation contributes to the value of understanding. Let us return to an earlier quote from Michael Riordan, one of the MIT researchers at the time:

> Experimenters could finally talk to theorists in a language both understood… Feynman had again supplied a language, a strikingly simple mental image, to describe what might be going on in a remote and tiny realm (Riordan 1987, 152).

Such a quote sits nicely with PU. But *why* is it so important that experimenters and theorists have a *lingua franca* or "strikingly simple mental images"? Suppose that experimenters and theorists continued to talk past each other. For instance, no matter how much the experimenters studied their current algebra, it just didn't have any traction in the way they designed their experiments. Quite plausibly, theorists would offer potential explanations, but experimenters would be unreliable in providing relevant evidence to test those hypotheses. In short, the experiments that squarely ruled out the vector meson dominance model and the Regge exchange model would be either poorly designed or never designed in the first place.

This suggests that expressive languages, fecund visual models, and qualitative reasoning more generally are valuable only insofar as they allow scientists to evaluate explanations more reliably. Since reliable explanatory evaluation is central to the EK Model, the value of qualitative insight (a shared language, visual images, etc.) is its facilitation of good old-fashioned hypothesis testing.

This is given further credence when we consider people who are facile with linguistic or imagistic tropes, but who regularly fail to believe in correct explanations. Clearly, their understanding of relevant phenomena suffers. The EK Model diagnoses this correctly: in such cases, the tropes fail to serve their role of facilitating reliable explanatory evaluation.

3. *PU's "accepted logical and empirical requirements" should be replaced or supplemented by the EK Model's "reliable explanatory evaluation."* Let us suppose that we have a putative case of understanding satisfying PU, but that the scientists cannot evaluate explanations reliably. The lack of reliable explanatory evaluation might be understood in three ways. Each leads to an untoward result. Hence reliable explanatory evaluation is required of any acceptable instance of PU.

First, the scientists may believe that *T explains P* on the basis of *unreliable* processes, i.e. they could have easily formed the wrong doxastic state while nevertheless satisfying De Regt's "accepted logical and empirical considerations." For example, they could have easily believed that *T* does not correctly explain *P* despite considering the same logical and empirical requirements.

However, this proposal is potentially incoherent. For instance, a plausible empirical requirement is that scientists possess some evidence *E* that confirms the claim that *T correctly explains P*. However, such confirmation matters little if, given *E*, scientists' belief that *T correctly explains P* could have easily been false. If this is correct, then any instance of PU must satisfy the EK Model's requirement that some reliable process underwrite the explanation.

Admittedly, De Regt does not specify what these logical and empirical requirements entail. This suggests the second way of interpreting this scenario—the accepted requirements are modest enough that the relevant explanatory propositions could easily have been false. While such a case satisfies PU without satisfying EK, the understanding it licenses is dubious. Specifically, understanding could be achieved by having an explanation that could have easily been incorrect given the available evidence, e.g. so long as scientists could make the requisite qualitative inferences with the parton model, their inability to eliminate its rivals (vector meson dominance, Regge exchange) matters little. Yet, the scientists ran crucial experiments to eliminate these alternatives to the parton model, so this view of understanding conflicts with scientific practice. Additionally, this implies that understanding of (E1) and (E2) is achieved even if one can only draw qualitative consequences from one of these rivals, since they also satisfy these (weakened) empirical and logical requirements. So abandoning the EK's reliability requirement in this way weakens PU's plausibility.

Now, it is open to a proponent of PU to reply to this by insisting that understanding is one thing and confirmation is another. For instance, one might claim that, in the events described above, the real moment of understanding ends with Feynman's innovations, and that the experiments that follow are distinct from understanding. However, this puts further pressure on De Regt to address our second point about the value of understanding—why would qualitatively reasoning with a theory that satisfies *fairly weak* logical and empirical constraints be something worth having?

This suggests the final way that PU's proponents could deny the importance of reliable explanatory evaluation for understanding. They may grant that PU's logical and empirical requirements entail *some* kind of reliability requirement, while also denying that understanding involves reliable *explanatory evaluation*. On this view, scientists possess understanding if their explanation could not have easily been incorrect because it satisfies accepted logical and empirical requirements, and it plays the appropriate role in qualitative reasoning, even if the scientists have not partaken in reliable explanatory evaluation, i.e. generated plausible alternatives, comparatively assessed, and formed the appropriate doxastic attitude[18].

It is worth noting that this already concedes an important point to the EK Model: reliability matters. However, "the accepted logical and empirical requirements" might be distinct from the requirements of reliable explanatory evaluation, if, e.g. it is possible to satisfy the former without using the theoretical virtues that figure prominently in the latter. To that end, proponents of PU sympathetic to this line of defense might note that the theoretical virtues played no explicit role in our discussion of explanatory evaluation in §3.2.

However, this contradicts De Regt's remarks on this issue, for he explicitly treats the theoretical virtues as important components of understanding:

> Philosophers of science have listed and discussed the theoretical virtues that generally play a role in the evaluation of scientific theories—for example, accuracy, consistency, scope, simplicity, unifying power, and fertility…Scientists may prefer theories with particular pragmatic virtues because they possess the skills to use such theories, that is, to construct models for explaining phenomena

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[18] Given our earlier admission that our comparison with PU is incomplete, we grant that proponents of PU could argue that EK goes wrong primarily in taking the appropriate attitudes involved in understanding to be doxastic. Elgin (2004) gestures in this direction.

> by means of the theories. In other words, they have pragmatic understanding… of such theories (De Regt 2009, 31).

Consequently, De Regt does not have the resources to distance PU from EK in this manner. As for the dearth of explanatory virtues in our discussion of Bjorken scaling, we note that some virtues (most notably accuracy, consistency, and scope) are readily implied. Additionally, as noted above, other virtues often figure in the generation of plausible rival explanations. To that end, Cao (2010, 14-48) remarks upon current algebra's fertility, symmetry, and its points of contact with prior theory; similarly, Feynman's model exhibits virtues such as mechanism and analogy with accepted explanations. Furthermore, the relative weight of theoretical virtues is widely regarded as context-dependent; hence the absence of some virtues in this particular case is unsurprising.

To repeat, De Regt's account of understanding deserves further comparison with the EK Model, but we have already highlighted three advantages of the latter. First, it covers a broader range of cases of scientific understanding. Second, it more clearly accounts for why understanding is valuable. Third, the notion of reliable explanatory evaluation helps to unpack what De Regt means by the accepted logical and empirical requirements that figure in understanding.

Conclusion

We have presented a simple model of understanding—the Explanatory Knowledge or EK Model. We then showed how this model accounts for an episode in the history of science which functions as a kind of natural experiment for theories of scientific understanding.

Moreover, we have argued that the EK Model has certain advantages over two leading alternatives—Batterman's and De Regt's. All told, our EK Model is one of the few attempts to offer both necessary and sufficient conditions for understanding. Consequently, it is our hope that it will spark further discussion—and challenges—from philosophers of science and epistemologists interested in the concept of understanding.

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