CRUCIAL INSTANCES AND CRUCIAL EXPERIMENTS IN BACON, BOYLE, AND HOOKE

Claudia DUMITRU*

Abstract. My paper is an account of the tradition of crucial experiments prior to Newton. The starting point of my investigation is the second book of Francis Bacon's *Novum Organum* and his account of *instantia crucis*, a subset of the instances with special powers. I take a close look at both his claims about the certainty of crucial instances and at the examples he advances to support his account. From there, I follow the adoption of this concept in the circles of the early Royal Society, briefly touching on Robert Boyle's use of the phrase *experimentum crucis*, and then focusing on Robert Hooke's *Micrographia* and the two experiments that are said to be crucial in Observation IX in that work. Hooke's case is revealed to be a little more complicated than Boyle's, because the two experiments that he claims are crucial for refuting Descartes' theory of the nature of prismatic colors and confirming his own seem i) have a weaker confirmatory value and ii) to play a slightly different role than the examples Bacon and Boyle advanced.

Keywords: Francis Bacon, crucial instances, eliminative induction, crucial experiments, Robert Hooke, Robert Boyle

Introduction

There are two things usually mentioned in connection with the concept of the crucial experiment: the first is that it was introduced in the 17th century by Francis Bacon, as part of his account of eliminative induction; the second is that it was famously debunked at the beginning of the 20th century by Pierre Duhem in *The Aim and Structure of Physical Theory*. Between these two dates, one other landmark stands out: Isaac Newton's famous *Experimentum Crucis* from his 1672 *New Theory about Light and Colours*. Newton's case is particularly interesting because it raises two sets of important questions, one related to the contemporary dissemination of the Baconian methodology and the extent to which Newton himself was influenced by it, the other concerning the relation between Newton's early method as employed in his works on optics and his later "deductions from phenomena." My paper is a small contribution towards answering the former set of questions. A number of authors in the secondary

* University of Bucharest, Faculty of Philosophy, Department of Theoretical Philosophy, 204 Splaiul Independenței, București, e-mail: claudia.dumitru.mail@gmail.com

literature have noted that Newton's use of the phrase "*experimentum crucis"* is a nod to Bacon and that the *New Theory about Light and Colours* is at least superficially constructed as a Baconian induction.[1] This could be either because Newton found the methodology itself scientifically useful, or because he found the *mention* of it socially useful (since it was the methodology preferred by those he addressed, i.e., by the members of the Royal Society). Dana Jalobeanu has recently claimed that Newton's letter has the form of a Baconian natural history and that Robert Hooke read it as such and criticized it when it deviated from the Baconian canon (as it supposedly did in the matter of crucial experiments).[2] It would be useful, then, to take a closer look at the tradition Newton might have been reacting to (whether he conformed to it, or subverted it) by using the phrase "*experimentum crucis.*" I will do so by tracing the development of the concept of the crucial experiment from Bacon's *instantia crucis* to Robert Boyle's *experimentum crucis* and, finally, to Robert Hooke's use of both of these phrases in *Micrographia*.

One question immediately raised by this enterprise is whether one should assume a continuous history of the concept of the crucial experiment. This is important not only as concerns the relation between what "crucial experiment/instance" might have meant in the early modern period and what it came to mean in the 20th century, after Duhem, but also regarding the unity of this concept in the 17th century. It is not necessarily true that Boyle or Hooke were operating with the same concept Bacon had, although it is more than probable that they *thought* they were. What I propose, then, is a close reading of a selection of texts in which the phrase "crucial experiment/instance" appears and a reconstruction of the function and structure of the arguments involving it. This analysis will reveal a tension at the core of the initial Baconian concept of a crucial instance and some differences in the way this concept is later employed by Boyle and Hooke.

Bacon's Crucial Instances: Features and Challenges

Instances with Special Powers

In order to deliver the key points of Bacon's presentation concerning crucial instances, I will start with a short summary of the context in which these instances appear in the *Novum Organum*. While any retelling necessarily involves a series of interpretative choices, I have tried to avoid entering a discussion about Bacon's larger project and the meaning of various phrases or terms of art he uses, like "axiom," "nature," or even "induction." What follows is merely a condensed version of his presentation leading to the introduction of the instances with special powers, from the second book of the *Novum Organum*.

According to Bacon, the interpretation of nature starts from a corpus of observations and experiments organized in natural and experimental histories, and goes on to derive axioms of increasing generality by the means of the "true and legitimate induction"[3] (by which Bacon says he means a demonstratively certain form of induction proceeding by way of elimination, rather than enumeration[4]). From these axioms, new experiments are constantly derived. Most of the steps and elements of this process are merely named and briefly described in the second book of the *Novum*

Organum in anticipation of a future, never delivered work that would present them in detail. The first application of the process of exclusion, its results (the "first vintage"[5]), and the instances with special powers are the exceptions, in that Bacon outlines them more thoroughly and using examples.

To draw any conclusion, even a provisional one, about the cause or form of a simple nature, one needs a natural history of that nature, systematically organized in three tables: a table of essence and presence (including all the instances where that nature is present), a table of divergence or absence in proximity (including all the instances related to those in the first table, but in which the nature is absent) and a table of degrees (including all the instances in which that nature varies under different circumstances).[6] Once these tables are drawn, one can proceed to eliminate, on their basis, all the causes that are not exclusively and constantly associated with the nature under investigation. The instances that are left after this systematic elimination are used for deriving a first, preliminary conclusion about the cause of that nature.

Given the fact that the initial tables were not exhaustive, and that our notion of what counts as a simple nature may in itself be deficient, the first vintage only has a provisional and limited value, and Bacon is well aware of this.[7] To continue on the path of the true induction, the intellect requires a series of aids. The first of these aids – and the only one described in the *Novum Organum* – is the group of twenty-seven instances with special powers. Instances with special powers are, as Bacon poetically puts it, "like the soul amongst the ordinary instances."[8] Some of them aid the senses (for example, by making subtle processes perceptible, as in the case of summoning instances), most of them aid the intellect directly in some way (by easing its work of exclusion, like the solitary instances; or by warning against the power of habit, like the deviating instances etc.) and others are of use in the operative part of the enterprise (like multi-purpose instances, for example, that reduce the amount of work, due to their versatile applications).

The different functions of the instances with special powers, ranging from the practical to the more theoretical, have been emphasized in the secondary literature. At one end of the spectrum, we have their role as practical guides and shortcuts in the investigation. "They are," as Stephen Gaukroger has described them, "practical guides which enable one to seek out the most informative kinds of case, to avoid dead-ends, to collect the clearest and most unambiguous forms of evidence, and so on."[9] Lisa Jardine compares them to *experientia literata* in that they are both "part of an ad-hoc program for deriving working precepts of a rule of thumb kind and guidelines for future operations without recourse to Forms and principles."[10] Both *experientia literata* and the instances with special powers have a role in efficiently assembling the natural and experimental histories that will provide the stuff of induction. [11] This is a point made by Jardine, when she mentions that they "solve problems of procedure in the course of the organization of sense-experience prior to the inductive derivation of the form of a simple nature."[12] Their theoretical function is emphasized more strongly by Sophie Weeks, who notes that instances with special powers are "derived from the highest kind of *experimenta lucifera*"[13] (i.e., from experiments useful in the discovery of causes[14]). This observation acknowledges their importance in the process of induction and the deriving of axioms. Their function at this level is analyzed by Antonio Pérez-

Ramos as well, who argues that the role of these instances is to "serve as a deductive canon."[15] They are there to provide deductively sound links between the results obtained by induction. (This, together with Pérez-Ramos' claim that such instances are "sometimes falsification procedures of sorts, sometimes verificationist or probative attempts,"[16] is very close to what Mary Horton argued about Bacon's method. For Horton, instances with special powers were simply falsifiers, applied after the initial induction.[17]) While it is doubtful that this account satisfactorily covers all the varieties of instances with special powers, including the ones which are explicitly designed to be of operative use, it does seem well suited for crucial instances, which are Pérez-Ramos' examples of choice as well. On that note, we can now move the discussion towards the structure and function of the crucial instances.

Crucial Instances

Crucial instances and the instances of divorce belong to a category of instances with special powers that aid the intellect by "warning against false forms or causes."[18] What sets these two types of instances apart, Bacon tells us, is the fact that the instances of divorce "decide nothing but only advise on the separability of one nature from the other."[19] This statement could be read in two ways. It could refer to the fact that the two types of instances perform the same function – that of infirming the causal connection between two natures – but with different degrees of certainty. However, it could also mean that the instances of divorce have only an eliminative function, while crucial instances lead to an affirmative conclusion as well. I think the latter interpretation is supported by the way Bacon describes the crucial instances, in Aphorism XXXVI:

> [W]hen in the investigation of any nature the intellect is finely balanced, and so that it is uncertain as to which of two or sometimes more natures the cause of the nature under investigation should be attributed or assigned (on account of the frequent and normal concurrence of many natures), Crucial Instances indicate that the partnership of one of the natures is (in relation to the nature under investigation) constant and indissoluble, while that of another is variable and separable whence the question is settled, and the former nature is accepted as the cause while the other is set aside and rejected.[20]

In other words, when two causes seem to account equally well for a nature, one must find a fact that can only be explained by one and not by the other, in order to be able to decide between the two. This statement presents the crucial instances as having both a negative function (that of disproving some explanations), and a positive one (that of confirming one of the causes). The fact that they are placed among instances that warn against false causes, while their distinguishing feature is that they show the causal connection between two natures to be "constant and indissoluble," seems to indicate that these two functions, the negative and the positive, cannot be separated. This would work well with the logical structure behind the concept of the crucial experiment as described by Duhem and usually employed in the philosophy of science, as a decision taken within a set of collectively exhaustive and mutually exclusive theories.[21] If we can be certain that these two criteria are met for our set of explanations, then disproving n-1 explanations and confirming the one that is left are equivalent. But can this view be reconciled with Bacon's own examples of crucial instances? For that, we need to take a closer look at some of his examples.

An instance of refutation: On the ebb and flow of the sea

I will break down this example, Bacon's first, into successive steps, both for ease of presentation and because I think the argumentative structure is, to a certain degree, common to all of the examples, so it is worth taking a closer look at it and at the questions it raises. Since the goal is to draw some conclusions about the concept of the crucial instance in general, I will constantly refer to the other examples as well.

> [**Step 1: announcing the subject under inquiry**] [L]et the nature under investigation be the ebb and flow of the sea, which is repeated twice a day and with a six-hour interval between each high and low tide, yet with a certain amount of variation coinciding with the lunar cycle.
>
> [**Step 2: presenting the competing explanations, here a & b**] Now the plain fact is that this motion must of necessity either be caused by the advance and retreat of the waters, in the way that water rocked in a bowl does, which when wetting one side of the bowl deserts the other [**a**]; or be caused by the raising and falling back of waters from the depths, in the way that water does when boiling and then sinking back [**b**]. Now the doubt arises as to which of the two causes the ebb and flow should be ascribed.[22]

By far, the most constant feature in all ten of the examples is the clear laying out of the divergent causes the intellect has to choose between. In this example, we are told that the nature under investigation is by necessity ("necesse prorsus est..."[23]) caused by one of two things. The same situation occurs in example 2[24] and again in example 5, where we know that "of necessity heavy or weighty bodies either tend from their intrinsic nature to the centre of the Earth (…), or they are attracted or seized by the corporeal mass of the Earth itself."[25] I take this wording to indicate the fact that another option cannot present itself – in other words, that the disjunction is exhaustive.

However, not all of the examples presented by Bacon have this particular phrasing, and, even among those that do, it is clear that some of them are open to the charge of not being logically exhaustive. After all, as Peter Urbach puts it, we don't *a priori* know that weightiness is not the result of things being "pushed by angels, or tugged by leprechauns" to Earth.[26] This raises a few questions about the concept of a crucial instance as employed here. Do we need to assume that our set of explanations is exhaustive for the crucial instances Bacon presents to function the way he claims they do? Can we settle for testing the best or most plausible theories available at the moment?

> [**Step 3: consequence derived from one of the explanations: a→c**] But if one accepts the first claim, it necessarily follows that when there is a high tide on one side of the sea, there must at the same time be a low one on the other [**c**]. So then the inquiry comes down to this.[27]

There are two important points to notice about this step. First, how Bacon derives a consequence from just one of the explanations presented, without discussing why the other is incompatible with it. This arguably does not pose any problems for this example (which is fairly straightforward), but it might for others that are more complex. For instance, in example 5, Bacon states that if bodies are attracted to the Earth, instead of moving towards it because of their intrinsic nature, then that force of attraction should be stronger the closer we get to the center of the Earth.[28] It's not immediately transparent from just his presentation why the explanation relying on the bodies' intrinsic nature should exclude the option of them accelerating the closer they get to Earth. (And this comes down again to the question of whether we are testing all possible explanations, or specific theories with their specific developments and background assumptions that might render them incompatible with a specific consequence.)

The second point that I wanted to emphasize is the abstract nature of this step. We are not given the crucial instance directly. Instead, we are invited to derive (testable) consequences from a proposed explanation. This action, together with the initial parting of the ways, seems to receive greater importance in the presentation than the actual crucial instances do. In fact, three of the remaining nine examples do no pinpoint one clear, detailed crucial instance. In example 8 (on "the motion through air of missiles"), Bacon gives a trivial example of elasticity ("among others") to show that violent motion resides in the body itself and is not produced by air.[29] In example 7, we are told that the instances that qualify as crucial for deciding the nature of the moon, "**if there are any**" [emphasis mine], would be those that showed that not only solid bodies can produce reflections. Bacon offers some examples "in the nature of Crucial Instances on this matter" and then says that better ones could perhaps be found.[30] The emphasis throughout the examples seems to be more on figuring out the aspect we want to test for (the implication **a→c**) than on the specific way in which we can test it.

> [**Step 4: an instance providing an apparent refutation of c**] Now Acosta, and some others (after careful investigation), have observed that high tides happen on the coast of Florida at the same time as on the opposite coasts of Spain and Africa, and

> that low tides are also simultaneous, and not the reverse, namely high tide in Florida coinciding with low in Spain and Africa. (…)
>
> [**Step 5: rejecting the refutation**] For there could still be a progressive motion of the waters flooding opposite shores of the same channel at the same time; i.e. if the waters were driven and forced from elsewhere (…). We must therefore see whether there is a basin through which the waters could ebb and fall back at the same time. And here the Southern Ocean comes to our aid, which, no smaller than the Atlantic but rather wider and more extensive, would be well able to do the job.[31]

While these two steps are not common to all of the examples, they are interesting insofar as they show Bacon being aware of the challenges testing a hypothesis against reality can bring. Notice how he does not reject the results obtained by Acosta. He actually validates them with the same phrase he will use in example 2 to refer to the results this investigation might establish *if successful*: "diligenti facta lnquisitione." This apparent refutation of **c** prompts him to establish an auxiliary condition **d** ("no other sea or place remains where the waters could at the same time ebb or retire"[32]), such that **(a & d)** →**c**. Contemplated more seriously, the questions raised by this step might hint to a problem of holistic underdetermination. In the face of an apparent refutation/confirmation, how do we decide if we need to reach for auxiliary conditions or if we should just accept the result and end our inquiry?

There are two other examples in which we are told that the investigation would need to continue, if certain results were obtained. Example 4 (on the motion of rotation from west to east) proposes a way to test whether this motion is real: "if one finds in any trustworthy history that there has been any comet, be it higher or lower, which did not go round (albeit very irregularly) in manifest consent with the diurnal motion but rather in the opposite direction, then indeed one should conclude that some such motion could exist in nature." [33] However, if one cannot find such a result, "we should smell a rat, and go looking for other Crucial Instances on the matter."[34] (Graham Rees describes this example as Bacon's speculative preoccupations almost getting the better of him, since, prior to providing the instance, Bacon strongly suggests which of the two explanations he favors.[35]) Again, in example 6 (on "the verticity of an iron needle stroked with a loadstone"), we are told to make an experiment in which to place an iron needle on a magnet with the poles set towards the Earth's east-west. If, after removal from the magnet, the needle starts turning towards north-south, we may assume the magnetic influence of the Earth to be the cause. But if it does not, "we must treat that cause [the Earth's presence] with suspicion and make further inquiries."[36] This is not yet a clear refutation of that cause, nor a confirmation of the alternative.

> [**Step 6: finding an instance that refutes c (and, with it, a)**] Now then at last have we come to the Crucial Instance on this subject. If we find for certain that, when there is a high tide in

> Spain and Florida in the Atlantic, there is also a high tide on the coasts of Peru and eastern China in the South Sea, then this Decisive Instance should certainly rule out the claim that the ebb and flow of the sea which we are investigating results from progressive motion.[37]

This step as presented here focuses on the prospective refutation of the cause under investigation. It remains to be established if this is the primary role of crucial instances in general (with their confirmatory role, if they have one, being an indirect result of refutations applied to an exhaustive and exclusive disjunction), or if that is just a feature of this example (with Bacon focusing on the refutation perhaps because he anticipates the results) and crucial instances in general can directly confirm a cause as well.

> [**Step 7: a possible objection**] Now a decision for or against this seems safe, provided we assume that the Earth is stationary. But if the Earth turns, it could well be that the different rates of rotation of Earth and sea (in point of speed or impetus) produce a violent piling up of the waters or high tide, followed (when the waters can stand no more accumulation) by a falling back or ebb.
>
> [**Step 8: rejecting the objection**] But even on this assumption, the claim that an ebb tide must necessarily be happening at the same times as a flood tide is happening elsewhere remains just as true.[38]

Finally, like in the steps 4 and 5 above, these remarks seem to indicate awareness of the fact that the explanations we are testing depend on a system of assumptions and auxiliary conditions, but also a certain optimism about testing them, as long as the implication **a→c** has been correctly drawn.

An instance of confirmation: On the rising and falling motion of the sea

I will briefly discuss Bacon's second example and the ways in which it relates to the first. Although this aspect is obscured by the translation, I think the second example hinges on the success of the inquiry in the first one. Here is the Latin text announcing the subject of the investigation for the second example, followed by the OFB translation:

> Similiter, sit Natura Inquisita posterior ille Motus ex duobus quos supposuimus, videlicet Motus Maris se Attollens et rursus Subsidens; **si forte ita acciderit, ut (diligenti facto examine) reiiciatur Motus alter, de quo diximus, Progressiuus.**[39] [emphasis mine]

> In the same way, let the nature under investigation be the second of the two motions we have supposed, namely the rising and falling motion of the sea, **to see if perhaps (after careful examination) we can dispose of the other motion we mentioned, the progressive.**[40] [emphasis mine]

The Spedding edition and the Jardine one have the bolded fragment as "if on careful examination we reject the former motion of which I spoke, - the progressive"[41] and, respectively, "if, after careful examination, we do in fact reject the other motion we mentioned, the forward motion."[42] That is to say, if the first crucial instance presented has refuted one possible nature as the cause of the ebb and flow of the sea, the alternative cause should be taken as fact and we can now proceed to investigate its causes as well. This strongly suggests that the first crucial instance had an indirect confirmatory effect, and I think it is supported both by the Latin text and by the actual construction of the example, in which no further mention is made of the progressive motion.

The second example also answers the question we had regarding step 6 of the previous example, by making it clear that a crucial instance can also directly confirm a cause. We are given three possible causes for the rising and falling of the sea: the water comes from the interior of the Earth and retreats back into it periodically (so there is actually *more* water in the seas at the time when they rise), the same mass of water contracts or rarefies periodically (the quantity stays the same, but the density changes), the water is raised by a magnetic force acting on it from above (with no changes whatsoever to its quantity and density). After presenting these options, Bacon tells us to leave aside the first two and focus on the third, the rising by magnetic action. Like in the first example, we are to derive a consequence from this explanation and then test it:

> Now at last we come to the Crucial Instance on this subject. It goes like this: if we find that on the ebb the surface of the waters arches up in the middle and subsides on the coast, and that at the floods the surface is more flat and level, with the waters retiring to their starting point, then by this Decisive Instance we should certainly accept elevation by magnetic force; if this does not happen, the verdict should go clean against it.[43]

But why do we need the clear parting of the ways and awareness of the competing explanations, if a crucial instance can confirm an explanation directly? A possible answer to this question might be found if we see Bacon as drawing a distinction between supportive and positive instances, as Adolf Grünbaum suggests.[44] A positive instance would be one that can be derived from a theory (given the proper initial conditions), while a supportive instance would be a type of positive instance that has "the probative significance of conferring a stronger truth presumption on T than T has without that instance."[45] Supportive instances are able to do this not because they agree with a theory, but because they also serve as refutations for *stated* rivals of that theory. If this account is right, then crucial instances are the best examples among Bacon's instances with special powers to support it, given how the presentation of the rival alternatives is embedded into their mechanism. We can see a further case in support of this hypothesis in example 8 where we are told that a cause is "assuredly the true one, as innumerable experiments show."[46] And yet, we still have to test that cause through crucial instances, a step which makes more sense if we accept a qualitative difference in the evidential support provided by those innumerable experiments and that provided by crucial instances (or by instances with special powers in general).

Assessing Crucial Instances

What can we conclude about crucial instances if we read the way Bacon describes them in general together with his actual examples? Specifically, how can we unite his claims about the certainty provided by the crucial instances with the actual structure of his examples? The value crucial instances have for the investigation and the certainty of their results are emphasized numerous times in the text. As a group, they "shed the greatest light and carry great authority, so that the whole round of interpretation sometimes ends in or is perfected by them;"[47] through them "the question is settled;"[48] they are what men should use instead of "probabilistic reasoning."[49] When presenting individual instances and the evidence they bring in support or against an explanation, Bacon uses language such as: "this Decisive Instance should certainly rule out the claim…" [Tum certe per hanc Instantiam Decisoriam abiudicanda est Assertio…][50] (in instance 1, but similar expressions using the adverb "certe" appear in the second, third and fourth examples as well[51]) and "we must lay it down (…) for certain" […pro certo ponendum est] [52] (in instance 10). Why is Bacon, who warned us about the shaky foundations of incomplete induction prior to introducing the instances with special powers (and who has only covered one category of aids for induction so far), using such linguistic markers of certainty to refer to this particular type of instances?

I think the answer must lie in the structure of the arguments in which the crucial instances are embedded. As I pointed out above, the steps that are constantly present and stated in a clear and confident way in the examples are the parting of the ways and, to an extent, the deriving of consequences from one of the explanations. Those are precisely the steps that establish the "deductive credentials," to borrow a phrase from Pérez-Ramos,[53] of the arguments, their logical structure. And, as long as we think of those crucial instances that are directly confirmatory as supportive instances (meaning that their value always comes from confirming one hypothesis *while* refuting others), this logical structure is highly compatible with the classic Duhemian view of the crucial experiment. Even in the case of those instances that are said to confirm one explanation, their claim to certainty must ultimately come from the fact that the other explanations *could* be shown to be incompatible with the phenomenon observed.

There is one problem left and it is a problem that has appeared multiple times during the analysis of the examples: Is the assumption that all the logically conceivable candidates have been covered when presenting the causes for each nature embedded in the mechanism of the crucial instance (explicitly or not)? If it is, that would explain the alleged demonstrative authority of the crucial instances, but it would make most of the examples poor illustrations of it. If it is not and we assume a sort of gradualist position in which new explanations might always appear at later stages of research, the difference between crucial instances and probabilistic reasoning looks more like one of degree, which might raise further concerns regarding the certainty of Bacon's entire inductive project. The way this question is answered ultimately depends on the general view one has of Bacon's epistemology, its goals and limits. The point remains that anyone trying to use this concept per Bacon's indications would have to deal with this tension, either by acting as if they are dealing with jointly exhaustive options or by using a weaker version of the concept of crucial instance, unaccompanied by this language of certainty.

Boyle's *Experimentum Crucis*

A clear echo of the Baconian crucial instances can be recognized in the phrase "*experimentum crucis*," first used by Robert Boyle in his 1662 treatise, *A Defence of the Doctrine Touching the Spring and the Weight of the Air*. The question there is between two theories, both of which admit the existence of a sort of spring of the air, but that assign different properties and different roles to that spring. Boyle lays out the parting of ways: the spring of the air tends either outwards (as in his own theory), or inwards (as in the theory of his opponent, the Jesuit Francis Linus). Are the phenomena observed in Torricellian tubes to be explained by atmospheric pressure (air *pushing* on the mercury in the bowl) or by a sort of resistance to vacuum (the air rarefied to extend into the space left by the mercury *drawing* the mercury up to restore itself)? Boyle declares that, in normal circumstances, both theories might be able to account for the phenomena, so we must search for an experiment that shows an effect only one of the theories can explain:

> And such an experimentum crucis is afforded us by M. Paschal, who observed that, the Toricellian experiment, being made at the foot, and in different parts of a very high mountain, after he had ascended an hundred and fifty fathom, the quick-silver was fallen two inches and a quarter below its station at the foot of the mountains, and that, at the very top of the hill, it had descended above three inches below the same station. (...) And since this noble phenomenon seems to follow from ours and not upon our author's hypothesis, it seems to determine the controversy.[54]

The effect observed in this experiment, the fact that the mercury column in the Torricellian tube falls, the higher we climb, is exactly what Boyle's theory would have predicted, whereas Linus' theory wouldn't have predicted any effect, for the relation between mercury and air predicated on resistance to vacuum would have no reason to change with altitude. Here we have an almost perfect example of a Baconian crucial instance: a phenomenon to be explained (the behavior of mercury in

Torricellian tubes), two main ways of explaining it (appealing either to inwards, or to outwards pressure of the air), deriving a consequence that would only follow from one of the explanations and not the other (in this case, the behavior of mercury in Torricellian tubes at different altitudes) and finding a way to test it (through Pascal's Puy-de-Dôme experiment). What is interesting about this fragment is not that we are presented with an example from scientific practice – Pascal's experiment - that seems to closely align to the Baconian methodology (which might not necessarily be the effect of Bacon's influence), but that the enterprise is implicitly cast in the canon of Baconian science by Boyle's choice of words, by the phrase "experimentum crucis." Crucial experiments are an important element of Bacon's legacy, a fact which will be made explicit by Robert Hooke in *Micrographia*. For his part, Boyle seems to be investing the crucial experiment with great demonstrative authority (though one must also take into account the context in which this experiment is invoked and the ways in which rhetoric might be at play).

Hooke's Crucial Experiments and Crucial Instances

Three years after Boyle, Robert Hooke uses the phrase "*experimentum crucis*" in his *Micrographia*, in Observation IX. That section is dedicated to a hypothesis about the nature of colors, starting from the phenomenon of color as observed in thin plates of Muscovy glass (mica). This particular observation, Hooke tells us, turns out to be a crucial experiment:

> This Experiment therefore will prove such a one as our thrice excellent Verulam calls *Experimentum Crucis*, serving as a Guide or Land-mark, by which to direct our course in the search after the true cause of Colours.[**1**] Affording us this particular negative Information,[**2**] that for the production of Colours there is not necessary either a great refraction, as in the Prisme;[**3**] nor Secondly, a determination of Light and shadow, such as is both in the Prisme and Glass-ball.[**4**] Now that we may see likewise what affirmative and positive Instruction it yields, it will be necessary, to examine it a little more particularly and strictly; which that we may the better do, it will be requisite to premise somewhat in general concerning the nature of Light and Refraction.[**5**]"[55] [numbers added by me]

Let us parse this fragment more closely. I will start with the fragments of sentence I labeled [3] and [4], because they are essential for understanding the methodological point the rest of the paragraph makes. To understand [3] and [4], one has to accept, as Hooke does, that the colored rings seen in plates of Muscovy glass have to be accounted for in any theory about the production of color. In the case of these rings, and in a variety of other instances (liquids pressed between two plates of glass, various metallic surfaces, water bubbles, glass bubbles etc.), we see that colors appear wherever you have a transparent and thin body, surrounded by reflecting media of different refractions from it.[56] From this, we can draw some conclusions about what conditions are truly necessary for the production of colors. Any condition that doesn't apply to these instances cannot be said to be a prerequisite for the production of colors, since colors quite obviously can be (and are) obtained without it.

The theory that fails to account for these phenomena is Descartes' theory of color from *Meteora*. Descartes studies the production of the rainbow first in water droplets and spherical water flasks made to resemble them, and then in prisms. The conclusion he draws from these experiments is that, for the production of colors, one needs i) net refraction and ii) a determinate, restricted beam of light. The production of color at refraction is due to the spinning motion the impact with the refracting surface imparts to the globules of aether that constitute light. Different speeds of rotation correspond to different colors. But if a second refraction reverses the effect of the first and restores the globules to their initial speeds of rotation, no colors are perceived. This is why light passing through a sheet of glass with parallel faces does not produce color.[57] Similarly, prismatic colors are obtained only on the edges of the light beam, where it borders with shadow,[58] hence the need for a determinate light beam. (According to A.E. Shapiro, who invokes an observation of Kuhn's on the matter, this last point comes from the fact that the spectrum was observed too close to the prism for the colors to have separated completely.[59] As a consequence, what Descartes (like everyone else prior to Newton) was seeing after the prismatic refraction was a white spot fringed with red and blue, which led him to assume that color was actually formed at the edges of the light beam.)

Hooke's observations on mica plates contradict some of these Cartesian conditions for the production of colors. First of all, it cannot be true that one always needs a refraction unmatched by a contrary refraction in order to have colors, for we do see colors in mica plates after two refractions that should have cancelled each other out. (To be precise, light is refracted through the upper layer of the plate, reflected by the lower layer, and then refracted again, *at the same angle* as in the first refraction, through the upper layer.) Secondly, there is no determinate beam of light involved in the production of colors in the case of the mica plates. These two facts, mentioned at [3] and [4] in the fragment above, serve to refute Descartes' theory of color. (It must be mentioned, however, that Descartes does indicate that his two conditions, the refraction and the shadow, do not apply across all cases, which would take away at least some of the force of Hooke's complaint.[60] This is an observation Newton makes as well, on his notes on *Micrographia*.[61])

What is interesting here is that this instance has not yet proven crucial – at least not in the way Boyle's example was. Indeed, we are told at [1] that this experiment will guide us in our search for the true cause of colors, not end it, and at [2] that it provides us with negative information. While it might have refuted Descartes' theory, it did nothing to confirm an alternative theory. In fact, an alternative theory has not even been presented at this point. Why is it important, as [5] tells us, to examine this example more closely and also to posit some general premises about light before being able to draw a conclusion? It seems to be because Hooke is attempting to build a theory that would satisfy the exigencies the crucial experiment revealed. In this case, crucial instances play a role not only in choosing between two theories or in justifying one theory, but also in the construction of the theory itself.

Hooke's theory of colors as developed here says that colors are produced when the wave front (Hooke calls it "pulse") is made by refraction to fall obliquely to the rays (because the light passes through a medium in which it is transmitted faster,[62] so, depending on when they hit the refracting surface, certain portions of it will have reached further in the same amount of time).[63] This does not *prima facie* explain the phenomenon observed in the plates of Muscovy glass (and it might be, as A.E. Shapiro says, that it takes a whole different theory to explain it[64]), but it is an alternative to Descartes' general theory of prismatic colors. Hooke introduces a second crucial instance that would allow for a direct comparison between his own obliquity theory and Descartes' theory for the production of colors.

> Which, because it is very much to our present purpose, and affords such an Instancia [sic] crucis, as no one that I know has hitherto taken notice of, I shall further examine. For it does very plainly and positively distinguish, and shew, which of the two Hypotheses, either the Cartesian or this is to be followed, by affording a generation of all the colors in the Rainbow, where according to the Cartesian Principles there should be none at all generated. And secondly, by affording an instance that does more closely confine the cause of these Phænomena of colours to this present Hypothesis.[65]

In this case, Hooke noted that, according to Descartes' own theory, there should be no colors observed in the passing of a light ray through a ball or cylinder of glass or water, because the refractions should cancel each other out. This would be devastating for Descartes' theory because it was explicitly supposed to cover such cases like refractions through a drop of water or through a glass. By contrast, Hooke's theory is vindicated, for, he claims, calculations of the refractions and reflection in a ball of water have indicated the same "obliquity of ondulation" he was talking about.[66]

Having established this, Hooke then gives an account for the phenomenon of the mica plates. The rings of color on them are explained by the fact that the light actually splits: part of it is reflected by the upper surface of the plate, and part of it is refracted through it and then reflected by the lower surface of the plate and then refracted again through the upper. That produces two distinct pulses, one stronger and one weaker, but, since they are so close together, the eye perceives them as one, exactly as it does in the case of prismatic colors.

What lesson can we draw from the way crucial experiments are used in *Micrographia*? The fact that Hooke presents the crucial experiment before having two fully-formed theories to compare seems less important in itself, since it can well be the result of rhetorical presentation. (And, after all, there is nothing in Bacon to forbid this, even if, as we have seen, Bacon always emphasizes the parting of the ways at the beginning.) What is important is that, in Hooke's presentation, the overall accent seems to be on the negative function of the crucial instances. What both of the instances decide for certain is the discarding of Descartes' theory. The first experiment is not explicitly presented as giving the same support to Hooke's own hypothesis, though, because the hypothesis has not yet been advanced. The second experiment is closer to Bacon's and Boyle's examples, but even so, it could be argued that to "more closely confine the cause of these Phænomena of colours to this present Hypothesis" is different from strictly confining it to that hypothesis. One should point out, however, that the "affirmative and positive Instruction" is still there in Hooke's use of the phrase, just as it was for Bacon and Boyle. What seems to vary is its degree of certainty.

Conclusion

The conceptual pattern behind the crucial experiment as laid out by Bacon, and adopted by both Boyle and Hooke, seems to have had a tension at is core, visible even in Bacon's own examples. Crucial instances were associated with a great degree of certainty in Bacon's presentation, and their confirmatory role seems to be preserved in Boyle's use of them. Someone appealing to a crucial experiment as a means of establishing one explanation as definitively true wouldn't have been in obvious disagreement with this tradition. Hooke's use of crucial experiments is both more reserved and more nuanced. He does not present his *experimentum crucis* as a way of deciding between two fully-formed theories, but as a way of refuting one theory and setting up conditions its replacement must meet, which results in a less powerful confirmatory value. This is, of course, partly due to rhetorical presentation, but it also affords a glimpse into how crucial experiments and eliminative induction are carried in the actual scientific process and of their use in both constructing and justifying theories, themes that can be very fruitful in a future investigation of Newton's use of crucial experiments.

Acknowledgments. Research for this paper has been supported by CNCS grant PN-II-ID-PCE-2011-3-0719: *From natural history to science: the emergence of experimental philosophy*.

References

[1] See Dear, P., "The meaning of experience", in *The Cambridge History of Science, Vol. 3: Early Modern Science,* eds. L. Daston & K. Park (Cambridge: Cambridge University Press, 2008), 107-131 and Lohne, J.A., "Experimentum Crucis", *Notes and Records of the Royal Society* 23 (1968): 169-99.

[2] See Jalobeanu, D., "Constructing Natural Historical Facts: Baconian Natural History in Newton's First Paper on Light and Colors", in *Newton and Empiricism,* eds. Z. Biener & E. Schliesser (Oxford: Oxford University Press, forthcoming).

[3] Bacon, F., *Novum Organum*, trans. G. Rees and M. Wakely, in *The Oxford Francis Bacon, Vol. 11: The Instauratio Magna Part II: Novum Organum and Associated Texts* (Oxford: Clarendon Press, 2007) (henceforward OFB XI), 215-17.

[4] Bacon, F., OFB XI, 31-33.

[5] Bacon, F., OFB XI, 261.

[6] Bacon, F., OFB XI, 217, 221, 237.

[7] Bacon, F., OFB XI, 261.
[8] Bacon, F., OFB XI, 445.
[9] Gaukroger, S., *Francis Bacon and the Transformation of the Early-Modern Philosophy* (Cambridge: Cambridge University Press, 2004), 153.
[10] Jardine, L., "Experientia Literata or Novum Organum? The Dilemma of Bacon's Scientific Method", in *Francis Bacon's Legacy of Texts*, ed. W. A. Sessions (New York: AMS Press 1990), 55.
[11] See Dana Jalobeanu, "Core experiments, Natural Histories and the Art of *experientia literata*: The Meaning of Baconian Experimentation", *Society and Politics* Vol. 5, No. 2 (2011): 89-103.
[12] Jardine, L., *Francis Bacon: Discovery and the Art of Discourse* (London: Cambridge University Press, 1974), 124.
[13] Weeks. S., *Francis Bacon's Science of Magic* (PhD Dissertation, University of Leeds, 2007), 243.
[14] Weeks. S., (2007), 153.
[15] Pérez-Ramos, A., "Francis Bacon and Man's Two-Faced Kingdom" in *Routledge History of Philosophy, Vol 4: The Renaissance and Seventeenth Century Rationalism*, ed. G. Parkinson (London and New York: Routledge, 1993), 138.
[16] Pérez-Ramos, A., (1993), 138.
[17] See Horton, M., "In Defence of Francis Bacon: A Criticism of the Critics of the Inductive Method", *Studies in the History and the Philosophy of Science* 4 (1973): 241–78.
[18] Bacon, F., OFB XI, 445.
[19] Bacon, F., OFB XI, 339.
[20] Bacon, F., OFB XI, 319.
[21] See Duhem, P., La théorie physique, son objet et sa structure, 2nd ed. (Paris: Chevalier et Rivière, 1914), 153-154. For a brief overview, see also Lakatos, I., "The Role of Crucial Experiments in Science", *Studies in History and Philosophy of Science* A 4 (1974): 309.
[22] Bacon, F., OFB XI, 321.
[23] Bacon, F., OFB XI, 320.
[24] Bacon, F., OFB XI, 323.
[25] Bacon, F., OFB XI, 329.
[26] Urbach, P., *Francis Bacon's Philosophy of Science* (La Salle, Ill: Open Court, 1987), 170.
[27] Bacon, F., OFB XI, 321.
[28] Bacon, F., OFB XI, 329.
[29] Bacon, F., OFB XI, 333.
[30] Bacon, F., OFB XI, 331-333.
[31] Bacon, F., OFB XI, 321.
[32] Bacon, F., OFB XI, 323.
[33] Bacon, F., OFB XI, 327.
[34] Bacon, F., OFB XI, 327.
[35] Rees, G. "Francis Bacon's Semi-Paracelsian Cosmology and the Great Instauration", *Ambix* 22 (1975): 167.
[36] Bacon, F., OFB XI, 331.
[37] Bacon, F., OFB XI, 323.
[38] Bacon, F., OFB XI, 323.
[39] Bacon, F., OFB XI, 323.
[40] Bacon, F., OFB XI, 323.
[41] Bacon, F., *Novum Organum*, in *The Works of Francis Bacon: Volume 5*, eds. J. Spedding, R. L. Ellis, and D. D. Heath, (Boston: Houghton, Mifflin and Company, 1900), 256.
[42] Bacon, F., *The New Organon*, ed. by L. Jardine & M. Silverthorne (Cambridge: Cambridge University Press: 2000), 161.
[43] Bacon, F., OFB XI, 325.

[44] Grunbaum, A., "Is Falsifiability the Touchstone of Scientific Rationality? Karl Popper versus Inductivism", *Boston Studies in the Philosophy of Science* 39 (1976): 213–52.
[45] Grunbaum, A., (1976): 217.
[46] Bacon, F., OFB XI, 333.
[47] Bacon, F., OFB XI, 321.
[48] Bacon, F., OFB XI, 321.
[49] Bacon, F., OFB XI, 339.
[50] Bacon, F., OFB XI, 322 (Latin)-323 (English).
[51] Bacon, F., OFB XI, 324-327.
[52] Bacon, F., OFB XI, 338 (Latin) – 339 (English).
[53] Pérez-Ramos, A., (1993), 138.
[54] Boyle, R., *A Defence of the Doctrine Touching the Spring and the Weight of the Air in The Philosophical Works of the Honourable Robert Boyle Esq. Abridged, Methodized, and Disposed Under the General Heads of Physics, Statics, Pneumatics, Natural History, Chymistry, and Medicine*, ed. W. Peter Shaw, and J. Innys (London, 1725), vol. 2, 665.
[55] Hooke, R., *Micrographia: or, Some physiological descriptions of minute bodies made by magnifying glasses*, (London: J. Martyn and J. Allestry, 1665), 54.
[56] Hooke, R., *Micrographia*, 53.
[57] Descartes, R., *Les Météores* in *Oeuvres De Descartes*, ed. V. Cousin, (F.G. Levrault, 1824), vol. 5, 270.
[58] Descartes, R., *Les Météores*, 270.
[59] Shapiro, A.E., "Kinematic Optics: A Study of the Wave Theory of Light in the Seventeenth Century," *Archive for the History of Exact Sciences* XI (1973): 190.
[60] "Mais j'avoue bien que l'ombre et la réfraction ne sont pas toujours nécessaires pour les produire; et qu'en leur place, la grosseur, la figure, la situation et le mouvement des parties des corps qu'on nomme colorés, peuvent concourir diversement avec la lumière, pour augmenter ou diminuer le tournoiement des parties de la matière subtile." in Descartes, R., *Les Météores,* 275.
[61] *Newton's Notes to the Micrographia* in *Unpublished Scientific Papers of Isaac Newton*, ed. A. R. Hall and M.B. Hall (Cambridge, 1962), 403 quoted in Shapiro, A.E., (1973), 192.
[62] Hooke adopts Descartes' position, according to which light propagates faster in a denser medium.
[63] Hooke, R., *Micrographia*, 57-8.
[64] Shapiro, A.E., (1973), 200-1.
[65] Hooke, R., *Micrographia*, 59.
[66] Hooke, R., *Micrographia*, 59.