Discovery and Instrumentation: How Surplus Knowledge Contributes to Progress in Science

George Borg
Department of History and Philosophy of Science
University of Pittsburgh

Discovery and Instrumentation: How Surplus Knowledge Contributes to Scientific Progress

An important fact about human labor is that it can result not just in reproduction of what it started with, but in something new, a surplus product. When the latter is a means of production, it makes possible a mechanism of change consisting of reproduction by means of the expanded means of production. Each iteration of the labor process can differ from the preceding one insofar as it incorporates the surplus generated previously. Over the long-term, this cyclical process can lead to the self-transformation of labor and, through it, of human societies and cultures. In this paper, I argue that this mechanism of change is also at work in the history of science. I argue that the form this mechanism takes in science is that of a feedback loop between discovery and instrument construction. This process requires the integration, and transformation into material form, of different kinds of knowledge. Based on this mechanism, I defend a concept of scientific progress as transcendence of the limitations of native human epistemic abilities. I also criticize narrowly biologistic approaches to the history of science for ignoring the role of surplus generation in transforming the labor process, and discuss some problems associated with viewing science as labor.

Keywords: Scientific progress, discovery, integration, ability, labor, historical materialism, technology, knowledge, instruments

1 Introduction

The philosopher of science Thomas Kuhn, in his 1962 *The Structure of Scientific Revolutions*, asked:

> Why should the enterprise sketched above [modern science] move steadily ahead in ways that, say, art, political theory, or philosophy does not? Why is progress a perquisite reserved almost exclusively for the activities we call science? (Kuhn [1962] 1996, p. 160).

Kuhn was putting his finger on the peculiar nature of scientific progress, namely that it appears to be continuous and cumulative in some sense. In this paper, I will provide an explanation of this progress by relating science to the more general practice of laboring. An important fact about human labor is that it can result not just in reproduction of what it started with, but in something new, a surplus product. When the latter is a means of production, it makes possible a mechanism of change consisting of reproduction by means of the expanded means of production. "Means of production" must here be understood in a broad sense, to include not just tools in a narrow sense, but also material means of representation and communication (Lefèvre 2005). Each iteration of the labor process can differ from the preceding one insofar as it incorporates the surplus generated previously. Over the long-term, this cyclical process can lead to the self-transformation of labor and, through it, of human societies and cultures.

In this paper, I will provide a largely theoretical argument that this mechanism of change is also at work in the history of science. More specifically, the thesis I will defend in this paper is that surplus knowledge contributes to progress in science. The basic argument is this. Labor makes progress by producing surplus use-values (objects of utility). Science makes progress as does the labor process, except that the specific use-value that it produces is knowledge. Therefore, science makes progress by producing surplus knowledge.

The paper is structured as follows. In section 2, I argue that the form taken in science by the mechanism of reproduction by means of the expanded means of production is that of a feedback loop between discovery and instrument construction. This process requires the integration, and transformation into material form, of different kinds of knowledge. In section 3, I argue that this process suggests a concept of scientific progress complementary to those that have so far been advanced in the philosophical literature on scientific progress, and defend the concept of progress as transcendence of native human epistemic ability. In section 4, I criticize narrowly biologistic approaches to the history of science for ignoring the role of surplus generation in transforming the labor process, and discuss some problems associated with viewing science as labor. I offer concluding remarks in section 5.

2 The dialectic of discovery and embodiment

My view is that the specific product of scientific labor, scientific knowledge, contributes to scientific progress. There is a sense, already recognized by philosophers of science, in which scientific knowledge may be said to contribute to scientific progress: that is when knowledge accumulated in a scientific episode is said to *constitute* progress.[1] That is not the sense I intend. Rather, I mean that the knowledge accumulated provides a starting-point for future work. Again, there is an obvious sense in which this is true, for the acquisition of new knowledge inevitably

---

[1] See Mizrahi (2010) and Niiniluoto (2015) for reviews of philosophical accounts of scientific progress.

suggests lacunae to be filled and new questions to be answered. What I would like to draw attention to, however, is that the knowledge accumulated provides a starting-point for future work in the sense of contributing to a *stock of knowledge* from which future scientists can draw.[2]

As will be explained in more detail in the following sections, instruments represent an important way in which the stock of knowledge can be incorporated into the scientific labor process (or ordinary material labor processes, for that matter). I claim that an important way in which instruments contribute to scientific progress is by making possible a *dialectic of discovery and embodiment.* Scientists start from the stock of past results or knowledge. Using this knowledge, they produce instruments that they then use to discover new things about the world.[3] If successful, new items will be added to the stock of knowledge. The augmented stock can then be used to build new or improved instruments, thus renewing the cycle.

---

[2] This function of scientific knowledge was described by the noted chemist Carl Djerassi in Sturchio & Thackray (1985):

> I have a very different opinion of what a publication is. It is really to pay back to the scientific pool of knowledge from which we borrowed so much, because that's all that science is really—stepping on someone else's shoulders. Put it back in there, and let other people select what they need or what they do not need. Some of the things that you yourself think are trivial may sometimes be exactly the trivial things that someone else needs to jump on very quickly.

Though Djerassi seems to have in mind the use of past results to solve immediate research problems, my focus is on another use, connected with tool use, that contributes to progress in the long-term.

[3] I do not claim that the production of new instruments is the only way to make new discoveries. New theoretical ideas, as well as new sorts of experiments using old instruments, can also contribute to discoveries. For reasons provided below, however, I think instruments have distinctive properties that contribute to discovery differently than ideas or new experiments.

On this conception of scientific progress, the stock of knowledge is viewed as a means of production for on-going research. It is a means for the production of the material means of discovery, the instruments. The latter are used to acquire new knowledge. The overall product of the process is a transformed stock of knowledge. Transformed how?

According to Mizrahi (2013), scientists make judgments about progress according to the following pattern:

1. Survey the body of knowledge *B* in field *F* at time *t* prior to discovery *D*.
2. Estimate what was known (*B*) in *F* at *t*.
3. Identify a lacuna, imprecision or error in *B* at *t*.
4. Spell out how *D* improved on *B* by adding new knowledge, correcting imprecision or exposing errors and correcting them.

Here, the "body of knowledge *B* in field *F*" is similar to my 'stock of knowledge,' except that for reasons I will provide below, my 'stock of knowledge' is not field-specific but involves the totality of scientific and technological knowledge. Admittedly, the contours of this totality are vaguely defined. But I think the history of scientific innovation bears out that the latter often involves the creative integration of ideas and practices from multiple fields (Harman & Dietrich 2018, pp. 9-10). What combination of fields contributes to innovation in a particular episode depends on the specifics of the episode, one obvious constraint being what fields the scientists are familiar with. These specifics cannot be determined *a priori*—in chemist Carl Djerassi's words, it is up to the players to "select what they need or do not need." Vagueness is a virtue in this case.

Paraphrasing Mizrahi, we are interested in cases where a discovery *D* improves on the stock of knowledge *S* by adding new knowledge, correcting imprecision or exposing errors and correcting them. This improvement yields a transformed stock of knowledge *S'*, which is distinguished from *S* in virtue of containing more knowledge, being more precise or having fewer errors.

I have used the term ‘surplus knowledge’ to designate certain features of the relation of new knowledge to the stock of knowledge. Surplus knowledge is not simply new, recently acquired, but stands in a definite relation to pre-existing knowledge. It is knowledge that is acquired by means of pre-existing knowledge, and which transforms the latter in the sense specified above. Tentatively, for the sake of clarity I suggest the following analysis of surplus knowledge:

(SK) Discovery *D* is an item of surplus knowledge if and only if (i) *D* was acquired by means of stock of knowledge *S* and (ii) its addition to the stock yields an improved stock *S’*, where the improvement consists in adding new knowledge, correcting imprecision or exposing errors and correcting them.

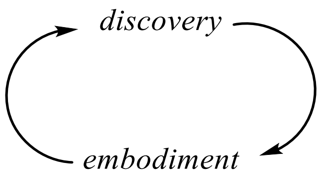
According to (SK), a discovery that does not yield an improved stock of knowledge does not count as surplus knowledge. A situation where this sort of non-progressive discovery occurs is one where a discovery *D* merely cancels out a prior claimed discovery *C*. For example, the invention of the telescope represented a form of knowledge, knowledge of how to observe distant objects. By means of this knowledge, Galileo discovered that Venus has phases, just like the moon. This situation was inconsistent with Ptolemaic theory, so it was eliminated. If matters had stood there, the phases of Venus could hardly have counted as “surplus,” given the loss of what European astronomers had thought for centuries they knew about the solar system. Luckily, there was another theory competing with the Ptolemaic, the Copernican system, and since it was consistent with Venus’s phases (among other reasons) it replaced the Ptolemaic.

It also follows from this analysis that if a discovery is not achieved by means of the stock of knowledge but nevertheless yields an improved stock *S'*, it would also not count as surplus knowledge. For example, were a UFO to visit my home and an alien species to come out, then perhaps I could plausibly claim to have discovered those aliens for humanity. Even in this case, one might question whether this discovery was made without relying on prior scientific knowledge, since the identification of a new species presupposes scientific concepts, like that of a 'species,' as well as empirical knowledge of already known species. Setting aside such considerations, however, cases like this one are best described as *windfalls*, acquisitions that cost no labor to the acquirer. Unfortunately for scientists, their importance is minimal.

A more realistic scenario is one where a discovery has consequences that go beyond the discovery itself. For example, the discovery of the double-helical structure of DNA was not in itself a momentous discovery; as far as molecular structures go, this one was fairly boring. But, *in addition*, the structure solved the puzzle of genetic inheritance, and led to important applications like gene editing. Are these additional discoveries windfalls or SK? It would seem the latter, since such consequences depend on the stock of knowledge as well, though different parts of it than the initial discovery. The double helix was discovered by means of X-ray crystallography, chemical information about the base composition of the molecule, and mechanical model building. Establishing that the structure was the genetic material, however, required evidence of its duplication mechanism as well as of its role in protein synthesis. Indeed, it was only when the outlines appeared of a mechanism for DNA's involvement in protein synthesis that the biochemical community began to take a serious interest in the structure (Olby 2003). This example illustrates a point I will make later for instruments, that some degree of integration with other knowledge is usually necessary to exploit new discoveries.[4]

In this chapter, I will focus on additive improvements to the stock of knowledge, which is much more common than the spectacular cases of theory overthrow that philosophers have tended to focus on. Nevertheless, in the more interesting cases, the relation between surplus knowledge and the stock of knowledge will not merely be additive. As will be discussed in greater detail in the following subsections, the expanding stock of knowledge does not remain external to scientific work, but releases possibilities for the development of that work. This release occurs because the new knowledge reveals new, useful employments of the old knowledge.

Schematically, the dialectic of discovery and embodiment may be presented thus:



$$1)\ k_1, k_2, \ldots k_i \xrightarrow[\text{(a)}]{\text{production of}} \text{instruments} \xrightarrow[\text{(b)}]{\text{discovery}} k_{i+1}, k_{i+2}, \ldots k_n$$

$$2)\ k_1, k_2, \ldots k_n \xrightarrow{\text{repeat (a) and (b)}} k_1, k_2, \ldots k_n, k_{n+1} \ldots k_m, \text{etc.}$$

---

[4] In the context of a critique of empiricism, Karl Popper ([1960] 1985) made the following remark on the role of prior knowledge in scientific progress:

> Knowledge cannot start from nothing—from a *tabula rasa*—nor yet from observation. The advance of knowledge consists, mainly, in the modification of earlier knowledge. Although we may sometimes, for example in archaeology, advance through a chance observation, the significance of the discovery will usually depend upon its power to modify our earlier theories. (55)

Figure 1. The dialectic of discovery and embodiment. Scientists start from the stock of past results or knowledge. Using this knowledge, they produce instruments that they then use to discover new things about the world. If successful, new items will be added to the stock of knowledge. The augmented stock can then be used to build new or improved instruments, thus renewing the cycle.

Here, each k_j is some instance of knowledge. The initial store of knowledge is represented by k_1, k_2, … k_i, the "surpluses of knowledge" by k_{i+1}, … k_n and k_{n+1}, … k_m.

Some qualifications are in order. The "knowledge" at issue in this iterative process has to be understood broadly, in a twofold sense to be described shortly. The first sense has to do with the form of knowledge, and the second with its source. Corresponding to the first sense is a process of integrating knowledge I call 'form-integration.' Corresponding to the second sense is another process of integrating knowledge I call 'source-integration.'

2.1 *form-integration*

First, the knowledge at issue in the dialectic of discovery and embodiment involves not just theoretical knowledge, but also empirical knowledge and various kinds of know-how. The conception of knowledge I employ follows Mizrahi (2013). Basing his argument on evidence from scientists' reflections on progress, Mizrahi argues that scientists employ a broad conception of progress that includes different kinds of knowledge. The four kinds he identifies are:

(EK) *Empirical Knowledge*: Empirical knowledge usually comes in the form of experimental and observational results.

(TK) *Theoretical Knowledge*: Theoretical knowledge usually comes in the form of well-confirmed hypotheses.

(PK) *Practical Knowledge*: Practical knowledge usually comes in the form of both immediate and long-term practical applications.

(MK) *Methodological Knowledge*: Methodological knowledge usually comes in the form of methods and techniques of learning about nature. (Mizrahi 2013, p. 380)

The reason a broad conception of knowledge is necessary is that scientific instrument production and use require more than just theoretical knowledge but also empirical knowledge and know-how. Theoretical knowledge may provide basic principles of design, as for example spectrometers are designed based on principles of quantum mechanics and electromagnetism. But empirical knowledge may be required for calibration or data interpretation. The rationale for using the instruments is usually based on methodological knowledge, and in fact their use is often called a “technique” or “method.” Moreover, instrument construction involves a great deal of practical knowledge, for example knowledge of how to grind lenses in the case of the telescope (van Helden 1983) or of how to produce a vacuum in that of the cyclotron (Baird & Faust 1990).

I call the process of combining these four kinds of knowledge ‘form-integration,’ because it involves integrating different kinds of knowledge distinguished according to their form: theoretical, empirical, practical, or methodological.

In terms of the Figure 1 schema, form-integration may be represented thus:

$$\begin{array}{l} TK_1 \\ EK_1 \\ MK_1 \\ PK_1 \end{array} \xrightarrow[\text{(a)}]{\text{integration in production of}} \text{instruments} \xrightarrow[\text{(b)}]{\text{discovery}} TK_2 \text{ or } EK_2 \text{ or } MK_2 \text{ or } PK_2$$

Figure 2. Integration of different forms of knowledge (theoretical, empirical, methodological, or practical) in the dialectic of discovery and embodiment.

The production of instruments typically requires the integration of different forms of knowledge. Their use can lead to the discovery of TK, EK, MK, or PK. The example of the clock will be discussed in section 2.4.1.

2.2 *source-integration*

The second sense in which the knowledge involved in the process has to be understood broadly is that the process can only fully realize its potential for progress if it concerns collections of instruments and discoveries, not just individual instruments. The reason is that discoveries made by means of an individual instrument cannot necessarily be used to improve that very instrument. For example, the knowledge of the moon's surface afforded by Galileo's telescope could not be used to improve the telescope itself.

True, strictly recursive improvements of instruments may be conceivable for certain kinds of improvement, such as for increasing precision. In his well-known account of the development of temperature standards, for example, Hasok Chang describes a succession of increasingly precise instruments, starting with the hands and ending with the high-precision Beckmann thermometer, for estimating warmth.[5] Each instrument in the sequence provided a standard for assessing the reliability of its successor. In the terms of the broad conception of knowledge above, the methodological knowledge (MK) represented by each instrument in the sequence provided the starting-point for the design and validation of a more precise successor.

But this kind of strictly recursive progress only captures part of what is involved in instrument construction and use. In the early development of the telescope and microscope, for example, it was recognized that both theoretical and practical knowledge might be useful, the former in the

---

[5] Chang (2004), pp. 47-48 summarizes the process of developing numerical thermometers starting from the senses; Chang (2007), pp. 9-11 extends the analysis to Beckmann thermometers.

form of optical theory and the latter in the form of lens-crafting knowledge.[6] Instrument development tends to be holistic, drawing on many sources and kinds of knowledge. Indeed, one of the things instruments allow us to do is to make use of knowledge on a far greater scale than it is possible for the individual human user to know him- or herself. This ability arises from the fact that we can use an instrument without knowing all the things necessary to make it.

I will call the process of combining knowledges from different sources ‘source-integration,’ because it involves integrating different kinds of knowledge distinguished according to their source, which in this paper will be a practice or field. The telescope example involved integrating knowledge from the science of optics with knowledge from the practice of lens-crafting. As this example also illustrates, the two kinds of integration can overlap. But they need not, as when theoretical knowledge from different sciences is combined.

In terms of the schema of Figure 1, source-integration may be represented thus for the case of the telescope:

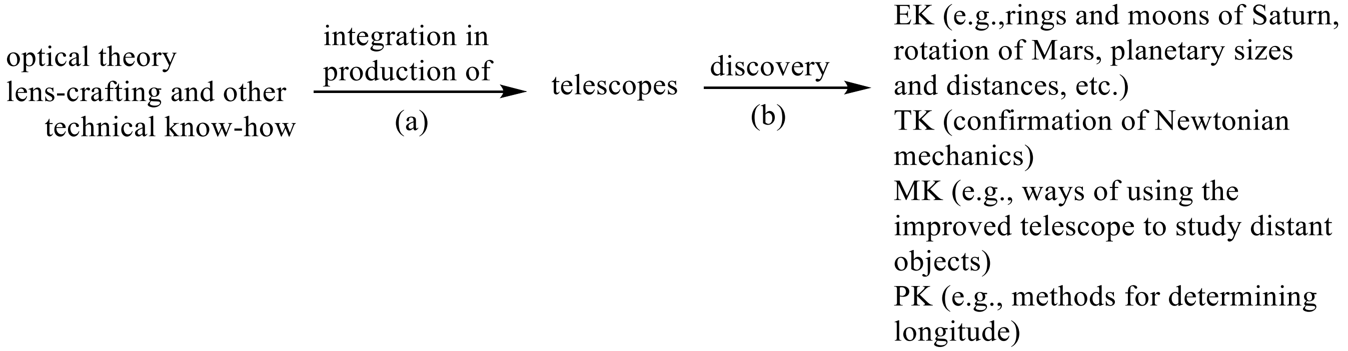


Figure 3. Integration of knowledge from different sources in the 17th century dialectic of discovery and embodiment involving the telescope.

---

[6] Spelda (2017) documents this recognition by 17th century natural philosophers. According to Smith (2015), pp. 381-391, both theoretical and practical knowledge contributed to the development of the microscope and telescope, but practical knowledge led the way.

In general, both surplus knowledge and integration are required for instrument development. True, sometimes integration by itself, combining long-established items of knowledge, can result in a new instrument. Conversely, surplus knowledge may also be sufficient, as in the recursive example just discussed. But in general, some degree of integration is necessary to exploit new discoveries, and a new discovery is necessary to make some combination of knowledges useful. Examples will be given below.

2.3 *"Embodiment"*

A final qualification is that "embodiment" is difficult to define precisely. Perhaps one way of putting what is meant by this term, for my purposes, is that it involves finding some functional substitute in material form for whatever items of TK, EK, MK and PK are needed to build the instrument. Though he does not categorize knowledge in exactly the same way, Davis Baird (2004) provides an example of this process in his account of the development of direct-reading spectrometers:

> we can see in it how various kinds of knowledge were integrated into a material medium to produce a measuring instrument. Model knowledge is built into the instrument in several ways, including the material representation of wavelengths of light emitted by important elements in the "exit slits" of the instrument ... Working knowledge is built into the instrument, again in several ways, including the use of a diffraction grating to disperse light into the constituent wavelengths ... Theoretical knowledge is also built into the instruments, of which the theory of condenser discharge is a particularly clear example ... Functional substitutes for human discriminatory skills are built into the instrument too. With a spectrograph, where photographic film is employed instead of photomultiplier tubes, humans have to determine how dark—or "dense"—a "spectral line" is; instruments called densitometers helped to refine this skill. With a direct-reading spectrometer, photomultiplier tubes and electronics are crafted to provide a functional substitute for

> this skill. The material medium of the instrument encapsulates and integrates all these different kinds of knowledge. All are necessary for the instrument to render information about a specimen. (Baird 2004, p. 70)

As the instrument is built, so the knowledge required to build and use it is "built into" the instrument as well.

Instruments are powerful vehicles for the dialectic of discovery and embodiment. Why? After all, the accumulation of theoretical knowledge may be sufficient to enable further discovery. For example, according to Hempel (1966, pp. 76-77), a good theory will allow us to discover phenomena that were not known at the time the theory was formulated. Nevertheless, the possibility of embodying knowledge in instruments paves the way for greater progress in knowledge than would be possible without it.

Why? The usual answer is that instrumentation provides access to objects of inquiry that are inaccessible by means of our native human abilities. However, two further features of instruments also contribute to the growth of knowledge. First, and as noted in chapter 2, a complementary, but less obvious, answer that more directly affects the temporal characteristics of scientific research is that the instrument's contribution is not necessarily fixed once and for all but can be enhanced over time, more so than human abilities. The basic reason is that technology is improvable in a much deeper way than are our native abilities. The degree to which the latter are improvable is constrained fundamentally by human biology. In contrast, the improvement of instruments is, in principle, only constrained by the laws of nature, though in practice it must be adapted to human users.

Second, there is the feature, alluded to earlier, that we can use an instrument without knowing all the things necessary to make it. What might be called the "black-box-ability" of the instrument allows a much greater amount of knowledge to be brought to bear in research than would otherwise be possible.

Through these properties, instruments extend our observational and computational powers. Some of the new knowledge yielded can then be embodied in new instruments by way of their improvability. Something similar can happen with humans. Human computational powers can be improved by the discovery of algorithms like the rules of arithmetic. This would be another recursive case, where a discovery made by means of "instruments"—the mind and means of mathematical representation—could be used to improve the powers of the instruments themselves. So the native human abilities can engage in this dialectic as well, but not to the same extent as artifacts due to the constraints imposed by humans' natural endowment.

Instruments also provide *scaffolding* for the integration of new knowledge into the labor process. By 'scaffold,' I intend a structure that allows a new structure to be constructed from it. The old structure may be physical or conceptual, a design for example. Many instruments are not developed *de novo*, but rather from the modification of precursors or precursor designs. The precursor or precursor design provides a scaffold for the development of new instruments. The old knowledge embodied in the precursor or precursor design provides a structure within which new knowledge can be exploited.

2.4 *Some examples*

I will now provide a few historical examples of how source-integration, form-integration, and embodiment work together to produce change in science.

2.4.1 *Clocks*

The clock provides an example of an instrument with extremely important applications both inside and outside science. According to Landes (1987, 2000), the invention of the mechanical clock was a seminal event in the history of methods of measuring time, though its importance was only made possible by later developments. The European Middle Ages inherited two types of time-keepers from antiquity, the sun-dial and the water-clock. Both were based on the same principle: the continuous measurement of a continuous phenomenon. They both had major context-dependent defects. Sun-dials don't work at night nor when the sky is cloudy, the latter being a serious impediment in cloudy regions. Water-clocks are very sensitive to changes in temperature, which makes their proper functioning vulnerable to daily and seasonal temperature variations. The mechanical clock, invented around 1300 CE, was relatively free of these defects, yet that was not what made it a revolutionary time-keeper. What made it revolutionary was its principle: instead of tracking the passage of time by imitating its continuous flow, it made beats according to an (ideally) regular rhythm and counted them.

According to Landes, this "digital principle" made possible all subsequent improvements in time-keeping technique. All clocks based on this principle, starting with the first mechanical clocks, comprised the same five basic design features (Landes 2000, pp. 6-10 and 413):

1. A source of energy (e.g., falling weights, spring or battery)
2. An oscillating controller (e.g., balance, quartz crystal)
3. A counting device (e.g., escapement, solid-state circuit)
4. Transmission (e.g., wheelwork, electric current)
5. Display (e.g., hands, liquid-crystal display)

Though the earliest mechanical clocks used a foliot crossbar to control the rhythm, subsequent controllers, such as the pendulum (invented by Huygens in 1657), the tuning fork, quartz, and atoms, were all based on the same principle. Though the inventor(s) of the original mechanical clock could not have anticipated these later versions, the recourse to an oscillator and the other design features provided a scaffold within which subsequent discoveries and inventions could be exploited. For example, in the early 20th century, quartz crystals were being used to emit radio signals, based on the piezoelectric effect discovered by Pierre and Jacques Curie at the end of the 19th century. Though the signals emitted by the first such crystals were unstable, improvements in the preparation of crystals and in their integration within resonating circuits resulted in stable high-frequency resonators. The physics of high-frequency resonators could then be exploited in the invention of quartz clocks. High-frequency resonators are both less prone to dampening, and keep a more stable rhythm, than low-frequency. Further modifications were required, however, to take advantage of these properties. Thermal effects on crystals are small relative to mechanical clocks, but for scientific measurements they are non-negligible. Laboratory quartz clocks were eventually equipped with a thermostatic enclosure with a variance of 1/10000 °C. To counter variations of frequency caused by accident or by changes in power supply, the quartz was inserted into a closed resonance system in which fluctuations were detected and corrected by a servomechanism.

These improvements produced quartz clocks that kept time with a precision of a hundredth of a millisecond per day. Ultimately, the development of high-frequency clocks permitted measurements of phenomena occurring on tiny timescales, in some cases on the order of femtoseconds. According to Landes, the result of the high-frequency revolution in clocks was that the measurement of time and frequencies became much more widespread across scientific domains, especially in astronomy, telemetry, interferometry, physics, and, I might add, chemistry in the form of new areas of research like femtochemistry. Furthermore, the merits of high frequencies made possible a number of applications based on the use and control of short time intervals and of very transient phenomena, including multiplying the number of communications simultaneously transmittable through the same wire and improving computer processing speeds.

Viewing this episode as an example of form-integration, we might say that an instance of practical knowledge (PK), the clock based on the digital principle, provided a scaffold on which theoretical and empirical knowledge (TK and EK) could be exploited. The integration of these knowledges into the scaffold then allowed new methodological knowledge (MK), empirical knowledge, practical knowledge and theoretical knowledge to be acquired.[7] This example also illustrates the use of instruments to extend our observational reach as well as their capacity for improvement.

2.4.2 *The mass spectrometer*

The mass spectrometer provides an example of an instrument built expressly for scientific purposes.[8] In mass spectrometry, the components of a sample are ionized and then separated by various arrangements of electric and magnetic fields. TK is employed here in the form of the laws governing the motions of charged particles. The mass-to-charge ratio of each kind of ion is measured, and this information allows the components of the sample to be identified. Prior to the 1940s, the photographic plate was the most common method of detection, which required the skill of measuring spectral line density that Baird alludes to in the passage quote above. Starting in the 1940s, the photographic plate tended to be replaced by electronic detectors, which produce an amplifiable signal. This modification enabled automatic strip chart recording of the mass spectrum, which simplified and accelerated spectrum recording compared to the photographic method. Strip chart recorders yielded an analog recording, however, which had to be converted into tabular form

---

[7] For example, Ahmed H. Zewail's (1999) Nobel lecture on femtochemistry reviews the various observations, methods, theoretical concepts and models, and applications that emerged through the study of chemical bond dynamics on the femtosecond scale.

[8] The following relies on Grayson (2004) and Nier et al. (2016).

through a labor-intensive process. The earliest use of computers (1958) in mass spectrometry was that of a digitizer that could tabulate the data as the spectrum was being generated. The Mascot digitizer was itself fairly crude, in that it was unable to do anything else but digitize the output of the spectrometer to which it was hard-wired. But digitization eventually enabled new applications of the computer to mass spectrometry in the 1960s. The DENDRAL algorithm was developed to interpret the spectra of unknown compounds, albeit with limited success. High-resolution mass spectrometry, which allows deduction of elemental composition, relied heavily on computers to digitize the data from the detector and process them into exact mass and intensity information. Library search algorithms were developed to match the spectra of unknowns with those of reference compounds. In the 1970s, techniques and instrumentation were developed that allowed the spectrometer to be coupled with a gas chromatograph and a data system. The GC-MS-DS was capable of generating several hundred spectra per half hour, which could eventually (1990s) be compared via library search algorithms to libraries containing hundreds of thousands of reference spectra. In contrast, only a few spectra per hour could be prepared by an operator using a strip chart recording machine of the 1940s and 1950s.

In this example, the spectrograph of the 1930s provided a scaffold for the exploitation of new technologies—electronic detectors, digitizers, computers, software, and instrument-instrument interfacing technologies. The process of integrating these technologies into the mass spectrometer resulted in instrumentation with capabilities that far exceeded what was possible with the old spectrograph.

The mass spectrometer was not an isolated case, but rather part of a far-reaching transformation in how chemistry was done known as the “Instrumental Revolution.”[9] For our purposes, what is

---

[9] Overviews of this episode may be found in Steinhauser (2014), Reinhardt (2006), and Morris (2002).

interesting about the latter is that it illustrates the dialectic of discovery and embodiment on *a social scale.*

2.4.3 *The Instrumental Revolution in chemistry*

This was an episode in which knowledge produced in diverse disciplines was combined in the form of new instruments for chemical analysis. Various scientific and social developments—the discovery of quantum phenomena, the emergence of computer science and physical organic chemistry, the needs of the petrochemical and rubber industries during the Second World War, the prioritizing of output by university administrations—converged to make the embodiment of scientific and technological knowledge possible and sought after as a means for solving chemical problems. This process resulted in the emergence of many high-tech methods of chemical analysis, of which some of the better known are nuclear magnetic resonance (NMR), mass spectrometry (MS), ultraviolet spectroscopy, infrared spectroscopy, Raman spectroscopy, and X-ray crystallography.

By analogy with Figure 1, the epistemic component of the convergence process might be illustrated, in a highly simplifying way, as follows:

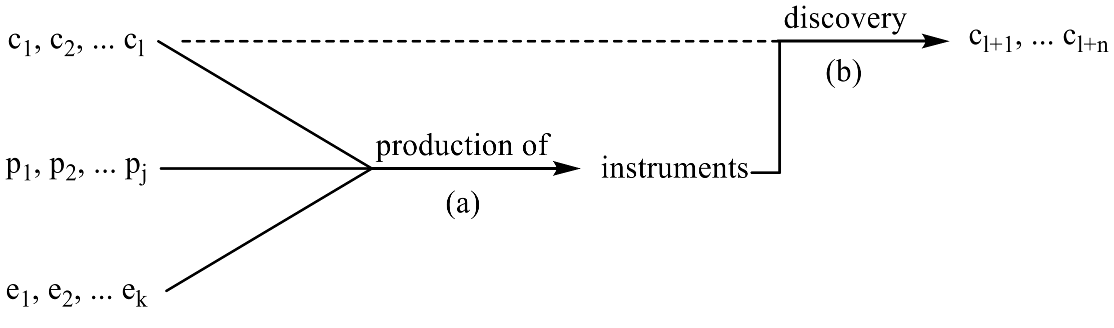


Figure 4. The Instrumental Revolution expanded the set of instruments available to chemists for analytical purposes by combining knowledge from different sources (chemistry, physics, engineering sciences, etc.) in the production of new instruments.

The series on the left represent instances of a kind of knowledge: the c_i's chemical knowledge, the p_i's physical knowledge, and the e_i's "engineering knowledge," a broad notion intended to cover computer science, electrical engineering, and various forms of know-how.[10] There is expansion, as chemistry acquires more instruments than it had at the beginning. There is also reproduction, as the new instruments allow chemists to continue doing chemical analysis. In addition, most of the old knowledge was retained, since the new methods were compatible with the old. There was thus accumulation not just of the stock of instruments, but of chemical knowledge. Indeed, the surplus knowledge afforded by the new methods was vast, for the transformation not only accelerated traditional chemical analysis but made possible many new lines of inquiry. Moreover, some of the knowledge obtained was used to develop new generations of instruments.[11]

The diagram also illustrates a mechanism of expansion: the combination of knowledge from different sources in the production of the new instruments, which would not have been possible with a more insular mode of development. This is a case of what I called 'source-integration' above. In this respect, the episode illustrates, on a social scale, a pattern of innovation observed by Harman & Dietrich (2018) at the level of individual scientists: the creative integration of ideas and practices from multiple fields. In the case of the Instrumental Revolution, however, the integration was driven not just by the nature of human creativity, but also by the technical requirements of applying knowledge of physical phenomena to chemistry. Each of the new techniques was based

---

[10] Baird & Faust (1990) argue that such know-how is essential for the construction of scientific instruments. Kletzl (2014), pp. 122-123 argues that there exists "engineering theory," consisting of systematic propositional language of how to manufacture an artifact, in contrast to the "explanatory theories" of natural science.

[11] See Becker et al. (1996) for a survey of the new lines of inquiry and instruments made possible by the development of NMR spectroscopy.

on a physical phenomenon. For example, NMR is based on the detection of transitions between energy levels of nuclear spins in bulk materials in the presence of an external magnetic field. The initial phenomenon, however, was generally useless for other than physicists interested in measuring nuclear magnetic moments, and instrument specialists like Herbert Gutowsky or Richard Ernst,[12] until a host of supporting knowledges and technologies were brought to bear. Mechanization was required to develop instruments that had the speed and control needed to produce data informative enough to compete with traditional chemical data. For example, carbon is the key structural element in organic chemistry. The ^{13}C NMR effect was discovered in 1957 by means of early NMR spectrometers. But the combination of only a 1.1% natural abundance of ^{13}C, the only carbon isotope with a nuclear spin, and its relatively low intrinsic sensitivity initially prevented the routine exploitation of this effect. The latter was achieved in large part through technical improvements including the introduction of computers (which allowed the signal-to-noise ratio to be improved), the incorporation of techniques for stabilizing the magnetic field, and the employment of more powerful magnets. In 1972, the first routine ^{13}C NMR spectrometer for organic chemists was brought to market. Further improvements, notably the development of Fourier transform technology, allowed the ^{13}C NMR effect to be applied to the study of biochemical systems.[13] In general, black-boxing, an empirical approach to data interpretation, a

---

[12] See Reinhardt (2006) for detailed accounts of the contributions of these and other instrument specialists to the development of the new techniques.

[13] The instrument was the Varian CFT-20. I rely here on Becker et al. (1995), sections 3, 6 and 10 for the history of ^{13}C NMR. This history illustrates both steps shown in Figure 1, with the discovery of the effect being the outcome of step 1, the development and application of which led to a host of structural, mechanistic and methodological discoveries in organic chemistry and biology.

new division of labor and various technical improvements were other elements required to make the methods attractive to chemists outside of chemical physics.[14]

This pattern of integration is typical of the dialectic of discovery and embodiment. As noted above, the process illustrated in Figure 1 can only fully realize its potential for progress if it involves collections of instruments and discoveries, not just individual instruments. These collections can stretch across fields. The process therefore requires the convergence of a totality of labor processes. As in ordinary material production, so in science: innovation in one process needs the support of many other processes.

3 Progress as transcendence of the limitations of native human epistemic abilities

Historical materialists hold that the transformation of the labor process over the long-term moves humans farther and farther away from the constraints of their biological origins.[15] In this section, I will argue that the surplus-knowledge theory described in the previous section explains one of the more striking features of 20th century and contemporary science, the increasingly important role of automated or semi-automated instrumentation in scientific research. The philosopher of science Paul Humphreys has suggested that "one of the principal achievements of science has been to transcend the limitations of humans' natural epistemic abilities" (Humphreys 2004, p. 6). The reasons he gives are that the evidence of the human senses, as well as human computational abilities, are more error prone, and severely limited in scope, compared to what can be achieved with instruments.

---

[14] Reinhardt (2006) describes the efforts of instrument developers to adapt the methods to chemical needs. Feeney (1999) describes the role of technical improvements in making NMR applicable to chemistry.

[15] Marx & Engels (1978 [1845-6]), p. 150; Engels (1987 [1895-6]); Novack (1980), ch. 1; Damerow (1996), ch. 11; Sève (2014), pp. 285-291. I will say more about this claim in section 4.

I submit that these limitations suggest a backward-looking goal relative to which progress can be made. According to Niiniluoto (2015), a goal may be backward-looking or forward-looking, depending on whether it refers to the starting-point or destination point of an activity. Humphreys' suggestion suggests a kind of progress away from our natural endowment: we might say that an episode of science constitutes scientific progress if it shows the transcendence of limitations of native human epistemic abilities. For comparison, consider three other accounts of the concept of scientific progress:

(E) An episode constitutes scientific progress precisely when it shows the accumulation of scientific knowledge. (Bird 2008, p. 279)

(S) An episode constitutes scientific progress precisely when it either (a) shows the accumulation of true scientific belief, or (b) shows increasing approximation to true scientific belief. (Bird 2008, p. 279)

(I) An episode constitutes scientific progress when it shows the adoption of a practice in which an instrument (technique) with more capabilities replaces one with fewer.[16]

(S), (E) and (I) are called the *semantic*, *epistemic,* and *instrumental* accounts of progress.[17] For notational congruence, I will use (H) to denote the concept of progress as transcendence of limitations of native human epistemic abilities.

---

[16] Adapted from Kitcher (1993), p. 117. The original reads: "Instruments and experimental techniques are valued because they enable us to answer significant questions. One instrument (or technique) may do everything another does and more besides. If so, then we make *instrumental* (or *experimental*) progress by adopting a practice in which the former instrument (technique) replaces the latter."

[17] See Mizrahi (2010) for a discussion of these and other accounts of progress.

(H) An episode of science constitutes scientific progress if it shows the transcendence of limitations of native human epistemic abilities.

By ‘transcendence’ I merely mean (following Humphreys) that the instrument is less error-prone, or of broader scope, than a human ability that it *enhances*. I use the latter verb in the three-pronged sense of Humphreys (2004, ch. 1). Humphreys uses the verb to denote three ways in which limitations of native human abilities may be overcome: by extrapolation, by conversion, and by augmentation. *Extrapolation* takes place by extending an existing modality of human ability, like vision, along a given dimension. Paradigmatic examples are the optical telescope and microscope, which bring very distant and very small objects within the range of visual detection. *Conversion* occurs when phenomena that are accessible to one sense are converted into a form accessible to another. Sonar devices that have visual displays are one example. *Augmentation* gives us access to features of the world that humans are not naturally equipped to detect in their original form, such as alpha particles, positrons and spin.

In addition to enhancement, transcendence can also be brought about through *replacement*, which occurs when an instrumental ability replaces a human ability.[18] Replacement may involve the other operations. For example, the replacement of ocular detection telescopes with photographic plate detection in the late 19th century involved extrapolation, since it greatly increased the quantity of data obtainable in the visible portion of the electromagnetic spectrum (Bigg 2000). On the other hand, the replacement of photographic detection with electronic detectors somewhat later involved augmentation because it gave astronomers access to celestial

---

[18] I thank an anonymous referee for pointing out that transcendence can involve enhancement as well as replacement.

phenomena outside the visible portion of the spectrum, such as the Cosmic Microwave Background dating from the very early universe.

So a more precise formulation of (H) is:

(H’) An episode constitutes scientific progress if it shows the adoption of a scientific practice in which an instrument that is either (a) less error-prone or (b) of broader scope enhances or replaces a native human epistemic ability.

For brevity, however, I will use ‘transcend’ in what follows, it being understood to have the meaning just given.

I have worded (H) as a sufficient condition, not a necessary condition, since we want to allow for other kinds of scientific progress. My purpose here is neither to endorse nor refute these other accounts, but merely to propose a complementary account that fits certain trends in modern science.

Of the three other accounts listed, (H) is most similar to (I). (H) may even seem to be a special case of (I), in which the instrument that is replaced is a native human ability. But viewing (H) thus presupposes that native human abilities are instruments. This presupposition itself, however, requires that we have already *conceptually* transcended native human abilities, in the sense of viewing them as merely one kind of instrument among other possible ones by which it could be replaced (I will say more about the nature of this conceptual transcendence shortly). So native human abilities can only be subjected to the process described in (I) if they have already been subjected to a conceptual analogue of the process referred to in (H). I conclude that (H) is independent of (I).

On the other hand, (H) may be subsumable under the epistemic account of scientific progress. Since (H) concerns abilities, then the kind of knowledge involved would have to be know-how, presumably the methodological knowledge (MK) discussed in section 2.1. As noted by Mizrahi (2013), however, this is not usually the kind of knowledge proponents of the epistemic account have in mind, for they tend to be focused on propositional knowledge, TK in particular.

The term ‘natural’ or ‘native’ human epistemic ability’ is somewhat of a misnomer, since very few of our epistemic abilities are completely natural, in the sense of resulting solely from our biological endowment. Most human abilities require socialization and education, as well as material means. So in order to clarify its meaning, I will venture the following tentative definition:

> X is a native human epistemic ability if and only if an individual human Y can use ability X to acquire knowledge, *and* biological facts about humans are required for the success of the exercise of X.

This definition is intended to retain the biological foundation of human abilities, while not supposing that the former is sufficient for the success of the latter, since facts about socialization, education, material means etc. may also be required for success.

3.1 *Examples: mathematical and observational abilities*

I will now provide two examples of “native” human epistemic abilities. Recall the computation example of section 2.3. We are not born with mathematical ability. It has to be acquired through socialization and education. For most people, any but the simplest calculations require material means of mathematical representation, like pencil, paper and a symbol system. Nevertheless, mathematical ability is a native human epistemic ability, because an individual human can use it to acquire knowledge, and biological facts about humans—that they have brains with certain features, motor skills that permit symbol manipulations—are required for the success of the individual human's exercise of the ability.

In contrast, consider the situation where the individual human Y, rather than carrying out a pencil-and-paper calculation, types instructions into a computer which tell the computer to carry out the calculation. Clearly, Y uses mathematical ability to acquire the same knowledge as in the previous case. But biological facts about humans are no longer required for the success of the exercise of the ability, for it is not Y's ability but the computer's. The success of the calculation is determined by facts about the computer software and hardware. So the mathematical ability Y uses is no longer a native human ability. Where biological facts about humans are, of course, still central is the operation of the computer, which has to be adapted to human operators, and the use of its output, which has to be useable by humans (e.g., the answer should not be in binary code).

Observation provides another example. Hacking (1983) argued that observation is a skill. Knowledge of how to observe is acquired through scientific practice. These skills can be transmitted from master scientist to apprentice, and when this happens the untrained sense perception of the apprentice is augmented by the new skills. The apprentice can use his ability to observe in order to acquire knowledge, and biological facts about human senses and cognition are required for the success of the exercise of her ability. An example alluded to in section 2.3 is the determination of the density of spectral lines on a photographic plate, mentioned in Baird's discussion of direct-reading spectrometers.

In contrast, consider the situation where the apprentice, now a mature scientist himself, replaces his old spectrograph with a spectrometer equipped with an electronic detector. Clearly, he can use the observational ability of the instrument to acquire the same knowledge as with the spectrograph (and more). But biological facts about humans are no longer required for the success of the observation. The latter is determined by facts about how the machine detects the ions generated from the sample and how the detected signals are amplified and processed into mass-to-charge and intensity information. Where biological facts about humans are still central is, as in the calculation example, the operation of the machine and the use of its output.

In both the calculation and the observation cases, we started with a situation in which a native human ability was used to acquire knowledge, and ended with one in which an analogous machine-based ability was used to acquire the same knowledge. On the assumption that in the given case the machine is either less error-prone, or has broader scope, than the human ability, then the latter has been transcended. This makes it an episode of (H).

3.2 *The mechanism responsible for progress (H)*

Assuming that I have provided grounds for thinking that (H) is a reasonable concept of a variety of progress [to borrow a phrase from Kitcher (1993)],[19] further questions are how well it fits the history of science and what mechanisms are responsible for it. I will start with the latter question. I submit that the surplus-knowledge theory described in section 2 explains this kind of progress. The extension of knowledge shows that native human abilities involved in scientific work are subsumable under more general abilities associated with general types of instruments. Ocular observation may again provide an example. In his classic 1982 discussion of the concept of observation in science and philosophy, Dudley Shapere argued for an extension of the philosophical concept of observation beyond its previous associations with perception, such that there can be observation by or with scientific instruments. Though he does not use the term, his argument was based on the impact of what I am calling surplus knowledge on scientists'

---

[19] I thank an anonymous referee for suggesting this phrasing from Kitcher.

understanding of their own practice of observation. Physical science claims to discover the existence of entities and processes that are not accessible to the human senses. It further claims to discover that those senses are receptive to only a limited range of types of events that form part of an ordered series of types of events, the electromagnetic spectrum in the case of the eye. This spectrum encompasses a range of wavelengths on the order of 10^{22}, of which only about 10^{-19} is accessible to human vision. As a result of the extension of knowledge about vision, then, it is realized that the eye is just a particular sort of electromagnetic receptor, capable of detecting electromagnetic radiation in a certain range, there being other sorts of receptors capable of detecting other ranges of the spectrum. The extension of knowledge thereby leads to the generalization of the notion of a receptor or detector, which subsumes the eye as one type.

A further generalization occurs when it is recognized that there are other fundamental interactions besides electromagnetic ones: strong, weak and gravitational interactions. As a result, ocular detection abilities become subsumable under the even more general ability to detect one of the fundamental physical interactions. This general ability is associated with a type of instrument, the ‘receptor’ or ‘detector,’ which is capable of detecting one of these interactions and the entities engaging in it.

For Shapere, this process of generalization was a theoretical matter, resulting from the accumulation of theoretical knowledge. For it to have practical significance, however, that knowledge needs to be embodied in instruments. From what was said in section 2, it follows that two conditions are necessary. First, the auxiliary knowledge must be available for form- and source-integration to be possible. Second, the appropriate scaffolding must be available for embodiment. If these and other conditions (fit with scientists’ goals being an obvious one) are met then the surplus knowledge can be applied in research.

Shapere's account of observation in science illustrates the reflexive character of scientific knowledge: as the latter accumulates, it sheds light on scientific practice itself, in particular by showing how native human epistemic abilities are subsumable under more general abilities that can also be exercised by instruments.

3.3 *Fit with the historical record*

How well does (H) fit the historical record? Space does not permit a survey, so I will take mass spectrometry as a fairly typical example of technologically driven transformations in bench-top science in the 20th century.[20] The reader will recall the brief account of the development of mass spectrometry in section 2.4. Table 1 shows which native human epistemic abilities were transcended in that episode:

Abilities	*How Exercised*	*How Transcended*
Ocular detection	Reading of photographic plates	Electronic detectors, amplifiers
Data processing	Tabulation of analog recording data	Digitizers, minicomputers
Problem-solving	Interpretation of spectra	Interpretation algorithms
Memorial	Data storage, instrument control, multi-tasking	Hard disks, RAM, CPUs
Pattern recognition	Comparison of spectra of unknowns to references	Pattern recognition algorithms
Searching abilities	Searching of spectral libraries	Search algorithms

---

[20] Humphreys (2004) has more examples, though his focus is not historical.

Manipulative	Instrument control; sample handling and transferring between instruments; densitometering	Computer control; automated sample handling and direct instrument coupling; automatic recording

Table 1. The transcendence of native human epistemic abilities in mass spectrometry.

The left-hand column lists various abilities that were involved in the production and use of mass spectra by means of the spectrograph and early spectrometers. The center column lists the ways in which those abilities were exercised in this field. The right-hand column lists the means by which those abilities were transcended. Computerization obviously played a large role, but advances in electronics, separation techniques and instrument interfacing technology were also important. As noted in section 2.4, the replacement of photographic plates by electronic detectors made computerization possible, and electronic detectors are themselves based on the photoelectric effect. Besides massively increasing the scope of mass spectrometry, the replacement of "manual" methods appears to have reduced the likelihood of errors (Serum 2016). The development of mass spectrometry therefore seems like a good candidate for (H).

4 How to be scientific about scientific change without being reductionist

A famous proponent of another backward-looking notion of scientific progress was Thomas Kuhn. As is well-known, he suggested that we may have to abandon the notion of progress as approaching closer and closer to the truth. To replace it, he proposed a Darwinian move, in which the idea of an evolutionary process with a distinct goal was to be replaced by the idea of an evolutionary process that has moved steadily away from primitive beginnings. Though he acknowledged that "the analogy that relates the evolution of organisms to the evolution of scientific ideas can easily be pushed too far," he immediately added that "it is very nearly perfect" with respect to the question of whether there is progress through scientific revolutions:

> The process described in Section XII as the resolution of revolutions is the selection by conflict within the scientific community of the fittest way to practice future science. The net result of a sequence of such revolutionary selections, separated by periods of normal research, is the wonderfully adapted set of instruments we call modern scientific knowledge. (Kuhn ([1962] 1996, pp. 171-2)

I note in passing that he does not say much about what scientific knowledge is adapted to, except that the process leads to "an increase in articulation and specialization." van Fraassen (1980) makes an even stronger claim than analogy, holding that "science is a biological phenomenon, an activity by one kind of organism which facilitates its interaction with the environment." He uses this claim to appropriate the no-miracles argument for scientific realism on behalf of constructive empiricism:

> I claim that the success of current scientific theories is no miracle. It is not even surprising to the scientific (Darwinist) mind. For any scientific theory is born into a life of fierce competition, a jungle red in tooth and claw. Only the successful theories survive—the ones which *in fact* latched on to actual regularities in nature. (van Fraassen 1980, pp. 39-40).

David Hull's (1988) theory, that the history of science is the result of selective pressures operating on scientific theories, works this idea out in detail.[21]

By emphasizing the commonalities between science and ordinary labor I have implicitly taken a naturalist approach to the study of scientific progress. Darwinian theories of scientific progress

---

[21] See Renzi & Napolitano (2011) for a longer analysis of the various evolutionary analogies that have been used to describe or explain scientific change.

are a major alternative naturalist approach in philosophy of science. From the perspective adopted in this paper, however, the analogy or identification of science with natural selection amounts to a misrecognition of the peculiar character of the evolution engendered by the labor process, insofar as it attributes a feature of a particular kind of human labor—scientific progress—to a mechanism that has nothing specifically to do with human labor.[22]

The reproduction of animals is characterized by the development of the individual from birth to death, by its physical reproduction in interaction with nature, and by the reproduction of the characteristics of the species by means of procreation and genetic inheritance. The only mechanism of change is random variation of individuals followed by natural selection of mutants with a selective advantage in a given environment.

The labor process is special because it can bring about a material result over and above the means of subsistence required for individual survival, and it can do so as a systematic and planned outcome. This result consists in the produced means of production, paradigmatically represented by tools of material production but also including cognitive tools like material representations and symbol systems (Damerow (1996), ch. 11; Sève (2014), pp. 285-291). Under appropriate social conditions, such as the existence of a social division of labor, these material means can be accumulated, creating an environment of implements that forms the starting-point for renewed

---

[22] The following is indebted to the discussion of cultural evolution in Damerow (1996), ch. 11. In a somewhat similar vein, Gerson (2014) discusses problems with understanding cultural evolution by analogy with biological evolution, though without Damerow's emphasis on the development of material culture as a cause of divergence between them.

In the context of a reconsideration of Kuhn's image of science, both Marcum (2018) and Renzi & Napolitano (2018) discuss problems with understanding scientific change by analogy with Darwinian natural selection. I thank an anonymous reviewer for sharing these references with me.

cycles of reproduction with expansion. The expanding environment of implements does not remain external to the labor process to which it owes its existence, but in turn releases the inherent possibilities of the process. The feedback between the accumulated means of production and the labor process means that the process of accumulation is not linear but rather expands and accelerates exponentially. This acceleration is not merely quantitative, but includes essential qualitative changes based on the reflexive character of the tools: because the environment of implements is constantly changing, the techniques and organization of the labor process are also constantly changing. As a result, the development of the individual human takes place under constantly changing initial conditions. The reproduction of the characteristics of the species in the individual can no longer be satisfied by reproduction through procreation and genetic inheritance, but requires socialization and education. It follows that to the extent that reproduction of the individual involves the transmission of the characteristics of the species—in particular the ability to use and produce tools—to the individual, this reproduction is from the outset an essential cause of the development of society and simultaneously an effect of it.

The fact that the labor process can result in a surplus is a very important one for understanding human history. This fact makes possible *a new mechanism of change, over and above random variation and selection*: reproduction by means of the expanded means of production. Each iteration of the labor process differs from the preceding one insofar as it incorporates the surplus generated previously.

So far we have only been considering one aspect of the labor process, that it is capable of generating a surplus product. As pointed out by the philosopher and historian Wolfgang Lefèvre, in addition to a surplus product, surplus *knowledge* can also be obtained (Lefèvre 2005, section 3.1). Lefèvre claims that, in the utilization of definite means for tackling specific problems, more knowledge can be acquired than was necessary to invent the means, because "by applying a material means in the labor process, its material nature can reveal new ways of application and employment, which were not given along with the original ends" (Lefèvre 2005, p. 215). This fact explains the growth of knowledge in general. It also, Lefèvre argues, explains the growth of *scientific* knowledge. Like ordinary material labor, science also makes use of material means. The material means of science include not only things that resemble, or in fact are, production apparatuses, like certain observational instruments or, say, distillation apparatuses. They also include "material means of scientific thinking" like diagrammatic representations or numerical notations. The material means of thinking "delineate a horizon of what results scientists can achieve and even what results are conceivable or probable." The application of the material means of science generates a surplus of scientific knowledge, as more knowledge is gained in applying them than was needed to invent them.

Lefèvre's account raises two questions. First, given that all forms of labor use material means, then an explanation may be needed of how progress in science differs from progress in any other kind of labor. Such an explanation is especially welcome in light of the widespread belief (among philosophers of science, at least) that science is exceptionally progressive relative to other kinds of *intellectual* work.

Lefèvre provides a partial answer. It is that science transforms the realization of potential knowledge inherent in tools into a systematically performed social enterprise. The free exploration of the possibilities tools present is ruled out in ordinary labor, due to the utilitarian aims and economic considerations that impose narrow limits on how the means are employed. In contrast, "free exploration constitutes the core of science." Thus, the fundamental difference between science and other forms of labor would be that free exploration of the uses of tools is systematically performed in the former but not in the latter (Lefèvre 2005, p. 218).

A second question is what role the specific products, resulting from the application of scientific means, play in the acquisition of new knowledge. Lefèvre focuses on how the discovery of new uses or ways of using the material means leads to new knowledge. He provides the example of Greek geometry:

> It is not the nature of the means themselves but their *use* for purposes of cognition that renders them scientific means. To give an example: The inventors of Greek geometry did not invent the compass and ruler on which this geometry essentially rests. Living in a society that used these instruments in several practical domains, they rendered them scientific instruments by making a specific use of them. They employed them not to design the ground plan of a temple or for another practical goal, but to gain insight in the regularities of constructions that can be accomplished by compass and ruler. (Lefèvre 2005, p. 218)

The geometer, like the architect, may use a compass to draw a circle, but instead of using the circle to design a temple, the former thinks abstractly about the properties of circles. On this view, the product of tool use is a secondary matter; what counts is the use that is made of it. In the end, it seems that what differentiates scientists from other workers is that the former think abstractly about the results of tool use, whereas the latter think with regard to practical purposes.

This difference helps explain how science began. In modern science, however, instruments of science are constructed and employed specifically because of the particular form and content of the knowledge they yield about the world, not only to explore what happens when they are used in new ways. My discussion of discovery and integration aimed to address this additional function by shifting the focus onto the products of scientific tool use and how scientists use these to transform their own practice.

To conclude this section, I think the evolutionary views of the history of science discussed at the beginning of the section can yield valuable insights into processes of innovation and the transmission of ideas in science. But they run the risk of reductionism, insofar as they evacuate features of science that are specific to human evolution. In particular, an evolutionary approach must take into account how humans' relationship to nature is mediated. Historical materialists have aimed to correct reductionist distortion by studying the ways in which labor, as a specifically human activity, mediates that relationship. Labor gives human evolution the character of expanded reproduction. The latter puts humans on a different developmental trajectory than other species, for the changing environment of use-values alters the nature of the labor process, and hence the skills and abilities that can be marshalled therein. My suggestion in this paper has been that this process is also at work in the history of science.

5 Conclusion

According to Chang (2007), "[s]cientific progress remains one of the most significant issues in the philosophy of science today. This is not only because of the intrinsic importance of the topic, but also because of its immense difficulty. In what sense exactly does science make progress, and how is it that scientists are apparently able to achieve it better than people in other realms of human intellectual endeavour? Neither philosophers nor scientists themselves have been able to answer these questions to general satisfaction." The approach taken in this paper has been to compare science to ordinary labor rather than to other intellectual endeavors like art, religion, philosophy, morality or politics, as is usually done.[23] Though I by no means purport to have provided a general

---

[23] The list in the text is from Niiniluoto (2015). Sarton (1927), pp. 3-4 contrasts science to religion, art, and social justice; Kuhn (1996 [1962]), p. 160 to art, political theory, and philosophy; Resnik (2000), p. 253 to literature,

answer to the questions Chang raises, I claim to have offered grounds for thinking that one of the mechanisms by which science makes progress is similar to how ordinary labor makes progress. In addition to the question of fit with the history of science, future development of the view outlined here should answer the question of why and by means of what social mechanisms scientists engage in the processes described in sections 2 and 3. The approach taken here also suggests a difference with the other realms of intellectual endeavor to which science is usually compared. None of these has a comparable cycle of discovery and embodiment to power its growth. None of these has a similar ability to transcend the limits of native human abilities.

6 Acknowledgments

I thank John Norton, Michael Dietrich, and two anonymous reviewers at *Perspectives on Science* for helpful comments and suggestions on earlier drafts of this paper.

7 References

Baird, D. (2004). *Thing Knowledge.* Berkeley: University of California Press.

Baird, D., & Faust, T. (1990). "Scientific Instruments, Scientific Progress and the Cyclotron." *The British Journal for the Philosophy of Science,* 41(2): 147-175.

Becker, E. D., Fisk, C. L. & Khetrapal, C. L. (1996). "The Development of NMR." Pp. 1-153 in *Encyclopedia of Nuclear Magnetic Resonance, Volume 1: Historical Perspectives.* Edited by D. M. Grant and R. K. Harris. New York: John Wiley & Sons.

---

philosophy, law, religion, and music; Okasha (2002), p. 1 to art, music, theology, history, astrology, and fortune-telling; and Smith (2010), p. 574 to "other areas of inquiry."

Bigg, C. (2000). “Photography and the Labour History of Astrometry: the *Carte du Ciel*.” Pp. 90-106 In *The Role of Visual Representation in Astronomy: History and Research Practice.* Edited by K. Hentschel and A. D. Wittmann. Thun and Frankfurt am Main: Verlag Harri Deutsch.

Bird, A. (2008). “Scientific Progress as Accumulation of Knowledge: A Reply to Rowbottom.” *Studies in History and Philosophy of Science,* 39: 279-281.

Chang, H. (2004). *Inventing Temperature.* Oxford: Oxford University Press.

—(2007). Scientific Progress: Beyond Foundationalism and Coherentism. *Royal Institute of Philosophy Supplement,* 61: 1-20.

Damerow, P. (1996). *Abstraction and Representation: Essays on the Cultural Evolution of Thinking. Boston Studies in the Philosophy of Science, v. 175*. Translated by R. Hanauer. Dordrecht: Kluwer Academic Publishers.

Engels, F. (1987). “The Part Played by Labour in the Transition from Ape to Man.” Pp. 452-464 in *Dialectics of Nature* in *Karl Marx Frederick Engels Collected Works, Volume 25*. Edited by David McLellan. Moscow: Progress Publishers. First published in 1896 in the magazine *Die Neue Zeit* (Jahrgang XIV, Bd. 2, 1895-1896, Nr. 44: 545-54).

Feeney, J. (1999). “Development of High Resolution NMR Spectroscopy as a Structural Tool.” Pp. 199-216 in *Invisible Connections: Instruments, Institutions, and Science.* Edited by R. Bud and S. E. Cozzens. Bellingham: SPIE Optical Engineering Press.

Gerson, E. M. (2014). “Some Problems of Analyzing Cultural Evolution.” In *Developing Scaffolds in Evolution, Culture and Cognition.* Edited by L. R. Caporael, J. R. Griesemer and W. C. Wimsatt, Cambridge, MA: MIT Press.

Grayson, M. A. (2004). “Exploring the Evolutionary Relationship Between Computers and Mass Spectrometry.” *American Society for Information Science and Technology,* 190-202.

Hacking, I. (1983). *Representing and Intervening.* Cambridge, UK: Cambridge University Press.

Harman, O. & Dietrich, M. R. (2018). *Dreamers, Visionaries, and Revolutionaries.* Chicago: The University of Chicago Press.

Hempel, C. G. (1966). *Philosophy of Natural Science*. Englewood Cliffs, N.J.: Prentice-Hall.

Hull, D. L. (1988). *Science as a Process*. Chicago: The University of Chicago Press.

Humphreys, P. (2004). *Extending Ourselves.* Oxford: Oxford University Press.

Kitcher, P. (1993). *The Advancement of Science.* Oxford: Oxford University Press.

Kletzl, S. (2014). "Scrutinizing Thing Knowledge." *Studies in History and Philosophy of Science*, 47: 118-123.

Kuhn, T. S. (1996). *The Structure of Scientific Revolutions (3rd ed.).* Chicago: University of Chicago Press. First edition 1962.

Landes, D. S. (1987). "Techniques et révolutions scientifiques : l'exemple de la mesure du temps. » *History and Technology,* 4: 531-541.

—(2000). *Revolution in Time (revised and enlarged edition)*. Cambridge, MA: Harvard University Press. First edition 1983.

Lefèvre, W. (2005). "Science as Labor." *Perspectives in Science,* 13: 194-225.

Marcum, J. A. (2018). "Revolution or Evolution in Science? A Role for the Incommensurability Thesis?" Pp. 155-174 in *The Kuhnian Image of Science.* Edited by M. Mizrahi. London: Rowman & Littlefield International.

Marx, K. and Engels, F. (1978 [1845-6]). *The German Ideology*. In *The Marx-Engels Reader, 2nd Edition.* Edited by R. C. Tucker. New York: W. W. Norton & Co.

Morris, P. J. T., ed. (2002). *From Classical to Modern Chemistry: the Instrumental Revolution* Cambridge: Royal Society of Chemistry in association with the Science Museum, London and the Chemical Heritage Foundation.

Mizrahi, M. (2010). *What is Scientific Progress?* Ph.D. Dissertation. The City University of New York.

— "What is Scientific Progress? Lessons from Scientific Practice." *Journal for General Philosophy of Science*, 44: 375-390.

Nier, K. A., Yergey, A. L., and P. J. Gale., eds. (2016). *The Encyclopedia of Mass Spectrometry, Vol. 9, Part A: The Development of Mass Spectrometry.* Waltham, MA: Elsevier.

Niiniluoto, I. (2015). "Scientific Progress." In The Stanford Encyclopedia of Philosophy. Edited by E. N. Zalta.

Novack, G. (1980). *Understanding History, 3rd Edition.* Pathfinder Press.

Okasha, S. (2002). *Philosophy of Science.* Oxford: Oxford University Press.

Olby, R. (2003). "Quiet Debut for the Double Helix." *Nature*, 421: 402-405.

Popper, K. (1985). "Knowledge Without Authority." Pp. 46-57 in *Popper Selections*. Edited by D. Miller. Princeton: Princeton University Press. Part of a lecture read before the British Academy in 1960.

Reinhardt, C. (2006). *Shifting and Rearranging.* Sagamore Beach: Science History Publications/USA.

Renzi, B. G. & Napolitano, G. (2018). « The Biological Metaphors of Scientific Change." Pp. 177-190 in *The Kuhnian Image of Science.* Edited by M. Mizrahi. London: Rowman & Littlefield International.

—(2011). *Evolutionary Analogies: Is the Process of Scientific Change Analogous to the Organic Change?* Newcastle: Cambridge Scholars Publishing.

Resnik, D. B. (2000). "A Pragmatic Approach to the Demarcation Problem." *Studies in History and Philosophy of Science*, 31(2): 249-267.

Sarton, G. (1927). *Introduction to the History of Science, vol. 1*. Carnegie Institution of Washington. 1962 reprint.

Shapere, D. (1982). "The Concept of Observation in Science and Philosophy." *Philosophy of Science*, 49(4): 485-525.

Serum, J. W. (2016). "Reflections on the History of Computers in Mass Spectrometry." Pp. 189-196 in *The Encyclopedia of Mass Spectrometry, Vol. 9, Part A: The Development of Mass Spectrometry*. Edited by K. A. Nier, A. L. Yergey, and P. J. Gale. Waltham, MA: Elsevier.

Sève, L. (2014). *Penser avec Marx aujourd'hui, Tome III : « La philosophie » ?* Paris : La Dispute.

Smith, A. M. (2015). *From Sight to Light: The Passage from Ancient to Modern Optics*. Chicago: The University of Chicago Press.

Smith, G. E. (2010). "Revisiting the Accepted Science: the Indispensability of the History of Science." *The Monist*, 93(4): 545-579.

Spelda, D. (2017). "The Role of the Telescope and Microscope in the Constitution of the Idea of Scientific Progress." *The Seventeenth Century,* October: 1-20.

Steinhauser, T. (2014). *Zukunftsmaschinen in der Chemie.* Frankfurt am Main: Peter Lang GmbH.

Sturchio, J. L. & Thackray, A. (1985). "Carl Djerassi." Interview. Philadelphia: Chemical Heritage Foundation.

van Fraassen, B. (1980). *The Scientific Image.* Oxford: Oxford University Press.

Van Helden, A. (1983). “The Birth of the Modern Scientific Instrument, 1550-1700.” Pp. 49-84 in *The Uses of Science in the Age of Newton.* Edited by J. G. Burke. Berkeley: University of California Press.

Zewail, A. H. Femtochemistry: Atomic-Scale Dynamics of the Chemical Bond Using Ultrafast Lasers (Nobel lecture). *Angewandte Chemie International Edition,* 39(15): 2586-2631.