

# 4 Encapsulating Knowledge

The true instrumental method of analysis requires no reduction of data to normal pressure and temperature, no corrections or computations, no reference to correction factors nor interpolation on nomographic charts. It indicates the desired information directly on a dial or counter and if it is desired to have the answer printed on paper—that can be had for the asking. It is strange and difficult to comprehend why the last few steps have not been taken by the analyst in bringing his instruments to this stage of perfection. They are minor details, the absence of which in his motor car, office equipment, or telephone he would not tolerate for a moment.

RALPH MÜLLER “Instrumentation” (January 1947)

## 1. MEASURING INSTRUMENTS

During the 1940s, innovations in spectrometry brought certain applications of spectrometric instruments to the stage of perfection described above by Ralph Müller. Through the wedding of photomultiplier tube electronics with commercial emission spectrographs, analysts in several economically important industries, such as magnesium, steel, and aluminum, could in minutes determine the percentage quantities of various elements in “the melt.” The information was available fast enough to direct the production of the metal (Saunderson et al. 1945; Hasler et al. 1948).

In a general sense, analytical instruments, such as the spectrometer, tell us something about a “specimen”; they measure it in some manner by generating a signal through an interaction with it. This signal undergoes a series of transformations that ultimately results in information for those using the instrument.

Measuring instruments, from relatively simple rulers to complex spectrometers, are ubiquitous in science, technology, and, indeed, many aspects of daily life. Measuring instruments present a third kind of thing knowledge. They are not models, although their operation requires them to include material representations of the spaces of possible measurement outcomes—the scale on a rule, for example. Neither are they instances of working knowledge, although again their operation requires reliable performance—working knowledge. A thermometer must produce “the same” phenomenon—the mercury must rise to the same height in its tube when subjected to the same conditions. It is something that “surely will happen to everybody in the living future who shall fulfill certain conditions,” in Peirce’s words. Measuring instruments are a kind of hybrid, combining model and working knowledge.

It is common to say that measuring instruments “extract information” from a specimen (Sydenham 1979; Taylor et al. 1994; Rothbart and Slayden 1994). I think it more philosophically prudent to say that an instrument interacting with a specimen generates a signal, which, suitably transformed, can then be understood as information about the specimen. There are two reasons for this. The first is methodological. It is vital to recognize that instruments interacting with specimens create phenomena and in so doing, these instruments constitute working knowledge. Putting aside any interpretation of the meaning of an instrument’s output, the behavior of the instrument has to be public, regular, and reliable; these

are necessary constituents of valid measurement. But these necessary features also are the sufficient features of working knowledge. Measurement requires our ability, as Ian Hacking puts it, “to produce, in laboratory conditions, a stable numerical phenomenon over which one has remarkable control” (1983a, p. 237). The second reason is metaphysical. Information is semantic in nature; it carries meaning and hence eliminates possibilities. To understand the signal as information, it therefore needs to be placed in a field of possibilities. Recognizing such a field of possibilities requires thought, a contribution of the human instrument maker and user.

Instrumentally encapsulated knowledge, the kind of thing knowledge presented in a measuring instrument, consists of the material integration of the two kinds of thing knowledge considered in chapter 2 and chapter 3. At a fundamental level, measurement requires a phenomenon—the working knowledge of chapter 3. Here is the signal generated by the instrument interacting with the specimen. But it is a field of possibilities, typically—although not always—understood theoretically, that drives the choice of signal generated and the transformations that are made to the signal as it is rendered “a measurement.” These choices, then, encapsulate in the material form of the instrument a representation of this field of possibilities—model knowledge. When the integration of both forms of material knowledge is done seamlessly, the instrument appears to extract information from nature.

This much is the main message of this chapter. But details of how this kind of encapsulated knowledge can be accomplished puts informative and persuasive flesh on these bare bones. To this end, I describe how the “direct-reading” spectrometer encapsulated knowledge, primarily from spectrochemical analysis and electronics, to make its particular kind of chemical measurement possible.

## 2. ENCAPSULATING ANALYSIS

Direct-reading spectrometers were developed simultaneously and independently in several places during the mid 1940s. Several academic laboratories looked into the possibility of using photosensitive electron tubes to read spectra (Duffendack and Morris 1942; Rank et al. 1942; Dieke and Crosswhite 1945). Laboratories in two industrial settings produced what ultimately became the two first commercially available direct-reading spectrometers. M. F. Hasler and his co-workers at Applied Research Laboratories (ARL) developed a direct reader they dubbed the “quantometer” (Hasler and Dietert 1944).<sup>1</sup> ARL’s quantometer was developed in the mid 1940s with the support of the Aluminum Company of America (ALCOA), where quantometers found their first use. By the late 1940s, ARL was marketing the quantometer for general use in spectrochemical analysis in metals manufacturing (Hasler et al. 1948). Independently and simultaneously, Jason Saunderson and his co-workers at the Dow Chemical Company developed their own direct-reading spectrometer (Saunderson et al. 1945; Saunderson and Hess 1946). Initially developed for internal use in Dow’s production of magnesium alloys, the Saunderson direct reader ultimately was licensed to Baird Associates

for commercial development, manufacture, and sale (Carpenter et al. 1947).<sup>2</sup>

Direct-reading spectrometers depend on the ability of their makers to put in material form the knowledge and skills necessary for reliably making such analytical measurements. In the language of technology studies, these instruments “de-skill” the job of making these measurements. They do this by encapsulating in the instrument the skills previously employed by the analyst or their functional equivalents. These skills include a knowledge of the “spectral fingerprints” of the elements of interest, and of which of these spectral lines are best used for quantitative measurements. They include the accurate normalizing of the spectral lines involved, as to both place and intensity. They include reading the intensity of the spectral lines and determining percentage concentration from spectral intensities. They include encoding and displaying this information. The instrument is “skilled” as the analyst’s job is “de-skilled.”

The development of the direct-reading spectrometer is interesting for a variety of reasons. For my purposes here, 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 (see below, § 4, esp. fig. 4.5). Working knowledge is built into the instrument, again in several ways, including the use of a diffraction grating to disperse light into constituent wavelengths (see below, § 3, esp. fig. 4.1). Theoretical knowledge is also built into the instrument, of which the theory of condenser discharge is a particularly clear example (see below, § 4, last paragraph). 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.

Yet this description can be misleading. Here I analyze the instrument’s unified operation into epistemic parts. But the whole is not simply the sum of the parts. One cannot enumerate so many distinct items of knowledge of these various different kinds. The instrument presents an epistemic synthesis, seamlessly joining representation and action to render information. This synthesis does and must take place in a material medium.

### 3. THE INSTRUMENTAL BACKGROUND OF THE DIRECT READER

A spectrograph starts out with a light source (which might, for example, be the sun, the discharge of an electric arc, or a candle flame). The light is passed through a narrow slit; the different wavelengths are separated spatially by a dispersing device, such as a prism or a grating; and the dispersed light is then focused on some recording or observing surface. When a *photographic* record of the dispersed light is made, the instrument is called a *spectrograph*;

when the dispersed light is focused on an eyepiece, it is called a *spectroscope*. Direct readers, which produce concentration readouts, are called *spectrometers*.

Passing the light through a slit produces an image of a sharply defined line—the slit. By dispersing this light in two dimensions as a function of wavelength, a spectrometer produces multiple images of the entrance slit, each at a single wavelength. The placement of a slit image is a function of wavelength; one can determine the wavelengths of light present in the light source by noting the placement of the slit images.<sup>3</sup>

The main function of either a prism or a grating is to *disperse* the different wavelengths of light. Within an instrument, dispersion can be measured in terms of the number of angstroms per millimeter into which the element spreads out the light (1 angstrom, Å, is  $1 \times 10^{-8}$  cm). A grating spectrograph with a dispersion of 5 Å per mm spreads light with wavelengths that differ by 5,000 Å across one meter.

For the spectrochemical analysis of metals—among other analytical concerns—grating spectrographs have many advantages over prism spectrographs. There is an interesting story behind the development and acceptance of grating spectrographs (for some of which, see chapter 10). However, for current purposes, I need only note that by the end of the 1930s, commercial grating spectrographs suitable for quantitative analysis—that is, with adequate precision, dispersion, and resolving power—were available (D. Baird 1991). These instruments were modified to make direct readers.

The story behind the development of high-quality gratings is of some interest in the present context. A grating is a surface into which many parallel grooves have been scratched, or “ruled”—more than 30,000 per inch in some gratings. In “transmission gratings,” the grooves are, in fact, slits through the grating material. In the more common “reflection gratings,” the grooves are grooves on a reflective surface.

A grating separates the different wavelengths of light because of the phenomenon of diffraction. Suppose a beam of light is passed through a screen with a narrow slit and then through a second screen with several closely spaced slits—a transmission grating. A series of images of the original slit can be focused on a target screen. This happens because the light waves emanating from each of the slits in the transmission grating interfere with one another. The “interference pattern” of images of the slit has a central bright line. On either side of this bright line are dark areas where the wave fronts cancel each other out. Then there are two more bright lines—images of the slit where the wave fronts augment each other—called “first-order” images of the slit. On either side of the first-order images, there are second-order images, and then third-order images, and so on. The distance from the central bright line to these other images is a function of wavelength. Given information about the grating, one can determine wavelength by measuring the distance from the central slit image to the first-, second-, third-, etc., order images (see fig. 4.1).

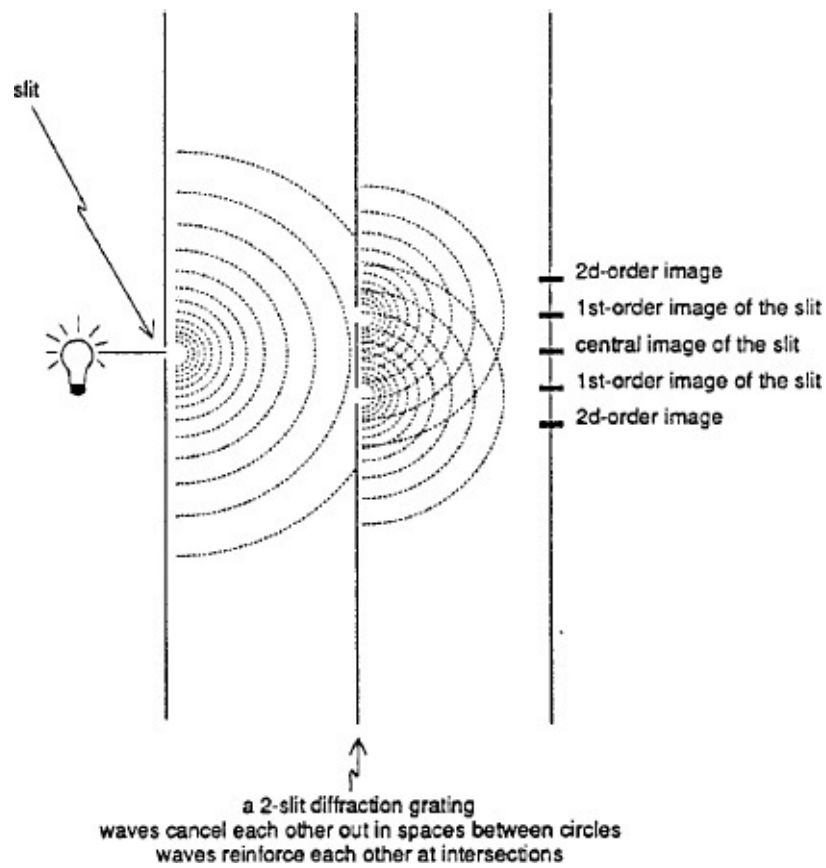


FIGURE 4.1 Diffraction schematic (1991)

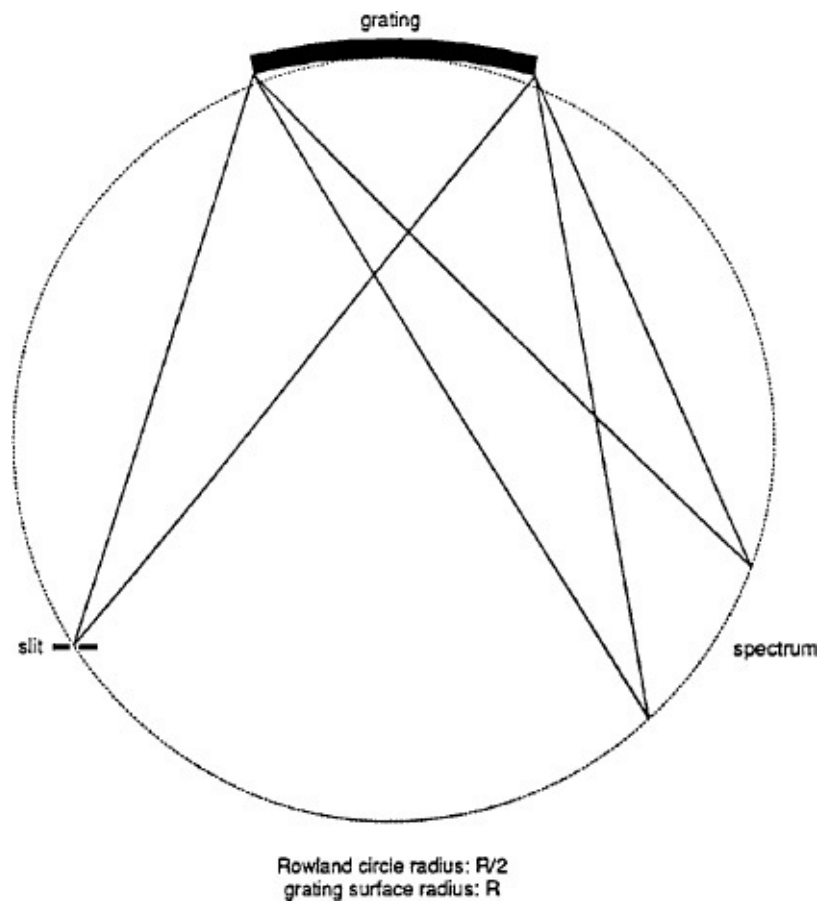


FIGURE 4.2 Rowland circle (1991)

In 1882, Henry A. Rowland developed both a device for making gratings on concave surfaces and the theory of concave grating spectroscopes (Rowland 1882, 1883). By appropriately using a concave grating, one need not have additional mirrors or lenses to focus the light; the concave grating can both disperse and focus the light. This has several advantages. In the first place, it allows for a simpler optical path, with fewer elements to align. It also produces a brighter image, since there are fewer optical elements to absorb or deflect the light. Finally, it cuts down on the amount of scattered light, or “noise.” Rowland showed that if a grating were ruled on a surface with a radius of curvature  $R$ , then, by placing the slit and the grating on a circle with radius  $R/2$ —the “Rowland circle”—the spectrum produced would be in focus on the circumference of this circle (fig. 4.2). For many years, Rowland’s “ruling engine” was the only source of gratings of high enough quality to compete effectively with prisms for spectral analysis (Rowland 1902, pp. 691–97).

Spectroscopy works as a method for chemical analysis because each element emits its own characteristic wavelengths of light. Thus, by looking at the wavelengths of light emitted, one can analyze the nature of the elements present in the light source. This has been known since the work of Gustav Kirchhoff and Robert Bunsen in the 1860s (Kirchhoff and Bunsen 1860a, 1860b, 1861a, 1861b), and prism spectroscopes had been commercially available since about that time (Bennett 1984). But spectroscopy did not become a common method of chemical analysis until the 1930s.

There were many reasons for this. In his 1941 historical discussion of spectrochemical analysis, Frank Twyman notes that some elements would not produce spectra when excited in a flame; they required the higher energies supplied by an electric arc, but until this century electric current was not a readily available commodity for a research chemist. Photographic methods had to be further developed so that the results of a spectrum analysis could be recorded for later careful study. The maze of spectrum lines produced by any slightly complicated material was such that “wet” methods of analysis seemed easier. Wavelength tables of common spectrum lines for the elements were not available until well into the first quarter of the twentieth century (Twyman 1941, pp. 34–36; Harrison 1939b). Indeed, the spectroscope was primarily a tool of physicists studying optics and was built to be maximally adjustable to allow the greatest amount of optical experimentation. “[S]ummarizing all the mentioned investigations, I come to the conclusion that quantitative spectroscopic analysis has shown itself as impractical,” Heinrich Kayser asserted around 1910 in volume 5 of his *Handbuch der Spectroscopie* (8 vols., 1900–1932; quoted in Meggers and Scribner 1938, p. 3).

All of this began to change during the 1920s. Electricity had become readily available, and photography was by then widely used by researchers. Indeed, Eastman Kodak made special emulsions for spectrographic work, on both glass plates and 35 mm film. The quantum theory began to make some sense of the maze of spectrum lines, and the Depression produced a group of workers willing to grind out the MIT wavelength tables of the elements (Harrison 1939a; Twyman 1941, pp. 34–36; Laitinen and Ewing 1977, p. 131). Once analysts began to use and gain experience with spectrographic analysis, the advantages of speed and sensitivity became

increasingly apparent.

Metals turned out to be an important proving ground for spectrochemical analysis. Metals are hard to analyze by classical wet methods. Within the metals industry, speed was vital. Wet analyses could take days, whereas spectrographic analyses would take hours. By 1944, direct readers performed in a matter of minutes analyses that had earlier taken weeks (Laitinen and Ewing 1977, pp. 116–17).

#### 4. DIRECT READING

At a general level, quantitative spectroscopic analysis works because the greater the presence of a given element in the sample, the more intense that element's spectral lines will be. Thus, with photographic instruments, an analyst determines the amount of an element in a sample by examining the intensity—or darkness—of the various spectral lines recorded on a photographic plate or film. However, many variable conditions in the production of the light used for a given analysis make this direct use of line intensities problematic for measuring concentrations. The conditions of the arc or spark producing the light can vary enough that line intensities for the same concentration will vary as well. Other sources of variability in the instrument and sample preparation also contribute to variations in line intensity not correlated with variations in concentration.

A significant step came in 1931 with Walther Gerlach and Eugen Schweitzer's "internal standard method" (Gerlach and Schweitzer 1931, ch. 5). Here, instead of directly measuring a line's intensity, one measures the ratio of an unknown's line's intensity to the intensity of a major constituent in the mixture. Thus, to determine the concentration of calcium, say, in magnesium alloy, a magnesium line would be used as the "internal standard;" the intensity of a calcium line would be measured in comparison to the intensity of a magnesium "standard" line. Since all of the exogenous factors affecting line intensity affect both the internal standard line and the line for calcium, the relative intensity of these lines remains unchanged by these exogenous factors. Spectroscopists plot a "working curve" of the logarithms of the ratio of intensities of the unknown's line— $I_x$ —to the internal standard's line— $I_o$ —against the logarithm of the concentration of the unknown. The ratio of the intensities of these lines can then be used to measure—albeit indirectly—the concentration of the unknown (see fig. 4.3).

The significant technical development that made the direct reader possible was the invention of photomultiplier tubes. The initial motivation for developing photosensitive tubes came from the television industry (White 1961, p. 15). By 1940, scientists at RCA had developed a photosensitive tube that would amplify the initial electric response to the light signal 2,000,000 times (Zworykin and Rajchman 1939; Rajchman and Snyder 1940). With the advent of the war, these tubes found a wide variety of uses, from checking for defective fuses in grenades (White 1961, p. 143) to generating jamming signals to counteract enemy radar (Saunderson 1997).

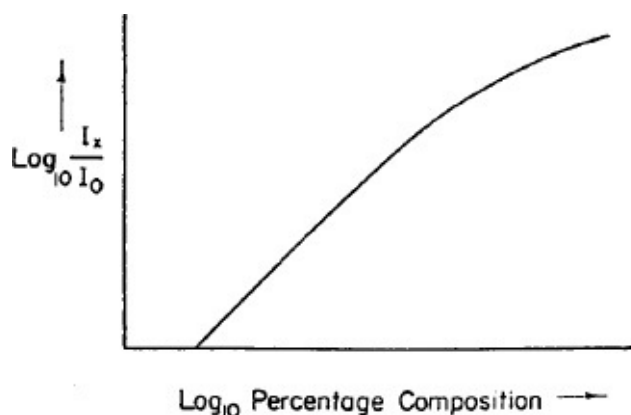


FIGURE 4.3 Spectral analysis working curve (from Harrison et al. 1948). Reprinted by permission of Pearson Education.

These tubes achieve their amplification through the carefully controlled phenomenon of secondary emission. A light beam striking the initial cathode causes it to emit electrons. These electrons are drawn to (or “electrostatically focused on”) a second “dynode.” Their impact on this dynode produces more secondary emissions; between four and five new electrons are produced for each electron impacting the dynode. These are drawn to a third dynode, and further amplification. The process continues for a total of nine stages, achieving a total amplification of more than 2,000,000 (Rajchman and Snyder 1940) (see fig. 4.4).

The operating characteristics of these tubes make them ideal for use in a direct-reading spectrometer. They are extremely sensitive—due, of course, to their high degree of amplification:

A spectral line so weak as to require an exposure of several hours with a photographic plate will, when measured with a multiplier tube, give a current of the order of 0.01 microampere, sufficient to give a good sized deflection with a sensitive galvanometer. Thus, in the application of electron multipliers to spectrochemical analysis, the photocurrents are usually of such size as to require no further amplification. (Saunderson 1947, p. 25) Also, the tubes respond linearly to increases in light intensity (Rajchman and Snyder 1940, p. 22). Another nice feature of these tubes is that—if not mistreated—they can be used indefinitely (Saunderson 1947, p. 25).



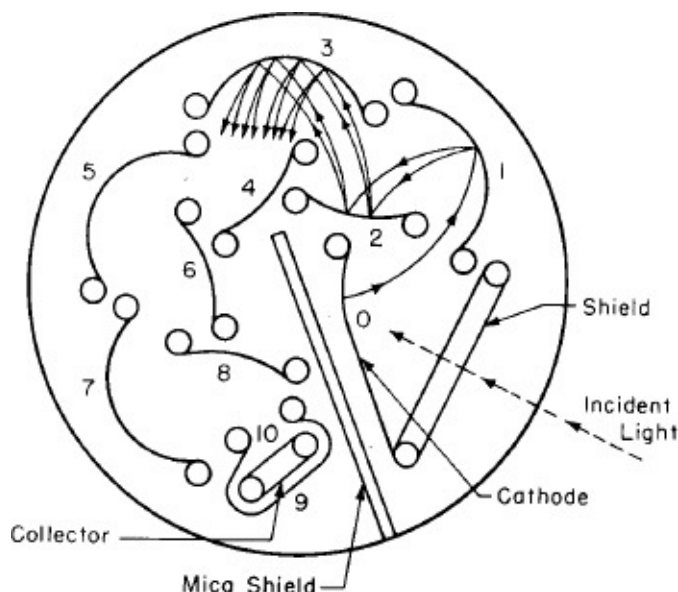


FIGURE 4.4 Schematic diagram of a photomultiplier tube (from Saunderson 1947). Reprinted by permission of the Materials Information Society.

In a direct-reading spectrometer, instead of recording light on photographic film, light is used to produce currents in photomultiplier tubes. In the Dow direct reader, “exit slits” were positioned on the Rowland circle to collect light of predetermined wavelengths—those useful for determining concentrations of preselected elements of interest. Thus, an exit slit was positioned to collect light at 3,934 Å—a “calcium line.” Currents produced in the photomultiplier tubes behind these exit slits would charge condensers, one condenser for each tube. The amount of charge accumulated in a given condenser, then, would reflect the amount of light that reached that condenser’s photomultiplier tube.

To determine concentrations by the internal standard method, electronics were used to determine the relative amounts of charge accumulated on the internal standard’s condenser as compared to the unknown element’s condenser (see fig. 4.5).

During the sparking, charge is accumulated on the condensers connected to each exit slit’s photomultiplier tube. In figure 4.5., condenser C<sub>2</sub> accumulates charge produced by the magnesium—Mg—reference or “internal standard” photomultiplier tube, while C<sub>1</sub> accumulates charge for zinc—Zn—the unknown element’s tube. The amount of time it takes the condensers to discharge, then, determines relatively how much charge each condenser has accumulated.

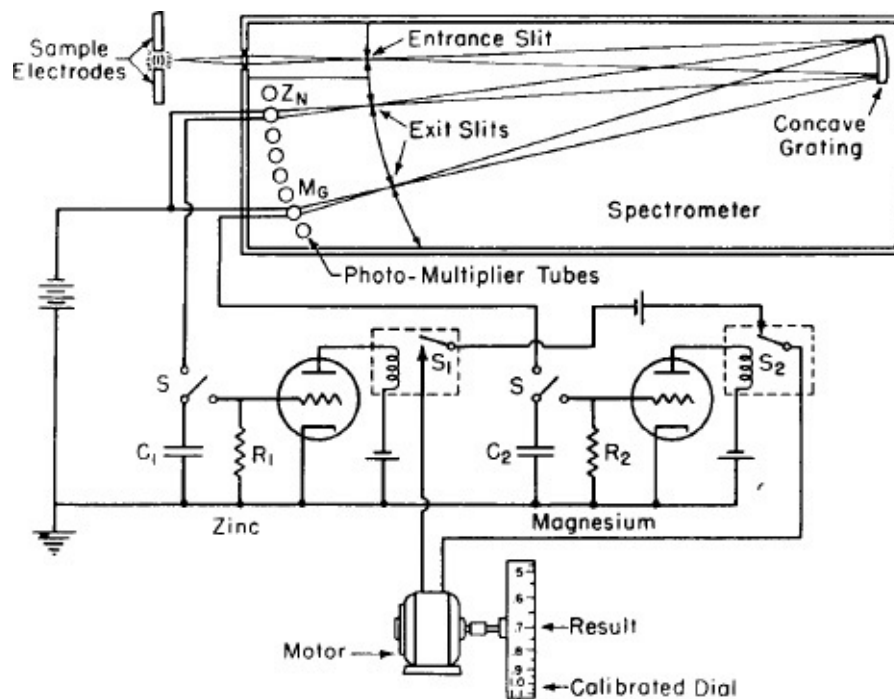


FIGURE 4.5 Schematic diagram of a direct-reading spectrometer (from Saunderson 1947). Reprinted by permission of the Materials Information Society.

The theory of condenser discharge allows a fairly straightforward determination of the relationship between the ratios of the light intensities reaching their respective photomultiplier tubes (Saunderson et al. 1945, p. 682). One can show that the difference in the amount of time it takes the two condensers to discharge,  $\Delta t$ , is proportional to the ratio of the logarithms of the intensities of the light hitting the two relevant photomultiplier tubes.<sup>4</sup> What is needed to make a working instrument, then, is a way

$$E = E_0 e^{-t/RC}$$

Given that the two condensers,  $C_1$  and  $C_2$ , for reference and unknown, have accumulated voltages of  $E_1$  and  $E_2$  respectively, the time each takes respectively—to measure the relative time of discharge and to have this measurement connected to a scale that is calibrated for the relationship between light intensity and concentration.

## 5. DOW CHEMICAL AND DIRECT READING

In his informative history and assessment of the analytical instrument industry, Frederick White cites six factors that drove the development of instrumentation: the military, universities, electronics, government, nonphysical sciences, and patent and copyright law (White 1961, ch. 5). Although all of these contributed significantly, the importance of the role played by the military, particularly in the context of World War II, cannot be overestimated.

World War II interrupted the practice in the United States of importing materials and instruments from Europe, which had already begun to erode during World War I. The demands

of the war for various materials, from aircraft-grade aluminum and magnesium alloy to rubber, resulted in a massive effort to find new sources of raw materials or the means to manufacture synthetic substitutes. In all such cases, instruments were needed to ascertain the properties of the new materials:

The millions of crystals needed for special war communications provided a tremendous impact on x-ray diffraction; and the synthetic rubber program, as well as the need for penicillin, provided important stimuli in the development of infrared. Even the shortage of India mica had its effect in the development of superior electrical components. The search for substitute, synthetic, or new materials was one of the major factors which made scientists aware of their complete dependence on instrumentation. (White 1961, p. 41)

The result was a tremendous increase in demand for analytical instruments. Baird Associates, one relatively small instrument-making firm, saw its revenue jump from \$27,486 in 1942 to \$353,645 in 1946 (1953) (see chapter 10, table 10.1). World War II was good to the fledgling analytical instrumentation industry.

The exigencies of the war called for greater efficiency. Chemical analyses were needed more rapidly, at lower cost, and were conducted by less highly trained personnel. This accelerated the shift from wet chemical techniques toward instrumental techniques:

It also saw a shift in scientific thinking, a greater emphasis being given to a physical rather than to a chemical approach. Metallurgy was transformed from a pathological to a clinical or predictive science, as it was necessary to ascertain in advance the operational behavior of crucial parts under various conditions of stress. This demanded a more intimate understanding of structural materials—by the use of new instrumental techniques. An immense saving in time and manpower was effected by spectrographic analyses, and spectroscopy was indispensable for supplying the aluminum needs of the wartime aircraft industry. (White 1961, p. 41)

It was in this context that Jason Saunderson went to work for the Dow Chemical Company in 1939. He had received his Ph.D. in physics from the University of Michigan at the age of twenty-six.<sup>5</sup> His dissertation, under the supervision of D. S. Duffendack, focused on the scattering of electrons by thin foils of metal. However, he had worked in Ralph Sawyer's spectroscopy lab (for \$.50 an hour) to earn extra money. It was this experience that paved the way to his being hired to work in Dow's spectroscopy lab.

By 1943, Dow was producing large quantities of magnesium alloy for airplane construction. Calcium was a critical element in magnesium alloy. If made with too much calcium, the metal would not roll properly; if made with too little, the metal would burn when welded. The tolerance was very narrow. Without a means to determine the amount of calcium in the melt before the alloy was poured, a large quantity of metal had to be scrapped. Wet

chemical methods were much too slow, as were photospectrographic methods. Saunderson conceived a way to use photomultiplier tubes to yield information on concentrations in the melt virtually immediately.

Work began in January 1944, and an operational instrument was up and running by September. In the meantime, Dow had gone ahead—on the unverified promise of a successful instrument—and built a spectroscopy lab in the basement of the foundry. This required a considerable investment, for the lab had to be air-conditioned—to control both temperature (for optical stability) and humidity (for electronic reliability)—and connected to the foundry floor by pneumatic tubes. Interviewed in 1997, Saunderson guessed that Dow risked more than \$50,000 on his “32-year-old’s” idea.

## 6. DIFFICULTIES

As is always the case, and as figure 4.6. suggests, the path from idea to working instrument involved a variety of difficulties. Here I briefly consider four areas that posed problems—optical, electronic, mechanical, and material.

Figure 4.6. shows that a significant number of additional optical elements had to be added to fit the photomultiplier tubes physically with the exit slits. An aluminum line—3,944 Å—was only slightly more than a millimeter from a calcium line—3,934 Å—as the instrument dispersed light to 8 Å per millimeter (Saunderson et al. 1945, pp. 683–84). However, these difficulties, subtle as their optical solution had to be, were not new or unusual, although line choice and photomultiplier tube sensitivity were.

One might think that the easy solution to the aluminum/calcium crunch would be to choose different lines that are further apart. However, the lines used were dictated by the behavior of the photomultiplier tubes. In a “photo”-spectrographic instrument, weak lines—lines of low light intensity—were preferred to strong lines. Strong lines tended to be “hollow,” appearing almost as two lines. The hollowness was the result of reabsorption of light in the spark. The most intense radiation came from the hottest—central—part of the spark. However, as this light passes through the cooler parts of the spark, some of its energy is reabsorbed there. A hollow line is not ideal for photographic intensity reading. In contrast, with a direct-reading instrument, strong lines were preferred because, while sensitive, the photomultiplier tubes worked more accurately with higher-intensity light.

The use of photomultiplier tubes posed a second problem. The cathodes that initially received the light in the photomultiplier tubes turned out to be finicky. Saunderson and his co-workers studied the relationship between where light hit the initial cathode and the output of the tube. The result is shown in figure 4.7. (Saunderson et al. 1945, p. 685). Curves (a) and (b) in figure 4.7. show how slight variations where the tube’s cathode received light resulted in large variations in the tube’s output. Curve (c) in figure 4.7. was obtained when a ground quartz plate was used to “fuzz” the line over the cathode to produce stable average sensitivity.

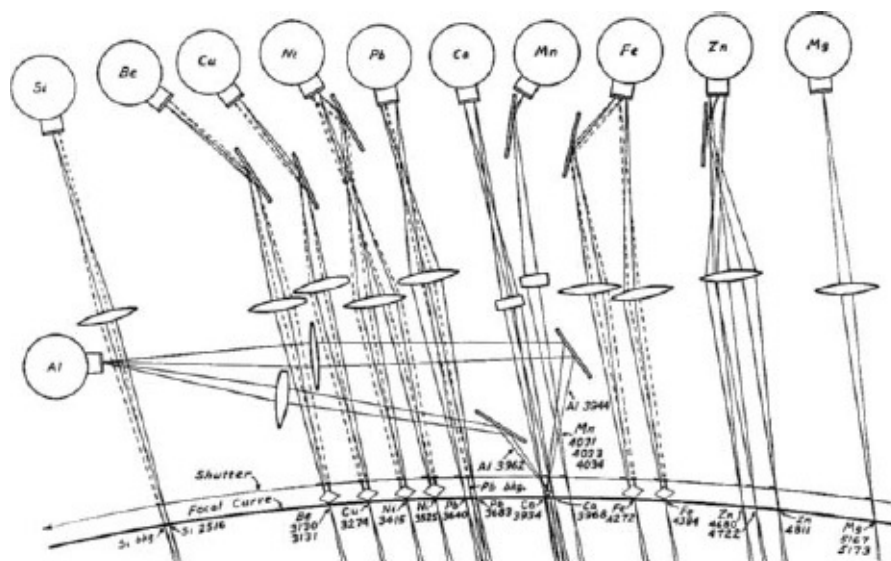


FIGURE 4.6 Direct-reading spectrometer optics diagram (from Saunderson et al. 1945). Reprinted by permission of the Optical Society of America.

Where Saunderson brought optical expertise to the direct reader project, V. J. Caldecourt brought electrical expertise. He developed a way to solve the problem of dark current. Photomultiplier tubes produce current when not illuminated, called “dark current.” It was this property of the tubes that made them useful in the production of radar-jamming signals. However, in spectrochemical analysis, dark current is noise, a source of error. To control for this, Caldecourt devised a system for subtracting out the dark current contribution:

During the sparking period, the reversing relays are operated periodically with a cam system. The relays are reversed once a second, and synchronized with this reversing is the motion of the shutter [allowing light to enter the spectrometer]. With the shutter in position to pass the spectral lines, the relays are in one position, and with the shutter in the background position, the relays are reversed. Thus the condensers are alternately charged with the photo-current from the intensity of the line + background and then discharged with the photo-current from the intensity of the background.... It will be noticed that this method eliminates the effect of dark current upon the final charge on the condenser. (Saunderson et al. 1945, pp. 687–88)

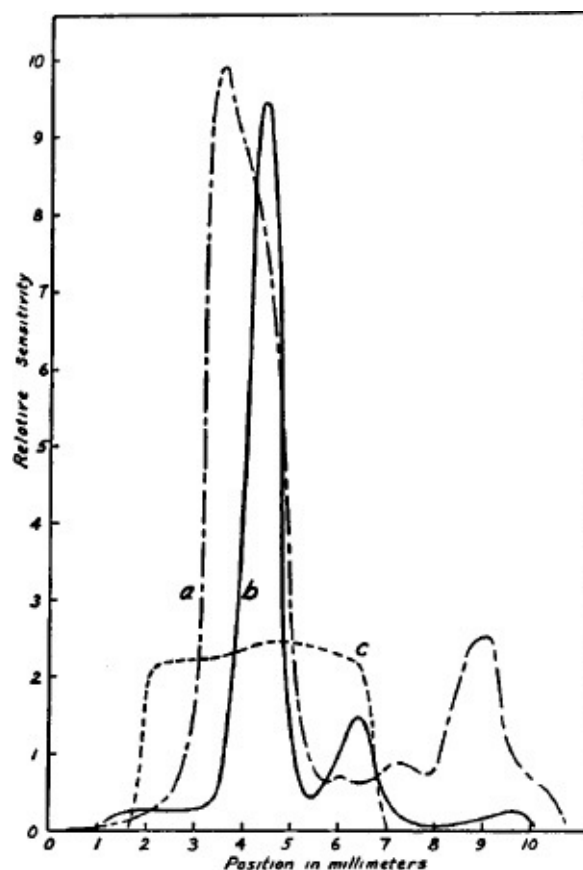


FIGURE 4.7 Photomultiplier tube sensitivity graph (from Saunderson et al. 1945). Reprinted by permission of the Optical Society of America.

The Saunderson direct-reading spectrometer measured the charge that had accumulated on the condensers by determining how long it took the condensers to discharge. Initially, a “quick and dirty” approach had this information recorded by a line drawn on electrical marking paper advancing at an even rate for the time of condenser discharge. Line lengths were read manually against calibrated scales. This proved cumbersome and time-consuming.

In short order, this approach was replaced by rotating drums: a drum with a calibrated scale on it would rotate for the time of discharge. The trick was to control drum rotation. An electric motor drove a shaft continuously. Shaft rotation was connected to recording drums by means of pulleys and “dental cloth” belts. While the drive shaft turned continuously, each drum was allowed to rotate only when “its” condenser was discharging. Drum rotation was stopped by snagging the dental cloth with a steel phonograph needle controlled by relays sensing the discharge of the condensers.

Finally, Saunderson had to obtain photomultiplier tubes. These tubes had high war priority because of their use in radar jamming and were thus difficult to obtain. However, as Saunderson relates the story, Dow persuaded the government that the control of magnesium alloy production was a high enough priority that a supply of tubes was also made available for this project.

## 7. A SUCCESS STORY

Saunderson's instrument was a great success. Within a month of its installation, it was routinely analyzing 4,000 samples a month. In 1952, Saunderson was awarded the Willard H. Dow Memorial Award for Research in Magnesium for his work developing the direct reader. The award citation reads: "This new tool has been a very significant contribution to the rapid advancement of magnesium technology and represented pioneering work in the whole field of analytical techniques" (Nelson 1952).

A company publication, the *Dow Diamond*, published an article about the direct reader in March 1946. The article tells a story from the foundry floor:

"Will you send this sample down?" the older man asked his companion, ...

"Sure thing," the new employee answered, carefully breaking the glass from around the solid cylinder of grayish-white magnesium. He... placed the sample cylinder inside... a pneumatic tube carrier....

..."Why do you take so many samples for analysis?"

"Well, the hard thing to understand is that in making magnesium alloys, you just don't add one part of aluminum, two parts of calcium, and three parts of something else. Those elements are put in there in very close amounts, accurately measured.... And while this molten mag is in the pots, it's changing those percentages, so on some alloys we run tests every 15 minutes. The alloys are changing because the flux and metal react all the while, so if tests aren't run often, we'll be pouring a batch of metal that wouldn't pass inspection. And you know what that means."

The new man looked a little puzzled, "Not exactly." ...

"There was a time when you'd have learned in a day what rejected metal means. It had to be melted, alloyed again, analyzed further and finally cast again. We were running as high as 15 percent rejected metal for a while. Then we got even closer specifications on a special mag for aircraft parts, which would have made rejects even higher. But about that time we got this new analysis machine, and since then we get the tests made in a few minutes, where it used to take half an hour and even longer. That's what caused a lot of the rejects—that half hour when percentages were changing all the while. That's all different now—with this new machine ..."

Before he could finish his sentence there came the clatter of the carrier as it fell out of the pneumatic tube into a waiting basket. (Dow Chemical Company 1946, p. 2)

The title of the *Dow Diamond* article is revealing too: "Mechanical Brain for Magnesium Analysis." Saunderson's instrument did not simply measure molten alloy for needed information. It took care of all the previously time-consuming cognitive chores of normalization, recording, and interpretation, and the results came in a format that was immediately useful. In the words of Ralph Müller that serve as an epigraph to this chapter, the Saunderson direct reader was a "true instrumental method of analysis": an instrument with "cognitive skills" that allowed it to provide the desired information in final form. It amounted to a mechanical brain.

In 1947, Saunderson's instrument was licensed to Baird Associates for commercial

manufacture and sale. Baird further developed the instrument to make it useful in other metal industries. The first Baird/Dow direct reader was sold to the Timken Roller Bearing Company in 1947. E. R. Vance, the Timken chemist who made the decision to purchase a direct reader, was awarded a \$1,000 prize by Timken for this decision (Vance 1947, 1949). In 1952, Saunderson came to work for Baird Associates, where he further developed his direct-reading spectrometer. (More details of this work are given in chapter 7.)

## 8. MATERIAL KNOWING IN THE MATERIAL WORLD

At the beginning of this chapter, I listed a number of skills, or their functional equivalents, that had to be encapsulated in the instrument for it to serve as a reliable, useful means for making elemental concentration measurements on molten alloy. These include knowledge of the spectral fingerprints of the elements of interest, the accurate normalizing of spectral lines as to both place and intensity, the determination of relative intensities of light energy reaching different exit slits, and the encoding and displaying of this information. My story here is of how all this was accomplished.

Knowledge of spectral fingerprints is built into the placement of the exit slits. Normalizing of line placement and intensity is accomplished by precision optical alignment on a mechanically stable frame (an issue I have not discussed), and condenser-discharge electronics was used to put Gerlach and Schweitzer's "internal standard method" in material form. Photomultiplier tubes and the associated electronics allowed the instrument to make relative intensity determinations. Encoding and displaying the signal, now given in the form of information, was accomplished with dental tape, phonograph needles, servomotors, and more electronics.

The knowledge encapsulated by the direct reader is of a variety of different "fields," optics, electronics, and spectrochemical analysis among them. The particular knowledge encapsulated in the direct reader synthesizes knowledge from these various fields in an integrated way. Two fundamentally different kinds of thing knowledge get integrated in materially encapsulated knowledge: working knowledge and model knowledge. Analytically, we can distinguish these in the direct reader.

The instrument includes a model of (some) spectrochemical knowledge. A strip of metal is bent into a Rowland circle, with a radius determined by the radius of the concave grating used in the instrument. Exit slits are cut into this strip of metal at points that correspond to specific wavelengths of light emitted by the elements of interest, a material representation of (some of) the spectrochemistry of these elements. By shaping the strip of metal in a certain way and then by cutting slits in it at specific points, we get a material presentation of a selection among a field of possibilities. Information is built into the instrument, and this then allows us to take information from the signal produced by the instrument.

This signal is also essential to the instrument. The instrument, in interaction with the sample or input, has to create a phenomenon. When accurately calibrated, the instrument produces



reliable outputs for given inputs. By preparing samples with known concentrations of various elements of interest, instrument makers and users confirm the reliability and validity of the numerical regularities produced by the instrument. In this way, they confirm the phenomenon produced by the instrument interacting with the sample. In this sense, the instrument stands as working knowledge.

This is analysis. We can distinguish the model knowledge, built into the instrument as a strip of metal in the shape of the Rowland circle, from the working knowledge, constituted by the instrumental crafting of a reliable phenomenon. In the instrument, both epistemic modalities are synthesized to produce a reliable, informative, and useful instrument.

Another part of the direct reader nicely illustrates the synthesis of two epistemic modalities. The electronics that transforms the light energy captured by the photomultiplier tubes into concentration readouts shows how the two kinds of knowledge are integrated into encapsulated knowledge. On the one hand, there is the theory that relates the variables of time, voltage, and resistance for the phenomena of condenser discharge—pretty standard theoretical knowledge. On the other hand, it is the instantiated physical phenomena of condenser discharge, an instance of working knowledge, that allows the instrument maker to deploy a material encapsulation of this theoretical knowledge. This allows the instrument to convert relative amounts of collected light energy into relative times of condenser discharge—and thence into a concentration readout. The final circuit is the synthesis of both modalities. It synthesizes the theoretical knowledge of condenser discharge with the working knowledge constituted by the phenomenon of condenser discharge. The result presents a material functional equivalent of the skill of determining relative spectral line intensities, which previously required human work with spectrograms and densitometers.

The difficulties that Saunderson had to overcome were material. “In principle,” the direct reader worked well in January 1944. “In material reality,” nine months of hard work were necessary to make it do so. It is easy to conceive the “ideal” photomultiplier tube, where output does not depend on where on the cathode the light hits. The actual material object does not behave this way. In order to achieve an accurate enough direct reader, Saunderson et al. had to deal with this annoying behavior of the tubes. This was true of many of the specific detailed problems that had to be materially solved to make an accurate working instrument, which included line choice (and hence exit slit placement), dark current, and stopping and starting the drums. And these, of course, are merely a sampling of the difficulties that Saunderson and his colleagues had to surmount to get their instrument working. They also confronted a host of other problems. The two points that I wish to emphasize here, however, are, first, that it is a solution to such detailed problems, which litter the path from “clean” idea to working material instrument, that makes instrument development possible, and, second, that these problems more often than not are material.

The first point is widely known. Edison put it well: “It has been just so in all my inventions. The first step is an intuition, and comes with a burst, then difficulties arise—this thing gives out and then that—‘Bugs’—as such little faults and difficulties are called—show themselves and months of intense watching, study and labor are requisite before commercial success—or

failure—is certainly reached” (quoted in Friedel et al. 1987, pp. 28–29). The initial idea—although very important, indeed, necessary—is the easy step.

The second point is central to my epistemic thesis. A “skilled” instrument is not simply the material encapsulation of propositional knowledge, of ideas. It brings together ideas and material realities. If, contrary to fact, instruments were simply the instantiations of ideas, one could readily argue that knowledge is fundamentally a matter of ideas, which can be instantiated in instruments. This is not how it is. Materials and ideas are both necessary, and materials do not behave like ideas (on this point, see chapter 7). It was Saunderson’s understanding and ability to manipulate both the ideas and the material realities involved in direct reading that made his instrument, his contribution to thing knowledge, possible.

This point about the material aspects of encapsulation can be more directly seen in terms of the high degree of thermal and mechanical isolation necessary for the instrument’s accuracy. In order to work reliably, to produce the necessary phenomena for measurement, the instrument has to be built to withstand the thermal and mechanical conditions of its use. The instrument had to be designed and built to withstand these conditions. While these conditions could be altered—as Dow Chemical did in building an air-conditioned analytical laboratory in the basement of the foundry—an understanding, at the level of manufacturing practice, of how to control for mechanical and thermal variations had to be built into the instrument. This understanding is part of the working knowledge encapsulated in the instrument. Without it, the instrument would not produce a phenomenon, and measurement would not be possible. In contrast, for its commercial success—even simply its value to Dow as a “one-of” addition to their magnesium foundry—the direct reader had to provide the desired information in a timely and cost-efficient manner. Such economic knowledge, however, is not encapsulated in the instrument, for it is neither working nor model knowledge.

The net effect, when the instrument is well calibrated and operating correctly, is a useful tool for measuring elemental concentrations in metal alloy melts. It also is encapsulated thing knowledge synthesizing working knowledge, model knowledge, theoretical knowledge, and functional equivalents to skill knowledge.