The Chemical Histories of Soot and Buckminsterfullerene

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By

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To Leata

TABLE OF CONTENTS

Acknowledgements x

Introduction 1
Fake News and True Stories

Chapter 1 4
The Anecdote Begins

Chapter 2 7
Chemistry the Central Science

Chapter 3 12
Faraday

Chapter 4 17
Combustion Science

Chapter 5 22
The Structure of Soot

Chapter 6 27
Mikhail

Chapter 7 32
From Russia Without Love

Chapter 8 37
Linked In

Chapter 9 44
The Model

Chapter 10 50
Discovery!

Chapter 11 58
Buckminsterfullerene

Chapter 12 65
Baum

Chapter 13 71
Smalley

Chapter 14 75
Kroto

Chapter 15 80
Curl

Chapter 16 84
ZOHLCKS

Chapter 17 88
Human Chemistry

Chapter 18 96
C&EN Reports a Controversy

Chapter 19 101
Incitement

Chapter 20 107
Kroto and Radovic Dialogue

Chapter 21 114
Showdown in State College

Chapter 22 120
The Article Appears

Chapter 23 127
Stonewall

Chapter 24 131
Ebert for the Defense

Chapter 25 135
Fullerenes from Soot, but Soot from Fullerenes?

Chapter 26 139
Smalley

Chapter 27 142
Kroto

Chapter 28 145
Curl

Chapter 29 148
Baum

Chapter 30 152
Frenklach

Chapter 31 158
Soot Formation Science

Epilogue... 161
Whither Soots?

Bibliography 165

Index 174

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INTRODUCTION

FAKE NEWS AND TRUE STORIES

We read a lot, most of us.

Much of our reading is to satisfy trivial or mundane purposes—ball scores, calories from fats, installation instructions, edicts from corporate…

Why do we read accounts, fiction and nonfiction? That is, stories? Real or imaginary?

I believe it is mostly to learn—and by learn, I mean to capture information for our hungry minds. There is a trivial purpose too. We want to be amused. We may have to "suspend disbelief," i.e., ignore obvious untruths, but we want the rest to ring true. We want the truth—about what happened, yes, but about why it happened, and why people behaved as they did. Certainly we hope to find the truth in a news article. We know that we are taking our chances with newspapers though. There's not enough space—even if we have the reading time—to cover most stories accurately. And most stories have unknown parts anyway—parts that are guesses by the writer, or parts that reflect opinions by the publisher. And then, many of the stories in the paper are not written to inform in the first place. They are written to persuade. Too often we are frustrated by stories that barely tell what happened, give no inkling of why it happened, and why the people involved did what they did.

What if we are looking for truth about science? Not "scientific fact," but science, meaning the work and the people who do the work of developing new knowledge. The newspaper certainly carries some of these stories—the overdue detection of significant gravitational waves[1], the competition to map the human genome[2], the discovery of the neutron[3]. To

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[1] Guarino, Ben and Kaplan, Sarah. "Gravitational wave from black hole collision 1.8 billion light-years away sensed in U.S. and Italy". *Washington Post*, September 27, 2017.

[2] Buerkle, Tom. "The 'Wondrous Map' of Gene Data: Historic Moment for Humanity's Blueprint," *The International Herald Tribune* and *The New York Times*, June 27, 2000.

[3] Special Cable. "DISCOVERS NEUTRON, EMBRYONIC MATTER; Dr. James Chadwick Describes It as Halfway Between Electricity and Helium. FIRST STEP

learn more though, we usually have to look to magazines and books, forfeiting immediacy for the sake of accuracy. Some of the best science stories are in magazines for general readers, like The New Yorker and Atlantic Monthly; increasingly, e-zines like Slate have excellent stories. Anthologies come every year[4] with collections of these excellent stories. There are wonderful books and wonderful writers.

A successful story seems true—it has enough detail, it has no maddening discrepancies, like the typical breaking news story, and the fictional characters or the nonfictional real people behave in ways we can understand. For some fiction, we have to ignore some things, but those things are usually obvious—the point of the story is usually not to fool us. For other fiction, there may be no magic or superheroes or demons, but fiction is still not held to the same standard as nonfiction. We know when we read historical fiction that it is fiction.

The problem with nonfiction is that it may seem to be true, but not be.

The following story is about many things. It involves many people, places all around the world, and a time span of a couple hundred years. The core of it though, is much more compact. It could be thought of as taking place over a couple of years, and happening to two or three people. It is very much about particular people, and yet the people are representative of types. What occurs is very specific, but is a more universal experience. It seems very true, because it is.

Science is fascinating, but it is daunting. Nonscientists, and often scientists themselves need help to understand it. Scientists themselves have an interest in our understanding their work, but there are others, the journalists, who find their métier in the helping.

Ah, you say. You are about to tell me a story of the sensational and tragic misuse of the power of science, of the transmogrification of something bad into something good. The world destroying potential of nuclear power, or the horror of biological warfare. Or maybe you are about to tell me a somewhat less sensational story, about callous big pharma, the disappearance of species, the scientific ignorance that threatens our future.

Well no. This story is more ordinary yet. There are no human casualties, no punishable crimes occur, no physical violence. It does not involve popular science, nuclear power, space travel, or science that most people

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IN EVOLUTION Scientists Say Results Rank With Finding of Electron, Proton and X-Ray. DISCOVERS NEUTRON, EMBRYONIC MATTER", The New York Times, February 28, 1932.

[4] e.g., Montgomery, Sy, and Green, Jaime. 2019. *The Best American Science and Nature Writing 2019*. New York: Houghton, Mifflin, and Harcourt Publishing Company.

are even vaguely aware of. It is real science though, and has the character that we expect of science, practical application and intellectual appeal. The people are fascinating, and we could be they. Just as they did we have ethical problems, frustrations, and sometimes, great inspiration in our work.

Taking a narrow view, there are five main characters in the story, four scientists and a journalist. The oldest was born 5–10 years before the rest, so they are close enough in age that they began to come into their own within the same few years and saw the same external world, albeit from their own perspectives.

OK, here we go.

1

THE ANECDOTE BEGINS

Where were you in 1971?

In the late sixties and early seventies the world population growth rate, which had grown for all of human history, reached its peak. The world was becoming crowded, and the species as a whole seemed to know.

In January Egypt's Aswan High Dam opened and three US astronauts lifted off to travel to the moon.

February. Great Britain saw storied Rolls-Royce go bankrupt. Earthquakes in Los Angeles and Italy killed almost 100 people, and tornados killed almost as many in Mississippi. Apollo 14 astronauts successfully landed on the moon and returned to earth.

And then it was March. A grey day in central Europe, at Flughafen Wien-Schwechat, Austria…

As he descended the plane's airstairs in the Vienna airport, 23 year old Mikhail Frenklach had no idea what to expect. Mikhail, his sister Vera, his father Efim, his mother Rimma, and Grandma Rosa just hours before were Russians. They were about to become Michael, Dvora, Haim, Rivka, and Raisa, Israelis. Along with several other Jewish families they had flown on a Russian aircraft from Moscow. Mikhail was filled with the confidence of youth, but the flight and the previous year had been unnerving.

The Soviets had allowed them to leave with only 100 American dollars each, the foreign currency provided for them by the Soviet government. They could not take any of their own money, nor any object they could not carry. One of their party, a dentist, in an attempt to circumvent this restriction, had secreted a diamond in one of his teeth. Somehow the authorities had found him out and he had not even been allowed to board. He would never be heard from again.

Although the flight was not a specially chartered one, and even though there were other passengers, from ordinary people to celebrities (There was a star athlete aboard), the craft had made an unscheduled landing in Kiev[1] and the family subjected to one last unannounced search. The Soviet

[1] Now Kyiv

state often claimed ownership of personal possessions, even the most intimate and precious. Grandma Rosa, upset and crying, had to surrender her only remembrance from her own mother, a small gold chain, at the Kiev stop.

The family had lived for months in a state of psychological hypertension. They were shunned by their non-Jewish neighbors, and even by some Jews, most of whom were afraid to be associated with them after they had filed the emigration application. Their ordinary world had changed to a new one. They had been people of the Soviet Socialist Republic. Now they were seen by many as enemies of the people. Mikhail's mother had feared that her accomplished son would be banished to some remote part of the vast country as a laborer, exiled. These were not empty fears. The radio engineer Volodya Slepak, another applicant for emigration, would be exiled to Tsokto-Khangil, a place in Siberia so far from Europe that the Russian language was not even spoken there. It was Volodya's and his family's misfortune to be more widely known than families like the Frenklachs. It made him a better example on which authorities could demonstrate their power[2].

Mikhail/Michael was a special case, a graduate student of promise in the prestigious Dmitri Mendeleev Institute of Chemical Technology, chartered as Moscow Industrial College in 1898. They offered the finest training in the country, perhaps equal to the finest anywhere, in industrial arts. In 1969 Mikhail had completed the Institute's undergraduate curriculum, which consisted of three years of basic studies followed by two of advanced work on special projects, essentially a Master's degree. But now, he no longer had an academic career.

The OVIR (Department of Visas and Registration) had required a special document, a kharakteristika, to inform his employer, the Mendeleev Institute, of his desire to emigrate. The form he submitted had come to the attention of Komsomol, the All-Union Leninist Young Communist League. As a result Mikhail had to face questioning and harassment at the hands of dozens of "invited" fellow students in a packed campus hall, where he was contemptuously declared to be a traitor to the Motherland.

Less ceremoniously, the Institute expelled him from his graduate work in the department of Basic Organic and Petrochemical Synthesis. This, despite the fact that he was a high achiever. He had made all "5"s ("A"s) some semesters, and had narrowly missed first prize in the undergraduate

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[2] Potok, Chaim. 1996. *The Gates of November: Chronicles of the Slepak Family*. New York City: Alfred A. Knopf Inc.

research competition. Nor was he just a grind. He was part of an Institute-wide prize-winning comedy and musical group (no political themes allowed!) who enjoyed literature and music. No matter. He could no longer participate in college life or pursue graduate studies.

But at the bottom of the airstairs, along with an eager crowd waiting for the athlete celebrity, was a group of Israelis, citizens of his brand new country, a country no older than he was. He would always remember a sense of a relief; the repressive old world was gone. He was entering a new larger more open world. Just as, at the same age, his scientific forebear Michael Faraday, a ruffian from the mean streets of London, had been brought officially as a valet for the great Sir Humphrey Davy, to the great cities of Europe 158 years before, Frenklach had made a grand and momentous transition.

2

CHEMISTRY THE CENTRAL SCIENCE

Science journalism has been around as long as the enterprise of scientists has been recognized as a thing, including when it was merely called natural philosophy. A great part of science journalism is for everyone. It serves an educational function for society. Another part of science journalism, simply referred to as “the literature,” is for scientists themselves. The scientists themselves are the journalists, publishing the results of their work in periodicals. Now the literature consists of thousands of scientific journals, some published as often as weekly.

There are two superb journalistic accounts of the discovery of Buckminsterfullerene, a remarkable spherical molecule with 60 carbon atoms. It is unusual for a story about chemistry, one that is not actually a physics story (about nuclear energy) or a biology story (about medicine, or recombinant DNA) to appeal enough to a general audience to be published. Chemistry has always had a public relations problem. But the discovery of a new form of the element of life, a new allotrope, seemed like a winner, and two science writers, Hugh Aldersey-Williams and Jim Baggott both went for it. Not long after their books were written, a Nobel Prize was awarded for the “…discovery of fullerenes”. An American reporter, Rudy Baum, too busy to spend the time writing up a history which he knew better than the two British authors, having covered it for his magazine from the beginning, was scooped. He would be a major figure himself in another story, one in which buckminsterfullerene was beside the point.

Both the British authors though devote only a few words to an argument over the idea that such curling carbon networks are involved in the formation of flame soot. In the lens of these recounters it was not more than a minor scientific dispute, with pettiness on one side and arrogance on the other.

> Though made in good faith, this model was rejected outright by many in the soot community. The Rice group and Kroto had not consulted with them, had not referenced their papers, and had no solid evidence for what

> they proposed. Even after these first skirmishes, the fullerene camp would continue to incur the wrath of the soot community for its selective use of evidence from the combustion literature and for its cocksure ability to rediscover what others had long known. (Aldersey-Williams, 1995, 188)[1]

> What they saw was a bunch of chemical physicists relatively unfamiliar with the substantial body of accumulated knowledge in soot chemistry running around claiming to have solved all the problems of the field in one fell swoop. And with a mechanism that made no sense to those who knew better. They were outraged. (Baggott, 1996, 118)[2]

That lens, though, has considerable aberration. The portrayal of the scientific argument as a journalistic misadventure is an interesting story in its own right, not a footnote, and illuminates the classic and seemingly permanent tension between science and its observers.

That said, the story is to be read and appreciated only for itself. It is an anecdote. One can't draw conclusions from a single story, any more than one can develop new knowledge from one experiment. However, when a story is put in context, and other anecdotal information is added, the optics change. On its face this is a story about two different scientific projects, but when seen in the light of the real people who worked on them and the journalist that tried to bring the story to a wide audience it is a rich slice of human experience. The story, when amplified with context, is much more than a single bit of data.

Science and Journalism

Science journalism has been around as long as the enterprise of scientists has been recognized as a thing, including when it was merely called natural philosophy. A great part of science journalism is for everyone. It serves an educational function for society. Another part of science journalism, simply referred to as "the literature," is for scientists themselves. The scientists themselves are the journalists, publishing the results of their work in periodicals. Now the literature consists of thousands of scientific journals, some published as often as weekly.

Science journalism then, may be thought of as a range of enterprises. At one extreme, there are articles for general dissemination of scientific

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1 Aldersey-Williams, Hugh. 1995. *The Most Beautiful Molecule: The Discovery of the Buckyball*. New York: John Wiley & Sons.

2 Baggott, Jim. 1996. *Perfect Symmetry: The Accidental Discovery of Buckminsterfullerene*. Oxford: Oxford University Press.

knowledge, for the public, including scientists and nonscientists, and these articles are best when they may be read and understood by a relatively wide group of nonexperts. The other Platonic extreme, the literature, is for precise and accurate information exchange, and is usually not accessible to a nonexpert. The literature has rigorous standards, stated and unstated, for articles. These standards have evolved from *contretemps* in the early days.

In 1831, the natural philosopher Michael Faraday made a presentation to The Royal Society in London, an account of his experiments in electromagnetic induction, a gigantic advance in the understanding of electricity and magnetism. He was speaking to what was, for that time, an expert audience.

At the same time he sent a letter describing his work to J. N. P. Hachette[3] to be read at the Académie des Sciences in Paris. Hachette presented the letter by reading it aloud, and a garbled account of the reading was reported by the magazine Le Lycée, along with an article saying that two French scientists were the discoverers of the phenomenon.

Two Italian researchers, Nobili and Antinori, saw the Le Lycée number and consequently performed their own confirmatory experiments and published them, properly acknowledging Faraday. Unfortunately their publication mistakenly bore a date prior to Faraday's presentation, which was seen in London by William Jerden of the Literary Gazette, who reported to his readers that Nobili and Antinori had scooped Faraday.

To make a messy story neat, the affair was ultimately straightened out to the satisfaction of all, but Michael Faraday had learned a lesson. He never again presented his work before publication.[4] It is now a common practice, only rarely not followed, to publish *before* announcing results to the press. Best practice? Disseminate, but carefully.

Standards and practices across the range of journalistic reports vary. For example, retractions are common in the literature, often involving complete withdrawal of articles, and are voluntary on the part of conscientious authors, in stark contrast to the niggling resistance of the general press to even minor corrections, and a typical stubborn refusal to admit error.

This is not to say that the literature is courtly and polite. Science is highly competitive and publication in the literature is tantamount to

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[3] Jean Nicolas Pierre Hachette (1769 – 1834) may have been related to Louis Christophe François Hachette (1800 – 1864), whose name is borne by global publisher Hachette Livre. Hachette famously squabbled with mega online merchant Amazon in 2014.

[4] Forbes, Nancy and Mahon, Basil. 2014. *Faraday, Maxwell, and the Electromagnetic Field: How Two Men Revolutionized Physics*. Amherst NY: Prometheus Books, 80.

priority. Priority is the jewel, the prize of being the acknowledged leader in the field, albeit possibly for a very short time.

Faraday deserves priority for the first demonstration of a rudimentary electric motor in 1822. He published in The Quarterly Journal of Science, but he did not mention having overheard that W. H. Wollaston was working in the same area, for which he was taken to task by his mentor Humphrey Davy. Davy, who had championed Faraday before, turned antagonist, blocking his elevation to a fellowship in The Royal Society.[5] Today, referencing the work of others is an established requirement of publication in the literature.

There is a category of journal which is a bridge between the literature and the popular educational journals, the category of science and technology trade journals. The target audience of these periodicals is scientists and technologists within a particular segment of science and technology, as opposed to the general public. The authors are fulltime journalists, sometimes with advanced training in science themselves. The trade journal intends at a minimum to inform its readers as to news within the technology. Often it goes beyond this straightforward mission and veers into analysis of events. It commonly sports an editorial page, which is almost unheard of in the literature. The professional journalists hope to contribute to the education of their readers, who are often well informed and opinionated beyond their narrow specialties. The trade press creates stories and informative articles, generally not research reports.

The conflict between the soot community and the buckminsterfullerene community is part of our story, but the conflict was not initially perceived to be one by the communities. A trade journal saw it as a conflict though and simply declared it one.

Why would a journal do such a thing? To sell magazines? Not likely. There are no newsstands for trade journals, no provocative covers to be seen, no clever titles to boost subscriptions. The impetus was simply editorial choice. It was judged to be a thing, a story, by a reporter and an editor. In large part the conflict was actually created by the trade journal.

This anecdote, the story, is a metastory too then. It has an embedded story. It is a piece of journalism about science journalism, which arguably should, like other journalism, answer the questions who, what, when, where, and why. This story also asks questions of scientists and science journalists. Does science journalism play by the same rules as ordinary journalism? Is science journalism stricter, requiring strict objectivity? Is it the job of science journalists to discern disagreements among researchers

[5] Forbes and Mahan, *ibid.*

and to highlight them, to “fan the flames” of conflict between paradigmatic differences?

3

FARADAY

Michael Faraday might be regarded as the father of combustion science. He is often referred to in that way in literature reviews and presentations. Such citation reflects well on the importance of what is now one of the less glamorous sciences. Faraday is one of the giants of physics. Einstein ranked him with Newton and Maxwell. He was the man who conceived of the electromagnetic field. But to him, chemistry and combustion were the beating heart of natural philosophy.

It was with Michael Faraday that natural philosophy became science, and Faraday was one of the first science journalists in the scientific and industrial revolution of the 19th century, a particular authority on combustion. Beginning in December 1848 and continuing into the second week of the following January, he gave a series of six lectures to a "… juvenile auditory [young adults aged 15 to 20] at the Royal Institution of Great Britain" entitled "Chemical History of a Candle"[1] . Over the course of the six lectures, while he explained the structure and function of a commonplace object which was primarily used to provide light, he strove to introduce his audience to natural philosophy. He gave the lectures again, six years later, and a final time, six years after that. As many as 700 attended, arranged in a tiered semicircle around Faraday and his demonstrations.[2] The Christmas Lectures, which Faraday himself initiated in 1825, are still given every year by the Royal Institution. Faraday's attention to detail was remarkable. He is revered as one of the great experimentalists, and he was that, but his greatest contributions may have

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[1] Crookes, William, Ed. and Faraday, Michael. 1861. *A course of six lectures on the chemical history of a candle: to which is added a lecture on platinum. By Michael Faraday ... delivered before a juvenile auditory at the Royal Institution of Great Britain during the Christmas holidays of 1860-1*. New York: Harper & Brothers.

[2] The lectures have been memorialized by Professor Bill Hammack of the University of Illinois at Urbana-Champaign.

Hammack, Bill. 2016. *Michael Faraday's The Chemical History of a Candle*. Urbana, Illinois: The University of Illinois, Urbana come from his meticulous and deep observation. He pointed out how the heat from the flame liquefied the solid candle wax to the degree necessary to allow it to move by capillary action up the wick into the flame region. He explained that the shape of the candle was important because the excess melted wax needed to be able to pool shallowly on top of the cylinder, rather than "guttering," or spilling over the side, creating a groove, as inevitably occurs in a poorly shaped candle. He also revealed, by its shadow, the convective sheath of air which ascended and enveloped the flame, and pointed out and made visible the column of vapor rising in the flame's center. He identified the source of the brilliant glow of the flame as carbon particles, "soots," being heated to incandescence, and noted that the chemical composition of air was critical to its stable and efficient burning. With a dozen or so demonstrations he identified and quantified air's components and the components produced by the burning. Air was shown to contain 80% by volume of an "indifferent" gas, nitrogen, which moderated the combustion, as well as the reactive agent oxygen. He identified water and carbon dioxide as the chemical products by comparing the flame product with authentic water and carbon dioxide. His proposition: "There is no better, there is no more open door by which you can enter into the study of science, than by considering the physical phenomena of a candle." Faraday, despite the problems he had with its reporting and reporters, believed deeply in the dissemination of new knowledge.

He was born in London in 1791.[3] His father, a blacksmith, had moved the family from the northern English hamlet of Outhgill under the economic pressures stemming from the loss of the colonies in America and the prospect of contending with the French. He and his family were members of a Christian denomination, the Sandemanians that had broken off from the Scottish Presbyterians and believed that "The bare death of Jesus Christ, without a thought or deed on the part of man is sufficient to present the chief of sinners spotless before God."[4] Guaranteed salvation did not make him ethically complacent. He was unfailingly kind and generous.

The family was poor, and his education, such as it was, ended when he was only 13. He may have had a speech impediment, a difficulty with pronouncing his "r"s. He said that he was doomed forever to introduce

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[3] Forbes, Nancy, and Mahon, Basil. 2014. *Faraday, Maxwell, and the Electromagnetic Field*. Amherst NY: Prometheus Books.
The Forbes and Mahon book is the primary source of this short biography of Faraday.

[4] The inscription on the tomb of Robert Sandeman, the denomination's founder.

himself as Michael *Fawaday*.[5] First working as an errand boy, he soon signed on as an apprentice bookbinder. He did not become a bookbinder, but because of his remarkably liberal master, he plunged into the world of books, and one particular book, The Improvement of the Mind, by Reverend Isaac Watts, captivated him.

Besides assiduously working to improve his command of language, he formed the habit of recording, in a notebook, established facts. Facts, pieces of information that could be verified by observation, became very important to him. Watts' book advised him not to be too eager to construct general explanations from too sparse a group of facts. Faraday became a very careful observer and an even more careful theorizer, insisting on verifying, by experiment, any conjecture of natural philosophy before he accepted it as fact.

Following Watts' advice, he sought to hear knowledgeable lecturers on scientific topics. He became a member of the City Philosophical Society, a natural philosophy discussion group more accessible than the Royal Institution[6] , faithfully taking notes at every event. These notes, carefully written and illustrated, impressed his bookbinder master, who displayed them in his shop. At the lectures he made friends with others who were charmed by his optimistic outlook and pleasant demeanor, and who helped him develop strengths in speaking and writing, and introduced him to instrumental and choral music, particularly opera. Michael's remarkable powers of observation and recall, unmistakable in the notes, got the attention of a member of the Royal Institution, a Mister William Dance, who gifted him with tickets to hear Humphrey Davy, the natural philosopher and rage of the London intellectual scene.

When Faraday read or heard about new discoveries, he was compelled to verify them himself. He was encouraged in this enterprise not only by Watts' book, but by those of Jane Marcet, who wrote a series of books which included *Conversations on Chemistry*[7], in which she followed the fictional exploits of a teacher and two girl pupils, who experimented with common materials under her guidance. The teacher enjoined them (and her avid reader Michael Faraday) to draw conclusions only at length, after

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[5] Holmes, Richard. 2008. *The Age of Wonder: How the Romantic Generation Discovered the Beauty and Terror of Science*. NY: Pantheon Books

[6] Caroe, Gwendy, and Caroe, Alban. 1985. *The Royal Institution: An Informal History*. London: John Murray Publishers

[7] *Conversations on Chemistry*, not published under her name for more than a decade, went through many editions in England and in the United States, can be found on the internet. The Wikipedia article on Jane Marcet has links to digital copies.

careful experimentation, and rigorous examination, and still, to be open to a fresh perspective. Watts' and Marcet's writings admonished him to relentlessly and continuously examine his own ideas. And Marcet introduced readers to her own inspiration: Humphrey Davy. As The Royal Institution of Great Britain's lecturer extraordinaire, with the flair of the great illusionists, Davy astounded London audiences, including Marcet, with chemical demonstrations.

Soldiering on, his apprenticeship completed, Faraday went to work as a bookbinder. He longed for a life in natural philosophy, but did not shirk his duties in his new job. His assiduity impressed his employer so much that he was offered heirship to the business. Instead of the thrill of achievement though, Michael was deeply troubled. Was there no way to become "a philosopher," or must he resign himself to bookbinding?

A way appeared. At first it was just a shimmering ephemeral wisp of a way, but he took it, and found himself in the right place at the right time.

The flamboyant Sir Davy was the premier experimental chemist of that era, and as such, performed dangerous experiments as a matter of routine. In November 1812 he mixed a tiny quantity of a strong oxidizing agent, chlorine, with a powerful fuel, ammonium nitrate[8].The resulting explosion very nearly blinded him. He decided as a consequence to take on a temporary assistant. William Dance recommended the well-organized and punctilious Faraday who had the additional credit of being a faithful and neat recorder and bookbinder. Faraday took the temporary job, and when Davy fired an irresponsible helper later, turned over the supervision of the laboratory to him. He was offered a tiny attic room, candles, and 25 shillings a week as a chemical assistant to the great man.

As a result, at a critical time in his life, when he was about 22, he had the opportunity to travel with his boss who had accepted the Prix Napoléón from the Institut de France in Paris.[9] A sort of broadening world trip was ordinarily taken as a matter of course by British young men better heeled than Faraday, but ironically, because of the tension caused by the French revolution, he found himself in more rarefied company than many of those better bred, who stayed home during the upheaval. He became known and a favorite among the natural scientists of the continent. Even though Sir Humphry Davy was arguably the premier scientist of the time, his assistant came to be perhaps even more admired. A young man who

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[8] Ammonium nitrate was part of the explosive cocktail that Timothy McVeigh used to destroy the Alfred Murrah Federal Building in 1995, and the cause of explosion in Texas City, Texas in 1947 that killed 600 people in the worst industrial accident in the history of the United States.

[9] Holmes, *ibid*.

met him on the trip remarked “We admired Davy, we loved Faraday”, a comment which foreshadowed Davy’s eventual resentment of his young mentee. Faraday met and impressed Cuvier, Ampere, Berthollet, Gay-Lussac, Volta, generally every established natural philosopher they encountered.

Years later, when Davy died of heart failure, Faraday took over the chairmanship of the Royal Institution, and he did in due course receive a fellowship in the Royal Society. His duties at the Royal Institution were pressing and difficult, and Michael was somewhat frail. Offered prestigious academic posts, he eschewed them for what he considered a better use of his time. His long-suffering wife Sara, the love of his life, cared for him and nursed him back to health, but he suffered so serious a nervous breakdown that he had to withdraw from work, for a period of two years. Despite his health problems, he continued to explore the field of electricity and magnetism, to which he made fundamental contributions. His mental faculties deteriorated badly after 1862 and he died five years later, peacefully. His 1860 Christmas lectures on combustion were in fact the last public lectures he gave.

4

COMBUSTION SCIENCE

What, precisely, is combustion science, that field that Faraday pioneered?

Combustion is the technical term for burning. It is the interaction of an oxidizer (like oxygen in the air) with a fuel (often fossil fuel like coal, natural gas, or gasoline). Combustion releases heat and light. It is currently humanity's primary energy source and has been for all of history. Before the industrial revolution, the only concern was getting the most heat and light from the least quantity of fuel,[1] but now we often want combustion to yield a minimum of heat and light as it provides mechanical or electrical energy.

Some of the technical aspects of burning have been understood for a long time, and for the better part of two centuries we have investigated the combustion of fossil fuel and learned a good deal. We have learned that it has a dark side.

The gas carbon dioxide is the primary substance burning releases. It is largely transparent to the sun's rays, but it absorbs the infrared light generated when those rays fall on earth. This absorption heats the atmosphere. Plant life absorbs CO_2 and chemically recycles the carbon, and the oceans absorb and dissolve CO_2. About a hundred years before the famous Christmas lecture though, the amount of combustion of fossil fuels (at first coal, more lately oil and natural gas) carried out by humanity began to increase tremendously.[2] The plants and the ocean have not been able to accommodate all the CO_2 and its concentration in the atmosphere is increasing, and is increasing more rapidly.[3]

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[1] Whitesides, Russell Andrew. 2009. "Theoretical Investigations of Soot Surface Chemistry". Ph.D. dissertation, University of California Berkeley.

[2] Ashton, Thomas S. 1948. *The Industrial Revolution (1760–1830)*. Oxford: Oxford University Press

[3] National Oceanic & Atmospheric Administration Earth System Research Laboratory Global Monitoring Division, 2022. "Increase in atmospheric methane set another record during 2021". Accessed April 17, 2022.
http://www.esrl.noaa.gov/gmd/

Burning also invariably produces other materials which are hazardous to life, including other gases which load the atmosphere with corrosivity and poison. Even those of combustion's products which are chemically inert can interrupt life processes and trap heat, darkening and warming the atmosphere and the landscape.

We argue about the degree of hazard produced by the burning of fossil fuels. We argue about the cost and benefits of reducing our reliance on them. We argue about measures which might moderate the effects of combustion. While these great global arguments go on, so does the deepening and refining of our understanding of the process of combustion. Though the understanding does not settle the great arguments, it does have important practical implications.

Chemical bonds

Combustion is of course a chemical reaction. In a chemical reaction, one set of chemicals is transformed into another set. What is different about the transformed set is that the microscopic forces that hold the materials together, that actually determine the form of the materials that we see and by which we describe and identify them, are changed into different forces. We say that the bonds are changed.

We frame our understanding of chemistry in general on the notion of chemical bonds. Some bonds attach atoms to each other to form molecules, while others hold molecular assemblies of atoms to other atoms or assemblies of atoms, and others fix huge numbers of atoms in semi-infinite arrays. These various kinds of bonds are usually composed of electrons, most especially and usually pairs of electrons. If the attachment consists of a single pair of electrons, it is termed a single bond, and multiple bonds up to quintuple, or with five pairs of electron, have been identified. In that most fundamental chemical reaction, combustion, electrons move toward the atoms of oxidizer molecules and away from the atoms of fuel molecules. In consequence new bonds are formed as others disappear. This simple understanding accounts for the chemical identity of the substances formed during burning. The solid physical entities produced, i.e., ashes and soot, are assemblies of these substances.

As an example, consider the combustion of methane, or natural gas. Methane is a molecule, an assembly of atoms, four hydrogen atoms and one carbon atom. They are held together by single bonds. The pairs are like struts in a building, and in the case of methane, arranged around the carbon atom in just such a way that they are all equidistant from each other, each bond axis at 109.5 ° from each other in an arrangement termed "tetrahedral."

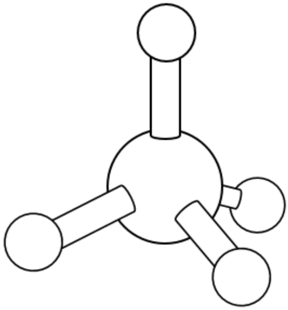

Fig. 4-1
"Ball and stick" model of methane, CH_4

Oxygen, the material we breathe to stay alive and which is produced for us by plant life, has two atoms connected by one bond. Combustion can be described by a so-called "chemical equation," *viz.*,

$$CH_4 + O_2 \rightarrow CO_2 + H_2O,$$

which shows that methane, given the "formula" CH_4, and oxygen, O_2, mix and somehow change their bonds into the bonds of two new molecules, CO_2, carbon dioxide, and H_2O, water, a fact which Faraday knew. The "equation" is really a shorthand description of a process, then. As written, it leaves out an important piece of information. Notice that there are four hydrogen atoms and two oxygen atoms in the starting materials, but the products have only two hydrogens and have a third oxygen. How can this be? The equation is more useful if balanced, if it shows a one-to-one equivalence of the atoms on both sides. Therefore, a better description of the process is

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O,$$

which shows that it takes two molecules of oxygen to burn one molecule of methane, and that 2 molecules of H_2O are released.

This equation, it turns out, is very useful in that it tells us how much water and how much carbon dioxide is formed from burning a certain amount of methane. It is not useful though to tell us how that transformation comes about in detail.

Toward that end it is possible to write equations which show the actual steps in a transformation, and these are called elementary reactions. It is found in fact, that chemical reactions usually change one bond at a time.

What we feel as heat is the rapid smashing together of gas molecules, and when methane and oxygen are hot enough, a molecule of each can crash into each other, and a possible elementary reaction, a first reaction step for the combustion of methane, is

$$CH_4 + O_2 \rightarrow CH_3 + HO_2,$$

which shows us that one of the bonds between hydrogen and carbon seems to have changed into a bond between hydrogen and one of the oxygen atoms. This crude picture is very useful. The actual chemical species portrayed do exist, and these products go on in a series of steps, other elementary reactions, to produce CO_2 and H_2O, the products which Michael Faraday recognized from the burning of candle wax. Candle wax is not the same as methane, but has a formula and bonds which are similar, $C_{(20\text{ to }40)}H_{(42\text{ to }82)}$. It shows carbon atoms and hydrogen atoms, bonded together.

Starting a fire often requires ignition, which in the case of a strike-anywhere match, is provided by the heat of friction of the match head against a rough surface. In other words, if there is sufficient heat, the reaction begins and the heat produced by the combustion sustains it until the fuel or the oxidizer is exhausted.

We know that a flame is a region of space occupied by hot, usually glowing gases. It may be fueled by city gas or propane or butane, or in a candle by solid wax, or in disastrous forest fires by timber, or in the flame of a match by a phosphorus compound. The fuel may flow as a gas into the flame area, or it may flow as a liquid guided by a wick, or it may simply be a flammable solid which has been set afire. At least this part of the chemistry is obvious.

The flame region is where combustion goes on. Substances in the gas phase, usually simple molecules, are moving at high velocities and crashing into each other continuously. The result of this crashing together, besides heat and light, is the degradation of the fuel substances to primary products so stable that crashing no longer breaks them into smaller pieces. These primary products are almost entirely carbon dioxide and water. Formed as gases, they continue to crash and move at high velocities until they escape the flame region, where most of their energy of motion is spent crashing into and warming air molecules beyond the flame perimeter.

The violent crashing together of cars results in destruction. There may be only a morass of safety glass chips, mangled metal and torn fiberglass and high tech plastic, hubcaps, and no intact cars left after a collision. So does the crashing together of fuel and oxidizer molecules in a flame destroy them, reducing them to fragments, but surprisingly, there is