CHAPTER 12

Robert Emerson and Eugene Rabinowitch: Understanding Photosynthesis

In the late 1940s and 1950s, the University of Illinois was home to the biologist Robert Emerson and the photochemist Eugene Rabinowitch, two brilliant scientists who played pioneering roles in explaining oxygenic photosynthesis. This fundamental process of converting light to chemical energy in plants, algae, and cyanobacteria turns carbon dioxide and water into the food and oxygen that sustains all life on earth.

The setting for this pathbreaking scientific work was the University of Illlinois, in particular, the Natural History Building (NHB) in Urbana, currently used by the geology department. The side entrance to this building, somewhat hidden by an old glasshouse on Mathews Avenue, leads to the building's basement and to a rather dingy corridor along which one walks south to a dark brown door labeled 157. The old door once led to the laboratory where Emerson and Rabinowitch worked.

In 1946, Emerson, then an assistant professor of biophysics at Caltech, accepted a joint position in the University of Illinois Department of Botany as director of the "Photosynthesis Project" (institutionally directly

under the Graduate College) and as research professor of botany. An experimentalist par excellence, Emerson had shown in 1932, when he was at Caltech, that only one out of hundreds of chlorophyll molecules actually engages in chemistry.[1] The rest are handmaidens who collect and funnel light energy to this special molecule. He stated, "We need only suppose that for every 2,480 (chlorophyll) molecules there is present in the cell one unit capable of reducing one molecule of carbon dioxide each time it is suitably activated by light." We now know that two such special chlorophyll molecules must be activated by light, the so-called reaction centers. Twenty-five years later, Emerson would discover at the University of Illinois that photosynthesis is more efficient when algae are exposed simultaneously to two beams of light, one in the far-red region and the other of shorter wavelength (red or blue). This major breakthrough in the field of photosynthesis later became known as the Emerson enhancement effect. The result led to our current understanding that there are two—not one—primary photosynthetic light reactions.

Emerson had come to Illinois on the condition that the university would also hire a physicist or physical chemist. He had in mind the well-known photochemist, Eugene Rabinowitch, who was then at the University of Chicago studying uranium chemistry at the Manhattan Project's Metallurgical Laboratory. By then, Rabinowitch was already well known for several major contributions. They included his discovery of the "Franck-Rabinowitch" cage effect in photochemistry (published with the 1926 physics Nobel laureate James Franck), in which one photon of light leads to a chain reaction, producing a large number of photoproducts; the photooxidation of chlorophyll in solutions; and his finding at MIT of the photogalvanic effect, the storage of solar energy in chemical reactions. He was also known for his definitive three-volume treatise on photosynthesis, published in 1945, 1951, and 1956, respectively.[2]

In 1947, Rabinowitch joined Emerson as co-director of the Photosynthesis Project. In this work, in mutual friendship and cooperation with Emerson, until the latter's death in 1959, Rabinowitch built and maintained one of the most prestigious photosynthesis centers in the world and co-directed (with others at UIUC) the teaching and research program in biophysics that evolved into the present Center for Biophysics and Computational Biology in the school of molecular and cellular biology.[3]

Rabinowitch had been trained in Berlin, where he had attended lectures by Albert Einstein, Max Planck, Max von Laue, Erwin Schrödinger, and Walther Nernst. His doctoral thesis was written under Fritz Paneth; his postdoctoral work was guided by James Franck. As a Jew, Rabinowitch

became a victim of anti-semiticism and was forced to leave Germany. In Copenhagen, where he went first, he built the first difference absorption spectrophotometer at the Niels Bohr Institute for Theoretical Physics (now the Niels Bohr Institute for Astronomy, Physics, and Geophysics). He also worked at University College in London in F. G. Donnan's laboratory.

Rabinowitch's research group in Urbana involved itself in studies of the storage of light energy in chemical systems and in the chemistry of chlorophylls. His 1945 book on photosynthesis had already discussed the possibility of two-light reactions in photosynthesis. He predicted in 1956 how the process might involve an intermediate called cytochrome, whose role in the two-light reactions was then discovered in 1961 by Louis N. M. Duysens of the Netherlands, long after his visit to Rabinowitch's lab. In 1960, after those working in Emerson's laboratory had discovered the enhancement effect, which ultimately led to the two-light reaction scheme, an English biochemist, Robin Hill, published a two-light reaction scheme based on theoretical grounds.

During these years in Urbana, Rabinowitch guided his graduate students to make some of the first biophysical measurements of the primary events in photosynthesis. Paul Latimer, Steve Brody, Tom Bannister, and others made the first biophysical measurements involving the quantum yield of chlorophyll *a* fluorescence (i.e., the number of photons given off by plants per photon absorbed by plants), the lifetime of this chlorophyll fluoresence (i.e., how long the excited chlorophyll molecules live), and other spectroscopic phenomena, including the sieve effect (the lowering of absorption of light when pigments are concentrated in specific areas) and selective scattering (scattering of light that depends on the absorption properties of the pigments).

Emerson's 1932 work had suggested that there are only a few chlorophyll molecules involved in chemistry. Bessel Kok in the Netherlands discovered one of them in 1956–57, about the same time Emerson discovered the enhancement effect in Urbana. Kok had called it "P700"—700 because it specifically absorbed 700 nm far-red light. At the same time, Rabinowitch's students discovered a spectral change at 680 nm (red light), and thought they had discovered the "other" chlorophyll molecule involved in photochemistry. Unfortunately, Daniel Rubinstein, another student of Rabinowitch, showed this observation to be an artifact of changes in light emission. Rabinowitch and I, however, knew that a P680 must exist. In 1965 we proposed the existence of this second special chlorophyll that engaged in chemistry.[4] It was not until 1969 that Horst T. Witt's group in Germany demonstrated its existence.

The basement corridor leading to Emerson's and Rabinowitch's laboratories is the same one that Otto Warburg, the 1931 Nobel laureate of physiology and medicine, had walked along when he visited Urbana in 1948 from Berlin, hoping to resolve a major controversy about photosynthesis that had arisen between him and Emerson, his 1927 doctoral student.[5] Originally trained in zoology at Harvard, Emerson had, under the influence of W.J.V. Osterhout, shifted his interests from animals to plants. He had gone to Munich to work for his Ph.D. under the Nobel laureate Richard Wilstätter on the subject of chlorophyll chemistry. But when Wilstätter ran into difficulties, because of the anti-semitic activities of certain students and faculty members, he advised Emerson to work instead with Warburg in Berlin.[6] It was in Warburg's laboratory that Emerson wrote his thirty-two-page thesis.

Warburg believed (and often stated) that "in a perfect world, photosynthesis must be perfect." He had published the result that a minimum of four light photons are needed to produce one molecule of oxygen. Using state-of-the art instruments, Emerson found however, consistently, that this minimum number is in fact eight.[7]

Rabinowitch later wrote of Warburg's stay at Urbana:[8]

> Like so many best-laid plans, it all went wrong. Warburg arrived in the midst of the heaviest thunderstorms I have experienced in my fifteen years in Urbana, and this proved to be an augury of his stormy stay in Urbana. Warburg had been accustomed to work with highly trained technical assistants and only rarely with colleagues or even graduate students with independent opinions. He was Warburg and he was right. Emerson, at first modest and helpful in his usual way, and full of respect for his famous teacher and guest, also was a stubborn man, particularly when it came to devising experiments, a matter in which he felt he also had great experience and sound judgement. After several months of fitful attempts at collaboration, and an unsuccessful attempt for a third person's arbitration, Warburg left in anger, without saying good-bye.

Emerson followed this bitter experience with his painstaking research aimed at resolving the controversy.

For his part, Warburg never forgave Emerson—or the rest of the group, which he would refer to as the "Midwest Gang." Andrew Benson, the co-discoverer of the path of carbon in photosynthesis, with 1961 Nobel laureate Melvin Calvin, recalled recently: "On a beautiful afternoon I drove Otto Warburg and Herman Kalckar to 'Hamlet's Castle' at Helsingör. . . . Warburg peered through an iron gate into the darkness below, 'Ach, that's a perfect place for that Midwest Gang.'"[9] Martin Kamen, the co-discoverer of

radioactive carbon-14, has attributed Warburg's misconception about the minimum quantum requirement of four rather than eight per oxygen, to the "implementation of Liebling's Law," known in the field as "ILL"[10] Kamen paraphrased the famous reporter A. J. Liebling: "If you are smart enough and work hard enough, you can pick yourself up by the scruff of the neck and throw yourself on the street." Thus, according to Liebling's law, Warburg adopted a faulty premise that hardened into dogma and then into belief, despite its consequences. Warburg himself realized, and once told the late Birgit Vennesland: "Of course, I have made mistakes—many of them. The only way to avoid making any mistakes is never to do anything at all. My biggest mistake was to get much too much involved in controversy. Never get involved in controversy. It's a waste of time. It isn't that controversy itself is wrong. No, it can be even stimulating. But controversy takes too much time and energy. That's what's wrong about it. I have wasted my time and energy in controversy, when I should have been going on doing new experiments."[11]

By 1955, Emerson had uncovered the major causes of error in Warburg's measurements. In 1957 he published the discovery of the two-light effect in the *Proceedings of the National Academy of Sciences* (USA).[12] These experiments were conducted in a darkroom at the back of the labyrinth of rooms that one entered through the door to the Room 157. Ruth Chalmers, the technician, who was called "Shorty" (as she was short), grew the algae that Emerson used. Carl Cederstrand, a research assistant trained in physics, calibrated and checked all the instruments. Emerson's results were initially published in *Science* as abstracts (1956, 1956, 1957, and 1958); his major presentation was at the 1958 annual meeting of the Phycological Society of America, held in Bloomington, Indiana. Hardly any major photosynthesis researchers were present.

The discovery of the Emerson enhancement effect settled the controversy between Warburg and Emerson in favor of Emerson. The evolution of one oxygen molecule requires the transfer of four electrons in two steps, from two molecules of water to carbon dioxide. Since two primary light reactions are needed for oxygen evolution, it was easy to convince everyone that oxygen evolution needs a minimum of eight photons. Einstein had stated long ago that we need one photon to transfer one electron. Thus the transfer of four electrons twice requires eight photons, as Emerson asserted, not four, as Warburg had insisted, per oxygen. It is interesting that in spite of this, Warburg wrote in his notebook (now in the hands of Professor Dieter Oesterhelt in Munich, Germany): "Finally, Emerson has confirmed my results." (I have often wondered whether Warburg thought that

Portrait of Robert Emerson sitting at his desk in 157 Natural History Building, Matthews Avenue, Urbana, Illinois, in April 1957.

he, rather than Emerson, should have been the one to find the two-light effect and discover the Emerson enhancement effect!)

By 1963, Emerson's discovery was accepted by most workers in the field. Bessel Kok and André Jagendorf wrote: "Soon followed the observation by the late Emerson of the enhancement effect in which lights of two different wavelengths proved to exert a greater effect if given simultaneously than if given individually. This enhancement of the net rate was rationalized by the observation of a push-and-pull effect of two different colors upon intermediate catalysts of the process. . . . Every so often someone manages to remove another stone from the wall through which we all want to see, and the crowds tend to flock around the new peep-hole."[13] In this case, the stone was removed by Emerson, working in the inner rooms behind the door to Room 157 in the Natural History Building.

At the time this discovery was made, I was lucky enough to be in Urbana as one of Emerson's first-year graduate students. Although my desk was flush with the wall of the darkroom in which the discovery was made, I was totally unaware of the importance of this work—that is, until I finished my course work and started conducting experiments of my own. To my surprise, I learned that although Emerson's enhancement effect is real, his concept that one light reaction is run by chlorophyll *a* and the other by an auxiliary pigment had to be replaced by the concept, put forth in my doctoral thesis under Rabinowitch, that both light reactions are run by chlorophyll *a* of different spectral types.[14] We postulated there that certain short

wavelength-absorbing chlorophyll molecules bring about a primary photochemical process different from the one caused preferentially by the long wave quanta absorbed by another spectral form of chlorophyll *a*. Later, Rajni Govindjee, my wife since 1957, proved, with Rabinowitch in 1961, and then with me in 1964–65, that the Emerson enhancement does indeed occur in photosynthesis, not in respiration, as Larry Blinks suggested in 1957.[15]

On a personal level, although Emerson and Rabinowitch were great friends, they were poles apart in their appearance, personalities, and habits.[16] Emerson was tall, muscular, slim, and upright. He always had a ready smile on his face and he walked with such long strides that I had to jog to keep pace with him. He was often tense, strong-willed, fussy, and demanding, although still very polite.

He was a perfectionist in his experiments, which he always conducted himself. As a student I felt that he had eyes in the back of his head. His desk faced east; mine faced west. By listening to the sounds I produced while manipulating my instruments, he could tell exactly when I was not following the correct protocol. He would gently walk up to me and ask politely, "May I show you how to do this?"

Wearing a red tie tucked in his shirt, he would stand at the lathe making parts for his apparatus, or sit at a lab bench blowing glass or fixing the bank of lights used in growing algae. He had the patience to sit all day in darkness peering through cathetometers at the dancing minisci of liquid in the Warburg manometers. He did not believe in speculating too much and often checked his work twenty times or more before presenting the results. He was also a great carpenter. He built a crib for his grandchildren and a bed for his family.

Emerson and his wife Claire, whom everyone called Tita, were New Englanders. He was a grand nephew of Ralph Waldo Emerson; she came from a distinguished Boston family. Both were steeped in New England tradition. They were generous, yet thrifty. He would not use a university three-cent stamp for a letter that was not strictly written for university business. He would argue at the University Senate that professors should not strive for higher salaries. He believed in the value of working with one's own hands. After a long day of hard work in the laboratory, he would walk home along Matthews Avenue to 806 Main Street, and go right to work in his garden, weeding, digging, and pruning until dark.

During the summer months, the Emersons lived almost entirely from the produce in their backyard, "despising store-bought fruit, chicken and vegetables," as had Emerson's professor, Otto Warburg.[17] Raising chickens in the backyard did, however, cause some problems for Emerson. On

August 12, 1950, the Emersons received a letter from the city regarding complaints from the neighbors about the "chickens being raised on the premises at 806 W. Main, Urbana. Is there anyway that you can get along without these chickens? If so, I believe your neighbors would appreciate your removing them."[18]

The Emersons were very kind to students, especially international ones. On my first birthday in Urbana, Emerson cooked breakfast for me in the laboratory on the pretext that he wanted me to learn to cook so I would not starve in the United States. Rajni and I were often invited to their home for dinner. Once, when they asked Rajni to cook an Indian dish, Emerson watched her work, as he so often did in the lab. As she began to tap the pan with the stirring spoon to remove the food stuck to it, he smiled gently and said, "May I show you how to do this?" He proceeded to remove the food from the spoon with another spoon, making the tapping unnecessary. This is an example of his deep concern with doing everything properly. He and Tita both admired perfection in human labor.

Politically, Emerson was a pacificist and a democratic socialist. In the period following Pearl Harbor, when many Japanese Americans were held in concentration camps, his heightened sense of social injustice brought him into a concentration camp and led to his efforts to develop the desert shrub guayule as a source of rubber that could be produced under U.S. conditions, without exploiting native labor in Southeast Asia.[19] More generally, Emerson asked in 1951 (on notecards): "Does Science have a responsibility toward man or only toward his personal comfort, pride, what Orientals call 'occidental self gratification'?" His answer: "Science ought to serve primarily the man rather than his comforts. Science can be one of the ways, like music, poetry, painting in which man discovers his spiritual limitations, learns to put down his vanity & selfishness, makes himself and his fellows into higher rather than lower form of life. Do not worry about technology, I don't advocate return to dark ages."[20]

Distrusting airplanes, Emerson almost always took trains. He flew grudgingly to New York when the train there from Indianapolis was discontinued. February 4, 1959, was the saddest day for Rajni and me when the ill-fated Electra crashed into the frozen East River near La Guardia airport because of a faulty altimeter. Emerson had lived for only fifty-six years.

Emerson was highly regarded by U.S. scientists. In 1949 he was the recipient of the Stephen Hales Prize of the American Society of Plant Physiologists (now called American Society of Plant Biology) and he was elected in 1953 to the National Academy of Sciences. His long-term Harvard friend,

Eugene Rabinowitch sizing up his height with Govindjee's bride, Rajni Govindjee, Emerson's last student and later Rabinowitch's student, on October 24, 1957, at the reception in Urbana after the wedding.

the late Kenneth Thimann, wrote of Emerson: "Bob is not a man whom you can ever forget. In some way Bob was the very symbol of uprightness; he loved the truth just as much he loved the underdog, and he scorned the untruthful and could not have anything to do either with it or with the man who promulgated it. . . . Everyone who has come into contact with Bob must have been inspired by him to some degree; it is impossible not to be, just as it is impossible not to remember with clarity his every gesture, his ready smile—often belying fierce disagreement—his enormous ability for friendship and real tenderness. This is a kind of immortality—at least survival for another lifetime—in the memories and even to some extent in the characters of other people, which it is given to very few men to achieve."

In contrast with Emerson, Rabinowitch was short and round, his belt buckle buoyed up by his paunch. Whereas Emerson typically wore a red tie to work, Rabinowitch often wore a bow-tie. He walked with joviality and some difficulty. And he was easygoing, gentle, even-tempered, and hilarious. He had fun with his height. A photo taken after my marriage to Rajni shows Rabinowitch checking whether he was taller than her. He was standing on his tippy toes.

Rabinowitch led his group in an unobtrusive and loose-reined manner, never intimidating those who worked under him. T. T. Bannister wrote: "In

his lab, intellectual life was accompanied by frequent hilarity, to which Earl Jacobs' banjo playing and Stanley Holt's progress reports on brewing experiments beneath his children's cribs contributed, and the hilarity was often infectiously sustained by Eugene's chuckling laugh which geysers up in a body designed for mirth."

Rabinowitch and his wife Anya gave the most fantastic parties; full of fun and enjoyment. Anya made Vodka, starting with grain alcohol, with glycerine as lubricant, and zubrovka, a special polish herb, as a flavor enhancer. Often I was the bartender, liberally serving drinks to everyone, including myself. Anya's Russian hors d'oeuvres were out of this world, and she was great to Rajni and me.

I was struck by Rabinowitch's tolerance. When there was conflict within the group, he was always fair and kind to all involved. When one of his postdocs decided not to discuss his research with him verbally, instead placing written comments on his desk at night, Rabinowitch would painstakingly respond in writing. He would leave his written responses on the postdoc's desk day after day. Another postdoc would send his papers off to journals without including Rabinowitch's name or even showing the work to his mentor. Rabinowitch only learned of the work when it was rejected. At that point, he would sit down, correct it, and return it to the postdoc with a smile.

Unlike Emerson, who was in every way a master craftsman, Rabinowitch often had difficulty when he tried to perform experiments himself. Once, while trying to help a graduate student put rubber tubing over a glass tube, he cut two fingers and a thumb. On another occasion he created a monster when trying to blow a glass bulb for an experiment. He would sit for hours with paper and pencil at a small desk cramped into a corner of the old Room 156 that once existed in the Natural History Building. His mind was free-associating and wide-ranging, as well as extremely sharp and imaginative. He built his ideas from his vast knowledge of chemistry and physics.

Rabinowitch came to live in three parts of the world and to use three different languages—Russian, German, and English—for studying, speaking, and writing. In addition, he knew French. When I interviewed him on January 5, 1964, at his home in Champaign (1021 West Church Street), he told me, "When I was a boy and I was asked what I wanted to become in life, I used to say I want to be everything everywhere, and fate has arranged it for me." He was born and spent his first twenty-one years in what was then St. Petersburg, the capital of the Russian Empire. After the end of World War I, he found himself in Germany, where he studied at the Uni-

versity of Berlin, became a German scientist, and wrote books and articles in German. After Hitler came to power, his life shifted to the English-speaking world—first to England for five years and then from 1938 the United States.

He also shifted his field of activity. His Ph.D. thesis at the University of Berlin was in inorganic chemistry, on the volatile hydrides, particularly tin hydride. When he left Germany, he first went to the Niels Bohr Institute for Theoretical Physics. Then, in 1947, when he finally got his first regular academic appointment, at Illinois, it was as a research professor of botany. In due time, it became a joint appointment in botany and biophysics.

To his several languages and scientific fields, Rabinowitch added journalism, poetry, and architecture. He told me he thought it was an interesting way of life, adding:

> But unless one is really extraordinarily gifted so that one can combine great achievements in one field with considerable amateur achievements in other fields, as ideally it has been possible for people like Leonardo Da Vinci, or Goethe, one ends this kind of dissipation by having not achieved anything particularly important in any one of the fields. The enjoyment of certain creative work and familiarity with different fields of intellectual endeavor does not leave one with the feeling that one has really achieved anything really worthwhile in any one of them. Still, I wouldn't like to exchange this for a moderate achievement in any special field, say, being a representative in Congress, in politics; or being a member of a couple of academies in science; or having received some sort of prizes in exhibitions as an artist.

Rabinowitch was very much concerned with science policy and politics, as well as with the problem of achieving peace in the world. He was the coauthor of the famous Franck Report urging the U.S. government to refrain from using nuclear weapons against civilian populations. The report was submitted to Secretary of War Henry L. Stimson in June 1945, a month before the first test of the atomic bomb, in Alamagordo, New Mexico. He was also the cofounder of the Pugwash conferences (the first held in 1957), aimed at bringing peace between the Soviets and Americans. He was the cofounder and editor of the *Bulletin of Atomic Scientists*, which showed the famous "doomsday clock" on its cover. The recipient of the 1995 Nobel Peace Prize, Sir Joseph Rotblat, wrote in 1973, after the death of Rabinowitch: "Eugene Rabinowitch was a man of many facets: a scientist and a teacher; a classics scholar and a modern philosopher; a poet and a man of letters; a journalist and an editor; a sociologist and a politician. But his main characteristic was simply as a human being, with a warm heart, filled with love and tenderness, not only for his family and friends, but for the

whole of mankind. This love for humanity, and his profound belief in the potential of science to ensure a happy life for all, were the guidelines throughout his whole life, the philosophy on which all his activities were based."[21]

Rabinowitch would be recognized with many honors, including honorary doctorates from Brandeis University (1960), Dartmouth College (1964), Columbia College, Chicago (1970), and Alma College, Michigan (1970). His Dartmouth citation read: "one of the few generalists remaining in our time."[22] In 1966, he received the Kalinga Prize, for the popularization of science from The United Nations Educational, Scientific and Cultural Organization. In 1960, the Immigrant League of Chicago recognized him as the "outstanding citizen of foreign birth." In 1965, the University of Illinois recognized him by giving him full membership in its most distinguished academic body, the Center for Advanced Study. Three years later, in 1968, he retired from the University of Illinois, and accepted a position as professor of biology and chemistry at the State University of New York at Albany. In 1972, he received the Woodrow Wilson International Center for Scholars Fellowship. He was a member of the American Academy of Arts and Sciences, but not of the National Academy of Sciences. According to Rotblat "There are reasons to believe that this omission was a snub by the establishment for his involvement in many social and political activities, including Pugwash."[23]

Rabinowitch also wrote poetry in Russian. This work includes a self-epitaph:

> The game is up, for much too long I tarried;
> My thoughts were scattered and my deeds were tame.
> No earthly trace behind, I bring the loads I have carried
> Back into night and nothing whence I came.[24]

ACKNOWLEDGMENT

I thank Lillian Hoddeson for editing this chapter and Rajni Govindjee for reading it closely.

NOTES

1. Emerson published this work with his undergraduate student William Arnold (now famous for many other discoveries in light emission by plants). Arnold's daughter, H. A. Herron, later wrote, "Emerson did not stand on ceremony—not everyone would put an undergraduate's name as coauthor of an important paper. But when the experiment involved using a Warburg apparatus, Emerson trusted no one but himself to fill the vessels. So he routinely arrived early and set up the experiment; then Bill came in to take the readings and do the calculations. Hans Gaffron visited and was shocked. 'Arnold is

supposed to be your assistant,' he said to Emerson, 'but you are doing the assisting.'" Govindjee, R. S. Knox, and J. Amesz, eds., "William Arnold: A Tribute," *Photosynthesis Research* 48: 1–46.

2. E. Rabinowitch, *Photosynthesis and Related Processes*, vol. I, vol. II (part 1), and vol. II (part 2) (New York: Interscience Publishers, 1945, 1951, 1956).
3. The original office door of the Photosynthesis Project, which also included a chlorophyll chemist Stanley Holt, is now lost to history.
4. E. Rabinowitch and Govindjee, "The Role of Chlorophyll in Photosynthesis," *Scientific American* 213 (1965): 74–83.
5. On November 12, 1948, *Science* published Warburg's photograph on its cover, doing experiments in the Natural History Building laboratory.
6. Although Warburg was also a Jew, he was considered "safe" to work with because he had been declared only a 25 percent Jew (even though he was actually a 50 percent Jew, as his mother was Christian). Thus, Warburg was allowed to be the director of a research institute.
7. Govindjee, "On the Requirement of Minimum Number of Quanta of Light for the Evolution of One Molecule of Oxygen in Photosynthesis," *Photosynthesis Research* 59 (1999): 249–54. Govindjee, "Lighting the Path: A tribute to Robert Emerson (1903–1959)," S43-001 (six pages) available at ‹http://www.publish.csiro.au/ps2001›: PS2001 Proceedings of the 12th International Congress on Photosynthesis. On line and CD" ISBN 0643-067116.
8. E. Rabinowitch, "Robert Emerson (1903–1959)," *Biographical Memoirs of the National Academy of Sciences* 25 (1961): 112–31.
9. Andrew A. Benson, "Following the Path of Carbon in Photosynthesis: A Personal Story," *Photosynthesis Research* 73 (2002): 29–50.
10. M. D. Kamen, "Liebling's Law ('ILL')" *Proceedings of the American Philosophical Society* 139 (1995): 358–67.
11. Birgit Vennesland, "Recollections and Small Confessions," *Annual Review of Plant Physiology* 32 (1981): 1–20.
12. R. Emerson, R. V. Chalmers, and C. N. Cederstrand, "Some Factors Influencing the Long-wave Limit of Photosynthesis," Proceedings of the National Academy of Sciences, USA 43 (1957): 133–43.
13. Bessel Kok and Andre Jagendorf, "Photosynthetic Mechanisms of Green Plants," National Academy of Sciences and National Research Council, Washington, D.C., Publication 1145, 1963.
14. Govindjee and E. Rabinowitch, "Two Forms of Chlorophyll a with Distinct Photochemical Functions," *Science* 132 (1960): 355–56.
15. Rajni, whom I had known quite well in India, was a year junior to me when we were both M.Sc. students of Professor Shri Ranjan during 1955–56. Rajni joined Emerson as a fellow of botany in the fall of 1957, one year after I joined as a fellow of physico-chemical biology. When we were married on October 24, 1957, in the University YMCA chapel, both the Emersons and Rabinowitches attended our wedding. Govindjee, "Milestones in Photosynthesis Research," in *Probing Photosynthesis*, ed. M. Younis, U. Pathre, and P. Mohanty (London: Taylor & Francis, 2000), 9–39.
16. To illustrate, I have taken the liberty of freely using some words of T. T. Bannister, who took his Ph.D. under Rabinowitch. T. T. Bannister, "The Careers and Contributions of Eugene Rabinowitch," *Biophysical Journal* 12 (1972): 707–18.
17. H. Krebs, "Otto Heinrich Warburg 1883–1970," *Biographical Memoirs of the Fellows of the Royal Society* 18 (1972): 629–99.

18. City Attorney Gene D. Weisiger to Robert Emerson, August 12, 1950.
19. M. S. Nishimura, F. N. Hirosawa, and R. Emerson, "Rubber from Guayule," *Industrial and Engineering Chemistry* 39 (1947): 1477–85: I. Ashkenazy, "As the Guayule Ball Bounces": *Westways*, LXIX (September 1977): 56–60. A good part of this research was done at Manzanar Relocation Center of the War Relocation Authority. The U.S. Army is also thanked for administrative support.
20. Emerson, 1951; original in Emerson's handwriting, on note cards, with the author.
21. Sir Joseph Rotblat (2000) "Fifty Pugwash Conferences: A Tribute to Eugene Rabinowitch," ‹http://www.pugwash.org/reports/pac/pac256/rotblat.htm›.
22. A biography of Eugene Rabinowitch can be found at ‹http://library.albany.edu/speccoll/findaids/ger075.htm#bio›.
23. Rotblat, "Fifty Pugwash Conferences."
24. Bannister, "The Careers and Contributions of Eugene Rabinowitch."