NATIONAL ACADEMY OF SCIENCES

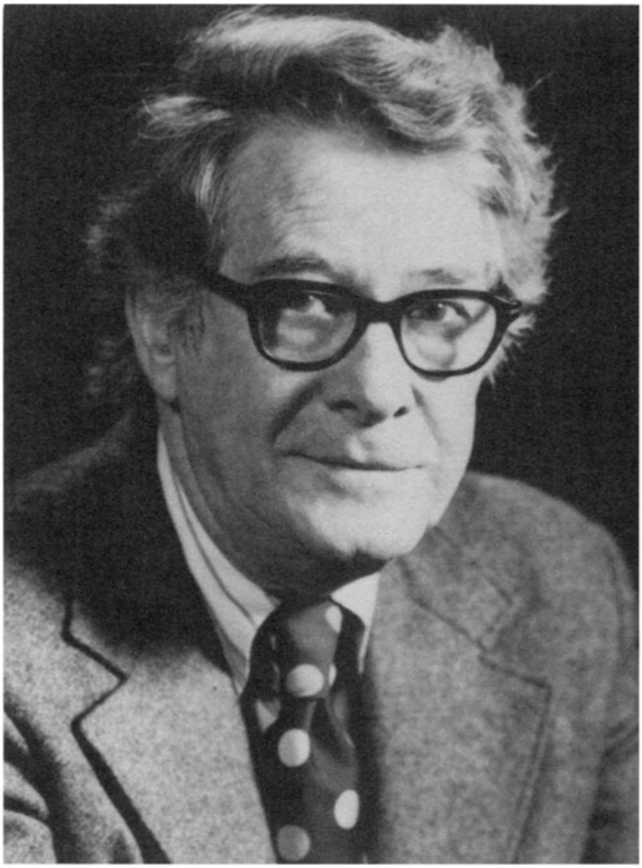
JOHN ROBERT RAPER

1911—1974

A Biographical Memoir by

KENNETH B. RAPER

Biographical Memoir



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JOHN ROBERT RAPER

October 3, 1911–May 21, 1974

BY KENNETH B. RAPER

PRIOR TO HIS UNTIMELY DEATH in 1974, John R. Raper was recognized as the foremost investigator of sexuality in the fungi. Beginning at the University of North Carolina in Chapel Hill and continuing at Harvard University, he gained wide recognition while still a graduate student for his imaginative researches on the hormonal control of sexuality in species of *Achlya,* a common genus of aquatic fungi. Further pioneering studies followed while he was a National Research Fellow at the California Institute of Technology and as a member of the botany staff at Indiana University; during World War II he was recruited as a radiation biologist for the Manhattan Project in Chicago and Oak Ridge. At the University of Chicago after the war, he further refined and extended his observations on the induction and regulation of sexual interactions in aquatic fungi by diffusible hormones that are produced in a sequential and invariant pattern. Then—as if sexuality in *Achlya* were too straightforward—he turned his attention to the more complicated phenomena in the higher fungi and chose as the primary object for experimentation a small wood-rotting basidiomycete, *Schizophyllum commune.* Following his return to Harvard in 1954, and for twenty years thereafter, John, his wife Carlene, and his students and associates were dedicated to understanding and revealing the bewildering intricacies of this complex system. They were singularly successful in this task, which led eventually to John's authoritative book, *Genetics of Sexuality in High Fungi.*

John R. Raper, the eighth child and seventh son of William Franklin and Julia Crouse Raper, was born on a farm near Welcome, North Carolina, on October 3, 1911. As the youngest in the family, he received special attention and consideration. But more was involved than his tender age: John was someone special, not just in our immediate household but in the community at large. He was handsome, he was smart, and he was talented. Whether he enjoyed performing before church and public school audiences, or whether he just accepted the role because it was expected of him, one cannot say. But perform he did, reciting in a singularly clear voice and singing with a tonal quality seldom heard in the rural community where we lived.

John was a lover of good music, a taste he acquired quite early and one that sustained him throughout his life. He grew up in a Moravian community where brass choirs were as much a part of special church services as were the "love-feasts," featuring coffee and hot cross buns. Although the latter delighted all of us, the music must have held a special fascination for John, for he was playing the trumpet almost by the time he could hold a horn to his lips. His proficiency with the instrument increased steadily: by the time he was a student at the university in Chapel Hill—and first trumpet in the newly organized North Carolina Symphony—he was seriously considering music as a profession. Fortunately, he chose biology—not that he would have been a poor musician, but fortunately because otherwise he could not have made the important discoveries and contributions that marked his career in science.

Concerning his childhood and adolescence, John has written in part:

My father had suffered a massive heart attack before my birth and I never knew him as a robust man. The hard work on the farm and largely the direction of its operations were thus left to my older brothers, each of whom in turn went away to high school (there being none locally), then college, and soon thereafter developed careers elsewhere. In the matter of education and independent development there was every possible encouragement from home save appreciable financial assistance. Born during the Civil War, my father was unable to secure the education and training he desired, and feeling that he had been trapped by circumstances, did what he could to insure that his children obtain the education he had been denied. Mother's attitude was somewhat different. Having grown up on a highly productive farm, her greatest wish was that one of her sons would take over the farm and operate it efficiently. No one of the seven accepted the challenge.

Most of our social activities revolved around the public school and three churches, Friedberg and Enterprise, Moravian, and Mt. Olivet, Methodist, among which the family membership oscillated. Services were attended by the whole family, occasionally at all three on the same Sunday! Our home was bone dry and dancing and card playing were not encouraged. As the youngest member of this rather strict paternalistic family, I was always the object of much affection if not frivolity.

My first four years of school were spent in a 3-room school with no pretensions beyond the elementary level. At this time, a new, consolidated school (for which my father was a leading organizer and donor of the building site) was opened, and my further education through high school was received there. Aside from two years in the fifth grade—for reasons never learned—secondary school was reasonably uneventful, and I graduated from high school in 2nd or 3rd place in a class of 11. I was not good in sports or in other extra-curricular activities, such as dramatics, for which some rudimentary opportunities were provided. I was reasonably proficient with the trumpet, but the school, with neither musical instruction nor performing groups, provided no outlet for musical expression. English grammar and literature were my preferred subjects, and French was enjoyable. Science instruction was very rudimentary and generated only mild interest.

About this time, cows became very prominent in my life. With the successive defection of my older brothers, there was no longer the labor force necessary to continue intensive tobacco farming, and a herd of miscellaneous cows became a major source of farm revenue. All through high school, usually with the help of a hired man, the care, feeding and milking of the cows was a constant preoccupation. Otherwise, I read avidly and widely and a reasonably good library at Winston Salem, some 10 miles distant, was routinely visited about once a week. It was there also that I discovered serious music *via* the record department of a furniture store in which an uncle worked; all available cash for some years went into classical recordings.

Poorly prepared, and under considerable stress, my first year at the University of North Carolina was quite difficult, and it was made more so by the necessity of working 30–40 hours per week. In the spring quarter, however, my first science course, Introductory Botany under Professor John N. Couch, kindled an intense interest such as I had not previously known. In the second year, more botany and introductory zoology sustained and heightened this interest, and the offer of a teaching assistantship in the Department of Botany for the following year was recognized as an opportunity to indulge more fully my newfound interest. Aside from a passing flurry of musical activity (see above), there has been no subsequent significant distraction from the pursuit of scientific interests. Major influences throughout this period in determining the selection of a particular field of specialization were the enthusiasm and dedication of three teachers with whom I early worked: John N. Couch and William C. Coker of the University of North Carolina and William H. Weston of Harvard. Kenneth Raper's influence was also considerable during my student days.

John's first contribution to science (1936) was an attempt to determine the pattern of sexual interaction between self-sterile strains of *Achlya bisexualis,* a heterothallic water mold, previously described by Coker. Approximately 500 new collections—mostly from streams and ponds near Chapel Hill—were examined; of these 500, 32 were self-sterile. Of the latter, 27 were identified as *A. bisexualis* and could be classified as female (8), male (7), and hermaphroditic-female (12). The last were of special interest because in the presence of strong males they behaved as true females.

In the autumn of 1936, John transferred to Harvard University and, as the recipient of an Austin Teaching Fellowship, resumed his researches on *A. bisexualis* under the guidance of Professor Weston. About a year later he isolated from the Charles River several cultures of a new and even more interesting *Achlya* that he described as *A. ambisexualis*. This specific name was chosen because some of the isolates possessed both male and female potential and could behave as either sex, depending on the stronger sexual character of a paired mate. For this and other reasons, increased attention was subsequently given to the latter species. It soon became clear that the mating process consisted of a number of well-defined steps or stages, that these occurred in an orderly and invariant sequence, and that each was associated with a visually evident developmental change in the paired culture. Additionally, because the stages appeared reciprocally in the two plants (thalli), and with these generally separated by some distance, it was reasonable to surmise that the successive changes observed in one plant were induced by diffusible substances, or hormones, produced by the other. Subsequent researches involving selected cultures and interspecific crosses amply confirmed this supposition; they also provided the first unequivocal proof of hormonal, or pheromonal (alternate term), control of sexual reproduction in lower plants. In fact, if one wished to demonstrate "courtship" in plants, no better example exists than that of the interacting male and female thalli of the water mold *Achlya*—which John so carefully described and so beautifully illustrated some forty years ago.

The sexual process in *Achlya* was shown to proceed in this manner. When strong male and female strains were implanted at some distance in an agar plate—or when they were grown on halved hemp seed floating in water—the terminal areas of the male hyphae began to branch profusely as the thalli approached each other. (The branches [antheridial] were quite thin, highly ramified, and at this first stage randomly distributed.) In the second stage, several hours later, the female hyphae nearest the activated male began to swell terminally or to produce short, lateral, club-shaped branches that in a few hours enlarged to form globose structures (oogonial initials). In the third stage the antheridial hyphae grew toward the oogonial initials and on reaching their surfaces became appressed against them. The fourth stage was again expressed by the antheridial hyphae. Soon after these applied themselves against the oogonial walls, protoplasm accumulated in their tips and transverse walls were laid down to delimit the male gametangia, or antheridia. The fifth stage followed soon thereafter and was marked by the appearance of crosswalls that delimited the swollen termini of the female hyphae and their club-shaped branches. The spherical structures thus formed were the oogonia, or female gametangia. Whereas elapsed time varied appreciably depending on cultural and environmental conditions, the entire process could be completed in thirty to thirty-six hours on agar—or in appreciably shorter periods when plants were cultivated in water. In either case the sequence was the same, and the intervals between stages were proportional. The reciprocating responses, and the markedly shorter time necessary for stage one to be expressed in water, strongly indicated that the formation of the antheridial branches was dependent upon some substances produced by the vegetative female plant; this in turn suggested that the female initiated the entire sexual process. These suppositions were then confirmed in different ways.

In one experiment male and female plants were separated by permeable membranes, either in the form of tubes or as sheets laid under the agar for some distance and then bent upward at 90 degrees. When the plants arrived at positions on opposite sides of the membranes, the male plant began to produce antheridial hyphae; six to eight hours later, oogonial initials were seen to emerge on the female plant, and as these matured the antheridial hyphae grew toward them and spread outward on the membrane nearest the oogonial initials. In another experiment, male and female plants were grown separately on halved hemp seeds in petri dishes. When these reached maturity, the water was drained off and fresh water was added and allowed to remain for twenty-four hours. Liquid from these vessels was then drawn through Seitz filters and added to plants of the opposite sex. Antheridial hyphae appeared on the male plants at seven hours and were very abundant at twelve hours. The response of female plants was less rapid but nonetheless positive. A perfusion experiment was the most dramatic of all. It was accomplished with a series of four connected micro-aquaria through which water flowed at a constant rate. The experiment was described in this way:

> In the first cell were placed two vegetatively mature female plants of *Achlya ambisexualis;* in the second, two male plants of that species; in the third, two females; and in the fourth, a single male. Beginning about 5–6 hours after the introduction of the plants, a few antheridial hyphae were formed on the male plants in cells 2 and 4, but no reaction was given by the female plants in cell 3.
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> Accordingly this experiment was repeated, but two female plants of *A. bisexualis* were placed in the first cell, since, as previously found, the male of *A. ambisexualis* reacts more strongly to this than to female plants of the same species; the plants in the remaining three cells were selected as before. Approximately 3 hours after the introduction of the plants, the male in cell 2 was seen to be reacting strongly. Two hours later the male plant in cell 4 was reacting vigorously. Twelve to fourteen hours after the initiation of the female reaction in cell 2, oogonial initials began to appear scattered over the entire female mycelium in cell 3. Following the beginning of the male reaction, directional growth of antheridial hyphae in the vicinity of the siphon tip in cell 4 began to take place, and at the end of another day this directional growth was fairly pronounced.

From these and other studies John concluded that four major hormones, alternately produced by the female and male plants, were responsible for initiating and regulating the sexual process in *Achlya*. These were designated hormones A, B, C, and D; they were characterized as follows: hormone A, produced by the mycelium of the female plant, induces the formation of antheridial hyphae on the male; hormone B, produced by the antheridial hyphae of the male plant, induces the formation of oogonial initials on the female; hormone C, produced by the oogonial initials, attracts antheridial hyphae to themselves and promotes delimitation of antheridia; and hormone D, produced by the antheridia, causes delimitation of the oogonia and subsequent differentiation of oospheres. For technical reasons, fertilization and maturation of oospheres could not be followed.

Upon receiving his doctorate from Harvard, John was awarded a National Research Fellowship. He subsequently went to work with Professor A. J. Haagen-Smit at the California Institute of Technology, his avowed purpose being to isolate and, if possible, chemically characterize hormone A. In this he was partially successful. Much was learned about the properties of hormone A: "a final fraction, weighing 0.0002 g and still impure, contained 37 percent of the initial hormone-A activity of 1,440 liters of filtrate from female plants and induced antheridial hyphal formation when tested in a dilution of 1/10,000,000,000,000." For several reasons—economic and otherwise—the work could not be continued at that time, but a very small amount of hormone-A concentrate was retained for future study. Not until a quarter of a century later was hormone A finally isolated and characterized by Trevor McMorris and Alma Barksdale at the New York Botanical Garden. It was found to be a sterol and renamed *antheridiol,* the first steroid hormone found in plants. It is of more than passing interest that in the course of their work they reexamined a concentrate of hormone A that John had sealed in a vial in 1943; upon assay, they found that little of its activity had been lost. More recently, McMorris and coworkers have resolved hormone B into three steroidal compounds, which have been designated oogoniol-1, oogoniol-2, and oogoniol-3.

Work on *Achlya* continued when John was at Indiana University; it was resumed when he returned to Chicago after the war. There at the university important events transpired, and about one of these he tells this story:

> During my first year at the University of Chicago after the war years as a radiobiologist, work was continued on the hormonal action of hormone A and the physiology of antheridial induction in *Achlya*. For this work, there was available a pitifully small supply of hormone A of high purity and standardized activity, and this vial of standard was dear to my heart—it being used only in critical experiments and then only in 0.01 ml portions.
>
> Imagine my horror upon returning from a lecture to find my assistant, a fair-haired, first-year graduate student (Carlene Allen), on her hands and knees in the middle of the laboratory sucking up this precious liquid with a tiny pipette. She had dropped the bottle, which had broken, and had intuitively gone about the rational business of recovering what she could of the hormonal solution with the equipment at hand. In a mixture of shock at the obvious carelessness on the one hand and my admiration of her initiative in making the best of a totally unnecessary and bad situation on the other, I could only urge the completion of the task and enjoin her not to cry over spilt hormone. There was, of course, no possibility of precise comparison of the activity of the recovered hormone with the original, and it may well be that the quantitative aspects of the work with *Achlya* underwent a slight discontinuity as a result of the accident.
>
> Forgiveness, however, was apparently not too difficult. Perhaps my failure to erupt into the violent display of temper that had been suggested in earlier and far less serious situations convinced her that I might be human after all. In any event, a couple of years later we were married, but over the years I've come to appreciate the monicker of "Spilly" bestowed on her by her family at a very early age.

Following their marriage, Carlene continued to work with John in the laboratory and soon became a full partner in his researches. In the years after his death, she obtained her doctorate from Harvard University and developed an independent research career centered upon the genetics of higher fungi.

In the early 1950s, John's attention began to shift increasingly to a quite different area of experimental mycology: the analysis of tetrapolar sexuality in the Basidiomycetes. Hans Kniep, H. R. R. Buller, and others had outlined the broad picture of the genetic control system and the developmental sequence from spore to spore. Additionally, Haig Papazian, one of John's students, had expanded this work and discovered several unusual features, including the appearance of rare, new, mating types, presumably as a result of recombination; the existence of hemi-compatible heterokaryons; and the frequent occurrence of morphological mutations in certain of the heterokaryons. Intrigued by these discoveries and impelled by his deep interest in the sexuality of all fungi, John spent the remainder of his professional career probing every facet of the biology of the Basidiomycetes, particularly *Schizophyllum commune*. Among the problems he addressed were the analysis of the genetic fine structure of the incompatibility system, the biochemical mechanism of incompatibility in the Basidiomycetes, the genetics of fruiting, the mutational dissection of the morphogenetic sequences of heterokaryosis, and the physiological consequences of compatible and incompatible mycelial interactions. His efforts and those of an ever-expanding group of students and associates raised *S. commune* to prominence as the best-understood representative of the Basidiomycetes; his laboratory, then at Harvard University, became a mecca for research in experimental mycology of the higher fungi. Some highlights of the *Schizophyllum* research conducted there are briefly noted below.

John demonstrated in great detail the immensity of the allelic alternatives of the incompatibility genes present in the worldwide population of *S. commune,* and he projected that no fewer than 20,000 resulting mating types had arisen during the evolution of the species. He proved the complex nature of both the A and B incompatibility mating type factors, and proposed a more refined picture of the requisites for sexual compatibility in terms of the α and β subloci that he had defined as mating genes for these factors.

He also provided evidence for the nature of each of these four incompatibility genes as regulators of development in the sexual cycle leading to mushroom production and sexual spore formation. He and his collaborators analyzed the complexity of these genes through mutational dissection. They demonstrated that single mutations in a mating-type gene could result in loss of allelic specificity and constitutive function of the relevant developmental pathway. This produced a homothallic, self-fertile mutant (a combination of two such mutations, one an *A* mating-type gene and one a *B* mating-type gene, converts the heterothallic mycelium to a homothallic mutant). He demonstrated further that secondary mutations in these mating-type loci resulted in a variety of regulatory alterations. These ranged from a near wild-type, nonparental allele capable of initiating a normal developmental pathway, through degrees of regulatory deficiencies of the pathway, to complete loss of function in which the genes are deleted. The latter have no allelic specificity and no capability of initiating sexual development. He and his associates also identified eighty loci, in all parts of the genome, which come to expression only when the development in the sexual cycle is initiated by the incompatibility genes. These loci were recognized in mutant form as modifiers of the normal course of development.

He assigned specific regulatory functions to each genetic factor—for example, nuclear migration by the two genes of the B factor, and clamp connection initiation by the two genes of the A factor. And he pushed our understanding of each of these processes to substantially higher levels of cytological and biochemical understanding. The hemi-compatible heterokaryons took their place along with the dikaryon and the homokaryon as well-defined developmental states with their own distinctive phenotypes and potentialities for exploitation in research.

John initiated the first series of attempts, using immunological as well as electrophoretic techniques, to identify the biochemical products of incompatibility interactions and thereby the physiological mechanisms of tetrapolar sexuality. His efforts to unravel the mating type system and its consequences led him into various related areas of the biology of *S. commune:* he investigated the inheritance of fruiting competence in dikaryotic strains and identified polygenic as well as single-gene controls over fruiting; he studied the origin and expression of morphological mutations that appeared within both homokaryotic and heterokaryotic mycelia and characterized a large number of these mutants; he devised techniques for dedikaryotization of established dikaryons; and he studied the kinetics of nuclear migration within hyphae and identified some of the physiological conditions underlying this process.

It was not just the sum of his work that was impressive but also the ingenuity and artistry of its style, design, and execution. He enjoyed utilizing the unique biological features of an organism to devise experiments for elucidating unsolved questions. He kept abreast of the latest advances in genetics, microbiology, and biochemistry and applied these toward the solution of problems relating to sexual development. He seized upon every seemingly irrelevant result in his search for clues and practical means for experimentation, and he carefully weighed each bit of information that accrued, recognizing in them valuable pieces of the larger puzzle. He probably knew that ultimate solutions would be unattainable within his lifetime, but he blazed a new and highly rewarding trail among eukaryotic, mycelial organisms—and he stimulated a great many others to follow his lead.

For three years during World War II, John's mycological researches were interrupted while he worked as an associate biologist in the Manhattan Project's Plutonium Division in Chicago and Oak Ridge, Tennessee. He was chosen for his reputation as an innovative scientist who was capable of pioneering in a totally new area of radiation biology. Investigations for the project centered on the effects of irradiating laboratory animals with beta and gamma rays, such tests commonly representing total body exposure to beta irradiation. Because limited information existed at the outset, the studies involved different isotopes; measurement of beta and gamma emissions; comparisons of type and geometry of radiation sources; fashioning of suitable exposure chambers; and standardizing terminology and methods of recording data so that dosage effects could be compared in different animals with regard to growth, health, and carcinogenesis. Without attempting to cite specific information concerning the tests, it was observed that when different animals were subjected to sublethal doses of total surface beta irradiation, some species (rats and mice) showed a significantly higher incidence of tumor formation than did others (rabbits and guinea pigs). And on the basis of absorbed energy, gamma rays were 1.75 times more effective than beta rays in producing lethality. Out of this exploratory work came a total of fifteen papers by John and his coworkers, published mostly as chapters in *Biological Effects of External Beta Radiation* (National Nuclear Energy Series, Div. IV, vol. 22E [1951]). Out of it also came a man chastened by the experience and frightened by the implications of what he had learned.

Not only was John imaginative in designing experiments, but he was innovative in improving culture methods and in fashioning needed instruments as well. While still in Chapel Hill he devised a method for freeing *Achlya* of the aerobic bacteria that always accompany it in nature. The method—which was simple and effective—consisted of allowing hyphae to grow downward through agar, pass under a vertical barrier, and grow back to the surface on the opposite side. Clean hyphal tips were then excised and recultivated. When work on *Schizophyllum* required the isolation of large numbers of single spores with no possibility of duality, John designed a small conical cutter (fashioned of stainless steel) that he mounted on a swinging arm attached to a metal collar fitted on a Leitz 6.3 × microscope objective. The cutter, which was 1.0 mm in diameter, could be accurately positioned over the microscope field by means of centering screws; it was activated by a spring cable release. Viewing with 20 or 25 × oculars, one could isolate spores almost as rapidly as they could be located, each atop a small agar plug waiting to be removed with a chisel-shaped needle. He was also coinventor of a cell press, which was similar to the French press but with much greater capacity. It was especially suitable for preparing large quantities of cell-free extracts in a well-preserved condition.

John was also a skilled photographer and master draftsman whose illustrations not only graced his own publications but those of other authors as well. For example, copies of delicately executed line drawings of *Achlya* appear on the covers of books by J. T. Bonner and by H. van den Ende. He was no less creative at home: in his basement workshop he fashioned many pieces of furniture—chairs, tables, chests, etc.—not to mention smaller pieces such as lamps, sconces, and decorative objects that he not only used but shared liberally with his less creative brothers, sister, and friends. John and his wife were especially fond of classical music, and he equipped his home with excellent facilities for playing records and tapes, of which he had a large and varied collection. He enjoyed good food, and he was adept in preparing special dishes that on occasion were served to house guests with obvious joy and pride. Thanksgiving at the John Rapers' was a warm tradition well remembered by several generations of students who couldn't make it home for the holiday. A bountiful dinner was always preceded by a walk around Thoreau's Walden Pond; it was followed by listening to music before an open fire.

John was a man of many talents who enjoyed life thoroughly and who enriched the lives of all the people who knew him—commonly serene, sometimes impulsive, occasionally quixotic, but never dull. In recognition of his outstanding accomplishments, John received many honors. He was awarded a Guggenheim fellowship and a Fulbright scholarship to carry on researches in Germany in 1960 and 1961, and he received the Award of Merit of the Botanical Society of America in 1969. He served as vice-president and president of the Mycological Society of America, and he was a fellow and secretary of the American Academy of Arts and Sciences. (As the holder of that office, he signed the letter of felicitation sent by that Academy on the occasion of the centennial of the National Academy of Sciences in 1963.) He was elected to the National Academy the following year. Active in university affairs, he was nearing the end of a four-year term as chairman of the Department of Biological Sciences of Harvard University at the time of his death.

John died on May 21, 1974, after a brief illness. Quite fittingly a memorial service was held in Harvard's Memorial Chapel that consisted primarily of choral music by J. S. Bach, Monteverdi, and Vittoria.

He is survived by his wife and coworker, Carlene; his son

Jonathan, a developmental neurobiologist and recipient of an appointment as research scientist at the Max Planck Institut für Virusforschung in Tübingen, Germany; his daughter Linda Carlene, a professional quilt artist; and, by a previous marriage, his son William, a high school teacher.

THE WRITER WISHES to express his appreciation to his brother John for having deposited with the Academy comments and reminiscences concerning his childhood and early adult life; to his wife, Dr. Carlene Raper, for his portrait and for her counsel and suggestions; and to Dr. T. J. Leonard for summarizing John's studies of sexuality in the higher Basidiomycetes.

BIBLIOGRAPHY

1936

Heterothallism and sterility in *Achlya* and observations on the cytology of *Achlya bisexualis*. J. Elisha Mitchell Sci. Soc., 52:274–89.

1937

A method of freeing fungi from bacterial contamination. Science, 85:342.

1939

Role of hormones in the sexual reaction of heterothallic *Achlyas*. Science, 89:321–22.

Sexual hormones in *Achlya*. I. Indicative evidence for a hormonal coordinating mechanism. Am. J. Bot., 26:639–50.

1940

Sexuality in *Achlya ambisexualis*. Mycologia, 32:710–27.

Sexual hormones in *Achlya*. II. Distance reactions, conclusive evidence for a hormonal coordinating mechanism. Am. J. Bot., 27:162–73.

1942

Sexual hormones in *Achlya*. III. Hormone A and the initial male reaction. Am. J. Bot., 29:159–66.

With A. J. Haagen-Smit. Sexual hormones in *Achlya*. IV. Properties of hormone A of *Achlya bisexualis*. J. Biol. Chem., 143:311–20.

Sexual hormones in *Achlya*. V. Hormone A′, a male-secreted augmenter or activator of hormone A. Proc. Natl. Acad. Sci. USA, 28:509–16.

1947

Effects of total surface beta irradiation. Radiology, 49:314–24.

1950

Beta rays: Biological effects. In: *Medical Physics*, vol. 2, ed. Otto Glasser, pp. 66–71. Chicago, Ill.: The Year Book Publishers.

Sexual hormones in *Achlya.* VI. The hormones of the A-complex. Proc. Natl. Acad. Sci. USA, 36:524–33.

Sexual hormones in *Achlya.* VII. The hormonal mechanism in homothallic species. Bot. Gaz., 112:1–24.

1951

Sexual hormones in *Achlya.* Am. Sci., 39:110–20.

Chemical regulation of sexual processes in fungi. In: *Plant Growth Substances,* ed. F. Skoog, pp. 301–13. Madison: University of Wisconsin Press.

With R. E. Zirkle and K. K. Barnes. Techniques of external irradiation with beta rays. Natl. Nuclear Energy Ser. Div., IV-22E:1–41.

With J. E. Wirth and K. K. Barnes. Gross effects of beta irradiation on restricted surface of rabbits. Natl. Nuclear Energy Ser. Div., IV-22E:42–61.

With R. E. Zirkle and K. K. Barnes. Comparative lethal effects of external beta irradiation. Natl. Nuclear Energy Ser. Div., IV-22E:62–76.

With K. K. Barnes. Gross effects of total-surface beta irradiation. Natl. Nuclear Energy Ser. Div., IV-22E:77–109.

With K. K. Barnes. Rate of recovery from total-surface beta irradiation. Natl. Nuclear Energy Ser. Div., IV-22E:110–20.

With K. K. Barnes. Additivity of lethal effects of external beta and gamma irradiation (I). Natl. Nuclear Energy Ser. Div., IV-22E:121–29.

With K. K. Barnes. Additivity of lethal effects of external beta and gamma irradiation (II). Natl. Nuclear Energy Ser. Div., IV-22E:130–36.

With R. S. Snider. Histopathological effects of single doses of total-surface beta radiation on mice. Natl. Nuclear Energy Ser. Div., IV-22E:152–78.

With K. K. Barnes. Effects of external irradiation with beta rays on the peripheral blood of rabbits. Natl. Nuclear Energy Ser. Div., IV-22E:179–84.

With J. E. Wirth. Reactions of human skin to single doses of beta rays. Natl. Nuclear Energy Ser. Div., IV-22E:193–99.

With P. S. Henshaw and R. S. Snider. Delayed effects of single exposures to external beta rays. Natl. Nuclear Energy Ser. Div., IV-22E:200–11.

With P. S. Henshaw and R. S. Snider. Effects of periodic total-surface beta irradiation. Natl. Nuclear Energy Ser. Div., IV-22E:212–26.

1952

Chemical regulation of sexual processes in the Thallophytes. Bot. Rev., 18:447–545.

1953

Tetrapolar sexuality. Q. Rev. Biol., 28:233–59.

1954

With J. P. San Antonio. Heterokaryotic mutagenesis in Hymmenomycetes. I. Heterokaryosis in *Schizophyllum commune.* Am. J. Bot., 41:69–86.

Life cycles, sexuality, and sexual mechanisms in the fungi. In: *Sex in Microorganisms,* pp. 42–81. Washington, D.C.: American Association for the Advancement of Science.

1955

Some problems of specificity in the sexuality of plants. In: *Biological Specificity and Growth,* ed. E. G. Butler, pp. 119–40. Princeton: Princeton University Press.

Heterokaryosis and sexuality in fungi. Trans. N.Y. Acad. Sci. (II), 17:627–35.

1956

With P. G. Miles and H. Lund. The identification of indigo as a pigment produced by a mutant culture of *Schizophyllum commune.* Arch. Biochem. Biophys., 62:1–5.

With P. G. Miles. Recovery of the component strains from dikaryotic mycelia. Mycologia, 48:484–94.

1957

Hormones and sexuality in lower plants. Symp. Soc. Exp. Biol., 11:143–65.

1958

With G. S. Krongelb and M. G. Baxter. The number and distribution of incompatibility factors in *Schizophyllum.* Am. Nat., 92:221–32.

With M. G. Baxter and R. B. Middleton. The genetic structure of the incompatibility factors in *Schizophyllum commune.* Proc. Natl. Acad. Sci. USA, 44:889–900.

With P. G. Miles. The genetics of *Schizophyllum commune.* Genetics, 43:530–46.

With J. P. San Antonio and P. G. Miles. The expression of mutations in common-*A* heterokaryons of *Schizophyllum commune.* Z. Vererbungsl., 89:540–58.

With G. S. Krongelb. Genetic and environmental aspects of fruiting in *Schizophyllum commune* Fr. Mycologia, 50:707–40.

With P. J. Snider. Nuclear migration in the Basidiomycete *Schizophyllum commune.* Am. J. Bot., 45:538–46.

1959

Sexual versatility and evolutionary processes in the fungi. Mycologia, 51:107–25.

Schizophyllum umbrinum Berkeley in culture. Mycologia, 51:474–76.

1960

The control of sex in fungi. Am. J. Bot., 47:794–808.

With M. G. Baxter and A. H. Ellingboe. The genetic structure of the incompatibility factors of *Schizophyllum commune:* The *A*-factor. Proc. Natl. Acad. Sci. USA, 46:833–42.

With Y. Parag. Genetic recombination in a common-*B* cross of *Schizophyllum commune.* Nature, 188:765–66.

Tetrapolarity in *Schizophyllum fasciatum.* Mycologia, 52:334–36.

1961

With S. Dick. Origin of expressed mutations in *Schizophyllum commune.* Nature, 189:81–82.

With K. Esser. Antigenic differences due to the incompatibility factors in *Schizophyllum commune.* Z. Vererbungsl., 92:439–44.

Incompabilität bei den Basidiomyceten *Schizophyllum commune.* Ber. Dtsch. Bot. Ges., 74:326–28.

Parasexual phenomena in Basidiomycetes. In: *Recent Advances in Botany,* pp. 379–83. Toronto: University of Toronto Press.

1962

With A. H. Ellingboe. Somatic recombination in *Schizophyllum commune.* Genetics, 47:85–98.
With A. H. Ellingboe. The Buller phenomenon in *Schizophyllum commune:* Internuclear selection in compatible dikaryotic-homokaryotic matings. Am. J. Bot., 49:545–49.
With M. T. Oettinger. Anomalous segregation of incompatibility factors in *Schizophyllum commune.* Rev. Biol. (Lisbon), 3:205–21.

1963

Patterns of sexuality in fungi. Mycologia, 55:79–92.
With E. A. Hyatt. Modified press for disruption of microorganisms. J. Bacteriol., 85:712–13.
Device for isolation of spores. J. Bacteriol., 86:342–44.
With G. N. Bistis. Heterothallism and sexuality in *Ascobolus stercorarius.* Am. J. Bot., 50:880–91.

1964

With K. Esser. The fungi. In: *The Cell,* ed. J. Brachet and A. E. Mirsky, vol. 6, pp. 139–244. New York: Academic Press.
With C. A. Raper. Mutations affecting heterokaryosis in *Schizophyllum commune.* Am. J. Bot., 51:503–12.

1965

With D. H. Boyd and C. A. Raper. Primary and secondary mutations at the incompatibility loci in *Schizophyllum.* Proc. Natl. Acad. Sci. USA, 53:1324–32.
With P. J. Snider. Nuclear ratios and complementation in common-*A* heterokaryons of *Schizophyllum commune.* Am. J. Bot., 52:547–52.
Introduction. In: *Incompatibility in Fungi,* ed. K. Esser and J. R. Raper, pp. 1–6. Berlin: Springer-Verlag.
With J. T. Mullins. Heterothallism in biflagellate aquatic fungi: Preliminary genetic analysis. Science, 150:1174–75.

1966

Life cycles, basic patterns of sexuality and sexual mechanisms. In: *The Fungi (II),* ed. G. C. Ainsworth and A. S. Sussman, pp. 473–511. New York: Academic Press.

With Y. Koltin. *Schizophyllum commune:* New mutations in the *B* incompatibility factor. Science, 154:510–11.

Genetics of Sexuality in Higher Fungi. New York: Ronald Press.

With C. A. Raper. Mutations modifying sexual morphogenesis in *Schizophyllum.* Genetics, 54:1151–68.

1967

The role of specific secretions in the induction and development of sexual organs and in the determination of sexual affinity. In: *Handbuch der pflanzen Physiologie,* ed. H. F. Linskins, vol. 18, pp. 214–34. Heidelberg, Berlin, and New York: Springer-Verlag.

With Y. Koltin and G. Simchen. Genetic structure of the incompatibility factors of *Schizophyllum:* The *B* factor. Proc. Natl. Acad. Sci. USA, 57:55–62.

With Y. Koltin. The genetic structure of the incompatibility factors of *Schizophyllum commune:* Three functionally distinct classes of *B* factors. Proc. Natl. Acad. Sci. USA, 58:1220–26.

With Y. Koltin. The genetic structure of the incompatibility factors of *Schizophyllum commune:* The resolution of class III factors. Mol. Gen. Genet., 100:275–82.

1968

With M. Raudaskowski. Secondary mutations at the *Bβ locus of Schizophyllum.* Heredity, 23:109–17.

With C. A. Raper. Genetic regulation of sexual morphogenesis in *Schizophyllum commune.* J. Elisha Mitchell Sci. Soc., 84:267–73.

On the evolution of fungi. In: *The Fungi (III),* ed. G. C. Ainsworth and A. S. Sussman, pp. 677–93. New York: Academic Press.

With Y. Koltin. Dikaryosis: Genetic determination in *Schizophyllum.* Science, 160:85–86.

Steroid sexual hormones in a water mould. Proc. Sect. Sci. Isr. Acad. Sci. Humanit., 11:1–8.

1969

With C.-S. Wang. Protein specificity and sexual morphogenesis in *Schizophyllum commune.* J. Bacteriol., 99:291–97.

With T. J. Leonard. *Schizophyllum commune:* Gene controlling haploid fruiting. Science, 165:190.

1970

Chemical ecology among lower plants. In: *Perspectives in Chemical Ecology,* ed. E. Sondheimer, pp. 21–43. New York: Academic Press.

With A. S. Flexer. The road to diploidy with emphasis on a detour. In: *Organization and Control in Prokaryotic and Eukaryotic Cells,* ed. H. P. Charles and B. C. J. G. Knight, pp. 401–32. New York: Cambridge University Press.

With J. H. Perkins. Morphogenesis in *Schizophyllum commune.* III. A mutation that blocks initiation of fruiting. Mol. Gen. Genet., 106:151–54.

With C.-S. Wang. Isozyme patterns and sexual morphogenesis in *Schizophyllum.* Proc. Natl. Acad. Sci. USA, 66:882–89.

1971

Growth and reproduction of fungi. In: *Plant Physiology, A Treatise,* ed. F. C. Steward, vol. 6, pp. 167–230. New York and London: Academic Press.

With A. S. Flexer. Mating systems and evolution of Basidiomycetes. In: *Evolution in the Higher Basidiomycetes,* ed. R. H. Petersen, pp. 149–67. Knoxville: University of Tennessee.

With R. M. Hoffman. Genetic restriction of energy conservation in *Schizophyllum.* Science, 171:418–19.

1972

With R. M. Hoffman. Lowered respiratory response to adenosine diphosphate of mitochondria isolated from a mutant-*B* strain of *Schizophyllum commune.* J. Bacteriol., 110:780–81.

With C. A. Raper. Life cycle and prospects for interstrain breeding of *Agaricus bisporus.* Mushroom Sci., 8:1–9.

With C. A. Raper and R. E. Miller. 1972. Genetic analysis of the life cycle of *Agaricus bisporus.* Mycologia, 64:1088–117.

1973

With C. A. Raper. Incompatibility factors: Regulatory genes for sexual morphogenesis in higher fungi. In: *Basic Mechanisms in Plant Morphogenesis,* pp. 19–39. Brookhaven Symposia in Biology no. 25. Upton, N.Y.: Brookhaven National Laboratory.

With C. A. Raper. Mutational analysis of a regulatory gene for morphogenesis in *Schizophyllum.* Proc. Natl. Acad. Sci. USA, 70:1427–31.

1974

With A. S. Flexer. Heterothallism in Basidiomycetes. In: *Mycology Guidebook,* ed. R. B. Stevens, pp. 524–39. Seattle: University of Washington Press.

With R. M. Hoffman. *Schizophyllum.* In: *Handbook of Genetics,* vol. 1, ed. R. C. King, pp. 597–626. New York: Plenum Press.

With R. M. Hoffman. Genetic impairment of energy conservation in development of *Schizophyllum:* Efficient mitochondria in energy-starved cells. J. Gen. Microbiol., 82:67–75.

With R. C. Ullrich. Number and distribution of bipolar incompatibility factors in *Sistotrema brinkmannii.* Am. Nat., 108:507–18.

1975

With R. C. Ullrich. Primary homothallism—relation to heterothallism in the regulation of sexual morphogenesis in *Sistotrema.* Genetics, 80:311–21.