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Motility

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Definition and Scope

Motility is the ability of living systems to exhibit motion and to perform mechanical work at the expense of metabolic energy. Motility and mobility are often confused. The distinction is clear in the simplest motions observed in living cells with the light microscope: Brownian motion of particles demonstrates their *mobility* under the influence of thermal agitation. On the other hand, their saltatory motion, a form of *motility*, may transport the same particles much greater distances using metabolic energy.

The scope of motility, as it is presently understood, includes a variety of diverse phenomena: (*a*) bacterial (prokaryotic) flagellar movement; (*b*) gliding in unicells (bacteria, blue-green algae, diatoms, and desmids, etc.); (*c*) saltatory motion of particles in cytoplasm; (*d*) organelle movements (deformation or translocations of chloroplasts, mitochondria, the costa and axostyle, acrosomal filament extension, etc.); (*e*) cytoplasmic streaming (in protists, plant, animal, and fungal cells); (*f*) ameboid movement (cell movement by means of cytoplasmic streaming in lobopodia, filopodia, axopodia, retraelopodia, etc.); (*g*) movements of tissue cells (degree of relatedness to ameboid movement uncertain); (*h*) platelet motility (shape change, transformation, and clot retraction); (*i*) contractility (of muscles, spasmonemes etc.); (*j*) axoplasmic transport in nerve; (*k*) mitotic movements; (*l*) cytokinesis (plant and animal types differ); and (*m*) eukaryotic flagellar and ciliary movement.

The coverage of the whole field of motility obviously is impossible in the available space. It is possible, however, to give the reader a general impression of the activity and ferment in the field, as well as some key references to the literature.

The Literature of Motility

Researchers have known of the principal phenomena of motility for a long time. Descriptive accounts can be found as early as van Leeuwenhoek's letters to the Royal Society. It is clear that fascination with movement as an attribute and manifestation of life motivated the minds of early biologists. However, science must develop both a conceptual framework and an armamentarium of methods before it can study complex phenomena and, in the case of cell motility, these prerequisites became available about two decades ago.

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The conceptual framework arose in branches of science that seemed at the time to have little relationship to biology: fluid dynamics, rheology, colloid and polymer chemistry, and thermodynamics. Biophysics and biochemistry were the interdisciplinary sciences through which these concepts found their way into the minds of cell biologists. Before 1960, the literature of motility was scattered and of uneven quality. Much of it was descriptive, poorly documented, unquantitative, and highly speculative. Conferences and symposia had a strong and catalytic influence on this field. In 1961, under the leadership of P. J. Gaillard and J. F. Danielli, a conference was held on "Cell Movement and Cell Contact" at Noordwijk, the Netherlands, at which a fruitful discussion on mechanisms of cell movement took place. Several of the papers given at that meeting are still widely quoted (e.g., references 1–4).

In 1963, a "Symposium on the Mechanisms of Cytoplasmic Particles" was held in Princeton, New Jersey, with the deliberate intention of promoting interaction between scientists studying different kinds of nonmuscle motility and muscle contraction. The volume, *Primitive Motile Systems in Cell Biology*, which was a result of that conference (5), had a profound influence on the development of the field. It stimulated motility researchers to explore the molecular basis of motility, using muscle as a model. It also stimulated some muscle researchers to look at nonmuscle systems. The conference also introduced microtubules to scientific audiences (6). Finally, the value of film as a means of documenting and communicating the phenomenology of motility was demonstrated.

There have been many meetings on motility since 1960. Those that resulted in publications are cited in Table I. The largest meeting was that held at Cold Spring Harbor (7), at which 92 papers were given, and 250 people attended. The field has grown so rapidly that it is almost impossible to have a true meeting of minds unless the subject matter (or the attendance) is restricted.

The most recent meetings of which the proceedings have been published are the First John M. Marshall Symposium held at the University of Pennsylvania in 1977 (9) and the Yamada Conference I on "Cell Motility Controlled by Actin Myosin and Related Proteins," held at Nagoya, Japan, in 1978 (10).

The journal literature on motility has grown at a rate substantially larger than the literature of cell biology as a whole. Papers on the subject can be found in more than 50 periodicals, including two new journals: *Cell Motility* (United States) and *Journal of Muscle Research and Cell Motility* (United Kingdom).

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TABLE I

Motility Symposia with Published Proceedings Since 1960

Year	Title	Organizer(s)/editor	Reference
1961	Cell Movement and Cell Contact	P. J. Gaillard and J. F. Danielli	*Exp. Cell Res.* Volume 8: Suppl.
1963	Primitive Motile Systems in Cell Biology	R. D. Allen, E. Bovee, D. Marsland, and L. I. Rebhun	(references)
1963, 1964	Conferences on Cell Dynamics	M. Rosenburg	(reference 8)
1967	The Contractile Process	A. Stracher	*J. Gen. Physiol.* 50: Suppl. 6
1968	Aspects of Cell Motility	P. L. Miller	*Symp. Soc. Exp. Biol.* Volume 22
1973	Locomotion of Tissue Cells	M. Abercrombie	*CIBA Symp.*
1974	Molecules and Cell Movement	S. Inoué and R. E. Stephens	Society of Gen. Physiologists Volume 30, Raven Press, New York, 1975
1975	Contractile Systems in Non-Muscle Tissues	S. V. Perry, A. Margreth, and R. S. Adelstein	Elsevier North-Holland, Inc., New York, 1976
1976	Cell Motility	R. D. Goldman, T. D. Pollard, and J. Rosenbaum	*Cold Spring Harbor Conf. Cell Proliferation* (1976).
1977	Conference on Cell Shape	J. P. Revel	Proceedings on the Conference on Cell Shape. Alan R. Liss, Inc., New York, 1977.
1977	Motility in Cell Function	F. A. Pepe, J. W. Singer, and V. T. Nachmias	Academic Press, Inc., New York, 1979
1978	Cell Motility: Molecules and Organization	S. Hatano, H. Ishikawa, and H. Sato	University of Tokyo Press, Tokyo, 1979
1979	Contractile Proteins in Plants	D. S. Fensom	*Can. J. Bot.* 58(7), 1980.

Steps to Understanding Motility

PHENOMENOLOGY: There is a strong tendency to oversimplify the descriptions of motile phenomena. In some cases hypotheses have served as "filters" preventing observers from recording details that did not fit with theory. To avoid this problem, investigators learned to utilize objective recording methods, such as film or videotapes, and to make them freely available to others. A pioneer in this effort was Lewis (11), who made splendid films of the movements of amebae, tissue cells in culture, and embryonic cells *in situ*. Scientific films have progressed a long way from *ad hoc* productions intended for a scientific meeting to documentary films that include dimensional, temporal, and experimental data. In Göttingen, the German Federal Republic supports a nonprofit "Institut für den Wissenschaftlichen Film," (IWF) the purposes of which are to make and to disseminate films of this type in collaboration with scientists from all over the world. The distributor of IWF films is the Audiovisual Services at Pennsylvania State University, University Park, Pa.

The latest wave in phenomenological documentation is television. Parpart (12, 13) was a pioneer, a generation ahead of most other biologists. As early as the 1960s, he used a videcon camera and monitor to permit more than one observer to study saltatory movements in *Arbacia* eggs (13). Most recently video cameras (some compatible with computers), recorders, projectors, and accessory instrumentation have been widely adopted; they are so convenient and inexpensive to use that they may well replace cinerecording for all applications except high-speed filming and presentation to large audiences.

BIOPHYSICS: Motility research depends heavily upon methods of observation and recording, especially with modifications of the light microscope. Improvements in optical microscopy, such as phase-contrast (14), interference, and differential interference contrast (15), dark-field (16), and fluorescence (17), microscopes, have all seen service in motility studies. Rectified polarizing microscopes (18) have had many uses in the detection of birefringence owing to microtubules in mitotic spindles (19), and phase-modulation methods (20), have been used to detect strain birefringence in ameba cytoplasm (21).

Some aspects of motility have required special devices for recording images at low light levels. Depending on the degree of sensitivity required, equipment has included silicon-intensified tube (SIT) video cameras or image-intensifier videcons (22). In general, the detection of calcium ions in cytoplasm requires devices of the highest sensitivity.

ULTRASTRUCTURE: Since 1960, the most important and rewarding, yet perhaps the least reliable, approach to the study of motile systems has been electron microscopy. The fault lies not with the investigators or instruments, but with the unsatisfactory state of the art of specimen preparation. The history of electron microscopy applied to motile systems can be divided into chapters according to the preparation method used, such as osmic acid fixation, potassium permanganate fixation, glutaraldehyde fixation, thin section-CTEM, critical point-dried whole mount-HVEM, and freeze-fracture, deep-etch. Presumably the list of useful preparation techniques and, hence, the list of new structures to be found, is not complete.

Perhaps the main contribution of electron microscopy to the study of motility has been the categorization of ultrastructural entities found in different systems. The concepts of "microtubule-dependent motility" and "microfilament-dependent motility" were derived ultrastructurally and, in some cases, led to a more precise molecular characterization of certain motile systems.

Often the results of ultrastructural analysis correlate well with and extend those of optical microscopy. In the mitotic spindles, the positions and orientations of microtubules corresponded well with the predictions of the Wiener theory based on form birefringence data (23).

In other cases, fixation alters or destroys ultrastructural details. For example, the most birefringent region of a moving ameba is its endoplasm (24), and the birefringence of this region can be modulated in vivo by an applied force (21). When the cell is broken, "flare medium"-packed fibrils consisting of actin filaments emerge and engage in extracellular

motility (25). Despite this evidence of functionally important endoplasmic ultrastructure, fixation by any presently known procedure causes the birefringence to disappear, and virtually no F-actin filaments remain when the fixed cell is sectioned and observed in the electron microscope.

Newer specimen preservation techniques show considerable promise of circumventing *some* of the fixation damage by rapid freezing, freeze-fracture, and deep-etch of fixed (26), or living material without cryoprotection (27, 28). However, these techniques may also produce artifacts of a different kind, and the results should be interpreted with caution.

MOLECULAR APPROACHES: The point of departure for the molecular basis of motility was muscle biochemistry, where the major proteins responsible for contractility were isolated and partially characterized before 1960. The pioneering effort to extend muscle biochemistry to a nonmuscle motile system was that of Loewy (29), who demonstrated an actomyosin-like, adenosine triphosphate (ATP)-induced solution of *Physarum* extracts.

The best review of the contribution of muscle biochemistry to motility research is that of Pollard and Weihing (30). A particularly important contribution was that of Huxley, whose sliding-filament theory (31) and method of decorating F-actin filaments with heavy meromyosin to determine their polarity (32) were easily adapted to other motile systems (33).

Independent of muscle biochemistry was the early work on tubulin. The discovery of microtubules (34) and the colchicine-binding assay for tubulin (35) laid the ground work for the development of research on microtubule-based motility (see Haimo and Rosenbaum, this volume).

The study of both actin- and tubulin-related motility have profited by the availability of antibodies to purified tubulin, actin, myosin, tropomyosin, and other proteins (36–38). The fluorescent-antibody technique of labeling contractile and cytoskeletal proteins has ushered in a new era of what might be called "biochemical morphology," especially of cells grown in culture.

Antibodies (fluorescent or not) can also be injected into living cells to inactivate certain proteins and, in this way, demonstrate their function. The pioneering effort in this regard was the injection of myosin antibody into sea urchin eggs, where it inhibited cleavages without preventing mitosis (39). Taylor and Wang (40) have injected fluorescently labeled G-actin into cells, where some of it has polymerized into F-actin. A different labeling procedure makes it possible to label tubulin and microtubule-associated proteins (41).

Mainstreams, Eddies, and Backwaters

Looking back over the past two decades, one notices that the principal gains in knowledge have been in those areas of motility research in which the problems were evident and the techniques for their investigation were at hand or could be developed. Examples include rotational and shuttle streaming, movements of ameboid and tissue cells, mitotic movements, muscle contraction, and ciliary and flagellar movement. The latter three are discussed elsewhere in this volume.

Some interesting forms of motility remain to be investigated with the same degree of thoroughness and, for that reason, may be considered as "backwaters" in the motility field. Examples are gliding in unicells, intracellular organelle movements, and modes of cytoplasmic streaming other than shuttle and rotational streaming. These subjects await new discoveries, concepts, and methods before they can join the mainstream of motility research.

Intermediate between these extremes are some "eddies" in which intense excitement has been generated as the result of new insights or findings. The discovery that bacterial flagella rotate rather than undulate (42, 43) is an example; this finding led to a flurry of activity aimed at understanding the molecular biology and genetics of the rotatory motor of bacteria (44). Other examples of such interesting eddies are saltatory movement, reticulopodial and axopodial movements in foraminifers and heliozoans respectively, and movement along the slime ways of *Labyrinthula*, a marine slime mold (45; N. Nakatsuji, S. Sher, D. Solomon, T. Nakatsuji, and E. Bell. Manuscript submitted for publication.).

Progress in the Mainstreams

SHUTTLE STREAMING IN *Physarum*: In motility research, nothing could be more in the mainstream than shuttle streaming in the acellular slime mold *Physarum*, where the most rapid flow of cytoplasm has been documented: 1,300 $\mu m \cdot s^{-1}$

The classical work of Seifriz (see references 46 and 47) on *Physarum* streaming laid the groundwork for the important studies of his student, Kamiya, who early in his career invented the important double-chamber method (48) of measuring the motive force for streaming. By using this and other quantitative methods of equal elegance and ingenuity, Kamiya and his students systematically investigated the effects on streaming of environmental factors, physiologically active substances, such as ATP, and drugs. Kamiya's reviews (48–51) should be consulted for details.

The most basic biophysical question to be asked about shuttle streaming in the early 1960s was the site of the motive force. Seifriz (46) had suggested that regions in the ectoplasmic gel (channel walls) contracted rhythmically, like beating hearts, and forced the streaming cytoplasm back and forth. Kamiya and Kuroda (52) showed that the velocity profiles for normal streaming and pressure-induced flow were identical. Therefore, it was assumed that a hydrostatic pressure gradient was the motive force. This assumption derived support from direct observations in polarized light; diffusely birefringent regions of fibrils periodically changed their length and birefringence (53). Wohlfarth-Bottermann (54) showed that cytoplasmic fibrils formed in response to the gravitationally-induced resistance to flow. In an effort to determine the site of the motive force in a double-chamber preparation, Allen et al. (55) constructed a differential thermometer into the agar floor of a Kamiya double chamber. With a sensitivity sufficient to display thermal noise of $2 \times 10^{-5\circ}$C, it was a simple matter to measure periodic temperature increases of ca. $10^{-3\circ}$ at each end inasmuch as it served as the source of the cytoplasmic stream. Therefore, it was concluded that the excess heat must be produced by the "tail" of the slime mold as a by-product of contraction.

In 1952, Ariel Lowey (29) demonstrated that *Physarum* extracts are sensitive to solation if ATP is added indicating the probable presence of an actin-myosin contractile system in slime molds. However, there were difficulties in isolating and purifying these proteins because of contaminants that altered their physical properties. In addition to Lowey, other pioneers in this effort were Nakajima (56) and Hatano and Oosawa (57) in Japan and Adelman and Taylor (58, 59) in the United States.

Ultrastructural studies carried out by many capable electron microscopists during nearly two decades failed to define the organization of the contractile material in *Physarum* until Nagai et al. (60) showed that during the transition from resting to contraction and relaxation, the parallel F-actin filaments that apparently are cross-linked by myosin dimers transform into a "felt-work" without straight F-actin filaments. A likely key to the explanation for this kind of ultrastructural transformation, which is very different from that in muscle, is found in the work of Matsumura and Hatano (1978), who showed that synthetic *Physarum* actomyosin undergoes reversible superprecipitation when ATP is added.

There is evidence of calcium control of the contractility and rheological changes in *Physarum* cytoplasm (62). Hatano and Oosawa (63) found that caffeine treatment causes slime molds to break down into "droplets" (cytoplasts) in which streaming proceeds in a narrow range of calcium concentration. Recently, Kuroda (64) reduced the droplets to models one step simpler in organization by removing their membranes in a modified "flare medium."

Physarum has turned out to be the only living nonmuscle material in which it has been possible to control and measure cytoplasmic contractility under physiological conditions. Kamiya et al. (65) described an apparatus in which isotonic and isometric contractions could be recorded alternatively. These studies have been continued in the laboratories of Kamiya (66) and Wohlfarth-Botterman (67) and have defined the way in which a "simple" nonmuscle contractile system responds to stretch and tension.

AMEBOID MOVEMENT: Until 1960 there had been four decades of virtual unanimity about the mechanism of ameboid movement (see reference 68 for an excellent review of the long history of this subject). Mast's (69) description of the phenomena of ameboid movement was in terms of the tail-contraction, sol-gel theory, to which he subscribed. Little research was done because methods were not available to study the molecular basis of tail contraction or sol $\rightleftharpoons$ gel transformations.

A serendipitous experiment, in which washed amebae were broken in glass or quartz capillaries, showed that cytoplasm could stream bidirectionally when released from the cell, in some cases for an hour or more (70). The responses to this report were mixed. Although the experiment was easy to repeat, many people did not believe the results. Others found reason to doubt the obvious interpretation that pressure cannot cause bidirectional flow, and sought ways to rationalize the result in terms of Mast's appealingly simple and long accepted theory.

In the early 1960s, as a result of the observed streaming in isolated cytoplasm, there was a period in which the number of hypotheses to explain ameboid movement exceeded the amount of solid information upon which any viable theory could be built. However, the development of these ideas was essential, and it was later possible to test some of them.

One, the frontal-contraction hypothesis, was that the motive force for pseudopod extension was a contraction localized at pseudopodial tips (71). This idea was based on the geometric details of streaming in isolated cytoplasm and was compatible with what was known about the details of streaming and pseudopod extension and retraction in intact cells.

An advantage of the frontal contraction hypothesis was that its predictions could be tested by biophysical methods. It was reasoned that endoplasm could be drawn forward by a tensile force from frontal contraction only if it exhibited viscoelastic behavior. Polarization microscopy showed not only that the endoplasm was birefringent (72), but also that endoplasmic birefringence could be modulated by tension applied to the tips by suction (21). The dynamics of change in birefringence established that the birefringence was a result of strain and not flow, showing that the endoplasm is, in fact, viscoelastic.

For more than a decade, the frontal-contraction hypothesis was the subject of considerable controversy (73–75; see also the discussion throughout *Primitive Motile Systems in Cell Biology* [5]).

In the meantime, other hypotheses were under consideration. For example, it was proposed that "active shearing" of concentric layers of cytoplasm could be responsible for streaming (76), and Bingley and Thompson (77) showed some evidence supporting the possibility of an electrophoretic mechanism. The most ingenious idea was the "domestic closet-bowl theory" (78). These hypotheses were not tested sufficiently to receive serious consideration in the literature.

The tail-contraction theory remained a subject of discussion until after 1970, when it was put to a direct test by a capillary suction experiment, in which it was shown that even high negative pressure gradients applied to the tip of one pseudopodium could not prevent others from extending (79). We can say that this result and others directly supporting the frontal-contraction hypothesis discredited the tail-contraction theory. Even the possibility that the tail might contribute to the motive force seems remote in the light of recent results which show that destruction of the tail by a microsecond laser beam does not instantaneously alter the rate of streaming (80). The shift in views regarding the mechanism of ameboid movement can be seen in the reviews of Jahn and Bovee (81), Seravin (82), Allen (71, 72), Allen and Allen (83), and Taylor and Condeelis (84).

One of the most important lines of investigation on ameboid movement was initiated by Thompson and Wolpert (85), who demonstrated streaming in extracts from pooled ameba cytoplasm. Pollard and Ito (86) continued this work and showed that streaming in extracts required both thick and thin filaments. Since that time, workers have learned a great deal about the molecular basis of motility. Most of the story is in an article by T. D. Pollard in this volume.

Perhaps the most dramatic and revealing experiment on ameboid movement was the demonstration that contractility, rheological behavior, and the streaming of isolated ameba cytoplasm could be brought under direct chemical control. Taylor et al. (25) showed that by controlling the concentrations of calcium ions, ATP, and magnesium ions, cytoplasm could be switched back and forth from states comparable to rigor, relaxation, and contraction in muscle. Furthermore, in a solution containing the correct balance of Ca^{++}, Mg^{++}, and ATP, streaming could occur in fountain or loop patterns similar to those in both the intact cell and broken cells in capillaries (70; see also reference 87).

Although contractility provides the motive force for ameboid movement, it has long been clear that the rheological (sol $\rightleftharpoons$ gel) cycle in cytoplasm is also central to the process. For a time, it appeared that changes in the degree of cross-linking between actin and myosin might account for the rheological cycle. A second possibility was that either or both types of filaments might disassemble, especially if the intracellular free calcium concentration were much below the micromolar level (88). A third possibility, suggested by extract experiments on *Dictyostelium* and proposed as the "solation-contraction coupling hypothesis" is that contraction can occur only when gel for-

mation, which is under the control of actin-binding proteins ("gelation factors"), is prevented by micromolar concentrations of free calcium ions or a pH above 6.8–7.0 (89). This hypothesis differs only in detail from that of Goldacre and Lorch (90), who also proposed solation-contraction coupling. The main problem with this hypothesis is that it fails to consider how the coupling could occur if the motive force is delivered at pseudopodial tips and the solation occurs in the tail.

Much of the recent work on the molecular basis of ameboid movement has used extracts of the small amebae *Dictyostelium* or *Acanthamoeba*. Unfortunately studies on extracts do not tell us what is going on in living cells, but instead indicate what could be happening and, therefore, what should be looked for. Whereas actin is presumably similar among the giant amebae and the smaller ones that are used for biochemical studies, the myosins are different in their molecular weights, solubilities, and enzymatic properties, and the actin-binding proteins hardly correspond at all (see review by Hitchcock [91; 84, 92]). Consequently, extraction experiments on one species can provide only clues as to what might be the case in another species.

With regard to the mechanisms of movement in the *Chaos-A proteus* group, it seems wiser to rely on biophysical evidence itself rather than on theoretical constructs that conflict with observation. Taylor (93) has made some very important observations on the effect of excess calcium ions injected into the cell. One of these effects appears to be a temporary loss of gel/sol differentiation. Cooling, which presumably allows calcium to enter the cell, has a similar effect (R. D. Allen. Unpublished observations.). In this case, the gelation that follows frontal contraction does not occur, with the result that the frontal contraction continues as the cytoplasm turns over the rim of the ectoplasmic tube. Thus, the tube continues to shorten anteriorly, and the contraction can continue when gelation fails. This situation seems to agree with the concept that contraction and gelation are separate, rather than coupled, processes.

Tissue Cell Movement

Tissue cell movement in animals bears some resemblance to ameboid movement. When tissue cells settle on a suitable substrate, they attach and spread (for a review, see references 94 and 95). In doing so, they form elongated processes of various shapes comparable with pseudopodia that are found on various ameboid cells—filopodia (thin, filamentous pseudopodia) and flat lamellipodia, some of which lift off the substratum where they are described as "ruffled membranes" (96, 97).

In fibroblasts, there is usually a ruffled membrane that extends in the direction of locomotion, and a tail that drags behind, attached to the substratum until it tears loose and recoils elastically toward the cell body. Harris and Dunn (98) found centripetal transport of particles on both surfaces of moving fibroblasts, including the ruffled membrane.

Movement in tissue cells is not restricted to surface movements and cell locomotion, for there is saltatory as well as Brownian motion of cytoplasmic particles. Often saltation is polarized in the long axis of the cell, parallel to the direction of locomotion.

Studies on tissue cell movement have, for the most part, lacked the kind of biophysical data that was generated in studies on amebae from 1960 to 1975. Consequently, the site of the motive force for movement in tissue cells remains obscure. Abercrombie (1) considered that the ruffled membrane on the advancing edge of fibroblasts was the "locomotor organelle" of the cell. If this turns out to be universally correct, then there may be a parallel to be drawn with present views of the mechanism of ameboid cell movement.

An important difference between ameboid cells and tissue cells of animals is in their rates of movement. With the exception of white blood cells, tissue cells in general move so slowly that time-lapse photography is necessary to record and study their movement. Tissue cells lay down points of attachment to the substrate; during locomotion some of these are broken and others are established. The surface-reflection interference microscope and its improvements have made it possible to study adhesion to the substratum (99–102). Revel et al. (103) have used scanning electron microscopy to study adhesion to the substratum.

The cytoplasm of fibroblasts is known to have viscoelastic properties from the behavior of iron particles moved inside the cell by a magnet. Crick and Hughes (104) characterized the cytoplasm as rather like "mother's work basket—a jumble of beads and buttons of all shapes and sizes, with pins and threads for good measure, all jostling about and held together by 'colloidal forces'."

An ultrastructural basis for viscoelastic behavior in cytoplasm became evident even in the earliest electron microscope studies of thin sections of moving tissue cells, for example secondary mesenchyme cells of sea urchins (105). By the mid-1960s it was evident that cytoplasm contained more than a single "linear element." The microtubule was the first to be identified on morphological grounds (34), and the identification of tubulin as the protein of which microtubules were made soon followed (35). By the mid-1960s, it was suspected that some of the smaller filaments were about the correct size to the F-actin, but not until the heavy meromyosin-labeling technique was available (33) could microfilaments be positively identified as F-actin and their polarity determined. The introduction of cytochalasin as a drug to disrupt microfilaments and to inhibit microfilament-based motility provided a second important tool with which to study the role of F-actin in nonmuscle motility (106).

A third type of filament intermediate in size between microtubules and microfilaments was the ~10-nm "intermediate" filament found in many tissue cells and neurons (107). So far it appears that these are not directly involved in cell motility. Excellent examples of cell ultrastructure showing all three types of filaments are found in the papers of Goldman and Knipe (108).

The central role of F-actin microfilaments in the ultrastructure attachment and motility of tissue cells was best shown in the work of Goldman et al. (109), who combined a number of techniques in demonstrating the different roles of actin.

The localizations of several cytoskeletal and contractile proteins have been determined on a number of cell types after fixation using fluorescent antibody techniques for actin (36), myosin (37), and α-actinin (111). The elegant images of symmetrical geometric localizations of these various proteins so far have not shed much light on the mechanisms of motility, other than to reassure us that the pieces of the puzzle are being put together. The "big picture" has not emerged.

The details of how the various cytoskeletal and contractile proteins are assembled in the cytoplasm has been investigated by high-voltage electron microscopy and stereo electron micrographs, which permit the observer to see the relationships of

cytoskeletal elements stereoscopically in thick sections or whole-mount, critical-point dried cells. With these techniques, preparations up to 2 μm thick can be seen with enough clarity to identify nearly all ultrastructural details visible in thin section. Thus Wolosewick and Porter (112) have depicted and described the microtrabecular lattice that envelops the microfilaments, microtubules and intermediate filaments, polysomes, etc. It is now clear that this lattice alters during motility, drug treatments, etc., but it is not yet certain what the microtrabecular lattice is biochemically, or what role it plays in cell movement.

Rotational Cytoplasmic Streaming in Characean Cells

The very rapid rotational streaming in characean cells was first observed by Corti in 1794. The large size of these cells has made them the ideal material in which to study streaming in plants (for reviews, see references 49, 50, 92).

In the frequently studied *Nitella* internodal cells, the cytoplasm streams in a spiral path beneath the spiral rows of chloroplasts embedded in the cortex. Two oppositely directed streams each occupy a little less than 180° of the cell circumference and are separated by "indifferent zones."

In 1956, Kamiya and Kuroda (113) made the important observation that the endoplasm exhibits shear only in its outer micron or two adjacent to the cortex. It was therefore suggested that the site of application of the motive force might be found at the corticoendoplasmic interface. It was also suggested that the motive force must be "active shearing" at this location.

In the same year, Jarosch (114) made some remarkable observations and ciné records of the behavior of filaments in cytoplasts obtained by stripping the contents from cut cells. He discovered that the cytoplasts contained chloroplasts and nuclei that could rotate on their own axes or "swim" in the cytoplasm. Many filaments very near or below the resolving power of the microscope could be seen to undulate, make serpentine movements, or form circles or polygons, which either rotated or served as substrates for the unidirectional motion of particles. These fascinating observations were discussed in terms of a theoretical model involving screw mechanics at a time when helical biopolymers and "treadmilling" in F-actin and microtubules had not yet been remotely considered (115). These unorthodox ideas provoked some amusement at the time but, in the light of newer findings, some of Jarosch's views should be reconsidered and tested by nanosecond fluorimetry techniques. However, as will be seen, some alternative theoretical schemes are easier to test.

The observations of Jarosch (114, 115) suggested that some kind of filaments might be found at the corticoendoplasmic interface, and this prediction was indeed confirmed. Kamitsubo (116) discovered the subcortical fibrils with the light microscope, and Nagai and Rebhun (117) observed ultrastructurally that each subcortical fibril was a bundle of from 50 to 100 microfilaments with diameters of 6–7 nm—about the size of F-actin—attached to the inner surface of the chloroplast rows.

Kamitsubo (118) continued his study of subcortical fibrils by showing that in centrifuged cells these fibrils could fold over to form polygons similar to those seen by Jarosch (114, 119).

Kamitsubo (120) also devised the "*Nitella* window technique" for banishing chloroplasts from an area ca. 100 μm in diameter, through which the subcortical fibrils and endoplasm could be seen clearly. He showed that cytoplasmic particles in the vicinity of the subcortical fibrils could suddenly "hitch on" and be transported at streaming velocity, whereas nearby particles engaged only in Brownian motion.

Similar *Nitella* window preparations were used by N. S. Allen (121) under improved viewing conditions to observe and record the undulations of a population of endoplasmic filaments considerably more numerous than the subcortical fibrils. The endoplasmic filaments could be counted, and their aggregate length was computed to be about 50 m for a cell 2 cm in length. Endoplasmic filaments are branches of subcortical fibrils; therefore it is not surprising that they can also cause particles to be transported along them.

The chemical nature of subcortical fibrils was revealed as F-actin by the experiments of Palevitz and Hepler (122), who successfully labeled them with heavy meromyosin and found that the polarities of microfilaments in a bundle were identical. The polarity with respect to the direction of streaming was later determined by Kersey et al. (123) to be counter to the direction of streaming. This finding was consistent with the hypothesis that a myosinlike molecule attached to particles might move along F-actin bundles by a sliding interaction similar to that in muscle.

Although the chemical nature of the subcortical fibrils is established and myosin has been isolated from *Nitella* (124), there is less information about endoplasmic filaments because of their destruction by fixatives. Even their existence has been called into question, because until recently the sole evidence for their existence has been films made with a sensitive differential-interference contrast microscope (121).

Recently, Allen and Ruben (27) and Allen (28) have demonstrated the existence of extensive loose bundles of 6–7 nm of microfilaments throughout the endoplasm by a rapid freeze-fracture, deep-etch technique carried out on unfixed cells without cryoprotection. In addition to the microfilaments, some of which exhibit the 37 nm helical repeat expected of F-actin, there are reticular "webs" of thinner filaments surrounding cytoplasmic particles in the vicinity of F-actin bundles. In some cases, it is possible to see thinner (ca 4 nm) filaments, which interact tail-to-tail and have a bifurcation leading toward two globular heads, suggestive of a putative oligomeric myosin network.

By opening characean cells at the ends and perfusing with appropriate physiological solutions, Williamson (125) was able to create a surviving membrane-free model system sensitive to cytochalasin and responsive to ATP. He could observe the adhesion of particles of the subcortical fibrils and that they did not move until exogenous ATP was added. Nagai and Hayama (126) have observed the ultrastructure of particles adhering to the subcortical fibrils in such preparations and have detected periodic structures believed to be myosin.

The subcortical fibrils have received greatest attention from workers interested in rotational streaming. However, it is now clear that these structures are but a small portion of the motile machinery, which extends throughout the endoplasm. Active shearing, whatever its mechanism, clearly takes place at the surfaces of endoplasmic filaments as well as subcortical fibrils.

Some Eddies

Space permits only the briefest mention of some of the areas of research, related to those discussed earlier, that offer opportunities for the next decade of discovery.

SALTATORY MOTION: It is commonly believed that sal-

tatory motion may be the most basic form of motility. Although there have been a number of classical descriptive papers, little progress has been made in understanding the molecular basis of the process (for review, see Rebhun [127]).

AXOPODIAL MOTILITY IN HELIOZOANS: Heliozoans are protozoans of the class Sarcodina that move by bending their stiff axopodia at their bases and feed by means of more typical ameboid food-cup pseudopodia (128). Tilney and Porter (129) described the ultrastructure of axopodia, which have a central rod consisting of a paracrystalline array of microtubules. For a while—as a result of this and other studies at the time—microtubules were regarded as part of the motive-force production mechanism in cells. Edds (130) performed a simple experiment to test this idea. He inserted a glass needle, with a diameter about that of the microtubular axoneme, through the cell and out the other side in such a manner as to cause an "artificial axopodium" to be produced. Particles saltated within this artificial axoneme at an almost normal rate, and were unaffected by concentrations of the microtubule-inhibitor colchicine, which was sufficient to cause other axopodia to collapse. This result clearly showed that the axonemal and other microtubules played no role in particle motions. Edds (131) demonstrated the presence of two kinds of filaments: thin filaments, which could be labeled with heavy meromyosin and are therefore F-actin, and unidentified thick filaments with an unusual morphology. Much more remains to be learned about the motility of the heliozoans, for they can be raised in mass culture for biochemical work.

RETICULOPODIAL NETWORKS OF FORAMINIFERS: The foraminifera are sarcodines that spread extensive reticulopodial networks for the purpose of feeding and locomotion. The filopodial strands within the networks exhibit bidirectional streaming marked by the transport of cytoplasm and particles at two or more velocities. The literature on the phenomenology is cited in Jahn and Rinaldi (132) and Allen (133).

The presence of microtubules in the reticulopodial network has been shown by several investigators (e.g., reference 134), and recently it has been found that there are close physical proximity, and therefore, likely interactions between microtubules and unidentified microfilaments, which do not appear to be actin (135).

At the light microscope level, it has been possible to observe the interaction of cytoplasmic particles with from one to a few microtubules and the "sliding" and "zipping" activities of microtubules in *Allogromia* as a result of the new AVEC methods of videomicroscopy (136, 137). The same method has revealed new details of microtubule-associated movements in neurons (axonal transport) and other vertebrate tissue cells (138). The same method has recently made it possible to record the transport of massive numbers of synaptic vesicles in intact axons (139) and in isolated axoplasm, where transport persists and can be studied for hours (140).

Foraminiferan reticulopodia may offer a unique opportunity to study a form of motility dependent upon an interaction between two types of linear elements.

MOTILITY OF AND ON *Labyrinthula* SLIME-WAYS: The marine slime mold, *Labyrinthula*, a parasite on eel grass, consists of spindle cells that move in a unique manner within a membrane-bounded "slime way" secreted by these cells. The slime ways themselves form lamellipodial extensions. Bell and co-workers have recently shown that the slime ways contain both actin and myosin and that the movement of spindle cells is regulated by calcium ions (see Nakatsuji et al. [Manuscript submitted for publication.] and Nakatsuji and Bell [45] for a review of most recent findings).

Conclusion

I have selected some of the systems in the mainstream of motility research for a brief progress report and have referred to reviews and symposium volumes where more references are available. I have also pointed out some of the conceptual and technical advances that have made motility research the vibrant field that it is today. It is possible to predict that, in the next decade or two, the eddies mentioned here will have grown into mainstreams and that few backwaters will remain.

REFERENCES

1. Abercrombie, M. 1961. *Exp. Cell Res.* 8(Suppl.):188.
2. Allen, R. D. 1961. A new theory of amoeboid movement and protoplasmic streaming. *Exp. Cell Res.* 8(Suppl.):17–31.
3. Ambrose, E. J. 1961. *Exp. Cell Res.* 8(Suppl.):54–73.
4. Taylor, A. C. 1961. *Exp. Cell Res.* 8(Suppl.):154–173.
5. Allen, R. D., and N. Kamiya, editors. 1964. Primitive Motile Systems in Cell Biology. Academic Press, Inc., New York. 642 p.
6. Roth, L. E. 1964. *In* Primitive Motile Systems in Cell Biology. R. D. Allen and N. Kamiya, editors. Academic Press, Inc., New York. pp. 527–546.
7. Goldman, R. D., T. D. Pollard, and J. Rosenbaum, editors. 1976. Cell Motility. *Cold Spring Harbor Conf. Cell Proliferation.* 3 volumes, 1373 p.
8. Peachey, L. 1968. Conferences on Cellular Dynamics. New York Academy of Sciences Interdisciplinary Communications Program, New York. 417 pp.
9. Pepe, F. A., J. W. Sanger, and V. T. Nachmias, editors. 1979. Motility in Cell Function. Academic Press, Inc., New York 479 pp.
10. Hatano, S., H. Ishikawa, and H. Sato. 1979. Cell Motility: Molecules and Organization. Tokyo University Press, Tokyo. 696 p.
11. Lewis, W. H. 1931. *Arch. Exp. Zellforsch.* 4:442–443.
12. Parpart, A. K. 1951. *Science (Wash. D.C.).* 113:483–484.
13. Parpart, A. K. 1964. *In* Primitive Motile Systems in Cell Biology. R. D. Allen and N. Kamiya, editors. Academic Press, Inc., New York. pp. 471–482.
14. Zernike, F. 1955. *Science (Wash. D.C.).* 121:345–349.
15. Allen, R. D., G. B. David, and G. Nomarski. 1969. *Z. Wiss. Mikrosk. Mikrosk. Tech.* 69:193–221.
16. Summers, K. E., and I. R. Gibbons. 1971. *Proc. Natl. Acad. Sci. U.S.A.* 68: 3092–3096.
17. Ploem, J. D. 1973. *In* Immunopathology of the E. H. Beutner et al., editors. Dowden, Hutchinson & Dross, Inc., Stroudsburg, pp. 248.
18. Inoué, S., and W. Hyde. 1957. *J. Biophys. Biochem. Cytol.* 3:831–838.
19. Inoué, S. 1964. *In* Primitive Motile Systems in Cell Biology. R. D. Allen and N. Kamiya, editors. Academic Press, Inc., New York. pp. 549–594.
20. Allen, R. D., J. M. Brault, and R. D. Zeh. 1965. *In* Recent Advances in Optical and Electron Microscopy. R. Barer and V. Cosslett, editors. Academic Press, Inc., New York. 77–114.
21. Francis, D. W., and R. D. Allen. 1971. *J. Mechanochem. Cell Motil.* 1:1–6.
22. Reynolds, G. W. 1980. *Microsc. Acta.* 83:55–62.
23. Sato, H., G. W. Ellis, and S. Inoué. 1975. *J. Cell Biol.* 67:501–517.
24. Allen, R. D. 1972. *In* The Biology of Amoeba. K. W. Jeon, editor. Academic Press, Inc., New York. pp. 201–247.
25. Taylor, D. L., J. Condeelis, P. L. Moore, and R. D. Allen. 1973. *J. Cell Biol.* 59:378–394.
26. Heuser, J. E., and S. R. Salpeter. 1979. *J. Cell Biol.* 82:150–173.
27. Allen, N. S., and G. Ruben. 1979. *J. Cell Biol.* 83:328a (Abstr.).
28. Allen, N. S. 1980. *Can. J. Bot.* 58:786–796.
29. Loewy, A. 1952. *J. Cell Comp. Physiol.* 40:127–156.
30. Pollard, T. D., and R. R. Weihing. 1974. *CRC Crit. Rev. Biochem.* 2:1–65.
31. Huxley, H. E., and J. Hanson. 1954. *Nature (Lond.).* 173:973–976.
32. Huxley, H. W. 1963. *J. Mol. Biol.* 7:281–308.
33. Ishikawa, H., R. Bischoff, and H. Holtzer. 1969. *J. Cell Biol.* 43:312–328.
34. Ledbetter, M. C., and K. R. Porter. 1963. *J. Cell Biol.* 19:239–250.
35. Weisenberg, R. C., G. G. Borisy, and E. W. Taylor. 1968. *Biochemistry.* 7: 4466–4479.
36. Lazarides, E., and K. Weber. 1974. *Proc. Natl. Acad. Sci. U.S.A.* 71:2268–2272.
37. Weber, K., and U. Groeschel-Stewart. 1974. *Proc. Natl. Acad. Sci. U.S.A.* 71:4561–4564.
38. Goldman, R. D., E. Lazarides, R. Pollack, and K. Weber. 1975. *Exp. Cell Res.* 90:333–344.
39. Inoué, S., and D. P. Kiehardt. 1978. *ICN-UCLA Symp. Mol. Cell Biol.* 12: 433–444.
40. Taylor, D. L., and Y.-L. Wang. 1978. *Proc. Natl. Acad. Sci. U.S.A.* 75:857–861.
41. Travis, J. L., R. D. Allen, and R. D. Sloboda. 1980. *Exp. Cell Res.* 125:421–430.

42. Mussill, M., and R. Jarosch. 1972. *Protoplasma.* 75:465–469.
43. Berg, H. C., and R. A. Anderson. 1973. *Nature (Lond.).* 245:380–382.
44. Adler, J. 1976. *Cold Spring Harbor Conf. on Cell Proliferation.* A:29–34.
45. Nakatsuji, N., and E. Bell. 1980. *Cell Motil.* 1:17–30.
46. Seifriz, W. 1937. *Science (Wash. D.C.).* 86:397–398.
47. Seifriz, W. 1943. *Bot. Rev.* 9:49–123.
48. Kamiya, N. 1940. *Science (Wash. D.C.).* 92:462–463.
49. Kamiya, N. 1959. *Protoplasmatologia.* 8(3a):1–199.
50. Kamiya, N. 1962. *In* Handbuch der Pflanzenphysiologie. W. Ruhland, editor. Springer-Verlag, Berlin. 17(2):979–1035.
51. Kamiya, N. 1968. *In* Aspects of Cell Motility. SEB Symposium 23. Cambridge University Press, Cambridge, England.
52. Kamiya, N., and K. Kuroda. 1958. *Protoplasma.* 49:1–4.
53. Nakajima, H., and R. D. Allen. 1965. *J. Cell Biol.* 25:361–374.
54. Wohlfarth-Bottermann, K. E. 1964. *In* Primitive Motile Systems in Cell Biology. R. D. Allen and N. Kamiya, editors. Academic Press, Inc., New York. pp. 79–108.
55. Allen, R. D., W. R. Pitts, Jr., D. Speir, and J. M. Brault. 1963. *Science (Wash. D.C.).* 142:1485–1487.
56. Nakajima, H. 1960. *Protoplasma.* 70:413–436.
57. Hatano, S., and F. Oosawa. 1966. *Biochim. Biophys. Acta.* 127:488–498.
58. Adelman, M. R., and E. W. Taylor. 1969. *Biochemistry.* 8:4964–4975.
59. Adelman, M. R., and E. W. Taylor. 1969. *Biochemistry.* 8:4976–4988.
60. Nagai, R., Y. Yoshimoto, and N. Kamiya. 1975. *J. Cell Sci.* 33:205–225.
61. Matsumura, F., and S. Hatano. 1978. *Biochim. Biophys. Acta.* 553:511–523.
62. Ridgeway, E. B., and A. C. H. Durham. 1976. *J. Cell Biol.* 69:223–226.
63. Hatano, S., and F. Oosawa. 1971. *J. Physiol. Soc. Jpn.* 33:589–590.
64. Kuroda, K. 1979. *In* Cell Motility: Molecules and Organization. S. Hatano, H. Ishikawa, and H. Sato, editors. Tokyo University Press, Tokyo. pp. 347–361.
65. Kamiya, N., R. D. Allen, and R. Zeh. 1972. Contractile properties of the slime mold strand. *Acta Protozool.* 11:113–124.
66. Kamiya, N. 1979. *In* Cell Motility: Molecules and Organization. S. Hatano, H. Ishikawa and H. Sato, editors. Tokyo University Press, Tokyo, pp. 399–414.
67. Wohlfarth-Botterman, K. E. 1977. *J. Exp. Biol.* 67:49–59.
68. de Bruyn, P. P. H. 1947. *Q. Rev. Biol.* 22:1–24.
69. Mast, S. O. 1926. *J. Morphol. Physiol.* 41:347–425.
70. Allen, R. D., J. W. Cooledge, and P. J. Hall. 1960. *Nature (Lond.).* 187:896–899.
71. Allen, R. D. 1961. *In* Amoeboid movement in "The Cell." J. Brachet and A. E. Mirsky, editors. Academic Press, Inc., New York. 2:135–216.
72. Allen, R. D. 1972. *Exp. Cell Res.* 72:34–45.
73. Jahn, T. L. 1964. *In* Primitive Motile Systems in Cell Biology. R. D. Allen and N. Kamiya, editors. Academic Press, Inc., New York. pp. 279–302.
74. Rinaldi, R. A., and T. L. Jahn. 1963. *J. Protozool.* 10:344–357.
75. Goldacre, R. J. 1964. *In* Primitive Motile Systems in Cell Biology. R. D. Allen and N. Kamiya editors. Academic Press, Inc., New York. pp. 237–253.
76. Subirana, J. A. 1970. *J. Theor. Biol.* 28:111–120.
77. Bingley, M. S., and C. M. Thompson. 1962. *J. Theor. Biol.* 2(1):16–32.
78. Kavanau, J. L. 1963. *J. Theor. Biol.* 4:124–141.
79. Allen, R. D., D. W. Francis, and R. Zeh. 1971. *Science (Wash. D.C.).* 174: 1237–1240.
80. Cullen, K. J., and R. D. Allen. 1980. *Exp. Cell Res.* 127:1–10.
81. Jahn, T. L., and E. C. Bovee. 1969. *Physiol. Rev.* 49:793–862.
82. Seravin, L. N. 1971. *Adv. Comp. Physiol. Biochem.* 4:37–111.
83. Allen, R. D., and N. S. Allen. 1979. Annu. Rev. Biophys. Bioeng. 7:497–526.
84. Taylor, D. L., and J. S. Condeelis. 1979. *Int. Rev. Cytol.* 56:57–144.
85. Thompson, C. M., and L. Wolpert. 1963. *Exp. Cell Res.* 32:150–160.
86. Pollard, T. D., and S. Ito. 1970. *J. Cell Biol.* 46:267–289.
87. Allen, R. D., and D. L. Taylor. 1975. *In* Molecules and Cell Movement. S. Inoué and R. E. Stephens. editors. Raven Press, New York. pp. 239–257.
88. Condeelis, J. S., D. L. Taylor, P. L. Moore, and R. D. Allen. 1976. *Exp. Cell Res.* 101:134–142.
89. Taylor, D. L., S. B. Hellewell, H. W. Virgin, and J. Heiple. 1979. *In* Cell Motility: Molecules and Organization. S. Hatano, H. Ishikawa, and H. Sato, editors. Tokyo University Press, Tokyo. pp. 363–377.
90. Goldacre, R. J., and I. J. Lorch. 1950. *Nature (Lond.).* 66:497–500.
91. Hitchock, S. E. 1977. *J. Cell Biol.* 74:1–15.
92. Allen, N. S., and R. D. Allen. 1978. *Annu. Rev. Biophys. Bioeng.* 7:469–495.
93. Taylor, D. L. 1977. *Cold Spring Harbor Conf. Cell Proliferation.* 797–821.
94. Grinnell, F. 1978. *Int. Rev. Cytol.* 53:65–144.
95. Vasiliev, J. M., and I. M. Gelfand. 1977. *Int. Rev. Cytol.* 50:159–274.
96. Abercrombie, M., J. Heaysman, and S. Pegrum. 1970. *Exp. Cell Res.* 59: 393–398.
97. Abercrombie, M., J. Heaysman, and S. Peagrum. 1970. *Exp. Cell Res.* 60: 437–444.
98. Harris, A., and G. Dunn. 1972. *Exp. Cell Res.* 73:519–523.
99. Curtis, A. S. G. 1964. *J. Cell Biol.* 20:194–215.
100. Izzard, C. S., and L. R. Lochner. 1976. *J. Cell Sci.* 21:129–159.
101. Izzard, C. S., and L. R. Lochner. 1980. *J. Cell Sci.* 42:81–116.
102. Bereiter-Hahn, F., C. H. Fox, and B. Thorell. 1979. *J. Cell Biol.* 82:767–779.
103. Revel, J. P., P. Hoch, and D. Ho. 1974. *Exp. Cell Res.* 84:207–218.
104. Crick, F. H. C., and A. F. W. Hughes. 1950. *Exp. Cell Res.* 1:37–80.
105. Tiney, L. G., and J. R. Gibbons. 1969. *J. Cell Sci.* 5:195–210.
106. Wessels, N. K., B. S. Spooner, J. F. Ash, M. O. Bradley, M. A. Luduena, E. L. Taylor, J. T. Wrenn, and K. M. Yamada. 1971. *Science (Wash. D.C.).* 171:135–143.
107. Goldman, R. D., and E. A. C. Follett. 1969. *Exp. Cell Res.* 57:273–276.
108. Goldman, R. D., and D. M. Knipe. 1972. *Cold Spring Harbor Symp. Quant. Biol.* 37:523–534.
109. Goldman, R. D., J. A. Schloss, and J. M. Starger. 1976. *Cold Spring Harbor Conf. on Cell Proliferation.* pp. 217–246.
110. Lazarides, E. 1975. *J. Cell Biol.* 65:549–561.
111. Lazarides, E., and K. Burridge. 1975. *Cell.* 6:289–298.
112. Wolosewick, J. J., and K. R. Porter. 1976. *Am. J. Anat.* 147:303–324.
113. Kamiya, N., and K. Kuroda. 1956. *Bot. Mag. Tokyo.* 69:544–554.
114. Jarosch, R. 1956. Plasmaströmung und chloroplastrotation bei Characeen. *Phyton (Argentina).* 6:87–107.
115. Jarosch, R. 1964. *In* Primitive Motile Systems in Cell Biology. R. D. Allen and N. Kamiya, editors. Academic Press, Inc., New York. pp. 599–622.
116. Kamitsubo, E. 1966. *Proc. Jpn. Acad.* 42:640–643.
117. Nagai, R., and L. I. Rebhun. 1966. *J. Ultrastruct Res.* 14:571–589.
118. Kamitsubo, E. 1972. *Protoplasma* 74:53–70.
119. Jarosch, R. 1976. *Biochem. Physiol. Pflanz.* (BPP). 170:111–131.
120. Kamitsubo, E. 1972. *Exp. Cell Res.* 74:613–616.
121. Allen, N. S. 1974. *J. Cell Biol.* 63:270–287.
122. Palevitz, B. A., and P. K. Hepler. 1975. *J. Cell Biol.* 65:29–38.
123. Kersey, Y. M., P. K. Hepler, B. A. Palevitz and N.K. Wessells. 1976. *Proc. Natl. Acad. Sci. U.S.A.* 73:165–167.
124. Kato, T., and Y. Tonomura. 1977. *J. Biochem. (Tokyo).* 82:777–782.
125. Williamson, R. E. 1975. *J. Cell Sci.* 17:655–668.
126. Nagai, R., and T. Hayama. 1979. *In* Cell Motility: Molecules and Organization. S. Hatano, H. Ishikawa, and H. Sato, editors. Tokyo University Press, Tokyo. pp. 321–338.
127. Rebhun, L. I. 1972. *Int. Rev. Cytol.* 32:92–137.
128. Kitching, J. A. 1964. *In* Primitive Motile Systems in Cell Biology. R. D. Allen and N. Kamiya, editors. Academic Press, Inc., New York. pp. 445–455.
129. Tilney, L. G., and K. R. Porter. 1965. *Protoplasma.* 60:317–344.
130. Edds, K. T. 1975. *J. Cell Biol.* 66:145–155.
131. Edds, K. Y. 1975. *J. Cell Biol.* 66:156–164.
132. Jahn, T. L., and R. A. Rinaldi. 1959. *Biol. Bull. (Woods Hole).* 117:100–118.
133. Allen R. D. 1964. *In* Primitive Motile Systems in Cell Biology. R. D. Allen and N. Kamiya, editors. Academic Press, Inc., New York. pp. 407–431.
134. McGee-Russell, S. M., and R. D. Allen. 1971. *Adv. Cell Mol. Biol.* p. 153–184.
135. Travis, J. L., and R. D. Allen. 1981. *J. Cell Biol.* 90:211–221.
136. Allen, R. D., J. L. Travis, N. S. Allen, and H. Yitmaz. 1981. *Cell Motil.* 1: 275–289.
137. Allen, R. D., N. S. Allen, and J. L. Travis. 1981. *Cell Motil.* 1:291–302.
138. Allen, R. D., J. L. Travis, J. H. Hayden, N. S. Allen, and A. C. Breuer. 1981. *Cold Spring Harbor Symp. Quant. Biol.* In press.
139. Allen, R. D., J. Metuzals, and I. Tasaki. 1981. *Biol. Bull. (Woods Hole).* In press.
140. Brady, S., R. Lasek, and R. D. Allen. 1981. *Biol. Bull. (Woods Hole).* In press.