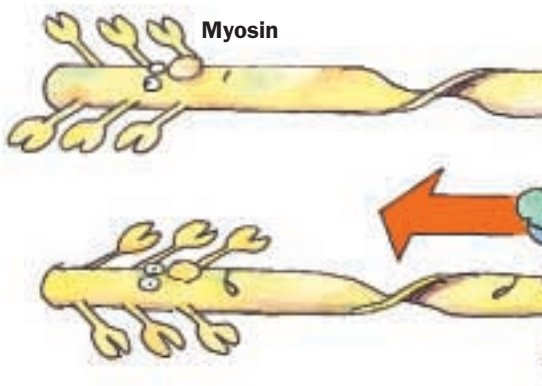
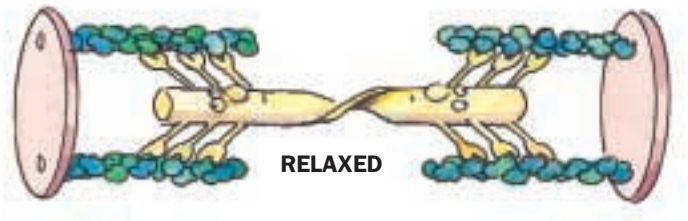
5.2 Multiplying Small Effects

Pumping Iron

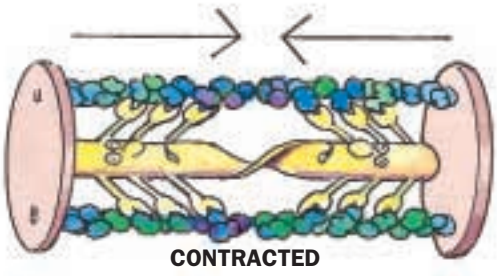
Out of the 70,000 or more different kinds of proteins made in human cells, we have selected two — actin and myosin — to show how small molecular events can produce large effects. Actin and myosin are the proteins that make muscle work. Inside muscle cells, actin and myosin genes are translated into many millions of copies of each of these proteins. They line up to form a biochemical ratcheting device that uses ATP for energy to shorten and lengthen itself. This tiny molecular machine leads to the action of a bulging biceps through the simple means of scaling up. Millions of actin-myosin combinations are strung end-to-end in long fibers, and these fibers are bundled together into dense, parallel, elastic cables — the muscle cells. Each microscopic contraction of an actin-myosin combination is amplified into contraction of a cell. Collective cell contractions produce an overall grand contraction — the action of a muscle.

1. Actin molecules are long and thin; myosin molecules are thicker and have many "arms" and "hands" sticking out from their sides. The hands touch the actin molecules.

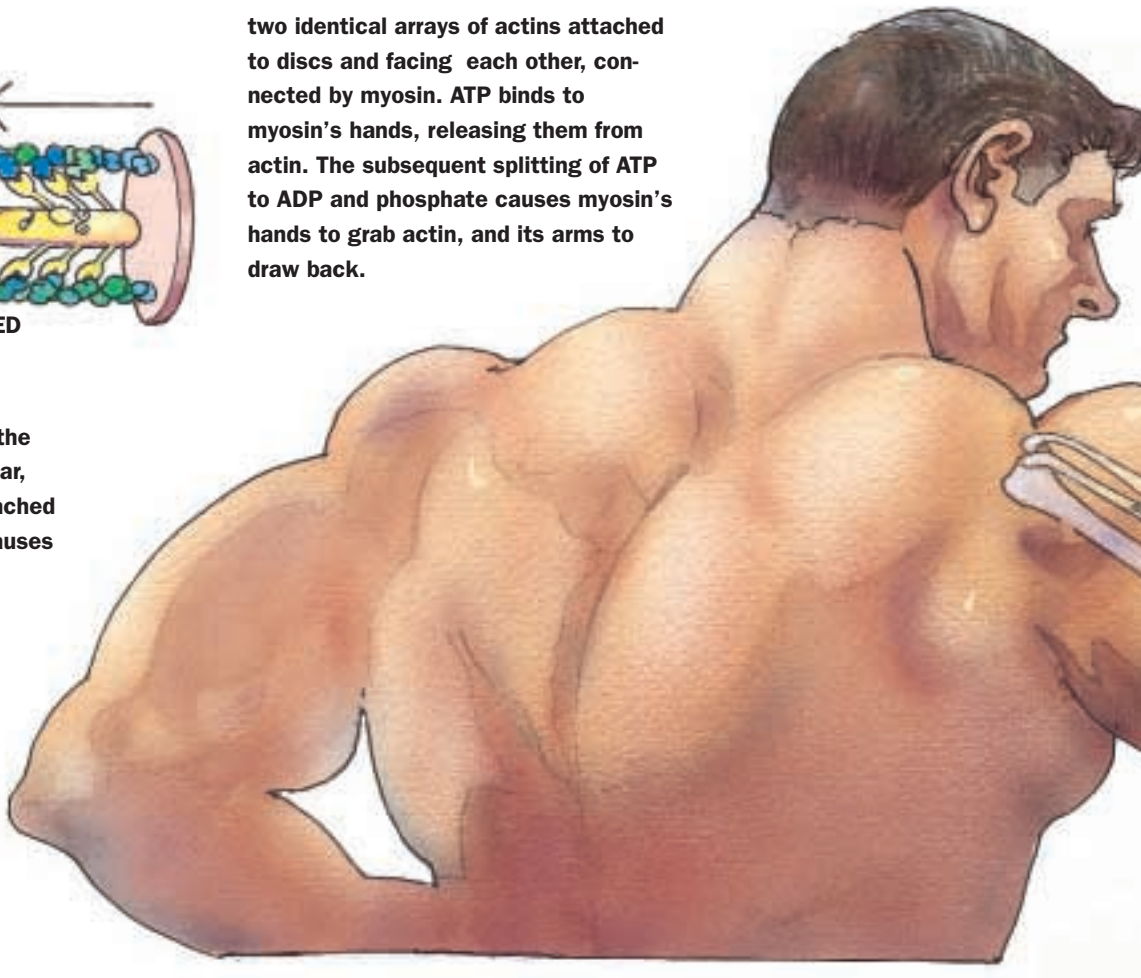




2. Each unit of contraction consists of two identical arrays of actins attached to discs and facing each other, connected by myosin. ATP binds to myosin's hands, releasing them from actin. The subsequent splitting of ATP to ADP and phosphate causes myosin's hands to grab actin, and its arms to draw back.



3. The release of ADP and phosphate from myosin causes the arms to make a stroke like an oar, pulling the actins with their attached discs toward each other; this causes contraction.



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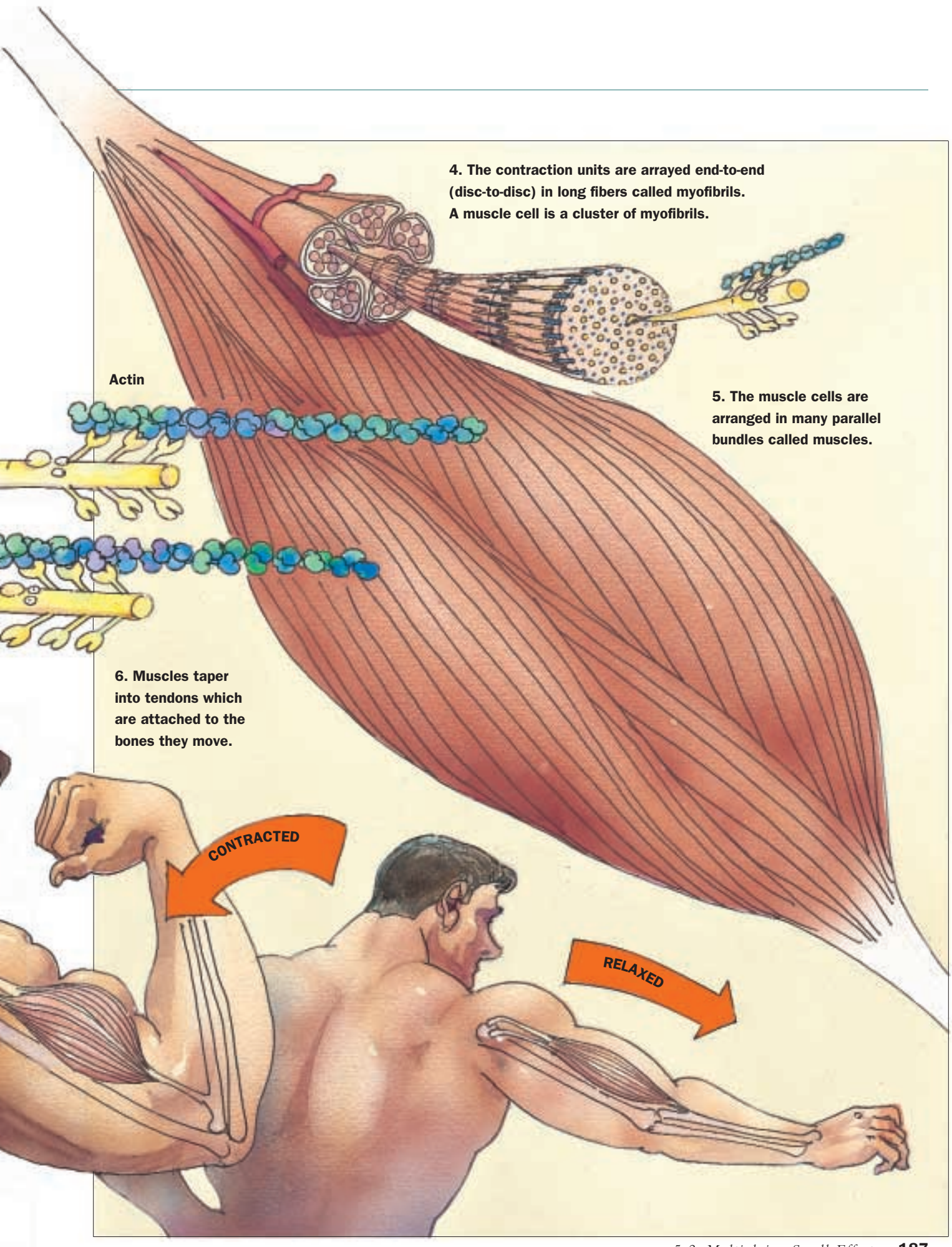

4. The contraction units are arrayed end-to-end (disc-to-disc) in long fibers called myofibrils. A muscle cell is a cluster of myofibrils.
Actin
5. The muscle cells are arranged in many parallel bundles called muscles.
6. Muscles taper into tendons which are attached to the bones they move.
CONTRACTED
RELAXED

It's the Same Molecules Everywhere You Look

A World of Swarming Chloroplasts

I was in a laboratory, using a very expensive microscope. . . . In the circle of light formed by the two eyepieces trained on the translucent leaf . . . I could easily see what I had come to see; the streaming of chloroplasts.
. . . Around the inside perimeter of each gigantic cell trailed a continuous loop of these bright green dots. They spun like paramecia; they pulsed, pressed and thronged. A change of focus suddenly revealed the eddying currents of the river of transparent cytoplasm, a sort of "ether" to the chloroplasts, or "space-time," in which they have their tiny being . . . they swarmed in ever-shifting files around and around the edge of the cell; they wandered, they charged, they milled, raced and ran at the edge of apparent nothingness, the empty-looking inner cell; they flowed and trooped greenly, up against the vegetative wall.

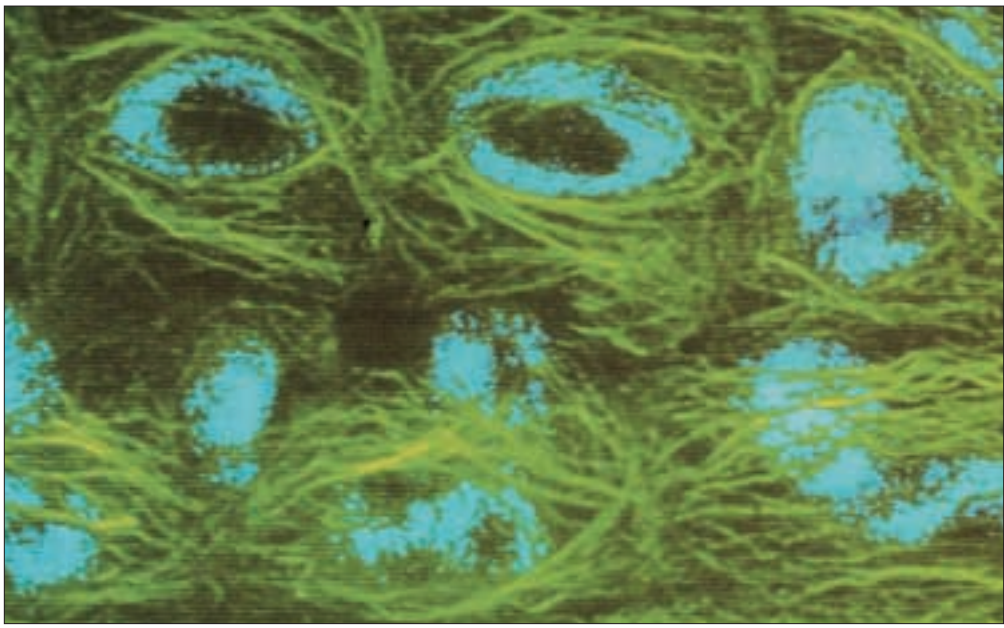
Annie Dillard, *A Pilgrim at Tinker Creek,* 1999

The eddying cytoplasmic currents (described in the observation above) that carry *Elodea's* chloroplasts are driven by exactly the same minuscule actin-myosin motors that make muscles contract and extend, that drive the slime mold's motion, and that allow white blood cells to engulf invading germs.

Microfilaments composed of the proteins actin and myosin can be found in animal, plant, fungal and bacterial cells. When ATP binds to the myosin molecules in these long fibers, the myosin contacts the actin molecules, causing the microfilaments to contract at the same time and in the same direction. This causes movement of the fluid part of the cell's contents. Interior organelles, vesicles, and molecules float on these currents like surfers on a wave, traveling rapidly throughout the cell.

Moving materials through a plant's root cells

In this laser scanning fluorescence micrograph, the actin in actin-myosin microfilaments shows up as bright green fluorescent threads, and each cell's nuclear DNA fluoresces blue. You can see how the microfilaments permeate the cell, circling the nucleus and enhancing the intracellular movement of molecules and molecular structures.



Acetabularia

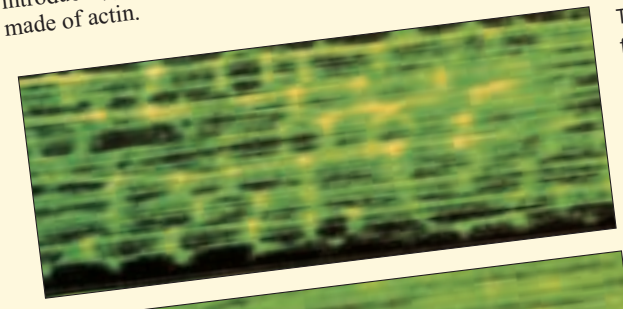
Acetabularia, whimsically called the mermaids wineglass, is a relatively enormous unicellular alga (it measures from 3 to 10 cm in length, and its "wineglass" cap is 1 to 3 cm in diameter). While its linear shape and filmy cap offer a large surface area for the diffusion of materials into and out of the cell, passive diffusion is not enough to move necessary molecules quickly throughout its volume. Cytoplasmic streaming, driven by actin-myosin interactions, is again the solution to this cell's traffic problem.

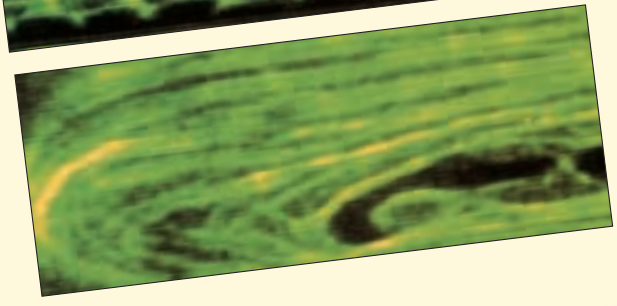
A forest of *Acetabularia* cells.

DOING Science

Allen, Nina S. 1974. Endoplasmic filaments generate the motive force for rotational streaming in *Nitella*. *Journal of Cell Biology* 63: 270-287.

This paper describes a clever experiment designed to show that the undulation of microfilaments in a large algal cell, *Nitella*, is the cause of the motion of particles throughout the fluid cell interior. *Nitella* were cultivated and collected. A window was cut into several cells using a mercury arc lamp, which allowed the experimenter to see into the cell and to film cytoplasmic streaming. The movement of particles in the cytosol was filmed by strobe light. The films showed particles moving in a serpentine pattern, which led to the conclusion that they were attached to unseen filaments. When a substance that inhibits actin-myosin interactions but does not affect other molecular structures in the cell was introduced, particle motion stopped. This led to the hypothesis that the filaments were made of actin.





The actin structure in *Nitella* forms an endless belt that provides enough momentum to sweep the entire cell content in a circle. (Only the actin in the actin-myosin complex flouresces.)

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