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A Long Way From Home: Transatlantic Sea Star Migration

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For a marine biologist strolling along the eastern coast of South America, finding some sea stars (popularly called starfish, and technically members of the class Asteroidea of the phylum Echinodermata) is not all that unusual. However, when closer inspection reveals the sea stars to be ones that are also found on the shores of the western coast of Africa, the marine biologist now faces an interesting question: How did these sea stars come to be so far from home?

It's a Long Way to Tipperary

Yes, adult sea stars can move by slowly crawling along the ocean bottom, but they cannot swim because they are negatively buoyant and unable to move their arms fast enough to "fly" through the water. Slow locomotion limited to the ocean floor is an inadequate means for traversing the vast distance of mountains and chasms that lie between Africa and South America. The hypothesis that this transoceanic migration might be completed over several generations of slowly crawling sea stars hits a snag because much of the deep ocean floor is uninhabitable by shallow-water species. Reflection on the predominant life cycle of echinoderms suggests another possibility. Most sea stars reproduce sexually by laying large numbers of eggs that hatch into swimming larvae, develop into juveniles, and then become adult sea stars. Larvae are slightly negatively buoyant, but they can maintain their vertical position in the water by the action of tiny "oars" on their body called cilia. Their swimming ability only allows them to remain adrift in the ocean until they develop into juveniles; they cannot overcome even the slightest ocean currents. When a larva is capable of becoming a bottom-dwelling juvenile it either becomes too dense to remain afloat, or it actively swims to the bottom where it begins a metamorphosis into the juvenile form. Could it be that ocean currents are responsible for carrying larvae across the Atlantic and depositing them on the shores of South America? Initially this hypothesis also hit a snag: The length of time that sea stars remain as larvae is far too short for ocean currents to transport them completely across the Atlantic basin. Somewhere in the mid-Atlantic the larvae would begin their metamorphosis to the juvenile form, drop out of their moving river of seawater, and sink to a premature death in the depths of the ocean.

Mathematics to the Rescue

Recently the hypothesis of transoceanic dispersal of sea star larvae via ocean currents received a boost when it was discovered that during the larval stage sea stars could reproduce asexually by cloning themselves. The cloning process produces a relatively younger sea star still in its larval stage. Because this new sea star can also clone, biologists have conjectured that a series of cloning events might produce a sufficient number of *generations* of larvae that remain adrift long enough for ocean currents to carry them from Africa to South America. Cloning dynamics and associated morphological changes that occur during sea star development are very difficult to study in nature, and laboratory studies might not match behavior in natural settings. As a result, mathematical models can play a useful role in (1) establishing the theoretical possibility that cloning enhances the likelihood of transoceanic migration of sea star larvae, (2) suggesting what empirical observations or data might best be sought to confirm or refute the hypothesis, and (3) generating new and testable hypotheses about the role of larval cloning and dispersal.

Although most of the mathematics involved in such models has been around for some time, the advent of faster and less expensive computers is stimulating much interest in contemporary mathematical modeling through the use of discrete simulations. In a matter of hours or days, a relatively simple computer program can simulate months of sea star cloning and drifting. The results of many such simulations can establish theoretical bounds on the parameters of cloning required for successful transoceanic journeys. In turn, these bounds, along with other insights gained from examination of the results of simulations, can suggest empirical experiments or data collections that can help refine the mathematical models, and ultimately confirm or refute hypotheses about the likelihood of successful trans-Atlantic dispersal of sea star larvae. Computer simulations can enhance our understanding of the biology and parallel the the interplay between theory and experiment that lies at the heart of physics.

Simulation Parameters: Recipes for Life and Death

The major currents in the Atlantic Ocean are very self-contained, and act as rivers in the ocean. Particles, bits of pollution, non-swimming organisms, and, in particular, sea-star larvae that enter such currents have a very high probability of remaining in them throughout the entire length of these "rivers." Neutrally buoyant particles, including sea stars (whose size is on the order of 0.5 mm) can be modeled by a random walk in a cross section of water that is steadily moved across the ocean. As the particles move nearer the boundary of the river (think of the rivers as having circular cross sections) they are reflected back toward the center of the river by the thermal gradient that helps define the river and its internal circulation. In the figures on these pages, the long dimension represents the horizontal dimension extending from one edge of the ocean to the opposite edge. The other two dimensions define the cross section of the current that in these simulations has been made circular. The bounding rectangle encloses the river. Each dot represents a sea star, and sea stars'

positions are updated once every day. Because the current is roughly constant in speed, the long axes of the diagrams are equivalent to time, as each dot moves roughly the same distance each day.

As the sea star is drifting through this river, life goes on...and so does death. Many sea stars are eaten, many may mature into juveniles and drop out of the river before being able to clone, some clone more than once, and some sea stars die from other causes. A simple simulation therefore might require the parameters below to bring the random walk of the larvae to life. Not all of the terms are technically accurate, but are used to help non-specialists gain a sense of the parameters' roles.

- Prey Ratio: percentage of sea stars eaten every day
- Maximum Age: age at which all larvae turn into juveniles and drop out of the river
- Puberty: age in days after birth or cloning before a sea star can produce a clone
- Gestation: number of days required to produce a clone
- Menopause: this is an asexual equivalent of sexual menopause, at which point a larva can no longer clone itself
- Minoff: the minimum number of clones per cloning (sometimes more than one clone is produced at one time by a single sea star — similar to a multiple birth)
- Maxoff: the maximum number of clones per cloning
- Cloneprob: the probability of any one sea star larva beginning a cloning cycle
- Initpop: the number of sea star larvae initially released into the current

Defining appropriate functions and values for these parameters, discretely stepping through each day and updating each sea star's position and age, and determining if a new clone has been released are the activities at the heart of this mathematical model. This project provides opportunities for gaining insight into mathematics, programming, and biology. ❑

- Initialize Population
- Predation: Delete a Percentage of Population at Random
- Increase all Sea Stars' Age by 1 Day
- Delete Larvae Turned Juveniles
- Clone: Check if Cloning is Possible: Randomly Select Larvae Able to Clone; Add New Cloned Larvae to Population
- Update all Sea Stars' Positions
- Allow Random Drift Within Current's Cross Section
- Increment All Sear Stars' Horizontal Position by 1
- Repeat Beginning with Predation

Table 1. One Possible Flowchart For A Sea Star Drift Program

References

These references provide biological background information only and might be of interest to biology teachers wanting to collaborate with computer programming teachers in supervising students' modeling work.

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Will Jaeckle is assistant professor of biology at Illinois Wesleyan University where thanks to Paul's interest in mathematical modeling, both are now spending many many hours watching simulated sea stars disperse across their computer screens. As their model is refined, Paul hopes the results might net him a trip with Will into the field to see sea star dispersal up close and personal.

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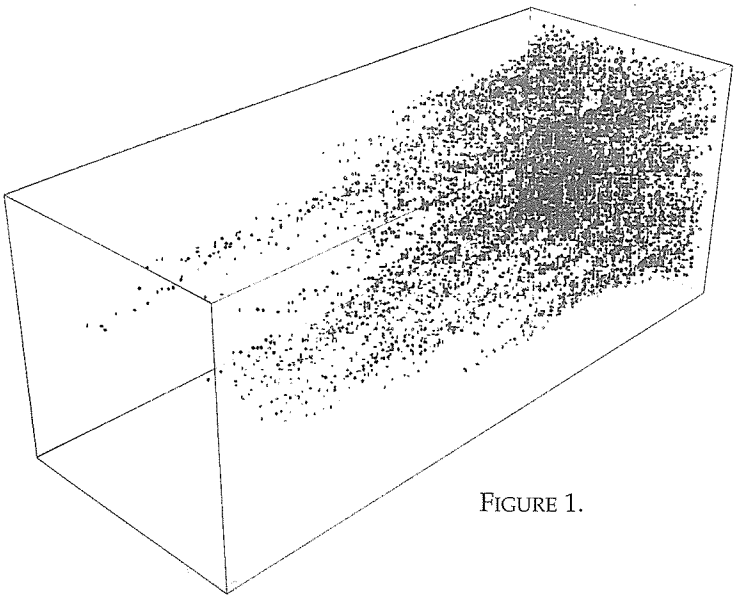

FIGURE 1.

Figure 1.
The parameters for this simulation do not result in sea star larvae persisting in the ocean current long enough to drift all the way across the Atlantic Ocean. The different shades correspond to different genetically identical "families" of larvae cloning generation after generation.

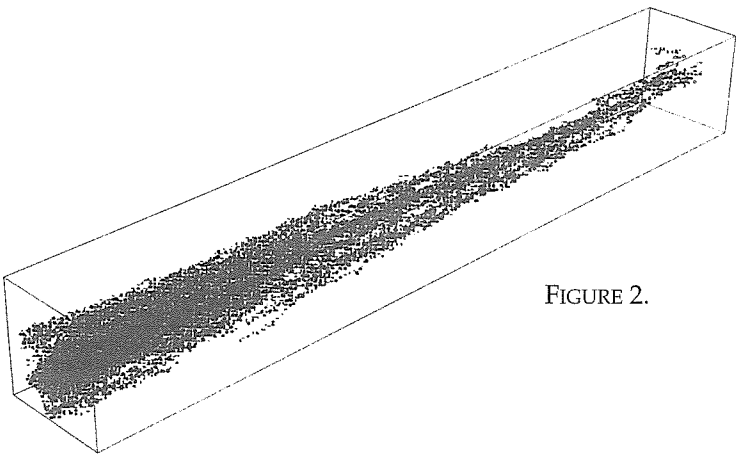

FIGURE 2.

Figure 2.
In this simulation, very few families of sea star larvae multiply and arrive in vast numbers on the other side of the ocean. This is very unlikely, and probably the result of a too low prey ratio, or a too high likelihood of cloning.

Figure 3.
This is a more reasonable simulation than the previous one, but not a very long-lived one.

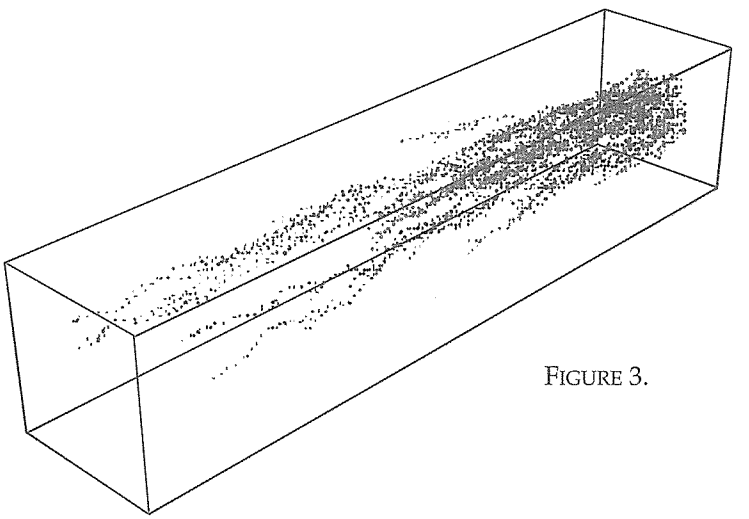

FIGURE 3.

The diagrams on this page reflect the variety of dispersal patterns that can result from various combinations of different values for the parameters of **Table 1**. Perhaps your students would enjoy developing their own simulations, running them, and seeing what insights they might gain into sea star migration, computer programming, and/or mathematical modeling.

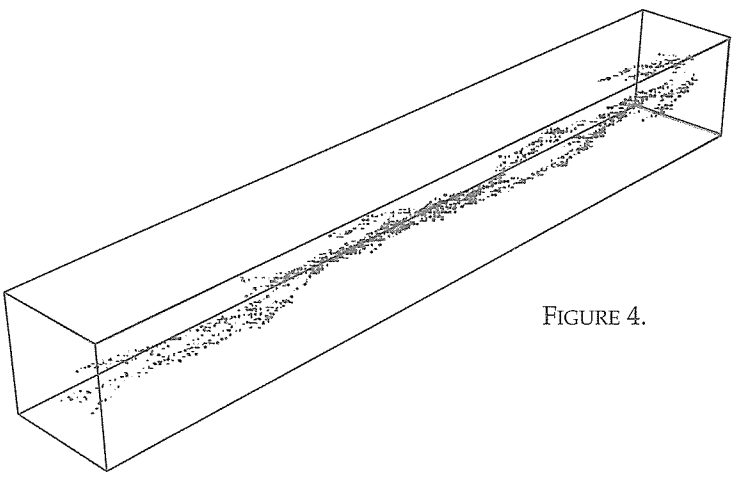

FIGURE 4.

Figure 4.
This simulation is most likely to reflect actual dispersal where very few sea star clones wind up remaining in the ocean current long enough to make it across the Atlantic Ocean.