Doctoral Thesis

Why Fish School

Allen Philips

Abstract

Fish have been observed to form shoals (swimming together), and schools (swimming together with coordinated motion) throughout recorded history.

Primary Conclusion: Fish shoaling and schooling is optimized evolutionary behavior because it reduces predation primarily by **hiding from predators.**

This conclusion will be demonstrated utilizing Fourier Series analyzing the spatial-frequency behavior of foraging fish with the temporal-frequency behavior of certain insects.

Secondary Conclusion: When predation is encountered, fish shoals collapse into schools to further shrink their spatial footprint and minimize their continued detection. The ocean is basically visually opaque and a separation of 100 meters is basically undetectable.

Concurrent complex attributes associated with fish aggregates are:

- Overwhelming of predation when encounters do occur
- Coordinated motion as individual and group escape behavior

The consequences of this determination are broad:

- Better modeling of fish population predictions.
- Better understanding of cooperative modelling.
- Mapping this causation onto other animal populations: bird flocks and migrating herds, etc.
- Forces revision of simple evolutionary game theory models (fish shoaling should devolve into individual fish competition over time if evolutionary game theory about selfish genes is correct).
- Implies groups compete evolutionarily, both inter-species and intra-species.
- Implies inter-species competition drives: altruism, senescence, and cancer frequency.
- Causes reconsideration on how human populations behave within groups.
- Suggests human instincts , although overlain and modified by intellect and social behavior, are significant
- Rewrites the narrative in biological academia and scientific literature.

Introduction

<u>Statement:</u> Fish form shoals primarily to 'hide' from the predator population.

This survival technique is accomplished by 'hiding' in the smallest possible region of a large space. In conjunction, a secondary reason is to overwhelm the predator population when contact occurs. Many additional reasons have been put forth, but they only enhance the primary survival technique and actually 'muddy' the waters of understanding.

Examples of **<u>inaccurate descriptions</u>** of the reason fish shoal and school:

1. Through better predator detection[1];
2. If fish swim in schools, it is less likely any one of them will be eaten[2];
3. A predator is less likely to attack several hundred or thousands of fish than one or two individuals[3];
4. Schools are conformed by thousands or hundreds of nearly identical fish who confuse predators and make it difficult to single out and attack one individual fish[4];
5. Sticking together helps fish avoid predators by relying on a team of eyes that could potentially detect a predator and then signal to the rest of the group that a predator is nearby[5];
6. Predators find it far easier to chase down and gobble up a fish swimming all alone rather than trying to cut out a single fish from a huge group[6].

An intuitive example is necessary to assist the audience in understanding the distinction between these anecdotal rationales (predators are scared of schools) and the substantive discovery (schools hide from predators over large spatial regions).

Temporal EXAMPLE: For termites, **hiding all year** round, is the predominant survival strategy. Yet, since they eventually deplete their food supply, they must move on. Flying one day a year in late fall may avoid predation locally altogether. If not, the behavior overwhelms the local predators so much that a fraction of the population always survives: a positive adaptation.

Summary: I will show in a mathematical model utilizing Fourier Transform, that the frequency of termite events in a temporal domain is the exact equivalent as the frequency of fish in a spatial domain.

Methods

I developed a very simple model of termite behavior over time-space-frequency demonstrating their survival mechanism. I then used the same model utilizing fish shoaling over the same time-space-frequency domain. I then demonstrate their equivalency graphically and by reference to Fourier transforms.

To create a time-space domain that could be mapped to the real world, I created a rectangular column, with time the vertical axis, and the base and cross section, the spatial plane.

The time axis was set to display one year, since that was the observational period for watching termites, 365 days.

Then, to be able to quickly visualize the results of the model, I selected a 2-dimensional area with similar units, a square of 19 x 19 acres, which resulted in 361 square acres for the space (a little less than a square mile).

Because this will be a model, and the objective is to communicate the results, I devolved the model by about 12% and came up with 400 units on the temporal axis, and 400 units (20 x 20) on the spatial plane, resulting in numbers most people can manipulate in their head.

Finally, I reduced the model to a minimalistic sample by more than 75% , while maintaining relationships, a 4x4 square spatial dimension, and a 16-day temporal dimension. Set minimum behavior rules

- Initially, prey and predator are constrained to initial assigned spaces
- prey and predators are distributed evenly about the spatial domain
- predators can consume up to 10 prey per day that are in their box
- more prey (an arbitrary number: I chose one prey for each unit space-time) than predators (one per unit area).

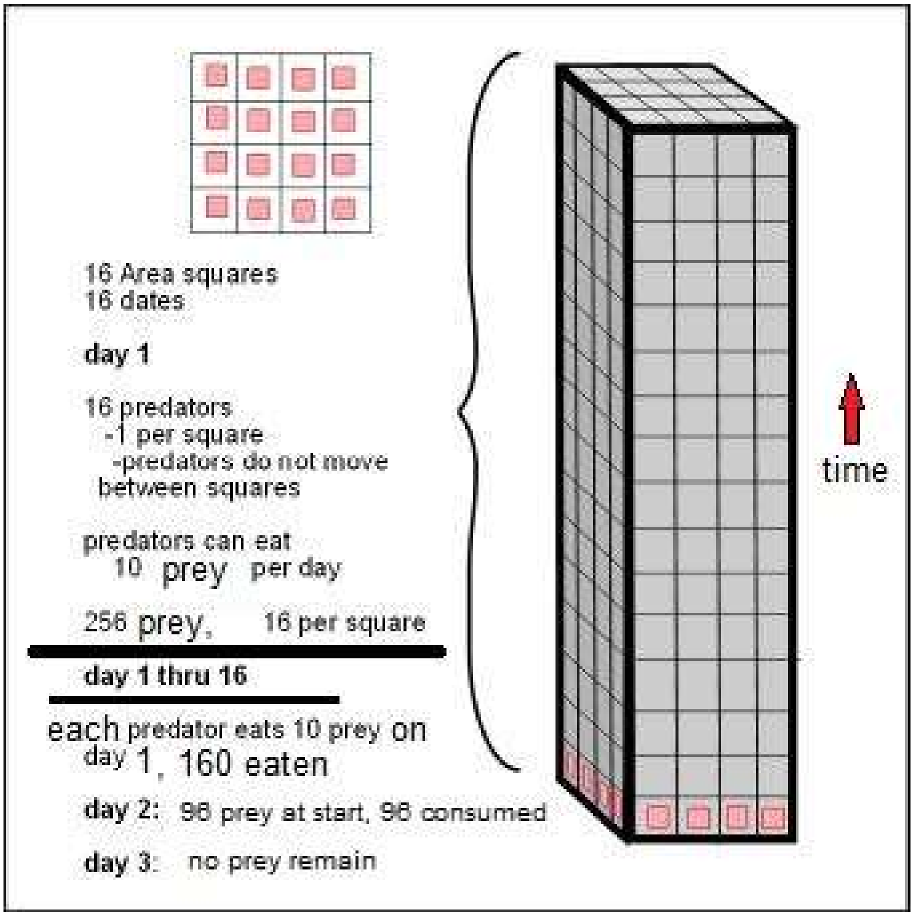
I conducted the analysis on the reduced model, then expanded the analysis to the large models.

Terms:

- Spatial Frequency – how often an event occurs across a landscape
- Temporal Frequency – how often an event occurs over time
- Fourier Transforms – a method of relating spatial frequency and temporal frequency using mathematical models and manipulation

Results

The initial run of the model was a 4x4 square spatial dimension, and a 16-day temporal dimension. The metrics were that predators and prey were evenly distributed spatial on day one.



Day one: 16 predators, one per square, 256 prey, 16 per square

Day two: 16 predators, one per square, 96 prey, 6 per square

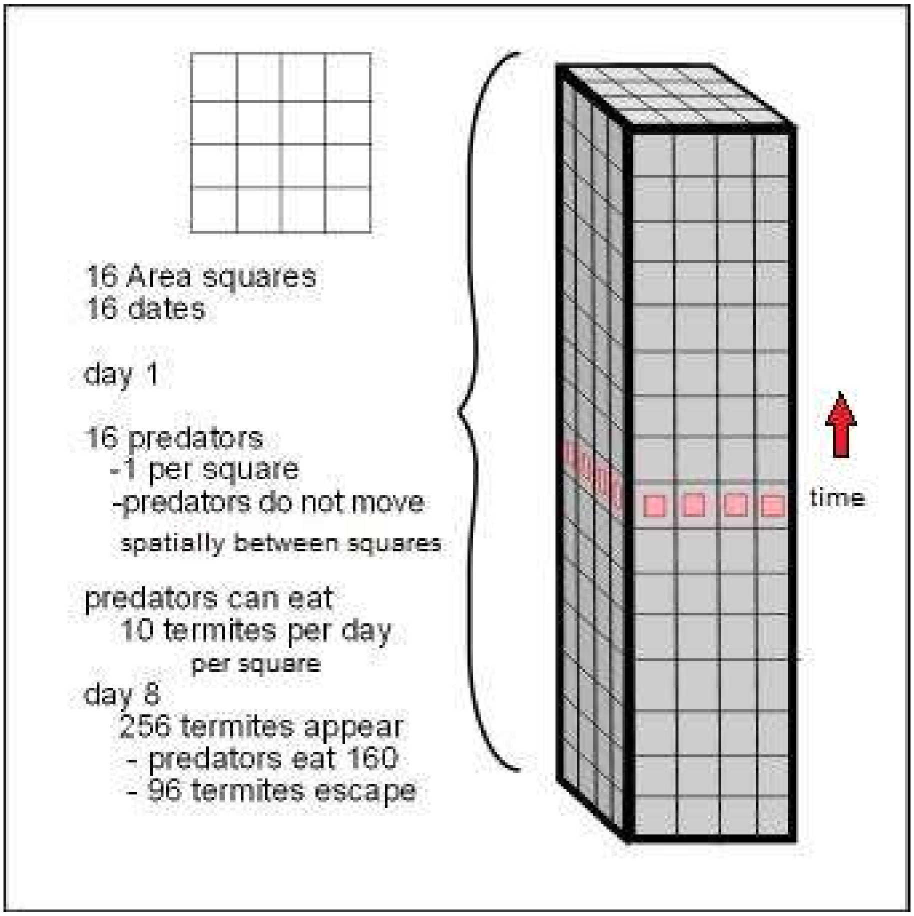
Day three: 16 predators, one per square, 0 prey, no survivors

Day sixteen: 16 predators, one per square, 0 prey, no survivors

Conclusion: In this model, the prey do not survive, whether termites or anchovies, without temporal or spatial separation from the predators

Note: Throughout this simple model, the dynamics of prey and predator boom and bust population fluctuations were not attempted to be shown because, although they may impact absolute numbers, they do not affect relationships or ratios.

The **temporal-frequency** run of the model was a 4x4 square spatial dimension, and a 16-day temporal dimension. The metrics were that termites only appear on one date.



Day one: 16 predators, 256 termites in hiding, 16 per square

Day seven: 16 predators, 256 termites in hiding, 16 per square

Day eight: 16 predators, 256 termites show up, all across the landscape, 16 per square

Each predator eats 10 termites, 160 termites eaten

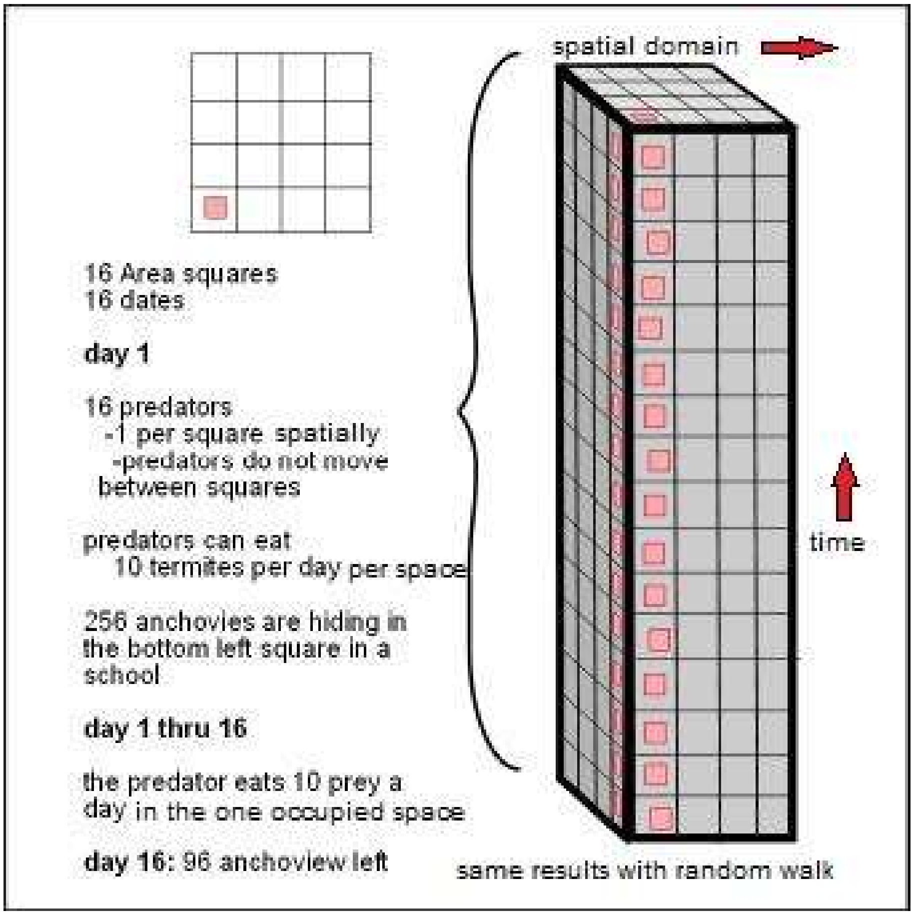
Day nine: 16 predators, 96 termites in hiding, 6 per square

Day sixteen: 16 predators, 96 termites in hiding, 6 per square

Conclusion: Termites survive by using 'temporal hiding' and overwhelming predation when contact occurs

This model is easy to understand and is 'intuitive'.

The **spatial frequency** run of the model was a 4x4 square spatial dimension, and a 16-day temporal dimension. The metrics for sardines were that they only appear in one square.



Day one:	16 predators, 256 anchovies in hiding, 256 on one square
	One predator eats 10 anchovies, 246 remaining
Day two:	16 predators, 246 anchovies in hiding, 246 on one square
	One predator eats 10 anchovies, 236 remaining
Day eight:	16 predators, 186 anchovies in hiding, 186 on one square
	One predator eats 10 anchovies, 176 remaining
Day nine:	16 predators, 176 anchovies in hiding, 176 on one square
	One predator eats 10 anchovies, 166 remaining
Day sixteen:	16 predators, 106 anchovies in hiding, 106 on one square
	One predator eats 10 anchovies, 96 remaining
Conclusion:	**Anchovies survive by using 'spatial hiding' and overwhelming predation when contact occurs**

Discussion

Comparing models: if we enlarge the boundaries of the simple model to match that of the year-long design, our numbers are increased (based on one prey per box), to 400 predators and 160,000 prey, but the ratios stay the same.

One can easily describe the predominate termite behavior as 'hiding' for most of the time, then hiding from, or overwhelming, the predator population during the infrequent interactions.

Note: Using the same parameters between temporal termites and spatial anchovies results in the same numbers of survivors.

The interactions within Earth's Biome evidently contribute to the evolutionary forces that drive the grouping of prey species, whether in a spatial-frequency domain or temporal-frequency domain.

There is a Fourier equivalency between the temporal frequency of the nuptial emergence of termites and the spatial frequency of fish shoals.

Therefore, the predominate rationale for the occurrence of forage fish forming shoals is to 'hide' across the large opaque openness of the ocean, then during the infrequent interactions forming schools and escaping into those opaque waters or overwhelming the predator population.

Conclusion

<u>Conclusion:</u> Fish principally form shoals and schools to 'hide' from the hunter population to reduce predation.

This survival technique is accomplished by 'hiding' in the smallest possible region of a large opaque space. Shoals, while large compared to schools, are minuscule compared to the size of the open ocean. In conjunction, shoals form schools when contact with predators occurs.

Schools are smaller, harder to detect and follow, than shoals. Schools swim quickly in a coordinated fashion in almost random patterns, possibly to escape continued predation by creating separation between the school and the initial location of attack.

All our video of contact is in clear water. However, the ocean is often murky with visibility in just a few feet. Coordinated and compact group motion with pressure sensing lateral lines can dart away and survive to live another day.

A secondary reason for shoals and schools is to be able to overwhelm the predator population when contact occurs.

Secondary behaviors also occur to enhance the primary objective of avoidance of predation and improving group dynamics.

<u>Concurrent Statement:</u> Fish shoals and schools **<u>are not</u>** harder for predators to attack than individual fish. When encountered, individual fish are harder to attack than fish shoals.

This is in contrast to currently accepted reasons[1,2,3,4,5,6]. As such, it is a significant contribution to our understanding.

Result Implications

One implication of this behavior is that Darwin's Theory of Evolution may need to be modified for groups.

1. Individuals working together improves the survival chances for the individual within the group.
2. First Order Game Theory and Selfish Gene Studies imply that individuals taking advantage of the group is the best decision for the individual.
3. Within a fish school being attacked, each individual has the same chance on being on the exterior or the interior of the ball as any other member of the school. This implies the instinctual behavior of the individual fish forces it to place itself periodically on the exterior of the group, benefiting the survival of the group in opposition to best strategy for the individual.
4. This fundamentally implies that an individual fish within a group maximizes the survival rates of is own genes if it:
    - Sacrifices itself for the group
    - The group survival rate is improved at a higher rate than the rate the individual fish is lost
    - On average, the individual's gene's survival rate is improved
    - In boom-and-bust environments, species survival is sometimes dependent upon group survival
    - In these scenarios, all members of the group are willing to sacrifice equally
5. The fact that fish shoals and other animal grouping continue to flourish runs counter to first order Game Theory. This is also supported by the dearth of pelagic foraging fish that do not form shoals and schools.

This means that the survival fitness of a group, which is different than the fitness of an individual, modifies the chance of the successful transmission of an individual gene.

This can be considered a complex, multi-ordered feedback system which modifies the reproductive success of individual genomes away from selfishness towards cooperation.

A final implication is about human behavior and genetics. If group success modifies individual reproductive success, then human pack behavior, altruism, senescence and cancer may have their roots in our genetic code.

Author

Allen Philips has a unique educational path

- US Naval Submariner 1971-1992
- Conservator and Steward of Dolphin Place, a PNW Native Plant Conservancy, 1973-date
- Master's Degree, Oceanography, University of Washington, 1990
- Sub-contractor, J.K. Parish, Coordinated Fish Motion Studies, University of Washington. 2002
- Sub-contractor, J.K. Parish, Marine Biology Laboratories, University of Washington, 2010
- Student/ Naturalist/ Sailor/ Master Electrician/ Philosopher, 1970-date

References:

1 - https://en.wikipedia.org/wiki/Shoaling_and_schooling

“Fish derive many benefits from shoaling behavior including defense against predators (through better predator detection and by diluting the chance of individual capture), enhanced foraging success, and higher success in finding a mate. It is also likely that fish benefit from shoal membership through increased hydrodynamic efficiency.”

2 - https://simple.wikipedia.org/wiki/Shoaling_and_schooling

“Fish get many benefits from shoaling. These include defense against predators: if fish swim in schools, it is less likely any one of them will be eaten. Also, it may help a fish find food, and a mate. The school may even swim faster than a lone fish.”

3. - https://www.aqueon.com/articles/schooling-fish

“A predator is less likely to attack several hundred or thousands of fish than one or two individuals.”

4 - https://www.visitloscabos.travel/blog/post/3-reasons-fish-swim-schools/

“Schools are conformed by thousands or hundreds of nearly identical fish who confuse predators and make it difficult to single out and attack one individual fish. An extreme but common response of schools attacked by predators is the formation of a circle.”

5 - https://oceanbites.org/science-says-fish-should-stay-in-school/

“Some species of fish swim together in large social groups called schools for several reasons. Sticking together helps fish avoid predators by relying on a team of eyes that could potentially detect a predator and then signal to the rest of the group that a predator is nearby.”

6 - https://www.youtube.com/watch?v=7F_f6KReJo8&t=25s

“First and foremost, schools protect fish from their enemies. It's the same rule our mothers taught us as youngsters, always stay in a group because there is safety in numbers. Predators find it far easier to chase down and gobble up a fish swimming all alone rather than trying to cut out a single fish from a huge group. The same holds in reverse. Fish can better defend their territory in a group. Bullies will think twice about facing an angry school of dozens or hundreds of fish.”

Why Do Fish School?”

7 - https://www.youtube.com/watch?v=wzaGHtZr-Pc reindeer form herds, confuses predators, stated as ***FACT!***

8 - researchers led by Catherine Peichel, a human biology researcher at the Fred Hutchinson Cancer Research Center in Seattle, studied sticklebacks,