Jeff Gore – Evolutionary Systems Biology – Evolutionary and Ecological Dynamics

Physics student at MIT – PhD in Biophysics – single molecule biophysics – population dynamics, quantitative systems biology

Not unrealistic at all to approach decision making of single cells at a game theory and quantitative systems biology level

Evolutionary and ecological dynamics:

evolutionary dynamics = allele freqs in a population

ecological dynamics = pop size, interactions of diff species

key principles to keep in mind:

1. The power of exponential growth, esp how something limiting appears rather quickly
2. Cooperative growth dynamics
   1. Can increase fitness
   2. Can lead to sudden collapse (i.e. deteriorating environments)
   3. Can be taken advantage of by non-contributors (“cheater” strategies)

When you are going to take a measurement, pause first and take a sec to think about what you expect – make a guess about what you expect. The way he does this in his lecture is with flash cards and asking for votes, in some cases has people turn to neighbors and discuss. I would sign people into a Kahoot and maybe try to have two desktops open and go back and forth in lecture – partly voting, partly formative assessment. Announce up front that this is my style, you can see straight up if you’re following along

Bacterial cell = how long to divide in an optimal environment? About 20 min

Start with a single cell. Let it divide for 2 days – what’s the mass of the resulting population? What do you expect after the weekend? Assuming unlimited resources

# divisions / day = 3 divisions / hour \* 24 hours / day \* 2 days = 2 ^ 144… 3000 Earths

Exponential growth quickly overwhelms you

How to model these kinds of phenomena with simple differential equations

Modeling population dynamics

dN/dt = rN

N = pop size

r = growth rate (per capita)

N(t) = N0ert

As t goes to infinity, what happens to N? – It depends…r could be multiple things, because we don’t know what r is, if r is negative or positive or zero. “Exponential growth” could also be exponential decay

Per capita growth rate as a function of the population size N : gamma == 1/N dN/dt. In the base case, r is constant and gamma = r

Something should limit the growth – nutrients, space = what we use to represent this is that r is actually a function of something else, some way to quantify resources. There are many ways to model the world – we could write another diffeq that represents glucose concentration, another that represents nitrogen availability, and so on…or we can assume that r is not constant but is a function of N

N, population size, is not the direct factor limiting growth, but N is a proxy for the factors that have been used up and are limiting growth. It’s a phenomenological model, a functional model describing how the populations grow, but not explicitly defining which resources are limiting.

Logistic growth dN/dt = rN (1 – N/K)

The simplest way that something can decrease is linearly. It might not way the best way to model your system, but it’s generally a good way to get started to develop intuition. Start with some per capita growth rate r, and now r decreases linearly over time. If you graph N on the x axis and gamma = 1/N dN/dt on the y axis, then gamma = r when t = 0 (y intersect), and the x intersect is some value N = K == carrying capacity

When you’re working with diffeqs, it’s helpful to think of the “fixed values” of N, where if N is that value it won’t change from that value. In this case, when dN/dt = 0: N=K.

Ask also about N = 0, and ask if it’s stable or unstable – if you move a little away from it in one direction or another, are you likely to move in one direction or another? We can look at the sign of dN/dt – around K, there’s a trend to push towards from both sides, so that’s stable. But if you think about having zero individuals, at zero you will always stay at zero, but as soon as there is one individual N will tend towards K. Therefore N=0 is unstable.

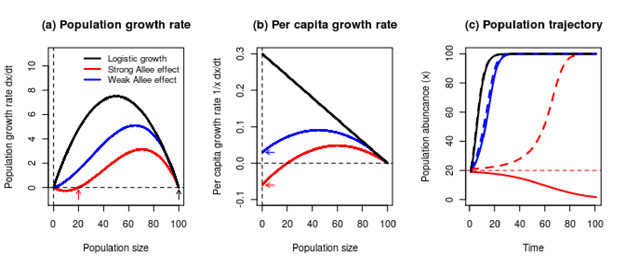
When you graph logistic growth, N tends towards K as t approaches infinity, regardless of whether N starts above or below K, as long as there is at least one individual.

(you can add a variety of complications to make things overshoot, oscillate, do a variety of extra things)

How do things change when you discuss cooperative growth?

With logistic growth, having more individuals is always bad for you as one individual in the population. Your per capita growth rate gamma is going to decrease. But maybe if there’s a cooperative effect, there’s a positive slope for per capita growth rate somewhere in the range of N.

Allee Effect – per capita growth initially grows with population size.



Consider the graph for the per capita growth rate (middle) and look at just the strong Allee effect (red).

There’s still a carrying capacity K but there’s also a value NC, N-critical, at which the per capita growth rate becomes negative. If N were ever to drop below NC, then N would fall to 0. (How do you ever get past the initial barrier of NC? The issue is that NC is something that evolves in an ecosystem, it isn’t initially present and it isn’t static over eons, but it can change slowly…but it’s a major issue and it’s a big reason for defining “critically endangered” and a serious focus in conservation biology.

What are some potential causes of Allee effects?

1. Need to find mates
2. Complex societies
3. Genetic diversity
4. Cooperative hunting
5. Herding/schooling
6. Predator satiation (not explicit cooperation, but if your population is above a certain size then your predators are full and that gets your population to more normal dynamics)

What if there is a deteriorating environment?

Let’s add in an increased death rate – each individual has some increase in mortality for some reason

dN/dt = rN(1 – N/K) – (delta)N

1/N dN/dt = r(1 - N/K) – delta

Delta just shifts our previous curve down vertically, decreasing the population size

The population will go extinct when delta = r

[Set 1/N dN/dt = 0, delta = r(1 – N/K), delta = r]

Death rate is going to start pulling things down as delta increases.

With the Allee effect, as delta increases the stable and unstable population size approach each other.

NC increases as K decreases. They eventually run into each other. In the mathematics, these two points collide and annihilate each other. This is a bifurcation in the dynamics of the system.

At some point, the minimum population size required for survival is becomes equal to the actual, and then beyond that there is a tipping point. A very small change in the death rate can lead to sudden catastrophic collapse.

This is something that people worry about a lot at fisheries, bee colonies

Modeling diseases – R and R0 parameter in infected and uninfected populations to determine

R here, something like rate of reproduction and rate of death

Need at higher levels to factor in evolutionary dynamics…individuals can acquire mutations to affect R, what are consequences of such evolution

Close interplay currently between experimental studies of evolution and theoretical prediction of how mutations should spread … for example, clonal interference – consider two competing beneficial mutations trying to spread through a population at the same time, but in a case like bacteria where there is asexual reproduction they can’t both win – can’t get those same mutations from competing lineages in the same individual, so there’s population-level competition between multiple mutations

Game theory in biology

What happens if one member of the population stops contributing to that public good?

We do NOT need to assume anything about the rationality of members of the population – don’t think through this like a classic game of he thinks she thinks, Vizzini vs the Dread Pirate Roberts, clearly I can’t choose the wine in front of you, clearly I can’t choose the wine in front of me – cells are not rational, they don’t think in the way the human brain does, they don’t connive…but even so, some of the same principles apply.

Game theory in biology:

* Mutations sample strategies
  + i.e. higher or lower expression of gene encoding some cooperative behavior
* payout = reproductive fitness
* differences in fitness = game solution

consider a symmetric two person game:

payoff(you, opp)

you = choose(A, B)

opp = choose(A, B)

payoff(A,A) = (3,3)

payoff(A,B) = (0,5)

payoff(B,A) = (5,0)

payoff(B,B) = (1,1)

The prisoner’s dilemma here highlights a classic thing: if you and your opponent both choose A, you both do OK but if either had chosen B, that person would have gotten a higher payout. So in a single encounter, there’s little incentive for cooperation. Given that your opponent chooses A, your best choice is to choose B to get more points even though it hurts your opponent. Given that your opponent chooses B, your best choice is to choose B to get any points. Yet if you need to play repeatedly, there may be an incentive for you to choose A and build trust. Having said that, there’s no clear case where playing A will be in your benefit here and it can clearly hurt you. 5 > 3, 1 > 0 … Nash Equilibrium is B.

Nash Equilibrium

Dilemma of cooperation – what can you do to sustain strategy A? repeated games in humans to get the psychology aspect…in biology we talk about mutations affecting behavior instead

Consider a bacterium that acquires a mutation inactivating an essential enzyme for digesting sugars, but it still lives with other bacteria that secrete that enzyme. Now it can freeload off its neighbors and it has an advantage relative to wild-type since it doesn’t have to spend resources making that enzyme and can spread in the population.

Note that evolution can decrease fitness when you have these game theory interactions at play

Consider some of John Maynard Smith’s writings – several of the major transitions in evolution occur when you get cooperative banding together of smaller factions of self-replicators to reproduce at a higher level of organization: eukaryotes, multicellularity, altruism