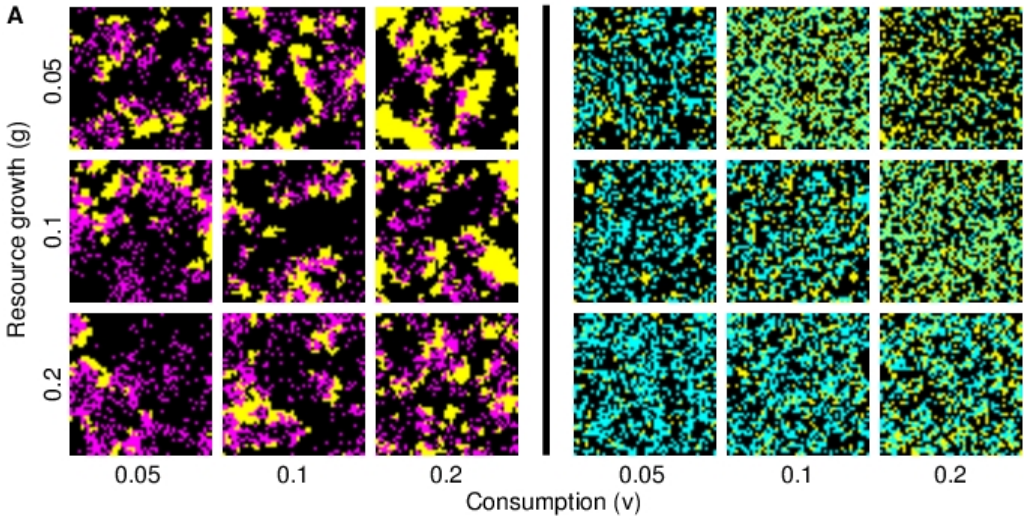
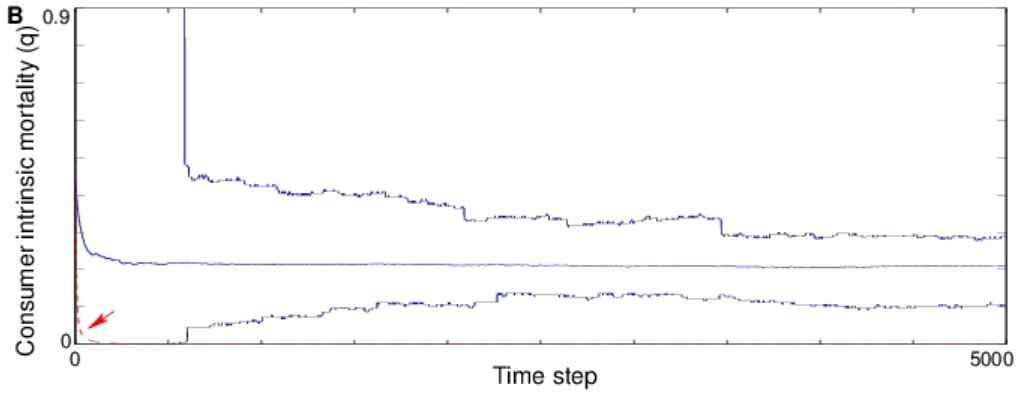
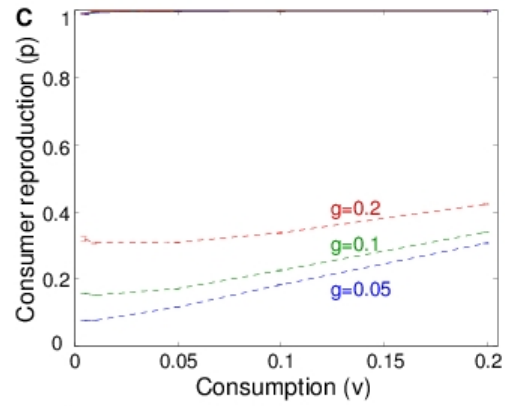
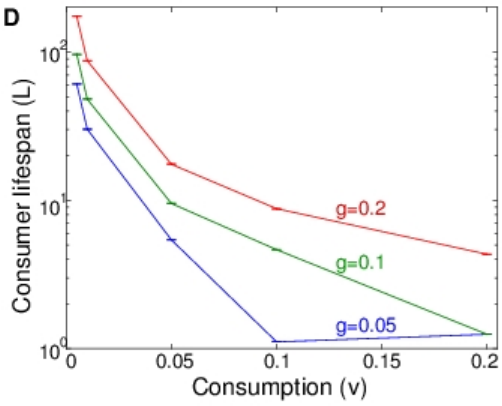
Death by Design? Spatial models show that natural selection favors genetically-limited lifespan as a lineal benefit

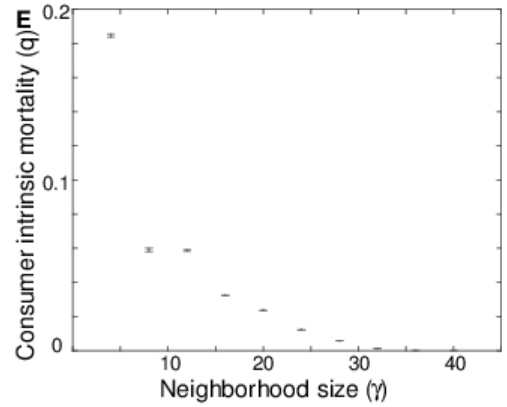
July 16 2015, by Stuart Mason Dambrot

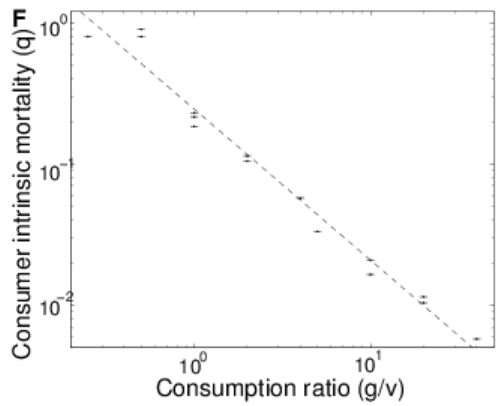

A
Resource growth (g)
0.05
0.1
0.2
0.05
0.1
0.2
0.05
0.1
0.2
Consumption (v)


B
Consumer intrinsic mortality (q)
0.9
0
0
5000
Time step


C
Consumer reproduction (p)
1
0.8
0.6
0.4
0.2
0
g=0.2
g=0.1
g=0.05
0
0.05
0.1
0.15
0.2
Consumption (v)


D
Consumer lifespan (L)
10^2
10^1
10^0
g=0.2
g=0.1
g=0.05
0
0.05
0.1
0.15
0.2
Consumption (v)


E
Consumer intrinsic mortality (q)
0.2
0.1
0
10
20
30
40
Neighborhood size (γ)


F
Consumer intrinsic mortality (q)
10^0
10^-1
10^-2
10^0
10^1
Consumption ratio (g/v)

Ascendance studies favor intrinsic mortality in numerical simulations with a spatial model. (a) Snapshots showing different spatial distributions of resources (yellow) and immortal (left, magenta) or mortal (right, cyan) consumers (50 × 50 subsets of 250 × 250 lattices). (b) History of evolving consumer intrinsic mortality q in one example trial ($g = v = 0.1$, $c = 0$, $\mu p = \mu q = 0.01$). Mean-field analysis (red, dashed; arrow) predicts mean q quickly goes to 0. Numerical simulations (blue, solid; population mean-maximum-minimum) show long-term stability of finite q and elimination of low-q strains from the population. (c),(d) Steady-state average values of (c) consumer reproduction probability p and (d) intrinsic life span $L = 1/q$, for different values of parameters g and v and for (c), (d) mortal (solid) and (c) immortal (dashed) populations. (e) Steady-state evolved q in mortal populations ($g = v = 0.05$, $c = 0$) for increasing neighborhood size γ. For high enough γ, consumers with $q = 0$ are not eliminated from the population. (f) Steady-state evolved q for the mortal populations of (d) approximately falls on a single curve [line is a power-law fit: $q = 0.245(g/v-1.07]$ when plotted as a function of "consumption ratio" g/v, for all g and v tested. All error bars show the standard error of the mean from ten independent trials. Credit: Justin Werfel, Donald E. Ingber, and Yaneer Bar-Yam, *Phys. Rev. Lett*. 114, 238103 (2015).

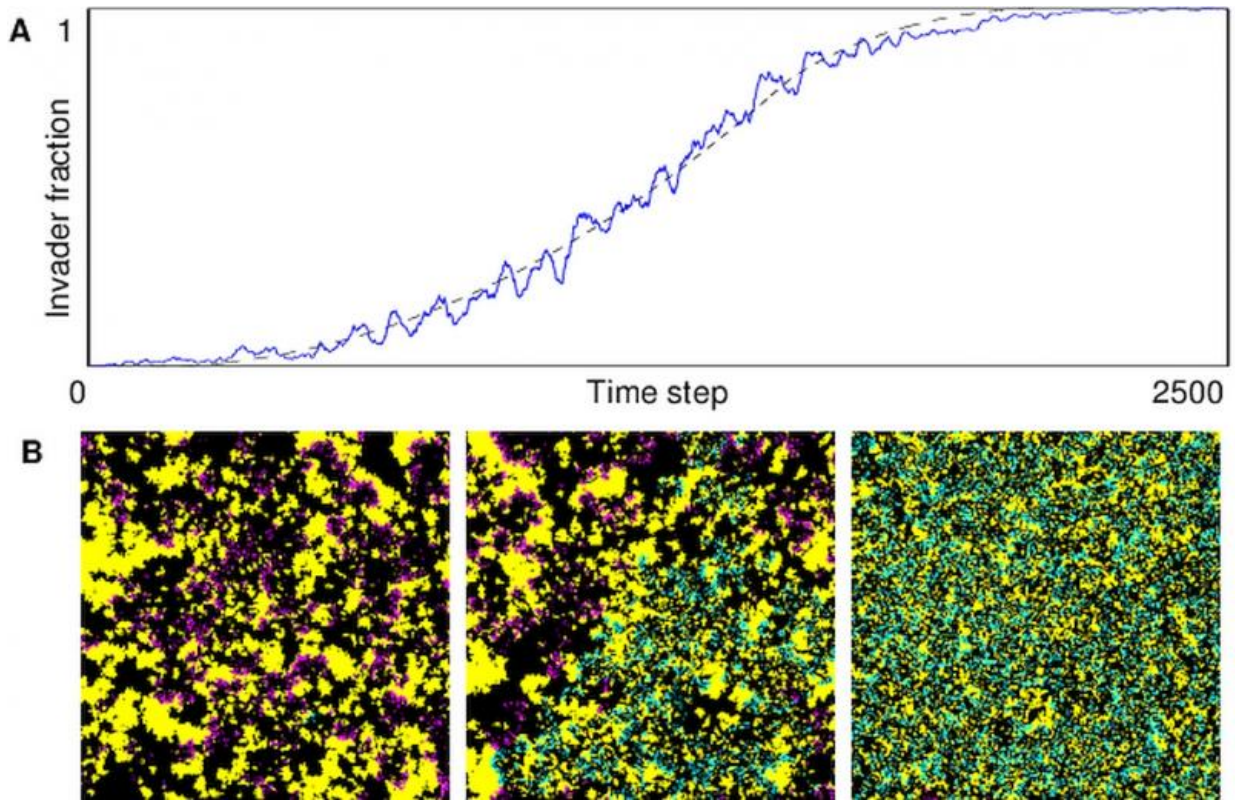
(Phys.org)—Standard evolutionary theories of aging and mortality, being based on mean-field assumptions – which analyze the behavior of large and complex stochastic models by studying a simpler model – conclude that programmed mortality resulting from natural selection is impossible. Recently, however, scientists at the New England Complex Systems Institute, and the Wyss Institute for Biologically Inspired Engineering at Harvard University, both in Cambridge, Massachusetts, using spatial models with local rather than globally-uniform reproduction, demonstrated that programmed deaths strongly result in long-term benefit to an organismal lineage by reducing local environmental resource depletion over many generations. (In *spatial models*, variables are distributed in space such that actions can affect the local

environment without affecting the global environment.) Moreover, the researchers found that these results continued to be favored when a large number of variations related to different real-world factors were applied to the spatial model, which they say supports their approach being applicable to a wide range of biological systems, and therefore that direct selection for shorter life span may be quite widespread in nature.

Dr. Justin Werfel discussed the challenges that that he and his colleagues faced in conducting their study published in *Physical Review Letters* – one being the use of spatial models with local reproduction to investigate mean-field assumptions-based standard evolutionary theories of aging and mortality asserting that programmed mortality is untenable because it opposes direct individual benefit. "The issue of space is critical because standard evolutionary theories are based on an implicit assumption that everything is effectively happening in the same place, in the sense that every place is like every other," Werfel tells *Phys.org*. "When you make that assumption, the result you get is that short-term reproduction is all that matters – that is, whatever lets you make more copies of yourself or your genes is favored, and anything that reduces that direct individual benefit is selected against. However, while that approximation makes it mathematically tractable to calculate the outcome of the model, it actually winds up giving you the wrong result."

In a spatial system, a trait that allows greater reproduction can be beneficial for a multigenerational time scale – but ultimately, on much longer time scales, carries a penalty in limiting the eventual number of descendants. "The mechanism," Werfel explains, "is based on long-term environmental feedback: depleting resources in an unsustainable way translates into your descendants inheriting an impoverished environment, and as a result being less successful. These spatial systems aren't tractable to mathematical analysis in the same way as those that make the simplifying approximation of complete mixing, so we need simulations to study them in a more empirical way."

Such simulations, applied to the evolution of self-limited lifespan, showed that programmed death robustly results in long-term benefit to a *lineage* by reducing local environmental resource depletion. "It seems intuitively obvious that a gene contributing to the death of its owner ought to be selected against. That idea is consistent with standard theories, which conclude that it's impossible for selection to act in favor of shortened lifespan directly – the only way a lifespan-shortening gene could be favored is if it also increases reproduction earlier in life, so that it gives a net benefit to the individual. However," Werfel continues, "what we see in spatial models is that longer-lived variants deplete their environment more, and as a result wind up with fewer chances to reproduce, so that self-limited lifespan actually winds up giving an advantage far enough down the line."



A successful invasion of immortal consumers by mortal ones. (a) The fraction of

invaders in the population (solid line) increases almost monotonically with time. The region dominated by mortals grows steadily: the dashed line shows the area of a circle (under periodic boundary conditions) whose radius increases at a constant rate (correlation r = 0.997). Resource growth g = 0.05, consumer consumption v = 0.2, consumer reproduction cost c = 0. (b) Snapshots at 50, 1350, and 2550 time steps [colors as in Fig. 2(a)]. Credit: Justin Werfel, Donald E. Ingber, and Yaneer Bar-Yam, *Phys. Rev. Lett.* 114, 238103 (2015).

The scientists also had to identify two additional factors: the spatiotemporal patterns that characterize environmental depletion, as well as the multi-generational feedback caused by these patterns. "Typically," Werfel explains, "longer lifespan *does* give a short-term direct advantage – namely, the expected number of descendants of a longer-lived variant may be greater than for a shorter-lived one for many generations into the future. The effect that ultimately makes limited lifespan favorable – which is based on the way the virtual organisms in the model shape their environment by using its resources over time – can take a very long time before the shorter-lived ones have the advantage. This is not captured by standard theories."

Finally, the researchers were faced with determining the validity of the implication that direct selection for shorter life span may be quite widespread in nature. "To understand what aspects of the model were responsible for the results it showed, and to make sure that those results weren't sensitive to things like specific assumptions or careful tuning of numerical parameters, we explored a wide range of changes to the model," Werfel tells *Phys.org*. These changes – which included modifying parameter values by more than an order of magnitude, allowing organisms to move around in their local environment, and using sexual as well as asexual reproduction – showed that lifespan self-limitation was favored in all cases, with two exceptions: when the range of movement was so large compared to the size of the world that the

system was effectively well-mixed, and where resources were so abundant that they were effectively inexhaustible. (A *well-mixed* system does not capture spatial distributions of specific properties.) "In the real world, of course, movement and resources are typically both limited; and the fact that the model gave the same result – that is, that self-limited lifespan was favored in the long run – for all the other kinds of changes we explored suggests that that result isn't sensitive to other details of the system, and so it ought to hold for a correspondingly wide range of real systems in nature."

Werfel next addressed the paper stating that *the robustness of the finding that self-limited life span is favored across model variations provides evidence for its applicability to a variety of biological systems*. "The fact that almost all the changes we made to the model continued to produce the same result – namely, that self-limited lifespan is favored – suggests that this result should also hold for biological systems in general without sensitivity to system details just as it's not sensitive to model details. As such, the mechanism we've identified, which allows selection for programmed death – which standard theories say is impossible for multicellular organisms – provides an additional explanation for empirical observations, including some which have been hard to accommodate with the standard theories. For instance," Werfel illustrates, "octopuses reproduce just once, after which they stop eating and starve to death – but if you surgically remove a particular gland, they start eating again. That at least strongly looks like a programmed death mechanism." Another example, he adds, is an effect frequently reported as a key prediction of standard theories: that high predation rates on a population should lead to the evolution of shorter lifespan – but the opposite has been observed with guppies, with populations that evolved under higher predation having longer intrinsic lifespan. "Our model predicts that result, because the increased death through external causes takes the place of death through internal causes. On the other hand," Werfel notes, "there are situations where our model would predict that

self-limited lifespan is *not* favored – for example, organisms under such high predation that no further self-limitation is needed, or those for which resources are unlimited. However," he adds, "that doesn't mean that we'd expect such organisms to be immortal. There are other factors that contribute to mortality – specifically, mechanisms described by standard theories of aging. In a situation with conditions such that the model predicts that self-limitation of lifespan isn't favored, we'd expect observed lifespan limits to be due to these other mechanisms."

In their paper, the scientists state that their findings have strong implications for human medicine, giving examples of likely translational applications and protocols regarding effective health and life extension. "The understanding of life and health extension based on standard evolutionary theories points to two approaches, both of which are limited," Werfel tells *Phys.org*. "Firstly, if aging is due to a collection of individual breakdowns, which evolution has pushed off to be as late as feasible, then each of these needs to be tackled and dealt with individually. Secondly, if there are effects contributing to late-life breakdowns as a side effect of early-life benefits, then intervening in these mechanisms necessarily involves tradeoffs and may not be a good idea. However, our findings suggest that evolution may have established mechanisms to tune and control lifespan, which could potentially be adjusted over a very wide range – and if so, there may be interventions that turn that knob, so to speak, and so could potentially allow very significant health and life extensions without accompanying tradeoffs for the patient. We therefore argue that it would be worth focusing more medical research in that direction, rather than ruling out the possibility *a priori* based on a theoretical understanding which our results indicate has been incomplete."

In summary, Werfel emphasizes that the standard evolutionary theories of aging and mortality do not explicitly state their assumption about spatial mixing – and since laboratory protocols are typically designed to

use well-mixed approaches to ensure that experimental conditions are the same everywhere, this approach doesn't seem like a controversial assumption or practice. "However," he notes, "spatial models show how things fundamentally change when space is taken into account. We created such a model to look at the evolution of intrinsic mortality, and were surprised to find the counterintuitive result that lifespan self-limitation is favored even in the absence of other conditions that could intuitively make it favorable – for instance, if animals had to stop reproducing at a certain age, or in a rapidly changing world where you needed new mutations always to be coming along to cope with the changing conditions, it would make sense to clear out old individuals and replace them with new ones." The study's key results show that even without such limiting conditions – that is, if an organism could live and keep reproducing indefinitely, and was just as adapted to the world as its offspring – the lineage would ultimately do better if genes encoded a mechanism that brings about death.

"Spatial models have contributed a great deal in recent years to our understanding of altruistic and cooperative evolutionary phenomena, and there are many cases where they can continue to help us gain insight," Werfel concludes. "I think the point about the qualitative behavior of a system changing when it's spatial vs. well-mixed is really critical – but is one that is not as widely recognized in biology as it deserves to be."

More information: Programed Death is Favored by Natural Selection in Spatial Systems, *Physical Review Letters* (2015) 114: 238103, doi:10.1103/PhysRevLett.114.238103

https://phys.org/news/2015-07-death-spatial-natural-favors-genetically-limited.html