An Evolvable Linear Representation for Simulating Government Policy in Zombie Outbreaks

Government policy

- Government intervention has proven to be quite ineffectual during many zombie outbreaks
- Command and control breaks down in sectors with outbreaks
- Civilians are uninformed or misinformed of locations for evacuations and medical supplies
- Policy initiatives that have been developed after humanity has been overrun can have disastrous impacts.

The Redeker Plan

- For example, consider the Redeker Plan
  - this was outlined in *World War Z*, a historical document about zombie attacks
- Individuals were selected for survival based on survivability, useful skills, and the protection of military and political officials
- However, the result doomed large segments of the general public
- Civilians were deliberately misinformed about safe areas to lure groups of zombies away from the real withdrawal.

Mismanagement

- The Redeker Plan was substantially mismanaged
- Although some survived, it was widely seen as reprehensible
- One of the primary problems was that it was made on the fly
- Having an established government plan during the early stages of an outbreak is therefore of primary importance.

Simulation models

- Zombie outbreak-planning for governments can be improved by using computer models
- Simulation allows various outcomes to be viewed, based on the sequence of actions selected
- Multiple models can be run to assess the typical and extreme impact of stochastic events
- This will allow for more accurate planning.

Evolutionary algorithms

- We use evolutionary algorithms (EAs) in order to search the space of possible government responses
- EAs are a global optimisation technique which can efficiently search complex, discrete model spaces
- Based on the principle of natural evolution
- An EA operates on a population of possible zombies outbreak policies, examining and comparing tens of thousands of policies in each modelling run.

Model assumptions

- No initial reanimation of the dead
- The only deaths are from zombie causes
- All humans killed will be resurrected as zombies
- There's a fixed incubation period before becoming a zombie
- Population is well-mixed
  - thus, it is equally likely for any zombie to meet any human.

The discrete-time model

- The model uses discrete timesteps
- These models have some differences compared to ODEs
  - eg equilibria are found differently
- The model is

$$
\begin{aligned}
Z_t &= Z_{t-1} + I_{t-d} - R_t \\
S_t &= S_{t-1} - I_t \\
I_t &= \beta Z_{t-1} S_{t-1} \\
R_t &= \alpha Z_{t-1} S_{t-1}
\end{aligned}
$$

  where Z are zombies, S are susceptibles, I are infected and R are removed (dead)
- β is transmissibility, α the kill rate, d a delay.

Infection Parameter

$$Z_t = Z_{t-1} + I_{t-d} - R_t$$
$$S_t = S_{t-1} - I_t$$
$$I_t = \beta Z_{t-1} S_{t-1}$$
$$R_t = \alpha Z_{t-1} S_{t-1}$$

- The virus infects humans in any one timestep based on
  - aggressiveness of the zombies δ
  - the percentage of immunity to the virus γ
  - the chance of a zombie encounter causing infection ω
- The infection term is a conjunction of these factors
- Thus, β=(1-γ)δω.

S: humans
Z: zombies R: dead
I: latently infected
β: transmissibility
α: kill rate d: delay

Aggression parameter

$$Z_t = Z_{t-1} + I_{t-d} - R_t$$
$$S_t = S_{t-1} - I_t$$
$$I_t = \beta Z_{t-1} S_{t-1}$$
$$R_t = \alpha Z_{t-1} S_{t-1}$$

- α quantifies human aggression
- A zombie is killed by a human depending on
  - weaponry and training ability ρ
  - the chance of encountering zombies while at an advantage φ
- Thus, α=ρφ.

S: humans
Z: zombies R: dead
I: latently infected
β: transmissibility
α: kill rate d: delay

A delay

$$Z_t = Z_{t-1} + I_{t-d} - R_t$$
$$S_t = S_{t-1} - I_t$$
$$I_t = \beta Z_{t-1} S_{t-1}$$
$$R_t = \alpha Z_{t-1} S_{t-1}$$

- Zombies do not immediately rise from the dead
- Instead, they are delayed for a number of rounds d
- This represents the infected proportion of the population being taken out of action due to sickness, then rising back to join the undead after the incubation period
- Thus, this is a delay discrete-time system
  - analogous to delay differential equations.

S: humans Z: zombies R: dead
I: latently infected d: delay
β: transmissibility α: kill rate

Government policies

- Government policies of various types change the infection rate β
  - via the application of health policies
- They also change the kill rate α
  - via military action and education
- S_t can be changed by the addition of personnel in military forces.

S: humans
β: transmissibility
α: kill rate

Additional factors

- There are three other factors:
  - *vax*, the level of scientific progress towards understanding the virus
  - *aware*, the threat and awareness variable
  - *army*, the number of additional troops dispatched in a call-up of military personnel
- The creation of a vaccine is based on the *vax* variable.

Equilibria

- There are two equilibria: no humans and no zombies
- If both human and zombies have a positive value, then there is a positive probability that a zombie will infect a human or that humans will infect a zombie
- Since humans and zombies interact, this is an intrinsic feature of the simulation.

Policy effectiveness

- An effective policy must steer the system away from the pure-zombie equilibrium
- This is done via manipulation of α and β
- It is desirable to have $\beta<\alpha$
- This means humans are killing zombies faster than humans are being infected
- The quicker the system is steered towards a large value of α/β, the faster the system approaches the pure-survivor equilibrium
- This provides a basis for assessing policy effectiveness.

β: transmissibility
α: kill rate

String representation

- We use a *string representation*
- This is an evolvable linear representation that can be used to model sequential actions taken to steer a state-conditioned discrete model
- String representations have been used to act as models for the design of starfighters
- And also for election strategies.

Time steps

- The actions in sequential policy are applied to the state variable per time step
- A time step represents a few days of the zombie outbreak
- We limit the action taken by the government to one per time step
- This represents the intrinsic inefficiencies of implementing government policy in a democracy
- Limitations include money, time, effort and logistical difficulties.

Costs and actions

- The cost of taking an action only represents initial investment in a policy
- The effects may persist for the remainder of the simulation, even when other actions are chosen
- Actions thus represent shifts in the pattern of governmental efforts
- State variables of the simulation represent inertia that limits the impact of those variables.

Actions that the government can take

Action	Symbol	Effect
Quarantine	Q	$\omega = (2\omega + 0)/3,$ $Aware = (2Aware + 0)/3$
Army	A	$\rho = (\rho + 1)/2 \ if \ (\mathbf{rand} < Aware),$ $S_t = S_t + 100,$ $Aware = (Aware + 0)/2 \ if \ (Z_{t-1} > S_{t-1})$
Kill	K	$\rho = (\rho + 1)/2,$ $\omega = (2\omega + 1)/3$
Warn	W	$\rho = (3\rho + 1)/4,$ $Aware = (2Aware + 1)/3$
Fearmonger	F	$\rho = (2\rho + 1)/3,$ $Aware = (3Aware + 1)/4$
Science	S	$Vax = (Vax + 1)/2 \ if \ (\mathbf{rand} < Aware)$
Vaccinate	V	$\gamma = (3\gamma + 1/4) \ if \ (\mathbf{rand} < Vax)$ $Aware = (Aware + 0)/2 \ if \ (Z_{t-1} < S_{t-1})$

- **rand** produces a uniformly distributed random number.

δ: aggressiveness
γ: immunity ω: infectivity
ρ: weaponry φ: advantage

Quarantine

- *Quarantine* includes the collection and burning of bodies
- Also working to reduce the ability of zombies to infect the population
- This can be accomplished via curfew and martial law
- There is not a specific group of quarantined zombies
- Rather, this action represents the isolation of infectious materials.

Army/Kill

- *Army* represents the directive of the government to call in military forces
- *Kill* represents citizens who arm themselves to defend their homes
- Often involves looting of weaponry sources
- Other provisions will also affect the defence ability of a survivor
  - food, water, fuel, medicine, radios
- Armed citizens in the form of a militia can also supplement local military forces.

Warn/Fearmonger/Science/Vax

- *Warn* deals with dissemination of information
  - eg TV and radio broadcasts
- *Fearmonger* represents misinformation or calls for outlandish action
  - eg recommendations to feed the zombies or calls for nuclear strikes
- *Science* represents learning more about the mechanisms that the virus uses for transmission
- *Vax* represents the development of a potential vaccine.

Public response to government policy

- Many actions are stochastic in effect
- Either because the action is random
  - eg developing a vaccine
- Or because they require approval by the populace
  - ie a declaration of war on the zombies
- Unfortunately, human behaviour is not always orderly
- Thus, good policy needs to take this into account.

People may resist martial law/quarantine

- Eg the tenement building at the start of *Dawn of the Dead*
  - a SWAT team discovered occupants dumping dead bodies into the basement
  - this led to a large reservoir of zombies
- Without SWAT intervention, the tenement would have been overrun by zombies
- The officers speculated that the dumping of bodies was due to respect for the dead
- Governmental health initiatives would not have allowed this.

Public approval

- In the model, the *aware* factor is built into all of the actions except *kill*
- The *kill* action is in many ways a default
- Citizens noticing a zombie outbreak will do their best to arm themselves and fight back
- Thus, public approval would not change from its current levels
- However, approval of government factors into most other actions.

Military and awareness

- The military may always be called in
- However, their use of weaponry will only be effective if they are fighting zombies alongside civilians
- Not just acting as crowd control against an angry armed citizenry
- This makes an increase in the weaponry rate dependent upon the degree of public awareness.

Loss of awareness

- If the number of zombies is substantially smaller than humans, there may be a loss of awareness
  - people may find the idea of zombies unbelievable
- The reverse happens in an attempt to deploy a vaccine
- The public only has sympathy for a vaccin-ation effort when they outnumber the zombies
  - otherwise military action will take precedence
- The change or cost of awareness is independent of the effect to the system.

Evolutionary Algorithms

- EAs are a branch of computational intelligence derived from the theory of evolution
- They are most effective for optimising discontinuous, stochastic or anisotropic problems
  - anisotropic problems are those when the property changes with the direction of measurement, like wood grain
- Discrete problems are natural targets for optimisation with an EA.

Fitness evaluation

- An EA operates on a population of chromosomes subject to fitness evaluation
- The fitness evaluation generates a figure of merit for each chromosome
  - in this case, the string of actions specifying a government policy
- It does this by running them through a simulation of a zombie outbreak
- The fitness function scores or ranks government policies on their abilities to solve the problem.

After fitness evaluation

- A *selection operator* then selects *parent chromosomes* in a manner biased in favour of high fitness values
- These parent chromosomes are copied and then probabilistically subject to the genetic operations of crossover and mutation
- The resulting structures are called *children*
- Some of the population may be selected and transferred into the population without crossover or mutation
- This is called *elitism*.

A stopping condition

- The process creates a new generation of chromosomes
- The process of creating a new population continues until some stopping condition is met
- This is usually a predefined number of iterations of the breeding step.

Optimal policy

- In our simulations, the chromosome is a string of actions representing a policy
- Each policy lasts for 10 timesteps
  - this requires a string of 10 symbols
- Each position in a policy is called a *locus*
- The fitness of a string is calculated by running the simulation of the outbreak
- The number of human survivors, minus military personnel, is the fitness of a policy
- The goal is to find a policy that reduces the number of human deaths.

Avoiding a retrograde policy

- We penalise the number of troops called up
- This prevents the government from just selecting the *army* action repeatedly
  - ie “throw bodies at the problem” in order to receive a better score
- This was the kind of policy action in World War II, Vietnam and the Redeker Plan
- However, the value of human life, whether civilian or military, is of equal weight
- This method of score rewards overall lives saved based on the area’s initial population.

Costs vs benefits

- Thus, an army unit ordered forward by a government using this system will do the most good
- Both in terms of their losses and also the population losses
- Tossing soldiers at a doomed sector without gain is thus avoided.

Size four single tournament selection

- In this method of selection, four policies are selected at random
- Children are generated by crossover
- Mutation is applied to copies of the two best policies
- These children replace the two worst policies
- The genetic operators are a two-point crossover operation and a single point mutation.

Two-point crossover

- In a two-point crossover, two loci on the chromosome are selected at random
- The actions between them are swapped between the parents
- Single point mutations change a single loci, selected from the parent at random
- The selected loci is changed to a new action selected uniformly at random.

Crossover and mutation examples

parent 1	W	W	Q	Q	S	V	...
parent 2	F	F	K	K	A	K	...
child 1	W	W	Q	**K**	**A**	V	...
child 2	F	F	K	**Q**	**S**	K	...

- A two-point crossover occurs in the fourth and fifth loci (in bold)
- *Quarantine* and *science* are swapped with *kill* and *army*

parent	W	W	Q	Q	S	V	...
mutant	W	W	Q	**K**	S	V	...

- Point mutations change the fourth loci from a *quarantine* to a *kill* action.

W: warn
F: fearmonger
V: vax

Experiments

- Thirty runs with differing random number seeds were run
- For 10,000 population updates
- This allows experiments to permit characterisation of the stochasticity of outcomes
- They also provide a sampling of the set of possible policies.

A small city

- The experiments investigated three topics:
  - the type of zombies chosen
  - the latency period of the virus
  - the initial government approval
- The city is relatively small
  - an initial population of 100,000 survivors
  - 10,000 zombies, representing an outbreak that has progressed to one zombie per ten survivors.

Parameter values

- Human advantage is set to $\Phi=0.0001$
- Initial weaponry is $\rho=0.1$
- This results in a removal rate of $\alpha=0.00001$
- Assumes the population is not well-trained in the use of firearms, at least initially
- Immunity begins are $\gamma=0.01$
- The viral effect is $\omega=1$
  - ie everyone who is bitten is infected
- This makes the initial β values within 1% of zombie aggressiveness δ.

β: transmissibility
α: kill rate
δ: aggressiveness
γ: immunity
ω: infectivity
ρ: weaponry
φ: advantage

Zombie aggressiveness

- Thus, the number of humans initially infected is solely dependent on the aggressiveness of the zombies
- This is chosen from $\delta \in \{\alpha/2, \alpha, 2\alpha, \ldots, 5\alpha, 10\alpha\}$
- Compares types of zombies which are killing humans from half to ten times the rate at which the humans are killing them
  - eg slow vs fast zombies
- If a group of humans survives when $\beta > \alpha$ initially, then this shows the value of optimising the governmental planning.

β: transmissibility
α: kill rate
δ: aggressiveness

Varying latency

- Values of 1, 3 or 5 timesteps were used to show the role played by latently infected zombies
- Zombies are not killed during latency because they appear to be normal humans
- The expectation is to see a greater impact from holding back the spread of the infection than from killing zombies
- Increases in latency will extend the outbreak
- This also makes it harder to contain.

Initial government approval

- Government approval was varied using values drawn from *aware*$\in$\{0.1,0.5,0.8\}
- These correspond to
  - hatred
  - no strong opinion
  - popular government
- A popular government, starting with strong opinion on their side, should have to spend less time working on improving public perception.

Probability of an observed action

- We want to compare the frequencies of action with the final set of policies
- Thus, we use a normal approximation to the binomial distribution to estimate the range of each of these actions
- The 95% confidence interval of a probability of an observed action is

$$Z_{95} = 1.96\sqrt{\frac{P(\text{action})\,[1 - P(\text{action})]}{N}}.$$

Results with no latency

- The latency rate was first set to 1
  - represents immediate return from the dead
- The impact of the government's optimised policy is successful in driving the zombies to extinction in all chosen δ values except δ=10α
  - this is true no matter the public perception of the government
- When δ=10α, there was no chance of human survival
  - ie zombies kill humans at such a high rate that humans are removed before the policies can be enacted.

α: kill rate
δ: aggressiveness

Increasing aggressiveness

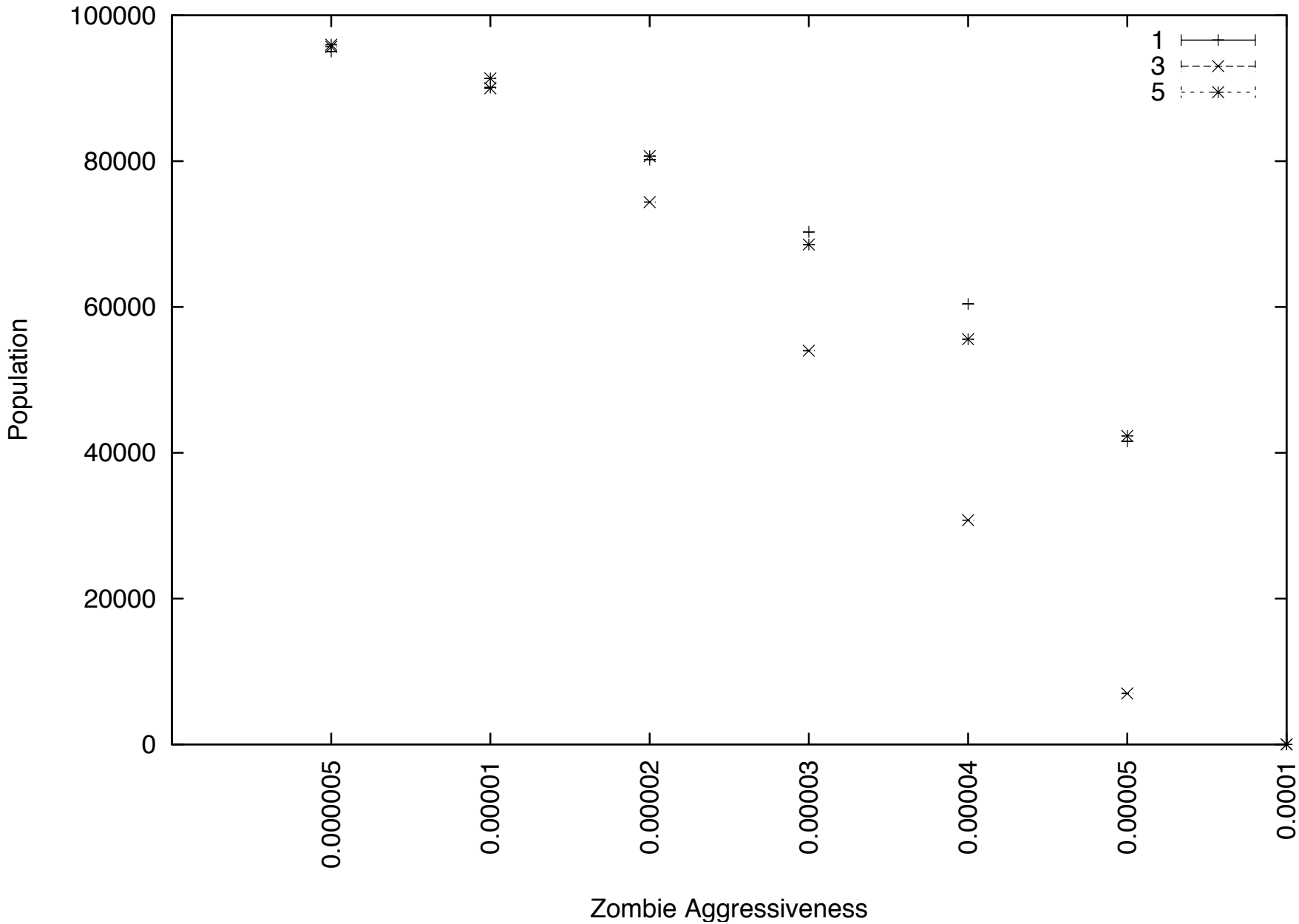
- As zombie aggressiveness increases, there is a change in effective policies from killing to quarantine
- Killing is risky, because it exposes humans to the virus
- Moreso when the zombies are more likely to bite
- Quarantine actions prevent the spread as humans are kept indoors and away from aggressive zombies.

Quarantine vs Kill

- The increased level of quarantine becomes statistically significant when $\delta=5\alpha$
- Thus, increasing the kill rate produces results when the rate of aggressiveness β of the zombies is sufficiently small compared to α, the human ability to kill them
- Otherwise, an aggressive quarantine is the preferred solution
- The influence of the government allows for a larger difference between α and β before quarantine is necessary.

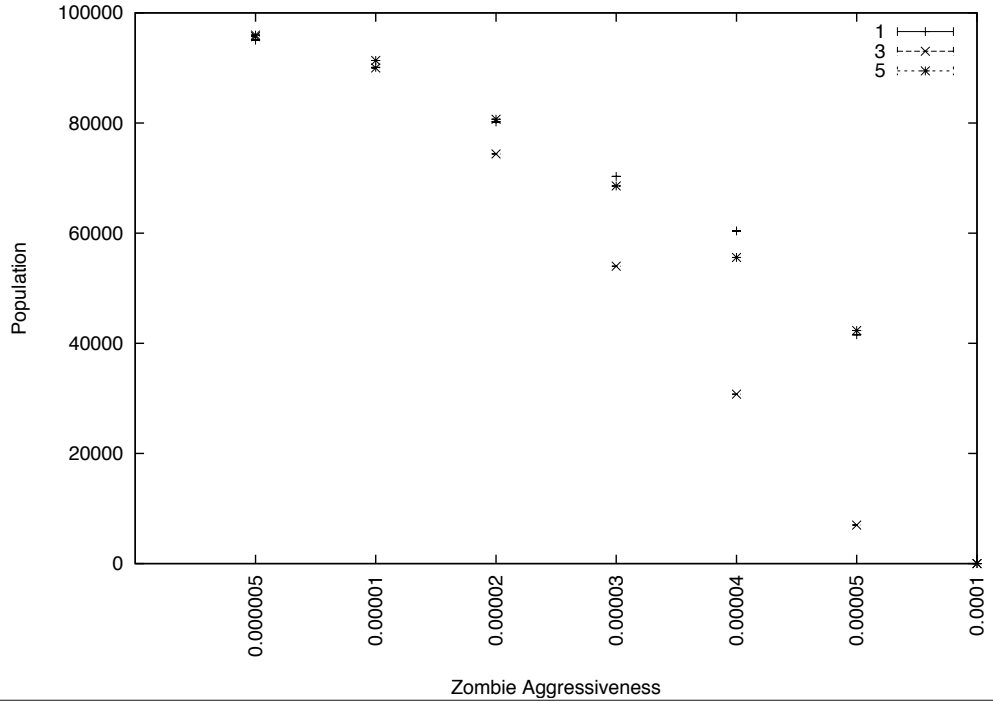
β: transmissibility
α: kill rate
δ: aggressiveness

Survival as a function of latency



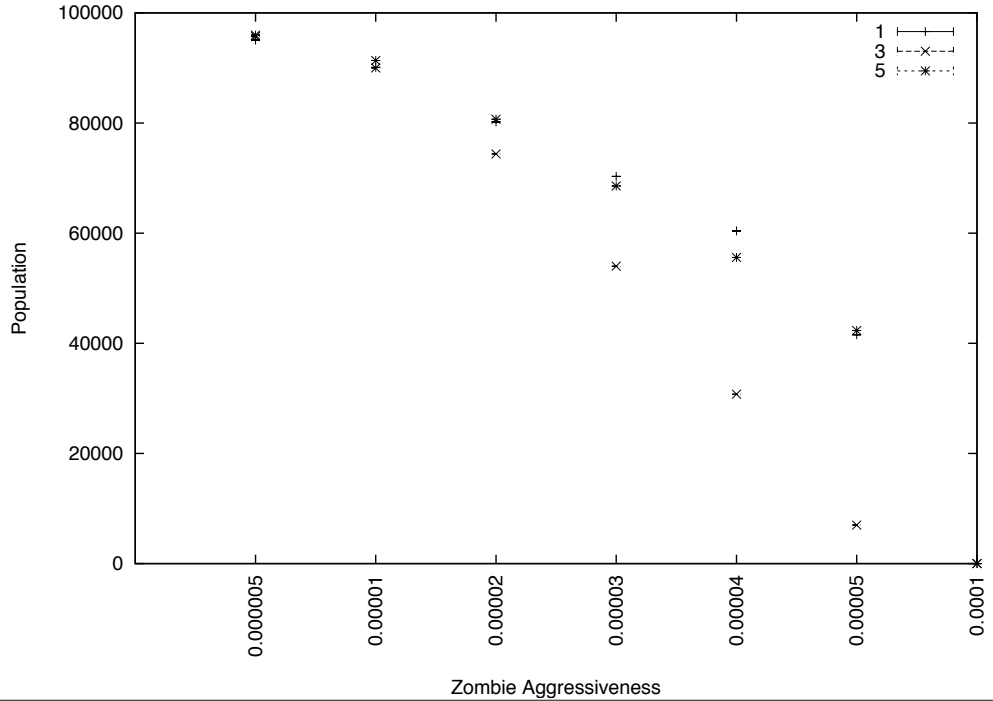
Surviving aggressive zombies

- Thus, the level of surviving humans falls as zombie aggressiveness increases
- Increasing latency makes survival less likely when zombies are aggressive
- That is, we’re most likely to survive when zombies come back to life immediately
- Even if they’re quite aggressive when they do.

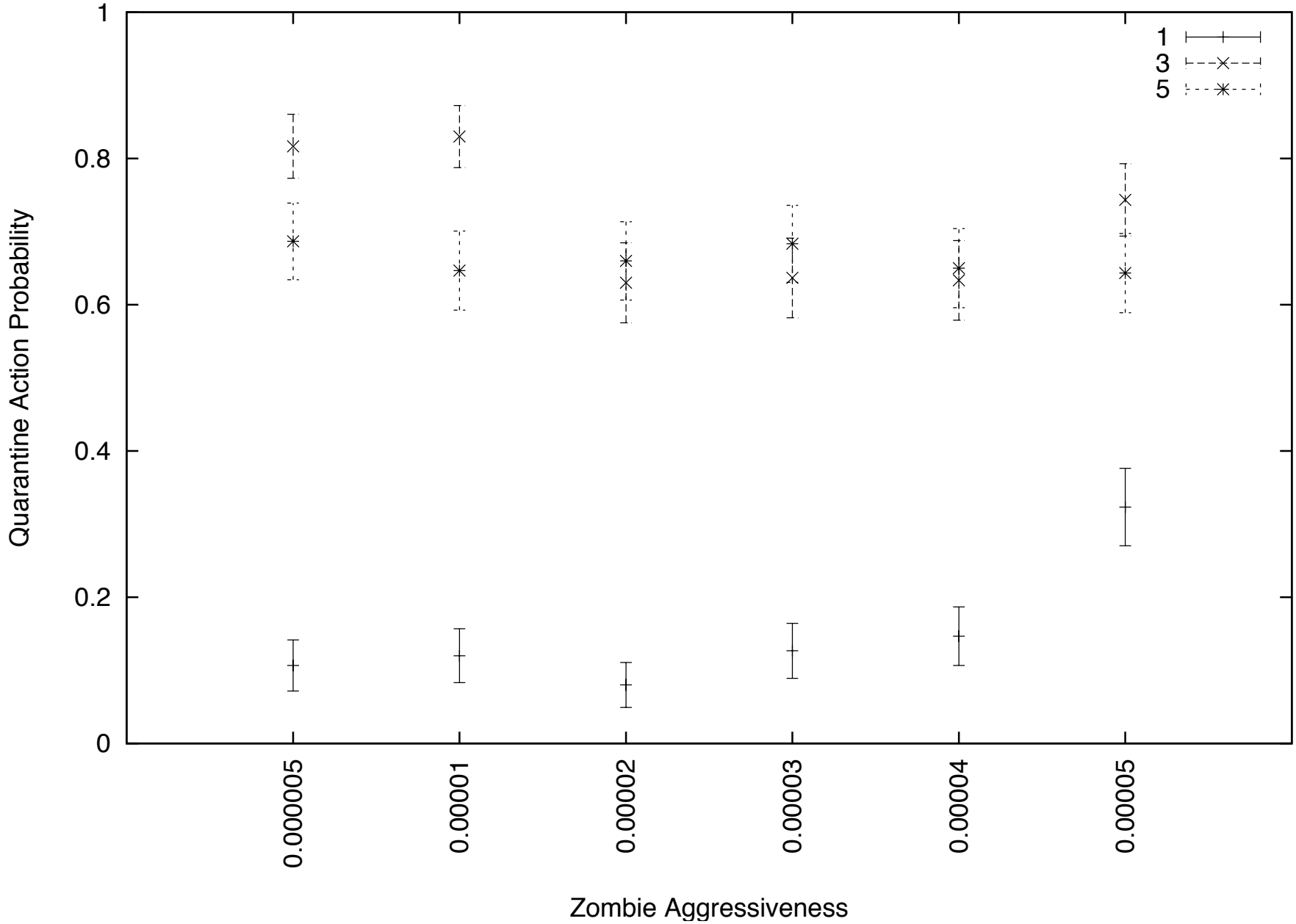


Medium latency poses a problem

- Notice, however, that the effects of latency are not straightforward
- Humans facing zombies with a short latency or a long latency have a higher survival rate than those faced with zombies who have a medium level of latency
- Thus, there may be an optimal latency towards which zombies may evolve.

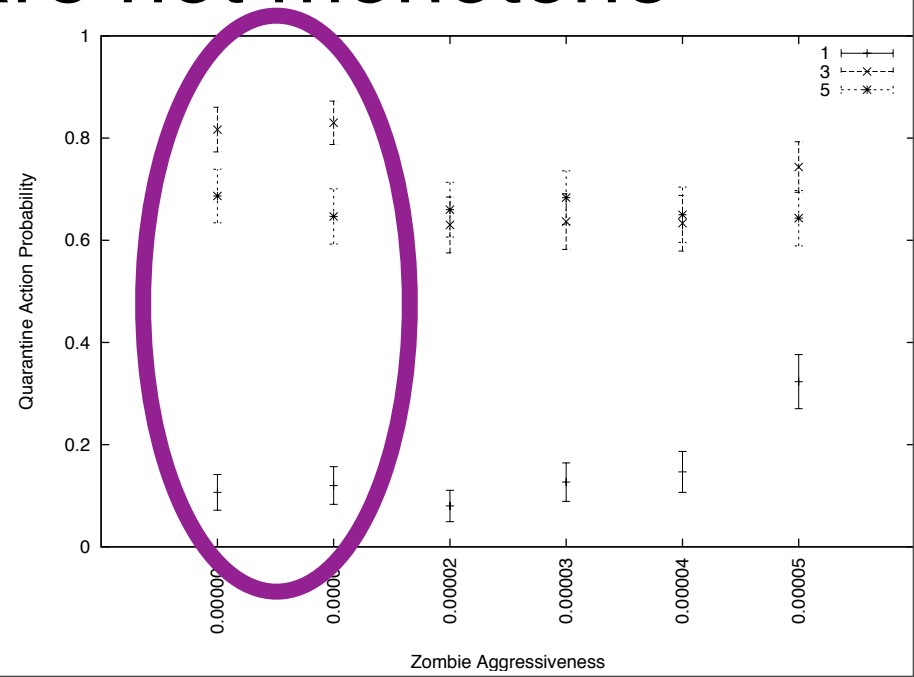


Quarantine as a function of latency



The value of quarantine

- Quarantine is not very effective if there is no latency
- However, as the latency rises, the value of quarantine rises significantly
- Interestingly, the effects are not monotone
- Moderately latent, low aggression zombies may be more susceptible to quarantine than either low or highly latent zombies.



Other factors

- The role of the government's initial awareness has no effect on the final population of survivors
- In hated-government scenarios, the *warn*, *kill* and *army* actions are more frequent
- In popular-government scenarios, these actions are exchanged for *fearmonger*
- However, these differences are not statistically significant for actions taken on the entire string.

Killing a large number of zombies

- At the start of a zombie outbreak, killing seems to be a favoured method
- This action is more effective when there are a large number of zombies
- Once the population of zombies is sufficiently reduced, the removal of the infection becomes more favourable
- Actions for this require a higher level of awareness.

Public opinion

- Actions like *army* depend on the state of public opinion
- Thus, a government which has less popularity will need to spend more time legislating in order to call in the military
- Our survival may therefore depend on how much we trust the government
- Zombies and survivalists may thus have more in common than they first thought.

Quarantine and popularity

- When zombie aggressiveness increases, stopping the spread of infection is a more effective way to save the population
- Therefore, quarantine events occur more often, no matter which government type is used
- A popular government, however, takes less damage.

Science and popularity

- The number of scientist actions is reduced in popular governments
  - although not by statistically significant amounts
- Since this is a probabilistic action based on *aware*, the scientist action is more likely to work for the popular government
- Thus, the popular government has to use violent actions less frequently.

Summary

- Government actions have a role to play in the effort to slow down the spread of a zombie virus
- Through actions such as quarantines and arming citizens, the government extends the life of the population when facing a variety of different zombie types
- Effective government policy can lead to saving a population from its doom
  - this is heightened when the number of humans infected for every zombie killed is greatly unbalanced in favour of the walking dead.

Comparison to real disasters

- During a real outbreak, the system can be used in an “online” capacity
- ie after an action is taken and a result is known, these new values could be used as the initial point for another iteration of the EA
- This allows the plan to be amended if necessary
- This is especially useful if the plan included stochastic events.

Time-dependent actions

- Changes to tentative policies can be made to allow for actions to be time-dependent
- Other effects could be changed to have time limits for the effects
- eg a vaccine may only have a short period of effectiveness as the virus mutates
- Or education/training information may degrade after some time.

Multiobjective EAs

- Multiobjective methods could also be used for fitness evaluation
- We examine only one objective: maximising the number of survivors
- However, there may be multiple, simultaneous objectives
  - eg reducing the number of zombies
  - maintaining popular opinion in favour of the government
- Multiobjective EAs optimise conflicting goals as part of the fitness evaluation.

Conclusion

- Thus, government policy can reduce the effects of zombie outbreaks
- Evolution allows for the system to
  - quickly search policies
  - evaluate them
  - provide a set of actions that can be put forward by governments
- It can be used to prevent the needless expense of life and resources
- Outbreaks in the future will not see the use of initiatives like the Redeker Plan.

Authors

- Daniel Ashlock (Guelph)
- Joseph Alexander Brown (Guelph)
- Clinton Innes (Guelph)

D. Ashlock, J.A. Brown, C. Innes. An evolvable linear representation for simulating government policy in zombie outbreaks (In: R. Smith? (ed) Mathematical Modelling of Zombies, University of Ottawa Press, *in press*.)