physicsworld
physicsworld.com
Volume 29 No 5 May 2016

ZOMBiE PHYSICS

When statistical analysis meets the undead

Mind over antimatter

The race to tell atoms and anti-atoms apart

Simple pleasures

Meet the physicist who studies tops

Something from nothing

The pros and cons of publishing null results

Zombie physics

What makes for a fun student project that provides useful results, a journal publication and a high-profile conference talk? **Stephen Ornes** describes how Alex Alemi and Matt Bierbaum spiced up their learning by mixing statistical physics with their love of zombie tales

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For Alex Alemi and Matt Bierbaum, two physics graduate students at Cornell University in the US, there really was no escaping the zombies – those fictional reanimated human corpses that feast on the living.

In autumn 2011 they were required to complete a project for a class on statistical mechanics taught at Cornell by James Sethna – a physicist who claims he's "constantly dragged into new topics by my students". Alemi had recently been reading *World War Z* and *The Zombie Survival Guide*, two popular and detailed books on zombies by US horror author Max Brooks. (*World War Z* uses a collection of individual narratives, in the style of oral history, to depict the harrowing spread of a zombie plague.) Brooks' books attribute the resurrection of dead humans to a vicious virus, and Sethna had mentioned disease modelling as a possible topic for his students to study. Merging the two ideas "seemed natural", Alemi recalls. "We thought we might as well study zombies."

Alemi and Bierbaum began with a simple premise, similar in spirit to models traditionally used in epidemiology – the study of how disease spreads and can be controlled. Every individual in the model belongs to one of three groups. Uninfected humans are in one. Zombies comprise another. The third group represents zombies that have been killed by humans – "by destroying their brain so as to render them inoperable", as the authors note in a paper they published in November 2015 in *Physical Review E* (**92** 052801). Their collaborators on that paper included Sethna and fellow Cornell physicist Chris Myers, who works with complex networks and studies infectious-disease dynamics.

In the model, humans and zombies can switch groups in two ways. Humans become zombies after being bitten, and zombies are removed once humans kill them by destroying their brain. With those ground rules in place, the physicists got to work on equations to describe the apocalyptic plague. Even after they finished the class, they continued to tinker on occasional weekends and nights. "Eventually it got to the point where we'd done some cool calculations and got some interesting results," says Alemi.

The work continued for years after the end of the course. By the time they finished tinkering with their model, they'd produced an online simulation (http://mattbierbaum.github.io/zombies-usa), complete with predictions for the best places to survive in case of a plague (figure 1). Alemi and Bierbaum presented their findings at the March 2015 meeting of the American Physical Society in San Antonio, Texas. As word of their work spread, they found themselves talking to a new audience – "people who might not be used to the formal ways people think about disease modelling", as Alemi recalls.

Zombies, despite their insatiable thirst for brains, have an undeniable appeal to a wide audience right now, with successful TV series including *The Walking Dead* and *iZombie*, as well as films such as *Pride and Prejudice and Zombies* (based on a parody novel by Seth Grahame-Smith) and *World War Z* (based on Brooks' book). They've also become a great way to showcase the statistical and mathematical tools of epidemiology. That's because even though brain-eating monsters are at the heart of the physicists' work, they lure in the curious to something more useful: an accessible way to talk mathematically about the spread of infectious disease.

"It's a matter of meeting the audience where they are," says Robert Smith?, a mathematician who studies infectious diseases at the University of Ottawa, in Canada. (Yes, the question mark is part of Smith?'s name.) "Now we've got people reading math papers with equations in them – people who would never normally read such a thing and would run a million miles to get away. You add zombies, and suddenly it's interesting."

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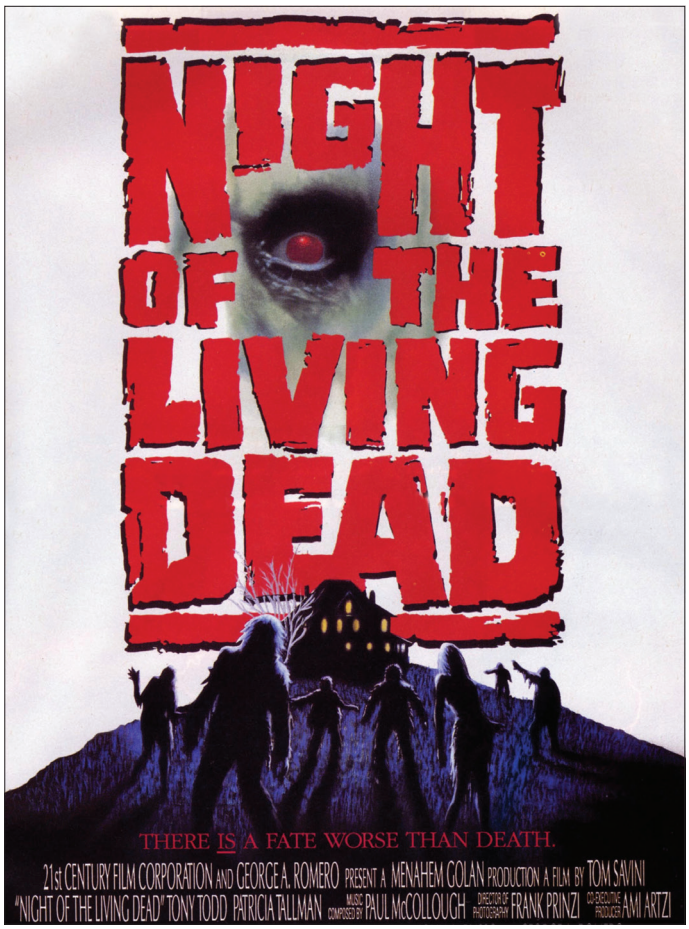
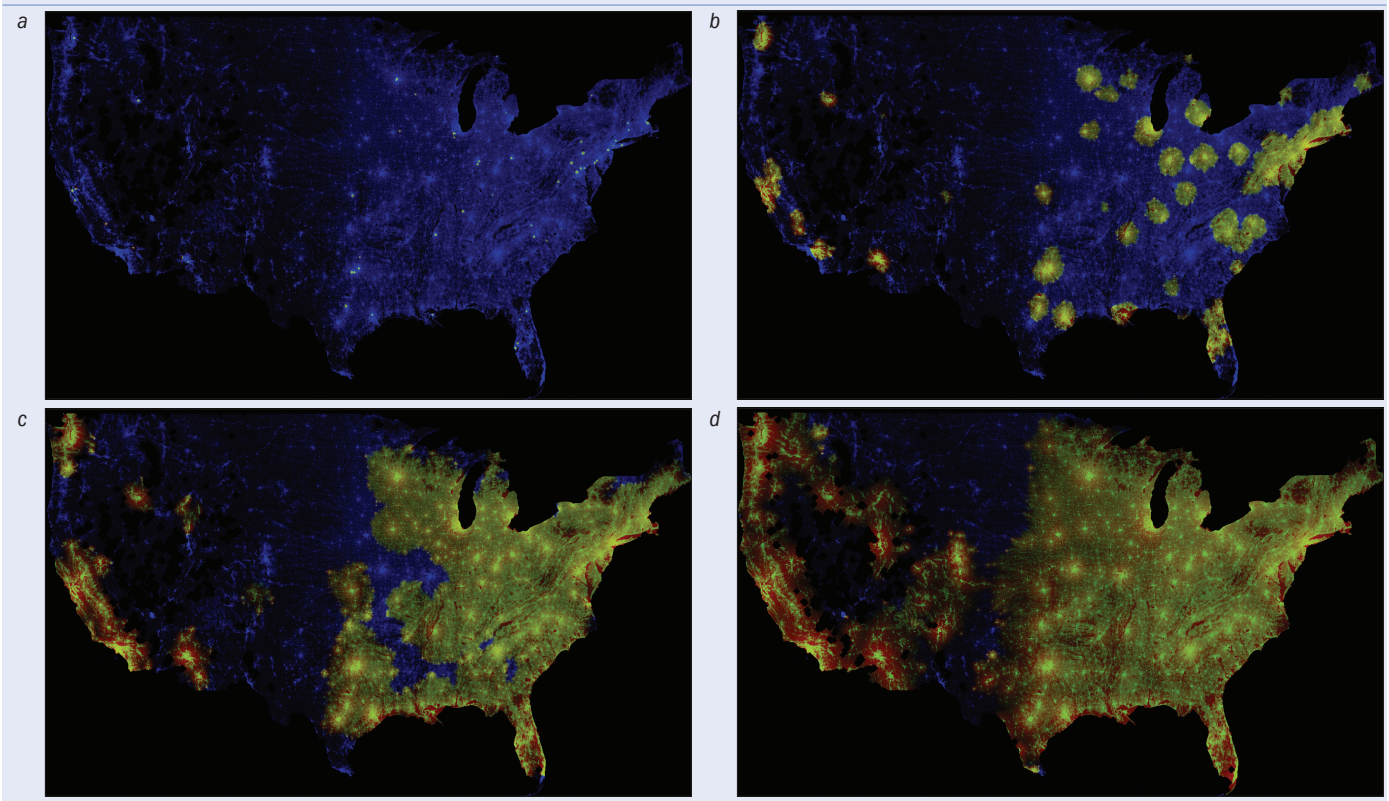
Zombie epidemiology

Alemi and Bierbaum weren't the first to study the zombie mathematical models – Smith? got there first. In a way, Smith? is like the researcher ana-



Clockwise from top left: Image Ten/Kobal Collection; Big Talk/WT 2/Kobal Collection; AMC; Spondoolie Entertainment/Vertigo Productions/Warner Bros. Television/DC Entertainment/Kobal Collection

1 Two days and two months later



Phys. Rev. E 92 052801

Simulation of a zombie outbreak in the continental US. Initially one in every million individuals is infected at random. Results are shown above at (*a*) two days, (*b*) one week, (*c*) three weeks and (*d*) two months after the outbreak begins. Shown here are the uninfected humans in blue, scaled logarithmically, zombies in red and zombies that have been killed by humans in green. All three channels are superimposed.

logue of a "patient zero" – that first infected human from whom an outbreak ensues. In a 2009 paper, he described what is arguably the first modern zombie model, using popular films such as the 1968 classic *Night of the Living Dead* to establish the biological characteristics of the slow-moving, cannibalistic creatures (*CMAJ* **181** E297). (He disregards the idea of a "fast zombie" as proposed in relatively recent films such as *28 Days Later*, and most models have followed suit.)

Scientific interest in zombies has spread "like a zombie invasion itself", says Smith?. "We sort of stumbled upon something that was really powerful – the idea that you could meld pop culture and academia together. People had studied popular culture with academia before, but they hadn't really crashed them together." Zombies, he thinks, catch the imagination of the public. "Pop culture has an incredible reach," he says.

In the last few years, the field of zombie research has grown as people come along "and apply their own techniques to zombies", Smith? notes. And the topic easily lends itself to a variety of ideas, from complex networks to stochastic modelling to differential equations. "The study [of zombies] doesn't have to be incredibly sophisticated, it has to be fun and entertaining. The jokes are just as important as the equations."

Alemi and Bierbaum say Smith?'s appeal to a wider audience was a powerful motivator in their own work. Popular-science books initially ignited Alemi's interest in physics, but at the same time, he says "There's a big gap between those descriptions and the actual practice of science – doing the math, working through computations." He wanted to bridge that gap with his paper, while at the same time contributing to the zombie literature.

Zombie phase transition

Many existing zombie models are deterministic, which means that the outcome is decided by the initial conditions. Either the zombies win, or the humans do. That approach involves looking at the zombie and human population as a whole, where the populations can take on any number. Unfortunately, that means that small, random events – such as a quick and unlikely kill at the beginning of the outbreak – are smoothed over. That's a problem with the highly random nature of zombie attacks, which happen on a decidedly personal level. "Even a ferociously virulent zombie infestation might fortuitously be killed early on by happy accident," Alemi, Bierbaum *et al.* noted in last year's paper in *Physical Review E*.

To accommodate those fluctuations, they added the possibility of random, one-on-one events and used a Gillespie algorithm – a probability tool from computational chemistry that's useful in situations where outcomes may depend on random events. That way, their simulation accounted for every single human–zombie interaction, making it possible, for

example, for patient zero to be killed and the whole plague nipped in the bud.

The researchers still had a problem, however. Even with a stochastic approach, the model described a scenario in which anyone could infect anyone – which meant that, hypothetically, a zombie in Atlanta could infect someone in Los Angeles. That would be a stretch, even in a zombie simulation. To fix this, the physicists turned to an approach familiar to condensed-matter physicists by treating each person or zombie as a node on a lattice and only allowing them to interact with individuals connected by bonds. Finally, they worked out a set of first-order differential equations to put the players in motion.

Once they started running simulations, curious patterns emerged. The simulation could be "tuned" according to whether people were more likely to kill zombies or if zombies were more likely to bite people. Adjusting those values revealed "a point below which the zombies die out, and above which they become too successful and eat everybody", says Sethna. That meant the system had a phase transition – a point beyond which the outbreak would stop. As in other areas of physics, interesting effects began to crop up around that critical point. The outbreak, for example, grew into a self-similar pattern that's characteristic of fractals, meaning that the map of the epidemic took on the same shape at large and small scales (figure 2).

Smith? says he applauds the model's exploration of that phase transition and the fractal patterns. "I thought it was really interesting, the way they looked at the knife-edge point between extinction and existence for the zombies. There's really fascinating behaviour there."

The physicists populated their model with data from the 2010 US Census to show what would happen to the more than 306 million individuals in mainland US (i.e. excluding Alaska and Hawaii) during a zombie plague outbreak. It wasn't pretty: the outbreak spread faster in the cities than in rural areas, which means the best way to survive such a disaster would be to head for remote, sparsely populated areas.

Smith? does note that Alemi and Bierbaum's new model is lacking in a couple of areas. First, "they don't consider the undead at all – there's no mechanism to raise the dead, which I feel is an important factor in zombies". And second, the researchers assumed that zombies are 1.25 times more effective at biting humans than humans are at killing zombies. Smith? thinks that number should be even higher. "It doesn't seem that realistic. Shooting a zombie is hard – you have to get the head, and it's hard to get something that's moving. The probability you can do that is pretty low."

The zombie future

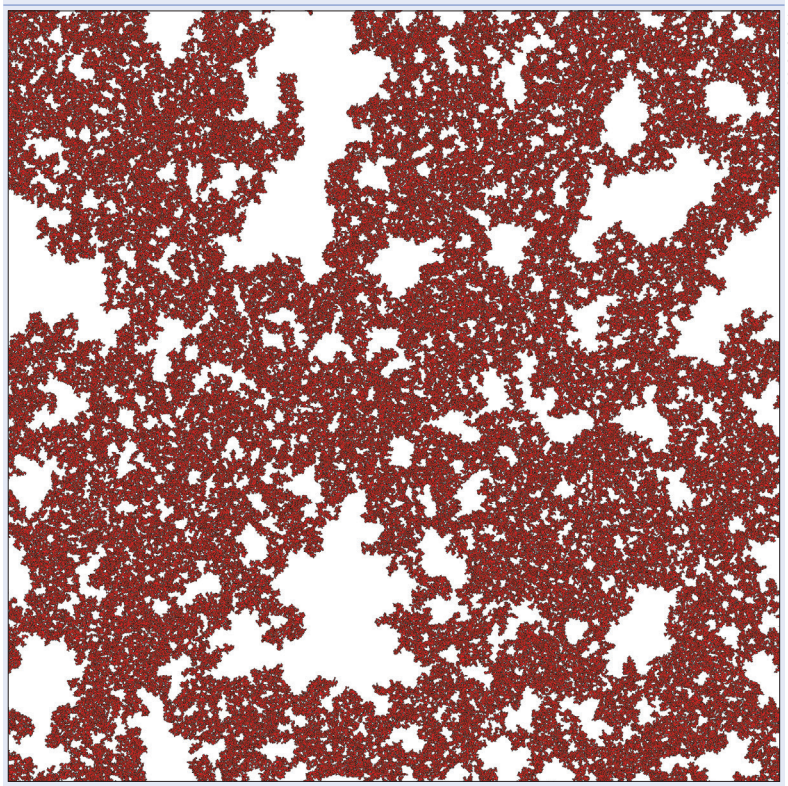
Most zombie outbreaks in fiction end with either widespread extinction or zombie eradication. Zombie modelling, though, continues to evolve. Bierbaum, for his part, says he'd like to see models that allow users to adjust parameters based on their favourite films – what does a real simulation of, say, *World War Z* look like? Alas, he probably won't be doing the heavy lifting: for him, the new zombie model is one of many projects he explored en route to his PhD. (Others have included the physics of mosh pits, plasticity and colloids.) Alemi also likely won't return to zombies in the near future: he recently left Cornell to take a job at Google. And Sethna has already been dragged into other topics by his new crop of students. Smith?, though, hasn't abandoned the undead: he is currently working on a book that expands current zombie models.

That book will add to a growing body of zombies-in-popular-science literature, which includes *The Calculus Diaries: How Math Can Help You Lose Weight, Win in Vegas, and Survive a Zombie Apocalypse* by Jennifer Ouellette (see December 2010 p44), and *Zombies and Calculus* by Colin Adams (see December 2014 p40).

Predictably, people who work on the models say they find their appreciation of zombie video games, films and television shows augmented. (With one exception: Sethna says he's managed to avoid most zombie media.) At the same time, Alemi, Bierbaum and Smith? all point to one film as a classic in the field: 2004's *Shaun of the Dead*, a comedic send-up of zombie flicks.

"Comedies can take all the zombie tropes and make fun of them," Smith? says. There are many good ones out there, but he says even his students come back to the same film. "After a while the kids come back to *Shaun of the Dead*." ■

2 Fractal undead



Phys. Rev. E **92** 052801

Example cluster resulting from the single population per site square lattice zombie model with periodic boundary conditions near the critical point α_c=0.43734613(57) on a lattice of size 2048×2048. Uninfected humans, zombies and zombies that have been killed by humans are shown in white, red and black, respectively.