A Rule-based Model for a Stochastic Simulation of a Zombie Outbreak
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Introduction
Zombies are fictitious elements gathered from our collective imagination that have attracted much attention during the last years, becoming prominent in books, movies, music and, more recently, video games. They represent an object that generates chaos and shows similarities with events of disease outbreaks at a large scale, leading to a state of catastrophe, affecting people both physically and emotionally.

Many models exists to describe the spread of diseases and the case of zombies is no exception, as demonstrated by a previous contribution that presented a simple model based on differential equations [1], very close to classic epidemiology descriptions. Later on, Crossley et al [2] elaborated on this model by translating it, almost directly without further improvements, to an agent-based stochastic model (ABSM). An ABSM to simulate a zombie outbreak that considers the heterogeneity of the subjects is an important step forward to include relevant features commonly overlooked in simpler models. However, the heterogeneity of the subjects should be encompassed with an univocal and unequivocal way to define every subject, dealing at the same time with the combinatorial explosion that emerges from complex dynamical systems. It is then natural to describe and simulate the dynamics of a zombie infection by using a highly descriptive and comprehensive tool such as the Kappa language [3]. By using Kappa, the system can be easily modeled on the premises of the Gillespie’s Stochastic Simulation Algorithm (SSA) [4]. The system is defined as a mixture of agents moving randomly in a given space, generating collisions between them that can lead to reactions expressed as Kappa rules. The modified SSA algorithm determines if there is any ensemble in the mixture that matches with any rule and executes it, making the corresponding changes in the quantities of agents, much alike to a stoichiometric equation.

Considering the philosophical point of view that organisms have no intrinsic purpose [5, 6] and that at a certain scale, the behavior of individuals follows patterns beyond themselves, is that we propose a rule-based model to produce a stochastic simulation of a zombie outbreak.

The basic unit of our model is a fictitious element -as far as we know- described in many tales through history, as an undead human being that, through various methods, has risen from a cataleptic state to one of pseudo-life, lacking a will of its own. Between the many legends around this being, its origin can be traced to the voodoo cult in which a dead man could be raised by a wizard, turning him into his slave. However, the actual and more spread concept, is the one made famous by the films of George A. Romero, among others, in which a zombie is a human being affected by a contagious disease that turns him into an almost mindless, roaming being with an insatiable hunger for human flesh. However, those films are also related to our work in more indirect ways, as zombies in those films represent a critic element against society in aspects such as discrimination [7] and consumerism [8] as the main driving forces of people’s behavior, which turns them into mindless cattle, once again the principle that the behavior of the masses is governed by general rules.

The Model
Following the presented stereotype, we can define a zombie Z as the vector of a disease, being a person that has manifested its symptoms and is capable of transmitting it to other susceptible individuals S. The actual mechanism of contagion is usually defined by three states [7–9]. The first stage is the infected I, representing the incubation period characterized by a short asymptomatic phase followed by a rapid decay of the state of
health. The second phase is a death-like state, with no apparent vital signs but suffering physiological changes induced by the pathogen that allow the individual $D$ to rise as a $Z$.

For the infection to occur, an $S$ must be in direct contact with some body fluid of a $Z$ \cite{9}, so, there must be an encounter that results in the defeat of $S$, typically manifested as $S$ being bitten by $Z$. On the other hand, the encounter could end in a victory for $S$, by somehow destroying $Z$, which turns it into an $R$ (removed), or a definitive death, as the $R$ individual cannot rise as a zombie again. The $R$ state is also formed by $S$ individuals that died from circumstances that do not involve interactions with $Z$ individuals. All the rules that involve $S$ individuals take into account their mental state, measured as discrete levels of hysteria. We interpret hysteria as an internal factor that affects interactions between $S$ and $I$ individuals with other agents of the systems. For some simulation scenarios -the SIDZET model- we have included some units -$E$ units- specialized in the extermination of $Z$ as well as treatments units $T$ that can prevent the transition from $I$ to $D$ by turning them into $S$ instead. The system is extended into various compartments, representing different cities, to study the effect that the topology of connectivity between cities could have in the outcome of the zombie outbreak.

Results and Conclusions

![Model SIDZET](image1.png)

![Exterminators](image2.png)

**Figure 1.** Simulation results from the SIDZET model. Evolution along time of the average result for 30 simulations (continuous line) and their respective standard deviation (dotted line). Left panel; general result of the simulation showing the number of $S$ (black), $I$ (red), $D$ (green) and $Z$ (blue) agents. Top right panel; number of healthy $E$ (black) and infected $E$ (red) units. Bottom right panel; number of $T$ units.

As seen of Figure 1, $S$ agents shown a steep decay accompanied by a transient increase in the number of $I$ followed by an increase in $Z$. After reaching a peak around the 8 day, there are discrete episodes of decay corresponding to the effect of the arrival of the $E$ units. The effect of the $T$ agents is barely visible at this scale, but it is the responsible of the small oscillations the $I$ curve. In spite of the presence of $T$ and $E$ agents, $Z$ always win. However, in average, a small number of survivors remain in some cities free of zombies, mainly the ones farther from the initial outbreak. Interestingly enough, it is possible to find, though in much smaller numbers, survivors in cities still overrun by zombies. These survivors have learned to deal with zombies and represent the usual hero-type that is ubiquitous in the collective imaginarium of zombies.
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References


