eyebrow is terrifying. This is a clear example of a 'missing self' immune response. Disease tolerance shows up in Richard Matheson's 1954 novella '*I am Legend*' as well as in the subsequent three movie adaptations '*The Last Man on Earth* (1964), *The Omega Man* (1971), and *I am Legend* (2007)'. Here the protagonist thinks that he is the last surviving human following a zombie/vampire (zompire?) plague. He misidentifies a human population that survived the infection but suffered some pathology as zompires. We learn that the protagonist has been killing the tolerant victims of the infection and these people are the true future of humanity; the protagonist is, unfortunately for him, an evolutionary dead end. These stories become more complicated and interesting when the infected cannot simply be cleared but have to be treated humanely; for example, the novel '*Raising Stoney Mayhall*' by Daryll Gregory and the comic book series *iZombie* by Roberson and Allred examines the lives of zombies and finds them to be rich and useful [3,4]. Many stories rely on the lethality of a disease to make it more frightening but the introduction of tolerance and recovery complicates plots; for example, the movie '*Warm Bodies* (2013)' explores a zombie apocalypse where the surviving humans try to clear the earth of zombies, not realizing some of the zombies are merely sick and will recover given time.

If we retrospectively examined the plot devices disease writers have concocted, perhaps we could identify mechanisms missed by scientists studying pathogens. I am partial to stories where the nervous system can be manipulated to cause disease and this manipulation is transmitted like a virus. These remind me of the growing field of neuroimmunity. Books in this genre include '*Snow Crash*' by Neal Stephenson and '*Lexicon'* by Max Barry where the machine language used by our brains is discovered and reprogrammed [5,6]. '*The Ring*' trilogy by Koji Suzuki does this as well [7]. In the first book of that series we encounter a terrifying monster that afflicts a victim when they watch a video, a mode of transmission that has yet to be described medically. In later books, we learn that this original world is just a computer model that is infected with a virus, but that virus is threatening to enter our world and must be stopped. Isaac Asimov's 1951 short story, *Hostess*, combines much of the biology described earlier [8]. This story involves an obligate mutualistic interaction between humans and an endosymbiotic intelligence. This parasitic intelligence coexists with our own and affects our behavior, inducing wanderlust. This is problematic because, although humans are tolerant of this parasite, alien species are not. Humans act as vectors, carrying this pathogen across the universe and interfere with aliens' attempts to limit the spread of the disease.

One problem we face in teaching the immunology of infections is that it is difficult to have the students actively observe a disease. We can make the students memorize life cycles and other properties of pathogens and show the students diseased tissues but what makes these processes interesting and difficult is that they are dynamic. By using movies and books we can give the students a substrate that they can observe and quantify on their own. We can let the students examine disease dynamics experimentally if we have them play the board game '*Pandemic'* or the computer game '*Plague Incorporated'*. In *Pandemic*, the players cooperatively attempt to block the spread of infections. In '*Plague Incorporated'*, the player takes on the role of the microbe and attempts to infect the planet. These games are basically a skin that is placed over a set of differential equations to make the equations more exciting; by playing the games repeatedly the student learns which rate constants are important to drive different types of outbreaks.

Perhaps the understanding that scientists and authors have something to learn from each other could lead to a new prospective and mutualistic relationship. Scientists could teach writers about disease ecology and show the writers story spaces that have yet to be explored. In return, these writers could direct their creative evolutionary thinking towards problems that have eluded scientific solutions. For example, how do we deal with the inevitable development of resistance to antimicrobials? How do we fight infections where hosts do not develop natural immunity or vaccination appears impossible? How do you tell these stories in ways that capture the public's attention, perhaps leading to changes in public health? It is common now to have multidisciplinary institutes that link biologists with engineers and business people; this approach could be strengthened further by the inclusion of creative writers.

[1]Department of Microbiology and Immunology, Stanford University, Stanford, CA 94305, USA

*Correspondence: dschneid@stanford.edu (D.S. Schneider).

http://dx.doi.org/10.1016/j.it.2016.02.001

References
1. Stoker, B. (1897) *Dracula,* Archibal Constable and Company
2. Glover, C.J. (1992) *Men, Women and Chainsaws: Gender in the Modern Horror Film,* Princeton University Press
3. Gregory, D. (2011) *Raising Stony Mayhall,* Del Rey
4. Roberson, C. and Allred, M. (2011) *iZombie,* Vertigo
5. Barry, M. (2014) *Lexicon: A Novel,* Penguin Books
6. Stephenson, N. (1992) *Snow Crash,* Spectra
7. Suzuki, K. (2004) *The Ring Series,* Vertical
8. Asimov, I. (1951) *Hostess,* Amazon

Special Issue: Communicating Science

Scientific Life

Communicating Science: Lessons from Film

Heather A. Berlin[1,*]

Films engage us visually, aurally, viscerally, and emotionally. Incorporating science themes into films has the potential to open up new

audiences to scientific ideas, pique their interests, and inspire them to engage in a broader discussion of the science itself. Here, I discuss several narrative techniques and strategies employed in film to effectively engage the audience around science themes, which may be useful tools for scientists looking to become better communicators.

Embracing Creative License

Scientific concepts and information reach the general public through a variety of channels, from formal education to digital media and the arts. One of the most powerful of these channels is film, which engages the viewer at multiple levels and reaches a potentially vast audience. The advent of computer-generated imagery (CGI) technologies has further expanded the visual range of film as a medium and as a tool for science communication. As scientists trained to focus on precision and accuracy in communication, we may often find ourselves responding to films by targeting inaccuracies or oversimplifications. I find it is more interesting to discuss the techniques involved in incorporating science seamlessly into storytelling, considering both the challenges and the opportunities science and storytelling offer one another. It is true that writers of screenplays often take liberties and use creative license, making a choice to bend scientific facts to fit the emotional demands of good storytelling. However, even these inaccuracies represent a form of engagement with science. Incorporating scientific themes into films, whether accurately or otherwise, has the potential to open up new audiences to scientific ideas and inspire them to engage in a broader discussion of science itself, which is invaluable. A good film can also teach scientists how to become better communicators and storytellers themselves, by revealing the human-interest and emotional core at the heart of a science-driven story.

Weaving Science into Film

Telling a good story remains the central challenge of filmmaking, whether or not a film is about science. In the best films, the central characters undergo conflicts of interest, struggles, or other challenges that engage the pathways in our brains related to empathy, triggering feelings of solidarity and affinity. The more engaged an audience is with the arc of a story and its characters, both emotionally and intellectually, the more likely they are to absorb and connect with the ideas that drive the story, including scientific concepts. However, those concepts rarely inhabit the world of the film for their own sake; instead, they serve as devices to drive the dramatic conflicts and character development forward. Stories only assist with science outreach as much as the science itself contributes to those stories.

Our brains have evolved a deep hunger for stories to help make sense of our social environment. The brain is a restless organ, always looking for patterns and craving closure and wanting to know how the story ends. Filmmakers are in the business of satisfying these narrative cravings via a process biologists call 'supernormal stimuli' or the artificial design of an enhanced stimulus that triggers an extreme version of an evolved response [1]. Even if a filmmaker's primary objective is to engage with the science, too much didacticism and detail will cause many viewers to lose interest. Filmmakers do not have the luxury of a captive audience with an obligation to pay attention, as in a classroom setting. Rather they are purveyors of entertainment, escapism, and diversion. At its core, entertainment is primarily a process of evoking an emotional response from an audience, whether amusement, awe, fear, intrigue, or any other neurochemical state that remains part of our evolutionary repertoire. And as researchers have demonstrated, our brains are better at retaining information when that information is tagged with a strong emotion [2,3]. Hence, simply 'communicating' scientific information will never be as effective as smuggling that information past the cognitive sentries dressed in an emotionally-charged disguise.

In addition to this intuitionist model of science communication, we should also acknowledge a growing public interest in science for science's sake, which complements but does not replace the need for good storytelling. This interest has been facilitated by the advent of the internet and the reference power of Google and Wikipedia, all of which brings science closer to the center of our public conversations. As a result, general audiences are demanding better science in their fiction, and at the same time filmmakers are hewing closer to real science, a virtuous circle that has produced a recent boom in excellent science films. Howling inaccuracies are still occasionally glossed over – my favorite example is the plot-triggering line 'the neutrinos have mutated!' from the Roland Emmerich film *2012* [4] – but people are becoming more likely to notice these liberties and filmmakers know they are more likely to be called out. Of course, audiences remain willing to forgive a certain degree of inaccuracy for the sake of creative license. A parallel but somehow less offensive butchering of science for the sake of story occurs in the opening scenes of *The Martian* [5] when Matt Damon's character is injured in gale force winds, which of course would be impossible with Mars' thin atmosphere. However, instead of just ignoring this oversight, it led to a press release from NASA [6][i] and a series of popular science articles [7][ii], as well as a frank discussion from the writer, Andy Weir, on NPR about why he felt this was a fact worth distorting [8][iii]. As a result, we have all learned more about Mars, which is a point for science.

In areas where the science is unsettled, there is even more forgiveness of poetic license. In *Interstellar* [9], Matthew McConaughey's character communicates with his daughter by time traveling his consciousness from within the center of a black hole, and then escapes the black