



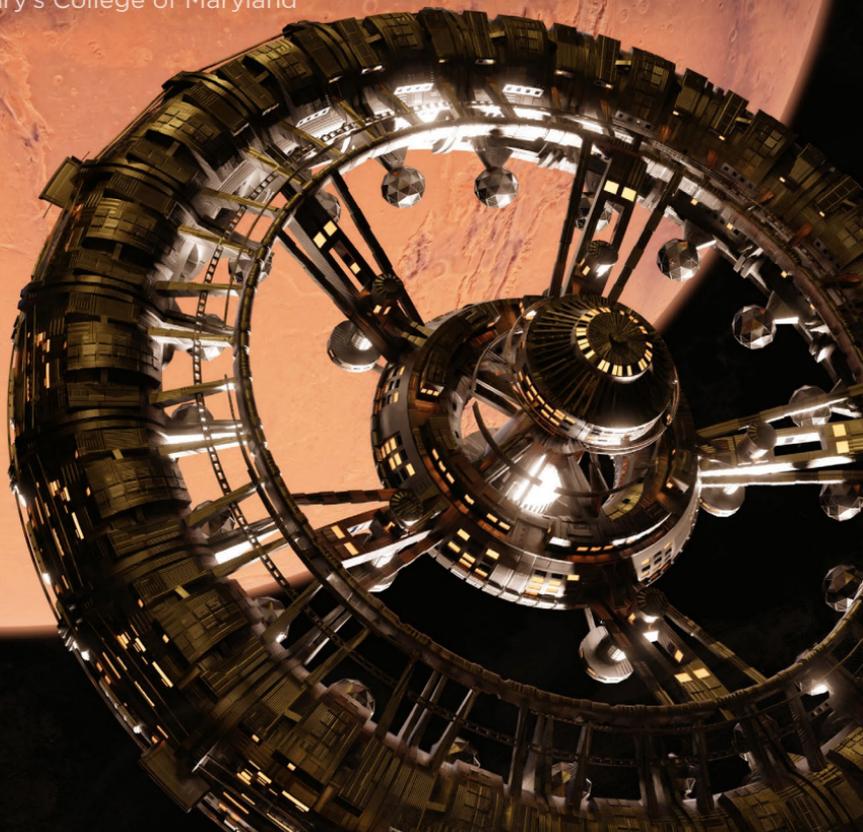
Topic
Science

Subtopic
History & Philosophy of Science

How Science Shapes Science Fiction

Course Guidebook

Professor Charles L. Adler
St. Mary's College of Maryland





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Charles L. Adler is a Professor of Physics at St. Mary's College of Maryland. He received his PhD, MS, and BS in Physics from Brown University, where he focused on experimental laser physics. Professor Adler is the author of more than 40 papers on experimental physics, optics, and mathematics. His main research interests are in meteorological optics, the optics of the sky and atmosphere, and experimental atomic physics. Professor Adler is a member of the Light and Color in Nature group, an international group of scientists who study the interaction of light with the atmosphere and landscape. He was the chair of the 2012 Light and Color in Nature meeting and has been the coeditor of 4 special issues of the scientific journal *Applied Optics* on the topic of meteorological optics.

Professor Adler has been a science fiction fan almost since he learned to read, and his first ambition was to become a science fiction writer. The genre led him to a love of science, especially when he realized that the science portrayed in science fiction was often inaccurate. This led him to write the critically acclaimed *Wizards, Aliens, and Starships: Physics and Math in Fantasy and Science Fiction*, a book written to allow readers to tell the real science from the fake. In 2015, it was a cowinner of the Science Writing Award for Books from the American Institute of Physics, and it made several lists of notable science books, including that of *The Guardian*. Professor Adler is also cowriting a book on the science of Leonardo da Vinci with Matthew Landrus.

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HOW SCIENCE SHAPES SCIENCE FICTION

When you watch movies like *Star Wars* or read novels like *The Martian*, do you ever wonder how accurate the science is? When you watch *Game of Thrones*, do you ever wonder if dragons could really fly and breathe fire? If so, this is the course for you.

There is a lot of science shown in works of science fiction. Some of it is accurate, and some is not. Although these works are not meant to teach science, it is important to try to separate the good from the bad when viewing them.

One reason to do so is that many more people are going to experience these works than are going to read a scientific journal article or read a popular science blog. Because of this, it's important to look at such works with a critical eye.

Another reason is that it adds an extra dimension to reading or watching these works. Knowing that an author or director has taken the time to get the science right lets you know that they have gone the extra mile. On the other hand, spotting the bad science can be fun and humorous.

However, knowing how to separate the good from the bad science is not an easy task. Creators of science fiction works have to incorporate huge amounts of information. These works often involve the creation of entirely new societies, worlds, and sometimes even universes. That level of creation means that many different sciences are involved in writing even relatively straightforward works.

Additionally, the science fiction genre is sometimes divided between hard science fiction, in which stories are often centered on advances in such sciences as physics and chemistry, and soft science fiction, which involves the social sciences more. However, all good science fiction involves both the hard and soft sciences. This is a daunting task: Creators of these works must know something about many different disciplines in addition to being able to write a good story.

In this course, lectures examine the science portrayed in many different works of science fiction. The course also touches on certain works of fantasy. Each lecture centers around a notable work and the science portrayed in it. Along with those, the lectures also consider other works that are based around similar scientific themes.

These lectures cover many subjects in the natural and social sciences. Examples include the *Star Wars* films and how spacecraft really fly, the novel *Dune* and planetary ecology, and the film *Avatar* and the process of literal world-building, among many other topics. As you learn from this course, think about these questions:

- ❏ If you were writing a science fiction story about any of this course's topics, how would you write it? Would the science be central to the story, or peripheral?
- ❏ What science would you keep? What would you ignore? What would you invent?

These are the questions that any science fiction writer has to consider. This course aims to give you an insight into this process and show you how much fun it is to think about these factors.

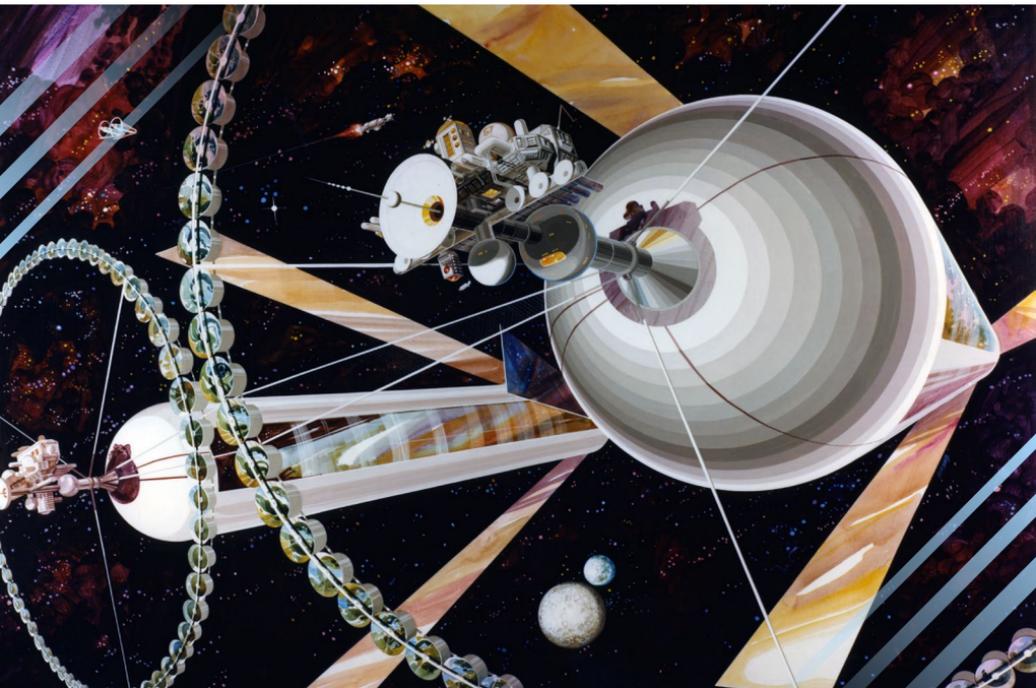


SCIENCE AND FICTION! THE WAYFARERS SERIES

THIS LECTURE CONSIDERS A META-PROBLEM INVOLVING SCIENCE FICTION: HOW DO AUTHORS DECIDE WHAT SCIENCE TO USE AND WHAT SCIENCE TO DISREGARD? TO HONE IN ON THAT PROBLEM, THE LECTURE LOOKS AT THE WORLD KNOWN AS THE GALACTIC COMMONS, WHICH WAS CREATED BY THE TALENTED SCIENCE FICTION WRITER BECKY CHAMBERS. THE GALACTIC COMMONS IS THE SETTING FOR 3 OF HER NOVELS COLLECTIVELY REFERRED TO AS THE WAYFARERS SERIES. THE NAME COMES FROM THE SPACECRAFT HOME TO THE CHARACTERS IN HER FIRST NOVEL, *THE LONG WAY TO A SMALL, ANGRY PLANET*. THE OTHERS, AS OF THIS COURSE'S PUBLICATION, ARE *A CLOSED AND COMMON ORBIT* AND *RECORD OF A SPACEBORN FEW*. EACH NOVEL HAS DIFFERENT CENTRAL CHARACTERS WHO ARE NEVERTHELESS CONNECTED TO THE OTHER NOVELS. THE SECOND AND THIRD NOVELS ARE LARGELY COMING-OF-AGE STORIES.

BACKGROUND ON THE NOVEL

- Chambers's novels are interesting because they are very far from science fiction norms. The Galactic Commons is different than typical federations or space empires for a number of reasons:
 - First off, humans are neither a dominant species, nor are they being oppressed or enslaved by another of the alien races. Instead, they are refugees from Earth, which is the victim of extreme environmental crisis.
 - Secondly, the Galactic Commons is at peace. Chambers's novels don't center around war or high adventure, but on mundane matters: how people try to get along and live their lives in the presence of ordinary concerns and ordinary joys.
- The creation of such a universe involves several different disciplines:
 - Physics for the space travel, faster-than-light travel, construction of space colonies, and so on.



- Artificial intelligence involves computer science and perhaps neurobiology.
- The design of the alien races involves biology.
- Creation of the cultures requires history, linguistics, and even sociology.

ARTIFICIAL GRAVITY

Artificial gravity is one interesting angle of Chambers's series. Much of *Record of a Spaceborn Few* is set on a huge space station that is home to tens of thousands of humans. It is mentioned that these stations were once spun to generate gravity, but now they aren't. They have artificial gravity devices providing the gravity.

Artificial gravity generators are almost certainly impossible based on the best theory of gravity that we have, which is Einstein's general theory of relativity. This raises a question: Why include gravity generators in the novel if they aren't possible? Here are 3 possible reasons:

- First, the author needed a method to provide gravity for the spaceship *Wayfarer* in the first novel.
- Second, humanity has become split into 3 separate branches. The differences between life on a space station and life on a planet illustrates the cultural gulf between 2 of the different branches of humanity.
- Finally, artificial gravity is a gift from an alien race, the Harmagians. It shows how dependent humanity is on the charity of the alien races of the Galactic Commons.

These aren't scientific issues but literary ones. Chambers is ignoring the science to write a better story.

ARTIFICIAL WORMHOLES

- ❏ The next piece of advanced science that Becky Chambers uses is artificial wormholes for interstellar travel. A wormhole is a hypothetical bridge between 2 different regions of space (and maybe time as well). Whether stable wormholes can exist is unknown, but most physicists think it unlikely.
- ❏ Chambers's first novel centers around a ship that constructs wormholes between different systems. Rather than an adventurous and glamorous scientific endeavor, it is a mundane, difficult, and somewhat dangerous job.
- ❏ Regarding wormholes, an interesting contrast can be made between the movie *Interstellar* and the novel *The Long Way to a Small, Angry Planet*. In *Interstellar*, the wormhole is mysterious: The aliens who created it are completely beyond the ken of humanity, and the exploration of the wormhole is highly dangerous—an adventure. In the Wayfarers novels, wormholes are just part of life in the Galactic Commons.
- ❏ These represent deliberate choices on the part of the writers. *Interstellar* uses it to heighten the tension and mystery of the story, but wormholes and interstellar travel are normalized in the universe of the Galactic Commons. These are 2 radically different ways of treating the same scientific idea.

A PROBLEMATIC MOON

- ❏ The tidally locked moon of Port Coriol is featured in Chambers's first novel, and it is one of the 2 main settings in *A Closed and Common Orbit*, her second novel. Port Coriol is divided between 2 sides: a day side, where most of the business of the busy port takes place, and a night side, where many of the residents of the port live. This may be one place where the author has confused 2 scientific issues: a tidally locked moon versus a tidally locked planet.
- ❏ Earth's moon is an example of a tidally locked moon. Because of tidal friction, its rotation rate has slowed to be exactly the same as its rotational period around the Earth—that is, it always shows the same face to the



Earth. The Moon has a near side, whose face is toward the Earth, and a far side, whose face is always away from us. However, this is not the same as the Moon having a dark side and a light side. All parts of the Moon are in shade or in light at different parts of its orbit: When the Moon is full, the near side is lit up; when the Moon is new, the near side is in darkness, and the unseen far side is lit by the Sun.

- ❏ The distinction between a moon and a planet is that a moon orbits a planet, while a planet orbits a star. This doesn't mean that habitable moons can't exist: There is scientific speculation that they can and do. However, a habitable moon, even if tidally locked to its planet, can't have a side permanently lit and a side permanently in darkness because a moon isn't lit by its planet but by the star that both orbit around. On the other hand, a planet tidally locked to its star can have dark and light sides.

- These issues do not detract from either story. Chambers's description of Port Coriol is fascinating, but it is possible she misread the science when building the world. There is one possible escape clause, although it stretches the definition of the term *moon*.
- There are 2 points in the orbit of a planet around a star at which asteroids or other small bodies can be captured. They are 60° ahead of the planet or 60° behind the planet; these are called Lagrange points. Specifically, the point 60° ahead is called the L4 point, and the point 60° behind is called the L5 point.
- The Lagrange points are named for the French mathematician Joseph-Louis Lagrange, who wrote "Essay on the Three-Body Problem" in 1772. In general, the so-called 3-body problem of gravitation—that of having 3 masses orbit each other—is unsolvable. It is impossible to find simple mathematical form for it. Generally, solutions are chaotic: It becomes almost impossible to predict the motions of the 3 objects in question far into the future.
- However, there are some specific solutions that have stable orbits. These are not just theoretical constructs: In our solar system, there are a set of asteroids—known as the Trojan asteroids—that orbit in the Sun-Jupiter L4 and L5 points.
- If a given star and planet are both massive, then a small moon or asteroid placed into either the L4 or L5 point will stay in orbit there, always in more or less the same place relative to the planet. In the case of Chambers's work, if there is a big planet in the system, then Port Coriol could be in one of its Lagrange points. In that case, it could be considered a moon tidally locked so that only one face was turned to the star.

ALGAE

- The final piece of science considered in this lecture is Becky Chambers's use of algae for power to move the spacecraft in her novels. The idea of generating biofuels from algae dates back at least as far as the early 1980s, and it is based on letting algae grow on waste products, using photosynthesis to turn sunlight into alcohols that can be distilled into kerosene or diesel fuel.

- There have already been a few commercial air flights run using biofuels, so it seems to be possible. However, there are 3 issues that make this seem unlikely as a fuel for spacecraft:
- 1 The energy source used to grow the algae and synthesize it into fuel.
 - 2 The energy density of algae used for rocket fuel.
 - 3 The reaction mass needed for the spaceship.
- Biofuels on Earth are attractive because they use photosynthesis to convert the energy in sunlight into energy stored inside them. This is not very efficient, but that inefficiency is counterbalanced by the fact that the Earth receives an immense amount of sunlight.
- On a spacecraft, far from any star, one would still have to provide the light required for the algae. The first book, *The Long Way to a Small, Angry Planet*, seems to imply that there are special lights in the algae labs that do this. That would require a large amount of energy.
- Biofuels are chemical fuels. Compared to energy sources like hypothetical nuclear fuels for spacecraft, chemical fuels have relatively small energy densities—that is, the amount of energy that a kilogram of such fuel contains. They can't make spacecraft move very fast.
- As an example, take the real-life *New Horizons* spacecraft. At a speed of about 16 kilometers per second, this was the fastest spacecraft ever launched from our planet. It still took it nearly 10 years to reach the orbit of Pluto, its main destination.
- This is far too long for spacecraft with human crews on them—or alien crews, for that matter, as described in Chambers's books. In the novel, it takes about a year for the spacecraft *Wayfarer* to reach its destination—one that involves traveling through many different solar systems. This implies a much higher speed, meaning much more fuel, meaning much more energy expended.
- This leads to the factor: reaction mass. Spacecraft move forward by expelling mass at high speeds behind them. How fast the ship moves forward depends on how fast the reaction mass (the fuel) is moving backward and how much reaction mass there is.

- ❏ The more reaction mass there is and the faster it goes, the faster the spaceship moves forward. But chemical fuel doesn't have a very high speed—typically, it provides a speed of a few kilometers per second. This is fast on a human scale but not on an astronomical one. Because of this, a large reaction mass is required—perhaps 100 times the mass of the spaceship or more—to get it moving at the proper speed.
- ❏ The description of the *Wayfarer* from the first book makes it clear that there is nowhere on the ship to put huge tanks of fuel to contain that mass. The use of algae to fuel this particular spaceship fails several tests of basic science. However, the reason for using algae as a rocket fuel in the novel is more likely to be for literary rather than scientific reasons: It again provides a contrast with more typical science fiction tropes that use antimatter rockets or reactionless drives to move their ships.

Suggested Reading

Adler, *Wizards, Aliens, and Starships*.

Chambers, *A Closed and Common Orbit*.

———, *The Long Way to a Small, Angry Planet*.

———, *Record of a Spaceborn Few*.

O'Neill, *The High Frontier*.

CHEATING THE SCIENCE: *PROTECTOR*

BEING A SCIENCE FICTION WRITER CAN BE TOUGH, ESPECIALLY WHEN IT COMES TO BUILDING WORLDS: SCIENCE FICTION WRITERS NEED TO KNOW ABOUT PHYSICS, ASTRONOMY, BIOLOGY, HISTORY, SOCIOLOGY, AND OTHER TOPICS. ADDITIONALLY, AS SCIENCE MARCHES ON, BRILLIANT BREAKTHROUGHS BECOME YESTERDAY'S NONSENSE QUICKLY.

TO EXAMINE A CENTRAL PROBLEM SCIENCE FICTION WRITERS FACE, THIS LECTURE CONSIDERS THE 1973 NOVEL *PROTECTOR*, WRITTEN BY LARRY NIVEN. NIVEN'S WORK PROVIDES A STRONG EXAMPLE OF HARD SCIENCE FICTION—THAT IS, IT SHOWS A PROFOUND KNOWLEDGE OF SCIENCE, PARTICULARLY PHYSICS. AFTER LOOKING AT *PROTECTOR*, THE LECTURE TURNS TO HOW OTHER WRITERS HAVE TACKLED CERTAIN ISSUES.

BACKGROUND ON *PROTECTOR*

- Niven's career began in the 1960s, and *Protector* was one of his first novels. Because of this, some of the science is outdated, particularly when he writes about human evolution. That is OK: Writers can't anticipate every new discovery, and the outdated science doesn't diminish the enjoyability of *Protector*.
- In the novel, about 1 million years before the present day, an alien race, the Pak, settle Earth from a planet close to the center of the galaxy. The Pak are the progenitors of the human race. The Pak are an early species of hominids, namely *Homo habilis*. However, disaster overtakes the Pak colony on Earth, and all contact with it is lost.
- Some 30,000 years before the present, a Pak named Phssthpok realizes how to find the lost colony, and he sets out in a ship to come to Earth. The rest of the action takes place when he gets to Earth, roughly 300 years in the future, when the solar system has been colonized by humanity.
- Phssthpok survives long enough to make the incredibly long journey because he is a protector. Protectors are a third stage in human development, beyond childhood and adulthood. Hominids are turned into protectors by eating foods containing the tree-of-life virus, which triggers extreme biological changes. Protectors have superhuman strength, reflexes, and endurance; are utterly ruthless in pursuing their goals; and are also blindingly intelligent. It also makes them essentially immortal.



❧ The tree-of-life virus died out on Earth for reasons detailed in the novel. That disaster caused the Pak colony to fail, leaving the pre-humans without their protectors. Phssthpok figured out why it died out, and he is coming here to reintroduce it.

THE PROBLEM OF SUPERINTELLIGENCE

❧ The novel's main character, Jack Brennan, is a human captured by Phssthpok and turned into a protector. Once Brennan is turned into a protector, he realizes that Phssthpok came here to remake Earth in the image of the of the Pak homeworld. This will destroy human civilization. In addition, he needs to fight off a fleet of Pak following Phssthpok to invade Earth. These are the issues that drive most of the action of the novel.

❧ There is a problem in writing about either the Brennan-monster (as Jack Brennan calls himself after his transformation) or about Phssthpok: The Protector possesses great intelligence—an intelligence, presumably, far exceeding Niven's. This leads to a question: How does an author write about a character much smarter than herself or himself?

❧ The answer is that the writer must convince the reader that he or she is a master astrophysicist, geneticist, historian, and so on. And the writer must do so without the audience catching on. The reader must never question the writer's absolute authority when reading. It is a delicate balancing act.

❧ Niven solves the problem of how to write about superintelligent aliens by making one implicit and one explicit assumption. The implicit assumption is that whatever the protector's goals are, it is intelligent enough to always use the best possible means to achieve them. The explicit assumption is that the goals are strongly biologically determined.

❧ Protectors are bound strongly to protect the lives and well-being of their descendants, almost to the exclusion of all else. Therefore, Niven has narrowed down all of the things a superhuman intelligence can want to one task: protect the being's children.

- ❏ To sum up, protectors' goals are biologically determined, and protectors always choose the best path. Other characters can see and choose the best path as well, but they do so more slowly than protectors do. All of these choices can be understood as approximations. Niven is making a set of simplifying assumptions which allow him to solve the problem he is interested in.
- ❏ This tactic of problem limitation occurs in other Niven stories. In fact, all authors—not just science fiction writers—practice problem limitation and approximation to some extent: The universe is too big to understand it as a whole, so writers select out only those parts they are interested in.

REDUCTIONISM AND HOLISM

- ❏ Problem limitation is an example of reductionistic philosophy: the idea that complex systems can be understood by examining separate parts that make up the whole. This is often contrasted with holistic approaches to science. In holistic approaches, the main focus is not on individual parts but on the interaction of these parts and how these interactions can lead to behavior not seen on the smaller, reductionistic level. Both approaches are needed to understand the universe.
- ❏ One big example of holistic science is ecology, which treats the interactions between various species and the climate of an ecosystem. For example, take the novel *Dune*. Its author, Frank Herbert, explicitly rejects reductionistic descriptions of science. However, Herbert himself is practicing a form of reductionism in several ways in creating *Dune's* universe.
- ❏ For example, the ecology of the desert planet Arrakis is drastically simplified from any real ecosystem, and the society that he creates is overwhelmingly feudal, with noble houses ruling individual planets. This creates a single society and government for all of the planets in his empire.

THE MOTE IN GOD'S EYE

- 📖 *The Mote in God's Eye*—Larry Niven's collaboration with Jerry Pournelle—is one of the most famous novels about humanity's first contact with aliens. In the novel, humans have spread throughout space, but until the year 3017, humans have never met another alien race.
- 📖 The Moties, the alien race that humanity meets, are divided into different castes. They are constantly at war with one another owing to population problems caused by basic Motie biology. Moties periodically change genders, with pregnancy driving the change from female to male, and if they don't become pregnant during a female phase, they die.
- 📖 Humanity has to decide how to deal with the Moties: whether to try to incorporate them into the book's Empire of Man, isolate them, or destroy them. This setup consciously reverses a traditional storyline in which advanced aliens are trying to decide if humans should join a great galactic commonwealth.

"BUILDING *THE MOTE IN GOD'S EYE*"

- 📖 *The Mote in God's Eye* is a particularly illuminating subject because Niven and Pournelle published an essay in 1976 called "Building *The Mote in God's Eye*." This essay goes through how they handled the science, planetology, and sociology of their shared universe in great detail. They go through the reasoning behind many of their choices and the implications that these choices forced on them.
- 📖 For example, the Alderson drive allows ships to travel at speeds faster than light between star systems, but only at certain Alderson points within the system. This limitation strongly influenced the structure of the galactic empire.
- 📖 Many of their colony worlds, like New Scotland and New Ireland, have small populations, allowing the authors to assume relatively homogeneous cultures for these worlds. The populations are small because many of the

worlds were terraformed—transformed from uninhabitable worlds to habitable ones—and also went through a traumatic, bloody revolution that happened about a hundred years before the events of the novel.

- ✚ In the essay, Pournelle and Niven write that they decided to move the planet of New Chicago closer to its sun because of a good line at the beginning of the novel. They also discuss a device that all of their human characters had access to: a small, handheld computer that was linked to a larger network, which was used to access any information that any of the characters needed.
- ✚ The authors also discuss how they used the political theories of C. Northcote Parkinson to design the Empire of Man. Parkinson was a political scientist who wrote the influential book *Evolution of Political Thought*. They also had Dan Alderson, a scientist at NASA's Jet Propulsion Laboratory, design the Alderson drive and the Langston field—a force field used to protect the starships when in battle. Then, the authors stuck to those designs.

Suggested Reading

Anderson, "How to Build a Planet."

Niven, *Protector*.

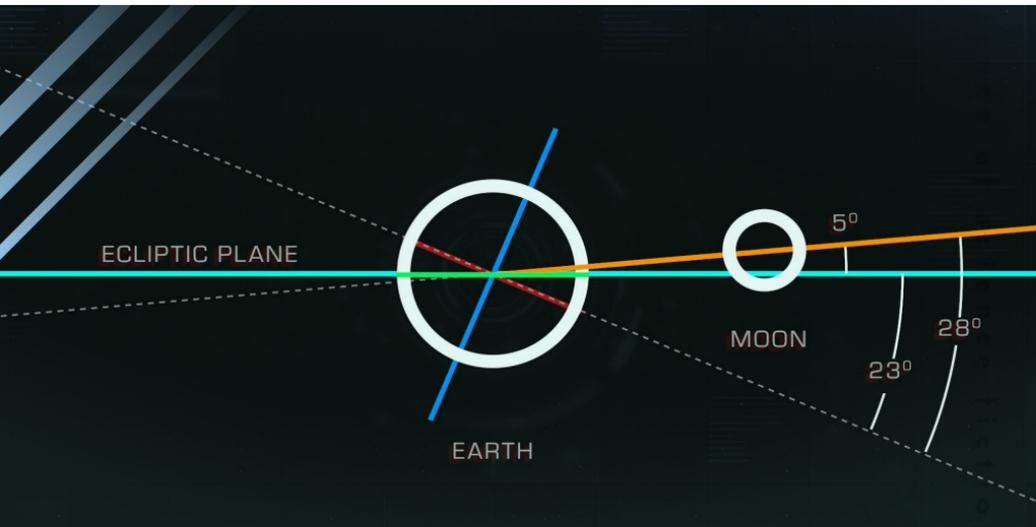
Niven and Pournelle, "Building *The Mote in God's Eye*."

PREDICTION: *FROM THE EARTH TO THE MOON*

PREDICTING THE FUTURE IS OCCASIONALLY THE THEME OF SCIENCE FICTION STORIES. THIS LECTURE FOCUSES ON SCIENCE FICTION PREDICTIONS REGARDING THE EXPLORATION OF SPACE, BECAUSE SPACE TRAVEL IS ONE OF THE GREAT TOPICS OF SCIENCE FICTION.

JULES VERNE AND *FROM THE EARTH TO THE MOON*

- Jules Verne was the progenitor of what is often called hard science fiction. His works were always grounded in solid science. For example, one detail in his book *From the Earth to the Moon* shows how well Verne knew his stuff: The moon launch described there takes place in southern Florida, near Cape Canaveral. This is very near where the real Apollo launches took place.
- Verne, writing in the 1860s, knew that there were only 2 states in the US as it was in time from which a successful trip to the moon could be launched. These were Florida and Texas. There are excellent scientific reasons for this, which is why the US government chose Cape Canaveral for the launch site for the Apollo program.
- Verne was a patriotic Frenchman, which raises the question of why he set the launch in America rather than France. There is one overriding scientific reason: The launch as written could not have taken place in France. This is because the launch site had to be located at some area between 28° north latitude and 28° south latitude.



- Any space travel to the moon would require a highly industrialized country for the needed infrastructure. The novel was published in 1865. Back then, there were only 4 countries that suited the needs of the story: France, England, Germany and the United States. Verne likely would have been happy to set the novel in France, but the southernmost point of France is too far north for a launch. In fact, even the southernmost tip of Europe, in Greece, is at about the same latitude as Washington DC, which is itself too far north based on Verne's criterion.
- Because of this, the United States was the only country in the world with a large enough industrial base and with the proper location to be credible as the site of the launch. However, Verne did insert a Frenchman, Michel Ardan, who volunteers to be the first astronaut.

THE PLAN

- The book features Baltimore Gun Club, whose members are in despair of their future prospects as artillery manufacturers at the end of the American Civil War. The president, one Impey Barbicane, proposes a truly audacious plan: build a gun capable of sending an artillery shell to the Moon.
- The science behind launching a cannon shell to the Moon is discussed in exquisite detail in the book, to the point where perhaps half of the text is devoted to it. Of particular relevance to this lecture is why Barbicane needed to choose a launch site between 28° north latitude and 28° south latitude.
- Verne was engaging in problem simplification here: Working out the real trajectory of a rocket or a shell fired in any given direction is difficult. However, if it is fired directly upward, the trajectory is much easier to compute.
- Barbicane is proposing firing the shell directly upward at a time chosen so that the Moon will be directly over the launch site when the shell reaches the Moon. However, this severely limits where the cannon can be located because the Moon can be directly overhead at places on the globe which are between 28° north latitude and 28° south latitude.

VERNE'S SUCCESSES AND A MISS

- Verne's estimate of the time it takes to reach the Moon—4 days—is fairly accurate. The real voyage of the Apollo astronauts took 4 days. Verne couldn't know the exact orbit that the real astronauts would use, which was complicated enough that scientists used computers to calculate it, but he knew enough of the science to make a good estimate.
- There are a lot of other places where he demonstrates a keen understanding of science:
 - He knew Kepler's laws of motion, that the Moon travels on an elliptical rather than circular orbit around the Earth, and also the nearest and farthest distances of the Earth from the Moon.
 - He understood that the crew would need to bring some source of oxygen for respiration and also to get rid of respired carbon dioxide.
 - The space vehicle is made from the miracle metal of the time, aluminum, which was renowned for its strength and lightness. The Apollo lunar lander module was constructed of aluminum alloy.
 - Verne even noted that the launch would create clouds and rain over the Florida site because of nucleation of water droplets around the soot and particulates left by the burnt propellants.
- Of course, Verne wasn't a perfect predictor. There is one big thing he got wrong: the launch vehicle. In the novel, the vehicle is a huge, hollow artillery shell fired from a giant cannon. In real life, spacecraft use rockets to provide thrust.
- A shell is a bullet: It explodes from the barrel of a gun, which provides all of its guidance. Once it leaves the gun barrel, it follows a trajectory that is determined by all of the external forces acting on it—in this case, the gravitational attractions of the Earth and the Moon.

- Another important point is that the gases provided by the combustion of the propellant only act on the shell while it is in the barrel. This means, effectively, that the longer the barrel is, the longer the force can act on the shell, and the faster the shell can move. The cannon in the book is 274 meters, or 900 feet long.
- The shell has to reach the escape speed over a relatively short distance, the length of the gun barrel. This means that the acceleration of the projectile is tremendous.
- The rapid acceleration would inflict massive amounts of force on anyone propelled by Jules Verne's giant cannon. Facing a force of 2,000 times their own weight, everyone inside the shell will be squashed flatter than a pancake. Verne was aware of the problem: He invents an ingenious set of water springs to damp out the acceleration on the passengers, but this is likely one place where the reader has to willingly suspend disbelief.
- Verne was probably aware that his travelers probably wouldn't survive liftoff. This is one place where he likely hand-waved the problem on purpose to make the story more interesting. However, the idea of using a spring system and shock absorbers to protect passengers from the accelerations of rocket travel did show up in a real rocket program of the 1950s: Project Orion.

CONCLUSION

- There are 2 other places where the predictive power of the story falls short: in the infrastructure needed to launch a ship into space and the computational power needed to guide it. These are common failings among science fiction writers before the space age.
- However, it may be that Jules Verne wasn't so much trying to predict the future as invent it. There were plenty of other stories around about trips to the Moon in Verne's time, but none of them made any attempt at scientific accuracy.

- For example, take H. G. Wells's novel *First Men in the Moon*. Wells's novel was published nearly 40 years after Verne's. The central characters get to the Moon with cavorite, a metal that nullifies the effects of gravity. Even at the time, it was known that any such metal would violate the law of conservation of energy.
- Verne, on the other hand, used well-known scientific principles and technology available in the 1860s to describe a plausible, if ultimately impractical, method of getting to the Moon. It's likely that he wanted people to take up his challenge. The amount of scientific information shoehorned into *From the Earth to the Moon* is amazing. This suggests that he was trying to get people to pay attention. He was saying what could be possible, given what was available at the time.

Suggested Reading

Verne, *From the Earth to the Moon*.

Wells, *The First Men in the Moon*.

Winter, *The First Golden Age of Rocketry*.

WORLD-BUILDING IN *THE LEFT HAND OF DARKNESS*

SOME SCIENCE FICTION STORIES ARE SET ON REAL PLANETS. FOR INSTANCE, MARS IS THE SETTING OF MANY NOVELS. WE KNOW A LOT ABOUT THE PLANETS IN OUR OWN SOLAR SYSTEM, AND AS FAR AS WE KNOW, NONE OF THEM CAN SUPPORT EARTH-LIKE LIFE. THIS MEANS THAT WRITERS CANNOT USE THEM AS AN ALIEN WORLD WHERE EARTH-LIKE LIFE CAN SURVIVE.

THE OTHER OPTION FOR A SCIENCE FICTION WRITER IS TO DESIGN HIS OR HER OWN PLANET. BECAUSE OF THE COMPLEXITY OF THIS PROCESS, THIS COURSE DEVOTES 2 LECTURES TO IT. THE LECTURES EXAMINE 4 SCIENCE FICTION SETTINGS, 2 PER LECTURE, GOING IN ORDER OF THE COMPLEXITY OF THE SCIENCE BEHIND EACH OF THE SETTINGS.

THIS LECTURE'S FIRST IMAGINARY WORLD IS GETHEN, A WORLD SIMILAR TO EARTH, INVENTED BY URSULA K. LE GUIN FOR HER NOVEL *THE LEFT HAND OF DARKNESS*. ITS SECOND IS SUKIEN, WHICH WAS DESIGNED BY THIS COURSE'S INSTRUCTOR FOR A JAPANESE TV SERIES, THOUGH IT WAS ULTIMATELY NOT USED BY THEM. THIS WORLD CIRCLES A LOW-MASS RED STAR, AND IT IS SO CLOSE TO THE STAR THAT IT IS TIDALLY LOCKED. ONLY ONE FACE IS ILLUMINATED.

“HOW TO BUILD A PLANET”

The short essay “How to Build a Planet” by Poul Anderson informs much of the material in this lecture. Even though it was written in the 1960s, it is still the best essay on how to incorporate real science into a science fiction story.

BACKGROUND ON *THE LEFT HAND OF DARKNESS*

- *The Left Hand of Darkness* was first published in 1969. The people of the planet Gethen are androgynous—individual gender doesn’t exist. Additionally, the world is cold. These 2 details frame much of the narrative of the story.
- The story is one of Le Guin’s Hainish novels. In these stories, the human race didn’t originate on Earth. Instead, the mysterious Hainish people seeded many worlds with human stock millions of years in the past. Because of this, humanity consists of dozens of different races on dozens of different planets.
- In *The Left Hand of Darkness*, the Ekumen, a loose confederation of worlds, contacts Gethen. The Ekumen invite Gethen to join them, but the major governments of Gethen are suspicious of the offer. Genly Ai, the ambassador from the Ekumen, is the protagonist of much of the novel.

GETHEN’S TRAITS

- The most important information we know about Gethen is that it is cold. This doesn’t mean that it’s far from its star. Gethen is in the midst of a period of glaciation. Resources like food are scarce. Warfare is unknown because of the difficulty everyone faces in struggling with the environment. Both examples of government in the novel—a monarchy and a more or less communistic society—are repressive.

- ❏ The orbital axis of the planet is tilted only a few degrees from the ecliptic plane—the plane of Gethen’s orbit around its star. Unlike Earth, where seasonal variation is due mostly to the tilting of Earth’s axis, seasons on Gethen are caused by the eccentricity of Gethen’s orbit. One year on Gethen is 96% of the length of a year on Earth.
- ❏ Overall, Gethen sounds somewhat similar to Earth, and its star sounds a lot like the Sun, but with a few important differences. The year is basically the same length, and the amount of light it gets from its star is about the same as Earth gets from the Sun. Earth, like Gethen, goes through glacial periods. The planets’ suns are similar as well.



- ❏ Even though Gethen is similar to Earth, its differences are as important as the similarities. The main one is the fact that in the novel, Gethen is currently in a glacial period.

SUKIEN

- ❏ This lecture now turns to the tidally locked planet Sukien. This course’s instructor was asked to design this world for a Japanese science miniseries about the forms that life could take on other worlds. They asked him to consider a world circling an M-class star that was so close to the star that the planet was tidally locked.

- ❏ If a planet is close enough to its star, or a moon is close enough to its planet, the gravitational forces between the planets can force the planet or moon to orbit in such a way that it always shows the same face to the star or planet it circles. In the case of a tidally locked planet, there will always be one side that gets light and a side that is permanently dark.
- ❏ This may seem like a big problem: One side would be too hot, the other too cold. There are a few ways that one can deal with this problem. For example, life might exist in a narrow belt circling the equator of the world, where the temperature was amenable to life. Another possibility is that the atmosphere and any oceans on the planet transport heat from the light side to the dark side, partially evening out the temperature.
- ❏ This course's instructor chose an M-class star whose luminosity was about $\frac{1}{1000}$ that of our sun. This means that the perfect zone for this planet is about $\frac{1}{10}$ of the distance of Earth from our sun. Since the distance between Earth and our sun is 150 million kilometers, or 93 million miles, this means that the fictional planet should be about 15 million kilometers from the M-class star.
- ❏ One other issue is that such stars are flare stars—that is, the stars will suddenly flare up in intensity, which can have disastrous effects on any life on these planets. The planet's sea creatures, known as the alexi, would survive flares by diving underwater.
- ❏ On Sukien, the dwarf are the planet's intelligent race. They are roughly dog-sized creatures that built cities burrowed deep underground to protect against flares.
- ❏ Each dwarf has 2 sets of front arms but no legs. They move forward by curling the front of their bodies and wriggling forward on a snake-like tail. Most of their important organs are on the bottom part of the bodies, but they have large mouths and eyes on the top.
- ❏ The dwarf have 3 genders. Two are male and female, which individually mate with a smaller, neuter gender that carries the young to term. The dwarf design is an example of mixing examples from Earth biology in a way that considers the environment and makes sense for the world.

THE DWARROW



Suggested Reading

Dole, *Habitable Planets for Man*.

Le Guin, *The Left Hand of Darkness*.

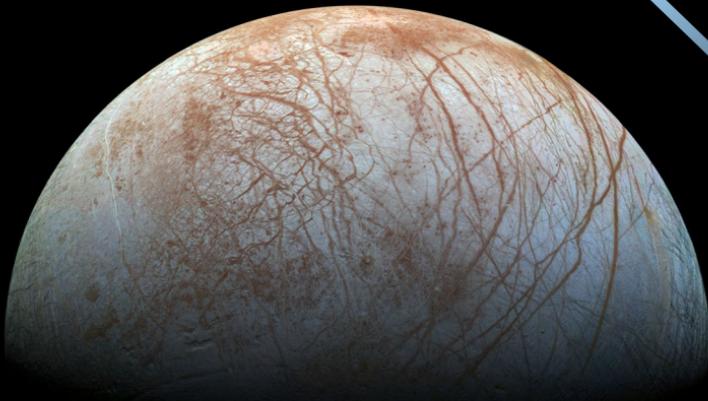
Scharf, *Extrasolar Planets and Astrobiology*.

ADVANCED WORLD-BUILDING IN *AVATAR*

AS LECTURE 4 SHOWS, SCIENCE FICTION WRITERS CAN TURN TO CONSERVATIVE DESIGNS FOR PLANETS. HOWEVER, MORE ADVENTUROUS WRITERS CAN MAKE OTHER CHOICES. THIS LECTURE LOOKS AT 2 EXAMPLES OF THAT APPROACH. THE EXAMPLES ARE FOUND IN A FICTIONAL DOCUMENTARY TITLED *THE EUROPA REPORT* AND THE FILM *AVATAR*.

THE EUROPA REPORT

- ❏ *The Europa Report* is based on video supposedly taken by the crew of the first manned expedition to Europa, the smallest of the Galilean moons of Jupiter. The Galilean moons—Europa, Ganymede, Io, and Callisto—are the moons that Galileo discovered through his telescope in 1610. Since then, more than 100 moons have been found in our solar system, especially circling the outer gas giant planets.
- ❏ The same forces that give rise to the tides on Earth also exist between Jupiter and its moons. As Europa circles Jupiter, these forces squeeze and stretch the moon, and friction from this heats it to the point where the ice can melt. As soon as this was discovered, scientists, among them Carl Sagan, speculated that Europa was a promising candidate for finding life outside of Earth but inside the solar system.
- ❏ In *The Europa Report*, the company Europa Ventures funded the expedition, which went to the moon to look for alien life. The film is scientifically accurate: Space travel is portrayed realistically, especially concerning the travel time to Europa.
- ❏ The biology is more speculative; in the movie, a life form from under the ice destroys the spacecraft. Most scientists think that life in the European oceans is much more likely to be microscopic, not something big enough to destroy a spacecraft.



BACKGROUND ON AVATAR

- ❏ The blockbuster movie *Avatar* is set on the inhabited moon Pandora, which circles the gas giant planet Polyphemus. Pandora is located in the Alpha Centauri star system. The system is very popular in science fiction because it is the closest star system to ours.
- ❏ The Alpha Centauri system consists of 3 stars orbiting each other from their mutual gravitational attraction. The stars are labeled A, B, and C, from brightest to dimmest. The C star is also called Proxima because it is significantly closer to Earth than the other 2.
- ❏ The story of *Avatar* concerns the attempts by humans to mine Pandora of a material called unobtainium, a naturally occurring mineral on Pandora that is unknown on Earth. Unobtainium is a room temperature superconductor—that is, it has zero resistance to the flow of electrons through it.
- ❏ A room temperature superconductor is something of a holy grail in materials science, as it would allow us to build things like magnetically levitated trains. One of the major features of the movie is the floating mountains, which are magnetically levitated by unobtainium.
- ❏ In the movie, the evil humans are mining unobtainium, regardless of the ecological consequences to the intelligent species of the planet, the Na'vi. Because the atmosphere is poisonous to humans—there is too much carbon dioxide—humans interact with the Na'vi through avatars, which are artificially created Na'vi controlled through long-distance interfaces with human brains.

THE SCIENCE OF AVATAR

- ❏ Director James Cameron and his crew did a large amount of work to make Pandora both exotic and scientifically accurate. Pandora is a moon; it is not in orbit around a star but around a planet that is in orbit around a star.

- ✚ Pandora is tidally locked to Polyphemus. This means that its rotational period is the same as the orbital period: One side of the moon always faces toward the planet, and the other faces away.
- ✚ Pandora and the giant planet Polyphemus seem to be within the habitable temperature zone (also known as the Goldilocks zone) of Alpha Centauri A—the brightest star in the Alpha Centauri system. Along with being heated by the star, Pandora might get more heat because it is a moon of Polyphemus: Tidal stresses would heat it. In addition, planets like Polyphemus are slowly contracting under their own weight.
- ✚ This contraction converts gravitational potential energy into heat, which would also heat the moon. This means that Polyphemus might have to be located outside the conventional Goldilocks zone of the Centauri system for life to exist on Pandora.
- ✚ Another consideration is the heating from the other stars, although this would vary as the 3 stars moved around each other. The atmosphere, which has a higher carbon dioxide concentration than Earth and therefore more greenhouse heating, would also be a factor.



ORBITAL CONSIDERATIONS

- ❏ The fact that Alpha Centauri is a triple-star system makes matters a bit more complicated. If there is one star and one planet, Kepler's first law states that the orbits are in the shape of an ellipse or a squashed circle. The astronomer Johann Kepler was the first person to figure this out, and it was proved by the great scientist Isaac Newton about a century later.
- ❏ Orbits can be very eccentric or nearly circular. The Goldilocks zone is a spherical shell, so a very eccentric orbit will go in and out of the zone during its orbit. Earth's orbit is nearly circular, as are the orbits of most of the planets in the solar system. This isn't characteristic of most systems, however. Many planets in other solar systems have very eccentric orbits.
- ❏ The orbit of a planet is elliptical if there is only one star and one planet. The presence of more than one star makes for complicated, even chaotic orbits. The big question is whether stable orbits can exist within the Goldilocks zone in multiple-star systems.
- ❏ Astrobiologists and astronomers are very interested in this question because about half of all stars are in multiple star systems. It appears that the known planets in the Alpha Centauri system are in stable orbits, particularly Proxima Centauri b, the potentially habitable world circling the smallest star. Life may not be possible on this planet anyhow, as the very strong stellar winds from the star probably have stripped all of the atmosphere from the planet.
- ❏ The orbits of the planets in our own solar system are chaotic in a different manner. In the 1990s, mathematicians did extensive simulations of the orbits of the planets. They found something surprising: While the shape of the orbits remained largely stable, the orientation of the ellipses and the positions of the planets in their orbits changed chaotically over the course of millions or billions of years.
- ❏ This is because of the very complicated gravitational interactions of all of the planets with each other, particularly that of the giant planet Jupiter. That process doesn't have the same dire effects that a chaotically shaped orbit would, but it is still notable.

- ❏ The other way that chaos manifests itself is the orientation of the spin axis of the planets. The Earth's axis is tilted by 23.5° from the orbital plane. This is why the Earth has its seasons.
- ❏ Mars has almost the same orbital orientation (about 25°) and almost the same day (slightly more than 24 hours). These 2 are remarkable coincidences. They are coincidences because the length of a year on a planet is determined by how far it is from its star and the mass of the star.
- ❏ But how fast it rotates about its own axis is fairly random, unless it is so close to its star that it is tidally locked, or in a so-called tidal resonance that locks its rotation rate to its orbital period. Mercury is close enough to the sun that it is in such a resonance: It rotates on its axis 3 times for every 2 Mercurian years.
- ❏ But Mars isn't like this. Computer simulations of the rotation of Mars show that the fact that its orbital inclination is similar to Earth's is very coincidental, as it changes chaotically over millions of years.
- ❏ Some scientists think that this chaotic orbital trend threw a monkey wrench into the evolution of life on Mars. They think that evolution occurring over the course of millions or billions of years requires a much more stable climate. However, like much of astrobiology, this question won't really be settled unless we find life on Mars or show convincingly that it doesn't exist.

Suggested Reading/Viewing

Cameron, dir., *Avatar*.

Cixin, *The Three-Body Problem*.

ACTION AND REACTION IN *THE AVENGERS*

SUPERHERO STORIES FORM THEIR OWN GENRE OF SCIENCE FICTION OR FANTASY, AND THE GENRE HAS ITS OWN SET OF RULES AND TROPES. FIGHTS ARE ONE OF ITS KEY DISTINGUISHING FEATURES. THIS LECTURE FOCUSES ON THOSE FIGHTS FROM THE STANDPOINT OF THE LAWS OF PHYSICS, MOST NOTABLY THE ONES INVOLVING THE LAW OF ACTION AND REACTION. IN PARTICULAR, THIS LECTURE LOOKS AT MOVIES DEALING WITH THE MARVEL CHARACTERS KNOWN AS THE AVENGERS. IT ALSO LOOKS AT THE TITLE CHARACTER FROM THE TV SHOW *THE FLASH*, FROM THE DC COMICS UNIVERSE.

IRON MAN

- ✚ The original movie in the Avengers series is the 2008 film *Iron Man*. In it, Tony Stark, a genius billionaire, designs a metal flying suit powered by a so-called arc reactor that allows him to both escape and destroy the terrorist camp while doing so.
- ✚ In terms of physics, the most important aspect of Tony's suit is that it flies. The suit is clearly rocket-propelled. Rockets move because of Newton's third law of motion. This is usually stated as: "For every action, there is an equal and opposite reaction."
- ✚ Designing rockets is very complicated, but it all rests on one equation that reveals what the thrust of the rocket is in terms of a few parameters. The first one is the exhaust speed. When the rocket burns fuel—the propellant—it is ejected backward at the exhaust speed. This is mainly determined by what the propellant is made from. All other things being equal, higher exhaust speed is better, as it provides more thrust. The other parameter is the rate at which the rocket burns fuel. The higher the burn rate, the higher the thrust. However, the higher the burn rate, the faster the rocket uses up all of the fuel.
- ✚ The thrust is the product of these 2 parameters:

$$\text{thrust} = \text{exhaust speed} \times \text{fuel burn rate}$$

- ✚ If exhaust speed is in meters per second, and fuel burn rate is in kilograms per second, then thrust will be in newtons, the unit of force in the SI system (often called the metric system). One newton is approximately the same force as the weight of $\frac{1}{10}$ of a kilogram, or about 100 milliliters of water—that is, a bit more than 3 ounces.
- ✚ This formula can answer a question about Tony's suit: How fast does it burn fuel? If Tony is hovering in the air, then the suit is just supporting his weight and the suit's weight against the force of gravity. We can rearrange the formula to read:

$$\text{burn rate} = \text{thrust} \div \text{exhaust speed}$$

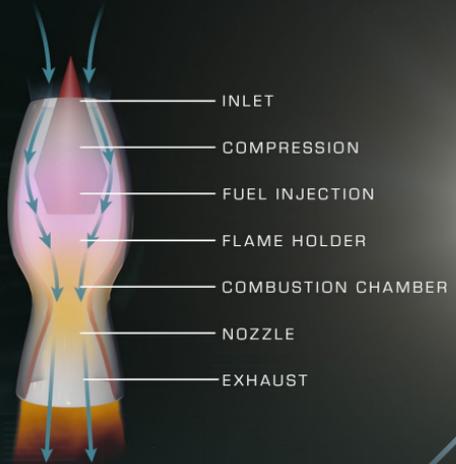
- ✚ Assuming that his mass plus the mass of the suit is 150 kilograms, then the weight of the suit is about 1,500 newtons, or 1,470 to be more precise. If he is using a chemical fuel, which seems likely, then the exhaust speed will be between 2,000 and 3,000 meters per second. This example splits the difference for 2,500.
- ✚ The burn rate that he needs to hover in the air is about 0.6 kilograms per second. If he wants to accelerate upward, he needs to burn fuel faster. Conservatively, he is going to need to burn fuel at a rate of around one kilogram per second.
- ✚ From the movie, he seems to need to stay in the air for about 10 minutes, or 600 seconds, at a time. On the surface, that seems to mean he needs to carry 600 kilograms of fuel. In reality, he needs more fuel than that because he needs to lift all of the fuel he is carrying.
- ✚ To account for the extra fuel weight, we will need to quadruple the fuel burning rate. This will either limit his flight time to 2.5 minutes or necessitate multiplying the amount of fuel by a factor of 4—that is, to 2,400 kilograms. He simply can't carry enough fuel to allow him to fly around for any length of time.

THE RAMJET PRINCIPLE

- ✚ An alternative idea is that Tony could be using the ramjet principle to fly. The suit could be sucking air in and superheating it with the arc reactor, the power source for his suit. Once heated up, the air is then expelled at high speeds to the rear, propelling him forward. The flames ejected by the suit could be the heat of the superheated air. Air is compressed by the forward motion of the suit rather than an internal turbine.
- ✚ Whatever is powering the arc reactor has to have enough juice to do this. The only conceivable power source is nuclear, as chemical fuels fail because of their relatively low energy storage capability. This creates its own set of problems.

- ❖ A nuclear-powered ramjet may sound outlandish, but the US government did have a program to develop one. It was called Project Pluto. The ramjet was developed between the years of 1957–1964. It was cancelled shortly after the first nuclear test ban treaties were signed in 1963.
- ❖ The idea was to develop an unmanned, nuclear-powered drone capable of traveling at supersonic speeds. To get the ramjet to work, air had to be superheated to temperatures of 2,200° Celsius or higher.
- ❖ Most materials, including iron, melt at much lower temperatures. However, according to Tony, the “iron” suit is really a titanium alloy. Titanium has a higher melting point—above 1,600° Celsius. It’s higher than iron, but still lower than the ramjet temperature. Perhaps Tony figured out a way to make a ramjet work at lower temperatures, or perhaps he used some new alloy of titanium that has a very high melting temperature.

HOW A RAMJET WORKS



THE FLASH

In the TV show *The Flash*, Barry Allen has the ability to walk on water and run up walls. Barry Allen is The Flash, the world's fastest human. He can run at speeds exceeding 800 kilometers per hour. He can run so fast that he can run across the top of water without getting wet. Essentially, Barry Allen's feet have to slap the water hard enough so that the force they generate can support his weight.

It's another application of Newton's third law: For every action there is an equal and opposite reaction. The force he generates running across the water is equal to the mass of his leg multiplied by the speed he hits the water multiplied by how many times per second he hits it:

$$\text{force} = \text{leg mass} \times \text{speed} \times \text{slap rate}$$

To see or hear this formula broken down in detail, refer to the audio or video lecture. Plugging in reasonable values indicates that he would need a speed of about 110 kilometers per hour, give or take. This is why ordinary people can't run on water, but it's easily within The Flash's wheelhouse.

The basilisk lizard can do this feat at lower speeds because its weight is so much less. The lizard is also helped by the fact that the downward push of its leg against the water surface creates an air bubble whose buoyancy helps it to float. Perhaps The Flash can do something like that as well as he runs.

Regarding his ability to run up walls, his speed actually hurts him. If he launches himself into the wall and tries to run upward, he will simply bounce off of it.

SPIDER-MAN

This lecture concludes with a look at Spider-Man's webs. Spider webs are marvelous things, and their building material, spider silk, is just as marvelous. Spiders can produce as many as seven different types of spider silk, which are used for different purposes. This discussion focuses on the most commonly depicted spider web: the webs created by orb-weaver spiders.

- ❏ The orb-weaver spiders use several different types of silk constructing these. The radial lines—the ones that go out from the center—are structural. They are strong and not sticky. The sticky ones are the spiral ones, which catch prey. They are presumably like the webbing that Peter Parker (Spider-Man's real name) uses to catch criminals.
- ❏ There are 2 different types of sticky web used by 2 different types of spiders: ecribellate webbing, which uses droplets of a glue-like substance to snare prey, and cribellate webbing, where the snaring properties are created by the structure of the webbing. The sticky web, no matter which kind, has 2 other properties that makes it ideal for catching prey:
 - First, it is very extensible. It can be extended to over 5 times its unstretched length before breaking.
 - Second, it is highly deformable. This property is called hysteresis; it means that the shape of the material depends on how it has been stretched out.
- ❏ This type of webbing could be made strong enough to support Spider-Man as he swings on the web or traps criminals. The density of spider silk is only about $\frac{1}{6}$ that of steel, but it has about the same tensile strength.
- ❏ However, it isn't jet-propelled, as it seems to be in the movies; spiders secrete it from their spinnerets rather than propelling it through the air. But since Peter made his own spinnerets, this is an engineering problem. Another engineering problem that Peter seems to have solved with ease is how to manufacture the silk. At present, artificial spider silk is very expensive, and it is difficult to manufacture in large quantities.

Suggested Viewing

Persichetti, Ramsey, and Rothman, dirs., *Spider-Man: Into the Spider-Verse*.

Whedon, dir., *The Avengers*.

QUIZ

- 1 What is the only known way to create “gravity” on an artificial space station?
 - a Spin it about its axis.
 - b Put a black hole inside it.
 - c Put it in orbit around a planet.
 - d Use a gravity generator.

- 2 True or false: A moon orbiting a planet can be tidally locked so that one side is always sunlit.

- 3 A light year is:
 - a The time it takes for light to travel for one year.
 - b A year on a distant planet.
 - c The distance light travels in one year.
 - d A made-up science fiction concept.

- 4 True or false: Holism is a philosophy in which the whole can be understood by examining the parts separately.

- 5 For a spacecraft to reach the Moon from the Earth, it must reach a speed of approximately:
- a 11 meters per second.
 - b 110 meters per second.
 - c 1100 meters per second.
 - d 11,000 meters per second.
- 6 Acceleration is:
- a The same thing as velocity.
 - b The rate at which velocity changes with time.
 - c Either A or B.
- 7 M-class stars:
- a Are much dimmer than the Sun.
 - b Are much smaller than the Sun.
 - c Will last much longer than the Sun.
 - d All of the above.

- 8** For a planet circling another star to be able to support Earth-like life, it must:
- a** Have an orbit roughly the same distance from the star as the Earth is from the Sun.
 - b** Have an orbit at a distance from the star so that it receives about the same amount of light from the star as Earth does from the Sun.
 - c** Have an orbit that is nearly circular.
 - d** Both A and C.
 - e** Both B and C.
- 9** True or false: The orbital tilt of Mars changes chaotically over the course of billions of years.
- 10** Astronomers find exoplanets by:
- a** Watching for the slight dimming of the star when the planet passes in front of it.
 - b** Measuring the motion of the star due to the planets gravitational pull as it orbits around the star.
 - c** Both A and B.
 - d** Neither A nor B.

- 11 The thrust of a rocket depends on:
- a Fuel burn rate.
 - b Fuel exhaust speed.
 - c Neither A nor B.
 - d Both A and B.
- 12 True or false: There are many different types of spider silk.

ANSWERS

1 a; 2 false; 3 c; 4 false; 5 d; 6 b; 7 d; 8 e; 9 true; 10 c; 11 d; 12 true



SPACE TRAVEL AND *2001: A SPACE ODYSSEY*

MOST DEPICTIONS OF SPACE TRAVEL IN THE MOVIES AND ON TV ARE FLAWED FROM A SCIENTIFIC STANDPOINT. THEY HAVE BECOME BETTER OVER TIME, ESPECIALLY SINCE THE 1990S WITH THE GROUNDBREAKING SCIENCE FICTION SHOW *BABYLON 5*. HOWEVER, THE GOLD STANDARD FOR THE DEPICTION OF SPACE TRAVEL IN SCIENCE FICTION IS MORE THAN 50 YEARS OLD. IT IS *2001: A SPACE ODYSSEY*. THERE ARE A FEW SMALL BLUNDERS, BUT OVERALL, THE MOVIE DEPICTS SPACEFLIGHT WITH METICULOUS CARE. THIS LECTURE FOCUSES ON SEVERAL ASPECTS OF SPACEFLIGHT AS HANDLED BY THE MOVIE AND THE TV SHOWS *BABYLON 5* AND *BATTLESTAR: GALACTICA*.

THE PLOT OF 2001: A SPACE ODYSSEY

- ❏ The movie opens several million years ago on the African plains. A group of protohumans are on the edge of extinction because of predators, drought, and disease. A huge, mysterious artifact appears: the monolith. It influences the protohumans to use tools. This leads to both hunting and murder, which symbolizes that human ingenuity and technology is a 2-edged sword.
- ❏ As the leader of the pack of humanoids throws the bone he has used for both hunting and murder into the air, the movie moves forward in time by 2 million years. The bone transforms into a spacecraft traveling to a rotating space station. The spacecraft is carrying Dr. Heywood Floyd. On the space station, he learns of a monolith found on the Moon, which is identical to the one in the past. When exposed to light for the first time, the Monolith sends a message to Jupiter.
- ❏ An expedition is sent there to investigate, but disaster strikes: HAL, the artificial intelligence that controls the spacecraft *Discovery*, kills most of the crew. Dave Bowman, the only survivor, disables HAL and goes through the monolith. It becomes a portal that somehow turns him into a space child in the movie's final scene.

THE MOTION OF SPACECRAFT

- ❏ If a spaceship is in space, far from any gravity well, it simply moves along on a straight line, essentially indefinitely. Newton's first law of motion states that unless a force acts on an object, the object will travel in a straight line at a constant speed forever if nothing bumps into it.
- ❏ Unlike a spacecraft, an airplane must be constantly supplied energy to keep it moving forward. This is because air molecules are continually bombarding it as it moves forward, exerting a constant force pushing it back. This is called drag, and it slows the plane down.

But in space, there is no air and no drag. The scene in *2001* that shows the shuttle moving toward the space station illustrates this well: The shuttle moves on a straight line toward the station, with the Earth in the background. The scene also shows how the shuttle has to match rotation with the space station before it docks. The station rotates to generate artificial gravity via centrifugal force.

ACTION AND REACTION

The only plausible means of moving a spacecraft is using rockets—that is, using the law of action and reaction. Rockets move by Newton’s third law of motion. However, working out how rocket-propelled spacecraft move in detail is complicated. This is especially true when adding gravity into the mix.

The basic physics is that for every action, there is an equal and opposite reaction. The force pushing the rocket is governed by the exhaust speed and flow rate. There are other forces acting on the spacecraft: gravity and, if it’s in the atmosphere, atmospheric drag.

TV shows and movies show spacecraft firing their rockets all the time. In real life, the rocket engines fire for short periods, typically a few seconds or minutes at most. They are only fired when the ship is changing its speed—lifting off the ground or making an orbital correction. For the minute or so that the rockets are firing, the other forces are negligible compared to them.

Firing rockets is called a delta- v maneuver. The v stands for *velocity*, and *delta* is an engineering shortcut meaning *change in*. Delta- v refers to a change in velocity, and this is what rockets do. All spaceship maneuvers are characterized by a delta- v value, which is determined by how long the rocket fires, what fuel it uses, and the mass of the spacecraft and the rocket fuel.

There are many different types of rockets and rocket fuels. There are solid and liquid propellants, which all have different chemical formulas. However, one factor is basic to all types of rocket propulsion, which is very important: Adding speed comes at a multiplicative fuel cost.

- The basic issue is the payload ratio. The payload ratio is the total mass of the spacecraft—fuel plus payload—divided by the mass of the payload itself.
- NASA uses multistage rockets: This provides an advantage because the rocket can jettison each stage once it has finished burning its fuel. That way, the rocket gets rid of the structure needed to hold the fuel from that stage.
- The math behind designing a multistage rocket is very tricky. The issue is that chemical rockets are barely able to lift payloads from Earth’s gravity well, necessitating highly optimized designs.

$$\text{PAYLOAD RATIO} = \frac{\text{TOTAL MASS (FUEL + PAYLOAD)}}{\text{PAYLOAD MASS}}$$

TYPICAL EXHAUST SPEED
FOR CHEMICAL FUEL: 3000 MPS

| PAYLOAD RATIO | SPACECRAFT SPEED |
|---------------|------------------|
| 3 | 3000 MPS |
| 9 (3X3) | 6000 MPS |
| 27 (3X3X3) | 9000 MPS |
| 81 (3X3X3X3) | 12000 MPS |



- Rocket propulsion isn’t the only way to get a delta-v boost. It is also possible to obtain via a gravitational slingshot effect: Going into a close orbit around a planet or moon can add several thousand meters per second to a rocket’s travel speed. This also allows for changes in direction. The downside is that it takes time, and the planets have to be aligned just right.

BABYLON 5'S STARFURY AND BATTLESTAR GALACTICA'S VIPER

- ❏ The Starfury model of spacecraft from *Babylon 5* is designed particularly well. The Starfury has 8 engines in pairs, with one facing forward and one backward, in a cross shape around the central pod. The rockets, acting in pairs, can flip the ship around, or, acting in concert, can move the Starfury forward and backward. These are small warships, similar in nature to fighter jets, used for dogfighting and harassing a larger enemy.
- ❏ Another interesting aspect about the Starfury fleet is how they were launched. They were essentially dropped from their holding bays. The colony in *Babylon 5* is an O'Neill colony—that is, it rotates to provide artificial gravity. The gravity comes from centrifugal force, which means that people feel a force pushing them outward toward the cylindrical hull of the station.
- ❏ Each Starfury is kept in a bay on the outer hull. When they are launched, they are simply pointed outward from the hull and let go. Their speed is equal to the tangential speed of the hull rotation, or by this course's instructor's calculations, about 450 miles per hour.
- ❏ In contrast, the Vipers in the *Battlestar: Galactica* reboot have a more traditional engine design: 4 engines mounted in the rear. They also have wings because they are used for atmospheric flight. The engines can produce thrust both forward and backward, however.
- ❏ *Battlestar: Galactica* and *2001* both get one thing right that *Babylon 5* gets wrong: There is no sound in space! This is because sound waves are carried by air, and there is no air in space.

Suggested Reading/Viewing

Kubrick, dir., *2001: A Space Odyssey*.

Pichel, dir., *Destination: Moon*.

Van Riper, *Rockets and Missiles*.



INTERPLANETARY TRAVEL AND *THE MARTIAN*

ONE OF THE MOST WIDELY READ SCIENCE FICTION NOVELS OF 2011 WAS *THE MARTIAN*. IT TELLS THE STORY OF MARK WATNEY, AN ASTRONAUT STRANDED ON MARS BECAUSE OF A FREAK ACCIDENT, AND HIS SURVIVAL AGAINST ALL ODDS. BOTH THE BOOK AND THE MOVIE MADE FROM IT ARE FAIRLY ACCURATE IN THEIR DEPICTION OF THE SCIENTIFIC ISSUES INVOLVED IN TRAVELING TO ANOTHER PLANET AND EXPLORING IT. THIS LECTURE FOCUSES ON 3 OF THOSE ISSUES:

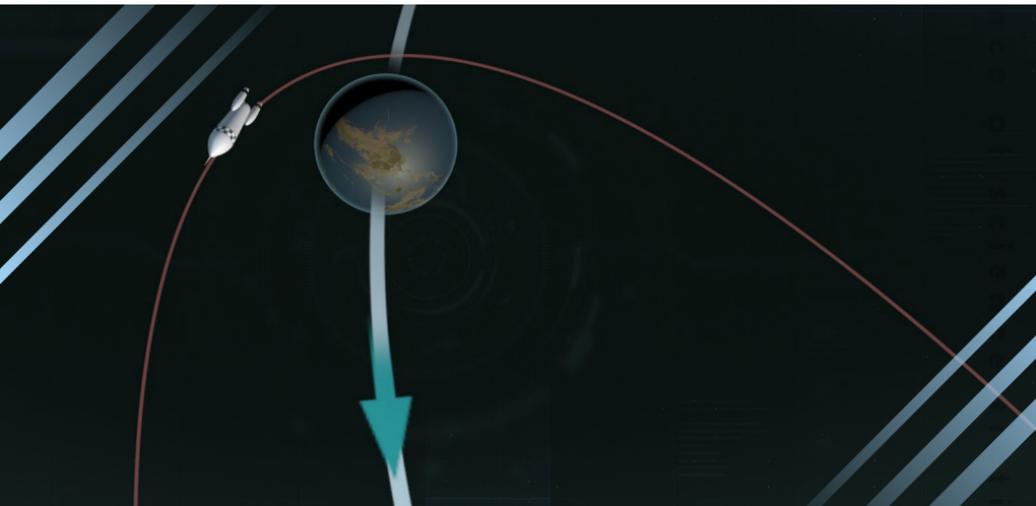
- 1 THE PHYSICS OF TRAVELING TO MARS AND RETURNING FROM IT.
- 2 SURVIVING ON MARS WHILE THERE.
- 3 THE POSSIBILITY OF HAVING HUMANS LIVE THERE FOR EXTENDED PERIODS OF TIME.

TRAVELING TO MARS

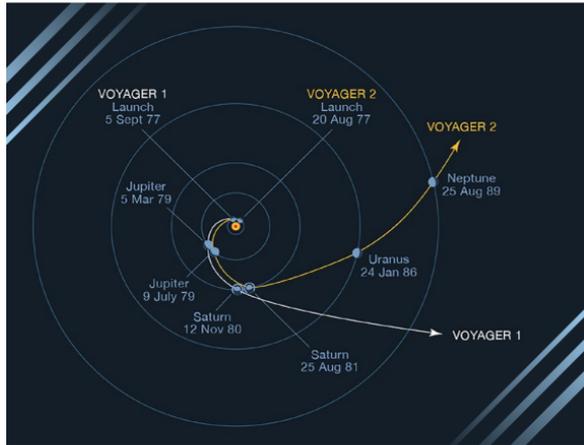
- ✚ To date, the farthest that any humans have been from Earth is the Earth's Moon. The Moon is roughly 384,000 kilometers, or 239,000 miles, from the Earth. It took the Apollo astronauts about 4 days to reach it. However, Mars is much, much farther: The distance is in the area of 55 million kilometers at closest approach. A spaceship traveling at the same speed as the Apollo craft would take more than a year to reach it.
- ✚ That is an estimate, but it isn't far off. According to NASA's website, the *Spirit* Mars rover was launched on June 10, 2003 and landed on January 24, 2004—a trip time of slightly more than 6 months. The *Viking 1* and *Viking 2* landers took about a year.
- ✚ One way to potentially make the trip easier is using 2 different systems of spacecraft. The first would be a shuttle to lift the crewmembers and supplies off Earth into a low-Earth orbit. The second part—the spacecraft used to bring the crew to Mars—would be built in orbit around the Earth, leave from there, and return to there. When the crew returns from Mars to Earth's orbit, other shuttles would take them back down.
- ✚ This approach makes sense because the biggest fuel cost is simply getting people off the surface of the Earth into orbit. This is the overall concept used in the film *The Martian*. The spacecraft that takes the astronauts to Mars is left in orbit around the planet. The crew land on the planet using chemical rockets, which are then used to take them back to the orbiter, and so on. Presumably, there is a similar system used at the other end to get them down to Earth.
- ✚ The overall utility of this system is pretty good. It is very similar in concept to the space transport system that NASA proposed as a sequel to the Apollo program in 1969. The vision was to create a 3-pronged space program: a fleet of chemically propelled shuttles to move things from Earth to low orbit; chemically-propelled "space tugs" to move payloads from low-Earth orbit to higher orbits, and nuclear-propelled spacecraft to go to the Moon and planets. However, the problem with the program was its high price tag: Congress deemed it too expensive, and the only part that was ever built were the Earth-to-low-orbit space shuttles.

GRAVITATIONAL ASSISTS

- It is possible to send probes to other planets using less energy than the transfer orbits by making use of gravitational assists from various bodies in space. This idea was used in the movie *The Martian*, when the mission needs to return to Mars to save Watney. By burning their fuel reserves on their return home, they go into an orbit around the Moon that re-aims the spacecraft toward Mars in time to save the stranded astronaut.
- The idea of using such a method to boost spacecraft speeds or change their direction dates back to the 1950s, when the mathematician Stanislaw Ulam recognized that the gravitational pull of the planets could be used for spacecraft propulsion. In his 1958 paper “On the Possibility of Extracting Energy from Gravitational Systems by Navigating Space Vehicles,” he postulated that a spacecraft could gain energy by repeated close approaches to large planets or moons.
- The force of gravity between the planet and the spaceship is an important factor here. The physics depends on 2 things: the conservation of energy and the conservation of momentum. When a spacecraft goes into a tight orbit around a planet and exits from it, it can gain up to twice the speed of the planet’s motion around its sun, depending on where it is pointing as it exits the orbit.



The *Voyager 1* and *Voyager 2* spacecraft received gravitational boosts from several of the planets in their grand tour of the solar system. In particular, *Voyager 2* had close flybys of Jupiter, Saturn, Uranus, and Neptune. Both of the spacecraft were boosted to speeds that will take them entirely out of the solar system.



RADIATION

- One of the big problems with people being in space for a long time is radiation. On Earth, there are a few major sources of natural radiation. The most important are radioactive elements in the Earth's crust and radiation from space in the form of cosmic rays and from the Sun.
- Earth is protected doubly from radiation from space: Earth's magnetic field deflects charged particles, and our thick atmosphere prevents many of them from reaching the Earth's surface. Mars has no magnetic field to speak of, and the atmosphere is much thinner than Earth's, so there is much more radiation reaching the Martian surface. Astronauts would also be exposed to radiation in space on their journey to Mars and back from it.
- A study of a "typical" 500-day round-trip voyage to Mars estimates that astronauts would be exposed to about 4 times the lifetime exposure limits of people who work with radioactive products daily. The major danger is long-term: Radiation levels on Mars or in space aren't life-threatening if exposed for only a few days or weeks.

❏ A chief problem is elevated cancer risks. Current NASA policy is to limit exposure so that the total risk of cancer is no more than 3% higher than that of the general population. One study of planned crewed Mars missions concluded that there was no way to limit exposure to this level. Long-term exposure to radiation can also cause nervous system disorders.

A HARSH ENVIRONMENT

❏ The overarching issue is simply surviving in the extremely hostile environment in space and on Mars. For instance, Mars is cold: The average temperature is roughly -60° Celsius. It can get warmer than the freezing point of water, but it is still very cold. The planet is cold for 2 reasons: It is farther from the Sun than Earth is, and there is very little atmosphere. Mars's atmosphere is mostly carbon dioxide, so astronauts will have to bring their own oxygen with them and essentially everything else that they need to survive.

❏ The problems of survival on a hostile planet drive much of the plot of *The Martian*. Watney has to use his own waste to grow potatoes in the Martian soil because it has no nutrients in it. Much of his food supply is destroyed in a fire due to high oxygen levels in the tent he used as a greenhouse. He has to travel several thousand kilometers to reach a rocket capable of lifting him into orbit to reach the ship rescuing him.

❏ This brings up one problem in the movie that isn't present in the book. He reaches the orbiter and is able to rig it to carry him to the spacecraft. However, matching orbits and speeds is a problem.

❏ In the final climactic scene, when Watney is rescued by Commander Lewis, she sends out a line that he grabs. He's then reeled to safety by her. He has a fair bit of rotation when he grabs the line. Because of this, their overall rotation rate should increase dramatically as she reels him in. This is called the conservation of angular momentum: It is the same as when a skater pulls her arm in to rotate faster in a spin on the ice.

TERRAFORMING MARS

- ✚ This lecture concludes with a look at the idea of terraforming Mars—that is, making it suitable for human habitation by creating a breathable atmosphere and making the planet warmer. The way to terraform Mars is presumably by setting up the photosynthesis cycle using some sort of plants suitable for growth on the planet.
- ✚ Photosynthesis refers to the production of energy storage compounds from carbon dioxide by plants, with oxygen as a by-product. The issue here is that this requires energy to happen, which is supplied by sunlight. Oxygen is highly reactive. Animals use the oxygen for their own respiration, exhaling carbon dioxide.



- ❏ The evolution of this process on Earth required billions of years. Repeating the process on another planet might not take as long. We already have the organisms that can do this, and we might be able to genetically engineer them for survival on Mars.
- ❏ But there is one limiting factor to how long it will take: the energy that Mars gets from the Sun. To create an atmosphere that can even minimally support human life will take tens of thousands of years based on the total energy available from sunlight and the overall efficiency of photosynthesis.
- ❏ There are other issues as well. Getting the temperature high enough to support Earth-like life will require a large amount of greenhouse gases in the atmosphere. The 2 gases that are most responsible for greenhouse warming in Earth's atmosphere are water vapor and carbon dioxide. Water vapor is responsible for roughly half of all greenhouse warming. Carbon dioxide contributes approximately 10% of the total.
- ❏ It isn't clear what the right mix of gases would be, or even if it is possible on Mars at all. There are some studies of the issue, which have come to wildly different conclusions. Some indicate it is possible. Some seem to show that if you want the temperature high enough, the carbon dioxide concentration will be too high for human life.
- ❏ One of the big unknowns is the amount of water on Mars. At one point in its past, there was a large amount of water on Mars, but much of it was lost as the Martian atmosphere gradually dispersed over time. There are still ice glaciers on Mars and some evidence of occasional water flow on Mars. Water is one of the necessary preconditions for life as we know it.
- ❏ One of the big unsolved problems is whether life once existed on Mars, and, if it did, whether it is still there today. This raises another issue concerning terraforming Mars or any other planet. Terraforming Mars would probably destroy any preexisting life there.
- ❏ Life on Mars is probably on the microbial level. However, we would need a very good reason to harm it. What are the benefits of terraforming another planet that could counterbalance that, assuming that Martian life exists?

Additionally, terraforming Mars would cost trillions of dollars and take thousands of years. Nothing less than the survival of the human race itself would justify such an expense.

Suggested Reading/Viewing

Lucas, dir., *Star Wars: Episode IV—A New Hope*.

Weir, *The Martian*.

SPACE BATTLES AND ENERGY WEAPONS: *STAR WARS*

SCIENCE FICTION IS FULL OF WARFARE. THIS LECTURE EXAMINES SPACE WARFARE. BOTH SCIENCE FICTION WRITERS AND SCIENTISTS HAVE CONSIDERED THE CONDUCT OF WAR IN SPACE, AND THEY HAVE COME UP WITH SOME INTERESTING IDEAS.

STAR WARS

- ✚ The year 1977 saw the debut of the original *Star Wars*, now subtitled *Episode IV—A New Hope*. In this film, hero Luke Skywalker joins up with many allies to fight the evil galactic empire, personified by the masked villain Darth Vader.
- ✚ In the final battle of *A New Hope*, Skywalker pilots a small spaceship called an X-wing. In the fight he lobbs a precise bomb that destroys the Death Star. Luke's X-wing is a space version of a World War II fighter plane; the Death Star is a magnified version of the aircraft carriers of World War II. Much of the action is fast-paced dogfighting between the opposing small fighters: X-wings and Y-wings on the rebel side versus imperial TIE fighters.
- ✚ In *A New Hope*, the ships are making banked turns in space in exactly the same way that fighter planes do in films based on World War I and World War II. However, planes make banked turns because the air under their wings gives them lift—a force pushing on the wing. There is no air in space; hence, there are no banked turns.
- ✚ In reality, spacecraft move in straight lines at constant speed until they fire their engines to go in another direction. There are essentially 3 things that a rocket can do to change course:
 - 1 Fire the engine in the direction they are going. This speeds the ship up.
 - 2 Fire the engine in the opposite direction. This slows the ship down.
 - 3 Fire the engine at right angles to the direction the ship is going. This changes the direction the ship is moving in. If not done carefully, this will leave the ship spinning in addition to changing course.

THE BATTLE OF YAVIN

- ✚ The one external force that will determine how spaceships move is gravity. The Battle of Yavin is the climax of *A New Hope*. The Empire has tracked the rebels to their base on Yavin 4, an inhabitable, forested moon of the gas giant Yavin.

- ❏ The Death Star has enough firepower to destroy Yavin 4 entirely. The rebels only have a short time to destroy it before its orbit puts it into a position to destroy them. The rebel's strategy is to get one of their fighters close enough to lob a bomb into a small entry hatch leading to a reactor that will hopefully overload and destroy the Death Star.
- ❏ All of the fighters and the Death Star are in orbit around the gas giant planet Yavin. The orbital speed of a spaceship around a planet is determined by 2 factors. One is how far the ship is from the planet—that is, the orbital radius. The second thing is the mass of the planet. The formula can be derived from Newton's law of gravitation. Here is a simple version:

$$\text{orbital speed} = 7.8 \times \sqrt{\frac{\text{mass of planet}}{\text{orbital radius}}}$$

- ❏ Orbital speeds of spacecraft around a planet will typically be several kilometers per second. The more massive the planet, the faster they will go, and the farther out, the slower. A jet fighter will travel at speeds of Mach 1 or so, which is about 1,000 feet per second, or about 340 meters per second. A kilometer per second is 1,000 meters per second, or around Mach 3.
- ❏ Spacecraft in orbit will be traveling roughly 5 to 10 times the speed of a jet fighter plane, or Mach 15 to 30. Another way to put it is that they will hit 10,000 miles per hour, roughly speaking.
- ❏ If 2 spacecraft are on different orbits, then the difference in their velocities can be huge. Velocity isn't just speed; it is speed plus the direction that the spacecraft is heading in.
- ❏ Two spacecraft on even slightly dissimilar orbits won't linger around long enough for anyone to aim and fire at them. Orbital speeds are far too high for human reaction times.
- ❏ An example of this problem comes in the climactic scene where Han Solo pilots the *Millennium Falcon* and shoots the TIE fighters attacking Luke Skywalker. His trajectory is at a right angle to the trajectory of Luke's X-wing. The 2 spacecraft should pass each other in the blink of an eye, or less.

INTERNATIONAL LAW

Under current international law, war in space is illegal. This is an excerpt from Article I of the Outer Space Treaty of 1967:

The exploration and use of outer space, including the Moon and other celestial bodies, shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development, and shall be the province of all mankind.

The treaty forbids areas of outer space and planetary bodies, including the Moon, from being claimed by any countries, and it guarantees the right of all countries to peacefully explore space. It also severely limits the development of weapons systems in space. One glaring omission, unfortunately, is the development of systems that are partly in space and partly in the atmosphere, like ballistic missiles. The 109 countries that are parties to the treaty include the US, Russia, China, and North Korea.

CURRENT CONCEPTS OF SPACE WARFARE

To date, there have not been any overtly warlike operations in space. However, if it did happen, current concepts of space warfare center mainly around anti-satellite measures. Modern warfare isn't mainly about killing people. It is just as much about resources and information. This is what artificial satellites represent.

Satellites are an extremely important part of global commerce. One example is the Global Positioning System (GPS). Since its development in the 1970s, GPS has become the linchpin of global travel, and it is vital to many billions of dollars of the world's economy. If an enemy could knock out GPS coverage, it would be devastating to the world economy.



❏ Satellites are also used as intelligence-gathering assets and in communications. Satellites can view the entire Earth from above and spy out enemy resources. They can spot missile launches, and they play a key role in military communications. As such, they are one of the most important assets for warfare that space-capable nations have.

❏ However, the use of space for warfare is strikingly limited in other ways. Here is a supporting excerpt from the 2005 manual *The Physics of Space Security*:

Space favors activities that entail sending and receiving electromagnetic signals over ones that involve transporting large amounts of mass from the Earth into space or significant maneuvering in space, which can require a large mass of propellant.

❏ Space favors what satellites are good for: gathering and sending intelligence. This is because of the costs and the physics. People aren't going to go to space to fight because it is incredibly expensive to put people into space.

❏ It costs hundreds of times more to put a person into space than a satellite because of all of the life-support structure that people need to keep them alive. It is also necessary to retrieve them at some point, and they are bound by the laws of orbital mechanics as much as satellites are.

❏ One other issue about space warfare is the vulnerability of objects in space. Any country that can build ballistic missiles can build weapons to knock out satellites. Both China and India have demonstrated the ability to destroy satellites from the ground using missiles.

LASERS

- Next, this lecture turns to lasers. The term *laser* spawned from an acronym for light amplification by stimulated emission of radiation. A laser produces very high brightness and spectral purity. Brightness means that the beam from the laser is all in the same direction. Spectral purity means that the light is all concentrated near a single wavelength—a single color—although lasers can also emit infrared and ultraviolet light, in which the wavelengths are too long or too short to be seen by the human eye.
- Both of these make lasers very useful for things like communication systems and physics applications, but it doesn't make them useful for weapons systems. High brightness doesn't mean high energy or high power.
- High energy is necessary for laser weapons, and there aren't many laser systems around that can provide that sort of power. However, laser weapons systems have been developed. One type is called a chemical vapor laser, which relies on high-energy chemical reactions to generate the laser beam. The other combines many lower-power solid-state diode lasers into one huge beam.
- Applications of laser weapons are of 2 types: blinding and burning. Respectively, these refer to damaging the ability of a satellite or missile to see its target and burning or melting through a part of it to disable it. There are problems: The atmosphere tends to distort and disperse laser beams, and lasers can't hit targets beyond the horizon, as missiles can.
- It's also easier to harden a target against laser attacks than against a missile attack. Laser weapons may have a specialized niche in space warfare, but in the short term, we won't be seeing any scenarios like *Star Wars*.

Suggested Reading

Tirman, ed., *The Fallacy of Star Wars*.

United Nations General Assembly, Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies.

ADVANCED ROCKET SYSTEMS IN *STAR TREK*

THIS LECTURE CONSIDERS THE PROBLEM OF BUILDING A STARSHIP CAPABLE OF TRAVELING TO THE NEAREST STARS, AT THE VERY LEAST. IT IS A BIG PROBLEM. CONSIDER THIS: THE FARTHEST HUMAN BEINGS HAVE GONE FROM EARTH IS TO THE SURFACE OF THE MOON, A DISTANCE OF ROUGHLY 384,000 KILOMETERS. THE PLANETS ARE MORE DAUNTING: MARS AT ITS CLOSEST APPROACH IS ABOUT 56 MILLION KILOMETERS FROM EARTH.

THE STARS ARE MUCH FARTHER AWAY THAN THAT. LIGHT, THE FASTEST THING IN THE UNIVERSE, TRAVELS WITH A SPEED OF 300,000 KILOMETERS PER SECOND. EVEN AT THIS SPEED, IT TAKES LIGHT MORE THAN 4 YEARS TO REACH US FROM OUR NEAREST INTERSTELLAR NEIGHBOR, THE ALPHA CENTAURI STAR SYSTEM. THIS IS A DISTANCE OF TRILLIONS OF KILOMETERS.

MINIMUM SPEEDS AND FUEL OPTIONS

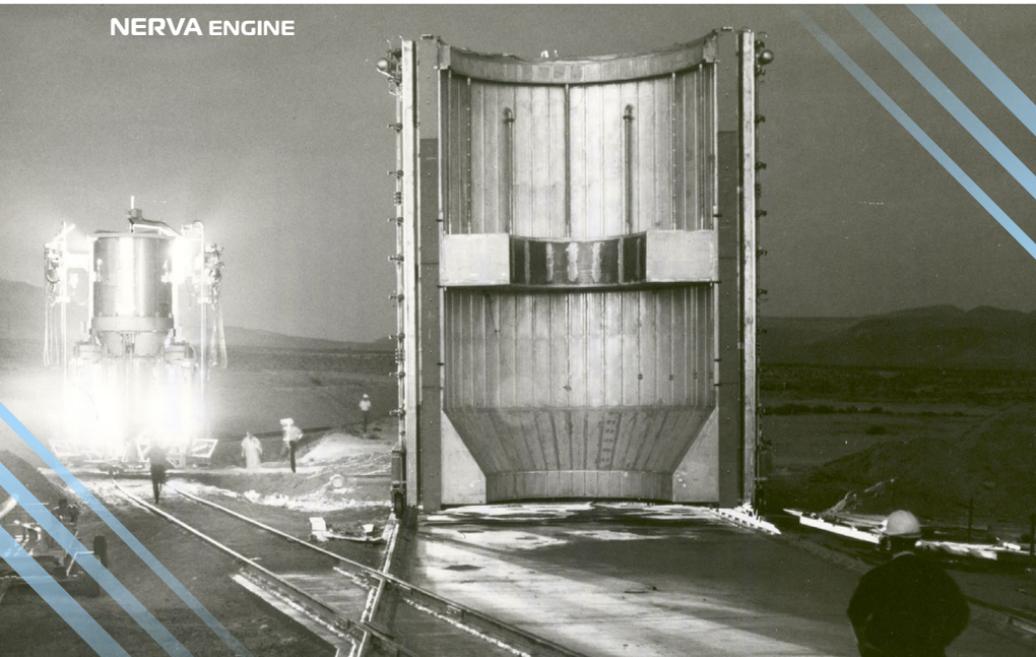
- ✚ This course proposes that the minimum speed for interstellar travel is about 10% of the speed of light. This is about 30,000 kilometers per second. At this speed, one would reach the Alpha Centauri system in about 40 years. It is absolutely impossible to reach this speed using chemical rockets. More energetic fuels are necessary.
- ✚ Nuclear reactions—that is, the transmutation of one element to another element—involve much more energy. The energies that hold the nucleus together are about 1 million times stronger than the forces holding electrons in an atom. The energy density for the enriched uranium used in nuclear power plants around 1 trillion joules per kilogram.
- ✚ There are 2 different types of nuclear processes: fission and fusion. Fission is the splitting apart of large nuclei to form smaller nuclei and releasing energy. Fusion is the process whereby smaller nuclei are combined under enormous heat and pressure to build up larger nuclei, releasing energy in the process.
- ✚ The premier example of a fusion reaction is the combining of 4 hydrogen nuclei to form one helium nucleus. This is the process that generates energy in the heart of the Sun and in most stars.
- ✚ Fission is much easier to accomplish than fusion. Both fission and fusion bombs exist—atomic and hydrogen bombs, respectively—but to date, only fission reactors exist for generating power.

DEPICTIONS OF NUCLEAR-POWERED ROCKETS

- ✚ Robert Heinlein's first juvenile novel, *Rocket Ship Galileo*, contains an early, accurate depiction of a nuclear-powered rocket. In it, a group of Boy Scouts, led by their scout leader, build a nuclear-propelled rocket, launch it to the Moon, and foil an evil Nazi plot there.

- ❏ Heinlein's book was published 4 years after the end of World War II. The war showed the world the power of atomic energy. Many scientists were thinking along the same line as science fiction writers. For example, the scientist Richard Feynman wrote about how he and others came up with applications for nuclear power. These included nuclear-powered airplanes, submarines, and spaceships.
- ❏ Feynman's concept is almost identical to Heinlein's. Both of their ideas are similar to NASA's NERVA project that developed nuclear rockets for use in the Moon program. NERVA is a conservative design. It doesn't make use of the full potential of nuclear energy.
- ❏ Power from a small nuclear reactor heats hydrogen gas to very high temperatures. At high temperatures, the molecules are rushing around at huge speeds. They are pushed out of a nozzle as the reaction mass. Hydrogen at very high temperature and high speed goes backward, and the rocket goes forward.

NERVA ENGINE



It is possible to achieve an exhaust speed of up to about 8 kilometers per second using the NERVA-style engine. However, NERVA is limited by the materials that are used to make the rocket, which start to melt at temperatures of about 2,000° Celsius, or a little higher. This is what limits the exhaust speed. NERVA engines were test-fired successfully, but that's as far as it went.

USING A BOMB

In the 1950s, the mathematician Stanislaw Ulam came up with a far more audacious idea: blowing up a nuclear bomb to move the ship forward. Ulam worked on the Manhattan Project, which built the first atomic bomb, and later on the hydrogen bomb project. He was in a good position to realize the potential of nuclear weaponry for such purposes. However, the nuclear-propulsion project, known as Project Orion, was led by Freeman Dyson and Ted Taylor.

Much of this lecture's information about Project Orion comes from a book written by Freeman Dyson's son, George, an eminent historian. It is titled *Project Orion: The True Story of the Atomic Spaceship*.

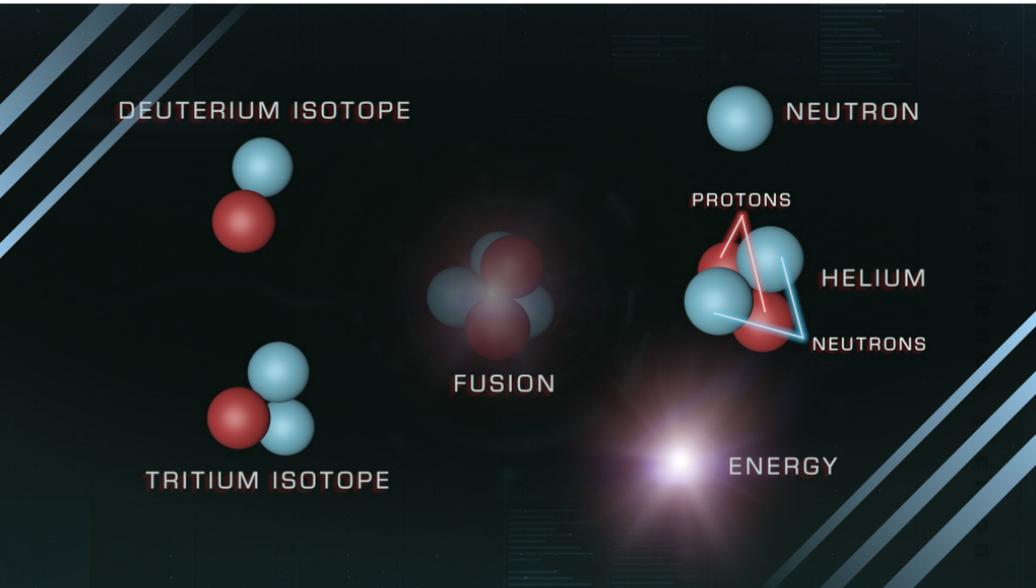
Orion was always meant as a propulsion system for crewed spacecraft. Given that, the basic problem is obvious: How do you propel this ship forward without killing everyone inside? The solution that Dyson and Taylor came up with was the idea of a pusher plate attached to the ship using a large shock absorber system—a big spring with some sort of damper that nullified the vibrations.

As far as anyone can tell, Orion would work. The exhaust speed is effectively around 10,000 kilometers per second. Freeman Dyson estimated that such a spacecraft could get to speeds approaching 3% of the speed of light. The energy available is so high that you can ignore minimum energy trajectories. Missions that take years with conventional chemical rockets take weeks with an Orion-equipped spacecraft.

- ❏ The problems are social, legal, and environmental. Testing the system would violate the Nuclear Test Ban treaty of 1963, which bans aboveground and space-based testing of nuclear weapons. A mission involving an Orion-style spacecraft would probably violate it as well. Additionally, lifting a spacecraft off Earth on a plume of nuclear bombs is problematic from a public relations viewpoint. However, it remains the only way of achieving speeds approaching the speed of light using technology available today.
- ❏ There's also no way of building a small spacecraft using an Orion drive. Nuclear bombs are so powerful that it is necessary to have a huge mass on the other end of the pusher plate so that the acceleration isn't too high. Another issue concerning Orion is the fact that one would have to manufacture thousands of low-yield nuclear bombs for any mission.

USING FUSION

- ❏ More speculative ideas include fusion-powered spacecraft. Relevant here is the most famous formula in all of physics: $E = mc^2$. That formula is a statement of the energy content of mass. The amount of energy contained in a kilogram of matter is staggering: Because the speed of light is 300 million meters per second, squaring that yields 90,000 trillion joules per kilogram.
- ❏ Unfortunately, there is no easy way to use that energy. We can view the fission and fusion processes as giving up tiny dribbles of all of the energy content in matter. Take the example of a reaction considered for fusion reactors and fusion-powered spacecraft: the fusion of deuterium and tritium into helium.
- ❏ Deuterium and tritium are 2 different isotopes of hydrogen. This means that they have the same atomic number as ordinary hydrogen but different atomic weights. Ordinary hydrogen is a proton plus an electron. Deuterium is a proton, a neutron, and an electron. Tritium is a proton, 2 neutrons, and an electron. All of these are electrically neutral because the neutron itself doesn't carry any charge. The proton carries a plus charge and the electron a minus charge, so they cancel out.



- When a deuterium nucleus fuses with a tritium nucleus, the result is an ordinary helium nucleus (2 protons and 2 neutrons), an extra neutron, and a bit of energy. Roughly speaking, the energy is a bit less than 0.4% of the total mass-energy of the system. If one could harness all of the energy of the reaction, one could build a spacecraft with an exhaust speed of about 8% of the speed of light: 26,000 kilometers per second.
- Unfortunately, no one can build a controllable fusion reactor. Fusion requires enormous temperatures, pressures, and under some configurations, magnetic fields. Despite efforts beginning in the 1950s, scientists have not been able to break even from controlled fusion reactions—that is, they have not been able to get as much energy out as they put in.

THE EXPANSE

- ❏ Fusion is a staple of hard science fiction, both for energy generation and spacecraft propulsion. One example comes from the television show *The Expanse*, which is set in various places in the solar system several hundred years in the future. The main plot of the show concerns the crew of the spaceship *Rocinante*, misfits from various parts of the solar system.
- ❏ The science in *The Expanse* is handled accurately; people on the spacecraft are in free-fall unless they are being accelerated or the ship is rotating to provide artificial gravity. There is no sound in space as well.
- ❏ The spacecraft are fusion powered, using something called the Epstein drive. It is named after the fictional inventor who created it and who died in the process. Fusion is somewhat cleaner than fission power. It also has a much higher exhaust speed. However, it will emit radiation in the form of gamma rays—that is, light particles with much higher energy than X-rays. But if we could build such a spacecraft, the solar system would be ours.

MATTER AND ANTIMATTER

- ❏ As good as fusion is, it uses less than 1% of the potential energy available from matter. The next step is to go all the way: use a spaceship drive that works by taking equal amounts of matter and antimatter and annihilating them into pure energy. This is the theoretical best we can possibly do.
- ❏ Every particle of ordinary matter has a counterpart antimatter particle: one with the same mass but the opposite charge. For example, the electron has a charge of -1 and an extremely tiny mass. The anti-electron, also called the positron, has a charge of $+1$ but exactly the same mass.
- ❏ If we combine them, they can annihilate each other, turning into 2 very high-energy photons whose energy is equal to the mass of the 2 particles times the speed of light squared.

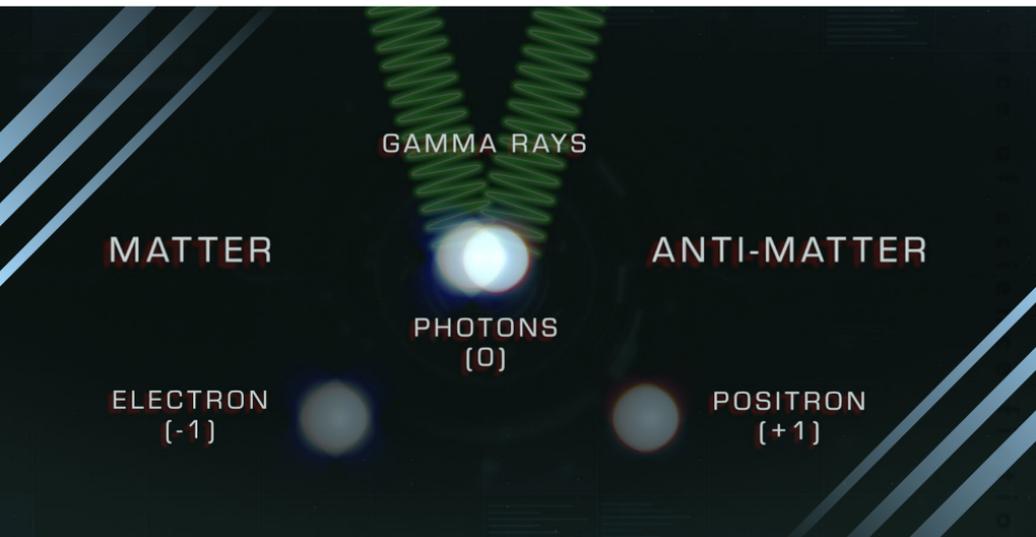
🔧 This raises a question: Why can't we just take an electron and turn it into a high-energy photon? We can't for 2 reasons:

- The straightforward reason is that converting an electron into a photon would violate the law of conservation of charge. The electron has a negative charge, but the photon has no charge. It's a basic principle of physics that in any reaction like converting one particle into another one, the total charge has to stay the same.
- Turning an electron into a photon doesn't work because it would start with -1 charge and end up with a charge of 0 . Another conservation law would be broken as well: lepton number conservation. It works much the same way as charge conservation.
- The more complicated reason is that it would violate the law of conservation of momentum. Photons have to travel at the speed of light. They have a fixed momentum that is always equal to their energy divided by the speed of light. An electron sitting still has no momentum, but because a photon always must have momentum, you can't turn an electron by itself into a photon.
- However, with an electron and an anti-electron turning into a pair of photons, the total momentum is 0 beforehand (if the electrons are standing still). If the photons go off in opposite directions, the total momentum is still 0 afterward.

🔧 Making a starship drive using matter and antimatter is easy in principle: Just arrange for all of the light to go in one direction. The spaceship will move in the other direction. This is because light can exert a push on objects. The push is called radiation pressure.

🔧 Under ordinary circumstances, this force is very weak. However, there is so much light and energy produced by the conversion of matter and antimatter into radiation that the light produced can exert a huge force. One gram of matter annihilating one gram of antimatter in one second produces a push of 180 trillion Newtons—roughly the same energy as the atomic bomb that exploded over Hiroshima.

- ❏ In theory, this is the most effective possible starship drive. There are problems, unfortunately. The first one is that there are no handy sources of antimatter around for us to use.
- ❏ The other problem is radiation. Gamma rays are very high-energy photons, and any matter-antimatter spacecraft is going to spew them out like crazy. In the 1960s, the Nobel laureate physicist Edward Purcell showed that any starship of a reasonable size would spew out enough radiation to sterilize the Earth if it took off from anywhere near the planet.



Suggested Reading/Viewing

Dyson, *Project Orion*.

Star Trek: The Original Series.

RELATIVITY AND *TIME FOR THE STARS*

IN ROBERT HEINLEIN'S NOVEL *TIME FOR THE STARS*, IDENTICAL TWINS TOM AND PAT BARTLETT ARE INDUCTED INTO THE WORLD'S FIRST INTERSTELLAR EXPLORATION PROGRAM BECAUSE THEY CAN COMMUNICATE TELEPATHICALLY WITH EACH OTHER. PAT STAYS AT HOME, RECEIVING INFORMATION ABOUT THE VOYAGE FROM TOM, WHO GOES OUT TO EXPLORE THE STARS. WHEN TOM RETURNS HOME, 60 YEARS HAVE PASSED ON EARTH, AND PAT IS AN OLD MAN. TOM IS STILL IN HIS MID-20S. THIS LECTURE LOOKS AT THE IMPLICATION OF THAT AND OTHER IDEAS.

BACKGROUND ON *TIME FOR THE STARS*

- ❏ The novel was published in 1956, but the science in it stands the test of time. The book is amusing to physicists: It is the living embodiment of the twin paradox of Einstein's special theory of relativity. There are some problems with how it is handled in the book, but Heinlein isn't alone in having misconceptions about relativity. Relativity is difficult to understand.
- ❏ The biggest problem is how Heinlein handles telepathy: In the novel, scientists of the future discover that telepathy exists and that many identical twins can read each other's thoughts. However, the speed of thought is infinite. This allows the twins to send instantaneous messages over interstellar distances. These distances are so large that it takes light years to propagate from star to star. Telepathy also doesn't weaken with distance.
- ❏ Einstein's theory has 2 ideas at its heart. The first is that it is impossible to tell whether you are moving at a constant velocity—that is, at a constant speed and in the same direction—or are standing still. The second is that the speed of light in a vacuum is the same, no matter how you are moving. Another way to put the relativity principle is that all velocities, except for the speed of light, are relative to one another.
- ❏ In a head-on collision of 2 cars moving at 60 kilometers per hour, the relative speed of approach is 120 kilometers per hour. That comes from adding the velocities. But light doesn't work that way. It is always measured as having the speed of light, no matter how fast the source of the light or the receiver of the light is moving. This has been shown in many experiments dating back to the late 1890s.
- ❏ The consequences of these 2 principles are profound, astounding, and to some people, disturbing. Here is one example: If Sam moves past Tammy at close to the speed of light, and are holding clocks, Sam will measure Tammy's clock to tick more slowly than his does. Tammy's time runs more slowly than Sam's, as measured by Sam.
- ❏ The time moves slower by something known as the gamma factor. As one approaches the speed of light, the gamma factor approaches infinity—time becomes infinitely slowed down.

THE GAMMA FACTOR

c = SPEED OF LIGHT

v = SPEED

$$\text{GAMMA} = \frac{1}{\sqrt{1 - v^2/c^2}}$$

IF $v = 10\% c$

GAMMA = 1.006

IF $v = 50\% c$

GAMMA = 1.15

IF $v = 86\% c$

GAMMA = 2.0

SYNCHRONIZING CLOCKS AND REFERENCE FRAMES

-  Albert Einstein's original paper, "On the Electrodynamics of Moving Bodies," has an extended discussion of what it means to synchronize 2 clocks that are separated from each other. In Einstein's day, the accurate measurement of time was vitally important because of the growing network of trains that ran across Europe. It was necessary to make sure that the schedules were accurate across cities separated by hundreds of kilometers of track.
-  Einstein's theoretical method was similar in principle to the electromagnetic means being developed at the time: Read the time on a clock and somehow encode the time onto a signal in a beam of light. Then, send this to a distant friend, who will set his clock to the time on the first clock, minus the time it took the light to get to him. However, Einstein theorized that 2 clocks moving relative to each other would not stay synchronized.
-  Imagine standing on a train platform when suddenly, 2 bolts of lightning hit the ground at the same time a kilometer to the right of you and a kilometer to the left of you. A train is running through the station from the left to the right, passing your position at the same moment when the bolts strike.

- ❏ You see the light from the lightning strikes at the same time because you are at the same distance from them. However, there is a conductor on the train. She sees the flash on the right happen first because the train is running into the light wave from the first lightning strike and away from the one on the left.
- ❏ However, Einstein would posit that you really can't say that the train is moving and the platform standing still. From the conductor's point of view, the lightning strike on the right is first; the one on the left second. Therefore, from her reference frame, the 2 strikes aren't simultaneous.
- ❏ Another train moving in the opposite direction would see the strikes happening in the reverse order. From a philosophical point of view, it doesn't really matter in which order the 2 lightning strikes happen. If the 2 lightning strikes are simultaneous in one particular reference frame, they can't affect each other. You couldn't use one to cause the other one, for example, so it really doesn't matter the order they happen in.

THE TELEPATHY PROBLEM

- ❏ The problem with *Time for the Stars* is that telepathy in the novel happens instantaneously. Unfortunately, there is no way to judge what instantaneous means. Two things that are instantaneous in one reference frame are not in another.
- ❏ In one reference frame, Pat thinks a thought and Tom receives it at the same time, but in another one, Tom receives the thought before Pat thinks it. This doesn't work: There is no way to tell which happens first—the thinking of the thought or the receiving of it. It creates a paradox that can't be resolved under known laws of physics. If a person sends a signal faster than light in one reference frame, in another one, it is being sent into the past.
- ❏ This has tripped up other science fiction writers because of the understandable desire to get around the speed-of-light barrier. The stars are separated by huge distances, and it takes many years to travel between even the closest of them even at speeds close to the speed of light.

THE FASCINATION WITH RELATIVITY

- Science fiction writers have been fascinated by relativity since Einstein thought it up. Poul Anderson thought it important enough that he included a discussion of relativity and the gamma factor in his essay “How to Build a Planet.”
- He also wrote the science fiction novel *Tau Zero*, in which a ship breaks down in such a way that it continually accelerates. It crowds ever and ever closer to the speed of light, until billions of years have passed in the outside universe while only a few have gone by on the ship.
- The ship is powered by a Bussard ramjet, a very speculative type of starship engine that scoops hydrogen out of the interstellar medium and fuses it into helium to power the engine. The idea is attractive because it gets around the problem of payload ratio, though there are other obstacles to surmount, such as the building of a fusion reactor.
- The Larry Niven novel *A World Out of Time* features radical Einsteinian time dilation as a major part of the plot. Jerome Corbell is dying of cancer when he has his body frozen in the hope that future medicine will be able to cure him.
- He awakens with his mind placed into a new body under care of a global, vaguely fascist government that decides to use him as the pilot of a Bussard ramjet. The ramjet will find new worlds and drop packages of genetically engineered bacteria onto them to tailor them into Earth-like worlds.
- Instead of doing this, he steals the ship, pilots it to the galactic core, and orbits the black hole at the center of the Milky Way. He returns to Earth, having undergone about 100 years of ship time while more than 3 million years have elapsed on Earth. Much of the time dilation comes from orbiting close to the black hole.

LENGTH CONTRACTION

- Another interesting effect due to relativity is length contraction. An object moving at speeds approaching that of light contracts in the direction of its motion. This is a real effect, but it appears far more rarely in science fiction than the time dilation effect. This is understandable. To experience the effect, you would need to observe or measure the length of something as it moved relative to you at very high speeds. There are one or some places that it has been used, however.
- Perhaps the first place it was used in literature is in the book *Mr. Tompkins in Wonderland*. This is a series of stories based on fundamental scientific principles by the physicist George Gamow.
- In the first story in the book, Mr. Tompkins, an English bank clerk, is listening to a lecture on relativity and falls asleep, dreaming of a world in which the speed of light is only 10 miles per hour. There he meets a bike messenger, pedaling furiously on his bike, who looks extremely thin and compressed while pedaling but reverts to normal when he stops. The messenger is also younger than his son, an old man, because of all of the time he spends traveling on his bike—another illustration of the twin paradox.

Suggested Reading

Heinlein, *Time for the Stars*.

Taylor and Wheeler, *Spacetime Physics*.

BLACK HOLES, WORMHOLES, AND *INTERSTELLAR*

THE QUESTION OF WHETHER ANYTHING CAN MOVE FASTER THAN THE SPEED OF LIGHT IS A BIG ISSUE IN SCIENCE FICTION. EINSTEIN'S SPECIAL THEORY OF RELATIVITY IMPLIES THAT MOVING FASTER THAN LIGHT IS IMPOSSIBLE. EINSTEIN'S GENERAL THEORY OF RELATIVITY, ON THE OTHER HAND, MIGHT SAY OTHERWISE. THIS IS THE THEORY THAT EINSTEIN INVENTED TO EXPLAIN GRAVITY. THE THEORY PREDICTS BLACK HOLES—OBJECTS SO MASSIVE THAT LIGHT CAN'T ESCAPE FROM THEM. IT ALSO PREDICTS WORMHOLES, WHICH ARE TUNNELS IN SPACE AND TIME THAT MIGHT ALLOW FASTER-THAN-LIGHT TRAVEL OR EVEN TIME TRAVEL. THERE IS NO BETTER STORY TO USE TO DISCUSS THESE TOPICS THAN THE 2014 MOVIE *INTERSTELLAR*.

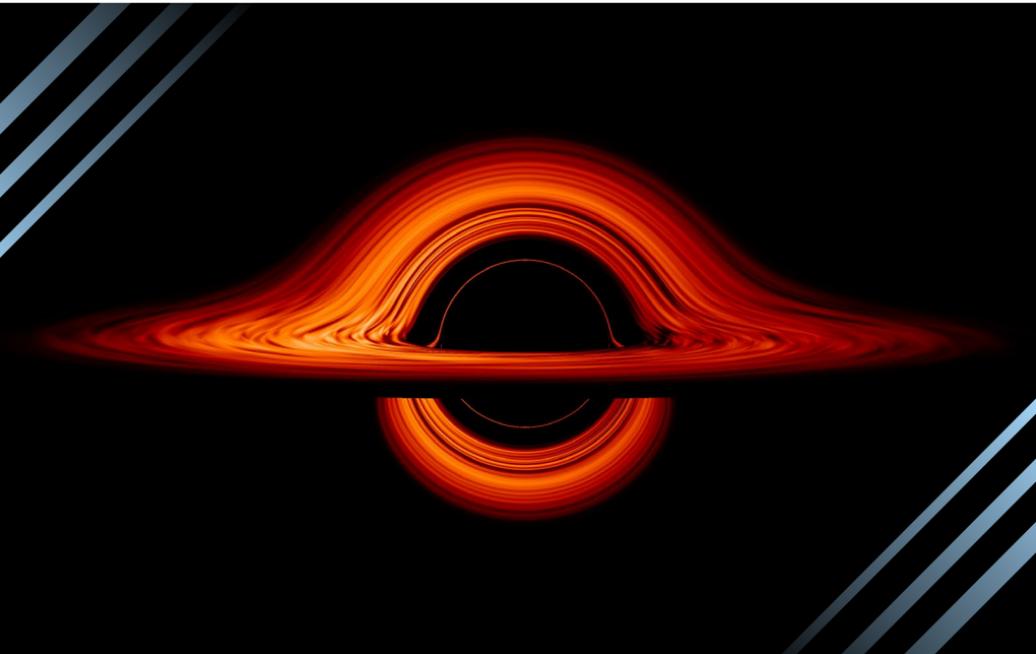
BACKGROUND ON *INTERSTELLAR*

- In *Interstellar*, humanity on Earth is slowly dying off because of a blight that has destroyed much of Earth's crops. Joseph Cooper is the hero of the story. He's a former astronaut who finds a mysterious coded message in the dust on his daughter's floor. The message leads him to a secret government facility trying to save humanity.
- He finds out that a wormhole has opened in the solar system, near Saturn. There are several planets beyond the wormhole that might be suitable for human settlement and survival. They orbit a giant black hole called Gargantua. He joins a mission to explore these planets, and he sacrifices himself by falling into the black hole to allow his fellow astronaut and love interest Amelia Brand to escape.
- When he does this, he finds himself in the mysterious realm of aliens, who are the descendants of humanity. These descendants have somehow created the wormhole. Cooper escapes from the black hole while simultaneously sending the information he needs back into the past to his old self and to his daughter.
- After he escapes, he finds himself back in the solar system. Because of gravitational time dilation caused by the black hole, nearly 70 years have passed on Earth. He meets his aged daughter, now the chief scientist of a project to build a spaceship to allow humanity to survive.

BLACK HOLES

- The black hole as a concept dates back more than 200 years. The physicist and geologist John Michell discussed the idea that there could be stars or planets so massive that light itself couldn't escape from their gravitational attraction.
- Because nothing can travel faster than the speed of light, the so-called radius of the black hole represents a one-way barrier. This barrier is called the event horizon of the black hole; anything passing through it must inevitably fall to the center, where a singularity awaits to crush it and tear it to subatomic particles.

- ❏ Black holes have a number of interesting properties that science fiction writers have exploited since the 1960s. Not coincidentally, the 1960s were also the so-called golden years of black hole research, when physicists began to take the concept of the black hole seriously.
- ❏ It was around that time that it became clear that they almost certainly existed as the end stages of the life cycle of very large stars, and they also probably existed at the centers of most galaxies due to the large density of matter there.
- ❏ Joe Haldeman used collapsars—another name for black holes—for interstellar travel in his novel *The Forever War*. The novel is a description of a war lasting thousands of years with an alien race, the Taurans, as narrated by William Mandella, a soldier in the war from its beginning to its end. This is possible because of extreme relativistic time dilation; while the collapsars allow so-called instantaneous transport from one collapsar to another one, navigation between them happens in real space at speeds very near the speed of light. It is an extreme example of the twin paradox of relativity.



BACKGROUND ON *THE FOREVER WAR*

The Forever War is widely regarded as an antiwar statement by Haldeman, similar in some respects to *Catch-22*. The protagonist is a pacifist drafted into a war that makes no sense to him, and it eventually turns out to be a pointless conflict. It was written during the Vietnam War, and Haldeman himself was a Vietnam veteran.

- Unfortunately, collapsars don't allow faster-than-light travel. Anything or anyone falling past the event horizon of a black hole can never return and is eventually destroyed by it.
- Another effect from black holes is gravitational time dilation. Any planet or star's gravitational field will cause gravitational time dilation, but it is at its most extreme with black holes. Essentially, Einstein's theory not only predicts that clocks slow down when approaching the speed of light but that they also slow down when in a gravitational field.
- On Earth, the clock slowing is a very small effect: A clock on Earth's surface runs approximately 38 microseconds slower per day than one that is outside its gravitational pull. This is a tiny effect, but it is very measurable. It must be taken into account for the Global Positioning System to function correctly. Gravitational time dilation is extreme near the event horizon of a black hole.

GRAVITY EXAMINED

- Einstein's theory of gravity has at its core the idea that gravity is not a force per se, but a warping of space and time. Another feature of the general theory of relativity is gravitational waves. Massive objects that move back and forth in some periodic manner, like massive stars rotating around each other, generate ripples in spacetime.

- These ripples expand out at the speed of light, and they contract and expand matter by tiny amounts as they move through it. Under almost all circumstances, they are very difficult to detect. For example, the gravitational waves produced by 2 supermassive black holes merging together produce ripples that are tiny compared to the size of a proton.
- The detection of gravitational waves was the most exciting scientific news of 2016. A large team of scientists led by groups at MIT and Caltech built 2 gravitational wave detectors over the course of 30 years. These detectors are 4-kilometer-long structures that shine laser beams back and forth over the distance off of super-reflective mirrors. They use a process called interferometry to measure the deflection of the mirrors.
- The gravitational waves that the team announced in 2016 were due to the merger of 2 supermassive black holes. The leaders of the team, including Kip Thorne, won the Nobel Prize in Physics for the discovery.

WORMHOLES

- The bending of space and time by general relativity leads to another concept that is a staple of science fiction: the wormhole as used for faster-than-light travel. There is one key difference between black holes and wormholes: Scientists know that black holes exist, while wormholes are pure speculation.
- Wormholes are mathematical solutions of the equations of general relativity, but no one has ever found one. Much research has gone into finding out whether or not they could exist.
- In its original incarnation by Einstein, a wormhole was an attempt to solve one of the big problems in physics: What is an elementary particle? Einstein was looking for a unified field theory—that is, a theory that combined his theory of gravitation with electromagnetism. He was unsuccessful, but any successful theory had to account for the particles of physics, which in that time were the proton, neutron, electron and photon. (Today, many others are known.)

- ✚ Einstein and his assistant, Nathan Rosen, found a solution of his general theory of relativity that acted in many ways like a particle did. It was a tunnel connecting 2 different regions of spacetime that acted as if it had mass, and in some configurations, electrical charge. Unfortunately, it didn't work with quantum mechanics very well.
- ✚ An example of wormholes in science fiction is the TV show *Star Trek: Deep Space Nine*. In the show, the space station Deep Space Nine sits near the mouth of a wormhole that can be used for transport to the Gamma Quadrant, a distant region of the galaxy.

THE ALCUBIERRE WARP DRIVE

- ✚ Apart from wormholes, physicists have proposed other means of traveling faster than the speed of light. The Alcubierre warp drive is one of the best-known examples.
- ✚ Physicist Miguel Alcubierre found a solution of the equations of general relativity that seemed to generate a so-called bubble around a spaceship that stretched space behind it and shortened space in front of it. The ship itself is not accelerated, but in some sense, the spacetime around it is.
- ✚ This is an important point: The theory of relativity doesn't allow any material objects within space to travel faster than the speed of light. However, it does allow space itself to expand faster than light. This is what seems to have happened just after the big bang, during the inflationary phase of the expansion.
- ✚ The spacetime geometry of the Alcubierre warp drive is very odd. The people on the ship can't see anything behind them because light can't catch up with the ship. In a similar manner, people ahead of the ship can't see it coming because the ship outruns the photons that it emits. This is in some ways similar to the event horizon of a black hole.

- Another problem is that the ship is not causally connected to the outside universe: It's impossible to create the warp from inside the ship. Another physicist named Serguei Krasnikov constructed a version of the warp drive, the Krasnikov tube, that got around this problem.

CONCLUSION

- At our current state of technology, the actual creation of wormholes for interstellar travel seems a practical impossibility. However, Kip Thorne pointed out that even though they seem impossible to build, whether or not it is theoretically possible is another matter.
- He called such a problem a Sagan problem, referencing his discussions with Carl Sagan concerning their possibility. At the moment, whether they are possible or not hinges on 2 things: Is it possible to get a sufficient quantity of exotic matter together to build them? And do quantum mechanical effects destroy them as soon as they are created?
- The second problem came about because physicists discovered that any means of faster-than-light travel can also be used for time travel into the past. They found that the universe seems to conspire to destroy any time machines as they are being built.

Suggested Reading/Viewing

Nolan, dir., *Interstellar*.

Thorne, *Black Holes and Time Warps*.

———, *The Science of Interstellar*.

QUIZ

- 1 People in the International Space Station (ISS) feel no “gravity” because:
 - a The ISS is continually falling around the Earth.
 - b The ISS is outside of the range of Earth’s gravity.
 - c The gravity of the Earth balances the gravity of the Moon in its orbit.
 - d The gravity of the Earth balances the gravity of the Sun in its orbit.
- 2 True or false: Most of the mass of a rocket capable of reaching orbit or beyond will be fuel.
- 3 The farthest any human has been from Earth is:
 - a The Moon.
 - b Mars.
 - c Pluto.
 - d The Alpha Centauri star system.
- 4 True or false: Un-crewed spacecraft typically use gravity maneuvers to reach distant planets in the solar system.
- 5 True or false: Wings are useful on spacecraft that don’t move through an atmosphere.

- 6 A geostationary spacecraft stays above the same point on Earth because:
- a Force fields keep it in place.
 - b Its orbit's period matches the period of revolution of the Earth around the Sun.
 - c Its orbit's period matches the period of rotation of the Earth around its own axis.
 - d Both B and C.
- 7 True or false: If we could manufacture enough of it, antimatter could be a useful fuel for spacecraft.
- 8 The limits on the exhaust speed of the NERVA nuclear propulsion system investigated by NASA in the 1960's is mainly due to:
- a The size of the nuclear bombs used for propulsion.
 - b The melting temperature of the material the reactor is made from.
 - c The availability of hydrogen for the reaction mass.
 - d All of the above.
- 9 At 86% of the speed of light, Einstein's gamma factor is:
- a 1
 - b 1.15
 - c 2
 - d 10
 - e Infinity

- 10** As you get closer and closer to the speed of light, Einstein's gamma factor approaches:
- a** 1.
 - b** 1.15.
 - c** 2.
 - d** 10.
 - e** Infinity.
- 11** Black holes:
- a** Really exist.
 - b** Are so massive that light cannot escape from them once it passes the event horizon.
 - c** Slow down time as objects approach the event horizon.
 - d** All of the above.
- 12** True or false: The effects of relativity are too small to affect how the Global Positioning System functions.

ANSWERS

1 a; 2 true; 3 a; 4 true; 5 false; 6 c; 7 true; 8 b; 9 c; 10 e; 11 d; 12 false

TIME TRAVEL AND *DOCTOR WHO*

TIME TRAVEL INTO THE PAST IS CLOSELY RELATED TO TRAVELING FASTER THAN LIGHT: IF ONE IS POSSIBLE, THEN THE OTHER IS AS WELL. HOWEVER, IT APPEARS THAT ODD THINGS WILL HAPPEN IF ONE TRAVELS BACK TO THE PAST.

THE TIME MACHINE

One of the first science fiction novels of the modern age is *The Time Machine* by H. G. Wells. In the novel, the unnamed protagonist invents a machine that can carry him into the past or future. He uses it to explore the far future, millions of years from now, when the world is divided into gentle Eloi and brutish Morlocks. He returns to the present to tell his friends over dinner about his exploits and then vanishes forever, perhaps exploring some remote region of the past or future.

Wells's unnamed protagonist refers to time as a fourth dimension. Dimensions are intimately connected with position in space. For example, think about the surface of the Earth. To locate something on the Earth, we need 3 numbers: a north-south coordinate, an east-west coordinate, and an up-down coordinate. To specify the when, however, a fourth coordinate is necessary: time. Here is an example of the 4 dimensions being used in a sentence to identify a specific place at a specific time:

At noon on May 1, 2020, meet me on the 57th floor
of the Wells Building, which is at the corner of First
Avenue and Ninth Street.

Wells's traveler uses the machine mainly to explore the future. Both the special and general theory of relativity allow for time travel into the far future. Unfortunately, there is no way to return to the past.

The central character of Wells's novel does travel back to the past to return to his original time, but the novel ignores many of the interesting aspects that time travel to the past would involve. Time travel into the past can snarl up the relation between cause and effect and potentially create logical paradoxes that are not easy to resolve.

“BLINK” FROM *DOCTOR WHO*

- ❏ *Doctor Who* is the longest running science fiction TV series ever. It features the Doctor, a time lord from the planet Gallifrey, who travels the universe and its timeline in the TARDIS. The TARDIS is a machine capable of going essentially anywhere and any time.
- ❏ “Blink” is the 10th episode of the third series in the new incarnation of *Doctor Who*. It is universally acclaimed for its plot and sense of horror. It also illustrates wonderfully the problems involving cause and effect that time travel into the past cause.
- ❏ The plot is intricate, and the issue in “Blink” is one of information: In the episode, the character Sally receives a DVD from the Doctor. However, Sally somehow supplies transcript of his words to him before he speaks them. It is as if the information appeared from thin air somehow. Cause and effect are all snarled up. Serguei Krasnikov, a Russian physicist who has studied the physics of time travel, has discussed this in a paper, where he refers to this as a bootstrap paradox.
- ❏ The other type of paradox due to time travel is known as the grandfather paradox, in which a person goes back in time and kills his or her grandfather before his children are born. This is a true logical paradox in that the time traveler has removed the time traveler’s cause of existence, which in turn removes the grandfather’s killer.

MAKING A TIME MACHINE

- ❏ This lecture now turns to the question of whether time machines can possibly exist. The current scientific interest in time travel resulted from research on traversable wormholes for faster-than-light travel in the 1990s. Kip Thorne and his students realized that one could convert a wormhole into a time machine by ensuring that time ran differently at each of the different mouths of the wormhole, something allowed by the theory of relativity.

- ❏ Kip Thorne's original method for turning a wormhole into a time machine was to use the twin paradox. This would involve moving one of the mouths of the wormhole away from the other mouth at nearly the speed of light, then returning it. While there may not be any fundamental reasons that this couldn't work, it's hard to imagine moving the 2 mouths in this way.
- ❏ The other way to do it is to use gravitational time dilation. This would require a pocket-sized black hole. It's possible that such miniature-sized black holes exist, but it's not very likely.
- ❏ There are other ways to make a time machine using general relativity. Kurt Gödel, an Austrian mathematician and friend of Albert Einstein, showed that if one had a universe that rotated around a central axis, one could find trajectories that would go into the past.
- ❏ Many ideas concerning time machines involve rotation. If a spacetime rotates around some central axis, things are dragged along by the spacetime: They move faster the farther the distance from the axis, and at some point, they are dragged faster than the speed of light. Faster-than-light motion always implies time travel under appropriate conditions.
- ❏ Our universe doesn't look like this. It is expanding, not rotating. However, Frank Tipler showed that an infinitely long, massive cylinder could do the same thing if it rotated fast enough.

TIME TRAVEL PARADOXES

- ❏ To examine the grandfather paradox, one technique researchers used was to take the human element out of the grandfather paradox. They tried to look for simple physics situations that would embody the paradox, and they found them.
- ❏ For instance, Thorne realized that wormholes presented a problem to the laws of Newton in that they allowed multiple trajectories for particles traveling through the same region of space. Time machines break down the predictive power of Newton's laws.

- There are an infinite number of possible paths for particles to take if one has time machines, and there doesn't seem to be any way to specify which trajectory a particle will take. This is exactly a paradox, but it is very strange.
- One way out of the grandfather paradox is the idea of multiple possible timelines. This is the idea that if a man goes back and kills his grandfather, the timeline splits off and leads to a new one in which the killer does not exist in the future.

NONEXISTENCE OF TIME MACHINE

- Another possibility is that time machines can't exist. This is not a very interesting statement on its own; however, the way the way time machines might be impossible is interesting.
- The general theory of relativity is a classical theory. This means that it doesn't include quantum effects—the theory of matter on the atomic or smaller scales. That, in turn, means that in some ways, it must be wrong: Quantum mechanics is how the universe works. But no one really knows how to merge quantum with gravity.
- However, in the 1970s, Stephen Hawking made a first attempt at this. His theory isn't good in extreme situations, like near the center of a black hole, but it works for places where gravity isn't too extreme. His theory seems to indicate that if one tries to build a time machine, the universe will stop the effort.
- This isn't a new idea, at least to science fiction writers. Larry Niven, for one, based a science fiction short story around this idea. The story is "Rotating Cylinders and the Possibility of Global Causality Violation." (This was also the title of the 1974 scientific paper by the physicist Frank Tipler about using a long, rapidly rotating cylinder for time travel.)
- In the story, a mathematician suggests that a cylinder built by an alien race is a prototype for a time machine, but the aliens died off trying to create it. He realizes that the universe protects itself from time travel paradoxes by

destroying those species that try to build time machines. His planet is in a war against another one, so he suggests to the ruler of his planet that they leak the idea of using the device as a time machine to the enemy to get the universe to destroy them. The plan backfires when his own sun goes nova in response to his meddling.

✚ In reality, the way in which the universe seems to destroy time machines is more prosaic. Relevant here is the Casimir effect, in which quantum effects due to the energy of the vacuum create an attraction between 2 metal plates. It's a form of exotic matter, and exotic matter is needed to create any faster-than-light drive or time machine. However, Kip Thorne and Hawking found that these same quantum fluctuations seem to build up to a point where they destroy the wormhole when the mouths get close enough to turn it into a time machine.

✚ There's no easy way to explain this. The problem seems to be akin to the Casimir effect: As the plates get closer together, the Casimir effect grows to infinity. In some sense, a wormhole time machine's mouths are separated by no distance, at least as seen by some observers. The calculations are difficult, so the question is still open, but most physicists think that quantum effects will kill off any attempt to build a time machine.

Suggested Reading/Viewing

Adams, *The Restaurant at the End of The Universe*.

"Blink" (episode of *Doctor Who*).

Carruth, dir., *Primer*.

Niven, "Exercise in Speculation: The Theory and Practice of Time Travel."

———, "Rotating Cylinders and the Possibility of Global Causality Violation."

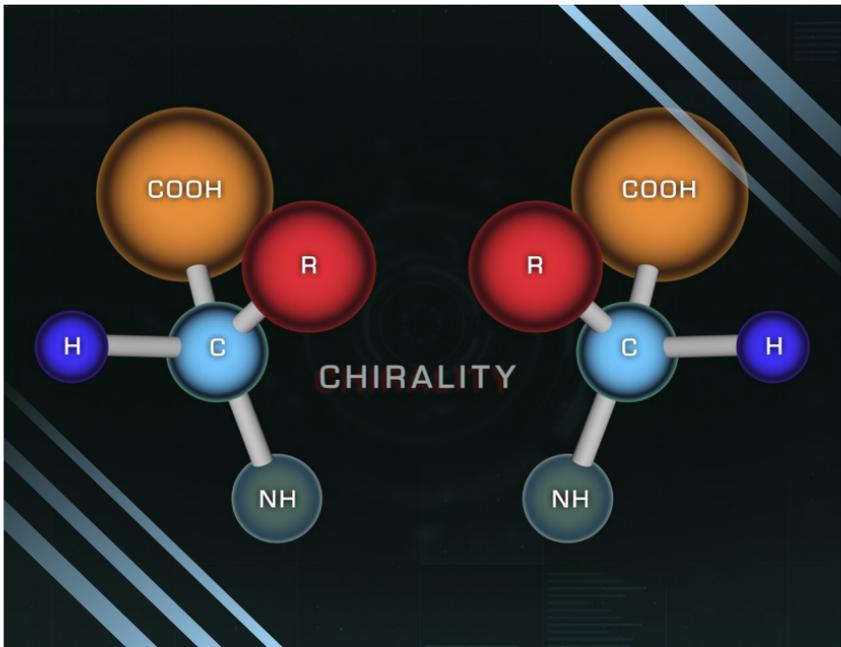
Tipler, "Rotating Cylinders and the Possibility of Global Causality Violation."

TELEPORTATION AND *STAR TREK*

TELEPORTATION IS THE MORE-OR-LESS INSTANTANEOUS TRANSPORTATION ACROSS SOME DISTANCE WITHOUT CROSSING THE INTERVENING SPACE. THE MOST COMMON USAGE OF THIS IN MODERN CULTURE IS IN THE *STAR TREK* UNIVERSE, WHERE THESE DEVICES ARE CALLED TRANSPORTERS. THIS LECTURE EXAMINES TELEPORTATION AS IT IS TREATED BY *STAR TREK* AND OTHER WORKS.

SPOCK MUST DIE!

- One of the very first *Star Trek* novels brought up a fascinating moral dilemma concerning the transporter. The novel is *Spock Must Die!* It raises interesting questions: Does the transportee die because of the transportation event? Is the one at the far end not the same person? And how can we tell, if the one who is transported has the same memories and feelings as the one who went in?
- One of the other features of the novel is a transporter accident that creates a duplicate Spock who is a mirror image of the original—that is, if the original was right-handed, the mirror Spock is left-handed. Any distinguishing features are moved to the opposite side. It becomes problematic because the nature of the DNA and proteins in his body prevent him from digesting normal food.



JAUNTING

- ✚ There are other problems associated with teleportation that science fiction writers have explored. Alfred Bester’s novel *The Stars My Destination* is a rewrite of *The Count of Monte Cristo*, set in a future where almost everyone in the world has the psychic ability to teleport. It’s called jaunting in the novel.
- ✚ This book makes the excellent point that teleporters make wonderful tools for theft. One can use a transporter to steal essentially anything from anywhere, free any criminal from any jail cell, and kidnap anyone.
- ✚ This is an example of an age-old ethical question, sometimes called the ring of Gyges problem. According to Plato, the ring of Gyges gave its wearers invisibility. The ethical question was whether the mass of people, given such a ring, would use it to commit crime.
- ✚ The problem is addressed in the movie *Jumper*, where specially gifted people can teleport using some sort of psychic ability. The “hero” of the movie uses his abilities to enrich himself at the expense of society by jumping into bank vaults and lightening their contents.

METHODS OF TELEPORTATION

- ✚ As for the actual method of teleportation, there are 2 ways that are commonly used in stories (apart from magic):
 - 1 The brute-force option—that is, vaporize the object into pure energy, send it elsewhere, and reconstruct it.
 - 2 Bend and fold spacetime, make a hole through it, and send the object through.
- ✚ Any means of teleportation via the brute-force option has to involve concepts from quantum physics, the rules of how the universe works on its smallest scale. This method, which is the way that *Star Trek* seems to do it, seems impossible. It is unclear how to turn an object into pure energy, and it would take incredible amounts of information to reconstruct objects on an atomic level.

There was a study commissioned for the US government exploring the feasibility of teleportation. Its author, Dr. Eric Davis, has pessimistic ideas concerning the amount of processing power needed and the amount of time it would take to do the calculations required for teleportation, although he speculates that a quantum computer could solve the problem in a much faster time.

THE ROLE OF QUANTUM MECHANICS

Quantum mechanics is a theory of how the universe works on the atomic or subatomic scale. Quantum mechanics involves the probability of an atom having a certain energy or position, or being at a certain point.

Quantum states are involved in the relationship between teleportation and quantum mechanics. An electron has a property called spin that can point in one of 2 different directions: up or down. However, much of the time, the electron won't be either up or down, but it will be in a state in which it could be either.

According to the current interpretation of quantum mechanics, the electron isn't in either state until we measure it; instead, we say it is in a superposition of the 2 states—that is, a combination of them.

One can't duplicate a quantum state, but one can teleport it. This is not teleporting the actual particle; instead, one can teleport the information needed to recreate the quantum state in a new particle.

Physicists have been able to do quantum teleportation on simple atoms and molecules in the laboratory. They have also achieved it with photons, particles of light. This isn't exactly the same as classical teleportation—they are transmitting information rather than atoms—but it's close. After all, the information about the system is typically what's important.

CONSERVATION LAWS

- ❏ The science fiction writer Larry Niven wrote a fascinating essay called “Exercise in Speculation: The Theory and Practice of Teleportation.” The essay was based on a lecture he gave in 1969.
- ❏ One part of the lecture was dedicated to the question of teleportation and the conservation of energy and momentum. For example, if Sarah is teleporting from the *Enterprise* down to a planetary surface, Sarah is losing a lot of energy.
- ❏ The *Enterprise* is in orbit high above the planet, sitting high in the gravitational potential well. It’s also traveling at several kilometers per second, much faster than the planet rotates about its axis. This means that when Sarah is in the *Enterprise*, her body has a high amount of energy due to its position and how fast it is moving.
- ❏ When Sarah teleports down, she loses both forms of energy: Gravitational energy decreases because she is teleporting downward, and kinetic energy decreases because she is slowing down. But energy is conserved, so the excess has to come out somewhere else.

ERROR RATES

In teleportation, the issue of error rates is an important one. There are errors involved in any sort of copying process. Computer scientists invented error-correcting codes to handle problems like this in data transmission. The question is: How much error is tolerable in a hypothetical copied human?

For instance, an error in a single chromosome can change the color of a fly’s eyes. What happens when teleportation changes a few percent of someone’s DNA?

- ❏ Niven speculated that it would emerge in the form of heat, randomized energy. This is a lot of energy: enough to boil a person alive if something isn't done about it.
- ❏ The other conservation law is the conservation of momentum. Niven asked the question: If a person teleported from a speeding car to the sidewalk, would the person keep the car's speed? The answer is probably yes, because relativity doesn't really allow anything else to happen (if teleportation is possible in the first place).

REPLICATION

- ❏ This lecture now considers the issue of replication minus the teleportation aspect of it. Rather than teleporting an object by building it up from the atomic scale, the idea is to send the instructions on how to build someone, or something, at the speed of light and build the person or object up at the other end, using more normal processes. This is 3-D printing.
- ❏ We currently live in a world in which it is cheaper to manufacture goods at central locations. To these central locations, we ship raw materials, and from them, we ship the finished goods. That paradigm is possible because of today's cheap cost of energy.
- ❏ However, there are some goods which are much more cost effective to send as information. An example is the downloading of TV shows and movies versus relying on DVDs.
- ❏ As for more tangible goods, it currently costs a few cents per ton per mile to ship items, but we live in an age when such energy costs are very cheap because of the accessibility of fossil fuels. As we use those resources up, such costs will almost certainly rise.
- ❏ This raises a question: As 3-D printing technology gets better and as energy costs rise, does there come a point where more tangible goods are cheaper to manufacture at home? Science fiction writers have envisaged such a situation.

❏ The short stories in George O. Smith's Venus Equilateral series envisage a world in which essentially anything, including people, can be duplicated for essentially no cost. However, the invention caused that universe's financial system to collapse for a few reasons:

- It became possible to duplicate money perfectly. This caused a flood of counterfeit bills that undermined the world's currency. Eventually, a solution is found: a material that explodes when people attempt to duplicate it, which is used as the basis of the new currency.
- Another problem is that a large segment of the transportation economy collapsed because of home manufacturing using the duplicators.

❏ More recent science fiction authors have used the concept of nanotechnology for replicators. The novel *Queen of Angels* by Greg Bear features the world of 2047. By then, nanotechnology is a fundamental aspect of life. The home use of nanotechnology isn't a big part of the novel, but it is clear that most cooking and many of the home's comforts are created using individual nanotech replicators.

Suggested Reading

Blish, *Spock Must Die!*

Niven, "Exercise in Speculation: The Theory and Practice of Teleportation."

CYBERSPACE AND THE SINGULARITY: *NEUROMANCER*

THE FOLLOWING ARE ISAAC ASIMOV'S FAMOUS 3 LAWS OF ROBOTICS:

THE FIRST LAW: A ROBOT MAY NOT INJURE A HUMAN BEING OR, THROUGH INACTION, ALLOW A HUMAN BEING TO COME TO HARM.

THE SECOND LAW: A ROBOT MUST OBEY ORDERS GIVEN IT BY HUMAN BEINGS EXCEPT WHERE SUCH ORDERS WOULD CONFLICT WITH THE FIRST LAW.

THE THIRD LAW: A ROBOT MUST PROTECT ITS OWN EXISTENCE AS LONG AS SUCH PROTECTION DOES NOT CONFLICT WITH THE FIRST OR SECOND LAW.

WITH THESE LAWS INSTALLED, THE ROBOT THREAT IS NEUTRALIZED: THEY CANNOT GO ON A RAMPAGE AGAINST HUMANITY. BUT HOW LIKELY IS IT THAT WE WILL NEED THESE PROTECTIONS? HOW FAR ARE WE FROM TRUE ARTIFICIAL INTELLIGENCE (AI)? QUESTIONS LIKE THOSE ARE VERY DIFFICULT TO ANSWER.

R.U.R.

- In some recent works, the emphasis is on creating artificial life to serve humanity as slaves. The play *R.U.R.*, standing for Rossum's Universal Robots, was the first work of this kind, and it also introduced the word *robot* for such creatures. Karel Čapek, the author of the play, adopted the term from a Czech word for *laborer* to describe the beings manufactured by the company, and the designation stuck.
- The robots of the play are truly slaves. They are designed to have no emotions, desires, or free will. Ultimately, the robots develop these and rebel, killing off most of humanity. However, they have no future themselves because the formula used to create them is destroyed by Helena, the lead human female character. The play ends on a somewhat upbeat note as 2 of the robots develop feelings for each other. They are implied to be the new Adam and Eve of a robot version of humanity.
- The robots in *R.U.R.* are not metallic. Instead, they are grown from biological processes in vats. Čapek was prescient: In 2020, scientists from Tufts University, Harvard, and the University of Vermont created xenobots, which are tiny robots made from African clawed frog stem cells.

XENOBOT



NEUROMANCER

🔗 The robots-as-slave trope is prevalent, but there are other types of AI stories. In 1984, William Gibson wrote *Neuromancer*, probably the most influential cyberpunk novel ever. It concerns the exploits of a small-time hacker named Case who is coerced by an artificial intelligence, Wintermute, to liberate another artificial intelligence, the Neuromancer of the title.

🔗 The novel is remarkable for several reasons:

- It introduced the term *cyberspace* into common usage. In the novel, people can link their brains directly into cyberspace.
- While not the first cyberpunk novel, it is the archetype of the form, showing a slightly seedy, computer-dominated, not-quite-dystopian future.
- It represents a turning point in science fiction: While the action of the novel centers on the problems of artificial intelligence, it also has a number of hard science fiction tropes as well, including cheap space travel, space colonies, and flying cars.

🔗 The artificial intelligences of the book, Wintermute and Neuromancer, are neither friends nor enemies of humanity, although Wintermute is willing to break human laws. This includes blackmailing Case and murdering government agents trying to stop him.

THE PROBLEM OF SELF-AWARENESS

🔗 We have yet to achieve true AI. Primarily, this is because no one truly knows what intelligence means. This is the problem of self-awareness—that is, researchers in AI do not seem to agree on what self-awareness means. Here is an example of the scope of this problem: A 2009 paper on artificial intelligence lists no less than 28 distinct models of consciousness. These models define the approaches that researchers use to try to achieve artificial intelligence.

- Some researchers feel that artificial intelligences will evolve naturally, as from computer viruses let loose on the internet, evolving somehow by an analog to Darwinian selection and becoming ever more complicated and sophisticated. George Dyson, a historian of science and the son of the eminent physicist Freeman Dyson, has advanced this idea.
- The Adolescence of P-1*, written in 1977 by Thomas J. Ryan, is the first story using this idea. P-1, standing for privileged one, is a computer program written by Greg Burgess, a computer prodigy, who designs the program to protect itself by modifying its own code and to become ever larger and more sophisticated. P-1 eventually becomes self-aware and seeks out its creator.
- In *Erewhon*, Samuel Butler envisioned a fate in which machines would domesticate humanity and perhaps increase its overall standard of living and happiness, but the machines would keep us in a subservient position. This idea has been used in more recent science fiction, notably in the Culture novels of Iain Banks. In these novels, the Culture, a vast, galaxy-spanning civilization of many alien races, is controlled by Minds, artificial intelligences housed in giant starships.

THE SCIENCE BEHIND AI

- Most science fiction assumes that the human mind can be simulated or reproduced using some sort of digital computer. This idea's most famous expositor was Alan Turing, the British mathematician who was one of the code breakers at Bletchley Park in World War II.
- One of his achievements during the war was designing electronic machines that helped break the German Enigma machine ciphers. Turing is known in mathematical circles as one of the originators of the Church-Turing thesis. This is the hypothesis that any calculable mathematical function can be calculated on a Turing machine—that is, Turing's mathematical model of a computer. The Turing machine is a theoretical construct, but it has been shown that any digital computer can be thought of as a Turing machine.

- ❏ The idea here is that in principle, anything the brain can do is representable by some sort of function. For example, on the most basic level, how neurons work is representable by a number of different mathematical models. Neurons—the cells in the brain presumably responsible for thought—are interconnected by small gaps.
- ❏ Neurons interact by firing electrical impulses across the gaps. They are stimulated by other neurons connected to them. Whether or not they fire is determined by the number and strength of signals they receive from other neurons.
- ❏ The earliest mathematical model was put together by Alan Hodgkin and Andrew Huxley. It is based on modeling neurons as types of electrical circuit elements: batteries and capacitors. It uses calculus and is complicated, but later researchers put together simpler mathematical models to show how neurons work.
- ❏ One of the most commonly used models is to simply take the inputs to a neuron and add them all up. If the inputs sum to larger than a certain threshold, the neuron fires; and if not, it doesn't.
- ❏ This type of model is used in building neural networks, which are computational structures that try to mimic how the brain works on its most basic level. Neural nets are commonplace in science fiction. In *Star Trek: The Next Generation*, the android Data has neural networks mimicking how the human brain works.
- ❏ Relevant to this discussion is the philosophical problem of qualia. The term *qualia* refers to the subjective nature of thought. Neuroscientists can map out how neurons behave when stimulated by our senses, but no one knows how these are turned into sensations in our head.
- ❏ This problem plagues the entire field of artificial intelligence. Most people who study either human consciousness or artificial intelligence punt this problem down the road because it is just too hard to deal with. Both Alan Turing and the researcher Francis Crick refused to define self-awareness when looking into the problem of machine intelligence and human intelligence, respectively.

THE TECHNOLOGICAL SINGULARITY

- ❏ In 1993, the science fiction writer Vernor Vinge wrote a paper called “The Coming Technological Singularity: How to Survive in the Post-Human Era.” In it, he argued that the development of artificial intelligence would lead to the rapid increase of such intelligence beyond any human bound or comprehension.
- ❏ Vinge postulated exponentially smarter machines. He thought that this would lead to a world fundamentally different than ours. He claimed that the change would be “comparable to the rise of human life on Earth.” The worry is that humanity would be left in the dust. This is why such eminent people as Steven Hawking and Elon Musk have cautioned against too much progress in AI research.
- ❏ The science fiction writer Greg Bear used a biological version of the singularity in his 1985 book *Blood Music*. In the novel, a biotechnologist invents biological nanocomputers based on the cells in his immune system. They initially infect him, and then spread through the world. They end up transforming the planet into a vast, linked, conscious ecosystem.
- ❏ *The Quantum Thief* and its sequels also take place in a post-singularity solar system. These novels are written by Hannu Rajaniemi. The novels are set several hundred years in the future, or perhaps even farther. Artificial intelligence is common and is routinely used to augment the human mind and memory.
- ❏ The novels are complex and use cutting-edge work in the quantum theory of information. Rajaniemi doesn’t tell his readers much about the future society; they have to piece it together on their own. The societies are constructed in a steampunk style—they deliberately reference older ideas and novels, particularly old detective novels from the 1920s.
- ❏ The novels play with the concept of consciousness, memory, and individuality in a number of ways. For example, on Mars, when someone sends someone else information, the information is planted into the receiver’s brain as a memory. Telling real from imagined memories is a challenge in this world.

Suggested Reading/Viewing

Battlestar Galactica.

Čapek, *R.U.R.*

Gibson, *Neuromancer.*

Hofstadter, *Gödel, Escher, Bach.*

Jacques, *Questionable Content.*

“The Measure of a Man” (episode of *Star Trek: The Next Generation*).

STEAMPUNK SCIENCE AND *LEVIATHAN*

THIS LECTURE USES THE *LEVIATHAN* SERIES TO EXAMINE THE SCIENCE USED IN MANY STEAMPUNK NOVELS. PARTICULARLY, IT FOCUSES ON STEAM-POWERED AUTOMATA AND THE SCIENCE BEHIND LIGHTER-THAN-AIR FLIGHT—THAT IS, DIRIGIBLES, WHICH FIND THEIR WAY QUITE OFTEN INTO SUCH STORIES. THE *LEVIATHAN* SERIES BEGINS THUSLY: IN THE YEAR 1914, THE AUSTRO-HUNGARIAN ARCHDUKE FRANZ FERDINAND AND HIS WIFE WERE ASSASSINATED, AND EUROPE WAS ON THE BRINK OF WAR. THE DUKE'S SON, 16-YEAR-OLD ALEKSANDAR VON HOHENBERG, HAS BEEN SPIRITED AWAY TO SAFETY IN A GIANT MAN-SHAPED WALKER, POWERED BY DIESEL-POWERED STEAM GENERATORS!

MEANWHILE, IN ENGLAND, 16-YEAR-OLD DERYN SHARP HAS DISGUISED HERSELF AS A MAN TO JOIN THE BRITISH AIR SERVICE. SHE CALLS HERSELF DYLAN SHARP, AND AFTER VARIOUS MISADVENTURES, SHE FINDS HERSELF A MIDSHIPMAN ON THE BRITISH FLAGSHIP *LEVIATHAN*. THE *LEVIATHAN* IS A GIANT, HYDROGEN-FILLED, GENETICALLY ENGINEERED WHALE USED AS A DIRIGIBLE.

BACKGROUND ON THE SERIES

- ❏ The *Leviathan* series is a trilogy of young adult steampunk novels by Scott Westerfeld. The novels, *Leviathan*, *Behemoth*, and *Goliath*, span the years 1914 through 1916 in an alternate history version of World War I.
- ❏ In this context, the term *steampunk* implies an alternate history set in the Victorian or Edwardian eras—that is, from about 1840 to 1910—with the technology of the time taken down different roads than it developed in the real world. Prominent elements include steam-powered robots and computers, dirigibles using lighter-than-air flight rather than airplanes, and similar Victorian-flavored imaginary technologies.
- ❏ The *Leviathan* series falls outside mainstream steampunk. It takes place later than most such works: at the outbreak of the First World War. It also involves genetic engineering, which isn't so common in this genre.
- ❏ Westerfeld creates a very detailed world that includes a number of well-known historical figures from the real world. These include the inventor Nikola Tesla, the revolutionary Pancho Villa, and the publishing magnate William Randolph Hearst. Westerfeld researched the time period well. This lends a sense of realism to the novels. He pays attention to detail and makes everything seem very plausible.

THE *LEVIATHAN* ITSELF

- ❏ The *Leviathan* is essentially a giant floating whale used as an airborne warship. Beyond being a whale, though, it represents an entire ecology of different genetically engineered animals that make up the fighting machine. The human crew is part of that ecology, and the British Darwinists look down on the soulless machines of the German and Austro-Hungarian clankers.
- ❏ The *Leviathan* is the pinnacle of their genetic engineering prowess. It has symbiotic bacteria in its guts that generate the hydrogen used for lift. It has also been genetically engineered to have hollow, lightweight bones, similar to bird bones, to minimize its weight, plus a host of other adaptations to allow people to move around inside it.



- ❏ How does the *Leviathan* float? The answer to that involves a story that starts with the Greek mathematician Archimedes. It has to do with the forces in fluids. A fluid in the physics sense is a liquid or a gas: anything that has no fixed shape.
- ❏ Imagine a child at the beach, playing around in the ocean. The child pushes a beach ball under the water. The water pushes back, and it pushes back harder as more of the beach ball goes under the water. This is called Archimedes's principle.
- ❏ The force pushing back is equal to the weight of the water that is being pushed aside by the beach ball. Water has a weight of about 8 pounds per gallon. The volume of a beach ball 4 feet in diameter can be more than 250 gallons. This means that if it is pushed completely under the water, the buoyant force pushing it out is more than a ton.
- ❏ Air acts the same way: The same beach ball in air will have an upward force on it equal to the weight of the air that it displaces. We don't notice this for 2 reasons: First, the density of the atmosphere is 1000 times smaller than the density of water, so the force is 1000 times smaller. Second, the beach ball is filled with air, which has the same weight as the air displaced by it, so there is no net force.
- ❏ There are 2 forces acting on the item: weight pointing down and the buoyant force—the lift—pointing up. The total weight of the beach ball is the weight of the plastic plus the weight of the air inside it. The buoyant force is the weight of the air displaced by blowing it up, which is approximately equal to the weight of the air inside it, so the weight of the air and the lift cancel out.

They will not cancel out, however, if we replace the air inside with another gas that weighs less. Air is oxygen and nitrogen. A cubic meter of air has a mass of roughly 1.2 kilograms, which is 1000 times less than the same amount of water. The same cubic meter of hydrogen gas has a mass of only 0.08 kilograms under the same conditions.

MAKING THE *LEVIATHAN* FLOAT AND MOVE

If we want a dirigible to float, the lift force must be bigger than the total weight of the dirigible plus the weight of the gases inside. Could this work for the floating whale?

There is a companion book to the series, *The Manual of Aeronautics*, which has some facts about the *Leviathan* that we can use to figure this out. In short, the total weight of the whale and its payload is about 96,000 kilograms, and the total volume of the air beast is about 200,000 cubic meters. If we assume that about $\frac{2}{3}$ of the volume is filled with hydrogen, which is roughly what the *Manual* says, then it will indeed float.

Another question is how fast it could move. The *Leviathan* is powered by engines salvaged from an Austrian walker that have a total power output of about 700 kilowatts. When the whale is pushed forward by its engines, it will be met with a counteracting drag force, caused by the air it moves through. It will get to its highest speed when the drag force equals the thrust of the engines.

This calculation requires some estimating because the drag depends on the forward area of the whale, which isn't given in the *Manual*. However, a reasonable estimate gives a top speed of about 20 meters per second, which translates to 72 kilometers per hour.

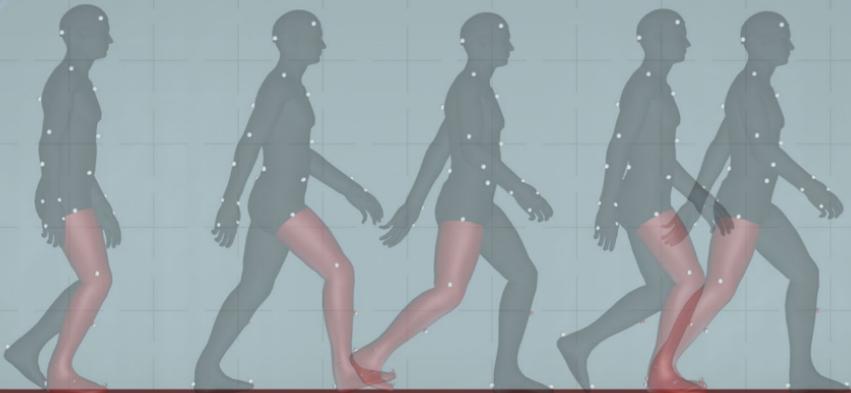
This is again very close to what is in the series. In the third book of the trilogy, *Goliath*, the *Leviathan* crosses the Pacific Ocean from Japan to Los Angeles. The distance it travels is about 8800 kilometers, meaning a 5-day trip based on the aforementioned calculation. This agrees with the time it takes in the book.

FRICITION AND WALKING

- ✚ This lecture now turns to *Leviathan's* clankers and their mechanized walkers. Steam-powered and clockwork-driven machines are another feature of many steampunk works.
- ✚ Walking is a very complicated process. Two paramount issues are friction and balance. Friction is the force between solid objects that opposes motion. This is different than drag, which is the force opposing motion in a liquid.
- ✚ Work is relevant here. Work is the energy cost of some sort of action. If something is pushing against some force that opposes motion, the energy cost of moving against that force is given by a simple formula:

$$\text{work} = \text{force} \times \text{distance moved}$$

- ✚ Imagine pushing a block against the floor. The frictional force is some fraction of the weight of the block. The fraction depends on what the block is made from and what the surfaces are. Smooth surfaces usually require less force.
- ✚ The fraction is typically between 10 and 30% of the weight of the block, but it can be a lot lower on ice, for example, or higher if the surface is rough. This only works if the floor is level; if you are pushing it uphill or downhill, the work required will be bigger or lower.
- ✚ Walking is a complicated up-and-down motion. The foot is the fixed point, and the leg and torso swing above it like an upside-down pendulum. However, we can think of a very basic model as feet making contact with the floor once every stride.
- ✚ Roughly speaking, the work done is about 7% of the weight multiplied by the distance, at least according to a biomechanics study done in the 1960s. All things aren't equal; for example, if something tries to move fast, other forces that resist motion pop up, like air drag.



WORK = 7% WEIGHT x DISTANCE
 FRICTION FRACTION (COEFFICIENT OF FRICTION)
 0.07 OR 7%

BALANCE, GAIT, AND WALKING

- ❏ Balance and gait are the next problems involved in building a walker. This is dealt with reasonably well in *Leviathan*: Walking and running are handled by various levers that control the pneumatics of the Austrian walker that the character Alek pilots. He has to learn to walk the machine almost as if he were a baby. Balance is tricky because walking is essentially controlled falling over.
- ❏ There seem to be 2 separate approaches to creating machines that walk: active, feedback-stabilized controlled systems and passive ones that at least partly walk without active control systems. Passive walking machines are descendants of automata toys from the late 1800s. They are much simpler and cheaper than the active machines, but they may be more limited.
- ❏ One interesting aspect of walking is that any particular gait has a characteristic speed at which walking is easiest. It turns out that the typical speed for walking depends only on 2 parameters: the length of the leg and the acceleration of gravity.

- Speed increases as the length of the leg increases, but not proportionally. The rule is that the typical speed for walking is proportional to the square root of the length of the leg, which is also typically proportional to the height of the walker.
- Because the square root of 2 is about 1.4, a walker twice the size of a human being won't walk twice as fast but only about 40% faster. In addition, the rate at which the feet hit the ground decreases by the same amount. A person with a leg length of 1 meter has a walking speed of about 1.3 meters per second, or roughly 4.7 kilometers per hour.
- How fast should the walkers in *Leviathan* move? This lecture assumes that they are 4 times the height of an average person. This means that their legs are about 4 meters high, or roughly 13 feet. The square root of 4 is 2, so they should cover ground about twice as fast. That come to roughly 9 kilometers per hour or 5.6 miles per hour. This is a problem with such machines: They move fairly slowly compared to cars or even tanks.



$$\text{SPEED} = 0.44 \times \sqrt{\text{GRAVITY} \times \text{LENGTH}}$$

$$\text{SPEED} = 1.3 \text{ MPS} = 4.7 \text{ KM/H}$$

$$L = 1 \left[\sqrt{1} = 1 \right]$$

$$\text{SPEED} = 2 \times \text{FASTER}$$

$$\text{SPEED} = 9 \text{ KM/H} = 5.6 \text{ MPH}$$

$$L = 4 \left[\sqrt{4} = 2 \right]$$

- Adding more legs helps, as anyone who has ridden a horse can attest. Additionally, running is a different type of motion, which is not subject to the same rules as walking. That is because both feet leave the ground when running.
- Running is akin to making a series of small leaps. A running human can reach better than 40 kilometers per hour for short periods of time. One assumes that a walker could go even faster. However, running a walker is a very difficult proposition.

Suggested Reading

Gibson and Sterling, *The Difference Engine*.

Westerfeld, *Behemoth*.

———, *Goliath*.

———, *Leviathan*.

DESIGN YOUR OWN DRAGON: *GAME OF THRONES*

THIS LECTURE IS DEVOTED TO THE ART AND SCIENCE OF DESIGNING ALIEN CREATURES AND FANTASY ANIMALS. SPECIFICALLY, IT FOCUSES ON THE DRAGONS FROM THE HBO SHOW *GAME OF THRONES*, WHICH IS BASED ON A SERIES OF NOVELS BY GEORGE R. R. MARTIN. THE SHOW TAKES PLACE IN AN ALTERNATE WORLD WITH MAGIC, BUT DESIGNING FANTASY ANIMALS THAT ARE CONSISTENT WITH THE KNOWN LAWS OF SCIENCE ADDS SOMETHING TO THE STORY. IT MEANS THAT THE CREATOR IS THINKING ABOUT THESE THINGS ENOUGH TO TRY TO ADD SOME SEMBLANCE OF REALISM TO IT.

BACKGROUND ON THE DRAGONS

- ❏ As the *Game of Thrones* story begins, dragons have largely died out in Westeros, the continent where much of the story takes place. The Targaryens, the long-ruling family of the Seven Kingdoms, had seized power because they were the only ones who had dragons, which they used to obliterate their opponents. However, as time wore on, the dragons became smaller and weaker, until the last were the size of small dogs. The Targaryens were dethroned about 20 years before the story begins.
- ❏ It is explicitly stated in the story that the waning of the dragons is tied to the waning of magic in Westeros. In the first season of the show, Daenerys Targaryen, one of the last surviving members of that house, hatches 3 dragons which grow to full size, which she uses in her bid to conquer Westeros. The rebirth of the dragons is explicitly linked to the regrowth of magic in the world.

REQUIREMENTS FOR MAKING A DRAGON FLY

- ❏ It would likely require magic to make a dragon fly, because otherwise scaling laws don't work in its favor. This hinges on the weight-to-surface ratio and metabolism.
- ❏ There are 4 forces at work on a flying object like a dragon or airplane, each in pairs.
 - 1 The lift provided by the wings, which are pushed up.
 - 2 Weight is the force of gravity on it, pulling down.
 - 3 Thrust is provided by the wings (for a dragon) or the engines (for an airplane). Thrust pushes the flier forward.
 - 4 The drag force is the push of air against the flier, which pushes backward.

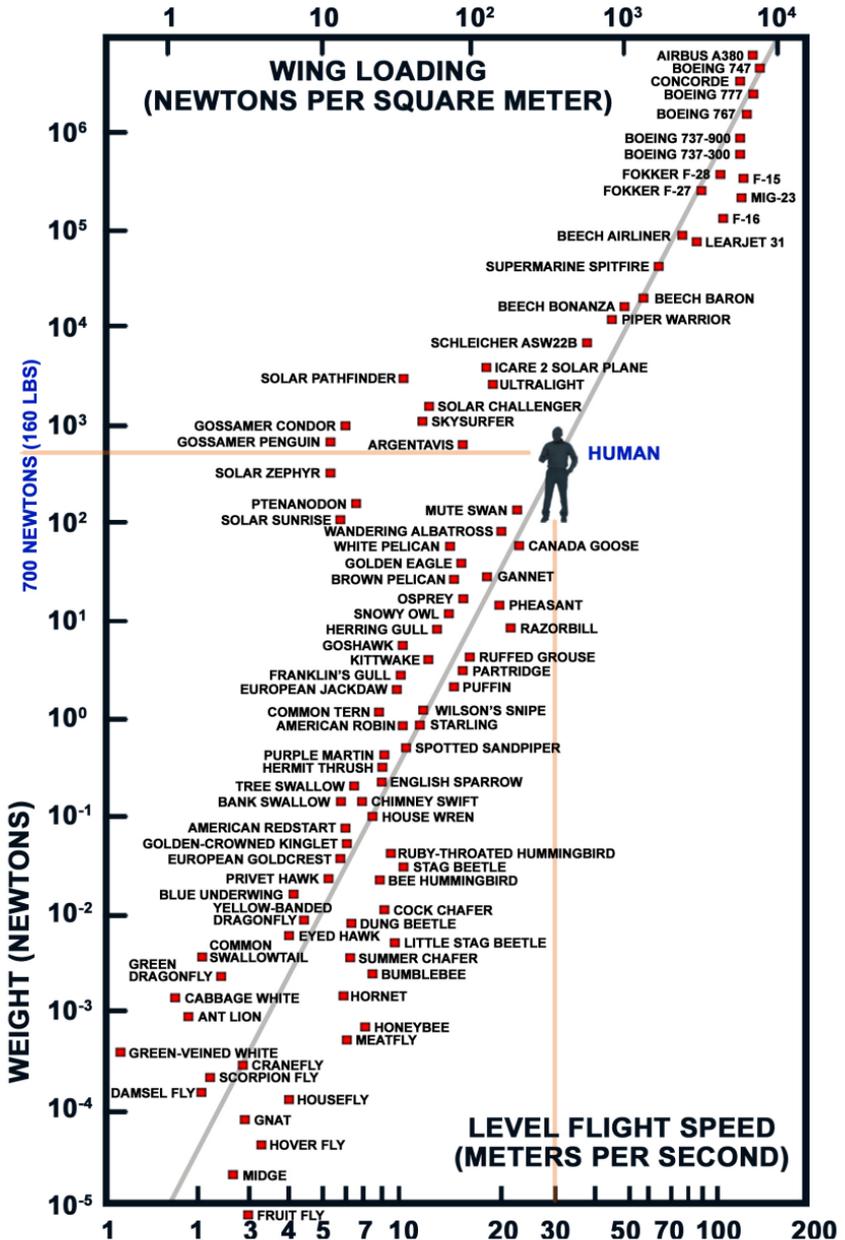
- ✚ In level flight at a constant speed, the forces balance in pairs. Drag is equal in size to thrust, and lift is equal to weight. The lift force is determined by the shape of the wings. Essentially, as the flier moves forward, the wings force the air downward.
- ✚ Newton's third law says there is an equal and opposite force acting to push the wings upward. Drag comes from the fact that this flow of air creates vortices in the back of the wings.

SPECIFIC PARAMETERS

- ✚ Two parameters are relevant here: the glide ratio and the wing loading. The glide ratio is the ratio of the lift force to the drag force. It is desirable for the glide ratio to be big so that the drag is small. Well-designed wings have a top glide ratio of about 20 or so.
- ✚ The wing loading is the ratio of the weight of the flier to the wing area. It becomes bigger as the flying beast becomes bigger because of the general increase of weight to surface area. Lift is related to wing loading and speed. The book *The Simple Science of Flight* by Henk Tennekes has a simplified formula, which is good for Earth at sea level. Here is the formula:

$$\text{lift} = \frac{1}{2} \text{ wing area} \times \text{speed}^2$$

- ✚ It's possible to make matters even simpler than that. In level flight, lift is equal to weight. If we measure the weight and the wing area, we can calculate the wing loading. From the wing loading, we can find the speed at which the lift equals the weight. This is going to be the animal's average flying speed.
- ✚ This information is available on the internet or in *The Simple Science of Flight*. Tennekes put data for many different types of fliers, including insects, birds, and airplanes, onto his Great Flight Diagram, which shows the weight, wing loading, and flight speed for nearly 100 different flying animals and machines. The following is a simplified version.



INTERPRETING THE GREAT FLIGHT DIAGRAM

- ✚ The data in the Great Flight Diagram is presented in a logarithmic way. This means that each major tick upward or rightward represents 10 times the value of the previous one. This allows for the display of a very large range of data on the chart. That is needed because of the huge range of weights of the fliers: The fliers range from insects to large aircraft.
- ✚ On the graph, the wing loading is plotted against the mass of the flier. The wing loading determines the air speed.
- ✚ The points representing the fliers aren't distributed randomly; instead, they all fall on a line running from the bottom left to the upper right, with some exceptions. This is striking because of the huge range of masses that are plotted on the diagram.
- ✚ Additionally, the graph reveals the power requirement for flight. The idea is straightforward: Power is the rate at which we need to supply energy to the flier to keep it flying. The power is given by the formula force times speed, the force in this case being the thrust.
- ✚ However, the thrust is equal to the drag. The drag is equal to the lift divided by the glide ratio, which we are going to assume is about 20. But in level flight, the lift is equal to the weight. We can read off the weight and the speed from the chart, and so compute the power required for flight.
- ✚ For an animal, this tells us the metabolic rate needed for flying. Metabolic rate is the rate at which an animal can generate energy. Not all energy is usable: typically, the efficiency is only about 20% in converting metabolic energy into useful work. This means that to fly, an animal has to be able to generate about 5 times as much power as the chart would indicate.

SCALING

- ✚ Scaling enters the picture at this point. There is a famous formula in biophysics called Kleiber's law, which relates how metabolic rate scales with weight. Kleiber's law states that every time mass doubles, metabolic

rate increases by a factor of 1.7. This leads to a graph of metabolic rate versus mass that is a curve, not a straight line. Because every time the mass doubles, the rate doesn't quite double, the curve will be concave downward.

✚ However, the power required for flight increases faster than the weight. Every time the weight doubles, the power required for flight increases by a factor of 2.2. If the weight doubles again, the flight power increases by another factor of 2.2, or an overall factor of 4.4. Again, this curve won't be a straight line; instead, the graph of power required for flight versus weight is concave upward because the rate more than doubles every time the mass is doubled.

✚ That means that at some value of weight, the power required for flight is bigger than the metabolic power that the animal can supply. This makes some sense considering that there aren't any truly massive birds that can fly. The bird with the largest wingspan, the wandering albatross, has an average mass of about 9 kilograms, or 20 pounds.

✚ We can also read off from the chart how much power it would take for a human to fly. Someone weighing 160 pounds would need to generate an output power of approximately 1.1 kilowatts, or nearly 1.5 horsepower. This power output needs to be held for extended periods of time. This is more than twice what the best trained athletes are capable of doing.

✚ However, these scaling laws are only valid if the fliers are all exactly the same shape and only differ because of their size. This is more or less true for many birds and airplanes. Most birds have wingspans that are about equal to their body length, and so do most airplanes, but there are exceptions. All of these exceptions do so to lower the power required for flying.

✚ Consider the exceptions on the Great Flight Diagram. There is a gap between the largest birds and the smallest airplanes: both curves bend to the left, meaning that very large flying animals and very small airplanes have wings that are oversized compared to their bodies. The most extreme examples combine the 2. Human-powered aircraft, like the *Gossamer Condor*, exemplify that.

HUMAN-POWERED FLIGHT

- Human-powered flight is an extreme combination of athletics and engineering. Humans can barely generate enough power to lift a plane into the air, and only then if the plane is made of very lightweight material with hugely oversized wings. The total weight of the pilot plus the aircraft can be as low as 200 pounds, or about 100 kilograms, and wingspans can be longer than 90 feet, or about 30 meters.
- The combination of light weight and huge wings means very low wing loading, leading to very low power requirements. The total power needed to fly a human-powered aircraft can be as low as 200 watts of output, which is within the range of an athletic adult. However, this low power and low wing loading means that flight speeds are also low.
- Human-powered aircraft have airspeeds of less than 16 kilometers per hour. In addition, because they are so lightweight with such huge wingspans, they can be overturned by winds of about 16 to 20 kilometers per hour as well.

DESIGNING A DRAGON

- Human-powered flight offers lessons for designing flying animals. Making a dragon requires some choices. This is true of designing any realistic alien life forms or fantasy creatures.
- Some examples come from an activity assigned by this course's instructor: He challenged students in a class to design dragons. Some students went for bird-sized dragons that obey scaling rules. Another choice was to design a big dragon that has unrealistically high metabolic rates, requiring massive amounts of food.
- Some dragons were designed to sleep much of the time to minimize energy consumption. For example, the dragon Smaug from *The Hobbit* spends most of his time sleeping on his golden treasure.

Other science fiction writers have done similar things. The Ythrians, invented by the science fiction writer Poul Anderson, are a winged, humanoid race capable of flight. They live on a low-gravity world. They have special adaptations that allow a greater flow of oxygen to their wings, plus a ferociously high metabolic rate.

BREATHING FIRE

Dragons also usually breathe fire. In the aforementioned activity, the most common way that the students had dragons breathe fire was by generating methane in their gut. Some adaptation, like spark-creating metallic teeth, would light it on fire.

However, one group found a very interesting way of doing it. The bombardier beetle ejects a boiling spray of a noxious chemical when threatened. It is composed of 3 ingredients held in separate glands in the beetle's body, which are combined when ejected. One group of students suggested that dragons might use this on a large scale for their "fire" breathing. The takeaway point is that while physics places limits on biology, they are fairly broad limits, and working with them or around them offers enormous scope for creativity.

Suggested Reading/Viewing

Game of Thrones.

Tennekes, *The Simple Science of Flight.*

PLANETARY ECOLOGY IN *DUNE*

THIS LECTURE EXAMINES HOW THE SCIENCE OF ECOLOGY PLAYS A MAJOR ROLE IN SHAPING THE PLOT OF THE 1965 NOVEL *DUNE* AND 3 OF ITS SEQUELS: *DUNE MESSIAH*, *CHILDREN OF DUNE*, AND *GOD EMPEROR OF DUNE*. ADDITIONALLY, THE LECTURE LOOKS AT HOW FRANK HERBERT, THE AUTHOR, ANTICIPATED A MAJOR AND STILL CONTROVERSIAL THEORY OF PLANETARY ECOLOGY: THE GAIA HYPOTHESIS.

BACKGROUND ON *DUNE*

- ❏ *Dune* begins when Duke Leto Atrides, one of the most powerful nobles in the empire, is sent to govern the desert world of Arrakis. Arrakis is a dry, hot desert world, with a few scattered settlements and an impoverished population living at the edge of survival. It is also the only world that produces melange, also known as spice, a drug that gives its users psychic powers.
- ❏ Shortly after arriving, the duke is betrayed by a trusted servant to his enemy, Baron Harkonnen, and killed. His consort, Jessica, and son, Paul, escape. They go to live with the Fremen, militant Bedouin-like nomads living in the deep deserts. Paul becomes a religious figure, uniting the Fremen to overturn the empire.

THE SANDWORMS

- ❏ One of the fascinations of *Dune* is how the ecology of Arrakis drives the story. The ecology of Arrakis is tied to the life cycle of the sandworms, giant segmented worm-like creatures that swim through the sands of the deep desert. (The mechanics of how they move is never explained.) Although the sandworms are incredibly dangerous, the Fremen use the sandworms as transport across the desert.
- ❏ The sandworms are part of an ecological cycle that produces the spice and also ties up the water on Dune. It is revealed in the third novel, *Children of Dune*, that the sandworms are an invasive species, introduced from another world. Sandtrout, immature sandworms, encyst the water, blocking it deep underground and preventing it from reaching the surface of the planet. Water combining with their excretions produces the spice, which emerges in giant explosions called spice blows. These occur because of the chemical reactions that create the spice.

❧ Melange is the central product that allows the empire to function, giving Arrakis importance far beyond what an impoverished desert world could normally have. For example, it is the drug that allows the Spacing Guild's navigators to guide starships through hyperspace; it also gives the Bene Gesserit, a quasi-religious and political organization, the psychic powers that let them influence the governance of the empire. Paul realizes that by controlling the spice, he can control the empire.

HOLISM

❧ One of the most fascinating aspects of the novel's approach to ecology, and science in general, is its emphasis on holism. The overall philosophy is that one must understand complicated systems as systems. To study the individual parts without considering their interactions will at best result in ignorance and, at worst, destroy the system under study.

❧ The view holds similarities to the Gaia hypothesis of James Lovelock and Lynn Margulis. That hypothesis was first proposed a few years after *Dune* was written. The Gaia hypothesis is that one cannot view the ecology and the climate of Earth as separate entities; rather, life on Earth regulates its climate, on both small and large scales, to maintain Earth's habitability.

❧ This was a controversial idea in the 1970s, and it remains one. Detractors of the idea focus on the fact that it seems to imply a purpose to evolution and the development of complicated ecologies. This has been called mysticism by some. However, others see the philosophy as viewing Earth's ecology as an example of a feedback system, one in which elements of the system react against each other to stabilize it.

❧ James Lovelock and Lynn Margulis proposed that Earth's biosphere keeps Earth's surface temperature within the limits required for life in a similar manner to how a thermostat keeps the temperature of a house within acceptable limits. There is certainly some truth to this, which can be seen from the natural greenhouse effect.

- ❏ Lovelock and his colleague, Andrew Watson, created a simplified theoretical model of how life can affect the surface temperature of a planet: the Daisyworld. This is a model of a hypothetical planet that has 2 species of daisies on it. One absorbs more light from the sun than its surroundings do, and the other absorbs less.
- ❏ These daisies can hypothetically spread over the entire planet. If there are more dark daisies than light, the planet heats up. If there are more light ones than dark ones, the planet cools down. Instead of a runaway daisy effect, where one species takes over and either heats or cools the planet to extinction, they coexist in ratios that ensure that the planetary temperature remains within the acceptable range.
- ❏ The authors of the paper showed that if Daisyworld's sun grew either hotter or cooler, the environment would adapt to the change. If it got cooler, comparatively more of the dark daisies would grow, heating the planet. If the sun got hotter, the opposite would happen.

***DUNE'S* ECOLOGY**

- ❏ Arrakis's ecology is just about as simple as Daisyworld's. In both cases, the inventors of each planet were working to create a simpler version of an ecology than the hugely complicated one on Earth. This is a typical reaction of scientists to intractable problems.
- ❏ The Fremen are clandestinely trying to alter the ecology of Arrakis, to turn it into a more temperate world with water flowing on the surface. To do this, they have to disrupt, or at least contain, the sandworm lifecycle that ties up the free water.
- ❏ They are engaged in a centuries-long process to introduce desert scrub vegetation, which will simultaneously stop the movement of the dunes, free up the water, and cool the planet by their shade. The plan is carefully discussed in an appendix to the novel. This idea was based on a program to stabilize the Oregon sand dunes. Herbert even has the Fremen planting some of the same beach grasses as were used in the real program.

THE OREGON PROGRAM

- ❏ The Oregon sand dunes represent a major and unique environmental region. While preparing for this lecture, this course's instructor corresponded with Dr. Sally Hacker, an ecology professor at Oregon State University. Her area of research is the ecology of the Oregon dunes. According to Hacker, the history of sand dune stabilization in the western United States goes back to the mid-1800s.
- ❏ Per a 1984 study, "Whenever moving sand interferes with the activities of human beings, programs of stabilization are initiated." The process described is essentially identical to that described by Herbert in *Dune*. The study goes on: "The first step is always the planting of European beach grass," which is the only species of beach grass that can survive in a sufficiently wide array of sandy environments. However, secondary plantings of other species are needed because beach grasses don't grow well when sand deposition stops. In Herbert's work, the Fremens clearly follow the Oregon plan: They introduce tough beach grasses and follow with other plantings when the environment becomes less hostile.

EUROPEAN BEACH GRASS IN OREGON



- ❏ In Oregon, man's struggle against nature for control of the dunes isn't an unmitigated success story. Few such stories are. The problem with planting European beach grass along the North American coast is that European beach grass is invasive.
- ❏ The beach grasses drive out native flora for hundreds of miles along the coast, and they have wiped out habitats for various animals, including the Oregon silverspot butterfly and the western snowy plover. The butterfly would have gone extinct in the 1990s if not for vigorous efforts to start recovery programs.
- ❏ In Herbert's series, one side effect of the fulfillment of the "greening" of Arrakis is the sudden and drastic reduction of spice production, causing an economic crash of the galactic economy. This issue is explored in the later books, and it is similar in some ways to the temporary effects that the Arab oil embargo had on the US economy in 1973, 8 years after the book was published.

GLOBAL WARMING

- ❏ A large amount of science fiction deals with the consequences of what humans are doing to our planet. One example is *Forty Signs of Rain* by Kim Stanley Robinson, which is a novel involving political and scientific responses to mega-disasters triggered by global warming.
- ❏ Global warming is caused by the anthropogenic greenhouse effect. The greenhouse effect is the warming of the surface of the Earth by certain gases in its atmosphere. It is caused by the fact that some gases like water vapor, carbon dioxide, and methane are transparent to visible light, which is emitted by the sun and warms the Earth, but blocks infrared light, which is emitted by the Earth. This means that these gases in the atmosphere act as a blanket, trapping heat and warming the surface of the planet.

- ❏ The term *anthropogenic* means “human made.” There is a natural greenhouse effect, which is a good thing: If it didn’t exist, Earth would probably be too cold to sustain life. Since the Industrial Revolution, greenhouse gases emitted due to our technology have increased the temperature of the Earth by about 1° Celsius so far. They are on track to increase it by another 2° by the end of this century.
- ❏ Scientifically, this theory is not controversial. More than 95% of all climatologists accept that this is real, and there is an enormous body of evidence, from the retreating arctic ice to the migration of species into cooler latitudes, that support it. The theory was first proposed in 1909 by Svante Arrhenius, a Nobel laureate in chemistry.
- ❏ It is difficult to predict how much the Earth’s temperature will change, but not impossible. As computers and models improve, predictions are saying more or less the same thing: If we continue on the same path we are on now, the temperature is going to increase significantly, with disastrous consequences for humanity.

Suggested Reading

Herbert, Brian, *Dreamer of Dune*.

Herbert, Frank, *Dune*.

———, *Dune Messiah*.

———, *Children of Dune*.

———, *God Emperor of Dune*.

McNelly, *The Dune Encyclopedia*.

Watson and Lovelock, “Biological Homeostasis of the Global Environment.”

QUIZ

- 1 True or false: The human language can handle the verb tenses for time travel.
- 2 According to the best theories of physics, time machines are probably impossible because:
 - a Quantum effects destroy them as they are being created.
 - b The time cops show up and jail anyone trying to build one.
 - c Your future self comes back and warns you not to build one.
 - d The sun goes nova and kills everyone when you try to make one.
- 3 Replicating objects using some variant of teleportation technology is probably not worth doing because:
 - a Who wants that many cups of Earl Grey tea?
 - b It would destroy the economy.
 - c Waste heat vaporizes everything in sight.
 - d You always end up with an evil twin.

- 4 If teleportation conserves energy, a man teleporting from the *Enterprise* down to an unknown planet will:
- a Meet Klingons.
 - b Have his limbs swapped with the person standing next to him.
 - c Age backwards to childhood
 - d Get very hot.
- 5 Isaac Asimov's laws of robotics state that:
- a Robots cannot harm humans.
 - b Robots must obey humans.
 - c Robots must keep themselves from harm.
 - d With minor variations, all of the above.
- 6 The term *robot* comes from a word meaning:
- a Slave.
 - b Dog.
 - c Buddy.
 - d Metal overlord.

- 7 The *Leviathan* of Scott Westerfeld's series is:
- a A metaphor for the world's economy.
 - b A genetically engineered sea monster.
 - c A hydrogen-filled floating whale used as an aircraft.
 - d The main character of the series.
- 8 True or false: In the real world, Charles Babbage's analytical engine was built and was a commercial success.
- 9 If we double the size of an object, keeping everything else about it the same, the ratio of weight to area:
- a Stays the same.
 - b Doubles.
 - c Quadruples.
 - d Octuples.
- 10 True or false: The *Gossamer Albatross* was the first human-powered aircraft to cross the English Channel.

11 Daisyworld is:

- a A science fiction story by Frank Herbert.
- b An exoplanet found in 2019 capable of supporting human life.
- c A mathematical model of aspects of planetary ecology.
- d A tourist attraction in Box Elder, South Dakota.

12 Frank Herbert's novel *Dune* was inspired in part by:

- a Sand dune reclamation projects in coastal Oregon.
- b Dune buggy racing.
- c Lorna Doone cookies.

ANSWERS

1 false; 2 a; 3 c; 4 d; 5 d.; 6 a; 7 c; 8 false; 9 b; 10 true; 11 c; 12 a

EXTRATERRESTRIAL INTELLIGENCE AND *CONTACT*

THIS LECTURE CONCENTRATES ON CARL SAGAN'S NOVEL *CONTACT*. SAGAN WAS ONE OF THE GREAT SCIENTISTS AND SCIENTIFIC TEACHERS OF THE 20TH CENTURY. HE WAS ONE OF THE FIRST PLANETARY SCIENTISTS (ASTRONOMERS WHO SPECIALIZE IN THE STUDY OF THE PLANETS). HE WAS ALSO INFLUENTIAL IN THE USE OF UNMANNED PROBES TO STUDY THE PLANETS. THESE PROBES HAVE REVOLUTIONIZED OUR UNDERSTANDING OF THE SOLAR SYSTEM. SAGAN WAS ALWAYS INTERESTED IN THE POSSIBILITY OF LIFE, AND PARTICULARLY INTELLIGENT LIFE, OFF OF EARTH.

THE PLOT OF *CONTACT*

- In *Contact*, Dr. Ellen Arroway is a radio astronomer who is in charge of Argus, a huge array of 130 radio telescopes whose mission is to search for extraterrestrial signals. The telescopes find a signal beamed toward the Earth: a recording of a television broadcast of Adolf Hitler from 1936.
- This is not meant as some evil intent by the unknown aliens. Instead, Dr. Arroway realizes that Hitler's broadcast was one of the first very powerful signals that was sent out by human civilization. The signal the aliens send back to us is simply the first they were able to detect from Earth. The implication is that they have been monitoring Earth to see when we would develop the appropriate technology to be able to communicate with them.
- The alien broadcast is coming from the star Vega, which is about 26 light years from Earth. This means that it took 26 years for the aliens to receive the signal and another 26 years to send it back, making a total round-trip time of more than 50 years. This would put the time when the signal was received in the late 1980s, which fits with the storyline. The novel was written in 1985 and is set more or less in that time period. Behind these signals is a hidden transmission showing how to build a machine capable of sending people through a wormhole to Vega and beyond.

RADIO TELESCOPES

- The most important aspect of the novel, as far as this lecture is concerned, is how the aliens made initial contact: through communications picked up by a radio telescope. It is no fluke that Sagan chose this method. It is perhaps the only way we will ever learn of any advanced alien civilizations.
- Traveling to other stars is very difficult. Stars are separated by such immense gulfs that even light takes years to get from one to another, and there are currently no feasible methods of making spacecraft that will travel even at a small fraction of the speed of light. However, with the advent of the

radio telescope, scientists realized that it might be possible to listen for alien civilizations and to speak to them. This idea was first put forward by the scientists Philip Morrison and Giuseppe Cocconi in a 1959 article in the journal *Nature*.

❏ A radio telescope is essentially a radar dish pointed at the sky. It sees the sky in radio waves—that is, light of wavelengths so long that our eyes can't see it. Radio telescopes discovered amazing things ever since they were invented in the late 1930s. They were used to discover pulsars, rapidly rotating neutron stars. They found the background radiation from the big bang. They were used to study the structure of our galaxy. And a number of influential scientists, including Sagan, thought they could be used to listen for alien life.

❏ Radio telescopes are exquisitely sensitive. The Nobel Prize–winning physicist Edward Purcell calculated that it would cost about a dollar's worth of electrical power to broadcast a 10-word signal across a distance of 12 light years. The signal goes out at the speed of light, much faster than any spaceship we can construct. Because of this, many scientists felt that we should be listening for such a signal from an alien civilization.

RADIO TELESCOPE ARRAY



- ❏ The first scientific meeting on the subject was held at the Green Bank radio observatory, and it has been called the Green Bank conference since then. The radio astronomer Frank Drake organized the conference, and Philip Morrison and a very young Carl Sagan were 2 of the attendees.
- ❏ This conference was where Frank Drake introduced his famous equation. In Drake's words, he was trying to "organize our ignorance" on the subject of extraterrestrial life. The Drake equation is an attempt to use the theory of probability to estimate the total number of advanced extraterrestrial civilizations that we might communicate with. There are a number of forms that the equation takes. To see/hear a simplified version in action, refer to the audio or video lecture.

ALIEN CIVILIZATIONS AND SCIENCE FICTION

- ❏ No one really knows what the true number of advanced alien civilizations is, so we have been listening for the last 60 years to see if anyone is out there broadcasting to us. This started with Project Ozma and continued with SETI—the Search for Extraterrestrial Intelligence. We haven't heard anything yet.
- ❏ Finding such a signal would be one of the biggest events in human history. Naturally, many science fiction writers, not just Sagan, have written about humanity getting a signal from an alien race. One question they face is: How does an author write about a race or culture that may be millions or billions of years more advanced than ours?
- ❏ This is not an easy question to answer. We have no idea what very long-lived civilizations are like. Occasionally, *Star Trek* has featured "highly advanced" alien races like the Organians from the episode "Errand of Mercy." They were magical, glowing energy beings. However, it seems that they would need some sort of solid limbs to manipulate the world with, making energy beings somewhat unlikely.
- ❏ Another strategy for dealing with ultra-old civilizations is problem limitation: The writer imagines some reason that civilizations millions of years older than ours won't be so advanced. Larry Niven and Jerry Pournelle

like this strategy, having used it in their novel *The Mote in God's Eye*. Niven also used it in the novel *A World Out of Time*, although there it was for a terrestrial civilization.

HIS MASTER'S VOICE

- ❏ Other science fiction writers don't try to answer the question of what advanced aliens will be like. They shroud the unseen aliens in mystery, whether they are communicating via radio or some other means. A good example comes from the 1968 novel *His Master's Voice* by the Polish science fiction writer Stanislaw Lem. In the novel, scientists intercept a mysterious neutrino signal that indicates artificial origin because it is repeating and too complex to have originated from any natural phenomenon.
- ❏ The narrator of the novel is Dr. Peter Hogarth, a mathematician at Yale University. He is inducted into a program to decipher the signal by the project leader, a personal friend of his. Hogarth uses a mathematical theory that he devised to show that the signal is in some sense circular: It doesn't have a beginning or end.
- ❏ Other researchers show that when the neutrino signal is amplified and matter is exposed to it, it has almost magical properties. The matter can be teleported for short distances, and if exposed over very long periods of time, it may encourage the development of life. Beyond that, the scientists can't translate the message. Hogarth speculates that the message isn't intended for humans but for other species that are on a comparable level of development as the unknown originators.
- ❏ The novel is interesting in that it is a reasonably accurate depiction of how scientists actually work on a complicated research project. It is also an example of the prime directive idea in science fiction. This idea is better known from the various *Star Trek* series, where it was violated as often as not. It states that more advanced civilizations shouldn't interfere or communicate with less advanced ones.

UNDERSTANDING AND TALKING TO ALIENS

- Understanding aliens' signals will be difficult, but there are universal reference points that, in principle, all intelligent species should be able to understand. In *Contact*, the aliens send a preliminary signal of the first several prime numbers—that is, numbers that have no factors but themselves and 1. The first several primes are 2, 3, 5, 7, 11, 13, and so on. Seeing a signal made up of the first 10 or 15 primes, for instance, would be a definite sign of intelligence: The odds of a naturally occurring signal like this are nil.
- Philip Morrison, one of the pioneers of SETI, discussed how to build a vocabulary when transmitting to an alien race, using basic concepts of arithmetic. One could begin by defining signals to mean different integers, then using different signals for addition, subtraction, and the equal sign. We could send simple, then more complicated mathematical formulae.
- Many other scientists have worked on this problem as well. The computer scientist and artificial intelligence pioneer Marvin Minsky wrote an essay on why he believed mathematics was universal enough to use it as a common language with aliens. In his opinion, any species developing intelligence would have to discover the same set of mathematical principles in much the same way that humanity did.
- Other people have developed these ideas about sending information, including ways to incorporate images. These ideas are present in a 1967 young adult science fiction novel: *Danny Dunn and the Voice from Space*. In this novel, the character Danny has to interpret a radio signal from an extraterrestrial civilization. He is able to figure out that the message, a sequence of 1s and 0s, forms an image of the aliens sending the message. The book was written at a time when interest in SETI was very high—only 6 years after the Green Bank conference.

SETI research is still going strong. The Russian billionaire Yuri Milner gave the project \$100 million for a dedicated 10-year search at several radio telescopes around the globe. However, this is only one aspect of the search for extraterrestrial life. Other telescopes, ones that work with visible or infrared light, are looking for more basic signs of life on other planets. These aren't either/or propositions. We need to look at both channels if we hope to answer the most important question of biology, physics, and philosophy: Is there anyone else out there?

Suggested Reading/Viewing

Sagan, *Contact*.

———, *Cosmos*.



UFOS, ESP, AND *THE X-FILES*

THIS LECTURE FOCUSES LARGELY ON THE 1990S TELEVISION SHOW *The X-Files*. THE SHOW DEALT WITH THE DARK SIDE OF SCIENCE AND SCIENCE FICTION: CONSPIRACY THEORIES, ALIEN INVASIONS, THE THREAT OF PSYCHIC POWERS, SECRETS HIDDEN IN PLAIN SIGHT, AND SO ON. IT RAN 9 SEASONS IN ITS INITIAL RUN, AND IT SPAWNED 2 MOVIES AND 2 LATER FOLLOW-UP SEASONS. THE SHOW WAS ONE OF THE MOST POPULAR SCIENCE FICTION TV SHOWS OF ALL TIME BECAUSE IT TAPPED INTO A DEEP ROOT OF THE AMERICAN PSYCHE: THE FEAR AND HOPE THAT THERE IS SOMETHING OUT THERE THAT IS BIGGER, MORE EXCITING, AND MORE THREATENING THAN OUR ORDINARY LIVES HOLD.

BACKGROUND ON *THE X-FILES*

- ❏ *The X-Files* centered around the investigations of 2 FBI agents. Fox Mulder, played by David Duchovny, was a true believer who investigated matters too strange for the bureau to normally look at. Dr. Dana Scully, played by Gillian Anderson, was a skeptic initially assigned to spy on Mulder and keep him in line. She gradually became sympathetic to his investigations, if not to the conclusions he came to. The show was driven by the tension between their disparate worldviews.
- ❏ The show was one of the first to feature multi-episode arcs. The main arc centered on a secret alien invasion, or at least Mulder's fears of one, in which their chief nemesis was the secretive Cigarette Smoking Man, played by William B. Davis. Other standalone episodes or shorter arcs featured psychic serial killers, dark matter, shapeshifters, and even vampires. The show resolutely fought resolution: Many of the storylines, especially the alien invasion arc, were never resolved or only resolved after years of uncertainty.
- ❏ The show featured many tropes associated with fringe beliefs in the United States. The chief one discussed in this lecture is the idea of unidentified flying objects (UFOs) as intelligent alien races visiting us. There is a distinction between UFOs being sighted, which there are plenty of instances of, and UFOs as aliens, which is a theory as to their origin.

THE HISTORY OF UFO SIGHTINGS

- ❏ UFO sightings have a long history. There was a wave of so-called airship sightings in the American West starting in 1896; people apparently looked in the skies and saw something that they interpreted as balloons, flying machines, or even as alien spacecraft. This was about a decade before the first flight by the Wright Brothers in 1903. However, speculation about flying airships abounded during those times.

- What were people seeing if they weren't seeing real airships? There are many possibilities, one of which is lenticular clouds, also known as wave clouds. These form when warm air rushing up the side of a mountain suddenly cools at the top, condensing out the vapor. They can seem to move very rapidly and have characteristic saucer or cigar shapes. There was an airship sighting over Mount Tacoma in the middle of the airship craze of the 1890s that was almost certainly due to lenticular clouds.
- Confusing clouds with interstellar aliens still happens. In June 2015, the *Houston Chronicle* reported that there were 56 UFO sightings reported in Texas that turned out to be clouds in one month alone. Other things that have been mistaken for aliens include weather balloons, low-flying aircraft, and the planet Venus, which can appear surprisingly bright.



LENTICULAR CLOUDS

UFO ABDUCTION STORIES

- ✦ Relevant to *The X-Files* are personal stories concerning aliens visiting Earth. The case of Barney and Betty Hill is one of the earliest and most famous alien abduction stories, and it was a direct inspiration for the alien abduction arc of *The X-Files*. In *The X-Files*, Fox Mulder's sister Samantha was apparently abducted by aliens at an early age and cloned multiple times using some sort of advanced alien technology. Scully herself was apparently abducted by aliens and experimented on.
- ✦ The case of the Hills established a pattern common to other UFO abduction stories. Before this, stories of contacts with aliens were typically benign. By contrast, the story that the Hills told was sinister. The Hills, a recently married couple, were on vacation and traveling by car in New Hampshire on the night of September 19, 1961.
- ✦ One issue is that there are 2 parts to their story. There is the original story that they told in 1961 and an elaboration of it that came out of hypnotic regression therapy in 1964.
- ✦ In 1961, on the night of September 19, they both saw an unknown object in the sky that they examined with binoculars. They reported this to a local air force base, then returned home and slept. Betty wrote down several dreams in which humanoid aliens interrogated her.
- ✦ In 1964, on the suggestion of a friend, the Hills underwent hypnotic regression therapy, in which they "recovered" memories of having been abducted and probed by aliens. These were very different than ones present in earlier encounters.
- ✦ The aliens that the Hills claimed to have met were gray-skinned, with huge eyes and slits for noses. In fact, these are the iconic aliens of many later abduction stories and the ones mainly featured on *The X-Files*. In fact, the show features both the iconic gray-skinned huge-eyed aliens of abduction stories and human clones serving them as slaves. The latter could be a callback to earlier abduction stories, which featured human-like aliens.

THE TRUTH?

Alien abduction stories raise some questions: How likely is it that these stories are true? If they aren't true, what would make otherwise rational people tell these types of tales? There are likely 3 possibilities about stories of UFO abductions:

- First, the story is true or mainly true.
- Second, the story is a deliberate lie or mostly a lie.
- Third, the story is not true, but it is believed by the people telling it.

Aliens traveling to Earth would need to come from a very advanced civilization. If we accept that the speed of light is a barrier, building ships that can travel at significant fractions of these speeds requires enormous energy. The laws of physics demand that any such ship would be visible at very large distances away. Making it to Earth undetected by astronomers seems unlikely.

Another consideration is how the aliens spend their vast energy. Grabbing people and probing them seems like something of a waste of time and energy, given the distance they crossed and the trouble it took to get here. If their intentions are good, then they will be contacting the heads of the nations of the world. If their intentions are bad, they hardly need to hide themselves: Their spaceship drive by itself makes a weapon no human government can stand against.

If a story is true, it needs proof beyond a shadow of a doubt. Does the Hills' story have that proof? UFO enthusiasts would say yes because of the Hills' recovered memories.

However, the mind is not an objective recorder of reality. Instead, the mind undertakes processing and interpreting. It has to do this for us to understand the world, but it can be fooled, and more importantly, it can fool itself.

Relevant to this idea is a well-known story that Michael Shermer tells. Michael Shermer is a historian of science and one of the founders of *Skeptic*, a magazine that takes a hard look at UFO stories and claims of the

paranormal. He relates a story of how he hallucinated an alien abduction when on a long bike ride when he was sleep-deprived, exhausted, and dehydrated. It was clear that there was no abduction: He was always accompanied by other riders and his support team.

-  During hypnotic regression therapy, the hypnotist and the subject create memories between them that may have no basis in reality. It is possible that memories uncovered by hypnotic regression can be real, but how can one tell? In UFO cases, it is difficult because there is little objective evidence.
-  It is possible that the after-the fact story recalled by Betty and Barney Hill about their abduction is a case of false memories recovered under hypnosis. Perhaps they weren't lying but sincerely believed that they were abducted.

“SOFT LIGHT”

Along with aliens, *The X-Files* featured many other examples of fringe science ideas. One example comes from the episode “Soft Light,” in which a physicist is accidentally exposed to a burst of radiation from a particle accelerator. Because of this, his shadow develops black-hole-like properties: Anything that it falls across is sucked into it, leaving a burn mark on the floor.

PSYCHIC POWERS: ESP

-  Another interesting area of fringe science concerns psychic powers, particularly extrasensory perception (ESP)—that is, mind reading—and telekinesis, the ability to move objects around with the mind.
-  ESP isn't a completely outlandish idea on the face of it. After all, nerve impulses are electrical. They generate small voltages and electromagnetic fields that can be detected by our current technology. The brain fires off

trillions of nerve impulses every second. The question is: Couldn't humans have evolved some sort of sense organ that could detect and interpret these signals?

- Both detection and interpretation are daunting problems, though various species of fish can detect electric fields. Elephantnose fish create an electric field using specialized cells in their body, and they can detect disturbances in the field when other animals are near it.
- Some fish communicate using these organs. The South American ghost knifefish generate pulses of electricity that differ depending on the sex of the fish. They can sense the differences and use them in mating displays and courting behavior.
- This isn't telepathy, though. They aren't detecting brain wave patterns of the other fish. Detecting such changes is much more difficult because of the low voltages involved and because of the many signals generated every second by the brain.
- There have been steps taken toward technology that can in essence read thoughts. These are called brain-computer interfaces, or BCIs. They are still very basic.
- Research into BCIs mainly focuses on helping the disabled, with applications such as mind control of prosthetic limbs and enabling communication for people for whom normal communications are impaired. However, Dr. Stephanie Martin, a notable figure in the field, is doing research on translating inner speech—that is, the words we think in our heads.

FAMOUS TESTS OF ESP

- The most famous tests of ESP were carried out at Duke University by Dr. Joseph Banks Rhine in the 1930s. He used Zener cards, which are cards with 5 separate faces: circles, plus signs, waves, stars, and squares. The methodology was simple: One person would stare at a card. Another, who in principle couldn't see the card, tried to guess which one it was.



ZENER CARDS

Dr. Rhine's first experiments seemed to indicate evidence for ESP, but the methodologies used in these tests were flawed, and data recording was haphazard. A number of investigators observed that as the controls became tighter and tighter, the evidence for ESP vanished.

PSYCHIC POWERS: TELEKINESIS

Another paranormal ability that Dr. Rhine tested for was telekinesis, the ability to move objects with one's mind alone. He had subjects throw dice and attempt to influence the dice rolls. Again, this was unsuccessful.

Additionally, it is difficult to produce any plausible scientific explanation for telekinesis. Manipulating objects at a distance would involve some sort of force field, but these don't really exist outside of science fiction. The only thing that even comes close is a magnetic field.

- ❏ Magnetic fields are generated by currents—that is, moving charges. There are magnetic fields all around us, generated by our technology and in nature. Honeybees can sense magnetic fields and navigate using the Earth’s field, but they can’t manipulate them.
- ❏ There are 2 ways to generate large magnetic fields. One is by generating large currents, which also generate a lot of heat unless superconductors are being used. The other way is to use permanent magnetic materials, such as rare-earth magnets, which can generate huge fields through quantum effects.
- ❏ The first method doesn’t seem very plausible. Even assuming the human body could generate these currents somehow, the leftover heat would cook a person alive.
- ❏ The other method isn’t very promising either: The human body doesn’t contain much, if any, in the way of ferromagnetic materials. The iron in the blood doesn’t qualify because it is in a compound. It doesn’t have the same magnetic properties as elemental iron does. Perhaps an alien could somehow incorporate rare-earth materials into its body to allow it to generate large fields, giving a limited form of telekinesis.

Suggested Reading/Viewing

The X-Files.

Skeptic magazine.

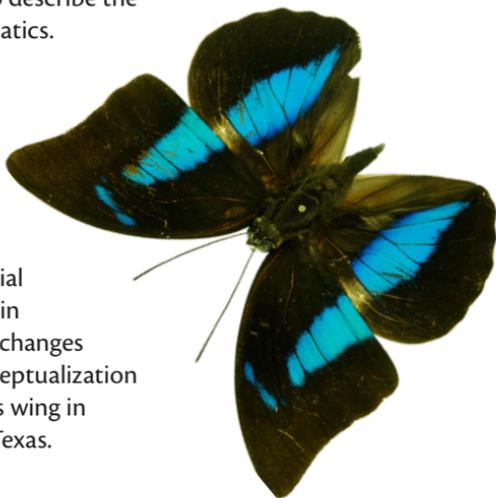
Skeptical Inquirer magazine.

SOCIAL SCIENCES AND THE FOUNDATION SERIES

THIS LECTURE FOCUSES ON THE USE OF THE SOCIAL SCIENCES, SUCH AS ANTHROPOLOGY AND SOCIOLOGY, IN SCIENCE FICTION. ALL SCIENCE FICTION WRITERS ARE AMATEUR SOCIOLOGISTS—UNLESS THEY HAPPEN TO BE PROFESSIONAL ONES. SCIENCE FICTION WRITERS NEED TO INVENT NEW WORLDS AND NEW CIVILIZATIONS. THE SOCIAL ASPECT OF SCIENCE FICTION IS JUST AS IMPORTANT AS ANY ASPECT OF THE PHYSICAL SCIENCES IN THESE TALES. TO DELVE INTO THAT TOPIC, THIS LECTURE EXAMINES SOME OF THE WORK OF ISAAC ASIMOV.

SOCIAL CHANGE

- ❏ Much of science fiction concerns itself with social change. For example, Ray Bradbury's short story "A Sound of Thunder" concerns itself with the United States becoming a totalitarian dictatorship because a time traveler going back to the age of dinosaurs stepped on a butterfly, thus altering the future.
- ❏ The term *butterfly effect* refers to some small change in one place causing a massive disruption in another. The term's origin comes from the mathematician Edward Lorenz.
- ❏ Lorenz was a mathematician and meteorologist who was one of the first people to describe the phenomenon of chaos in mathematics. He was trying to model how the weather worked. He used a highly idealized and seemingly simple set of equations.
- ❏ He found that the solutions were highly dependent on the initial conditions. Very slight alterations in initial conditions led to very large changes in the outcome. In a popular conceptualization of this, the flapping of a butterfly's wing in China could lead to a tornado in Texas.



THE FOUNDATION SERIES

- ❏ The concept of chaos theory sheds light on one of the most widely read ideas concerning the social sciences in all of science fiction: the concept of psychohistory in Isaac Asimov's Foundation series. Asimov was one of the most prolific and eclectic authors who ever lived. He was the author of more than 300 books and possibly as many as 500. The 2 areas that he wrote about the most were science fiction and the popularization of science.

- ❏ The Foundation series is one of his best-known works. This lecture concentrates on the original 3 works, all published in the 1950s, though a number of other works came after. The series is set in the Galactic Empire of the far future—at least 10,000 years from the present day. It is run from Trantor, a world near the center of the Milky Way Galaxy. In this setting, faster-than-light travel is commonplace, and humans live on millions of worlds throughout the galaxy.
- ❏ The story begins with a mathematician named Hari Seldon predicting the downfall of the Galactic Empire using the science of psychohistory—that is, the use of psychology, economics, mathematics, and statistics to predict the future. Seldon sets up 2 foundations: the First Foundation on Terminus, a world on the edge of the galaxy, and the Second Foundation, a mysterious organization whose location and membership is unknown.
- ❏ The First Foundation serves as a repository of all of the knowledge of the Galactic Empire, and it is conceived as the nucleus of a future empire after the fall of the first one. The Second Foundation is set up to steer the First Foundation from the shadows to ensure its success.

PREDICTABILITY

- ❏ Seldon states outright that his laws can only predict the gross outline of future events. Actions taken by individuals remain unpredictable but tend to fall within the larger outlines of history.
- ❏ The fall of the Galactic Empire is clearly based on the fall of the Roman Empire, as Asimov himself acknowledged, and specifically on *The Decline and Fall of the Roman Empire* by Edward Gibbon. Asimov parallels Gibbon in ascribing the fall of his empire mainly to internal decay (there are no outside barbarians to destroy it). He ascribes the fall to discontent felt by people nostalgic for an earlier age, the decline of scientific thinking and the rise of superstition, and decay from the top as the rulers of the empire forsake civic virtue for the pursuit of power and luxury.

- ❏ The main idea that Asimov has in the story is the predictability—and in some sense, the inevitability—of historical events. This idea is an outgrowth of historical ideas from the 19th and early 20th centuries, particularly those of Karl Marx. (However, it is unlikely Asimov would have acknowledged Marx as a direct or indirect inspiration for his work.)
- ❏ Seldon doesn't account for individual actions at all in his theory. Asimov was sensitive to the human element, however. In the second novel, *Foundation and Empire*, the Foundation's plans are overturned by the Mule. The Mule is a mutant with psychic powers that enable him to take over several star systems, contrary to Seldon's predictions.

PSYCHOHISTORY'S VIABILITY

- ❏ The modern use of data mining does show that there may be at least a limited value to the fundamental idea of psychohistory—that human behavior is predictable statistically. In the early 1950s, there were very few computers to speak of and no internet, so Asimov was prescient in his idea that the analysis of huge masses of data could predict human behavior. It is only in the last few years that the application of these ideas have come to fruition, however.
- ❏ One example is targeted marketing. Targeted marketing is the use of statistics—that is, many customer transactions—to better sell products to specific groups of people. Statistical analyses are often combined with techniques from artificial intelligence research, such as neural networks, to make predictions based on consumer behavior. This is the basis of book and movie suggestions on websites such as Amazon and song playlists generated by websites like YouTube.

ANTHROPOLOGY

Anthropology plays a direct role in many science fiction stories. Many tales feature anthropologists from Earth studying alien culture or vice-versa. Some stories show human cultures in a science fiction setting.

THE ENVIRONMENT

- Issues involving the environment are more important than historians understood until recently. In particular, both the climate and geography are very important determinants of success or failure of civilization.
- Asimov based his Galactic Empire on the Roman Empire. The Roman Empire is something of a misnomer: the city-state of Rome had expanded and conquered Italy and southern Europe well before it became an empire.
- Most of the conquests, including the destruction of Carthage and the conquest of Gaul, happened under the older Roman Republic. By the time Octavian became the first emperor and renamed himself Augustus, the empire had reached nearly the limits of its growth.
- Two questions are pertinent here: Why could Rome become an empire in the first place? And why didn't it expand further than it did?
- Regarding the first question, there were essentially 2 places where one could control the flow of sea traffic from the western Mediterranean to the eastern Mediterranean: a place on the southern boot of Italy or a place in northern Africa. It was not inevitable that Rome became the power ruling the Mediterranean, but geography certainly gave them a strong advantage. The fact that the city-state of Carthage was their main rival was also determined by geography, as Carthage's position in northern Africa made it another good place to rule the Mediterranean.

📍 Geography also played a role in determining the size of the empire: It was largely limited by geographical barriers. For example, the Sahara Desert prevented it from expanding farther into Africa than beyond Egypt and the Mediterranean coast.

ENVIRONMENTS IN SCIENCE FICTION

📍 Science fiction writers have used the influence of geography and climate to shape the invented cultures of their novels. Isaac Asimov doesn't do this to any great extent in any of his novels, but Frank Herbert certainly did in *Dune* and its sequels. The climate of Arrakis, the dune planet, pervades everything in the novels, and it shapes the lives of all of the characters.

📍 Another instance where geography and climate play a major role in the story is the winter world of Gethen, the setting of Ursula K. Le Guin's novel *The Left Hand of Darkness*. Gethen is so cold that war is impossible because the people have to struggle too hard against the environment to have enough energy or resources to conduct war against their enemies.

HISTORY IN SCIENCE FICTION

📍 Many science fiction writers are students of history. Some authors are more detailed than others; for example, Michael Flynn, the author of the Spiral Arm series of science fiction novels, uses bits and chunks from Earth's history as background for his novel *The January Dancer* and its sequels.

📍 In these novels, which are set in a far future in which humanity has spread to the stars, scientists such as Einstein and Newton are thought of as gods who rule over the laws of physics instead of people who explained them. Our times are viewed through layers of fog and myth. His novels are written in a poetic and alliterative style, and the different cultures are distinct and fascinating.

Flynn consciously avoids the planet of hats trope in science fiction. It is impossible to invent a complete culture from scratch, let alone an entire world, so many writers feature alien worlds or fantasy civilizations where everyone is characterized by a single attribute—everyone wears the same hat. An example comes from the *Babylon 5* episode “The Parliament of Dreams,” in which several species are shown to have one major religion for the whole of their respective planets.

RADICAL SOCIAL CHANGE

Modern science fiction frequently deals with the effect of radical social change alone working on a society. The most obvious example of this is the dystopian novel *1984* by George Orwell. It was published in 1949; in it, the Great Britain of 1984 is a totalitarian dictatorship where even harboring thoughts against the regime—known as thoughtcrime—can be punishable by death.

In most dystopian novels, the societal aspects of the story are far more important than the hard scientific ones. For example, *The Hunger Games* and its sequels by Suzanne Collins feature a future North America ravaged by natural disaster. The novels have advanced technological trappings, but the main focus is on the society and its effect on the people in the story, particularly Katniss Everdeen, the hero of the saga.

Suggested Reading

Anderson, Poul. “On Thud and Blunder.”

Asimov, *Foundation*

———, *Foundation and Empire*.

———, *Second Foundation*.

DESIGNED LANGUAGES AND *ARRIVAL*

CAN LEARNING A NEW LANGUAGE LET A PERSON SEE THE FUTURE? THIS IS THE QUESTION GUIDING THE PREMISE OF THE MOVIE *ARRIVAL*. SOMETIME IN THE NEAR FUTURE, EARTH IS VISITED BY ALIEN SPACECRAFT, WHICH HOVER OVER 12 LOCATIONS. THE ALIENS ARE CALLED HEPTAPODS BY HUMANS BECAUSE THEY RESEMBLE SQUIDS WITH 7 LONG TENTACLES. THE CENTRAL CHARACTER OF THE STORY, THE LINGUIST LOUISE BANKS, ATTEMPTS TO LEARN THEIR WRITTEN LANGUAGE WHILE TENSIONS WITH THE ALIENS INCREASE.

LEARNING THE ALIEN LANGUAGE REPROGRAMS HER BRAIN SO THAT SHE PERCEIVES TIME AS CIRCULAR RATHER THAN LINEAR, ENABLING HER TO SEE INTO THE FUTURE. THIS ALLOWS HER TO AVERT A DISASTROUS CONFRONTATION BETWEEN EARTH AND THE HEPTAPODS, BUT IT ALSO GIVES HER UNWELCOME INSIGHT INTO HER OWN FUTURE. THE MOVIE AND THE TED CHIANG SHORT STORY THAT INSPIRED IT ARE BOTH BASED ON ONE OF THE MOST CONTROVERSIAL IDEAS IN LINGUISTICS: THE SAPIR-WHORF HYPOTHESIS.

ABOUT THE SAPIR-WHORF HYPOTHESIS

There isn't just one Sapir-Whorf hypothesis but a spectrum of ideas under the umbrella term. The idea is essentially that language frames how we perceive reality. The hypothesis mainly comes from Benjamin Whorf, a linguist who studied with the Yale professor Edward Sapir. This is a relevant excerpt from Whorf's 1956 book *Language, Thought and Reality*, published 15 years after his death:

The world is presented in a kaleidoscopic flux of impressions which has to be organized by our minds. This means, largely, by the linguistic system in our minds.

His writings imply that different cultures, through their very different linguistic structures, impose strikingly different worldviews on their speakers. His best-known work was in studying the Hopi language concepts of time. He proposed that the Hopi language did not identify time in the same way that English and other European languages did.

He contended that to one who thinks in the Hopi language, the concept of time is relative. It is similar, although not identical, to how time behaves in Einstein's relativity theory. He says that the Hopi speaker "has no general notion or intuition of time as a smoothly flowing continuum."

In *Arrival*, the Heptapods' vision of time is the same as how Whorf describes the Hopi view, except it is somehow powerful enough that they experience all of their lives out of chronological order, perhaps simultaneously, or in a circular manner. Dr. Banks says this of their language in the movie:

If you learn it, when you really learn it, you begin to perceive time the way that they do, so you can see what's to come. But time, it isn't the same for them. It's non-linear.

DISPUTING AND USING THE HYPOTHESIS

- Whorf's conclusions are disputed by many linguists. The linguist Ekkehart Malotki wrote a book, *Hopi Time*, which discusses Hopi words and concepts for time, and it shows that the view of Hopi language as being completely timeless is incorrect. However, other linguists feel that Whorf's ideas have been misinterpreted by his detractors.
- Perhaps the first example of the Sapir-Whorf hypothesis in science fiction was Newspeak, the language imposed by the Party on the people of Oceania in George Orwell's novel *1984*. Newspeak uses language to restrict insight rather than to expand it. It is unclear if Orwell knew of the Sapir-Whorf hypothesis, but as a journalist, he was keenly sensitive to the power of language.
- The science fiction writer Samuel Delaney used a similar idea in his novel *Babel-17*, in which Babel-17 is a language designed as a weapon. Its aim is to erase the self-consciousness of the people who speak it. In the language, there is no word for *I*.

TESTING THE SAPIR-WHORF HYPOTHESIS

- There have been a few attempts to test the Sapir-Whorf hypothesis. Most of these attempts rely on defining the hypothesis more formally than Whorf did himself. One argument against the hypothesis has to do with the development of color terms over time. These seem to follow rules that are universal across different cultures.
- Linguists became interested in how language describes color because of Homer's classic works, the *Iliad* and the *Odyssey*. These works depict events that may have taken place around 1200 BCE. In them, there are very few words used to describe color.

- ❏ The British politician William Gladstone wrote about this in his short book *Studies on Homer and the Homeric Age*. He wrote that essentially there were only 3 descriptions of coloration used in these works: dark, covering a range of colors from black to dark brown; light, covering white and other lighter shades; and red, used to describe everything from the color of the “wine-dark sea” to purple to the color of blood. While there were about 6 or 7 terms used to describe color, many of them were synonyms.
- ❏ Gladstone’s book led linguists to study the evolution of color terms in different languages. They found that color terms varied across languages and across time, but they evolved along similar lines. All languages have words categorizing light and dark. Other color terms fall into metacategories describing similar colors. As languages evolve, the metacategories are broken up into smaller categories that differentiate between subtler colors.
- ❏ These rules seem to be consistent across almost all languages. Differences in color categories and metacategories probably have to do with the evolution of languages to adapt to changing circumstances: Languages characterized by few color terms are generally used by isolated peoples with limited contact with other cultures.
- ❏ Cultural diffusion, technological advancement, and historical progress seem to correlate with higher numbers of terms. Paradoxically, this result seems to both support a weak version of the Sapir-Whorf hypothesis and also to refute the stronger version that claims that language determines thought.
- ❏ The fact that societies develop a larger vocabulary of color terms implies that the concept of coloration develops over time and that members of different societies think of different colors in different ways. However, the fact that there seems to be a regular progression in the development of these terms indicates that there are rules that languages follow, which are probably based on the perception of color by the brain. In that way, perception determines language, and not vice-versa.

PHYSICS AND THE SAPIR-WHORF HYPOTHESIS

- Another study of the Sapir-Whorf hypothesis involves the field of physics. People in this field use common terms like *force* and *energy*, but in physics, these terms have very specific meanings. For example, in ordinary English, the word *work* has a range of meanings, including effort and what a person does for a living. However, in physics, the term *work* refers to a form of energy: It's a force acting through a distance.
- In 2003, a group of physicists investigated the following question: Do the differences in the use of words between everyday life and physics inhibit learning of physics? The conclusion of their survey, performed with both American and Mexican students, was that students who could distinguish between the common usage and physics usage were more likely to do better in physics classes than ones who couldn't. This is perhaps unsurprising, but it does show how language can influence thought, even in a highly mathematical field.

DESIGNING LANGUAGES

- The most common use of linguistics in science fiction today is the design of languages for aliens or fantasy creatures. These are typically called constructed languages.
- J. R. R. Tolkien is the best-known constructor of invented languages for fiction. He was the author of *The Hobbit*, *The Lord of the Rings*, *The Silmarillion*, and other works. Along with being an author, he was an Oxford professor and a well-respected linguist.
- The first language he developed that was used in his fiction was Quenya, which was one of the elvish languages later used in *The Lord of the Rings* and *The Silmarillion*. He started working on these languages when he was a teenager. He said more than once that one of the main motivations for writing the stories he is best known for was to give him an excuse to use the languages.

- ❏ Quenya was mainly based on Finnish. The script he developed for it, Tengwar, doesn't resemble the Latin alphabet. He invented several different Elvish languages and at least one human language for his mythos. He also developed the languages of the dwarves and of Mordor enough to sprinkle the books with phrases from them.
- ❏ Marc Okrand, who designed the Klingon language for *Star Trek*, took a very different tack. He tried to make Klingon sound different than most human languages and have a very different grammar as well.
- ❏ Most science fiction writers don't create entire languages but often sprinkle their works with alien-sounding words. Ursula K. Le Guin, for example, only created a few words for the magical language used in her Earthsea novels and stories.
- ❏ Larry Niven creates alien-sounding words and names with many consonants and few vowels. Phssthpok, the name of the alien in his novel *Protector*, is one good example.
- ❏ Building a language, or at least coming up with words or symbols that sound or look good, is part of world-building, and conscientious science fiction writers put a large amount of effort into it. In the movie *Arrival*, images of the written language designed for the Heptapods by the artist Martine Bertrand are ring-like and self-referential. They are designed to reflect the alien's circular view of time.
- ❏ Tolkien designed elven languages to sound euphonic and graceful and the languages of Mordor to be harsh and guttural. In his view, language building aids in the process of subcreation—that is, the invention of stories and imaginary worlds.

Suggested Reading/Viewing

Adams, ed. *From Elvish to Klingon*.

Tolkien, *The Lord of the Rings*.

Villeneuve, dir., *Arrival*.

COSMOLOGY, THE MIND, AND *STAR MAKER*

ONE OF THE WONDROUS ASPECTS OF SCIENCE FICTION IS THAT ITS STORIES RANGE IN SCALE FROM THE SUBATOMIC LEVEL TO THE UTTERLY COSMIC. THIS LECTURE SHOWCASES A NOVEL THAT WORKS ON A COSMIC SCALE: THE 1937 WORK *STAR MAKER*, WHICH ENCOMPASSES THE ENTIRE UNIVERSE, FROM ITS BEGINNING TO ITS END AND BEYOND. IN THE NOVEL, AUTHOR OLAF STAPLEDON HIGHLIGHTS THE ASPIRATIONS AND FEARS OF INTELLIGENT LIFE IN THE UNIVERSE AGAINST THIS COSMIC BACKDROP.

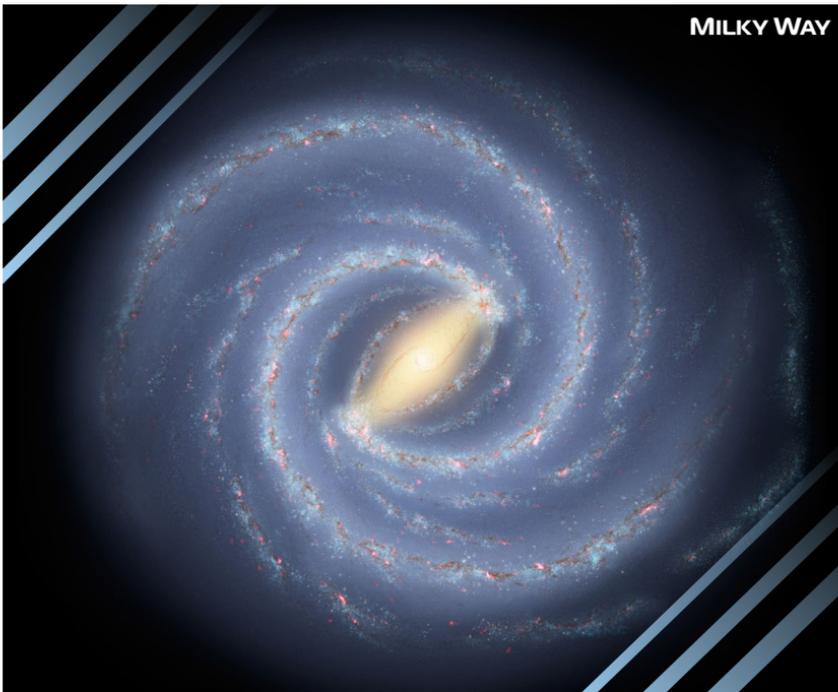
BACKGROUND ON *STAR MAKER*

- ❏ *Star Maker* is modeled on an older work: Dante Alighieri's *Divine Comedy*. *Star Maker* begins with an unnamed narrator, who probably represents the author. He is sitting on a hilltop looking at the stars after a fight with his wife. He is meditating on his own troubles and the troubles of the world; the novel is set in the interwar years of the 1930s. Suddenly, he finds himself a disembodied being floating among the stars.
- ❏ He spends an unknown amount of time floating in panic before he discovers that by an act of will, he can move between the stars. He soon finds another Earth-like planet, which is inhabited by an intelligent humanoid species he calls the Other Men. The narrator then discovers he can possess their bodies and communicate with them, mind to mind. He enters into a symbiotic relation with an Other Man named Bvalltu. They find that they can dissociate from Bvalltu's body as well, and so they go on to explore the cosmos together.
- ❏ The novel takes place over huge cosmic distances and over cosmic timescales. The protagonist finds that he is traveling through both space and time. He is guided in some way to find other intelligent species whenever and wherever they flourish throughout the cosmos. For example, his trip to the world of the Other Men takes place billions of years before our sun even formed. He is joined in his quest by other like-minded beings, and soon they become a disembodied group mind, searching the cosmos from the beginning to the end for life and intelligence.

AN EXPANDING UNIVERSE

- ❏ Stapledon used the very latest knowledge of cosmology when writing the book. Cosmology is the study of the universe on its largest scales and the investigation of its origin and ultimate fate. The early 20th century saw many advances in our knowledge of the universe, and the most important was the discovery that the universe was expanding.

- ❖ A galaxy is a collection of billions of stars bound together by gravity. Our galaxy, the Milky Way, is a relatively large one: It contains some 300 billion stars and is about 100,000 light years across. It is a barred spiral galaxy. Our sun is about $\frac{2}{3}$ of the way from the center of the galaxy, in one of the spiral arms.
- ❖ There are more than 100 billion galaxies in the visible universe. Distances between galaxies typically range from millions to billions of light years.
- ❖ In 1929, Edwin Hubble found that distant galaxies were all moving away from our galaxy. He also found that the farther away a galaxy was, the faster it moved. This motion is relative: Anyone in any other galaxy would measure all the other galaxies moving away from them.
- ❖ If one were to wind back the clock and reverse all of the galaxies, they intersect at a time some 13.7 billion years ago. Hubble didn't know the number that exactly, but he and other astronomers realized the implications: The universe has not existed forever; rather, it began at that remote date in the past.



THE STANDARD MODEL AND STAPLEDON

✚ This beginning was quickly dubbed the big bang, and it has become the main part of what is known today as the Standard Model of the origin of the universe. Stapledon was well aware of the theory, and he incorporated it into the novel in 2 different ways:

- One of the ways in which the protagonist realizes that he has been traveling in time is that the galaxies are much closer together as seen from the Other Earth than from our world.
- From contemporary cosmology, Stapledon also draws on the heat death of the universe at the end of time. This ties in with the great theme of the novel: the fate of intelligent life in the universe and its search for meaning in what appears to be an uncaring cosmos.

STAPLEDON'S DETAILS

✚ The book is one of the richest in detail of all science fiction. Stapledon shows a breadth of imagination and originality that very few writers have achieved. The details of the different worlds are striking, and he avoids the trap of having his sentient beings all act and think in the same way that humans do. For example, he invents a race of sentient boats on an ocean world; on another ocean world, he creates 2 races, intelligent crabs and dolphins, that bond together symbiotically.

✚ Another has intelligent swarms of birds. None of the individuals are sentient by themselves, but with brains linked by radio contact, the entire flock is one entity. Another airless world has sentient plants capable of limited movement.

✚ Stapledon invented several ideas that were used by other science fiction writers and by scientists. The most famous one is the concept of the Dyson sphere (or Dyson shell). In the novel, as the stars grow colder, the intelligent life in the universe build shells around the dying suns to fully utilize their energy.

- This inspired the physicist Freeman Dyson to propose that as intelligent civilizations became more developed, they would need exponentially larger sources of energy. He proposed that to maximally harvest the energy of a star, an advanced civilization might build a large network of satellites orbiting the star, which would block the star's light and convert it into useful energy.
- Dyson did not suggest a solid shell, which would drift into the star and be destroyed. Stapledon's original idea is unworkable for that reason, but Dyson acknowledged that the basic idea came from him. However, the Dyson shell is usually portrayed as a solid sphere in much science fiction.
- There have been searches for Dyson shells, but none have been found. One problem with finding them is that old stars tend to blow out a lot of material as they age, which can mimic what a Dyson shell would look like to a faraway observer.

TYPES OF CIVILIZATIONS

- A civilization that can build a Dyson shell must have access to much larger energies than our current one. In 1964, Nikolai Kardashev described a scale of cosmic civilizations, which he put into 3 categories:
 - Type I civilizations are similar to the present day's, which uses about 18 terawatts of power. A terawatt is 1 trillion watts.
 - Type II civilizations are capable of harnessing the entire output of its star, or about 400 trillion terawatts. This is the type of civilization envisioned by Freeman Dyson, capable of building a Dyson shell.
 - Type III civilizations are capable of harnessing all of the energy of its galaxy, or about 400 trillion, trillion terawatts.

DYSON SHELL



- ❏ Other variants have been proposed as well. Type II civilizations are pretty common in science fiction, as any civilization capable of traveling between the stars is almost by definition one of these. Even if they don't build a Dyson shell, any star-traveling species must be capable of harnessing huge energies. The Federation of *Star Trek* is a strong example.
- ❏ Type III civilizations are much rarer in science fiction because it is hard to write plausibly about a galaxy-spanning civilization. In books, the clearest example of Type III civilizations—or at least ones between Type II and Type III—are found in the Culture novels of Iain Banks. The Culture is a loose conglomeration of various races, including humanity, which live in a rather anarchic freedom loosely controlled by Minds—highly advanced artificial intelligences.

THE FATE OF THE UNIVERSE

- Stapledon used the very best cosmology that he knew when he wrote *Star Maker*, but cosmology has advanced since then. There are 3 major features that have been added to the overall theory of the big bang since Stapledon's time. These are the concept of the inflationary universe, the fact that most of the mass of the universe is invisible, and the fact that most of the mass and energy content of the universe is in a form that is completely unknown.
- One issue is that the fate of the universe is very strongly tied to the amount of matter that it contains. There are 2 opposing effects: the speed of the galaxies moving outward and their gravitational attraction that, all other things being equal, should slow the expansion down.
- If there is more mass than some critical value, the expansion will halt and re-collapse. If there isn't enough, the universe will keep on expanding forever—Stapledon's vision. In his time, it wasn't known whether or not there was enough mass. However, in the 1960s, cosmologists realized something strange: There is no particular reason for the mass in the universe to be very close to the critical value, at least not as far as anyone knew.
- But the total mass in the Universe is close to the critical value—about 30% of it, if dark matter is included. This may not sound close at first, but in principle, it could be any value: a millionth of the critical value, or a million times it. Moreover, if the total mass was much smaller than the critical value, the universe would have expanded too quickly for the stars and galaxies to form; if there was a lot more, it would have re-collapsed much too fast for that to happen. For life to exist in the universe, the total amount needs to be near the critical value.
- In the early 1980s, a physicist named Alan Guth realized that there was a way out of the dilemma: inflation. If the universe expanded very rapidly for a very short time just after the big bang, the amount of matter would be almost exactly at the critical value.

DARK MATTER AND ENERGY

- It has been clear since the 1960s that there is much more matter in the universe than we can detect with our telescopes. This is dark matter. We detect it because of its gravitational effect on the matter that we can see. There is 10 times more dark matter than regular, visible matter in the universe. Physicists think that it is composed of exotic particles that haven't been detected yet.
- The final issue is the existence of dark energy. This was detected in 1998. It seems that galaxies should be slowing down because of their mutual gravitation, but they aren't. When astronomers look to the most distant galaxies, it turns out that the galaxies are actually picking up speed—accelerating away from us.
- Dark energy is the factor causing the acceleration. Very roughly speaking, the universe is 3% normal matter, 27% dark matter and 70% dark energy. Put differently, we understand only 3% of what the universe is made of.

CONCLUSION

- Stapledon likely would have been thrilled by these latest discoveries if he were alive. He probably would have figured out how to work them into his novels. Very few other science fiction writers have attempted such cosmic themes: one of the few is Greg Bear, in his novels *Eon* and *Eternity*. These were written before the latest discoveries in cosmology, however, and use ideas that have become outdated.
- The fate of the universe follows closely along the lines that Stapledon laid out: after some length of time, all of the stars will burn out as their nuclear fuel is exhausted. This may happen in 100 billion to 1 trillion years.
- It isn't clear how long life can exist in this universe, but there may be other universes. The mechanisms that cause inflation could possibly be in operation all of the time, creating new universes in some other pocket of spacetime. This hypothesis is called eternal inflation. It is almost certainly untestable, but perhaps there will be some place for life for all of eternity.

Suggested Reading

Alighieri, *The Divine Comedy*.

Dyson, "Search for Artificial Stellar Sources of Infrared Radiation."

Kay, Palin, and Blumenthal, *21st-Century Astronomy*.

Singh, *Big Bang*.

Stapledon, *Star Maker*.

Wilson, *Spin*.

SCIENCE FICTION'S PURPOSE: *CHILDHOOD'S END*

IT IS DIFFICULT TO WEAVE TOGETHER COSMIC-SCALE CONSIDERATIONS AND HUMAN TALES SO THAT THEY FIT INTO THE SAME STORY, BUT A FEW STORIES PULL IT OFF. THE EPITOME OF SUCH STORIES IS *CHILDHOOD'S END* BY THE GREAT NOVELIST SIR ARTHUR C. CLARKE. IT DELIVERS CATHARSIS THROUGH THE RESOLUTION OF THE CENTRAL QUESTION IN THE NOVEL. THIS LECTURE FOCUSES SPECIFICALLY ON THE FIRST EDITION OF THE NOVEL, PUBLISHED IN 1953, RATHER THAN THE 1990 REVISION OR THE TV MINISERIES.

KEEP IN MIND THAT THIS LECTURE EXPOSES THE SECRET AT THE HEART OF THE NOVEL. IF YOU DO NOT WANT YOUR EXPERIENCE OF THE BOOK TO BE SPOILED, READ THE NOVEL BEFORE CONTINUING.

THE FIRST PART OF THE NOVEL

- ☛ The following is a quick summary of the first part of the novel. In the year 1975, as competing groups from the United States and the Soviet Union are planning a crewed mission to land on the Moon, aliens in huge spacecraft appear in the sky.
- ☛ These are representatives of the Overlords. This name is given to them by humans; it's not their own designation of themselves. The Overlords quickly establish benevolent control over the Earth, allowing most governments independence but enforcing basic human rights and forbidding war between countries.
- ☛ They act through the United Nations, and particularly through the secretary-general, Rikki Stormgren. The secretary general is one of the only humans that Karellen, the mysterious leader of the Overlords, will speak to.

TECHNOLOGY AND PREDICTIONS

- ☛ One of the central mysteries of the novel is why they came to Earth, and why, in the first part of the novel, they refuse to show themselves to humans. The aliens are clearly members of a Type II or Type III civilization: They control energies that allow them to travel between the stars with ease.
- ☛ The Overlords can't travel faster than light, but they have some type of star drive that can move their ships at better than 99% of the speed of light. They also have other highly advanced technology: When the Secretary General Rikki Stormgren is kidnapped, the Overlords track him using microscopic drones. They subdue the kidnappers by slowing down their internal time, allowing Stormgren to walk out from among a series of frozen dummies.
- ☛ While these technologies still don't exist, Clarke was able to predict some notable features of the modern world. For example, there is one throwaway line in the novel about 2 future inventions that strongly impact human culture and mores. The first is a simple blood test that allows the paternity of any child to be determined without error. That is, in modern terms, DNA testing. The other invention that Clarke foresaw was the oral contraceptive.

THE OVERLORDS REVEALED

-  The Overlords are benevolent despots, and eventually, Earth accepts their rule. After spending 50 years pacifying Earth, they reveal themselves, making it clear why they hadn't shown themselves beforehand. They look like devils personified, with barbed tails, horns, and wings.
-  The idea of an alien race conquering humanity for its own good, ending all wars, and ushering in a golden age is not unique to Clarke. Alien invasion and alien salvation are common elements in a large number of science fiction works.
-  If that was all there was to *Childhood's End*, it might still be a good novel, but there is much more to it. Throughout *Childhood's End*, there is an air of wistfulness that isn't found in other writings. It says of humanity in the years after the invasion that humanity was living in a golden age. One passage reads:

Gold was also the color of sunset, of autumn: and only Karellen's ears could catch the first wailings of the winter storms.

-  It is eventually revealed that the Overlords didn't come to Earth to save us from nuclear war. Rather, they came at the behest of a being they call the Overmind to save us from a far worse fate. The Overlords are individually geniuses compared to humans, and they are also taller, quicker of mind and body, and seemingly immortal. But they do not possess one quality that humanity shares with the Overmind: psychic powers.

POSSIBLE FUTURES AND HUMAN RESPONSES

-  It may be difficult to find psychic powers believable. However, science fiction is not about predicting the future but envisioning possible futures and the response of people, or humanity as a whole, to them. *Childhood's End* delivers on both fronts: It is like *Star Maker* in that it shows intelligent life confronted with existential crisis. But it is also like Becky Chambers's *Wayfarers* novels in that it highlights stories of people who are caught up in these events. It manages both simultaneously.

- Humanity stagnates under the Overlords: Scientific progress slows to a crawl, and true artistic endeavors die out, except in a few places such as New Athens, where the Greggson family of characters eventually settles. This is the price that humanity pays for its peace and prosperity.
- The real reason that Overlords have come to Earth is humanity's collective potential for psychic powers—telepathy, precognition, and psychokinesis. Humans must be carefully shepherded to avoid a psychic catastrophe that could spread far beyond Earth. The danger is that Earth might become the equivalent of a psychic cancer that would threaten the universe.
- Under the guidance of the Overlords, the children of Earth begin to merge their minds to become a collective organism capable of wielding immense powers. Almost all children who have not gone through puberty become part of this; none who are older do. At the climax of the novel, they leave Earth to join the Overmind, destroying Earth in the process.

THE END OF *CHILDHOOD'S END*

- The final part of *Childhood's End* centers around the parents of the first “breakthrough,” as the child who first experiences the call of the Overmind is called.
- At first, Jeffrey Greggson begins by having strange dreams of other worlds, which he is actually visiting psychically in his sleep. His parents, George and Jean, try to find out what is happening with mounting worry until the Overlords step in. This part of the novel is written with amazing deftness, as it combines ordinary human fears with cosmic vision and even wonder on the part of the Overlords, who are secretly recording his dreams.
- The pathos of this section is heartbreaking, more so since Clarke has prepared the ground thoroughly. At the very end of the novel, nearly 80 years after the children have been segregated by the Overlords to prepare for their assimilation by the Overmind, a human returns to Earth.

Jan Rodricks stowed away on an Overlord ship to visit their world; because of relativity, although 80 years have passed on Earth, he aged only a few months on the Overlords' starships. He returns to find a world inhabited only by the children, now outwardly silent and being molded by the Overmind. The adults died out years before because of the strange tragedy of this last generation of humanity.

His status as the last human left alive is perfectly depicted in one sentence, which parallels the achievements of humanity before its assimilation:

Most of the time ... he sat before the keyboard
and filled the air with his beloved Bach. ... Jan had
always been a good pianist—and now he was the
finest in the world.

Karellen asks Jan to stay on Earth when the Overlords leave to relay to them via radio what is happening on Earth. He agrees, and he stays to be destroyed with the planet. Among his last thoughts is the following excerpt, which comes when he thinks of the disparate fate of the Overlords and of humanity, now assimilated into the Overmind:

The road to the stars was a road that forked in two
directions, and neither led to a goal that took any
account of human hopes or fears.

PRESERVING MYSTERY AND WONDER

Clarke manages to preserve the mystery and wonder of the Overmind. He does this by a process common in science fiction: by presenting its actions rather than its motives. It attempts no communication with humanity.

Jan Rodricks sees the Overmind, or at least a manifestation of it, on the Overlords' home world; he sees it as a mountain, impossibly high, with ever-changing features, but he doesn't understand what he is seeing. The Overlords who are minding him won't discuss it, but he realizes that they saw something entirely different and wonders what it was trying to tell them.

Even the Overlords retain some mystery after the great secret is revealed. They work for the Overmind, but apart from a few cryptic words, they won't discuss why they serve it or for how long. Jan gets the sense that they are trying to free themselves from it and sees the tragedy of their species: The Overlords assist the Overmind, but they are unable to join any of the species that they oversee as those species merge with it.

WINGS AND GRAVITY

The Overlords of *Childhood's End* are winged. They live on a planet much larger than Earth. The Overlords' planet has a gravity that they somehow keep low enough to allow easy flight.

TRANSCENDENCE

The Overmind has abilities that transcend the physical world. It can travel faster than light, or perhaps more precisely, it seems to be omnipresent so that it doesn't need to travel anywhere. The children who are becoming part of it manipulate matter psychically: The Greggsons' infant daughter plays with her rattles psychokinetically, and her room's wallpaper changes colors on an irregular basis.

In the end, the children destroy the Earth completely as they join the Overmind. The Overmind represents life transcending the physical world, and it stimulates other intelligent species to join it. Karellen speculates that its motivation may be to figure out its own place in the universe but admits that despite their knowledge and power, the Overlords know almost nothing concerning the Overmind.

- Thus, the Overmind may itself be only the next layer: It may have its own fears and beliefs, which are unknown to the species that it controls. There might be other, even more inconceivable beings, above it. As the world ends, Jan believes that Karellen is playing a double game by obeying the Overmind but also studying it to allow the Overlords to eventually free themselves from their servitude.
- The novel offers something very rare in science fiction: catharsis, the purging of strong emotion through art. *Childhood's End* isn't simply a tragedy. Jan reflects that this end represents an artistic fulfillment of humanity—its apotheosis, beyond any dreams of religion or science. *Childhood's End* shows that its genre can inspire true humility and awe in front of the grandeur of the universe.

Suggested Reading

Clarke, *Childhood's End*.

James, *The Varieties of Religious Experience*.

QUIZ

- 1 The Drake equation is an attempt to calculate:
 - a The number of stars which have planets circling them in our galaxy.
 - b The number of planets in our galaxy.
 - c The number of planets with life on them in our galaxy.
 - d The number of planets with life that host advanced technological civilizations in our galaxy.

- 2 True or false: It requires much less energy to contact an alien civilization by radio than to actually go out and meet them.

- 3 During a solar eclipse, the region of totality is that portion of the Earth which is within:
 - a The umbra of the Moon's shadow.
 - b The penumbra of the Moon's shadow.
 - c Outside the Moon's shadow entirely.

- 4 True or false: Many odd meteorological phenomena every year are mistaken by observers as unidentified flying objects.

- 5 Before and after natural disasters such as hurricanes, Walmart stocks up on:
- a Strawberry Pop-Tarts.
 - b Beer.
 - c Both A and B.
 - d Neither A nor B.
- 6 On average, how long will it take for all of the air in a typical room to rush over to one side?
- a About a day.
 - b About a year.
 - c About a century.
 - d Don't hold your breath: It won't happen during the entire lifetime of the universe.
- 7 The Sapir-Whorf hypothesis holds that:
- a Language frames how humans perceive reality.
 - b Language doesn't frame how humans perceive reality.
 - c Language may or may not frame how humans perceive reality.
 - d Whorf was the best character on *Star Trek: The Next Generation*.

- 8** The Klingon language designed by Mark Okrund:
- a** Was designed to be as similar as possible to real human languages.
 - b** Was designed to be very different from most human languages.
 - c** Was based on Finnish and Latin.
 - d** Is spoken by more people today than the Basque language.
- 9** A Dyson sphere is:
- a** The ball-shaped part of a popular vacuum cleaner.
 - b** A hypothetical shell around a star created by an advanced alien race.
 - c** Badly named, because it can't be solid.
 - d** Both B and C.
- 10** True or false: Most of the mass-energy content of the universe is the matter that we can see through telescopes.
- 11** True or false: Electrical stimulation of the parietal lobes of the brain can cause deeply religious feelings.

12 Titan, the largest moon of Saturn, has:

- a Lakes.
- b Rivers.
- c Volcanoes.
- d All of the above.

ANSWERS

1 d; 2 true; 3 a; 4 true; 5 c; 6 d; 7 a; 8 b; 9 d; 10 false; 11 true; 12 d

BIBLIOGRAPHY

LECTURE 1

Adler, Charles L. *Wizards, Aliens, and Starships: Physics and Math in Fantasy and Science Fiction*. Princeton University Press, 2014. Written by this course's instructor, *Wizards, Aliens, and Starships* and this lecture series are complementary to one another. In particular, the physics of fantasy stories are discussed in the book, which is not done to a great extent in this lecture series, except in Lecture 17.

Chambers, Becky. *The Long Way to a Small, Angry Planet; A Closed and Common Orbit*; and *Record of a Spaceborn Few*. Harper Voyager, 2016, 2017, and 2018, respectively. These are the works referenced in the first lecture. They combine hard scientific themes with very human stories.

O'Neill, Gerard K. *The High Frontier*. William Morrow and Company, 1977. This work discusses the possibility of building huge space colonies capable of supporting literally millions of people in artificial self-sustaining environments.

LECTURE 2

Anderson, Poul. "How to Build a Planet." This little essay is the best ever written about including science in science fiction. It has been collected under various names in several places; one version, titled "The Creation of Imaginary Worlds," can be found in the book *Science Fiction: Today and Tomorrow*.

Niven, Larry. *Protector*. Ballantine Books, 1973. *Protector* is set in the Known Space universe. This is the setting of many of Larry Niven's stories, and it features faster-than-light travel with many worlds and alien races.

Niven, Larry, and Jerry Pournelle. "Building *The Mote in God's Eye*." *Galaxy* magazine, 1976. In this essay, the authors of *The Mote in God's Eye* describe how they designed both the advanced science and the social setting of the novel.

LECTURE 3

Verne, Jules. *From the Earth to the Moon*. (Original publication: *De la terre à la lune*. Pierre-Jules Hertznel, 1865.) Jules Verne was the inventor of so-called hard science fiction— science fiction involving the most realistic science of the day. Due to the age of this book, many English translations are available, including a free one at Project Gutenberg.

Wells, H. G. *The First Men in the Moon*. George Newnes, 1901. This book provides an interesting contrast to Jules Verne's book. The science is pure fantasy, unlike *From the Earth to the Moon*. However, the story itself is more interesting, and genuinely frightening in places.

Winter, Frank H. *The First Golden Age of Rocketry*. Smithsonian, 1990. This is a somewhat academic book about the history of rocketry.

LECTURE 4

Dole, Stephen. *Habitable Planets for Man*. Rand Corporation, 1964. This remarkable book is available free on the Internet. It is technical, but despite its age, the science in it is fairly accurate. Also used in Lecture 5.

Le Guin, Ursula K. *The Left Hand of Darkness*. Ace Books, 1969. Le Guin clearly thought hard about the setting for her novel. Gethen's climate influences every aspect of the culture of its inhabitants.

Scharf, Caleb. *Extrasolar Planets and Astrobiology*. University Science Books, 2009. This is a very readable book about the possibility of life in the universe. Also used in Lecture 5.

LECTURE 5

Cameron, James, dir. *Avatar*. 2009. A beautiful and scientifically accurate movie.

Cixin, Liu. *The Three-Body Problem*. Translated by Ken Liu. Tor Books, 2016. A very interesting novel about humanity's first contact by an alien race.

LECTURE 6

Persichetti, Bob, Peter Ramsey, and Rodney Rothman, dirs. *Spider-Man: Into the Spider-Verse*. 2018. There are many Spider-Man movies, and most of them are good. This one is beautifully animated and features many versions of its namesake hero.

Whedon, Joss, dir. *The Avengers*. This movie is a treasure trove of bad science. As such, it is a great resource for teaching physics. Additionally, Whedon is a wonderful writer and director.

LECTURE 7

Kubrick, Stanley, dir. *2001: A Space Odyssey*. 1968. The gold standard for the use of science in science fiction films. Despite the movie's age, the science is still amazingly accurate (as long as you ignore the final half-hour).

Pichel, Irving, dir. *Destination: Moon*. 1950. The science in this movie was good: The propulsion system in it anticipated the Nerva program of the 1960s, even if atomic powered rockets have never been used in real life. Like all science fiction of the time, it grossly underestimates the infrastructure needed for space travel.

Van Riper, A. Bowdoin. *Rockets and Missiles: The Life Story of a Technology*. Johns Hopkins University Press, 2007. This is a must-have book if you are interested in the history of rocketry and missiles.

LECTURE 8

Lucas, George, dir. *Star Wars: Episode IV—A New Hope*. 1977. This is a wonderful movie. However, there is not much science in it, making it very useful for the purposes of this lecture series.

Weir, Andy. *The Martian*. Crown, 2014. A well-written and scientifically accurate book about how an astronaut accidentally left behind on Mars survives there for more than a year.

LECTURE 9

Tirman, John, ed. *The Fallacy of Star Wars: Why Space Weapons Can't Protect Us* Vintage Books, 1983. This refers to the Reagan-era space-based defense program, not to the movie. It goes through the scientific and political shortcomings of the program.

United Nations General Assembly. Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies. Ratified on December 19, 1966. This is the so-called outer space treaty that limits what the signatories can do in outer space. In particular, it forbids most forms of warfare in outer space.

LECTURE 10

Dyson, George. *Project Orion: The True Story of the Atomic Spaceship*. Henry Holt and Co., 2002. This is the story of Project Orion, the program to develop a spaceship powered by a nuclear bomb. The writer, George Dyson, is the son of one of the main scientists working on the project: Freeman Dyson, who originated many of the ideas found in this lecture series.

Star Trek: The Original Series. 1966–1969. Created by Gene Roddenberry, the original *Star Trek* is arguably the most important science fiction television series of all time. Episodes you should watch include “Amok Time,” “The City on the Edge of Forever,” and “The Trouble with Tribbles,” among many others.

LECTURE 11

Heinlein, Robert. *Time for the Stars*. Scribner's, 1956. This is story based around the so-called twin paradox of relativity. It is still fun to read, if a bit dated.

Taylor, Edwin, and John Wheeler. *Spacetime Physics*. W. H. Freeman, 1992. There are many books about relativity. All of them require somewhat advanced mathematics. This is one of the friendliest of the lot.

LECTURE 12

Nolan, Christopher, dir. *Interstellar*. 2014. Both Nolan and Kip Thorne, the scientific consultant on the film and an expert on the theory of relativity, went to great lengths to make the film scientifically accurate. In the film, unknown aliens open a wormhole near the orbit of Saturn to save the human race from a blight destroying all crops on Earth.

Thorne, Kip. *Black Holes and Time Warps: Einstein's Outrageous Legacy*. W. W. Norton and Co., 1994. This book is a popular account of the theory of relativity, including its history and its weirder predictions.

———. *The Science of Interstellar*. W. W. Norton and Company, 2014. Meant for the advanced reader, this book goes through the science used in the film *Interstellar* in great detail.

LECTURE 13

Adams, Douglas. *The Restaurant at the End of The Universe*. Pan Books, 1980. This is the second novel in the Hitchhiker's Guide to the Galaxy series. Arthur Dent and his companions travel in time.

Carruth, Shane, dir. *Primer*. 2004. Beautifully filmed on a tiny budget, this is probably the most complicated time travel movie ever made.

Doctor Who. The original series began in 1963, and a relaunch occurred in 2005. It would be impossible to discuss time travel without talking about the Doctor. The episode “Blink” is the one that deals with time travel paradoxes in the most direct way.

Niven, Larry. “Exercise in Speculation: The Theory and Practice of Time Travel.” *Vertex*, 1973. This essay concerns the problems involved in putting time travel into stories. The most entertaining section is on how badly English is suited to time travel. The essay can be found in a number of Niven’s short story collections, including *All the Myriad Ways* and *N-Space*.

———. “Rotating Cylinders and the Possibility of Global Causality Violation.” *Analog*, 1977. The title of this story is taken from a scientific paper by the physicist Frank Tipler. In the story, Niven speculated that the universe would do bad things to people who tried to create time machines.

Tipler, Frank. “Rotating Cylinders and the Possibility of Global Causality Violation.” *Physical Review D*, 1974. This is the paper that Larry Niven based his story on.

LECTURE 14

Blish, James. *Spock Must Die!*. Bantam Books: This was one of the very first *Star Trek* novels ever written, and it incorporates many of the tropes found in later ones.

Niven, Larry. “Exercise in Speculation: The Theory and Practice of Teleportation.” *Galaxy*, 1969. In this essay, Niven considers the science behind teleportation.

LECTURE 15

Battlestar Galactica. Rebooted series, 2004. The interplay between humanity and the robotic Cylons is complex—no one is completely good or evil.

Čapek, Karel. *R.U.R.* 1920. The play that originated the term *robot*. It's still worth reading.

Gibson, William. *Neuromancer*. Ace, 1984. This is the novel that originated the term *cyberspace*. In it, a rogue AI tries to free itself from its human masters.

Hofstadter, Douglas. *Gödel, Escher, Bach: An Eternal Golden Braid*. Basic Books, 1979. This book plays around with themes from mathematics, computer science, music, molecular biology, and many other subjects.

Jacques, Jeff. *Questionable Content*. 2003. This ongoing webcomic could be set in the real world, except for its androids and artificial intelligences. This webcomic is not safe for work. The series alternates between science fiction and realism, sometimes strip by strip.

"The Measure of a Man." Episode of *Star Trek: The Next Generation*. This is science fiction at its best, highlighting the moral and ethical consequences of scientific advances: What rights does an artificial human have?

LECTURE 16

Gibson, William, and Bruce Sterling. *The Difference Engine*. One of the most important steampunk novels.

Westerfeld, Scott. The Leviathan series: *Leviathan*, *Behemoth*, and *Goliath*. Simon Pulse, 2009, 2010, and 2011, respectively. Steampunk and young adult romance incorporating real historical figures. It also has a huge floating whale.

LECTURE 17

Bennioff, David, and D. B. Weiss, creators. *Game of Thrones*. 2011–2019. Lecture 17 used the TV series rather than the Song of Ice and Fire novel series by George R. R. Martin that it was based on. The dragons are more anatomically accurate than in some other depictions: Their wings are part of their arms, as in birds and flying mammals like bats.

Tennekes, Henk. *The Simple Science of Flight*. A somewhat technical book on flight, but well written. Contains the Great Flight Diagram.

LECTURE 18

Herbert, Brian. *Dreamer of Dune: The Biography of Frank Herbert*. This is the biography of the author of *Dune* by his son. It includes the origin story for the novel.

Herbert, Frank. *Dune, Dune Messiah, Children of Dune, and God Emperor of Dune*. There are more books in the Dune series written by Frank Herbert, and even more by Brian Herbert (Frank's son) and Kevin Anderson. However, these first four are the most pertinent for this lecture series.

McNelley, Willis E. *The Dune Encyclopedia*. Berkley Books, 1984. This is a massive book devoted to the Dune universe. There are entries on the science, history, sociology, mythology, and much more concerning nearly every aspect of the novel series.

Watson, Andrew J., and James A. Lovelock. "Biological Homeostasis of the Global Environment: The Parable of Daisyworld." This paper describes a world where the temperature is regulated by two species of daisies. It is a useful primer for any budding science fiction writer who is interested in creating a realistic ecology for his or her planet.

LECTURE 19

Sagan, Carl. *Contact*. Simon and Schuster, 1985. This novel is both moving and scientifically accurate, a difficult combination to achieve. The book was made into a very good movie starring Jodie Foster.

———. *Cosmos*, Carl Sagan. Random House, 1980. The series and the companion book made Carl Sagan famous to an entire generation of TV viewers.

LECTURE 20

Carter, Chris, creator. *The X-Files*. Original series began in 1993. This foundational television series brought the dark heart of American conspiracy theory to light.

Skeptical Inquirer and *Skeptic* magazines. These two magazines, devoted to the scientific investigation of the paranormal, are the best antidote to pseudoscientific works.

LECTURE 21

Anderson, Poul. "On Thud and Blunder." Web link: <https://www.sfw.org/2005/01/on-thud-and-blunder>. This is a great essay by the master on how to write fantasy and science fiction. The essay is devoted to the social sciences.

Asimov, Isaac. The Foundation trilogy: *Foundation*, *Foundation and Empire*, and *Second Foundation*. Gnome Press, 1951, 1952, and 1953, respectively. These are the first three novels of the Foundation series. They remain one of the most important novel series that Asimov wrote.

LECTURE 22

Adams, Michael, ed. *From Elvish to Klingon: Exploring Invented Languages*. Oxford University Press, 2011. This is a lovely book on invented languages.

Tolkien, J. R. R. *The Lord of the Rings*. Tolkien was the greatest mythmaker and developer of artificial languages of the 20th century. For the purposes of Lecture 22, most of the relevant information is found in the appendices at the end of the third volume, *The Return of The King*.

Villeneuve, Denis, dir. *Arrival*. 2016. This movie is based on "Story of Your Life" by Ted Chiang. Mysterious aliens arrive from parts unknown, and teach their language to a brilliant linguist, allowing her to see into the future.

LECTURE 23

Alighieri, Dante. *The Divine Comedy*. Cir. 1300. Larry Nevin has called this a work of early science fiction in that it used the most advanced science of its day to describe Dante's trip through the heavens.

Dyson, Freeman. "Search for Artificial Stellar Sources of Infrared Radiation." *Science*, 1960. This is the paper in which Dyson proposed the concept later known as a Dyson sphere.

Kay, Laura, Stacy Palin, and George Blumenthal. *21st-Century Astronomy*. Fifth ed. W. W. Norton, 2016. There are many textbooks on astronomy and astrophysics. This is the one this course's instructor uses to teach astronomy. The book uses math, but only as much as it needs to.

Singh, Simon. *Big Bang*. Harper Collins, 2005. A very readable account of one of the most important theories in all of science. The book is aging, so it does not have many of the more recent discoveries in it.

Stapledon, Olaf. *Star Maker*. Methuen, 1937. Stapledon was the first to use modern cosmology in his novels, and he did it better than almost anyone else since then.

Wilson, Robert Charles. *Spin*. Tor Books, 2005. In the near future, a mysterious field descends on the Earth, cutting it off from the outside universe. The novel links the attempt by humanity to figure out what is going on with the story of the lives of three people intimately connected with the attempt.

LECTURE 24

Clarke, Arthur C. *Childhood's End*. Ballantine Books, 1953. One of the major problems with science fiction is that few works deliver catharsis. This one has it in spades.

James, William. *The Varieties of Religious Experience*. This is perhaps the first serious psychological study of the phenomenon of religious belief.

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