Consolidation of Fine-Tuning

Executive Summary:

In this project we will consolidate the idea of fine-tuning across disciplines. The major components of this effort will be the production of a book and a website.

Hoyle famously calculated that the combined energy level of Beryllium and a Helium nucleus needed to form Carbon 12 via the triple alpha process, had to be in extremely close correspondence with an excited state of Carbon 12, and this has subsequently been often cited as evidence of extreme fine-tuning in astrophysics. However, this has been disputed in recent work, as apparent coincidences may be causally linked.

Another classic example is due to Dicke, who noted that the observed universe must be sufficiently old to allow the production of heavy elements through nucleosynthesis, independently of measurements of the Hubble expansion. This is commonly cited as a further example of fine-tuning, and similar multiverse interpretations have been motivated to account for this.

Fine-tuning is an interdisciplinary issue, with applications ranging from biology to philosophy, covering mathematics, physics, astronomy and others in between. This issue is often addressed without a detailed understanding of the systems in question, which leads to confused and ill-informed arguments which cannot be resolved without closer examination of the underlying problem. Our goal is to present a comprehensive review of the physics in which fine-tuning arguments are employed, and provide the correct arena for examining its nature.

Our activities will include:

- The production of a field-manual on fine-tuning written by experts in the substantive areas of interest in conjunction with the project personnel.
- The creation of an interactive website through which issues of fine-tuning can be explored by a broad audience of the public.
- The holding of a series of 4 seminars/year throughout the project with the field area experts to hold master classes with interested researchers, instilling collaborative efforts and producing a set of filmed interviews for distribution online.
- A project final conference which will bring together contributors and experts across fields to disseminate findings and the current status of fine-tuning within physics.

Technical Abstract:

"Fine-tuning" can be interpreted in several contexts, however, broadly speaking the term refers to having a narrow range of some parameter space for which an observed phenomenon takes place. In arguing that a system requires fine-tuning, a number of inputs are required: The broad theory space from which individual parameters are drawn, a measure on this space to allow us to specify what is meant by "narrow", and a clear statement of the phenomenon so that all ranges of parameters which lead to the

phenomenon can be identified. To make arguments explicit we must provide all the aspects of reasoning employed in producing a physical result.

This project will seek to provide these necessary details by writing a comprehensive field manual of fine-tuning. In producing a field manual to fine-tuning we will distribute these tools to the large array of fields in which issues arise. Our efforts will be centered on the production of a field manual for fine-tuning in which a consistent narrative of fine-tuning, detailing the inputs, assumptions and simplifications necessary to explain substantive phenomena, and representing the relevant physics in an accessible manner.

What Big Question will this project help answer?:

We will examine the question "Is the universe in which we live fine-tuned for our existence?" This project will give a framework in which questions of fine-tuning in a variety of settings, and as such allow for researchers to pose questions of naturalness of their theories in a universal manner. There are a multitude of fields in which the conditions of our existence can be probed, from biologists studying the right conditions on a planet for polymer chains to form into long enough chains to form proteins, through to the cosmologist investigating what range of cosmological constants would allow for these planets to even form in the first place. Taken individually, questions of fine-tuning can be considered to be big questions in their own right - "Is the Earth designed for life?","Does the universe maximize planetary production?" are questions of great importance when we seek to contextualize our existence. As a collection their intersection becomes far more significant: Perhaps the universe does not produce many planets but many of those it does are friendly to life, or the probability of life forming on any one planet is small but across the multitude of possibilities for planetary configurations the probability becomes large. It is therefore necessary to both consider problems from the narrow perspective of their direct relevance, examined in detail, and also form a broad view of how these systems interact on larger scales which may place these specific details into context.

Fine-tuning can present separate challenges, and within a single model distinct charges of tuning can be leveled: A system may exhibit a broad range of initial conditions for which a desired phenomenon occurs, yet within that model individual parameters (such as coupling constants) may appear fine-tuned. However a separate model in which these parameters are allowed to vary may show fine-tuning in the initial conditions. From differing assumptions about the system in question, radically different conclusions about the degree of fine-tuning required can be drawn.

Whether the universe could have existed in any different form, and if it indeed is highly specified to lead to our existence is a question that has enticed philosophers for centuries. Interpretations have ranged from Leibniz's belief that we lived in the best of all possible worlds, through to the Everett interpretation of quantum mechanics in which every possible event is played out somewhere in the multiverse. In all such interpretations there is the question of whether our experience is in some manner typical, the result of random chaotic conditions, or an incredibly special instance of what might be. These are questions of the largest scale, and questions to which we will give quantitative answers.

Any approach to the question of fine-tuning has broad ramifications within science, giving quantifiable measures physical models, biological systems, and the probability of the universe existing as we observe it. Furthermore the question has impact far beyond the scope of most science, raising questions for philosophy and theology. Whilst these questions will remain outside the remit of the project, placing these issues within a quantifiable scientific context will allow for a more informed and well founded discussion.

Project Description

Recent discussions of fine-tuning are adapted to specific problems at hand, and ad-hoc arguments are often invoked in an uncoordinated approach. We feel that it is timely to examine fine-tuning in a more systematic manner, presenting a comprehensive review of the established systems which exhibit the need for fine-tuning. Our aim would be to enable researchers in disparate disciplines to benefit from a detailed examination of fine-tuning in a variety of scenarios. These should allow us to highlight common techniques and algorithms, and encourage synthesis. A key step in this process will be the production of a "field manual" on fine-tuning along with an interactive website through which information will be disseminated.

Our project is timely in part because of the explosion of interest in fine-tuning issues and also because little has been done in the field since the seminal contributions of Barrow and Tipler, Weinberg, and Tegmark et al. The Standard model of particle physics has enjoyed a large degree of success, describing with great accuracy physical phenomena. The Large Hadron collider has allowed physicists to measure the missing link of this model, the Higgs Boson, which endows other hadrons with mass. The mass of the Higgs Boson is at the lower end of the predicted range which is suggestive of fine-tuning. The failure to detect evidence of super-symmetry, an otherwise compelling addition to physics beyond the standard model, suggests even further fine-tuning may be needed. Indeed, if we are to detect evidence of super-symmetry at higher energy scales, the next step may be to proceed to a 100TeV collider. This would require an extreme degree of fine-tuning. An obvious question is how far should we go before the needed fine-tuning becomes implausible.

The well-known disparity of 120 orders of magnitude between the predicted value of the cosmological constant from quantum cosmology and the measured value has been described as the greatest problem in physics. This has been addressed as a fine-tuning problem and a popular solution has been to invoke a multiverse in which our highly improbable domain is one of a huge, possibly infinite, number of universes each with differing values of the cosmological constant.

Fine-tuning arguments are not confined to physics. The origin of life involves similar controversies that involve improbable combinations of molecules to develop strands of RNA and potential building blocks of life. To what extent fine-tuning plays a role in this issue remains to be explored in a more quantitative manner. In fact, the environment where life develops is as important and this relates to the numbers of habitable planets in our galaxy, and beyond. Exoplanet research is a nascent field and developing rapidly, with some thousands of exoplanets detected, however an Earth twin has yet to be discovered. The future of this field will involve spectroscopy with telescopes such as the James Webb telescope (to be launched in 2018), yet templates for spectroscopic signatures of life, and especially intelligent life, remain to be developed in any detail. Identifying fine-tuning issues will enable us to develop a Bayesian approach to analyzing the probability of life and how one might design future searches.

One aspect that we expect to be innovative is the way in which we choose to communicate scientific knowledge. In particular, the field manual and website will be formatted in such a way that there is a line of reasoning which can be traced to source components with equations and descriptions presented in parallel. This will make the reasoning used more modular in its nature, allowing users to easily branch out from the standard route wherever they should choose.

The Field Manual and Website

Introduction

The field manual on fine-tuning is the central aspect of the proposed project. We believe that this will become the key text on fine-tuning used across disciplines and research areas. It will be written by field experts whose knowledge and experience allow them to go into far greater depth of exposition not only about the issue of fine-tuning itself, but also what the precise nature is of the role it plays within each scientific context.

On examining research literature on the issue of fine-tuning, one often finds that there is a great deal of "assumed knowledge" which is required in order to understand the topic at hand. Of course, in cutting edge research this is appropriate - one should not re-justify extant results - however in a text that proposes to serve as a basis for a thorough treatment of the subject all such knowledge must be explained. It is our goal to place before our readers not only the content of work on fine-tuning, but also the context in which that work is done. For example, in discussions of the cosmological constant the claim is often made that this parameter is small compared to its "natural" value. We shall explain to our audience the reasoning behind the "natural" value assigned, since this does not occur from observational but rather aesthetic reasons.

Furthermore, since we will be disentangling the science from the philosophy involved, a large emphasis will be placed on connecting the derivation of results with the reasoning employed in reaching those results. Care will be taken to highlight exactly what the necessary conditions and assumptions were to arrive at a particular result, and at what stage these were employed. This will allow readers to quickly examine the result of altering certain lines of reasoning, and follow the new paths that are opened upon adopting different positions at stages throughout the process. To do this, step by step derivations will be given with clear exposition at each step of the way. Also, when reference is made to established results there will be a clear path through which the reader can trace these results. The context in which these results were established will also be given.

The field manual will be produced in parallel with an accompanying website. The purpose of the website will be to give an interactive environment in which the inputs (both in terms of aesthetic/philosophical considerations and data) can be altered and the resulting physical derivations found. Whilst it will overlap in materials and substance with the website, the manual will be an entirely self-contained and consistent production.

The substance of the manual will cover the necessary physical processes for life to exist. This will be broken down into fourteen separate chapters. In each case the role of fine-tuning, be it in terms of initial configurations, ranges of physical constants, etc, will be explicitly stated, and arguments or derivations will be as self-contained as possible. Each chapter will be presented with appendices giving the standard or assumed results used in the derivations.

The substantive areas covered will be taken from the following list:

- Quantum Gravity and Scale
- Higgs Particle
- Inflation
- Dark Energy
- Dark Matter
- Primordial Nucleosynthesis
- Galaxy Formation
- Star Formation
- Stellar Nucleosynthesis
- Galactic Habitability Zones
- Exoplanets
- Planetary Conditions
- Origin of Life
- Multivariate Complexity

The issue of fine-tuning has a wide-ranging impact across a variety of fields. From practical issues in the physics literature through to philosophical and theological implications, fine-tuning informs research directions, tests principles and incites debate. Our field manual must, therefore, be both accessible and useful to readers from a variety of backgrounds. Our primary audience will consist of three groups: Philosophers and theologians for whom the manual will serve to inform the precise status and nature of fine-tuning, scientific researchers who will use the manual as a reference for how techniques and algorithms are applied to these issues, and advanced undergraduate students for whom it will serve as a teaching resource.

Expository Style

To facilitate a clear discussion of the derivations and assumptions used, we propose a novel layout for derivations of results in the field manual. These pages will consist of two columns: The mathematical derivation of a result will be presented in steps down the left column, whilst justification will be given down the right column. At each stage in the derivation it will be made clear exactly what new information or assumptions are being made, so that it is clear where branching points can be made. Before each important derivation there will be a clear statement of the four separate components that are required to perform the calculation. These can be categorized as assumptions, simplifications, data and theoretical inputs.

Assumptions

In order to make any derivation one must assume a theoretical framework in which the calculations are to be made. As an example, in deriving the expansion rate of the universe, one assumes that supernovae are "Standard Candles", that is that they have the same known luminosity. Stating such assumptions at the front of any derivation, and indicating clearly what role they play, will allow the consequences of challenging these to be made obvious. Furthermore a clear definition of the framework in which the derivation is made (e.g. Newtonian Mechanics) will allow the reader to more easily explore the results of similar derivations in alternative paradigms.

Simplifications

To quote Rovelli, "There is no physics without approximations". In many derivations a series of simplifications of the system under consideration are made, in order to yield a problem that is mathematically tractable. Often these will be assumptions about symmetries of the system under consideration, or the smallness of certain parameters allowing for their neglect in comparison to more dominant effects. A clear statement of such simplifications will allow the reader to both recognize situations in which these are not viable and explore the consequences of their relaxation, and extension to scenarios in which parameters previously assumed small are no longer negligible.

Data

The data which is necessary for any derivation will be clearly provided with sources. This will allow users of the field manual to update any derivations in the light of new information and to trace directly how changes to experimentally observed quantities affect conclusions. Efforts will be made to ensure that the output of each derivation provides an algorithmic process by which data can be converted into derived quantities - following the standard candle example above, there will be an algorithm for turning the observed frequencies into expansion rates in any given theory.

Theoretical Inputs

Theoretical inputs arise through the application of the simplifications made in the assumed theoretical framework. These will consist of equations or relationships which have been found separately and are referenced during the derivation. In so far as is possible any theoretical input will be a standard formula that is easily referenced and made available, with citations/links as appropriate. Authors will be strongly encouraged to add appendices to their chapters in which these equations are derived from elementary material in the field. An example of the layout of the field manual during these derivations is given in the following pages. The example given, the derivation of the mass of the inflaton, is used solely for demonstrative purposes of the layout, not as an example itself of fine-tuning.

This format will be translated into an online website which will allow a more dynamic branching of ideas, and linking of topics of interest. The website will be designed to allow arguments to be made modular in nature - it will be possible to take known derivations and alter their course dynamically, changing a constant to a field or an assumed geometry for example. The aim will be to produce results which are easily amenable to being perturbed about the standard derivation so that users can ask "what if" type questions without having to become field experts. Further, this modular setup will allow the manual to adapt to new experimental inputs that potentially overthrow accepted results. By directly linking how and where key variables, constants and interactions are used in each derivation, it will be possible to see directly how altering these will affect not just one system, but rather the whole encompassed physics. Arguments will be laid out in layers of detail which can be expanded and contracted as the user wishes - if there are certain aspects of an argument that are of particular interest it will be possible to take this reasoning down into smaller components so that a precise point of disagreement or change can be pinpointed.

As an example, should it be found that the electron mass varies over time, an active search of the website will identify where this constant occurs in spectral emission lines, orbits of planets etc. This is a key aspect of fine-tuning that has been overlooked greatly, as focussing on narrow problems may indicate that if the mass of the electron were to differ, say, then the light emitted by the sun would not be absorbed by chlorophyll as we know it. However, a more complete analysis would see that the absorbtion was also dependent on the electron mass and may vary in a sympathetic way such that the complete system is unaffected by the change. It is by viewing these systems in context that we can really see to what degree they are indeed the result of some fine-tuning, rather than falling victim to some version of Adams' puddle argument, in which a sentient puddle of water would consider it a remarkable coincidence that there happened to be a hole in the ground into which its shape fit so exactly.

The field manual will be an ambitious undertaking, spanning disciplines and backgrounds to bring together a complete picture of the current state of fine-tuning. We believe that it will serve as a resource for a wide range of students and researchers and serve as a base for a great deal of new investigation. It will allow those with ideas in one field to explore their broader ramifications and allow those with aesthetic and philosophical interests access to the science on which established results are based. The modular explanatory style of the manual is central to this.

Substantive Areas

The substantive areas chosen reflect the status of fine-tuning in several physical contexts necessary for the evolution of life. The over-arching theme of the manual will be one of explaining how each of these processes exhibits fine-tuning and how that can be seen in the correct physical context. The narrative flow will be broadly temporal and hence a hierarchy of necessity: Later chapters may require the results of their predecessors to hold, for example the formation of galaxies is necessary for them to have habitability zones. However each chapter will be self-contained as a reference, and readers will not be assumed to have cumulative knowledge, and so should be able to pick up at the beginning of any individual chapter. The following is meant to give examples of our proposed topics: some will be combined. We envisage a total of 8 or 10 chapters.

Quantum Gravity and Scale

The question of how one reconciles general relativity and quantum theory is one of the longest standing problems of physics. Hawking and Penrose proved that all classical cosmological models exhibit singularities and hence the energy scales involved are unbounded from above. However from dimensional analysis we expect that there will be quantum gravitational effects at the Planck scale, and therefore a quantum theory of gravity arises not just as requirement of theoretical completeness, but rather as a necessary phase of cosmological evolution. The ratio of the Planck scale to the GUT scale - the scale at which the particle physics of the standard model becomes important is an example of fine-tuning. These issues of scale determine the complexity of structures that can be formed through the combination of forces.

Higgs Particle

The Higgs boson, perhaps the most feted of all recent physical discoveries, has a mass of around 125 GeV which is far below the Planck mass which is obtained by combining Planck's constant, Newton's constant and the speed of light in such a way that the resulting object has units of mass. This is an example of the hierarchy problem of theoretical physics - why the weak force is so much stronger than gravity. The expected quantum corrections to the bare mass of the Higgs boson should force the observed mass to be far higher than it is, unless there is a very precisely correlated radiative correction to cancel this effect. Explanations for this fine-tuning issue have again turned to physics beyond the standard model (in which the Higgs mass cannot be calculated). Supersymmetric arguments, in which each particle has associated partners have been employed, but the continuing lack of observation of any evidence of these at the LHC has called the idea into question. It is also postulated that some natural scale from a more complete theory of gravity would reduce the effective Planck mass, which could in turn provide some explanation for both the Higgs and dark energy problems.

Inflation

Inflation describes a phase in the evolution of the early universe in which space underwent a rapid accelerating expansion, with any given region increasing in volume by a factor of around 10^{20} in around 10^{-30} seconds. The quantum fluctuations that happened during this phase of expansion give rise to perturbations of matter from which all large scale structure (such as galaxies, galactic clusters etc) is formed. Inflation itself was originally invoked to answer a set of fine-tuning issues: The absence of magnetic monopoles, the apparent flatness of the universe and the equal temperatures found in causally disconnected regions. However inflationary models give rise to fine-tuning issues of their own. The physics of inflationary models predominantly invokes matter fields to provide the necessary cosmological dynamics. These fields require very specific conditions to provide expansions which are compatible with observed phenomena, such as the presence of a long phase of "slow-roll" of a particle on its potential. To frame this correctly, one must address issues of measure and probability in the space of initial conditions for physical systems and the related dynamics.

Dark Energy

The relationship between the cosmological constant, a geometrical term that arises as a constant of integration in Einstein's theory of relativity, and dark energy, the vacuum energy of the quantum fields which make up the matter content of the universe, is a primary example of "fine-tuning". Arguments of dimensional analysis and "naturalness" for its value give rise to predictions which fail by 120 orders of magnitude, and is oft dubbed "The worst prediction in the history of theoretical physics". In fact the observed value is close to the maximum that would allow life to form - if it were much higher no structure could form at all. Attempted resolutions of this problem have included anthropic reasoning, appeals to a multiverse and new physical symmetries which force down the "natural" value. However each attempt at explanation invokes principles beyond those normally applied in physics, and these have wide-ranging philosophical implications. A clear exposition of the exact nature of the fine-tuning involved will better arm those in these debates to explore their relevance.

Dark Matter

The matter from which the Earth is composed, and that which comprises the particles of the standard model - baryonic matter - comprises just 4% of the energy density of our observed universe. The rest is dark energy (68%) and dark matter (27%). It was invoked to explain the flatness of galactic rotation curves, accounting for the "missing mass" of galaxies by forming halos around their edges. Dark matter only interacts with baryonic matter through the gravitational force, and as such is hard to detect: however gravitational lensing, as for example exhibited around the Bullet Cluster, has provided evidence for its existence. The distribution of dark and ordinary matter appears to be equal across galaxies, indicating that the conditions under which these galaxies formed were very precise. This gives rise to the fine-tuning issue of dark matter, and its related implications to cosmological dynamics.

Primordial Nucleosynthesis

Primordial nucleosynthesis describes the fusing of protons, neutrons and electrons to form atoms. In particular, this phase considers the first three minutes beyond the big bang during which the quark-gluon plasma present cooled enough for Hydrogen (both a protium and deuterium) and Helium (in He-3 and He-4) to form along with smaller amounts of Beryllium and Lithium. These went on to form the first stars, which were in turn responsible for the second phase, Stellar nucleosythesis. The distribution of elements present at the end of this phase is of vital importance in the production of galaxies, with the correct distributions between elements being key to the later formation of stars with the necessary rates of fusion for life.

Galaxy Formation

The formation of galaxies arises from the gas cloud of hydrogen and helium which is clumped due to primordial fluctuations. The majority of these form into thin, rapidly rotating disk or spiral galaxies, which would be likely to be pulled apart in interactions with other galaxies. Recent theories of galaxy formation include the dynamics of dark matter haloes. These are thought to be responsible for slowing disk contraction. The formation of a disk galaxy is a fine-tuning issue: If the disk contracts too quickly the central super-massive black hole will become dominant and stars will no longer form. If it contracts too slowly there will only be a very small active galactic nucleus and few stars will form. It seems therefore that a balance exists in most galaxies between the forces due to dark matter and the rotation that lead to the correct conditions for stars to exist in large numbers.

Star Formation

Stars are basic astrophysical units formed of hydrogen undergoing nuclear fusion to produce helium, and in the process releasing the heat and light necessary to support life on planets. Furthermore, through the process of stellar nucleosynthesis, early stars provided the elements from which those planets, and life thereon, is formed. The formation of stars is critically dependent on fundamental constants of nature, and the interplay of the fundamental forces of gravity and the electromagnetism which control interactions. These in turn determine the mass and density of the stars that can be formed. If the gravitational force is too strong, it will overcome the radiative pressure of light emission and thus the body will quickly collapse into a black hole, if too weak the star will not become hot and dense enough to undergo fusion.

Stellar Nucleosynthesis

Stellar nucleosynthesis describes the production of the heavier elements by nuclear fusion during the evolution of a star, and is responsible for the distribution of all heavy elements in a galaxy. It is through the fusion, then explosion, of massive first generation stars, followed by subsequent generations of intermediate mass stars, that the majority of the matter which composes planets, asteroids and dust is formed. One of the key elements necessary for the evolution of life is carbon, which is produced by the "triple-alpha process" during stellar nucleosynthesis. This process is one in which the properties of the carbon atom exhibit signs of fine-tuning. Hoyle first calculated this required a resonance in Carbon-12 at around 7 MeV and described " the chance of my finding such an atom through the blind forces of nature would be utterly minuscule". Had the resonance occurred at higher energy there would be too little carbon for life to form, and had it been lower the stars would have burnt out their helium into carbon too fast for planets to form. It is therefore stated that this process must be fine-tuned - Hoyle himself even invoked the anthropic principle to explain it.

Galactic Habitability Zones

The galaxy we inhabit, the Milky Way is approximately 100 thousand light years across and consists of on the order of 200 billion stars. Given these vast numbers a naive estimate might conclude that there would be a plethora of solar systems comparable to our own in which intelligent life could form. However, such an analysis would ignore the fact that only a fraction of the galaxy actually lies in what we would call a “habitability zone” - a region in which the physical conditions do not preclude the formation of life. In the outer regions of the galaxy, there are insufficient metals to form terrestrial-type planets in large numbers, and in the inner regions the frequency of supernovae and gamma ray bursters would arguably preclude any life surviving long enough to evolve. There is, therefore, a limited region in our galaxy in which life itself could form - had our galaxy formed differently such a region may not have existed at all.

Exoplanets

Despite long-standing predictions of their existence, planets outside of our solar system - “Exoplanets” - are a recent observational discovery. Most of those which have been discovered exist in systems which have greatly different characteristics than our own, such as heavy planets in close orbit around the central star. This can be explained in part by the fact that these systems are easier to observe than those whose planets are in a formation closer to that we inhabit, but the observations open questions about how precise the conditions of a proto-planetary disc must be in order for habitable planets to form, a clear fine-tuning issue. The study of exoplanets is a new and important field of astrophysics. Since the first direct discovery in the 90’s, the number has increased to over a thousand. The majority of those found are unsuitable for life, being too hot or cold, or too close to the host star, lacking water etc. The question of how often planets are found in the “Goldilocks Zone” - the region where life is not prohibited - will reveal how fine-tuned our system is.

Planetary Conditions

The predominant models of the formation of the Earth (and other inner solar-system planets) hold that this began as a slow accumulation of dust. This process continues, with an estimated 40,000 tons per yr of cosmic dust falling to ground, but was more intense in the period of the planet’s formation known as the “Late Heavy Bombardment” during which there was a large shower of meteorites and comets reaching the surface. This dust which formed in the late evolution of previous stars upon reaching the red giant phase of their evolution, and contains complex organic compounds, a prerequisite for the evolution of life. Other special situations contribute to the necessary conditions for the evolution of life on Earth, including the orbital eccentricity and axial tilt of the Earth as well as the presence of the moon and in particular its orbital characteristics. Since the time of Newton, it has been known that the moon is responsible for the tides, which in turn lead to the presence of tidal pools that, in one view, provided the conditions for evolution. Further, specific geological conditions have contributed, such as tectonic plates which lead to deep sea hydrothermal vents, thought to be the home of the common ancestor found to all DNA - an aquatic organism which lived at high temperatures.

Origin of Life

The evolution of life requires the presence of a host of complex chemical structures such as amino acids which form into proteins (long chain polyamides, of which there are over 100 thousand varieties in the human body). This chemistry in turn requires a set of specific planetary and astrophysical conditions, such as the production of the correct frequency of light to cause certain reactions to take place. As new stars give out specific and variable emissions in the ultra-violet these condition can be delicate. A further example would be the presence of a molten iron outer core in the Earth which produces the geo-magnetic field. This field in turn shields the planet from solar wind and accompanying radiation which would otherwise erode the atmosphere and prevent life.

Multivariate Complexity

The study of Multivariate Complexity arises from analysis in computer science. It involves a search for characteristics of a problem other than the sheer size of an input data set, for example, which determine the difficulty of computing solutions. In practical terms this involves understanding input parameters which are unknown and finding efficient algorithms for determining the problem in the absence of these. The advantage of such an analysis is that problems can be assessed from a variety of angles using a wide range of parameters and their combinations. The relation to fine-tuning in physics is made apparent when one takes a holistic view of the combined issues discussed. Are there ways in which combinations of physical constants, or configurations can be assessed together which reduce the apparent complexity of their nature?

Example Layout
Inflationary Cosmology

The following is an example of the layout of the field manual, discussing the derivation of how inflationary cosmology is fine-tuned. This would appear after introductory material on the subject which places the information in context. Inflation allows us to examine two ways in which a system can be fine-tuned: The first is the fine-tuning of a particular parameter, in this case the inflaton mass. The second is the fine-tuning of initial conditions - inflation requires a sufficient period of "slow roll" and thus the dynamics must begin with the particle high in its potential. What is being displayed is the derivation of the mass of the inflaton. Had this value been larger the universe may not have undergone a sufficient expansion to remove magnetic monopoles, and would recollapse before life could form, had it been much lighter its effects may have been outweighed by other particles with similar result.

At this point the reader will have been introduced to the Cosmic Microwave Background, and basic cosmology in terms of an expanding universe measured through the Hubble parameter. The established physics used will be the Friedmann equation and the Raychaudhuri equation, taken as theoretical inputs from their context of homogeneous, isotropic solutions to General Relativity. An example of the linked content on the Friedmann equation is given in the following section - in the online version this will be arrived at by clicking the link in the derivation, in the book this would be supplied as an appendix to the chapter. In the full field manual, the descriptions will be more complete at each stage.

Our goal is to derive the mass of the theorized particle, the inflaton, in terms of cosmological observations from the CMB. Let us first give the assumptions, simplifications, data and theoretical inputs we will use:

Assumptions

A1 General Relativity	The geometry of the universe is well described by Einstein's theory of relativity during the time of inflation
A2 Quantum Field Theory	The inflaton obeys quantum field theory on a curved background.
A3 Flatness	Space has no curvature
A4 Inflaton	The inflaton is a scalar field with mass

Simplifications

S1 Homogeneity and Isotropy	Space has the same properties at each point and in each direction
S2 No Backreaction	Fluctuations do not have an effect on the dynamics of the background modes
S3 One field	The inflaton is the only matter field present
S4 Slow Roll	The inflaton is not accelerating, and its energy is mostly potential

Data Inputs

A - Amplitude	The amplitude of fluctuations of the scalar field. Obtained from Planck/WMAP [Citation/Link]
n_s - Spectral Index	A measure of how the power spectrum changes with scale. Obtained from Planck/WMAP [Citation/Link]

Theoretical Inputs

$A = \frac{H^2}{\pi\epsilon}$	This relates the amplitude to the Hubble parameter. (A2)
$\epsilon = -\frac{\dot{H}}{H^2}$	The spectral index measures how fast the Hubble paramter changes. (A2, S3)
$H^2 = \frac{8\pi\rho}{3}$	Friedmann's equation [Citation/Link]. (A1,A3,S1)
$\dot{H} = 4\pi\dot{\phi}^2$	Raychaudhuri's equation [Citation/Link] (A1,S1,S2,S3)
$\rho = \frac{\dot{\phi}^2}{2} + V(\phi)$	Energy density of a scalar field [Citation/Link] (S2,S3)
$\epsilon_v = \frac{1}{16\pi}\left(\frac{V_{,\phi}}{V}\right)^2$	Definition of potential term slow roll parameter (S4)
$V(\phi) = m^2\phi^2/2$	Assumption of a quadratic potential term (A4)

Derivation

$\frac{V_\phi}{V} = \frac{1}{\phi}$	Using form of potential above.
$1 - n_s = 4\epsilon$	For a quadratic potential second derivatives of the potential are constant and assumed far smaller than first derivatives.
$m^2 = \frac{3H^2}{4\pi\phi^2} - \frac{\dot{\phi}^2}{\phi^2}$	Rearranging Friedmann equation with the above potential to separate out the mass term
$m^2 = H^2\epsilon_v(3+\epsilon)$	Replacing ϕ and $\dot{\phi}$ from inputs in terms of the observations of spectral index and amplitude of fluctuations.
$m^2 = H^2(3\epsilon + \epsilon^2)$	Making the slow roll approximation $\epsilon = \epsilon_v$. Implicitly here we are assuming that the inflaton is not accelerating greatly, and so terms in which $\ddot{\phi}$ appear can be neglected in favor of those in which they do not.
$m^2 = 3\pi\epsilon^2 A + O(\epsilon^3 A)$	Using definition of amplitude from above.

Here we have derived the mass of the inflaton to lowest order (in the spectral index), in terms of the inputs spectral index and amplitude.

At this point it is simple for the reader to adjust the inputs for themselves, as they can clearly see how, for example, the form of the Friedmann equation came into the argument. Note that when the Friedmann equation is mentioned, there is a citation or link (depending on whether one is viewing the document online or in print). The citation will be such that the reader can quickly find a simple derivation of the Friedmann equation from, say, the established physics of General Relativity. In the online version the text will link to a similar page to that shown, in which this derivation is performed outlining all the steps along the way. As such there is a direct line from the cutting edge research to well established results, with a clear map at each step of the way.

If the reader wishes to perform an analogous calculation in the context of Loop Quantum Gravity, say, where the Friedmann equation takes a different form, it is simple to track how this alters the calculation of the inflaton mass. Likewise should a researcher wish to loosen the assumption of slowly rolling fields, or quadratic potentials, it can be seen easily exactly where these assumptions have come in to the argument and where the derivations will diverge.

Fundamental constants and inputs will also be colour-coded in the manual. For example, let us consider the Hubble parameter. In the online version, these will form links to a central page for each constant or measured parameter in which the role of that parameter is laid out: The dynamical nature of the online version will feature a list of all derivations in which the Hubble parameter is used, and a list of the experiments and justifications for the values assigned. In the print version there will be a separate subchapter for each of these important parameters giving similar material about their derivation and use, listing all derivations in the manual which use the parameter, and giving references to how their values were measured/established. This will allow researchers to more easily trace the knock-on effect of making changes.

Example Appendix
The Friedmann Equation

Here we show what would be a chapter appendix on the Friedmann equation. This would be linked to from any derivation in which Friedmann models are assumed, and show the reader how this model comes about from General Relativity. For simplicity here we will present the flat case only, with a much fuller depiction given in the full field manual.

The Friedmann equation describes the dynamics of a homogeneous, isotropic solution to Einstein's equations. These systems form the backbone of modern cosmology, and are used as the background modes for cosmological evolution - most models consist of perturbations of the Friedmann models. This equation relates the hubble parameter to the energy density of space. The standard notation used is to relate $H = \frac{\dot{a}}{a}$ to $\rho = T_{00}$ where the Hubble parameter H is expressed in terms of the scale factor a, and the energy density ρ is the $0-0$ entry of the stress-energy tensor T (with the other diagonal entries being interpreted as pressure P).

Assumptions

A1 General Relativity	The geometry of the universe is well described by Einstein's theory of relativity during the time of inflation
A2 Homogeneity and Isotropy	Space has the same properties at each point and in each direction
A3 Flatness	Space has no curvature

Theoretical Inputs

$R_{ab} - \frac{1}{2}Rg_{ab} = 8\pi G T_{ab}$	Einstein's Equation (A1)
$R = R(t) \;\; g = g(t)$	Variables only depend on time, not space (A2)
$R_{11} = R_{22} = R_{33}$	No preferred direction in space (A2)
$g_{00} = -1$	Choice of rescaling time (A1)

Derivation

g and R diagonal	The metric is a symmetric matrix, so there exists a basis in which it is diagonal
$R = R(t)$	Variables only depend on time, not space (A2)
$R_{11} = R_{22} = R_{33}$	No preferred direction in space, so the eigenvalues of R should be identical (A2)
$ds_s^2 = a^2(t)(dx^2 + dy^2 + dz^2)$	Curvature must be constant, space is flat (A3) therefore space must be the usual Euclidean 3-space with spatial distance a multiple of the distance given by Pythagoras' Theorem
$g_{11} = g_{22} = g_{33} = a^2(t)$	Direct consequence of the above
$R_{00} = -3\frac{\ddot{a}}{a}$ $R^i_i = \frac{\ddot{a}}{a} + 2\frac{\dot{a}^2}{a^2}$	Using definition of Ricci Scalar in time direction and spatial directions
$R = 6\left(\frac{\ddot{a}}{a} + \frac{\dot{a}^2}{a^2}\right)$	Taking trace of the above
$3\frac{\dot{a}^2}{a^2} = 8\pi\rho$	From the $0-0$ term in Einstein's equation. This is the Friedmann equation.
$3\frac{\ddot{a}}{a} = -4\pi(\rho + 3P)$	From the $i-i$ terms in Einstein's equation. This is the Raychaudhuri equation.