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Lexicon of Theory Qualities

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Abstract: A brief lexicon of theory qualities is given with the intent of facilitating discussions that compare theories. First, several elementary definitions are put forward for a theory and its points in parameter space. A categorization of qualities of theories then follows. Finally, the lexicon is presented, including the theory qualities of concordant, calculable, consistent, consilient, finetuned, natural, testable, falsifiable, diverse, and more. The goal of this lexicon is to be easy to understand and functional in relevant physics research settings, not to be philosophically all-encompassing.

1 Introduction

Theories abound. For example, there are hundreds of theories that explain the apparent dark matter of the universe. To cast judgments on these theories requires putting them in different categories. Some theories are just "toy theories" and are not meant to be taken too seriously in detail, but seriously in the principles espoused. Some theories are "finetuned theories" that predict high sensitivity to observables by tiny changes in the underlying parameter values of the theory. And yet other theories are touted as fully "calculable", meaning that precise answers for observables can be obtained when input parameters are specified. There are many other such qualities that enable theorists to sort them into bins and argue for preference of one theory over another. Such activities have impact in the development of science since resources are finite, and choices must be made to throw support toward developing new experiments that may look for one theory over another. As an example, belief in the speculative Higgs boson resulted in tremendous investment in high resolution photon detectors to see its narrow decays $h \to \gamma\gamma$ [1].

Discussion of theory qualities is greatly facilitated by having precise definitions of the qualities of which we speak. A consistent vocabulary that has reliable meaning to a reader or listener also improves understanding and discourse. This is especially true when constructing a verbal theorem whose justification can only be followed and agreed to when all the terms have well-understood meaning.

The goal of this article is to specify the meanings of various theory qualities useful in assessing and comparing theories of high energy physics and cosmology, in particular. Most terms are not new, but the articulation of some of them may be slightly different than what readers may have experienced elsewhere, for the simple reason that terms do have different meanings among different authors. That fact is a key impetus of this work. Second, the goal is further to form a "basis set" of definitions that cover much of what one might want to articulate in theory assessment discussions.

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The body of this article consists of two main parts. The concept of a theory and its parameter space is first set forth. It is in that section that the distinction between *model* and *theory* is made, and the idea of a *theory point* is precisely defined. The second part is in the form of a glossary of theory qualities. These theory qualities are restrictive, meaning the application of a quality restricts oneself to a subset of the space of all possible theories. "Simple theories" is contained within the full set of all possible theories, and it is a subset. In most theories, as in this example, the quality modifier (i.e., "simple") must be given sufficient precision to restrict the result to a proper subset of all theories.

2 A theory and its parameter space

One cannot get far without first deciding on what a theory is. For our purposes, a **theory** is one that has **input parameters** with a corresponding **parameter space**, a specified domain of applicability (e.g., below M_W in the Fermi theory) and rules by which to use those input parameters to compute observables (masses, cross sections, decays rates, etc.).

In the next section we will define many qualities of theories, which are restrictive premodifiers. Before proceeding directly to that, let us first discuss parts of a theory. As we have already said, a theory has a parameter space. The parameter space to one person could be the coupling constants in a theory with well-defined symmetry. To another it could include the n in $SU(n)$ symmetry. Either way, when speaking of a theory, the reader must know explicitly or implicitly what inputs are considered variable. It goes without saying that the author must also know this.

Furthermore every theory has its **domain of applicability** is the space of observables that it purports to be able to compute. For example, Fermi's theory of four-fermion interactions has a domain that does not include energies well above the scale of Fermi's constant $G_F^{-1/2} \simeq 293\,\text{GeV}$. The domain of the Standard Model and General Relativity does not extend beyond the Planck scale $M_P \simeq 10^{-19}\,\text{GeV}$. The purported domain of applicability often can only be articulated when the maximum tolerated uncertainty in the calculation is stated. For example, Newton's laws of motion are never valid, but they are valid to a good approximation over many cases. The domain of applicable for Newton's laws is dependent on how precise the practitioner needs their calculation.

It must be emphasized that the specification of a theory must be complete at least implicitly, including knowing its parameter space (which includes the range over which parameters are allowed to vary), and the domain of applicability of the theory. Once a theory is specified completely, one is in the position to discuss a **theory point**. A theory point is the theory evaluated at one point in its parameter space. Theories with at least one continuous parameter, such as the top quark Yukawa coupling in the Standard Model, have an infinite number of theory points, since there are an infinite number of Yukawa couplings on the real line that give an infinite number of top quark values within its finite error bars.

In the literature the word "model" is often used. For example a model to some is equivalent to what is here a "theory point". E.g., YUa, YUb, etc. in [2] are theory points in a specific

$SO(10)$ grand unified theory with a well-defined parameter space, but are referred to in [2] as "benchmark models." For others, a "model" is equivalent to a "theory". For example the "Standard Model" is a theory. This latter viewpoint is adopted in this taxonomy — a "model" is another term for a "theory". When "model" is used in an equivalent way as "theory point", such as in the example given above from [2], the term "theory point" is advocated.

One also frequently comes across the phrase **corner of parameter space**. For us that signifies a proper subset of all the theory points that are in the range of input parameters of a theory. Furthermore, we define it to mean a small fraction of theory points when compared to the full set of theory points flatly distributed across the parameter space. A corner of parameter space still contains an infinite number of theory points if it is specified as a small region in the parameter space of continuous variable(s). For that reason it must be emphasized that to call a corner of parameter space "small" has meaning only with respect to a pre-conceived distribution on the input parameters of the theory. What looks to be a small region of parameter space (i.e., small fraction of theory points) in a flatly distributed space maybe become a huge region of parameter space on some other distribution of parameters that peaks within the region.

3 Qualities of a theory

Now that we have defined what a theory is, with its input parameters, parameter space, and points, we are in position to discuss qualities of those theories. That is the subject of this section.

As pointed out in the introduction, the qualities of interest are restrictive qualities, in that they project out subsets of the full space of all possible theories. For example, a "concordant theory", discussed below, selects out only theories that are consistent with experimental data. Many of the qualities of a theory specify the theory's relationship to experimental data, "Testable", "falsifiable", "concordant", etc., are all concerned with how a theory fares in its confrontation with past, present and/or future experimental data. The class of qualities that refers directly to empirical status is the first class of qualities.

A second class of qualities appeals to our extra-empirical sensibilities with respect to a theory. A "finetuned" theory, or a "natural theory" or a "simple theory" or a "beautiful" theory are not primarily interested in the confrontation of experiment and theory, but rather what ranking of likelihood or interest should we place on different theories that are (nearly) identical in their ability to conform with present data but have different approaches to solve outstanding problems in physics, such as the nature of the dark matter or the origin of electroweak symmetry breaking.

A third class of qualities of a theory expresses in what way a theory is adequate or inadequate with respect to a would-be perfect theory. For example, a "calculable theory" is one that enables precise-enough calculations of observables when provided the theory's input parameters. The complementary set of "un-calculable theories", or theories that are partially calculable, warns that it is not a perfect theory, in the sense that a theorist wants something better that may exist (a calculable theory). A "dual theory" is one that is equivalent in some specific way to another theory, and may improve upon the adequacy of the overall theory description.

An "effective theory" is also in this third class, since by definition it has no ambitions to be a complete theory and has at least implicitly a range of validity specified that does not cover all physically realizable situations. Thus it is "inadequate" from the point of the full theory or even its UV complete theory. For example, the Fermi theory is an effective theory and it never claimed to be valid well above the Fermi scale.

Finally, there is a fourth class of qualities of a theory requires it to possess certain objects, such as specific types of fields/particles (two Higgs doublet theory, vectorlike fermion theories, string theory, etc.) or certain types of symmetries (conformal field theories, supersymmetric theories, gauge theories, grand unified theories, etc.). This fourth class of theories is not terribly subtle in their definitions (e.g., we know what it means to say two-Higgs doublet model), and furthermore given the semi-infinite number of such qualifiers we leave these out entirely from out lexicon below.

Finally, inspired by Cassirer's reference to the Aristotelian concepts of form-cause as "dark qualities", we define *dark qualities* as qualities of a theory that are "worthless"[2] and "must be banished from research" [3]. There is argument of what constitutes dark qualities of theories. Candidates for dark qualities include a theory being simple, beautiful, falsifiable and natural.

In the next section the key theory qualifiers of the first three classes are listed and defined, which will conclude this article.

4 Lexicon of theory qualities

Authentic theory: An *authentic theory* is one that has a point in its parameter space – the *authentic theory point* – that is *concordant* with any conceivable experiment that could possibly be performed in the theory's domain of applicability. It is an empirically inaccessible theory because there is no moment in time when one can conclude that all conceivable experiments have taken place.

Beautiful theory: A theory with aesthetic value in the eyes of the beholder. There is no universally agreed upon criterion by which a theory is judged beautiful. Sometimes it is viewed to be synonymous with simple.

Calculable theory: A calculable theory, or computable theory, is one that enables observables to be computed with finite uncertainty. The degree of calculability that a theory has is a measure of how uncertain the observables can be determined given the input parameters.

[2]A theory quality being "worthless" does not mean an *authentic* theory cannot have that quality, especially if the quality is in the eyes of the beholder, such as "beauty." More accurately, then, one might instead propose they are "non-prejudicially worthless."

Coherent theory: Equivalent to *consistent theory*. This is related to, but should not be confused with, the coherence theory of truth [4].

Concordant theory: A *concordant theory* is one that has within its parameter space at least one point in agreement with, or at least not in conflict with, currently available experimental data. A *concordant theory point* is a point in parameter space that agrees with experiment.

Consilient theory: A theory whose validity and principles are supported by multiple lines of evidence from a diverse set of approaches..

Consistent theory: *Mathematically consistent*: A theory that is not in violation of established mathematics and whose calculated observables are single-valued over the input parameter space. *Experimentally consistent*: equivalent to *concordant theory*.

Correct theory, more correct theory: A *correct* theory is an authentic theory. A *more correct* theory is one that is closer to the authentic theory by some measure (e.g., particle content, symmetries, etc.) than another theory it is being compared to.

Diverse theory: A *diverse* theory is a concordant theory that has at least one *theory point* that makes qualitatively different experimental predictions than are possible from the *standard theory* or from other *concordant theories* previously identified or commonly analyzed.

Dual theory: A second, different description of a theory with different parameter space that has equivalent observable consequences to the first description. For more subtle applications, see [5, 6].

Effective theory: An incomplete low-energy theory that incorporates all high-energy dynamics into its low-energy fields and coupling constants.

Empirically adequate theory: Equivalent to *concordant theory*.

Falsifiable theory: A *falsifiable theory* is a theory whose entire parameter space could conceivably be ruled out (i.e., shown to be *non-concordant*) by a specified collection of experiments and analysis that can be done in the future. A *promptly falsifiable* theory is falsifiable in the near future, whereas an *asymptotically falsifiable* theory is one that can be falsified in principle but not in the near future. The concept of falsifiability was set forth by Popper [7], albeit in a somewhat different formulation as the above. Cf. *testable theory*.

Finetuned theory: Finetuning is a measure of the sensitivity of an output (observables) with respect to variations of input(s). A finetuned theory is one burdened with a high degree of finetuning of its parameters.

Mathematically consistent theory: See *consistent theory*.

Minimal theory: A theory that is argued to be the most simple theory that accomplishes a desired task, such as explaining a phenomenon, or achieving grand unification, or overlaying supersymmetry, etc.

Natural theory: For some, a natural theory is one that has no finetuned parameters [8]. Alternatively defined, a natural theory has the quality of at least one theory point being probable (or at least not improbable) in light of an *a priori* probability distribution on input parameters [9].

Parsimonious theory: Equivalent to *simple* theory.

Phenomenological theory: A theory of mathematical rules that reproduces the observable data at a desired precision but is not based on any principles that go beyond what is already known.

Predictive theory: A predictive theory is one that can compute more distinctive observables than there are input parameters.

Proto-theory: A *proto-theory* is a collection of hypotheses that can only be made into a theory when additional simplifying assumptions are made whose compatibility with the original hypotheses is uncertain.

Simple theory: a theory is declared to be *simple* only in comparison with another theory, e.g., the *standard theory*, based on a clearly defined counting rubric, such as a comparison of the number of assumptions and/or parameters required to compute observables in overlapping domains.

Speculative theory: a theory with degrees of freedom that go beyond the *standard theory*, and which in principle has observables that deviate from the *standard theory.* It is often put forward as an explanation for as-yet unexplained phenomena (e.g., dark matter), or as additional organization principles on known data (e.g., grand unified theories).

Standard theory: The *standard theory* is the prevailing *concordant theory.* In particle physics one usually identifies the Standard Model as the standard theory.

Swampland theory: A seemingly consistent low-energy effective theory, which upon closer scrutiny is inconsistent with another cherished principle, such as string theory, superluminal propagation, the weak gravity conjecture, etc. [10].

Tautological theory: The *tautological theory* merely states that whatever observable is measured is the value of that observable. It has an infinite number of parameters, which are all conceivable observables $\mathcal{O}_i$. Whenever it is asked what prediction the *tautological theory* has for $\mathcal{O}_i$ it returns $\mathcal{O}_i^{\rm th}$ with infinite uncertainty, which is then fit to the data $\mathcal{O}_i^{\rm expt}$. This theory is a concordant theory. However, it is not calculable, nor predictive, nor falsifiable.

Testable theory: A *testable theory* is one that contains at least one point in parameter space that is capable of yielding evidence for new physics beyond the *standard theory* in future experiments. A *promptly testable theory* is one that is testable in the near future, and an *asymptotically testable theory* is one that can be tested in principle but not in the near future. Note, testable theories are not necessarily falsifiable. A falsifiable theory requires all points in theory parameter space yield evidence for new physics beyond the *standard theory*, whereas a testable theory requires only one point.

Technically natural theory: A technically natural theory is short-hand for a technically natural point in theory parameter space. The theory point is technically natural if there are no small dimensionless ratios of parameters, or if there are, an enhanced symmetry emerges when the ratio is dialed to zero [11]. For example, m_e/m_W is tiny, but as $m_e/m_W \to 0$ a chiral symmetry emerges where e_L and e_R can transform independently.

Toy theory: A theory that is not meant to explain all phenomenon but rather to illustrate the key principle(s) that an authentic theory must at least approximately possess, or a theory that is dramatically simpler than a better concordant theory while not being far off in its computation of targeted observables.

True theory: Equivalent to *authentic theory*.

Ultraviolet complete theory: Not necessarily the theory of everything, but completely absorbs the infrared theory and extends the effective theory to a higher scale. An example is the Standard Model being the UV complete theory of the Fermi theory of β decay. To say that a theory is an ultraviolet complete theory requires reference, either explicitly or implicitly, to the infrared theory that it is completing.

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