Formal Patterns of Scientific Reasoning I: A Rational Reconstruction of the Research Programmes of Contemporary Cosmology

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Abstract

In this paper we present some guidelines for a particular formalization of patterns of scientific research. We follow closely the methodology of scientific research programmes *introduced by Lakatos in the 70s. The formal basis of this rational reconstruction is taken from the methods of defeasible and ampliative reasoning in AI. These are applied to the representation of the process of construction and comparison among different argumental supports for explanations or predictions. This allows a formal representation of the different drives of the* programmes *when confronted with either positive or negative evidence. To show the importance of a formalization of these patterns of reasoning we systematize the current discussion in cosmology between the proponents of the standard Big-Bang model and those of the inflationary model. This discussion has been enriched with recent observational evidence.*

1 Introduction

Any scientific theory is intended to represent knowledge about a certain fragment of reality. Moreover, its main purpose is to facilitate the explanation of certain behaviors in the field as well as the prediction of not-yet observed phenomena. Theories are expressed in a mixture of natural and formal languages, emphasizing the clarity and accuracy of statements. This also should allow objective and independent confirmation, and –in a foreseeable future– the elaboration of computer-aided tools. As knowledge in a field improves, so do the theories that represent it. In particular, the improved theories must accommodate the presence of new phenomena or the failure of predictions made by the former theories [5].

One of the main goals of the philosophy of science of the 20th century was to develop a clear and articulate picture of how theories are proposed, reformed, and abandoned in the presence of new information. While the initial contributions (mostly from the members of the Vienna Circle, and also from one of their most vehement critics, Karl Popper), presented a normative or *prescriptive* formulation [21], later studies changed this stress, focusing their attention towards a more *descriptive* analysis of how science is actually carried on.

The so-called *sociological approach*, championed by Thomas Kuhn [9], emphasized the notion of *paradigm*, which involves not only the explicit, intersubjective knowledge represented in the theories, but also the system of beliefs held by scientists and propagated through the educational system and the mechanisms of promotion of scientific research [10]. A synthesis between both extreme views, was finally advanced by Imre Lakatos, who not only showed how scientific research proceeds in actuality but also offered a methodological prescription that became particularly influential in the development of current theories in certain branches of the social and biological sciences [11, 12].

Although the goal of Lakatos was philosophical in nature, his methodology of research programmes[1] seems to have more in stock for the study of methods of knowledge representation and reasoning (KR&R) [15]. In Artificial Intelligence (AI) and KR&R, as is stated by a well known definition [18], the goal is to design computational systems able to handle information in ways that could be deemed "intelligent".

As some experts have claimed, this quest can be better understood in epistemological terms [8]. That is, the goals sought in KR&R are very similar with the well known objectives pursued in most scientific inquiries [26]. This similarity is also operational and methodological. Therefore, it should be natural in KR&R to look at the philosophy and theory of science for advice, and in particular at a methodology that has been shown to be rigorous but flexible enough to adapt itself to very different contexts.

One major difference between Philosophy of Science and KR&R, and one that makes the adaptation of methods of the former to the latter a hard task, is that philosophical characterizations are not syntactically formalized, at least to the extent needed to yield the blueprints for computational systems. This contention, however, disregards the fact that different philosophical approaches to science exhibit uneven degrees of systematization. For instance, Hempel's H-D paradigm [6] and Popper's falsationism [22] are perhaps easy to reconstruct in the context of explanation generation [23], but are hard to formalize in the discovery context. Kuhn's sociological account of the *paradigms* is certainly much harder to reconstruct in logical terms. Lakatos' methodology, on the other hand, features not only a very well balanced epistemology, but also has a potential to be translated into a formal and operational framework.

In this paper we will show how to embed the basic ideas in the methodology of research programmes in the framework of *nonmonotonic and defeasible reasoning*, and of *ampliative reasoning.* That is, in the form of a logic system that allows defeasible, non-deductive inferences [17]. Moreover, we will illustrate the main features of this formalization by showing how the research programme of contemporary cosmology has responded to new evidence that arose in the last few years. The importance of this example goes beyond the mere illustration of the formalization of patterns of scientific inquiry and stands as one of the most debated topics in contemporary science.[2]

In Sec. 2 we will sketch Lakatos' methodology of the *Scientific Research Programmes.* In Sec. 3, an argumentative formalization of the *programmes* will be discussed. In Sec. 4, the example of contemporary cosmology (the "Big-Bang" *vs.* the "Inflation" programmes) will be presented in terms of the formalization introduced previously. Finally, in Sec. 5 we discuss the conclusions and present ideas for further work.

2 The Methodology of Scientific Research Programmes

Imre Lakatos presented, in the early 70s, a challenge to both the *falsationism* of Karl Popper and the analysis of scientific revolutions advanced by Thomas Kuhn. In fact, he took the most significant ideas from both, but leaving aside the rigidity of the former and the sociological burden of the latter [13]. On the descriptive side he showed that in a given field of knowledge several theories may coexist, in a mutual competing state. Each theory, and the associated methods of inquiry, constitute a *programme.* It is reasonable to expect that new programmes arise while others dissappear, due to new discoveries and insights.

Scientific theories are never completely true nor completely unable to yield verifiable consequences. For this reason, scientific research programmes remain open to change and evolution. In addition to this, there is also a selective pressure arising from competition among programmes. Thus, a scientific discipline can be regarded as the dynamic quest of a group of programmes to increase their confirmation or empirical progress.

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[1] We keep using the British spelling proposed by Lakatos.

[2] A similarly "hot" topic, but far more politically loaded, is the debate on global warming [25].

A scientific research programme consists of a theory plus a range of operational procedures and inference mechanisms. Its *hard core* is the knowledge set considered central for the programme and can be identified with the theory itself. The final goal of the programme is, in fact, to either expand the core (amassing new evidence confirming its claims) or to protect the core from negative evidence. In this last case the *negative heuristic* is to build a *protective belt* of auxiliary hypotheses that, added to the core, yields the negative evidence as a consequence.

That is, if evidence e is not a consequence of the theory $\mathcal{T}$, the negative heuristic is to find an hypothesis h such that from the theory plus h it follows that e. The *positive heuristic*, instead, seeks to systematize the protecting belt and make it a consequence of the core by means of new laws. In fact, if this goal is achieved, what formerly constituted the protecting belt becomes part of the area of knowledge dominated and systematized by the hard core of the programmes.

Therefore, the size of the protective belt is certainly an indicator of the relative success of a programme (the explanatory power and the empirical progress being other good indicators of the success of a programme). This is particularly important for the competition among programmes. A theory whose protective belt steadily diminish, or whose explanatory and empirical power steadily increases, becomes a *progressive* programme, which competes advantageously with rival programmes. In turn, if a theory whose belt increases because it needs to be continuously subject to the application of the negative heuristic, becomes a *degenerating* programme, which is certainly prone to be abandoned. Thus, more progressive programmes gradually achieve more credibility and support, and therefore replace the less successful ones (which are not *refuted* but *abandoned*).

3 A Formal Representation of a Programme

Scientific statements can be schematically classified as being of three classes [2]. The first one involves the particular statements that describe states of affairs. They usually adopt the form of ground atomic formulæ. A formula of this class states that its terms (representing objects or entities) verify its propositional function (representing properties, features, etc.). The class of statements of this type is denoted $\mathcal{N}_1$.

A second class of statements involves those that represent empirical generalizations. That is, it includes the lawlike statements[3] relating observational terms and relations. Thus a statement of the form *"Objects that have the observable property p normally have property q."* can be represented with a *prima facie* implication $p(X) \succ\!\!\!- q(X)$ where p and q are observable properties and X is a variable that can be substituted for a term[4]. Statements of this type form the class that we denote by $\mathcal{N}_2$, These sentences can be used with the *modus ponens* inference rule only when $p(X)$ can be inferred for a ground substitution for X. The resulting chains of inferences are isomorphic to standard deductions, and usually recieve the name of *arguments* [16, 24].

Finally, statements in $\mathcal{N}_3$ represent the *theoretical* propositions. That is, their validity is not subject to direct observation. Statements at this level constitute the hard core of research programmes. Included here are the statements that establish the connection between theoretical and observational statements.

Carl Hempel, a distinguished member of the Vienna Circle, defined a theory as a *covering* by statements of a corresponding evidence set E, which it intends to systematize [5, 6]. That is, a theory constitutes a corpus of hypothetical knowledge from which all the evidence should be deducible under the standard first order consequence relation $\vdash$. Namely, if the theory is $\mathcal{T} \subseteq \mathcal{N}_2 \cup \mathcal{N}_3$ it must be such that for each $e \in E \subseteq \mathcal{N}_1$, $\mathcal{T} \vdash e$. If e has been already observed, $\mathcal{T}$ provides an *explanation* for it, while otherwise it yields a *prediction* of e.

Two heuristics may be applied to confront the theory with the evidence. If e is not correctly explained or predicted, the negative heuristic prescribes to look for a $c \in \mathcal{N}_1$ such that now $\mathcal{T}, c \vdash e$. The set of these *auxiliary hypotheses*,

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[3] In many fields of inquiry it is customary to use probabilistic laws. Since this introduces a higher degree of precision than what is actually needed to describe Lakatos' methodology we will not use them in our presentation.

[4] This definition can be slightly generalized to the case where X stands for a tuple of variables, and both $p(X)$ and $q(X)$ are sets (conjunctions) of literals.

C is the *protective belt* of $\mathcal{T}$. That, is C "protects" $\mathcal{T}$ from refutation.

In case the evidence follows from $\mathcal{T}$, the positive heuristic pushes forward the programme. This means that new inferences should be drawn from $\mathcal{T}$ while at the same time C must lead to a set of law like statement $\mathcal{S} \subseteq \mathcal{N}_2$ such that the theory is extended to $\mathcal{T}' = \mathcal{T} \cup \mathcal{S}$. Notice that according to the negative heuristic the programme engrosses C. The positive heuristic, instead, "discharges" C and engrosses the scope of the hard core. To summarize: we define a programme as $\mathcal{P} = \langle \mathcal{T}, C, E \rangle$, that is, characterized by a theory, its protective belt and the set of available evidence. Notice that since $\mathcal{T} \subseteq \mathcal{N}_2 \cup \mathcal{N}_3$, the hard core is $\bar{\mathcal{T}} \subseteq \mathcal{T}$ such that $\bar{\mathcal{T}} \subseteq \mathcal{N}_3$.

We can regard lawlike generalizations $a(X) >\!\!\!- b(X)$ as material implications *only* for the *modus ponens* inference rule (that is, contraposition, left strengthening, right weakening, and similar uses are explicitly left out). Thus, these rules can be "fired" in MP only when their antecedent is fully instantiated, *i.e.*, there is a ground substitution for X such that all the literals in $a(X)$ have been inferred. Then, the inference system, then, will chain inferences in a way very similar to (classical) deductions, with the addition of inferences in which a fully activated defeasible rule was used. This chains of inferences are *(sub)-theories* in Brewka [1] and Poole [20], and *arguments* in Loui [16] and Vreeswijk [27]. We will adopt this later denomination. If a lawlike generalization can be regarded as a *prima facie* material implication, then an argument for e is a *prima facie* proof for e. We can then extend the (classical) consequence operator $\vdash$ to the new operator $\mid\!\sim$ to represent that there is an argument for a given ground literal in theory $\mathcal{T}$.

Suppose that under evidence $E_1 \subseteq E$ there is an argument for the (set of) ground literal(s) e_1. This is denoted by $\mathcal{T}, C, \cup E_1 \mid\!\sim e_1$, In this case we say that the programme $\mathcal{P}$ *predicts* (or explains) the observable fact e_1 given the previous evidence that E_1 is verified. It should be noted that because of the nature of defeasible rules, there may be programmes that in certain cases predict both an observation and its negation[5]. Therefore, if a conclusion is to be drawn it must arise as a result of a process of comparison among arguments. This means that an order relation among arguments must be defined such that $\mathrm{Arg}_1 \succeq \mathrm{Arg}_2$ iff Arg_1 *defeats* Arg_2. In this work we will not consider any special kind of defeater. The reader may consult for instance the work of Loui [16], where four kinds of defeaters are considered (more evidence, directness, preferred subarguments, specificity), which can be included in the following discussion if needed.

Then, given a programme $\mathcal{P}$, a set of confirmed evidence E_c, and a new observed fact e to be explained, then the status of $\mathcal{P}$ can be sumarized in the following cases:

- **Confirmation**: If there is at least one argument for e given $\mathcal{P}$ and the confirmed evidence, then $\mathcal{P}$ is strongly confirmed. If there are arguments both for and against e (*i.e.*, supporting $\neg e$), but there is at least one undefeated argument for e, then $\mathcal{P}$ is partially confirmed. As the name suggests, a strongly confirmed programme is also partially confirmed. In any of these situations, the confirmation indicates that the programme is in a progressive phase.

- **Anomaly**: If there is at least one argument for $\neg e$ given $\mathcal{P}$ and the confirmed evidence, then $\mathcal{P}$ is facing a strong anomaly. If there are arguments for and against e but there is at least one undefeated argument for $\neg e$, then $\mathcal{P}$ is facing a partial anomaly.

- **Indetermination**: If there are no arguments for or against e, then the programme is facing a *surprising* fact. If there are arguments for and against e but no argument is ultimately undefeated, then the programme is facing a *lacuna*.

Then, the situations that a programme may face as a result of its confrontation with new evidence, clearly indicate which procedure must be employed. If the evidence strongly confirms $\mathcal{P}$, then the positive heuristic should be applied. This means that either a new prediction e' must be obtained and tested, or a new rule $\mathcal{R} \subseteq \mathcal{N}_2$ must be found, such that the theory is expanded,

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[5] Consider for instance the very well known example where we have the defeasible rules *birds fly* and *penguins don't fly*.

$\mathcal{T}' = \mathcal{T} \cup \mathcal{R}$, verifying that $\mathcal{T}' \vdash c$ for some $c \in C$. If $\mathcal{P}$ is partially confirmed, then the defeated arguments against the observed fact e give a clue about rules in $\mathcal{T}$ or auxiliary hypotheses in C that should be given up.

In the strongly anomalous cases, either the programme has to be (partially) given up, or the auxiliary hypotheses must be accommodated to protect it from this refutation (*i.e.*, the programme enters a degenerative phase). In the case of a partial anomaly, perhaps the situation can be escaped with a ranking among the rules in $\mathcal{T}$. It is not clear whether the negative or the positive heuristic should be used in the cases in which the evidence shows that there exist lacunae in the programme, or if the ranking among rules in $\mathcal{T}$ must be modified. On the other hand, if a surprising fact is found, it seems that the theory must be expanded to include new statements, either new rules in $\mathcal{T}$ or new auxiliary hypotheses in C, so that at least an undefeated argument for e can be found.

The account of confirmations, anomalies and indeterminations is useful for the comparison among programmes. With this we can refine the *empirical success* relation among programmes. According to Lakatos, the important fact about programmes is the explanatory power (a programme that generates good predictions is not abandoned, notwithstanding the anomalies it faces). However, this should have a limit[6]. Then, it seems sensible to consider that a program $\mathcal{P}_a$ is *strictly more successful* than a program $\mathcal{P}_b$ iff both every confirmation for $\mathcal{P}_b$ is also a confirmation of $\mathcal{P}_a$, every anomaly of $\mathcal{P}_b$ is also an anomaly of $\mathcal{P}_a$, but there exists at least a confirmation of $\mathcal{P}_a$ that is not confirmation of $\mathcal{P}_b$ or an anomaly of $\mathcal{P}_b$ that is not anomaly of $\mathcal{P}_a$.

4 Research Programmes in Cosmology

During the 1950s and the beginnings of the 1960s two research programmes in the field of cosmology were in competition. Cosmology is concerned with the study of the universe as a whole. That is, it studies the origin, structure and dynamics of the universe. This inquiry has a long history, but the observation of the *redshift* of the light from distant stars lead to the existence of only two programmes, the *Big-Bang* ($\mathcal{P}_{BB}$) and the *Steady-State* $\mathcal{P}_{SS}$ programmes.

The hard core of the former consists on the idea that the universe was created in a single event, some billions of years in the past and that it has been expanding since then. The hard core of the Steady-State programme included the idea that the universe was never created *ex nihilo*[7], but that new matter and energy are continuously created everywhere, and therefore the universe is steadily expanding. That is, if $BB(u)$ represents *"The universe was created in a Big Bang."*, $SS(u)$ represents the statement *"The universe is permanently created."* and $\mathcal{PHY}$ the entire corpus of contemporary Physics, we have that $\mathcal{PHY} \cup \{BB(u)\} \subseteq \mathcal{T}_{BB}$ and $\mathcal{PHY} \cup \{SS(u)\} \subseteq \mathcal{T}_{SS}$.

If follows that $\mathcal{PHY}, BB(u) \mathrel{|\!\!\sim} e(u)$ and $\mathcal{PHY}, SS(u) \mathrel{|\!\!\sim} e(u)$, where $e(u)$ means *"The universe expands."*. The lawlike expression $e(X) \mathrel{>\!\!\!-\!\!-} rs(X)$ means that if X expands it exhibits a redshift ($rs(X)$) completes both theories. That is, $\mathcal{T}_{BB} = \mathcal{PHY} \cup \{BB(u)\} \cup \{e(X) \mathrel{>\!\!\!-\!\!-} rs(X)\}$ and $\mathcal{T}_{SS} = \mathcal{PHY} \cup \{SS(u)\} \cup \{e(X) \mathrel{>\!\!\!-\!\!-} rs(X)\}$.

Both programmes, therefore, found confirmation in the evidence of redshift that was firmly established as a fact in the 30s. So far, both were equally successful. But in 1965, cosmic background radiation was detected, demonstrating that the universe has a low but uniform temperature. We represent this observation by $\mathrm{CBR}(u)$. The fact was that $\mathcal{PHY}, BB(u) \vdash \mathrm{CBR}(u)$ while $\mathcal{PHY}, SS(u) \nvdash \mathrm{CBR}(u)$. That is, BB was confirmed by more facts than SS, having at least the same anomalies (none, in this case). In other words, P_{SS} was more successful that P_{BB}.

Although the proponents of SS, applying the negative heuristic, eventually found some auxiliary hypotheses to protect the hard core, the programme never recovered from not being able to predict such an important consequence as the existence of background radiation [19]. Therefore, BB became the dominant research programme in cosmology for almost twenty years. But meanwhile, $\mathcal{PHY}$ was expanded to $\mathcal{PHY}'$ by the inclusion of the theories of grand unification, that saw the electromagnetic, weak and strong forces

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[6] If not, inconsistent programmes would always be preferred.

[7] Out of nothing

as result of a symmetry break of a single grand force at different temperatures.[8]

Some physicists postulated an alternative cosmology, called the *inflationary model* Inf, while BB became known as the *standard model* [19]. The former is defined by $INF = \{\mathcal{PHY}', BB(u), Inf(u)\}$, where $Inf(u)$ is the claim that the universe underwent a very short period of "inflation". That is, there was an extremely rapid expansion in the early universe that justifies its actual macroscopical isotropy, but this expansion also magnified the underlying quantum fluctuations, originating the fine structure of the universe. It is important to note that $Inf(u)$ constitutes in fact a set of theoretical claims that cannot be seen as part of a protective belt in BB. Therefore BB and INF began a competition that has not yet a clear winner.

One inference that was drawn around 1980 was that $\mathcal{PHY}', BB(u) \mid\!\sim m(u)$, were $m(u)$, to be interpreted as *"Magnetic monopoles are abundant in the universe."* is a sentence that can be checked out by astrophysical observations. The fact is that $m(u)$ is not observable, thus becoming a partial anomaly for BB [4]. On the other hand, INF yields the prediction that the initial quantum fluctuations at the origin the universe are the seeds for galaxies and other cosmic structures in an otherwise smooth texture (at very large scales). Let us represent this by means of the statement $g(u)$. On the other hand, $BB \not\mid\!\sim g(u)$, That is, the Big Bang theory has no explanation for the overall macroscopic isotropy in the universe.

It seems that this is another succes of INF over BB, but further elaborations found that $g(X) \succ\!\!-\!\!- \neg ht(X)$, where $ht(u)$ is *"The temperature of the universe is homogeneous."*, which is an empirical fact that can be actually measured. That is, we have here the possibility to test another claim of the inflationary model. In fact, measurements made by the satellite COBE have shown that $\neg ht(u)$ is the case, but in a magnitude much lower than implied by $Inf(u)$ [3]. Therefore the actual homogeneity of the temperature in the universe constitutes an anomaly for INF.

Finally, INF predicts that the universe is "flat". That is, the mass in the universe is just enough to keep the expansion from accelerating. If we denote this claim by $f(u)$ we have that, again, $BB \not\mid\!\sim f(u)$. In turn we have that $f(X) \succ\!\!-\!\!- \bar{e}(X)$, where $\bar{e}(u)$ indicates that the expansion decreases or remains constant [28]. The rate of expansion of the universe is also another empirical property that can experimentally tested. Recent observations about the behavior of certain types of supernovae seem to indicate that the expansion *increases* [7]. If so, this indicates that we have a strong anomaly for INF.

Therefore, although it is too early to claim that any of these two programmes has won the debate, it seems that thus far that BB is more successful than INF, being empirically more progressive and having less anomalies.

5 Conclusions and Further Work

We have shown some guidelines for the formalization of Lakatos' methodology of scientific research programmes. Although this is just the beginning, it paves the way for an eventual full computational implementation. As discussed, methods of ampliative reasoning like the evaluation of the relation of defeat among arguments seem to be instrumental for the design of such a system. In turn, the patterns of scientific reasoning in the formal framework discussed in this paper may prove useful for the design of systems of KR&R. In fact, since the methodology of research programmes is a stylized representation of the dynamics of inquiry processes, this application should follow quite naturally.

Beyond the interaction between KR&R and philosophy of science, this paper has another point of interest. That is, the illustration of how the formalization of patterns of scientific reasoning may be useful to systematize the state of affairs in scientific debates. Our choice of cosmology intends to clarify the issues at stake in a very exciting field of knowledge. Since the pieces of evidence and the lines of reasoning applied there are quite complex, their simplification and systematization should help for their understanding.

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[8] It is interesting to note that while $\mathcal{PHY}$ is a precondition for BB, the success of the latter was influential in the creation of the theories of grand unification [14].

As said, much more is to be done. For one thing, nothing has been said about the formal languages in which we represent scientific knowledge, nor about the complexity of reasoning. These issues are crucial for an eventual computational implementation. But, as exhibited in the analysis of the example of cosmology, a careful choice of the level of discussion may simplify the task. In particular, reasoning at the "conceptual" level, as promoted in this paper, facilitates the disclosure of central themes and the comparison among them.

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References

[1] Gehrard Brewka. Cumulative Default Logic: in Defense of Nonmonotonic Default Rules. *Artificial Intelligence*, 50(2):183–205, 1991.

[2] Claudio Delrieux. The Rôle of Defeasible Reasoning in the Modelling of Scientific Research Programmes. In *Proceedings of the IC-AI 2001 Conference*, pages 861–868, CSREA Press, ISBN 1-892512-81-5, 2001.

[3] J. Gribbin. *In the Beginning: After Cobe and Before the Big Bang.* Bulfinch Press, London, 1993.

[4] A. Guth. *The Inflationary Universe.* Addison-Wesley, Reading, MA, 1997.

[5] Carl G. Hempel. *Aspects of Scientific Explanation and Other Essays in the Philosophy of Science.* The Free Press, New York, 1965.

[6] Carl G. Hempel and Paul Oppenheim. The Logic of Explanation. *Philosophy of Science*, 15:135–175, 1948.

[7] C. Hogan, R. Kirshner, and N. Suntzeff. Surveying Space-Time with Supernovae. *Scientific American*, 280(1):28–33, 1999.

[8] David J. Israel. What's Wrong with Nonmonotonic Logic? In *Proceedings of the First National Conference on Artificial Intelligence*, pages 99–101, Los Altos, CA, 1980. American Association for Artificial Intelligence, Morgan Kaufmann Publishers.

[9] Thomas Kuhn. *The Structure of Scientific Revolutions.* Pitman, London, 1960.

[10] Thomas Kuhn. *The Essencial Tension.* Univ. of Chicago Press, Chicago, 1978.

[11] Imre Lakatos. *Mathematics, Science and Epistemology. Philosophical Papers Vol II.* Cambridge University Press, 1978.

[12] Imre Lakatos. *The Methodology of Scientific Research Programmes. Philosophical Papers Vol. I.* Cambridge University Press, 1978.

[13] Imre Lakatos and Alan Musgrave. *Criticism and the Growth of Knowledge.* Cambridge University Press, 1970.

[14] Lederman, L. and Schramm, D. *From Quarks to the Cosmos: Tools of Discovery.* Scientific American Library, New York, 1995.

[15] Hector Levesque. Making Believers out of Computers. *Artificial Intelligence*, 30(1):81–108, 1986.

[16] Ronald P. Loui. Defeat Among Arguments: A System of Defeasible Inference. *Computational Intelligence*, 3(3), 1987.

[17] Ronald. P. Loui. Process and Policy: Resource-Bounded non-Demonstrative Reasoning. *Computational Intelligence*, 13(1):132–156, 1997.

[18] John McCarthy. Artificial Intelligence, Logic and Formalizing Common Sense. In Richmond H. Thomason, editor, *Philosophical Logic and Artificial Intelligence*, pages 161–190. Kluwer Academic Pub., 1989.

[19] D. Overbye. *Lonely Hearts of the Cosmos: The Story of the Scientific Quest for the Secret of the Universe.* Little Brown and Co., New York, 1999.

[20] David L. Poole. On the Comparison of Theories: Preferring the Most Specific Explanation. In *Proceedings of the Ninth International Joint Conference on Artificial Intelligence*, pages 144–147, Los Altos, CA, 1985. International Joint Conference on Artificial Intelligence, Morgan Kaufmann Publishers.

[21] Karl Popper. *The Logic of Scientific Discovery.* Hutchinson, London, 1959.

[22] Karl Popper. *Conjectures and Refutations.* Routledge and Kegan Paul, London, 1963.

[23] Hans Reichenbach. *Experience and Prediction.* University of Chicago Press, Chicago, IL, 1963.

[24] Guillermo R. Simari and Ronald P. Loui. A Mathematical Treatment of Defeasible Reasoning and its Implementation. *Artificial Intelligence*, 53(2-3):125–158, 1992.

[25] F. Singer. Hot Talk, Cold Science: Global Warming's Unfinished Debate. Independent Institute Press, Washington D.C., 1998.

[26] R. Stalnaker. *Inquiry.* MIT Press, Cambridge, Massachusetts, 1984.

[27] G. A. W. Vreeswijk. Abstract Argumentation Systems. *Artificial Intelligence*, 90(2):225–279, 1997.

[28] S. Weinberg. *Dreams of a Final Theory.* Pantheon Books, New York, 1992.