A SURVEY OF RESEARCH STRATEGIES

Ronald E. McRoberts
North Central Forest Experiment Station
USDA Forest Service
1992 Folwell Avenue
St. Paul, Minnesota 55108

Abstract. Two features of science which distinguish it from non-science are its unique goal and its unique method. The method of science consists of three major activities: Problem identification, Discovery, and Justification. Problem identification is briefly discussed with respect to the Kuhnian concept of paradigm and with respect to Leary's measure of the productivity of scientists.

The endpoint of Discovery is the formulation of one or more hypotheses. A critical attribute of hypotheses is their testability. Fully testable hypotheses may be corroborated or disproved on the basis of evidence. A high degree of statistical power is necessary to assure the full testability of some hypotheses.

Justification has three components: Research Strategy, Empirical Test, and Inference. Research strategies may be classified with respect to two factors: logical intent and number of hypotheses. The syllogistic structure and key features of seven research strategies are discussed in the context of the two factor classification. A principle of modern science is that inferences be made only on the basis of tests consisting of comparisons of hypotheses or their predictions with empirical data. The strength of an inference based on an empirical test depends on the syllogistic structure of the corresponding research strategy.

Mario Bunge (1967) asserts that science has a unique goal and a unique method that distinguish it from non-science. He states that the goal of the factual sciences is "to build conceptual mappings of the patterns of facts - i.e., factual theories." With respect to method, he asserts that "the scientific method is a mark of science, ... no scientific method, no science." In discussing the components of scientific method, Hans Reichenbach (1938) emphasized the distinction between the context of Discovery and the context of Justification. The starting point for Discovery is an identified problem or gap in the current state of knowledge, and the ending point is one or more hypotheses, models, or solutions proposed to solve the problem or fill the gap. The starting point for Justification is the set of hypotheses, models, or solutions, and the ending point is a justifiable inference concerning them. A brief survey of Discovery and Justification strategies follows.

DISCOVERY

One of the important distinctions between Justification and Discovery is that there is a logic of Justification, while Discovery has usually been considered a creative enterprise for which no logic can be constructed. Strategies that have been used to discover hypotheses include the following:

- Trial and Error
- Systematic Search
- Serendipity
- Inspiration
- Illumination of the well-prepared mind
- Analogy
- Derivation from Theory
- Induction
- Retroduction

The latter two, Induction and Retroduction, are frequently considered Justification strategies, but, as will be discussed later, it may be more proper to consider them Discovery strategies. A recent innovation, which may ultimately lead to a logic of Discovery, involves applying the techniques of artificial intelligence to discovering hypotheses (Langley, et al 1987). The consensus at this point is that there are no right or wrong ways to achieve Discovery; in essence, anything goes!

Although anything goes in Discovery, the resulting hypotheses must satisfy certain criteria. One of these is the testability criterion. A hypothesis is testable if it is sensitive to comparisons with empirical evidence. If the comparison is favorable, the outcome is corroboration; if the comparison is unfavorable, the outcome is contradiction or disproof. Corroboration is used in the sense of supporting but not conclusively proving. The testability criterion has two parts: if the hypothesis is correct, corroborating evidence must be detectable, and if the hypothesis is false, contradicting evidence must be detectable. Note that some hypotheses do not satisfy both parts of the criterion. Universal hypotheses such as 'all swans are white' can only be disproved, while existential hypotheses such as 'there are signals that travel faster than the speed of light' can never be disproved. The degree of testability of most hypotheses is much more subtle than these examples illustrate, and must be determined before experimentation.

For many hypotheses the degree of testability depends on experimental design. In testing a statistical hypothesis, choices are made for the significance level, say .05, a test statistic, and the corresponding critical value. There is confidence that if the hypothesis is correct there is a 95 percent chance of detecting corroborating evidence. Thus, half the testability criterion is satisfied, in probability, simply by choosing a significance level. Satisfying the other half of the criterion is usually not so simple. First, it is necessary to state what would be sufficient evidence to disprove the hypothesis, and then determine the chances of detecting those conditions if they exist. This is the matter of statistical power. If the probability of detecting the conditions is very small, then the hypothesis is not fully testable. The reporting of nonsignificant results from experiments with low statistical power has been called "scientific fakery" (Anonymous 1985a).

JUSTIFICATION

Justification strategies may be classified with respect to two factors, logical intent and number of hypotheses (Figure 1). The logical intent of Justification strategies has traditionally been corroboration. Only since the influential

Logical intent	Number of hypotheses: 0	1	2+
Proof			
Corroboration	Induction/ Retroduction	Hypothetico-Deduction	Multiple Hypotheses
Contradiction		Research Programs	
Disproof		Falsification	Strong Inference

Figure 1. Justification strategies.

work of Karl Popper (1968) have negation oriented strategies been seriously considered. Although the categories of logical intent are shown here in their natural order, they are discussed in the chronological order of their development. Strategies that begin without hypotheses provide little justification and probably should be considered Discovery strategies. Single and multiple hypotheses strategies, particularly with a negation oriented logical intent, provide powerful alternatives to traditional strategies. The strategies resulting from combining the categories of logical intent with zero, one, or multiple hypotheses are described in terms of their key features.

PROOF

The Greeks believed that truth in the form of universal structures existed despite the variability they saw in actual observations. Greek scientists sought to discover these truths by way of intellectual or rational insight. Well into the 15th and 16th centuries, disciples of Greek science ridiculed attempts to reconcile knowledge with observation. For them genuine knowledge of the natural world through empirical science was impossible.

However, with the Renaissance this view changed. By the 17th century Francis Bacon's (1960) *Novum Organum* had become the fundamental treatise on the logic of scientific method. In this work Bacon insisted upon a gradual passage from concrete facts to broad generalizations and upon the use of controlled experimentation, not just observation. The phenomenal successes of Newton who used and extended Bacon's methods firmly established empiricism as a fundamental principle of science.

However, in his exaltation of induction and experiment, Bacon held that general laws could be established with complete certainty by using these almost mechanical processes. It was not until David Hume's (1966) Treatise of Human Nature in the 18th century that the myth of scientific proof by inductive methods was completely debunked. With empirical and experimental methods in hand and a clear understanding of the impossibility of proof by inductive methods, modern science emerged.

CORROBORATION

As stated earlier, corroboration is used in the sense of supporting but not conclusively proving. Corroboration strategies are loosely based on a valid, logical argument form called Modus Ponens. The essence of Modus Ponens is that if the antecedent, p, of a conditional proposition is established, then the consequent, q, must logically follow. Scientific corroboration strategies, unfortunately, usually attempt to establish the consequent and then imply the antecedent. They are guilty of what Copi (1967) calls the "Fallacy of Affirming the Consequent". Thus, corroboration strategies do not follow a valid argument form, and their conclusions are not necessarily valid. Closer examination of specific corroboration strategies clarifies the issue.

0 HYPOTHESES - Induction: Induction might be defined as the ever increasing accumulation of hard facts, F, which can be understood by means of tentative generalizations, G. A key feature of induction is that the facts are acquired before the generalizations are formulated. The generalization is usually not tested on data other than that from which the generalization has been formulated, and it is usually uncertain if the second part of the testability criterion has been satisfied. Successfully meeting the second criterion would seem to be mostly a matter of chance with Induction. Carl Hempel (1966) states:

> Scientific knowledge is not arrived at by applying some inductive inference to antecedently collected data, but rather by inventing hypotheses as tentative answers and then subjecting them to empirical test.

Induction would be better considered a Discovery strategy than a Justification strategy.

0 HYPOTHESES - Retroduction: Hanson (1958) describes retroduction as the following sequence:

1. A surprising phenomenon, P, is observed,
2. P would be explainable if hypothesis H were true
3. Therefore, there is reason to think H is true.

Retroduction, like induction, is guilty of affirming the consequent. Also, like induction, the phenomenon is observed before the hypothesis is formulated, and so it remains uncertain if the second part of the testability criterion is satisfied. Retroduction would also be better considered a Discovery strategy.

1 HYPOTHESIS - Hypothetico-Deduction: Hypothetico-deduction is used as a strategy for corroborating single hypotheses. The hypothesis, H, is discovered by any means available to the researcher. From the hypothesis, H, a prediction or deduction, D, is derived, which is then compared to empirical evidence. The evidence is acquired after the hypothesis is stated and therefore should be appropriate in kind and amount to satisfy the second part of the testability criterion. Nevertheless, Hypothetico-Deduction is still a corroboration strategy and, as such, suffers from an invalid argument form.

2+ HYPOTHESES - Multiple Hypotheses: In addition to an invalid argument form, single hypothesis strategies also may suffer from scientists' attachment to their hypotheses. The moment a scientist offers an apparently satisfactory hypothesis it becomes that scientist's personal possession. Hanson pointed out that even when scientists are free from such attachments, observations are generally not free from observer bias. An example (Figure 2) due to Hanson and also discussed by Brown (1977) demonstrates that the response of an observer's senses to external stimuli may depend on the hypothesis in mind. Furthermore, Hanson contends that it is not possible for multiple responses to occur simultaneously. Lack of objectivity may be a serious problem when attachment and observer bias occur. These difficulties may be partially avoided by using the "method of multiple hypotheses" as proposed by Chamberlain (1897). With this strategy, each problem is surrounded with hypotheses and a series of experiments is performed to distinguish among them. Chamberlain points out that this strategy "distributes the effort and divides the affections." The structure of the argument is essentially a series of Hypothetico-Deductive arguments and therefore still suffers from an invalid argument form. However, when multiple hypotheses are used, scientists may perceive the same observations from multiple perspectives.

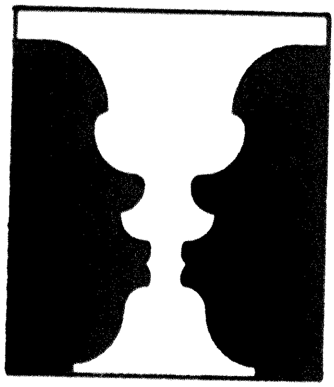

Figure 2. A vase or faces kissing?

DISPROOF

Karl Popper (1968) suggested that the problem of the invalidity of the induction argument could be avoided by shifting from corroboration strategies to disproof strategies. He argued that conclusive disproof is possible because it takes only a single counterexample to disprove a hypothesis. The basis of disproof strategies is the valid argument form, Modus Tollens. The essence of this argument is that if the negation, ~q, of the consequent, q, of a conditional proposition is established, then the negation, ~p, of the antecedent, p, must logically follow. Although corroboration strategies do not follow a valid argument form, disproof strategies do. Popper argues that science advances by disproof because hypotheses are conclusively eliminated from further consideration. For Popper, the only results regarded as corroborating evidence for hypotheses are new and interesting failures to detect counterexamples where they would be most expected to occur.

1 HYPOTHESIS - Falsification: The falsification strategy requires a clear statement of the hypothesis and a clear statement of the conditions under which the hypothesis would be abandoned. The objective is to disprove the hypothesis by acquiring evidence establishing the falsifying conditions. Just as there is a clear distinction between the objectives of corroboration and falsification strategies, there is also a clear distinction between their experimental designs. Corroboration designs must provide for acquiring both supporting and contradicting evidence to satisfy both parts of the testability criterion. Designs for falsification experiments concentrate resources to provide maximal opportunity to detect counterexamples. If the conditions are detected, conclusive disproof is established. Failure to detect the conditions is construed as corroborating evidence because the hypothesis has withstood an extremely rigorous test.

2+ HYPOTHESES - Strong Inference: The problem with falsification, as Platt (1964) pointed out, "is that disproof is a hard doctrine." It is not easy to continually place hypotheses representing years of labor onto the cutting edge. This difficulty can be partially alleviated by using Chamberlain's method of multiple hypotheses. In fact the full potential of the multiple hypotheses concept is not realized until it is combined with a disproof intent and a logical tree structure. Platt dubbed this strategy "strong inference". The steps of the strategy are as follows:

1. Surround the problem with an exhaustive set of hypotheses whose deductions are mutually exclusive.

2. Arrange the hypotheses into a tree structure on the basis of similar and dissimilar features,

3. Perform falsification experiments at branching points to eliminate one branch or the other.

Consider the problem of determining the cause of the Cretaceous-Tertiary extinction (Why did the dinosaurs die?). The following list of hypotheses, although not complete, illustrate the strategy:

Oceanographic changes
Atmospheric changes
Climatic changes
Geo-magnetic reversal
Solar flares
Meteors or comets
Nemesis: a solar companion
Supernova
Solar movement: moving through galactic arm

This completes the first step, surrounding the problem with hypotheses. If the set of hypotheses is not exhaustive, then the surviving hypothesis may later be falsified itself. If the deductions from the set of hypotheses are not mutually exclusive, then there will be difficulty in falsification at some branching points. The second step is to arrange the hypotheses into a tree structure (Figure 3). This is not necessarily the only tree structure possible. The final step is to distinguish among the hypotheses on the basis of falsification experiments at succeeding branching points beginning at the left.

Walter Alverez, the Nobel laureate physicist, and his son Luis (1980) have reported what they believe constitutes a falsification of the terrestrial branch. They base their assertion on detection of elevated iridium levels at the Cretaceous–Tertiary boundary. They contend that because such levels are unknown on the basis of natural terrestrial processes the cause must be extra-terrestrial. Whether they are right or not, the example illustrates the way the strategy works. Platt attributes much of the recent rapid advances in molecular biology to use of this strategy. When the premises are sufficiently satisfied, the Strong Inference strategy can be a powerful tool.

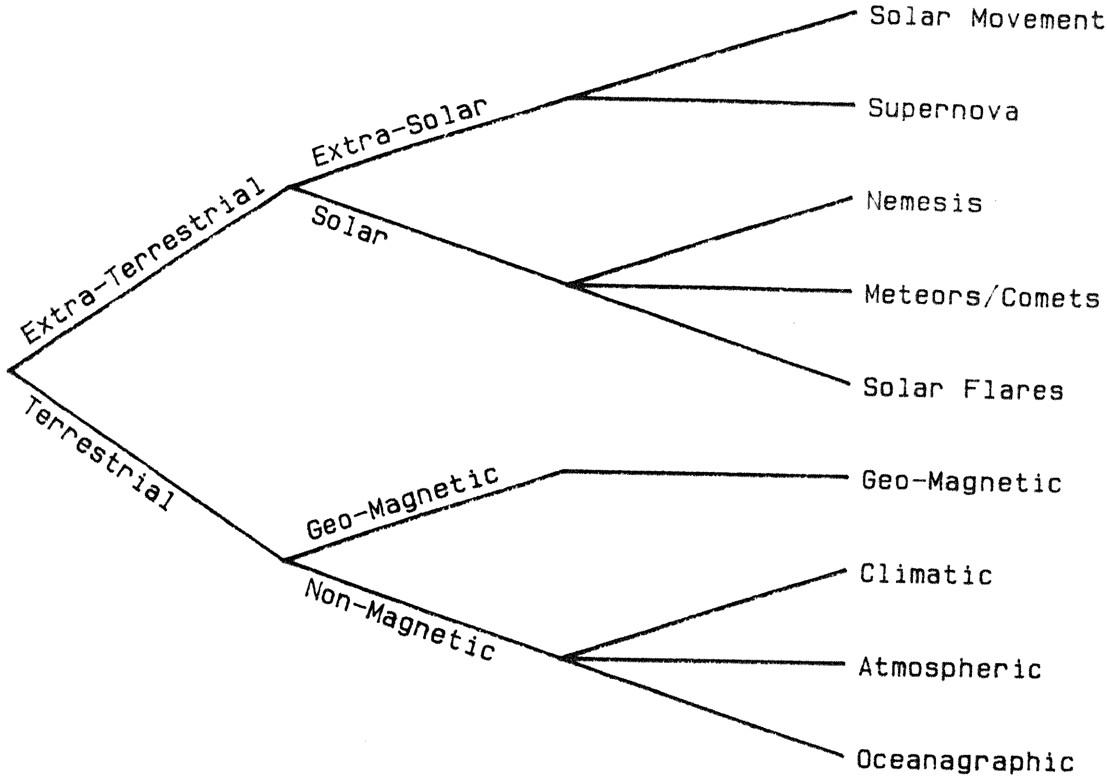

Figure 3. A tree structure for C-T extinction hypotheses.

CONTRADICTION

Disproof strategies suffer, in general, from reluctance on the part of researchers to accept their conclusions. Skeptical non-falsificationists are frequently unwilling to ascribe the power of conclusive disproof to Popper's counterexamples. This is particularly true when a favorite hypothesis or an established theory is the candidate for disproof. Non-falsificationists admit the contradiction between the evidence and the hypothesis but relegate such results to the category of anomalies rather than counterexamples.

There is justification for this attitude. Hypotheses are rarely tested in a vacuum. Virtually every test of a hypothesis is actually a test of the hypothesis in conjunction with paradigms, theories, supporting hypotheses, and additional assumptions concerning methodology, instrumentation, and observation. The falsification is of the conjunction and may be attributed to any of the conjuncts. For many reasons it may be appropriate to attribute the falsification to a conjunct other than the basic hypothesis. The history of science abounds with examples of such actions later being justified.

Research Programs: In an attempt to shore up Falsification, Lakatos (1980) developed a strategy he called Research Programs. The procedure is to first specify the protected hard core, C, of propositions that are currently considered established. The supporting and/or tested hypotheses, H, are then formulated and the falsifying conditions, ~D, are specified. The falsifying conditions are now seen as the negation of a deduction, D, from the conjunction of H and C. As in Falsification, an experiment is designed and performed in an attempt to detect the falsifying conditions. If such a counterexample is detected, the falsification is attributed to the supporting and/or tested hypotheses, H, not to the hard core, C. Research continues with this hard core as long as progress occurs. The decision to discontinue the research program or alter the hard core occurs by consensus among scientists working in the program.

As an example, consider the numerous attempts that have been made to measure continental drift. One current method, Very Long Baseline Interferometry or VLBI, uses dish antennas on opposite sides of the Atlantic to record radio signals from the same quasar, an extremely distant and therefore stationary reference point. The differences in arrival times permit precise estimates of the distance between the two receivers. The annual rate at which North America and Europe are separating has been estimated by this method at 2.0 centimeters per year (Anonymous 1985b). Unfortunately, the precision of the VLBI method is only about 2 or 3 centimeters per year. Based on the data, it might be logical to conclude that the rate is not significantly different than zero and that there is no evidence for continental drift. However, VLBI scientists contend that atmospheric interference, bending of the signal in the ionosphere, and the unsteadiness of the Earth introduce noise into the signal that prohibits achieving a precision of about 3 millimeters. In this example, it is clear that the continental drift hypothesis is a part of the protected hard core and that it is actually the instrumentation that is being tested.

The logical intent of the research programs strategy has been labeled contradiction. Logically, it is negation oriented like disproof, but it is less conclusive due to the lack of logical validity for protecting the hard core.

SUMMARY

Discovery and Justification are different components of scientific method and require strategies with different features. Discovery strategies must satisfy only one demand: they have to work. Justification strategies must satisfy the demands of an imprecise, but fairly well agreed upon logic. Some Justification strategies satisfy these demands better than others. The classification of Justification strategies in Figure 1 and the ensuing discussion are intended to help scientists better distinguish among such strategies and select the appropriate one.

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