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INTERFIELD THEORIES*

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This paper analyzes the generation and function of hitherto ignored or misrepresented *interfield theories*, theories which bridge two fields of science. Interfield theories are likely to be generated when two fields share an interest in explaining different aspects of the same phenomenon and when background knowledge already exists relating the two fields. The interfield theory functions to provide a solution to a characteristic type of theoretical problem: how are the relations between fields to be explained? In solving this problem, the interfield theory may provide answers to questions which arise in one field but cannot be answered within it alone, may focus attention on domain items not previously considered important, and may predict new domain items for one or both fields. Implications of this analysis for the problems of reduction and the unity and progress of science are mentioned.

1. Introduction. Interactions between different areas or branches or fields of science have often been obscured by current emphasis on the relations between different scientific theories. Although some philosophers have indicated that different branches may be related, the actual focus has been on the relations between theories within the branches. For example, Ernest Nagel has discussed the reduction of one branch of science to another ([27], ch. 11). But the relation that Nagel describes is really nothing more than the derivational reduction of the *theory* or *experimental law* of one branch of science to the theory of another branch.

We, in contrast to Nagel, are interested in the interrelations between the areas of science that we call *fields*. For example, cytology, genetics, and biochemistry are more naturally called fields than theories. Fields may have theories within them, such as the classical theory of the gene in genetics; such theories we call *intrafield theories*. In addition, and more important for our purposes here, interrelations between fields may be established via *interfield theories*. For example, the fields of genetics and cytology are related via the chromosome theory of Mendelian heredity. The existence of such interfield theories has been obscured by analyses such as Nagel's that erroneously conflate

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theories and fields and see interrelations as derivational reductions.

The purpose of this paper is, first, to draw the distinction between field and *intra*field theory, and, then, more importantly, to discuss the generation of heretofore unrecognized *inter*field theories and their functions in relating two fields.¹ Finally we wish to mention the implications of this analysis for reduction accounts and for unity and progress in science.

By analysis of a number of examples we will show that a field is an area of science consisting of the following elements: a central problem, a domain consisting of items taken to be facts related to that problem,² general explanatory factors and goals providing expectations as to how the problem is to be solved,³ techniques and methods, and, sometimes, but not always, concepts, laws and theories which are related to the problem and which attempt to realize the explanatory goals. A special vocabulary is often associated with the characteristic elements of a field.⁴ Of course, we could attempt to associate institutional and sociological factors with the elements of a field, but such an attempt would fail to serve the purpose of our discussion. We are interested in conceptual, not sociological or institutional, change. Thus, the elements of a field are conceptual, not sociological, of primary interest to the philosopher, not the sociologist.

The elements are also historical. Fields emerge in science, evolve, sometimes even cease to be. (We have not yet explored the latter phenomenon of decline.) Although any or all of the elements of the field may have existed separately in science, they must be brought together in a fruitful way for the field to emerge. Such an emergence

¹We are not using 'theory' in the sense of 'deductive system'. In spite of the difficulties of providing a general analysis of 'theory', we have retained the term because the developments with which we are concerned are called 'theories' by their originators. Furthermore, the interfield developments are solutions to theoretical problems, as we shall see.

²'Domain' is here used in the sense analyzed by Dudley Shapere ([33]).

³Stephen Toulmin emphasizes the importance of explanatory problems and goals in [38], chs. 2, 3.

⁴A special vocabulary is not a formal language, but a specialized part of the natural language. Nor is a special vocabulary a theoretical vocabulary, since the terms in it may be associated with the domain or techniques of the field as well as its problem solutions. A term may become part of the special vocabulary by specialization within the field (e.g., 'mutation' became specialized in genetics) or may be introduced as a new term (e.g., 'epistasis' was introduced in genetics). Further examples of such terms are the following: in genetics—'test cross', 'cis', 'trans', 'locus'; in cytology—'meiosis', 'mitosis', 'karyotype', 'chromosome'; in biochemistry—'respiratory quotient', 'ligase', 'citric acid cycle'; in physical chemistry—'bond angle', 'secondary structure', and 'optical rotation'. For further discussion of special vocabularies see [20] and [21].

is marked by the recognition of a promising way to solve an important problem and the initiation of a line of research in that direction. For instance, what comes to be the central problem of a field may have been a long-unsolved puzzle and the techniques may have been used elsewhere, but the field emerges when someone sees that those techniques yield information relevant to the problem. Or, perhaps, a new concept is proposed, giving new insight into an old puzzling problem and generating a line of research.

Because the convergence of the elements of a field can be identified historically, the emergence of a field can often be dated. Then, scientists who were part of the new field can be identified: they used the techniques of the field to solve its central problem. Others who had worked on the central problem in other ways or who had used the techniques for other purposes were not members of the field. The lone precursor who worked on the problem with the techniques but did not found an ongoing line of research, may, with hindsight, be called a geneticist, a biochemist, or whatever, even though the field (and perhaps even the term designating the field) did not exist at the time.

Of the terms current in philosophy of science which refer to categories broader than theory, the one which has most similarities to 'field' is Stephen Toulmin's 'discipline'.⁵ What Toulmin classes as a discipline, we would probably also class as a field. Included in his examples of disciplines are genetics along with physics, atomic physics, chemistry, biochemistry, biology, and evolutionary biology ([38], pp. 141, 145, 146, 180). From these examples we see that Toulmin encounters a difficulty which is also a problem for an analysis in terms of fields: criteria seem to be needed to distinguish between disciplines, subdisciplines, and supradisciplines. For instance, is atomic physics a subdiscipline of physics or is atomic physics the discipline and physics the supradiscipline? Toulmin gives no way of distinguishing disciplines from smaller or larger units; as a result, his examples are somewhat confusing.

⁵Other current broader categories include Imre Lakatos's "research programme," in [19] and Thomas Kuhn's "paradigm" or "disciplinary matrix" in [18]. These have fewer similarities to fields and are fraught with more difficulties than Toulmin's analysis. For further discussion see [8].

Two further comments about fields are in order here. This analysis is not intended as a demarcation between science and nonscience. There may well be fields of nonscience with some of the same elements indicated here for scientific fields. Criteria other than those we have provided would be necessary to distinguish nonscientific fields from scientific ones. Secondly, this analysis does not presuppose that all of science can be neatly divided into mutually exclusive fields. Such division would not be expected of things which evolve. Further investigation is necessary to determine the limits of applicability of the term 'field' in other cases.

In this paper we discuss fields that are within the broader scientific areas of biology and chemistry, but we do not give criteria for distinguishing more inclusive from less inclusive categories. We suspect that the level at which an analysis is carried out may depend on the questions being asked and the historical period being examined. For example, historical examinations of science in the nineteenth century might well ask the question—when did biology emerge as a field in science? But twentieth century historians of biology are more likely to treat fields within what has become the broader area of biology. Thus, the formulation of time-independent criteria for the delineating of fields will be difficult and might even serve to obscure important aspects of the historical development of science.

Toulmin's lists of the components of a discipline are numerous: "body of concepts, methods, and fundamental aims" ([38], p. 139); "a communal tradition of procedures and techniques for dealing with theoretical or practical problems" ([38], p. 142); "(i) the current explanatory goals of the science, (ii) its current repertory of concepts and explanatory procedures, and (iii) the accumulated experience of the scientists working in this particular discipline" ([38], p. 175). Taken collectively, these components are similar to the elements of a field.⁶

Although similarities exist between field and discipline, there are several reasons why we have not adopted Toulmin's term. First, even though the components of disciplines are similar to those of fields, they are not identical. The central problem, domain, and techniques will play important roles in our analysis; they are not found in Toulmin's lists. Furthermore, we find it difficult to use or to analyze such components as "accumulated experience of scientists." But most important, Toulmin's notion of a discipline is embedded in an epistemology: knowledge is the result of a selection process much like the selection processes proposed by evolutionary theory for biological organisms. Although Toulmin's analysis is provocative, we would rather not commit our analysis to his "evolutionary epistemology." The legitimate use of an evolutionary analogy, we believe, can only be discovered by a detailed investigation of science, for example by examination of interactions among the elements of fields.

Examples of fields will now be examined in more detail. Cytology in its early days had the central problem—what are the basic units of organisms? This problem was solved by the postulation of the

⁶In comparing fields and disciplines, Toulmin said that the field is what the discipline is concerned with. "A discipline is an activity." (Private conversation with LD, 12 March 1974).

cell theory and its subsequent elaboration and confirmation in the nineteenth century. Afterwards, the problem for cytologists (or cell biologists as they have come to be called) became the characterization of different types of cells, of organelles within cells, and of their various functions. The problem is tackled primarily with the technique of microscopic analysis.

The field of genetics, on the other hand, has as its central problem the explanation of patterns of inheritance of characteristics. The characteristics may be either gross phenotypic differences, such as eye color in the fly *Drosophila*, as investigated in classical genetics, or molecular differences, such as loss of enzyme activity, as investigated in modern transmission genetics. The patterns of inheritance are investigated with the technique of artificial breeding. The laws of segregation and independent assortment (Mendel's Laws), once their scope was known and they were well-confirmed, became part of the domain to be explained. For many of the early geneticists, though not all, the goal was to solve the central problem by the formulation of a theory involving material units of heredity (genes) as explanatory factors. In attempting to realize the goal, T. H. Morgan and his associates formulated the theory of the gene of classical genetics. Extension of the theory and techniques from *Drosophila*, Morgan's model organism, to microorganisms marked the modern phase of the field of genetics, a phase which may be called modern transmission genetics.

The central problem of biochemistry is the determination of a network of interactions between the molecules of cellular systems and their molecular environment; these molecules and their interrelations are the items of the domain. As was the case with genetics in which laws became part of the domain, here too, the solution to a problem may contribute new domain items. For example, the Krebs cycle was part of the solution to the problem of determining the interactions between molecules and became, in turn, part of the domain of biochemistry; its relation to other complex pathways then posed a new problem. Many techniques of biochemistry are aimed at the reproduction of *in vivo* systems *in vitro*, that is, the "test tube" simulation of the chemical reactions that occur in living things.

The determination of the structure and three-dimensional configuration of molecules has become the concern of physical chemistry.⁷

⁷Determination of the structure and three-dimensional configuration of molecules was not, at the turn of the century, the concern of physical chemists, like Wilhelm Ostwald, who were interested only in energy relations in biological systems. However, organic chemists (for example, Emil Fischer) were interested in the structural analysis of molecules. But by 1910 even Ostwald, who had been influenced by Ernst Mach's

Thus, the central problem of physical chemistry is the determination of the interactions of all parts of a molecule relative to one another, under varying conditions. The domain of physical chemistry is the parts of molecules and their interactions. Physical chemistry has evolved complex techniques for the determination of the structure and conformation of molecules: x-ray diffraction, mass spectrometry, electron microscopy, and the measurement of optical rotation.

With these examples of fields in mind we may contrast fields and *intrafield* theories. A field at one point in time may not contain a theory, or may consist of several competing theories, or may have one rather successful theory. Well-confirmed laws and theories may become part of the domain and a more encompassing theory be sought to explain them. Although theories within a field may compete with one another, in general, fields do not compete, nor do theories in different fields compete. Furthermore, one field does not reduce another field; reduction in the sense of derivation would be impossible between such elements of a field as techniques and explanatory goals.⁸

Even though fields do not bear the relations formerly thought to exist between theories, fields may be related to one another. Indeed, our main concern here is with the relations between fields which serve to generate a different type of theory, the *interfield theory*, which sets out and explains the relations between fields. Our task now is to discuss the conditions which lead to the generation of interfield theories. The discussion of general features of generation will be followed by examples of interfield theories: the chromosome theory of Mendelian heredity bridging the fields of cytology and genetics; the operon theory relating the fields of genetics and biochemistry; and the theory of allosteric regulation connecting the fields of biochemistry and physical chemistry. The examples will then serve as a basis for characterizing the general functions of interfield theories.

2. The generation of interfield theories. An interfield theory functions to make explicit and explain relations between fields. Relations between fields may be of several types; among them are the following:

positivistic view of science, admitted that molecules exist, thus removing scepticism about the application of the kinetic techniques of physical chemistry to problems about the structure of molecules. For an excellent account of the interaction between physical chemistry and organic chemistry, see [12].

⁸We are not taking a stand as to whether, in some possible cases, a theory in one field may be derived (in the sense of reduction) from a theory in another field. However, our examples here do not indicate that any such reduction has occurred; on the contrary, a main point of this paper is that an analysis in terms of interfield theories, not reductions, is the appropriate analysis in these important cases in biology.

(1) A field may provide a *specification of the physical location* of an entity or process postulated in another field. For example, in its earliest formulation, the chromosome theory of Mendelian heredity postulated that the Mendelian genes were *in* or *on* the chromosomes; cytology provided the physical location of the genes. With more specific knowledge, the theory explained the relation in more detail: the genes are part of (in) the chromosomes. Thus, the relation became more specific, a *part-whole* relation.

(2) A field may provide the *physical nature* of an entity or process postulated in another field. Thus, for example, biochemistry provided the physical nature of the repressor, an entity postulated in the operon theory.

(3) A field may investigate the *structure* of entities or processes, the *function* of which is investigated in another field. Physical chemistry provides the structure of molecules whose function is described biochemically.

(4) Fields may be linked *causally*, the entities postulated in one field providing the causes of effects investigated in the other. For example, the theory of allosteric regulation provides a causal explanation of the interaction between the physicochemical structure of certain enzymes and a characteristic biochemical pattern of their activity.

These types of relations are not necessarily mutually exclusive; as the examples indicate, structure-function relations may also be causal.

Several different types of reasons may exist for generating an interfield theory to make explicit such relations between fields. First, relationships between two fields may already be known to exist prior to the formulation of the interfield theory. We shall refer to such pre-established relationships as *background knowledge*. For example, prior to the proposal of the operon theory, the fields of genetics and biochemistry were known to be related; to cite one of many instances, the physical nature of the gene was specified biochemically as DNA. Thus, further relations could be expected between the fields and might lead to the generation of an interfield theory.

Secondly, a stronger reason for proposing an interfield theory exists when two fields *share an interest in explaining different aspects of the same phenomenon*.⁹ For example, genetics and cytology shared an interest in explaining the phenomenon of heredity, but genetics did so by breeding organisms and explaining the patterns of inheritance

⁹To say that two different fields share an interest in "the same phenomenon" is only to say that scientists believed and had good reasons to believe that they were dealing with the same phenomenon.

of characters with postulated genes. Cytology, on the other hand, investigated the location of the heredity material within the cell using microscopic techniques. Since they were both working on the problem of explaining the phenomenon of hereditary, a relation between them was expected to exist.

Furthermore, *questions arise in each field which are not answerable using the concepts and techniques of that field*. These questions direct the search for an interfield theory. For example, in genetics the question arose: where are the genes located? But no means of solving that question within genetics were present since the field did not have the techniques or concepts for determining physical location. Cytology did have such means.

In brief, an interfield theory is likely to be generated when background knowledge indicates that relations already exist between the fields, when the fields share an interest in explaining different aspects of the same phenomenon, and when questions arise about that phenomenon within a field which cannot be answered with the techniques and concepts of that field.

Questions about the relations between fields pose an *interfield theoretical problem*: how are the relations between the fields to be explained? The solution to an interfield theoretical problem is an interfield theory. Dudley Shapere, in discussing theoretical problems, says: "Theoretical problems call for answers in terms of ideas different from those used in characterizing the domain items. . . . These new ideas, moreover, are expected to 'account for' the domain" ([34] p. 22). Shapere's analysis is for an *intrafield* theory, in our terminology, but we may extend it to our case by saying that new ideas are introduced to account for the relationships between the two different domains of the different fields. The new idea which the theory introduces gives the nature of the relations between two fields, such as the types of relations discussed in (1), (2), (3) and (4) above.¹⁰

¹⁰Shapere's analysis differs from ours in another respect. For Shapere, items that are related to one another and demand explanation make up *one* domain. In fact, "related items about which there is a problem demanding a theory as an answer" is one of the alternative definitions of a domain supplied by Shapere. Hence, once relations are seen between two domains of two different fields, Shapere would probably regard the situation as the formulation of a new single domain encompassing the other two. However, we have introduced discussion of a field and domains that are characteristic of particular fields, distinctions not explicitly discussed by Shapere. And our primary concern is with such relationships between fields. Hence, although it is possible to say that a new domain is formed as a result of the discovery of relations between different domains, we do not wish to so characterize the situation. We prefer to regard the domains of different fields as separate but related and the interfield theory as providing an explanation of the relations.

Suppose a relation between fields is suspected to exist because the fields share an interest in explaining aspects of the same phenomenon. Familiar types of relations between fields can then be considered, for example, causal, part-whole, or structure-function. The most likely relation (as indicated by considerations which will not be examined in this paper) can be chosen and particularized for the case in point. Thus a new idea is introduced specifying the nature of the relations between fields, that is, an interfield theory is formulated.

We will now turn to the examination of detailed examples of interfield theories in order to illustrate the general features of their generation just discussed and to analyze their functions in more detail.

3. The chromosome theory of Mendelian heredity. Cytology emerged as a field in the 1820s and 30s with improvements in the microscope and the proposal of the cell theory. By the late 1800s, as a result of their investigations of the structures within cells, cytologists asked the following question: where within the germ cells is the hereditary material located? A widely accepted answer by 1900 proposed the chromosomes (darkly staining bodies within the nuclei of cells) as the likely location. (For further discussion see [40], [6], and [15].)

On the other hand, theories of heredity had been proposed in the late nineteenth century but none had the necessary ties to experimental data to give rise to a field of heredity until the discovery of (what have come to be called) Mendel's laws in 1900. Although Mendel had worked with garden peas, noted their hereditary characteristics, crossed them artificially and proposed a law—he formulated only one—characterizing the patterns of inheritance, he did not found a field. Genetics emerged between 1900 and 1905 with the independent discovery of Mendel's law by Hugo de Vries and Carl Correns and with the promulgation of Mendel's experimental approach by William Bateson. Although Bateson did not (for reasons too complex to examine here), other geneticists postulated (what have come to be called) genes as the causes of hereditary characteristics. (For further discussion see [7], [8], and [10].)

Thus, by 1903 cytology and genetics had both investigated hereditary phenomena but asked different questions about it. At least some geneticists postulated Mendelian units to account for the patterns of inheritance of observed characteristics. Cytologists, on the other hand, proposed the chromosomes as the location of the hereditary material in the germ cells. Genes were, thus, hypothetical entities with known functions; chromosomes were entities visible with the light microscope with a postulated function.

But questions arose in each field which were not answerable with

the techniques and concepts of the field itself. Genetics was unable to answer the question: where are the genes located? Its techniques were those of artificial breeding which provided no way of determining physical location. Cytology was known to provide a way of investigating the cells and their contents and thus was the natural field to turn to in search of an answer to the question about the location of genes. On the other hand, cytologists had no way of investigating the functioning of chromosomes in producing *individual* hereditary characteristics. Theodor Boveri had, however, investigated the loss of one (or more) *entire* chromosome(s) and the changes in *many* characteristics in the developing embryo that such loss produced ([2]).

In addition to there being questions in each field which could not be answered within that field, more important in the historical generation of the chromosome theory was the fact that properties of the chromosomes and genes showed striking similarities. At least three properties of chromosomes and genes had been found independently in the two fields (see items 1, 2 and 3 of Table 1). Both Walter Sutton ([37]) and Theodor Boveri ([3], pp. 117-118) were struck by the remarkable similarities and were independently led in 1903 and 1904 to postulate the chromosome theory of Mendelian heredity as a result. The theory (using the modern term 'gene') is the following: the genes are in or on the chromosomes. The theory solves the theoretical problem as to the nature of the relations between genes

Table 1. Relations Between Chromosomes and Genes

CHROMOSOMES	GENES
1. Pure individuals (remain distinct, do not join)	1. Pure individuals (remain distinct, no hybrids)
2. Found in pairs (in diploid organisms prior to gametogenesis and after fertilization)	2. Found in pairs (in diploid organisms prior to segregation and after fertilization)
3. The reducing division results in one-half to gametes	3. Segregation results in one-half to gametes
4. <i>Prediction:</i> Random distribution of maternal and paternal chromosomes in formation of gametes	4. Characters from maternal and paternal lines found mixed in one individual offspring; independent assortment (often) of genes
5. Chromosome number smaller than gene number	5. <i>Prediction:</i> Some genes do not assort independently in inheritance; instead are linked on the same chromosome
6. Some chromosomes form chiasmata, areas of intertwining <i>Prediction:</i> An exchange of parts of chromosomes at chiasmata	6. More combinations of linked genes than number of chromosomes; "crossing-over" occurs

and chromosomes by introducing the *new idea* that the chromosomes are the physical location of the Mendelian genes. Although August Weismann ([39]) had, in 1892, postulated that the chromosomes were composed of hierarchies of hereditary units, which he called “bio-phores, determinants, and ids,” his was not a theory of *Mendelian* units. That the units which obeyed Mendel’s law were located in or on the chromosomes was a *new idea* proposed by Boveri and Sutton.

The ambiguity as to whether the genes were “in” or “on” the chromosomes was resolved in favor of the “in” with further development of the theory in the hands of T. H. Morgan and his associates in the 1910s and 20s ([24], [25], [26]). Thus, the relationship between genes and chromosomes postulated by the interfield theory became that of part to whole, and the theory explained the correlated properties because parts would be expected to share at least some properties of their wholes.

But the theory did more than explain properties of genes and chromosomes already known. It also functioned to predict new items for the domains of each field on the basis of knowledge of the other. For example, item 4 of Table 1 is a prediction Sutton made about the behavior of chromosomes on the basis of the behavior of genes. This prediction corrected a misconception of cytologists. Mistakenly, Sutton said ([37], p. 29), cytologists prior to the formation of the chromosome theory of Mendelian heredity had thought that the sets of chromosomes from the mother and father remained intact in their offspring and separated as units in the formation of gametes (sexual cells; in animals, eggs and sperm) in offspring. However, the independent assortment of hereditary characteristics, and therefore the genes which cause them, led to a reexamination of the behavior of the chromosomes, with the subsequent finding that the maternal and paternal chromosomes are distributed randomly in the formation of gametes ([37], [5]). The prediction for cytology of random segregation of chromosomes as a result of independent assortment of genes was thus substantiated.

Predictions went both ways. The knowledge from cytology of the small number of chromosomes compared to larger numbers of genes led both Boveri and Sutton to the prediction that some genes would be linked in inheritance, in other words, that exceptions to independent assortment would occur. The finding of linked genes substantiated this prediction. (See item 5 of Table 1.) The finding of predictions made on the basis of the theory served to provide support for the theory. As a result, both genetic and cytological evidence provided confirmation.

Not only did the theory predict new domain items for each field, it also served to focus attention on previously known but neglected items. For example, item 6 shows the correlation between the new finding in genetics that some genes “cross-over” or become unlinked and the previously known chiasmata, or areas of intertwining between chromosomes. Chiasmata had been seen by cytologists prior to their correlation with crossing-over, but no function for them was known so they had not been considered important. With the correlation to a property of genes by Morgan ([24]), chiasmata took on a new significance and subsequent investigation showed that they were indeed areas of exchange between parts of chromosomes as predicted by the genetic evidence. This is an example of the change in relative importance of a type of domain item; an item previously considered peripheral became a center of investigation.¹¹

After the formulation of the theory and its confirmation, new findings about genes raised parallel questions about chromosomes and vice versa. New types of experiments were designed using the techniques from both fields. Calvin Bridges, a coworker of T. H. Morgan, was one of the most successful practitioners of the new method of research ([4]). Thus, the theory generated a new line of research coordinating the techniques and findings of both fields.

In summary, the chromosome theory of Mendelian heredity is an interfield theory bridging the fields of genetics and cytology. It was generated to unify the knowledge of heredity found in both fields and thereby to explain the similar properties of chromosomes and genes. It functioned to focus attention on previously neglected items of the domains and to predict new items for the domains of each field. It further served to generate a new line of research coordinating the fields of cytology and genetics. Success in finding the predictions of the theory and in developing the common line of research resulted in the confirmation of the theory and the fruitful bridging of two fields of science.

4. The operon theory and theory of allosteric regulation. The chromosome theory was an important first step, eventually leading to the development of an explanation of how the genetic material acts as a carrier of information in biological systems. Once the DNA component of the chromosome was shown to carry the genetic information, then the problem of the *control* of such information emerged. The regulation of gene expression was seen to be of particular significance for an understanding of the development of organisms from embryc

¹¹ Shifts in importance of domain items were discussed by Shapere ([33], pp. 532–533).

to adult. All cells of a multicellular organism have an identical complement of genes, but in different cells, different genes are expressed at different times. In short, differentiation occurs and must be explained. Even in unicellular organisms, gene expression varies with stages in the life cycle and, as we shall see in discussing the operon theory, with changes in the surrounding medium that affect the intracellular environment. The operon theory and the Monod-Wyman-Changeux theory of allosteric regulation are both theories of the control of gene expression: the operon theory of the control of protein *levels* (the quantity of a protein in a cell) and the theory of allosteric regulation of the control of protein *activity*.¹²

Biochemists became interested in one aspect of the control of protein levels, *enzyme adaptation* (later called *enzyme induction*), some fifty years after its discovery in 1900 by Dienert ([9]). Dienert had described a process by which cells adjust the availability of an enzyme in response to the presence of specific metabolites (substances required for growth). This finding was later thought to suggest that gene expression is reversibly controlled by biochemical changes in the environment. For example, the bacterium *Escherichia coli* produces higher levels of the lactose-metabolizing enzymes when lactose precursors, the galactosides, are available. However, these enzyme levels are radically reduced in the absence of galactosides.

Further, transmission studies (artificial breeding and recording of characters transmitted to offspring) showed that the capacity to regulate enzyme levels in response to metabolites could be altered by mutation (heritable changes in the genes). Certain mutants in the lactose-metabolizing system within the bacterium were discovered; the mutants produce the enzymes required for the metabolism of lactose whether or not the lactose precursors are available. This mutation (*i*-, or inducer-negative) was found to be located at a site on the bacterial chromosome distinct from the sites of the genes for the lactose-metabolizing enzymes. This suggested that changes at a site somewhat distant from the genes for the lactose-metabolizing enzymes could affect the expression of those genes. Further investigation of mutants of this *i* gene and the critical experiment of Pardee, Jacob, and Monod in 1959 ([29]) implicated an *i* gene *product* as the controlling substance responsible for the repression of the lactose-metabolizing enzymes.¹³

¹²The theory of allosteric regulation discussed here is the Monod-Wyman-Changeux theory ([23]). This theory of allosteric regulation is not the only conformational theory set forth to explain the regulation of protein activity; the other major account is Koshland's "induced fit" theory ([17]).

¹³A more detailed examination of the genesis of the operon theory has been undertaken by Schaffner in ([30]) and ([32]).

The control of these enzymes by an *i* gene product was incorporated into the proposal, in 1961, by Jacob and Monod ([16]) of a theory of the operon, a causal theory of biochemical changes that effect specific, heritable patterns of gene expression. Two kinds of genes were postulated: *structural genes*, like the genes for the lactose-metabolizing enzymes, carry the information that determines the molecular structure of enzymes, or carry the information for some proteins other than enzymes (for example, hormones); *regulatory genes*, of which the *i* gene represents only one type, are involved in the control of structural genes. Further, the operon theory postulates that the *lac* (lactose-metabolizing) system of *E. coli* is an *inducible* system; enzyme synthesis is induced by the presence of metabolites. Induction, that is, transcription of the lactose-metabolizing genes into a *cytoplasmic messenger* (mRNA) for protein synthesis, depends on the state of another regulatory gene called the *operator*. The structural genes whose activity is coordinately controlled, as are the lactose-metabolizing genes, form a unit of control, the *operon*. Transcription of the operon begins at the operator if the operator is not blocked by the *i* gene product, called the *repressor*. However, the repressor is not always in complex with the operator; the repressor itself is controlled by its interaction with *inducer*, in the case of the *lac* system, the galactosides. When inducer is available, the repressor binds the inducer and cannot bind the operator. And transcription of the operon proceeds. On the other hand, when inducer is absent, the repressor binds the operator and transcription is blocked. (See Figure 1.)

Questions about the physical nature of the repressor, whether a

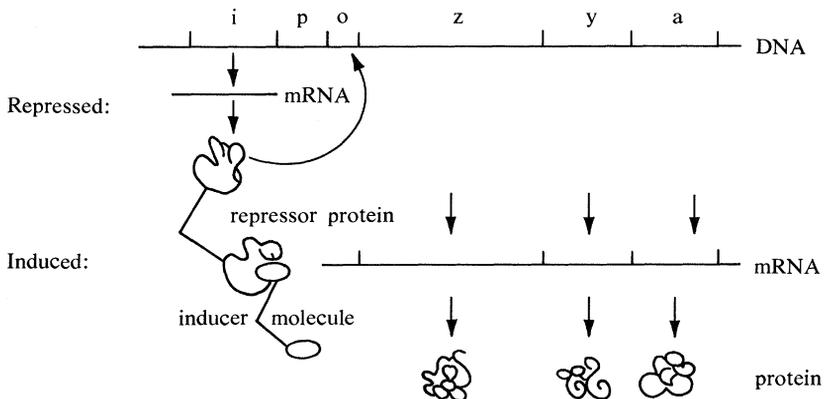


Figure 1. The *lac* operon of *Escherichia coli*. The repressed and induced states are illustrated.

polynucleotide like mRNA or a protein, were raised in the 1961 proposal. However, the *genetic* studies upon which the proposal was based could not provide an answer to questions about the physical nature of the repressor. Subsequent to the 1961 proposal, *biochemical* findings implicated a protein repressor. Yet the *lac* repressor was not isolated until 1966; the biochemical test used to isolate the protein was its affinity for galactosides, a property predicted by the operon theory on the basis of genetic findings. As the theory also predicted, the protein was shown to be absent or functionally impaired in the *i* mutant strains of bacteria. Finally the repressor protein was shown to bind an operator, as the theory predicted.¹⁴

Significantly, the protracted failure to isolate the repressor in the five years after the 1961 proposal led to questions about the mode of interaction between repressor, inducer, and operator.¹⁵ It was thought that a better understanding of the inducer-repressor interaction would facilitate isolation of the repressor. The characteristic biochemical pattern of activity of the repressor (a sigmoid activity curve) was seen by Monod and his colleagues to be similar to that of a class of "regulatory enzymes" and to hemoglobin, the "honorary enzyme." Thus the operon theory served to direct new attention to an area of investigation in biochemistry, the functional similarities of a group of proteins. In addition to questions about the shared pattern of activity, questions about the possibility of shared structural features among such proteins were raised, thereby involving an area of investigation within physical chemistry, the structure or conformation of molecules.

Protein function (as revealed by a characteristic pattern of activity) was thought to be associated with protein structure as early as 1894; in that year Fischer ([11]) proposed his "lock-and-key" model of enzyme catalysis. In 1965, Monod, Wyman, and Changeux ([23]) proposed a causal theory to relate changes in protein structure to changes in protein activity. According to this theory of allosteric regulation, the alteration of protein activity (in the case of the repressor, its affinity for operator) is due to a reversible change in the conformation of the protein when it binds its regulatory metabolite (inducer).

¹⁴A protein repressor was strongly suggested by the work of Bourgeois, Cohen, and Orgel ([1]). The repressor was isolated by Gilbert and Müller-Hill ([13]), who also showed that repressor binds a DNA sequence, the operator ([14]).

¹⁵On the one hand, failure to isolate repressor led to an attempt to characterize its mode of action in the theory of allosteric regulation proposed by Monod, Wyman, and Changeux ([23]). On the other hand, failure to isolate the repressor was seen by Stent ([35]), as justification for the proposal of a new, competitor theory that prescribed a very different function for the *i* gene product.

The theory predicts that the regulatory protein (repressor) will have two nonoverlapping sites: one, the *active site*, has a structure complementary to the substrate (operator) and therefore binds it; another, the *allosteric site*, has a structure complementary to the regulatory metabolite (inducer) and binds it. (See Figure 2.) The conformational change brought about by the formation of a protein-metabolite complex is called an *allosteric transition*, "which modifies the properties of the active site, changing one or several of the kinetic parameters which characterize the biological activity of the protein" ([22]. p. 307).

In both theories, the operon theory and the theory of allosteric regulation, two fields (genetics and biochemistry on the one hand and biochemistry and physical chemistry on the other) share a concern with the investigation of aspects of a phenomenon (with the operon theory, regulated gene expression and with the theory of allosteric regulation, regulated protein activity). Both theories are posed against a considerable body of background knowledge; extensive relationships between genetics, biochemistry, and physical chemistry had already been established. As a result, good reasons could be advanced for entertaining the hypotheses that patterns of gene expression are related to certain biochemical entities and processes and that the activity of proteins is related to their physicochemical conformation.

In both cases, no one field had all the concepts and techniques

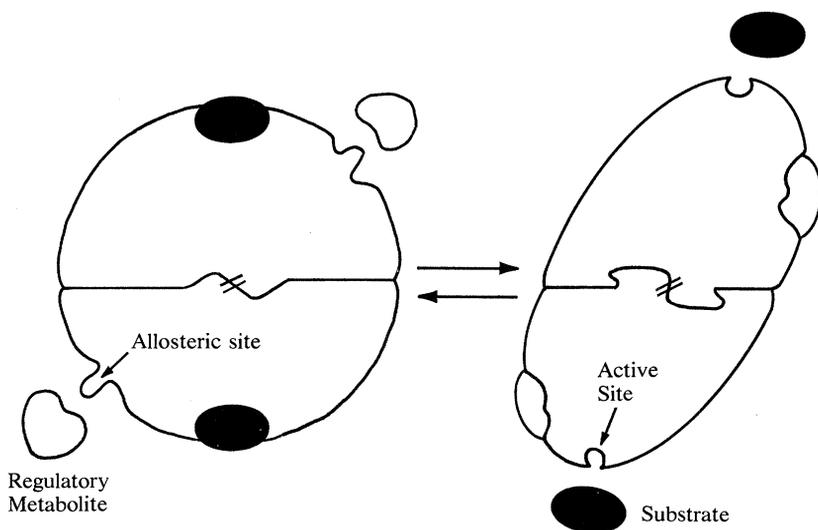


Figure 2. An allosteric transition in a symmetrical protein with two subunits.

to answer all the questions that arose concerning the phenomenon. Genetics provided the transmission studies of the *i* mutant and characterized the active *i* gene product as a cytoplasmic substance. The physical nature of the *i* gene product was determined by a biochemical test. And the structural features of the repressor required to explain its characteristic pattern of biochemical activity could only be supplied by physicochemical techniques.

Both the operon theory and the theory of allosteric regulation are causal theories. The operon theory is an account of biochemical causes and genetic effects; specific biochemical interactions explain the patterns of inheritance characteristic of the regulated system of genes. The theory of allosteric regulation explains the characteristic pattern of activity (the function) of certain proteins by a specific and reversible sequence of structural change. Both theories supply answers to theoretical problems by introducing new ideas about the relationship among items of different domains.

5. The function of interfield theories. In summary, an interfield theory functions in some or all of the following ways:

(a) To solve (perhaps "correctly") the theoretical problem which led to its generation, that is, to introduce a new idea as to the nature of the relations between fields;

(b) To answer questions which, although they arise within a field, cannot be answered using the concepts and techniques of that field alone;

(c) To focus attention on previously neglected items of the domains of one or both fields;

(d) To predict new items for the domains of one or both fields;

(e) To generate new lines of research which may, in turn, lead to another interfield theory.¹⁶

6. Conclusion. Because our examples represent significant developments in science, because they have important similarities in generation

¹⁶In the above discussion we have not viewed the interfield theory as functioning to establish a new, third field with relations to the previously separate fields. We believe the situation is made unnecessarily complicated by doing so. However, just as Shapere might regard the two domains as joined (see above, note 10), the interfield theory could be seen as forming a new field. For example, 'cytogenetics' and 'molecular genetics' seem to be used to refer to the areas between genetics and cytology related by the chromosome theory and between modern transmission genetics and biochemistry related, in part, by the operon theory. Some scientists who used techniques from both original fields, such as Bridges did, might be considered members of the "interfield theory field." This cumbersome analysis is a possible interpretation but not the best, we think.

and function, and because other examples of theories sharing these characteristics may be found in other cases, we have attempted to set forth the characteristics common to this type of theory, the interfield theory.

Let us now suggest why interfield theories have been ignored by philosophers of science. Philosophers have not usually discussed areas or fields of science, much less relations between them; instead they have concentrated on theories and on the relations between those, and thus have tended to view fields as theories. Furthermore, theories were viewed as being of the same type, interpreted axiomatic systems, and the relations between theories also were thought to take a single form, namely derivational reduction.¹⁷ After a derivational reduction had occurred, one theory had been “eliminated,” at least in the sense that it had been explained as a deductive consequence of a more general theory. Reduction analyses were taken to provide an interpretation of the unity of science. For example, Oppenheim and Putnam ([28]) interpreted the unity of science as the cumulative microreduction of theories. And progress was identified with successful reductions.

Although the above overview of a tradition in philosophy of science may be simplistic in certain respects, it is sufficient to show how a concentration on reduction relations between theories would have obscured the nature of fields of science and relations between them established by interfield theories which are not reductive. An interfield theory, in explaining relations between fields, does not eliminate a theory or field or domain. The fields retain their separate identities, even though new lines of research closely coordinate the fields after the establishment of the interfield theory.

But our analysis of interfield theories does not merely serve to bring to the attention of philosophers of science a type of theory which has been ignored. In addition, our analysis suggests and provides a foundation for the further development of a conceptual apparatus for understanding the generation and function of theories. The advantage of paying attention to the developmental and functional characteristics of theories is shown by the fact that we have discovered similarities among theories that might not have been noticed otherwise. Although the relationships between genetics and biochemistry and between biochemistry and physical chemistry may be seen, at first glance, as in some way reductive, it is unlikely that anyone would claim that cytology is reduced to genetics (or vice versa) by the

¹⁷See F. Suppe’s Introduction to ([36]) for a detailed account of this tradition in the philosophy of science (the “Received View”) as well as criticisms of and alternatives to it.

chromosome theory. In other words, our analysis shows important similarities between the generation and function of relationships which, on the older analysis, are in the different categories of “reductive” and “nonreductive” and would not have been seen as similar. It also indicates that there are important relations in science which are not reductive at all.¹⁸

One is led to ask: what accounted, on the older analysis, for the different ways of categorizing these two types of cases? Again, our analysis proves illuminating. Although all three cases are examples of interfield theories, the relationships between fields which they establish are not identical. The operon theory and the theory of allosteric regulation primarily establish *causal* links; the chromosome theory, on the other hand, establishes a *part-whole* relation between genes and chromosomes. We suspect that causal relations are more likely to appear reductive than part-whole relations. Of course, this speculation is only a starting point for further investigation of these and other cases.

Not only does our analysis call attention to similarities and differences overlooked in reductive analyses, it also casts doubt on the view that the unity of science is to be analyzed merely as a series of reductions, realized or potential. Provided with a new analysis of the relations between fields, it becomes natural to view the unity of science, not as a hierarchical succession of reductions between theories, but rather as the bridging of fields by interfield theories. The unity of science analyzed as a hierarchical classification scheme of scientific theories, graded according to generality, is precisely the picture provided by Oppenheim and Putnam ([28]) as a “working hypothesis.” Our preliminary analysis suggests another, new working hypothesis: unity in science is a complex network of relationships between fields effected by interfield theories.

Progress, too, receives a different analysis. Much of the progress of modern biology results from the development of interfield theories and the progressive unification (bridging) of the biological and physical sciences. With the chromosome theory, genes were associated with

¹⁸Kenneth Schaffner ([31]) through examination of cases from the history of modern biology, including the operon theory, seems to be moving toward a similar view with his claim that derivational reduction is “peripheral” to developments in modern biology. We believe that our analysis of interfield theories explains the phenomena that Schaffner notes: “These principles and causally relevant entities [of the operon theory] represent both ‘biological’ and ‘chemical’ principles and entities; Jacob and Monod did not work at the strictly chemical level but at levels, ‘intertwining’ the biological and chemical” ([31], p. 135). For further development of the analysis of interfield theories as an alternative to reduction, see ([21]).

intracellular organelles; subsequently, with the development of the Watson-Crick model, the genes were identified with segments of DNA molecules with a specific type of structure. The operon theory provided further links between genetics and biochemistry, and the theory of allosteric regulation served as a bridge between biochemistry and physical chemistry. In sum, the chromosome theory was the first of a series of interfield theories, the operon theory and theory of allosteric regulation among them, that advanced our understanding of the relationship between the biological and physical sciences and resulted in progress in modern biology.

We have used a methodology here which ties philosophy of science, not to formal logic, but to the history of science, the proper subject matter of philosophy of science. But we must be clear about what our analysis has produced. We are not proposing a general analysis applicable to all varieties of theory, progress or unity in science. Indeed, we have no reason to prejudge the still open question as to whether there is *one* analysis applicable to all theories or instances of unification and progress. We have found *a* type of theory prevalent in modern biology which helps us understand one way in which unity and progress occurs. Further examination of other cases from the history of biology and the history of other sciences will reveal the extent to which this analysis may be generalized.

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