A History of Mechanical Inventions (Revised Edition)
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CHAPTER IV

The Emergence of Novelty in Thought and Action

I

Mechanical invention is a special type of innovation, which may seem to present only a very limited aspect of the general problem of the emergence of novelty in thought and action. But such a judgment of the scope and importance of the process of mechanical invention is superficial. Invention in the field of mechanics is, in fact, broadly representative of every feature of the general process of invention. At the lower levels, mechanical invention involves little more than some improvement in the skills required for the making of simple tools, and, as long as invention is essentially empirical, even the development of relatively complex mechanisms does not seem to involve abstract thought or organized scientific knowledge. But abstract concepts do exert a palpable influence upon the process of mechanical invention, and as early as the fifteenth century there was sufficient knowledge of mechanics to establish a clear distinction between pure and applied science. From this period, the process of mechanical invention was so definitely associated with the formulation of highly generalized concepts and propositions that it exhibits all the characteristics of innovation in any of the conceptual fields, though the concrete application of scientific principles gives a special form to the synthesis achieved. The problems of mechanical invention, therefore, require consideration of a large portion of the total field.

Mechanical invention is important also as a field of study because the character of the material admits of a more rigorous historical treatment than is possible in many portions of the history of philosophy and

the arts. The more important aspects of the history of science must be included in any serious analysis of the history of mechanical invention. Only painting and sculpture afford comparable opportunities for the study of cumulative change in highly objective concrete forms, and in these fields the problems created by the greater freedom of symbolic expression present difficulties of appraisal that are not encountered in dealing with mechanical apparatus that is strictly utilitarian. The history of mechanical invention thus presents an unusually significant body of material for the analysis of the emergence of novelty in thought and action. Many of the primary features of the process can be securely established for the whole array of fields by critical study of this single field.

The emergence of novelty in the larger sense of the word must be taken to mean novelty to the social group. We distinguish between the mastery of the currently known skills and concepts and the improvement of skills, the advance of knowledge, and the formulation of new value judgments in art or social action. But this distinction already implies the accumulation of a body of knowledge and skills that represents a substantial cultural accomplishment. If a distinction is to be made, it would be necessary to distinguish between the behavior changes occurring in immature animals and the modifications of behavior in adults that were not associated with the process of maturation. A fledgling bird has new experiences when it leaves the nest and learns to fly, but such achievements are not novelties in the sense of invention. Even though flying is an act of skill that is not immediately mastered in its entirety, it is not an example of behavior directed or modified by insight. The action of the bird is dominated by its physical structure; these behavioral phenomena present problems in the development of organic structure. They belong in the field of organic evolution, rather than in the field of mental and social evolution.

Koffka characterizes insight as action in a particular situation in a special way, "though the animal possesses no special devices for the particular act . . . The dynamics of the process are determined by the intrinsic properties of the data."[1] In the discussion of this proposition, Koffka first considers an experience of a mountain climber in the Alps. A difficult descent through a chimney left him hanging in mid-air without enough rope to reach a safe ledge below. When he tried to reach another ledge by swinging, the rope slipped from his feet and he found himself unable to support all his weight by his hands. He seized the rope in his teeth and was able to swing himself to safety. The use of the mouth for an unusual function is an act that shows insight. Koffka also analyzes the train of thought involved in the solution of a problem in algebra by a person with elementary knowledge but no assured mastery of quadratic equations. This discussion is primarily concerned with the demonstration that insightful behavior does not necessarily yield a full solution in a single flash of insight. This phase of the exposition is of course of great importance, but it is significant to observe that full-length psychologic analysis combines in a single expository passage experiences that take place on such different levels as the experience of the mountain climber and the mathematical achievement of the young student of algebra. "Problems in perception and in thinking . . . have to be investigated at 'different levels' . . . but this difference in level is a difference in our knowledge of things and not a difference in the things themselves."[2]

II

Although historical analysis will ultimately require some formal discussion of the differences in levels at which novelty emerges in thought and action, it would be premature at this time to attempt to draw up a comprehensive and accurately graded array of the levels of perceptive and thoughtful action that we must consider. It is desirable, however, to present enough material to stress concretely the fact that many levels exist. The progressive emergence of new acts of skill results in the body of empirical experience that is represented by the arts and crafts. The manipulative skills are, of course, supplemented by empirical knowledge of materials that is quite as distinctive of craftsmanship as are the manual skills and proficiencies. Broadly speaking, these empirical achievements occur at the lowest level of behavior, dominated by perception rather than by thought.

At a somewhat higher level we find much mechanical invention, based upon empirical knowledge. The formulation of many individual symbols and of particular abstract concepts must be taken to occur at a somewhat lower level than any attempt to organize the symbols and concepts in systems, or to use them as a basis for synthetic value judgments. The organization of conceptual thought and of aesthetic and religious symbols into systems of considerable compass carries us to another level, with as many distinct fields as there are classes of concepts and symbols. As the formulation of a body of scientific knowledge takes place at this level, mechanical invention based on orderly scientific knowledge must be conceived as taking place on a still higher level. Similarly, the formulations of patterns of thought and action in the various fields must be conceived as occupying a higher level than the abstract concepts upon which they are based. Although transcendental idealism is justly insistent upon the fundamental importance of abstract concepts and the analytic truths, the idealists misrepresent the processes of thinking and of valuation when they represent abstract concepts as the highest and ultimate level of thought.

Patterns of thought and action are to be found in a wide array of fields, which may disclose a great degree of independence of each other. The more important classes of these patterns may be listed: social conventions, with or without explicit ethical content; religious rituals and dogmas; systematic interpretations of nature, expressed in symbols or in abstract concepts; concepts of social structure, embodied in legal concepts of varying degrees of generality and systematization; finally, political and social ideals associated with various policies for social action.

Even a preliterate society will exhibit thought and action at every level, though symbolic expression will be the predominant mode of formulation. In some manner, the whole field of thought and action must be covered. It is difficult to imagine a social group at such an elementary state of organization that all the different levels are not represented by some positive achievement. The different levels are successive only in a somewhat formal sense. Achievements at the higher levels imply that some preceding achievement at a lower level is essential to the accomplishment of the particular pattern, concept, or mode of action. Individual and group relations and actions, whether taken singly or as a group, certainly involve a wide range of mental activity at a number of levels. Under analysis, what we classify as simple acts involve a complex synthesis of acts of skill and judgments of values.

In the pluralistic approach, which is stressed in earlier descriptions of the structure of events in time, inner consistency of thought among the various classes and at different levels is not presumed. No logical or genetic interdependence among the various concepts and patterns of action can be assumed without positive evidence of such interdependence. In any given culture, sharp antitheses may develop between religious ritual or dogma and social conventions, or between symbolic or scientific interpretations of the system of nature. Political structures may be inconsistent with economic structures, or with social ideals widely held by important groups in any given society. The continuous

For the theory of invention, Köhler's experiments with chimpanzees made at Tenerife are of unusual importance. The primary purpose of the experiments was to determine whether or not these apes were capable of achieving acts of insight. Both the character of the techniques used and the results throw much light upon the nature of the act of insight at a low level dominated by visual perception. The experiments were designed to test the use of implements, the making of implements, the handling of forms, and the capacity to learn through imitation. The experiments on the use of implements exhibit so clearly the bearing of the whole series upon the process of innovation that we can concentrate attention on this portion of the material.

> [Tschego] is let out of her sleeping-place into the barred cage in which she spends her waking hours; outside the cage and beyond the reach of her exceptionally long arms lies the objective; within the cage, somewhat to one side, but near the bars, are several sticks.
>
> Tschego first tries to reach the fruit with her hand; of course, in vain. She then moves back and lies down; then she makes another attempt, only to give it up again. This goes on for more than half an hour. Finally she lies down for good and takes no further interest in the objective. The sticks might be nonexistent as far as she is concerned, although they can hardly escape her attention as they are in her immediate neighborhood. But now the younger animals, who are disporting themselves outside in the stockade, begin to take notice, and approach the objective gradually. Suddenly Tschego leaps to her feet, seizes a stick, and quite adroitly pulls the bananas till they are within reach. In this manoeuvre, she immediately places the stick on the farther side of the bananas . . .
>
> Nueva was tested three days after her arrival . . . A little stick is introduced into her cage; she scrapes the ground with it, pushes the banana skins into a heap, and then carelessly drops the stick at a distance of about three-quarters of a metre from the bars. Ten minutes later, fruit is placed outside the cage beyond her reach. She grasps at it, vainly of course, and then begins the characteristic complaint of the chimpanzee: she thrusts both lips—especially the lower—forward, for a couple of inches, gazes imploringly at the observer, utters whimpering sounds, and finally flings herself on to the ground on her back—a gesture most eloquent of despair, which may be observed on other occasions as well. Thus, between lamentations and entreaties, some time passes, until—about seven minutes after the fruit has been exhibited to her—she suddenly casts a look at the stick, ceases her moaning, seizes the stick, stretches it out of the cage, and succeeds, though somewhat clumsily, in drawing the bananas within arm's length. Moreover, Nueva at once puts the end of her stick behind and beyond the objective, holding it, in this test as in later experiments, in her left hand by preference. The test is repeated after an hour's interval; on this second occasion, the animal has recourse to the stick much sooner, and uses it with more skill; and, at a third repetition, the stick is used immediately, as on all subsequent occasions.[3]

Some observations on the whole series of implement experiments are also highly significant. After comment on the use of hats and shoes to reach fruit, Köhler continues:

> A far more important factor than the external resemblances or differences between stick, hat brim, and shoe, is in the case of both Tschego and Koko the *location of the implement* both in relation to the animals themselves and the objective. [Nueva was not tested in this manner, for some reason.] Even sticks that have already been used often both by Tschego and Koko seem to lose all their functional and instrumental value, if they are at some distance from the critical point. More precisely: if the experimenter takes care that the stick is not visible to the animal when gazing directly at the objective—and that, vice versa, a direct look at the stick excludes the whole region of the objective from the field of vision—then, generally speaking, recourse to this instrument is either prevented or, at least, greatly retarded, even when it has already been frequently used . . .[4]
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> We found, however, that although to some degree the use of the stick as an implement depends on the geometrical configuration, this is only so on first acquaintance. Later on, after the animal has experienced frequently the same conditions, it will not be easy to hinder the solution by a wide optical distance between objective and implement.[5]

These passages have been quoted at some length because the function of the experimenter seems to be somewhat less fully recognized than the full analysis of the experiments requires. Despite the great effort made to avoid artificial tests, the experiments did involve some special features, which throw much light upon the nature of insight and the circumstances under which an act of insight can be achieved. In this connection, it is important to revert to Koffka's concept of the act of insight: "the animal is forced by the situation to act in a special way although it possesses no special devices for the particular act."[6]

The fact that the apes failed to achieve the act of insight under some conditions shows that the situation must assume a special form if the solution is to be found. In the experiments with the apes, the geometric configuration was controlled by the experimenter. From some configurations a solution followed with no delay, or with slight delay. Other configurations completely prevented the achievement of any solution. The results of these experiments, therefore, turned upon the *setting of the stage* by the experimenter. This was true not only of the series on the use of implements, but of the other series. A solution emerged only when the geometric configuration presented all the elements of the problem and a possible solution.

In a very perceptive analysis of the story of Archimedes and the crown, Arthur Koestler describes the act of insight in terms that are consistent with the Gestalt concepts, but with slightly different emphasis.

The essential point is that at the critical moment both fields F_1 and F_2 were simultaneously active in Archimedes' mind, though on different levels of consciousness. [Here F_1 represents the problem of the crown, F_2 the contexts associated with his bath and the overflow when filled too full.] In other words, the creative stress kept the problem on the agenda even while the surface of consciousness was busy with other fields. Without this constant pressure, the favorable chance constellation would have passed unnoticed—and joined the legion of man's missed opportunities for a creative departure from the stale habits of thought which numb his powers and dim his eyes . . .

After the event, it is easy to make the creative process appear as an act of deductive reasoning, and to represent it in the form of a syllogism . . . But if it is as easy as that, why had nobody before Archimedes ever made use of this syllogism? Because nobody before him had brought the two premises, which belonged to two different mental fields, to bear upon each other. The scheme gives the impression that the mental achievement consisted in drawing the conclusion. In fact, the achievement was to bring the two premises under one roof . . . The solutions of problems are not "invented" or "deduced"—they are "found"; they "occur."

Because *post factum* the previously separate mental fields merge into one, and the jagged bisociative act is smoothed out into a now continuous associative flow, all revolutionary innovations appear after a while as trivial and obvious, and we marvel less at the discovery itself, than at the apparently abysmal stupidity of the mental stage preceding it: 'How silly of me not to have seen it before.' We can add to our mental equipment, *but we cannot subtract from it.* The mutual attunement of two mental processes, *once achieved, cannot be undone.*[7]

Understanding of the act of insight depends upon a clear perception of the conditions that make it possible. In his formal thinking, the transcendentalist held that the intuitive thought was unconditioned, inexplicable, and mystical, but even Emerson said that no revelation occurs unless we "besiege the shrine." Alert attention to a problem was, even to him, a necessary condition for the achievement of intuitive insight. It is this phase of the process that the Gestalt psychology has stressed with so much perspicacity. Once these tensions have been set up, sooner or later some favorable configuration of thought or things will *reveal* the solution by the "intrinsic properties of the data." The point that we have missed for so long is the particularity of the data that touch off the dynamic process. When a new relation is involved, a highly specific pattern must be presented to a mind actively engaged upon the problem which can be solved only by the perception of this particular relation.

For purposes of generalized exposition, this analysis of the individual act of insight can be formalized as a genetic sequence of four steps. The first step is the perception of a problem, which is conceived as an incomplete or unsatisfactory pattern. Typically, the problem is an unfulfilled want. Gratification is made effectively possible by some fortuitous configuration in events or in thought, which present to the individual all the data essential to a solution. This step can be called the *setting of the stage.* For the great apes at Tenerife, this vital step was really the work of the experimenter; for the general process of invention this step is dependent upon pure chance, or upon the mediated contingency of a systematic effort to find a solution by trial and error. At low levels of empiricism, trial and error is commonly presented as aimless fumbling; at substantial levels of scientific activity, the trial-and-error approach is described as systematic experimentation. The setting of the stage leads directly to the act of insight by which the essential solution of the problem is found. But this does not bring the process to an end. Newly perceived relations must be thoroughly mastered, and effectively worked into the entire context of which they are a part. The solution must, therefore, be studied critically, understood in its fullness, and learned as a technique of thought or action. This final stage can be described as critical revision.

The process can be symbolized in a diagram (Fig. 7). The incomplete pattern is represented by an incomplete circle. The setting of the stage is symbolized by an offset arc of a circle separated slightly from the gap in the incomplete pattern. The act of insight is shown by the circle complete. The critical revision is represented by a complete, but more massive, circle. Progressive synthesis is suggested by arrows leading in toward the various steps in the process. The discontinuities in the process are indicated by the gaps between the arrows and the steps in the process, and by the broken line between the perception of the incomplete pattern and the setting of the stage. The process is legitimately conceived as a whole, because it rests upon a sequence that is explicitly genetic. There are, however, discontinuities in time and indeterminate resistances, so that it cannot happily be described as a sequence of reflex actions, or as a necessary process in the sense of a mechanically determined process.

Full analysis of the meaning of necessity would be out of place here, but it is important to suggest the precise nature of the issues created by any attempt to apply a concept of necessity to the events of history. In the most direct meaning of the concept, any important step, once taken, must lead to the next step, and ultimately to a full solution. This concept of the process overlooks the significance of the discontinuities that are inherent in a genuine concept of novelty and for this reason are symbolized in the diagram. The action in such processes takes place against resistances of undetermined magnitude. For some, or even many, individuals, successful solution of the problem is unlikely. For a limited number of individuals, successful solution of the problem can occur under special conditions, but these conditions cannot be created deliberately by the individual seeking a solution. The achievement of a solution cannot be presumed at any particular time, and it is an abuse of language to represent it as certain and "necessary" irrespective of a determinate time of accomplishment. It is important to distinguish between events that are probable, or even highly probable, and events that are certain. After the fact, as Koestler points out, the accomplishment seems logically necessary, but we do not know how many things we have failed to accomplish.

The positive significance of the time factor is illustrated by the development of the concept of zero and the system of positional numeration. Reference has already been made to the emergence of a system of numeration based on powers of 60 from some early date in the second

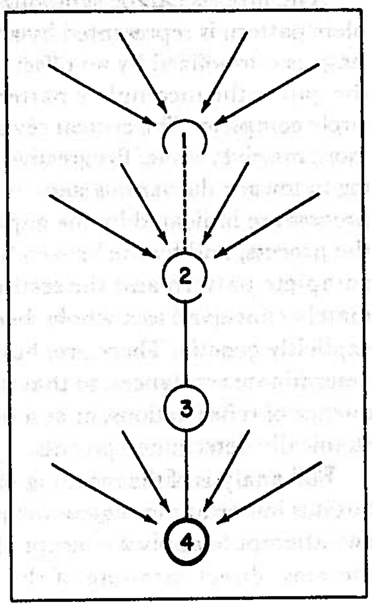

Fig. 7. The emergence of novelty in the act of insight: synthesis of familiar items: 1, perception of an incomplete pattern; 2, the setting of the stage; 3, the act of insight; 4, critical revision and full mastery of the new pattern.

millenium before the Christian era. The absence of values in particular positions was long indicated by the leaving of a vacant space, at times emphasized by the use of a sign for separation. Ultimately, the sign of separation acquired special significance as a symbol for zero. The development was not complete at the time of the decline of the Babylonian culture. Both the incompleteness of the indigenous development and the failure of the Greeks to take interest in this system of numeration are noteworthy. The implications of the zero concept and of the positional system were not powerful enough to produce a final achievement at this time. The Hindu accomplishment came after an interval of a thousand years, as the result of an independent development of the zero concept in conjunction with a positional system based on powers of 10. It is difficult to reconcile a concept of necessity with historical phenomena which show clearly that events which might have developed logically from other events failed to occur.

At higher levels of judgment and policy formation, records of policy and of action in pursuit of particular policies show instances of errors of choice. Incomplete analysis, incomplete knowledge of conditions, failure to identify the concepts relevant to the situation may lead to action that is incorrect. This action may result in positive disaster, or it may yield a less satisfactory result than might have been achieved. Success is not inevitable. A theory of emergent novelty yields a concept of soft determinism. Choices at any given time are limited by the geographic and by the social environment, but over a period of time significant modifications of both the geographic and the social environments are possible. The life of the organized social group is less limited and less restricted than the life of any particular individual, but the individual is not without choice nor without means to modify his environment by his actions.

IV

Emergent novelty becomes truly significant only through cumulation. Although the higher animals show some power of insight in their behavior, their behavior is restricted by the narrowness of the time span in which they live. The accumulation of experience in the individual and the group becomes important as soon as organized communication has been achieved. The accomplishments of the social insects suggest the existence of organized systems of communication, but observation and inference present so many difficulties that we cannot deal with such problems with much confidence. Cumulative achievement becomes significant in human society at the dawn of culture in the Old Stone Age.

Cultural achievement is a social accomplishment based upon the accumulation of many small acts of insight by individuals. The massiveness of this social process was long ignored or misunderstood. Trancendentalism focused attention upon a small number of innovations, and there was a strong tendency to identify long sequences of achievement with a single item. A conspicuous result of this disposition to put a part for the whole was the frequency of bitter controversies over the claims of various inventors to a particular invention. The history of printing, of the steam engine in various forms, of the power-driven airplane, all furnish illustration of the inconclusiveness of discussions focused on questions that were not accurately formulated. These disputes all rest upon the false assumption that the achievement was so simple and specific that it could properly be identified with the work of a single person at a given moment.

These popular attitudes are justified in their emphasis upon the special importance of some inventions. The position is not really inconsistent with the concept of a massive social process of cumulative synthesis. The social process as a whole may be described as a sequence of *strategic* inventions which draw together many individual items of novelty as well as many familiar elements. The history of the reciprocating steam engine involves at least five strategic inventions: the atmospheric engine of Newcomen; the low-pressure engine of Watt; the high-pressure engine of Trevithick and Evans; the steam locomotive of Hackworth and Robert Stephenson; the compound engines. In many instances, it is not possible to cite a single inventor even for a particular stage in this long development. There are quantitative differences in the achievement which admit, and really require, differentiation in the description of the accomplishment.

The process of cumulative synthesis can be symbolized in a diagram (Fig. 8). The achievement of the *strategic* invention involves all the separate steps that may be found in the emergence of a single item of novelty, but in respect of a strategic invention the process involves synthesis on a high level, comprising both new and old elements. Furthermore, the act of insight does not necessarily result in a solution. Great insight may be required to perceive the inadequacy of a pattern of thought or action that has been sanctioned by tradition for so long a period that most members of the social group do not question the adequacy of a mechanism or a concept or a symbol that is in fact utterly inadequate. Acts of insight may also do no more than set the stage for the achievement of the solution. Similarly, new acts of insight may be essential to the accomplishment of critical revision of an achievement that contains the essential elements of a true solution, but in some form that is not wholly practical.

In the diagram, the development of the strategic invention is symbolized by the large arcs or circles, marked with Roman numerals. Arrows converging toward the focal points of synthesis are designed to suggest the incorporation of familiar items in the new synthesis. The number of items involved at each step is purely arbitrary. The diagram merely indicates the combination of "several" or "many" items, familiar and novel, at each stage in the process. For economy of space the diagram shows one complete sequence in strategic innovation, and part of another. In historical analysis, it would be unusual not to find that several strategic inventions were involved in any achievement of large social importance.

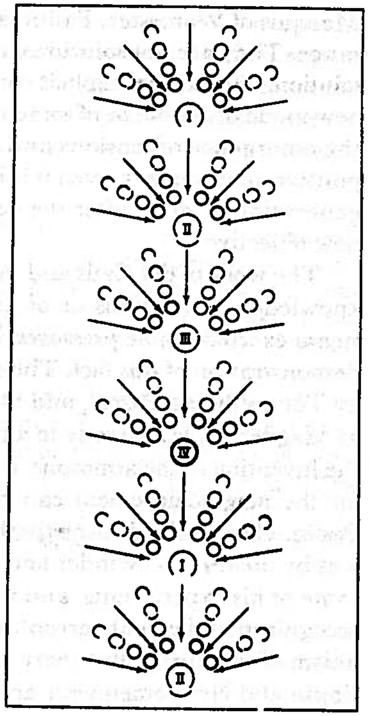

Fig. 8. The process of cumulative synthesis. A full cycle of strategic invention, and part of a second cycle. Large figures I–IV represents steps in the development of a strategic invention. Small figures represent individual elements of novelty. Arrows represent familiar elements included in the new synthesis.

The relation of this concept of process to concrete historical material will be most adequately understood if we apply it to the history of the reciprocating steam engine. The emergence of an "unsatisfactory pattern" was impossible until there was considerable knowledge of the properties of steam and of the phenomena of air pressure. It was necessary to distinguish steam from air. It was necessary to perceive the possibility of producing a vacuum by the condensation of steam in a closed vessel. It was essential to understand the primary phenomena of atmospheric pressure. Each of these scientific discoveries involved a major break with the traditions of classical and medieval science. They were achievements of primary magnitude, whose significance was not exhausted by their relation to the development of the steam engine. In a study of the history of the analysis of gases and their properties, or in a study of meteorology, these achievements would rank as strategic innovations. Items of knowledge may be parts of more than one whole. The bare emergence of an unsatisfactory pattern in the history of the steam engine may be dated by the jet fountain of Solomon des Caus, or better from the Raglan Castle "water-commanding" engine of the Marquis of Worcester. Failures are thus of explicit historical importance. They are not solutions, but they are not without relation to a solution. They reveal explicit consciousness of the potentialities of some new mode of action, or of some new contrivance. They are evidence of the emergence of tensions and strivings that are likely to result in a positive achievement, even if it be long postponed and realized only a generation or more after the earliest recognizable emergence of the new objective.

The work of des Caus and Worcester did not require any accurate knowledge of vacuums or of air pressure. They perceived that live steam exerted usable pressures, but they hardly achieved more than a demonstration of this fact. The measurement of atmospheric pressure by Torricelli and Pascal, and the studies of vacuums by von Guericke at Magdeburg led directly to a type of experimentation that suggested the invention of the atmospheric engine. The actual setting of the stage for the new achievement can be taken to be the work of Dionysius Papin. He perceived correctly that the proper mode of using pressures was by means of a cylinder and piston. Von Guericke used a piston in some of his experiments, and it may well be that his work should be recognized as the vital perception of this new use of the familiar mechanism of the pump. But there is no clear documentary evidence that Papin and Newcomen were actually dependent upon von Guericke's

work. Papin's work clearly set the stage for Newcomen's fine achievement. The atmospheric engine was the first strategic invention in the history of the reciprocating engine.

We know the background quite adequately. We have latterly had thoroughly satisfactory evidence of the early state of the engine, so that we can now definitely set aside the accounts that described an engine without a self-regulating set of valves. But we have no details on the work of Newcomen at the critical period. The engine was developed in minor details, and in Smeaton's time larger engines were built, but critical revision was less significant than was the case with the steam engine in its later forms.

Watt's inventions were an outcome of careful study of the performance of the Newcomen engine. Excessive fuel consumption, great losses of heat, the failure to utilize the expansive power of steam were shown by direct analysis to make the engine a very ineffective means of utilizing the heat energy produced by the fuel. These new techniques of analysis revealed an unsatisfactory pattern. In Watt's experience it is not easy to identify a step that illustrates adequately a setting of the stage that is clearly distinguishable from the perception of an unsatisfactory pattern. The experiments with heat and the study of the engine cover both phases of the general process. We have, however, a precise description of the crucial act of insight. The experience described occurred two years after Watt's first work with the engine and six years after his first studies of heat.

> I had gone to take a walk on a fine Sabbath afternoon. I had entered the Green and passed the old washing house. I was thinking of the engine at the time. I had gone as far as the Lord's house when the idea came into my mind that as steam was an elastic body it would rush into a vacuum, and if a connection were made between the cylinder and an exhausting vessel it would rush into it and might there be condensed without cooling the cylinder. I then saw that I must get rid of the condensed steam and injection water if I used a jet, as in Newcomen's engine. Two ways of doing this occurred to me: First, the water might be run off by a descending pipe, if an offlet could be got at a depth of 35 or 36 feet, and any air might be extracted by a small pump. The second was, to make the pump large enough to extract both water and air . . . I had not walked farther than the Golf house, when the whole thing was arranged in my mind.[8]

A great deal of difficult work remained to be done before a model could be constructed, and the building of the engine involved many new engineering problems. Nevertheless, there is an unusually clear basis for recognizing that the solution of the problem was achieved during this Sunday afternoon walk. If the concept then achieved had been less adequate, we might properly set a later date for the solution of the problem, but the actual task proved to be the realization in actual mechanism of the apparatus conceived at that time. The concept itself did not require revision. Supplementary inventions were necessary to develop the full power of the engine, as a double-acting engine with steam applied alternately to each side of the piston. The usefulness of the engine was also greatly extended by changes of design that made it possible to produce rotary motion. These developments and the positive innovations in engineering practice can be adequately described as novelties occurring at the stage of critical revision.

The later history of the engine admits of differences of interpretation, so that no position can properly be taken without more critical analysis than is possible in this connection. There are strong grounds for treating the high-pressure engines and the compound engines as distinct strategic inventions. They involved special theoretical and practical problems, and were achievements essential to the realization of the full potentialities of the reciprocating engine. The only alternative is to give great extension to the period of critical revision, and such a view puts too little emphasis on the great number of new inventions essential to the final achievement. The general concept of a process of cumulative synthesis will thus enable us to analyze a sequence of inventions in considerable detail. In some instances, documentary material might be less adequate than is the case in the history of the steam engine. In some instances we may have a richer documentation. So much of the earlier history of electricity occurred since 1750 that extant records in that field are more complete and the progress of science and invention is more fully reported.

V

The concept of a cumulative process forces us to recognize that a particular act of insight may not lead to a solution of the primary problem toward which it is directed. It may be dominated by any one of the four basic stages in the development of a strategic invention or discovery. The greater part of the effective documentation on the act of insight is so directly connected with major novelties that we are likely to find the total body of illustrative material more sharply differentiated than we might suppose. It is, therefore, important to consider illustrative material covering all four types of the act of insight at high levels of synthesis.

A striking instance of an act of insight as a perception of an unsatisfactory pattern occurs in Lord Rutherford's description of the development of the important revisions of the concept of the structure of the atom. In 1895, Lenard had passed electrons through a thin window in the discharge tube, and observed them outside the tube. He suggested that the atoms might contain spheres of positive electricity associated in some manner with negative charges. Within a year or two, J. J. Thompson had developed the idea and demonstrated by calculation the distribution of negative electrons in a sphere of positive charge. Rutherford describes the experiments that led to a new distribution of charge within the atom:

> Now I myself was very interested in the next stage, so I will give you it in some detail, and I would like to use this example to show how you often stumble on facts by accident. In the early days I had observed the scattering of alpha-particles, and Dr. Geiger in my laboratory had examined it in detail. He found, in thin pieces of heavy metal, that the scattering was usually small, of the order of one degree. One day Geiger came to me and said, "Don't you think that young Marsden, whom I am training in radioactive methods, ought to begin a small research?" Now, I had thought that too, so I said, "Why not let him see if any alpha-particles can be scattered through a large angle?" I may tell you in confidence that I did not believe they would be, since we knew that the alpha-particle was a very fast massive particle, with a great deal of energy, and you could show that if the scattering was due to the accumulated effect of a number of small scatterings the chance of an alpha-particle being scattered backward was very small. Then I remember two or three days later Geiger coming to me in great excitement and saying, "We have been able to get some of the alpha-particles coming backwards . . ." It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you. On consideration I realized that this scattering backwards must be the result of a single collision, and when I made calculations I saw that it was impossible to get anything of that order of magnitude unless you took a system in which the greater part of the mass of the atom was concentrated in a minute nucleus. It was then that I had the idea of an atom with a minute massive center carrying a charge. I worked out mathematically what laws the scattering should obey, and I found that the number of particles scattered through a given angle should be proportional to the thickness of the scattering foil, the square of the nuclear charge, and inversely proportional to the fourth power of the velocity."[9]

After further experimentation, a new concept of the structure of the atom was formulated which contributed an important element to the development of modern physical and chemical theory.

If we analyze the entire incident in terms of a Gestalt pattern, the outstanding act of insight is to be found in the reaction of Rutherford to the emergence of a few particles from the side of the foil that they had entered. The deep impression caused by this observation was produced by the realization that current concepts of atomic structure were utterly inadequate. Mathematical analysis ultimately redefined the problem and there emerged the concept of an atom with a minute but massive nucleus. This second act of insight provided the essential features of a solution, which was then verified and developed by further experimentation and mathematical analysis. The incident as described thus shows two clearly defined acts of insight and the substantial critical revision of the schematic concept that constituted the effective solution of the problem. The description given does not suggest any determinate setting of the stage. It is possible that such a step was not identifiable in this particular experience, or it may have occurred in such an obscure form that it was not noticed and therefore not reported.

The history of the incandescent lamp happily affords an illustration of an act of insight that clearly set the stage for the final solution of the problem. The episode is of special significance because the effort to achieve a satisfactory incandescent lamp engaged the active attention of a number of talented inventors working intensively in a highly competitive spirit. Positive efforts to produce an effective incandescent lamp can be dated from Moses G. Farmer's platinum lamps of 1858 and 1859 and carbon lamps tested by Joseph W. Swan in 1860. The Swan lamps were based on carbonized cardboard and paper, so that many elements of the final solution were embodied in the Swan lamp. The Farmer platinum lamp, a specially shaped strip of foil burning in open air, was used as part of the lighting system in his own home in Salem. Neither these nor the later lamps, prior to Edison's basic carbon lamp, were of any practical value. These efforts are an indication of the perception of an incomplete pattern in respect of a strategic invention. They are inventions, in the strict sense of the word, but they raise more problems than they solve, so that they have no separate significance of their own, apart from the larger strategic invention to which they lead. Kay's flying shuttle set the stage for a power loom, but it had much utility in its original form. It entered into the sequence of achievement both as an immediate accomplishment and as a basis for important future development.[10]

Both Farmer and Swan laid aside all work with the electric lamp until 1877. Hiram S. Maxim, William E. Sawyer and his associate Albon Man, and Edison all began or resumed work on the lamp in that year, and in the following year St. George Lane-Fox joined the number of inventors working systematically on the lamp. There were others active in the field, but the major accomplishments were the work of these men. The intensity of this effort affords some measure of the difficulties encountered. But it is especially impressive to see how closely unsuccessful experiments approached what proved ultimately to be a solution of the problem of producing an efficient long-lived lamp. Looking back over these experiments, three elements in the problem were clearly of major significance. The superiority of the high-resistance lamp over the low-resistance lamp was at first recognized only by Edison. Swan was working toward higher resistances at the time of Edison's achievement of a long-lived lamp. The effect of occluded gases in the lighting element and in the glass of the bulb and its stem was not understood until the summer or early fall of 1879. Edison and Swan independently recognized the importance of this phenomenon, and introduced techniques to correct the difficulty.[11] The maintenance of a high vacuum was of critical importance for either the carbon or the platinum lamp. The melting point of carbon is about 3500°C, which seems to provide a comfortable operating margin for the temperatures of 1500–1600°C that ultimately came to be used for carbon lamps. But carbon volatilizes at 1700°C, so that the critical conditions of operation are really rather narrowly defined.[12] The problems of using nitrogen or other gases instead of a vacuum were also incompletely understood by the inventors at the beginning of the period of intensive work. The gas tends to reduce the rate of vaporization of the illuminant, so that it seemed to be a useful means of increasing the life of the lamp. But the gas also conducts heat away from the illuminant and reduces its efficiency. With small lamps and low temperatures, the loss of illumination more than offset the increased length of life. The lamp was not strong enough to be useful. At the higher temperatures later used in lamps, the loss of efficiency in illumination was not important.[13]

The conditions requisite for success were quite narrowly defined. High resistance was essential to adequate illumination. The maintenance of a high vacuum was necessary to insure length of life. As the melting point of platinum was too low to make it practical, and the rare earths could not then be prepared as filaments, carbon was in effect the only material that could at that time serve as an illuminant. It was unfortunate that the use of a carbon filament seemed to be eliminated by direct experiment over a long period of time. Swan, Sawyer, and Edison had all used carbonized paper in various forms in 1877 and 1878. Edison declared publicly that carbon had been tried, and that it would not serve. Swan, working for an illuminant with low resistance, was using a slender rod of carbon in his lamp of 1878. It was for these reasons that the discovery of the importance of the occluded gases did not lead directly to a solution of the problem. Edison's discovery came when he was still working with the platinum lamp and had abandoned carbon. The improved vacuum was a gain for the platinum lamp, but it did not provide a solution.[14]

The resumption of experiments with carbon was touched off by an entirely unexpected flash of insight which is described in the feature article that was published in the *New York Herald*, December 21, 1879. The incident is dated by Jehl in August 1879, though the account now available is based on the feature article prepared later with the assistance of Edison and the laboratory staff. "Sitting one night in his laboratory reflecting on some unfinished details, Edison began abstractedly rolling between his fingers a piece of compressed lampblack mixed with tar for use in his telephone. For several minutes his thought continued far away, his fingers in the meantime mechanically rolling out the little piece of tarred lampblack until it became a slender filament. Happening to glance at it the idea occurred to him that it might give good results as a burner if made incandescent. A few minutes later the experiment was tried, and, to the inventor's gratification, satisfactory, although not surprising, results were obtained. Further experiments were made, with altered forms and composition of the substance, each experiment demonstrating that at last the inventor was on the right track.[15]

These early carbon lamps, however, were not really long-lived lamps. The incident resulted in a series of experiments on the production and testing of carbonized filaments, but work with metals was not discontinued. Work continued for the better part of two months. A carbonized sewing-thread filament was produced and put to test October 20, 1879. The lamp burned for forty hours, and was immediately recognized as clear proof that the solution of the problem had been found. October 21 was thereafter celebrated as Lamp Day. In the laboratories, the work after that date was treated as critical revision and development. New work remained to be done, but it was of subordinate

importance. Classification of these various moments is not without difficulty, but the August incident is more adequately described as a setting of the stage than as the actual achievement of a solution. The novel element in the new series of experiments was the reduction of the carbon to a filament. Earlier work had been based on thin strips, or even rods. There was novelty, too, in the application of the full understanding of the importance of eliminating the occluded gases.

The experience of Watt in the invention of the condensing engine has been described. The incident illustrates vividly the character of an act of insight directly associated with the solution of the major problem in a sequence of *strategic* invention. To complete the array of the steps in the emergence of a strategic invention we need an illustration of an important act of insight at the stage of critical revision. Fulton's work on the steamboat is most adequately described in these terms. He did not invent an engine, nor even build the engine installed. He did not invent paddle wheels. Nor was he the first to produce a vessel propelled by steam. His attention was concentrated upon the computation of the resistance of the vessel in water, the effectiveness of paddle wheels of different form, the calculation of the total work to be done by the engine, and the proper scale of the engine needed by a particular vessel. No new mechanical effects were projected, but a number of mechanisms were combined in calculated magnitudes. We know now that there were errors in Fulton's computations, but the fact remains that after his demonstration steamboats were equipped with more powerful engines than had been used in earlier and unsuccessful experimental craft. Fulton saw clearly the necessity for positive analysis of the problems of power engineering in the marine field. The work was well enough done to meet the requirements of the more urgent practical problems, though the technique of tank experimentation was inadequate.

VI

When we associate the act of insight with the varied phenomena involved in strategic invention, differences emerge between such acts of insight and the concept of intuition as developed in the idealistic philosophies. The act of insight is neither unconditioned, nor to be accepted as true without verification, nor can it be assumed to yield a final solution. Although the concept of intuitive perception of truth is clearly an attempt to describe characteristic features of the act of insight, the concepts are by no means identical. The act of insight carries with it strong emotional coloring. Because it relieves a complex of tensions and unfulfilled desires, it brings with it an overpowering sense of achievement. Koestler describes it as the eureka process, because of this feeling that the problem has finally been solved. These characteristic emotional attitudes undoubtedly occur, but in all fields that admit of verification it frequently appears that the new idea was either wholly wrong or incomplete. It is possible to argue that fields which require verification lie outside the realm of the pure thought in which truths are directly perceived through intuition. But the acceptance of such a position requires a vigorous act of faith.

The act of insight as conceived by the empiricist is intended to provide a different analysis of an array of phenomena that are covered only in part by the interpretations of the idealists. When developed under critical analysis, some features of the act of insight require us to place less emphasis on the emotional tones associated with discovery and invention. These creative acts differ in many ways from the critical analysis that occupies so much of our attention, but the act of insight does not rise above the contingency of our knowledge and our action upon specific contexts. Because these activities are conditioned, analysis is possible; but because they are conditioned they must be conceived as contingent upon the relevant contexts. Acts of insight seek particular modes of action or thought as a means of achieving specific ends. They do not seek absolutes or eternal verities.

We return to the original question, how do new things happen? Is it possible to answer the question without invoking some external force, and without the bare restatement involved in describing these activities of the mind as "unconscious" or "subconscious"?[16] That an adequate answer is possible, we may well believe; that we are now ready to answer the question admits of some doubt.

Our analysis certainly redefines the question. It is not necessary to explain the final act of insight; the task now consists in explaining how the stage is set to suggest the solution of the perceived problem. Stage settings occur conspicuously in two general forms: in the field of direct perception and in the field of imaginative construction. The conditions effecting a setting of the stage in the field of perception involve an element of chance. In the field of imagination, we are involved in all the difficult problems of the analysis of memory and the phenomena of past perceptions not readily available to organized conscious interests.

There is a highly suggestive passage in Koestler, concluding a discussion of the experiments with apes.

All of Köhler's chimpanzees sooner or later learned the use of implements, and also certain methods of making implements. A dog, however skillful in carrying a stick or basket between his teeth, will never learn to use a stick as a rake to get a piece of meat placed outside its reach. In other words, the chimpanzees were *ripe* to discover the use of tools by exploiting the hazard of favorable circumstances. The factor which accounts for this ripeness is the high coordination between eye movements and finger movements which emerges on the evolutionary level of the Primates. It is this coördination which leads to the urge to push objects about with branches and sticks. Sooner or later the favorable constellation will occur which leads to the individual eureka process. In other words, the statistical probability for a relevant discovery or bisociation increases in proportion as the (still separated) behavior fields in question become established, developed, and facilitated by repetition. This will later give us certain clues to the puzzling phenomena of the recurrent multiplicity of important discoveries in the history of science, of the parallel development of totemistic rites in unconnected civilizations, and the independent development of certain primitive forms of art in different continents.[17]

The chance that appears in such phenomena is not the random chance of a universe without pattern or organization. It does not present an antithesis to a determinate mechanical universe. The chance that appears in such events exhibits the contingency of systems of events that disclose patterns and exhibit many interdependencies in a universe that is not wholly determinate. To afford a significant setting of the stage a particular pattern must occur simultaneously and in perceived connection with another pattern with which it may be combined in a new synthesis. It is a chance occurrence in the sense of being unforeseen and unplanned. The timing of its occurrence is indeterminate, but it is part of a pattern of events, because various events and processes must occur in sequence. The succession of events is orderly and logical, and discloses patterns, but the intervals in which the events succeed each other and the circumstances of their occurrence are indeterminate. The measure of individual achievement lies in the timing: the very superior person does not accomplish things that would never be done by another; he achieves results sooner than persons of less capacity would achieve them. It is an error to assume that any given individual is uniquely necessary. But it is also an error to assume that a given percentage of superior persons guarantee the development of culture at a given rate without regard to individual differences and qualities. If we lived in a completely determinate and closed universe, new things could not happen. What was implicitly present might become explicit, but there would be nothing at the end of the process that was not present at the beginning.

The emergence of a system of general concepts and the accumulation of a body of scientific knowledge enable inventors to work at levels of abstract concepts that makes it possible to use imaginative constructions. These constructions may assume the form of general concepts, or they may be applications of general principles to practical ends. They may exist as purely abstract symbols or they may be objectified in the form of diagrams and drawings. They are not wholly detached from perceptual fields, but they are not limited to immediate perceptions or to memories of past experiences. The boundary of imaginative construction is reached when actual models are made and tested. Imaginative constructions do not occupy the field of invention to the exclusion of work at levels of perception, even when philosophic and scientific knowledge is far advanced, but much fundamental work in science and the earlier stages of inventive effort take place at a level of imaginative construction.

Despite the limited scope of the scientific work of classical antiquity, imaginative constructions were probably of some importance even in the fields of mechanical invention and engineering. In fields of speculative metaphysics imaginative constructions were a dominant factor even then. Such developments become progressively important in the mechanical field after the initiation of systematic work in science in the thirteenth century.

Much work in the field of imaginative construction clearly involves elements of chance as in the field of perception. Concepts or systems of concepts are at times suggested by some perceived event, or concepts pass through the mind in the stream of consciousness in varying patterns so that a selection may be made from some incidental configuration. The essential problem of all novelties emerging in the imaginative field consists in the analysis of acts of insight that have no discernible stage setting. There seems to be a direct passage from the perception of an incomplete pattern to the achievement of a solution. In no case do we find achievements in which there is not clear evidence of tense effort to find a solution for a specific problem, but in some instances there is no evident stage setting. We face a dilemma. It may be that we merely lack an accurate and complete description of the incident; or it may be that it presents a special case.

It is tempting to ascribe these classes of acts of insight to the activities of the "unconscious" mind, or the "subconscious" mind. Koffka discusses with care the difficulties involved in these concepts. These terms can be replaced with many advantages by a more adequate distinction between the physiologic and the conscious fields of behavior.[18]

This position is stated even more vigorously by Cannon. After a careful description of the experience of the act of insight in the course of research work, he proceeds:

> There is much discussion of what lies back of the experience of having hunches. They have been ascribed to the operations of the "subconscious" mind. This expression seems to me to be a confusion of terms, for it involves the concept that a mind exists of which we are not conscious. I am aware that in psychology this view has been held. Indeed, one psychologist with whom I discussed the matter declared that wherever nerves coördinated the activity of muscles, a mind is present . . . The attitude thus expressed was extreme. It may be taken, however, as a basis for criticizing the assumption that there is mind wherever nervous activity goes on, when in fact there is no evidence to support the notion. Numerous highly complex responses which can be evoked from the spinal cord and many nice adjustments made by the part of the brain that manages our normal posture are wholly unconscious. There is no indication whatever that anything which we recognize as mind is associated with these nervous activities.
>
> To me as a physiologist, mind and consciousness seem to be equivalent, and the evidence appears to be strong that mind or consciousness is associated with a limited but shifting area of integrated activity in the cortex of the brain. The physiologist assumes that underlying the awareness of events as it shifts from moment to moment, there are correlated processes in the enormously complicated mesh of nervous connections in the thin cortical layer. Such activities could go on, however, in other parts of the cortex and at the same time be unrelated to the conscious states. They would be similar in character to the activities associated with consciousness, but would be extraconscious. Our knowledge of the association between mental states and nervous impulses in the brain is still so meager that we often resort to analogy to illustrate our meaning. The operation going on in an industry under the immediate supervision of the director is like the cerebral processes to which we pay attention; but meanwhile in other parts of the industrial plant important work is proceeding which the director at the moment does not see. Thus also with extraconscious processes. By using the term "extraconscious processes" to define unrecognized operations which occur during attention to urgent affairs or during sleep, the notion of a subconscious mind can be avoided.[19]

Montmasson presents a generalized theory of invention based upon the concept of "unconscious" mental activity, but whenever it is possible to find evidence of a stage setting, it is clearly unnecessary to ascribe the genesis of an act of insight to the "unconscious" activities of the mind. There are, thus, cogent reasons for rejecting the "unconscious" mind as the essential explanation of the act of insight even when it is not clearly attributable to an evident incident of stage setting.

In addition to mere lack of information, there is another possible explanation of the problem. Once we formulate thought in generalized concepts and accumulate knowledge and techniques of analysis, the process of giving explicit expression to what is implicit in a concept takes on a very specific meaning. Koffka analyzes a train of thought that might occur in the solution of a problem in algebra by a person with knowledge of elementary principles. When the area of a rectangle is given as *b* square meters, and one side is *a* meters longer than the other, the subject is presumed to work out a solution. He is presumed to formulate the problem as an equation without great difficulty, and finds himself confronted with the equation $x^2 + ax = b$. Random fumbling might occur, but it would lead nowhere. He cannot fall back on vaguely remembered procedures, because he has had no instruction in quadratic equations. It may happen, however, "that he gets a 'hunch' from the data themselves and tries this hunch out. This would no longer be random activity, but activity determined by the nature of the task and in so far insightful."[20]

Although it is not possible to derive a theory of evolution from the concept of an autonomous process of development from the implicit to the explicit, it is a very different matter to recognize that the implications may be powerful enough to make it possible to dispense with some stage-setting configuration that is an independent element not contained in the definition of the problem. In mathematics, and in many fields of thought concerned with symbols organized in less rigidly defined systems, implications may well serve to give dynamic movement to thought. The process, however, is less mechanical than the dialectic processes as conceived by Hegel and Marx. It is noteworthy, however, that both Hadamard and Poincaré presume a degree of activity in the "subconscious" mind in the field of mathematical invention that is clearly inconsistent with a simple or general procedure from the implicit to the explicit.[21] But the occasional emergence of an act of insight from implications of an incomplete pattern cannot be excluded.

The experience of Rutherford cited above might well be interpreted as a case in which the definition of the problem set in motion procedures of analysis that led to the formulation of a new concept of the structure of the atom without any clearly defined stage setting. There is little purpose in speculating about possible interpretations without analysis of the entire laboratory record. At the present juncture, much light would be thrown on the process of invention by the analysis of the records of a few notable inventors. Many kept elaborate records of experimental work done, and some inventors certainly left records that

would merit analysis from this point of view. We have already reached the limit of analysis in terms of the rather casual autobiographical statements based on letters, incidental records, and interviews.

The interpretation of the historical record should not, however, be confused with the proof or verification of the general theory. The completion of the analysis of the processes of innovation will necessarily be the work of the psychologists. Only advances in the understanding of psychology can give us the kind of knowledge about physiologic and psychologic processes that will enable us to exclude the appeal to "subconscious" and "unconscious" processes. Only more complete psychologic analysis can furnish full awareness of the complexity of the act of insight and the range of problems to which it gives a "solution." These achievements are now sufficiently foreseeable to justify the use of the theory in its present form, as a means of giving added significance to the historical records of invention and discovery. It is not necessary for the historian to have a complete analysis of the psychology of the process. The historian needs primarily assurance that there is no longer justification in seeking to explain the activities of superior persons by assuming that their processes of thought are different. We need only to know that the quality and importance of great achievements are due to the cumulative synthesis of a very large number of small achievements. These accomplishments are the result of processes of thought and action common to all humanity, and, at a slightly lower level, to the primates. With such a theory, even at a level of incomplete verification, the historian can proceed to develop the techniques of analysis that will reveal the grosser features of the processes by which man makes himself.