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Research Trails

1.1 Maps of Knowledge

By its very nature, scientific work is minutely specialized. Scientists often compare themselves to masons, each adding a few tiny bricks to the vast edifice of human knowledge. Science grows by a systematic division of labour, where the domain of action of each worker is narrowly limited and the work to be done within each domain is highly skilled. The practical expertise and understanding needed to undertake a serious scientific investigation usually takes many years to acquire. However much we may deplore it, almost all research nowadays has to be done by specialists.

All professions are to some degree specialized. A lawyer may tend to specialize in cases of a particular kind, and become known as an expert on, say, patents, or marine insurance. An architect may gain a reputation for designing schools, or churches, or museums. In any substantial enterprise, such as a coal mine, or a steel works, there will be people known to have very specific skills which are essential to the enterprise and which may have taken half a lifetime to learn. But no other occupation is so finely and distinctly subdivided into 'specialties' as science.

What do we mean by a scientific specialty? As in other occupations, individual scientists bring to their work a wide range of skills acquired by personal experience. Most of these skills are *tacit* (Polanyi 1958); they cannot be defined precisely, or catalogued systematically. But science differs from other highly technical activities in that its goal is the production of organized knowledge (Ziman 1984). As every scientist knows, a research report is unacceptable unless it cites previous work on the subject. This is not just a convention. Philosophers are now beginning to realize that a genuine scientific question cannot even be formulated without reference to a background of existing knowledge (de Mey 1982). Whatever other skills may be needed, a researcher must be more or less familiar with what is already known scientifically about the problem to be tackled. When someone is needed to undertake research on a particular subject, the natural choice is a scientist who is already well informed on that subject, whether by formal education or by previous research on closely similar problems. A high degree of

subject specialization is thus an indispensable condition for progress in every field of science.

From this point of view, any distinct subdivision of scientific knowledge may be considered a subject specialty. It is the extreme narrowness and specificity with which such knowledge can be so divided that differentiates scientists so minutely from one another. The very fact that science is an organized body of knowledge implies that every research project or discovery has its recognized place in a larger scheme. But there is no way of setting up such a scheme without defining distinct categories of knowledge according to some rational criteria. The information produced by research in a mature scientific discipline, such as chemistry or neurophysiology, may be classified according to a number of well-defined and precise ordering principles – general theories, species of organism, classes of compound, techniques of investigation, and so on – and can thus be subdivided into innumerable 'subjects' for specialized research.

To appreciate the depth to which scientific knowledge can be divided into distinct categories, it is only necessary to look at one of the standard classification schemes used by librarians and editors to arrange and index journal articles, research reports, books, and other scientific documents. The archetype of most such schemes is the Universal Document Classification system, where the various categories and subcategories are arranged in a hierarchy, according to the successive digits of a decimal number. The internationally approved scheme for physics, for example (ICSU 1975), assigns to each subject an alphanumeric address tag of five characters.Thus, a subject on which I used at one time to specialize is clearly defined and tagged:

72.15.C ELECTRICAL AND THERMAL CONDUCTION IN AMORPHOUS AND LIQUID METALS AND ALLOYS

But this alphanumeric tag is not arbitrary. It shows that this subject is part of a larger category:

72.15 Electronic conduction in metals and alloys

This, in turn, is a subdivision of:

72. Electronic transport in condensed matter,

which is just one of the ten subsections of:

70. CONDENSED MATTER: ELECTRONIC STRUCTURE, ELECTRICAL, MAGNETIC, AND OPTICAL PROPERTIES

– one of the ten 'subdisciplines' of physics as a whole (Fig.1). In other words, physics can be broken down into several thousand 'subjects', each classified hierarchically to the fourth decimal digit.

It might be objected that physics is a peculiarly well-ordered science, because of its analytical approach to nature. But even such an empirical, practical discipline as forestry can be classified into a quasi-decimal hierarchy of 'Divisions',

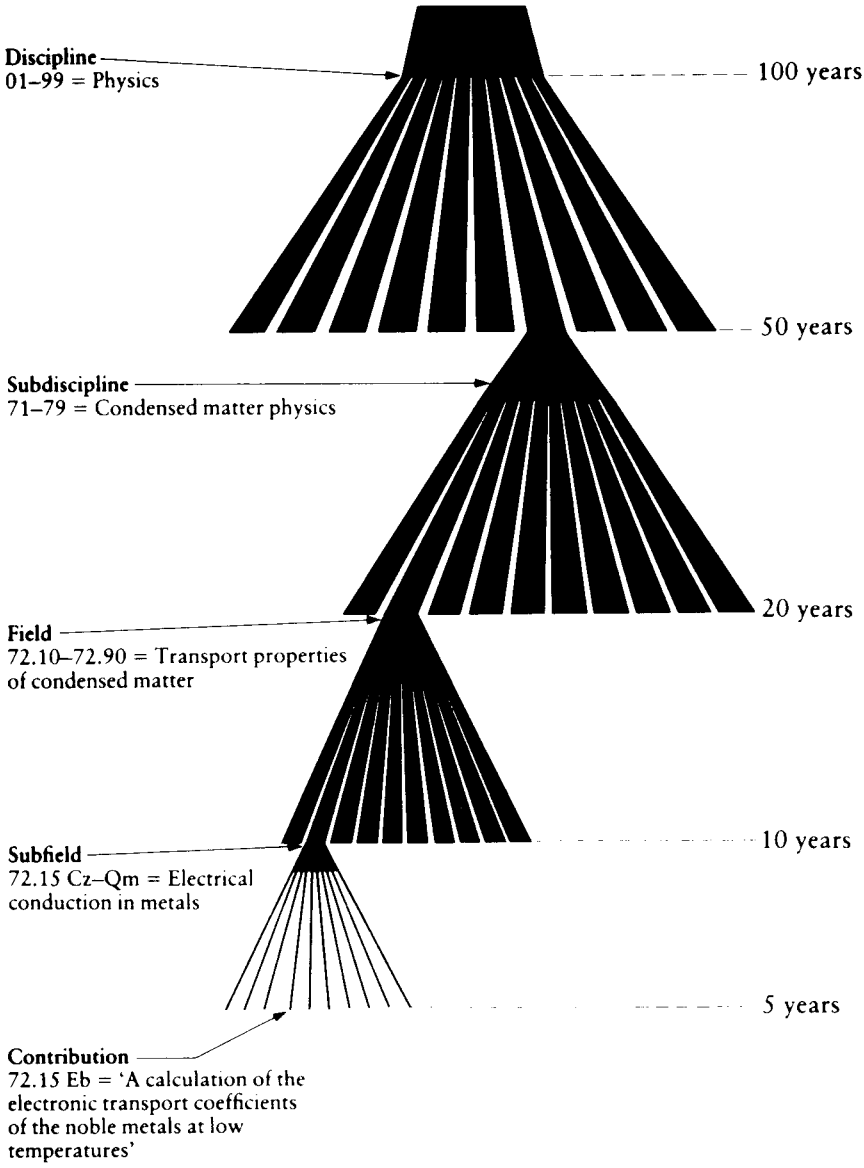

Fig. 1

'sectorial groups', and 'working groups' on the same lines (IUFRO 1982). All such classification schemes are, of course, essentially artificial, and do not pretend to represent the actual structure of knowledge in detail. A hierarchical scheme cannot, for example, represent the numerous cross-connections corresponding,

say, to the results obtained with the same technique on a number of different compounds, or to the fact that many quite different physical systems satisfy the same mathematical equations. Yet the specialties defined by the conventional classification schemes do not differ profoundly from those generated by more objective procedures, such as the detailed analysis of the citations from one scientific paper to another in a particular field of research (Garfield 1979). After all, the conventional schemes are designed in consultation with working scientists, and thus conform to the conceptions that scientists themselves have of the boundaries and interrelations of the various subjects on which they do research and on which they are counted as experts by their colleagues.

The practice of setting up such schemes on a decimal base is clearly quite arbitrary. But suppose we think of this base as a 'metric', like the grid lines on a map, showing the scale on which we are working. Using this metric, we can set up a terminology indicating the actual degree of specialization required of scientists in their work. Thus, we may say (Fig. 1) that a typical scientific discipline can be divided into about ten *sub-disciplines*, each of which is divided into about ten *fields*, and so on. Indeed, as we have seen in the case of physics, the information to be classified may be so well defined that it can be assigned to one of a thousand *sub-fields* (such as the category **72.15 : Electronic conduction in metals and alloys** referred to above) without risk of ambiguity.* If, for example, I were to say that 'the research specialty of a typical academic scientist is seldom more than one or two fields in extent' I would mean (very roughly) that it would cover only one or two per cent of all the subject matter of a major academic discipline, and thus, by implication, that there might be 50 or 100 different sorts of specialist in that domain of science alone.

It must be emphasized, however, that the extent to which scientists actually specialize in their work is not governed simply by the characteristics of scientific knowledge. As we shall see, the breadth and shape of a scientific career depends on many other factors, such as personal inclination, institutional traditions and managerial imperatives. All that I am saying at this point is that the primary definition of a scientific specialist is by his or her 'subject', and that this refers to a relatively well-defined and limited segment of the enormous body of concepts, data and methods known to science. In more metaphorical language, scientists specialize in particular 'areas', or 'regions' of the 'map' of knowledge. These specialty regions are not clearly delineated on this map, but they naturally tend to conform to typical features of the scientific 'landscape' – a powerful theoretical paradigm, say, or a particularly challenging problem, or the discoveries made

* This terminology follows neither Chubin (1976) nor Gieryn (1978), who use the theoretically loaded words 'specialty', and 'problem area' where a purely conventional term such as 'field' begs less of a question.

possible by a new technique. That is why it is essential to understand some of the characteristics of such landscapes, before following the trails of those who set out to explore them.

1.2 Changing scientific landscapes

Science is essentially a *progressive* enterprise: it is dedicated to *change*. This is not to say that the accumulation of scientific information and understanding is necessarily for the better: it is simply to observe that every 'map' of scientific knowledge is in constant flux. The whole notion of subject specialization must take account of this process of *cognitive change*, which is thus one of the most important factors in the life of every scientist, and a major aspect of the present study.

Every scientific specialty is being transformed continually by internal discoveries or external influences. Sometimes this transformation is slow and uninteresting, as in the accumulation of data by routine methods: at other times, an exciting new discovery opens up many old problems for solution, and suggests many new ones. In the latter case, the subject may grow rapidly, both in the amount of research being done and in its intellectual scope.

But a scientific specialty cannot expand by a large factor without rupturing the classification scheme by which it was defined. A scientific 'breakthrough' is not simply the discovery, or the opening up, of a region of the scientific landscape which has not previously been explored: it usually implies a significant change in all existing conceptions of the territory around it, and thus amounts, in effect, to a change of the 'landscape' itself. It is not enough to obtain a whole lot of new answers to old questions. If there is to be genuine progress, this information must be brought under intellectual control, and made the basis for new theories, new concepts, new techniques – and new scientific questions. Thus, for example, once it became clear that 'continental drift' was a real process, almost every fact and theory of geology had to be re-assessed and reinterpreted, and the new subject of 'plate tectonics' came into being.

The history of every science, the biography of every scientist, bears witness to the universality of radical cognitive change. We need not enter here into the scholarly debates about the way in which such 'scientific revolutions' actually occur, nor whether they represent a change to a state of knowledge that is 'incommensurable' with what it was before (see, e.g. Ziman 1984). What we can say is that, after such a revolution of thought, the way in which scientists had previously classified the objectives and results of research no longer holds good. The time has come to draw new 'maps' of the subject, and to delineate on them new specialty boundaries.

Everybody has heard of the great scientific breakthroughs that revolutionize whole disciplines. What is not always appreciated is that the same process of cognitive change occurs at every level of specialization, down to the narrowest 'subfield' of research. In my own former subject of theoretical physics, for example, research on the highly specialized topic of the electrical conductivity of liquid metals was revolutionized some 20 years ago by the discovery of a simple formula that at last made sense of most of the existing experimental data. On a much broader scale, 'the physics of condensed matter' began to be recognized as a distinct subdiscipline about 50 years ago, when it became clear that quantum theory could be applied to the behaviour of electrons in metals. But this was only one episode in the vast transformation of physics as a whole, following on the discovery of nuclear and atomic phenomena at the beginning of the century.

The same sort of process can be observed in every active domain of research. Generally speaking, the narrower the scope of a specialty, the shorter the time scale on which it will be seen to change. Citation analysis shows, for example, that the effective lifetime of a primary paper in physics is only about five years (see, e.g. Ziman 1985): if it has not made its mark by then, and been incorporated into a larger movement of change, then the chances are that it will fall into oblivion. My guess is that the lifetime of an active 'subfield' of physics is about ten years, and that 'fields' of research grow and decline in periods of the order of 20 years. A typical 'subdiscipline', such as nuclear physics, probably retains its identity for 40 or 50 years, whilst the transformation period of physics itself, considered as a major 'discipline' within the natural sciences, might be something like a century.

These estimates of the time scale of cognitive change in science are, of course, purely notional. I have chosen physics as my example because it is the only discipline that I know well enough to make such guesses. The general scale of change may be somewhat different in other sciences, and certainly varies greatly from specialty to specialty. Some major disciplines, such as cell biology, have evidently changed out of all recognition in a few decades, whilst there are numerous minor fields which have remained essentially unchanged for long periods. The main point is that the landscape of every science – and of the sciences as a whole – is being continually reconceived and remapped. The occasional grand revolutions that attract the attention of historians and philosophers do not account for all the radical change that is actually occurring in science. This change is going on all the time, at different rates on different scales.

The most obvious type of change in the landscape of science is the appearance of a new subject combining information, concepts or techniques from previously distinct domains of research. Thus, the modern discipline of molecular biology is not simply a revolutionized form of, say, the established discipline of

biochemistry, but combines elements from genetics, microbiology, chemistry and physics. The development of entirely new *interdisciplinary* subjects is characteristic of the history of science, and again takes place on every scale. In fact, what might seem to outsiders as the 'internal' transformation of a discipline or subdiscipline would usually be described be described by experts as the appearance and growth of a new 'field', combining elements from previously unrelated areas of research in order to tackle new problems. This often occurs when research is deliberately focussed on some practical problem of political or economic significance. In agricultural research, for example, a new 'problem area' – that is, a potential new specialty – is created whenever the intellectual resources of several different biological disciplines are brought to bear on an urgent problem such as the prevention of a particulary serious plant disease or the improvement of the yield of a major crop.

It is important to note, however, that interdisciplinary subjects do not remain unspecialized for long. As each new region of the scientific landscape is explored and mapped, it is subdivided into 'fields' and 'subfields' just like any traditional scientific discipline. Where the subject matter is diverse, and many different approaches are possible, it may not be easy to place these new specialties on a simple hierarchical classification, or even to represent their relationships by adjacency on a two-dimensional diagram. Nevertheless, as we saw in the case of forestry (§1.1), experts recognize the existence of such categories, and are accustomed to defining themselves and each other in relation to them.

1.3 The scope of a personal specialty

Research scientists are individually credited with special expertise over particular domains of scientific knowledge. These *personal* specialties are defined by reference to current 'maps' of knowledge, but they are not actually specified on such maps. Inspection of the subject classification scheme of a discipline, for example, will give an idea of the problems, concepts, techniques, etc. on which such personal specialties might be centred, but it will not indicate their position or scope. In fact, as we shall soon see, the latter is itself a highly individual trait: scientists not only locate themselves very unsystematically over the scientific 'landscape'; they also vary greatly in the area of science over which they are accorded or claim special expertise.

This individual diversity is vital in all that follows. The present investigation would be pointless if the division of labour in science were strictly formalized and controlled. Research work is not divided like clinical medicine into *professional* specialties, where practitioners must take examinations to qualify as 'specialists' in particular branches of the subject (§3.1). Many stiff examination hurdles may

bar the way into a research career, but once these are cleared there are no official limitations on the subjects on which a scientist with a degree in a particular discipline might in principle carry out research (§4.2). It might be foolish for a PhD in botany to try to make observations in astrophysics, but it would not be illegal to do so. For this reason, there is little to be learnt from data on occupational specialization (e.g. Fiorito 1981) based solely on academic degrees and other official professional qualifications.

A much finer-grained classification is needed to demonstrate the actual diversity and specificity of work in research. For example, in the manpower surveys carried out by the American Institute of Physics (Porter 1975, 1976), more than ten 'employment specialties' were distinguished within the single subdiscipline of *nuclear physics*, and more than 20 in the subdiscipline of *optics*. In other words, these surveys suggest that a working scientist usually has no difficulty in defining an area of personal expertise on the scale of a research 'field', such as *nuclear spectroscopy* or *atmospheric and space optics*, whose scope might be less than one per cent of the extent of a conventional 'discipline' such as *physics* or *electronic engineering*.

This estimate of the actual extent of specialization in scientific work is confirmed by direct study of the range of subjects covered in the output of individual research scientists. Taking a standard subject classification scheme as his starting point, Gieryn (1979) found that research in astronomy could be classified into about a hundred 'problem areas'. Astronomy may be considered an academic discipline in its own right, but it is not so large as physics or chemistry, so that each of these is probably somewhat smaller than what I would call a typical research 'field'. Gieryn then looked at the papers published by more than 2000 American astronomers over the period 1973–5, and found, in the majority of cases, that the work of each astronomer was concentrated into just two or three such areas. In other words, judging from his or her published work, the personal specialty of a typical astronomer would appear to be about one 'field' in extent at any one time.

The terms that scientists themselves use to describe their personal research specialties are consistent with this estimate of their size. A hydrologist remarks that at one time he was 'doing chemistry of sea water, chemical oceanography', and that this was quite different from the chemistry of river water. Research on the endocrine function in fish is clearly differentiated from human endocrinology, even though the underlying physiological mechanisms are thought to be closely related. An experimental physicist reports that all of his research up to a certain date had been at very low temperatures:

'. . . most of my life it had been below 4° and the last five years below ten millidegrees . . . '.

Table 1.1

Number of problem areas	Cumulative percentage
1	20
2	40
3	60
4	70
5	80
6-7	90
8+	100

Most working scientists evidently see themselves as occupying only one or two of the thousands of 'fields' into which the labour of the scientific enterprise is divided.

Any quantitative estimate of the size of the typical unit of subject specialization in science is obviously highly suspect, and should not be accorded the intellectual dignity of arithmetical manipulation. But such a unit could not be very much larger than a 'field' simply because of the enormous rate at which scientific knowledge accumulates. Remember that something like 100,000 scientific papers are published in a major scientific discipline each year. To keep up with the literature in a single research 'field' one would need to be aware of the contents of one per cent of these – that is, of a thousand original papers. This task is not quite as heavy as it seems, since the quality of the scientific literature is so uneven that one can safely ignore at least 90per cent of it. Nevertheless, to remain perfectly informed over the whole of such a 'field' one would have to become acquainted with the actual research results of something like a hundred papers each year, and arrive at some personal opinion as to their validity. A single 'field' thus provides plenty of material on which to become a 'subject specialist', without looking further afield.

This is not to suggest that every scientist has to be a world authority on his or her subject in order to do good research. In practice, some scientists do try to follow this counsel of perfection, and work only in very narrow areas, whilst others have wider interests. This comes out clearly in Gieryn's study of the publication records of astronomers. For example, the cumulative percentages of the sample who had published at least one paper in each of several distinct 'problem areas' are shown in Table 1.1. Thus, although the majority of the scientists in this group seemed to be working in what would be, by our present reckoning, just one or two 'fields', there were a significant proportion who did not appear to be nearly so specialized in their research. It is interesting to note, moreover, that the publications of each of these more 'diversified' scientists were

not always concentrated into a single broader category of the subject classification scheme (e.g. into what we would call a single 'subdiscipline'), but were sometimes distributed quite widely over astronomy as a whole. In the absence of further detailed evidence on this point, we should not give too much weight to the data of Table 1.1, but they do give a rough indication of the variability, from individual to individual, of the extent of subject specialization in an active domain of scientific research.

1.4 Persistence

At any given moment, a scientist may say that he or she is a specialist in a particular 'field' – *the behaviour of aphids on cereal crops*, for example, or *computer modelling of airflow at high Mach numbers*. But a particular specialty is not necessarily a permanent personal attribute. A few years later, the same scientists might report that they were now interested mainly in, say, *the application of pesticides to fruit trees*, or *the formation of droplets in fluid jets*. Quite apart from the changes that naturally occur in the definition and classification of scientific 'subjects' (§1.2) an individual scientist's personal specialty may change radically in the course of his or her career. In fact, the circumstances and consequences of this familiar feature of scientific life are the main theme of this book.

But before we enter into a detailed discussion of these circumstances and consequences, we need to have some quantitative notion of the scale of this phenomenon? To what extent, and in what manner, do researchers actually change their 'subjects' during their scientific careers? These are straightforward questions, which could be answered by direct analysis of the published work of a number of mature scientists in a particular area of research. Such a collection of personal *curricula vitae* would not tell the whole story of specialization and change in contemporary scientific careers, but it would indicate the characteristic patterns of such change. The *research trails* that individual scientists actually follow across the cognitive landscape (Chubin & Connolly 1982) must be considered the primary evidence in any study of the way in which they respond to the peculiar demands of their vocation.

Unfortunately, there is little systematic information on this subject. Excellent data for such an investigation are undoubtedly available in the personnel files of major scientific institutions, but they have not been studied from this point of view. Once more, all that we have to go on is Gieryn's analysis of the published work of American astronomers over the period 1950–75 (Gieryn 1978, 1979). Since this study covered only one relatively narrow discipline, it cannot be relied on as a quantitative account of career patterns in all scientific work, but it does give a good idea of the prevalence of various types of research trail in this particular, rather 'academic' branch of science.