1

A Conceptual Vocabulary of Interdisciplinary Science

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It is a most unfortunate consequence of human limitations and the inflexible organizations of our institutions of higher learning that investigators tend to be forced into laboratories with such labels as 'biochemistry' or 'genetics.' The gene does not recognize the distinction – we should at least minimize it.

G.W. Beadle, 'The Genetic Control of Biochemical Reactions,' *The Harvey Lectures*, 1944–5

The reality I want to report on is much more complicated and, consequently, the concept of interdisciplinarity more ambiguous.

Marc De Mey, 'Cognitive Science as an Interdisciplinary Endeavour,' Practising Interdisciplinarity Conference, Vancouver, 1997

For most of the twentieth century, the question of knowledge has been framed by disciplinarity. In recent decades a different view has emerged. Research is becoming increasingly interdisciplinary. New social and cognitive forms have altered the academic landscape, new practices have emerged, and disciplinary relations have realigned. Talk of *re*negotiation, *re*organization, and *re*configuration abounds. As a result, even the most basic terms – 'discipline' and 'interdisciplinary' – are no longer adequate. A new conceptual vocabulary is needed.

Defining Interdisciplinary Science

Understanding is complicated by the current 'jungle of phenomena' (Huber 1992: 195). Ask three scientists what interdisciplinarity means, and they will likely give three answers. A geologist might reply plate tectonics, a life scientist molecular biology, and a physicist materials science. On the Internet, a multitude of websites support interdisciplinary interests as wide-ranging as global networks, information science, pharmacy, psychiatry, chaos theory, the environment, robotics, system dynamics, and electrical engineering. In the first half of this century, interdisciplinarity was not a major force in science. By mid-century, cross-fertilizations across the sub-branches of physics, grand simplifying concepts, the emergence of systems theory, and new fields such as biochemistry, radioastronomy, and plate tectonics marked increased activity. The most prominent event was the Second World War. Formation of institutes and laboratories to solve military problems legitimated interdisciplinary problem-focused research (IDR) and accustomed academic administrators to large-scale collaborative projects on campus. The Manhattan Project and operations research reinforced an instrumental discourse focused on technical problems akin to Peter Weingart's notion of pragmatic or opportunistic interdisciplinarity (1995: 6). After the war, many projects were dismantled, though influential laboratories continued to operate. Over the ensuing decades new laboratories and institutes were established in nuclear science, radiobiology, biophysics, marine physics, and atomic research (Etzkowitz 1983: 214–5).

Government support was a strong legitimating factor in the new social contract between government and academy. In the late 1950s, the U.S. Department of Defense (DoD) funded the first materials research laboratories and, by the early 1960s, the Interdisciplinary Research Laboratories. In the 1970s, international economic competition created added pressure for a new technology initiative. At least two areas of cutting-edge technology – computers and biotechnology – were closely tied to academic science (*New Alliances* 1986: 7). In response, the National Science Foundation (NSF) launched new initiatives. In the late 1970s, NSF provided seed money through the University–Industry Cooperative Research Centers. In 1985, NSF established an Engineering Research Centers program, followed by a Science and Technology Centers program. The long–term role of centres is unclear, but they have altered organizational structures and cultural practices of research (Turpin and Hill 1995). When centres existed primarily on a private basis and in applied research, they were not regarded as serious threats to academe. In recent decades, they have proliferated, due to accretion of problem- and mission-oriented research (Halliday 1992: 23).

New organizational structures have also emerged, including offices of technology transfer, industrial liaison programs, joint mergers and ventures, research networks, consortia, contract research, and entrepreneurial firms. They are not always interdisciplinary. Yet, research is typically problem-focused and often collaborative. Innovations in product design utilize new ideas and methods born at the interfaces of disciplines. The areas attracting the greatest attention today are advanced engineering materials and methods, computer sciences and complex systems software, molecular biology, and biomedical specialties (Sproull and Hall 1987: 3). Heightened links with product innovation and new discoveries support Weingart's contention (this volume) that interdisciplinarity is a discourse of innovation. The term 'innovation' connotes everything from new ideas to product design, though it tends to be equated with improvements in sociotechnical systems of manufacture and increased performance of products, services, and costs (Kline 1995: 180).

Instrumentality is not the only discourse of interdisciplinary science. Epistemological interests span traditional questions about knowledge, sociological studies of practices, and post-modern critique. Instrumental discourse driven by a policy agenda or social problems demands accommodation of problem solving but leaves existing disciplines and institutions intact. Interdisciplinarity forged in critique demands their reconstitution, akin to notions of 'critical interdisciplinarity' (Klein 1996) and interpenetration of existing discourses (Fuller 1993). It also promotes second-order reflection, akin to Weingart's notion of reflexive interdisciplinarity. Strategic and critical discourses are not always separate, though. Both critique and instrumentalism shape the environmental field.

Several movements have promoted unified knowledge, most notably the Unity of Science campaign in the 1930s and 1940s. The search for grand simplifying concepts – the second law, the mass-energy equivalence, and quantum mechanics – also promoted general theory. So has general systems. Transdisciplinary ambitions persist, but a different level of activity has gained attention more recently. The first prominent notice appeared in 1972, when the Organization for Economic Cooperation and Development identified development of science as the first need for interdisciplinarity. This need is manifested in an apparent contradiction: increasing specialization limits the focus of research, though it also leads to intersections of disciplines (OECD 1972: 44).

In a landmark study, Darden and Maull (1977) examined how theories bridge two fields. They depicted science as a network of relations, not a hierarchical succession of reductions. The term 'field' designates a central problem, domain of related items, general explanatory factors and goals, techniques and methods, and related concepts, laws, and theories. 'Interfield theory' designates relations between entities or phenomena in different fields and their explanatory role. In science, integrations are typically local. Exemplars include the bridging of genetics and cytology through the chromosome theory of Mendelian heredity, relating genetics and biochemistry through the operon theory, and connecting biochemistry and physical chemistry through the theory of allosteric regulation.

Nearly a decade later, a conference on life sciences focused on problems that lend themselves to interdisciplinary investigation. The case studies were biochemistry, the evolutionary synthesis, and cognitive science. Editor William Bechtel (1986: 46–7) identified five patterns of disciplinary relations:

- developing conceptual links using a perspective in one discipline to modify a perspective in another discipline
- recognizing a new level of organization with its own processes in order to solve unsolved problems in existing fields
- using research techniques developed in one discipline to elaborate a theoretical model in another
- modifying and extending a theoretical framework from one domain to apply in another
- developing a new theoretical framework that may reconceptualize research in separate domains as it attempts to integrate them

Several lines of inquiry characterize recent studies. The literature on management continues to grow. Increased attention is also being paid to local practices in specific domains, such as Marc De Mey's study of cognitive science, and in organizational structures, such as studies of centres by De Mey, Sam Garrett-Jones, Rogers Hollingsworth, Sabine Massen, Eric Scerri, and Stephen Turner, all in this volume. Paralleling the expanding field of knowledge studies, multiple methods are employed, including genealogy, ethnography, interviews and surveys, bibliometrics, discourse analysis, archival research, organizational analysis, social theory, and critique. Disciplinary histories are also being updated.

Physics is a striking case. In 1972 the National Research Council (NRC) in the United States declared there was 'no definable boundary' between physics and other disciplines (*Physics in Perspective* 1971: 67). In 1986, the Council highlighted new disciplines arising from interfaces of physics and other sciences, plus applications in technology, medicine, and national defense (National Research Council 1986). Almost all significant growth has occurred at 'interdisciplinary borderlands' between established fields. The five prominent areas of fundamental research are biological physics, materials science, the physics–chemistry interface, geophysics, and mathematical physics and computational physics. The six outstanding areas of technical applications are micro-electronics, optical technology, new instrumentation, the fields of energy and environment, national security, and medical applications.

New developments have blurred boundaries by relocating scientific and technological work away from discrete sites to problems and puzzles characterized by unpredictability, complexity, and a quickening pace. In many areas of advanced technology, the intellectual boundary between engineering and physics is vanishing, creating a continuum that speeds innovation and technology transfer. The postgraduate demands of many scientists and engineers are pulling them inexorably into the continuum. At major synchrotron facilities the cultures of physicists and chemists are merging, and, in macromolecular research, boundaries among chemistry, physics, and biology are blurring.

The NRC defines new patterns of interaction as 'true interdisciplinary science.' Traditionally, techniques and discoveries were transferred from physics to other disciplines. Today, both physicists and chemists are building on and enriching areas to create new subfields. Even the NRC acknowledges the limits of this picture. Synergistic interactions between physicists and chemists far from the traditional interface have usually occurred in spite of department structures. Institutions are not always ready to adapt to complexity, promote borrowing, or accommodate effective problem solving (Carole Palmer, personal communication, 16 October 1996).

An apparent paradox emerges. New programs, centres, and activities proliferate. However, interdisciplinarity is impeded. There is no paradox, Weingart (this volume) rightly contends, only terminological confusion. Interdisciplinarity and specialization are parallel, mutually reinforcing strategies. The relationship between disciplinarity and interdisciplinarity is not a paradox but a productive tension characterized by complexity and hybridity.

Complexity and Hybridity

An old saying comes to mind – interdisciplinarity exists in the 'white space' of organizational charts. Many activities, such as De Mey's 'wandering professor,' are not tracked. While lamenting the lack of systematic data, Weingart (this volume) repeated a telling estimate. One expert speculated that only about 20 per cent of projects in targeted research programs of the German government encouraged interdisciplinarity. However, the rate was apparently higher in a standard funding program that is supposedly disciplinary. Interdisciplinary activity does not always fit the preconceptions administrators have (Bechtel 1986: 4, 29).

Activities are located across an expanse of sites and relations. An enormous amount of interdisciplinary traffic occurs in less visible forms such as common interests and problems; shared use of facilities, instrumentation, and databases; and borrowed tools, methods, results, concepts, and theories. The least visible activities are often in disciplines, in interdisciplinary traditions, new practices, and research on strategic and intellectual problems. Instruments also play a key role. When it comes to big machines such as spectroscopies, Turner remarked (this volume), chemistry begins to look like physics.

One signal, specialty migration, is familiar. Migration implies boundedness, but specialties possess no inherent boundaries. They are defined by relative concentrations of interests. The underlying metaphor of migration, Hoch (1987) cautioned, may be ill-conceived. Most migration occurs because research areas are in constant reformulation. Boundaries shift and overlap because ideas and techniques do not exist in fixed places. Researchers carry them through multiple groups (Becher 1990: 344; Chubin 1976: 464, note 35). Interdisciplinarity, Turner observed, starts by creating novel divisions of labour for novel ends. Consequently, 'frontier' is a popular metaphor of interdisciplinarity, connoting expansion into uncharted domains and 'the cutting edge.' Understandably, interdisciplinarity is associated with pathbreaking ideas, discoveries, and lines of investigation. Yet, the frontier metaphor creates a rigid realism. The space of interdisciplinary work is not just *out* there – interdisciplinary activity these days may be *in* the heart of disciplinary practice. In some areas knowledge production is no longer occurring strictly within disciplinary boundaries, especially in the Human Genome Project, biotechnology, molecular biology, risk assessment, and technology assessment (Gibbons et al. 1994: 138, 147).

These developments suggest that territorial metaphors may be obsolete. Spatial metaphors – turf, territory, boundary, and domain – highlight formation and maintenance. Boundary formation occurs as categories and classifications stake claims. Organic metaphors – boundary crossing, interdependence, and interrelation – highlight connection. Organic models compare intellectual movements to processes in ecology and the evolution of plant and animal species. 'Ecology,' Winter (1996) recalls, derives from a Greek word, *oikeos*, meaning household or settlement. The verbs associated with *oikeos* suggest inhabiting, settling, governing, controlling, managing, and other activities in a complex interweaving of fields of social action. Knowledge, simply put, cannot be depicted in a single metaphor. Spatial dynamics of place and organic dynamics of production occur simultaneously. Spatial and organic models may even be combined to form a third type, highlighting interactions between social groups and environments. Organism and environment, Winter emphasizes, imply one another mutually. Both are territorial, competitive, and expansionist. The underlying idea is to make and reinforce jurisdictional claims, analogous to territorial claims humans and animals make in ecological niches. Organism and environment also exploit resources to produce new life forms and settlements.

The simultaneity of spatiality and organicism – of location and generation – is apparent in the hybrid character of interdisciplinary activity. Hybridization is a biological metaphor connoting formation of new animals, plants, or individuals and groups. A hybrid emerges from interaction or cross-breeding of heterogeneous elements. In organizational theory, the metaphor marks tasks at boundaries and in spaces between systems and subsystems (Gibbons et al. 1994: 37). Communities that facilitate interdisciplinary research exhibit properties that Gerson (1983) attributed to intersections in science. An intersection is a system of negotiating contexts. Most intersections involve techniques, specialized skills, and instruments. Intersections, though, also occur in interpretive phases, from borrowing vocabulary and ideas to theoretical explanations, such as new groundings of 'valance' and 'gene' in other disciplines.

Intersections are accommodated in a variety of hybrid communities, from centres and programs to projects, networks, invisible colleges, and matrix structures. Matrix structures are alternative forms superimposed on organizations dominated by disciplines or functions. Matrices have long facilitated innovations in the realms of pharmacy, engineering, and social and technological problem solving (Pearson, Payne, and Gunz 1979: 114; Klein 1990: 121–39). In science policy circles, 'hybrid community' has a technical meaning, designating a group of researchers, politicians, bureaucrats, and others who formulate a research program. New organizations such as the Work Research Institute in Norway are hybrid, problem-solving communities. They encompass organizational frameworks of policy making and social research as well as the new hybrid discourse coalitions in which problems are defined, investigated, and handled (Mathiesen 1990: 411–13; Hagendijk 1990: 58–9). These organizations are interinstitutional as well as interdisciplinary.

Two additional concepts – trading zone and enclave – shed light on intersections. Galison (1992) proposed the concept of 'trading zones' to explain heterogeneous interactions of scientific cultures. Interactions range from a stabilized 'pidgin zone,' a linguistic term for an interim form of communication, to a 'creole zone,' a main subculture or native language of a group that develops a new hybrid role and professional identity. Trading zone is also an economic metaphor connoting exchange of goods, trade agreements, and embargoes (Fuller 1992, 45–6). Lowy (1992), Fuller (1993), the authors in a special issue of the journal *Social Epistemology* (1995), and Klein (1996) have extended the notion of trading zones to explain disciplinary interactions.

Turpin and Hill call the organizational structures emerging from research centres 'enclaves of collaborating research practitioners' (1995: 10). These structures create new boundaries of alliance, identities, and professional roles. They operate partially as counter-cultures and partially as components of new cultures. Some individuals participate fully, others in a transitory fashion. Historically, such enclaves mark the growing diversification of strata formation and crossing of political, sectoral, and occupational formations (Eisenstadt 1992: 57). Enclaves are loci of changing roles and cultural orientations. The enclaves where interdisciplinary interests are segmented often exhibit a 'semi-liminal' character.

Hybridization connotes both form and process. Dogan and Pahre (1990) view hybridization as a characteristic of knowledge production today. As innovative scholars move from the core to margins of their disciplines, specialties are recombined continuously, with two results:

1 formally institutionalized subfields of one or another formal discipline or permanent committees or programs that regularize exchanges
2 informal hybridized topics, such as development, that may never become institutionalized fields

The higher up the ladder of innovations, the greater the chances boundaries will disappear, Dogan asserts (1995: 103). Hybrids, moreover, beget other hybrids, especially in natural sciences where higher degrees of fragmentation and hybridization occur. Their formation is not continuous. Yet, specialty interaction is a prominent feature of knowledge production today. The second type of hybrid is difficult to map, because relations cannot be easily defined in spatial terms. The current interface between physics and chemistry has been crossed so often in both directions, the authors of an NRC report remarked, that 'its exact location is obscure; its passage is signaled more by gradual changes in language and approach than by any sharp demarcation in content.' Interactions and cross-fertilizations that characterize the interface have been sources of continual advances in concept and application across the science of molecules and atoms, surfaces and interfaces, and fluids and solids (National Research Council 1986: 53).

Two prominent activities – borrowing and problem solving – further illuminate the hybridity and complexity of interdisciplinary activity.

BORROWING

A great deal of crossfertilization occurs in the daily flow of influence signified by the metaphor of borrowing. The simple borrowing of tools, data, results, and methods does not tend to transform boundaries. Yet, concepts from one level may permeate to other levels in a process called 'pivoting' (Kedrov 1974) and 'whirlpool effects' (Intrilligator 1985). Methods of mathematics, statistics, and systemology are used in mechanics, physics, chemistry. Methods used in the latter disciplines are used, in turn, in astronomy, geosciences, and biosciences (Dahlberg 1994: 68). Borrowing is an important signal. When, over time, genetic techniques became primary tools and knowledge of mechanics of gene action and regulation provided primary insights for many basic problems, borrowing became more frequent as a mode of unification in biology (Burian 1993: 312).

Borrowing is difficult to map. Sometimes a borrowing is assimilated so completely it is no longer considered foreign, or it transforms practice without being considered 'interdisciplinary.' Many physical techniques have become so fully integrated into biological research that their origin may be forgotten; for instance, electron microscopy, X-ray crystallography, and spectroscopies. Current pressure on scientists to do interdisciplinary work derives in part from borrowing techniques and instruments to address problems raised in another discipline (Bechtel

1986: 282–3). One of Scerri's interviewees remarked, 'The philosophy of our lab is to try to steal as many technologies as we can from other disciplines and apply them to our problem' (this volume).

Palmer's study of one institute lends insight. The institute houses research programs in physical sciences, engineering, computational science, life sciences, and behavioural sciences. Research exhibits a dual action. Centrifugal forces help move people, things, and ideas outward into other domains. Centripetal forces hold elements together in established frameworks. Diversity of membership opens up networks, skills, and ideas otherwise not accessible to individuals. Concrete things are a pivotal feature of boundary crossing:

> Data (numbers) and data sources (rabbits) are shared between labs and sometimes brought together for comparative analysis. Databanks of raw data are amassed and then added to by allied researchers. Molecules built by one research group are analyzed by another, with both sides bringing insights to the final results. It is common for apparatus to be borrowed and applied in new ways and to different types of data. New computational technologies are often combined with established disciplinary science to 'push the frontier end of studies' in the area. (Palmer 1996)

Concepts and theories are also influential sources of interaction. Hübenthal (1991) identifies 'concept interdisciplinarity' as a specific type, citing system theory, cybernetics, information theory, synergetics, game theory, semiotics, and structuralism. Star and Griesmer (1988) proposed the term 'boundary concept' to explain heterogeneous interactions between different professional groups. Concrete and conceptual objects are robust enough to maintain unity across fields but plastic enough to be manipulated. Weakly structured in common use, they are strongly structured at individual sites. As negotiable entities, they simultaneously delimit and connect. In cognitive terms, they facilitate hybrid intellectual work. In social terms, they facilitate inter-group alliance. In this volume, Maasen, commenting on the transfer of concepts in research groups, recalled Bono's (1995) observation that concepts act as sites and media of exchange. Boundary concepts exhibit both generality and particularity. The theory of the genetic code and protein synthesis exhibits features of universality and broad scope, plus particularization to specific organisms (Schaffner 1993: 320).

Chaos is a timely example. Traditionally, Hayles (1990) explains, turbulence was viewed from the perspective of fluid flows. Today it has become a general phenomenon. When concepts circulate within a cultural field, they stimulate cross-fertilization. Yet, they bear traces of local disciplinary economies. Literary theorists value chaos because they are concerned with exposing ideological underpinnings of traditional ideas of order. Chaos theorists value chaos as the engine that drives a system towards a more complex kind of order. Hayles theorizes interdisciplinarity as an 'ecology of ideas' that neither demands unity nor overrides differences. Commonalities and differences create dual emphasis on cultural fields and disciplinary sites. The discourse of chaos is both fragmented and unified: 'Any description presupposes a frame of reference that limits, even as it creates, what is said.' What is known is a function of what is noticed and considered important. Both spatial and organic dynamics operate. Activities 'locate' in intersections but continue to circulate across spheres (1990: 135, 144).

PROBLEM SOLVING

Palmer highlights an added feature of scientific work – researchers tend to work *on* problems not *in* disciplines. Problems are focal points where disciplinary social worlds intersect. The figurative common ground of problem areas such as oscillating reactions, photosynthesis, and membranes is fluid. It changes as science progresses through discoveries and interactions between fields (Palmer 1996: 57, 119). All problems, moreover, are not the same. Reynolds identified three kinds of problems (Sigma Xi 1988: 21):

- *Problems of the first kind:* intellectual problems in a traditional discipline;
- *Problems of the second kind:* multidisciplinary problems that are basically intellectual not policy-action in nature but cannot be successfully undertaken within boundaries of one discipline;
- *Problems of the third kind:* distinctly multidisciplinary problems generated increasingly by society and distinguished by relatively short-time courses calling in some cases for a policy-action result and in other cases for a technological quick fix.

With problems of the first kind, disciplinary boundary work is strongest. Problems of the second kind heighten boundary crossing. Boundary concepts such as 'text,' 'discourse,' 'interpretation,' and 'culture' have been catalysts for interaction across humanities and social sciences. 'Role,' 'status,' and 'area' have cross-fertilized social sciences.

The multi- and interdisciplinary nature of research problems is often highlighted in centres: when, for instance, a polar research centre addresses problems of ice core research, polar ecology, Antarctic tectonics, and glaciology (OSU 1991: 18). The urgency of problems of the third kind has heightened the discourse of instrumentality.

In describing this change, Gibbons et al. (1994) proposed the concept of Mode 2 knowledge production. Mode 1, the traditional form, is primarily academic, homogeneous, and hierarchical. It is dominated by disciplinary boundary work and comprised of ideas, methods, values, and norms of Newtonian science. Mode 2 is non-hierarchical. It is distinguished by heterogeneously organized forms, transdisciplinarity, and closer interaction among scientific, technological, and industrial modes of knowledge production. Mode 2 has garnered wide attention in science policy circles. Weingart (this volume) judges the claim overstated and empirical evidence weak. Nonetheless, Mode 2 provides a name for traits closely associated with innovation and boundary crossing. Human resources have become more mobile, and organization of research is more open and flexible. The weakening of disciplinary boundaries has been accompanied by collapse or erosion of monopoly power. As organizational boundaries of control blur, 'competence' is redefined and criteria of quality broaden.

Multidisciplinary competencies, as Garrett-Jones and Tim Turpin forecast in this volume, are becoming more than a secondary 'add-on' to disciplinary identities. In the future, portfolios of identities and competencies must be managed. As resources, knowledge, and skills are continuously reconfigured, Gibbons et al. add, both theoretical and practical knowledge are generated in new configurations of intellectual and technological work. Since exploitation of knowledge requires participation in its generation, discovery and application are more closely integrated. In a dynamic and socially distributed system with feedback loops, markets set new problems more or less continuously. In human genome discourse, Rheinberger (1995) predicts, boundaries of basic research and medical applications will be inverted. The opportunistic ideology of medical application and goals-directed research will produce keys for attacking 'fundamental' problems in other areas, such as developmental biology, protein folding and function, and the brain (Gibbons et al. 1994: 178).

Metaphors of knowledge shift in turn. Gibbons et al. liken organizations that carry projects at the forefront of science, technology, and high-value enterprises to a spider web. Connections are spun continuously, with growing density and connectivity. Problems in genetics, electronics, mathematics, and physics possess an intrinsic intellectual interest nourished by the research and practical interests of other users. Older terms – 'applied science,' 'technological or industrial research,' 'technology transfer,' 'strategic research,' 'mission-oriented research,' 'research and development' – are no longer adequate. In the linear model, science led to technology and technology satisfied market needs. In many advanced sectors of science and technology today, however, knowledge is being generated *in* the context of application. New social contracts between industry and academe make 'interchange' a more appropriate word than 'transfer.' A greater number of scientists, moreover, are working on problems outside traditional specialties and entering into new social arrangements.

Research, Garrett-Jones and Turpin add, is not unidirectional. Clark coined the term 'restless research' to describe research that moves out in many directions from traditional university settings (1995, 195). Definitions of a 'good' scientist and science become more pluralistic. Problem solvers, problem identifiers, and strategic brokers are working with knowledge resources held in government laboratories, consultancies, and other businesses (Gibbons et al. 1994: 23, 32, 37, 65, 76, 145). Skilled 'boundary riders' must 'beat the boundaries' in order to relocate science into productive and localized forms (Turpin and Hill 1995: 16). Managers in higher education, in turn, are beginning to operate in a parallel mode.

The current push of high technology and international competition has made 'collaboration,' 'competitiveness,' 'problem solving,' 'systems,' 'complexity,' and 'interdisciplinary' new descriptors of knowledge. Instrumental discourse has not rendered IDR central to the academy. Yet, problem complexity, economic competition, costs of instrumentation and facilities, the desire to transfer knowledge rapidly to application, and the interchange of applied and basic research have heightened the legitimacy of hybrid organization and modes of knowledge production. As new 'technostructures' intersect with traditional university departments, new commercial strategies are accompanied by changes in organizational values, structure, culture, and intertextuality of scientific discourses with elements of public political discourse and popular discourse (Stehr and Ericson 1992: 196). Grappling with the need to address complex problems, governments are making decisions that increase the likelihood of the deinstitutionalization of science as greater control passes to non-scientists. Elzinga (1985) coined the term 'epistemic drift' to account for the shift from strictly internalist criteria and reputational control to externally driven criteria that are more open to external regulation in the policy arena. The likelihood of interdisciplinary work involving at least one party who does not work at a university also increases (Fuller 1995: 204).

When interdisciplinarity is cast as a principal means of achieving targeted objectives, the problem of interdisciplinarity is drawn closer to the general problem of knowledge policy (Fuller 1995: 33). Outcomes may be determined more by a power battle between disciplinary groupings and hybrid communities than by scientific validity, social need, or the legitimacy of integration and collaboration (Hoch 1990, 45). Discourses of epistemology and second-order reflection are also shortchanged, as motivation and social consequences are minimized or even ignored.

The Disciplinary Question

Another popular metaphor – knowledge 'explosion' – signifies a development that further strains conventional notions and standard models. By 1987, there were 8530 definable knowledge fields (Crane and Small 1992, p. 197). By 1990, roughly 8000 research topics in science were being sustained by related networks (Clark 1995: 193). A significant number of specialties today are 'hybrid creatures' (Clark 1995: 245; Winter 1996: 24). Intensification of interests in new areas has produced new domains that fall between older disciplines, such as sociobiology and biochemistry, and at extremes of prior capability, such as particle physics and cosmology. Extensification of interests has produced new areas that draw together disciplines to model more complex phenomena, such as concrete economic and public health problems (Fuller 1988: 285). Disciplines also routinely experience the push of prolific fields and the pull of strong new concepts and paradigms (Jantsch 1980: 306).

Invoking the metaphors of mapping and geography, Becher (1990) highlights the variety of current forms and practices. The earth is comprised of many topographical patterns; cross-national connections; economic, functional, and occupational similarities; and broad social and cultural features. Their counterparts in knowledge territories include *basic characteristics* (e.g., quantitative and qualitative, pure or applied), *shared theories or ideologies* (e.g., catastrophe theory, Marxism), *common techniques* (e.g., electron microscopy, computer modelling), and *sociocul-*

tural characteristics (e.g., incidence of collaborative work, nature of competition).

These forms and practices are not the result of a simple increase in the number of activities – they also represent a change in kind. Specialization works against systematic integration by leading to greater fragmentation, but it also gives rise to a characteristic style of connection or mutual interdependence that provides some sense of unity (Winter 1996: 6). Becher (1990) uses the analogy of a biological culture viewed under a microscope. At close range, a discipline is a constantly changing 'kaleidoscope of smaller components,' varied in form but still related through a general process of specialization. Individual cells are in a 'state of constant flux' – subdividing, recombining, and changing shape and disposition. One of the salient features of subdisciplinary groupings is their relative lack of stability compared with parent disciplines. Some sub-units even exhibit an 'anarchic tendency' to appear more closely allied with counterparts in heartlands of other disciplines. These groupings create 'counter-cultures' that may conflict with and even undermine the parent disciplinary culture.

The current extent of boundary crossing at this level suggests that specialty interactions may be more reliable indicators of interdisciplinary activity than the emergence of new hybrid disciplines, even perhaps of knowledge production in general (Lepenies 1978: 302; Dogan and Pahre: 64). Academic subject labels are also strained. Traditional labels may suffice for teaching but are less accurate for research or faculty identity (Pinch 1990: 299). Palmer found that 'physics,' 'chemistry,' 'psychology,' and 'biology' were not meaningful knowledge domains for researchers working in an interdisciplinary institute (1996: 207). To call someone a biologist doesn't tell much about what she/he or her/his professional peers do (Bechtel 1986: 279). One biochemist reported that her approach has become more integrative as her field has grown more multidisciplinary on an international scale (Palmer 1996: 56). In one university, moreover, the subject area of 'biology' is spread across thirteen discipline-based departments and seventeen interdisciplinary programs (Clark 1995: 142).

Disciplinary loyalties, Turner (this volume) rightly notes, undermine interdisciplinary work. Yet, the pull of disciplinary careers is not so strong as it used to be. Changes in the organization of scientific research have weakened the monolithic character of departments. Disciplines have become decentralized into smaller units that exert day-today social control over what is studied and how. These units neither certainly nor inevitably lie within conventionally defined boundaries. Alternative sites – programs, centres, institutes, and laboratories – have further weakened disciplinary control over subject definition, conceptual approaches, cognitive structures, goals, and norms (Whitley 1984: 12, 18–20).

The view of disciplinarity that emerges does not deny the value of specialization, the inevitability of differentiation, the inertial strength of institutionalized formations, or the regulative mechanisms that discipline interdisciplinary work (Stocking and Leary 1986: 57; Calhoun 1992: 184). It does, though, dispute oversimplifications. Standard models stress stability, predictability, autonomy, maturity, progress, unity, and consensus (Salter and Hearn 1996). Discipline, however, is not a neat category (Becher 1990: 335). Disciplines vary in the ways they structure themselves, establish identities, maintain boundaries, regulate and reward practitioners, manage consensus and dissent, and communicate (Squires 1992: 203). Heterogeneous practices, hybrid activities, and interdisciplinary fields have rendered disciplines fissured sites. Comprised of multiple strata and influenced by other disciplines, a discipline is a 'shifting and fragile homeostatic system' that evolves and adapts to changing environments (Heckhausen 1972: 83; Easton 1991: 13).

This view of disciplinarity also challenges the popular notion that a successful interdisciplinary practice becomes 'just another discipline.' 'Border interdisciplinarity,' 'interdisciplinarity of neighbouring disciplines,' 'borderland interdisciplinarity,' 'zone of interdependence,' and 'zone of proximal development' are names for high-level integration. The reconstructive capacity of interdisciplinary research alters the architectonics of knowledge by strengthening connections outside the discipline 'proper.' Connections weaken divisions of labour, expose gaps, stimulate cross-fertilization, and fix new fields of focus. They also imply new divisions of labour, redistribution of resources, realignment of institutional structures, and redefinitions of epistemological and ontological premises (Landau, Proshansky, and Ittelson 1961).

All hybrid disciplines are not the same, however. Interrelations may be postulated between entities examined in one discipline and entities in another. The conceptualization of genes as part of chromosomes linked genetics to molecular biology. Or, two disciplines may become conceptually connected while retaining different but overlapping foci, principles, or theories. Physics and chemistry were linked through the bridge laws of thermodynamics. Or, one discipline may be absorbed into another, as astronomy was absorbed into physics. Or, two disciplines may join into a more general discipline through translatability of their fundamental principles, as geometric and arithmetic sciences became unified into mathematical science (Paxson 1996).

Likewise, outcomes differ. Cognitive science is an interdisciplinary field. At this point, however, it does not constitute a new discipline that stands alongside artificial intelligence, cognitive psychology, theoretical linguistics, cognitive anthropology, and philosophy. Practitioners share resources through interdisciplinary programs, societies, conferences, and journals while remaining identified with their 'home' disciplines. A psychologist working in the field is likely to hold an appointment in psychology and belong to the American Psychological Association and subscribe to its journals. Bechtel calls such affiliations 'cross-disciplinary research clusters.' In contrast, molecular biology became a new 'way of life' in biological research. Its 'technical fallout' exceeds and subverts boundaries of existing biological disciplines (Rheinberger 1995: 175). In cognitive science the central problem – what processes underlie cognition? – was already a topic of inquiry in the disciplines being bridged. In cell biology, the task of explaining cell function in terms of cell structures was not a central task in contributing disciplines (Bechtel 1986: 295).

Hybrid disciplines are not handled uniformly, either. Biochemistry, for example, is structured as an independent department, joined with a department of biochemistry and biophysics, merged into a department of physiology and chemistry, and organized by an interdisciplinary committee composed of members of departments of biology and chemistry (Bechtel 1986: 16). The biological metaphor of a niche implies formation of a new species, variation, or mutation. Survival is indeed tied to the ability to create new niches. Not all interdisciplinary work, though, results in a new niche. The speciation model, De Mey remarked (this volume), is only a loose metaphor. It does not necessarily extend to all levels of aggregation in science. The biological counterpart is an ecosystem, not a single species. Yet, restricted speciations, such as De Mey's example of spatial cognition, arise.

Most scientists working across disciplinary boundaries are not attempting to achieve ontological simplification and unification (Bechtel 1986: 42–3). The redrawing of boundaries through 'ontological gerrymandering' is more typical (Woolgar and Pawluch 1984: 216; Fuller 1988: 197). Only partial spheres tend to be integrated, and convergence often means tolerance, not a change of world-view (Hübenthal 1994: 61;

Falersweany 1995: 167). In a critique of general theories, Van der Steen (1993) charges that selected case studies have been overemphasized and limits to integration minimized. 'Peripheral integration' is more common. The modern synthetic theory of evolution, for instance, does not cover all disciplines that may pertain. Their generality resides in terminology, not substantive unity. When concepts of taxis and kineses in animal orientation carry a conceptual overload, the result is 'pseudo-integration,' not unity. The concepts cannot account for a great diversity of phenomena. Encompassing theories of evolution have a loose structure. As integrative force moves outward from the core of evolutionary biology, it becomes more peripheral. When used for a heterogeneous category of processes, selection and allied concepts become diluted notions that express a limited array of analogies.

Conceding overstatements, Burian (1993) insists the evidence is representative of many cases. Coherence and integration are typically achieved in middle-range norms that play a guiding role in long-term treatment of biological problems. To recall Darden and Maull (1977), theories in biology are typically interlevel. Innovations do not tend to span whole disciplines or even major parts, but rather a few subfields (Dogan and Pahre 1990: 13). Less formal higher-order norms operate at a meta level or as rules of thumb. Middle-range theories are not wide-ranging, but they are not mere summaries of data either. They are midway between extremes. Schaffner cites two examples. Neurosciences and biological theories are interlevel prototypes that embody causal sequences; they are related through strong analogies. Interlevel models are levels of aggregation; they contain component parts that are often specific in intermingled organ, cellular, and biochemical terms (Schaffner 1993: 321).

The norm of unification has value. It improves the content of biological knowledge and offers greater coherence of description and explanation. The specificity of cases, though, means that different terminologies do not map easily onto each other and may yield contradictions. Nonetheless, they overlap in regard to entities, process, or mechanisms. Significant change in disciplinary relations may take the form of a progressive blurring and amalgamating of distinctions between mechanisms and generalizations.

In sum, local sites and interlevel integration are prominent features of interdisciplinary science. 'The task of interdisciplinary research,' Hübenthal cautions, 'is not to be solved with a global interdisciplinary theory that cannot supply concrete directives for subject-overlapping research on a specific topic. It must be pursued within individual sciences in daily usage' (1994: 55, 57). The level at which bridging or integrating is attempted affects the kinds of problems that arise (Bechtel 1986: 7). Generalizations must be supplemented with details of specific connections and more finely structured elements. The applicability of integrationist ideals, the value of pursuing them, and their consequences depend on a variety of local historical circumstances, including the power of available techniques, the character of conceptual contacts between pertinent disciplines, and current opportunities. In short, generality and particularity coexist.

Landscaping Knowledge

Over the course of this century, metaphors of knowledge have shifted from the static logic of a foundation and a structure to the dynamic properties of a network, a web, a system, and a field. Perceptions of academic reality, though, are still shaped by older forms and images. Simplified views of the complex university only add to the problem of operational realties that outrun old expectations, especially older definitions that depict one part or function of the university as its 'essence' or 'essential mission' (Clark 1995: 154). Repeating the same metaphors, Goldman (1995) cautions, impedes understanding of new knowledge and relationships. Even the metaphor of levels, so pervasive in science, presumes a hierarchy and a foundational logic at odds with images of free-floating constructions and non-linear, non-vertical perspectives that are multidimensional and multidirectional. A wider range of physical and topological or architectural metaphors describes relations of elements that make up innovations and their contexts – dimensions, joints, manifolds, points of connection, boundedness, overlaps, interconnections, interpenetrations, breaks, cracks, and handles (Clark 1995: 222–3).

Bechtel defines interdisciplinarity as an 'ongoing process for discovery,' not an attempt to systematize what is known (1986: 43–4). The real benefit, Salter and Hearn (1996) contend, is not necessarily in subject matter or new journals and publications. Interdisciplinarity is a set of dynamic forces for rejuvenation and regeneration, pressures for change, and the capacity for responsiveness. It is the necessary 'churn' in the system. Interdisciplinarity entails knowledge negotiation and new meanings, not one more stage in 'normal' science. There is a danger, though, in perceiving interdisciplinarity and innovation at the single moment of inception, as isolated events. They continue throughout the circulation, diffusion, elaboration, revision, modification, and appropriation of new ideas, and their incorporation into intellectual and social life. Social practices and their material bases generate openings for ideas that lead to development of newer practices that help, in turn, to institutionalize new ideas (Goldman 1995: 212).

Interdisciplinary cognition, Paulson (1991) proposed, lies in the attempt to construct meaning out of what initially seems to be noise. The idea of self-organization from noise emanates from information theory. When there is noise in an electronic channel during transmission, the information received is diminished by the ambiguity of the message. The message received is neither pure nor simple. Importing terms and concepts from other disciplines creates a kind of noise in the knowledge system. Perceived as unwanted noise in one context, variety and interference become information in a new or reorganized context. New meaning is constructed out of what first appears to be noise as the exchange of codes and information across boundaries is occurring, whether the activity is borrowing, solving technical problems, developing hybrid interests, or disrupting and restructuring traditional practices.

The metaphor of noise acknowledges the roles of disequilibrium and complexity. The subtle subversion of meanings introduced by the improper creates a space for mobile, shifting meanings, the exchange of meaning among different discourses, and new positions and practices (deCerteau 1984; cited in Bono 1995: 132). The starting point of interdisciplinarity, Roland Barthes declared, is an 'unease in classification.' From there a 'certain mutation' may be detected. It must not be overestimated, however: 'It is more in the nature of an epistemological slide than a break' (Barthes 1977: 155). Noise, Paulson explains, is a signal: 'What appears to be a perturbation in a given system, turns out to be the intersection of a new system with the first.' What is extra-systemic at one level may be an index of another level, another system with a new kind of coding (1991: 44, 49). Interdisciplinarity implies idiosyncrasy, but novel work can create a new common wisdom (Bazerman 1995: 195).

The analogy to postmodernism is striking. Heightened boundary crossing in knowledge is paralleled by widespread crossing of national, political, and cultural boundaries. A central feature of this process is reversal of the differentiating, classificatory dynamic of modernity and increasing hybridization of cultural categories, identities, and previous certainties. New forms of interdependence and cooperation call attention to a worldwide changing cultural configuration that places all cultural categories and boundaries at risk (Bernstein 1991; Muller and Taylor 1995: 258). Contests of legitimacy over jurisdiction, systems of demarcation, and regulative and sanctioning mechanisms continue. Yet, boundaries are characterized by ongoing tensions of permanency and passage. Intersecting pressures created by new corporate research models have not simply blurred organizational boundaries – they represent a new phase in the relation between knowledge and society. Turpin and Hill (1995) acknowledge the link between post-modernism and the apparent paradox of a global sea change coexisting with heightened local conditions of knowledge production and personal relations. In this instance, relational and articulational dimensions, border-crossing, seepage, and hybridity take on heightened roles. If framed only in terms of instrumental discourse, however, the critical function of epistemological discourse is absent.

The implications for knowledge studies are striking. Once framed by questions of epistemology, knowledge studies today are defined by intersections of individuals from an eclectic assortment of fields such as philosophy, sociology, education, English, cultural studies, political science, economics, and anthropology (Pahre 1995: 242). Some approaches, Harvey Goldman explains, denote a deep structure of intellectual or linguistic enterprise, such as episteme, discursive formation, mental equipment, paradigm, disciplinary matrix, generative grammar, and language games. Other approaches illuminate the structure of practices, institutions, and relations, such as field, complex of power/knowledge, regime of truth, invisible college, exemplar, network, system, and grid. Others yet point to a broad social and collective mental foundation of mentalité, habitus, cultural unconscious, hegemony, and culture. These and other tools are being brought to bear on a fuller conception of interests, histories, structures, and relations that account for production of knowledge that goes beyond reproduction of the conventional (Goldman 1995: 213, 221).

The next step in interdisciplinary science is already under way. Burian forsees the next decade of work in biology addressing difficult questions regarding the matching of tools, organisms, institutions, and conceptual frameworks required to solve major problems (Burian 1993: 311). The task for philosophers of science is to specify conditions that promote integration and to formulate criteria to evaluate integrations (Ven der Steen 1993: 222–3). There is no universal interdisciplinary language. Even powerful cross-fertilizing languages, such as mathematics and general systems, have limits. Interdisciplinary work requires the creation of what Hollingsworth and Hollingsworth (this volume) call 'horizontal communication' within an 'interdisciplinary/integrated culture.' A working language emerges through the negotiation of meanings. The dynamics of negotiation are captured in Hollingsworth and Hollingsworth's notion of triangulating depth, diversity, and tensions, and in Rainer Bromme's triangulation of diversity, difference, and tension (this volume). The resulting 'common ground' is not an artificial unity that eschews differences. The boundary between disciplinarity and interdisciplinary 'flows,' Bromme's image, depends on difference.

Greater interest in the exigencies that move people to traverse disciplinary domains and practices does not mean that calls for a general practice of interdisciplinarity will cease. The two are not necessarily contradictory. A general crisis could be expressed in what appears to be many local crises (Bazerman 1995: 193). Declarations by scientists about the desirability of interdisciplinary research, Weingart cautions in this volume, can no more be taken at face value than normative appeals will change scientists' attitudes. Neither can knee-jerk dismissals. One of Scerri's interviewees proclaimed there is no 'real interdis-ciplinarity.' It is a bogus argument. Proponents overstate the extent, opponents understate it.