

Conceptual Foundations of Phonology as a Laboratory Science¹

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1. INTRODUCTION

The term ‘laboratory phonology’ was invented more than a decade ago as the name of an interdisciplinary conference series, and all three of us have co-organized laboratory phonology conferences. Since then, the term has come into use not only for the conference series itself, but for the research activities exemplified by work presented there. In this paper, we give our own perspective on how research in laboratory phonology has shaped our understanding of phonological theory and of the relationship of phonological theory to empirical data.

Research activities within laboratory phonology involve the cooperation of people who may disagree about phonological theory, but who share a concern for strengthening the scientific foundations of phonology through improved methodology, explicit modeling, and cumulation of results. These goals, we would argue, all reflect the belief that phonology is one of the natural sciences, and that all of language, including language-specific characteristics and sociolinguistic variation, is part of the natural world. In what follows, we explore the ramifications of this position for the relationship of data and methods to phonological theory; for the denotations of entities in that theory; and for our understanding of Universal Grammar and linguistic competence.

2. WHO AND WHAT

The Conference in Laboratory Phonology series was launched at the Ohio State University in 1987 by Beckman and Kingston to provide a forum for people doing laboratory research in phonology. The proceedings of this meeting also inaugurated a book series from Cambridge University Press. Subsequent conferences were hosted by University of Edinburgh, University of California at Los Angeles, Oxford University, Northwestern University, and the University of York (UK), with the seventh conference to be held in 2000 at the University of Nijmegen. The conference has attracted people from very diverse intellectual backgrounds. American nonlinear phonology has been well represented by scholars such as Clements, Hayes, Leben, McCarthy, Selkirk, Steriade, and Vogel; Articulatory Phonology by Browman, Fowler, Goldstein, and Zsiga; Declarative Phonology by Broe, Coleman, Local, and Scobbie, and Optimality Theory by Steriade and Gussenhoven. Many of the participants — such as Cutler, Kohler, Ladefoged, Marslen-Wilson, Munhall, Nolan, Shattuck-Hufnagel, Stevens, and Werker — are not associated with any particular school of phonological theory. About two thirds of the participants are phonologists or phoneticians affiliated with linguistics departments. Most of the rest are affiliated with departments of psychology, electrical engineering and computer science, or communication sciences and disorders.

Despite the diverse backgrounds of the participants, a number of common goals and values have been reflected in the papers delivered at the conference. Papers have either reported experimental research on the mental representation of sound structure and its physical correlates, or else built on such research in a substantial way. The goal of such research is to address issues in phonology which are not effectively addressed using traditional types of data (namely: field transcriptions, informant judgments, and symbolic records of morphological alternations). The research presented at the meeting has drawn heavily on results and methodological advances in related sciences, including psychology, life sciences, and acoustics.

3. LINGUISTICS AND THE SCIENTIFIC STUDY OF LANGUAGE

Laboratory phonologists are scientists who use laboratory methods to discover and explain the sound structure of human language. Their philosophical stance is generally that of researchers in the mature sciences, such as biology and physics. Specifically, most laboratory phonologists have abandoned the doctrine of dualism. They view language as a phenomenon of nature, albeit a particularly complex one. Language as a cognitive system

imputed to individuals is thus to be explained in terms of general facts about the physical world (such as the fact that the resonances of an acoustic tube are determined by its shape); in terms of specific capabilities of the human species which arose through evolution (including both gross anatomical properties, such as the position of the larynx, and neurophysiological properties); and in terms of the interactions of the organism with its environment during development. In this view, social interaction is subsumed under the same umbrella, as a phenomenon of nature. Human societies, like all other mammalian social groups, are natural collections of individuals. And social interactions form part of the natural environment for the species, which influence individual members through natural (physical) mechanisms, such as propagation of sound and light waves, physical contact, and pheromones.

On the basis of this viewpoint, we reject the traditional distinction between knowledge of natural phenomena and knowledge of social conventions (with social conventions differing from natural phenomena in being arbitrary).² We hold that social conventions ARE natural phenomena, so that there is no inconsistency in viewing language both as a social phenomenon and as a cognitive capability of the human species which is instantiated in individuals. Though social conventions vary considerably and surprisingly, so do the phenomena produced by many other physical systems, such as the weather. This does not mean that the variation is unbounded or that no relevant scientific laws can ever be formulated. Tools for building theories of such systems include statistics and stability theory, and we believe that these tools will play a significant role in our future theories of language.

Laboratory phonologists tend to believe that the scientific study of language both should and can progress. One reflection of this expectation is the long citation times for key works, such as Chiba and Kajiyama (1941) for perturbation analysis of vowel formants, and Fant (1960) for the linear acoustic theory of speech production. The idea that science progresses is very controversial in the philosophical literature. We would like to touch on this controversy because the relativists' position in it has been so influential amongst the leaders of generative linguistics. Much work by relativists, such as Kuhn (1962) and Feyerabend (1975), leaves the impression that shifts in scientific thinking are arbitrary outcomes of individual taste and power struggles within the scientific community. Espousal of Kuhnian thought has done much to glamorize conceptual upheavals within linguistics. Pullum (1991) acidly documents a climate in which authors of research papers take no responsibility for either facts or theoretical claims presented in prior work. This situation often provokes indignation amongst phoneticians and psycholinguists, and can lead them to moralistic invocations of work by positivists, such as Carnap, who espouse the traditional ideal of progress in science. However, as Laudan (1996) points out, positivists tend to define progress so narrowly that even the most successful sciences fail to live up to their definitions. For example, the suggestion (by Putnam, 1978, and others) that real science is strictly cumulative, with each new framework subsuming all of the successes of its predecessors, would leave humankind with no extant example of a real science, not even physics or chemistry. Naive positivism is not a useful guide to productive scientific activity.

Our stance on this issue is a highly pragmatic one. Over its history, science has proved successful. A comparison between the state of scientific knowledge now and its state when it was closer to its beginnings (for example, at the time of Roger Bacon in the 13th century) reveals overall progress, in terms of the diversity of phenomena for which predictive theories exist, the detail and accuracy of the predictions, and the contributions of scientific knowledge to people's ability to thrive in their environment. Kuhn fails to explain the successes of science, by failing to explain how even two people — let alone humankind in general — can come to an agreement on matters such as the theory of electro-magnetism or the germ theory of disease. Recent work in the positivist tradition, such as Quine (1954/1966; 1960; 1961), also fails to account for the evident progress in science, through overemphasis on the logical underdetermination of scientific theories and the elusiveness of the ultimate truth. Therefore, we do not subscribe to either the relativist or the positivist position on science. We are more

impressed by more recent work in philosophy of science, such as Hull (1988, 1989) and Laudan (1983, 1996), which treats science as an adaptive human activity. Both of these works reflect intimate familiarity with the everyday conduct of science, and seek to elucidate how scientists actually do cooperate to advance the state of human knowledge despite the logical and social impediments discussed by the relativists and the positivists.

Some of the hallmarks of successful scientific communities which Hull and Laudan discuss are particularly relevant to the laboratory phonology community. One is cooperation within a group of critical size and diversity. Like biological populations, scientific communities atrophy and ultimately fail if they are too small or too homogeneous. Achieving such critical size and diversity was a primary goal of the founders of the Laboratory Phonology conference series. A second hallmark of a successful community is maintenance of a common vocabulary — which can be used by opposing parties in an argument — even at the expense of gradual drift in both the meanings of technical terms and the empirical domain under discussion. As documented in Hull (1989), this was one of the chief reasons for the success of Darwinism over creationism. A third is the existence of ‘auxiliary theories’ — such as theories about how particular instruments work — which are also shared amongst people with different theories or research priorities. The laboratory phonology community has benefited from a plethora of auxiliary theories — covering matters from acoustic transmission to psychological distance, in areas from statistics and probability to physiology and neuroscience — which have permitted substantial agreement on the validity of experimental results and constructive debate about the relationship of these results to theory. Lastly, successful scientific communities recognize the value of mathematical formulation and use mathematics to make precise theoretical predictions. We develop this idea further in the next section.

4. FORMALISM AND MODELING

Formalizing theories mathematically is a crucial step in making them predictive. The field of mathematics is generally divided into two major areas, discrete mathematics and continuous mathematics. Discrete mathematics includes logic and formal language theory. Continuous mathematics includes calculus. When generative linguistics was launched by Noam Chomsky and his mentor Zellig Harris, it relied exclusively on discrete mathematics. Chomsky is in fact responsible for important results in formal language theory, which are widely applied in computer science. Much of his early work makes natural language seem like computer languages, and poses for natural language the type of questions which arise in designing programming languages, compilers, and other discrete algorithms. The identification of formal linguistics with linguistics formalized by discrete mathematics persists to the present day.

We believe that the identification of formalism with discrete formalism is erroneous and is deeply misleading in its influence on research strategy. The laboratory phonology community uses both discrete mathematics and continuous mathematics. It continually debates and evaluates what type of formalism is most apt and incisive for what types of linguistic phenomena. One reason for this stance is the strong ties of the community to research in speech synthesis. About one third of the authors of papers in the Laboratory Phonology books have worked on speech synthesis systems, and many continue to be active in speech synthesis research. The first speech synthesis was made possible by simultaneous breakthroughs in the acoustic theory of speech production and in the application of formal language theory to phonological description. The acoustic theory of speech production uses Laplace transforms (which belong to continuous mathematics) to model vocal tract transfer functions; Fant (1959) is noteworthy for its elegant discussion of how this particular tool supports deep understanding of the physical situation. The first comprehensive formalization of phonology — using discrete mathematics — is due to Chomsky and Halle (1968), with key concepts already developed in Hockett (1953, 1954) and Chomsky (1964). These two ingredients — a well-behaved characterization of the speech signal and a comprehensive and

mathematically coherent system for encoding the phonology — are prerequisites for any viable synthesis system.

Although the synthesis systems just sketched involve a discrete phonology and a continuous acoustic phonetics, subsequent and related work which we review below has substantially eroded this division of labor. The relevance of continuous mathematical tools for the classical question of phonology ('What is a possible language sound system?') is shown by work on phonetic grounding of phonology, by work on the role of statistical knowledge in adult phonological competence, and by work on the development of phonology in the child. There are thus both continuous and discrete aspects to the problems presented by language sound structure, even at the level of phonotactics and morphophonological alternations. We do not understand why most work in generative phonology declines to employ the tools of continuous mathematics.

It is widely recognized in the history and philosophy of science that formalization not only tests and consolidates theories; it also drives empirical exploration. Work on the articulatory and acoustic nature of phonological categories uses a methodology adopted from physics, in which the behavior of the basic equations of the theory is explored with respect to issues such as stability, linearity, invertability, and effects of boundary conditions. This exploration guides the selection of cases to be examined instrumentally. Cases in point include studies of the stability of vowel targets under natural and artificial perturbations (e.g., Lindblom, 1963; Lindblom et al., 1979; Maeda, 1991; Edwards, 1992); explorations of nonlinearities in the articulatory-to-acoustics mapping (e.g., Stevens 1989, Keating 1984, Kingston 1990); and explorations of the invertability of this mapping (e.g., Atal et al. 1978; Badin et al., 1995; Loevenbruck et al., 1999). The collected fruits of this research strategy have supported every one of the many Laboratory Phonology papers which interpret acoustic data or which used speech synthesis to create controlled stimuli.

There has been a similar give-and-take between formal models of the categorical aspects of sound structure, and empirical investigation. Almost all synthesis systems up through the 1980's used the phonological formalization of Chomsky and Halle (1968) approach, because it was the only fully formalized model available. Its very exactness made it possible to identify the scientific penalties for ignoring nonlocal aspects of phonological representation. In the decade after it appeared, evidence about nonlocal dependencies was provided both by theoretical phonologists working on stress, tone, vowel harmony, and nonconcatenative morphology (such as Goldsmith, 1976; Liberman and Prince, 1977; McCarthy, 1985) and by experimentalists working on syllable structure, fundamental frequency, and duration (such as 't Hart and Cohen, 1973; Bruce, 1977; Harris, 1978; Bell and Hooper, 1978; Fujimura and Lovins, 1977; Klatt, 1976). This body of evidence in the end led to formal models of 'nonlinear phonology'. Although the formalization of nonlinear phonology by linguists was initially sketchy, limitations of the SPE approach for morphophonemic parsing and for synthesizing reflexes of prosodic structure and intonation drove efforts for more complete formalization. A formalization of nonlinear intonational phonology, with related fundamental frequency synthesis algorithms, was published in Pierrehumbert and Beckman (1988). Additional work on formalizing nonlinear phonology for purposes of segmental synthesis was carried out independently by Hertz (1990, 1991) and by Coleman and Local (Coleman 1992; Coleman and Local 1992; Coleman 1994). Other work on formalizing nonlinear phonology includes Hoeksema (1985), Bird and Klein (1990), Kornai (1991), Coleman (1998), Scobbie (1991), and Bird (1995).

5. METHODS, FRAMEWORKS, AND ISSUES

The recent history of phonological theory has been marked by the invention of many frameworks, such as Lexical Phonology, Declarative Phonology, Government Phonology, and Optimality Theory. Frameworks are packages of assumptions about the fundamental nature of language, and the research strategy for empirical investigation is driven by top-down reasoning about the consequences of the framework. Frameworks correspond to

paradigms in the Kuhnian view of science. One framework can replace another via a paradigm shift, if incorporating responses to successive empirical findings makes the prior framework so elaborate and arcane that a competitor becomes more widely attractive.

In contrast, laboratory phonology is not a framework. As we pointed out in Section 2, it is a coalition amongst groups of people, with some working in one or another of the various current frameworks, and others working in no phonological framework at all. As we mentioned in Section 3, the Kuhnian view of science is not prevalent among the members of the coalition as a whole, and our own view is that the Kuhnian attitude is at best an unhelpful guide to the conduct of laboratory work. Here we would like to develop some further consequences of this fact for the relationship among methodology, issues and theories.

When a phonology student first embarks on experimental research, one of the most important lessons to assimilate is the need to operate both below and above the level of abstraction of a typical linguistic framework. On the one hand, the descriptive issues are extremely minute compared to those usually discussed by phonologists working in a particular framework. For example, a phonologist might begin with the observation that English, German, and Polish all exhibit a contrast between voiced and voiceless stops. In a laboratory experiment, the exact extent of the voicing, its statistical variation, and the dependence of these factors on structural position would all be at issue, as may be seen from the example of Keating (1984). An observation made in a few minutes in the field might suggest a hypothesis whose evaluation requires months of work in the laboratory.

On the other hand, almost any substantial fragment of a phonological framework turns out to be too specific and too rich in assumptions to be experimentally tested as such. For example, Feature Geometry packages together at least four assumptions which could in principle stand or fall separately (see Clements 1985; McCarthy 1988). The articulatory characterization, rather than the acoustic or aerodynamic characterization, is implied to be primary. The inventory of relevant articulatory features and feature combinations is held to be finite and universal. The features are held to be organized into a tree (rather than a directed graph or a lattice). Subclassification and markedness are related to a single underlying mechanism. A single suite of laboratory experiments on features could not test all of these specific claims simultaneously. To develop a research program in the general area of Feature Geometry, the laboratory researcher must instead identify and unbundle the framework's leading ideas.

Similarly, particular proposals about metrical or autosegmental theory, such as Goldsmith (1976), Liberman and Prince (1977), Selkirk (1984), Halle and Vergnaud (1987), and Hayes (1995), all package together many assumptions about the representation of phonological patterns and about the way that phonological representations interact in determining individual outcomes. No one has run experiments designed to test any of these frameworks; it would not be possible to do so. However, a comparison of these five frameworks brings out the fact that they make related, but not identical, claims about the kinds of nonlocal interactions that are available in natural languages. The interplay of local and nonlocal factors in speech production and perception is very much amenable to experimental investigation, as shown (for example) by Beckman, Edwards and Fletcher (1992); Pierrehumbert and Talkin (1992), Choi (1995), and Smith (1995) for production; and Miller and Dexter (1988), Johnson (1990), Huffman (1991), and Ladd et al. (1994) for perception.

Given the rapid pace of change in theoretical linguistics, and the great expense and labor of laboratory research, the shrewd experimentalist will not devote an experiment to even the most central claim of any single linguistic framework. Instead, he or she will look for a topic which represents a source of tension across many frameworks, or which has remained unsolved by traditional methods over many decades.

One class of topics which lend themselves to advances using experimentation are theoretical issues. In using this term, we do not mean issues which arise as corollaries of the main assumptions of individual frameworks. Rather, we mean the issues which can be formulated after a deep and sustained effort to compare different frameworks. Issues at this level of abstraction which have been tackled using laboratory methods include: the interaction

of local and nonlocal aspects of the cognitive representation of sound structure (e.g., Bruce, 1977, 1990; Kubozono, 1992; Coleman, 1994; also the references cited two paragraphs ago); the coherence and independence of putative levels of representation (e.g. Lindblom, 1963; Harris, 1978, Rialland, 1994); the extent and objective consequences of underspecification (e.g., Odden, 1992; Pierrehumbert & Beckman, 1988; Keating, 1990a; Choi, 1995); the relation of qualitative and quantitative aspects of phonological competence (e.g., Keating, 1984, 1990b; Pierrehumbert and Beckman, 1988). In fact, easily half of the papers in the *Laboratory Phonology* books have some connection to the issues just listed.

Methodological advances can be just as important as theoretical ones in the progress of science. Established sciences use diverse methods. As pointed out in Laudan (1983), people who disagree theoretically may still share methods. These shared methods are one reason why research paradigms in the established sciences are not as incommensurate as Kuhn claims, and they contribute to the cohesion of research communities which are diverse enough for long-term vitality. In addition, theories which unify results from many methods are more robust and more predictive, on the average, than those based on fewer methods, much as the five-prong chair base is more stable than the three-legged chair, which is in turn more stable than the one-legged chair. Overcoming the confining reliance of phonological research on the single method of internal reconstruction has been a high priority goal for many laboratory phonologists. Research in this field uses an extreme diversity of methods, including: acoustic analysis of speech productions under various elicitation conditions in the field or the laboratory; judgments and reaction times obtained during identification, discrimination, or prototypicality ratings of natural or synthetic stimuli; direct measurements of articulator movements using electropalatography, x-ray microbeams and other recently developed articulatory records; measurements of brain activity; statistical analysis of lexicons; longitudinal analysis of speech produced by children with speech disorders; novel word games; induction of speech errors; priming patterns in lexical decision and other psycholinguistic tasks; patterns of attention in babies.

Related to the idea of a method is the idea of an auxiliary theory. Auxiliary theories are established theories, whether broad or modest in scope, to which debate at the forefront of research can uncontroversially refer. Theories of how particular instruments work provide examples. Probably the single most important auxiliary theory in our field is the acoustic theory of speech production. This theory relates critical aspects of speech articulation to eigenvalues of the vocal tract, which can in turn be related to peaks in the spectrum. It is thanks to this theory that two researchers can compare the formant values of the vowels in their experiments, agreeing on observations such as ‘The /i/ in Swedish is more peripheral in the vowel space than its closest counterpart in English.’ Such agreement can in turn provide the basis for experimental work directed towards more abstract issues. For example, it provides the basis for current research on the role of general learning mechanisms in phonological acquisition (Kuhl et al., 1992; Guenther and Gjaja, 1996; Lotto et al., 2000; Lacerda, in press).

In connection with the goals of the present volume, we would like to point out that auxiliary theories help to provide denotations for phonological terms, along the lines suggested by Kripke (1972) and Putnam (1973) for scientific vocabulary in general. Putnam takes up the issue of the reference of scientific terms in common use, such as ‘electricity’ or ‘vaccination’. As he points out, ordinary people do not in any deep sense understand the reference of these terms; however, the denotations are sufficiently established by access to experts who do have the requisite knowledge that they can also be everyday lay terms. In a similar sense, the denotation of the word ‘vowel’ is provided by the acoustic theory of speech production, and related work on vowel perception and the like. The denotation of the term ‘articulatory gesture’ is provided by the scientific community's present expertise in measuring articulatory events and relating them in a rigorously predictive way to their acoustic consequences. Insofar as we know the denotation of the term ‘syllable’, it is provided by work such as Bell and Hooper (1978), Derwing (1992), Treiman et al. (2000).

We would also like to adopt from the medical world the concept of a syndrome, defined (as in the OED) as ‘a characteristic combination of opinions, behaviors, features, social factors’. In the history of the life sciences, discovery of a medical syndrome has repeatedly anticipated and shaped scientific theory by perspicuously uniting facts which point towards deeper conclusions. For example, the documentation of the Broca’s and Wernicke’s aphasia syndromes led the way towards present neurolinguistic theory.

One of the major contributions of laboratory phonology to the field of phonology has been the careful documentation of syndromes in language sound structure. The diverse and opportunistic methodology of this community has permitted its documentation of syndromes to be both novel and thorough. One type of contribution is that a more accurate documentation of a previously reported syndrome can render moot a theoretical dispute by showing that the supposed facts driving the dispute are not true. For example, armchair impressions about the applicability of the English Rhythm Rule fueled disputes in the various frameworks of metrical theory, such as Liberman and Prince (1977) and Hayes (1984). However, these impressions have been superseded by far more detailed instrumental studies, such as Shattuck-Hufnagel et al. (1994) and Grabe and Warren (1995). These studies both demonstrate that the Rhythm Rule applies in more contexts than reported in the previous phonological literature, and also suggest that the classic cases in English are as much a matter of accent placement as of stress or rhythm as such. This careful documentation of the syndrome at once vitiated Cooper and Eady’s (1986) earlier skepticism and allowed laboratory phonologists to isolate those cases in which stress shift might be more purely a matter of rhythm (e.g., Harrington et al., 1998).

Documenting a new syndrome can raise new theoretical issues. For example, Pierrehumbert (1994a), Frisch (2000), Treiman et al. (2000), Beckman and Edwards (2000) and Hay, Pierrehumbert, and Beckman (in press), all document a syndrome relating lexical statistics, well-formedness judgments (which are opinions), and behaviors on various speech tasks. As discussed in Dell (2000), this syndrome reveals the limitations of an entire class of phonological frameworks, including all standard generative models.

A syndrome which has considerable theoretical importance at present time is that of the semi-categorical process. Repeatedly, experiments have shown that facultative or phrase-level processes which are transcribed as categorical in the traditional literature, actually require continuous mathematics if examined in detail. Browman and Goldstein (1990a) discuss examples in which putatively categorical fast speech rules are shown through x-ray microbeam studies to be cases of gradient gestural overlap. Both Silverman and Pierrehumbert (1990) and Beckman et al. (1992) show that lengthening and tonal realignment at prosodic boundaries is better handled by a quantitative description than by the phonological beat addition rules proposed in Selkirk (1984). Zsiga (1995) used electropalatographic data to show that the palatalization of /s/ in sequences such as miss you is not categorical, thereby contrasting with the categorical alternation found in pairs such as confess, confession. Silva (1992) and Jun (1994) use acoustic and electroglottographic data to evaluate a post-lexical rule of lenis stop voicing proposed in Cho (1990). They show that apparent voicing at phrase-internal word edges is an artifact of the interaction of independent phonetic factors, which govern the precise timing of the laryngeal features in general.

One way of interpreting such results is as an indication that phonology proper covers less, and phonetic implementation covers more, than traditional approaches supposed. Papers from the first few Laboratory Phonology conferences suggest an implicit consensus in favor of this interpretation. More recently, however, many laboratory phonologists (including us) have begun to interpret these results differently. The steady encroachment of gradience into the traditional domain of phonology raises a number of more fundamental issues: how gradient processes are represented the mind, how they relate to less gradient processes, whether any processes are truly categorical, and how categoriality — insofar as it exists — actually originates. We take up these issues in the next section.

5. CATEGORIALITY

Most, though not all, standard phonological frameworks presuppose a modular decomposition of phonology and phonetics in which one module (phonology) is categorical and free of gradient cumulative effects. Thus it is to be formalized using discrete mathematics. The other module (phonetics) has continuous variation, it exhibits gradient cumulative effects, and it is to be formalized using continuous mathematics. The two modules are related by a discrete-to continuous mapping called the ‘phonetic implementation rules’. Pierrehumbert and Beckman (1988) provide a very thorough development of this modular framework for the case of tone and intonation. Pierrehumbert (1994b), in a subsequent reassessment of her earlier stance, assigns it the acronym MESM (Modified Extended Standard Modularization).³

The MESMic approach is adopted, in different ways, in at least two papers in the present volume (those by Meyers and by Harris and Lindsay), as well as in Bromberger’s earlier (1992) paper. Meyers endorses MESM and seeks to develop its typological consequences. Bromberger (1992) takes the categorical entities of phonology to be mental entities, and the continuous spatio-temporal events of phonetics to be in the world. Phonological entities thus denote classes of entities in the world, in the same way that words (such as ‘dog’) denote classes of physical objects in the world in the extensional treatments of semantics developed by philosophers such as Tarski and Quine. Other work developing the denotational relationship of phonology to phonetics includes Pierrehumbert (1990) and Coleman (1998). When embedded in this approach, phonetic implementation rules represent an explicit mathematical model of reference, within the limited domain of language sound structure, by encoding the expert scientific understanding of the denotations of the elements of the description. Phonetic implementation rules can seem complicated and elaborate, and many speech researchers have held the hope that the right conceptual framework would render the mapping between phonology and phonetics direct and transparent. But this hope, we would argue, is not well-founded. Although the relationship between a sound percept and a phonological category may seem very direct to an individual listener, it still presents to the scientist a dazzling degree of complexity and abstractness. It requires powerful mathematical tools to formalize this relationship.

To appreciate the problems with the assumption that it is possible to define a ‘direct mapping’ which is somehow simpler or less abstract than ‘phonetic implementation’, consider a layman’s versus a scientist’s understanding of the basic terms of color perception. The percept of ‘red’ or ‘green’ may appear intuitively to be ‘direct’. One might imagine that such color terms correspond directly to particular light spectra. However, detailed experimental studies show that the correspondence is mediated by the exact frequency response of the cone cells in the retina, by the behavior of the optical nerve in integrating responses from cone cells of different types, and by sophisticated higher-level cortical processing which evolved to permit constancy of color percepts under varying conditions of illumination (Thompson et al., 1992). The color terms of specific languages in turn involve a learned categorization of this perceptual space; just as with vowel inventories, this category system is neither arbitrary nor universal (Berlin and Kay, 1991; Lucy, 1996). A complete scientific model of the meanings of color terms would need to describe the interaction of these factors. The intuitive ‘directness’ of our perceptions does not relate to any particular simplicity in the scientific theory, but rather to the unconscious and automatic character of the neural processing involved.

The modularization of phonetics and phonology that was still assumed by most laboratory phonologists up through the early 1990’s is no longer universally accepted, and we ourselves believe that the cutting edge of research has moved beyond it. A series of problems with MESM arises because the two types of representations it employs appear to be completely disparate. The approach thus fails to provide leverage on central problems of the theory, notably those relating to the phonetic grounding of phonology. It has been accepted since Jakobson, Fant and Halle (1952) that phonological categories are phonetically grounded.

However, every effort to detail this grounding comes up against an apparent paradox, arising from the fact that phonological categories are at once natural and language specific.

Phonological categories are natural in the sense that the actual phonetic denotation of each category shapes its patterning in the sound system. For example, as exhaustively documented by Steriade (1993) and Flemming (1995), neutralization of distinctive prenasalization or distinctive voicing typologically affects stops in unreleased positions, where bursts are not available as cues to the nasal contour or the voicing contrast. That is, the phonological rules that affect the stops (or, in a more modern formulation, the positional licensing constraints for the stops) reflect their actual phonetic character. Similarly, high vowels tend to participate in alternations with glides whereas low vowels do not. High vowels have a closer, or more consonant-like, articulation than low vowels and this phonetic property is what exposes them to being contextually interpreted as consonants.

The phonological categories are also natural in the sense that physical nonlinearities — in both articulation and acoustics — have the result that phonetics is already quasi-categorical. These nonlinearities appear to be exploited as the foundations of phonemic inventories. For specific proposals of this nature, see Stevens (1972, 1989), Browman and Goldstein (1990b), and Kingston and Diehl (1994).

But phonological categories are also language-specific. Despite the similarities of the vocal apparatus across members of the species — and the ability of people of any genetic background to acquire any language — phoneme inventories are different in different languages. It is easy to think of languages which simultaneously display unusual phonemes while lacking certain typologically more typical phonemes. For example, Arabic displays an unusual series of pharyngeal consonants but lacks a /p/. More theoretically trenchant, however, is the fact that analogous phonemes can have different phonological characterizations in different languages. For example, the phoneme /h/ patterns with obstruents in some languages (such as Japanese, where it alternates with geminate /p/ and with /b/), but with sonorants in others. Some languages (such as Taiwanese) treat /l/ as a stop, whereas others (such as English) treat it as a continuant.

Experimental studies also show that there are no two languages in which the implementation of analogous phonemes is exactly the same. When examined in sufficient detail, even the most common and stereotypical phonetic processes are found to differ in their extent, in their timing, and in their segmental and prosodic conditioning.⁴ For example, Bradlow (1995) shows that the precise location of Spanish vowels in the acoustic space is different from that for English vowels, even for typologically preferred point vowels. Laeuffer (1992) shows that French and English differ in the extent of vowel lengthening before voiced stops (or vowel shortening before voiceless stops). Moreover, though the interaction of the effect with prosodic position is broadly similar for the two languages, there are also differences in detail relating to the allophonic treatment of syllable-final obstruents. Zsiga (submitted) demonstrates a difference between Russian and English in the extent of subcategorical palatal coarticulation across word boundaries. Caramazza and Yeni-Komshian (1974) demonstrate that Quebecois and European French differ not only in the well-known assibilation of /d/ and /t/ before high vowels, but also in the modal VOT values of all voiced versus voiceless stops, including the dentals before non-high vowels. Hyman (to appear) discusses the strong tendency for a nasal to induce voicing of a following oral stop closure in nasal contour segments and in nasal-stop sequences (cf. Maddieson & Ladefoged, 1993), but shows that, despite this tendency, some languages instead devoice stops after nasals.

Results such as these make it impossible to equate phonological inventories across languages; there is no known case of two corresponding phonemes in two languages having fully comparable denotations. Therefore phonological inventories only exhibit strong analogies. In fact, we would argue that there is no symbolic representation of sound structure whose elements can be equated across languages; the overwhelming body of experimental evidence argues against anything like Chomsky and Halle's (1968) phonological surface representation. In Chomsky and Halle (1968) and more recent work

such as Chomsky (1993), Chomsky & Lasnik (1995), and Chomsky (1998), this representation (now known as ‘PF’ for ‘Phonetic Form’) is conceived of as symbolic, universal, and supporting a uniform interface to the sensorimotor system (Chomsky, 1995, p. 21).⁵ Similar criticisms apply to the IPA if this is taken to be a technically valid level of representation in a scientific model (rather than the useful method of note-taking and indexing which it most assuredly is). The theoretical entities which can be absolutely equated across languages are the continuous dimensions of articulatory control and perceptual contrast. Languages differ in how they bundle and divide the space made available by these dimensions.

In view of such results, what is the character of the ‘implicit knowledge’ which the linguist imputes to the minds of individual speakers in order explain their productive use of language? Obviously, anything that is language particular must be learned and thus represents implicit knowledge of some kind. Since languages can differ in arbitrarily fine phonetic detail, at least some of this knowledge is intrinsically quantitative. This should not come as a shock, since learned analog representations are known to exist in any case in the area of motor control (e.g., Bailly et al., 1991; Bullock & Grossberg, 1988; Saltzman and Munhall, 1989). Although MESM asserts that the relationship of quantitative to qualitative knowledge is modular, this assertion is problematic because it forces us to draw the line somewhere between the two modules. Unfortunately, there is no place that the line can be cogently drawn. On the one hand there is increasing evidence that redundant phonetic detail figures in the lexical representations of words and morphemes (see Fougeron & Steriade, 1997, on French schwa; Bybee, 2000, on word-specific lenition rates; Frisch, 1996, on phonotactics). Thus phonology has a distinctly phonetic flavor. But, on the other hand, the detailed phonetic knowledge represents the result of learning, and therefore has a distinctly phonological flavor. Also nonlinearities in the domains of articulation, acoustics, and aerodynamics mean that even the physical speech signal already has a certain categorical nature.

In short, knowledge of sound structure appears to be spread along a continuum. Fine-grained knowledge of continuous variation tends to lie at the phonetic end. Knowledge of lexical contrasts and alternations tend to be more granular. However, the sources of categoriality cannot be understood if these tendencies are simply assumed as axiomatic in the definitions of the encapsulated models, as in MESM. A more pragmatic scientific approach is to make the factors that promote categoriality a proper object of study in their own right, without abandoning the insight that lexical contrasts and morphological alternations are more granular than phonetics alone requires. One way to do this is to view the discrete (or quasi-discrete) aspects of phonology as embedded in a continuous description, arising from cognitive processes which establish preferred regions in the continuous space and which maximize the sharpness and distinctness of these regions. That is, instead of viewing the discreteness of phonology as simply *sui generis*, we view it as a mathematical limit under the varied forces that drive discretization. The complexity of phonological categories can then be appreciated as fully as we appreciate the complexity of color perception.

Some specific factors contributing to discretization are already under active exploration. First, there is the idea that phonology prefers to exploit nonlinearities in the physical system; the nature of the preference is however controversial. Stevens (1989) proposes that languages prefer vowels whose acoustics remain stable under small changes in articulation; Lindblom and his colleagues (Liljencrants & Lindblom, 1972, Lindblom et al. 1983) hold, in contrast, that language prefer vowel systems for which minimal articulatory effort produces maximal contrasts. Similarly, Pisoni (1977) argues that the preference for voiceless stops effectively exploits psychoacoustic nonlinearities which render the stop bursts both objectively distinctive and psychologically salient; Summerfield (1981) and others, by contrast, point to boundary shifts with place of articulation, as well as to the attested integration of the VOT cue and the F1 cutback cue, as evidence for language-specific articulatory habits as the source of the discretization of the VOT continuum. (See Benkí 1998

for a recent review of these two opposing views, and Damper 1998 for new evidence on the role of psychoacoustic nonlinearities.)

Second, the use of speech sounds to contrast meanings requires that the sounds be robustly discriminable. This factor does not define any single region of the phonetic space as preferred, but it tends to push apart preferred regions in relation to each other. Results related to this factor include the finding by Johnson, Flemming, and Wright (1993) that the ‘best’ vowels are more extreme than the most typical vowels, and a substantial body of work by Lindblom and colleagues on deriving vowel inventories from considerations of contrastiveness (see Lindblom, 1992, for a summary review of successive refinements to the original ‘dispersion’ model over the last two decades).

Third, connectionist modeling demonstrates the generic tendency of neural networks to warp the parameter space that is being encoded. Guenther & Gjaja (1996) show that when a neural network is trained on steady state vowel tokens selected from Gaussian distributions centered on the average F1/F2 values for a language’s distinct vowel categories, a language-specific warping of the F1/F2 space occurs in the perceptual map even with unsupervised learning — i.e., even when the vowel categories are not provided as the output nodes in training and testing. Makashay & Johnson (1998) show that when this sort of network is trained on a more natural distribution of tokens (i.e., steady state vowels that reflect normal inter-gender variability), there is less clear convergence to vowel ‘prototypes’; however, distinct vowel categories re-emerge if F0 is included in the parameters of the space, to allow the model (in effect) to correlate inter-token variability with speaker identity. Damper & Harnad (in press) show related results for neural network modeling of VOT categories. They demonstrate that the sharp S-shaped boundary that is a hallmark of classical ‘categorical perception’ is exhibited by a broad class of connectionist models, when the model is trained on tokens that cluster around the endpoints of the continuum. However, (as Damper, 1998, shows) the input to the model must be spectra that have been passed through an auditory front-end in order for the boundary to shift with place instead of falling at the center of the continuum (as predicted for perceptual learning in general by Macmillan, Braida, & Goldberg, 1987).

Last, we may consider issues of cognitive complexity. Lexical contrasts and morphological alternations involve knowledge not of sounds alone, but of the relationship between sounds and meanings in the lexicon. As discussed in Werker and Stager (2000), children begin to master the association between wordform and lemma at about 14 months by manipulating extremely coarse-grained phonetic contrasts. This is so despite their exquisite sensitivity to speech sounds as such, and despite a pattern of response to fine phonetic detail that is already language-specific at 11 months, as demonstrated by Werker and Tees (1994), among others. Given the amount of neural circuitry which must be established to encode the relationships between wordforms and word meanings, there may be limits on the ultimate extent of phonological differentiation possible. (See Beckman and Pierrehumbert, in press, for further development of these ideas.)

6. COMPETENCE AND PERFORMANCE

In the previous section, we developed a picture of implicit knowledge of sound structure which marks a significant departure from the most phonetically sophisticated generative model, namely MESM. This picture has important consequences for the understanding of linguistic competence and the competence-performance distinction. The following quote from Chomsky (1995, p. 14) may serve to introduce our discussion of this issue:

We distinguish between Jones’s competence (knowledge and understanding) and his performance (what he does with the knowledge and understanding). The steady state constitutes Jones’s mature linguistic competence

A salient property of the steady state is that it permits infinite use of finite means, to borrow Wilhelm von Humboldt’s aphorism. A particular choice of finite means is a particular language, taking a language to be a way to speak and understand, in a

traditional formulation. Jones's competence is constituted by the particular system of finite means he has acquired.

We find much to agree with in this quotation. Language does put finite means to infinite use. To explain the diverse and productive linguistic behavior that people exhibit, we impute abstract, implicit, and synoptic knowledge of language to individuals. The ability to acquire and apply such knowledge is a hallmark of the human species. However, the concept of linguistic competence carries with it in the generative literature a number of further axiomatic assumptions to which we take strong exception.

One assumption concerns the relationship of the various types of data gathered by linguists to theories of linguistic competence. Much of the generative literature assumes that well-formedness judgments provide the most direct and revealing data about competence, with other types of data presenting difficulties of interpretation which compromise their relevance. This assumption is articulated particularly clearly in an essay by Soames (1984), who undertakes to define linguistics proper in an *a priori* fashion on the basis of the data it deals with. However, studies in the sociolinguistics and psycholinguistics literature (e.g., Labov, 1973; Bard et al, 1996) cast serious doubt on the reliability and predictiveness of well-formedness judgments. Well-formedness judgments are opinions. They are high-level meta-linguistic performances which are highly malleable. They do not represent any kind of direct tap into competence, but are rather prone to many types of artifacts, such as social expectations, experimenter bias, response bias, and under-sampling. Hence, well-formedness judgments are just one type of evidence among many, and not a particularly good type of evidence as currently used (see the constructive criticisms of Bard et al., 1996).

All data about language come from performance, and all present difficulties of interpretation relating to the nature and context of the performance. Like scientists in other fields, we must assess the weight to assign to various types of data; statistics provides one tool for making such an assessment. But no matter how we weight the data, we must acknowledge that all data ultimately originate in performance. The notion that some data represent 'mere performance' does not in itself constitute sufficient grounds for discarding data.

A second assumption involves universals. Discussion in Chomsky (1995) articulates his conception of linguistic competence in terms of a universal grammar (UG): UG provides an overarching description of what all mature human languages have in common; simultaneously, it is claimed to describe the initial state of the child who embarks on language acquisition. This dual characterization of UG forces the view that language acquisition is a process of logical instantiation. UG provides logical schemata which describe all languages, and the child, armed with the schemata, instantiates the variables they contain so as to achieve a grammar of a particular language.

This understanding of UG is not logically necessary, nor is it supported by the available results on acquisition of phonology. At its root is the assumption that to achieve a formal model of language, the model must be formalized using the resources of logic. However, it is clear that phonetics must be formalized using continuous mathematics, and the experimental literature on phonological development makes it clear also that phonological knowledge depends in an inextricable fashion on phonetic skills, including the gradual acquisition of spatial and temporal resolution and coordination (see, e.g., Locke and Pearson 1992; Elbers and Wijnen, 1992; Edwards et al., 1999). As speakers acquire more practice with a category, the variance in their productions of the category gradually reduces, and this process continues well into late childhood (Lee et al., 1999). When children are first acquiring a phonological contrast, they often fail to reproduce an adult-like phonetic expression of the contrast. For example, Finnish children often produce disproportionately long geminate consonants. When children are acquiring the American English or Taiwanese Chinese contrast between aspirated and unaspirated initial stops, the VOT values for the aspirated stops contrast may be exaggerated, or they may be so small as to appear to fall into the unaspirated category (Macken and Barton, 1980; Pan, 1994). Similarly, an adult-like

control of the spectrum of /s/ that differentiates it robustly from both /T/ and /S/ in English may not be achieved until five years of age, or even later in children with phonological disorder (Baum and McNutt, 1990; Nittrouer, 1995). As discussed in Scobbie et al. (2000), the trajectory from insufficient (or ‘covert’) phonetic contrasts to robust mature contrasts is a gradual one. Hence it cannot be modeled as a process of logical instantiation, but only using statistics over a continuous space.

Additional patterns in acquisition which demand a statistical treatment are provided by investigations of babbling and early word productions, as well as by patterns of perceived substitution in children with and without phonological disorder. For example, vowel qualities in the earliest stages of variegated babbling show the impact of the frequencies of different vowels in the vowel space of the ambient adult language (de Boysson-Bardies et al., 1989). Consonants in later stages of variegated babbling that are concurrent with the acquisition of the first 25 words in production reflect cross-language differences in the relative frequencies of different places and manners of articulation (de Boysson-Bardies & Vihman, 1991). Also, coronals are more frequent than either labials or dorsals in both English and Swedish, and children acquiring these languages already show language-specific differences in the fine acoustic details of coronal stops by the age of 30 months (Stoel-Gammon, Williams, & Buder, 1994). This is so even though they may not yet have learned to robustly differentiate the spectra for dorsal place from coronal place of contact, making /t/ for /k/ one of the most commonly perceived substitutions in English-acquiring children (Edwards, Gibbon, and Fourakis, 1997). Finally, although infants at the reduplicated babbling stages universally produce multisyllabic productions with simple CV alternations, children acquiring English (but not those acquiring French) show a marked increase in monosyllabic babbles, and in babbling productions ending with consonants, beginning at the first word stages (Vihman, 1993). This difference reflects the predominant shapes of the most frequent words in the two languages.

In connection with these observations, we would reiterate our opposition to dualism. A mature language is instantiated in individual brains. The physical state of these brains represents an equilibrium state which is reached from an initial condition — the human genetic endowment — through interactions with the physical environment. For physical systems in general, it is a conceptual error to equate the initial conditions with generalizations over the equilibrium states which may evolve from these conditions. For example, the current state of our solar system (with nine planets moving nearly on the same plane on elliptical orbits around the sun) is an equilibrium state. Insofar as this solar system is typical — with its sun, its small number of discrete planets and its orbital plane — one might imagine a kind of ‘meta-grammar’ of equilibrium states of the form:

(1) Solar system --> Sun, planet+

With a binding condition for orbital planes:

(2) For all i , $\text{Plane}(\text{planet}[i]) = \text{Plane}(\text{planet}[i+1])$

However, the initial condition for our solar system was an unformed cloud of debris containing a mixture of heavy elements from a previous supernova explosion. Neither (1) and (2) nor any discrete abstraction of them sensibly describes an unformed cloud of debris; nor is the current state sensibly viewed as the logical instantiation of the parameters of such a cloud. Describing how the planets arose from the debris requires gravitational field theory. That is, the discreteness of our own solar system does not arise from logical instantiation of the discrete elements of a meta-grammar. Instead, it arises as the discrete limit of continuous processes, much as we have shown for the case of phonological acquisition.

A third objection to Chomsky’s conception of competence is its continued reliance on the assumption of an idealized uniform speaker/hearer community. According to Chomsky, this idealization is justified by the obvious absurdity of imagining that language acquisition would proceed better in a varied speech community than in a uniform community. However, there is much evidence that uniformity impedes the process of language acquisition, and that variability facilitates it, yielding exactly the result that Chomsky believes to be absurd. This

evidence comes from several areas of research. Experiments on second language learning show that learners who are exposed to varied examples of a phonemic category learn the category better than those who are exposed repeatedly to the same example (Logan et al., 1991). The variation in examples permits the learners to generalize to new cases and to transfer perceptual learning to production (Bradlow et al., 1997). Research on first language acquisition of affixal categories similarly points to the role of variability in the morphological context — e.g., of exposure to a sufficient number of different roots before the affix can be abstracted away as a productive independent morpheme. Thus, for the English past tense affix, Marchman & Bates (1994) show that (contra the model and claims of Pinker & Prince, 1988), the single best predictor of when over-regularized past tense forms begin to appear is the number of different verbs that the child has acquired. That is, acquiring a large variety of regular past tense verb forms permits the child to project the principles of regular past tense formation, overpowering the high token frequency of some irregular verbs. Derwing & Baker (1980) similarly show that the syllabic plural allomorph is acquired later than the two consonantal allomorphs, in keeping with its lower type frequency.

Such results gain an intuitive interpretation when one reflects that VARIABILITY CAUSES THE NEED FOR ABSTRACTION. The entire point of an abstraction such as the morpheme *-ed* or the phoneme /i/ is that it represents the same thing across differences in the root to which it is affixed or in the speaker's larynx size and vocal tract length, the speech style and effort of articulation, the segmental and prosodic context, and other kinds of systematic token-to-token variability. If these sources of variability did not exist, then lexical items could be encoded directly in terms of invariant phonetic templates. Abstractions are cognitively expensive. They are learned because variability makes them necessary. There is no reason they should be learned in the absence of variability.

Laboratory phonologists share with other phonologists the aim of developing an explanatory theory of language. Overall, the issue is where the deep structural regularities of language come from. Work in the Chomskian tradition has emphasized the possibility that humans have a genetically innate predisposition to language, which is manifested through logical instantiation of the universal schemata of UG. However, there are also a number of other potential sources of deep, abstract, and universal characteristics of language. These include necessary or optimal properties of communication systems as such (as explored by Wiener, 1948, in his work on cybernetics; also much subsequent work in information theory); objective consequences of the characteristics of the human vocal and auditory apparatus; and general cognitive factors (such as general facts about categorization, memory, and temporal processing). For the laboratory phonology community as a whole the interplay amongst these various possible factors is treated as an open question.

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FOOTNOTES

1. This paper is a substantially reworked version of a position paper on laboratory phonology published in *Current Trends in Phonology I* (Durand & Laks, 1996). For comments on previous drafts of this paper, we are grateful to Ann Bradlow, John Coleman, Jacques Durand, Jan Edwards, Stefan Frisch, Jen Hay, Patricia Keating, Chris Kennedy, John Kingston, and Moira Yip. Although none of them are likely to agree with everything we have said here, we have benefited greatly from their suggestions about both substance and exposition. We are particularly grateful to David Hull, for fruitful discussion of the philosophy of science, and to the readers of *Current Trends in Phonology I* and the audience at *Current Trends in Phonology II*, for their responses to the earlier version of this paper. Work on the paper was supported by NSF Grant No. BNS-9022484 to Northwestern University; and by an Ohio State University Distinguished Scholar award and NIH Grant No. 1 RO1 DC02932-01A2 to Mary Beckman. Part of D. R. Ladd's work on the paper was carried out while a visiting scholar at the Max-Planck Institute for Psycholinguistics, Nijmegen.

2. The best-known type of arbitrariness in language is de Saussure's *l'arbitraire du signe*, or the apparently arbitrary association of lexemes (word sound patterns) with word meanings. *L'arbitraire du signe* bears some discussion in connection with the point we are making here.

Clearly, the association of wordforms with word meanings is not determinate; different languages use extremely different lexemes for highly analogous concepts. Even onomatopoeic terms differ across languages. However, de Saussure was incorrect in assuming that any nondeterminate relationship is arbitrary. In a stochastic system, nondeterminacy still obeys laws, when the probability distributions of outcomes are examined. As on-line tools begin to make possible large-scale research into lexical structure, we expect that discoveries into the laws of lexeme-meaning associations will become available. For example, Willerman (1994) develops a model of why function words are disproportionately comprised of unmarked phonemes in many languages (cf. Swadesh, 1971). In a similar vein, we would not be surprised to learn that basic-level categories are typically denoted by shorter words.

3. The acronym MESM is an allusion to the syntactic framework of Revised Extended Standard Theory which Chomsky launched (Chomsky 1977) and subsequently abandoned in proposing first Government and Binding theory, and then Minimalism.

4. Arguably, there are even no two idiolects in which the implementation of analogous phonemes is exactly the same. Here, however, we emphasize the systematic characteristics which are shared amongst members of a speech community, because these necessarily represent some kind of implicit knowledge which emerges during language acquisition. Idiolectal differences could result from idiosyncratic anatomical or neural properties.

5. The fundamental similarity between the PF representation of current Minimalist theory and the surface phonological representation of Chomsky and Halle (1968) can be deduced from quotations such as the following:

Let us recall again the minimalist assumptions that I am conjecturing can be upheld: all conditions are interface conditions; and a linguistic expression is the optimal realization of such interface conditions. Let us consider these notions more closely.

Consider a representation α at PF. PF [sic] is a representation in universal phonetics, with no indication of syntactic elements or relations among them.... To be interpreted by the performance systems A[rticulatory]-P[erceptual], α must be constituted entirely of legitimate PF objects, that is elements that have a uniform language-independent interpretation at the interface [to the articulatory-perceptual system]....

To make ideas concrete, we must spell out explicitly what are the legitimate objects at PF and LF. At PF, this is the standard problem of universal phonetics. (Chomsky, 1993, pp. 26-27; italics in the original)

This characterization of PF involves objects which are categorical and which support a universal phonetic interpretation. These assumptions are critical to some work in the Minimalist framework, such as Halle and Marantz's (1993) theory of Distributed Morphology (DM). DM claims that the PF level is the result of instantiating the lexical items in the morphological representation with phonological segments and features which can be manipulated by categorical rules and constraints. Thus, it presupposes the modular division between a language specific categorical component and a universal quantitative phonetics which is clearly nonviable.

It is possible, however, to read much of the Minimalist literature in a different light — as an abdication of Chomsky and Halle's original claim that sound structure as such has a 'grammar', in the sense of an abstract computational system which is capable of generating novel forms. As Jackendoff (1997, p. 15) points out, in the Minimalist program 'the fundamental generative component of the computational system is the syntactic component; the phonological and semantic components are "interpretive".'; see also the discussion in Burton-Roberts (this volume). One almost might interpret this research program as acknowledgment in advance by its proponents of some of the problems we raise regarding efforts to explain implicit knowledge of sound structure in terms of a categorical phonological module. At the same time, the Minimalist Program appears to make no pretense that its key concepts (such as grammaticality, universal grammar, or linguistic competence) in any way pertain to language sound structure, and we are possibly being unfair in attacking these concepts as if they were claimed to pertain. However, this interpretation strikes us as regrettable, for many reasons.

First, it leads one to disregard the ways in which phonology and phonetics are grammar-like, enabling the speaker to create morphological neologisms, to make additions to the lexicon, and to produce regular allophonic patterns when saying novel phrases and sentences. To the extent that there are abstract parallels in sound structure across languages, these suggest the kind of deep universals which are the traditional target of linguistic theory. Even if these quasi-grammatical properties of phonology are embedded in an understanding of the physical world and of general cognitive capabilities, they are still scientifically important and tell us something about the human capacity for language.

Second, it leads one to disregard the ways in which morphological and syntactic relationships are echoed in quantitative effects in the phonetics (e.g., Hay et al., in press; Fougeron and Steriade, 1997; Sereno and Jongman, 1995), which surely are the reflexes of the fact that phonetic knowledge is intertwined with the linguistic system rather than being decoupled from it.

Third, the interpretation undermines the effort to find parallels between phonology and syntax in the way that they relate to physical events in the world and to the language user's conceptualization of these events. It may turn out that, thanks to its restricted physical domain and advanced instrumentation, phonology is simply in the lead in an enterprise in which syntax will eventually catch up. If the relationship of syntax to this 'world understanding' is eventually proven to resemble that of phonology (as we have described it here), then the Minimalist Program will have been carried through to its logical — truly 'minimalist' — conclusion.