What phonology is and why it should be

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Only mind sees, only mind
hears, all else is deaf and blind.

EPICHARMUS OF KOS
as translated by Karl Popper

1 Introduction

This chapter[1] proposes an overview of phonology as a theory in the tradition of scientific realism, a rationalist investigation of a property of the human mind. I begin in §2 by a brief overview of realism in phonology, where I suggest that tension between empiricism and realism has played out in the history of phonology through the use of phonetic substance as an epistemological and explanatory assay in phonological theory. The chapter proceeds in §3 with a discussion of phonology as a natural object, a part of the innate linguistic endowment of *Homo sapiens*. In §4 I discuss phonology's place in cognition, arguing that phonology is a modular information-processing system that mediates between mind and the exterior physical world. In §5 I present an overview of phonological theory in that light, suggesting that an adequate theory of phonology requires

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an account of representations, of computations that operate over those representations, and an interface between phonology and other linguistic modules.

Much of what I will say in this chapter suggests that phonology is not an empiricist or instrumentalist science, but that is not to say that careful observation plays no role in understanding phonological knowledge in human beings. Rather, phonologists should be circumspect in the conclusions they draw from observable sound—useful models generalize over data and provide explanation of sound patterns, but sound is not *reproduced* in phonological knowledge, it is *correlated* to it.

2 Phonology as scientific realism

At the end of the 19th century, two ideas which emerged from Neogrammarian thought moved linguistics beyond the practice of taxonomic classification and universal principles of sound change. The first was Baudouin de Courtenay's shift away from the articulatory and perceptual properties thought to be the drivers behind Neogrammarian sound change and towards a conception of abstract linguistic structure that was a property of human minds (Baudouin de Courtenay 1870 [1972]). The second was Ferdinand de Saussure's conception of language as a system of relationships between meaning and form which entailed a synchronic mode of inquiry (Saussure 1916 [1967]). By the mid 1950s these two ideas came to bloom in generativism in the form of an ontological commitment to inquiry into the nature of abstract, synchronic linguistic knowledge (Chomsky 1965)—knowledge that underlies the range of possible forms of human language. The most basic ambition in every domain of linguistics *qua* knowledge is to provide an explanation for why linguistic knowledge is the way it is, instead of some other way.

Phonology occupies a fraught position in this enterprise. Syntax is generally set in an epistemological approach of scientific realism, a theory of unobservable structure (see for example Lasnik & Uriagereka 2022) that nevertheless is intended to be a theory of something real, or at least the approximate truth (see Boyd 1983 and Chakravartty 2007). One standard assumption in syntax holds that syntactic structure does not directly reproduce linear word order (though see Kayne 1994 for an argument against this view). Knowledge of syntax has no directly-measurable physical correlate, though it is discoverable through the use of analytic tools such as constituent tests. An adequate theory of syntax confirms the existence of abstract structure through its power to extract generalizations and to provide explanation concerning speaker knowledge of that structure. Phonology, however, is strung somewhere between a theory of unobservable properties of the mind and directly measurable physical phenomena observable in the senses—compared to syntax, it is not as immediately clear what the empirical remit of phonology is.

The origin of modern phonology is a claim about something in the human mind: the phoneme, a symbolic marker in the mind that includes only those properties of a class of speech sounds that are linguistically relevant, and nothing else (Baudouin de Courtenay 1870 [1972]: 211f.). Its discovery is a triumph of rationalist science (see van der Hulst 2013), arguably the single most important discovery in the field of linguistics (Goldsmith & Laks 2019: 323), and inherent in the claim that the phoneme exists in the mind is an ontological distinction between phonology *qua* mental phenomenon in the brain and the physical realm of phonetics outside of it (Durand & Laks 2002: 11).

For Saussure (1916 [1967]: 166), the essence of phonemes was their distinctive property: "dans la langue il n'y a que des différences."[2] What is linguistically significant in the structuralist phoneme cannot properly be understood in terms of mechanical processes—they are symbolic counters embedded in a system of contrasts (Sapir 1925: 37ff.). In structuralism, the object of phonological inquiry was the abstract network of relationships between symbolic markers, distinct from the physical correlates of those markers (Trubetzkoy 1969).

In Sapir's 1907 grammar of Takelma, for example, he argued that a glottalized affricate [tˀs] stood in opposition to a plain sibilant [s], and that the former's phonological status was in fact /sˀ/, despite its opaque realization as an affricate (see Silverstein 2022: 267f. for discussion). Sapir's argument was based on the theoretical system of contrasts between [pˀ tˀ kˀ] and [b d g]: [tˀs] is *phonologically* /sˀ/ because it stands in opposition to *phonological* /s/ in the same paradigmatic manner. The existence of /sˀ/ in the minds of speakers of Takelma is revealed not just through careful observation, it requires reasoned consideration of those observations through the lens of an abstract theory. While contrastive representational symbols are quite different in modern theories when compared to Baudouin's original conception (see Chabot 2022), most of them inherit an assumption that some phonological structure is abstract—a property of human minds.

It is also obvious that most phonological patterns hew relatively close to the bone of phonetics, which suggests that phonetics plays at least some role in shaping phonological patterns (Anderson 1981: 509). This opens

[2]In language, there are only differences.

up the tantalizing possibility that explanation in phonology may come about through measurable aspects of the phonetic signal. Such an approach requires explicitness on how much and what kinds of phonetic properties are relevant to explanation, since physical properties are without limit in their potential to yield measurable data points. The pendulum swings between theories that view phonology and phonetics as being more or less the same (Blevins 2004; Flemming 2001; Kirchner 1997, 1998), and those where phonology is ontologically distinct from phonetics (Foley 1977; Fudge 1967; Hale & Reiss 2000b, 2008; Odden 2013).

Since phonologists must look "beyond the veil" of sound and directly observable phenomena into the realm of abstract and unobservable knowledge, any theory of phonology *qua* knowledge in a phonetic world must determine what the content of that knowledge is, how it is represented, and how phonological structure emerges from it. In phonological epistemology, theories provide explanation for sound patterns, but explanation does not come about in the same way or form in every theory (see Halle 1975). The principle reason for this is the swinging pendulum between phonetics and phonology, which follows an arc traced by the relative influence of phonetics in phonological explanation (Carr 2000; Durand & Laks 2002).

3 What phonology is

3.1 Faculty of Language

In the view of Saussure (1916 [1967]: 25), the human capacity for organizing and using a language emerges from what he termed *Faculty of Language* (FL), a natural object distinct from the languages that humans use in social contexts. A language variety like Comanche is in part a social phenomenon, an aspect of a speech community. The capacity for acquiring and using language, however, is a property of human beings—what Haspelmath (2020) calls "linguisticality"[3]. In generativism, an equivalent distinction is made between I-language *qua* element of mind and natural object, and E-language, a cultural and social phenomenon (Chomsky 1986: 20ff.). Any given E-language is acquirable by any human because all humans share the capacities endowed by FL (Anderson 2008; Chomsky 2002; Jackendoff 2011; Rizzi 2004).

The FL hypothesis entails that human brains are built with dedicated architecture from which linguisticality emerges, analogous to the faculty

[3]See Crain & Pietroski (2001) for an overview of what has come to be known as the *nativist position*.

of vision or any other innate cognitive system (Anderson 2008; Chomsky 1980; Jackendoff 2002; Lenneberg 1967). Also like these capacities, FL has properties and characteristics that are amenable to scientific inquiry, in particular the domain-specific principles which determine how language is acquired and what the structure of grammar is like (Chomsky 1980). For example, phonology can grammaticalize nasalization and exploit it as a contrastive cue such that whether or not the velum is open and air passes through the nasal cavity can change the meaning of a word. On the other hand, loudness is not grammaticalized in the same way—in no language do words mean one thing when uttered quietly and another when uttered loudly. Thus, at the heart of any theory of FL is an effort to provide an explanation for the form of possible languages.

3.1.1 Phonological knowledge

What is meant by form, here, is not the whole of the information contained in the speech signal. It is, instead, the basis for a distinction made by Saussure (1916 [1967]) between *langue* and *parole*, where the former is an abstract system of grammatical structure, the latter is the use by speakers of that grammatical structure. Speech acts in the form of *parole* are the expression of formal structure, yet are impacted by a host of factors unrelated to that structure.

Linguistic form, then, emerges through the set of the principles of grammatical structure in language: it is *knowledge* of language. Knowledge is not of how to *do* things with language (Chomsky 1986: 10), it is not knowledge of behavior (see Chomsky 1959). Knowledge is internal, highly specialized, formal rather than functional. It is an intensional property of human brains (Chomsky 1995: 335), independent of the sensory-motor apparatus in the same way that visual cognition is independent of the mechanical details of the eye.

In generativism, syntactic knowledge takes the form of the symbolic vocabulary and hierarchical structure underlying speaker behavior rather than the directly-observable linear word order of utterances. Given the abstract nature of syntactic knowledge, morphosyntactic inquiry has always been an essentially realist enterprise, extracting generalizations from observed behavior, providing description and explanation of an ontologically-real property of human minds. This mentalist epistemology places linguistics firmly in the domain of cognitive science (Chomsky 1986: 4).

Indeed, the realist stance is inherent to generativism, which holds that the production of language in real-life situations is impacted by non-linguistic factors which can distort and deform observations concerning the underlying knowledge of form and structure. This is the basis for the distinction between *performance* and *competence* argued for in Chomsky (1965: 3) (see also Rey 2020 and Dupre in press). It is the latter—the knowledge itself—which is the object of inquiry in generativism, rather than externalized language (see also Jackendoff 1997: 2).

Observable language emerges from three contributing factors: that which is specific to FL, the individual experience of speakers in speech communities, and principles of cognition or biophysiology which are not specific to FL, such as developmental constraints, principles of efficient computation, or how the larynx works (Chomsky 2005: 6). The latter are "third factors", outside the remit of phonological theories *qua* theories of knowledge that distinguish between those observations emerging from the distinctive properties of FL and those which can be explained as being a property of general cognition or the anatomy of the speech organs (Anderson 2008: 805).

Theories of phonological knowledge must, to some degree, abstract away from purely observable phenomena in order to make claims and provide explanation for general principles characterizing those phenomena. There is a tension inherent in that abstraction, since phonological knowledge seems so often to be isomorphic with substantive phonetic descriptions. This suggests that phonological theory is, to some degree, about physiological facts inherent in the production and perception of sound, but the necessity for some abstraction opens up the logical possibility that phonology is entirely abstract. A critical aspect of any theory of phonology is determining exactly to what extent substantive properties constitute data that is within its remit, and what constitutes an explanation for the patterns in that data.

3.1.2 Phonology and speech

The distinction between the physical properties of speech sounds and their representation in the minds of human beings made by Baudouin de Courtenay (1870 [1972]: 211f.) was inherently rationalist. The empirical basis of inquiry in early structuralism was the mental classifications of speech sounds, manifest as a systematic relationship of oppositions that organized phonological systems (Saussure 1916 [1967]; Trubetzkoy 1969); the articulatory and acoustic dimensions of those speech sounds were abstracted away in phonemes. The notion of contrast implies comparison—one contrastive phoneme is not like another. Difference is the linguistically significant content of phonemes, but this must be a kind of symbolic difference because there is no invariant correlate for significant contrasts in raw instrumental recordings.

In the view of Sapir (1925: 39), the phoneme was a symbolic counter, an object with a paradigmatic function that represents sets of internally varying linguistic sounds. The counters have an ontological status in their function as contrastive objects relative to one another in structural networks in linguistic sound patterns. That is, phonemes are a kind of subjective reality for speakers who are not directly sensitive to the objectively-real acoustic signals of sound (Sapir 1933).

In generativism, however, the structuralist bulkhead between symbolic phonological knowledge and observable externalizations is more porous. Though Chomsky & Halle (1968: 3) argued that competence was the fundamental factor in performance, since the foundational work of the pre-generative era (Jakobson 1939; Jakobson et al. 1952; Jakobson & Halle 1956), the empirical basis of a great deal of phonological work has been fine-grained, quantitative, instrumental measurements of sound in the tradition of the physical sciences such as chemistry, geology, or physics, characterized by their remit over non-living things. The reasons for this are obvious: phonology and sound seem clearly related in that the explanation for the form of phonological patterns seems so often to be found in substantive facts.

Attention to sound was useful in generativism in part because the theory of phonology articulated by Chomsky & Halle (1968) was relatively flexible in its formalism, tolerating generalizations over sound patterns that referenced morphological, historical, and other non-phonological information. This mixing of levels meant that the formal theory was quite powerful, leading to analytical indeterminacy and overgeneration, as well as sapping the theory of explanatory power (see the famous Chapter 9 of Chomsky & Halle 1968). One ambition of much of the work done in the wake of Chomsky & Halle (1968) was to restrict the power of the formal theory by, among other things, limiting the ways in which it interacted with the morphosyntactic domain (see Scheer 2022b).

However, not only was the substantive realm—in both acoustic and articulatory terms—not subject to the same scrutiny, it was given formal status in an effort to imbue phonological theory with explanatory power (Chabot 2021). A number of proposals in a variety of frameworks that explicitly included substantive knowledge in phonological formalisms were proposed, including Natural Phonology (Stampe 1973; Donegan & Stampe 1979), Natural Generative Phonology (Hooper 1976; Vennemann 1971), Articulatory Phonology (Brownman & Goldstein 1986), Grounded Phonology (Archangeli & Pulleyblank 1994), and Optimality Theory (Hayes & Steriade 2004). All of these approaches are surface oriented and share a basic assumption that phonological knowledge is essentially directly reflected in its exponence. In these theories, it follows then that phonetic inspection reveals the nature of phonological knowledge, an epistemological philosophy made most explicit in Laboratory Phonology (Ladd 2011; Pierrehumbert 2000; Pierrehumbert et al. 2000).

3.1.3 Phonology is different

Phonetic inquiry in phonology has two essential empirical pillars. The first concerns facts about articulation, for example the configuration of the main articulators or laryngeal anatomy. The second concerns facts about acoustics, such as the relative energy of individual frequencies of the speech signal as it varies in time. Both of these levels of description are ontologically independent of the kinds of knowledge which characterized the contrastive relationships of structuralist phonology.

One consequence of this empiricist approach to phonology has been a general attitude among linguists that phonology is different from syntax (Bromberger & Halle 1989)—not just formally and empirically, but conceptually. Phonology is an edge property of linguistic competence, it lays at the threshold between the symbolic domain of morphosyntax and the gradient, continuous domain of phonetics. That is, phonological knowledge is about a *relationship* between mental representations and information about the physical world in terms of articulation and audition (Bromberger & Halle 1989: 53).

Virtually every post-Neogrammarian phonological theory has assumed that phonology is about something that happens in human minds. There is a tension inherent in this relationship between mind and sound, since explanation for why languages have the phonological properties that they do is potentially found at different levels of description depending on the theory. For one theory, explanation may be found in the internal mental states of humans, while in another explanation may lay in physical facts about articulation and perception of the external world (see §5).

3.2 Minimalism

This liminal position between cognition and the physical world has had consequences for the study of phonology, how that study is carried out, and the status of phonology as part of FL (Carr 2000; Fitch et al. 2005; Hauser et al. 2002; Samuels 2011a). In the minimalist program (Chomsky 1995, 2002), linguistic knowledge is assumed to be sparse, reduced to only those aspects which are conceptually necessary to the computational system underlying syntactic grammars and interface. These aspects are the "core" of linguistic knowledge, and are the only truly linguistic explanation for the form and properties of linguistic structure, because they are domain specific. Domain-general cognition and other non-linguistic explanations are "third factor" and external to the grammar (Chomsky 2005).

Knowledge is not about external, behavioral, or functional facts—meaning that if phonological knowledge is a part of core linguistic knowledge, it cannot be about external behavior, or what people do when they speak. If substantive facts in production are taken to be reflections of phonological fact, phonology is relegated to a peripheral property, a kind of sensory-motor conduit for the externalization of syntax (Chomsky 1995: 163). In minimalism, phonology and phonetics are collapsed into the Phonological Form (PF) module of grammar (c.f. the "inverted-T" model in Chomsky 1965), the domain of something related to linguistic knowledge but which does not emerge from the properties of FL the way core syntax does.

Fitch et al. (2005) and Hauser et al. (2002) argue explicitly for a distinction between what they call Faculty of Language in the narrow sense (FLN), or those aspects of language unique to FL and to *Homo sapiens*, and any general properties of cognition or traits in other species which contribute indirectly to language, Faculty of Language in the broad sense (FLB). FLN is everything specifically dedicated to linguistic knowledge; essentially the computational mechanism of syntactic recursion and the mapping to the interfaces (Fitch et al. 2005: 182). In this view, phonology's function as a mapping between syntax and the sensory-motor system means that it is part of FLB.

Inherent in the FLN/FLB distinction is a claim that phonological knowledge does not contain any language-specific content, despite the structures and principles revealed by all of the descriptive and theoretical work done in phonology (see also Jackendoff & Pinker 2005 and Pinker & Jackendoff 2005). Yet, phonological theory includes a variety of symbolic structural configurations, such as hierarchical syllable structure, contrastive representations, and timing positions. These theoretical objects constitute a kind of proprietary phonological knowledge that is not obviously about the externalization of syntax, since it is unclear what they should have to do with the interpretation of syntax (see Chabot 2021: 195).

Indeed, the higher-order symbolic aspects of phonological knowledge are organizational properties; they are modality independent and do not depend on auditory-vocal or visual-gestural sensory motor systems (Brentari 2019; van der Hulst 2000). These purely formal structures emerge from FL—they are the product of human minds. Ultimately, the FLN/FLB distinction is otiose, since phonology is, like syntax, innate and domain-specific cognition. A minimalist theory of phonology then is not a theory of externalization, rather it is a theory of the minimal necessary elements required for explaining abstract, symbolic phonological knowledge.

3.3 Phonology as a symbolic theory of knowledge

When the physiological facts that emerge from *the interaction* between abstract phonological knowledge and the sensory-motor system are conflated with the knowledge itself, it becomes impossible to be sure what the competence underlying performance is like, as explanation may lay in one or the other—or both—levels of description. In other words, while production is amenable to empirical observation through fine-grained instrumental measurement, it is not clear whether it is behavior or knowledge that is being measured. As far as the abstract structure of phonology is concerned, phonology is no more about functionalism than minimalist syntax is. This kind of phonological knowledge is a symbolic cognitive property that operates independently of substantive factors (Anderson 1981; Chabot 2021). Indeed, if a theory of phonology *qua* knowledge is taken seriously, this must be true, since phonology is also a property of sign language (Brentari 2011, 2019; Marshal 2011; Sandler 1993, 2012, 2014; Stokoe 1960 [2005]), where the physical properties of sound are irrelevant; phonology is a kind of internal, modality-independent knowledge.

This entails a formal approach to phonology—in the tradition of Saussure, Sapir, and Trubetzkoy—an approach argued for by Odden (2013) and the Substance-Free Phonology (SFP) program (see Blaho 2008; Hale & Reiss 2000b,a, 2008; Iosad 2017; Odden 2022; Reiss 2018; Samuels 2011b; Scheer 2022a; Volenec & Reiss 2020, 2022 *inter alia*). In SFP, phonology is purely symbolic—it is grounded in the mind and is deaf and blind to contingencies inherent in the production of speech. As such, it is less immediately obvious how inquiry proceeds in SFP, since physical properties are not reliable correlates for phonological identities.

The SFP approach is an application of rationalism that is about idealization; it is not about the content of the set of phonetic expressions, rather it is a set of hypotheses concerning the causal principles which intensionally generate that set. Substance-free theories view the object of phonological inquiry as about causal principles in the form of useful generalizations. The more observation relies on fine details of physical measurements, the more a theory commits to generalizations that are essentially recapitulations of the raw facts, and the less it explains.

4 Why phonology should be

4.1 Perception and representations

Any theory of phonology *qua* knowledge is a model of mental processes which are a property of mind—a theoretical object in the sense of Carnap (1966) that is not directly observable, with no temperature to be taken, no weight to be taken, no color to describe. A realist approach to scientific inquiry reveals the generalizable principles that characterize the mind, one of the chief functions of which is to relate us to the rest of the world (Searle 2004: 259). In cognitive science, communication between the physical world and the mind happens through mapping between "states of the world" to internal reconstructions of those states, or representations (Gallistel & King 2009: 43).

Such mappings are characteristic of perception (Levine 2005: 25), the source of virtually everything we know about the world external to our bodies (Pomerantz 2003). In perception, physical energy triggers specialized nerves in the sensory organs which convert that energy to neural signals through *transduction*—the process which translates between distinct domains, or "the bridge from the physical to the symbolic" (Pylyshyn 1984: 84). In this sense, phonology is like any other perception such as vision, audition, or olfaction (Hawkins 2010).

Perception of speech sounds begins with rapid changes in air pressure, characterized as continuous sine waves (Warren 2008). These waves arrive at the outer ear and move down the ear canal to the ear drum, which vibrates on contact with pressure changes. This in turn causes the vibration of three small bones—the ossicles—passing the vibrations to the liquid-filled cochlea. Those vibrations stimulate the movement of small hair cells, triggering neuronal activity in the cochlear nuclei located in the brainstem (Gazzaniga et al. 2014; Warren 2008). After transduction into action potentials, all perception is cognition; it is neural signals that give rise to experience.

Among the critical principles underlying perception (Pomerantz 2003), there are three in particular which can inform the discussion here:

1. Perception is non-veridical, it is a subjective reproduction and not fully accurate or faithful.

2. Perception requires memory, it relies on information stored in memory to make sense of percepts.

3. Perception requires internal representations of percepts.

Since perception is non-veridical, it follows that whatever we know of percepts is not of like-kind with the distal stimuli that give rise to them. Physical phenomena are not interpreted as they are, but rather as the neural signals they give rise to in sensory organs. In cognition, this means as symbolic objects which correlate to, or represent, physical phenomena in the mind. These representations are a relationship that holds between representing systems and represented systems (Gallistel & King 2009: 60), but there is no reason to assume these representations contain the properties of what they represent (Pylyshyn 2004: 2).

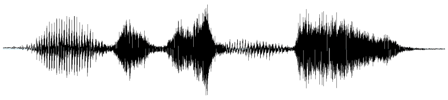
4.1.1 Gradiency is a property of the non-cognitive world

In perception, we do not perceive a "high-fidelity" external world as it is—we form a representation of it, a cognitively-interpreted world. Part of phonological knowledge must be about the kinds of internal representations we have for the percepts that correlate to speech, a kind of perceptual cognition that is exactly as Bromberger & Halle (1989) suggest: about a relationship between mental states and the external world. This relationship cannot be direct, it is interpretational, since there is, for example, no sound in our brain tissue that could be matched up to waves in the compressed and rarefied air of speech.

Brains, being finite objects, impose a limit on the resolution of representations. However, physical phenomena are gradient and continuous in the sense organs—the ear canal is a resonance chamber (Warren 2008: 7), amplifying the frequency of waveforms, while sense of color depends on the wave properties of light (Palmer 1999). Although continuous waveforms contain a potentially infinite amount of information, representational symbols must be efficiently stored and easily accessed (Gallistel 2008). Cognition, thus, trades in categorical and discrete phenomena (see Harnad 2005 and Ashby & Maddox 2011, *inter alia*); it treats variable input as invariant, producing discrete representations throughout perception. In the categorization of color, for example, the continuous and gradient spectrum of visible light is cut up into a set of discrete categories in which precise wavelength measurements have no meaning since there are only type-members of a category.

4.1.2 Phonological knowledge and categories

The waveforms that constitute sound are characterized by variability in their signal, but much of that variability is irrelevant to phonological knowledge and goes unperceived by speakers. Raw measurements of the physical



w a s p s n ɛ s t s

(a) Continuous waveform. (b) Discrete phonemic representation.

Figure 1: Acoustic and phonemic representations of the words *wasps' nests*.

properties of a speech signal do not provide an understanding of that signal in linguistic terms, since there is potentially no limit to the parameters by which it could be measured (Anderson & Lightfoot 2002). Accordingly, most theories of phonology cut up the continuous waveform into phonological representations that are invariable, discrete, and categorical (Cohn 1998; Keating 1996; Myers 2000).

That is, phonological knowledge is not about continuous and gradient properties in the physical world, but rather the categories that generalize over grammaticalized correlates in the signal, abstracting away from the non-significant variation inherent in it (see Figure 1). These categories, or segments, do not objectively exist in acoustic or articulatory terms. As Hammarberg (1976: 355) puts it:

> The segment has no physical existence of the kind demanded by those who would base science on pure objective observation. Nor can segments be inferred from the speech signal or the articulatory movements without resorting to the host of phonological suppositions. . . The ontological status of the segment is, and has always been, a fundamental problem in the the study of phonetics and phonology. But it should be perfectly obvious by now that segments do not exist outside of the human mind.

Segmentation results in a cognitive world that is not directly perceived by the senses, but rather "as it **might** be" (Tattersall 2019: 2), as one which imposes discreteness on what is in reality continuous. The segment *qua* phonological knowledge is a theory of the structure of the speech signal, an appropriate idealization that leads to explanation and understanding of the properties of speech (Anderson & Lightfoot 2002). In other words, knowledge about the raw data in the physical world is "cooked" by phonology (Hammarberg 1981: 262).

Higher-order representations above the segment such as the syllable are even more obviously symbolic in the way syntax is, but segments in continuous speech are as much the products of the human mind as other structures with no reliable or invariable correlate in the speech signal.

Phonology builds structure where there is none directly available in the senses. The function of phonology, then, is to mediate between the infinitely rich buzzing of the physical world and something that can be used by human minds to make sense of that world.

4.2 Phonology as cognition

Phonology, as a mapping between mental representations and the real world, is a kind of information-processing task carried out by cognition (Gallistel & King 2009). In cognitive science, an explanatory theory of complex information-processing tasks is argued by Marr (1982: 25) to emerge at different levels. Each level can be described independently of the others, although understanding at one level is a requirement for understanding at the next.

1. Computational: What is the goal of the computation, why is it appropriate, and what is the logic of the strategy by which it can be carried out?

2. Algorithmic: How can the computational theory be implemented?

3. Implementational: How can the representation and algorithm be realized physically?

Computational theories characterize the mapping from one kind of information to another. They include those computations which are built out of elementary features used by the brain to extract from the senses the information it needs to make sense of the world (Gallistel & King 2009: 59). In linguistics, formal theories of linguistic competence are the property of this level, they constitute the explanation for what people know. The algorithmic level is about the real-time properties that psycholinguistic theories traffic in (Embick & Poeppel 2015: 360). The third level, implementation, is where the operations characterized by the first and second levels are carried out: in the brains of human beings.

The relative independence of each level means that the computational theory—what is being computed by the brain—can be abstracted away from how and where that thing comes about in the brain. Where phonology is concerned, this entails that to have anything useful to say about the second and third levels, we need an explicit theory of *what* phonological computation is. In a Computational-Representational (CR) model of cognition (Embick & Poeppel 2015; Gallistel & King 2009; Poeppel & Embick

2005; Pylyshyn 1984; Thagard 2005), explanation for the form of phonological knowledge can be provided by an account of the representations (§5.2) and computations (§5.3) which characterize it.

4.3 Modular phonology

Fodor (1983) proposes an architecture for cognition built out of specialized functional units known as modules. Modules are distinct from higher cognitive domains such as attention, belief, and judgment—they operate in specific ways with specific symbolic vocabularies. One function of modules is to interpret information from the outside world (Fodor 1983; Nakayama 2005). Fodor (1983: 47ff.) provides nine features which collectively characterize modular systems, two of which are especially important to the present discussion because they can be used to determine some properties of phonological representations and computations: *domain specificity* and *informational encapsulation* (see Carruthers 2006 and Gerrans 2002 for discussion).

Domain specificity says that modules operate according to proprietary principles, using a particular vocabulary. That is, cognition is not a property of a general-purpose computing machine. Modular computation only makes sense within a specific module, being uninterpretable by another, since it works over proprietary classes of symbolic vocabulary (Coltheart 1999: 118). Translation of modular vocabulary is a function of an interface between modules, not of computation within them.

Modular phonology traffics only in phonological objects, its symbolic representations are not directly parsable by other cognitive domains (Hale & Reiss 2008; Reiss 2007; Scheer 2011). The consequence of the domain-specificity hypothesis is that a theory of phonological knowledge must be insensitive to physical properties such as acoustic waveforms and facts about human articulatory physiology, since these physical phenomena are not phonological symbols. Further, it does not recognize non-phonological linguistic objects such as FOCP structures or morphological labels such as "3SG", because this kind of information is not encoded in phonology-specific vocabulary (Iosad 2017; Newell & Sailor in press; Scheer 2011).

Informational encapsulation says that modules cannot see or be affected by information in other modules. In this way, modular computation is quick and efficient, as the processing system does not have to sort through all of an individual's knowledge (Coltheart 1999: 117). During modular computation, no information which was not present in the input can play a role in determining the output. Further, modules cannot produce partial outputs, only completed operations may send output to other modules.

Informational encapsulation and domain specificity work together to restrict, in a principled way, how phonology interacts with other modules, thus reducing the number of possible grammars that can emerge from FL. For example, while heads are basic functional units in syntax, they have no existence in phonology and there is no possible rule that could be conditioned by such objects. The different computational systems are in effect self-contained worlds that do not communicate with each other; phonology cannot "look inside" other modules and no information is available to phonology which is not directly inputted into it. In principle, nothing other than phonological vocabulary is required—the theory is entirely formal, its purview restricted to a theory of computations and discrete, symbolic representations (Reiss 2007: 55).

A modular approach to phonology places the emphasis on phonology as a cognitive process, rather than as a simple behaviorist description of stimuli and responses (Scheer 2011). Thus, it allows a better understanding of phonological knowledge, since it makes a sharp distinction between what is phonology *qua* knowledge and what is not (Cairns & Raimy 2009; Reiss 2009). In a non-modular framework, any linguistic pattern can be analyzed at any level of the grammar, seriously compromising the theory's explanatory and predictive power (see Janda 1987: 5). For example, a suppletive pattern of verb alternation in English could be analyzed as phonological in a theory that assumes that phonological rules are sensitive to the lexicon and syntactic tense information.

5 What a theory of phonology should be and what it should do

5.1 Phonology and unobservables

Baudouin de Courtenay, speaking in St. Petersburg in 1870, characterized linguistics as inquiry into the general properties operating in language (Baudouin de Courtenay 1870 [1972]: 55). He argues that this is not equivalent to collecting patterns and arranging them taxonomically, saying the "*descriptive* approach, an extreme empirical one, which sees its task in gathering facts and generalizing from them in a purely external manner, without attempting to explain their causes... reduces science to a purely empirical endeavor, to some sort of meaningless game." The principle ambition of a linguistic theory is to derive generalizations about human linguistic knowledge from empirical observations of linguistic data; that is, it is not to passively observe, but to actively evaluate and classify.

In phonology, this naturally means generalizations over phonological data (Chomsky & Halle 1968; Hurford 1971). This data is evaluated in the light of theories, and comes in the form of alternations, distributional regularities, or more broadly, as sound patterns. Phonological theories *qua* theories of knowledge can be evaluated in terms of two related metrics:

1. How well they account for sound patterns

2. The explanatory understanding they provide

Accounting for observed sound patterns requires a theory that, minimally, reproduces the patterns (see Chomsky 1965; Hurford 1977; Prideaux 1971). Explanation of sound patterns requires an account of the nature of the representations and computations underlying them (Odden 2013)—an explanatory theory characterizes the fundamental properties of FL (see Chomsky 1964: 29 and Dinnsen 1980: 172).

In Popperian science, the classic assay by which science can be distinguished from pseudo-science is falsifiability (Popper 1935 [1992]: 48), and falsfiability is often taken as a basic desideratum of any linguistic theory (see Carr 2000: 75 and Morley 2015: 22, for example). Phonological theories which are overly abstract or that make claims about some principle of the internal states of brains or minds are not always directly amenable to falsification, and have been criticized on those grounds (Pierrehumbert et al. 2000).

However, the validity of a theory is not just a consequence of its vulnerability to anomalous phenomena. It is also inherent in its power to make predictions (see Kuhn 1962: 146f.), a substantially more profound kind of understanding than mere taxonomic categorization or fine measuring because it allows a theory to reveal novel facts about the world. That is, a theory is not a single hypothesis meant to account for all potentially relevant facts, it is a series of related hypotheses about the world; a research program that makes "dramatic, unexpected, stunning predictions" (Lakatos 1978: 5). Phonological theories have a value in their *prognostic* nature, being useful for making observations which go beyond the set of narrow facts used to build them (see Basbøll 1980: 101, Ladefoged 1980: 198 and Vaux 2008: 30). Above all, in the realist perspective, the power of a theory comes from its explanatory value; a theory is thought to provide a true explanation for the data when that explanation is better than any other.

In this view, the task of a theory of phonology is not just to describe and generalize patterns, but also to categorize computationally *possible* phonological patterns (see Chabot 2021 and Hale & Reiss 2008: 171). The ultimate goal in this enterprise is to explain both what phonological knowledge is like and the properties of FL which allow phonological structure to emerge in speakers. Such an explanation minimally requires two interacting parts: a static theory of phonological representations, and a dynamic theory of phonological computations (Chomsky 1980). A full account also requires being explicit on some details concerning the translational interfaces between phonetics on the one hand and morphosyntax on the other.

5.2 Representations

By the end of the structuralist era the basic representation in phonology, the phoneme, was shattered into sub-phonemic features like [±voice] and [±nasal] (Jakobson 1939; Jakobson et al. 1952; Jakobson & Halle 1956). In generativism, features realized simultaneously are grouped into bundles that correspond to segments and play the same contrastive role as the structuralist phoneme, in addition to capturing natural class behavior (Chomsky & Halle 1968; Kenstowicz 1994). Various models of phonological primes concerning the details of valency (van der Hulst 2016; van der Hulst & van de Weijer 2018), content (Backley 2011; Harris & Lindsey 1995; Kaye et al. 1985), and organization (Clements 1985; Sagey 1986) have been proposed, but all of them share a view of phonological primes as a discrete and categorical unit[4].

Autosegmental theories (Goldsmith 1976, 1990) introduced further representational objects that interact with primes, including association lines and timing positions (Clements & Keyser 1983; Clements 1986; McCarthy 1981; Prince 1984), syllabic and prosodic structure (Kahn 1976; Nespor & Vogel 1986; Selkirk 1982), metrical structure (Hayes 1995; Idsardi 1992), and precedence relations (Idsardi 2022; Raimy 2009). In addition to being categorical, virtually all of this representational apparatus is symbolic and abstract, meant to account for a set of generalizations that is taken to be a linguistically significant reflection of knowledge.

Even theories which seek explanation for phonological knowledge in phonetics do not entirely dispense with the assumption that representations are categorical. For example, in Exemplar Theory (Bybee 2001, 2002; Frisch

[4]See the volume edited by Clements & Ridouane (eds.), especially Cohn (2011) for a discussion of features, and Durand (2005) for a general overview of phonological primitives beyond the narrow conception of features.

2018; Pierrehumbert 2001), speakers are assumed to have knowledge about the probability distributions of speech sounds, which explains variation in perception and production. This variation is grouped into categories that are built from exemplars—records of variation in the physical correlates (e.g. formant values, duration) of the category. However, given the biologically-imposed limitations on storage in the brain, exemplars only correlate to some of the variation in the speech signal, granularizing the parameter space for significant variation (Pierrehumbert et al. 2000).

Exemplar Theory blurs the competence/performance distinction, being as much a theory of what people do and of how categories are acquired as a theory of knowledge. This ambition is taken a step further in Articulatory Phonology (Brownman & Goldstein 1986, 1992), which seeks to unify phonetics and phonology into a single model, as differentially granular descriptions within the same component. Here, knowledge of representations takes the form of gestural scores in graphs of precisely-identified points in the vocal tract which effect the variable and gradient externalization of categorical representations that contain information about contrast. Since the categorical phonological representations are isomorphic with their phonetic correlates, they can be directly interpreted by the sensory-motor system.

The importance of phonetic measurements in the discovery procedure means these later two theories are both well-suited to the epistemological priority given to instrumental observation inherent in Laboratory Phonology (Cohn et al. 2018; Pierrehumbert et al. 2000), which assumes that phonological knowledge hews close to the bone of the physical world. It follows, in this view, that phonological knowledge is directly revealed through measurement of a wide array of physical correlates including both discrete and continuous mathematics, fine-grained variation, and statistical effects.

It is interesting to note that in Exemplar Theory and Articulatory Phonology both, variable, non-categorical representations are only at the featural or segmental level. The proposal to exploit gradient effects is never extended to higher-order structures like syllables, and more abstract objects such as empty timing positions and nodes do not seem to have any representational presence, since they have no phonetic echo. Furthermore, the generalizations made at the phonological level look much like the facts they are meant to explain.

However, Cohn (2007: 6) argues convincingly that phonologists should not conflate "*explanation of the source* of the patterns and the account of the *patterns themselves*." While phonological processes may come under grammatical control through phonetic effects (see Hyman 1976, 2008), the two domains are distinct: phonetic effects result from facts about human articulatory anatomy, coarticulation, aerodynamics, and the sensory motor system, while phonological processes are a form of knowledge (see also Hammarberg 1976: 361). Indeed, phonetic expression and phonological form need not even be isomorphic, since at the segmental level phonetic objects do not always behave phonologically as one might expect from the facts of their articulation (see Hamann 2014); there are fricatives that act like glides in Argentine Spanish (Harris & Kaisse 1999), a fortition of stops which surface as spirants in Campidanese Sardinian (Chabot in press.), a voiceless glottal fricative that acts like a non-laryngeal consonant in Yucatec Maya (Orie & Bricker 2000), a sibilant that acts like a vowel in Blackfoot (Goad & Shimada 2014), a sonorant that acts like a stop in Quechua (Gallagher 2019), a fricative [ð] that acts like a sonorant in Woods Cree (Starks & Ballard 2005), and so on. Relatedly, there are cases reported where objects which are phonetically indistinguishable from each other have different phonological properties, as in the case of Alaskan Inupiaq's "strong" and "weak" *i*, where the former causes palatalization but the latter does not (Compton & Dresher 2011).

In substance-free theories (Hale & Reiss 2008; Reiss 2018), representations are entirely void of phonetic information. Their role in grammar is much like that of the features of classic generativism in that they index natural classes and can be manipulated by phonological rules. The critical difference in the substance-free view is that features are not directly interpretable on any substantive terms, since they are purely symbolic. This purely formal approach establishes a modular bulkhead between gradient phonetics and categorical phonology, but it critically relies on an interface between the two domains that can translate from the symbolic mental objects in phonology to the physical expression of phonetics (§5.4).

The symbolic vocabulary of phonology includes abstract objects which cannot be directly isolated in the physical instantiation of utterances. That is, there is no direct record of them in the phonetic signal; evidence of their existence is revealed only through the generalizations which emerge through phonological behavior (see Kaye 2005). Comanche (Numic) provides an illustrative example of an interesting pattern belied by the phonetic facts. Similar to many Numic languages, in Comanche there is an alternation between the labial stop /p/ in initial positions and several allophones—[p], [v], [hp], and [hv]—which surface following morphological derivation that causes them to be medial instead of initial (Charney 1993: 9ff.). The conditioning environment is identical in each case: all four allophones co-occur in the intervocalic position. However, the exact allophone is predictable, since a given morpheme will always trigger the realization of the same allophone.

This presents an interesting problem. Since the conditioning context is always the intervocalic position, the explanation does not immediately seem to be at the level of phonology. Although the alternation seems to be an idiosyncratic property of specific morphemes and so an allomorphic property of the lexicon, this would require speakers to store four allomorphs for a great many lexical items. The analysis of a similar pattern that Sapir (1930: 62ff.) developed in his grammar of Piaute was phonological, and hypothesized a class of "final features" in the representations of the conditioning morphemes.

For Comanche, Charney (1993: 11) follows Sapir in assuming that conditioning morphemes include an inherent final feature in their underlying phonological representations that accounts for the pattern of alternation. The tradition in Numic scholarship is to mark final features as diacritics (1)[5]:

(1)	a.	LENIS	/VpV/ → [v]	
		/papi/	[pavi]	'older brother'
		/toja-paʔa⁼-ti⁼/	[tojavaʔati̥]	'on the mountain'
	b.	ASPIRATION	/VʰpV/ → [ʰv]	or [ɸ] or [v]
		/saa⁼piʰ-paʔa⁼/	[saapi̥ʰva]	'on the stomach'
			[saapi̥ɸa]	
		/kuit͡siʰ-paʔa=/	[kuit͡si̥va]	'on the throat'
	c.	FORTIS	/V⁼pV/ → [p]	
		/pa⁼pi/	[papi]	'head'
		/kʷasuʔu⁼-paʔa⁼/	[kwasjuʔupaʔa]	'on the shirt'
	d.	PREASPIRATION	/VHpV/ → [hp]	
		/aHpi/	[ahpi]	'father'
		/piH-potóóki/	[píhporóóki]	'motorcycle'

The LENIS form in (1a) has no final feature, it is the "true" intervocalic position and results in a lenited surface form, [v]. As for the forms in (1b-d), final features provide a kind of representational explanation for the variation seen in the realization of /p/: the difference is due to the distinct underlying forms of conditioning morphemes. The diacritics themselves, however, do not explain much, since they are essentially stipulated. Their presence can be reliably detected as a function of the surface form of /p/, but they merely recapitulate the description: /p/ is realized FORTIS when it follows the FORTIS diacritic.

[5]Data adapted from Charney (1993: 14).

The only way to both capture the phonological generalization and to provide explanation is to provide an explicit representational account of the pattern in phonological terms. Any autosegmental framework can do this by representing the FORTIS diacritic $^{=}$ as an empty timing position associated to lexical /p/, resulting in a representation where the segment is associated to two timing positions, even though it is not phonetically long—a *virtual geminate* (Ségéral & Scheer 2001). This explains two observations. The first is that /p/ surfaces as [p] here and not [v] because each allophone has a distinct structural configuration. The second is that /p/ does not lenite to [v] in this position since it is protected by *geminate inalterability* (Hayes 1986: 321).

The representation of PREASPIRATION is similar, producing an underlying /HC/, a configuration well-known in Germanic to be geminate (see for example Árnason 2011: 220ff. for Icelandic). Finally, it is interesting that ASPIRATION co-occurs with voiceless vowels. While the phonemic status of voiceless vowels in Comanche has been debated in the literature (see Armagost 1985 and Canonge 1957), it seems that each can be predicted based on the presence of the other in these contexts, with some variation concerning the realization of the aspiration, as in shown in (1b). That is, if there is aspiration in a surface form, it always follows a voiceless vowel. Since the context of lenited [v] is intervocalic, it would explain the conditioning context for [^{h}v] if it were also intervocalic, though distinct from the LENIS context in that it is conditioned by a preceding underlying voiceless vowel.

Thus the underlying representations of final features and the conditioning contexts of the pattern of allophony in (1) can be generalized using phonological vocabulary as in (2), where the segments are associated to autosegmental timing positions represented by X:

(2) a. /VpV/
X

b. /V̥pV/
X

c. /VpV/
X X

d. /VhpV/
X X

This cannot possibly be considered a complete analysis—it is meant to highlight the explanatory possibility inherent in one abstract approach. If the analysis relied only on surface-level observations, it would be impossible to provide anything other than an allomorphic account for the pattern in (1), entailing a loss of generalization since the pattern would be reduced to an idiosyncratic property of the lexicon.

However, it is possible to capture the underlying regularities in (1) through a phonological theory which posits abstract structures that do not correspond directly to a specific phonetic cue in the morphological environment. While these underlying structures in (2) cannot be recovered from simple surface inspection—they come about through interpretation in the light of the theory. The structures are abstract, but their existence is confirmed through the predictable effect that they produce on underlying /p/ and the explanatory power they provide (see Hyman 1970).

5.3 Computations

Though Sapir (1925) and the structuralists were concerned with contextual variation in sound patterns (see also Goldsmith 2008), it was not until generativism that patterns of predictable alternation began to be viewed as computational rule-based processes (Chomsky & Halle 1965, 1968; Halle 1962; Zwicky 1965). In the orthodox theory articulated in Chomsky & Halle (1968), speaker knowledge includes an ordered set of rules mapping between underlying forms and surface representations. As generative theories developed, research examined a number of questions concerning these rules, including their abstractness (Dresher 1981; Kiparsky 1968 [1973]), psychological reality (Hyman 1970; McCawley 1986), learnability (Donegan 1986; Hale & Reiss 1998; Halle 1978), computational tractability (Goldsmith 1993), generative power (Kiparsky 1972), and ordering (Kiparsky 1985).

One enduring question in the generative program is what a possible rule is (Reiss 2003: 335); that is, what kinds of computations can phonology effect? Essential to this question is determining how phonology interacts with with phonetic (Cohn 1998, 2007; Keating 1990) and morphosyntactic information (Newell 2008; Zwicky & Pullum 1986), as well as what shifting the "division of labor" between the three levels of description means for analysis and predictions (Bermúdez-Otero 2012). The division-of-labor question in particular has sparked a great deal of work on the scope of phonology, as the relative importance of phonetics and morphology in phonology has waxed and waned in different approaches.

In the initial formalism of Chomsky & Halle (1968), phonological rules had access to a variety of phonetic and morphological information, and this free-wheeling mixing of levels weakened generative theory in two ways. First, it meant that explanations for patterns often ended up being nothing more than pseudo-formal restatements of the generalizations themselves.

Second, the raw formal system had unlimited descriptive power, and was unable to make predictions about possible and impossible phonological processes—it overgenerated. One strategy to limit the power of the formal system was to limit the abstractness of underlying forms, in particular putative cases of absolute neutralization (Kiparsky 1968 [1973]), by reducing the ontological gap between underlying and surface forms. Following the assertion by Postal (1968: 55ff.) that there are natural relations between underlying and surface representations, substantive properties of underlying representations served as a ready formal means of preventing rules from generating phonetically unexpected or unnatural patterns (see Chabot 2021: 69ff. for discussion).

Asking what a possible rule is, then, is asking how rules are impacted by phonetics. The substance-free approach views phonetic effects as extragrammatical third factors, but many theories have taken the opposite tack, formalizing substantive facts and making rules sensitive to that content (as in Archangeli & Pulleyblank 1994; Hooper 1976; Stampe 1973; Donegan & Stampe 1979; Vennemann 1971, for example). In surface-oriented theories, there are lawful relationships between substantive elements in representations and the structural descriptions of rules, meaning that patterns in language which are not substantively motivated are not phonological, since rules have a functional motivation and are never phonetically arbitrary. Instead, non-substantive alternations must be interpreted as products of the morphosyntax or the lexicon. For example, since surface-oriented theories abjure abstract representations, only an allomorphic approach is available for making sense of the Comanche data in (1), accepting a loss of generalization in favor of computational simplicity.

Another major question concerning the form of computation is what the *function* of phonological computation is, and whether or not it is entirely serial, or if it is parallel. Rule-based computation proceeds serially, with the output of one rule being the possible input for a later rule; different rule orders have important implications for the kinds of language-specific surface patterns and cross-linguistic variation recorded in the literature (see Mascaró 2011 for discussion). Constraint-based theories assume that computation is partly or entirely parallel (Paradis 1988; Prince & Smolensky 1993 [2002]), with the function of transforming an underlying phonological lexical item into an optimal output form.

Like in rule-based theories, computation is about mapping between underlying forms and surface representations; the difference is that constraints are globally active, evaluating structures and penalizing those which would otherwise be ill-formed (after morphological concatenation for example). Constraints ensure that surface forms conform to general principles of well-formedness active in the grammar (see Odden 2011 and Uffmann 2011 for discussion). An assumption in classic Optimality Theory (OT) (Prince & Smolensky 1993 [2002]) is that markedness constraints are functionally motivated, sensitive to substantive properties in phonological representations. The interaction between the computational system and universal markedness constraints prevents grammars from producing phonetically unnatural output (Hayes & Steriade 2004), though it is still susceptible overgeneration that comes about through the mixing of levels and reference to morphosyntactic vocabulary; the theory imposes no constraints on the set of constraints.

The substance-free approach outlined in §5.2 is interesting in part because, despite its symbolic representations, it is compatible in both kinds of computational systems. While OT's markedness constraints are often substantive and so render the computational system sensitive to substance, by removing the requirement for all grammars to share the same universal set of constraints, OT can select optimal forms from among phonetically unnatural forms (Bermúdez-Otero & Börjars 2006; Iosad 2017). In rule-based formalisms, a number of substance-free accounts have been proposed (Bale et al. 2014, 2020; Reiss 2022; Samuels 2011b; Volenec & Reiss 2020).

Common to the entire SFP program is the modular hypothesis, which entails that computation works only over the symbolic vocabulary of phonology and thus is insensitive to substantive properties. Substance-free features are not records of any physical correlate, they are abstract symbolic counters for encoding differences. Substance-free computation is a symbolic theory in the Saussurean sense, where "[l]a langue est pour ainsi dire une algèbre"[6] (Saussure 1916 [1967]: 168). It is an algebraic theory in which computations operate over features, effecting changes in potentially unbounded sets of representations, not over sounds themselves (see Berent 2018).

If featural representations are not substantive, they may emerge on a language-specific basis as a function of what speakers need to build contrasts and natural classes (Dresher 2014; Odden 2022). If feature sets are not universal, they are potentially unbounded, but Hall (2007) and Dresher (2009) suggest that phonological computation operates *uniquely* over contrastive representations. The Contrastivist Hypothesis thus emphasizes the important role contrast plays in defining phonological systems, since only the number of features needed to make the contrasts of a particular language will emerge(Hall 2007: 20). This limits how computations interact with representations, placing limits on the set of possible phonological

[6]Language is in this sense an algebra.

grammars.

For example, in Comanche any iteration of a final feature is a good representative of its set; it is a kind of equivalence class. Rules apply to classes, not to sounds. In the case of the [p] allophone of /p/, the representation in (2c) is of a segment lexically associated to a single underlying segment that is associated to a second timing position through a computational process of association, shown as a dashed line (3):

(3) /k^{w}asuʔu$^{=}$-paʔa$^{=}$/ → [kwasjuʔupaʔa] 'on the shirt'

kw	a	s	j	u	ʔ	u		p	a	ʔ	a	
X	X	X	X	X	X	X	X	X	X	X	X	X

Like the empty timing position, this computation is abstract and non-veridical, producing a geminate structure with no concurrent increase in surface duration. It is domain specific and informationally encapsulated, conditioned only by and operating only over phonological representations. The interaction between the representational structure and the computational operation explains the observations concerning the pattern of allophony in Comanche in terms of speaker knowledge embedded in the mind.

5.4 Interfaces

The relationship between the abstract system of phonological knowledge and physical phenomena is limited to interactions at the interface between phonology and phonetics. The basic mapping function of all computational theories produces an output, in phonological production that means a surface form of representations. Surface forms are turned into motor instructions for speech, though how this happens is a psycholinguistic question rather than one about knowledge *sensu stricto*. Nevertheless, a theory of phonology needs an account of what the output of phonological computation is like, informed by how that output is interpreted at the interface between phonetics and phonology in production.

In Chomsky & Halle (1968), this interpretation was straightforward: the Naturalness Condition argued for by Postal (1968) assumes that mappings between surface representations and phonetic forms are not computational rules in the grammar, rather they are a kind of universal interface such that any representation could be directly interpretable phonetically. A feature such as [+nasal] can be interpreted phonetically by moving from a bivalent contrast to one that is scalar—for example [3.23nasal]—meant to represent the more gradient nature of surface representations. This allowed for feature bundles to be interpreted as phonetic cues in an essentially one-to-one way.

Generative theories of phonology differ in the details of this interface function, but most assume that features carry some inherent instruction for their physical production. Surface-oriented theories such as Articulatory Phonology (Brownman & Goldstein 1986, 1992) have the advantage of being explicit in how this process happens, as the more categorical representations "higher up" in the phonology are translated into coordinated gestural scores. In a sense, these representations are still symbolic models, but they include a great deal of information about timing and the movement of the articulators; presumably the instructions in gestural scores can be read into articulatory phonetics though direct translation.

In Element Theory (ET, see Backley 2011), a comparable relationship with the physical properties of speech is shared, and the basic representational unit, the element, characterizes the physical properties of segments. Here, this translational relationship is recast as one about acoustics instead of articulation—information about frequency peaks, Hz, and variable clines of energy intensity. Elements are "bigger" than features since a single element in an underlying representation is interpretable as a whole segment. In ET, this information is universally interpretable phonetically, but the details of that interpretation admit some slack. Despite their acoustic contents, one element may end up looking quite different on the surface in one language than it does in another, since the translation between the phonetic and phonological is not proscribed by any universal force or pressure—it happens as a function of the individual circumstances and needs of speakers, who need to maintain contrasts and build natural classes. There is then an inherent interface between phonology and phonetics, but one that is "noisy" since it admits variation and flexibility in its exact instantiation.

In formal, algebraic theories of phonology, a more elaborate interface is a conceptual necessity, since phonological representations are abstract and there must be a way for the discrete, symbolic representations of phonology to be mapped onto the continuous, gradient physical objects of speech, whether spoken or signed. The modular hypothesis says that physical properties are not directly interpretable in phonology, and one function of an interface is to transduce between the two distinct vocabularies. At the interface phonological features are translated into phonetic vocabulary for production and *vice versa* in perception (see Cohn 1998; Keating 1988, 1996; Hamann 2011; Kingston 2007, 2019; Reiss 2007 and Scobbie 2007 for discussion concerning the interface, as well as Boersma & Hamann

2008; Scheer 2014 for specific proposals). A modular interface relegates substantive effects in phonology to an extra-grammatical domain (see Barnes 2006 and Chabot 2021).

A modular interface also opens up the possibility that interpretation between phonological representations and phonetic instantiations happens in a modality independent fashion. Phonological knowledge of signed languages can be characterized as operating over basic atomic features in a categorical way (see Stokoe 1960 [2005]; Sandler 1993, 2012, 2014; Brentari 2011; Marshal 2011), and if that knowledge is embodied as abstract symbolic cognition, then phonological structure can be united across modalities (Samuels et al. 2022). In this view, phonetic interpretation happens in a language-specific way (cf. Boersma 1998; Cowper & Hall 2015; Cyran 2014; Keating 1985, 1988; Kingston & Diehl 1994; Pierrehumbert 2003).

An interface theory capable of mapping between abstract phonological structures and their phonetic correlates needs a language-specific scope (Chabot 2019; Scheer 2022a); any interface which must interpret abstract structure works this way, as for example the interface between phonology and the morphosyntax, which maps form and meaning in an arbitrary way. The interface between phonetics and phonology only interprets—it is purely translational and performs no computation itself. For example, it cannot insert or remove features or change association lines. A statement of the expression in Comanche of representational structures is provided for the singleton LENIS form (4a), and for the geminate FORTIS form (4b):

(4) a. /p/ ↔ [v]
|
X

b. /p/ ↔ [p]
⁄ ¦ |
X X

The interface relationship in (4) is non-veridical, since the two timing positions of the underlying representation in (4b) are not expressed directly as increased duration of the surface segment.

In §4 I discussed perception as an information-processing capacity which maps between representations in the mind and represented objects in the physical world that is, at least in part, non-veridical. The view of phonology that I present here is one such information-processing capacity, modular in nature, with domain-specific representations, computations, and interfaces which categorizes over a subset of grammaticalizable features in the speech stream, building symbolic structure in human minds. A theory of phonology is a theory of the knowledge of those things, its fundamental task is to determine what they are like. I have argued that there is no reason to assume that any mental representation contains the properties of the represented objects, and thus there is no reason that phonological representations are high-fidelity reproductions of sound, or that phonological computations should be constrained by the properties of the physical world in which sound exists.

6 Conclusion

The epistemological discussion herein concerns the nature and substantive content of phonological knowledge. Phonology *qua* model of cognition is abstract; it is a computational interpretation of the world, not a high-fidelity reproduction of it. Considering phonology this way allows for a very fine understanding the nature of that knowledge and what phonology shares with other cognitive systems. I have hoped to show that the extent to which a theory recapitulates substantive facts has an impact on that theory's empirical remit and explanatory value.

There is, however, a further consequence for phonological inquiry that follows from Marr's model of information processing (§4.2), in which the computational theory circumscribes the empirical domain of psycholinguistic and neurolinguistic research. For example, in the neurolinguistic domain, phonological theory can be used to investigate how the brain instantiates phonological representations and computations by identifying correlates between neurological structure and response patterns to aspects of phonological patterning, what Embick & Poeppel (2015: 360) refer to as *correlational neurolinguistics*. Determining what the computations performed in the brain are like is one of the principle research questions in cognitive science (Poeppel & Embick 2005). Since theories present a range of empirical stances, where a given theory falls along the arc of the pendulum which swings between substance-full and substance-free phonology has important consequences for what kinds of data inform investigations of the neurobiological instantiation of phonology. An explicit theory of the content of phonological representations limits the hypothesis space and provides a deeper kind of explanation for phonological structure. A Minimalist theory of phonology is a set of related claims concerning phonological knowledge, the basic assumption is that substantive facts about speech production are not necessary for explanation of those claims.

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