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*A subsymbolic approach to phonological primitives**

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1 Introduction

The basic claims in this paper are the following :

- (1) a. There are two non-substantive levels in phonological theory :
 - a subsymbolic (non-representational) level and
 - a symbolic (representational) level.
- b. The units of the subsymbolic level are the real phonological primitives. These primitives are pure forms ; as such, they lack any intrinsic phonetic content.
- c. The symbolic units of the representational level, such as features or components, are not primitive ; they derive from the *mise en forme* of substance by subsymbolic organization.

The idea underlying (1b) ultimately dates back to Trubetzkoy's (1939) 'logical classification of phonological contrasts' as well as to Hjelmslev's (1943) 'glossematic' theory. More recently, the evolution from the earlier CV-representation of the skeleton (McCarthy 1979, Halle & Vergnaud 1980, Clements & Keyser 1981, 1983) to an homogeneous chain of 'pure' units (Vergnaud 1982, Kaye & Lowenstamm 1983) was, in our sense, a major step towards the definition of an autonomous level of analysis in phonology. Such units are empty *per se* of any kind of substantive content, and represent mere timing positions, so that a new distinction could be made between 'deux réalités linguistiques différentes : les places que comporte un item lexical et les unités phonétiques (...) qui les occupent' (Encrevé 1988 : 146). Our point here is that just as the skeleton lacks qualitatively different primes like 'CV', so do the primitives of phonological material lack any symbolic content, unlike binary features or unary components such as 'I A U' and van der Hulst's (1994) 'C V'.

Concerning (1c), the derived nature of current symbolic units could also be paralleled with the nature of segments in skeletal representations :

just as segments result from the association of phonetic material with timing units, so do 'I A U' and the like emerge from operations of some kind on subsymbolic objects. It follows that just as the earlier linear representation of the spoken chain is actually generated by autosegmental theory, so must the shape of phonological systems result from the present theory. Our aim, thus, is ultimately a theory of system morphogenesis.

The crucial advantage of this approach is that it formally motivates phonological representations. In § 2, it is shown why current symbolic theories of phonological primitives (either binarist or unarist) are formally arbitrary. The problems met by previous work are solved within a theory based on (1a-c), in which infrasegmental symbols (§ 3) and, thereby, segments (§ 4) emerge from two operations on a set of two subsymbolic units x and y . Finally, we briefly discuss in § 5 some issues of the theory, namely the relation between consonants and vowels.

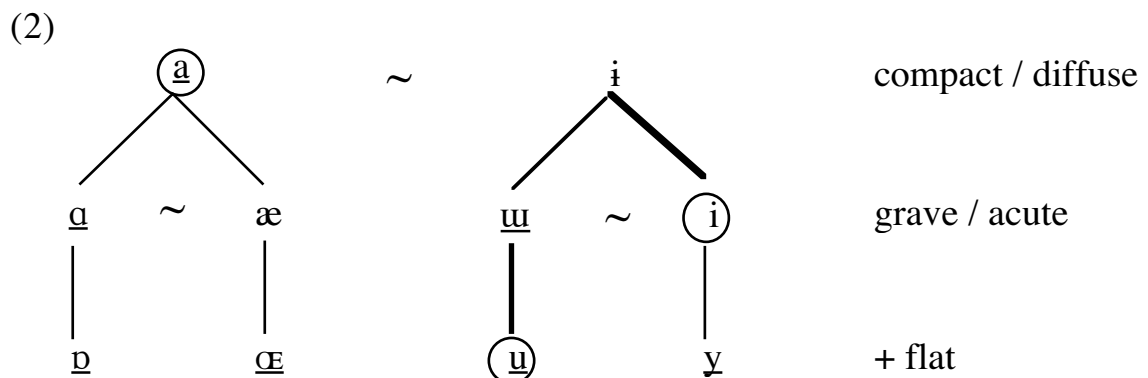
2 The arbitrariness of symbolic representations

Four problems arise from current symbolic representations of segments (and vowels in particular). They are all connected with the question of the naturalness of representations.

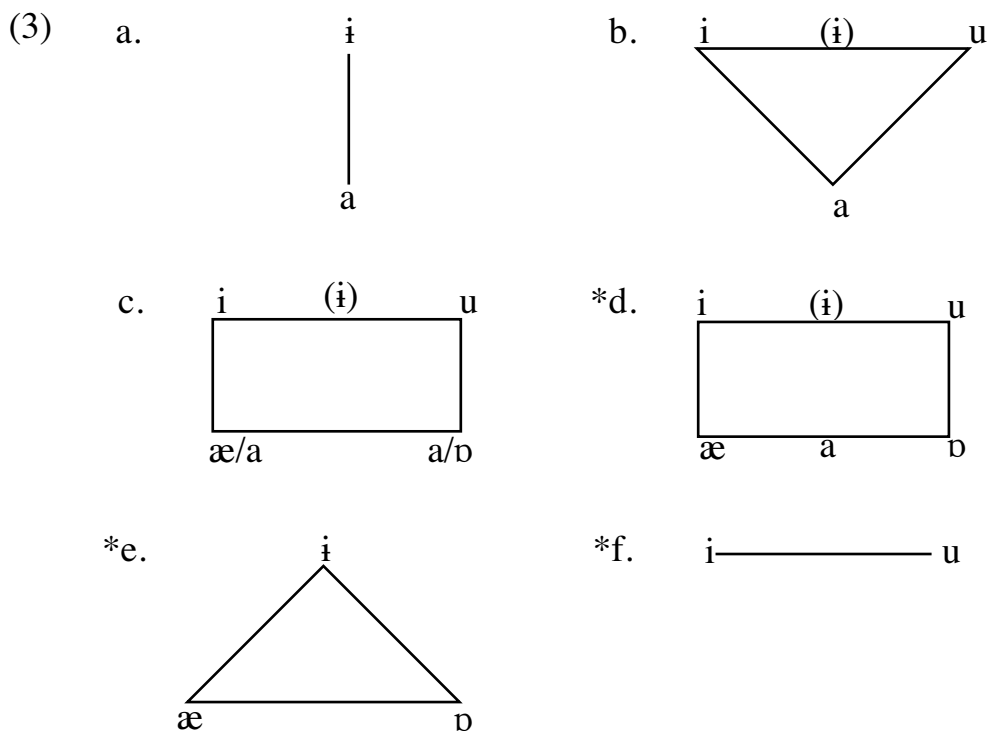
2.1 Why do languages have /i a u/ ?

The first problem with standard approaches to vowel structure is that, from Jakobson, Fant & Halle's (1952) features to Kaye, Lowenstamm & Vergnaud's (1985) elements, through Chomsky & Halle's (1968) classical theory, the optimal, unmarked relationships between infrasegmental components remain formally arbitrary. There is, indeed, no basic difference between *SPE* 'redundancy rules' and axiomatic statements such as : 'The optimal, unmarked stops are mellow ; the optimal, unmarked stridents are continuant' (Jakobson & Waugh 1979 : 140).

Let us take, for example, the hierarchical representation of vocalic features within Jakobson, Fant & Halle's (1952) binarist framework :



(Bold lines stand for optimal feature associations ; underlined vowels represent the marked term of each feature ; primary vowels are circled.) Only *ad hoc* stipulations imply that : (i) ‘grave’/‘acute’ is dominated by ‘compact’/‘diffuse’ ; (ii) ‘grave’/‘acute’ is optimally associated with ‘diffuse’ ; (iii) ‘flat’ is optimally associated with ‘grave’. As a result, nothing in this feature theory (nor in any other theory) tells us why, among the following vowel systems, (3b) is optimal, unmarked ; why (3a,c) are marked ; and why (3d-f) are never found, being virtually impossible, ill-formed systems :



(3a) stands for a ‘linear’ system, like those of some North-West Caucasian languages ; (3f) is its ‘horizontal’ counterpart, which would be allowed if ‘grave’/‘acute’ were the primary contrast. The ‘upside down’ triangle in (3e), which is the mirror image of (3b), would be a possible system if ‘grave’/‘acute’ were optimally associated with ‘compact’. Likewise, the impossibility of (3d) shows that a system can have more than two high vowels, but two low vowels at most ; in other words, there cannot be more low vowels than primary high vowels. Let us add that no language exhibits a /y/ ~ /u/ contrast instead of /i/ ~ /u/, as would be the case if ‘flat’ were optimally associated with ‘acute’.

The arbitrariness of formal accounts of feature organization was one of the major reasons for the appearance of unarist theories, in which the primary vocalic values are assumed to be primitive ; hence the I A U-‘components’ or ‘elements’ or ‘particles’ of dependency phonology (see, for example, Anderson & Ewen 1987), charm and government theory

(Kaye, Lowenstamm & Vergnaud 1985), and particle phonology (Schane 1984, Carvalho 1993, 1994), respectively ; such units are also posited in van der Hulst's earlier work (for example, van der Hulst 1989). However, problems of arbitrariness arise also from unarist theories.

The first is intrinsic circularity. Indeed, nothing but typological evidence tells us why there should be three and only three particular vocalic primes ; conversely, nothing but the presupposition of 'I A U' explains typological data. We are here, in a way, at the summit of arbitrariness, simply running after the facts. Moreover, there are still three obstacles that resist unarist theories.

2.2 Two relations for three primes

The second problem with 'IAU'-theories is that the logical and perceptual relations between the three vowel primitives are not of the same nature. Actually, all unarist theories fail to give a natural answer to the following questions : (i) why do I,U/A and I/U interactions involve 'gradual' *versus* 'equipollent' relations respectively (see Trubetzkoy 1939) ? (ii) why is the I,U/A relation perceptually 'continuous', while the I/U relation appears to be perceptually 'categorical' (see Stevens 1972) ? It should be noted that the first relation underlies the symmetry currently observed between /i/ and /a/, on the one hand, and between /u/ and /a/, on the other hand ; hence the well-known proportion /i/ : /e/ :: /u/ : /o/.

The fact that the three sides of the vowel triangle are not equivalent was at the source of the notion of 'charm', which has been the sole attempt to solve the problem. Given A⁺, I⁻ and U⁻ (I⁰, U⁰ in Kaye, Lowenstamm & Vergnaud 1988), where '+' and '-' (or '0') represent a sonority / constriction opposition, it was assumed that :

- (4) a. Two unlike-charmed elements attract each other.
- b. Two like-charmed elements repel each other.

Charm was also assumed in Carvalho's (1993) particle theory, where the 'sum' of I and U in /y/ was opposed to the (far more frequently observed) relation of 'complementarity' between I and A in /e/, and between U and A in /o/. However, the 'physicalistic' assertions in (4) imply that charm is an idiosyncratic property of the I A U-elements, such that I/U and A presuppose negative (or neutral) and positive charm, respectively. Now, these implicational statements seem as arbitrary as *SPE* 'redundancy rules' : what is the reason for assuming that I and U are like-charmed, but not I and A ? More specifically, why is a sonority value like '+' or '-' associated with a particular element ? The reason lies, of course, in the intrinsic content of the element. Thus, palatality ('I') and roundness ('U') are optimal when associated with tongue rising ('-'), while pharyngeal

constriction ('A') is optimal when associated with lowness ('+'). It is clear that the justification of such a system is strictly based upon the symbolic content of its primitives.

2.3 A dissymmetric triangle

A third problem within current approaches to vowel structure arises from markedness dissymmetry between the terms of the 'categorical' relation, i.e. between I and U. Actually, /i/ and /e/ are known to be unmarked *vis-à-vis* /u/ and /o/ : they appear as neutral vowels wherever there are no high ([i/u]) nor mid ([ə]) *schwas*. The examples are numerous, as is shown by the widespread cases of epenthetic /i/ and /e/, since many vowel systems (those, for example, of the /i e a o u/-type) lack any central vowel. Markedness dissymmetry is revealed by several other facts. In vowel reduction processes, for instance, palatality is often deleted when /e/ changes into the indeterminate vowel [ə], whereas roundness is preserved in /o/-reduction (as in Portuguese, Catalan, etc.). We could add the directionality of sound change : thus, while /u/ > /y/ is possible and commonly attested, a 'spontaneous' change like /i/ > /y/ seems impossible. Markedness dissymmetry is currently accounted for in terms of feature un(der)specification of /i/ and/or /e/ (see Archangeli 1984, 1988). The actual question, however, is the following : why are /i/ and /e/ more likely to be un(der)specified than any other peripheral vowel ? Now, unarist theories miss the point once again.

Let us assume that /a/ is marked *vis-à-vis* its 'empty' diffuse counterpart /i/ (cf. § 2.4). It follows from I/U dissymmetry that the A/I relation links a marked term to an unmarked term, while the A/U relation associates two marked terms. Indeed, /i/ and /a/ appear as fully antinomic vowels. On acoustic grounds, the mean values of F_2-F_1 show a complete opposition between the 'compact' vowel /a/ and the optimally 'diffuse' (i.e. 'acute') vowel /i/. In articulatory terms, there is a comparable contrast between /i/, which is [+high], [+front], [+ATR], and /a/, which is [+low], [-front] and [-ATR] : thus, 'emphasis' (pharyngeal constriction) 'est exactement le contraire de la palatalisation' (Delattre *apud* Jakobson & Waugh 1979 : 113).¹ Finally, functional evidence for this antinomy is brought by /i/-neutrality in RTR-harmony (Nez Percé, Khalkha Mongolian), and by /a/-neutrality in ATR-harmony (Ijo, Dagara).

The relation between the marked vowels /a/ and /u/ seems more subtle. Both are [+back] ; both are, in a way, 'compact' vowels, if we take into account the mean values of F_2-F_1 . It has often been observed that there is an acoustic and perceptual link between roundness and velarity (cf. Jakobson & Waugh 1979 : 111-117). It should also be noted that no language uses the contrast between velarization and pharyngealization (Ladefoged 1971 : 63f.) ; actually, both seem to be variants of what could

be called a ‘backness syndrome’. Would there be, then, some acoustic and perceptual analogies between roundness and pharyngeality ? Jakobson & Waugh (1979 : 116) mention the case of words borrowed from Arabic in Uzbek and some Bantu languages, where emphatic consonants are replaced by rounded consonants : as an example, in Swahili *swahili* ‘coast’, /s^w-/ comes from Arabic /ṣ-/. A comparable case is provided by the labiodental fricative of Portuguese words like *alfaiate* ‘tailor’, *alface* ‘lettuce’, etc., which derives from Arabic [ħ].

May we deduce from such analogies some particular affinity between the U and A-components ? The idea might seem paradoxal, since, as was outlined in § 2.2, there is a proportional relationship between /i/ and /u/ *vis-à-vis* /a/. But, precisely, this is not always the case, as is shown by rather different facts. For example, in Portuguese vowel reduction, /o/-roundness *and* /a/-lowness are preserved, whereas /e/-palatality is deleted (see Carvalho 1994) ; in Turkish vowel harmony, /a/ is sensitive to I- but not to U-harmony. Note that the contrary is not attested elsewhere : A is sensitive at least to its antinomic counterpart.

On the other hand, the paradox exists only if we set value on the idea of a vowel ‘triangle’. Now, this is a mere iconicity, which dates back to Hellwag (1781), and an inadequate iconicity, since it implies symbolic primitives with all their disadvantages. We shall thus seek another formalism and another type of symmetry, in which /a/ and /u/ are, say, two ‘states’ of the same thing.

2.4 Too many zeros ?

The fourth problem met by symbolic theories is that of the ‘zero vowel’. Three vowels at least are known to play such a role in the world languages : [ɨ], [ɯ] and [ə]. Hence the following dilemma. If these three vowels must be given the same representation because of their emptiness, then why is there such a phonetic variation of the ‘zero vowel’ ? If this variation accounts for different representations, then why do they all play the same role ?

There is a large amount of incertitude and arbitrariness about the vowels noted [ɨ] and [ɯ]. The choice between either of these symbols is probably due to mere notational convenience : thus, Turkish *ı* is currently noted [ɨ] in spite of its well-known backness and its low F₂.² It may also be the case that the variation between [ɨ] and [ɯ] reflects their perceptual proximity : both vowels are so closely related that there is no [ɨ] ~ [ɯ] contrast attested, according to the data supplied by Crothers (1978). We shall therefrom infer that there is only one ‘high *schwa*’, which will be arbitrarily noted /ɨ/. Its phonetic realizations vary from language to language between [ɨ] and [ɯ] ; in other words, its F₂ oscillates from ±1900 Hz to ±1200 Hz.

This claim is supported by the results of personal observations on the acoustic cues of /i/ within particular vowel systems. Its sole relevant characteristic is a low (and unmarked) F₁ ; hence the ‘diffuse’ feature of /i/ *vis-à-vis* /a/. Its F₂, however, appears to be phonologically redundant and, therefore, perceptually non-existent ; hence the ‘empty’ nature of /i/. Actually, it results from our research that the mean value of the F₂ of /i/ in a given system depends either on the F₂ of /a/, or on the F₂ of /i/ and /u/. The first case can be found in Turkish and Korean, where /i/ is realized as [u], its F₂ being equal to that of /a/ (ca. 1200-1400 Hz). The second case is illustrated by Polish, where /i/ is realized as [i], the F₂ of which (±1900 Hz) is equidistant between /i/ (±3000 Hz) and /u/ (±650 Hz), just as the F₂ of /a/ (±1400 Hz) is with respect to /ɛ/ (±1900 Hz) and /ɔ/ (±930 Hz), according to Patryn’s (1987) analysis.³ We shall assume here that both strategies are mutually exclusive in a particular language ; hence the unicity of the high null vowel.

It remains that the /i/ ~ /ə/ opposition is well attested, for example in Naga (where /i/ = [u]). How can this be represented ? We can certainly increase the number of symbolic primitives by adding |ə| (the central component in dependency phonology) or I⁺ (the ATR element in charm theory) in order to represent /ə/ and /i/ respectively. In this case, however, nothing except, once again, *ad hoc* stipulations tells us why those elements, and not |i|, |a|, |u| and I⁻, A⁺, U⁻, have some or all the properties of a null element : thus, French, Catalan and Portuguese /ə/ are often deleted, behave as epenthetic vowels, and, like Russian and Polish /i/, cannot occur word-initially.

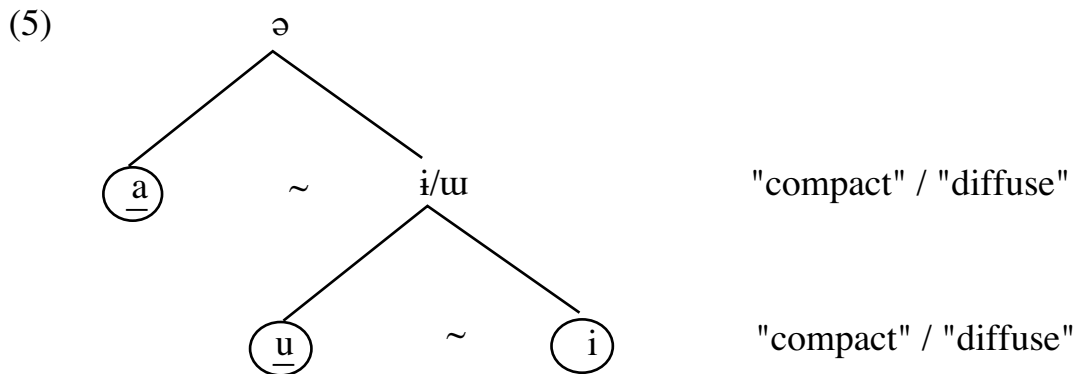
We can also decide that either of these vowels equals the empty set. This is the solution adopted by Schane (1984), who says that /i/ is without particles, and by Anderson & Ewen (1987 : 220) for [ə] as a reduced vowel, i.e. as ‘the product of the neutralisation of the other vowel components’. According to a relativistic trend which is now represented by Radical Underspecification Theory (see Archangeli 1984, 1988), the choice of /i/ or /ə/ would simply depend on language-specific parameters : thus, Ø = /ə/ in French, but Ø = /i/ in Russian, etc.. This representation of the empty vowel is formally motivated, contrary to the solution based on further primitives. Such a relativistic view, however, has two problematic consequences for naturalness. Firstly, just as in RUT, (‘complement’) rules are required in order to specify the phonetic value of the null segment for each language.⁴ Secondly, and above all, the phonological specificity of /i/ and /ə/ is obscured. Indeed, nothing, then, tells us why /ə/, contrary to /i/, which is always opposed to /a/, may function as a reduced vowel, resulting from the neutralization of some or all vocalic contrasts. Likewise, nothing, then, explains why I∧A∧U (i.e. ‘zero’) *and*

IvAvU (= /ö/) give /ə/-like vowels, i.e. equidistant (ca. 500 / 1500 / 2500 Hz) and therefore indeterminate formants, while I \wedge U = /i/ but IvU = /y/ ! In sum, there must be, not one, but two zero vowels : /i/ and /ə/ ; there are, then, two kinds of ‘zero’ in vowel systems. Any theory of infrasegmental structure must provide a non-arbitrary account of this.

3 Components *versus* operations

3.1 Four questions

The preceding remarks lead us to propose, as a mere working hypothesis, the graph in (5) for representing the structure of relations between primary vowels (circled below). Each ‘split’ stands for an opposition, the marked term of which is underlined :



The graph in (5) attenuates the four difficulties mentioned in § 2. Firstly, the arbitrariness of unmarked relations between features is ruled out : in (5) there is no hierarchical organization of qualitatively different oppositions, that is, of symbolic objects such as ‘compact’/‘diffuse’ *versus* ‘grave’/‘acute’, etc. (cf. § 2.1) ; the graph results from the reiteration of one single opposition, which could be labeled as ‘compact’ (marked) / ‘diffuse’ (unmarked), assuming that ‘compactness’ here follows from the F₂-F₁ differential (cf. § 2.3). The perceptual basis for this unique feature is the determination of F₁ at the first split, and of F₂ at the second split.

Secondly, contrary to dependency phonology, Schane’s particle theory, and van der Hulst’s (1989) notion of ‘dominance’, (5) formally motivates the existence of two different interactions between primary vowels (cf. § 2.2) : one between terminal vertices of different levels (/a/ and /u i/), the other between terminal vertices of the same level (/u/ and /i/).

Thirdly, I/U dissymmetry (cf. § 2.3) follows from the proportion in (5) /a/ : /i/ :: /u/ : /i/, where /u/ appears as a ‘second-degree compact’ (i.e. marked) vowel, while /i/ is, say, a ‘squared diffuse’ (unmarked) vowel.

Fourthly, the specific characteristics of each ‘empty’ vowel (cf. § 2.4) are also accounted for in (5). On the one hand, as the initial vertex, /ə/ is the ‘primeval soup’, the stage at which ‘symmetry’ is still ‘unbroken’, which is shown by formant equidistance. On the other hand, /i/ is the unmarked term resulting from the break of symmetry. While /ə/ is an ‘A/I/U-potential’, containing in itself the three primary values, /i/ is only an ‘I/U-potential’ which cannot be defined but *vis-à-vis* /a/.

However, the basic problems remain. Any attempt to formalize the graph in (5) involves four questions at least, three of which are mere reformulations of preceding points :

- (6) a. What defines the markedness values of the vertices in (5) ?
- b. Why is the number of splits limited to two in (5) ?
- c. What allows /i/-split and forbids /a/-split in (5) ?
- d. What determines perceptual ‘continuity’ between /a/ and /u i/ but ‘discreteness’ between /u/ and /i/ in (5) ?

The question in (6a) follows from naturalness considerations : according to the present approach, markedness, like any phonological object, must be shown to derive from the theory. As for (6b), it is clear that there must be only two splits, since there are only three primary vowels and two empty vowels. The question in (6c) involves the reasons for the impossibility of an ‘upside down’ triangle like the one in (3e). Finally, the interesting point in (6d) is to determine why the converse case (i.e. ‘discreteness’ between /a/ and /u i/, and ‘continuity’ between /u/ and /i/) is disallowed. These are the topics of the following chapters.

3.2 The subsymbolic organization

Within classic structural and generative theories, (privative) oppositions are viewed as *relations* between marked and unmarked terms ; hence the current componential conception of the segment, where components are the terms of the successive relations that progressively specify different indeterminate states (Praguian ‘archiphonemes’). It will be assumed here that, far from being a simple relation, any determination of antinomic markedness values is a complex *operation* on a given indeterminate state.

Let $p \rightarrow (q \sim r)$ be a split like the ones in (5), where p is the indeterminate state for the opposed markedness values q and r . We shall posit : (i) $p = (q * r)$, where p, q, r will be called ‘particles’, and $*$ is a binary operation; hence $\emptyset = (a * \dot{i})$ and $\dot{i} = (u * i)$ in (5) ; (ii) $q = \neg r$, that is, q and r are complementary particles in p ; such are, thus, \dot{i} and a in \emptyset , and i and u in \dot{i} . Hence the identity of $*$. If a and \dot{i} are complementary, then the binary operations on a and \dot{i} are also complementary, as are the *sum* and the *product*, the other two Boolean operations.

The vertices of (5) will then be viewed as particles, i.e. operations. Particles are elements of a Boolean algebra V such that :

- (7) $V = \langle x, y ; \oplus, \otimes, \emptyset, u \rangle$, in which :
- x, y are Boolean variables, i.e. arbitrary elements such that $x = 1$ if, and only if, $\neg x = 0$;
 - \oplus and \otimes are binary operations on $\{x, y\}$ such that

$$x \oplus y = (x \wedge \neg y) \vee (y \wedge \neg x) \quad [= (x \vee y) \wedge (\neg x \vee \neg y)],$$

$$x \otimes y = (x \vee \neg y) \wedge (y \vee \neg x) \quad [= (x \wedge y) \vee (\neg x \wedge \neg y)] ;$$
 - \emptyset and u are the Boolean zero and unit (henceforth noted ∂^0 and ∂^1 respectively).

As can be seen in (7a), x and y , like skeletal units, lack any intrinsic content. These are what we call ‘subsymbolic’ units (cf. §§ 1, 5.1).

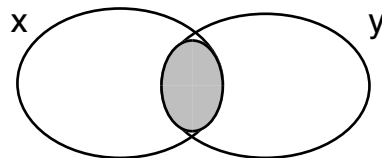
Particle *markedness* will be determined by the values of operations : a particle p is marked if, and only if, $p = 1$; p is unmarked if, and only if, $p = 0$. Hence the answer to the question in (6a). Particle identity follows from markedness :

(8) *Definition of particle identity :*

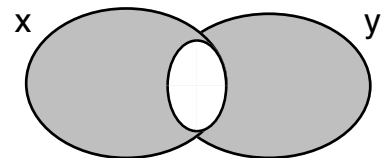
Two particles p and q of V are equal if, and only if, for any value of x and y , p and q are like-marked.

V has eight and only eight elements. The eight particles are defined in (9) for all values of x and y . Six of them (A, Y, I/U, E/O) have variable markedness values ; they will be said to be *chromatic* particles. ∂^0 and ∂^1 (read : ‘schwa’), which have constant markedness values, are *achromatic* particles.

(9) a. **A** = $x \otimes y$

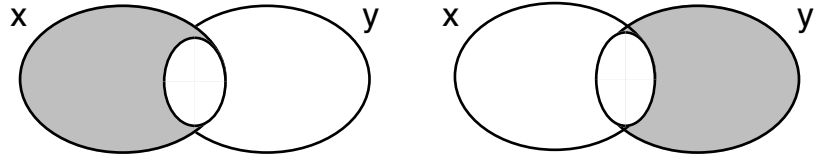


b. **Y** = $x \oplus y$



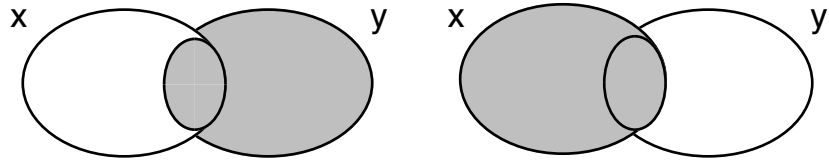
$x = y = 0$	$x \otimes y = 0 \otimes 0 = \mathbf{1}$	\neq	$x \oplus y = 0 \oplus 0 = \mathbf{0}$
$x=0 \ y=1$	$x \otimes y = 0 \otimes 1 = \mathbf{0}$	\neq	$x \oplus y = 0 \oplus 1 = \mathbf{1}$
$x=1 \ y=0$	$x \otimes y = 1 \otimes 0 = \mathbf{0}$	\neq	$x \oplus y = 1 \oplus 0 = \mathbf{1}$
$x = y = 1$	$x \otimes y = 1 \otimes 1 = \mathbf{1}$	\neq	$x \oplus y = 1 \oplus 1 = \mathbf{0}$

$$c. \mathbf{I/U} = x \otimes (x \oplus y) / (x \oplus y) \otimes y \quad [= x \oplus (x \otimes y) / (x \otimes y) \oplus y]$$



$x = y = 0$	$x \otimes (x \oplus y) = 0 \otimes 0 \oplus 0 = \mathbf{1}$	$=$	$(x \oplus y) \otimes y = 0 \oplus 0 \otimes 0 = \mathbf{1}$
$x=0 \quad y=1$	$x \otimes (x \oplus y) = 0 \otimes 0 \oplus 1 = \mathbf{0}$	\neq	$(x \oplus y) \otimes y = 0 \oplus 1 \otimes 1 = \mathbf{1}$
$x=1 \quad y=0$	$x \otimes (x \oplus y) = 1 \otimes 1 \oplus 0 = \mathbf{1}$	\neq	$(x \oplus y) \otimes y = 1 \oplus 0 \otimes 0 = \mathbf{0}$
$x = y = 1$	$x \otimes (x \oplus y) = 1 \otimes 1 \oplus 1 = \mathbf{0}$	$=$	$(x \oplus y) \otimes y = 1 \oplus 1 \otimes 1 = \mathbf{0}$

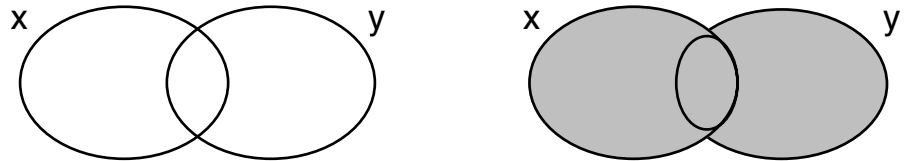
$$d. \mathbf{O/E} = x \oplus (x \otimes y) / (x \otimes y) \oplus y \quad [= x \otimes (x \oplus y) / (x \oplus y) \otimes y]$$



$x = y = 0$	$x \oplus (x \otimes y) = 0 \oplus 0 \oplus 0 = \mathbf{0}$	$=$	$(x \otimes y) \oplus y = 0 \oplus 0 \oplus 0 = \mathbf{0}$
$x=0 \quad y=1$	$x \oplus (x \otimes y) = 0 \oplus 0 \oplus 1 = \mathbf{1}$	\neq	$(x \otimes y) \oplus y = 0 \oplus 1 \oplus 1 = \mathbf{0}$
$x=1 \quad y=0$	$x \oplus (x \otimes y) = 1 \oplus 1 \oplus 0 = \mathbf{0}$	\neq	$(x \otimes y) \oplus y = 1 \oplus 0 \oplus 0 = \mathbf{1}$
$x = y = 1$	$x \oplus (x \otimes y) = 1 \oplus 1 \oplus 1 = \mathbf{1}$	$=$	$(x \otimes y) \oplus y = 1 \oplus 1 \oplus 1 = \mathbf{1}$

$$e. \partial \mathbf{0} = (x \otimes y) \otimes (x \oplus y)$$

$$f. \partial \mathbf{1} = (x \otimes y) \oplus (x \oplus y)$$



$x = y = 0$	$(x \otimes y) \otimes (x \oplus y) = 1 \otimes 0 = \mathbf{0}$	\neq	$(x \otimes y) \oplus (x \oplus y) = 1 \oplus 0 = \mathbf{1}$
$x=0 \quad y=1$	$(x \otimes y) \otimes (x \oplus y) = 0 \otimes 1 = \mathbf{0}$	\neq	$(x \otimes y) \oplus (x \oplus y) = 0 \oplus 1 = \mathbf{1}$
$x=1 \quad y=0$	$(x \otimes y) \otimes (x \oplus y) = 0 \otimes 1 = \mathbf{0}$	\neq	$(x \otimes y) \oplus (x \oplus y) = 0 \oplus 1 = \mathbf{1}$
$x = y = 1$	$(x \otimes y) \otimes (x \oplus y) = 1 \otimes 0 = \mathbf{0}$	\neq	$(x \otimes y) \oplus (x \oplus y) = 1 \oplus 0 = \mathbf{1}$

These eight particles are what we call ‘symbolic’ units (cf. §§ 1, 5.1). As will be seen, the symbolic content associated with the particles in (9) is no longer arbitrary ; actually, it follows from the theory.

3.3 The emergence of form and content

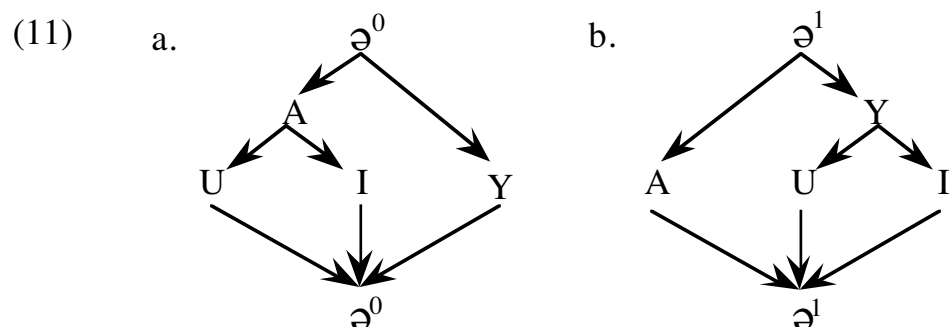
It follows from the above that $\partial^\alpha = (p * p) = (p \perp \neg p)$. Hence :

(10) a. *Theorem* : There are at most three different particles $p, q, r (\neq \partial^0, \partial^1)$ in V such that $\partial^\alpha = (p * q * r) = (p \perp q \perp r)$.

b. *Proof* : $\partial^\alpha = (p * (q * \neg q)) = (p \perp \neg(q * \neg q)) = (p \perp (q \perp \neg q))$.

The answer to the question in (6b) follows from (10a) : the basic shape of phonological systems is necessarily ternary. This is, thus, a demonstrable statement here, which is not the case with all other theories (cf. § 2.1).

Let G_{∂^α} be a circuit defined in V where ∂^α is the initial and terminal vertex, and where divergent and convergent edges map complementary operations. It follows from (10b) that there are two circuits G_{∂^α} such that $\partial^\alpha = (p * q * \neg q) = (p \perp q \perp \neg q)$ where q and $\neg q$ are *disjunct* particles, i.e. such that $q \neq \neg q$ if and only if $x \neq y$: cf. (9c,d). This is shown in (11), where $\partial^0 = A \otimes Y = U \otimes I \otimes Y = U \oplus I \oplus Y$ in G_{∂^0} , and $\partial^1 = A \oplus Y = A \otimes U \otimes I$ in G_{∂^1} ; ∂^α is reiterated for the sake of clarity.



Let us assume that each vertex of (5) corresponds to one and only one particle of V . It follows that vowel particles are those of one and only one of the complementary circuits G_{∂^0} and G_{∂^1} in (11). Let G_{∂^α} be the *vowel* circuit ; $G_{\partial^{-\alpha}}$ will be supposed to map *consonant* organization.

‘Moraicity’, that is, quantitative *markedness*, suggests the hypotheses in (12) on the phonological content of ∂^0 and ∂^1 . (The IPA symbols in (12) represent the segments resulting from the sole referred particle : cf. § 4.)

(12) a. $\partial^0 =$ ‘zero’, ‘consonant’ (/ʔ/)
 b. $\partial^1 =$ ‘mora’, ‘vowel’ (/ə/)

As a result, while A U I in (11b) are the current ‘A U I’ vocalic elements of unarist models, U I Y in (11a) are the primary consonantal places that could be represented as ‘P T K’ respectively. This complementarity-based

view of the relation between consonants and vowels is supported by the interesting ‘symmetry effect’ shown in (11). Indeed, both triplets of particles in (10b) have two and only two common elements. Now, while there is a large amount of evidence for equating ‘U’ to ‘P’, and ‘I’ to ‘T’, the remaining vocalic and consonantal elements ‘A’ and ‘K’ do not appear to be equivalent, contrary to Jakobson, Fant & Halle’s (1952) feature theory. We shall turn to this and related issues in § 5.2.1.

Vowel particles, i.e. the vertices of G_{∂^1} , have the phonological content given in (13), according to whether they are marked or unmarked :

(13) a.	A^1	= RTR	(/a,ɑ/)	A^0	= low	(/æ,a/)
b.	Y^1	= I^0+U^1	(/y/)	Y^0	= high	(/i,u/)
c.	$(I/U)^1 = U^1$	= round	(/u/)	$(I/U)^0 = I^0$	= front	(/i/)
d.	$(E/O)^1 = O^1$	= U^1+A^0	(/O/)	$(E/O)^0 = E^0$	= I^0+A^0	(/E/)

The main point here is that, unlike the symbolic representation in (5), where edges are determined by the intrinsic value of vertices, *the content of the vertices in (11a,b), i.e. of particles, is now determined by the value of edges, i.e. by operations.* Thus, moraic and non-moraic segments (i.e. ∂^1 and ∂^0) result from complementary organization of \oplus and \otimes . Hence the answer to the question in (6c) : why is ‘a’-split forbidden ? The sole possible reply in (5) was : ‘a’ does not split because it is ‘a’. In (11b), however, one should answer that A is ‘a’ because A cannot split (into disjunct particles). In other words, there cannot be */æ~i~ɒ/-like systems, since if the vowel triangle were ‘upside down’, it would not be a *vowel* triangle. The same can be said, for instance, about ‘i’-split, and ‘i’-unmarkedness. It is not relevant to say that ‘i’ splits by definition ; rather, Y in (11b) is ‘i’ because Y can split. Likewise, it is not the case that ‘i’ is unmarked because it is ‘i’ ; indeed, I in (11b) is ‘i’ because I is an unmarked vertex. More will be said in § 5.1 about the kind of explanation that is proposed here.

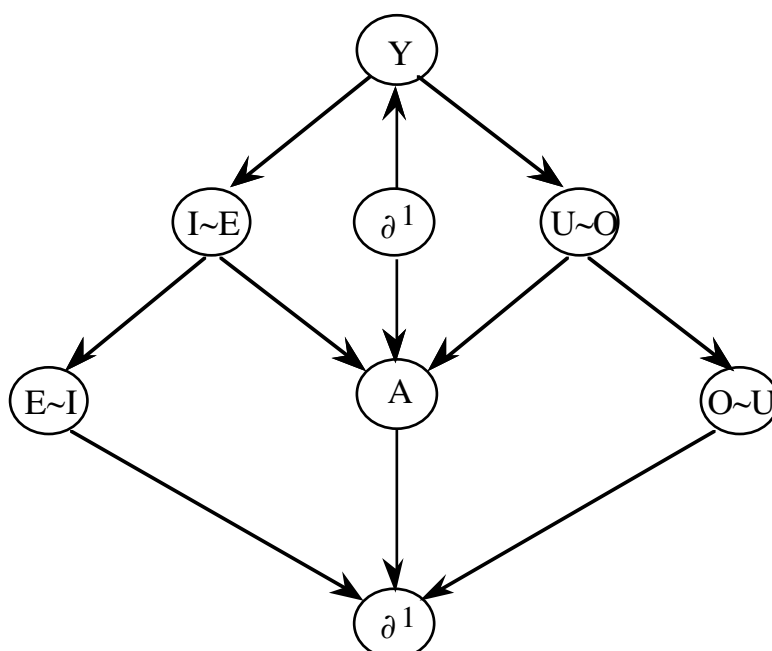
It should be noted that by ‘phonological content’ we also mean the kind of relations between particles. Thus, unlike the other particles, which are complementary in ∂^1 , I/U (and E/O) are, as was stated above, disjunct particles : as is shown in (9c,d), for $x = y$, we have $I/U = I$ or U and $E/O = E$ or O , ‘or’ being *exclusive*. Hence the answer to the question in (6d) : the exclusive nature of I/U- and E/O-markedness is the formal basis of the ‘categorical’ /i/ ~ /u/ contrast. On the other hand, the inclusive markedness of the remaining particles underlies ‘privative’ oppositions between p^1 and p^0 . Thus, as can be seen in (13), the phonological content associated with A^1 and Y^1 ‘comprises’ the one associated with A^0 and Y^0 respectively, while the converse is false. (The case of $\partial^1 \sim \partial^0$ is, of course, trivial, ∂^0 being a zero.)

4 From particles to segments

4.1 Definition of the segment

Let G_{∂^1} be the set of the ∂^1 -circuits defined in V where any vertex p is the sum of its successors ($\in \Gamma^+$) and the product of its predecessors ($\in \Gamma^-$) if $\text{Card } \Gamma^\alpha(p) > 1$. The simplest ∂^1 -circuit is given in (11b) ; a more complex one is shown in (14), where $I \sim E = I$ if, and only if, $E \sim I = E$, and $I \sim E = E$ if, and only if, $E \sim I = I$, etc.. (Once again, ∂^1 has been reiterated.)

(14)



Let G_{∂^1} be any element of G_{∂^1} ; it will be assumed that :

(15) *Definition of the (vowel) segment :*

A segment is a subgraph G_p of G_{∂^1} such that G_p is a p -circuit.

Conversely, let G_{∂^0} be any ∂^0 -circuit where, as in (11a), any vertex is the product of its successors and the sum of its predecessors ; consonants are subcircuits of G_{∂^0} .

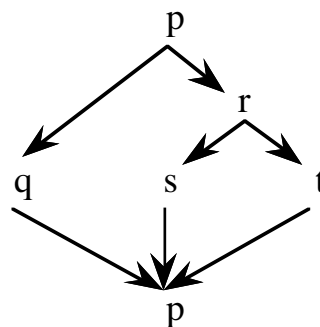
It follows from (15) that G_{∂^1} is itself a segment. Hence the remarkable property of $/\partial/$, which equals either 'I+A+U' or zero (cf. § 2.4) : indeed, we have $\partial^1 = A \oplus U \oplus I = A \otimes U \otimes I$ and $\partial^1 = I \sim E \oplus A \oplus U \sim O = E \sim I \otimes A \otimes O \sim U$, as can be seen in (11b) and (14) respectively.

Another interesting circuit is an one-vertex graph. Since no operation is defined in it, the unique vertex is indeterminate as to markedness (and

is weightless : cf. § 4.2). Such ∂ -particles will be viewed as the ‘timing positions’ of current theories. However, while in standard frameworks ‘extrinsic’ phonological material is associated with skeletal units, in the present theory segmental particles spring up, so to speak, from timing units, whenever ∂ -particles are determined as ∂^0 or ∂^1 (= ‘C’ ~ ‘V’), i.e. whenever ∂ -particles split to give place to more complex circuits (see on this topic Carvalho & Klein in preparation).

The minimal circuits involving more than one vertex that can be defined in $G_{\partial 1}$ are of the form in (16), where $p = q \oplus s \oplus t = q \otimes s \otimes t$:

(16)



Two further minimality constraints will be posited on segments : for any (16)-type circuit, it will be assumed that :

(17) *Minimality constraints on segments :*

- a. $p = t$ b. $q = s$

The reasons for the constraints in (17) will be exposed in § 4.3.

Let us consider the set of all possible sums in V :

(18)

a.	$\partial^1 = I \oplus O$	$\partial^1 = A \oplus Y$	$\partial^1 = \partial^1 \oplus \partial^0$	$\partial^1 = E \oplus U$
b.	$A = I \oplus E$	$A = \partial^1 \oplus Y$	$A = A \oplus \partial^0$	$A = O \oplus U$
c.	$Y = I \oplus U$	$Y = \partial^1 \oplus A$	$Y = Y \oplus \partial^0$	$Y = E \oplus O$
d.	$I = E \oplus A$	$I = \partial^1 \oplus O$	$I = I \oplus \partial^0$	$I = U \oplus Y$
e.	$U = I \oplus Y$	$U = \partial^1 \oplus E$	$U = U \oplus \partial^0$	$U = A \oplus O$
f.	$E = I \oplus A$	$E = \partial^1 \oplus U$	$E = E \oplus \partial^0$	$E = O \oplus Y$
g.	$O = E \oplus Y$	$O = \partial^1 \oplus I$	$O = O \oplus \partial^0$	$O = A \oplus U$
h.	$\partial^0 = q \oplus q$ (neutral particle)			

It follows that, for any particle p of V , there are, at most, $2 \times 4 = 8$ different (minimal) p -circuits (or segments) in $G_{\partial 1}$.

4.2 Particle weight

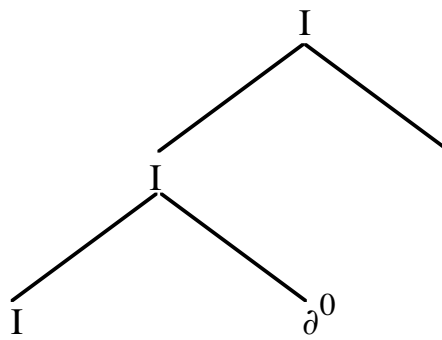
Particles have a segmental property : *weight*. Let σ be a segment of $G_{\partial 1}$, and p any particle of σ ; p -weight (W_p) is a numerical variable such that :

(19) *Definition of weight* :

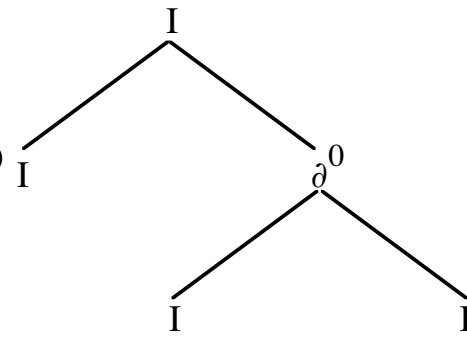
W_p equals the number of p -splits in σ .

Hence, for example, the following $W_I/W_E/W_A$ -ratios in ATR-systems :

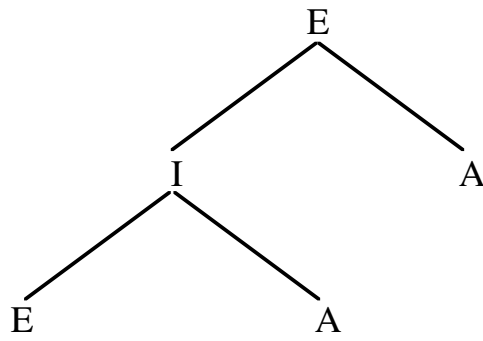
(20) a. /i/ (2/0/0)



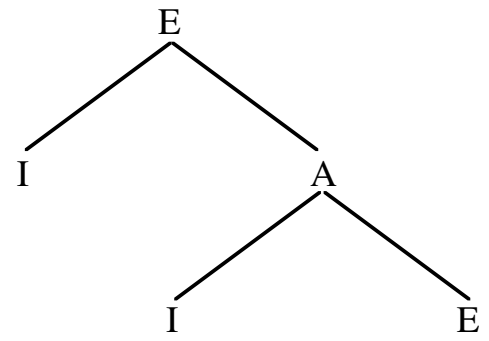
b. /ɪ/ (1/0/0)



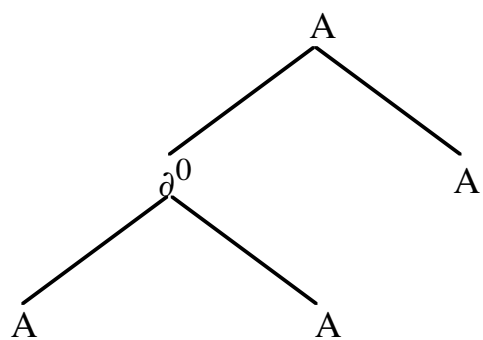
c. /e/ (1/1/0)



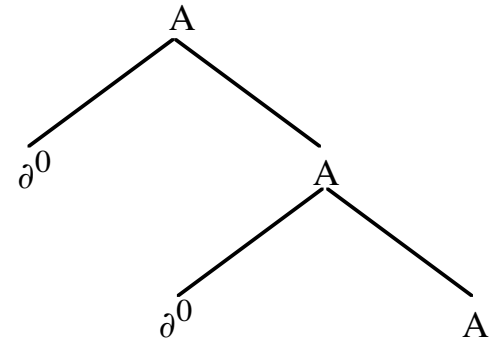
d. /ɛ/ (0/1/1)



e. /ɜ/ (0/0/1)



f. /a/ (0/0/2)



systems generally display the extreme degrees /i/ and /a/ ; variation is, thus, devolved upon mid vowels. Secondly, whereas /i/ ~ /e/ neutralization generally takes place at the expense of /e/, the (far more frequent) merger of /e/ ~ /ɛ/ is realized either as [e] or as [ɛ], according to languages and/or contexts. Thirdly, within a 4-h system, /e/ ~ /ɛ/ neutralizes first : /i/ ~ /e/ neutralization generally presupposes /e/ ~ /ɛ/ merger ; possible counter-examples are quite rare.

It follows : (i) that the ('primary') height scale has only three degrees ; (ii) that the mid degree (the 'archiphoneme' /E/) may give birth to an opposition which has often been viewed either as an entirely independent contrast on phonological terms (like [\pm ATR]), or as a 'secondary' height distinction (especially whenever systems lack further ATR-contrasts). Now, the present theory, which, as is shown in (20), implies *three* classes of *p*-circuits from the highest to the lowest vowel, according to whether *p* equals I, E or A, naturally fits this ternary conception of height.⁵

The second problem with (22)-type representations has already been outlined by Anderson & Ewen (1987 : 256-257) concerning Schane's (1984) particle phonology : if vowel height depends on a number such as the weight of a primitive, then what in the theory limits weight, and, thus, disallows an infinite number of height degrees ? Indeed, let *W* be the number of particles in a given segment, there is, in Carvalho's (1993, 1994) particle phonology, a linear relation between the maximal number of height degrees (*H*) and *W* such that $H = W + 1$: as is shown in (22b), if $W = 3$, then $H = 4$; if $W = 4$, then $H = 5$:

(23)		/i/	/e/	/ɛ/	/æ/	/a/
	I	A	A	A	A	A
	I	I	A	A	A	A
	I	I	I	A	A	A
	I	I	I	I	A	A
	$W_I =$	4	3	2	1	0
	$W_A =$	0	1	2	3	4

What, then, disallows, say, $W = 39$ in a given vowel system, which would therefore display 40 height degrees ? Obviously, it is not the case here that vowel height depends on weight ; rather, evidence for the limitation of *W* comes only from empirical observation of height scales throughout the world languages, and the reasons for determining any limit to the number of height degrees can be found only on external grounds, for example within human perceptual faculties (cf. Carvalho 1994 : 12-15). Such theories are, thus, based on a substantive explanation of the facts they should account for by themselves : they are poor and, once again, formally arbitrary theories.

Let us, however, consider the case within the present version of particle phonology. Let W be the number of splits in a given circuit ; it follows from the definition of the segment in (15), and from the minimality constraints in (17), that the number of segments allowed will not vary for $W \geq 2$. As an example, for the 2-split circuits /e/ and /ɛ/ in (20c,d) (where $W_I/W_E/W_A = 1/1/0$ and $0/1/1$ respectively), we shall still have *two* 4-split circuits (where $W_I/W_E/W_A = 2/2/0$ and $0/2/2$). The minimal circuits defined in § 4.1 are, thus, necessary *and sufficient* representations of segments. In other words, here vowel height (among other contrasts) really depends on weight, since the particle-based theory of segments predicts a limit to the number of vowels allowed.

5 Conclusion and perspectives

5.1 What is a subsymbolic explanation ?

The main advantage of a subsymbolic theory is its formal explanatory power. But what exactly does it explain ? And what do we mean by ‘explanation’ here ?

Concerning the first question, it must be emphasized that the present theory should not be viewed as a formal explanation of phonetic substance. Substance can only be ‘explained’ on substantive grounds. This has been done by a number of authors beginning with Stevens (1972) and Liljencrants & Lindblom (1972). However, phoneticians’ work cannot tell us why the ‘upside down’ triangle is impossible ; it can just explain why standard /i a u/-systems are acoustically and perceptually optimal. Likewise, nothing is said in such studies about the unmarked nature of /i/ *versus* /u/, nor on the problematic of the ‘zero vowels’. The reason thereof is obvious : just as substance needs substantive explanations, so do forms (such as systems) require purely formal explanations. Thus, what the present approach says is simply that there can be only one vowel triangle (cf. § 3.3). Why is it what it is, i.e. of the form /i~a~u/ rather than */æ~i~ɒ/ ? In other words, why do particles have the particular content specified in (12, 13) ? This is what phoneticians, and only phoneticians, can explain, in articulatory and acoustic/perceptual terms.

It follows that formal explanation is deductive work, which has been defined here as the *generation* of symbols from a small number of subsymbolic primitives. Indeed, the formal problems met by previous theories are solved by assuming : (i) two empty primitives x and y ; (ii) a set of operations ; and (iii) deducible elements such as A, I, U, etc., which are thereby formally motivated, contrary to the purely substance-based primitives of current theories. Two levels are, thus, necessary : the subsymbolic level (x, y) *and* the symbolic level (I, A, U...). Most theories simply lack the former, and the latter is thereby formally arbitrary. Van

der Hulst's (1994) Radical CV phonology may be viewed as a curious mixture of both : standard components are reduced to a couple of primitives 'C' and 'V' which still have symbolic content, unlike x and y , and lack symbolic naturalness, unlike I, A, U... For two reasons, thus, the representations allowed by Radical CV phonology are not formally motivated, nor has the theory any explanatory power.⁶

5.2 Issues and limits

We shall conclude by stressing two aspects of the present theory which may be viewed as topics for further research. One is an interesting issue of the Boolean framework adopted here ; any attempt to account for the other, however, probably requires a non-Boolean approach.

5.2.1 The consonantal particles

Unlike Schane's (1984) and Carvalho's (1994) particle phonology, this theory allows the definition of both vocalic and consonantal elements. Contrary to dependency phonology and government theory, this is done without further primitives. Vocalic units are defined in $G_{\partial 1}$; consonantal units are defined in its complement $G_{\partial 0}$. As shown in § 3.3, a particular issue of this is that, while the vocalic elements U and I 'correspond' to the consonantal elements 'P' ('labiality') and 'T' ('coronality') respectively, the vocalic counterpart of 'K' ('velarity') is Y. Hence four interesting perspectives for research.

Firstly, this 'effect of complementarity' formally motivates two phonological 'equivalences' : one between 'K' and /u/ (= Y^0), the other between 'K' and /y/ (= Y^1). The former has a clear basis in terms of articulation and markedness ; it is posited, for example, by Clements (1993). The latter is less obvious at first sight ; as a mere working hypothesis, however, we shall suggest that phonetic evidence for such a relation can be found in the well-known double *locus* of [k], according to whether the adjacent vowel is rounded or unrounded, that is, according to whether the vowel has either of the features conveyed by Y^1 .

Secondly, if '[+stop]' is assumed to be present, by default, in the three consonantal units 'P' = U = O-A, 'T' = I = E-A and 'K' = Y = ∂^1 -A, then A, specifically A^0 , can be viewed as representing, in $G_{\partial 0}$ as well as in $G_{\partial 1}$, its antinomic counterpart, i.e. 'aperture' (see on this topic Scheer 1995). Hence three further particles underlying spirants, which could be labeled as 'F' = O = U \vee A, 'S' = E = I \vee A and 'H' = A = \emptyset \vee A.

Thirdly, A^1 would be the 'pharyngeal' particle ('h') in $G_{\partial 0}$, just as it is the 'RTR'-particle in $G_{\partial 1}$. It follows from the inclusive markedness of A (cf. § 3.3) that a pharyngeal consonant is necessarily a spirant.

Fourthly, the ‘moraic’ particle ∂^1 , which is the neutral element of G_{∂^0} (as ∂^0 is in G_{∂^1}), would be the ‘sonority’-particle in G_{∂^0} , underlying sonorants as well as voiced consonants. Thus, the theory formalizes two interesting relations between vowels and consonants : one between low vowels and spirants, the other between ‘moraicity’ and ‘sonority’.

5.2.2 Particles as ‘energy’

Let $p = (q \oplus r)$ be a split in a given p -circuit ; what in the theory determines either q - or r -split ? For example, what generates either [+ATR] or [-ATR] vowels in (20) ? Likewise, given $p = (q \oplus r) = (q' \oplus r')$, what in a particular p -circuit determines either of these splits ? Thus, for example, why is I defined either as $(I \oplus \partial^0)$ or as $(\partial^1 \oplus O)$ in (21) ? The same problem arises from the determination of the initial vertex of G_{∂^0} : why is it either marked ($= \partial^1$) or unmarked ($= \partial^0$) ? In other words, since $\partial^1 = (A \oplus Y)$ and $\partial^0 = (A \otimes Y)$, what determines the nature of the operation involved ? At this level, the question has far-reaching consequences : if ∂^0 and ∂^1 are assumed to bear ‘consonanticity’ and ‘voweliness’ respectively, ∂^1 being the ‘mora’ and ∂^0 , say, the ‘antimora’, then the point at issue is that of the integration of such units, that is, the problem of the formal definition of the syllable.⁷

Hitherto, the segment has been viewed as a predeterminate object, as an *opus operatum*, an Aristotelian $\acute{\epsilon}\rho\gamma\omega\nu$; we actually need a theory in which the segment is a *modus operandi*, an $\acute{\epsilon}\nu\acute{\epsilon}\rho\gamma\epsilon\iota\alpha$. We could then assume that the edges of segments are not mere operations : they are vectors of force, much in the line of work by Goldsmith & Larson (1990), Goldsmith (1993) and Klein (1993). Segments should then be circuits where *energy* is variably distributed : the above distinction between an /i/-like vowel and its reduced counterpart could be accounted for in terms of unilateral preservation *versus* dispersion of energy in $I = (I \oplus \partial^0)$ and $I = (\partial^1 \oplus O)$ respectively. Such would be, indeed, the actual substance of particles and weight.

NOTES

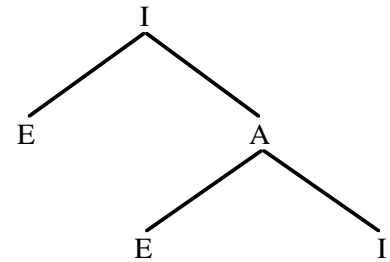
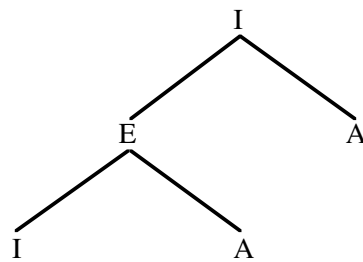
* We wish to thank Jean-Elie Boltanski for helpful comments on an earlier draft of this paper, and Christian Abry for critical remarks on the oral version. We are also indebted to Andrée Sarfati and Helen Dochney for crucial help in the preparation of the present version.

[1] Tongue root position is a basic articulatory feature, since it ‘governs’ tongue body position. Let us, for example, compare two [+ATR] vowels like the front vowel [i] and the central vowel [ɨ], on the one hand, and

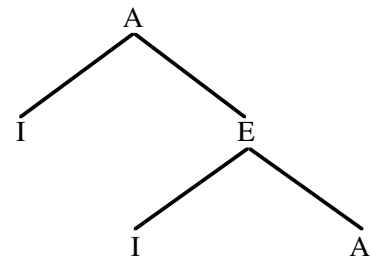
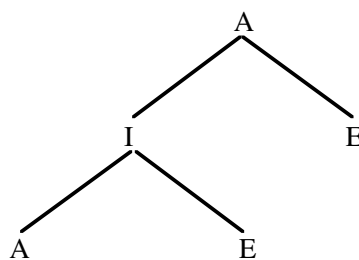
two front vowels like [+ATR] [i] and [-ATR] [ɪ], on the other hand. In the first case, both vowels display approximately the same degree of ATR-ness ; indeed, the pharyngeal cavity may even be larger for [i̠] than for [i], as is the case in Russian (Panov 1967 : 47). In the second case, however, [i]-palatality (i.e. height + frontness) is strengthened by ATR-ness, as is clearly shown by Lindau's (1975) work on Igbo ATR-harmony.

- [2] The contrary is less frequent but is also attested : based on Trubetzkoy (1939 : § 4.3), Anderson & Ewen (1987 : 213) note [u] for Russian *u*, which clearly is a central vowel in articulatory terms (Panov 1967 : 47).
- [3] In Russian, where /i/ is often realized as a diphthong, F₂ rises throughout the area typically allowed to the empty vowel, that is, from 1400 to ca. 1900 Hz (cf. Jones 1959).
- [4] Radical underspecification theory is based on the empirical identification of 'functionally asymmetric vowels', which vary from language to language. The 'empty' vowel is but a particular case of 'asymmetric' vowel : thus, /i/, /e/ and even /u/ (in Telugu, for example) are apt to play such a role. The problem with this view is that the more potentially asymmetric vowels you have, the more arbitrary the particular 'complement rules' are.
- [5] The more frequent an opposition is, the more representations it may have. Thus, /i/ ~ /ɪ/ and /ɜ/ ~ /a/ are based only on the contrasts shown in (20a,b) and (20e,f) respectively ; however, /e/ ~ /ɛ/ follows from three different structures : those in (20c,d) plus the following ones :

(24) a. /e/ (1/1/0) b. /ɛ/ (1/0/1)



 c. /e/ (1/0/1) d. /ɛ/ (0/1/1)



It will be assumed that this diversity involves language-specific government : I is the governing particle (and /ε/ is the ‘unmarked’ vowel) in (24a,b), while A is the governing particle (and /e/ is the ‘unmarked’ vowel) in (24c,d) ; there is no government relation between I and A in (20c,d). This relation accounts for several functional facts such as diphthongization, vowel reduction, etc. (cf. Carvalho 1994).

- [6] Furthermore, ‘C’ and ‘V’ are not the only actual primitives in the theory : gestural classes, which obviously have symbolic content, play a crucial role in Radical CV phonology.
- [7] This complementarity-based view of consonants and vowels resembles Klein’s (1993) definition of the syllable as the interface of articulatory and perceptual planes. The term of ‘energy’ below is also close related to what is labeled therein as the ‘weight’ of either of these planes. On the way how syllables and rhythm emerge from the skeleton within the present Boolean approach, see Carvalho & Klein (in preparation).

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