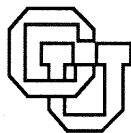


**Connectionism and Harmony Theory
in Linguistics**

Alan Prince, Paul Smolensky

CU-CS-533-91 July 1991



University of Colorado at Boulder
DEPARTMENT OF COMPUTER SCIENCE

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**Class notes from a 4-week course of the same name taught at the
Linguistics Institute, University of California at Santa Cruz,
sponsored by the Linguistics Society of America**

ANY OPINIONS, FINDINGS, AND CONCLUSIONS OR RECOMMENDATIONS
EXPRESSED IN THIS PUBLICATION ARE THOSE OF THE AUTHOR(S) AND DO NOT
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ACKNOWLEDGEMENTS SECTION.

Connectionism and Harmony Theory in Linguistics

LSA Linguistic Institute
University of California, Santa Cruz
LINS 247
July 1991

Topics

Spreading Activation & Harmony Maximization

Spreading activation

PDP-I:1,2

Harmony maximization

PDP-III:3[49-53]; PDP-II:14[7-38]; PDP-I:6

Goldsmith-Larson Dynamic Linear Model

Goldsmith, John:

Local modeling in phonology.

A dynamical computational theory of accent systems.

Prince, Alan:

Convergence of the Goldsmith-Larson Dynamic Linear Model of sonority and stress structure.

Closed-form solution of the Goldsmith-Larson Dynamic Linear Model of syllable and stress structure and some properties thereof

Inductive Learning & Error Minimization

Hebb rule

PDP-I:1[31-40]; PDP-III:4[83-86],5[90-93]

Delta rule

PDP-III:[86-89,93-96,121-130]; PDP-I:11

Past Tense Acquisition Model

PDP-II:18

Pinker, Steven & Prince, Alan.

Rules and connections in human language.

On language and connectionism: Analysis of a parallel distributed processing model of language acquisition. [Pinker & Mehler.]

Back Propagation

PDP-III:5[130-137]; PDP-I:8

NetTalk

Sejnowski, Terrence J. & Rosenberg, Charles R. Parallel networks that learn to pronounce English text.

Recurrent back propagation

PDP-I:8[354-361]

Elman, Jeffrey. Finding structure in time.

Continuity & Similarity

Hungarian Vowel Harmony Model

Hare, Mary. The role of similarity in Hungarian vowel harmony: A connectionist account.

Harmonic Grammar

Legendre, Geraldine, Miyata, Yoshiro, & Smolensky, Paul:

Can connectionism contribute to syntax? Harmonic Grammar, with an application.

Unifying syntactic and semantic approaches to unaccusativity: A connectionist approach.

Harmonic Grammar -- A formal multi-level connectionist theory of linguistic well-formedness: An application.

Harmonic Grammar -- A formal multi-level connectionist theory of linguistic well-formedness: Theoretical foundations.

Harmonic Phonology

Lakoff, George. A suggestion for a linguistics with connectionist foundations.

Touretzky, David S., Wheeler, Deirdre W, & Elvgen, Gillette. Rules and maps III: Further progress in connectionist phonology.

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Sources

Unless otherwise indicated, all articles are in the Reader.

'PDP-X:Y[a-b]' denotes 'PDP books, volume X, chapter Y, pages a-b'

On reserve in library & available through bookstore:

PDP-I: Rumelhart, David E., McClelland, James L., & the PDP Research Group. *Parallel distributed processing: Explorations in the microstructure of cognition. Volume 1: Foundations.* Cambridge, MA: MIT Press/Bradford Books.

PDP-II: McClelland, James L., Rumelhart, David E., & the PDP Research Group. *Parallel distributed processing: Explorations in the microstructure of cognition. Volume 2: Psychological and biological models.* Cambridge, MA: MIT Press/Bradford Books.

PDP-III: McClelland, James L. & Rumelhart, David. *Explorations in parallel distributed processing: A handbook of models, programs and exercises.* Cambridge, MA: MIT Press/Bradford Books.

Pinker & Mehler: Pinker, Steven, & Mehler, Jacques (Eds.) (1988). *Connections and symbols.* Cambridge, MA: MIT Press/Bradford Books.

Available through Institute:

Reader: Published articles and reports

Class Notes:

To be cited as:

Prince, A. & Smolensky, P. (1991). *Notes on Connectionism and Harmony Theory in Linguistics.* Technical Report CU-CS-533-91, Department of Computer Science, University of Colorado, Boulder.

Linguistic Background (incomplete)

LINS 247

Connectionism and Harmony Theory in Linguistics

P. Smolensky/ A. Prince

July, 1991

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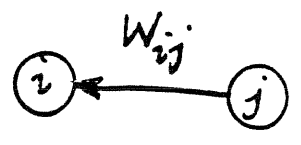
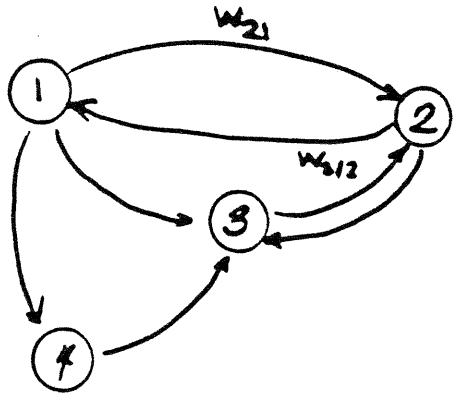
Optimization in Connectionism & Linguistics

- | | | |
|--------|--|---|
| I. | Spreading activation &
Harmony maximization | Phonological prominence:
stress, syllable structure |
| II-III | Inductive learning &
Error minimization | Past tense inflection (English)
Pronunciation (English)
Induction of grammatical categories
through distributional analysis (Eng) |
| IV | Continuity & similarity
Harmonic Grammar | Vowel harmony (Hungarian)
Unaccusativity (French) |
| V-VIII | Harmonic Phonology | <ul style="list-style-type: none">• Universal phonology• Typologies<ul style="list-style-type: none">• Syllable structure• stress systems• Phonologies of particular languages |

- Assignment:
- 5-10pp. paper due last class
 - Outline due one week before last class

- Materials:
- Reader (published papers/reports)
 - Class Notes (unpubl. drafts by PES; handouts; overheads)
 - Bookstore
 - Library

Summary of #/B



nodes - activation
connections - weights

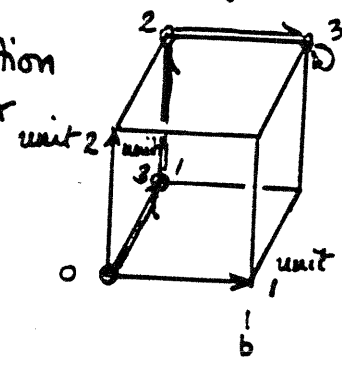
$$Net_i = \sum_j W_{ij} a_j$$

$$a_i = f(Net_i)$$

		units		
		1	2	3
Iteration	0	(0	0	0)
	1	(0	0	b)
	2	(0	b	b)
	3	(b	b	b)
	4	(b	b	b)
		⋮	⋮	⋮

time ↓

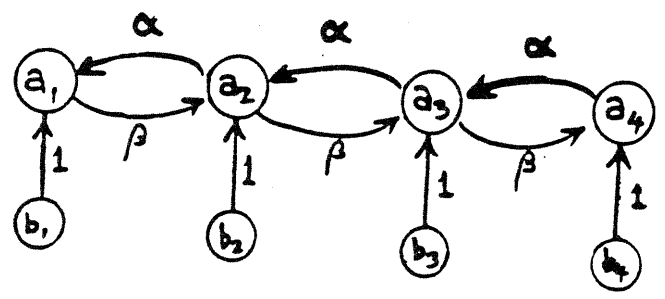
activation vector \vec{a}



'state space'
'dynamical system'

Analogy: spreading activation ~ derivation (e.g. autosegmental spreading)
→ 'structure building'

Goldsmith - Larson D.L.M.



prominence

- stress (over syllables)
- sonority (over segments)

Examples:

	α	β	final \vec{a}	$\vec{b} = (0 \ 0 \ 0 \ b)$	
1	0	0	(b b b b)		leftward spreading
-1	0	0	(-b b -b b)		leftward alternation
-1/2	0	0	(-1/2 b 1/2 b b)		damped " "
(1 1 1 1)	-1/2	-1/2	(1/2 3/2 3/2 1/2)		interdigitated near four units

* Connectionist computation is optimization.

I. The basic (low-level) computational mechanism of conn. is spreading activation.

1. Interesting things happen - in new & different ways - due to this novel mechanism.

1. Goldsmith & Larson's Dynamic Linear Model (DLM)

[2... to come]

2. High level understanding of spreading activation - global analysis - is possible through ...

1. ... Linear Analysis

1. The activation pattern is a vector in a high-dimensional state space evolving through time - a dynamical system

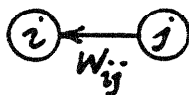
2. The connection strengths form a weight matrix which can be analyzed using linear algebra; e.g., the DLM can be solved in closed form.

[3. Related methods allow us to use vectors to represent and matrices to process structured data...]

2. ... Harmonic Analysis

1. In certain nets, activation spread steadily increases a numerical well-formedness measure on activation vectors -

$$\text{Harmony} = \sum_i \sum_j a_i w_{ij} a_j$$



2. Activation spread in these nets is an algorithm for

3. H maximization can be interpreted as (soft) constraint satisfaction

4. These constraints can be used to declaratively define grammar.
Global H maxima define the grammatical structures (competence)
Local H maxima are computed by connectionist nets (performance)

3. Activation has several interpretations

1. (Graded) truth value of a hypothesis.

2. Value of a (graded) linguistic quantity

1. DLM: (continuous) context-dependent prominence

[3. None - meaningless internal computational data]

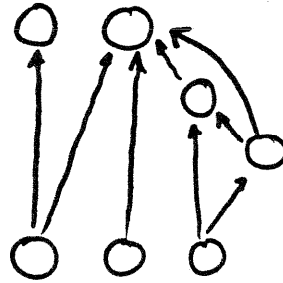
Harmonic nets:

1. activation rule: 'If Net > 0, excite, else inhibit'

2. connectivity:

either

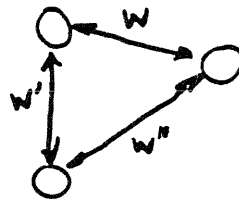
• feedforward



'all connections go up'

or

• symmetric



'all connections go both ways'

3. updating activations

either

• one-at-a-time ('asynchronous')

or

• smooth (unit activations change very little at each step)

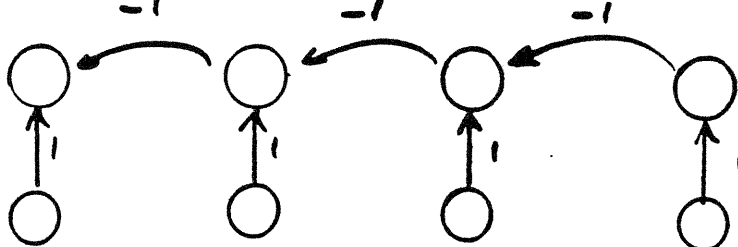
Notes:

1. Ensures $\Delta a_i \Rightarrow \Delta h_i > 0$ 'each update separately locally harmonic' [1,2]

2. Ensures $\Delta a_i \Rightarrow \Delta H > 0$ 'each update separately globally harmonic' [3-6]

3. Ensures $\{\Delta a_i\} \rightarrow \Delta H > 0$ 'all updates at once harmonic'

GL D.LM.



$$\vec{b} = \begin{pmatrix} 0 & 0 & 0 & b \end{pmatrix}$$

time ↓ $\vec{a} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & b \\ 0 & 0 & -b & b \\ 0 & b & -b & b \\ -b & b & -b & b \\ -b & b & -b & b \\ \vdots & \vdots & \vdots & \vdots \end{pmatrix}$

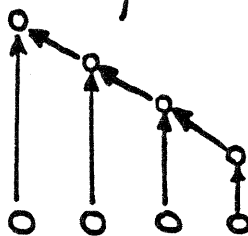
$$H = \sum_i \sum_j a_i w_{ij} a_j$$

$$0 + (-b)(-1)(b) = b^2 + (b)(-1)(-b) = 2b^2 + (-b)(-1)(b) = 3b^2$$

H monotonically increases ...

why?

1. Net is feedforward
'all arrows go up'



Ex: Look at other examples of GL D.LM. from Lecture 1

2. Only one activation value change at a time

Constraint satisfaction view:

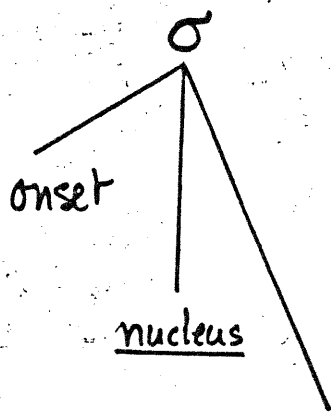


If $i+1$ is strong, i should be weak;
" " " weak " " " strong.

Every 'rule application' in this 'dynamical' is harmonic.

Syllabification in Berber

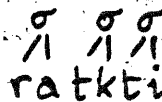
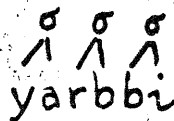
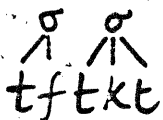
Berber F. Dell & M. El-Medlaoui, 1987, 1988



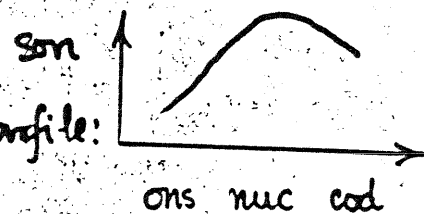
← = 1 segment (except phrase-initially)

← = 1 segment NOT NEC. A VOWEL prism: Br-br

coda ← ≤ 1 segment (except phrase finally)



What governs syllabification? 'Ideal' sonority profile:



Berber's 8-level sonority hierarchy:

a > n, i > r, l > m, n > z > f, s, x > b, d, g > p, t, k
 8 7 6 5 4 3 2 1

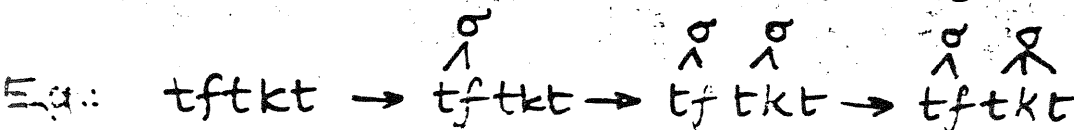
Dell-El-Medlaoui Algorithm:

FOR s = 8, 7, ..., 1

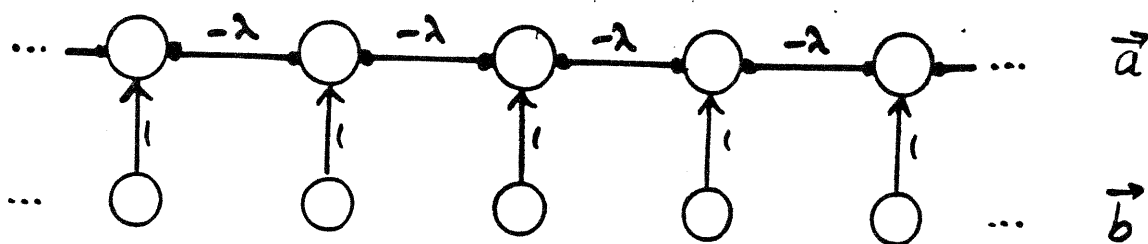
SCAN LEFT-TO-RIGHT

IF FIND $S_i S_{i+1}$ THEN BUILD $S_i S_{i+1}$
son = s

ATTACH any remaining unsyllabified segments as CODAS



Harmonic BrbrNet



Each $a_i \in [0, 1]$ during computation; finally,
 each $a_i = 0$ ('non peak') or $a_i = 1$ ('peak')
 ' $a_i = 1$ if segment i is a peak'

Each b_i is a measure of the sonority of segment i ;
 (In G-L, $b_i = \text{son}(s_i)$; here, $b_i = 2^{\text{son}(s_i)} - 1$; $\text{son}(s_i) \in \{1, 2\}$,
 'exponential sonority scale in Berber')

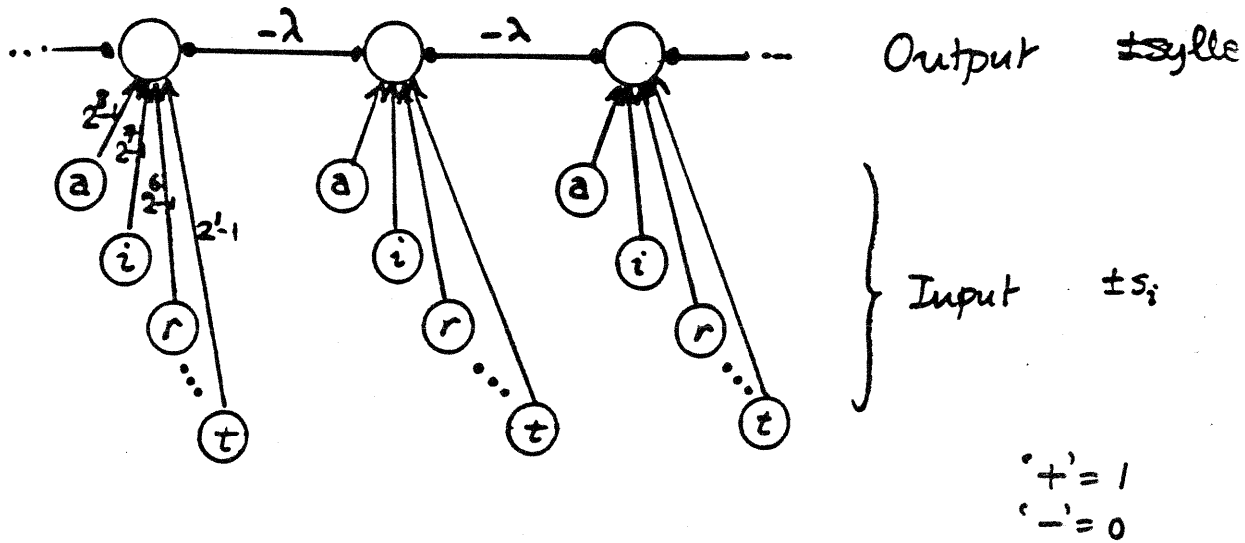
Activation rule:

To a_i add $c \cdot \text{Net}_i$; if this is > 1 , set $a_i = 1$
 " " " < 0 , set $a_i = 0$ c small
const

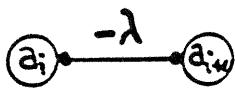
Note: 1. 'If $\text{Net} > 0$, excite, else, inhibit'
 2. Connections are symmetric.
 3. Activation updating is smooth.
 \therefore Harmonic

Theorem: 1. For sufficiently large λ , \vec{a} is a local H maximum
 iff $\forall i a_i \in \{0, 1\}$ and the syllabification satisfies
 the Berber syllabification constraints: *VV; *CCC
 2. For sufficiently large λ , \vec{a} is a global H maximum
 iff $\forall i a_i \in \{0, 1\}$ and corresponds to the correct Berber

Harmonic Grammar View of BrbrNet



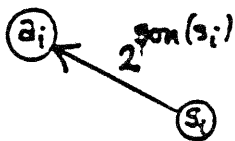
Grammar of soft rules:



* $(+s_{ylj}) \& (+s_{ylj+1})$ strength: λ

← subtract 'strength' from H if violate

← add 'strength' to H if satisfy



✓ $(+s_i) \& (+s_{ylj})$

strength: $2^{son(s_i)} - 1$

Principle of Harmonic Structural Assignment:

Assign the structure that maximizes H

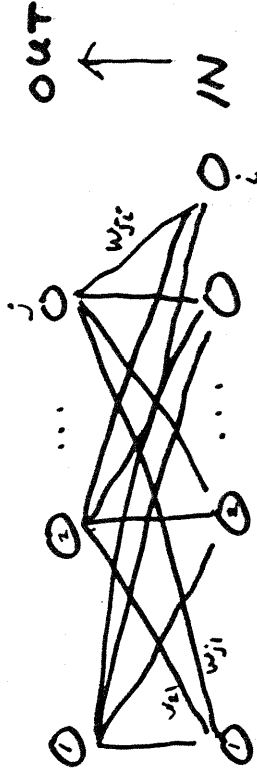
Learning from Experience

The problem: suppose we have a collection of Input Patterns P_1, \dots, P_n ,

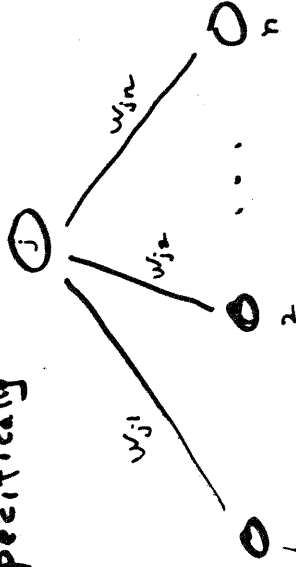
each matched with an output Target Pattern T_1, \dots, T_n .

- Can we get a NETWORK to LEARN to produce T_i given P_i ??

Concretely, find w_{ji} for



Specifically



We have

$$\text{net}_j = a_1 w_{j1} + a_2 w_{j2} + \dots + a_n w_{jn}$$

$$= \sum_i a_i w_{ji}$$

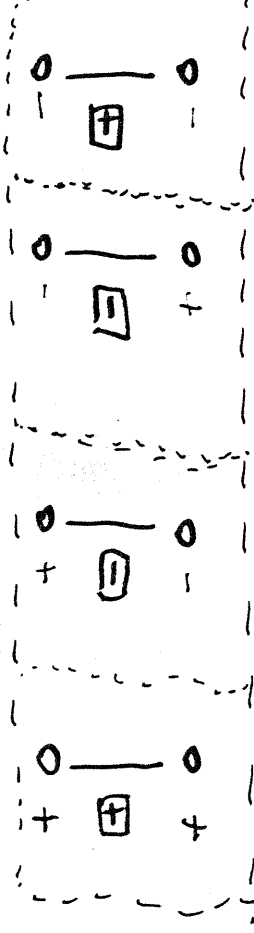
AND:
 - excite out_j if $f(\text{net}_j) > 0$
 - inhibit out_j if $f(\text{net}_j) < 0$

We therefore manipulate net_j to achieve desired goal.

The inputs are fixed so we work on the WEIGHTS.

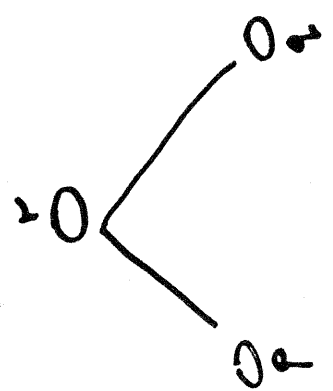
First Idea: Hebb Rule:

reward node-wise correlation.



- set $w_{ji} = a_j a_i$
 - sum over all input patterns

Example of Hebbian Learning



	p	q	r
\vec{p}_1	1	1	1
\vec{p}_2	1	-1	-1
\vec{p}_3	-1	1	-1
\vec{p}_4	-1	-1	-1

\vec{p}_1	w_{rp}	1	w_{rq}	1
\vec{p}_2		-1		1
\vec{p}_3		1		-1
\vec{p}_4		1		1
Σ		<hr/>		<hr/>
		2		2

Technical Background

Vector = $(x_1, x_2, \dots, x_n) = \vec{x}$

Helps us to speak of chunks as significant:

"Pattern" = vector

$\vec{p}_1 = (1, 1)$ $\vec{p}_2 = (1, -1)$

dot product $\vec{a} \cdot \vec{x}$

a number not another vector

$(a_1, a_2, \dots) \cdot (x_1, x_2, \dots)$

= $a_1x_1 + a_2x_2 + \dots + a_nx_n$

= $\sum_i a_i x_i$

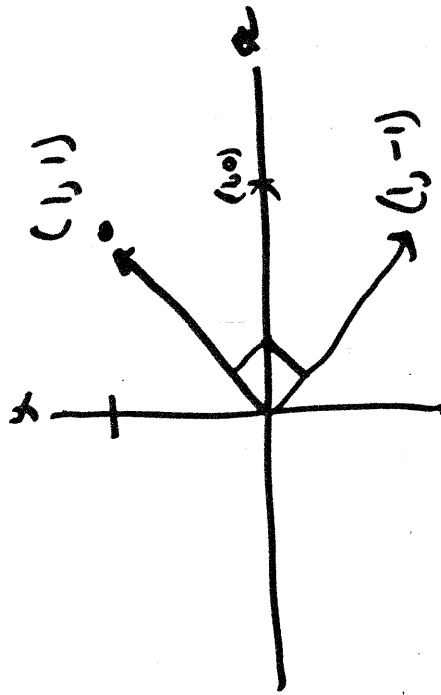
Dot Product measures angle between vectors of unit length.

$$\vec{a} \cdot \vec{x} = |\vec{a}| |\vec{x}| \cos \theta$$

Perpendicular (Orthogonal) Vectors

$$\vec{a} \cdot \vec{x} = 0$$

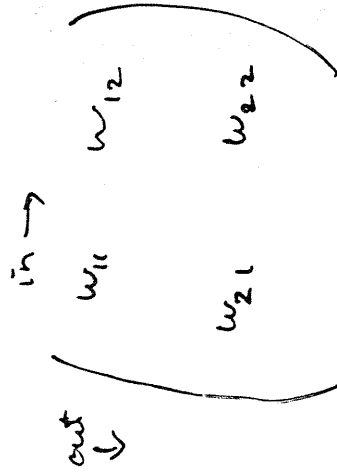
Dot Product, dividing out length, gives correlation.



Matrix - rectangular array

	col 1	col 2	col 3
row 1	11	12	13
row 2	21	22	23
row 3	31	32	33

EXAMPLE



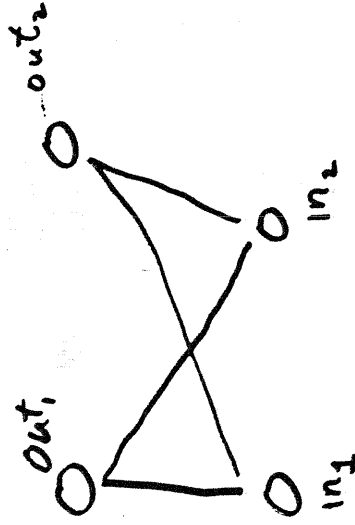
Two Interesting Cases

$$\begin{pmatrix} a & b & c \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix} = (ax + by + cz)$$

$$\begin{pmatrix} a \\ b \\ c \end{pmatrix} \begin{pmatrix} x & y & z \end{pmatrix} = \begin{pmatrix} ax & ay & az \\ bx & by & bz \\ cx & cy & cz \end{pmatrix}$$

Hebb en bref.

$$\vec{w}_j = \begin{pmatrix} out_1 \\ out_2 \end{pmatrix} \cdot (input)$$



$$W = \begin{pmatrix} out_1 \cdot in_1 & out_1 \cdot in_2 \\ out_2 \cdot in_1 & out_2 \cdot in_2 \end{pmatrix}$$

$$= \begin{pmatrix} out_1 \\ out_2 \end{pmatrix} \begin{pmatrix} in_1 & in_2 \end{pmatrix}$$

Adding Vectors

Adding Matrices

Rule: add corresponding elements.

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} + \begin{pmatrix} e & f \\ g & h \end{pmatrix} = \begin{pmatrix} a+e & b+f \\ c+g & d+h \end{pmatrix}$$

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} + \begin{pmatrix} x & y \\ z & w \end{pmatrix}$$

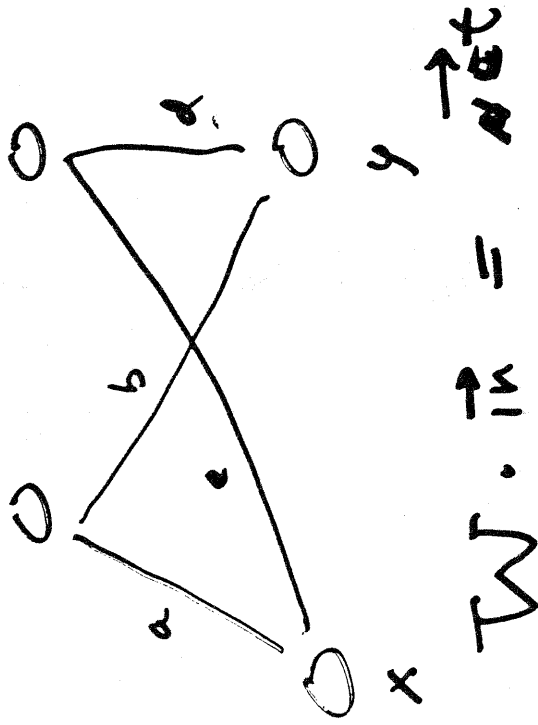
$$= \begin{pmatrix} a+x & b+y \\ c+z & d+w \end{pmatrix}$$

Multiplying Matrices

$$A \cdot B = C$$

$$c_{ij} = \text{row}_i(A) \cdot \text{col}_j(B)$$

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} ax+by \\ cx+dy \end{pmatrix}$$



$$W \cdot \vec{r} = \vec{A} \cdot \vec{t}$$

Total Hebb Experience

- Start off $w_{ji} = 0$
- $W = \sum_P \begin{pmatrix} \text{out}_1 \\ \text{out}_2 \\ \vdots \\ \text{out}_n \end{pmatrix} (\text{input} - P)$ add "see over patterns"

Q: What if a trained net faces a new input?

A: Compute $\vec{\text{out}}_{\text{new}} = W \cdot \vec{\text{input}}_{\text{new}}$

$$= \left[\begin{pmatrix} w_{11} \\ w_{21} \\ \vdots \\ w_{n1} \end{pmatrix} (\text{input}_1) \right] \cdot \begin{pmatrix} \text{in}_1 \\ \text{in}_2 \\ \vdots \\ \text{in}_n \end{pmatrix}_{\text{new}}$$

DOT

PRODUCT!

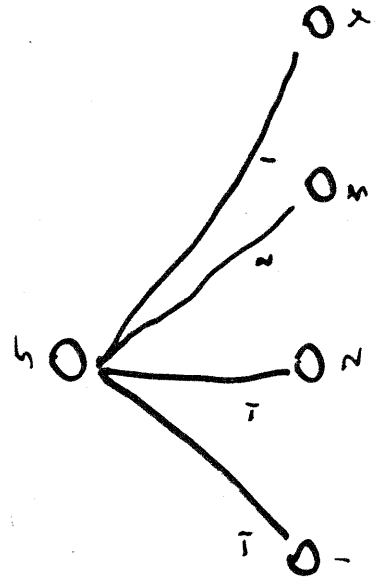
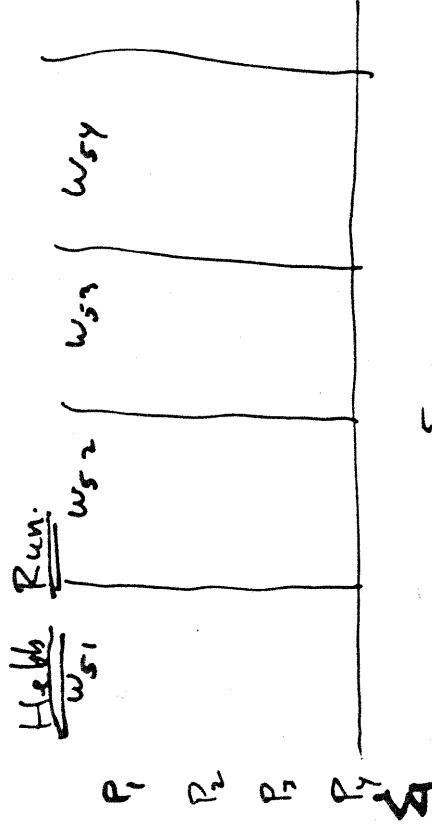
How the trained net behaves

- ① If $\vec{\text{input}}_{\text{new}} \perp$ all items in training set, output is 0 .
- ② If $\vec{\text{input}}_{\text{new}} \perp$ all but one, get a scaled version of the output for that one.
- ③ If $\vec{\text{input}}_{\text{new}}$ is non orthogonal (similar to several), output is a weighted sum of outputs proper to them. Weighted by degree of similarity. (dot. prod)

$$\vec{\text{out}}_{\text{new}} = \sum_k \begin{pmatrix} \text{out}_k \\ \vdots \end{pmatrix} \vec{\text{input}}_k \cdot \vec{\text{input}}_{\text{new}}$$

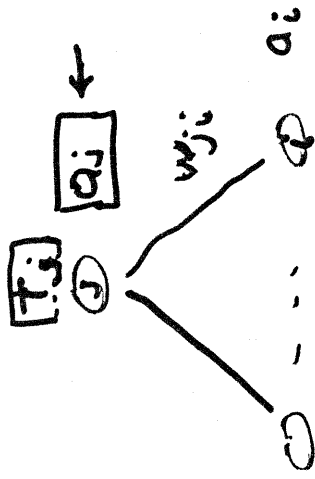
NON HEBB - LEARNABLE

	1	2	3	4	5
P_1	+	-	+	-	+
P_2	+	+	+	+	+
P_3	+	+	+	-	-
P_4	+	-	-	+	-



Hebb:
correct

Delta Rule



$$\Delta w_{ji} = \epsilon (t_j - a_j) a_i$$

$\underbrace{\epsilon (t_j - a_j)}_{\text{error } \delta_j}$

$$\Delta W = \epsilon \sum_k \begin{pmatrix} \epsilon \\ \delta_1 \\ \vdots \\ \delta_k \\ \vdots \\ \delta_n \end{pmatrix} (\text{input } -k)$$

Using the Delta Rule

INPUTS = $\{P_1, \dots, P_n\}$

OUTPUT TARGETS = $\{T_1, \dots, T_n\}$

Procedure:

- Present Input Set (1 by 1)
- Compare Output Produced by net to desired target
- Make step proportional to error (ϵ) in right direction

Do it again

And again

⋮

$$W \leftarrow W + \Delta W$$

What is Error?

$$E = \frac{1}{2} (err_1^2 + err_2^2 + \dots + err_n^2)$$

$$= \frac{1}{2} \sum (t_j - o_j)^2$$

"sum squared error"

$$\Delta w_{ji} = -\epsilon \frac{\partial E}{\partial w_{ji}}$$

No good:

$$"E" = |err_1 + err_2 + \dots + err_n|$$

"signed error"

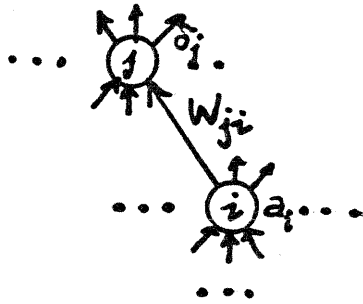
Perceptron Convergence Thm.

This procedure will find a set of weights that works if such a set exists.

BACK-PROP

Historical remarks

- * Learning internal representations - 'hard' vs 'easy' learning (Boltzmann learning; Harmony T. 'hidden units')
- * Technical breakthrough

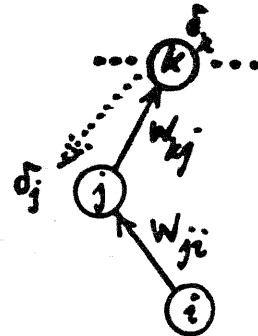


$$\Delta W_{ji} = \epsilon \delta_j a_i$$

$$\delta_j = \text{'error at j'}$$

= ??? for 'hidden' unit?

Define recursively: $\delta_j = \left(\sum_k \delta_k W_{kj} \right) f'(\text{net}_j)$ interior



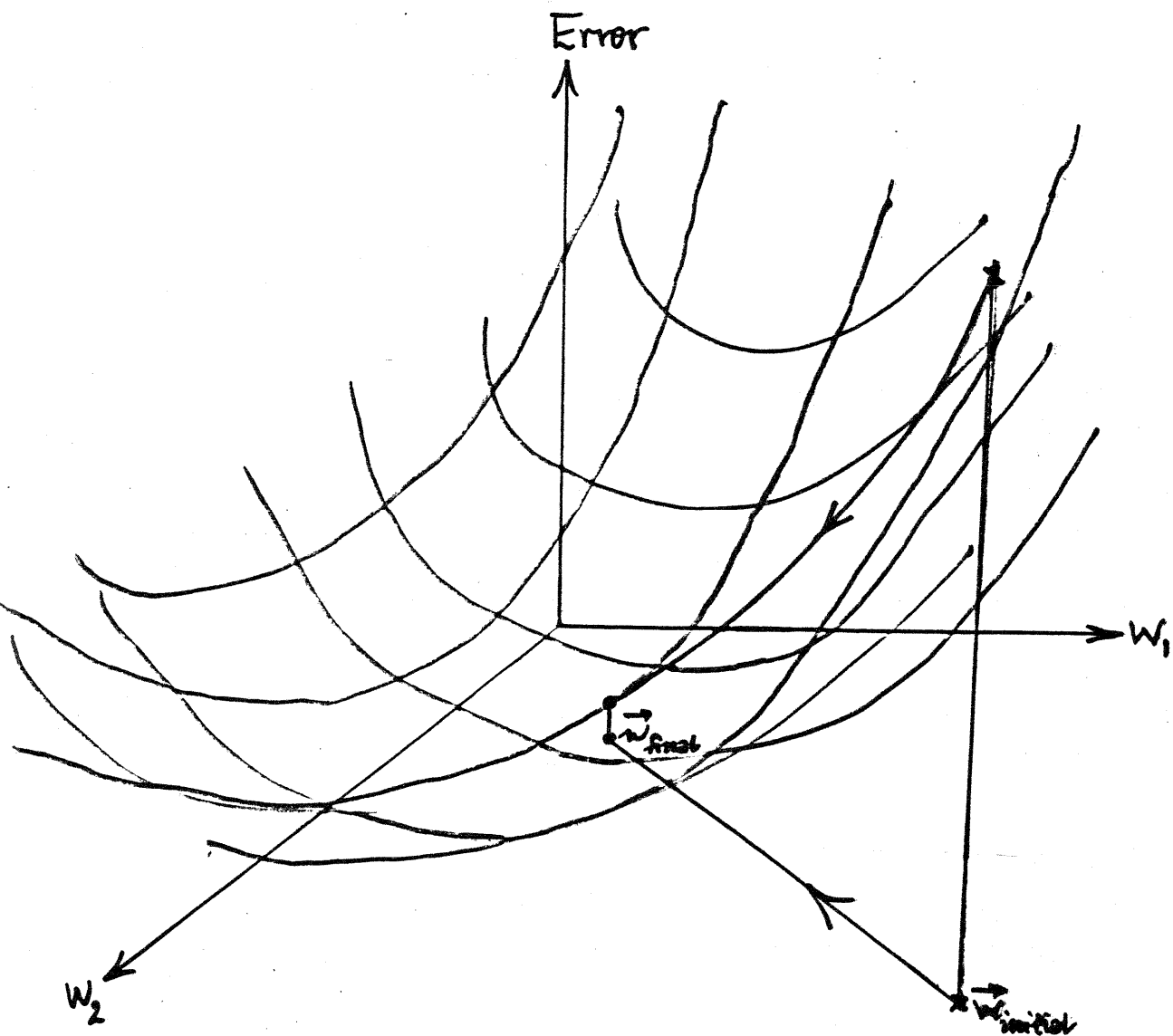
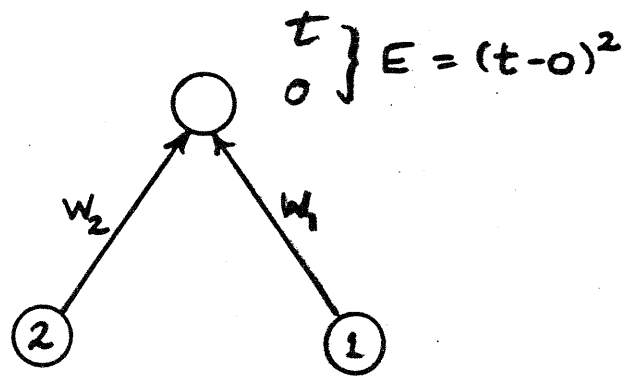
$$= (t_j - a_j) f'(\text{net}_j) \text{ output}$$

Gradient descent:

$\vec{\Delta W}$ = direction of steepest descent in Error

$$\Delta W_{ij} = -\epsilon \frac{\partial E}{\partial W_{ij}}$$

+ E } = conn. learning algorithm
 optimization technique



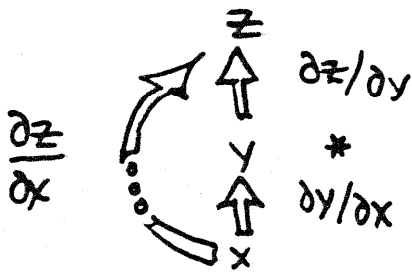
' $\Delta x \Rightarrow \Delta y$ ' := a change in x of amount Δx leads to a change in y of amount Δy

$\frac{\Delta y}{\Delta x}$:= rate of change of y w.r.t. x

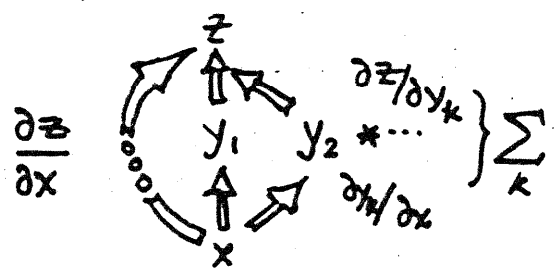
$\rightarrow \frac{\partial y}{\partial x}$ for very small $\Delta x, \Delta y$

Chain rule:

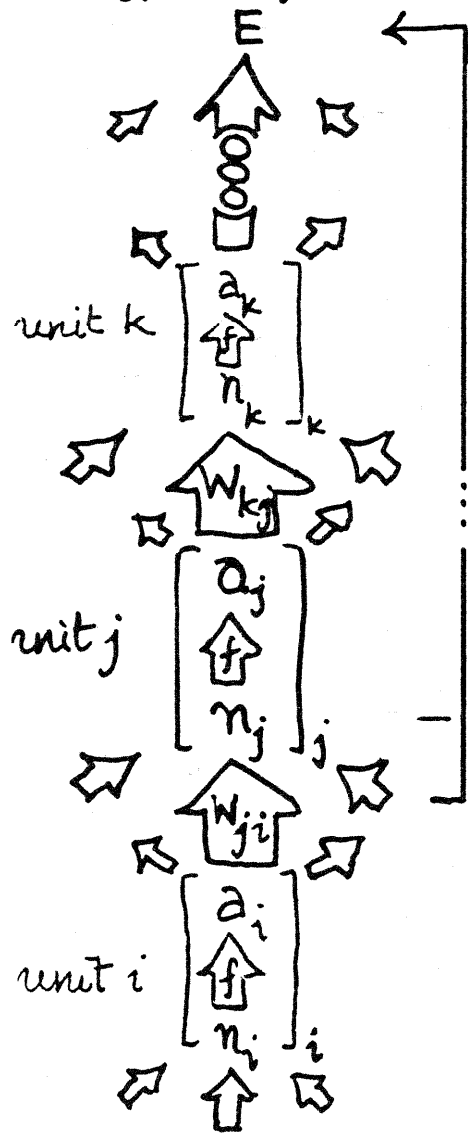
Additive property:



$$\frac{\partial z}{\partial x} = \frac{\partial z}{\partial y} \cdot \frac{\partial y}{\partial x}$$



$$\frac{\partial z}{\partial x} = \sum_k \frac{\partial z}{\partial y_k} \cdot \frac{\partial y_k}{\partial x}$$



$$\frac{\partial E}{\partial w_{ji}} = - \frac{\partial E}{\partial n_j} \cdot \frac{\partial n_j}{\partial w_{ji}} = \delta_j \cdot a_i$$

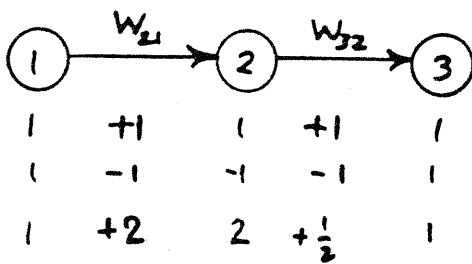
$$\delta_j = - \frac{\partial E}{\partial n_j} = \sum_k \frac{\partial a_j}{\partial n_j} \frac{\partial n_k}{\partial a_j} \frac{\partial E}{\partial n_k} = \sum_k f'(n_j) w_{kj} \delta_k$$

Definitions:

$$a_j = f(n_j) \quad \delta_j = - \frac{\partial E}{\partial n_j}$$

$$n_j = \sum_i w_{ji} a_i$$

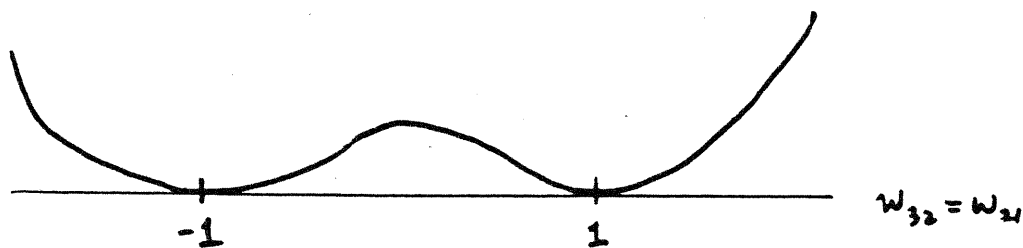
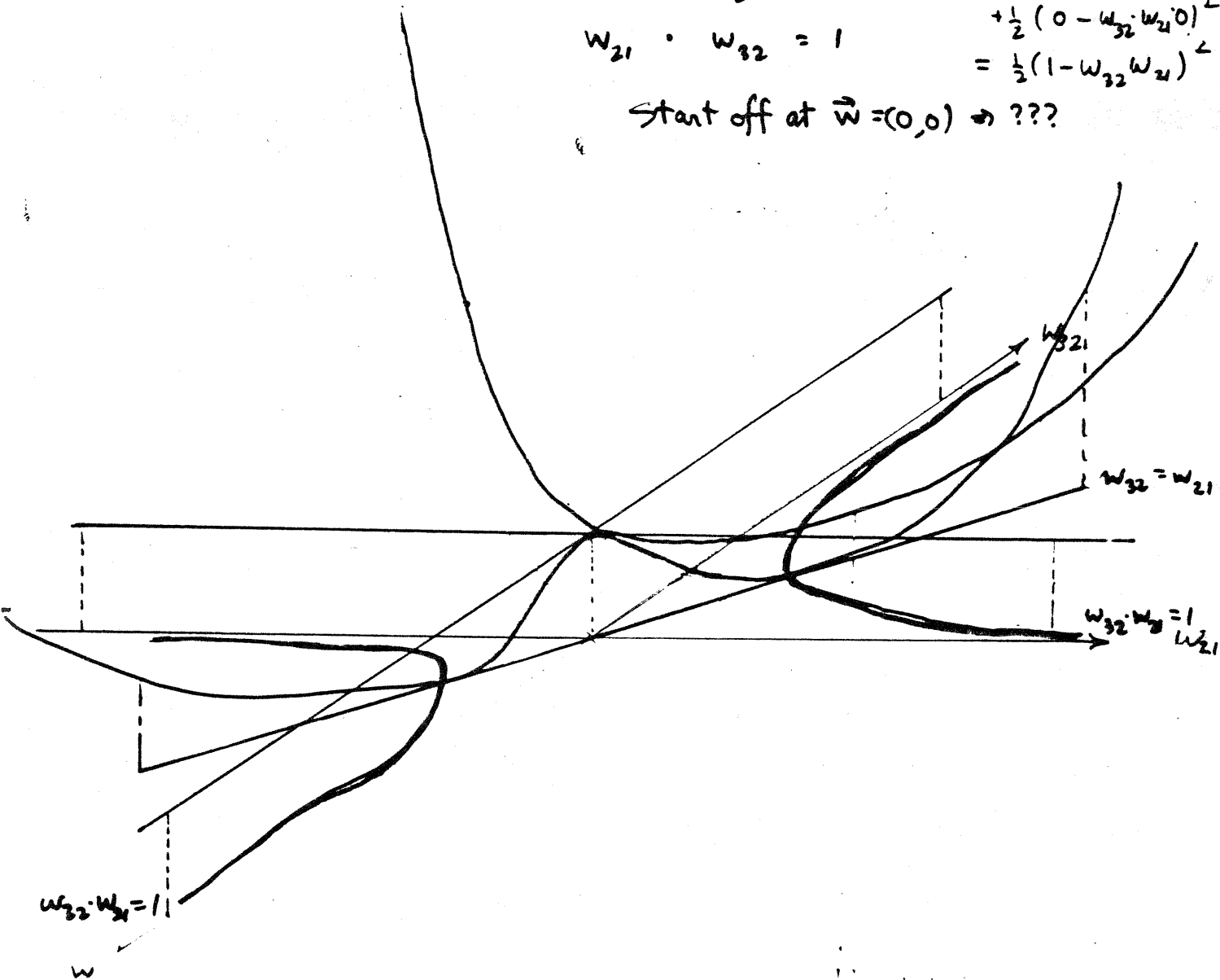
propagation has no convergence theorem why?



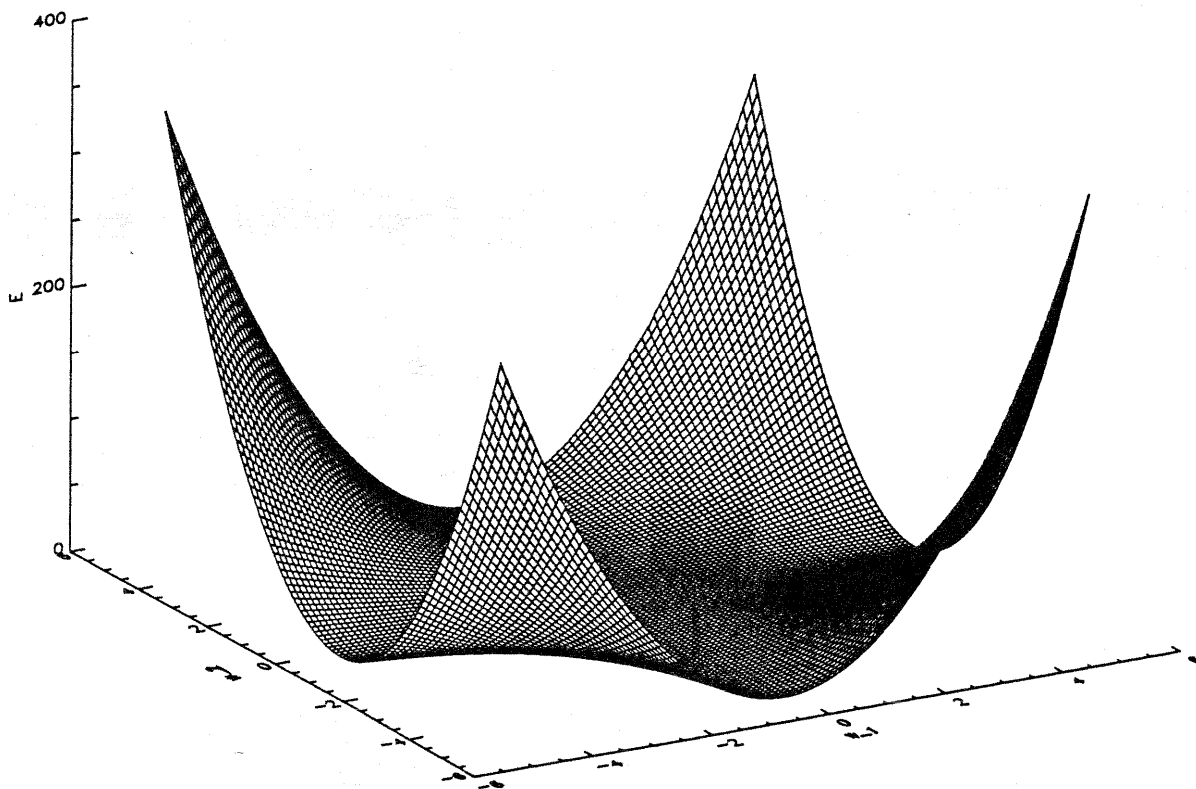
$a_i = \text{net}_i$ 'linear net'
 target = input 'auto-associative'
 $t_3 = a_1$ inputs: $\{0, 1\}$
 $a_3 = w_{32} a_2 = w_{32} \cdot w_{21} \cdot a_1$
 $E = \frac{1}{2} (1 - w_{32} \cdot w_{21} \cdot 1)^2 + \frac{1}{2} (0 - w_{32} \cdot w_{21} \cdot 0)^2 = \frac{1}{2} (1 - w_{32} w_{21})^2$

$w_{21} \cdot w_{32} = 1$

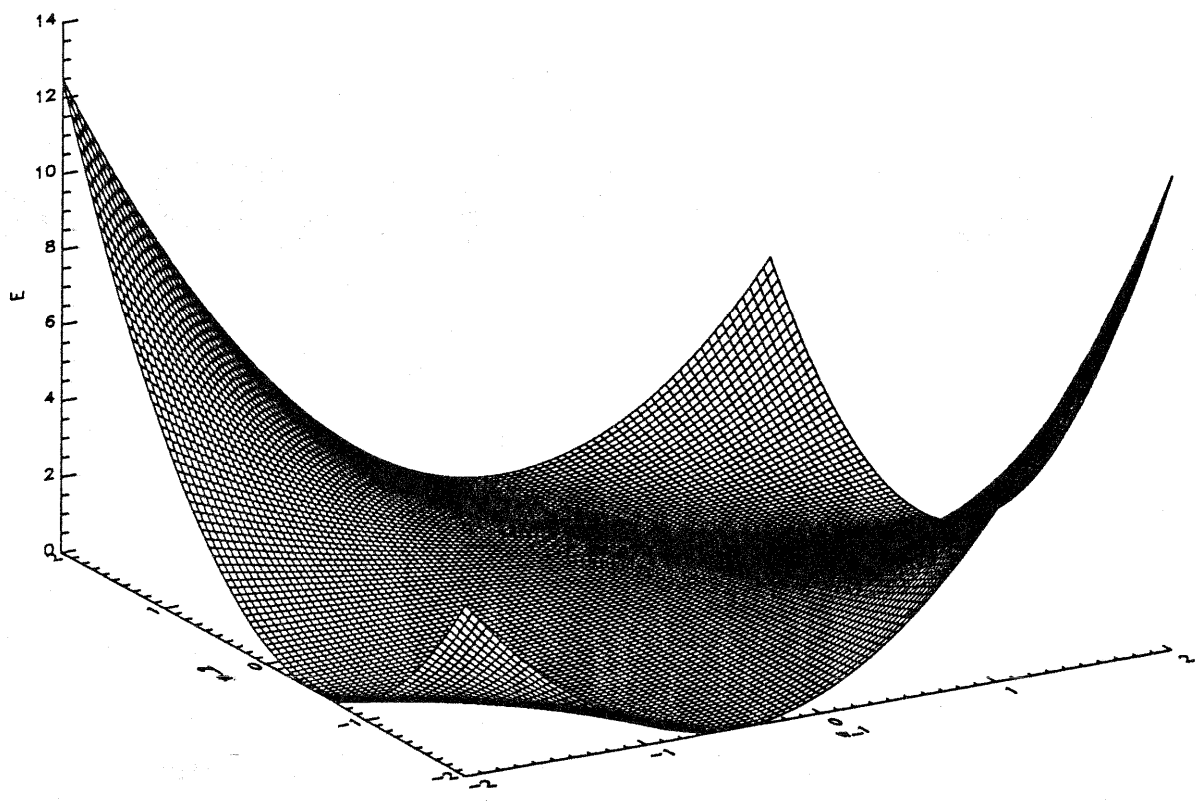
Start off at $\vec{w} = (0, 0) \rightarrow ???$

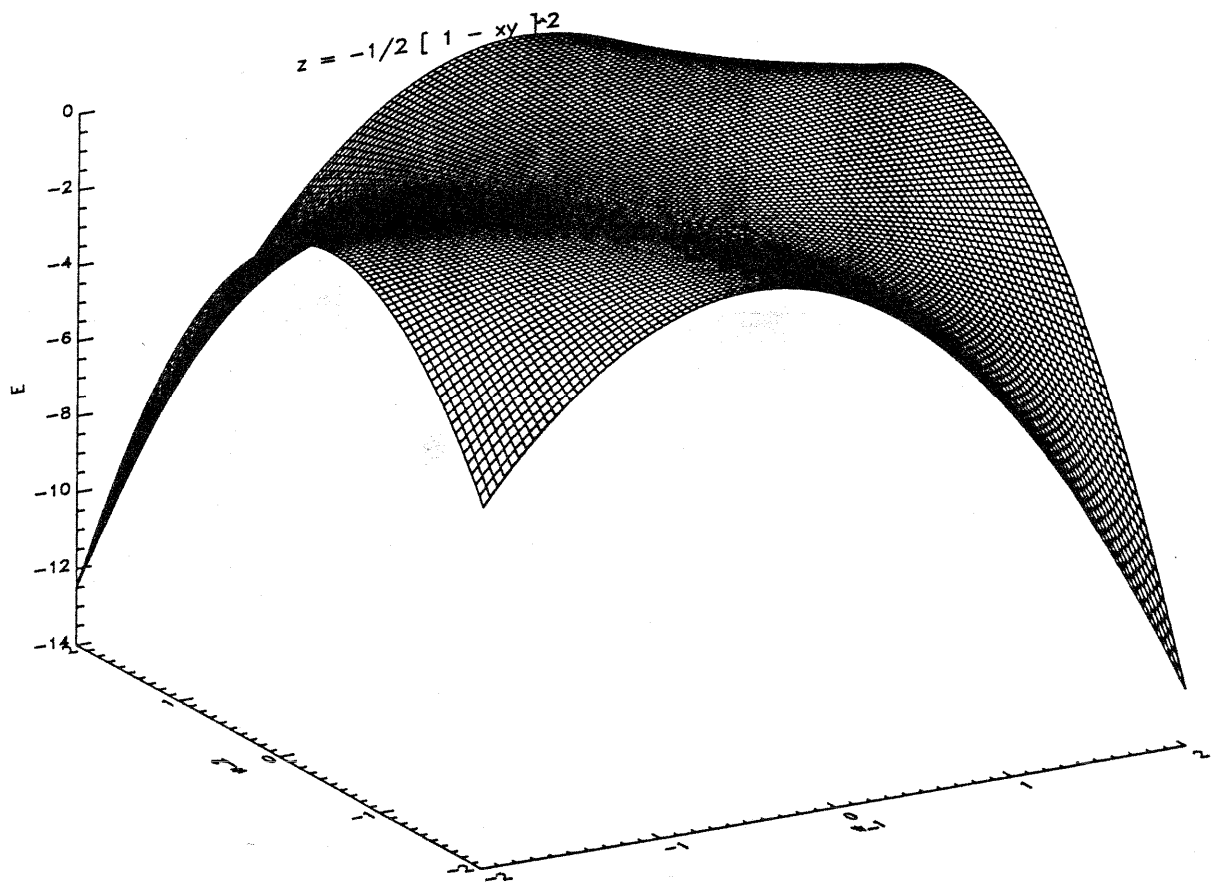


$$z = \frac{1}{2} [1 - xy]^2$$

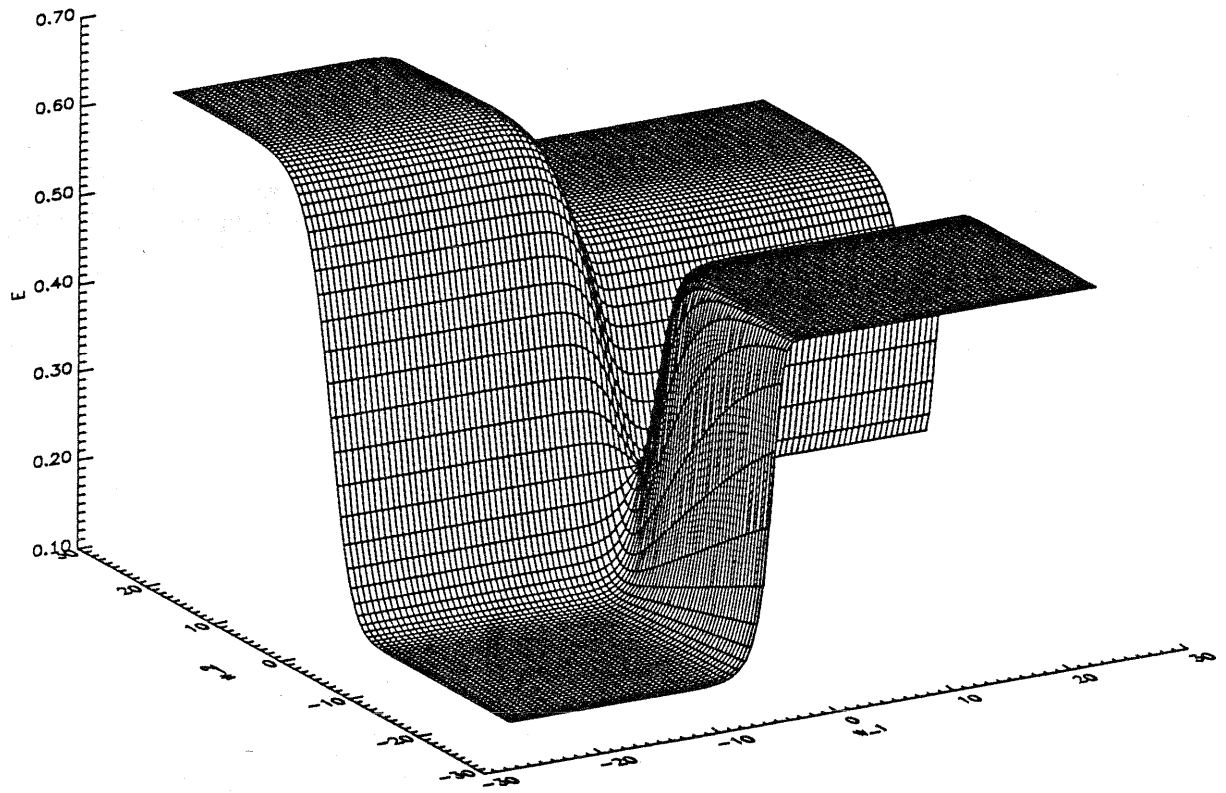


$$z = \frac{1}{2} [1 - xy]^2$$

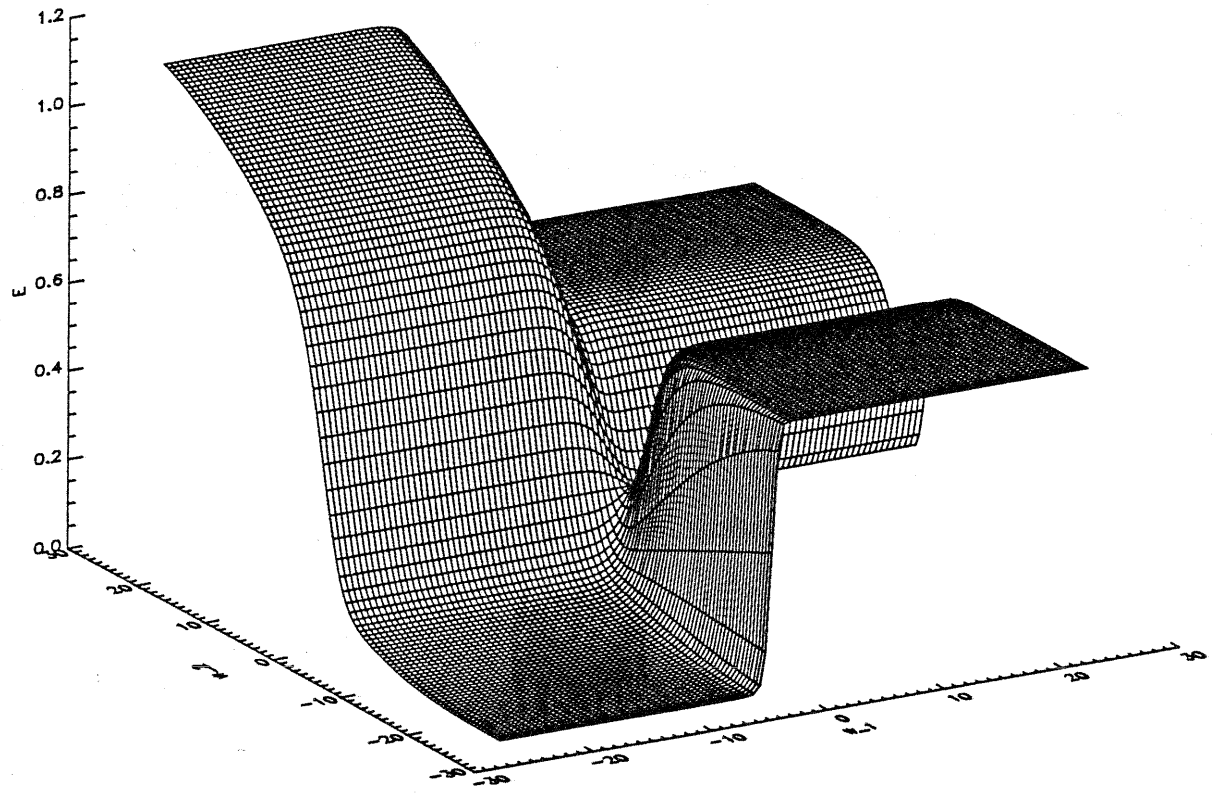




$$z = 1/2 [1 - f(y=f(x))]^2 + 1/2 [f(y/2)]^2$$

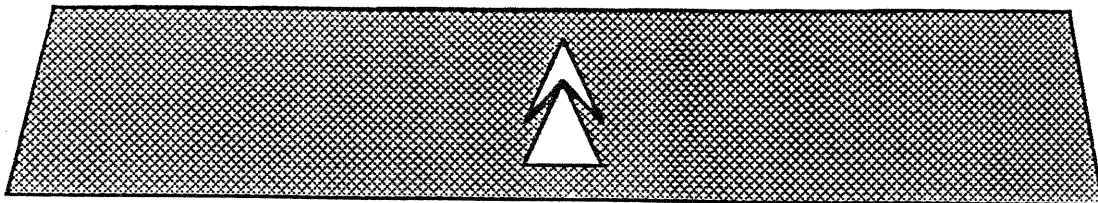


$$z = 1/2 [1 - f(y*f(x))]^2 + 1/2 [f(y/2)]^2$$

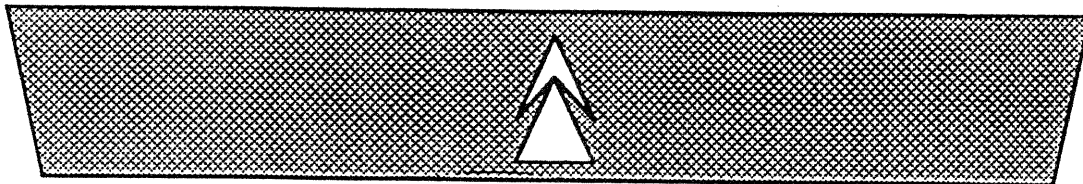


[[1]]

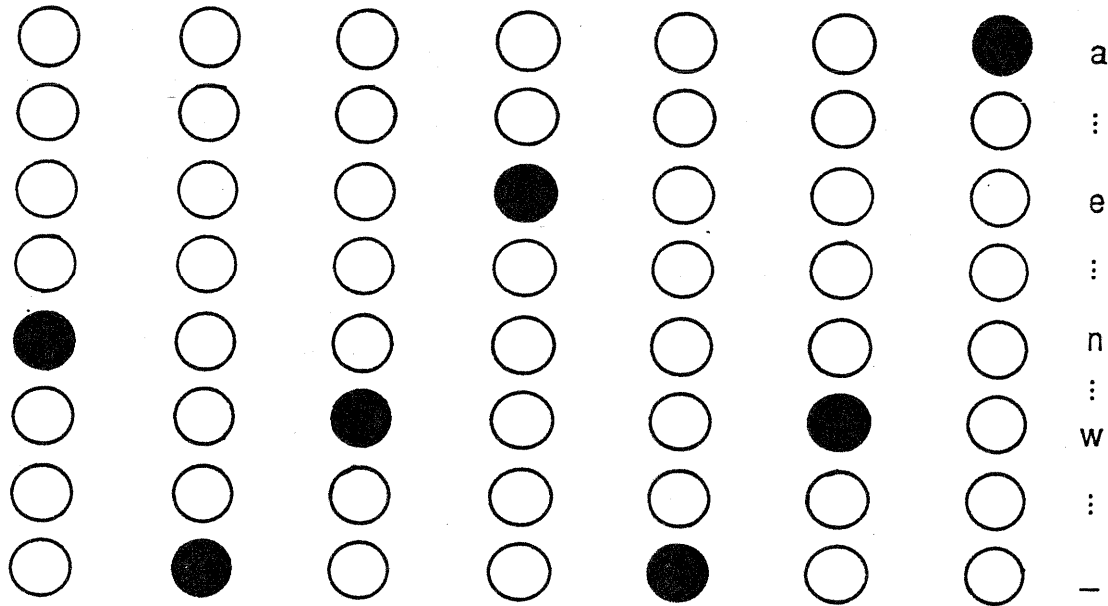
Output Units front back tensed stop nasal hi-freq lo-freq



Hidden Units



Input Units



n - w e - w a

a
:
e
:
n
:
w
:
_

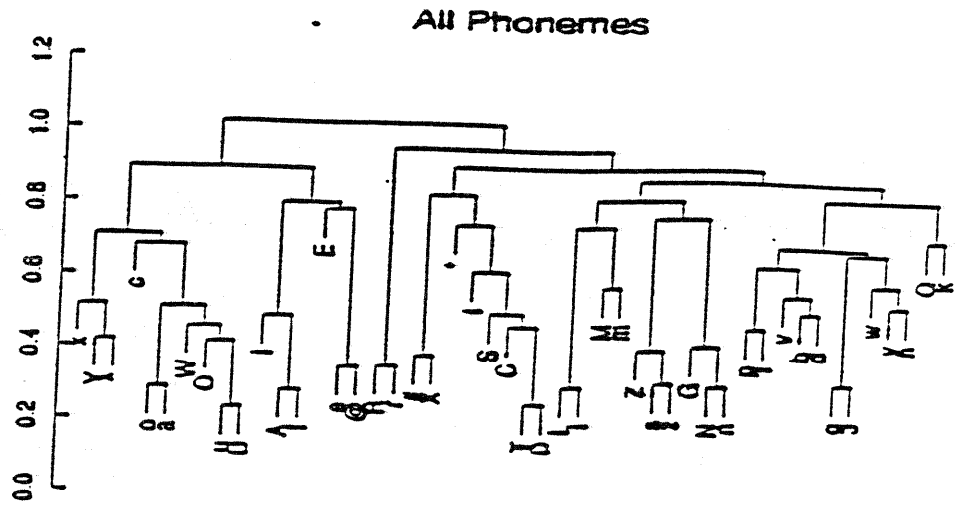


Figure 2: Hierarchical clustering results for 48 phonemes.

FIGURE 6

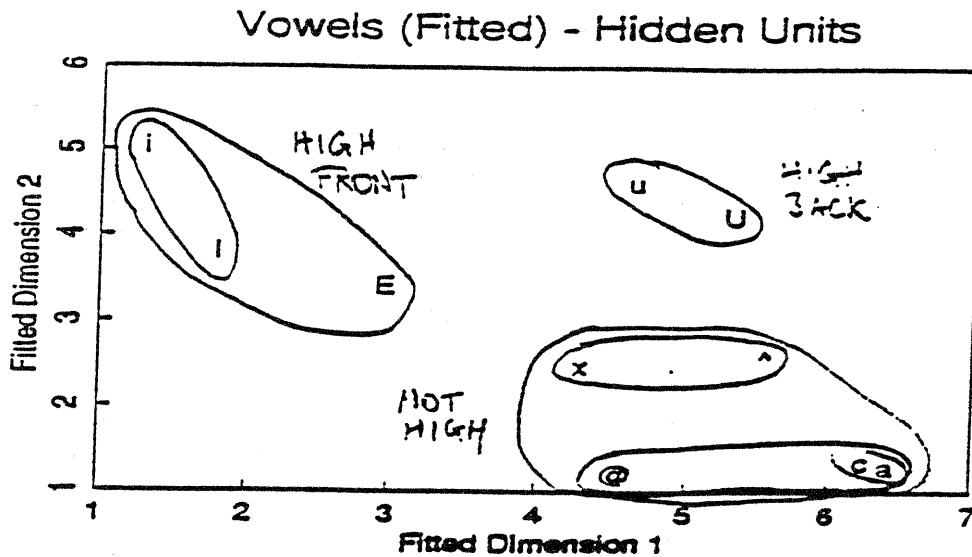


Figure 4: Fits based on linear regression of the three factor solution on the attribute dimensions "place of articulation" and "vowel height", plotted in Fig. 3. Data based on hidden unit activations. The groupings are based on a centroid hierarchical cluster analysis of the original correlation matrix.

Rosenberg
Cog. Sci. '87

Connectionist Learning

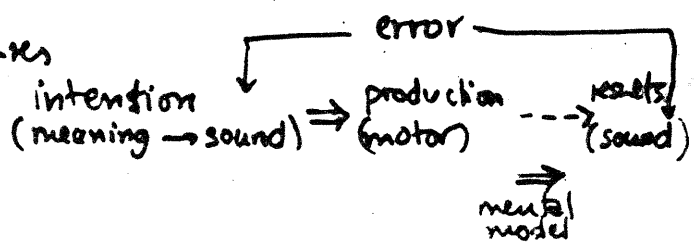
processing architecture
 +
 E function
 +
 minimization technique

} = connectionist learning algorithm

Extensions of back prop:

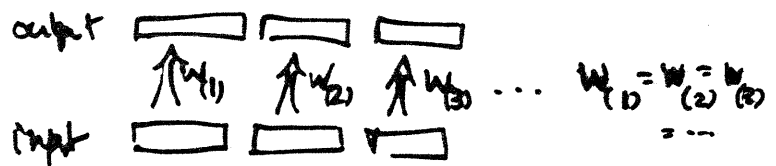
- More general processing architectures
- distal targets

Jordan:



* • constrained weights

eg: copiers for processing strings



* • recurrent networks

• Different E

- Occam's razor - simplicity vs accuracy
- particular kinds of target patterns eg: (0001000) for classification

Alternatives to supervised learning: no 'targets', new E

- Reinforcement learning
- Unsupervised learning
- * • 'Completion task': observe & predict, extracting structure
No negative evidence

* → Elman

Strategies & Principles of Connectionist Applications in Linguistics: A summary

Low-level strategy

1. Connectionist principle:

Learning is some kind of statistical analysis of co-occurrence.

Linguistic interpretation:

Temporal sequence of connectionist patterns → temporal sequence of linguistic units

Linguistic principle:

Linguistic categories can be induced from positive examples thru the prediction of the next item.

Example:

Inducing word boundaries, lexical categories: Elman

2. Connectionist principle:

Processing is activation-driven: The [continuous] activation of a unit is increased/decreased over time in proportion to the activation of its neighbors in the network.

Linguistic interpretation:

activation → feature value (e.g. accentual prominence, sonority, tone)
network neighbors → tier neighbors

Linguistic principle:

The [continuous] derived value of a feature is increased/decreased over time in proportion to the derived value of that feature for its left- and right-neighbors in the tier.

Example:

Goldsmith & Larson theory of stress & sonority

3. Connectionist principle:

Processing is similarity-driven.

Linguistic interpretation:

temporal sequences of activity patterns → segmental strings
connectionist unit → distinctive feature
similarity → sharing of distinctive features

Linguistic principle:

The tendency for a missing feature in segment s to be filled with a value consistent with that of a preceding segment s' is increased by
similarity between s and s'
similarity between s' and other segments near it
proximity in string/time of s' and s

Example:

Transparency in Hungarian vowel harmony: Hare.

Methodological aside:

Low-level strategy for application of connectionism to linguistics (radical):

Low-level connectionist networks [principles] → specific linguistic account/'model' [→ higher-level analysis (possibly)]

High-level strategy (conservative):

Low-level connectionist networks → high-level connectionist computational principles → linguistic principles defining a grammatical formalism → specific linguistic accounts

Note: This strategy is made possible only through technical innovations in the high-level analysis of connectionist computation.

High-level strategy

4. Connectionist principle:

Connectionist representations can be analyzed on a higher level as symbolic structures.

Linguistic interpretation:

Henceforth, all grammatical representations will be symbolic: traditional, unrevised. The rules too will be traditional in form, but their interpretation and interaction will be new. (Conservatism.)

5. Connectionist principle:

Processing (at both lower- and higher level) is harmony-driven.

Linguistic interpretation:

connectionist input → linguistic 'input' to grammar (string of words, phonemes)
connectionist well-formedness → linguistic well-formedness
pattern of activity arising from an input → structural description of the input
pattern of connections → grammar

Linguistic principle A:

Grammatical well-formedness is quantitatively measured by Harmony. The grammar assigns to any input the structural description that maximizes Harmony. This maximal Harmony value is the well-formedness of the structure: high for well-formed and low for ill-formed.

The terms in the Harmony function define a Harmonic Grammar, and may be interpreted as *soft rules* of the form:

If structural configuration X occurs in the structure, add H_x to the Harmony of the

structure.

The numbers H_x can be automatically determined from the data via back propagation.

Note: Harmonic Grammar permits (but does not require) the study of **very complex interactions of multiple factors**.

Example:

Unaccusativity phenomena in French: Legendre, Miyata, Smolensky

Problem: Understanding the *grammar* is almost as difficult as understanding the original *data*...

Linguistic principle B:

Optimality. A grammar is a *preference relation* \succ among structural descriptions; it assigns to any input that structure which is *optimal* (preferred by \succ to all other structures).

The preference relation \succ among structures is built up compositionally from preference relations among the substructures or subdimensions from which structures are built.

The basic preference relations and their means of combination are drawn from a universal repertoire.

6. Connectionist principle:

Learning is error minimization.

Linguistic interpretation: ???

Example applications: ???

We chose four diagnostic contexts:

Object Raising (OR)	La glace est facile à faire <i>fondre</i> .	Ice is easy to make melt.
Croire "believe" (CR)	Je croyais Marie déjà <i>sortie</i> .	I believed Marie to have already gone out.
Participial Absolute (PA)	<i>Parti</i> avant l'aube, Pierre est arrivé à destination le jour même.	<i>Gone</i> before dawn, Pierre arrived at his destination on the same day.
Reduced Relatives (RR)	La neige <i>fondue</i> a formé de la boue.	The <i>melted snow</i> formed mud.

Specifying HNet' based on linguistic analysis



Data: 760 French sentences generated from the four diagnostic contexts, 143 intransitive verbs, and 3 types of arguments with their acceptabilities judged by human informants in 5 graded levels.

Choice of constituents:

Inputs: We chose the following to code each of the 760 French sentences:

- (a) Argument: two semantic features - AN (animate) and VO (volitional).
- (b) Verb: two aspectual features - TE (telic) and PR (progressive); 143 individuated verbs as lexicon.
- (c) Context: four diagnostic contexts (OR, CR, PA, and RR)

Hidden: two hidden constituents, motivated linguistically by the unergative/unaccusative distinction.

Choice of constituent interactions:

175 independent quadratic terms representing pairwise constituent interactions. (143 lexical, 32 non-lexical)

E.g., we assume each diagnostic context can interact with (have preferences for) semantic features of the argument and aspectual features of the verb (include the terms $H_{OR,AN}$, $H_{CR,TE}$, etc.).

E.g., we assume each diagnostic context *cannot* interact with (have preferences for) individual verbs (eliminate terms $H_{OR,dire}$, $H_{CR,fondre}$, etc.)

Treatment of hidden constituents:

We assumed that the two hidden constituents are mutually exclusive: turn on one of the hidden units that maximizes H and turn off the other.



Results

• Examples of soft rules:

After training the HNet' on these data, we interpret the weights in HNet' as a set of soft rules:

- verb *s'asseoir* "walk" prefers hidden constituent 2 - if hidden constituent 1 is chosen, decrease H (well-formedness) by 4.5.
- verb *aller* "go" prefers hidden constituent 1 - if hidden constituent 1 is chosen, increase H by 3.4.

• The performance:

As a collection of these soft rules, the grammar embodied in HNet' could account for the signs [+ or -] of acceptabilities for all of the 760 sentences, and for the graded acceptabilities [5 levels] for all but 30 of them.

• Strong interactions among syntactic and semantic components:

The network achieved this performance with strong interactions among various syntactic and semantic components: almost every rule is strong enough to flip a decision between acceptable & unacceptable.

• Extendability of the grammar:

We tested how well the grammar generated can extend to new verbs. After training on 536 sentences with 87 verbs, we gave the network 80 sentences with 20 new verbs. The network could account for the signs of acceptabilities of all but 2 of the 80 sentences by adding an appropriate new lexical entry for each verb.

• Predictions:

The network was able to make certain predictions about acceptability patterns allowed for verbs and arguments with certain feature combinations. We are in the process of evaluating these predictions.

- Goal: Account for the acceptability judgements of 8393 Ss (3608 intransitive, 4785 transitive)

[an explanation in D.I.C.F.L.; for an exploration in T.I.C.F.L., see Prince & Smolensky, 1991]

Data:

- Constructions (11): OR, CR, PA, PE, RR; ON, PCL; PRQ, FOR, PR, IMP
- Targets: Subj, D.O.
- Embedded Predicate
 - Identity 408 = 183 transitive + 225 intransitive
 - Features Given aspectual features - TE, PR
 - Learned (arbitrary) features - $n = 6$
- Embedded Argument Structure
 - Transitives: Subj, D.O. } semantic
 - Intransitives: Arg } features: VO, AN, DEF, deep G.R. Subj, D.O.
- Acceptability judgements: +, +?, ?, -?, -

Account:

- Implemented as a local connectionist network
- Trained using backpropagation on judgements
- Current best account: of 8393 Ss:
 - 104 errors (1.2%) = 90 transitive (9.5%) + 14 intransitive (1.7%)

Account:

- As a set of Harmonic Grammar rules:
 - If construction = CR & target = D.O. & deep G.R. = D.O. then add .55 to harmony = well-formedness

If predicate = main 'die' & deep G.R. = Subj then subtract 2.6 from Harmony

:

If construction = CR & target = D.O. & subj = +VO then subtract 1.5 from Harmony interacting via the

Harmonic Structural Assignment Principle:

assign the structure that maximizes Harmony

- As the higher-level description of a lower-level connectionist network obeying certain general principles of connectionist representation & processing (in particular, pattern completion via Harmony maximization)
- Basic linking assumption:

Linguistic well-formedness = connectionist well-formedness = Harmony

Arizona Phonology Conference
 April, 1991
 Tucson

OPTIMALITY

Alan Prince
 Center for Complex Systems
 Brandeis University

Paul Smolensky
 Center for Opto-electronic Computing
 University of Colorado

(1) Optimization in Grammar Choice (Chomsky, 1951, 1965)

UG(D) => G₁, G₂, All G_i's agree on D.
 Eval { G_i } -> G*

Chomsky's idea was to find a coding for the operations and structures of grammar such that the length (i.e. shortness) of the encoding of G was the measure of G's value.
 - For phonology, we must determine Eval(Lexicon) + Eval (Rules).
 Otherwise, we can drive Eval(Rules) to optimum by no Rules.

(2) Optimization as a grammatical mechanism.
 Simple Case:
 Do-α (IN) -> OUT₁, OUT₂,
 WF (OUT₁ } -> OUT* The real output.
 More generally,
 B (IN, Do-α, OUT*) > B (IN, Do-α, OUT_j) "Greatest Benefit."

(3) The rap against optimization.

- a. Have to use numbers - parameter city; and use counting.
- b. Many messy tradeoffs if t > k, a > i, what then of ti vs. ka?
- c. Optimization is computationally intractable, in general.

(4) Counter-rap.

- c. It is not incumbent upon grammar to compute. Well-definition is all; not efficiency or even algorithmicity (Chomsky).
- a'. Actually ORDER, not counting, is the key.
- b'. We will argue that many cases of apparent tradeoff can be handled without tradeoff calculation, by a principle of combining orders.

(5) Optimization in a grammatical mechanism: the case of Berber Syllabification (Dell & El-Medlaoui 1987, 1988)

(6) ANY segment may be syllabic:

rA:k:ll	ʔA:rB:bi	lF:lK:l	A:lX:k	lX:zA:k:k	tzM:l
lM:z:h	lR:g:l	ll:d		lR:bA	

(7) ONSETS: syllables must have onsets, except phrase-initially.

(8) SONORITY: syllabification is sensitive to relative sonority.

a. tzM:l - *lZm:l vs. lM:z:h - *lmZ:h
 b. rat:ll:l - *ra:lL:wL:l i.e. ll:l - *LwL

c. D&E establish the following 8-point hierarchy:

a > ui > r:l > mn > z > fsx > b:dg > ptk

low V > high V > liq > nasal > voiced fric > voiceless fric > voiced stop > voiceless stop

(9) D&E's Algorithm (DEA)

Form core syllables (XY ("CV")), where X is any segment and Y is successively replaced by the features describing the steps of the sonority scale; in descending order. Iterate from Left to Right for each fixing of the nuclear variable Y.

(10) Secondary phenomena (to be ignored):

- a. obstruent de-syllabified # and #.
- b. sonorant C's optionally desyllabify - #.
- c. tautomorphic geminates never begin an onset. * + m m

(11) EXAMPLES:

/rat:ll:l/	->	{rA}{ll}ll	->	{rA}{ll}{ll}	lt	->	{rA}{ll}{ll}{ll}	{T}
/l-xzn-4/	->	lx{zn}l	->	lx{zn}l		->	lx{zn}l	{nA}
/l-xzn-a-s/	->	lx{zn}{nA}l	->	lx{zn}{nA}l		->	lx{zn}{nA}l	{nA}

'thou stored'
'she stored for him'

(12) DEA serves to optimize the quality of syllables: high sonority items like to be nuclei.

(13) But DEA per se makes no contact with this. E.g. Why descend the scale?

(14) Harmonic Syllabification (HS)

Form the best core syllable from free material in the domain, good (σ) = good (nuc). Iterate until you can do more, H₁ (Σ) = Σ.

(15) This is a fully 'Harmonic' process: ('Harmony' from Smolensky, 1986).
 Go to the most well-formed available state.

(16) Note that HS is different from DEA. HS has no directional bias, does not sensibly run in a direction (LR) to deal with sonority plateaux.

(17) Evidence for directionality weak anyway.

- a. /kiut/ kiw, *kyut but better onset (DE note)
- b. /fksx/ R:kSx, *R:kSx but no final syllabic obstruent.
- c. /bayn-n/ bayNn, *bay:nN both ok DEA P:1,2,3 only the first.
- d. /ugm/ u:gMn, ug:mN DEA fails. Nb. closed σ bad.
- e. /tbd:rim/ *t:bd:rim, only it.bD:rim

(18) Conclusion: optimization, with grades of well-formedness (representational Harmony), is a mechanism of grammar.

(19) To make this approach fly, we need two things:

- a. Ways of evaluating combinations of phonological dimensions where the dimensions themselves needn't have an internal wf'dness structure, but may be scalar. Harmony scale on dim. comb. [post-Praguean contextual markedness: SPE, Kean,....Archangeli & Pulleyblank]
- b. Ways of combining different relevant dimensional scales to make harmony scale.

(20) Dimensional Combination. Example: weight and stress. (Prince, 1990)

- a. Separate prominence (not markedness) scales: H > L, stress > unstress.
- b. Combine implicatively: if H, then stressed. (WSP == Hayes's 'quantity sensitivity').
 Good arc: H', L'. Bad is: H' [unstressed heavy]

(21) Weaker implications: if stressed, then Heavy.
 Good arc H', L'. Bad is: L' [stressed light]

(22) Combination respecting strength of implications:
 H', L' > L' > H'. This is a Harmonic ordering, expressing degree of centered of dimensions.

(21) **Combination of Harmony Scales.** Example: 'unbounded' stress systems like: Stress the rightmost heavy syllable, if no heavy then stress the rightmost syllable (R/R). Prince (1983) and Hayes (1991) see these as enhancements of prominence rather than 'unbounded foot' phenomena. We extend this result, thereby limiting feet to the authentic binary rhythmic units.

(22) **The pattern R/R.** Two factors:

- a. **WEIGHT.** Heavy syllables should be stressed.
- b. **POSITION.** Edgemostriness: Stress should be near the end.

(23) **WEIGHT dominates POSITION.** WEIGHT >> POSN. (Nb. One stress.)

(24) **WEIGHT** must be satisfied, if possible. But there can be several choices:

- a. cv.CVV.cv.cv.CVV.cv.cv.
- b. cv.cv.cv.CVV.cv.cv.

(25) Indeterminacies are resolved then by POSN. (24b) is chosen. $\leftrightarrow b a^*$.

(26) No indeterminacy in (cv)* = ...cv.cv.CV.

(27) This is **LEXICOGRAPHIC ORDER** — a generalization of alphabetic order. Alphabetically, strings are ordered first by initial character (= WEIGHT), then ties are broken by the ordering on the second character (= POSN), etc. pns > qaanaaa. NB: NO TRADEOFF

(28) **LEXICOGRAPHIC PRODUCT** of two orders,

$P * >> Q$,

total order on the the pairs (p,q) constructed from the orders on P and on Q; first ordering by P-dimension, then by Q-dimension.

(29) Example: alphabetic ordering itself: POSN * >> ALPHA.

(1,2,3,4,...) * >> (a,b,c,...)
 1a > 1b > 1c > ...2a > 2b > 2c...

(30) **Claim:** Lexicographic Order is the essential mode of combining Harmony scales.

(31) Berber Syllabification is also a kind of Lexicographic Order: analyses in which /m/'s are nuclei are absolutely preferred to competitors in which /m/'s are not but /z/'s are. We can say:

X's should be peaks >> /s' should be peaks, for x > y in sonority.

With suitable technical development, this might replace the serial (iterative) HS.

(32) **Prominence-driven Stress.** Claim: works by Lexicographic ordering PROMINENCE >> POSN, with development of notions of prominence and position.

(33) Hindi (modern) (Keilkar, 1968; Hayes, 1991)

"Stress falls on the heaviest available syllable, and in the event of a tie, the rightmost nonfinal candidate wins." (Hayes)

(34) Heaviness: CwC, CxCC ($\mu\mu$) > Cw, CxC ($\mu\mu$) > Cv (μ)

(35) Heaviest is best:

KIDHAR jaiNAAB as.BAAB ru.pi.AA REEZ.gaa.rii

(36) Among equals, last nonfinal is best:

$\mu\mu$ ru.KAA.yaa PUS.ta.kce roo.ZAA.naa
 $\mu\mu$ AAS.maa jaab aas.MAAN.jaab

(37) Analysis: WEIGHT >> POSN

But POSN is constructed from NONFINALITY, and RTMOSTNESS.

(38) NONFINALITY >> RTMOSTNESS

(39) WEIGHT >> NONFINALITY >> RTMOSTNESS.

(40) Piraha. (Everett & Everett, 84; Everett, 88; Levin, 85; Davis, 88; Hammond, 90; Hayes, 91).

"Stress the rightmost token of the heaviest syllable type in the last 3 syllables of the word."

(41) Parallels: 'rightmost heavy or rightmost syllable'. 'HEAVINESS' >> EDGEMOSTNESS

(42) What is 'Heaviest'? C = voiceless, G = voiced cons.

a. ?A.ba.gi	'toucan'	Cv > Gv
b. ?a.ba.PA	'Amapa'	rtmost Cv wins
c. so.AI.pi	'nose'	w > Cv
d. KAA.gai	'word'	Cw > Gw
e. ?oo.GAI.hi.ai	'banana'	Gw > w ; in 3 σ window; nb poo.
f. ka.pi.g.a.k.a.k.i.j.a.bao.BAO		rtmost: in window; nb. kai

(43) Full 'Heaviness' Hierarchy:

CVV > GVV > VV > CV > GV > V, where C = voiceless, G = voiced.

(44) Evidence that the stress is there:

- a. Some speakers treat it as a beat wrt hand-gestures.
- b. Some speakers devoice everything after stressed syllable.
- c. Some speakers delete everything after stressed syllable.
- d. May be some tropism of tone to stress.

(44) ISSUES:

- A) How is 3 syllable limitation established?
- B) How is 'heaviness' hierarchy established?

(45) Ans. to (A). *Domain of Stress is Minimal Prosodic Word, minWd.*

(Cf. Prosodic Circumscription (McCarthy & Prince, 1990), whereby a prosodically delimited subdomain serves, in lieu of the expected morphological category, as the domain of a process.)

(46) *What's minimal about 3?* Prosodic Hierarchy says Wd contains F contains σ . So, hierarchically-locally, minWd contains ONE F. Maximal such Wd = F + σ (or indeed σ + F).

(47) Piraha stress must lie in maximal minWd, for F = $\sigma\sigma$.

(48) Evidence for involvement of Wd category.

Closely-knit phrases show ONLY ONE STRESS when last word is 2 σ .

bao.sai # bi.SAI 'cloth # red'

?a.ba.pa # go.GI 'city-name # where-at'

BUT:

?i.sii.HOA # ai.BAI.?'i

?a.pa.PAI # ?i.ta.ha 'liquid fuel # much'

ka.H(A)J # ?o.ga.ba.GAI 'head # hurts'

'arrow # want'

Analysis: PWD = max minWd is established at j-edge of morph-word.

(Cf. Chen, Selkirk, Hewitt). Note RL orientation: final wins.

(49) PWD Parses. —Stress falls inside PWD. Must have }# .

ba0.{sai # bii.SAI}#
 {?a.pa.PAI}# {?iI.ta.ha}#
 {ka.H(A)}# ?o.{ga.ba.GAI}#

(50) ANS. to (44B). 'Heaviness' Hierarchy.
 CVV > GVV > VV > CV > GV > V
 a. xVV > yV in every case.
 b. C > G > nil This is just onset goodness! (R. Shacter).

Prominence Order = Weight >> Onset

(51) Full Story. IN:PWD >> WEIGHT >> ONSET >> RIGHTMOSTNESS.

(52) Malthill (Jhaa, 1958; Hayes, 1986, 1991)
 Stress penultimate, final, antepenultimate, dependent on foot structure AND VV location.

(53) In words with only SHORT VOWELS, stress is penultimate:

Saia pa.TiIa dhanaa.HEra bhinaa.SERa
 ja.han.NEma sun.NARA

This is actually a Moraic-Trochaic (RL) pattern (Hayes)
 — weak vowels in open syllables reduce; those in closed do not; nb. no closed final syllables.

(54) LONG VOWEL FINAL: Stress is FINAL for SHORT penult V—

a.dina.TAA gora.min.TII eka.hat.TAA

LONG V in antepenultimate stressed if VV followed by two LIGHT:

ji.muta.BAA.hana kaka.ROO.hari BAA.sana

PENULT LONG V is stressed:

pu.RUUKha SAA.bhaa ba.raha.MAA.saa

(55) ANALYSIS: Main Stress falls on MOST PROMINENT in final circumscribed window; when there is equality, penult is favored (Non-finality).

(56) Window: 2 units = FF, Fσ, σF. = 2F, if headless feet exist (H86)

(57) Elementary Prominence Orders:
 FOOT: Foot-heads > Nonheads;
 VV: VV > V

(58) Relation: VV >> FOOT

(59) As usual, PROMINENCE >> POSN
 for POSN = NONFINALITY >> RIGHTMOSTNESS

(60) Cases:

...[CVcv.CVcv] = = prom/rightmost Fhead. dhanaa.HEra
 ...[CVC.CVcv] ditto ja.han.NEma
 cv.[cv.CVV] prom wins. ku(0).ra.NAA
 ...[CW.CVcv] prom wins. BAA.sana
 ...[CVV.cvv] = = prom/nonfinality wins. SAA.bhaa

(61) Fact Note: Following Hayes, we assume ...cv.CVC.cv#
 galaa + bcnaa —> galabENna but CAA.rillo 'fourth'

VV shortens in nonfinal, non-mainstressed syllables. If wrong, then PROM = heavy.

(62) Awadhi (Saksena, 1971; Hayes, 1991). Exercise for auditor: Stress is penultimate, except that in light-heavy#, heavy is stressed.

(63) Broad Vista. To run grammar on optimization, we need to be able to say WHEN to perform an operation. I.e. when it is better to act than to do nothing:
 B(X->Y) > B(X->X)

(64) Basic Harmonic Condition: H(Y) > H(X). Well-formedness increasing: up Harmony Hill.
 But not sufficient: else Wd —> Tata.

(65) From universal perspective, need to order Transitions and combinations of Transitions and contexts to obtain markedness implications about processes.

(66) Example. LANGO Vowel Harmony — one property thereof. (Pulleyblank, Yes.)

a. ATR Harmony spreads forward from ALL vowels over a SINGLE CONSONANT:
 in V₁-C-V₂, V₂ harmonizes with 1st vowel.

b. But over TWO intervening Cs, the trigger V must be high:
 only in hi-CC-V do we get spread of ATR.

(67) Appears to involve complex TRADE-OFF in virtues of spreading from various sources, and difficulty of doing same in various environments. But there is NO TRADE-OFF.

(68) Approach. Suppose we know the following:

a. Spread ATR from HI > Spread ATR from NonHI. #HUR/HTV
 b. Spread over single C > Spread over CC. #DIST/ACE#

(69) Form the Lexicographic Product ~~XXXXXXXX~~ >> DISTANCE: (see vice versa)

Spread from HI over C > Spread from H over CC
 > Spread from NonHI over C > Spread from Non-Hi over CC.
 #LAWSE, IN, STRINE.

(70) Now, an individual language may insert DO-NOTHING anywhere in the order.
 All things preferable will be done, then.

(71) Insert DO-Nothing at bottom: any action is better than inaction: no constraint, full ATR harmony.

(72) Lango. Insert Do-Nothing above last element in order.
 Spreading-from-NonHI-over-CC is worse than Nothing:
 But everything else is better. So act accordingly. ###

Constraint Interaction and Harmony Maximization In Grammar

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I. Basic Idea -- General

A. Picks up two themes in modern linguistic thought (see attached bibliography; most of the entries are concerned with these):

1. Constraints or processes that give way or are conditional.
EG.

a. Do such-and-such EXCEPT when the result conflicts with some other constraint. Eg. Make final σ extrametrical EXCEPT in monosyllables. Eg. Foot form.

b. Do such-and-such ONLY when necessary to achieve wellformedness. Eg. Epenthesize a glottal stop ONLY to provide syllable with onset. Epenthesize a Vowel ONLY to make word big enough to hold foot.

2. Direct application of universal principles of markedness in the operation of individual grammars.

EG. Prefer syllables to have onsets. Prefer the collocation of +H and +ATR. In the standard theory (eg. SPE, ch. 1-8, et seq.), these are no more than observations made about what grammatical processes happen to end up doing. But they can form the foundation for principled theory of grammar itself; can be directly appealed to in specific grammars.

B. Rapport with mode of functioning of central species of connectionist networks: harmony increase to maximum.

C. Fundamental Harmonic Imperative: among the possibilities, choose the one that maximizes harmony (relative wf'edness).

II. What we need to carry out this project.

-Notion of preferences (approx = markedness)

-Ways of combining orders. (Lexlco. Direct.)

-Way of assessing harmony of structures, as determined by constraint order. (LOCS. Tableaux)

III. Constraint Domination. Some familiar basic types of constraint interactions.

A. Do something EXCEPT. A positively-regarded option is embedded lowdown.

1. Extrametricality: méns, *<mens> LexWD=PrWD >> EXH.

LexWD=PrWD. Lexical Words should be Prosodic Words, therefore contain feet.

EXH. Final syllables should be foot-loose.

2. Imbrication In Cibemba (Hyman, 1991):
Short Base Long Base

fik-ll -e *matik-ll-e
*fi-l-t -e mati-l-k -e

Generalization. Stems CVC suffix ll; Longer bases insert l after last vowel in bases.

Analysis. Take l to be default C. Then suffix /l/ to PrWd.

FB >> PrWdWF

FB. Feet should be binary at some level of analysis (σ , μ). PrWdWF. PrWd words should be consist exhaustively of well-formed units.

3. Foot Wf'edness. (#égo:#, *#é#, *#é#)

FB >> LexWD=PrWD >> EXH >> PARSE >> RH

RH. Rhythmic Harmony. Trochaic feet LL, H are better than LH. PARSE. All material should be parsed into prosodic structure. (= It's Prosodic Licensing).

Say Stray Erasure en route to the Phonetics.

4. Infixation 1: gr-um-adwet. *umgradwet. *gumradwet. Goodfirstsyll >> Leftmostness of prefix

Goodfirstsyll. No Coda.

Leftmostness of Prefix. 'Prefix' means affixal content is Leftmost in Affix+Stem collocation.

5. Infixation 2: metgo-go-t, *metgot-go.

Edge-preserve >> Rightmostness of suffix (light syll).

Edge-preserve. Segment at edge of base should appear at edge of reduplicated base (pa-prath)

Rightmostness of suff. 'Suffix' means affixal content is Rightmost in Affix+Stem collocation.

B. Do something ONLY. A rejectionist option is lowdown & overruled by a higher-order constraint - that is, the high-order constraint can force the disfavored option.

HAVE-ONSET >> FILL-NODES

HAVE-ONSET = σ should dominate ON constituent.

'Epenthesis' = Insert empty syllable structure (selkir, Itó).

FILL-NODES = nodes should dominate segments = AVOID epenthesis.

Universal Typology in Harmonic Phonology: 0th-order Syllable Structure

Paul Smolensky & Alan Prince
July 25, 1991

Fundamental Definitions

LOCS:

Suppose given:

- a *role-filler decomposition* of S specifying for each $s \in S$ a description of s as a multi-set M_s of role/filler pairs
- an ordering \supset of fillers
- a function *predom* specifying a *predominant element* of any multi-set M_s of role/filler pairs; define:

$$\text{residue}(M) = M \setminus \text{predom}(M)$$

Then the corresponding *Lexical Order on Composite Structures* S is the ordering on S defined recursively by:

$M_s \succ M_{s'}$, iff

$$\text{filler}(\text{predom}(M_s)) \supset \text{filler}(\text{predom}(M_{s'}))$$

or

$$\text{filler}(\text{predom}(M_s)) = \text{filler}(\text{predom}(M_{s'})) \text{ and } \text{residue}(M_s) \succ \text{residue}(M_{s'})$$

Two cases of interest:

Filler-driven LOCS: $\text{predom}(M_s) =$ any role/filler pair in M_s containing a maximal filler (w.r.t. \supset).

Role-driven LOCS: $\text{predom}(M) =$ a role/filler pair in M_s containing a maximal role, w.r.t. an ordering on roles \supset which must be further supplied

SDG: The Strict Domination Grammar

$$p_1 \succcurlyeq p_2 \succcurlyeq \dots \succcurlyeq p_n$$

is the preference relation \succ defined from a sequence p_1, \dots, p_n of Boolean predicates over possible structural descriptions, defined as the following role-driven LOCS:

- the 'roles' are the predicates p_1, \dots, p_n and the 'filler' of each role is the truth value of each predicate: $M_s = \{\pm p_1, \pm p_2, \dots\}$ where the sign of p_k indicates whether s satisfies predicate p_k (+) or not (-). [We sometimes write M_s more mnemonically by suppressing the $+p_k$ and writing the $-p_k$ as $*p_k$]
- the ordering on fillers is $+ \supset -$ ($T \supset F$; 'preferences')
- the ordering on roles is $p_1 \supset \dots \supset p_n$

[Aside: If in the definition of SDG we change the LOCS from role- to filler-driven, then the order we get is 'Prefer fewer marks', where a 'mark' is a violated preference.]

FUT(P): The *Factorial Universal Typology* determined by a set P of universal preferences is the typology arising from the strict domination grammars determined all possible permutations of the preferences in P .

[That is, as far as the grammatical module governed by the set P is concerned, FUT(P) characterizes the set of possible languages as exactly those arising from all possible orderings of the preferences in P .]

0th-order (C/V) Syllable Structure

Goal:

To explain the typology:

onsets: required/optional/ * forbidden;
 codas: * required/optional/forbidden

[nuclei: assume required by definition of syllable]

		onsets	
		required	optional
codas	forbidden	Σ_{CV}	$\Sigma_{(C)V}$
	optional	$\Sigma_{CV(C)}$	$\Sigma_{(C)V(C)}$

Main Claim:

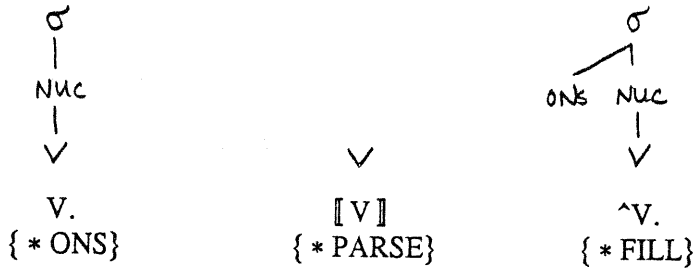
The universal typology of C/V syllable structures is $FUT(P)$, where the set of preferences P is:

- ONS:** Prefer syllables with onsets.
- COD:** Prefer syllables with no coda.
- PARSE:** Prefer parsed segments.
- FILL:** Prefer filled syllable positions.

Note: Best syllable is CV., which satisfies all preferences. Thus /CV/ is assigned CV. So it is not possible to prohibit onsets or to require codas.

Onsets (ignore -COD for now):

Look at underlying form with preferred coda (i.e., none) and an onset wanting repair (i.e., none): /V/;
 Possible structures:



Phonetic assumptions: unparsed segments are not realized (deletion); unfilled syllable positions are somehow realized (epenthesis).

The preferred structure is the one with the lowest mark; given an order

$$p_1 \gg p_2 \gg p_3,$$

the preferred structure is the one having { * p_3 }; the order of p_1 & p_2 don't matter. So rather than 3! = 6 cases there are 3 different ones (ignore {} for now):

- | | |
|---|------------------|
| 1a. ONS \gg {PARSE \gg FILL} \sim PARSE \gg ONS \gg FILL | Preferred: ^V. |
| 1b. ONS \gg {FILL \gg PARSE} \sim FILL \gg ONS \gg PARSE | Preferred: [V] |
| 2. {PARSE \gg FILL} \gg ONS \sim {FILL \gg PARSE} \gg ONS | Preferred: V. |

(Here, \sim denotes the equivalence of two orderings, that is, that they determine the same maximally harmonious forms.)

Using the first instance of each case, we can view the three cases hierarchically by letting

1-1: Prefer one-to-one pairing of segments and syllable positions

= either {PARSE \succ FILL} or {FILL \succ PARSE}

we get:

1. ONS \succ 1-1

a. 1-1 = {PARSE \succ FILL} Preferred: \wedge V.

b. 1-1 = {FILL \succ PARSE} Preferred: [V]

2. 1-1 \succ ONS

1-1 = {PARSE \succ FILL} \sim 1-1 = {FILL \succ PARSE} Preferred: V.

That is:

1. Onsets are mandatory, since ONS is the predominant preference

a. an onset is epenthesized;

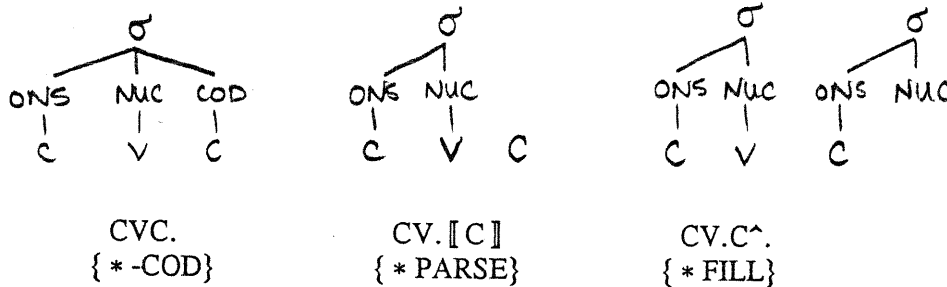
b. an onsetless nucleus is deleted.

2. Onsets are optional, since it is more important not to epenthesize or delete (1-1) than it is to have an onset.

Codas:

Same story, *mutatis mutandis*. Look at /CVC/ (preferred onset, coda needing repair).

Possible structures:



Cases:

1. -COD \succ 1-1

a. 1-1 = {PARSE \succ FILL} Preferred: CV.C \wedge .

b. 1-1 = {FILL \succ PARSE} Preferred: CV.[C]

2. 1-1 \succ -COD

1-1 = {PARSE \succ FILL} \sim 1-1 = {FILL \succ PARSE} Preferred: CVC.

That is:

1. Codas are prohibited, since -COD is the predominant preference

a. an extra nucleus is epenthesized;

b. a coda is deleted.

2. Codas are optional, since it is more important not to epenthesize or delete (1-1) than it is to lack a coda.

Note: For the onset discussion, the relevant case of FILL is 'Prefer filled onsets' (FILL_{ONS}), while for the coda discussion, it is 'Prefer filled nuclei' (FILL_{NUC}). These need not be assumed to be subsumed under a single general preference, FILL. Similarly, the relevant cases of PARSE are PARSE_V and PARSE_C for the onset and coda discussions, respectively. If there is but one general preference FILL and another such PARSE, then these general preferences must be relatively ranked once and for all in a given grammar, predicting that, PARSE_V \succ FILL_{ONS} iff PARSE_C \succ FILL_{NUC}, which in turn implies

that in any Σ_{CV} language, either onsets and nuclei are both epenthesized ($/V/ \rightarrow \hat{V}$. and $/CVC/ \rightarrow CV.C\hat{.}$) or nuclei and codas are both deleted ($/V/ \rightarrow [V]$ and $/CVC/ \rightarrow CV.[C]$). Presumably this is empirically false, so we must allow the two kinds of PARSE and two kinds of FILL preferences to each have their own place in the dominance hierarchy.

LAKIL - Hale, 1973; Wilkinson, 1978

uninflected	nonfuture	future	gloss
(A)			
kentapal	ketapal-in	kentapal-ur	dugong
ketar	ketar-in	ketar-ur	river
miyar	miyar-in	miyar-ur	spear
yaput	yaput-in	yaput-ur	snake, bird
yaraman	yaraman-in	yaraman-ur	horse
pirjen	pirjen-in	pirjen-ur	woman

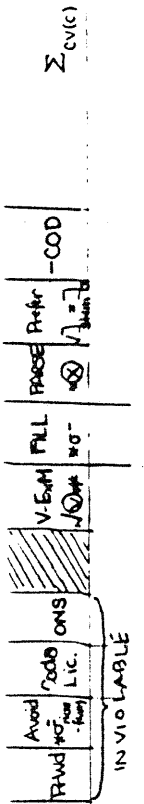
(B)				
-a	mela	mela-n	mela-ŋ	sea
	wanka	wanka-n	wanka-ŋ	arm
	kunja	kunja-n	kunja-ŋ	groin
-uV/→a	guka	guka-n	guka-ŋ	water
	kata	kaŋu-n	kaŋu-ŋ	child
	gawa	gawa-n	gawa-ŋ	wife
	keŋte	keŋti-n	keŋti-wuŋ	wife
	niŋe	niŋi-n	niŋi-wuŋ	skin
	pape	papi-n	papi-wuŋ	father's mother
	t'empe	t'empe-n	t'empe-ŋ	mother's father
-e	wiŋe	wiŋe-n	wiŋe-ŋ	interior

(C)				
	yalulu	yalulun	yaluluŋ	flame
	mayara	mayaran	mayaraŋ	rainbow
	wiwala	wiwalan	wiwalaŋ	bush mango
	karikar	karikarin	karikariwuŋ	butter-fish
	yiliyil	yiliyilin	yiliyiliwuŋ	oyster (sp.)

(D)				
-c	ŋurara	ŋuraraŋin	ŋuraraŋkuŋ	shark
	ŋaluk	ŋalukin	ŋalukuŋ	story
-a	putuka	putukan	putukaŋ	short
	murkunima	murkuniman	murkunimar	nullah
-u	gawuŋawu	gawuŋawun	gawuŋawuŋ	termite
	tipiti	tipitiŋin	tipitiŋiwuŋ	rock-cod (sp.)
	ŋapu	ŋaput-in	ŋaput-iwuŋ	older brother
-u	munjukumunju	munjukumunjun	munjukumunjuŋ	wooden axe
	t'umput'umpu	t'umput'umpun	t'umput'umpuŋ	dragon fly

(E)				
	yukara	yukarpan	yukaraŋ	husband
	wulunka	wulunkan	wulunkaŋ	fruit (sp.)
	wuŋait'i	wuŋait'in	wuŋait'iwuŋ	meat
	kantukan tu	kantukantun	kantukantuŋ	red
	karwakarwa	karwakarwan	karwakarwaŋ	wattle (sp.)

CVC-	uninflected	nonfuture	future	
	tera	ter-in	ter-ur	'thigh'
	yura	yir-in	yur-ur	'body'
	ŋita	ŋil-in	ŋil-ur	'neck'
	tjuita	tjil-in	tjil-ur	'hair'
	maŋa	maŋ-in	maŋ-ur	'hand'
	tuŋa	tuŋ-in	tuŋ-ur	'excrement'
	wunta	wun-in	wun-ur	'rain'
	kaŋa	kaŋ-in	kaŋ-ur	'grass'
	njuta	njitj-in	njitj-ur	'fire'



(A) Kentapa
 ken.ta.pa. ✓
 ken.ta.pa.⓪
 cen.ta.pa.⓪
 ken.ta.pa.⓪
 ken.ta.paa.

(E) yukarpa
 yukarpa. ✓
 yu.karpa.
 yu.karpa.⓪
 yu.karpa.a.

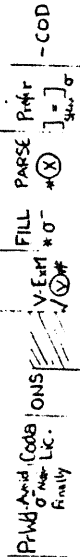
(B) wite
 wi.te. ✓
 wi.te.
 wi.te.⓪
 wi.te.e.
 wi.te.a.a.
 wi.te.a.

'MW)
wik
 wi.ka. ✓
 wi.k.
 wi.k.⓪
 wi.ΔΔ.⓪
 wi.⓪ΔΔ.
mar

(C) yolulu
 ya.lu.lu. ✓
 ya.lu.lu.
 ya.lu.lua
 ya.lu.lu.⓪

mar.ΔΔ. ✓
 mar.Δ.
 mar.⓪
 mar.ΔΔΔ.
 ΔΔ.mar.

(D) yaluk
 ya.lu. ✓
 ya.luk.
 ya.lu.ka.



Delet final V & prevnt non-coda C (do not epenthsize)

Do NOT delete non-coda epenthsize*

Insert final CV (do not 'reanalyze' across +

No final V deletion: block by minimal word con:

V-EM >> PARSE

Delete final V (but not preceding C)

Delete final non-coda C (do not epenthsize)*

Connectionism for Linguistics

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July 17, 1991

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Connectionist Computation

What is it? Low level characterization:

Data: activation values
Processing: spreading activation
Learning: associationist strength modification with experience

Why is it? Cognitive motivations:

Biological neural networks: abstract out a *computational* description

Psychological models of:

Perception
Memory
Associationist processing
Empiricist learning

Computation & linguistics

Psycholinguistics

Neurolinguistics
On-line processing
Acquisition
The form of grammar

If cognition is *connectionist* computation, what are the implications for grammar?

Relation between connectionist and symbolic computation

Eliminativism: Connectionist *replaces* symbolic
Implementationalism: Connectionist *implements* symbolic
Revisionism: Connectionist *revises/enriches* symbolic

[A major research program is required to pull this off; multiple levels.]

Grammar

Eliminativism: Grammar is a fiction.
Implementationalism: Grammar is unchanged.
Revisionism: **Grammar inherits new *kinds* of rules & representations from connectionist computation**

Requires *high-level* characterization of connectionist computation [which in turn requires a major research program to develop]

Computing done by linguist vs. computing done by speaker/hearer.

Examples of new ways of computing/thinking:

1. Continuous representations
2. Similarity-based processes
3. Parallel *soft* constraint satisfaction
4. Quantitative measures of well-formedness
5. Optimality as main organizing principle

Are these *good* ways of computing/thinking? You tell me.

Plan for lectures:

For $p \in \{1,2,3,4,5\}$

A. Develop high-level principle p of connectionist computation.

B. Propose a way of importing it into linguistics.

C. Develop an example application.

Logical progression of principles: 1 → 5 (lowest, 'most connectionist' → highest, 'most symbolic')

Conservative presentation of linguistic applications: 5 → 1 — wins.

Today: 5; Next week: 4 - 1

5. Optimality as an organizing principle of grammar

A. Connectionist principle:

Harmony maximization. In a central and interesting class of connectionist networks, activation flow creates from an input a pattern of activity that [locally] maximizes a numerical well-formedness measure, the *Harmony*:

$$\sum_i \sum_j a_i w_{ij} a_j$$

Linguistic interpretation:

connectionist input → linguistic 'input' to grammar (string of words, phonemes)

connectionist well-formedness → linguistic well-formedness

pattern of activity arising from an input → structural description of the input

pattern of connections → grammar

Here, all grammatical representations will be symbolic: traditional, unrevised. The rules too will be traditional in form, but their interpretation and interaction will be new. (Conservatism.)

B. Proposed linguistic principle:

Optimality. A grammar is a *preference relation* $>$ among structural descriptions; it assigns to any input that structure which is *optimal* (preferred by $>$ to all other structures).

The preference relation $>$ among structures is built up compositionally from preference relations among the substructures or subdimensions from which structures are built.

The basic preference relations and their means of combination are drawn from a universal repertoire.

Linguistic-internal motivation:

Grammars are more explanatory when they explicitly state well-formedness constraints rather than describing procedures to satisfy those constraints.

(Prefer principles to rewrite rules/transformations.)

Phonology has not made the progress towards this goal that syntax has — because the constraints are so often of the form, ‘prefer ... if possible’ rather than ‘obey ... or be ill-formed’.

(But re:syntax, cf. Sadock’s constraints on inter-component discrepancies.)

C. Applications in phonology [for many more, cf. Prince & Smolensky, LINS 247]

a. Berber syllabification

[insert brief statement of problem]

Idea: Dell—El-Medlaoui algorithm is trying to build the best syllables possible, as defined primarily by the goodness of their peaks. Replace the algorithm with a formal statement of this well-formedness metric.

More sonorous segments make better syllable peaks:

align sonority prominence hierarchy $8=7=...=1$ with syllable structure prominence hierarchy: peak=non-peak

$(8, \text{peak}) > (7, \text{peak}) > \dots > (1, \text{peak}).$

Given a syllabification s , let $M_s =$ the (multi-)set of peaks in s .

Let $\text{first}(M_s) =$ best peak of M_s , and let $\text{rest}(M_s) = M_s \setminus \text{first}(M_s)$.

Then recursively define:

$M_s > M_{s'}$ iff

$\text{first}(M_s) > \text{first}(M_{s'})$

or

$\text{first}(M_s) = \text{first}(M_{s'})$ and $\text{rest}(M_s) > \text{rest}(M_{s'})$

Note: This means of composing the ordering $>$ on peaks to an ordering $>$ on syllabifications is a generalization of alphabetical ordering of strings: reinterpret *first* as ‘left-most element’. It turns out to be useful quite generally in the theory, so we dub it Generalized Lexicographic Ordering, **GLO**. To define a GLO $>$, we must specify the sets M_s , the function *first*, and an ordering $>$ of individual elements of M_s .

b. Lardil

A **Strict Domination Grammar** is a preference relation $>$ defined from a sequence of Boolean predicates over possible structural descriptions

$$p_1 \gg p_2 \gg \dots \gg p_n$$

by the following case of GLO:

For a given structure s , let $M_s = \{\pm p_1, \pm p_2, \dots\}$ where the sign of p_k indicates whether s satisfies predicate p_k (+) or not (-). Let $first(M_s) =$ first element of M_s . On each predicate separately, $+p_k$ (preference satisfaction) $>$ $-p_k$ (preference violation).

Note: This is a form of *markedness theory*. Each ‘ $-p_k$ ’ is a kind of ‘mark’ on the structure, and the ordering $>$ gives a formal means of deciding which structure as a whole is least marked, by examining individual marks.

For clarity, we write ‘Prefer p_k ’ for p_k and ‘Avoid q_k ’ when $p_k = \sim q_k$.

The Lardil preferences:

- p_1 : Avoid subminimal words [less than one foot].
- p_2 : Avoid non-final defective syllables.
- p_3 : Avoid complex consonants in coda position [allowed: one non-back coronal].
- p_4 : Prefer filled onsets.
- p_5 : Prefer free final V.
- p_6 : Avoid defective syllables.
- p_7 : Avoid free material.
- p_8 : Prefer coincidence of stem & syllable boundaries.