The Benefits of Errors
Learning an OT Grammar with a Structured Candidate Set

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Cognitive Aspects of Computational Language Acquisition
Prague, June 29, 2007

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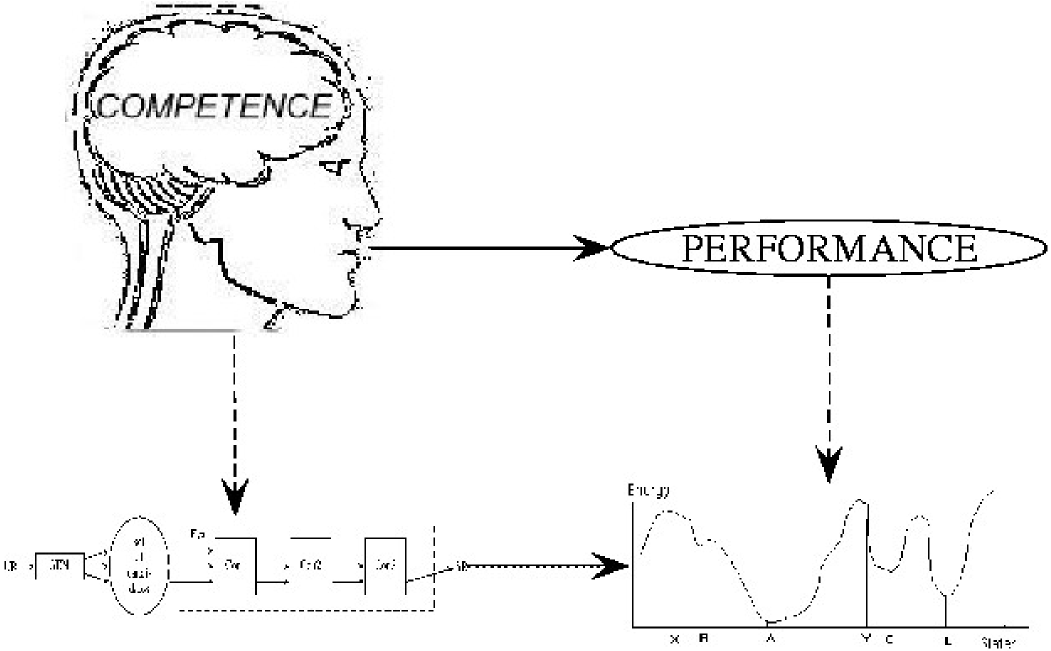
Overview

Learning task when performance is taken seriously:

- Performance models for Optimality Theory
- An example: string grammar
- Learning
- Conclusions: general approach, rather than concrete results
  (Sorry, no precision/recall/F-score in this talk!)
  Competence vs. performance, language vs. culture?

Competence vs. *performance*



Optimality Theory: a model of competence

Simulated Annealing: a model of performance

Bíró (2006): Finding the Right Words, p. 44.

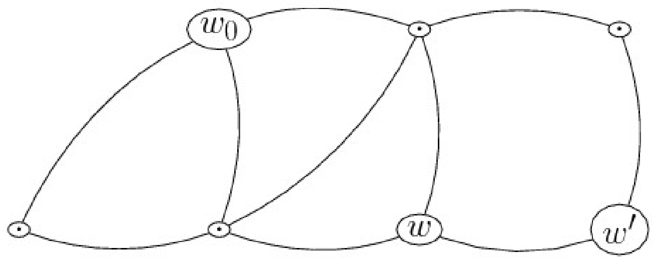
Adequacy of a performance model

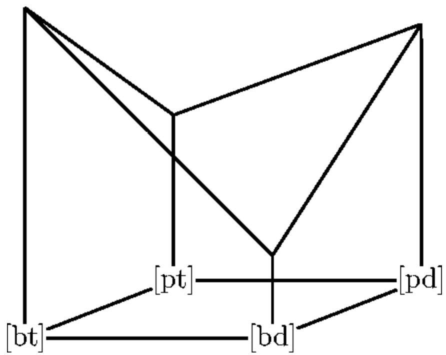
Performance model: an algorithm that realizes (implements) the grammar (*i.e.*, the model of competence), which

- usually finds the form grammatical w.r.t. grammar (☞),
- but also makes the same errors as humans do,
- with a similar frequency
- under various conditions (speech rate, style, etc.).

Moreover, *runtime* and *complexity* of algorithm is plausible.

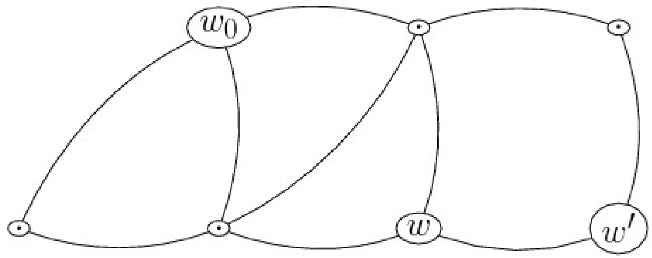
Performance models (simulated annealing) for OT

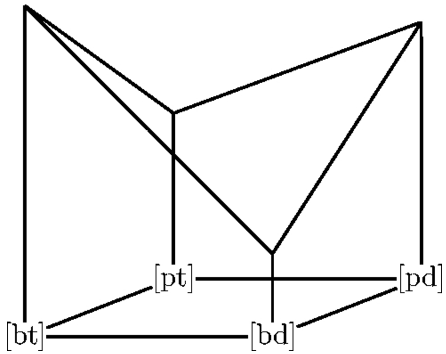




- Goal: to find the (globally) optimal candidate.
- Add a *neighbourhood structure* to the candidate set.
- Landscape's vertical dimension = harmony.
- Neighbourhood structure → local optima.

Performance models (simulated annealing) for OT





- Random walk. If neighbour more optimal: move. If less optimal: move early in the algorithm, don't move later.

- System can get stuck in local optima: errors produced.

- Precision of the algorithm depends on its speed (!!).

Errors and irregularities

ICS (Smolensky & Legendre 2006), SA-OT (Bíró 2006): both implement Optimality Theory with *simulated annealing*.

- ☞ *Grammatical forms* = globally optimal
- *!* *Performance errors*: frequency diminishes at slow (careful) production (as in traditional simulated annealing).
- ∼ *Irregularities*: frequency does not diminish at slow (careful) production (due to *strict domination*).

Not all forms in a language need be analysed as grammatical!

Consequences for language acquisition

Child is exposed to teacher's *performance distribution* (derived from teacher's competence + production mechanism):

- Grammatical forms, performance errors and irregular forms
- produced with different frequencies
- under various circumstances (time pressure, stylistic and sociolinguistic variations, etc.—parameters of SA-OT)

Can she reproduce the teacher's underlying *competence*?

Example: string-grammar 1

- *Candidates:* $\{0, 1, ..., P-1\}^L$
  E.g., $L = P = 4$: 0000, 0001, 0120, 0123,... 3333.

- *Neighbourhood structure:* w and w' neighbours iff one basic step transforms w to w'.

- Basic step: change exactly one character ± 1, $\mod P$ (cyclicity). Neighbours of 0022: 1022, 0012, 0322,...

- Each neighbour with equal probability.

Example: string-grammar 2

Markedness Constraints ($w = w_0 w_1 ... w_{L-1}$, $0 \leq n < P$):

- No-n: $*n(w) := \sum_{i=0}^{L-1}(w_i = n)$
- No-initial-n: $*\textsc{Initial}n(w) := (w_0 = n)$
- No-final-n: $*\textsc{Final}n(w) := (w_{L-1} = n)$
- Assimilation $\textsc{Assim}(w) := \sum_{i=0}^{L-2}(w_i \neq w_{i+1})$
- Dissimilation $\textsc{Dissim}(w) := \sum_{i=0}^{L-2}(w_i = w_{i+1})$

Example: string-grammar 3

- Faithfulness to UR σ:

$$\textsc{Faith}_\sigma(w) = \sum_{i=0}^{L-1} d(\sigma_i, w_i)$$

Example: string-grammar 4

$\mathcal{H}$: no0 $\gg$ ass $\gg$ Faith$_{\sigma=0000}$ $\gg$ ni1 $\gg$ ni0 $\gg$ ni2 $\gg$ ni3 $\gg$ nf0 $\gg$ nf1 $\gg$ nf2 $\gg$ nf3 $\gg$ no3 $\gg$ no2 $\gg$ no1 $\gg$ dis

Output frequencies for different t_{step} (=inverse speed) values:

output	`t_step` $= 1$	`t_step` $= 0.1$	`t_step` $= 0.01$	`t_step` $= 0.001$
☞ 3333	0.1174 $\pm$ 0.0016	0.2074 $\pm$ 0.0108	0.2715 $\pm$ 0.0077	0.3107 $\pm$ 0.0032
$\sim$ 1111	0.1163 $\pm$ 0.0021	0.2184 $\pm$ 0.0067	0.2821 $\pm$ 0.0058	0.3068 $\pm$ 0.0058
$\sim$ 2222	0.1153 $\pm$ 0.0024	0.2993 $\pm$ 0.0092	0.3787 $\pm$ 0.0045	0.3602 $\pm$ 0.0091
! 1133	0.0453 $\pm$ 0.0018	0.0485 $\pm$ 0.0038	0.0328 $\pm$ 0.0006	0.0105 $\pm$ 0.0014
! 3311	0.0436 $\pm$ 0.0035	0.0474 $\pm$ 0.0054	0.0344 $\pm$ 0.0021	0.0114 $\pm$ 0.0016
! others	0.5608	0.1776	$<$ 0.0002	–

$L = P = 4$, $T_{max} = 3$, $T_{min} = 0$, $K_{step} = 1$. Each candidate 4 times as w_0.

Globally optimal form: ☞ 3333. But 13 local optima: 2222, $\{1,3\}^4$.

Learning

Learning algorithms in Optimality Theory:

- Off-line learning algorithms: Recursive Constraint Demotion
  - Initial grammar from observations in pre-linguistic infants?
  - Produces typical "children errors": extra local optima
- On-line learning algorithms: Error Driven Constraint Demotion, Gradual Learning Algorithm.
  - Grammar improving gradually in childhood?

Learning

Assumptions and heuristics behind learning algorithms:

- Traditional OT: observed form is optimal
- SA-OT: observed form is locally optimal
- Moreover: more frequent form is more harmonic
  Not always true in trad. OT; even less true in SA-OT.

Nevertheless, some success!

Same performance, different competence after RCD

target	after RCD	after GLA
No0 15	No0 15	No0 15.000000
Ass 14	Ass 12	Ass 14.000004
Fai 13	Fai 4	Fai 6.100000
Ni1 12	Ni1 8	Ni1 10.400004
Ni0 11	Ni0 13	Ni0 13.000000
Ni2 10	Ni2 5	Ni2 7.100000
Ni3 9	Ni3 3	Ni3 -1.500000
Nf0 8	Nf0 14	Nf0 14.000000
Nf1 7	Nf1 10	Nf1 6.300000
Nf2 6	Nf2 6	Nf2 8.100000
Nf3 5	Nf3 2	Nf3 3.600000
No3 4	No3 7	No3 3.000000
No2 3	No2 11	No2 13.100004
No1 2	No1 9	No1 10.900006
Dis 1	Dis 1	Dis -1.000000

Constraint name + its rank.

target	after RCD	after GLA
315 2222	322 2222	298 2222
210 1111	221 1111	238 1111
☞ 196 3333	200 3333	225 3333
55 3111	53 1133	54 3311
49 1133	50 3111	45 1133
48 1333	45 1113	41 1333
48 3331	45 3311	40 1113
46 1113	42 3331	37 3331
42 3311	32 1333	35 3111
4 1331	4 1131	3 1331
4 3133	4 1331	3 3113
3 3113	2 1311	2 3133
2 1311	2 3113	2 3313
2 3313	2 3133	1 1131

Absolute frequency + output form.

GLA corrects children speech errors

target	after RCD	after GLA
No0 15	No0 2	No0 12.500014
Ass 14	Ass 14	Ass 12.299995
Fai 13	Fai 7	Fai -0.500000
Ni1 12	Ni1 9	Ni1 10.800001
Ni0 11	Ni0 15	Ni0 15.000000
Ni2 10	Ni2 13	Ni2 11.499998
Ni3 9	Ni3 11	Ni3 10.699999
Nf0 8	Nf0 8	Nf0 13.300017
Nf1 7	Nf1 6	Nf1 7.900000
Nf2 6	Nf2 1	Nf2 -12.200008
Nf3 5	Nf3 3	Nf3 9.000000
No3 4	No3 4	No3 3.700000
No2 3	No2 12	No2 11.400000
No1 2	No1 5	No1 3.300000
Dis 1	Dis 10	Dis 11.700005

target	after RCD	after GLA
302 2222	279 1111	292 2222
235 1111	277 2222	230 1111
☞ 208 3333	277 3333	194 3333
49 1113	39 1133	73 3311
49 3311	39 3311	52 1133
45 1333	38 2200	47 1113
44 1133	37 3111	45 3111
40 3111	35 1333	38 1333
37 3331	2 1113	37 3331
5 1331	1 1000	5 1331
4 3313		4 3133
2 3113		3 3313
2 3133		2 1311
1 1131		2 3113
1 1311		

GLA decreases freq. of 1111 and 3333. “Child form” 2200: extra local optimum.

GLA does not converge towards target

target	after RCD	after GLA
No0 15	No0 11	No0 20.200031
Ass 14	Ass 15	Ass 21.200026
Fai 13	Fai 8	Fai 7.600000
Ni1 12	Ni1 7	Ni1 5.299999
Ni0 11	Ni0 5	Ni0 13.300017
Ni2 10	Ni2 4	Ni2 7.500000
Ni3 9	Ni3 10	Ni3 -0.100000
Nf0 8	Nf0 14	Nf0 19.300018
Nf1 7	Nf1 12	Nf1 0.599994
Nf2 6	Nf2 3	Nf2 9.500005
Nf3 5	Nf3 2	Nf3 1.600000
No3 4	No3 1	No3 -14.000012
No2 3	No2 13	No2 18.900017
No1 2	No1 9	No1 7.400000
Dis 1	Dis 6	Dis -0.200000

target	after RCD	after GLA
300 2222	232 1111	250 1111
231 1111	216 2222	239 2222
☞ 214 3333	207 3333	226 3333
53 1133	201 0000	170 0000
51 3311	49 1133	36 2200
50 3331	34 3311	33 1133
46 1333	30 0022	31 0022
38 3111	29 2200	30 3311
33 1113	14 1113	3 1333
6 1331	11 3331	2 1113
1 1131	1 1333	2 3111
1 3113		2 3331

Constraint ranks diverge. 0000 is locally optimal.

Conclusions

- Overview of hill hiking algorithms in 2006 versions of OT: topology on candidate set, simulated annealing (cf. Proc.).
- Performance as the implementation of the grammar. E.g.: competence = OT, performance = SA-OT or ICS.
- Errors and irregularities are good for
  - asses the descriptive adequacy of the combined competence + performance model
  - language learning/acquisition, and evolution E.g.: some children language forms as extra local optima.

Competence vs. *performance*

Noam Chomsky:

"Linguistic theory is concerned primarily with an ideal speaker-listener, in a completely homogeneous speech-community, who knows its language perfectly and is unaffected by such grammatically irrelevant conditions as memory limitations, distractions, shifts of attention and interest, and errors (random or characteristic) in applying his knowledge of the language in actual performance. ... We thus make a fundamental distinction between *competence* (the speaker-hearer's knowledge of his language) and *performance* (the actual use of language in concrete situations)."
(Chomsky: *Aspects*, 1965, pp. 3-4)

Competence vs. *performance*

Paul Smolensky:

"... *competence* can be understood as an idealization of actual behavior—*performance*—in which we have removed the effects of limitations on computational resources: generally speaking, space, time, and precision." (Smolensky et al.: *The Harmonic Mind*, 2006, vol. 1, p. 228.)

Competence = grammar: is a *function*

$$input \mapsto correct\ output/parse/struct.\ description$$

Performance: *algorithm* that finds it. Or doesn't.

Competence: performance run infinitely slowly.

Competence vs. *performance*

Level	its product	its model	the product in the model
Competence in narrow sense: static knowledge of the language	grammatical form	standard OT grammar	globally optimal candidate
Dynamic language production process	acceptable or attested forms	SA-OT algorithm	local optima
Performance in its outmost sense + outside world	acoustic signal, information, message, etc.	phonetics, pragmatics, socioling., biology psychology	??

Language vs. Culture?

> *The tacit knowledge of a participant in a symbolic-cultural system is neither taught nor learned by rote. Rather each new participant [...] reconstructs the rules which govern the symbolic-cultural system in question. These reconstructions may differ considerably, depending upon such factors as the personal history of the individual in question. Consequently, the products of each individual's symbolic mechanism are idiosyncratic to some extent.* (Lawson-McCauley, 1990, p. 68., italics original)

Said about culture, as a difference from language.
I have now argued: it also holds for language!

Thank you for your attention!

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