IMPLEMENTING FINITE STATE GRAMMARS FOR UNDERSTANDING PROSODIC MANIPULATIONS IN INFANT-DIRECTED SPEECH

KRISTINE M. YU  UMASS AMHERST
SAMEER UD DOWLA KHAN  REED COLLEGE
MEGHA SUNDARA  UCLA

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COLLABORATORS

Sameer ud Dowla Khan

Megha Sundara

REED COLLEGE

The UCLA Phonetics Lab
Many subphonemic and gradient aspects of speech, whether segmental or suprasegmental, which were once considered to be beyond the speaker’s control, are now understood as part of the linguistic system stipulated by the grammar of a given language.

What are the linguistic functions of gradient modulations in the fundamental frequency contour?
What are the linguistic functions of gradient modulations in the fundamental frequency contour?
What are the linguistic functions of gradient modulations in the fundamental frequency contour?

- the entanglement of *extra-linguistic and linguistic factors* in conditioning f0 variation
CHALLENGES

What are the linguistic functions of gradient modulations in the fundamental frequency contour?

- the entanglement of *extra-linguistic and linguistic factors* in conditioning f0 variation
- **evolving hypotheses** about proposed intonational grammars
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- evolving hypotheses about proposed intonational grammars
- the generalizability of proposed grammars to a wider range of speech styles and contexts
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What are the linguistic functions of gradient modulations in the fundamental frequency contour?

- the entanglement of **extra-linguistic and linguistic factors** in conditioning f0 variation
- evolving hypotheses about proposed intonational grammars
- the **generalizability** of proposed grammars to a wider range of speech styles and contexts
- the **contextual dependence** of individual tonal elements on one another
What are the linguistic functions of gradient modulations in the fundamental frequency contour?

- the entanglement of extra-linguistic factors in conditioning f0
- evolving hypotheses about proposed intonational grammars
- the generalizability of proposed grammars to a wider range of speech styles and contexts
- the contextual dependence of individual tonal elements on one another

Proposed overall strategy:
To implement finite state intonational grammars
Case study of a *particular speech style/variety*

Infant directed speech (IDS)
CHALLENGE 1: ENTANGLEMENT OF EXTRA-LINGUISTIC AND LINGUISTIC FACTORS
What are the linguistic functions of gradient modulations in the fundamental frequency contour?
What are the linguistic functions of gradient modulations in the fundamental frequency contour?

- the entanglement of **extra-linguistic and linguistic factors** in conditioning f0 variation
What are the linguistic functions of gradient modulations in the fundamental frequency contour?

- the entanglement of extra-linguistic and linguistic factors in conditioning f0 variation

**Proposed strategy:**
Analyze f0 contours using intonational phonology
Higher and wider fundamental frequency (f0) range

Slower speech rate; more/longer pauses

IDS AS A SOCIO-AFFECTIVE SIGNAL

- Rising pitch contours for **eliciting attention**
- Sinusoidal and bell-shaped pitch contours used for **maintaining attention** and **positive rapport**

(Stern et al. 1982)
**BENGALI INFANT-DIRECTED SPEECH**

**Adult-directed speech**


- il> - ék - din - uttor - HaOa - eboN - Surjo - tőrko - korchilo - tader - modd - ke - beSi - Soktiman - <
BENGALI INFANT-DIRECTED SPEECH

Adult-directed speech

L*  uHa*  HaL*  H*  uHaL*  Ha*+H  LH%b*  H- L*  H-L*  L%

il>  èk  din  uttor  HaOa  eboN  Surjo  tôrko  korchilo  tader  modd  ke  beSi  Soktiman <
BENGALI INFANT-DIRECTED SPEECH

Adult-directed speech

Infant-directed speech
BENGALI INFANT-DIRECTED SPEECH

Adult-directed speech

Infant-directed speech

500 Hz
75 Hz
tones (18)
words (15)

500 Hz
75 Hz
tones (14)
words (16)
BENGALI INFANT-DIRECTED SPEECH

Adult-directed speech

Infant-directed speech
BENGALI INFANT-DIRECTED SPEECH

Adult-directed speech

Infant-directed speech
BENGALI INFANT-DIRECTED SPEECH

Not just wider f0 range, but different *kinds* of tones
STRATEGY: INTONATIONAL PHONOLOGY

What are the linguistic functions of gradient modulations in the fundamental frequency contour?
What are the linguistic functions of gradient modulations in the fundamental frequency contour?

Challenge:
STRATEGY: INTONATIONAL PHONOLOGY

What are the linguistic functions of gradient modulations in the fundamental frequency contour?

Challenge:

- the entanglement of extra-linguistic and linguistic factors in conditioning f0 variation
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Challenge:
- the entanglement of extra-linguistic and linguistic factors in conditioning f0 variation

Strategy:
STRATEGY: INTONATIONAL PHONOLOGY

What are the linguistic functions of gradient modulations in the fundamental frequency contour?

Challenge:

‣ the entanglement of extra-linguistic and linguistic factors in conditioning f0 variation

Strategy:

‣ Analyze f0 contours as well-formed sequences of tonal elements (sequences derived from a finite state tonotactic intonational grammar)
What are the linguistic functions of gradient modulations in the fundamental frequency contour?

Challenge:
- the entanglement of extra-linguistic and linguistic factors in conditioning f0 variation

Strategy:
- Analyze f0 contours as well-formed sequences of tonal elements (sequences derived from a finite state tonotactic intonational grammar)
  - Igarashi et al. (2013): Tokyo Japanese IDS only apparently not a wider f0 range; wider f0 range if looking just at boundary tones
TONOTACTIC GRAMMARS: TOKYO JAPANESE

(Pierrehumbert and Beckman, 1988; Maekawa et al., 2002; Venditti, 2005; Igarashi et al. 2013)
"Boundary pitch movement" tones: locus of f0 range expansion

(Pierrehumbert and Beckman, 1988; Maekawa et al., 2002; Venditti, 2005; Igarashi et al. 2013)
"Mainstream American English (MAE)"

"Mainstream American English (MAE)"

If a sequence can be generated via a path through the machine, then it is well-formed.

What are the linguistic functions of gradient modulations in the fundamental frequency contour?

Challenge:

- the entanglement of extra-linguistic and linguistic factors in conditioning f0 variation

Strategy:

- Analyze f0 contours as well-formed sequences of tonal elements (sequences derived from a finite state tonotactic intonational grammar)
- Igarashi et al. (2013): Tokyo Japanese IDS only apparently not a wider f0 range; wider f0 range if looking just at boundary tones
Challenge:

- the entanglement of extra-linguistic and linguistic factors in conditioning f0 variation

Strategy:

- Analyze f0 contours as well-formed sequences of tonal elements (sequences derived from a finite state tonotactic intonational grammar)

  - Igarashi et al. (2013): Tokyo Japanese IDS only apparently not a wider f0 range; wider f0 range if looking just at boundary tones
A grammar derives the set of well-formed tonal sequences over a lexicon of tonal elements, i.e., a tonal inventory.

Common for intonational grammars to be expressed/summarized as a lexicon.
**APPENDIX: SUMMARY OF CHICKASAW INTONATIONAL LABELS**

<table>
<thead>
<tr>
<th>Label</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>H*</td>
<td>Nuclear pitch accent: falls on a syllable in the rightmost word of the IP.</td>
</tr>
<tr>
<td>H^λ</td>
<td>Morpholexical pitch accent: lexically marked pitch accent in certain words.</td>
</tr>
<tr>
<td>!H*</td>
<td>Downstepped pitch accent: pitch accent with lowered Fo peak relative to an earlier pitch accent within the same IP.</td>
</tr>
<tr>
<td>&lt;</td>
<td>Late Fo event: marked on the actual Fo peak when it occurs after the syllable bearing the phonological pitch accent.</td>
</tr>
<tr>
<td>H%</td>
<td>Boundary tone: occurs at the end of statements and echo questions.</td>
</tr>
<tr>
<td>Ø%</td>
<td>Boundary tone: occurs at the end of statements.</td>
</tr>
<tr>
<td>L%</td>
<td>Boundary tone: occurs at the end of wh- and yes/no questions, non-main clauses, exclamations, and postposed nouns.</td>
</tr>
<tr>
<td>HL%</td>
<td>Boundary tone: occurs at the end of imperatives.</td>
</tr>
<tr>
<td>H, L</td>
<td>Accentual Phrase tones: aligned with different positions in the AP.</td>
</tr>
</tbody>
</table>

Gordon (2005)
### Table 4.1  Full inventory of pitch accents and boundary tones used in non-focused contexts in the current intonational phonological model of Bangladeshi Standard Bengali

<table>
<thead>
<tr>
<th>Association</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch accents</td>
<td>H*, L*, L*+H</td>
</tr>
<tr>
<td>AP boundary tones</td>
<td>Ha, La</td>
</tr>
<tr>
<td>ip boundary tones</td>
<td>H-, L-, HL-, LH-</td>
</tr>
<tr>
<td>IP boundary tones</td>
<td>H%, L%, HL%, LH%, HLH%</td>
</tr>
</tbody>
</table>

Khan (2014)
LEXICON AND FINITE/FINITE STATE GRAMMARS

- A grammar derives the set of well-formed tonal sequences over a **lexicon** of tonal elements

- A **finite** grammar is just a **list** of these well-formed sequences
  - No generalizations

Also common for intonational grammars to be expressed/summarized as a **finite grammar** (list)
Figure 14.13
Schematic $f_0$ contours.
WELL-FORMED FRIULIAN TONAL SEQUENCES: LIST

Table 4.5 Inventory of Friulian nuclear configurations, their schematic representations, and their use in sentence types

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Sentence types where it is used</th>
</tr>
</thead>
<tbody>
<tr>
<td>L* H%</td>
<td>Information-seeking yes/no questions, confirmation-seeking yes/no questions, reclaimatory wh-questions, non-final elements of a declarative enumeration</td>
</tr>
<tr>
<td>H+L* L%</td>
<td>Broad-focus statements, commands, imperative wh-questions, final element of an enumeration, final element of a disjunction</td>
</tr>
<tr>
<td>H*+L L%</td>
<td>Epistemically biased statements, information-seeking wh-questions, subject in SVO yes-no questions</td>
</tr>
<tr>
<td>L+H* H%</td>
<td>Counterexpectational wh-questions, non-final elements of a disjunction</td>
</tr>
<tr>
<td>L+H* L%</td>
<td>Contrastive narrow-focus statements, exclamatives, information-seeking yes/no questions, confirmation-seeking yes/no questions, requests</td>
</tr>
</tbody>
</table>

Roseano et al. (2015)
A grammar derives the set of well-formed tonal sequences over a **lexicon** of tonal elements.

A **finite** grammar is just a **list** of these well-formed sequences.

- No generalizations.

A **finite state** grammar compresses the list by encoding generalizations from *shared prefixes* in well-formed sequences.
`Rumu couldn’t remember the names of the gardeners of the queen of Nepal.’

Khan (2008)
BENGALI ACCENTUAL PHRASES

`Rumu couldn’t remember the names of the gardeners of the queen of Nepal.'  
Khan (2008)
Repdated L* Ha chunk is a coincidence, no generalization
FINITE STATE GRAMMAR FOR BENGALI*

*non-focus contexts, typical tunes, no “over-ride” of boundary tones

Khan (2008, 2014), Yu, Khan & Sundara (under revision)
FINITE STATE GRAMMAR FOR BENGALI*

*non-focus contexts, typical tunes, no “over-ride” of boundary tones

Khan (2008, 2014), Yu, Khan & Sundara (under revision)
CHALLENGES 2/3:
EVOLVING HYPOTHESES, GENERALIZABILITY TO LANGUAGE VARIETIES
## REVISIONS OF MAE TOBI

Revision from Pierrehumbert (1980) to Beckman & Pierrehumbert (1986) to ToBI (1994)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>H*</td>
<td>H*</td>
<td>H*</td>
</tr>
<tr>
<td>L*</td>
<td>L*</td>
<td>L*</td>
</tr>
<tr>
<td>H−+L*</td>
<td>H+L*</td>
<td>H+!H*</td>
</tr>
<tr>
<td>H*+L−</td>
<td>H*+L</td>
<td>H* (followed by downstep)</td>
</tr>
<tr>
<td>L*+H−</td>
<td>L*+H</td>
<td>L*+H</td>
</tr>
<tr>
<td>L*−+H*</td>
<td>L*+H*</td>
<td>L+H*</td>
</tr>
<tr>
<td>H*+H−</td>
<td>H*</td>
<td></td>
</tr>
<tr>
<td>Phrase accent (H−, L−), but no Interm. phrase level</td>
<td>Intermediate phrase tone (H−, L−)</td>
<td>Intermediate phrase tone (H−, L−, !H−)</td>
</tr>
<tr>
<td>Boundary tone (X%)</td>
<td>Intonation phrase tone (X%)</td>
<td>Inton. phrase tone (%X, X%)</td>
</tr>
<tr>
<td>Vocative tag has no pitch accent (X− X%)</td>
<td>Vocative tag does have a pitch accent. (X* X- X%)</td>
<td></td>
</tr>
</tbody>
</table>

(Jun 2011)
### GUSSENHOVEN (2004, 2016): REVISION OF MAE TOBI

<table>
<thead>
<tr>
<th>MAE_ToBI</th>
<th>MAE_ToBI (overt tones only)</th>
<th>Off-ramp alternative</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 H* H- H%</td>
<td>H* H%</td>
<td>H* H%</td>
</tr>
<tr>
<td>2 H* L- H%</td>
<td>H* L-H%</td>
<td>H* L H%</td>
</tr>
<tr>
<td>3 H* H- L%</td>
<td>H*</td>
<td>H*</td>
</tr>
<tr>
<td>4 H* L- L%</td>
<td>H* L%</td>
<td>H* L L%</td>
</tr>
<tr>
<td>5 L* H- H%</td>
<td>L* H-H%</td>
<td>L*H H%</td>
</tr>
<tr>
<td>6 L* L- H%</td>
<td>L* H%</td>
<td>L* H%</td>
</tr>
<tr>
<td>7 L* H- L%</td>
<td>L* H-</td>
<td>L*H</td>
</tr>
<tr>
<td>8 L* L- L%</td>
<td>L*</td>
<td>L*</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>H* L</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>H* L%</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>L* L%</td>
</tr>
<tr>
<td>12 L*+H L- L%</td>
<td>L*+H L%</td>
<td>L*H L%</td>
</tr>
</tbody>
</table>

**Table 1:** Representations of nuclear contours in MAE_ToBI (column 1) with graphic phonetic implementations, after Pierrehumbert 1980 (column 2). Column 3 repeats the representations without tones that have no overt target. Column 4 gives representations in an off-ramp analysis without phrase tones and with optional IP-boundary tones.
What are the linguistic functions of gradient modulations in the fundamental frequency contour?
What are the linguistic functions of gradient modulations in the fundamental frequency contour?

Challenges:
What are the linguistic functions of gradient modulations in the fundamental frequency contour?

Challenges:

- evolving hypotheses about intonational inventory, tonotactics
What are the linguistic functions of gradient modulations in the fundamental frequency contour?

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- evolving hypotheses about intonational inventory, tonotactics
- the generalizability of proposed grammars to a wider range of speech styles and contexts
What are the linguistic functions of gradient modulations in the fundamental frequency contour?

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Strategy:
STRATEGY: PARSE WITH FINITE STATE GRAMMAR

What are the linguistic functions of gradient modulations in the fundamental frequency contour?

Challenges:

‣ evolving hypotheses about intonational inventory, tonotactics
‣ the generalizability of proposed grammars to a wider range of speech styles and contexts

Strategy:

‣ **Write down current proposed grammar** as finite state grammar and **compile as finite state machine**
STRATEGY: PARSE WITH FINITE STATE GRAMMAR

What are the linguistic functions of gradient modulations in the fundamental frequency contour?

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STRATEGY: PARSE WITH FINITE STATE GRAMMAR

What are the linguistic functions of gradient modulations in the fundamental frequency contour?

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- evolving hypotheses about intonational inventory, tonotactics
- the generalizability of proposed grammars to a wider range of speech styles and contexts

Strategy:

- Write down current proposed grammar as finite state grammar and compile as finite state machine
- Check intonational transcriptions in new corpus by parsing them with finite state machine
- Diagnose problems → revisions to intonational grammar
DEFINING BENGALI GRAMMAR IN xfst (excerpts)

# Define licit AP-internal tone sequences

# Generate: { L* fHa, L* Ha }
define RisingAP [ "L*" [ "Ha" | "fHa"] ] ;

# Generate: { fH* La, H* La }
define FallingAP [ [ "fH*" | "H*" ] "La" ] ;

# Generate: { L++fH, L++fH La, L++H, L++H La };
define TrailingPeakAP [ [ "L++fH" | "L++H" ] ("La") ] ;

# Generate: { L+fH*, L+fH* La, L+H*, L+H* La }
define LeadingPeakAP [ [ "L+fH*" | "L+H*" ] ("La") ] ;
### Define set of licit pitch accents

```c
# A monotonal PA must not be followed by any other pitch accents (except possibly *)
# A bitonal PA may be followed by a bitonal or monotonal PA
# Or could just be a * tone
# * tones can intersperse everywhere, as many as you want

define MonotonalPA ["L*" | "fH*" | "H*"];

define BitonalPA ["L*+H" | "L*+fH" | "L+H*" | "L+fH*" ];

define PASEq [ [ MonotonalPA | [ [BitonalPA] ( BitonalPA | MonotonalPA ) ] | "*" ] / "*" ];
```
DEFINING BENGALI GRAMMAR IN xfst (excerpts)

`# Define repeating patterns within an ip/IP`  
```
define ipSequence [ [ APSequence ]+ (PASeq) ipTone ] | ipEdge];
```

`# An IP tone must be immediately preceded by a pitch accent or a lower boundary tone (AP or ip tone)`  
```
define IPSSequence [ [ [ ipSequence | APSequence ]+ (PASeq) IPTone ] | IPEdge ] ];
```
IMPLEMENTED FINITE STATE GRAMMARS
1. For each utterance in corpus, parse intonational transcription using finite state machine: accepted or not?

2. Over corpus, count up how many times each arc traversed to estimate arc weights (probability that an arc is traversed)
Failed to accept 1.5% of exemplars
- (21/1367 total; 9/549 in non-IDS, 12/818 in IDS)

Characteristics of the rejected exemplars were the same across speech styles
- New `stacked’ boundary tone fHaL%
- Unexpected sequences of pitch accents
- Distribution of weak accents (*), e.g.,

Characteristics of unaccepted tonal sequences provide direction for revisions to grammar (evolving hypotheses)
STRATEGY: PARSE WITH FINITE STATE GRAMMAR

What are the linguistic functions of gradient modulations in the fundamental frequency contour?
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Challenges:
Challenges:

- the **generalizability** of proposed grammars to a wider range of speech styles and contexts
STRATEGY: PARSE WITH FINITE STATE GRAMMAR

What are the linguistic functions of gradient modulations in the fundamental frequency contour?

Challenges:

‣ the **generalizability** of proposed grammars to a wider range of speech styles and contexts

Strategy:
What are the linguistic functions of gradient modulations in the fundamental frequency contour?

Challenges:

- the *generalizability* of proposed grammars to a wider range of speech styles and contexts

Strategy:

- Check if all IDS transcriptions are accepted by finite state machine
STRATEGY: PARSE WITH FINITE STATE GRAMMAR

What are the linguistic functions of gradient modulations in the fundamental frequency contour?

Challenges:

‣ the generalizability of proposed grammars to a wider range of speech styles and contexts

Strategy:

‣ Check if all IDS transcriptions are accepted by finite state machine

‣ Estimate arc weights on finite state machine using: (1) non-IDS corpus, (2) IDS corpus.
Challenges:

- the **generalizability** of proposed grammars to a wider range of speech styles and contexts

Strategy:

- Check if all IDS transcriptions are accepted by finite state machine
- Estimate arc weights on finite state machine using: (1) non-IDS corpus, (2) IDS corpus.
- See how probable IDS transcriptions are using non-IDS arc weights and vice versa

What are the linguistic functions of gradient modulations in the fundamental frequency contour?
HOW PROBABLE ARE IDS SEQUENCES?

Distribution for each speech style

IDS tonal sequences markedly more probable under IDS-tuned FSG than non-IDS-tuned FSG
HOW PROBABLE ARE IDS SEQUENCES?

IDS tonal sequences markedly more probable under IDS-tuned FSG than non-IDS-tuned FSG

Probability ratio = ratio of the probability assigned by the IDS-tuned probabilistic FSG to the probability assigned by non-IDS-tuned probabilistic FSG
HOW PROBABLE ARE IDS SEQUENCES?

IDS tonal sequences markedly more probable under IDS-tuned FSG than non-IDS-tuned FSG
CHALLENGE 4: CONTEXTUAL DEPENDENCE OF TONES
BAG OF TONES MODEL

Intonational phrase

<table>
<thead>
<tr>
<th></th>
<th>L%</th>
<th>LH%</th>
<th>HLH%</th>
<th>H%</th>
<th>HL%</th>
</tr>
</thead>
<tbody>
<tr>
<td>non-IDS</td>
<td>0.4</td>
<td>0.15</td>
<td>0.05</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>IDS</td>
<td>0.35</td>
<td>0.13</td>
<td>0.07</td>
<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Mean relative frequency

Yu, Khan & Sundara (2014)
**BAG OF TONES MODEL**

Ex: Count up how many times there was an HLH% in non-IDS vs. IDS

Yu, Khan & Sundara (2014)
FIRST-ORDER MODEL

Khan (2008, 2014), Yu, Khan & Sundara (under revision)
FIRST-ORDER MODEL

Computed probabilities of traversing an arc conditioned on probabilities of reaching that state emitting arc

Khan (2008, 2014), Yu, Khan & Sundara (under revision)
What are the linguistic functions of gradient modulations in the fundamental frequency contour?
What are the linguistic functions of gradient modulations in the fundamental frequency contour?

Challenges:

‣ the **contextual dependence** of individual tonal elements on one another

Strategy:

‣ **Compute probability of an individual tonal element conditioned on probability of paths that arrive at that state**
What are the linguistic functions of gradient modulations in the fundamental frequency contour?
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To implement finite state intonational grammars

- the entanglement of extra-linguistic factors in conditioning f0 variation
- evolving hypotheses about proposed intonational grammars
- the generalizability of proposed grammars to a wider range of speech styles and contexts
- the contextual dependence of individual tonal elements on one another
(2ND ORDER MODEL, IF MORE DATA)

Figure 2. A probabilistic model of intonation in American English

Figure 3. Second-order Markov model showing interactions between pitch accents and boundary tones

(Dainora 2006)
Gussenhoven (2004, 2016)

(22) \[
\left\{ \begin{array}{c}
\%H \\
\%L \\
L^*(H)
\end{array} \right\} \left\{ \begin{array}{c}
(L^*)H^*(L(H)) \\
(H)
\end{array} \right\} \left\{ \begin{array}{c}
(L^*)H^*(L) \\
L^*(H) \\
(L^*)H^*+H
\end{array} \right\} \left\{ \begin{array}{c}
H\% \\
L\% \\
\emptyset
\end{array} \right\}
\]

(23) I. a. The last trailing tone of a prenuclear pitch accent aligns rightmost.
b. Other trailing tones align leftmost.

II. a. Within a pitch accent, interpolations are linear.
b. Otherwise, unspecified speech is governed by the leftmost tone.

III. a. Within a pitch accent, downstep of H after H is obligatory.
b. Otherwise, downstep of H* is optionally triggered by a preceding H.
15.5.5  An extended tonal grammar

If the pre-nuclear fall–rise, downstep, L-prefixations, and leading-H are added to the mini-grammar of section 15.2.3, we arrive at (43). Clearly, although we still do not have a sizeable collection of exhaustive descriptions of intonation systems to measure this by, the intonation of English must be fairly complex. A coarse impression of the difference between English and French can be obtained by just comparing (43) as a typographical object with (35) in chapter 13. And we are not done yet, as English also has a vocative chant, to be discussed in the next section.

(43)

\[
\begin{align*}
\text{[[DOWNSTEP]]} & \left\{ \begin{array}{l}
\text{H}_t \\
\text{L}_t
\end{array} \right\} (L) \left\{ \begin{array}{l}
\text{H}^*(L(H)) \\
\text{L}^*(H)
\end{array} \right\}_n (H+) (L) \left\{ \begin{array}{l}
\text{H}^*(L) \\
\text{L}^*(H)
\end{array} \right\}_0 \left\{ \begin{array}{l}
\text{H}_t \\
\text{L}_t
\end{array} \right\}
\end{align*}
\]