A New Theory of WM in Sentence Processing: Revisiting Interference and the Magical Number 2

Richard L. Lewis

Department of Computer & Information Science

Ohio State University

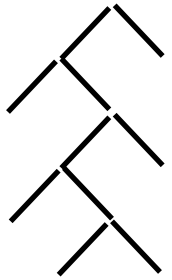
29 June 1997

Soar Workshop 17

A classic limitation of human processing

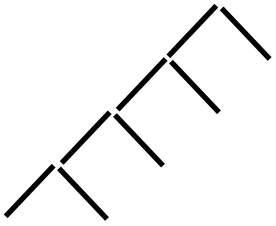
- Most people find one level of embedded clause easy to comprehend:
  The dog that the cat chased ran away.
- But double embeddings are very difficult (Miller & Chomsky 1963):
  The salmon that the man that the dog chased smoked tasted bad.

Center vs. right- and left-embedding



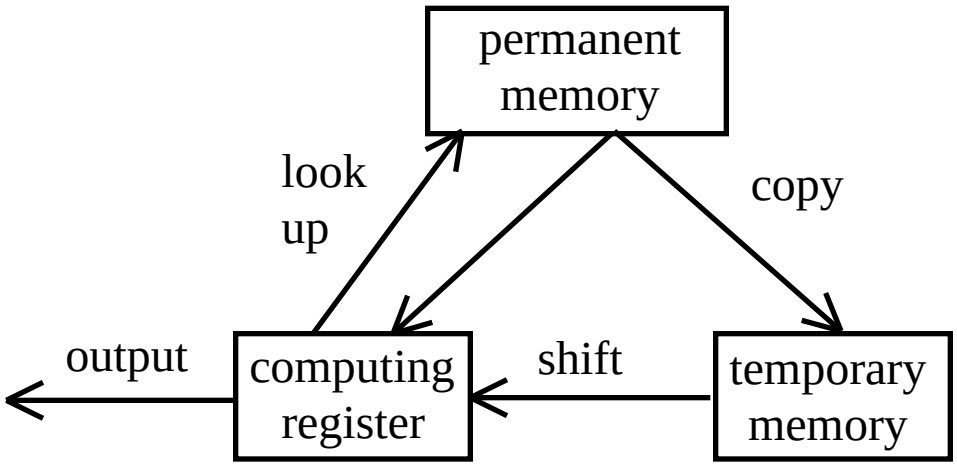
- Difficult center embedding:
  - [$_s$The salmon that [$_s$the man that [$_s$the dog chased] smoked] tasted bad.]

- Acceptable deep right/left embedding:
  - [$_s$I know that [$_s$John believes that [$_s$Sue thinks that [$_s$the woman claimed [$_s$the salmon tasted bad.]]]]]
  - We saw the cat that chased the mouse that ate the cheese that lay in the house that Jack built.
  - John's mother's neighbor's dog's tail fell off.



Center-embedding meets Magical Number 7 ± 2

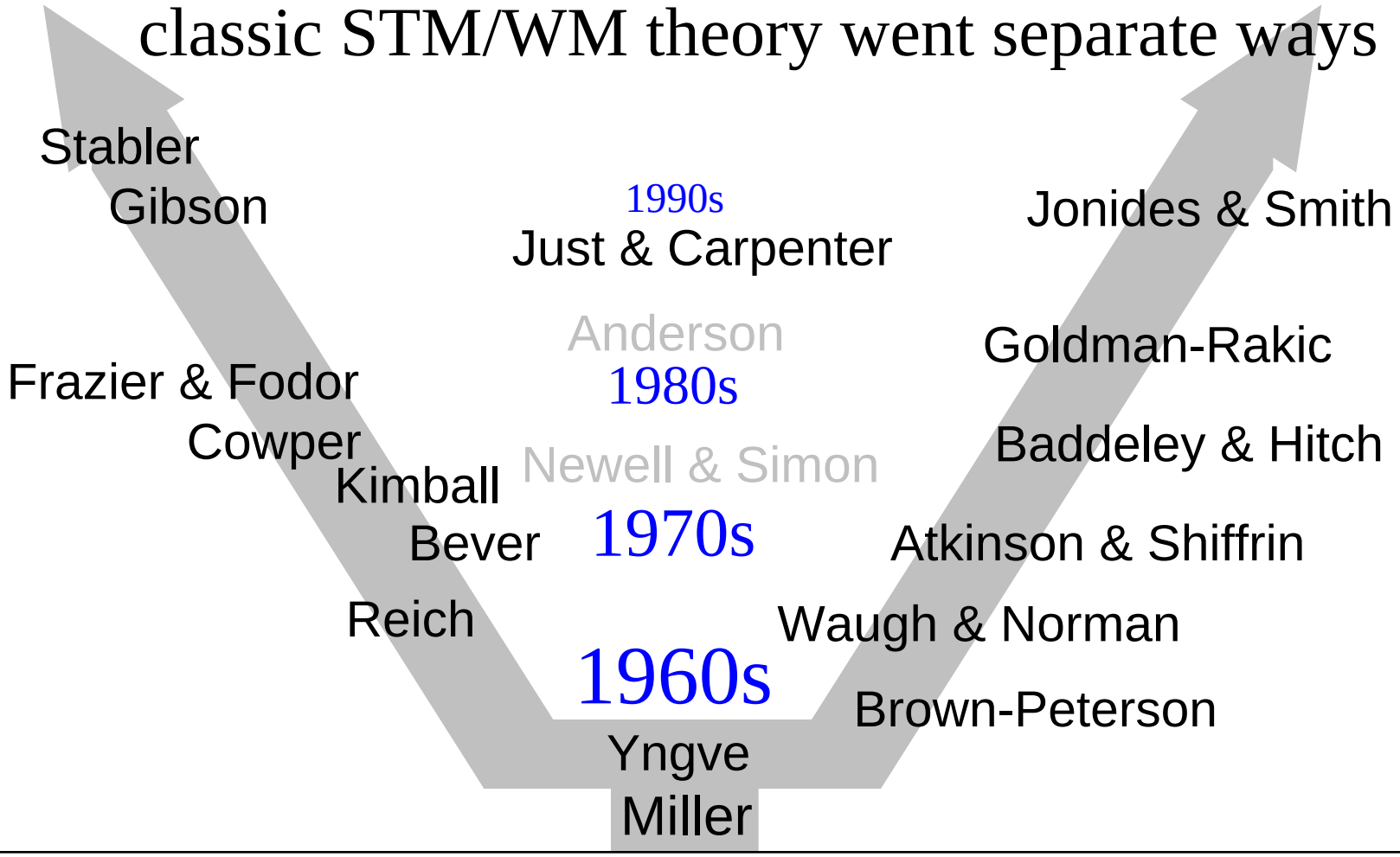
(Yngve 1960)



(register)	(temporary)
S	
NP	VP
T	N VP
the	N VP
N	VP
man	VP
VP	
V	NP
saw	NP
NP	
T	N
the	N
N	
boy	

The theoretical split

Almost immediately, embedding theory and classic STM/WM theory went separate ways



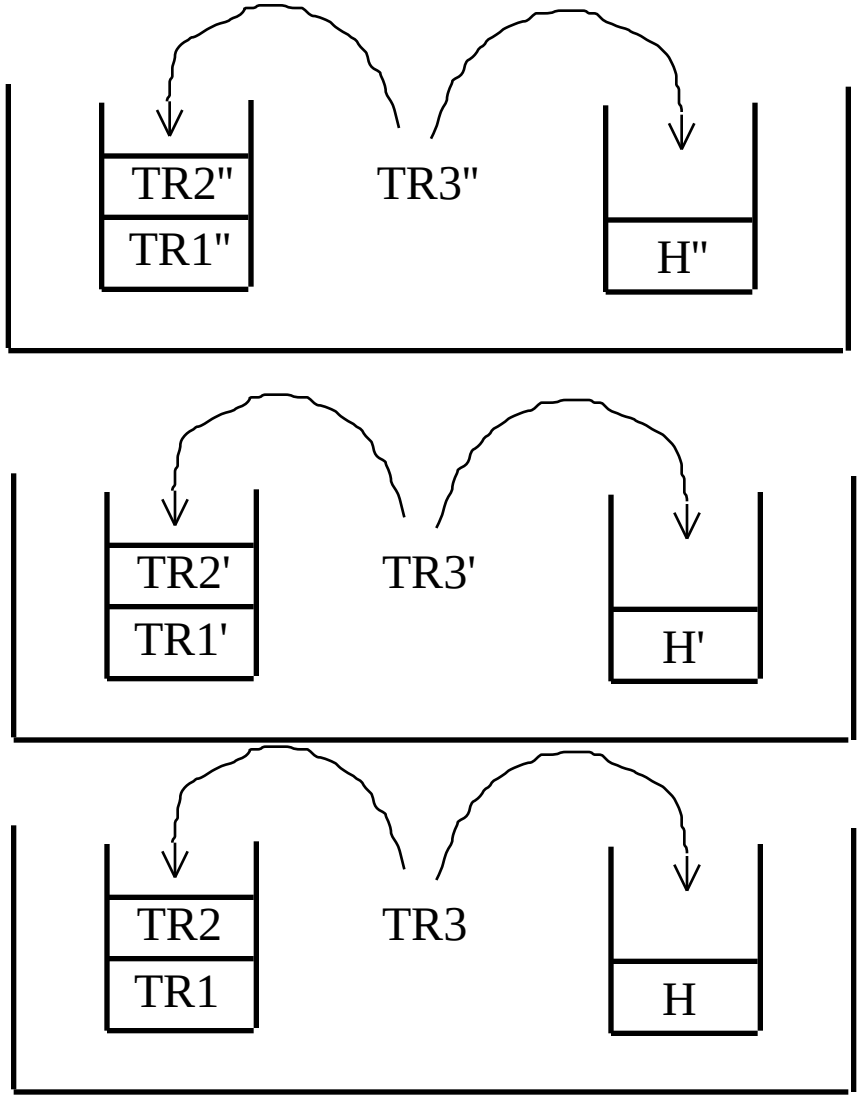
Embedding theories

METRIC or ARCHITECTURE	RESOURCE	LIMIT
Push down automaton (Yngve 1960)	Stack cells	7±2
Sausage Machine (Frazier & Fodor 1978)	Lookahead	6
Open syntactic requirements (Gibson 1991)		4
Register-vector FSM (Blank, 1989)	Clausal state	3
PARSIFAL (Marcus 1980)	Lookahead	3
Poker parser (Cowper 1976)	Tracks, hold cells	3
Connectionist net (Henderson 1994)	Stack, trees	3
Open sentence nodes (Kimball 1973)		2
Open case relations (Stabler 1994)		2
Subroutine arch. (Miller & Isard 1964)	Return memory	1
ACT (Anderson et al 1970)	Ctrl variables	1

Examples of good ideas that don't quite work

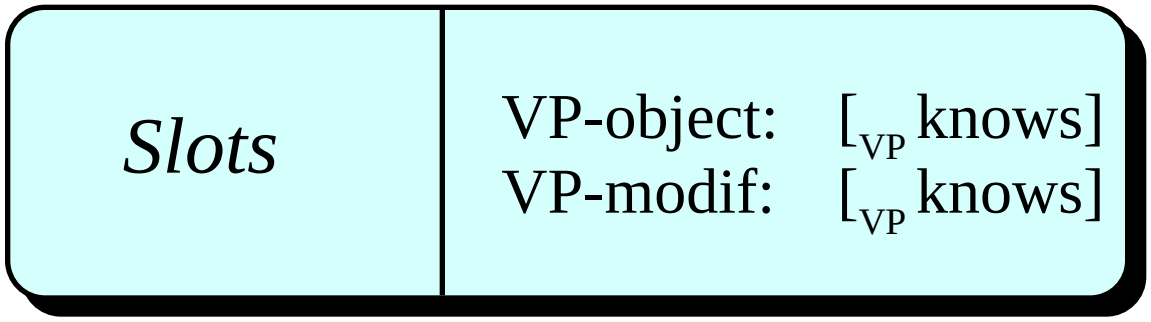
- Kimball's *Principle of Two Sentences*: Can't parse more than two sentences at once
  - [$_s$What [$_s$the woman that [$_s$John married] likes] is smoked salmon.]
- Limited buffer for holding uninterpreted NPs (say, two)
  - John-wa Bill-ni Mary-ga Sue-ni Bob-o syookai sita to it-ta.
    John Bill Mary Sue Bob introduced say

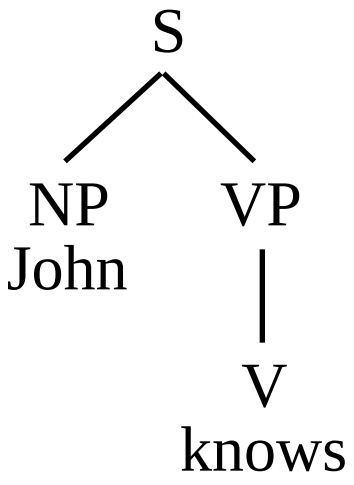
Cowper's (1976) Poker Parser



A theory of syntactic STM

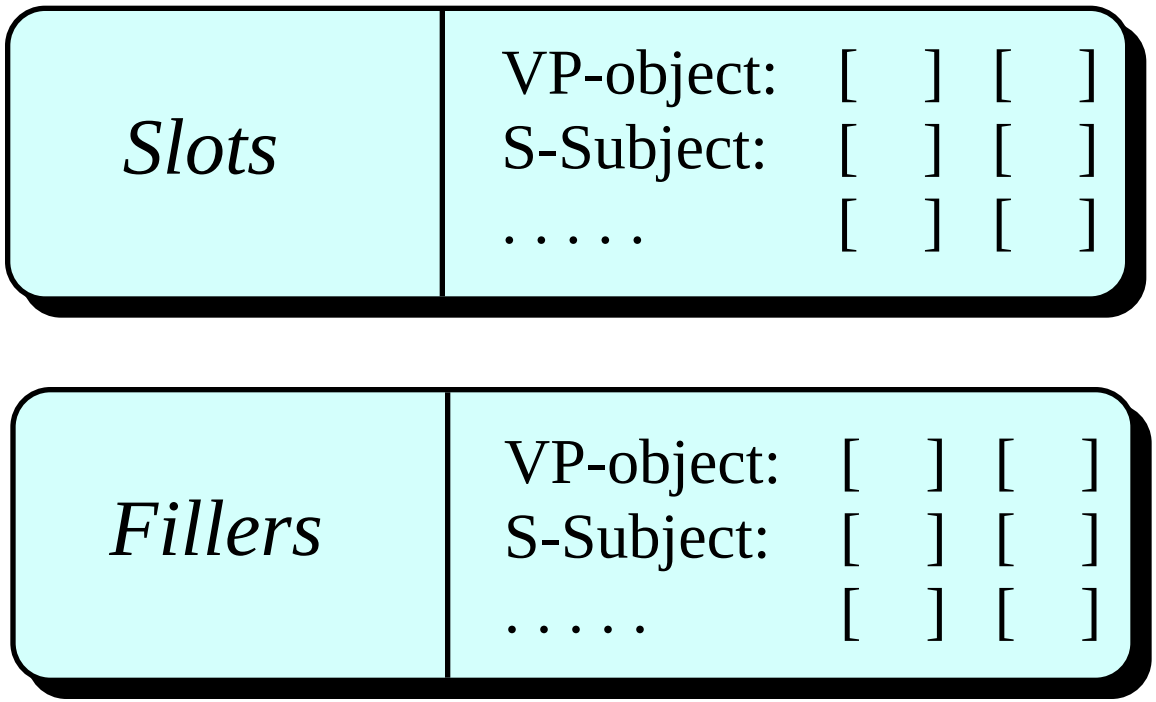
- In tradition of *computational architectures*
  - Part of NL-Soar model of comprehension
- Partial constituents are indexed by potential structural relations, with a severe limit on how much each relation can index





The Magical Number Two

- Each relation indexes at most 2 nodes



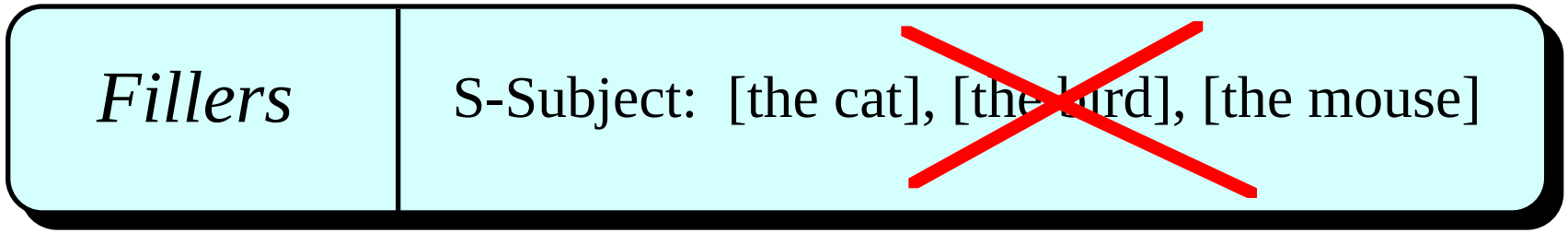
Classic center-embedding

- Single center-embedded object relative clause:
  The cat that the bird chased ran away.

Fillers	S-Subject: [the cat], [the bird]

Difficult center-embedding

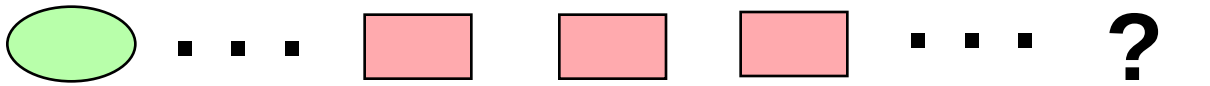
- Double center-embedded object relative
  The cat that the bird that the mouse chased scared ran away.



Why *this* structure for short term memory?

- **Yields a similarity-based interference theory of STM** (psychological). An important component of some traditional models of verbal STM.
- **Reduces match complexity** (computational). Key recommendation from independent theoretical work on match efficiency (Tambe, Newell & Rosenbloom 90): *Eliminate or minimize multi-valued sets in STM.*
- **Why TWO? Functional minimum.** (There's a thin line between aphasia and super-human performance)

Retroactive interference



TO-BE REMEMBERED **INTERPOLATED ITEMS/TASK** **TEST**

Conceptual/semantic	(Potter 1976)
Kinesthetic	(Williams et al 1969)
Odor	(Walk & John 1984)
Sign language	(Poizner et al 1981)
Tactile	(Miles & Borthwick 1996)
Tone	(Deutsch 1970)
Verbal/phonological	(Shiffrin 1973, Waugh & Norman 1965)
Visual	(Logie, Zucco, Baddeley 1990)

→ *STM/WM uses multiple codes, exhibits interference when items use similar codes*

Syntactic STM: Same principles, different domain

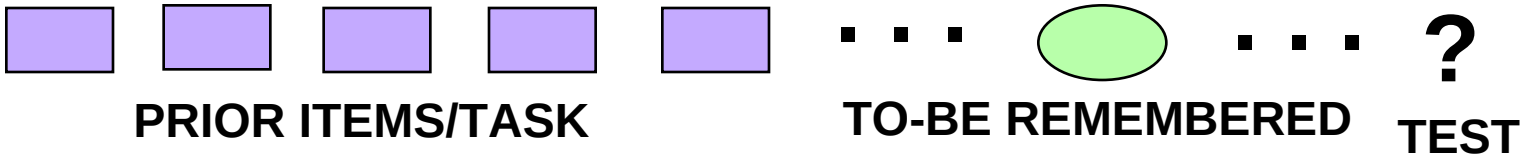
1. Evidence for multiple codes and similarity-based interference across codes
2. Evidence that classic verbal STM is *not* significant in syntactic parsing

→ Leads to positing part of STM based on syntactic codes, which also exhibits interference effects

Some empirical problems: Overpredicting difficulty

- Acceptable triple subject constructions
  - Isn't it true that examples sentences that people you know produce are more likely to be accepted? (De Roeck et al 1982)
  - The claim that the man that John hired is incompetent upset me. (Cowper 1976)
  - Taroo-ga Akira-ga Hanako-ga nakidasita to itta to omotteiru. (Babyonyshev & Gibson 1995)
    Taroo Akira Hanako started-crying said knows

Missing component: Proactive interference (PI)

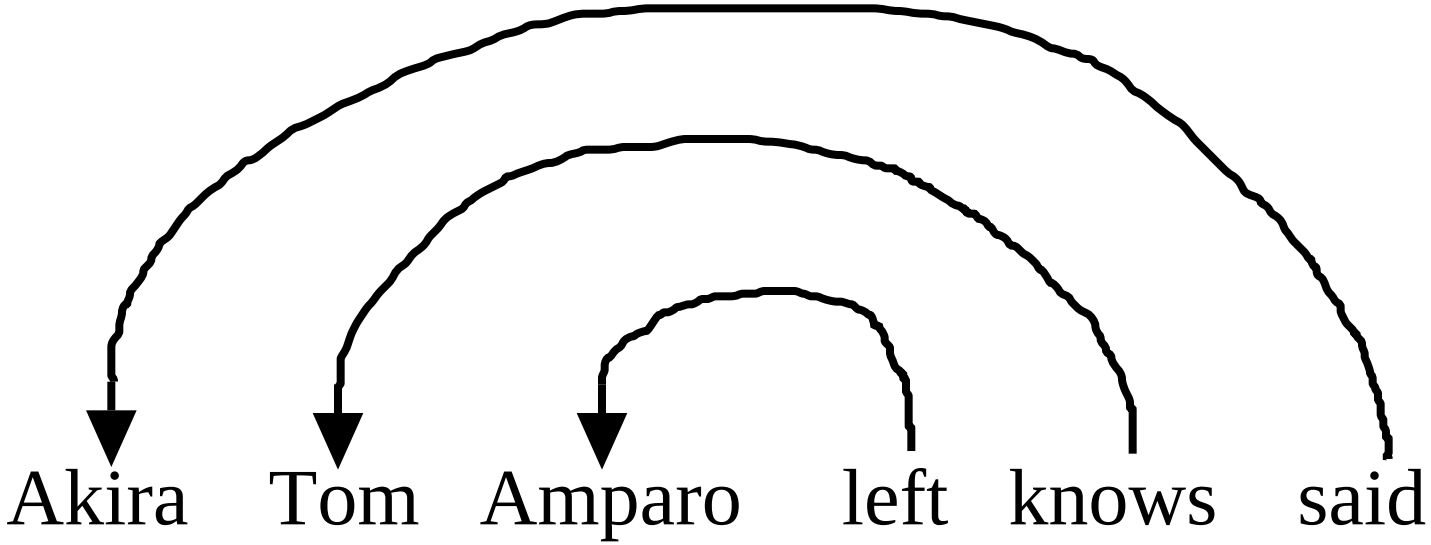


- Important factor in STM tasks
  - Explains excellent performance on first trial of Brown-Peterson task (Keppel & Underwood 1962)

Important features of PI

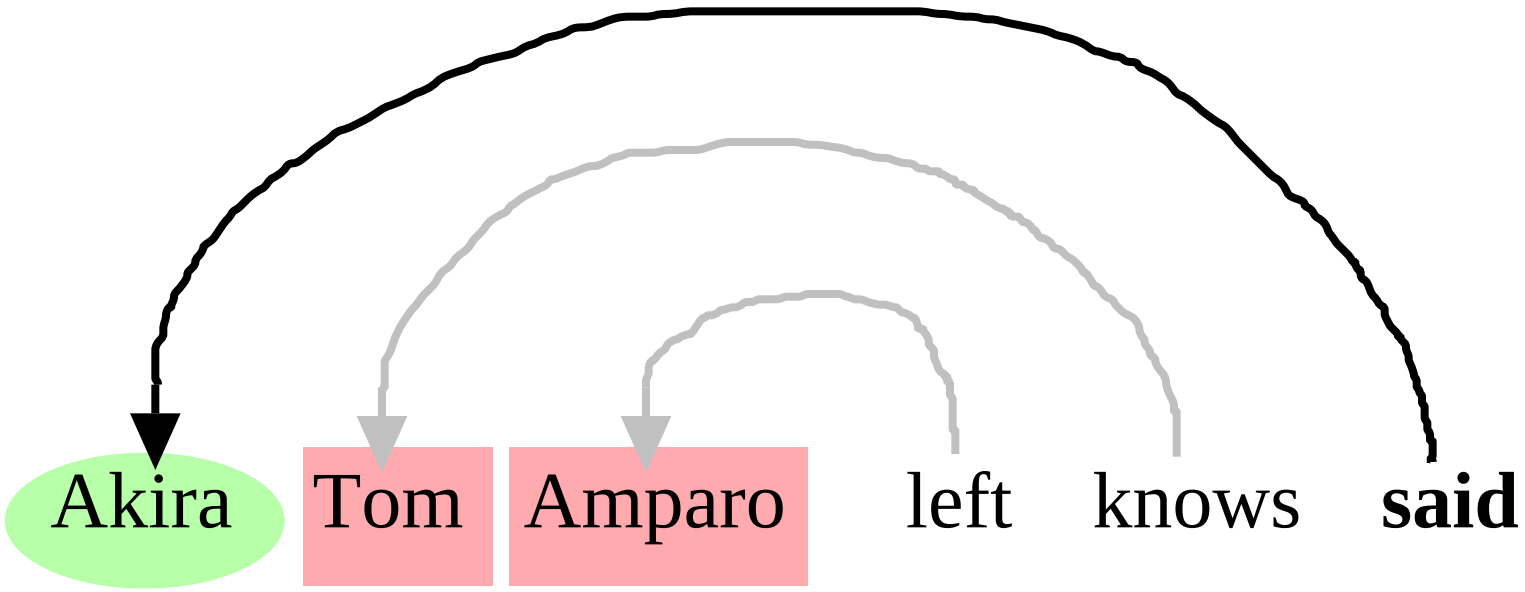
- Like RI, PI varies with item similarity
  - Semantic category effects (Wickens et al. 1963)
  - Phonological effects (Conrad 1965)
- Contributes to variety of errors: Intrusions (not all from within experiment), omissions, permutations
- No PI for immediate retrieval of most recent item (Wickens et al 1963)

Retroactive and proactive interference in parsing



(Akira said that Tom knows Amparo cried.)

Retroactive and proactive interference in parsing



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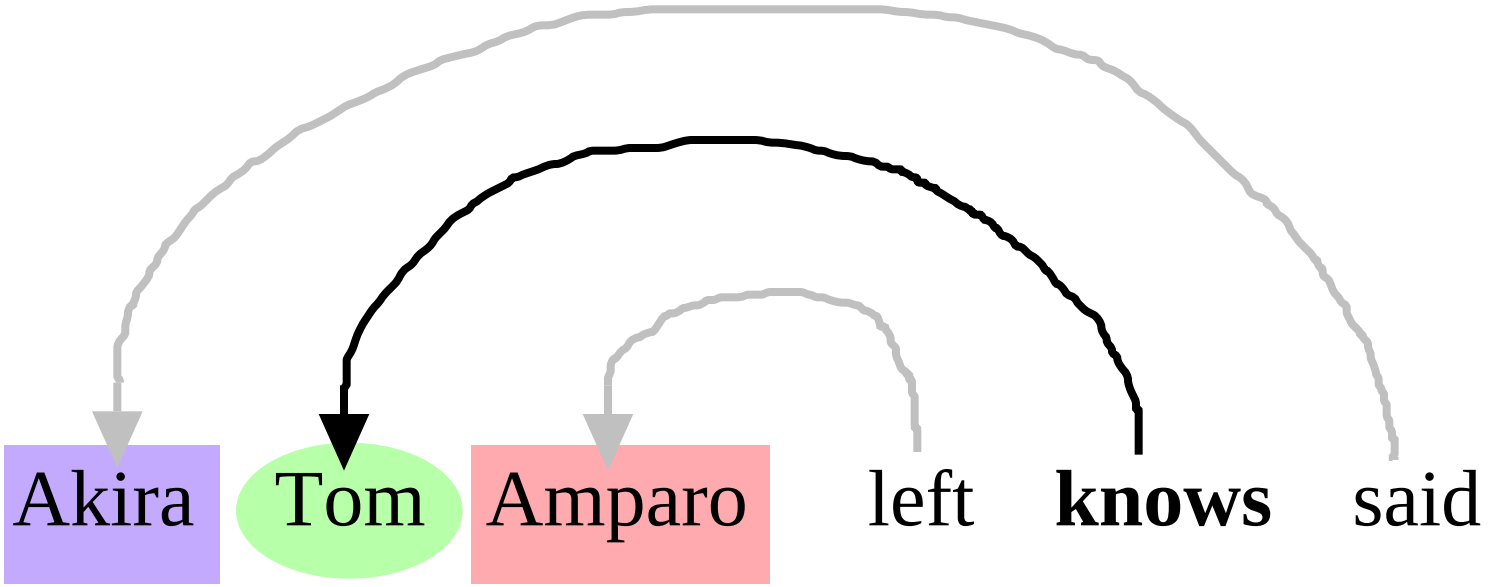
Retroactive and proactive interference in parsing



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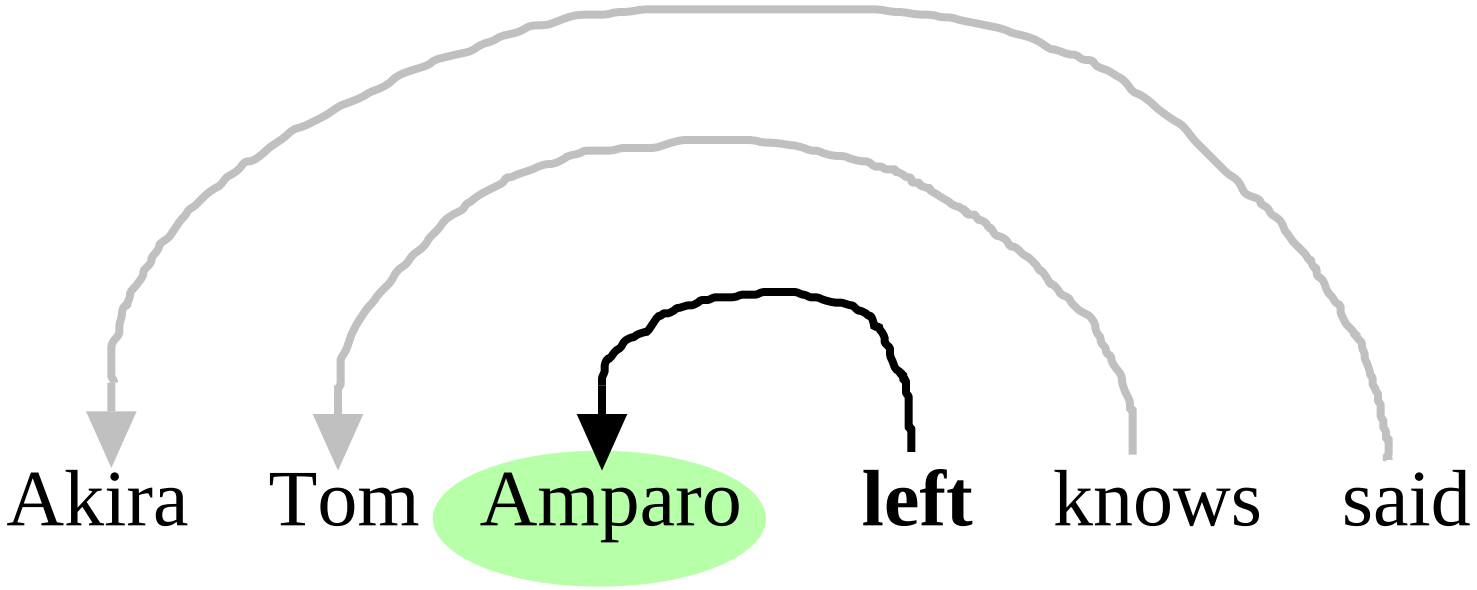
Retroactive and proactive interference in parsing



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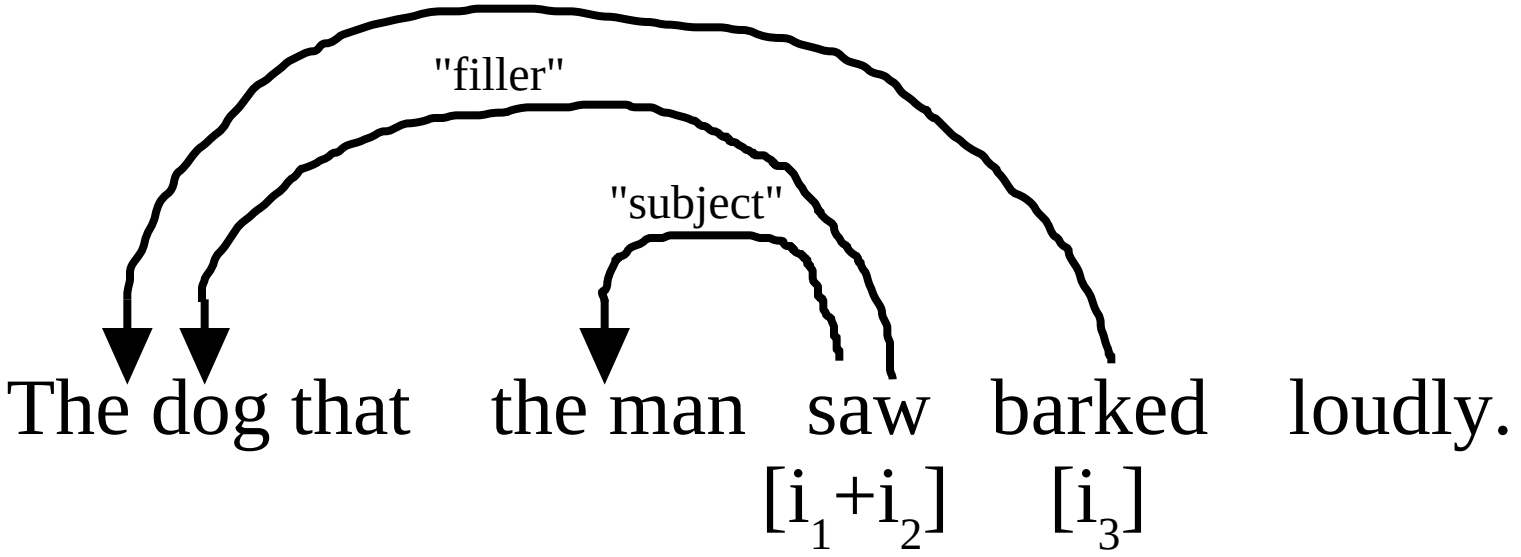
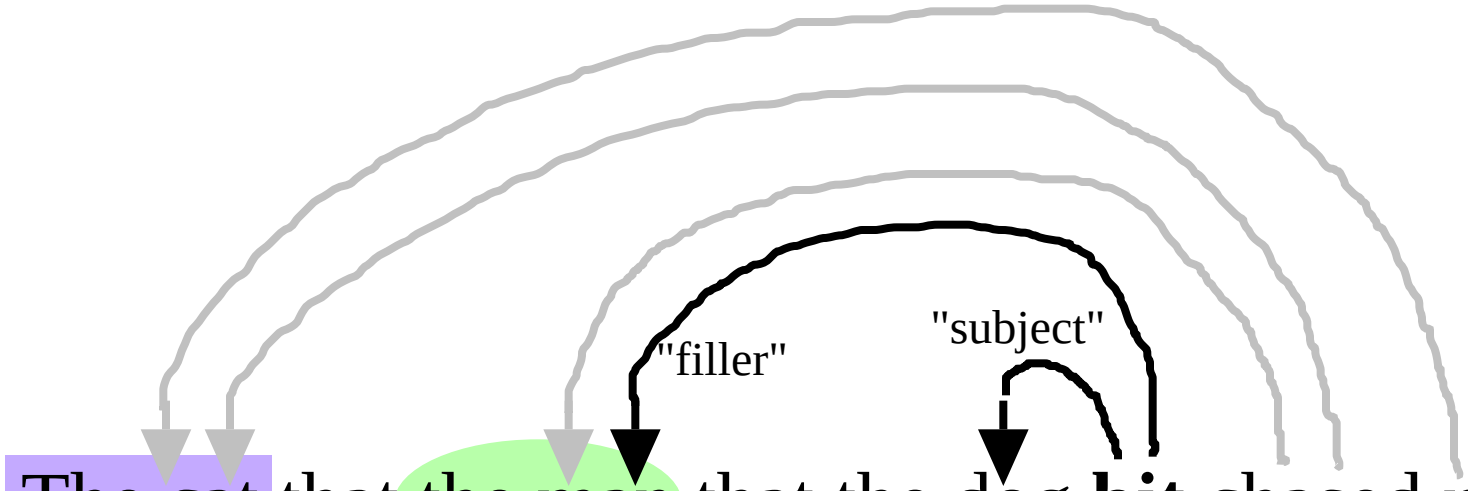
A measure of local processing difficulty



Processing difficulty at each point in the sentence is determined by the total amount of retroactive and proactive interference that must be overcome to establish the syntactic relations at that point.

Revisiting classic center-embedding



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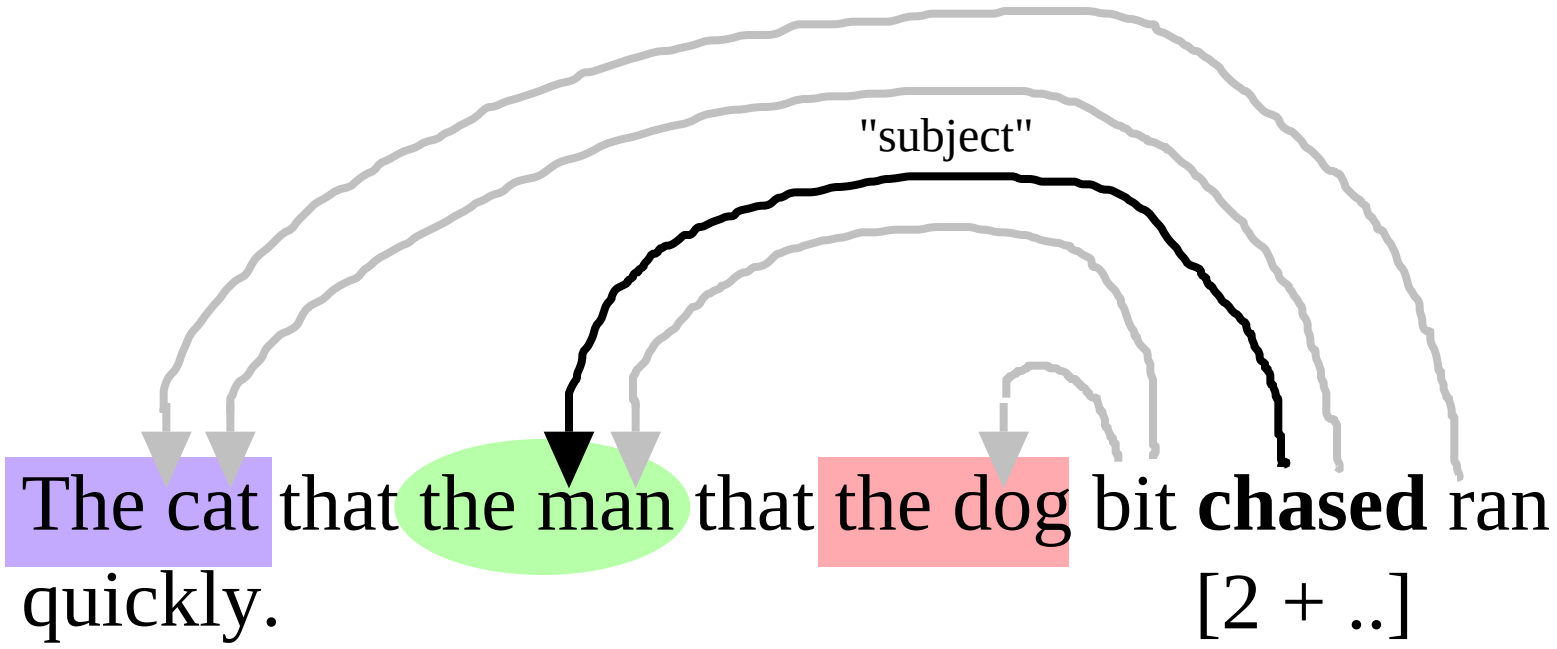

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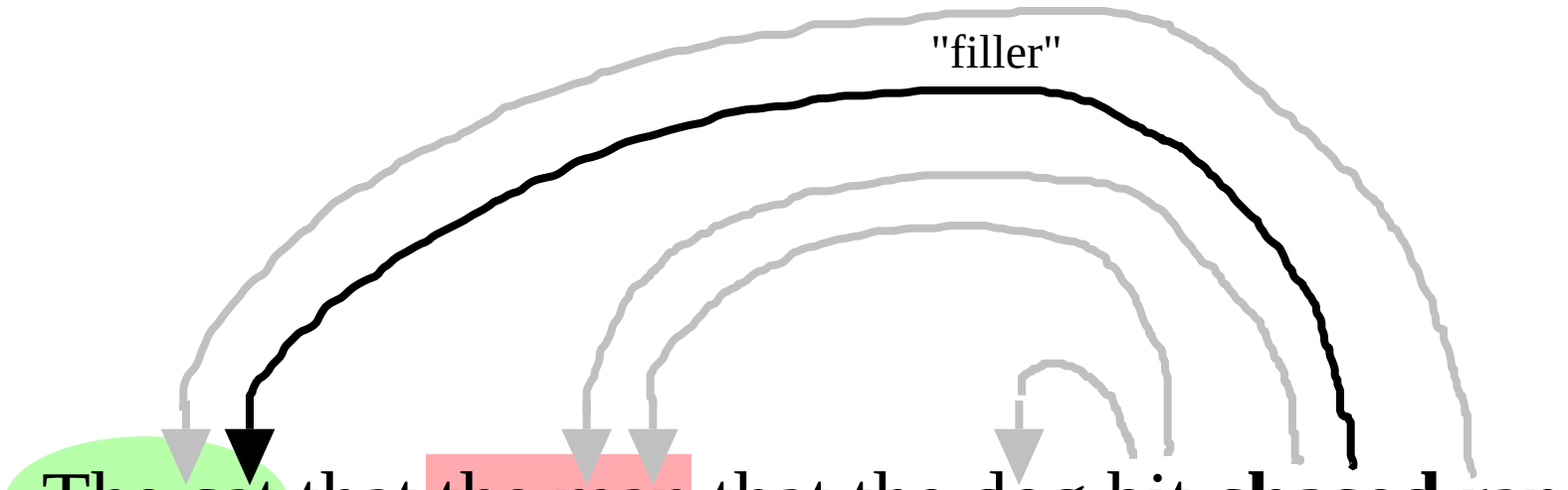

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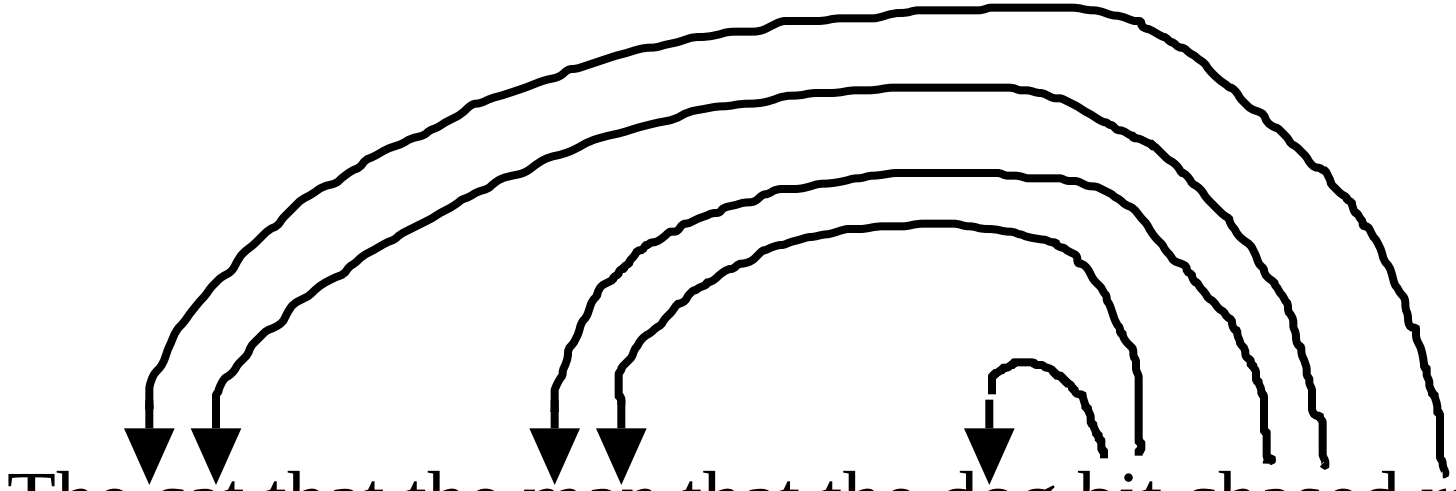


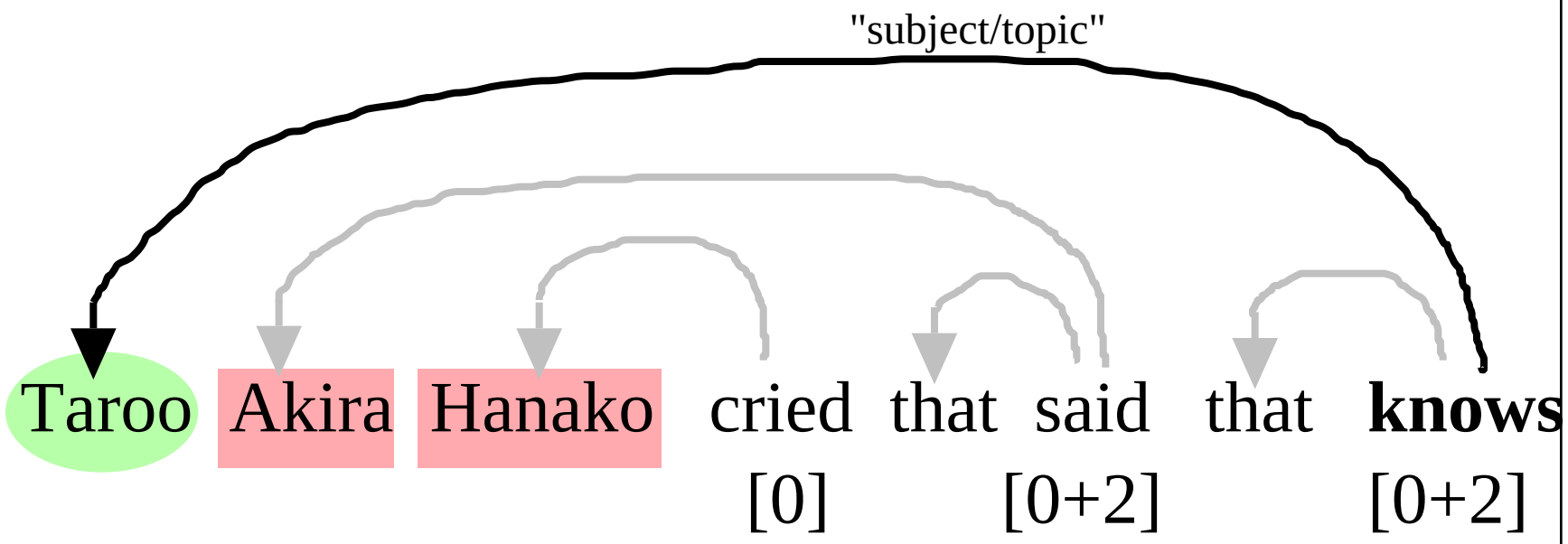
Claim: Given this simple metric, two is acceptable, three is unacceptably difficult.

Mixing relative and complement clauses

- Relative inside complement is acceptable (Cowper 1976; Gibson 1990)

Acceptable triple-subject Japanese center-embeddings

(Gibson & Babyonyshev 1995)



Taroo-ga Akira-ga Hanako-ga nakidasita to itta to omotteiru

Sample of other constructions

- Difficult:
  - Who did the information that the child that the medic found was ok surprise?
  - What the man that the student who flunked liked wanted was a candy bar.
- Acceptable:
  - What the man that Ellen married likes is smoked salmon.
  - Intelligent though the woman that John married is, she ....

Summary of empirical coverage

- Tested on 60 structures from English, French, German, Hebrew, Korean, Japanese,Spanish

CONSTRUCTION TYPE	TOTAL	CORRECT PREDICTION
Right/left branching	**2**	**2**
Embedded relatives	**16**	**16**
Subject sentences/topicalizations	**9**	**9**
Complements	**6**	**5**
Clefts	**7**	**7**
Stacking	**14**	**12**
Tough movement, etc.	**6**	**6**
TOTAL	**60**	**57**

Conclusion

- **Processing difficulty in parsing embeddings arises from similarity-based syntactic interference (both RI and PI)**
- **Simple theory, complex predictions**
  - Applies *general principles of memory* but yields *detailed domain-specific implications*
  - Excellent empirical coverage, cross-linguistically
  - Interacts with other aspects of sentence processing (in particular, ambiguity resolution)
  - Provides detailed constraints on computational architectures