When *Push* Comes to *Shove*: A Computational Model of the Role of Motor Control in the Acquisition of Action Verbs

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OUTLINE

- An Action-Verb Learning Task
- The Bodily Grounding Perspective
- X-schemas for Action Control
- Linguistic Linking Features
- Learning Verbs by Model Merging
- Results for English, Farsi and Russian

CROSSLINGUISTIC VARIATION IN HAND-ACTION VERBS

- Tamil ***thallu/ilu:*** push/pull, but implies jerkiness or suddenness (smooth motion requires a directional specifier)
- Tamil ***pudi:*** covers clutch, hold, restrain, catch; implies use of high force
- Spanish ***pulsar/presionar:*** press with the index finger *vs.* press with the palm
- Farsi ***hol-daadan/feshaar-daadan:*** two senses of pushing: move an object away from body *vs.* apply pressure to an unmoving object
- Farsi ***zadan:*** hit; strum, or play any musical instrument; object manipulation using quick motion

A COMPUTATIONAL TASK

- Given:
  - Training examples which pair an action with a verb
- Learn to:
  - label novel actions
  - obey verbal commands
- *Actions are those of the language learner. Thus, their representation includes goals and motor commands.*
- Data collection and evaluation:
  - Must understand x-schemas

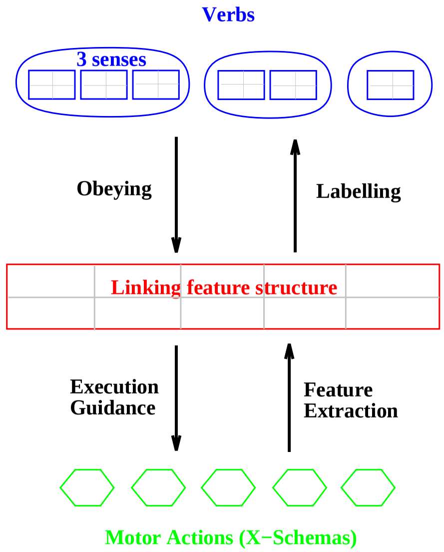
OR

- Use *Jack* animation package:
  - Realistic body and motions
  - Natural interface to x-schemas

BODILY GROUNDING

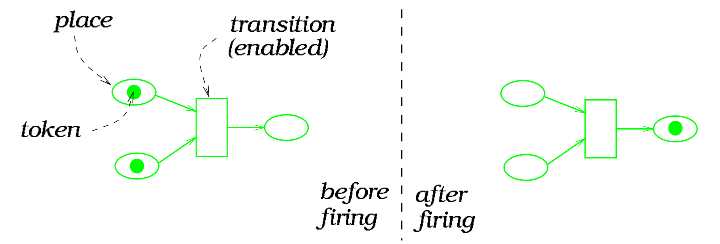
- Computing With Neurons
  - slow
  - simple messages
  - highly parallel
  - no central controller
  - sparse connectivity
- The Human Motor Control System
  - low-level synergies
  - parameterization (e.g. force, direction)
  - high-level coordination
  - concurrency and asynchrony

MODEL ARCHITECTURE

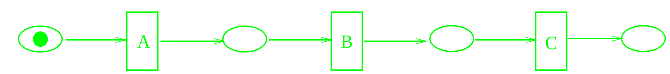


PETRI NETS

BASIC BUILDING BLOCKS

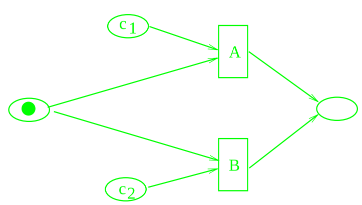


SEQUENTIAL EXECUTION

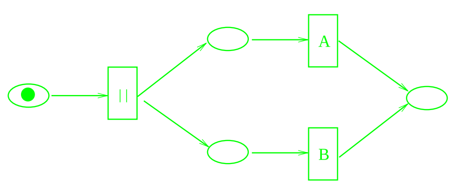


PETRI NETS 2

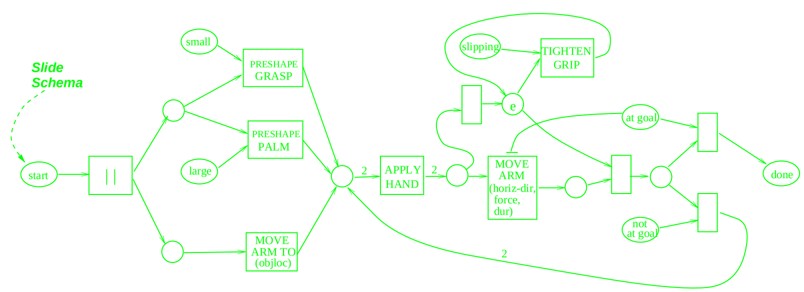
CONDITIONAL EXECUTION



CONCURRENT EXECUTION

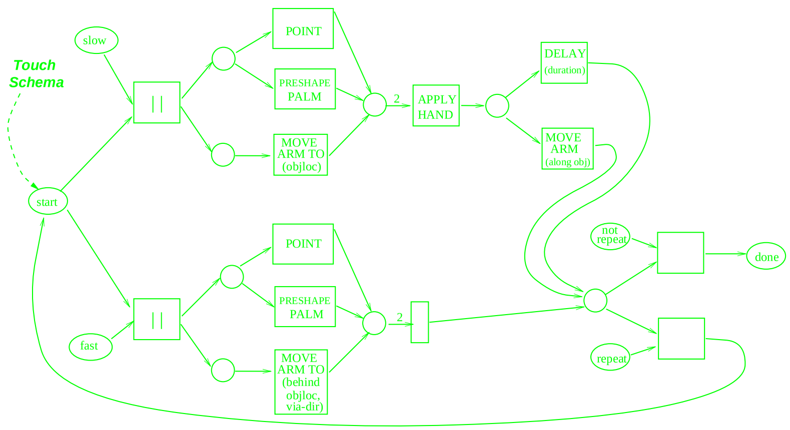


SLIDE X-SCHEMA

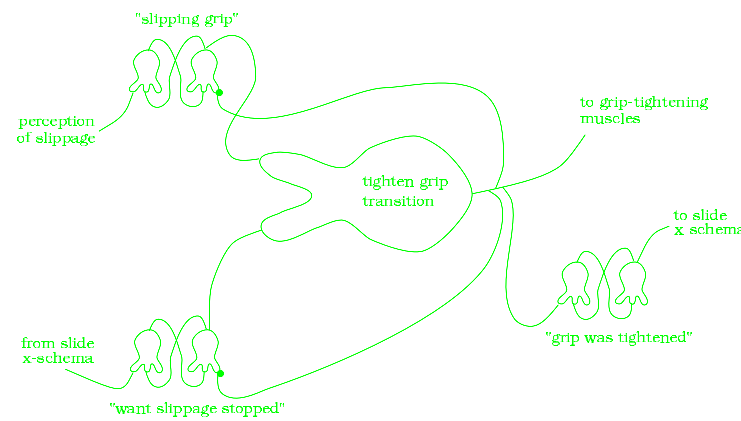


- Other x-schemas: DEPRESS, LIFT, ROTATE, TOUCH

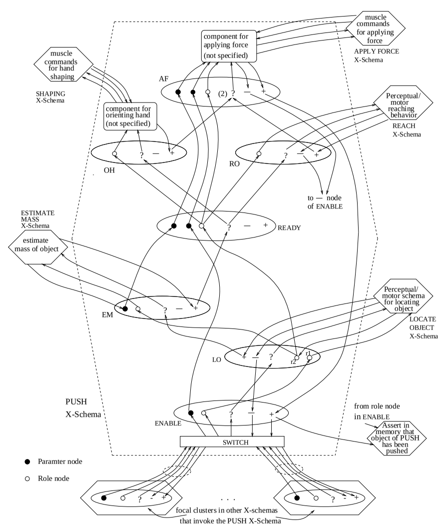
TOUCH X-SCHEMA



CONNECTIONIST ACCOUNT: X-SCHEMAS



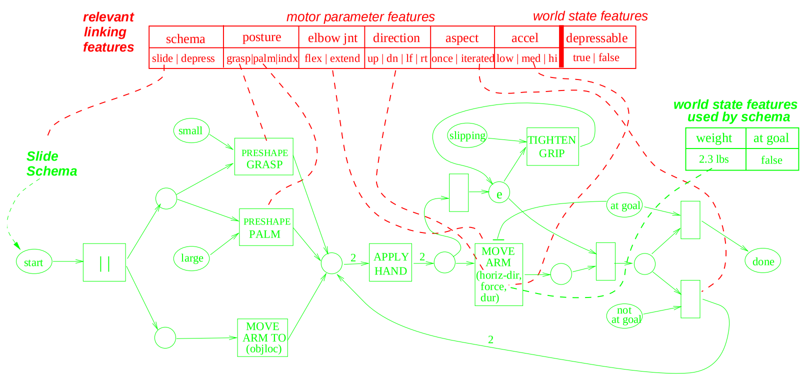
TEMPORAL BINDING OF PARAMETER VALUES



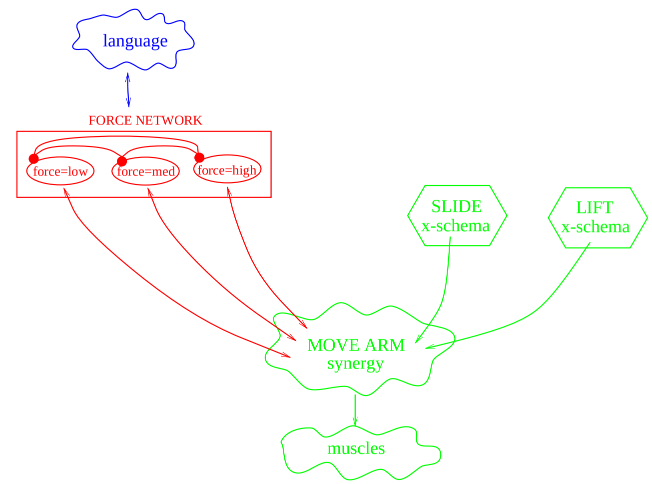
LINKING FEATURES

- Motivation: Extractable and linguistically adequate
- Features include:
  - Schema (which x-schema executes)
  - Hand Posture (grasp, palm, index finger, etc.)
  - Direction (toward, away, up, down, left, right)
  - Elbow Joint Motion (flex, extend, fixed)
  - Force (low, med, high)
  - Aspect (whether x-schema repeats)
  - Object Size (small, med , large)
  - Depressability (a sample object property)
- Extracted from:
  - Synergy parameters
  - Control flow and choice of synergies
  - Perceived world state

CONNECTING LINKING FEATURES TO X-SCHEMAS



CONNECTIONIST ACCOUNT: LINKING-FEATURES



TWO SENSES OF *PUSH*

PUSH: 2 senses

sense 1

schema		posture		direction	
slide	100%	palm	60%	away	50%
touch	0%	grasp	10%	toward	5%
		index	30%	up	15%
				down	30%

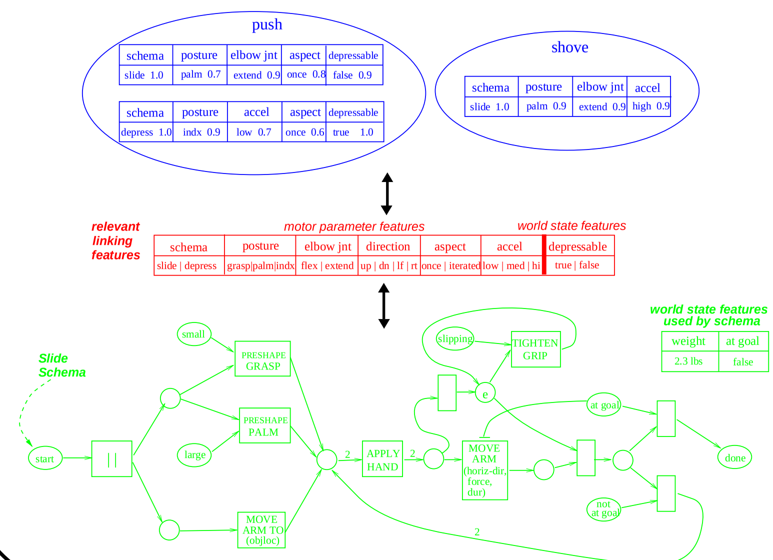
commonness 0.2

sense 2

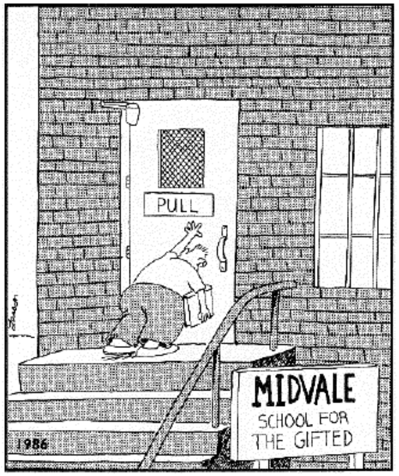
schema		posture		force	
slide	0%	palm	85%	low	10%
touch	100%	grasp	5%	med	30%
		index	10%	high	60%

commonness 0.1

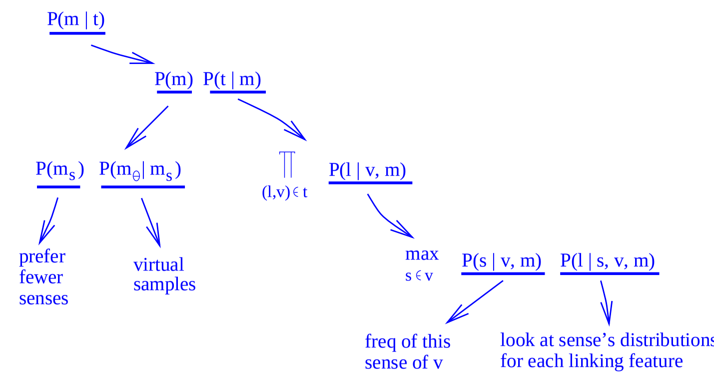
DETAILED VIEW OF MODEL



HOW TO LEARN VERBS?



RATING A LEXICON MODEL BY ITS POSTERIOR PROBABILITY

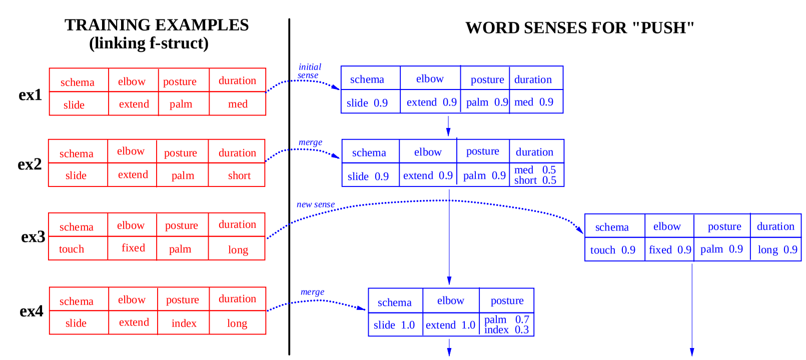


Key: m = model of lexicon; t = training set; v = verb; s = sense of verb; l = linking f-struct

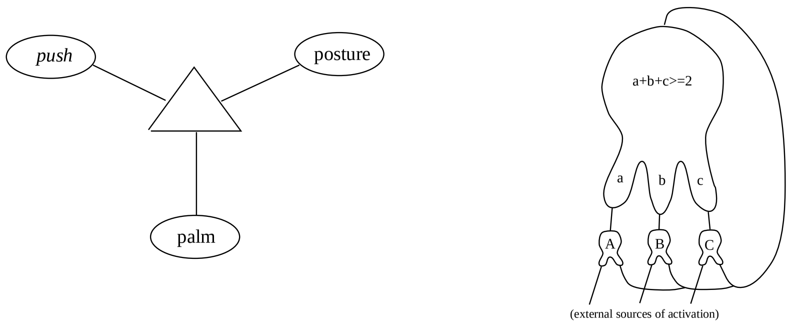
LEARNING WORD SENSES: BAYESIAN MODEL MERGING

- Basic algorithm:
  1. Create a new word sense for each training ex., generalizing each feature slightly.
  2. While there exist good candidate merge pairs:
     a) Choose best merge pair <$sense_1$,$sense_2$>.
     b) Replace with a new merged $sense_{12}$.
- Merging involves combining probability distributions to form (usually) more general word senses.
- Merge choice and stopping criterion use Bayes' Rule to trade off fit to data *vs.* desire for "simpler" models.

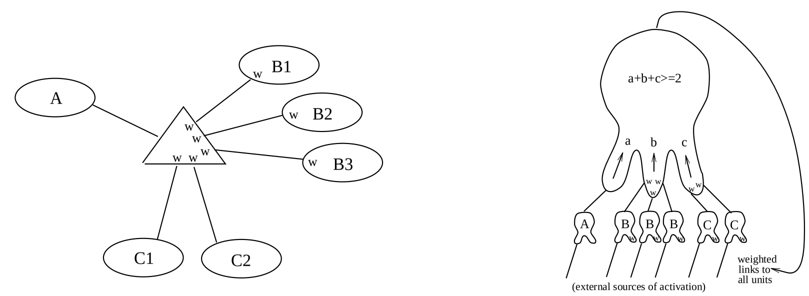
A LEARNING ILLUSTRATION



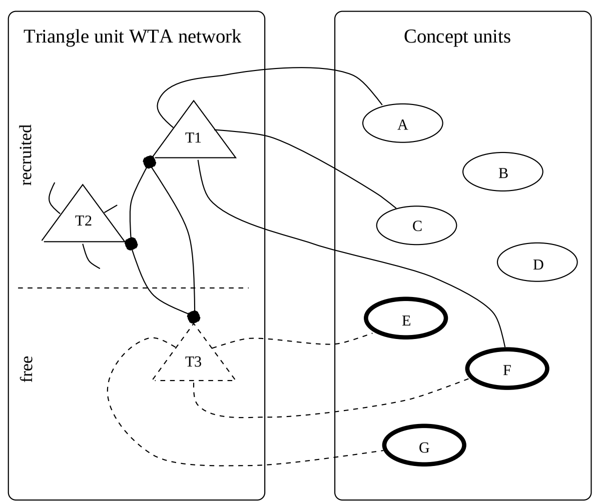
TRIANGLE NODES



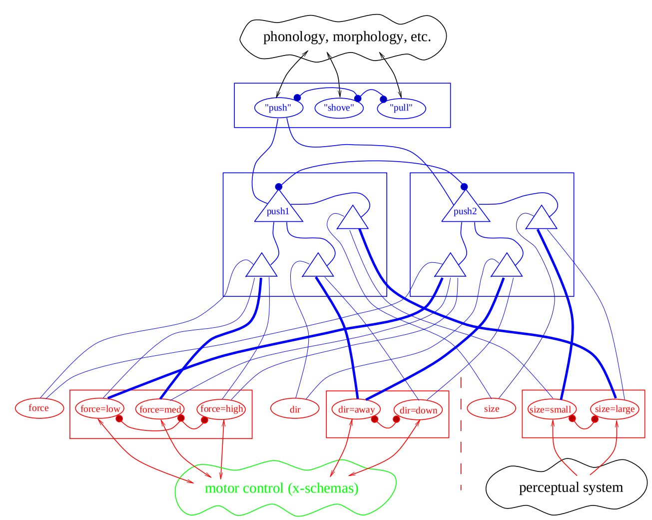
COMPLEX TRIANGLE NODES



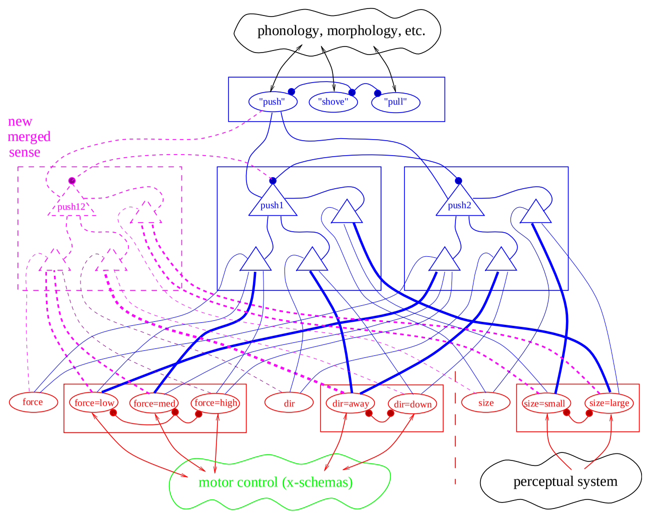
RECRUITMENT LEARNING



CONNECTIONIST ACCOUNT: VERB REPRESENTATION



CONNECTIONIST ACCOUNT: MERGING WORD SENSES



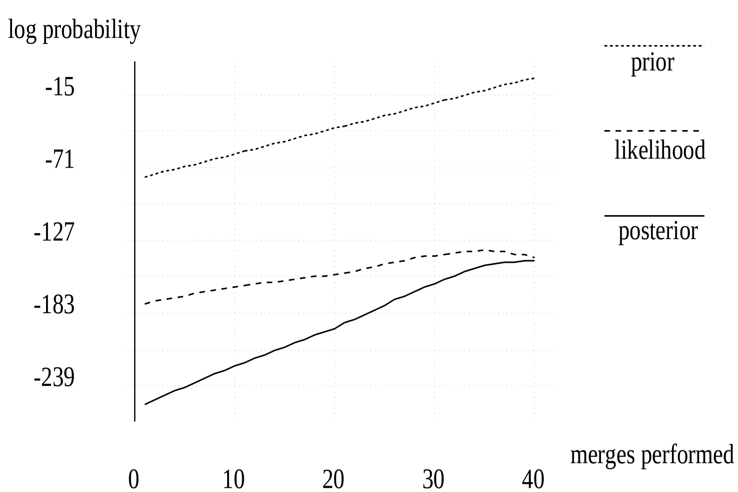
TRAINING RESULTS: ENGLISH

- 165 training examples; verb labels are:

push	pull	shove	yank
slide	press	touch	feel
slap	hit	tap	poke
lift	pick-up	heave	hold
turn	roll		

- Finds optimal number of word senses (21)
- 32 test examples: 78% recognition rate
  81% obeying rate
- Obeying *push*: chooses SLIDE or DEPRESS action as appropriate given the object type

TRAJECTORY OF LEARNING



LEARNED SENSES: *PUSH*, *SHOVE*

```
push74 (12 ex) {
   size {SMALL=0.785 large=0.214}
   elongated {true=0.071 FALSE=0.928}
   depressible {TRUE=0.928 false=0.071}
   contact {true=0.071 FALSE=0.928}
*  schema {slide=0.004 lift=0.004 rotate=0.004
             DEPRESS=0.983 touch=0.004}
   posture {grasp=0.055 wrap=0.055 pinch=0.055 palm=0.055
             platform=0.055 INDEX=0.722}
   elbow {flex=0.333 extend=0.333 fixed=0.333}
   force {low=0.466 med=0.2 high=0.333}
   accel {zero=0.062 low=0.312 MED=0.5 high=0.125}
   dir {away=0.166 toward=0.166 up=0.166 down=0.166
      left=0.166 right=0.166}
   aspect {once=0.5 iterated=0.5}
   dur {SHORT=0.6 med=0.266 long=0.133}
}

push78 (21 ex) {
   size {small=0.565 large=0.434}
   elongated {TRUE=0.608 false=0.391}
   depressible {true=0.043 FALSE=0.956}
   contact {true=0.086 FALSE=0.913}
*  schema {SLIDE=0.990 lift=0.002 rotate=0.002
             depress=0.002 touch=0.002}
   posture {grasp=0.481 wrap=0.037 pinch=0.037 palm=0.370
             platform=0.037 index=0.037}
   elbow {flex=0.041 EXTEND=0.916 fixed=0.041}
   force {low=0.333 med=0.416 high=0.25}
   accel {zero=0.04 low=0.32 MED=0.48 high=0.16}
   dir {AWAY=0.518 toward=0.037 up=0.037 down=0.037
      left=0.222 right=0.148}
   aspect {ONCE=0.739 iterated=0.260}
   dur {short=0.333 med=0.333 long=0.333}
}

shove27 (14 ex) {
*  size {small=0.187 LARGE=0.812}
   elongated {true=0.375 FALSE=0.625}
   depressible {true=0.062 FALSE=0.937}
   contact {true=0.312 FALSE=0.687}
   schema {SLIDE=0.985 lift=0.003 rotate=0.003 depress=0.003
             touch=0.003}
*  posture {grasp=0.15 wrap=0.05 pinch=0.05 PALM=0.65
             platform=0.05 index=0.05}
   elbow {flex=0.058 EXTEND=0.588 fixed=0.352}
*  force {low=0.058 med=0.294 HIGH=0.647}
   accel {zero=0.055 low=0.166 med=0.277 HIGH=0.5}
   dir {away=0.35 toward=0.05 up=0.05 down=0.05 left=0.25
      right=0.25}
   aspect {ONCE=0.625 iterated=0.375}
*  dur {SHORT=0.588 med=0.235 long=0.176}
}
```

RECOGNITION PERFORMANCE

```
Beginning recognition test...
  Scenario sc6: desired=push, output=push
  Scenario sc12: desired=push, output=push
  Scenario sc18: desired=pickup, output=pickup
  Scenario sc24: desired=feel, output=feel
  Scenario sc30: desired=shove, output=shove
  Scenario sc36: desired=heave, output=lift     *ERROR*
  Scenario sc42: desired=hold, output=hold
  Scenario sc48: desired=slide, output=push    *ERROR*
  Scenario sc60: desired=slap, output=slap
  Scenario sc66: desired=pull, output=pull
  Scenario sc72: desired=turn, output=turn
  Scenario sc78: desired=pull, output=pull
  Scenario sc84: desired=push, output=push
  Scenario sc90: desired=press, output=press
 Scenario sc96: desired=turn, output=turn
  Scenario sc102: desired=pickup, output=pickup
  Scenario sc108: desired=pull, output=pull
  Scenario sc114: desired=lift, output=lift
  Scenario sc120: desired=hold, output=hold
  Scenario sc126: desired=poke, output=poke
  Scenario sc132: desired=pull, output=pull
  Scenario sc138: desired=pull, output=pull
  Scenario sc144: desired=push, output=push
  Scenario sc150: desired=turn, output=turn
  Scenario sc156: desired=tap, output=touch    *ERROR*
  Scenario sc162: desired=slide, output=slide
  Scenario sc168: desired=yank, output=pull    *ERROR*
  Scenario sc174: desired=press, output=push *ERROR*
  Scenario sc180: desired=push, output=push
  Scenario sc186: desired=heave, output=lift    *ERROR*
  Scenario sc192: desired=press, output=push *ERROR*
  Scenario sc198: desired=push, output=push
  Correctly labelled 25 of 32 test scenarios (78%).
Recognition test done.
```

- Overall success rate is 78%
- Most errors are "close calls," due to frequency effects (common words overwhelm specific words)

COMMAND-OBEYING PERFORMANCE

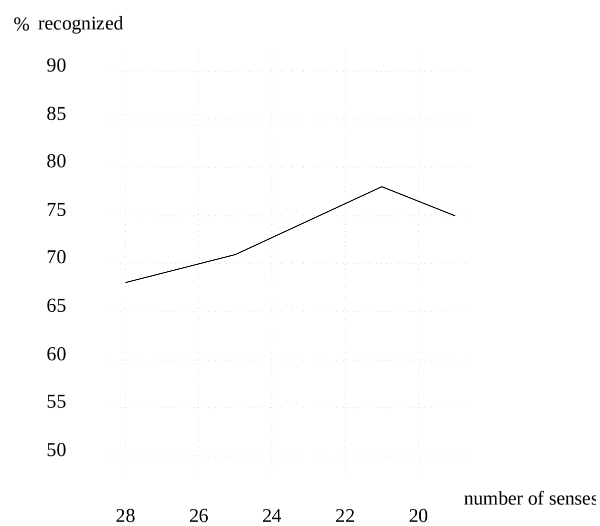
- If the command is *push*:

  and the initial world state is:
  {size=small elongated=false depressible=true contact=false}
  then these linking features are set:
  {schema=depress posture=index accel=med dur=short}

  but if the initial world state is:
  {size=large elongated=false depressible=false contact=false}
  then these linking features are set:
  {schema=slide elbow=extend accel=med dir=away aspect=once}

- Overall command-obeying performance (judged by subsequent labelling of the action) is 81%.

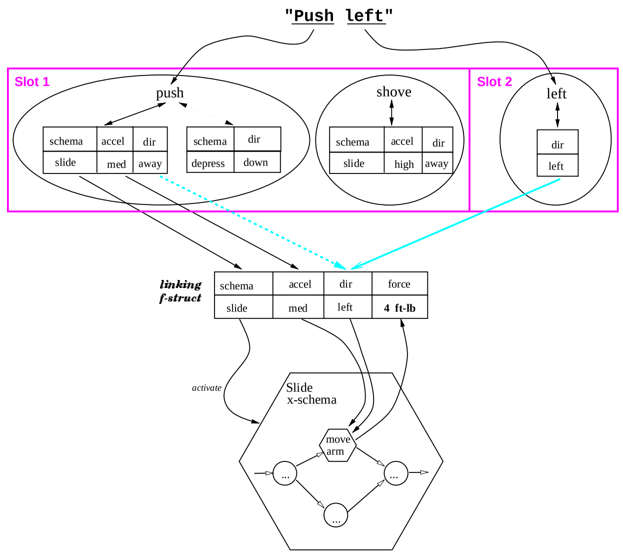
RECOGNITION RATE VS. NUMBER OF WORD SENSES



TRAINING RESULTS: FARSI

- Trained on 4 verbs
- Identical algorithm parameters
- Achieved comparable recognition rates and obeying rates
- *Hol-daadan* and *feshaar-daadan* distinguish 2 senses of English push (move away vs. apply pressure
- Learns 2 senses of *feshaar-daadan*: one for steady pressure, one for pressing a button

MULTI-SLOT ARCHITECTURE



MULTI-SLOT TRAINING RESULTS: RUSSIAN

- Actions labelled with 12 root verbs, 6 prefixes, and 2 suffixes
- Slower training; requires on-line version of learning
- Acceptable learning of root verbs; some spurious associations are captured
- Suffixes capture perfectiveness with two senses, coding for the **duration** and **aspect** features
- "Explaining away" of features hurts recognition performance

CONCLUSIONS

- Action-verb semantics are grounded in motor control
  - high-level control is most relevant
  - universal constraints render learning tractable
  - features link action to reasoning
- Action-based criterion for distinguishing word senses
  - Bayesian formalism provides basis for learning
- Reversible mappings needed for obeying commands
  - suggests hardwiring of features is necessary
- Recruitment learning leads to a connectionist account
- X-schema mechanism has more general application (e.g. aspect, metaphor) and provides a scientific language for linguistic inquiry

NEURAL THEORY OF LANGUAGE PROJECT AT ICSI/BERKELEY