Mathematical Linguistics & Typological Complexity

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SIGTYP Lecture Series
Nov 19, 2021

(Some) Big Questions

- Are there **laws** that govern linguistic knowledge?
- **Why** are those the laws?
- Do they relate to **typological gaps**, i.e.
  logically possible patterns we don't (seem to) find?
- What can we infer about **human learning processes**?

Cross-disciplinarity for the win

- Stand on the shoulders of giants.
- Cross-fertilization and multiple explanatory levels.
- Yields new generalizations and data.

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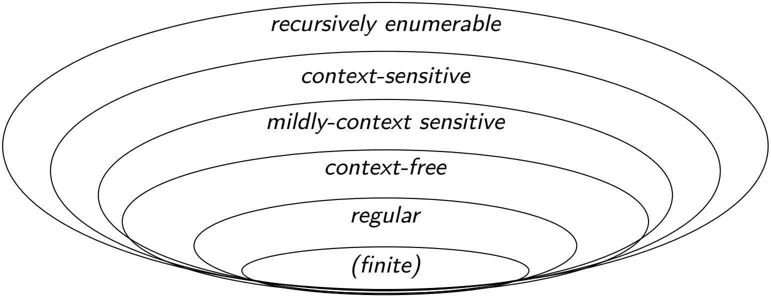
Outline

Computational Theories of Language

Languages (stringsets) can be classified according to the complexity of the grammars that generate them.



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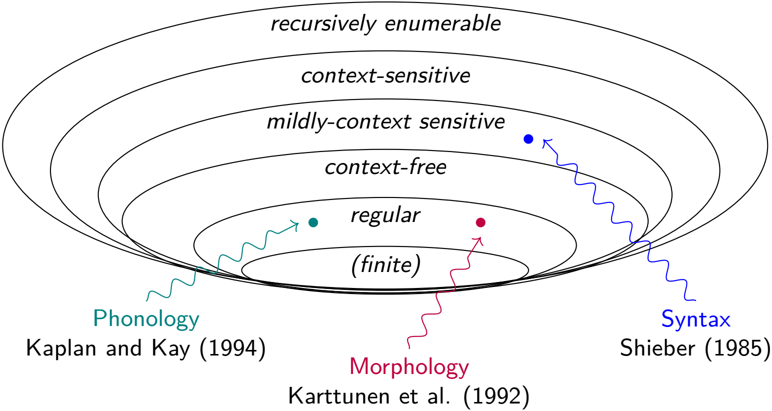
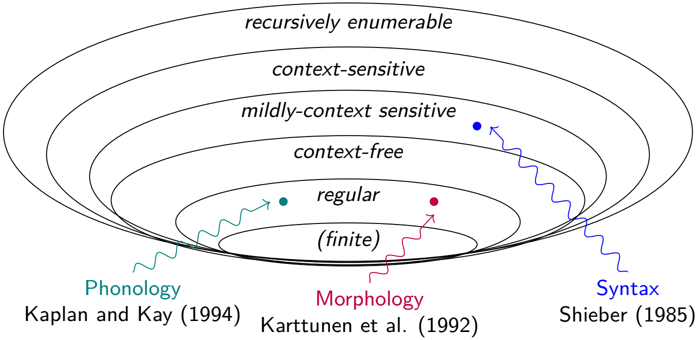


Precise Theories ⇒ Precise Predictions



Precise predictions for:

- typology → e.g. no center embedding in phonology
- learnability → e.g. no Gold learning for regular languages
- cognition → e.g. finitely bounded working memory

Classifying Patterns

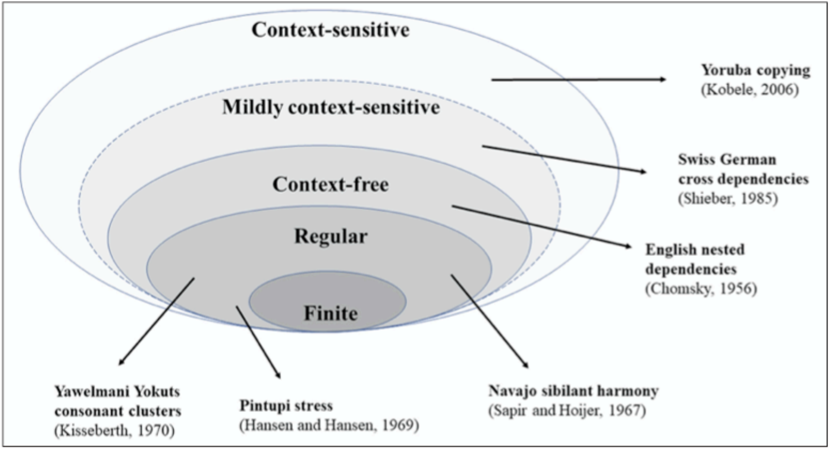
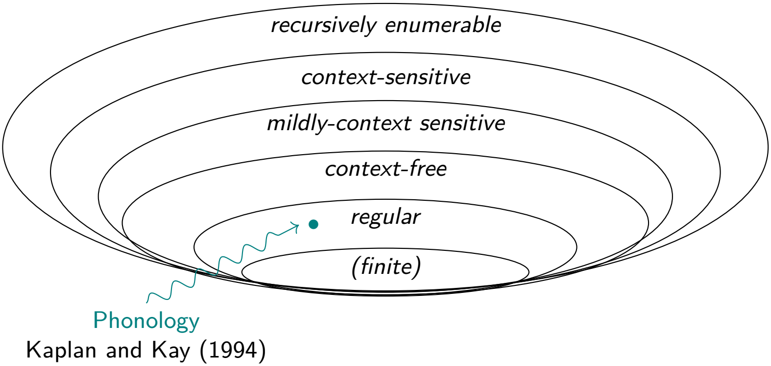
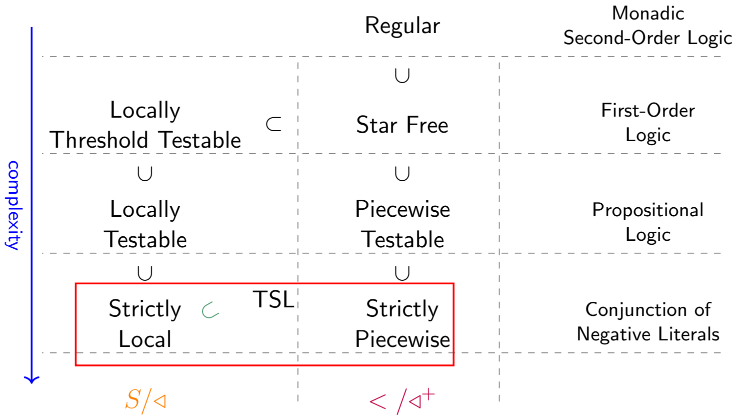


Figure 1: The Chomsky Hierarchy. Various features of natural language occupy different regions of the hierarchy. Figure reproduced from Figure 1 in Heinz (2010: 634) with permission.

Phonology as a Regular System



Beyond Monolithic Classes: Subregular Languages



- Multiple equivalent characterizations:
  $\Rightarrow$ algebraic, logic, automata...

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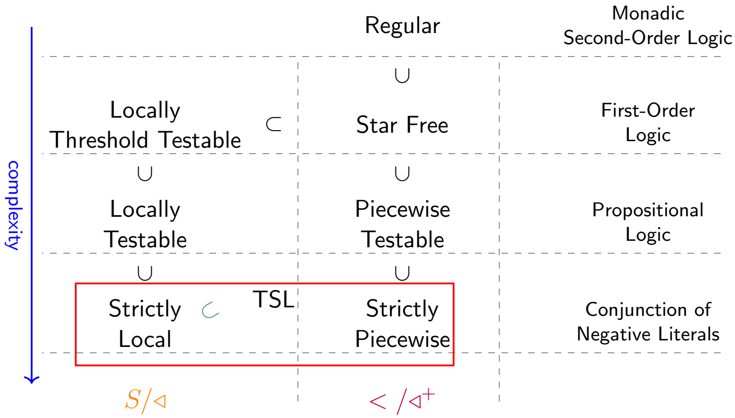

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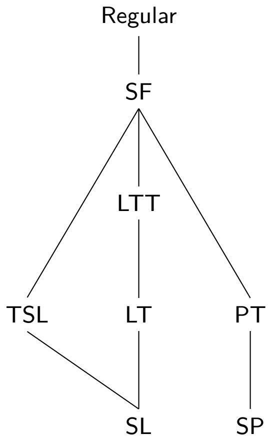
Phonology as a Subregular System

Subregular Phonotactics

- Majority of phonological patterns are **subregular** (Heinz 2011a,b; Chandlee 2014; Graf 2017:a.o.).

Most phonological and morphological rules correspond to p-subsequential relations.

(Mohri 1997)



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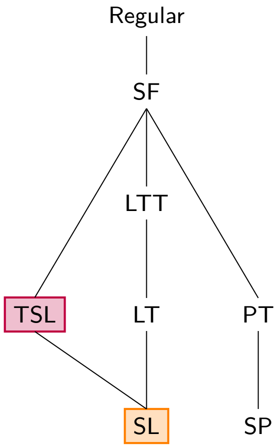
A caveat:
Mostly phonotactics today!



Local Dependencies in Phonology

1. **Word-final devoicing**
   Forbid voiced segments at the end of a word

(1) a. * rad
    b. rat

1. **Intervocalic voicing**
   Forbid voiceless segments in between two vowels

(2) a. * faser
    b. fazer

These patters can be described by **strictly local** (SL) constraints.

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Local Dependencies in Phonology are SL

Example: Word-final devoicing

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- **German**: ***z**$, ***v**$,***d**$ ($ = word edge).

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Example: Intervocalic voicing

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Unbounded Dependencies Are Not SL

- **Samala Sibilant Harmony**
  Sibilants must not disagree in anteriority.
  (Applegate 1972)

(3) a. * hasxintilawaʃ
b. * haʃxintilawas
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Example: Samala

* $ h a s x i n t i l a w a ʃ $

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Locality Over Tiers

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- **Problem**: SL limited to locality domains of size n;

Tier-based Strictly Local (TSL) Grammars (Heinz et al. 2011)

- Projection of selected segments on a tier T (Goldsmith 1976)
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- Unbounded dependencies are local over **tiers**

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Unbounded Dependencies are TSL

- Let's revisit Samala Sibilant Harmony

(4) a. * hasxintilawaʃ
  b. * haʃxintilawas
  c. haʃxintilawaʃ

- What do we need to project? [+strident]
- What do we need to ban? *[+ant][−ant],*[−ant][+ant]
  I.E. *sʃ, *sʒ, *zʃ, *zʒ, *ʃs, *ʒs, *ʃz, *ʒz

Example: TSL Samala

s ʃ ʃ ʃ

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Example: TSL Samala

Interim Summary: SL and TSL for Phonology

- Linguistically natural (Goldsmith 1976)
- Captures wide range of phonotactic dependencies (McMullin 2016)
- Provably correct and efficient learning algorithms (Jardine and McMullin 2017)
- Rules out unattested patterns (cf. Lai 2015, Aksenova et al. 2016, Graf & De Santo 2019, a.o.)

But:

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- Can we truly gain cognitive insights?

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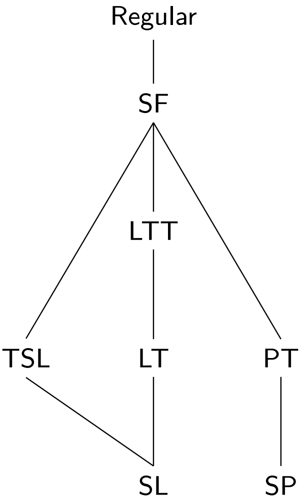
SL and TSL: So What?



- **But** not every long-distance pattern is TSL!
  (McMullin 2016, Mayer & Major 2018, De Santo & Graf 2019)

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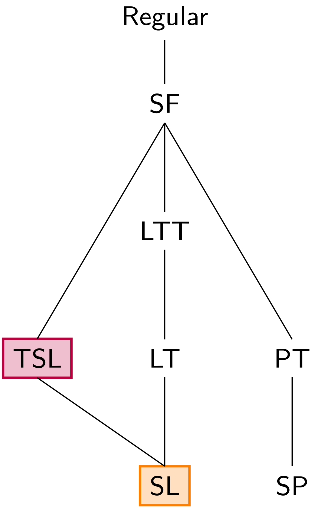

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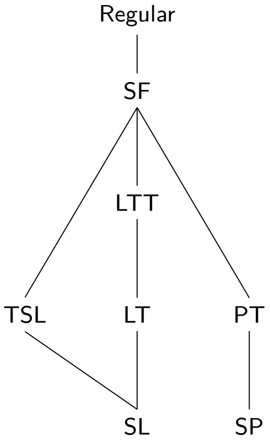
Concurrent Processes (De Santo and Graf, 2019)



Observation

- TSL is not closed under intersection

- We want to also account for multiple processes
  So we can cover the complete phonotactics of a language
- Multiple non-interacting processes in attested patterns

A TSL Outlier

Sibilant Harmony in Imdlawn Tashlhiyt (McMullin2016)

1) Underlying causative prefix /s(ː)-/

	Base	*Causative*	
a.	uga	sː-uga	"be evacuated"
b.	asːtwa	s-asːtwa	"settle, be levelled"

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2) Sibilant harmony

	Base	*Causative*	
a.	fia**ʃ**r	**ʃ**- fia**ʃ**r	"be full of straw, of discord"
b.	n**z**a	**z**ː-n**z**a	"be sold"

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3) Sibilant voicing harmony blocked

	Base	Causative	
a.	ukz	sː-ukz	"recognize"
b.	qːuʒːi	ʃ- quʒːi	"be dislocated, broken"

Sibilant Harmony in Imdlawn Tashlhiyt

Generalization (1/2)

Sibilants must agree in anteriority and voicing.

Grammar

$T = \{$ ʒ, s, z,ʃ$\}$
$S = \{$ *sʒ, *sz, *sʃ, *ʒs,*ʃs, *zs, *zʃ, *zʒ, *ʃz, *ʃʒ, *ʒʃ, *ʒz $\}$

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Sibilant Harmony in Imdlawn Tashlhiyt

Generalization (2/2)

Voiceless obstruents block agreement in voicing.

Grammar

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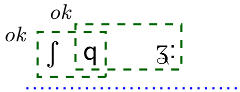

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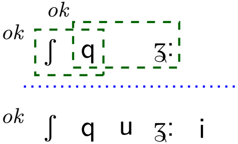

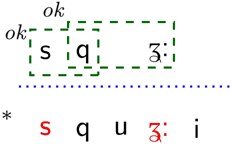

Multi-Tier Strictly Local (MTSL) Languages (1/2)

Sibilant Harmony in Imdlawn Tashlhiyt (Revisited)

Voiceless obstruents block agreement in voicing:

- T_1 = {ʒ, s, z,ʃ, q} S_1 = {*sʒ, *sz, *ʒs, *zs, *ʃz, *ʃʒ, *ʒʃ}

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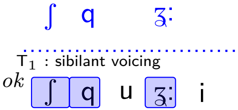

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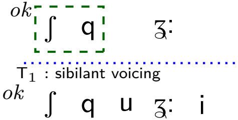

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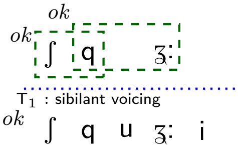

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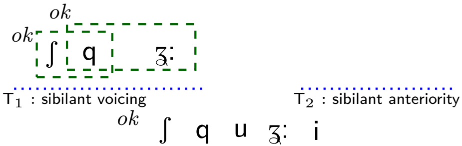
Voiceless obstruents block agreement in voicing:

- $T_1 = \{$ʒ, s, z,ʃ, q$\}$ $S_1 = \{$*sʒ, *sz, *ʒs, *zs, *ʃz, *ʃʒ, *ʒʃ$\}$

Unbounded agreement in anteriority:

- $T_2 = \{$ʒ, s, z,ʃ$\}$ $S_2 = \{$*sʒ, *sʃ, *ʒs,*ʃs, *zs, *zʃ, *zʒ, *ʃz, *ʒz $\}$



Multi-Tier Strictly Local (MTSL) Languages (1/2)

Sibilant Harmony in Imdlawn Tashlhiyt (Revisited)

Voiceless obstruents block agreement in voicing:

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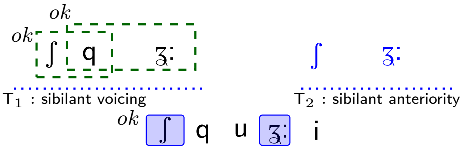

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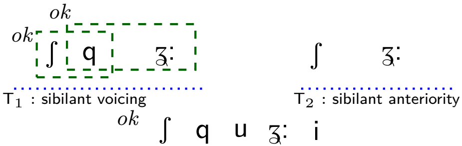

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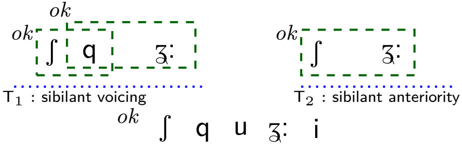

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* s q u ʒ: i

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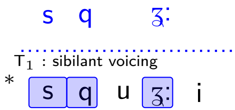

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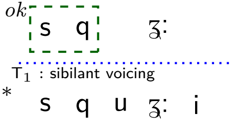

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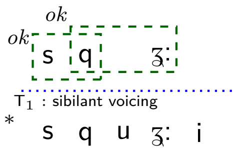

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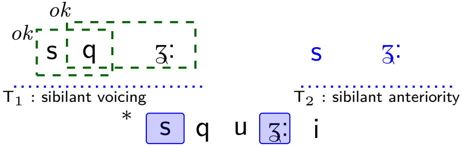

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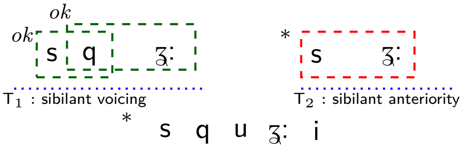
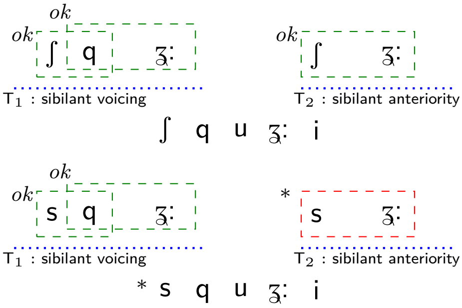


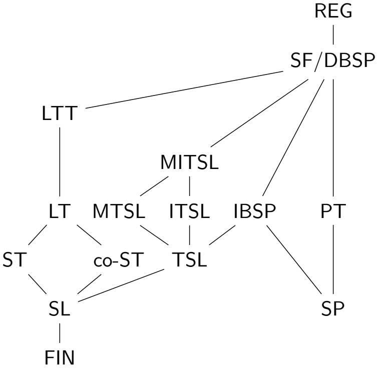
Accounting for Concurrent Processes

- MTSL: TSL closure under intersection
  (De Santo & Graf, 2019)



- Intersection closure accounts for multiple concurrent processes
- Can characterize the complete phonotactics of a language

A Plethora of Combination



- The goal is **not** identifying a single "correct" class
- Pinpoint fundamental properties of the patterns:
  SL: $\triangleleft$, TSL: $\triangleleft_T$, . . .

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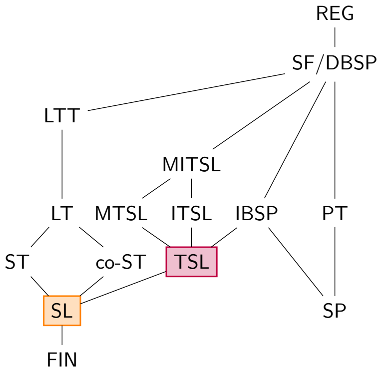

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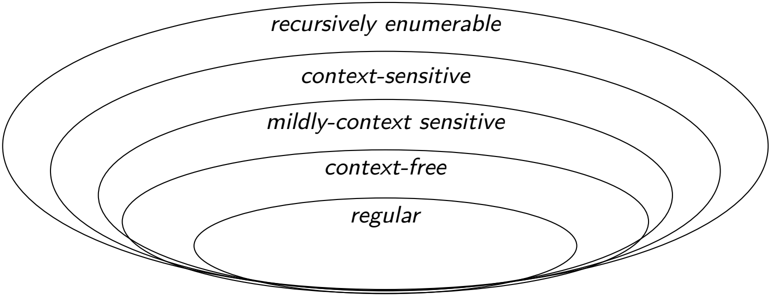
Cross-domain Parallels



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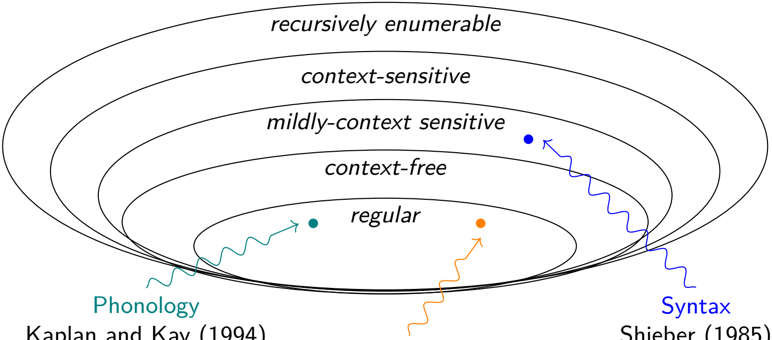
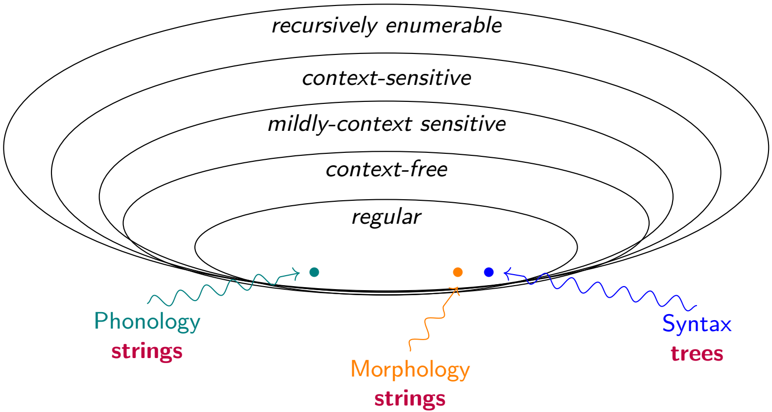


Phonology
Kaplan and Kay (1994)
strings

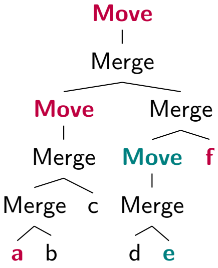
Morphology
Karttunen et al. (1992)
strings

Syntax
Shieber (1985)
strings

Cross-domain Parallels



Subregular Syntax



- Some results for syntax
  - regular tree languages (Michaelis 2004; Kobele et al. 2007)
  - subregular operations (Graf 2018)
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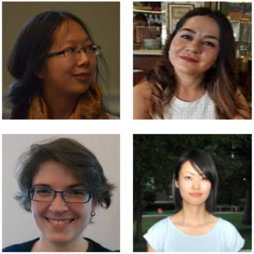

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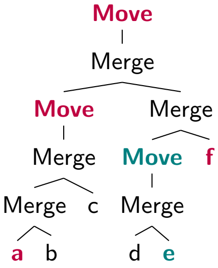

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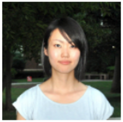

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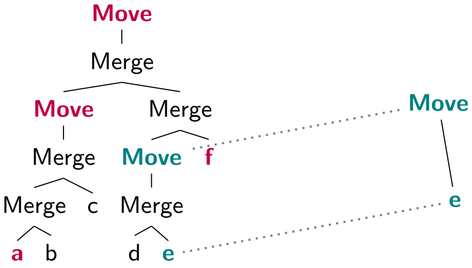

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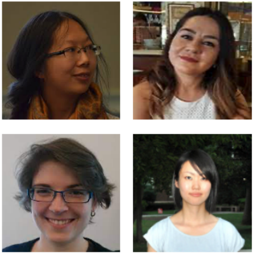

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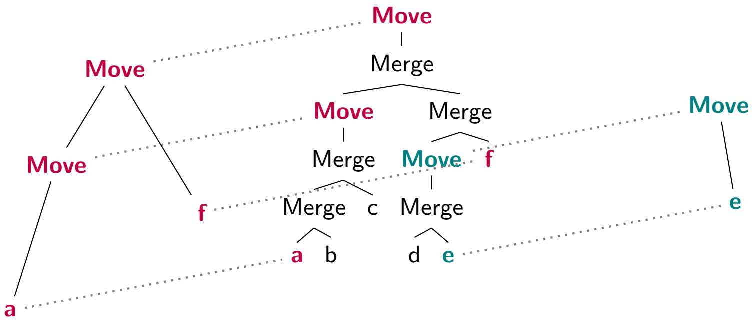

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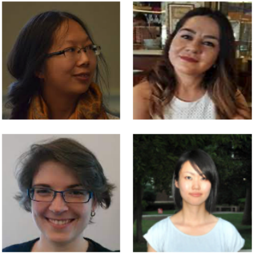

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Strong Parallelism

Subregular dependencies in phonology, (morphology), and syntax **subregular** over their respective **structural representations**.

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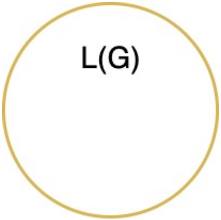
But:

- Typological variation is complex
- Our knowledge of attested pattern is limited

Outline

Artificial Grammar Learning (AGL)

- Can be used to test implicit learning abilities (Reber, 1976)



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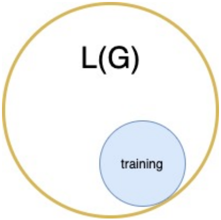

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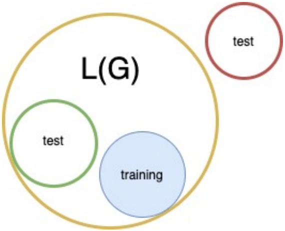

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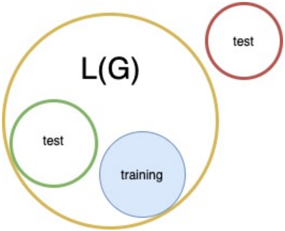

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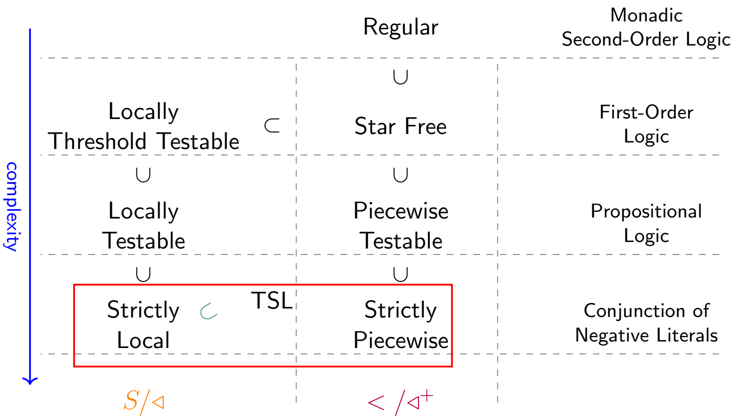
Testing Subregular Predictions



Example: Attested vs. Unattested Patterns

Attested: Unbounded Sibilant Harmony

- Every sibilant needs to harmonize

s ʃ

* $ h a **s** x i n t i l a w ʃ $

ʃ ʃ

ok $ h a ʃ x i n t i l a w ʃ $

Unattested: First-Last Harmony

- Harmony only holds between initial and final segments

s ʃ

ok $ h a **s** x i n t i l a w ʃ $

s ʃ

* $ **s** a t x i n t i l a w ʃ $

Lai (2015)

Learnable vs. Unlearnable Harmony Patterns

Regine Lai

Posted Online July 09, 2015
https://doi.org/10.1162/LING_a_00188

Linguistic Inquiry
Volume 46 | Issue 3 | Summer 2015
p.425-451

Keywords: phonotactics, learnability, computational phonology, formal theory, typology, dependencies

Lai (2015): Stimuli

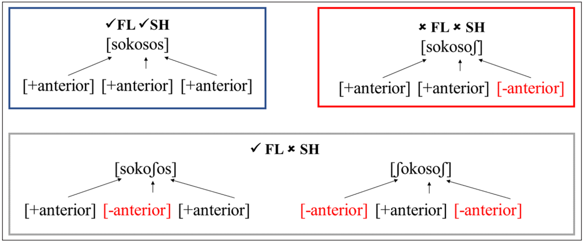


Figure 3: Comparison of SH and FL stimuli.

Lai (2015): Stimuli

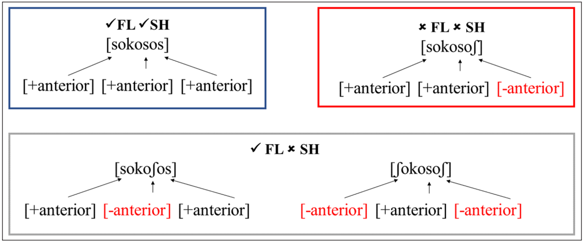


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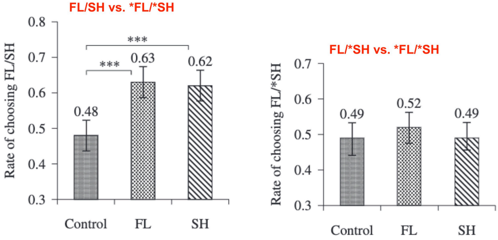
Table 6
Predicted results with respect to the control group for each test pairing if Sibilant Harmony and First-Last Assimilation grammars were internalized

	Pairs		
Conditions	FL/*SH vs. *FL/*SH (e.g., [s . . . ʃ . . . s] vs. [s . . . s . . . ʃ]) Rate of FL/*SH	FL/SH vs. *FL/*SH (e.g., [s . . . s . . . s] vs. [s . . . s . . . ʃ]) Rate of FL/SH	FL/SH vs. FL/*SH (e.g., [s . . . s . . . s] vs. [s . . . ʃ . . . s]) Rate of FL/SH
SH	∼ Control	> Control	> Control
FL	> Control	> Control	∼ Control

Lai (2015): Results



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- See Avcu and Hestvik (2020), Avcu et al. (2019) for replications

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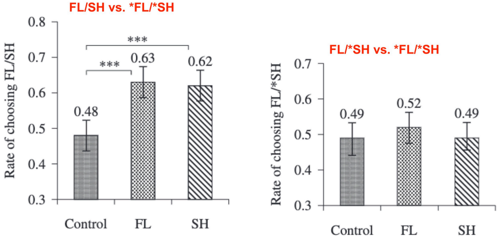

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A Plethora of Testable Predictions

Observation

- Attested patterns **A** and **B** are TSL.
- But combined pattern **A**+**B** is not TSL.

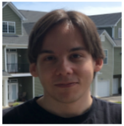
Prediction

- **A**+**B** should be harder to learn than **A** and **B**

Example: Compounding Markers

Morphotactics as Tier-Based Strictly Local Dependencies

Alëna Aksënova Thomas Graf Sedigheh Moradi



- Russian has an infix -*o*- that may occur between parts of compounds.
- Turkish has a single suffix -*sɪ* that occurs at end of compounds.

(5)

vod	**-o-**	voz	**-o-**	voz
water	-COMP-	carry	-COMP-	carry

'carrier of water-carriers'

(6)

türk	bahçe	kapı	**-SI**	(*-**SI**)
turkish	garden	gate	-COMP	(*-COMP)

'Turkish garden gate'

Example: Compounding Markers [cont.]

- Russian and Turkish are TSL.

Tier_1	COMP affix and stem edges #
Russian n-grams	**oo**, **$o**, **o$**
Turkish n-grams	**sisi**, **$si**, **si#**

- The combined pattern would yield **Ruskish**: stem^{n+1}-si^{n}
- This pattern is not regular and hence **not TSL either**.

Testable Predictions

- Can naive subjects learn Russian-like, Turkis-like, and Ruskish-like compounding?

Outline

Of Black Swans and Flying Pigs

Of Black Swans and Flying Pigs

Of Black Swans and Flying Pigs

- Not a single data point, but classes of phenomena
- Value of restrictive theories: predictive and explanatory
- We learn from falsifying them too!

Complexity as a Magnifying Lens

- We can compare patterns and predictions across classes
- We can also compare patterns within a same class

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Volume 1 Article 8

2018

Formal Restrictions On Multiple Tiers

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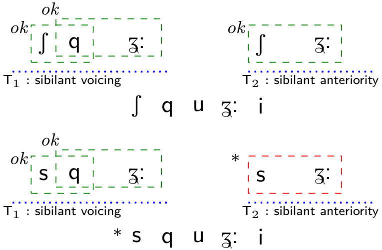
Testing Harmony Systems

Reminder:

- MTSL's multiple-tier idea...



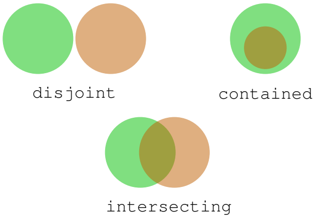


Figure 2: Theoretically possible tier alphabet relations

Testing Harmony Systems (cont.)

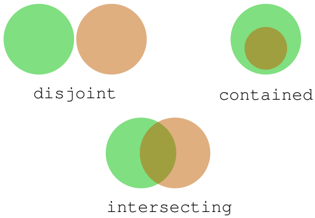
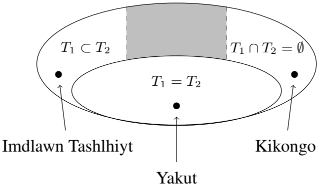


Figure 2: Theoretically possible tier alphabet relations



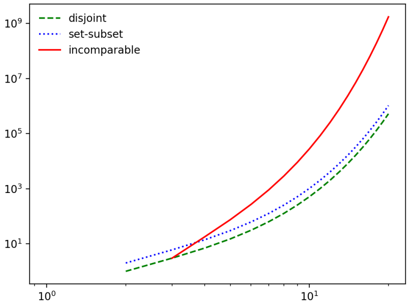


Figure 7: Growth of number of partitions of sets containing up to 20 elements (loglog scale)

Learnability Generalizations

Learning Interactions of Local and Non-Local Phonotactic Constraints from Positive Input

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Alëna Aksënova
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- Efficiently learn MITSL_2^2 grammars from positive data

Unlearnable Patterns

- No overlapping tiers with the same $^*\rho_1\rho_2$ restriction
  e.g. $T_1 = \{a, b, c\},\ T_2 = \{a, b, d\},\ G_1 = G_2 = \{^*ab\}$

- This is *predicted* from the structure of the grammar (see also Lambert et al. 2021)

From Blackbox to Blackbox

Multi-Element Long Distance Dependencies: Using SP*k* Languages to Explore the Characteristics of Long-Distance Dependencies

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- Strictly-piecewise Languages
  - Basically: Skip-gram models
  - Capture long distance dependencies over strings
  - Modulate parameters of variation:
    e.g., length of the dependency, alphabet size, etc.

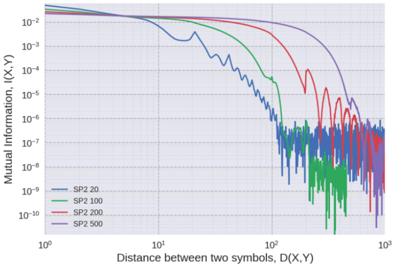
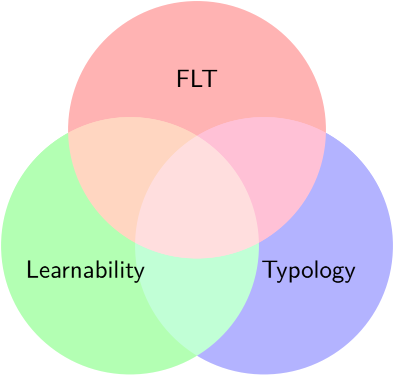


Figure 3: LDD characteristics of datasets of SP2 grammar exhibiting LDDs of length 20, 100, 200 and 500.

Theory Building

> *The problem that we cannot deduce [...] theories from data is a limitation, or* ***perhaps an attribute****, of all empirical science [...] Still, one may abduce hypotheses [...] Abduction is* ***reasoning from observations*** *[...] It consists of two steps: generating candidate* ***hypotheses*** *(abduction proper), and selecting the "best" explanatory one (inference to the* ***best explanation****).*
>
> *(van Roji & Baggio 2020, pg. 9)*

A Collaborative Enterprise!



Thank you!

Mathematical Linguistics and Cognitive Complexity

Aniello De Santo, Jonathan Rawski

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From Blackbox to Blackbox

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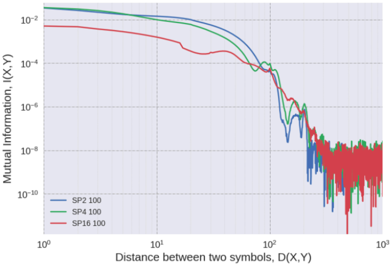

Figure 2: LDD characteristics of datasets of SP2, SP*4* and SP*16* grammar exhibiting LDD of length 100.

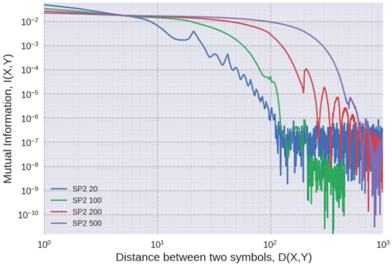

Figure 3: LDD characteristics of datasets of SP2 grammar exhibiting LDDs of length 20, 100, 200 and 500.

Example: Circumfixation in Indonesian

- Indonesian has circumfixation with no upper bound on the distance between the two parts of the circumfix.

(7) maha siswa
big pupil
'student'

(8) *(ke-) maha siswa *(-an)
NMN- big pupil -NMN
'student affairs'

- Requirements: exactly one *ke-* and exactly one *-an*

Tier_1	contains all NMN affixes	$	an			ke	ke	$
Tier_0	contains all morphemes	|	|			|	|	|
n-grams	an, ke, keke, anan	$	an	m	s	ke	ke	$

Example: Circumfixation in Indonesian

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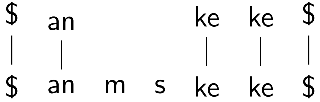
Tier$_1$	contains all NMN affixes
Tier$_0$	contains all morphemes
n-**grams**	**\$an**, **ke\$**, **keke**, **anan**



Example: Swahili *vyo*

Swahili *vyo* is **either a prefix or a suffix**,
depending on presence of negation. (?)

(9) a.

a-	vi-	**soma**	**-vyo**
SBJ:CL.1-	OBJ:CL.8-	read	-REL:CL.8

‘reads’

b.

a-	si-	**vyo-**	vi-	**soma**
SBJ:CL.1-	NEG-	REL:CL.8-	read	-OBJ:CL.8

‘doesn’t read’

Example: Swahili *vyo* [cont.]

(10) a. *

a-	**vyo-**	vi-	**soma**
SBJ:CL.1-	REL:CL.8-	OBJ:CL.8-	read

b. *

a-	**vyo-**	vi-	**soma**	**-vyo**
SBJ:CL.1-	REL:CL.8-	OBJ:CL.8-	read	-REL:CL.8

c. *

a-	si-	**vyo-**	vi-	**soma**	**-vyo**
SBJ:CL.1-	NEG-	REL:CL.8-	OBJ:CL.8-	read	REL:CL.8-

d. *

a-	si-	vi-	**soma**	**-vyo**
SBJ:CL.1-	NEG-	OBJ:CL.8-	read	REL:CL.8-

Example: Swahili *vyo* [cont.]

Generalizations About *vyo*

- may occur at most once
- must follow negation prefix *si-* if present
- is a prefix iff *si-* is present

Tier_1	contains *vyo*, *si*, and stem edges #	
Tier_0	contains all morphemes	
n-**grams**	**vyovyo**, **vyo**##**vyo**	"at most one *vyo*"
	vyosi, **vyo**##**si**	"*vyo* follows *si*"
	si##**vyo**, **$vyo**##	"*vyo* is prefix iff *si* present"

TSL Phonology: Accounting for Context

- **Unbounded Tone Plateauing in Luganda** (UTP)
  No L may occur within an interval spanned by H.
  (Hyman 2011)

(11)
a. LHLLLL
b. LLLLHL
c. *LHLLHL
d. LHHHHL

Example

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*L H L L H L

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L H L L H L

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Input-Sensitive TSL (ITSL) Languages

Defining Tier Projection

Tier projection controlled by:

1. label of segment

TSL
1

TSL languages are characterized by:

- a 1-local projection function;
- strictly k-local constraints applied on T.

Input-Sensitive TSL (ITSL) Languages

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Idea:

- Projection is an input-strictly local transduction Chandlee 2015)
- **What if**: the locality of E_T was higher than 1?

Input-Sensitive TSL (ITSL) Languages

Defining Tier Projection

Tier projection controlled by:

1. label of segment
2. local context

ITSL

1 + 2 — TSL

1

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Accounting for Context [cont.]

A ITSL analysis for UTP (DeSanto & Graf 2019):

- Project every **H**; project **L** iff immediately follows **H**
- Ban: **HLH**

Example

^{ok}**L H L L L L** ***L H L L H L**

Accounting for Context [cont.]

A ITSL analysis for UTP (DeSanto & Graf 2019):

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Example

H

^{ok}**L H L L L L**

***L H L L H L**

Accounting for Context [cont.]

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Example

H L

^{ok}**L H L L L L** $\qquad$ ***L H L L H L**

Accounting for Context [cont.]

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H L

^{ok}**L H L L L L**

***L H L L H L**

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H L

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***L H L L H L**

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H L

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Example

H L

^{ok}**L H L L L L**

***L H L L H L**

Accounting for Context [cont.]

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H L

^{ok}L H L L L L

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Example

H L	H
^{ok}L H L L L L	*L H L L H L

Accounting for Context [cont.]

A ITSL analysis for UTP (DeSanto & Graf 2019):

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Example

H L	H L
…………………………	…………………………
^{ok}L H L L L L	*L H L L H L

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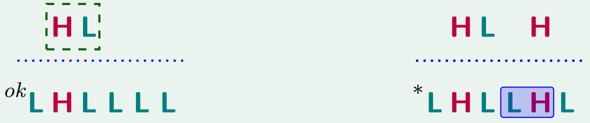
Example



Accounting for Context [cont.]

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Example

HL

^{ok}L H L L L L

H L H L

*L H L L H L

Accounting for Context [cont.]

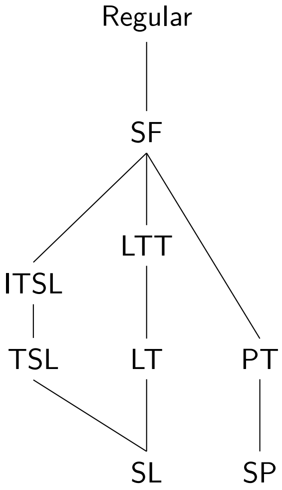
A ITSL analysis for UTP (DeSanto & Graf 2019):

- Project every **H**; project **L** iff immediately follows **H**
- Ban: **HLH**

Example

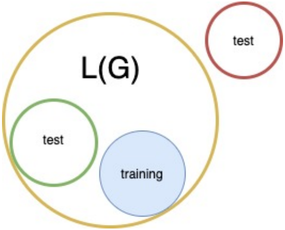
H L	H L H L
^{ok}L H L L L L	*L H L L H L

Finer Granularty



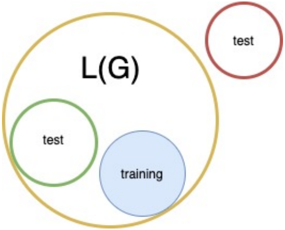
Outline

Testing Predictions with AGL



- It is a powerful technique
- We must be careful in drawing inferences from laboratory behavior
- Importantly: Common fallacies in experimental design

Testing Predictions with AGL



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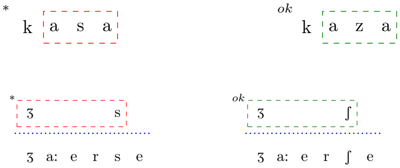
The Fallacy of Generalization

- Imagine we want to test the ability to learn long-distance dependencies:



- Assuming an alphabet $\Sigma = \{a, b, c, d, e\}$, the training samples could look like the following:

$$L_{loc} = \{abcd, aabcd, baacd, bcaae, \ldots\}$$
$$L_{dist} = \{abacd, bacad, bcada, bcaea, \ldots\}$$

What happens if we test on stimuli with similar distances?

$$L_{test} = \{abcad, abcad, bacda, abcea, \ldots\}$$

The Fallacy of Generalization

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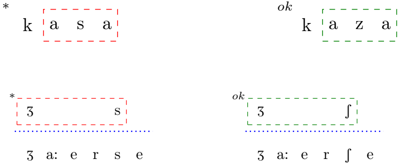

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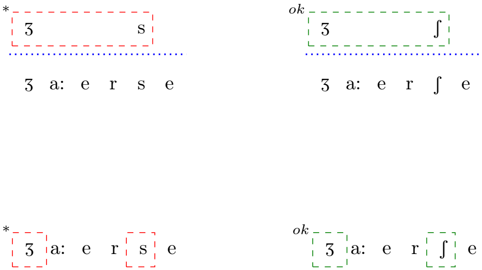
Picking the Right Primitives

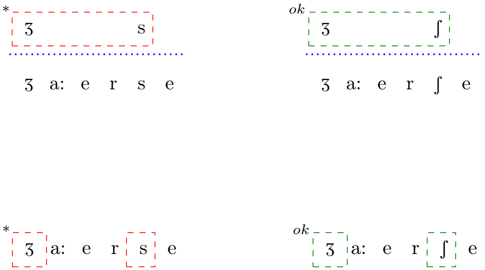
Long-distance relations?



- Stimuli are often ambiguous between overlapping classes
- Distinguishing between representation requires care

Picking the Right Primitives

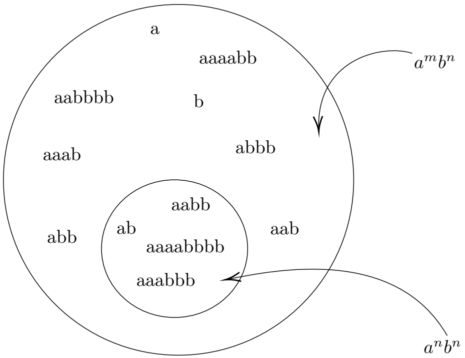
Long-distance relations?



- Stimuli are often ambiguous between overlapping classes
- Distinguishing between representation requires care

The Set/Subset Problem: Case 1

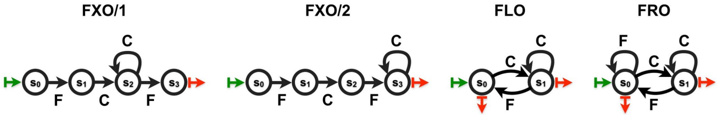
- Can participants learn $a^n b^n$?
- We must beware of $a^m b^n$



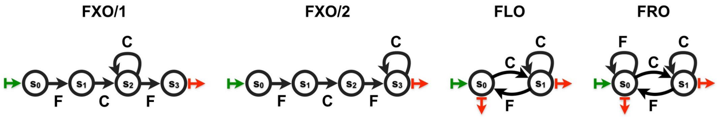
Evaluating Contrasts

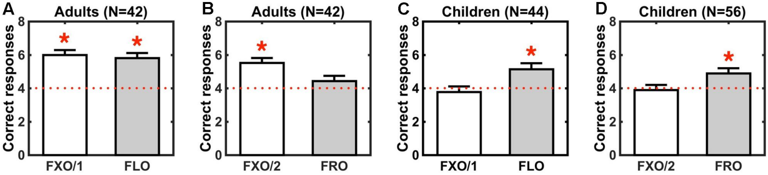
Developmental Constraints on Learning Artificial Grammars with Fixed, Flexible and Free Word Order

Iga Nowak[1,2] and Giosuè Baggio[2,3*]

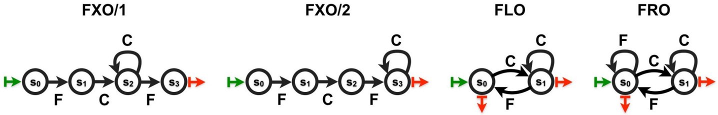


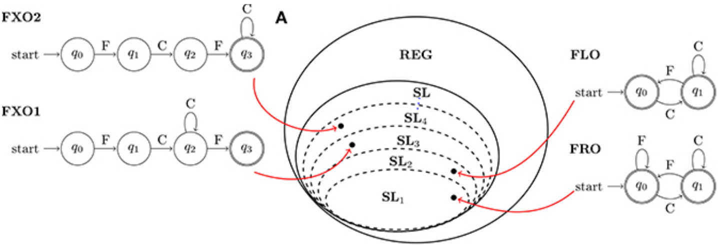
Nowak and Baggio (2017): Results





Complexity Measures and Other Issues (De Santo, 2017)





The Set/Subset Problem: Case 2

- Can participants learn a truly free-word order language?