

Building Machines that Discover Generalizable, Interpretable Knowledge

Kevin Ellis

2020

MIT

The premise of program induction

1. Represent knowledge as programs: as symbolic code

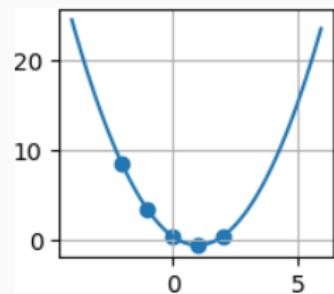
The premise of program induction

1. Represent knowledge as programs: as symbolic code
2. Learning=adding to that body of knowledge=
making new programs=program synthesis

Why program induction?

Why program induction?

strong generalization
+data efficiency

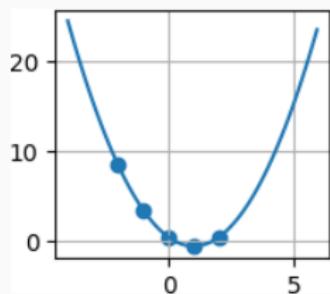


$$f(x) = (x-1)^{**2} - 0.5$$

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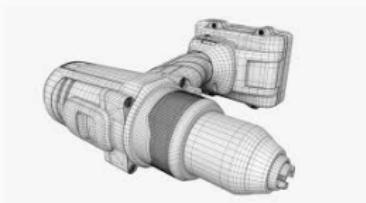
interpretability



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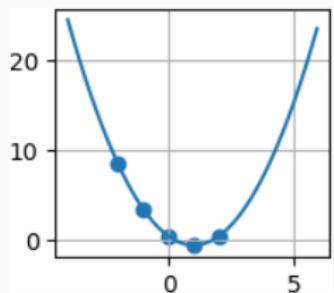


VS



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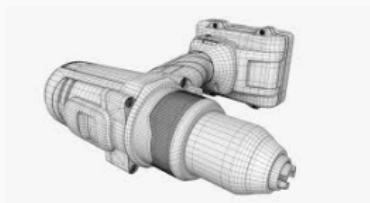


$$f(x) = (x-1)^{**2} - 0.5$$

interpretability



universal expressivity



Why didn't this old idea work?

Program induction goes back to the 1956 Dartmouth Workshop that founded the field of AI



A PROPOSAL FOR THE
DARTMOUTH SUMMER RESEARCH PROJECT
ON ARTIFICIAL INTELLIGENCE

J. McCarthy, Dartmouth College
M. L. Minsky, Harvard University
N. Rochester, I.B.M. Corporation
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main obstacle: combinatorial search is hard

Why try again?

better toolkits: neural+probabilistic+symbolic, and knowing how to combine them

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better compute+parallel algorithms

A lesson from the AI winter

We need an on-ramp of practical, tractable problems:

semantic parsing [Liang et al. 2011; Zettlemoyer et al. 2007]

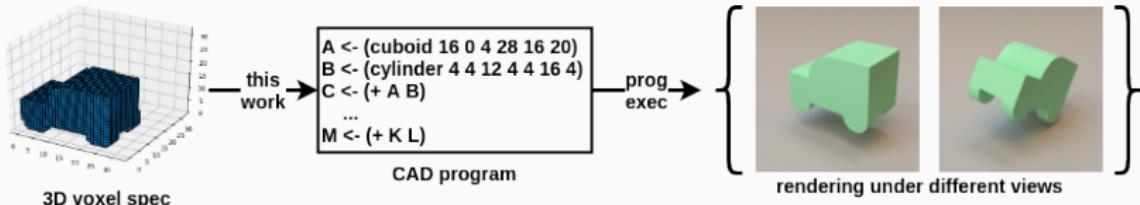
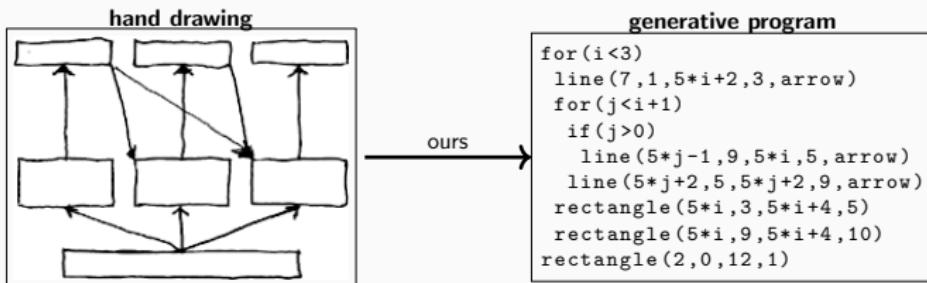
programming by examples [Gulwani 2011]

computer aided programming [Solar-Lezama 2008]

inverse procedural modeling [Kulkarni et al. 2015]

Perception, Synthesizing models, Learning-to-Learn

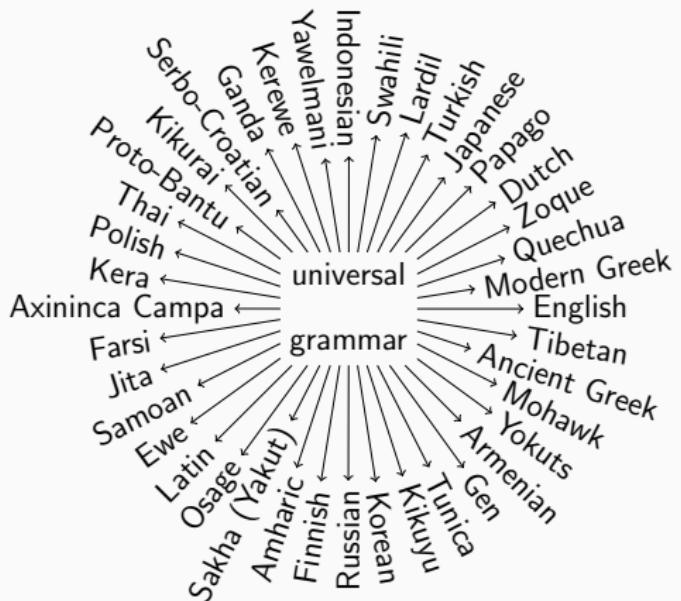
Theme #1: high-level visual understanding, pixels→programs



Perception, Synthesizing models, Learning-to-Learn

Theme #1: high-level visual understanding, pixels→programs

Theme #2: synthesizing human-understandable models



Perception, Synthesizing models, Learning-to-Learn

Theme #1: high-level visual understanding, pixels→programs

Theme #2: Synthesizing human-understandable models

Theme #3: learning to synthesize programs

List Processing

Sum List

$$[1 \ 2 \ 3] \rightarrow 6$$

$$[4 \ 6 \ 8 \ 1] \rightarrow 17$$

Double

$$[1 \ 2 \ 3] \rightarrow [2 \ 4 \ 6]$$

$$[4 \ 5 \ 1] \rightarrow [8 \ 10 \ 2]$$

Text Editing

Abbreviate

$$\text{Allen Newell} \rightarrow \text{A.N.}$$

$$\text{Herb Simon} \rightarrow \text{H.S.}$$

Drop Last Three

$$\text{shrdlu} \rightarrow \text{shr}$$

$$\text{shakey} \rightarrow \text{sha}$$

Regexes

Phone numbers

$$(555) \ 867-5309$$

$$(650) \ 555-2368$$

Currency

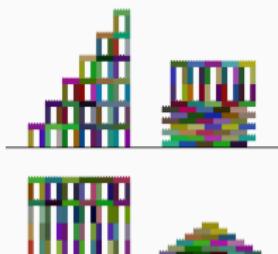
$$\$100.25$$

$$\$4.50$$

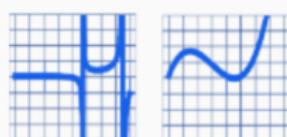
LOGO Graphics



Block Towers



Symbolic Regression



$$y = f(x)$$

Recursive Programming

Filter Red

$$[\blacksquare \ \textcolor{red}{\blacksquare} \ \blacksquare \ \blacksquare] \rightarrow [\blacksquare \ \blacksquare]$$

$$[\blacksquare \ \textcolor{red}{\blacksquare} \ \blacksquare \ \blacksquare] \rightarrow [\blacksquare \blacksquare \blacksquare \ \blacksquare]$$

$$[\blacksquare \ \blacksquare \ \textcolor{red}{\blacksquare} \ \blacksquare] \rightarrow [\blacksquare \blacksquare \blacksquare]$$

Physical Laws

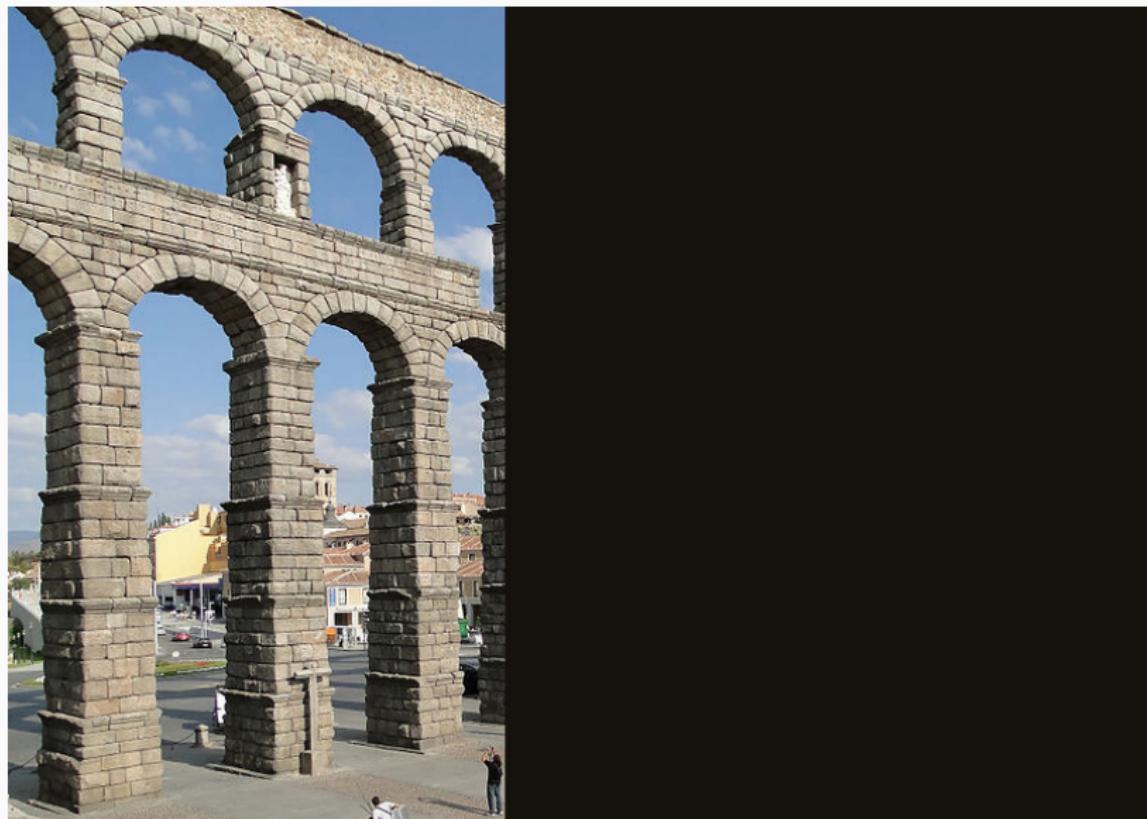
$$\vec{a} = \frac{1}{m} \sum_i \vec{F}_i$$

$$\vec{F} \propto \frac{q_1 q_2}{|\vec{r}|^2} \hat{r}$$

Program Induction and perception
model discovery
learning to learn

Vision is more than knowing what is where

Can you visually extrapolate this aqueduct?



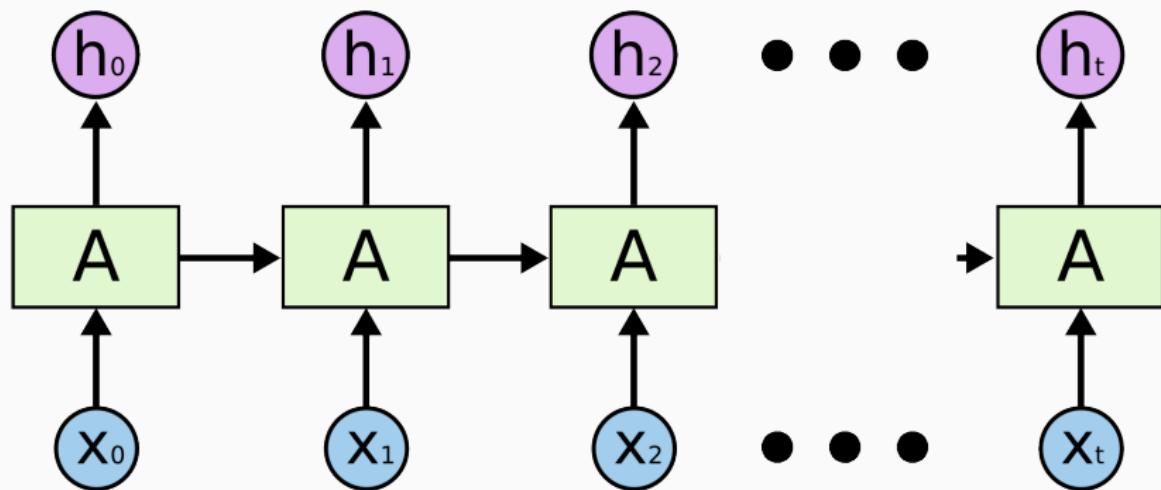
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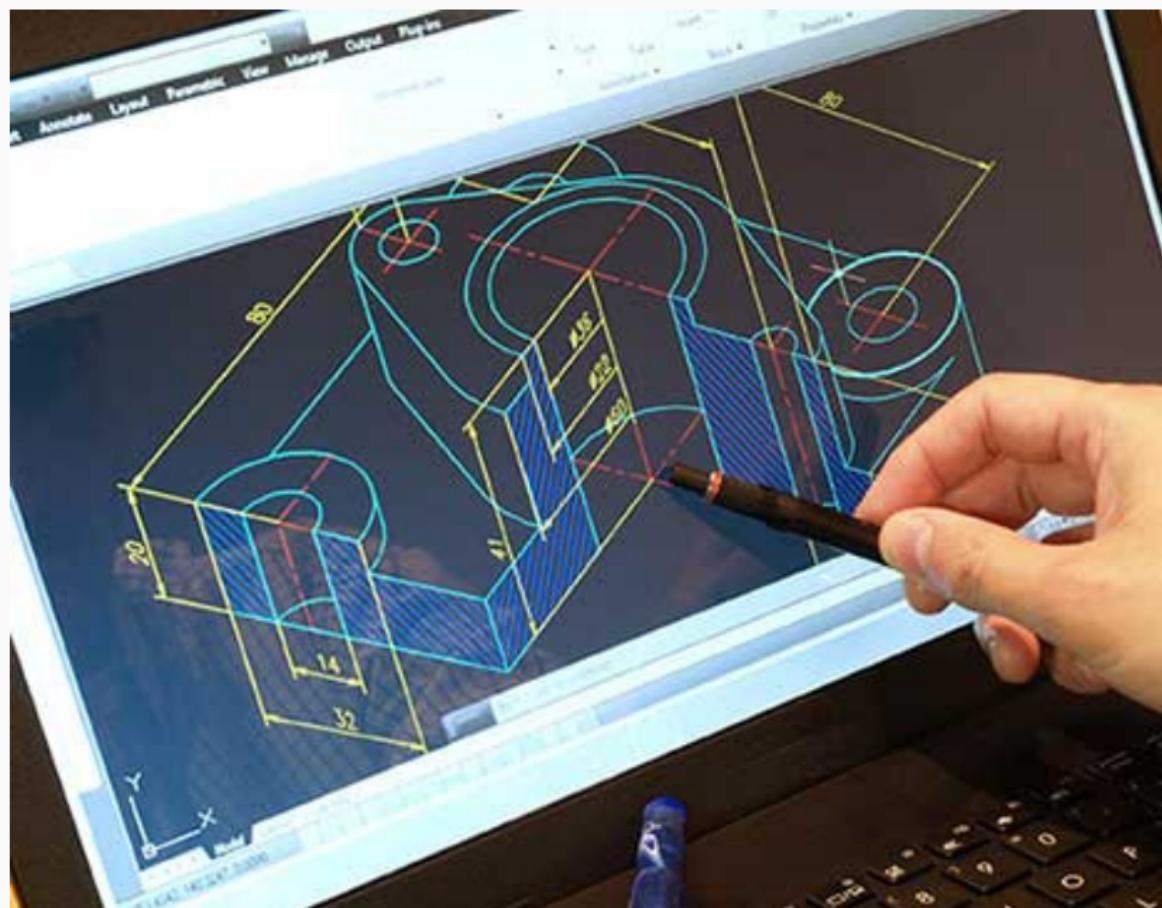


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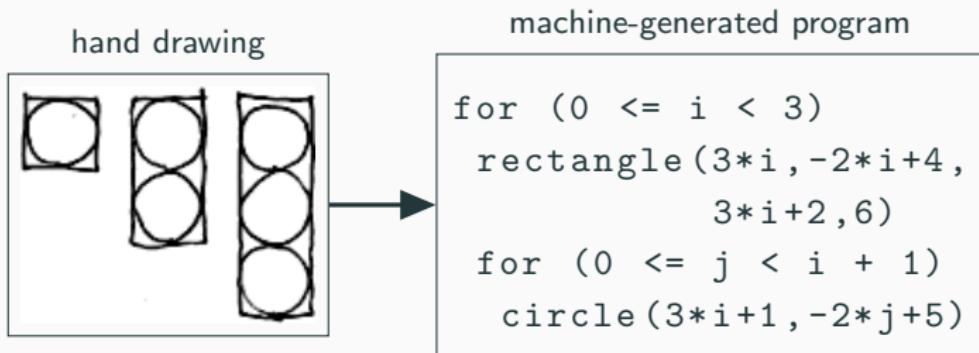
Can you infer what goes in the ellipses?



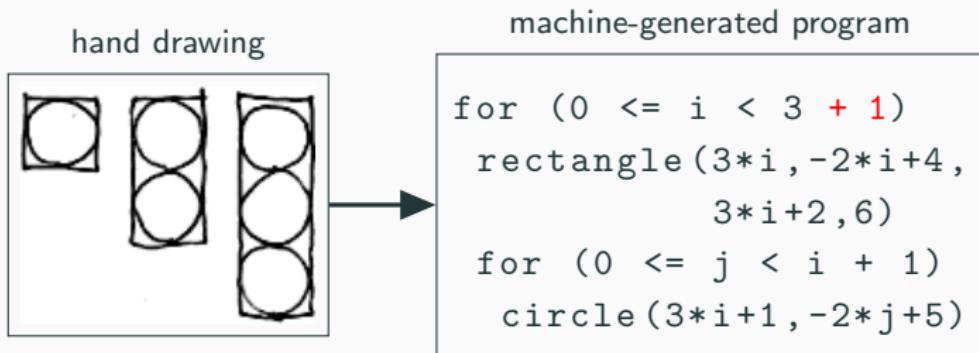
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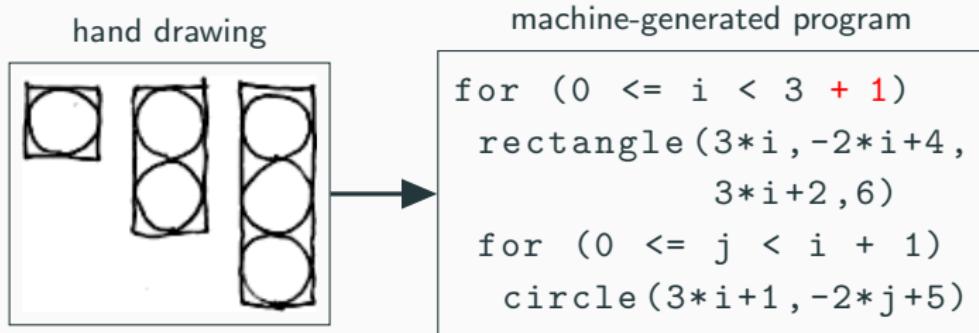
Learning to infer graphics programs from hand-drawn images



Learning to infer graphics programs from hand-drawn images

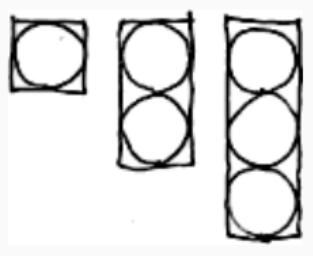


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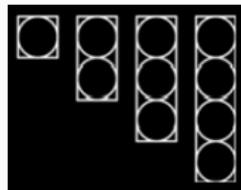
hand drawing



machine-generated program

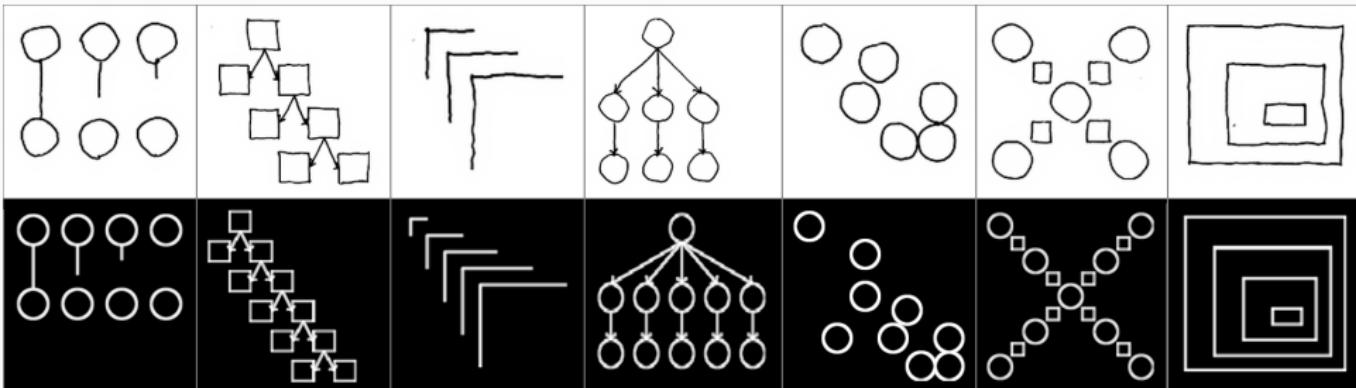
```
for (0 <= i < 3 + 1)
    rectangle(3*i, -2*i+4,
              3*i+2, 6)
    for (0 <= j < i + 1)
        circle(3*i+1, -2*j+5)
```

autogenerated extrapolation

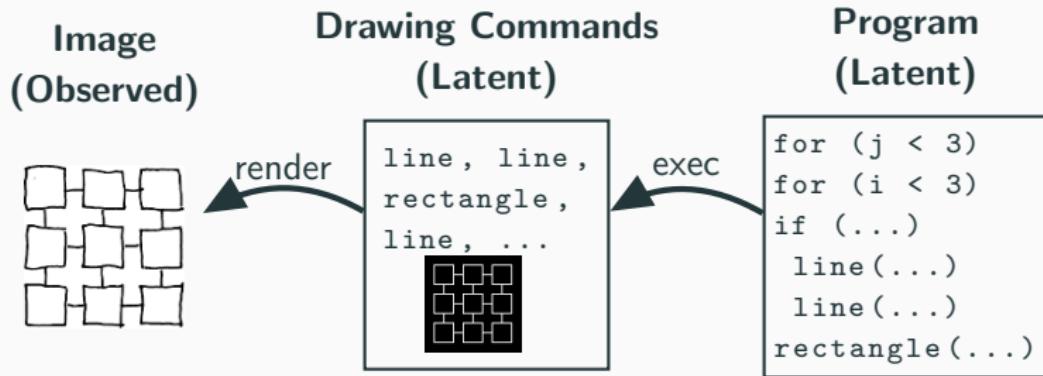


one-shot generalization / extrapolation

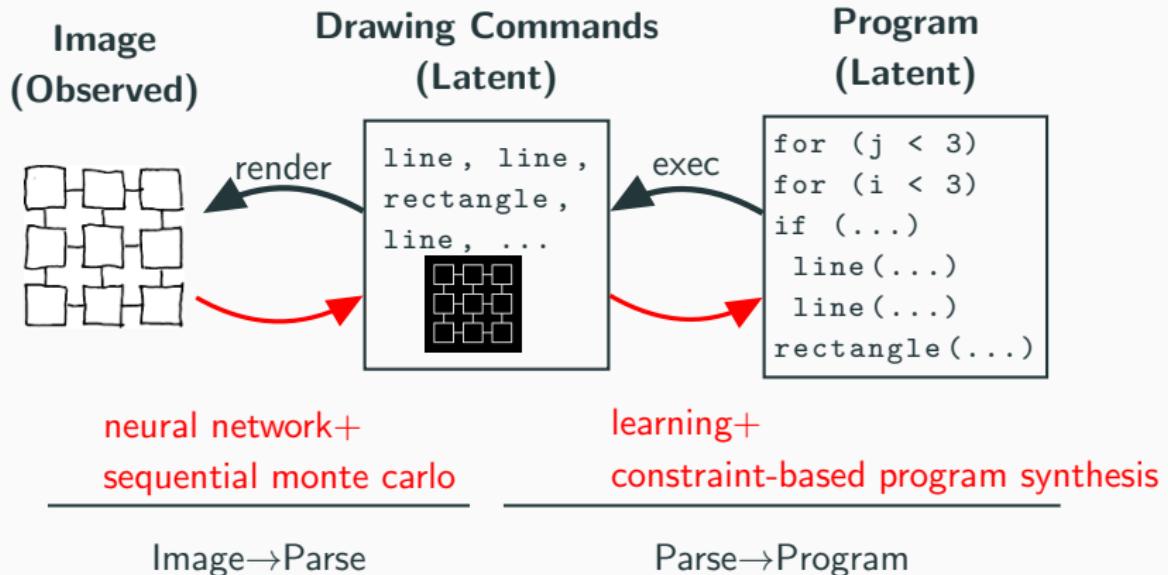
Extrapolation from a single image



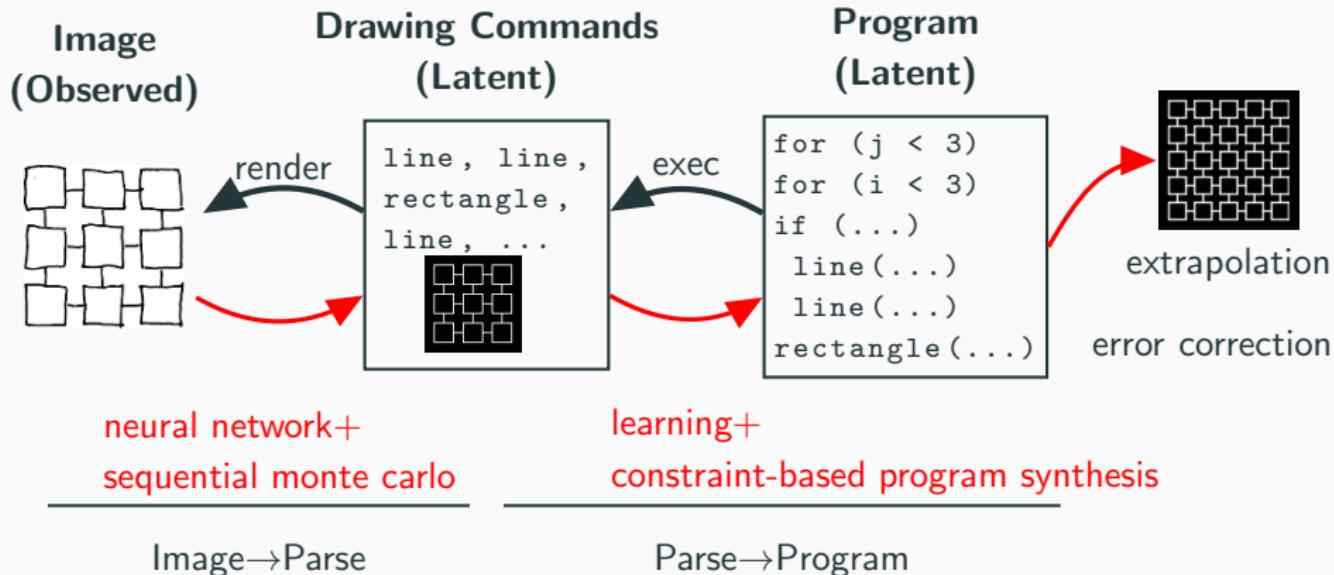
How to infer graphics programs from hand-drawn images



How to infer graphics programs from hand-drawn images

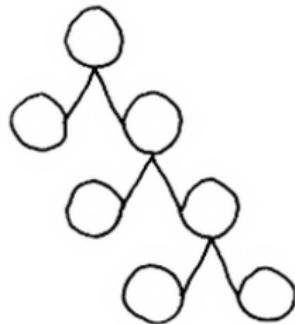


How to infer graphics programs from hand-drawn images



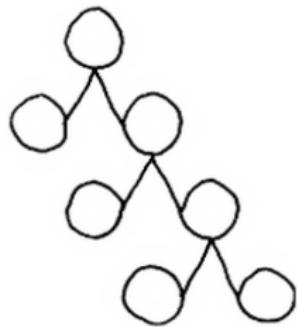
Top-down influences on perception

drawing

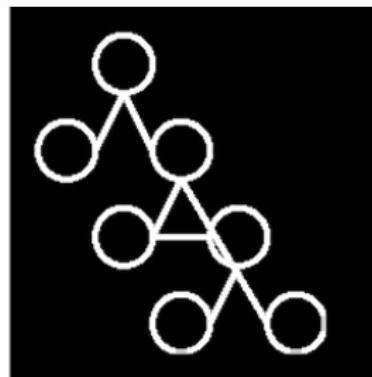


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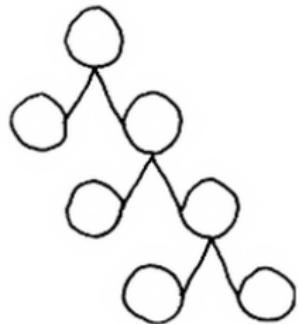


bottom-up neural net

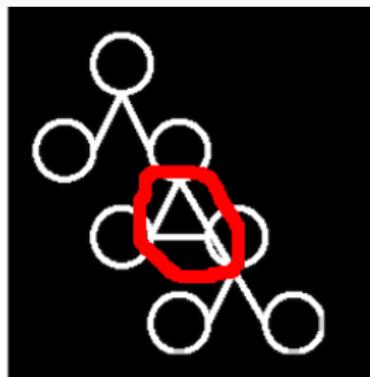


Top-down influences on perception

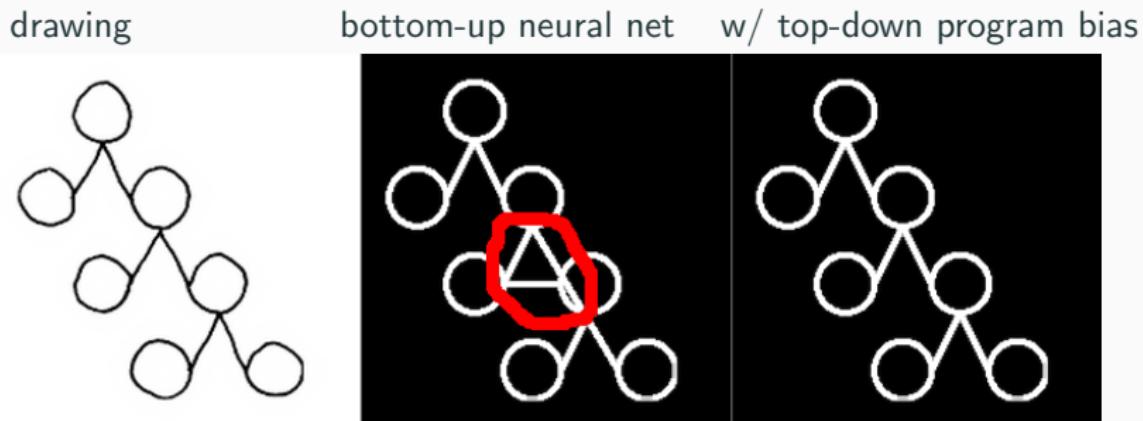
drawing



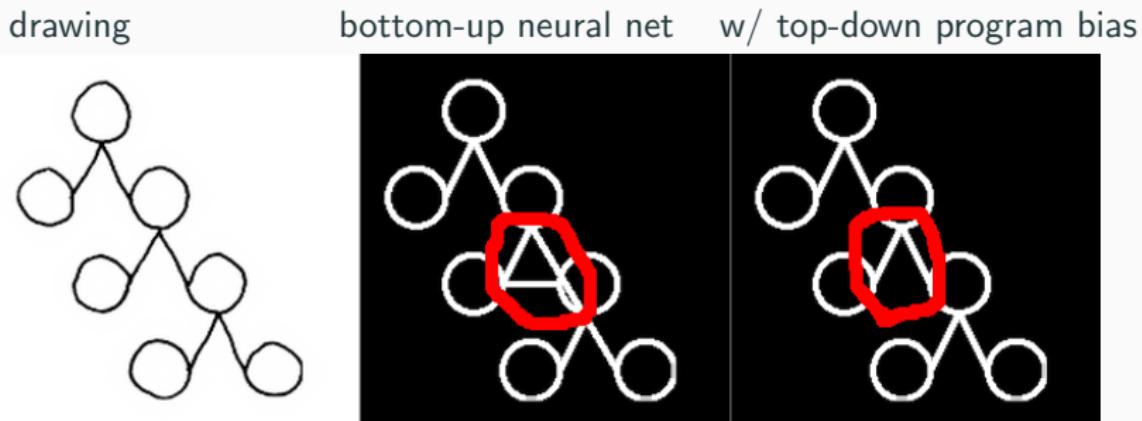
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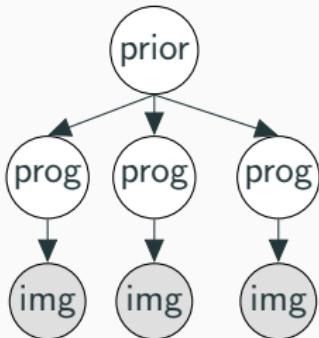
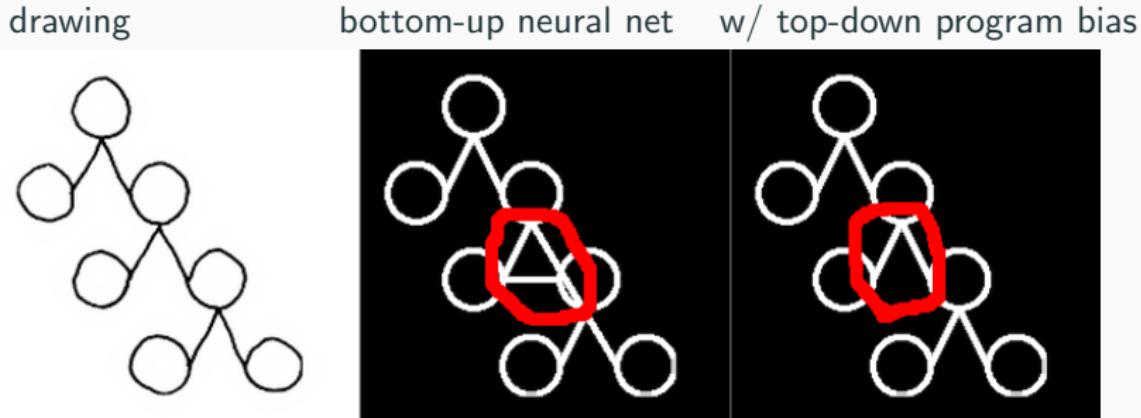
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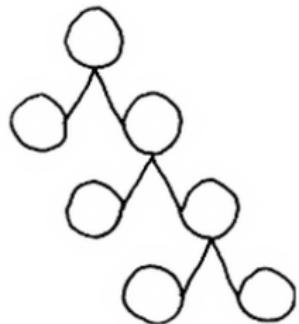
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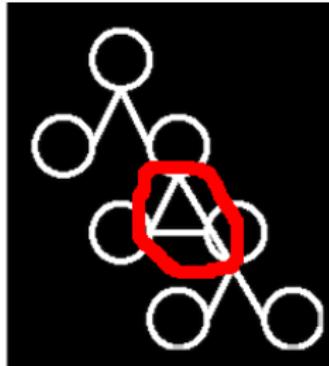
predicted program =
 $\arg \max_{\text{progs}} \mathbb{P} [\text{img} | \text{prog}] \mathbb{P} [\text{prog} | \text{prior}]$

Top-down influences on perception

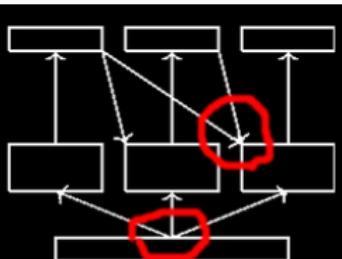
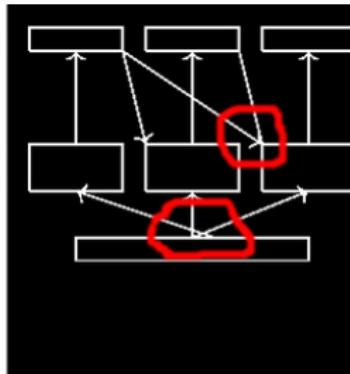
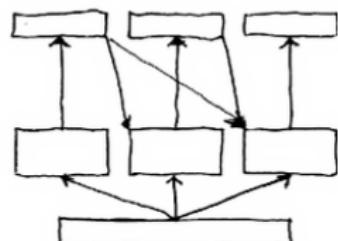
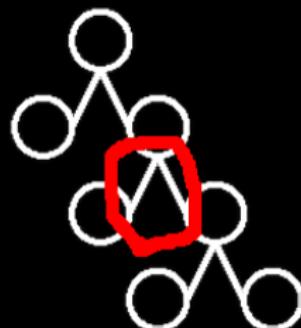
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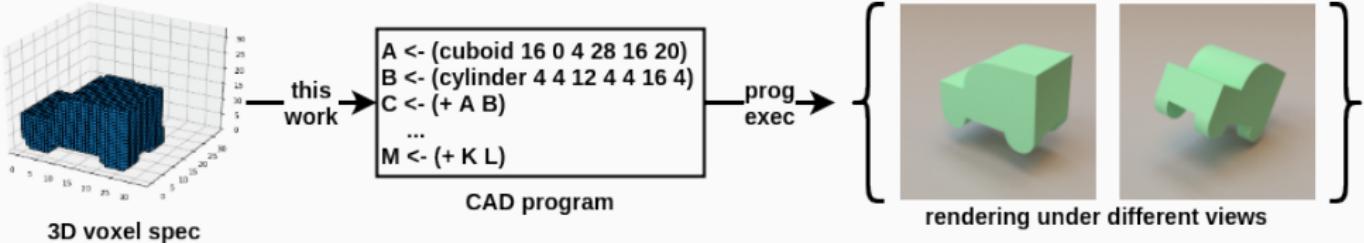
bottom-up neural net



w/ top-down program bias



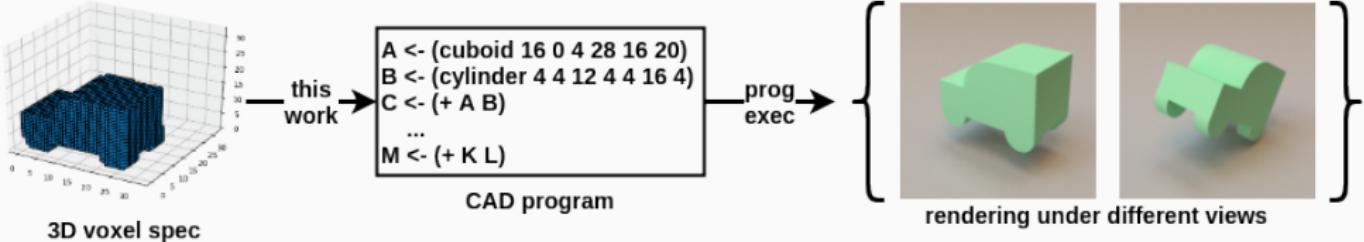
3D program induction



Ellis*, Nye*, Pu*, Sosa*, Tenenbaum, Solar-Lezama. NeurIPS 2019.

*equal contribution

3D program induction



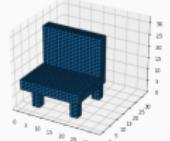
Challenge: combinatorial search!

Branching factor: > 1.3 million per line of code, ≈ 20 lines of code

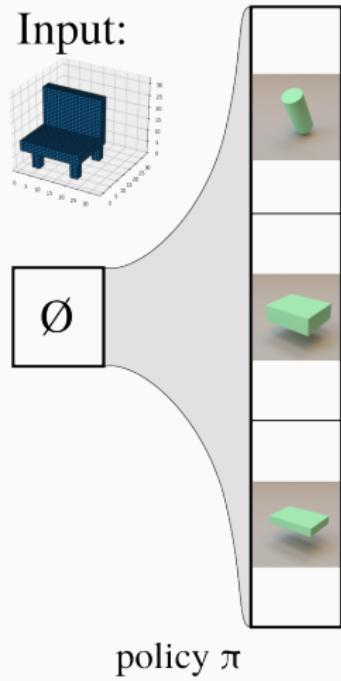
search space size: $(1.3 \text{ million})^{20} \approx 10^{122}$ programs

Solution: stochastic **tree search** + learn **policy** that writes code
+ learn **value** function that assesses execution of program so far;
analogous to **AlphaGo** [Silver et al. 2016]

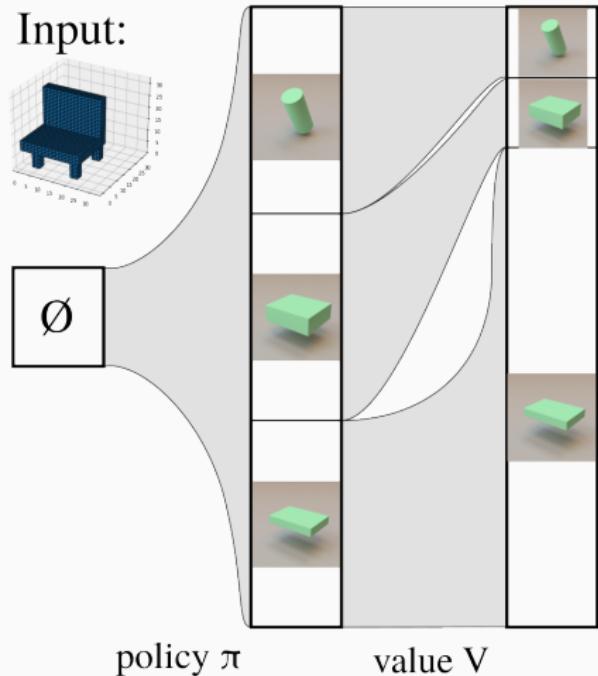
Input:



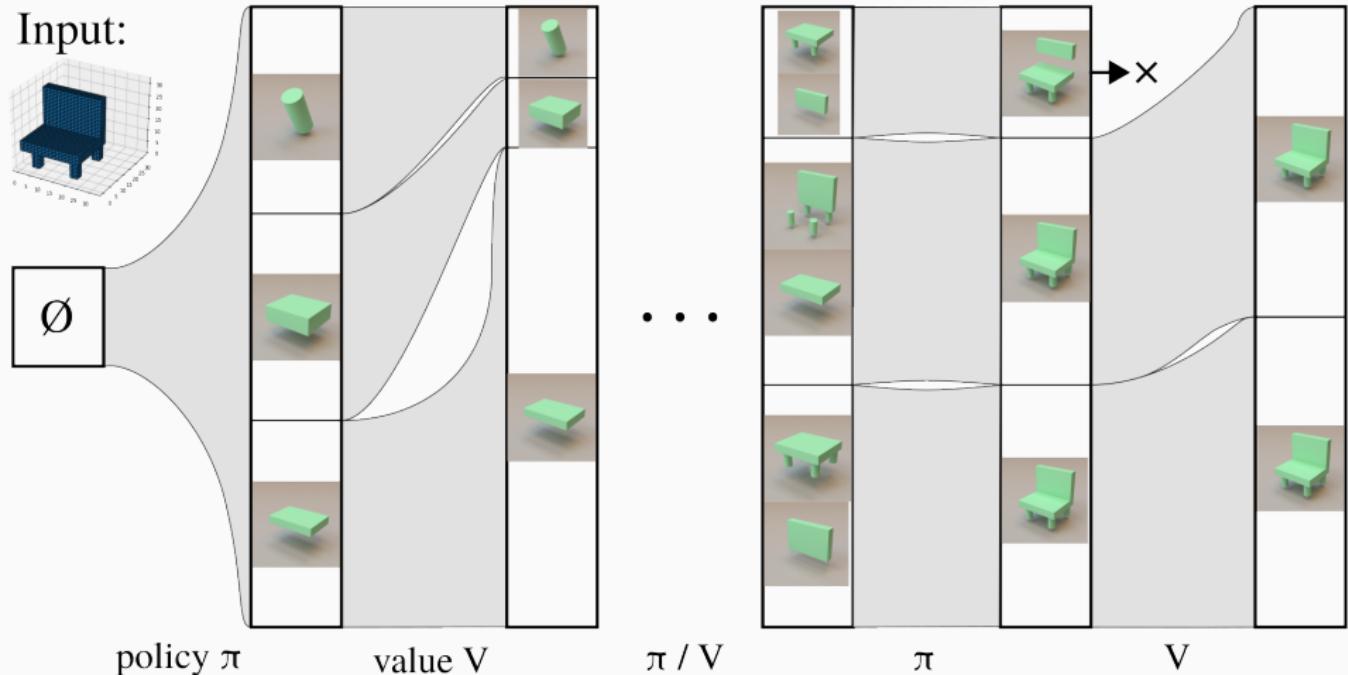
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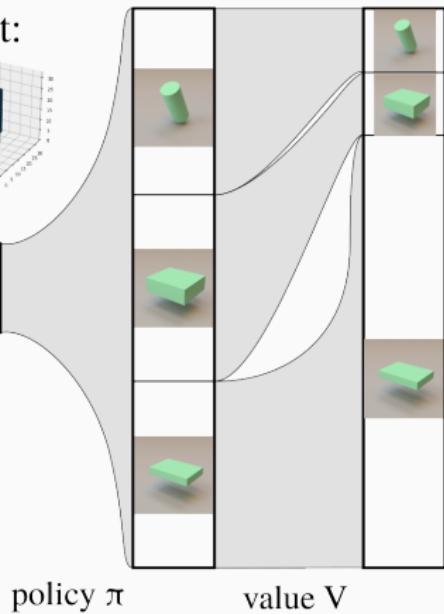
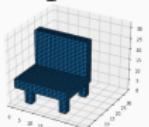
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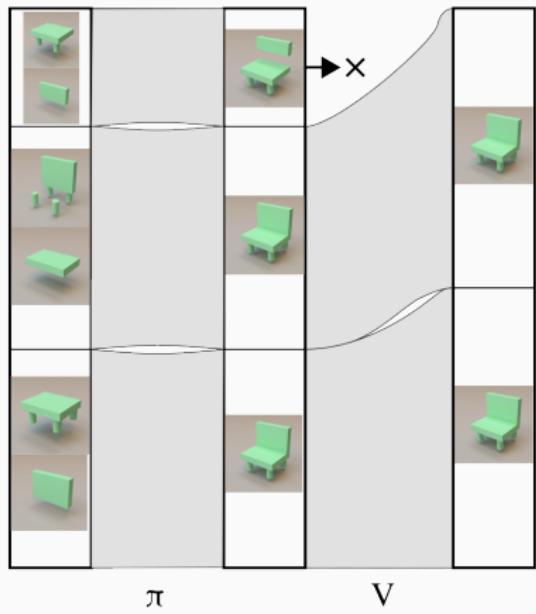
pp = partial program (state)

$\llbracket pp \rrbracket$ = render of pp

Input:



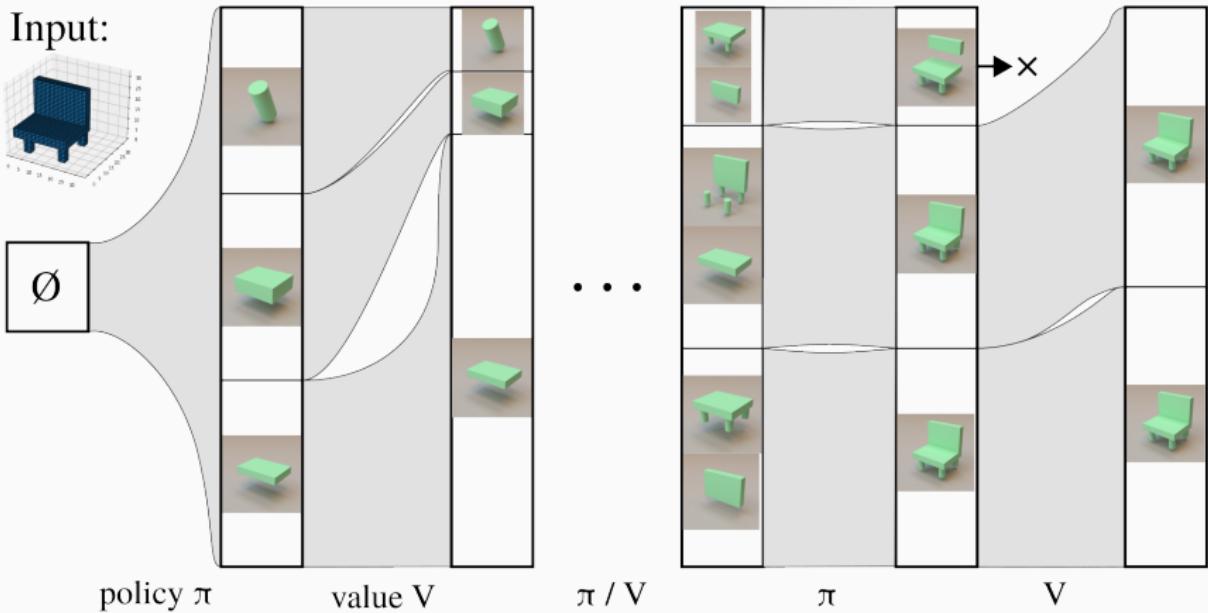
...



pp = partial program (state)

$\llbracket pp \rrbracket$ = render of pp

a = action (line of code). sample $\{a_t\}_{t=1}^T$, define $pp_t = a_{t-1}(pp_{t-1})$

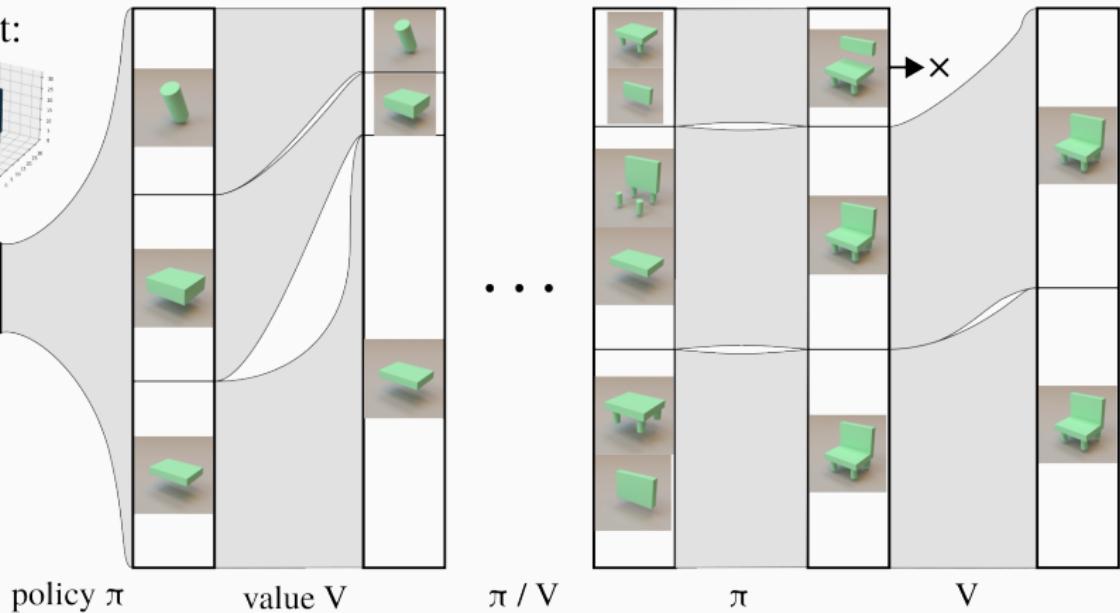
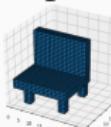


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$$\mathcal{L}^{\text{imitation}} = \sum_{t=1}^T \log \pi(a_t | pp_{t-1}, \llbracket pp_T \rrbracket)$$

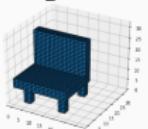
Input:



pp = partial program (state) $\llbracket pp \rrbracket$ = render of pp a = line of code (action)

$$V(\llbracket pp \rrbracket, goal) = \mathbb{E}_\pi [R \mid \llbracket pp \rrbracket, goal]$$

Input:



policy π

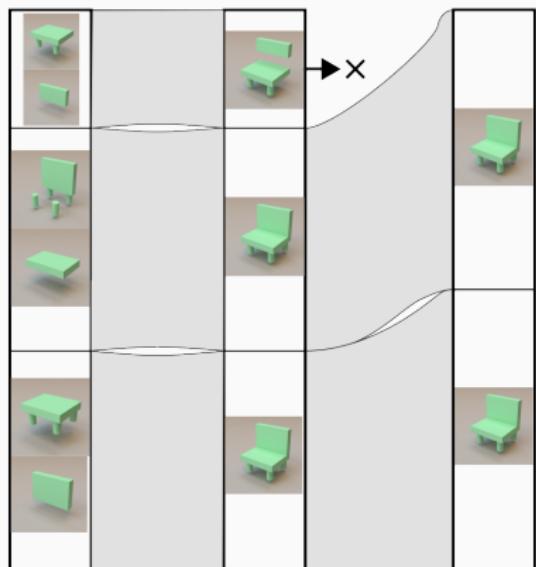
value V

π / V

π

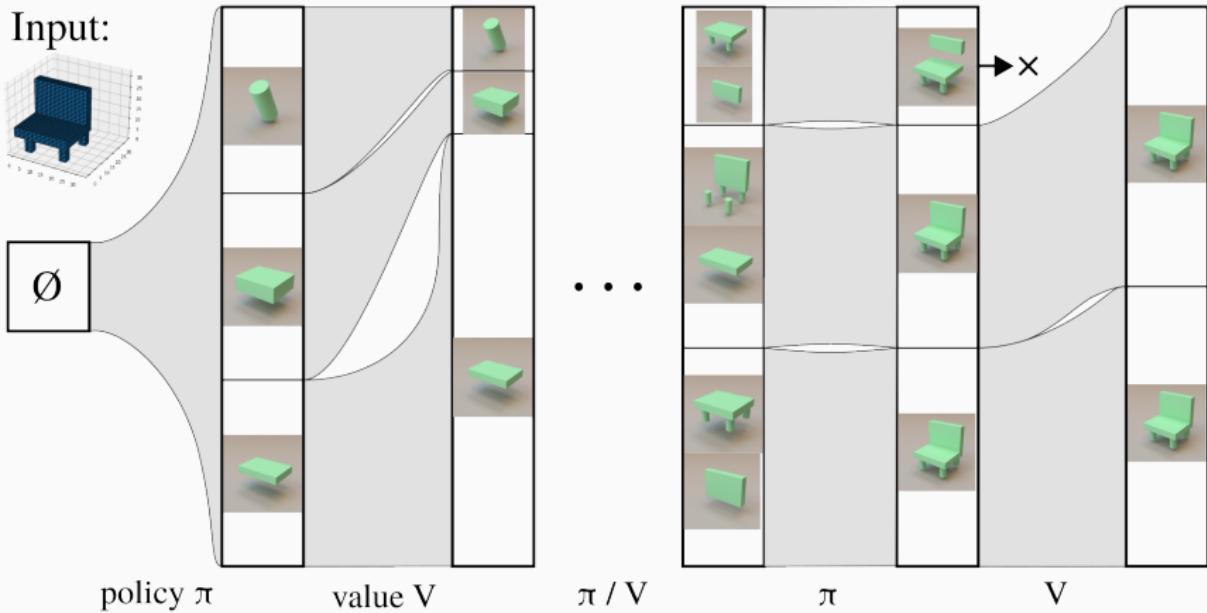
V

...



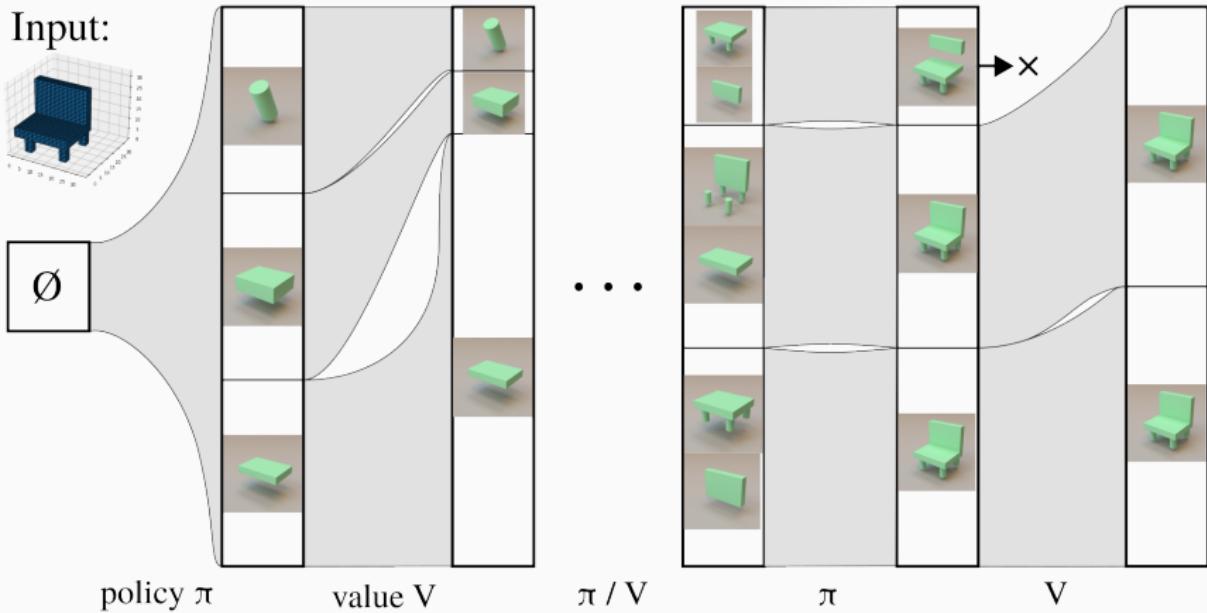
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$$= P(\text{rollout satisfies } goal \mid \llbracket pp \rrbracket, goal)$$

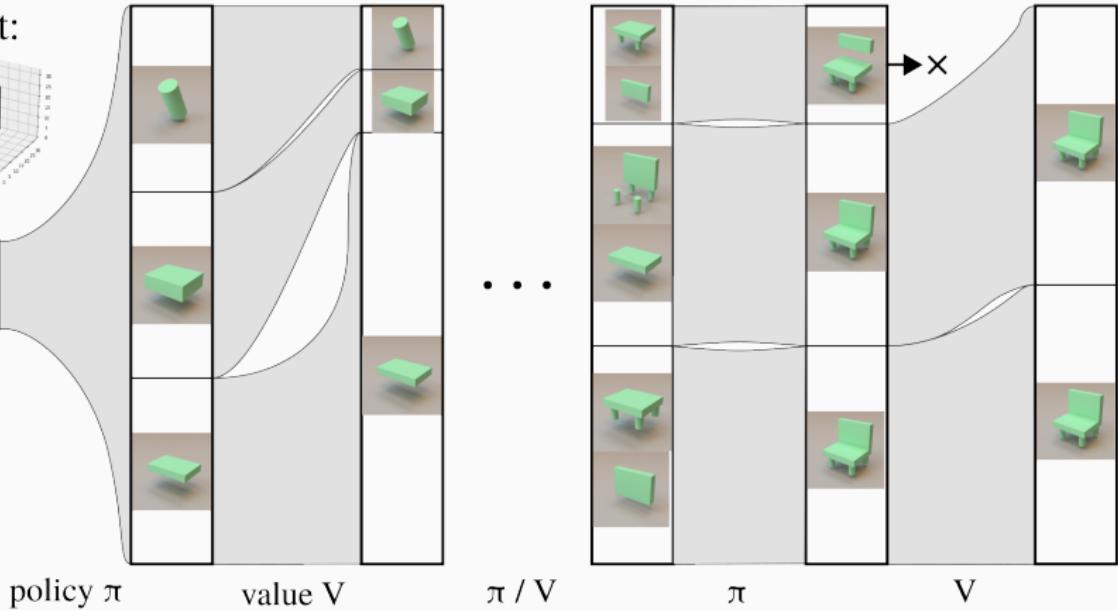
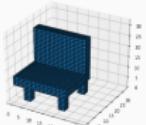


pp = partial program (state) $\llbracket pp \rrbracket$ = render of pp a = line of code (action)

$V(\llbracket pp \rrbracket, goal) = P(\text{rollout satisfies } goal \mid \llbracket pp \rrbracket, goal)$

$$\begin{aligned} \mathcal{L}^{\text{RL}} = & R \sum_{t \leq T} \log V(\llbracket pp_t \rrbracket, goal) + (1 - R) \sum_{t \leq T} \log(1 - V(\llbracket pp_t \rrbracket, goal)) \\ & + R \sum_{t \leq T} \log \pi(a_t | \llbracket pp_t \rrbracket, goal) \end{aligned}$$

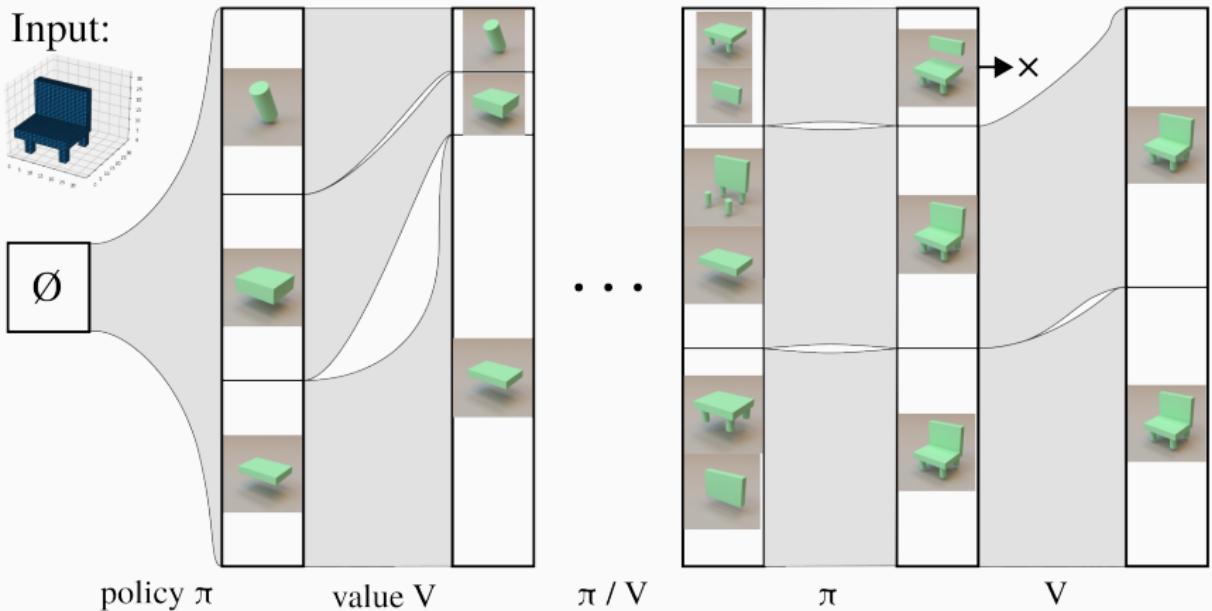
Input:



pp = partial program (state) $\llbracket pp \rrbracket$ = render of pp a = line of code (action)

Sequential Monte Carlo for search:

maintain population of particles (states)

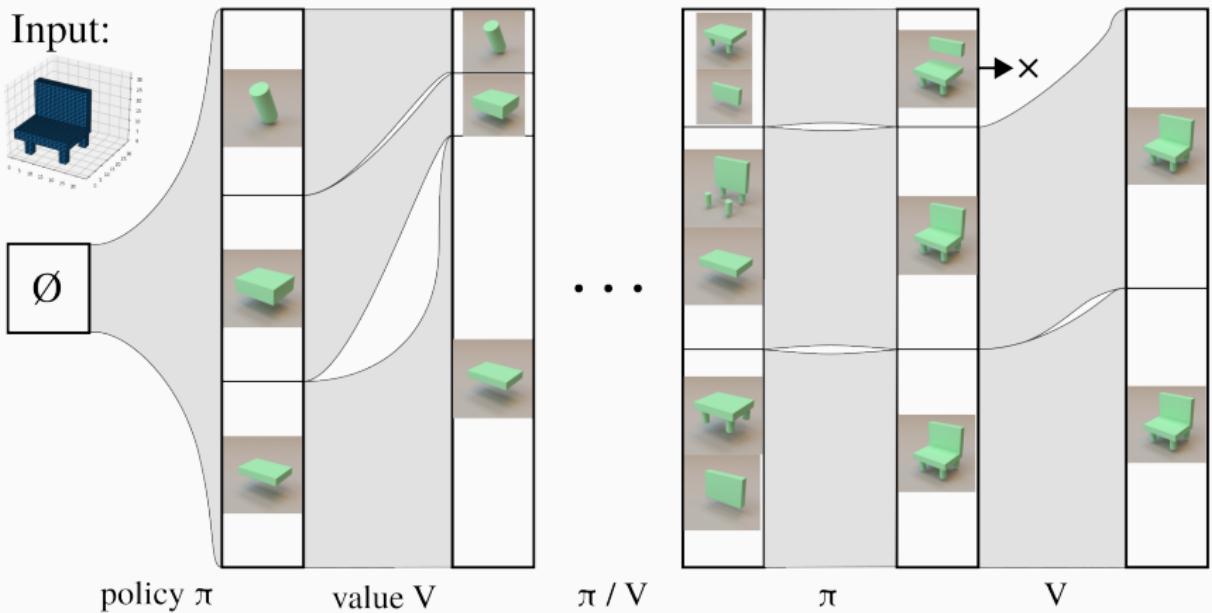


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Sequential Monte Carlo for search:

maintain population of particles (states)

1. sample from policy π to get new population



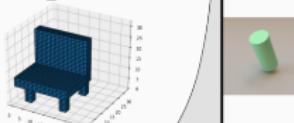
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Sequential Monte Carlo for search:

maintain population of particles (states)

1. sample from policy π to get new population
2. reweigh by value V , resample, goto 1

Input:



\emptyset

policy π

value V

π / V

π

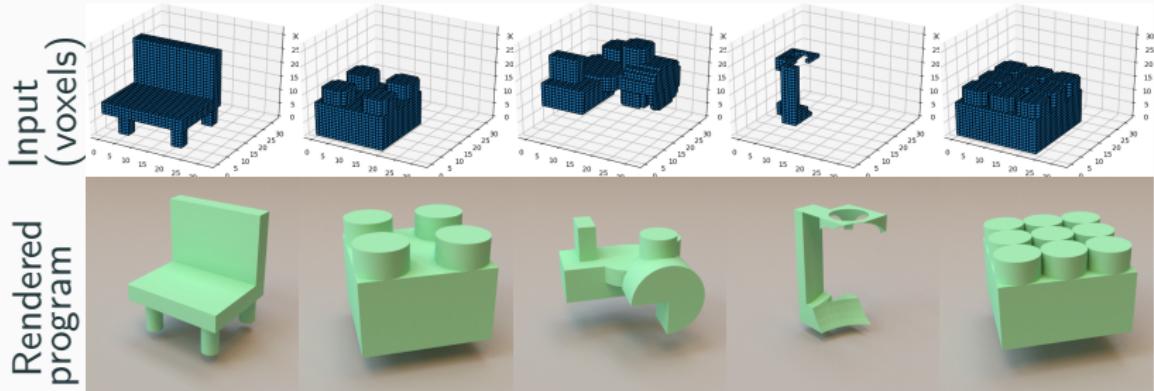
V

...

$\rightarrow x$



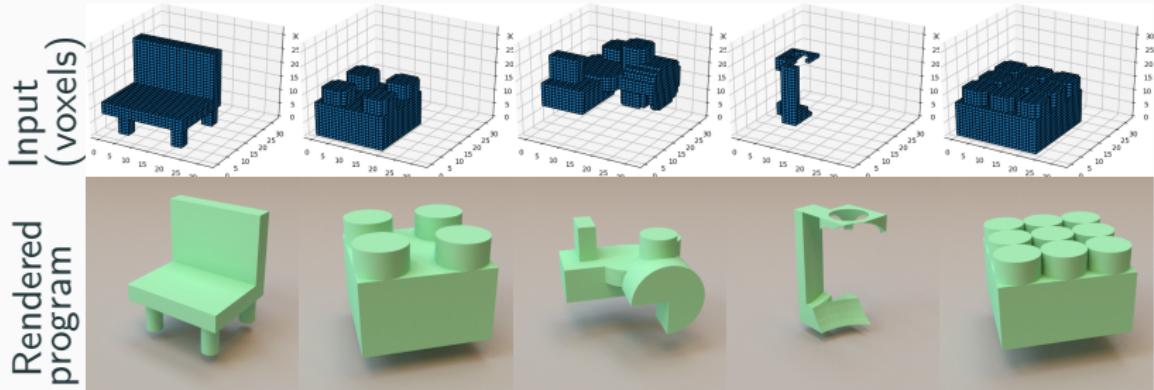
3D program induction



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3D program induction



same architecture learns to synthesize text editing programs (FlashFill, Gulwani 2012)

Ellis*, Nye*, Pu*, Sosa*, Tenenbaum, Solar-Lezama. NeurIPS 2019.

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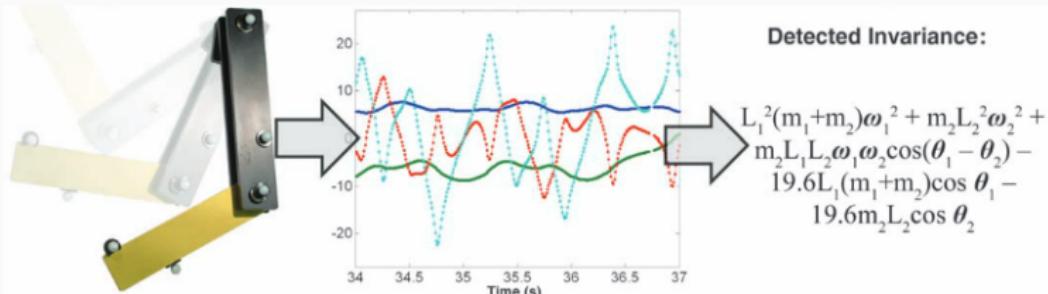
Lessons

The inductive bias from a programming language gives extrapolation, or strong generalization

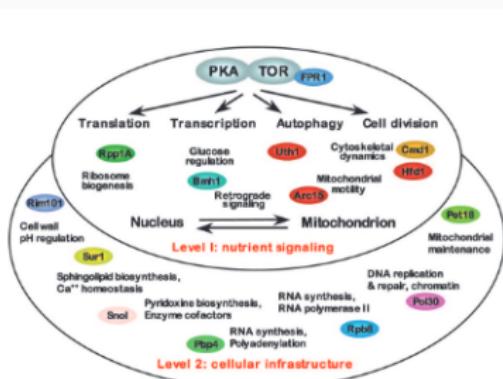
Combine the best of different techniques: neural nets for perception and pattern recognition, symbols for reasoning, Bayesian methods for uncertainty

Program Induction and perception
model discovery
learning to learn

Scientific discovery



Schmidt & Lipson: "Distilling Free-Form Natural Laws from Experimental Data"



Lezon et al. 2006
inferring genetic interaction networks

Discovering human-understandable models of language



Few-shot language learning experiment

Mandarin:

	adjective	adverb
“slow”	man	manmandə
“small”	xiao	xiaoxiaodə
“fast”	kuai	???

Few-shot language learning experiment

Mandarin:

	adjective	adverb
“slow”	man	manmandə
“small”	xiao	xiaoxiaodə
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Few-shot language learning experiment

Mandarin:

	adjective	adverb
“slow”	man	manmandə
“small”	xiao	xiaoxiaodə
“fast”	kuai	kuaikuaidə

stem+stem+də

Few-shot language learning experiment

Serbo-Croatian:

	masculine	feminine
“rich”	bogat	bogata
“mild”	blag	blaga
“green”	zelen	???

Few-shot language learning experiment

Serbo-Croatian:

	masculine	feminine
“rich”	bogat	bogata
“mild”	blag	blaga
“green”	zelen	zelena

Few-shot language learning experiment

Serbo-Croatian:

	mASCULINE	fEMININE
“rich”	bogat	bogata
“mild”	blag	blaga
“green”	zelen	zelena

add “a” to stem to make feminine

Few-shot language learning experiment

Serbo-Croatian:

	masculine	feminine
“rich”	bogat	bogata
“mild”	blag	blaga
“green”	zelen	zelena
“clear”	???	yasna

add “a” to stem to make feminine

Few-shot language learning experiment

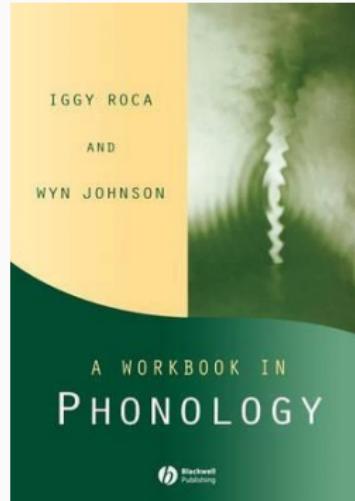
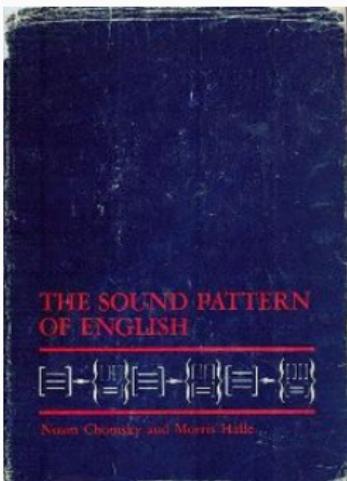
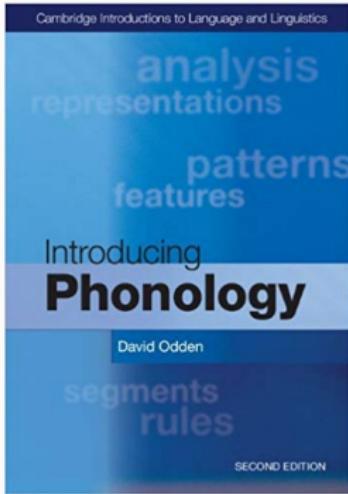
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“green”	zelen	zelena
“clear”	yasan	yasna

add “a” to stem to make feminine

insert “a” between two word-final consonants

$\emptyset \rightarrow a / C_C\#$



10 Sakha (Yakut)

Give a phonological analysis of the following case-marking paradigms of nouns in Sakha.

<i>Noun</i>	<i>Plural</i>	<i>Associative</i>	<i>ojuur</i>	<i>oyurdar</i>	<i>oyuurduun</i>	<i>'forest'</i>	
aýa	aýalar	aýaliin	'father'	üçügey	üçügeyde	'good person'	
paarta	paartalar	paartaliin	'school desk'	ejiy	ejiyde	'elder sister'	
tia	tialar	tialiin	'forest'	tomtor	tomtordor	'knob'	
kinige	kinigeler	kinigeliiñ	'book'	moyotoy	moyotoydor	'chipmunk'	
Jie	jieler	Jieliiñ	'house'	kötör	kötördör	'bird'	
iyé	iyeler	iyeliin	'mother'	bölköy	bölköydör	'islet'	
kini	kiniler	kiniliin	'3rd person'	χatiij	χatignar	'birch'	
bie	bieler	bieliin	'mare'	aan	aannar	'doo'	
oyo	oyolor	oyoluun	'child'	tiig	tiigner	'squirrel'	
χopto	χoptolor	χoptoluun	'gull'	sordoj	sordognor	'pike'	
börö	börölör	böröliün	'wolf'	olom	olomnor	'ford'	
tial	tiallar	tialliin	'wind'	oron	oronnor	'bed'	
ial	iallar	ialliin	'neighbor'	bödög	bödögör	'strong one'	
kuul	kuullar	kuulluuñ	'sack'	<i>Noun</i>	<i>Partitive</i>	<i>Comparative</i>	<i>Ablative</i>
at	attar	attiiñ	'horse'	aýa	ayataaýar	ayattan	'father'
balik	baliktar	balikiin	'fish'	paarta	paartata	paartattan	'school desk'
iskaap	iskaaptar	iskaaptiin	'cabinet'	tia	tiata	tiataaýar	'forest'
oyus	oyustar	oyustuuñ	'bull'	kinige	kinigete	kinigeteten	'book'
kus	kustar	kustuuñ	'duck'	Jie	jiete	jieteeýer	'house'
tünnük	tünnükter	tünnüktüün	'window'	iye	iyete	iyeteeýer	'mother'
sep	septer	septiin	'tool'	kini	kinite	kinitteeýer	'3rd person'
et	etter	ettiiñ	'meat'	bie	biete	bieteeýer	'mare'
örüs	örüster	örüstüün	'river'	oyo	oyoto	oyotooyor	'child'
tis	tiister	tiistiin	'tooth'	χopto	χoptoto	χoptottor	'gull'
soroχ	soroχtor	soroχtuun	'some person'	börö	börötö	böröttöñ	'wolf'
ox	oxtor	oxtuun	'arrow'	tial	tialla	tiallaaýar	'wind'
oloppos	oloppstor	oloppstuun	'chair'	ial	ialla	ialtan	'neighbor'
ötöχ	ötöxtör	ötöxtüün	'abandoned farm'	kuul	kuulla	kuullaaýar	'sack'
ubay	ubaydar	ubaydiin	'elder brother'	moχsoyol	moχsoyollo	moχsoyolton'	falcon'
asaray	saraydar	saraydiin	'bam'	at	atta	attan	'horse'
tiy	tiydar	tiydiin	'foal'	balik	balikta	baliktan	'fish'
atiir	atiirdar	atiirdiin	'stallion'	iskaap	iskaapta	iskaaptan	'cabinet'
				oyus	oyusta	oyustan	'bulf'
				kus	kusta	kustan	'duck'
				tünnük	tünnukte	tünnükten	'window'

Turkic Sakha (Yakut)

observed data

	SINGULAR	PLURAL
BED	oron	<u>oronnor</u>
MARE	bie	<u>bieler</u>
CABINET	is̥kaap	<u>is̥kaaptar</u>

138 total examples

Turkic Sakha (Yakut)

grammar (unobserved)

SINGULAR → stem
PLURAL → stem + lar

observed data



	SINGULAR	PLURAL
BED	oron	oronnor
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CABINET	is̥kaap	is̥kaaptar

138 total examples

Turkic Sakha (Yakut)

constraint-based
synthesis
[Solar-Lezama 2008]
test-driven synthesis
[Perelman et al. 2016]

grammar (unobserved)

SINGULAR → stem
PLURAL → stem + lar

$r_1: l \rightarrow d / [-\text{lateral} \ -\text{tense}]$
"l" becomes "d" next to "r", "t", but not "l"

$r_2: C \rightarrow [-\text{voice}] / [-\text{voice}]$
do not voice next to voiceless

$r_3: V \rightarrow [+\text{rounded}] / [+\text{rounded}] [-\text{low}]_0$

$r_4: [+\text{continuant} \ -\text{high}] \rightarrow [-\text{rounded}] / u \ C_0$
"harmonize" round vowels like "u", "o"

$r_5: V \rightarrow [-\text{back} \ -\text{low}] / [-\text{back} \ +\text{vowel}] []_0$
"harmonize" vowels to be not at back of mouth

$r_6: [-\text{sonorant} \ +\text{voice}] \rightarrow [+\text{nasal}] / [+\text{nasal}]$
"nasalize" consonant next to a nasal, like "m"

observed data



	SINGULAR	PLURAL
BED	oron	oronnor
MARE	bie	bieler
CABINET	iškaap	iškaaptar

138 total examples

Turkic Sakha (Yakut)

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[Solar-Lezama 2008]

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stems (unobserved)

BED : oron
MARE : bie
CABINET : ıskAAP

	SINGULAR	PLURAL
BED	oron	oronnor
MARE	bie	bieler
CABINET	ıskAAP	ıskAAPtar

138 total examples

Turkic Sakha (Yakut)

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stems
(unobserved)

observed data

BED : oron

BEDS

Turkic Sakha (Yakut)

grammar (unobserved)

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stems
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BED : oron

BEDS → oron+lar → oronlar

Turkic Sakha (Yakut)

grammar (unobserved)

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stems
(unobserved)

observed data

BED : oron

BEDS → oron+lar → oronlar → orondar

Turkic Sakha (Yakut)

grammar (unobserved)

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$r_4: [+ \text{continuant } -\text{high}] \rightarrow [- \text{rounded}] / u C_0$
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stems
(unobserved)

observed data

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BEDS → oron+lar → oronlar → orondar → orondor

Turkic Sakha (Yakut)

grammar (unobserved)

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stems
(unobserved)

observed data

BED : oron

BEDS → oron+lar → oronlar → orondar → orondor → oronnor

Turkic Sakha (Yakut)

grammar (unobserved)

SINGULAR→stem
PLURAL→stem+lar

$r_1: l \rightarrow d / [\text{-lateral} \ \text{-tense}]_l$
“l” becomes “d” next to “r”, “t”, but not “l”

$r_2: C \rightarrow [\text{-voice}] / [\text{-voice}]_C$
do not voice next to voiceless

$r_3: V \rightarrow [\text{+rounded}] / [\text{+rounded}]_V$

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$r_5: V \rightarrow [\text{-back} \ \text{-low}] / [\text{-back} \ \text{+vowel}]_V$
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$r_6: [\text{-sonorant} \ \text{+voice}] \rightarrow [\text{+nasal}] / [\text{+nasal}]_C$
“nasalize” consonant next to a nasal, like “m”

stems
(unobserved)

BED : oron

MARE : bie

CABINET : ıskap

RIVER : örus

observed data

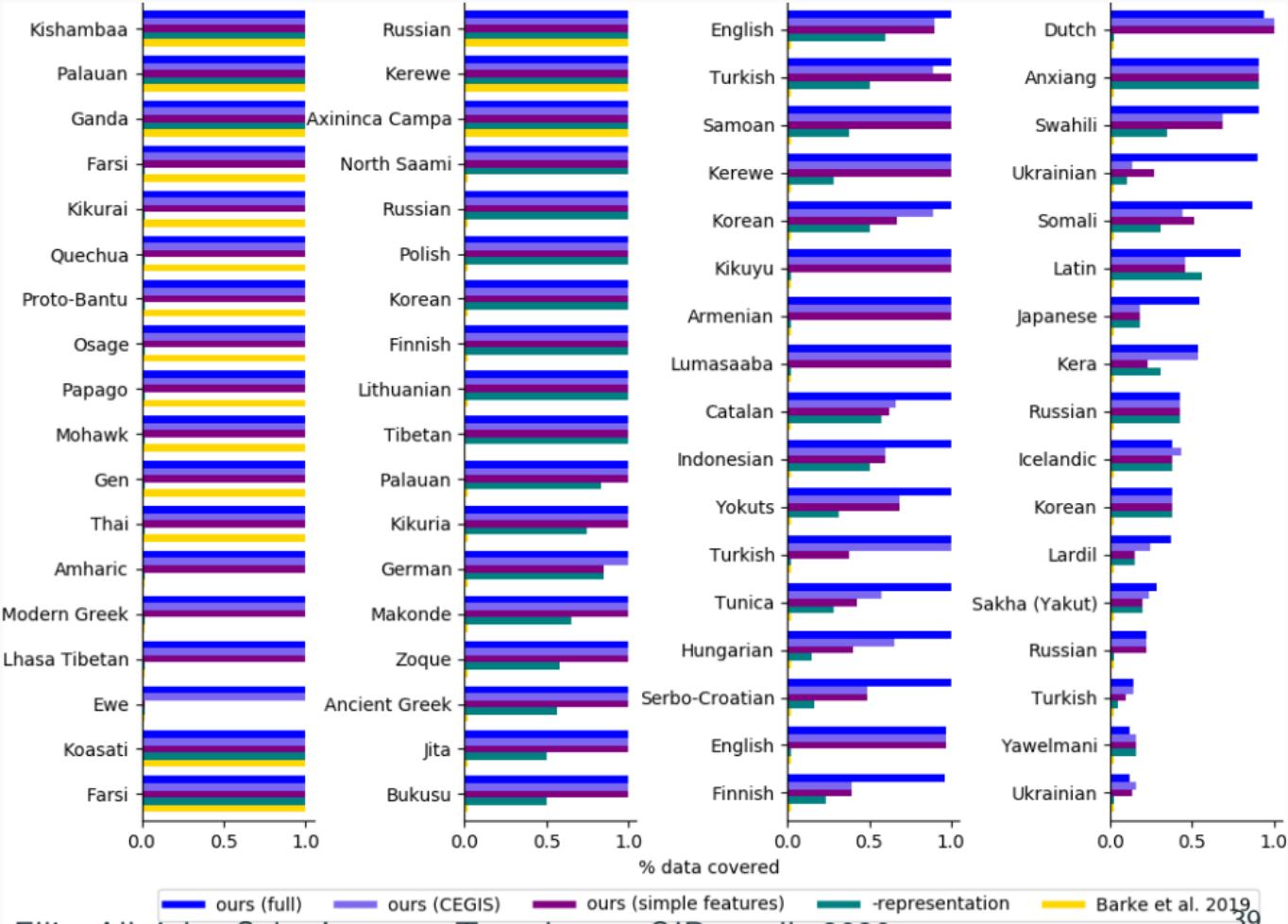
BEDS → oron+lar → oronlar $\xrightarrow{r_1}$ orondar $\xrightarrow{r_3}$ orondor $\xrightarrow{r_6}$ oronnor

MARES → bie+lar → bielar $\xrightarrow{r_5}$ bieler

CABINETS → ıskap+lar → ıskaplar $\xrightarrow{r_1}$ ıskapdar $\xrightarrow{r_2}$ ıskaptar

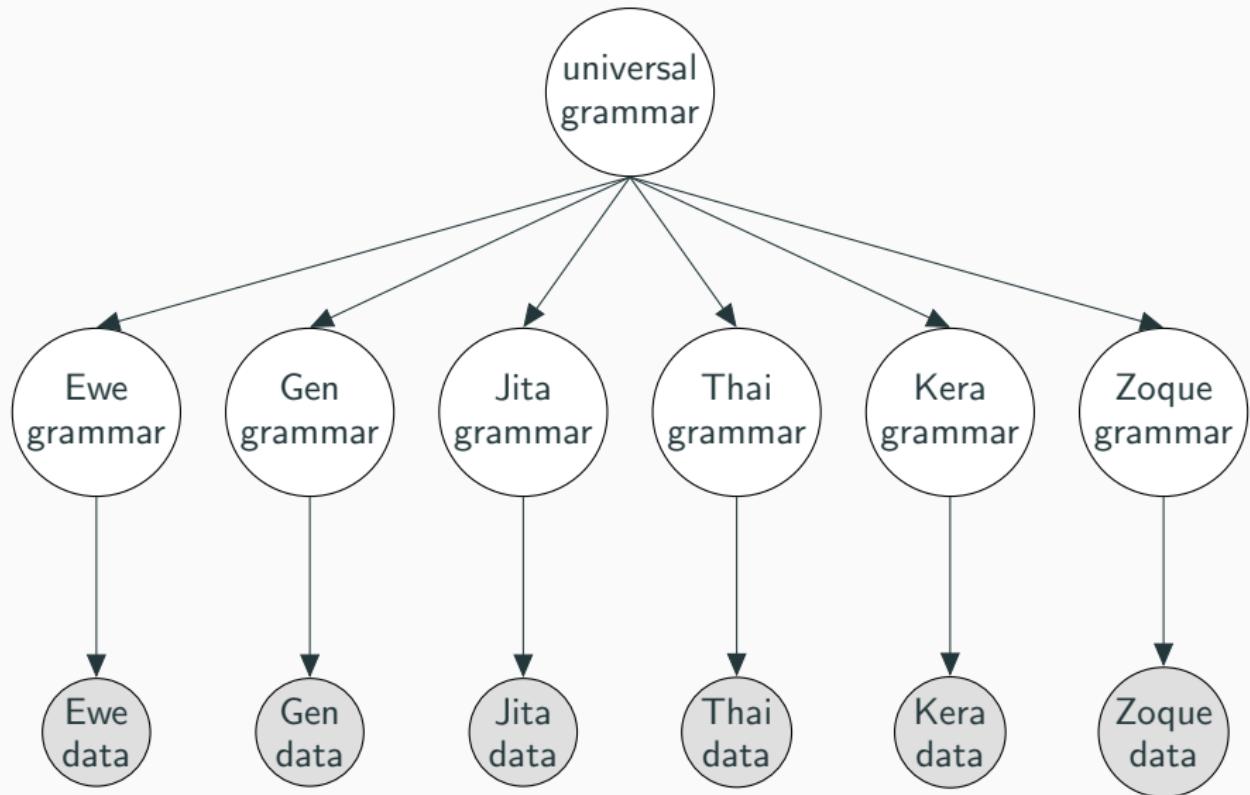
RIVER (ASSOC) → örus+lİN → öruslüN $\xrightarrow{r_1}$ örusdüN $\xrightarrow{r_2}$
 $\xrightarrow{r_3}$ örustüN $\xrightarrow{r_5}$ örüstüün

Kishambaa	Russian	English	Dutch
Palauan	Kerewe	Turkish	Anxiang
Ganda	Axininca Campa	Samoan	Swahili
Farsi	North Saami	Kerewe	Ukrainian
Kikurai	Russian	Korean	Somali
Quechua	Polish	Kikuyu	Latin
Proto-Bantu	Korean	Armenian	Japanese
Osage	Finnish	Lumasaaba	Kera
Papago	Lithuanian	Catalan	Russian
Mohawk	Tibetan	Indonesian	Icelandic
Gen	Palauan	Yokuts	Korean
Thai	Kikuria	Turkish	Lardil
Amharic	German	Tunica	kha (Yakut)
Modern Greek	Makonde	Hungarian	Russian
Lhasa Tibetan	Zoque	Serbo-Croatian	Turkish
Ewe	Ancient Greek	English	Yawelmani
Koasati	Jita	Finnish	Ukrainian
Farsi	Bukusu		



Legend: ours (full) (blue), ours (CEGIS) (purple), ours (simple features) (dark purple), -representation (teal), Barke et al. 2019 (yellow)

Distilling higher-level knowledge



Lessons

Higher-level knowledge matters (“universal grammar”). Get the basics of the representation correct

But *some* of this higher-level knowledge can be learned. You don't need millions of examples to learn it. But it's not a one-shot learning problem either

Program Induction and perception
model discovery
learning to learn

Learning to write code

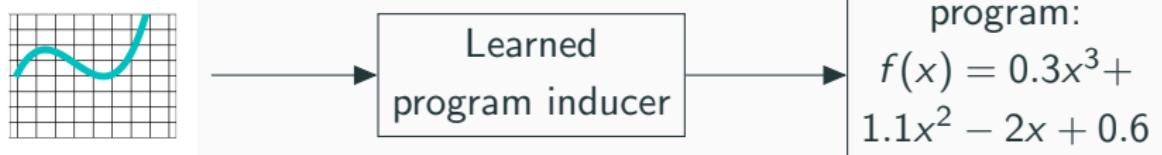
Goal: acquire domain-specific knowledge needed to induce a class of programs

- Library of concepts (declarative knowledge; domain specific language)
- Inference strategy (procedural knowledge; synthesis algorithm)

Learning to write code

Goal: acquire domain-specific knowledge needed to induce a class of programs

- Library of concepts (declarative knowledge; domain specific language)
- Inference strategy (procedural knowledge; synthesis algorithm)



Concepts: x^3 , $\alpha x + \beta$, etc

Inference strategy: neurosymbolic search for programs

Library learning

Initial Primitives

: 

map

fold 

if

cons

>

: 

Sample Problem: sort list

[9 2 7 1] → [1 2 7 9]

[3 8 9 4 2] → [2 3 4 8 9]

[6 2 2 3 8 5] → [2 2 3 5 6 8]

...

Library learning

Initial Primitives

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⋮

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⋮

⋮

Sample Problem: sort list

[9 2 7 1] → [1 2 7 9]

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⋮

Library learning

Initial Primitives

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Sample Problem: sort list

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```

```
[3 8 9 4 2] → [2 3 4 8 9]
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```
[6 2 2 3 8 5] → [2 2 3 5 6 8]
```

```
...
```

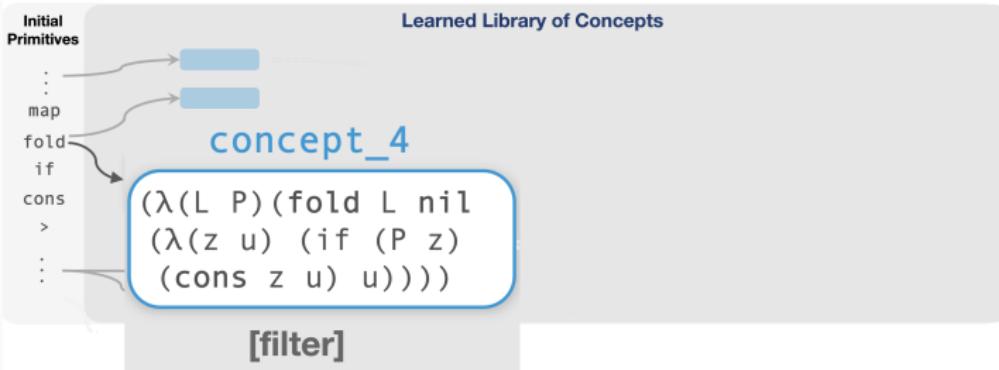
Library learning



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$[9\ 2\ 7\ 1] \rightarrow [1\ 2\ 7\ 9]$
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...

Library learning



Sample Problem: sort list

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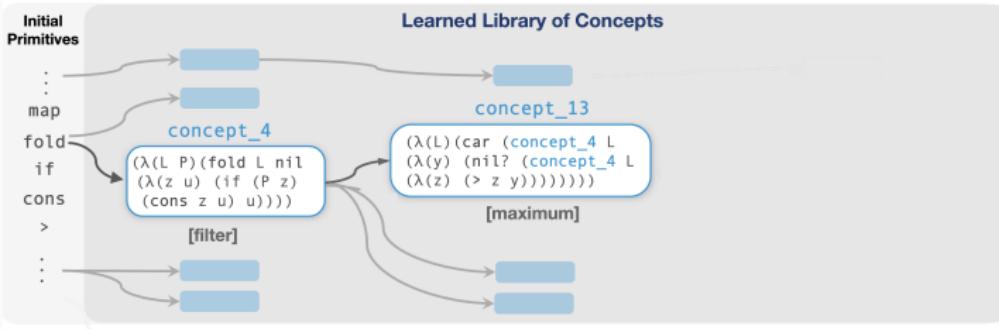
Library learning



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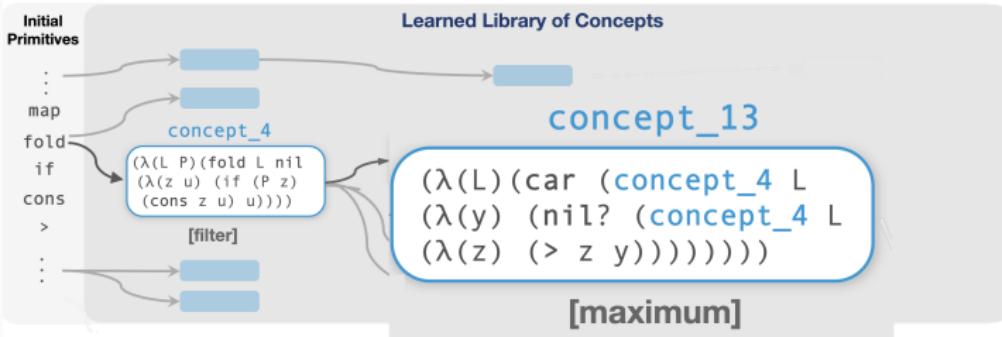
Library learning



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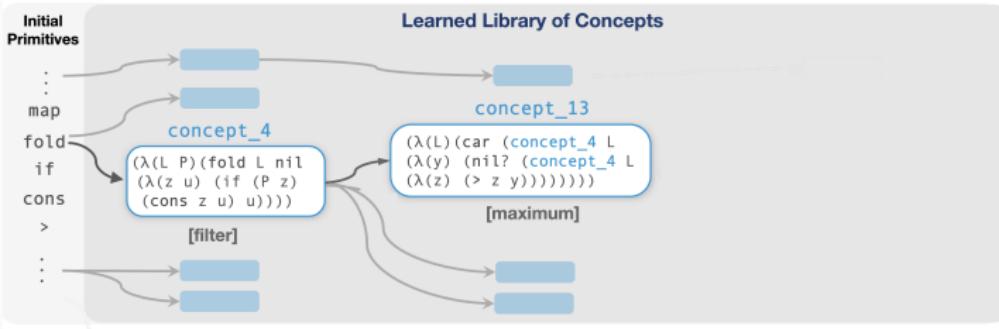
Library learning



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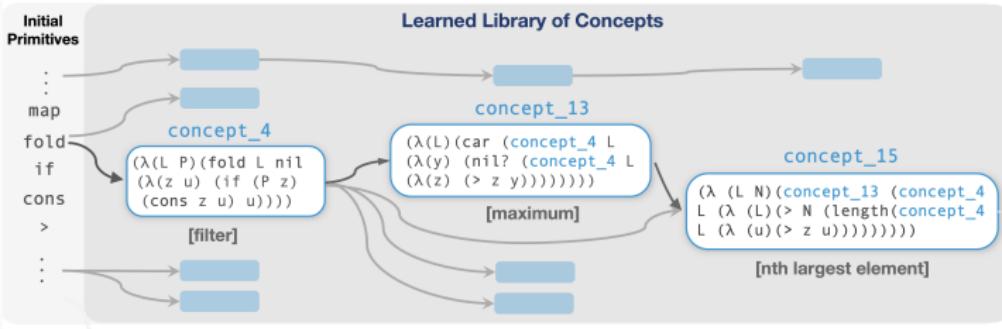
Library learning



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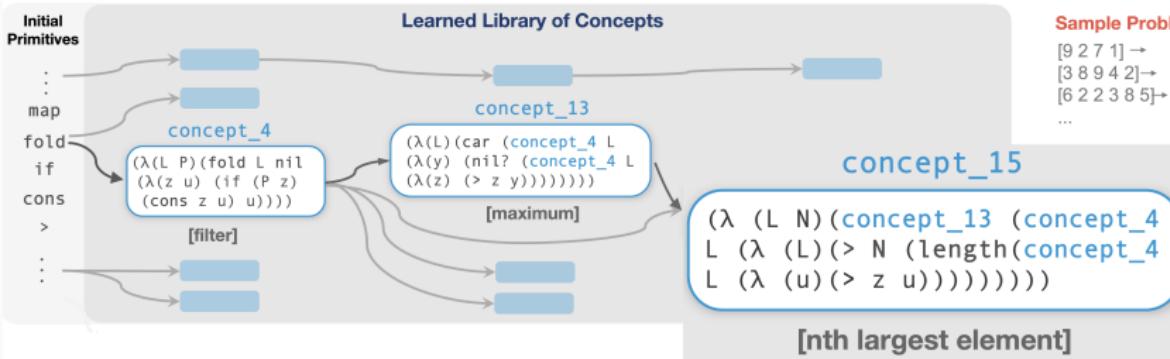
Library learning



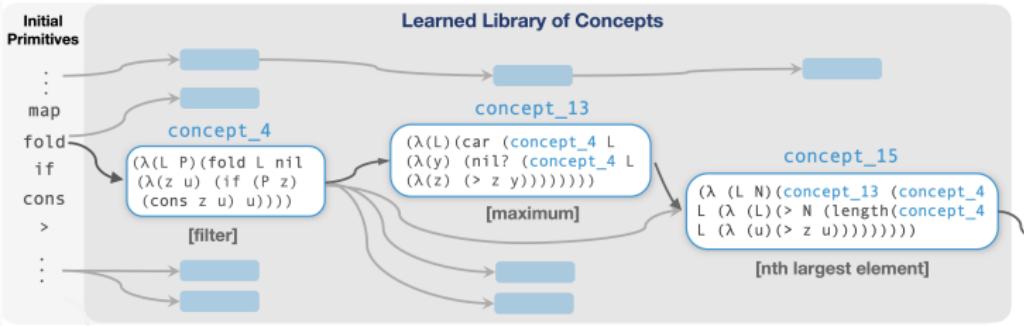
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Library learning



Library learning



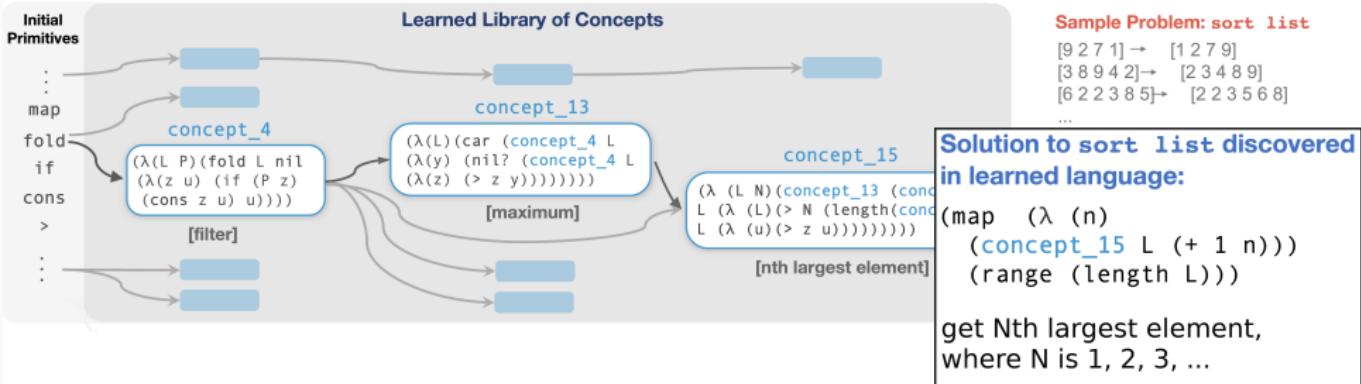
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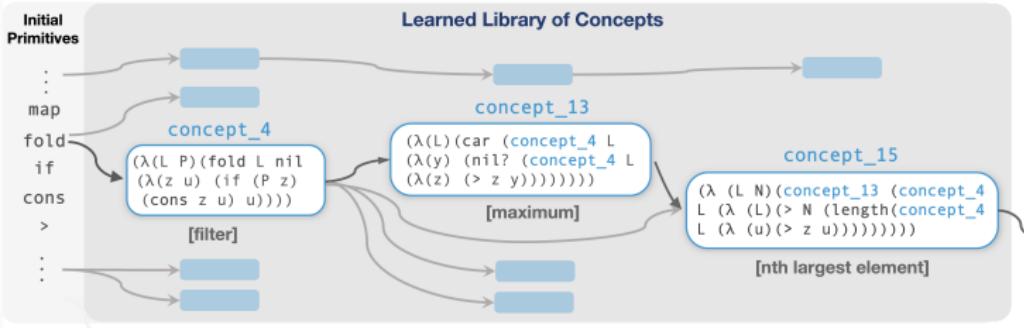
Solution to sort list discovered in learned language:

```
(map (λ (n)
  (concept_15 L (+ 1 n)))
  (range (length L)))
```

Library learning



Library learning



Sample Problem: sort list

$[9\ 2\ 7\ 1] \rightarrow [1\ 2\ 7\ 9]$
 $[3\ 8\ 9\ 4\ 2] \rightarrow [2\ 3\ 4\ 8\ 9]$
 $[6\ 2\ 2\ 3\ 8\ 5] \rightarrow [2\ 2\ 3\ 5\ 6\ 8]$
...

Solution to sort list discovered in learned language:

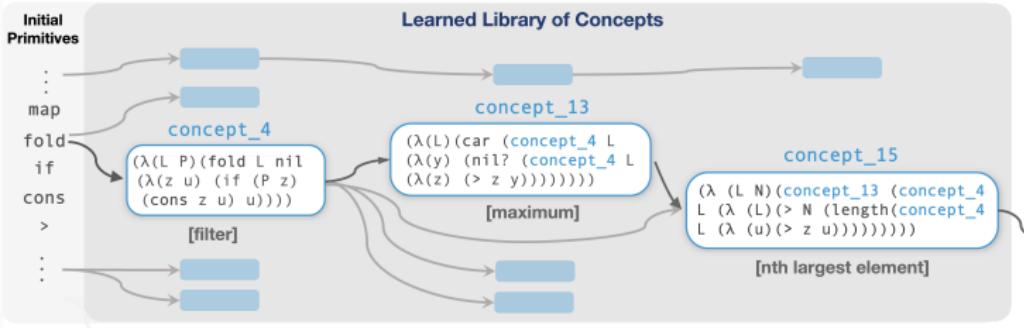
```
(map (λ (n)
  (concept_15 L (+ 1 n)))
  (range (length L)))
```

get Nth largest element,
where N is 1, 2, 3, ...

Solution rewritten in initial primitives:

```
(lambda (x) (map (lambda (y) (car (fold (fold x nil (lambda (z u) (if (gt? (+ y 1) (length
(fold x nil (lambda (v w) (if (gt? z v) (cons v w) w)))) (cons z u) u)) nil (lambda (a b) (if
(nil? (fold (fold x nil (lambda (c d) (if (gt? (+ y 1) (length (fold x nil (lambda (e f) (if
(gt? c e) (cons e f) f)))) (cons c d) d))) nil (lambda (g h) (if (gt? g a) (cons g h) h))) (cons a b) b)))) (range (length x))))
```

Library learning



Sample Problem: sort list

$[9 2 7 1] \rightarrow [1 2 7 9]$
 $[3 8 9 4 2] \rightarrow [2 3 4 8 9]$
 $[6 2 2 3 8 5] \rightarrow [2 2 3 5 6 8]$
...

Solution to sort list discovered in learned language:

```
(map (λ (n)
  (concept_15 L (+ 1 n)))
  (range (length L)))
```

get Nth largest element,
where N is 1, 2, 3, ...

Solution rewritten in initial primitives:

```
(lambda (x) (map (lambda (y) (car (fold (fold x nil (lambda (z u) (if (gt? (+ y 1) (length
(fold x nil (lambda (v w) (if (gt? z v) (cons v w) w)))))) (cons z u) u))) nil (lambda (a b) (if
(nil? (fold (fold x nil (lambda (c d) (if (gt? (+ y 1) (length (fold x nil (lambda (e f) (if
(gt? c e) (cons e f) f)))))) (cons c d) d))) nil (lambda (g h) (if (gt? g a) (cons g h) h))) (cons a b) b)))) (range (length x))))
```

induced sort program found in $\leq 10\text{min}$. Brute-force search
without learned library would take $\approx 10^{73}$ years

DreamCoder

- **Wake:** Solve problems by writing programs
- **Sleep:** Improve library and neural recognition model:
 - **Abstraction sleep:** Improve library
 - **Dream sleep:** Improve neural recognition model



cf. Helmholtz machine, wake/sleep neural network training algorithms

DreamCoder

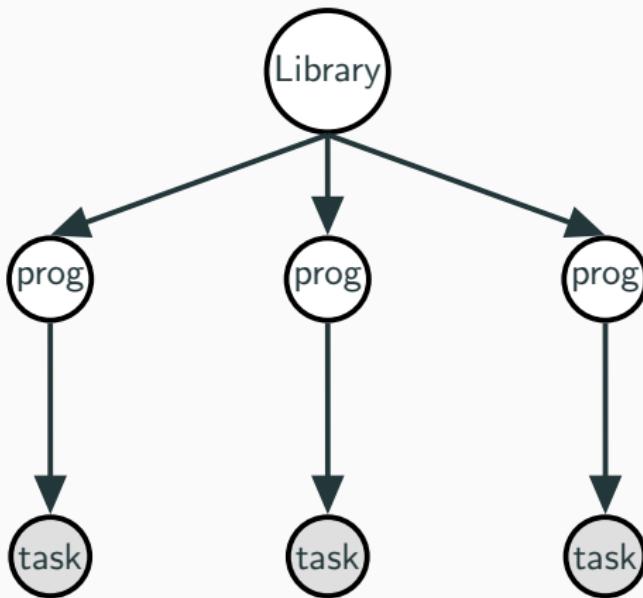
- **Wake:** Solve problems by writing programs
- **Sleep:** Improve library and neural recognition model:
 - **Abstraction sleep:** Improve library
 - **Dream sleep:** Improve neural recognition model



List Processing	Text Editing	Regexes		
Sum List $[1\ 2\ 3] \rightarrow 6$ $[4\ 6\ 8\ 1] \rightarrow 17$	Abbreviate Allen Newell → A.N. Herb Simon → H.S.	Phone numbers (555) 867-5309 (650) 555-2368		
Double $[1\ 2\ 3] \rightarrow [2\ 4\ 6]$ $[4\ 5\ 1] \rightarrow [8\ 10\ 2]$	Drop Last Three shrdlu → shr shakey → sha	Currency \$100.25 \$4.50		
Block Towers 	Symbolic Regression $y = f(x)$	Recursive Programming Filter Red $[\text{red red blue}] \rightarrow [\text{blue}]$ $[\text{red green blue}] \rightarrow [\text{green blue}]$ $[\text{red black red}] \rightarrow [\text{black blue}]$	Physical Laws $\vec{a} = \frac{1}{m} \sum_i \vec{F}_i$ $\vec{F} \propto \frac{q_1 q_2}{ \vec{r} ^2} \hat{r}$	LOGO Graphics

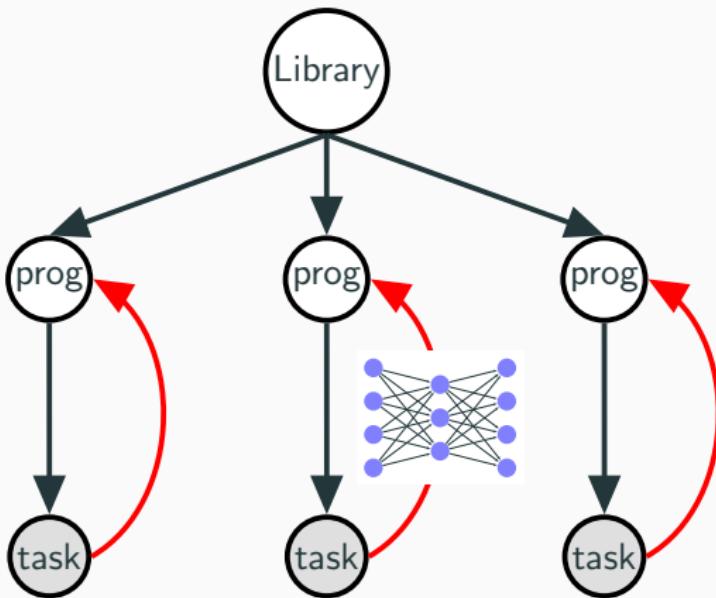
cf. Helmholtz machine, wake/sleep neural network training algorithms

Library learning as Bayesian inference

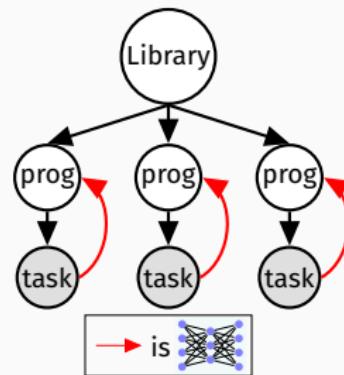


[Dechter et al, 2013] [Liang et al, 2010] [Lake et al, 2015]

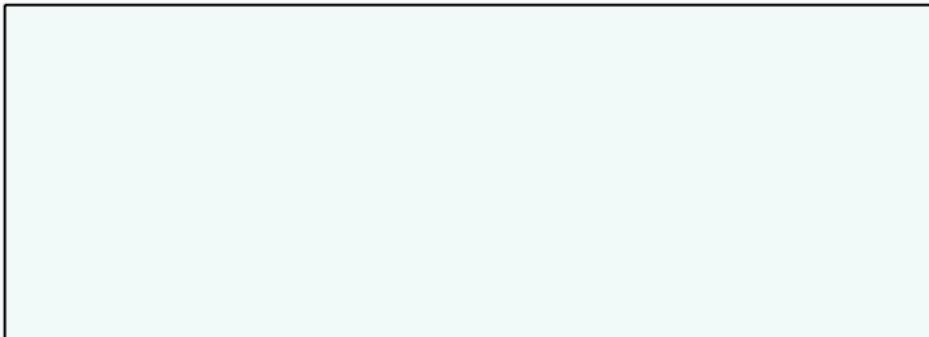
Library learning as neurally-guided Bayesian inference



library learning via program analysis +
new neural inference network for program synthesis +
better program representation (Lisp+polymorphic types [Milner 1978])



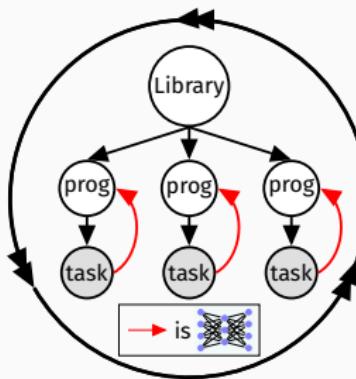
WAKE

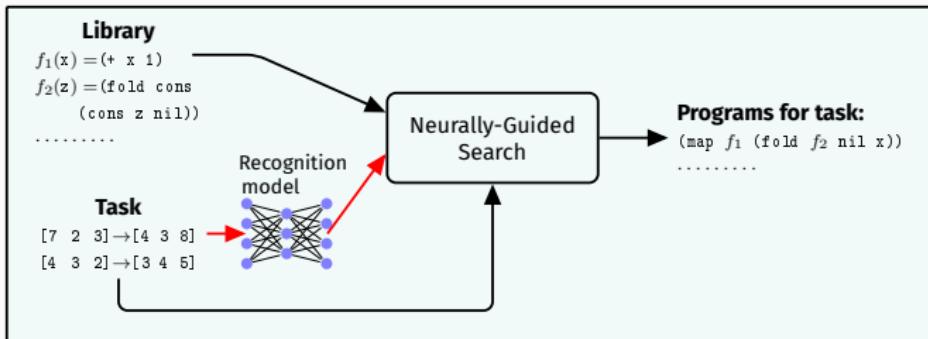
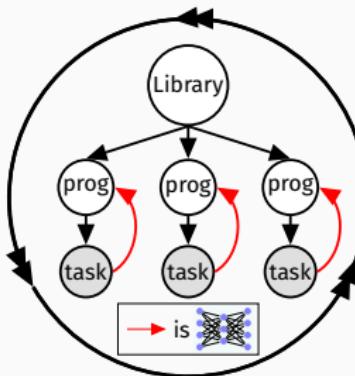


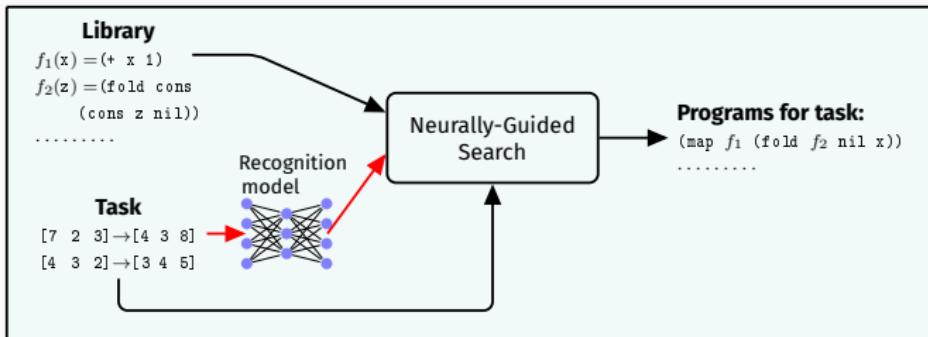
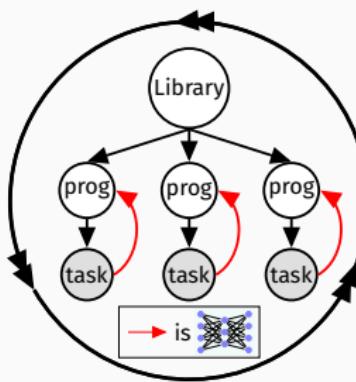
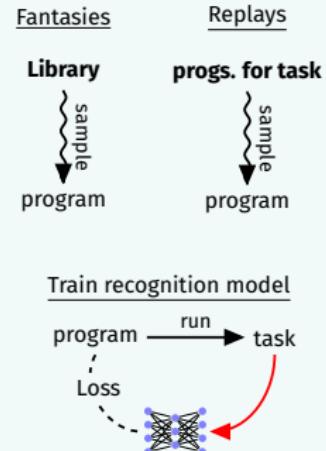
SLEEP: ABSTRACTION

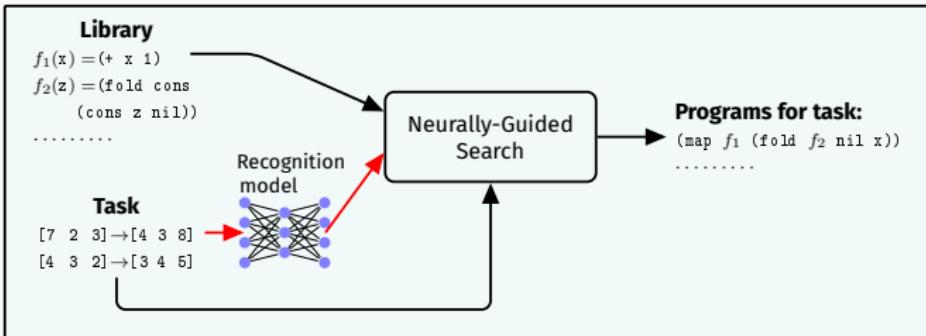
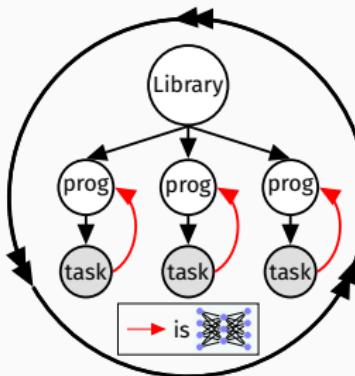
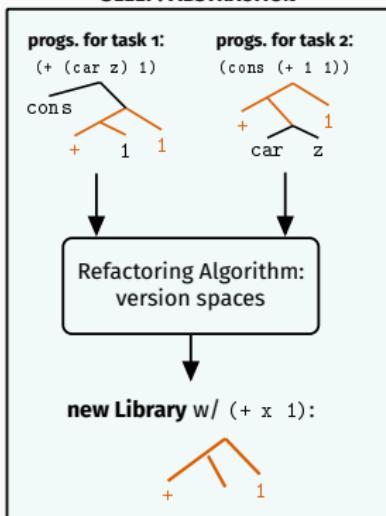
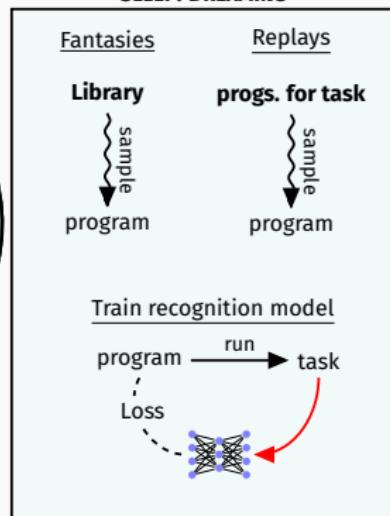


SLEEP: DREAMING

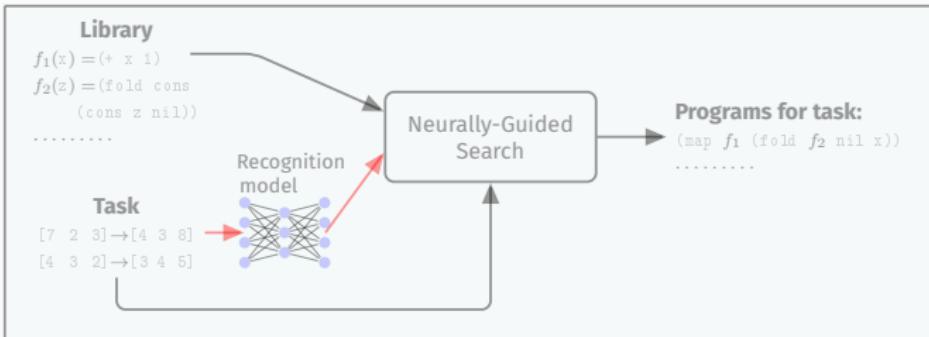


WAKE**SLEEP: ABSTRACTION****SLEEP: DREAMING**

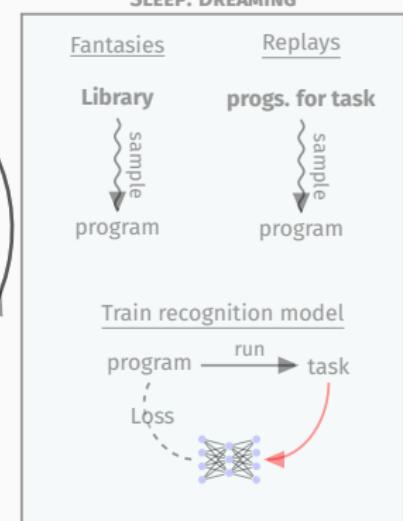
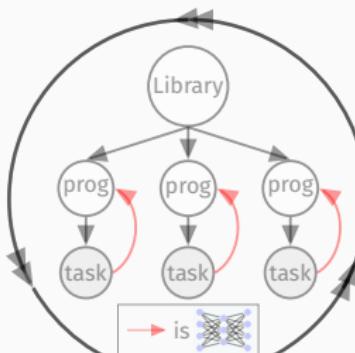
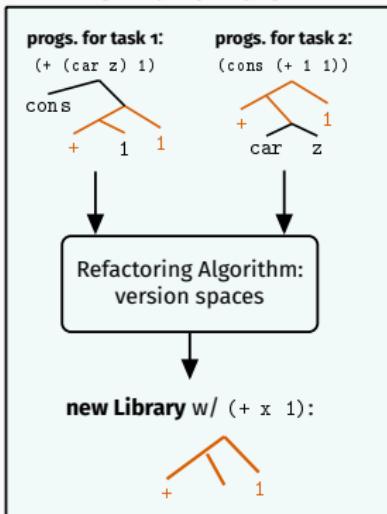
WAKE**SLEEP: ABSTRACTION****SLEEP: DREAMING**

WAKE**SLEEP: ABSTRACTION****SLEEP: DREAMING**

WAKE



SLEEP: ABSTRACTION



Abstraction Sleep: Growing the library via refactoring

$$5 + 5$$

Abstraction Sleep: Growing the library via refactoring

$5 + 5$

(+ 5 5)

Abstraction Sleep: Growing the library via refactoring

$5 + 5$

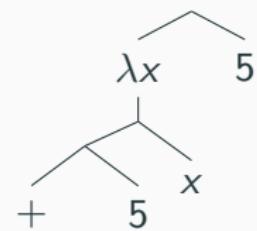
(+ 5 5)



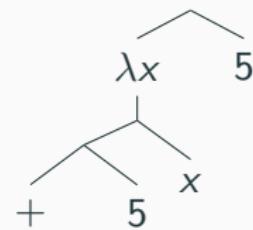
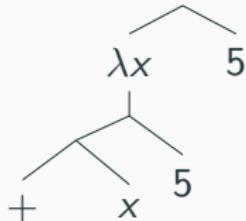
Abstraction Sleep: Growing the library via refactoring



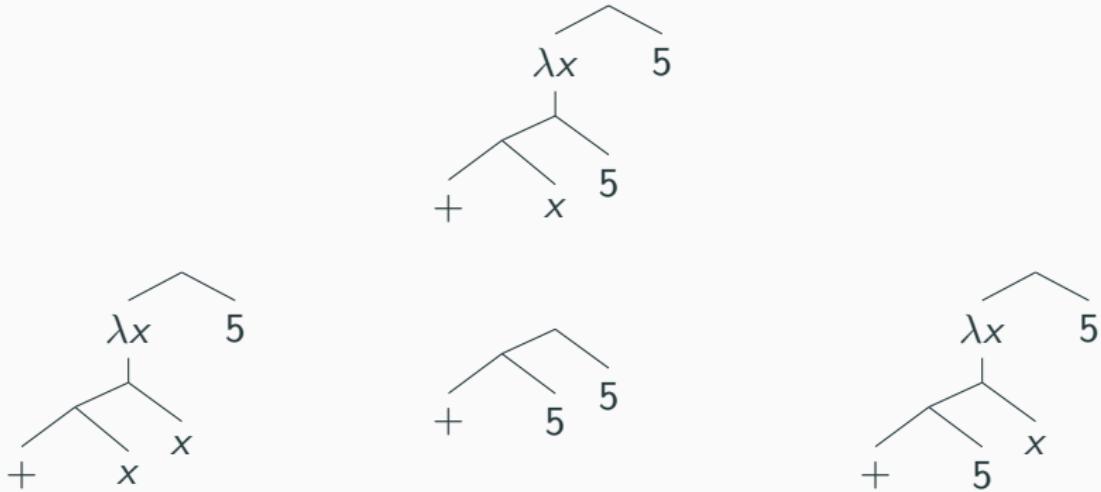
Abstraction Sleep: Growing the library via refactoring



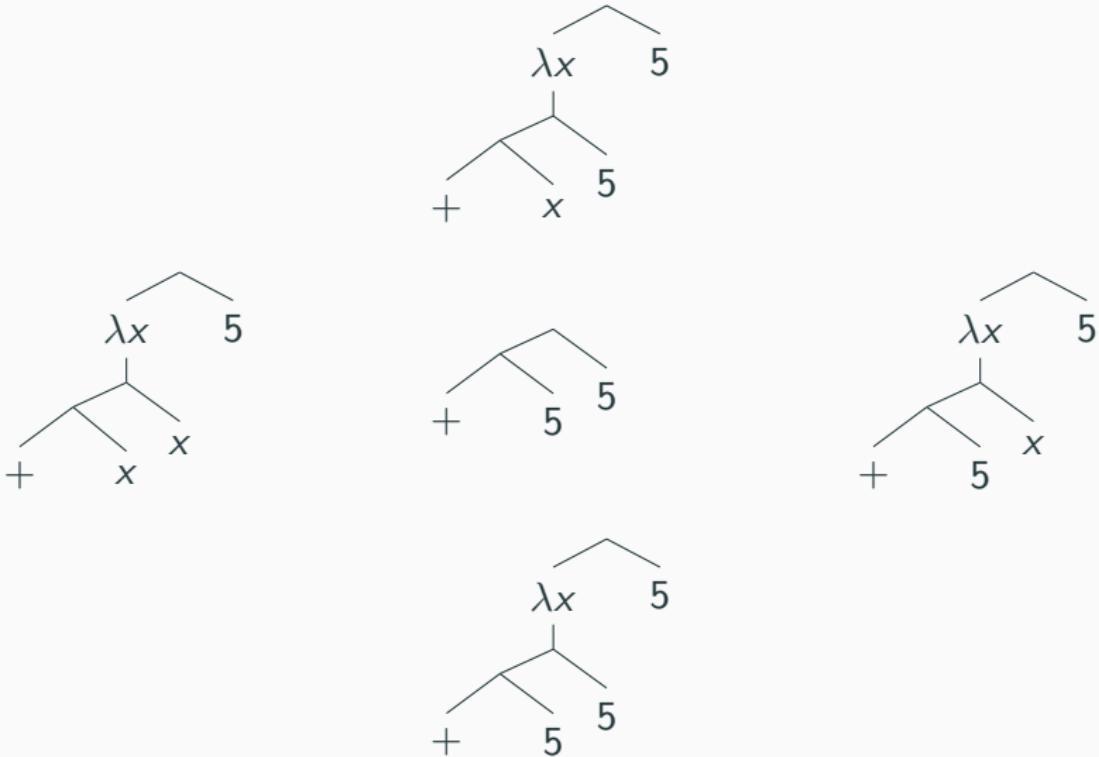
Abstraction Sleep: Growing the library via refactoring



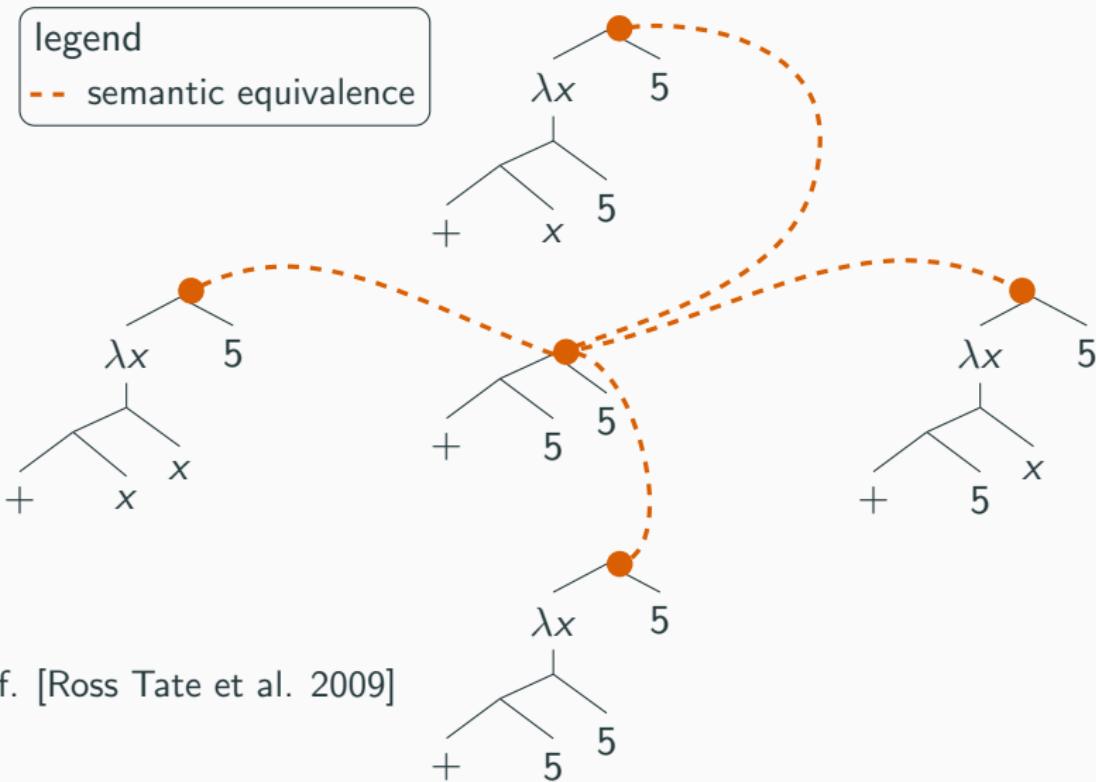
Abstraction Sleep: Growing the library via refactoring



Abstraction Sleep: Growing the library via refactoring



Abstraction Sleep: Growing the library via refactoring

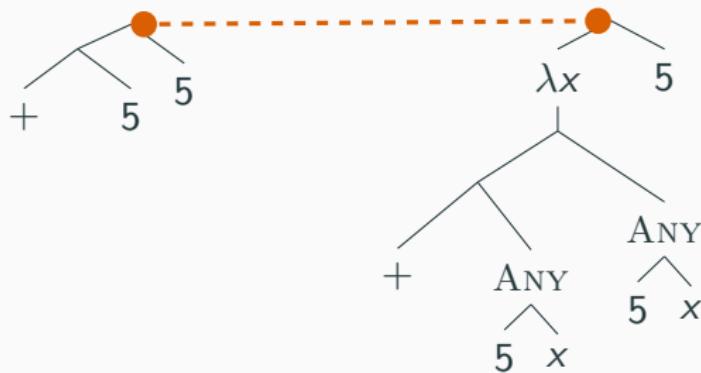


Abstraction Sleep: Growing the library via refactoring

legend

semantic equivalence

ANY nondeterministic choice



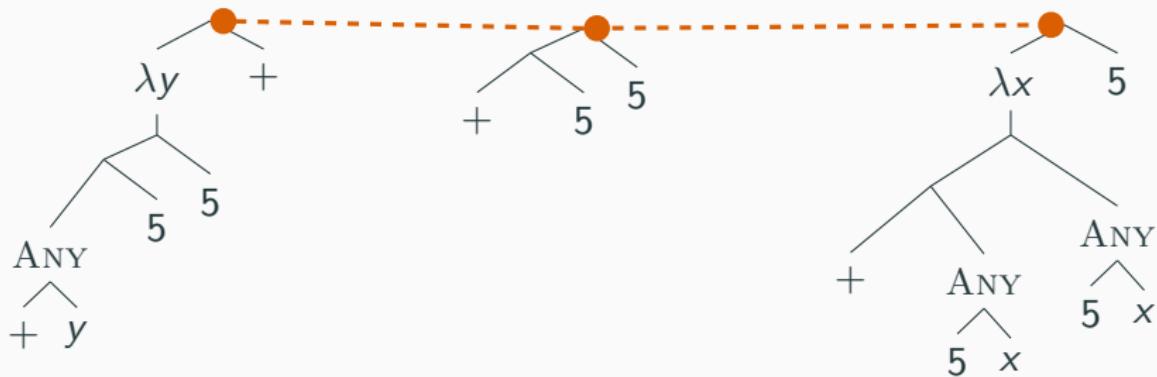
cf. [Gulwani 2012]

Abstraction Sleep: Growing the library via refactoring

legend

semantic equivalence

ANY nondeterministic choice

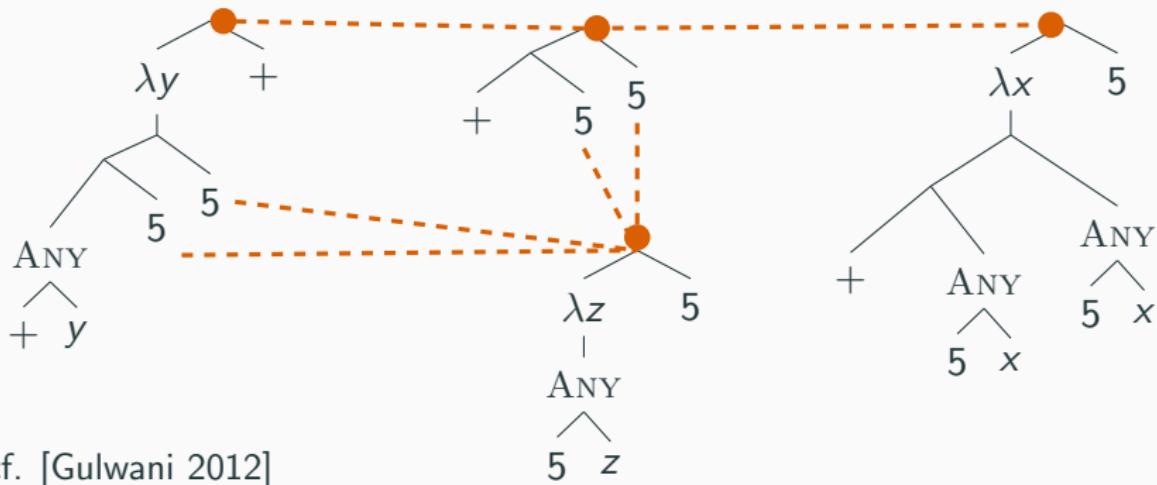


cf. [Gulwani 2012]

Abstraction Sleep: Growing the library via refactoring

legend

- semantic equivalence
- ANY nondeterministic choice

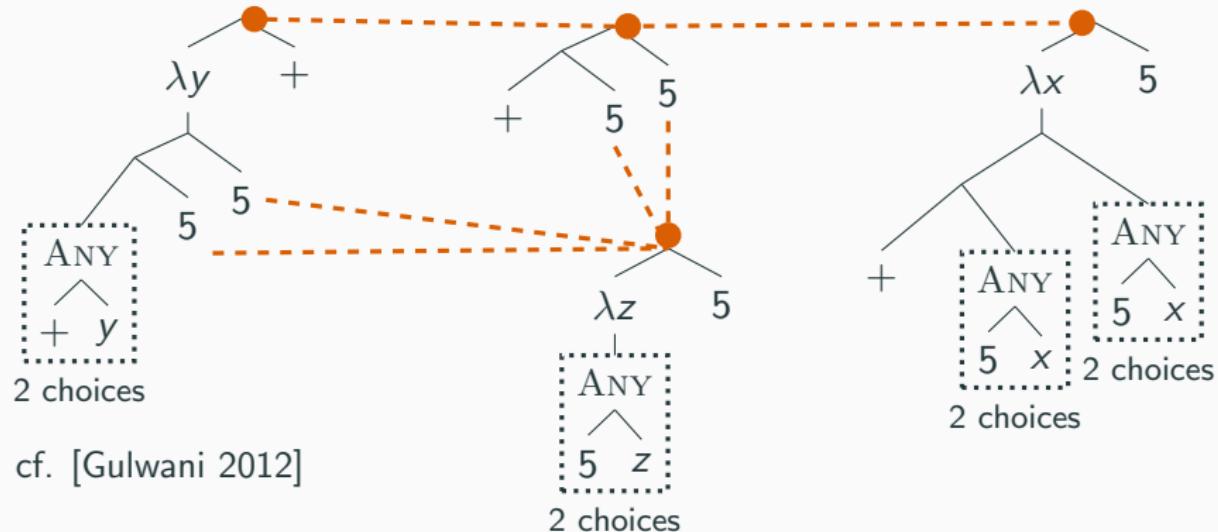


Abstraction Sleep: Growing the library via refactoring

legend

dashed orange line semantic equivalence

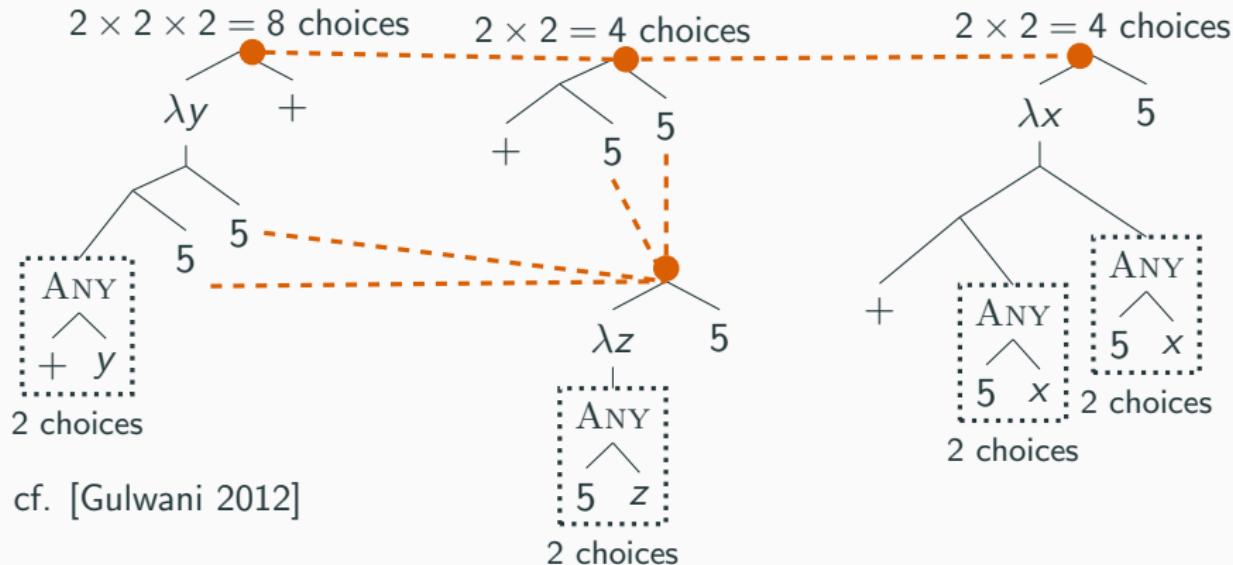
ANY nondeterministic choice

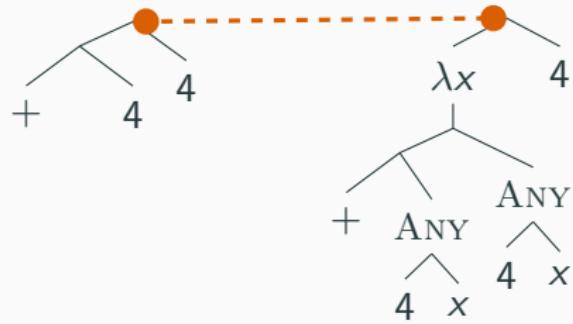
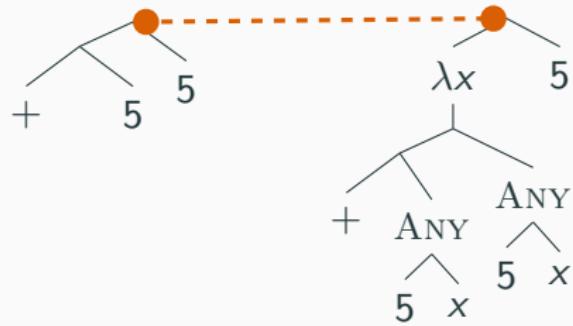


cf. [Gulwani 2012]

Abstraction Sleep: Growing the library via refactoring

legend
--- semantic equivalence
ANY nondeterministic choice

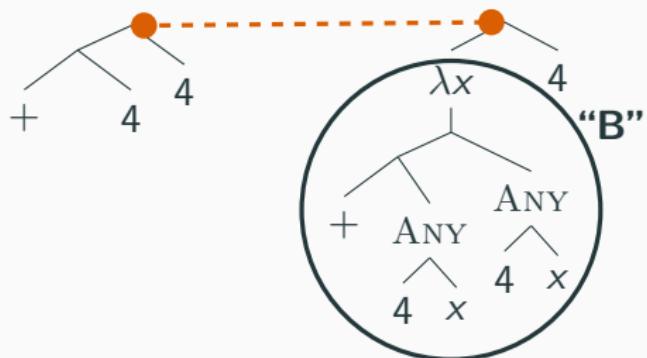
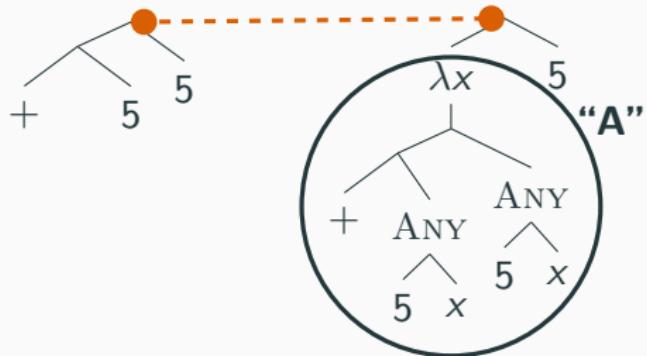




legend

— semantic equivalence

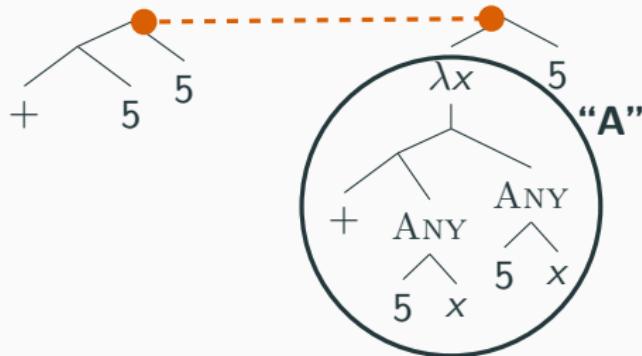
ANY nondeterministic choice



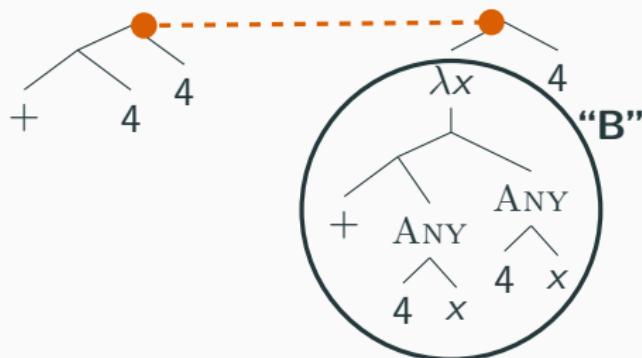
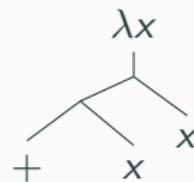
legend

— dashed orange line semantic equivalence

ANY nondeterministic choice



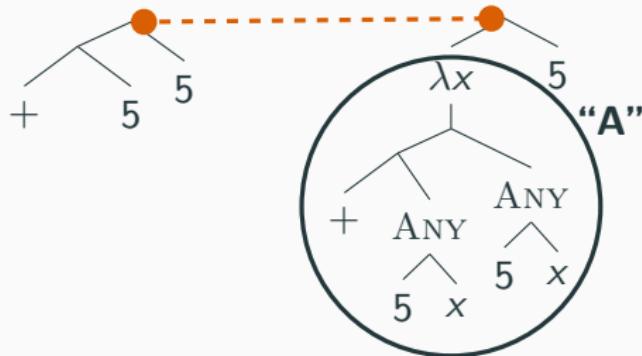
A intersect B:



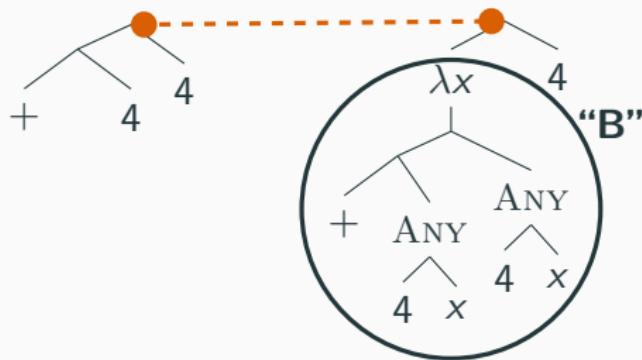
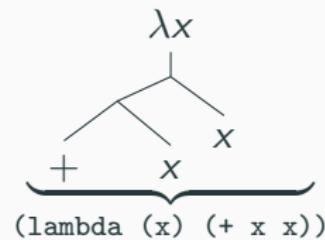
legend

— semantic equivalence

ANY nondeterministic choice



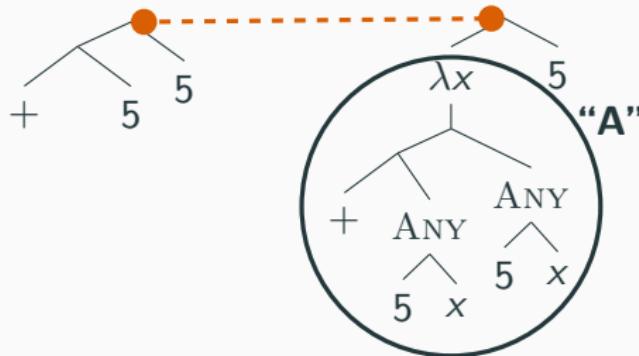
A intersect B:



legend

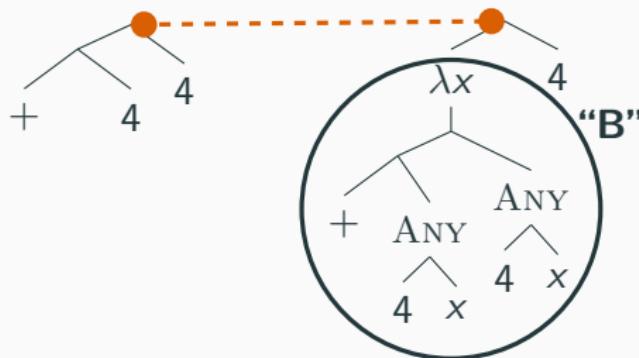
— semantic equivalence

ANY nondeterministic choice



A intersect B:

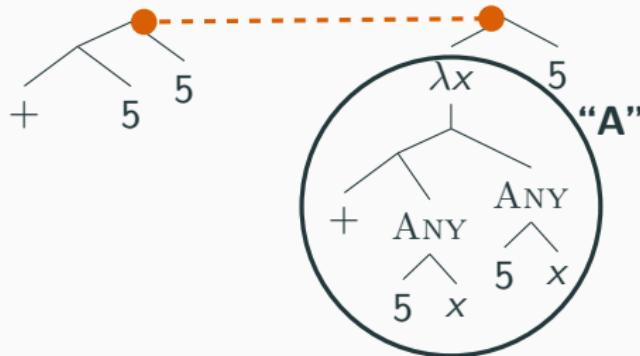
λx
 + x
 (lambda (x) (+ x x))
 = double



legend

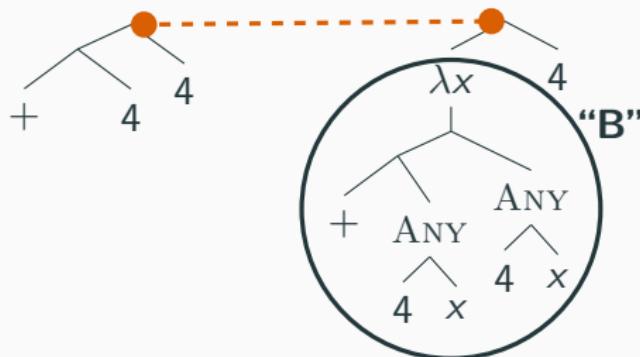
— dashed orange line semantic equivalence

ANY nondeterministic choice



A intersect B:

$$\begin{array}{c}
 \lambda x \\
 / \quad \backslash \\
 + \quad x \\
 \underbrace{\quad}_{(\text{lambda } (x) \ (\text{+ } x \ x))} \\
 = \text{double}
 \end{array}$$



w/o double	w/ double
(+ 5 5)	(double 5)
(+ 4 4)	(double 4)
(+ 3 3)	(double 3)
...	

legend

— semantic equivalence
 ANY nondeterministic choice

Abstraction Sleep: Growing the library via refactoring

Task: $[1\ 2\ 3] \rightarrow [2\ 4\ 6]$
 $[4\ 3\ 4] \rightarrow [8\ 6\ 8]$

Wake: program search

```
(Y (λ (r 1) (if (nil? 1) nil  
           (cons (+ (car 1) (car 1))  
                 (r (cdr 1)))))))
```

Task: $[1\ 2\ 3] \rightarrow [0\ 1\ 2]$
 $[4\ 3\ 4] \rightarrow [3\ 2\ 3]$

Wake: program search

```
(Y (λ (r 1) (if (nil? 1) nil  
           (cons (- (car 1) 1)  
                 (r (cdr 1)))))))
```

Abstraction Sleep: Growing the library via refactoring

Task: $[1\ 2\ 3] \rightarrow [2\ 4\ 6]$
 $[4\ 3\ 4] \rightarrow [8\ 6\ 8]$

Wake: program search

```
(Y (λ (r 1) (if (nil? 1) nil  
           (cons (+ (car 1) (car 1))  
                  (r (cdr 1)))))))
```

Task: $[1\ 2\ 3] \rightarrow [0\ 1\ 2]$
 $[4\ 3\ 4] \rightarrow [3\ 2\ 3]$

Wake: program search

```
(Y (λ (r 1) (if (nil? 1) nil  
           (cons (- (car 1) 1)  
                  (r (cdr 1)))))))
```

refactor

$(10^{14}$ refactorings)

```
((λ (f) (Y (λ (r 1) (if (nil? 1)  
                           nil  
                           (cons (f (car 1))  
                                 (r (cdr 1)))))))  
  (λ (z) (+ z z)))
```

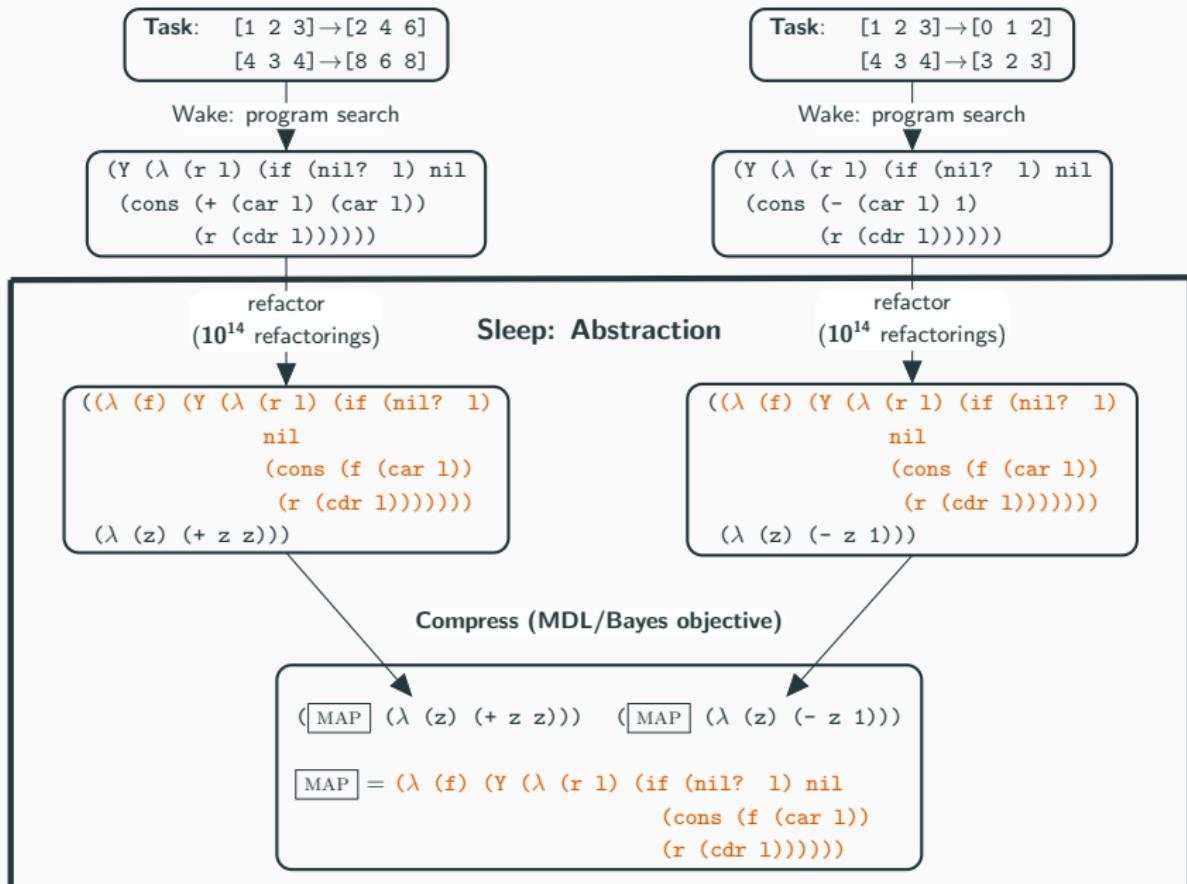
Sleep: Abstraction

refactor

$(10^{14}$ refactorings)

```
((λ (f) (Y (λ (r 1) (if (nil? 1)  
                           nil  
                           (cons (f (car 1))  
                                 (r (cdr 1)))))))  
  (λ (z) (- z 1)))
```

Abstraction Sleep: Growing the library via refactoring



Abstraction Sleep: Growing the library via refactoring

Task: $[1\ 2\ 3] \rightarrow [2\ 4\ 6]$
 $[4\ 3\ 4] \rightarrow [8\ 6\ 8]$

Wake: program search

```
(Y (λ (r 1) (if (nil? 1) nil  
           (cons (+ (car 1) (car 1))  
                  (r (cdr 1)))))))
```

Task: $[1\ 2\ 3] \rightarrow [0\ 1\ 2]$
 $[4\ 3\ 4] \rightarrow [3\ 2\ 3]$

Wake: program search

```
(Y (λ (r 1) (if (nil? 1) nil  
           (cons (- (car 1) 1)  
                  (r (cdr 1)))))))
```

these 10^{14} refactorings are represented in DreamCoder's exponentially more efficient refactoring data structure using 10^6 nodes, calculated in under 5min

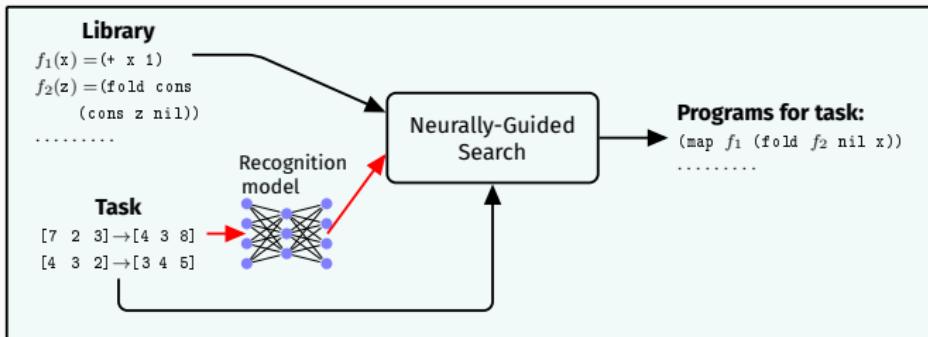
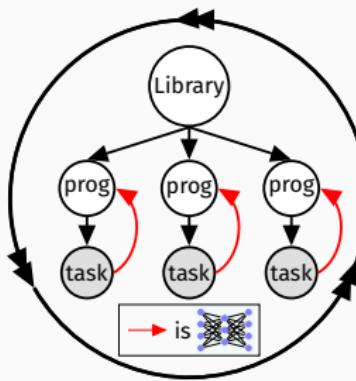
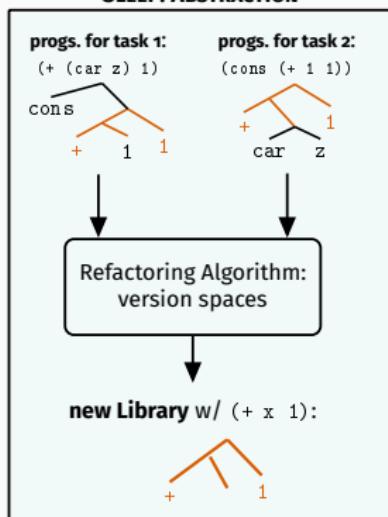
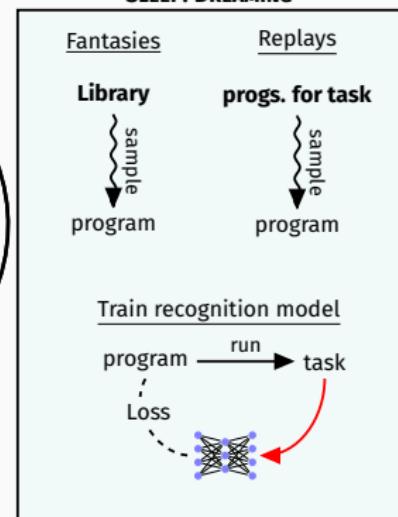
$(\lambda (z) (+ z z))$

$(\lambda (z) (- z 1))$

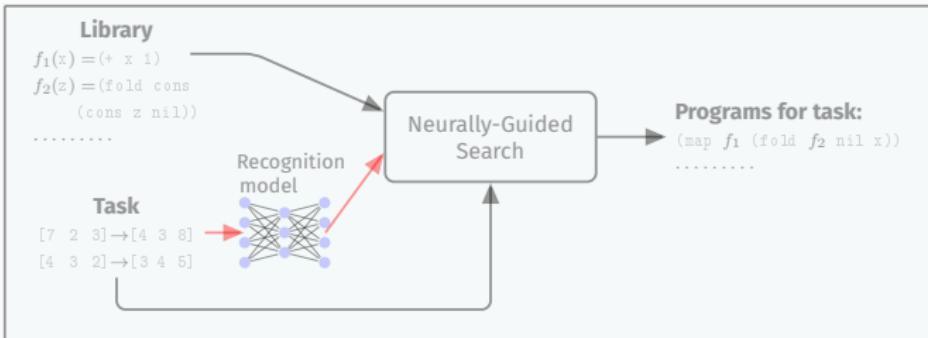
Compress (MDL/Bayes objective)

$(\boxed{\text{MAP}} (\lambda (z) (+ z z))) (\boxed{\text{MAP}} (\lambda (z) (- z 1)))$

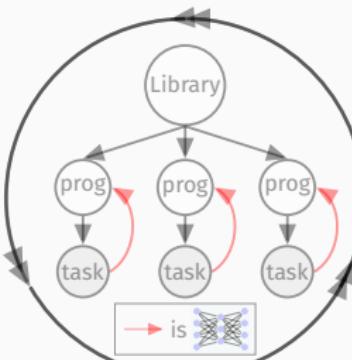
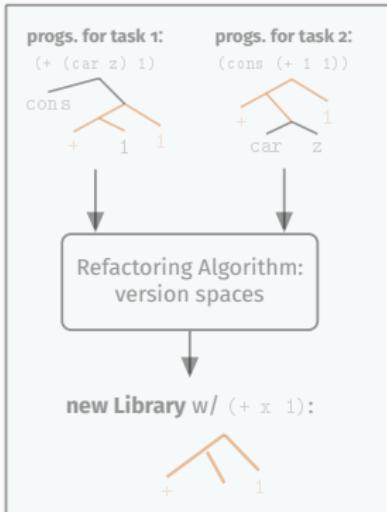
$\boxed{\text{MAP}} = (\lambda (f) (Y (\lambda (r 1) (if (nil? 1) nil
 (cons (f (car 1))
 (r (cdr 1)))))))$

WAKE**SLEEP: ABSTRACTION****SLEEP: DREAMING**

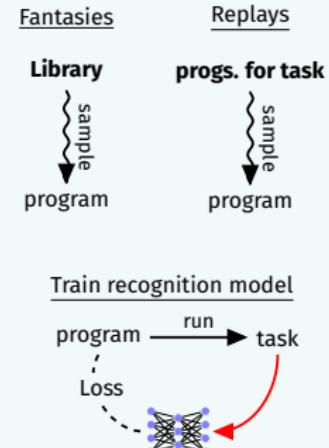
WAKE



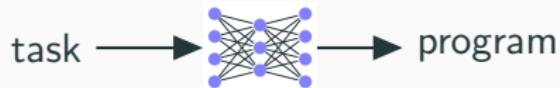
SLEEP: ABSTRACTION



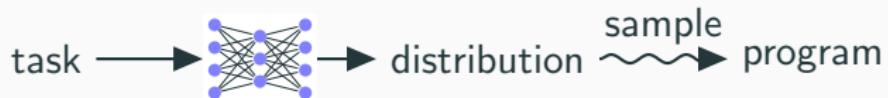
SLEEP: DREAMING



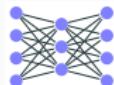
Neural recognition model guides search



Neural recognition model guides search



Neural recognition model guides search

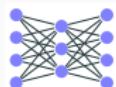


is a...

recurrent network (Devlin et al 2017)

unigram model (Menon et al 2013; Balog et al 2016)

Neural recognition model guides search

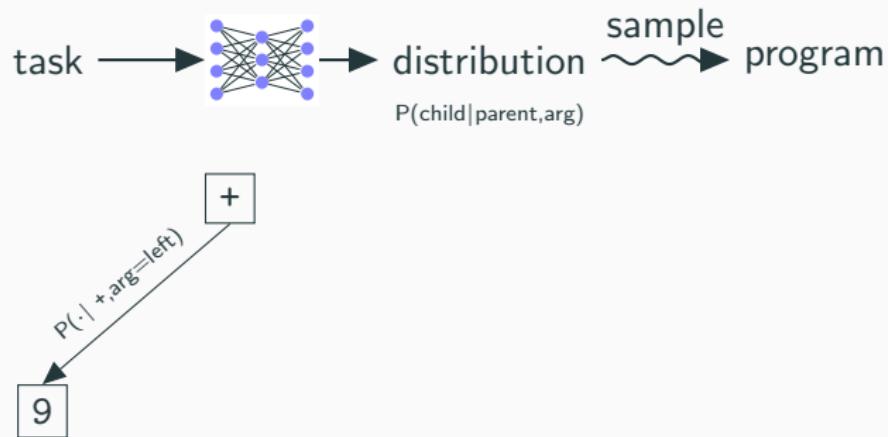


is a “**bigram**” model over syntax trees

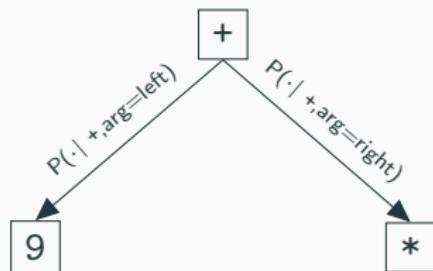
Neural recognition model guides search



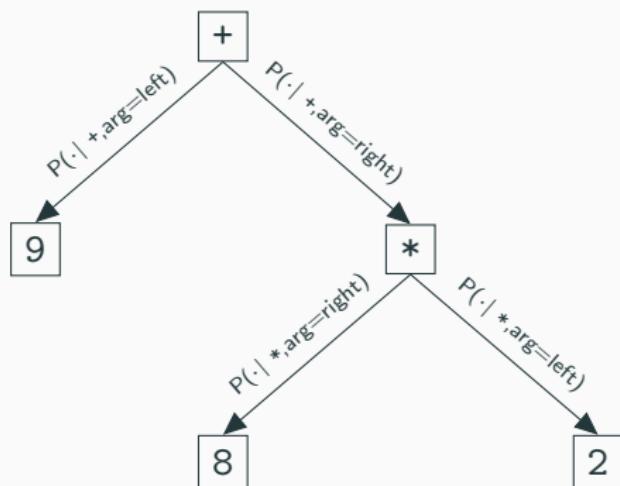
Neural recognition model guides search



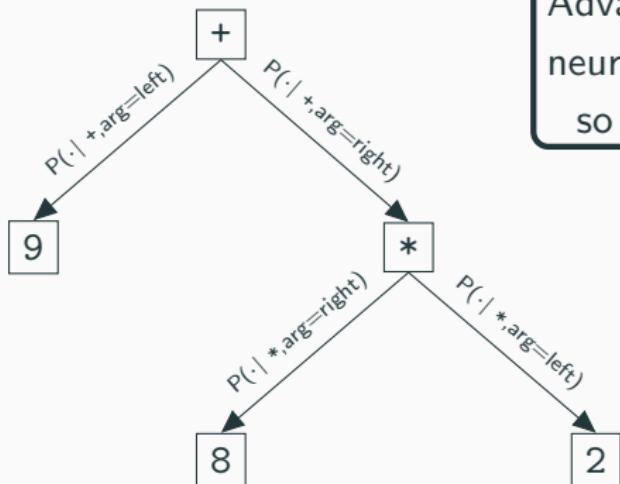
Neural recognition model guides search



Neural recognition model guides search

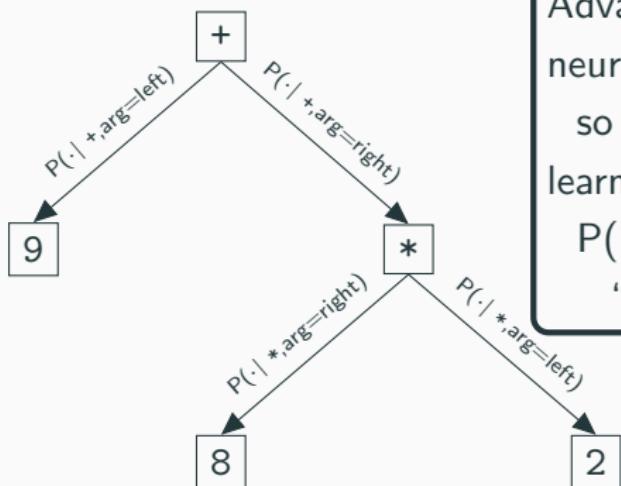


Neural recognition model guides search



Advantages:
neural net runs once per task,
so CPU bottlenecks instead of GPU

Neural recognition model guides search



Advantages:
neural net runs once per task,
so CPU bottlenecks instead of GPU
learns to break syntactic symmetries:
 $P(1|*,\text{arg}=\text{left})=0.0$
“do not multiply by one”

DreamCoder Domains

List Processing

Sum List

[1 2 3] → 6

[4 6 8 1] → 17

Double

[1 2 3] → [2 4 6]

[4 5 1] → [8 10 2]

Text Editing

Abbreviate

Allen Newell → A.N.

Herb Simon → H.S.

Drop Last Three

shrdlu → shr

shakey → sha

Regexes

Phone numbers

(555) 867-5309

(650) 555-2368

Currency

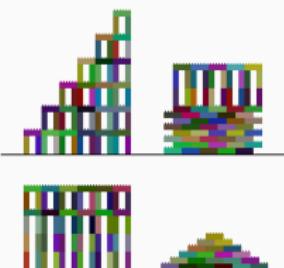
\$100.25

\$4.50

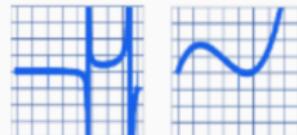
LOGO Graphics



Block Towers



Symbolic Regression



$$y = f(x)$$

Recursive Programming

Filter Red

[■■■■■■■■] → [■■■■]

[■■■■■■■■■■] → [■■■■■■■■]

[■■■■■■■■■■■■] → [■■■■■■■■■■]

Physical Laws

$$\vec{a} = \frac{1}{m} \sum_i \vec{F}_i$$

$$\vec{F} \propto \frac{q_1 q_2}{|\vec{r}|^2} \hat{r}$$

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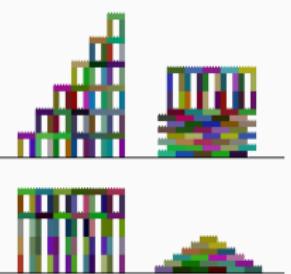
\$100.25

\$4.50

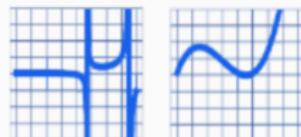
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[■■■■■■■■] → [■■■■■■■]

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[■■■■■■■■■■■■] → [■■■■■■■■■■■■]

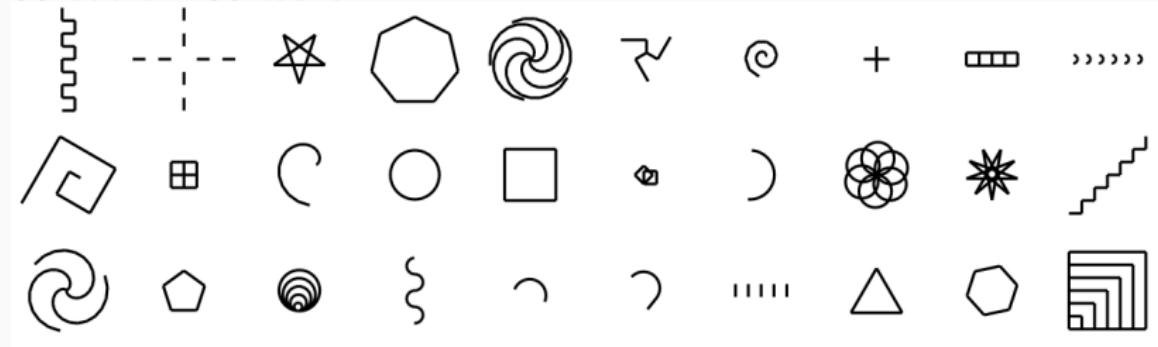
Physical Laws

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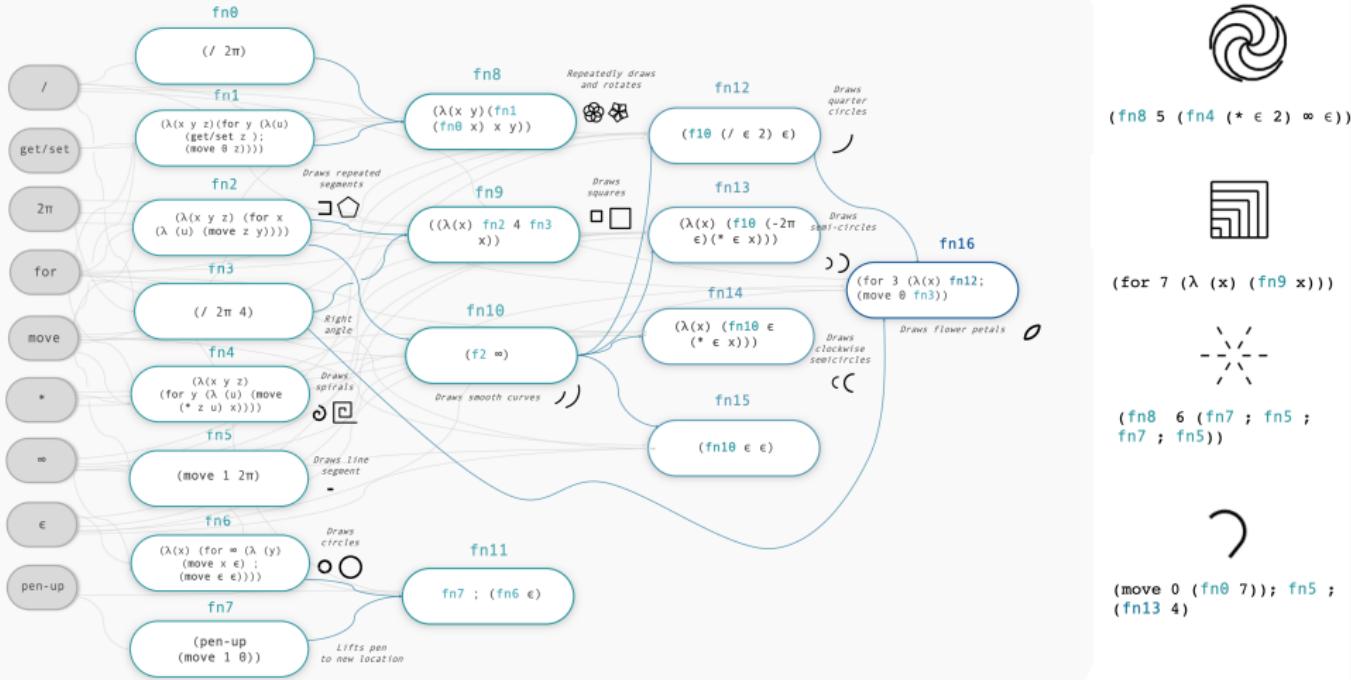
$$\vec{F} \propto \frac{q_1 q_2}{|\vec{r}|^2} \hat{r}$$

LOGO Turtle Graphics

30 out of 160 tasks



LOGO Turtle Graphics – learning an interpretable library



`(fn8 5 (fn4 (* ε 2) ∞))`



`(for 7 (λ (x) (fn9 x)))`

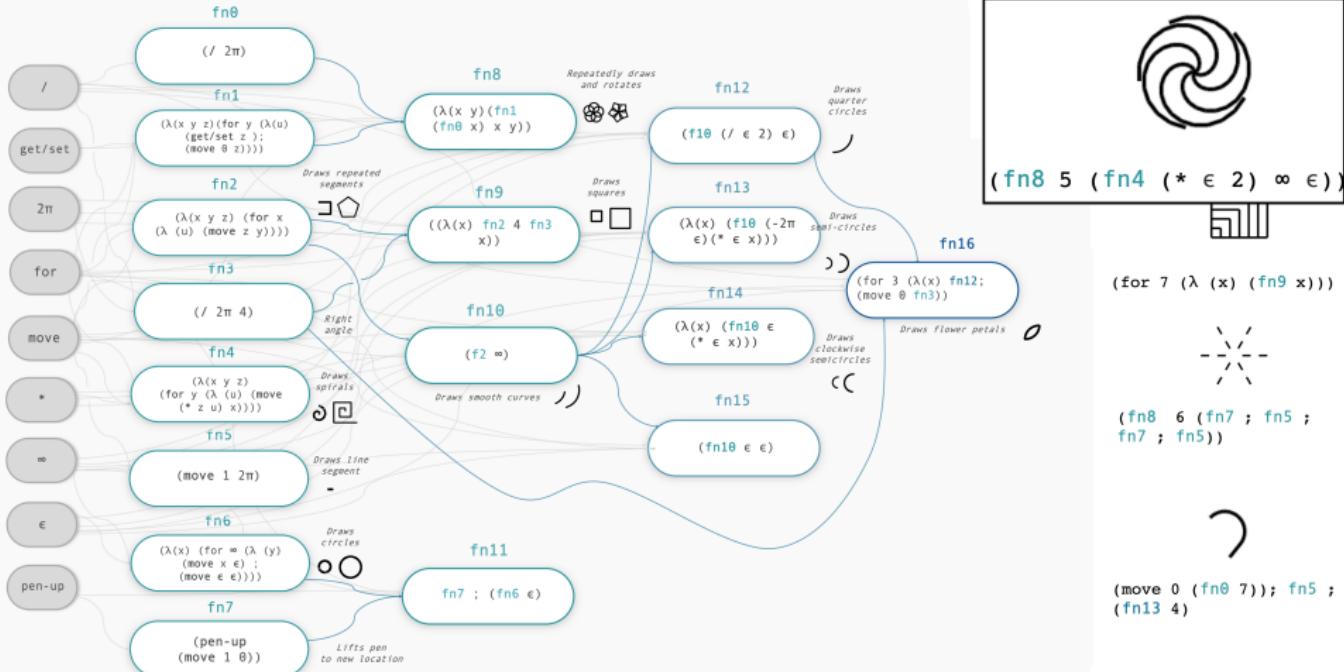


`(fn8 6 (fn7 ; fn5 ; fn7 ; fn5))`



`(move 0 (fn0 7)); fn5 ; (fn13 4)`

LOGO Turtle Graphics – learning an interpretable library



```
(move 0 (fn0 7)); fn5 ;
(fn13 4)
```

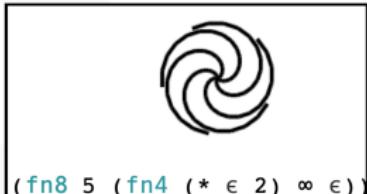
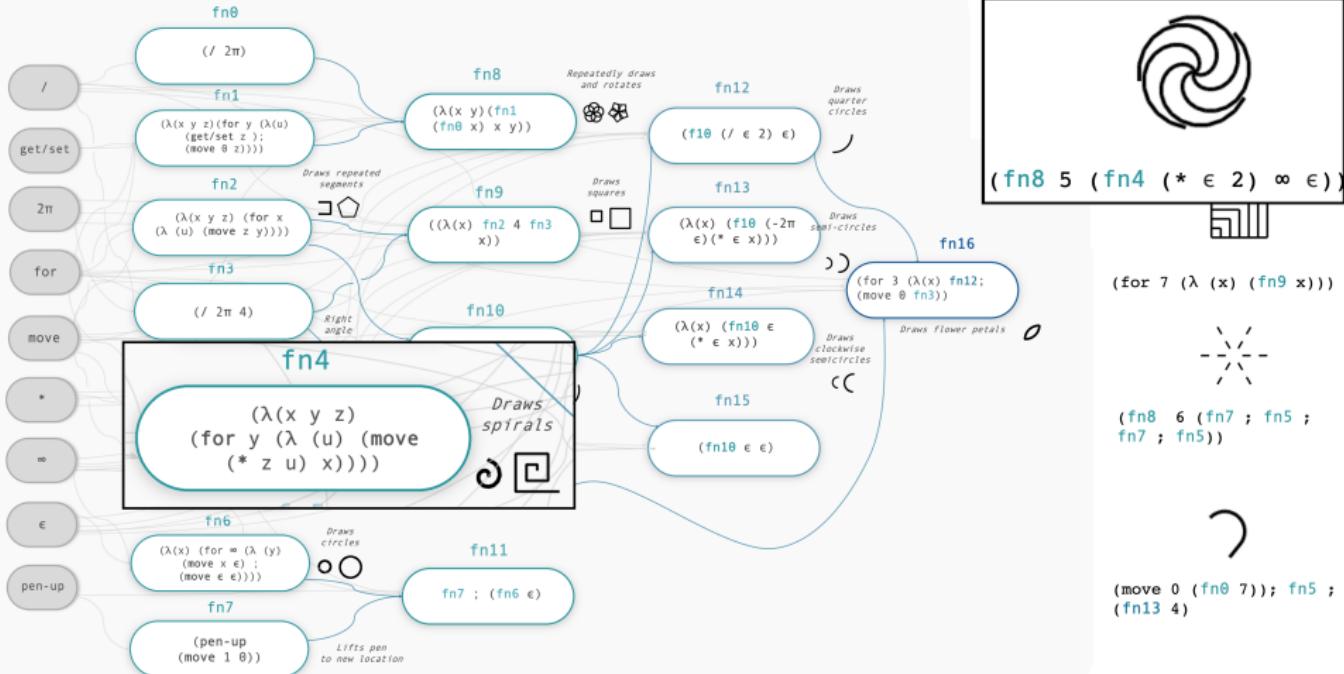


```
(fn8 6 (fn7 ; fn5 ;
fn7 ; fn5))
```



```
(for 7 (lambda (x) (fn9 x)))
```

LOGO Turtle Graphics – learning an interpretable library



$(fn8 5 (fn4 (* \epsilon 2) \infty \epsilon))$

$(for 7 (\lambda (x) (fn9 x)))$

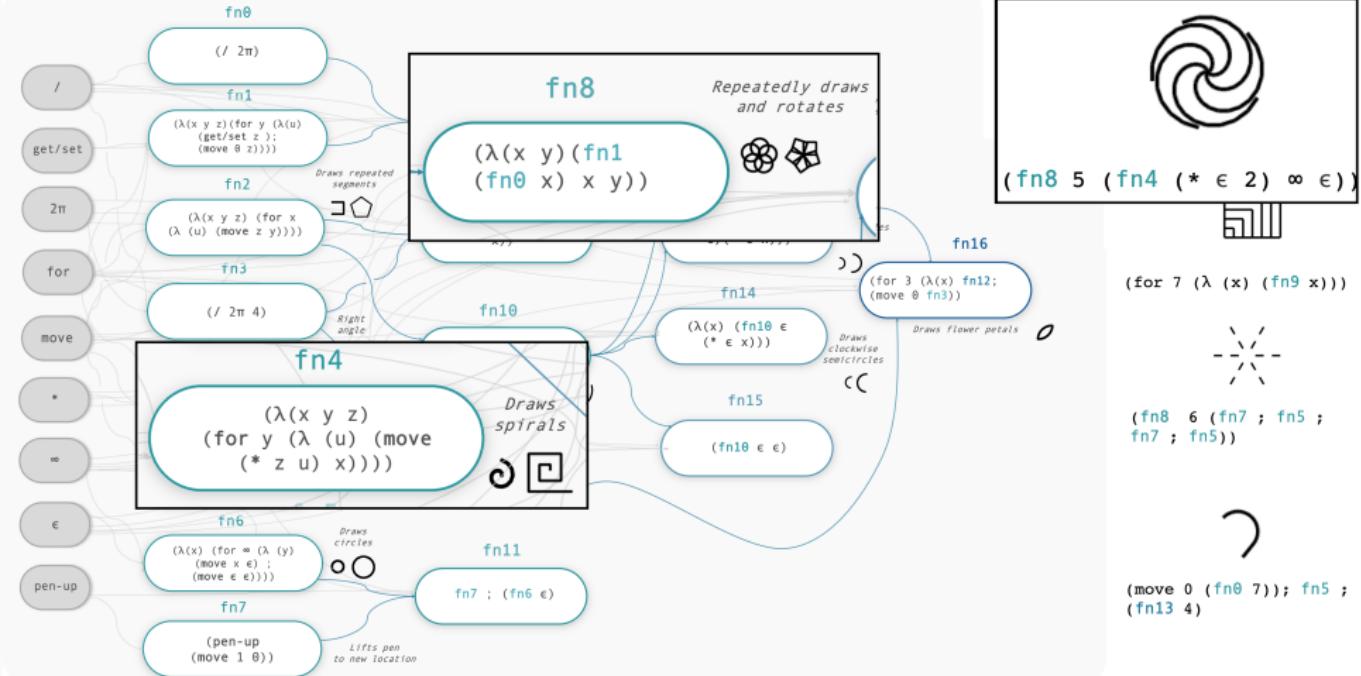


$(fn8 6 (fn7 ; fn5 ; fn7 ; fn5))$

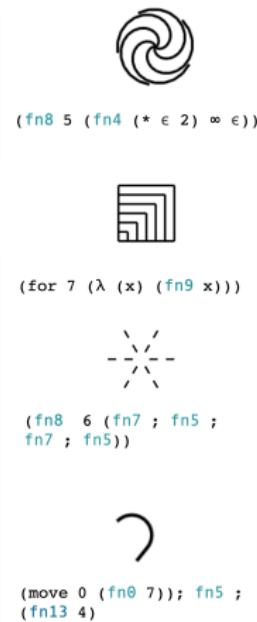
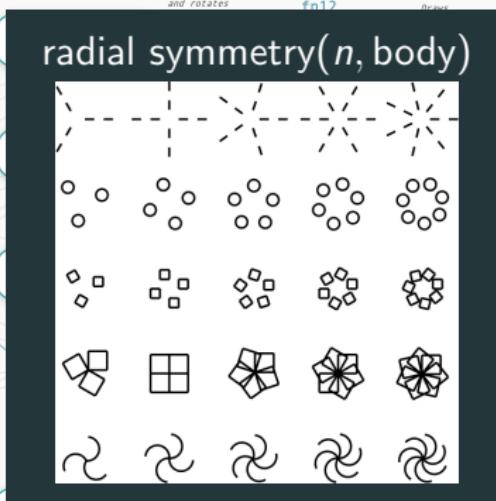
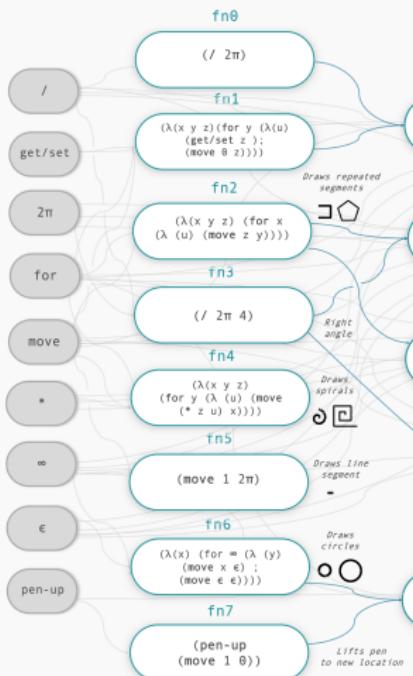


$(move 0 (fn0 7)); fn5 ; (fn13 4)$

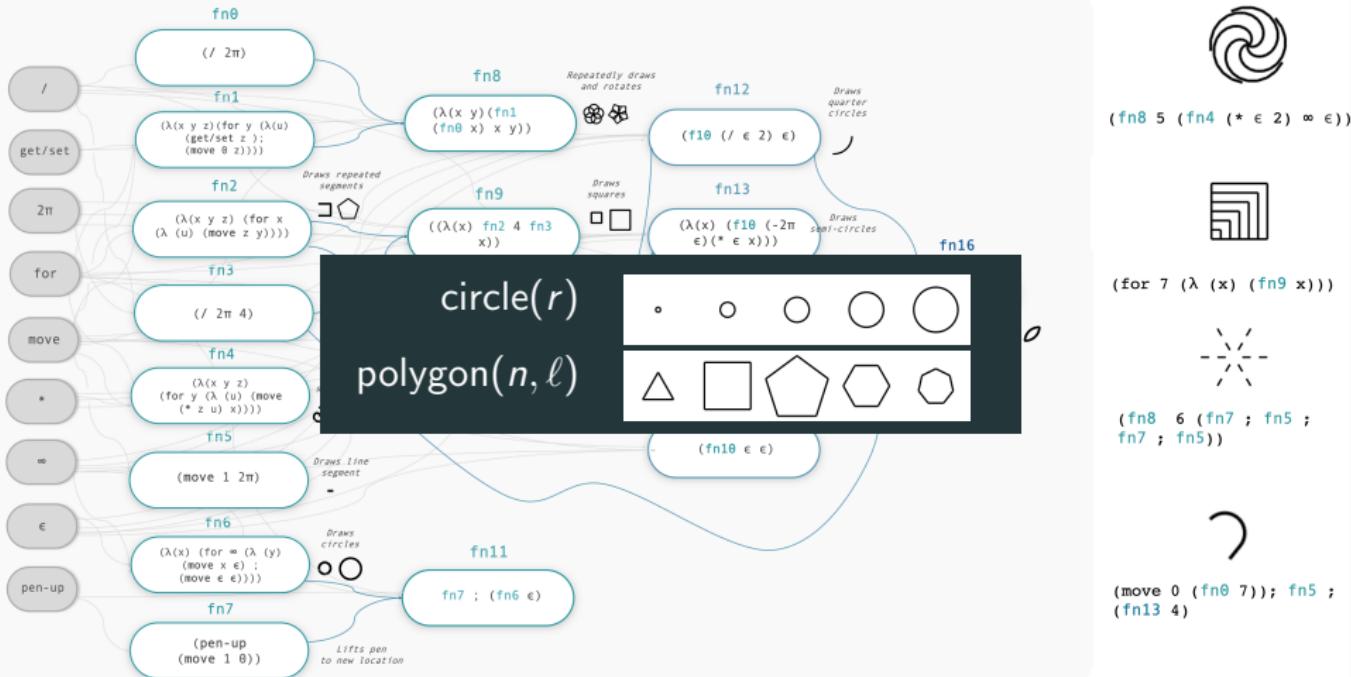
LOGO Turtle Graphics – learning an interpretable library



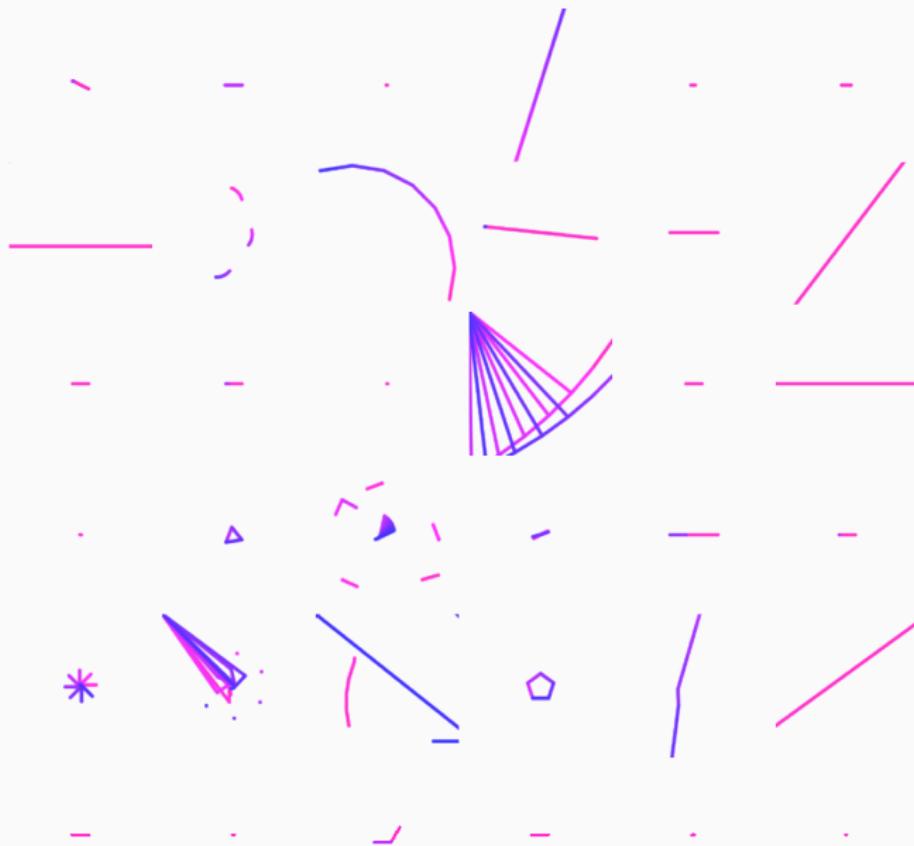
LOGO Turtle Graphics – learning an interpretable library



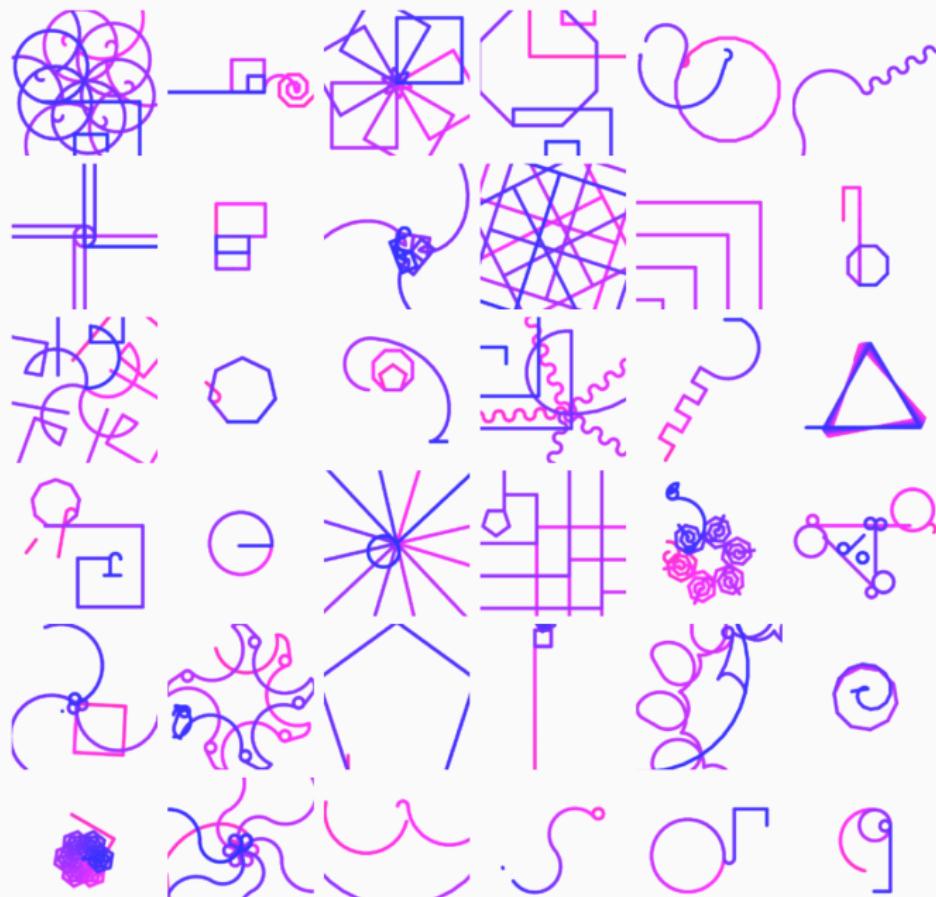
LOGO Turtle Graphics – learning an interpretable library



What does DreamCoder dream of? (before learning)

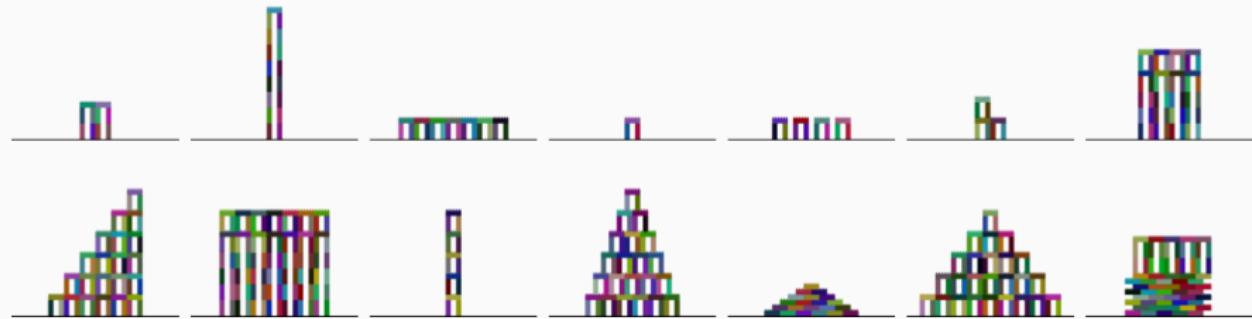


What does DreamCoder dream of? (after learning)



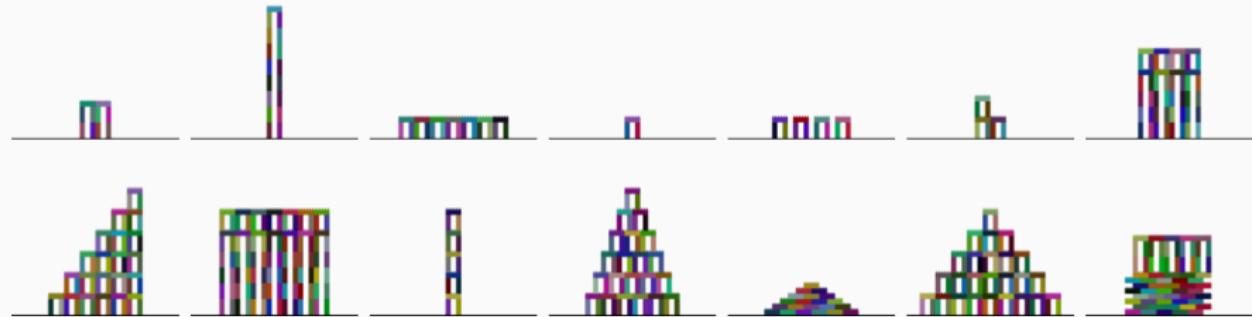
Planning to build towers

example tasks (112 total)



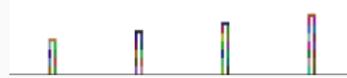
Planning to build towers

example tasks (112 total)

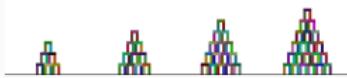


learned library routines (≈ 20 total)

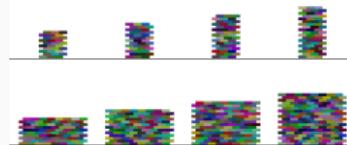
$\text{arch}(h)$



$\text{pyramid}(h)$



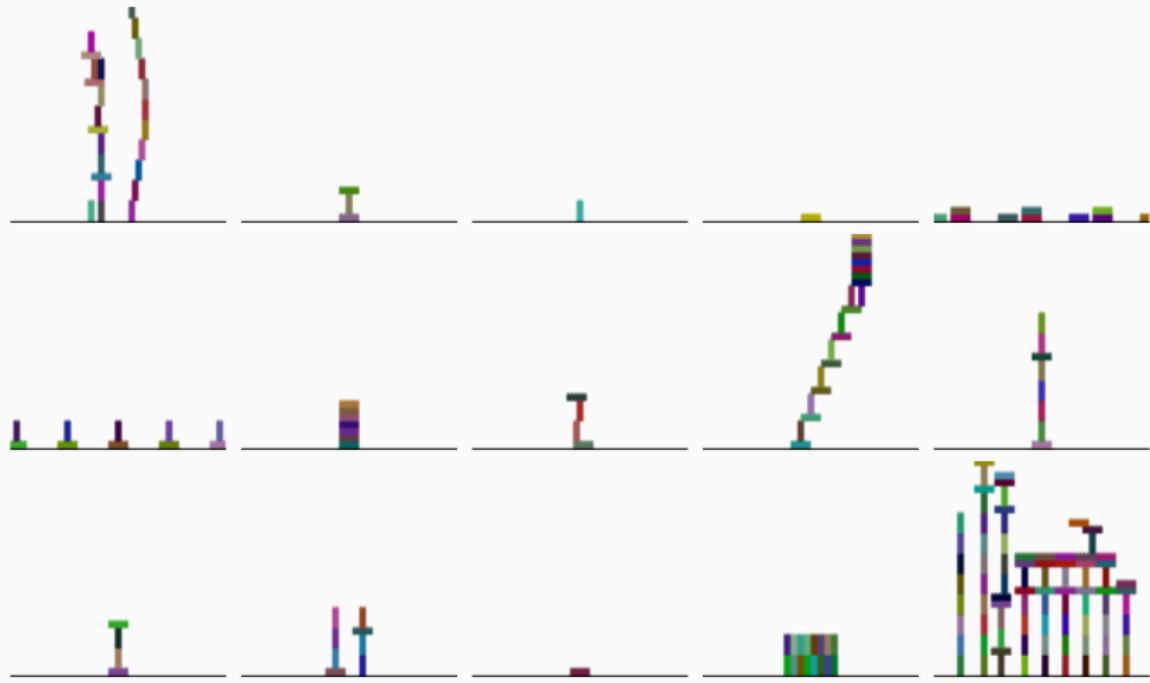
$\text{wall}(w, h)$



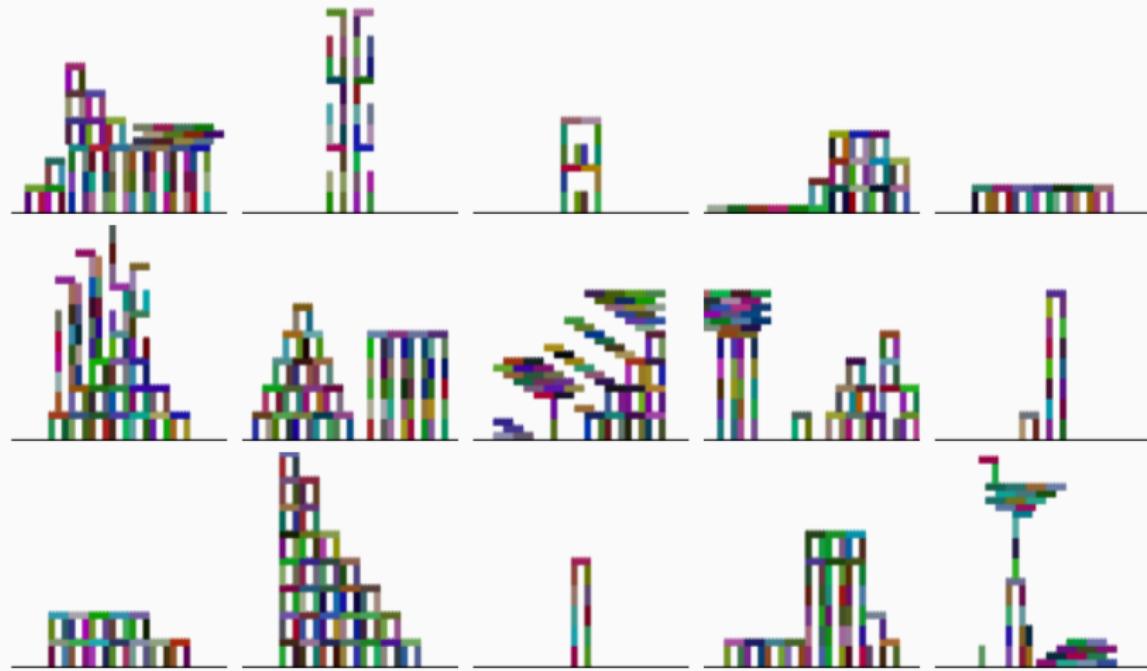
$\text{bridge}(w, h)$



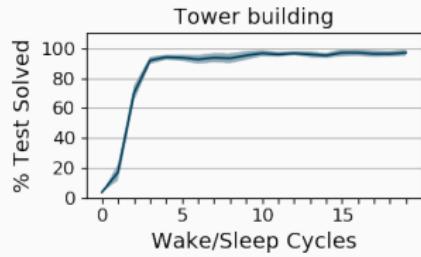
Dreams before learning



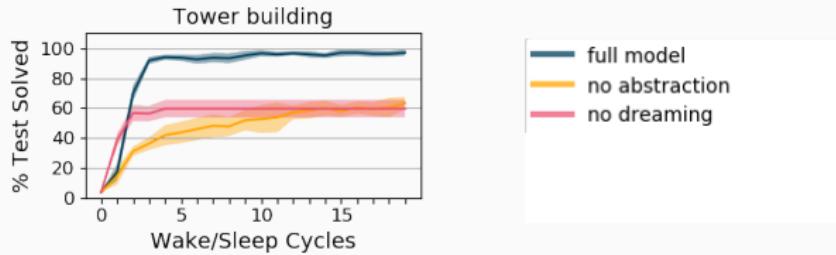
Dreams after learning



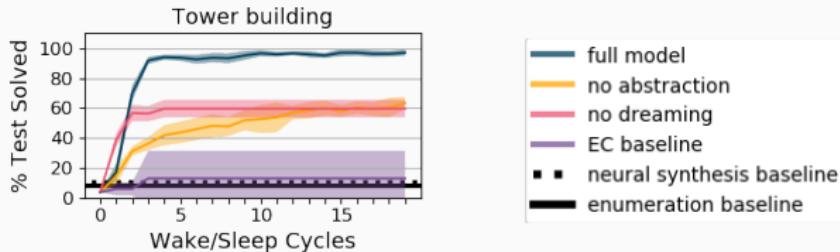
Learning dynamics



Learning dynamics

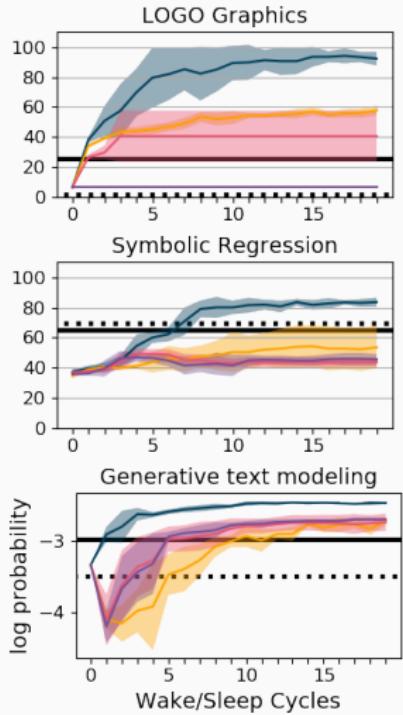
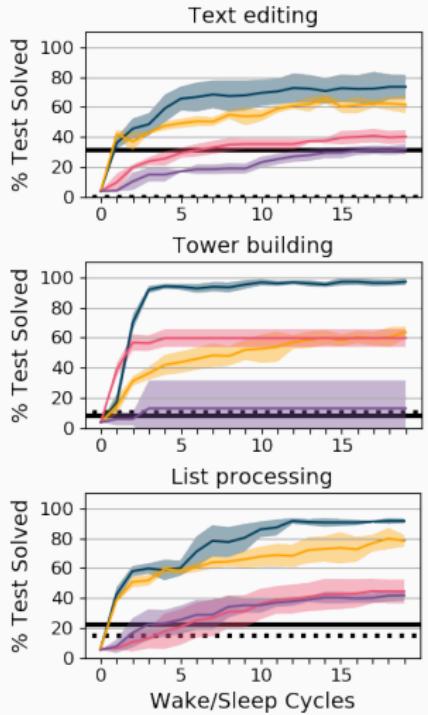


Learning dynamics



baselines: Exploration-Compression, EC [Dechter et al. 2013]
neural program synthesis, RobustFill [Devlin et al. 2017]
24 hours of brute-force enumeration

Learning dynamics



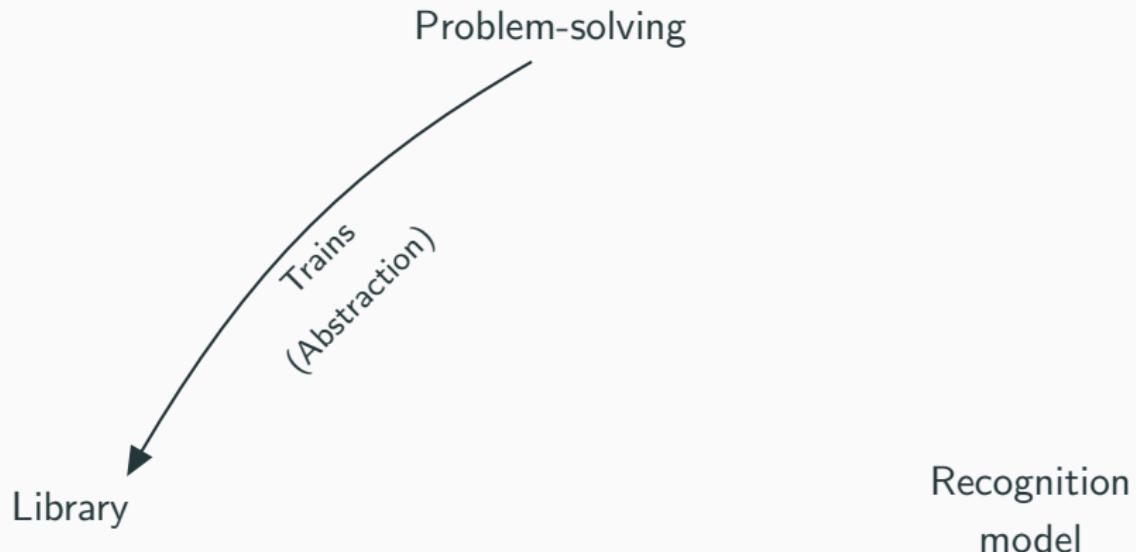
Synergy between dreaming and library learning

Problem-solving

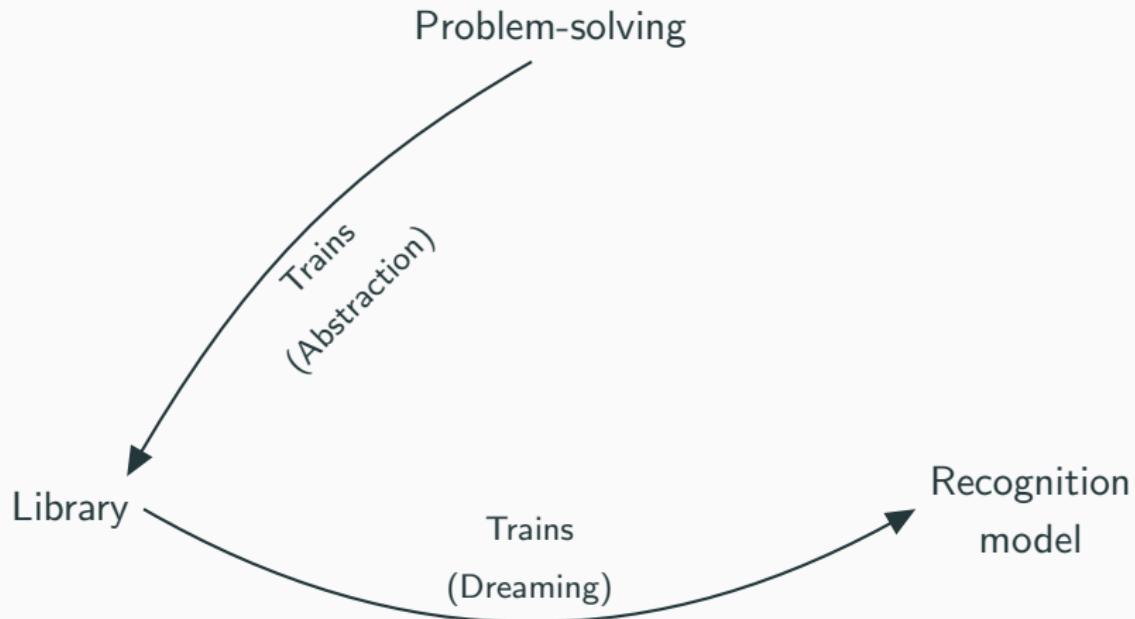
Library

Recognition
model

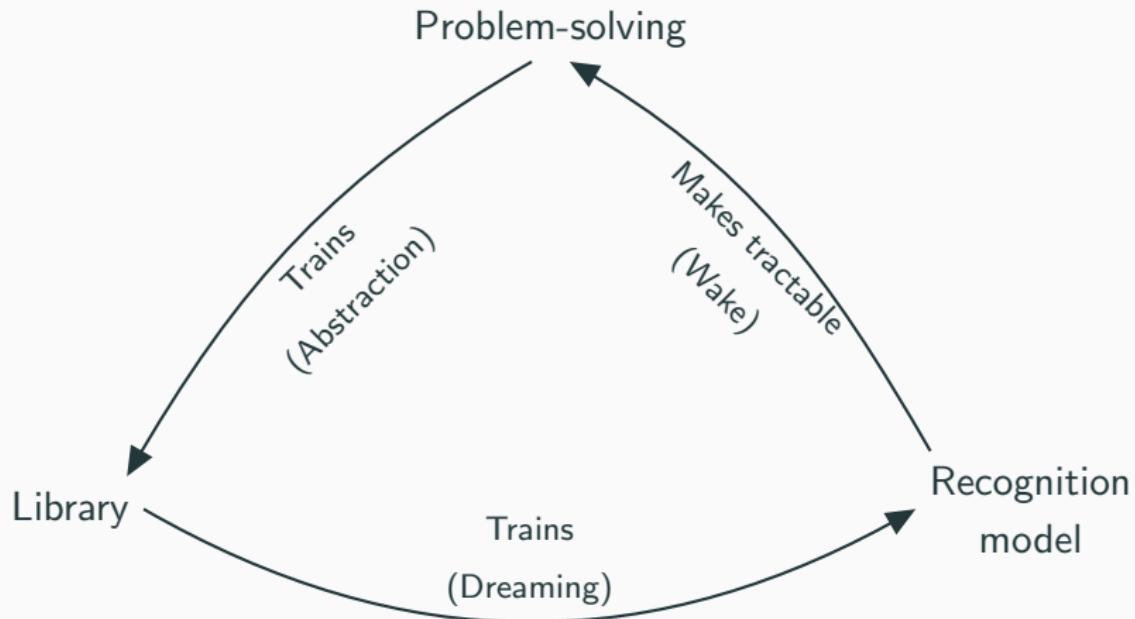
Synergy between dreaming and library learning



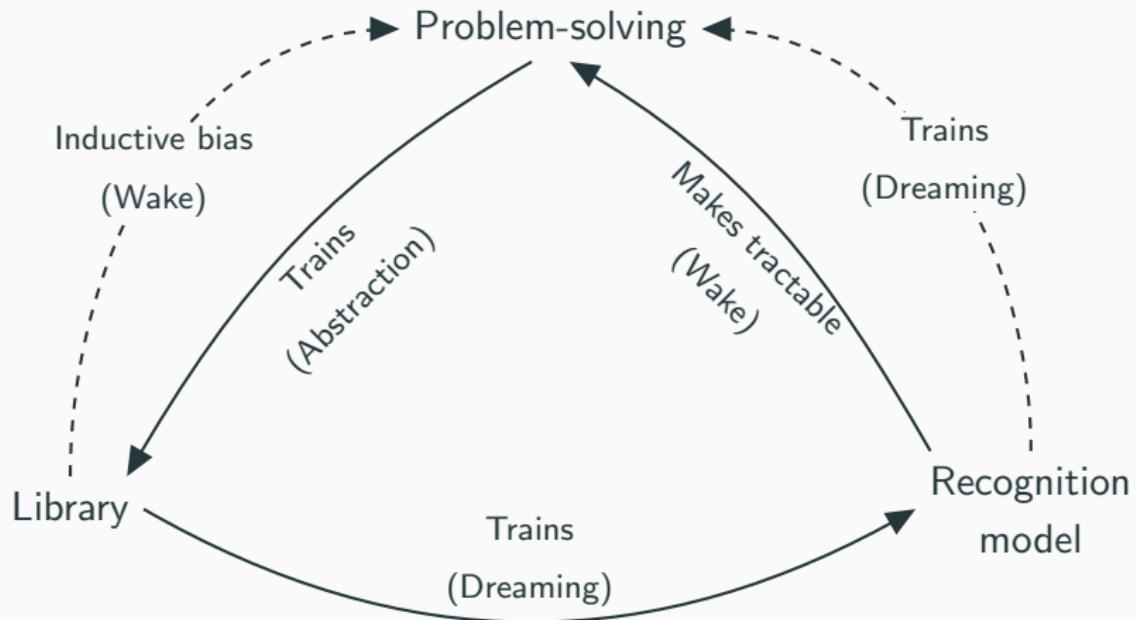
Synergy between dreaming and library learning



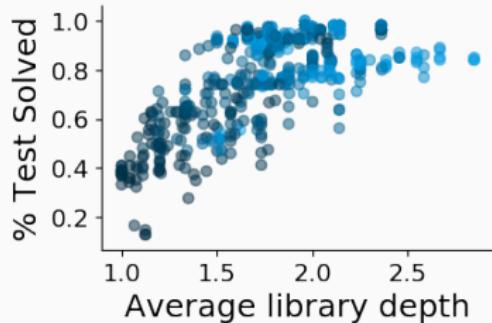
Synergy between dreaming and library learning



Synergy between dreaming and library learning



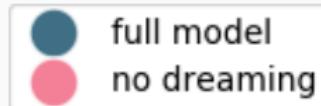
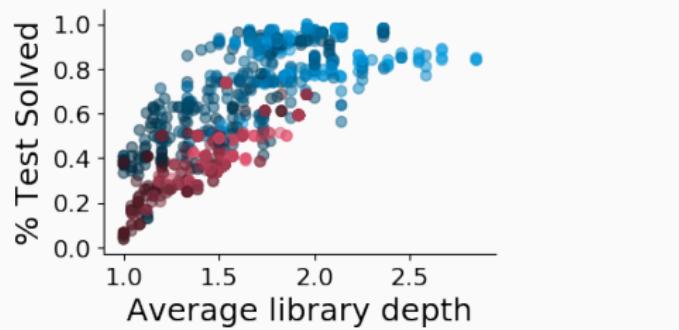
Evidence for dreaming bootstrapping better libraries



Darker: Early in learning

Brighter: Later in learning

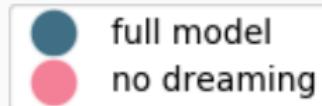
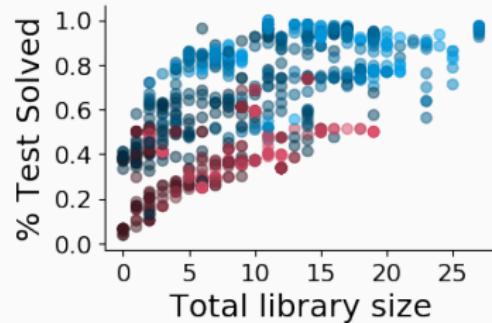
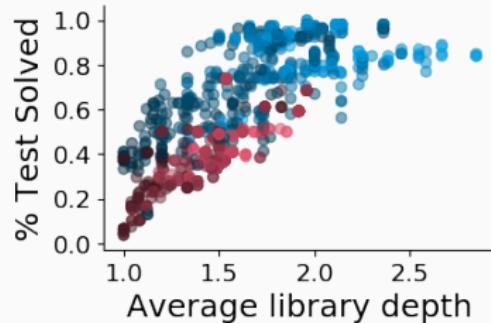
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Evidence for dreaming bootstrapping better libraries



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From learning libraries,
to learning languages

From learning libraries,
to learning languages

modern functional programming → physics

From learning libraries,
to learning languages

1950's Lisp → modern functional programming → physics

Physics Formula Sheet

Mechanics

$x = x_0 + v_{x0}t + \frac{1}{2}a_xt^2$	$a_t = \frac{v^2}{r}$	$ \vec{F}_{\text{spring}} = k x $
$v = v_0 + at$	$\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t^2$	$\text{PE}_{\text{spring}} = \frac{1}{2}kx^2$
$v_s^2 - v_{s0}^2 = 2a(x - x_0)$	$\omega = \omega_0 + \alpha t$	$T_{\text{spring}} = 2\pi\sqrt{\frac{m}{k}}$
$\bar{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{\text{net}}}{m}$	$T = \frac{2\pi}{\omega} = \frac{1}{f}$	$T_{\text{pendulum}} = 2\pi\sqrt{\frac{L}{g}}$
$ \vec{F}_{\text{friction}} \leq \mu \vec{F}_{\text{Normal}} $	$v = f\lambda$	
$\bar{p} = m\bar{v}$	$x = A\cos(2\pi ft)$	$ \vec{F}_{\text{gravity}} = G \frac{m_1 m_2}{r^2}$
$\Delta \bar{p} = \vec{F} \Delta t$	$\bar{a} = \frac{\sum \vec{F}}{I} = \frac{\vec{F}_{\text{net}}}{I}$	$ \vec{F}_{\text{gravity}} = m\bar{g}$
$KE = \frac{1}{2}mv^2$	$\vec{r} = r \times \vec{F}$	$\text{PE}_{\text{gravity}} = -G \frac{m_1 m_2}{r}$
$\Delta PE = mg\Delta y$	$L = I\omega$	$p = \frac{m}{V}$
$\Delta E = W = Fd\cos\theta$	$\Delta L = \tau \Delta t$	$KE = \frac{1}{2}I\omega^2$

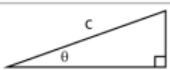
Electricity

$ \vec{F}_E = k \left \frac{q_1 q_2}{r^2} \right $	$\Delta V = IR$	$R = \frac{\rho l}{A}$
$I = \frac{\Delta q}{\Delta t}$		$P = I\Delta V$
$R_{\text{series}} = R_1 + R_2 + \dots + R_n$	$\frac{1}{R_{\text{parallel}}} = \frac{1}{R_1} + \frac{1}{R_2} + \dots + \frac{1}{R_n}$	

Geometry

Rectangle	$A = bh$	Rectangular Solid	$V = lwh$	Triangle	$A = \frac{1}{2}bh$
Circle	$A = \pi r^2$	Cylinder	$V = \pi r^2 l$	Sphere	$V = \frac{4}{3}\pi r^3$
	$C = 2\pi r$		$S = 2\pi rl + 2\pi r^2$		$S = 4\pi r^2$

Trigonometry



$$\begin{array}{ccccccc} c & & & & & & \\ & a & & & & & \\ & & & & & & \\ & & & & \theta & & \\ & & & & & & \\ & & & & \square & & \end{array}$$

$$c^2 = a^2 + b^2 \quad \sin\theta = \frac{a}{c} \quad \cos\theta = \frac{b}{c} \quad \tan\theta = \frac{a}{b}$$

Variables

a = acceleration
 A = amplitude
 A = Area
 b = base length
 C = circumference
 d = distance
 E = energy
 f = frequency
 F = force
 h = height
 I = current
 I = rotational inertia
 KE = kinetic energy
 k = spring constant
 L = angular momentum
 l = length
 m = mass
 P = power
 p = momentum
 q = charge
 r = radius
 R = resistance
 S = surface area
 T = period
 t = time
 PE = potential energy
 V = electric potential
 V = volume
 v = velocity
 w = width
 W = work
 x = position
 y = height
 α = angular acceleration
 λ = wavelength
 μ = coefficient of friction

Growing languages for vector algebra and physics

Initial Primitives

map
zip

cons

empty

cdr

power

fold

car

+

-

*

/

0

1

π

Physics Equations

Newton's Second Law

$$\vec{a} = \frac{1}{m} \sum_i \vec{F}_i$$

Parallel Resistors

$$R_{total} = \left(\sum_i \frac{1}{R_i} \right)^{-1}$$

Work

$$U = \vec{F} \cdot \vec{d}$$

Force in a Magnetic Field

$$|\vec{F}| = q |\vec{v} \times \vec{B}|$$

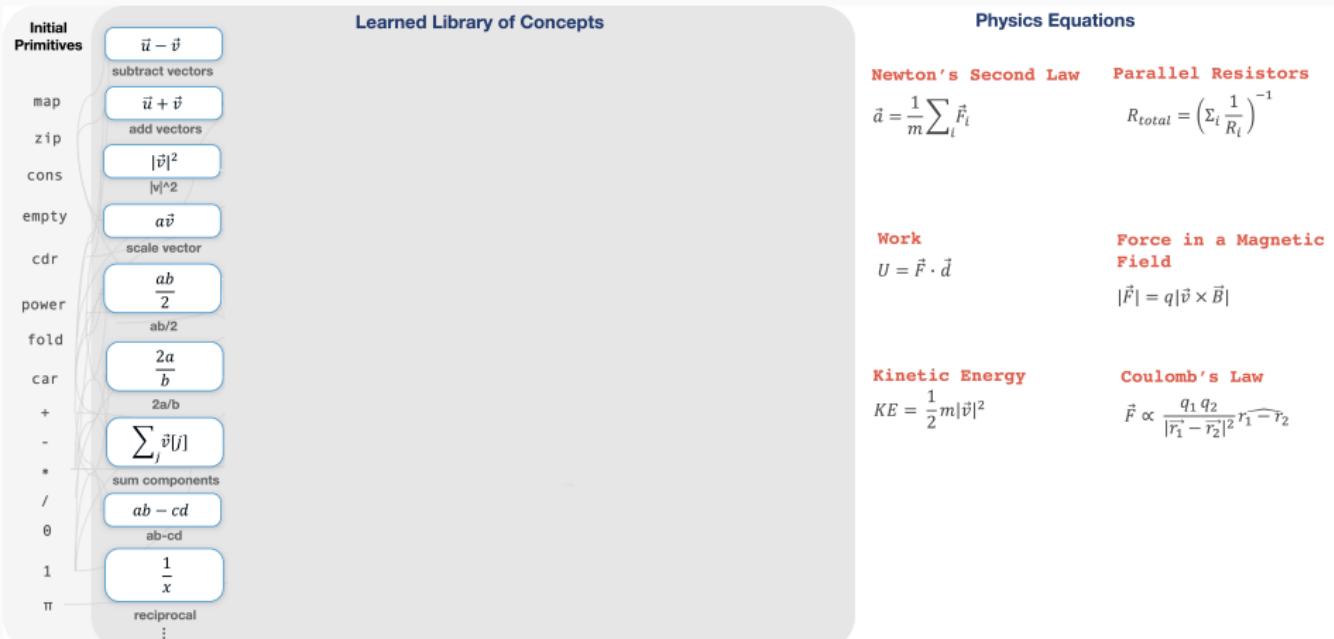
Kinetic Energy

$$KE = \frac{1}{2} m |\vec{v}|^2$$

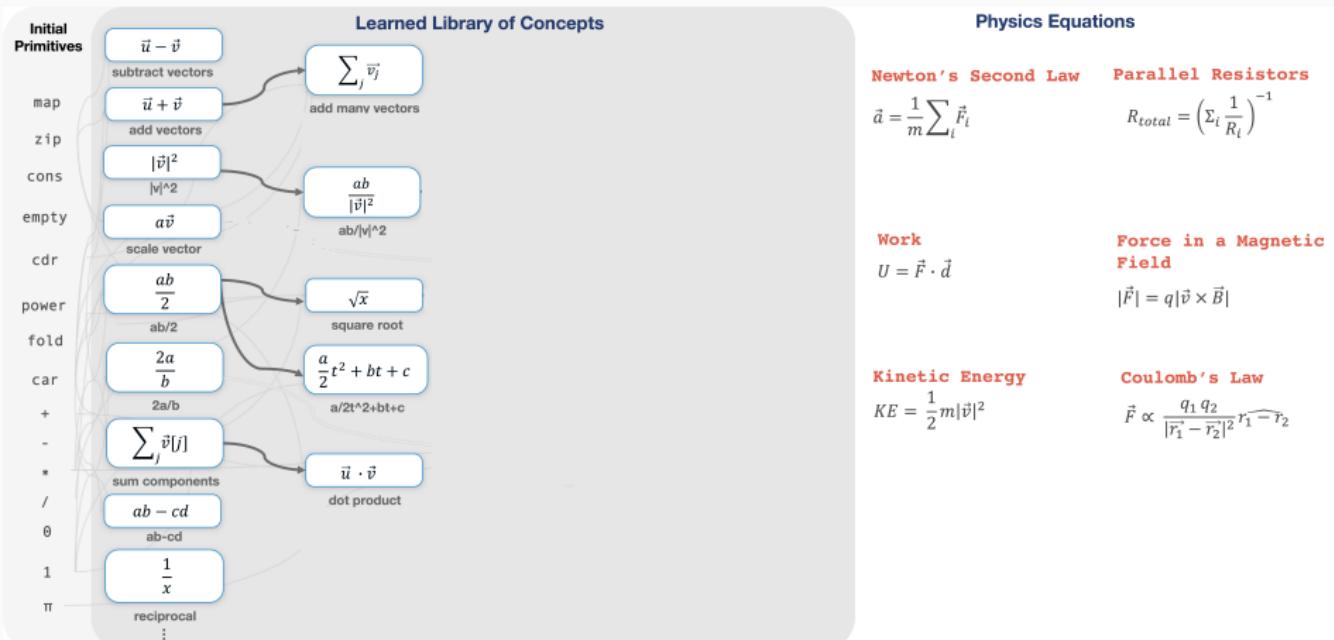
Coulomb's Law

$$\vec{F} \propto \frac{q_1 q_2}{|\vec{r}_1 - \vec{r}_2|^2} \hat{r}_1 - \hat{r}_2$$

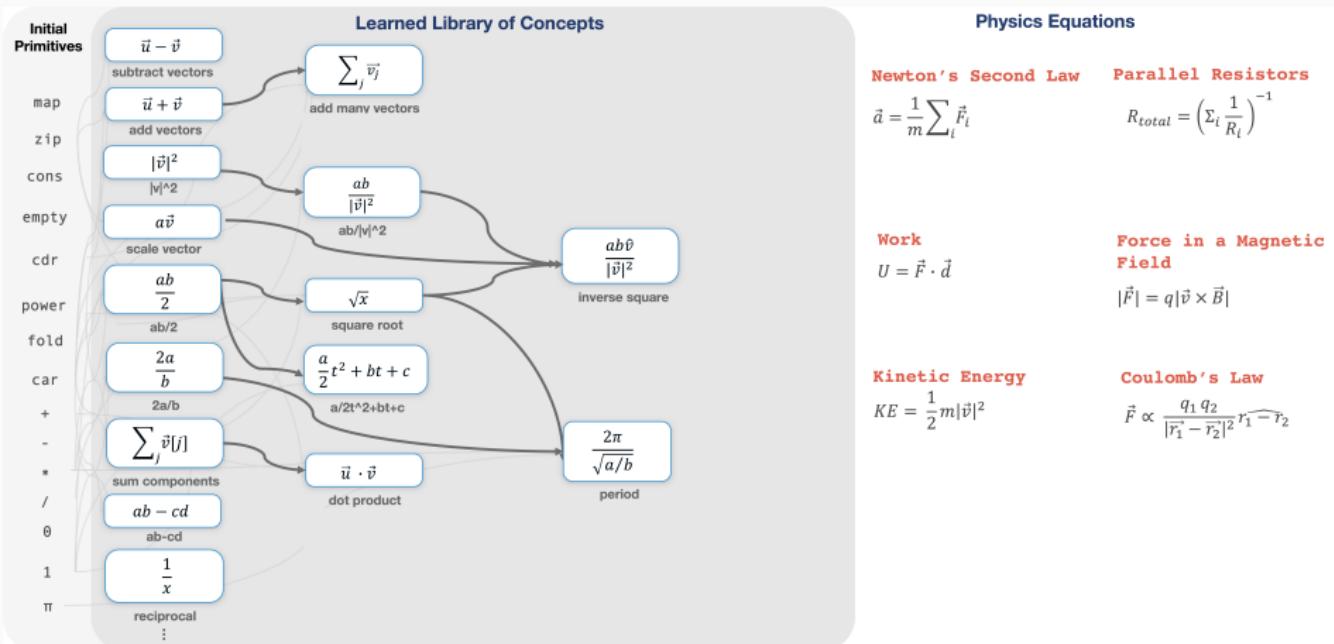
Growing languages for vector algebra and physics



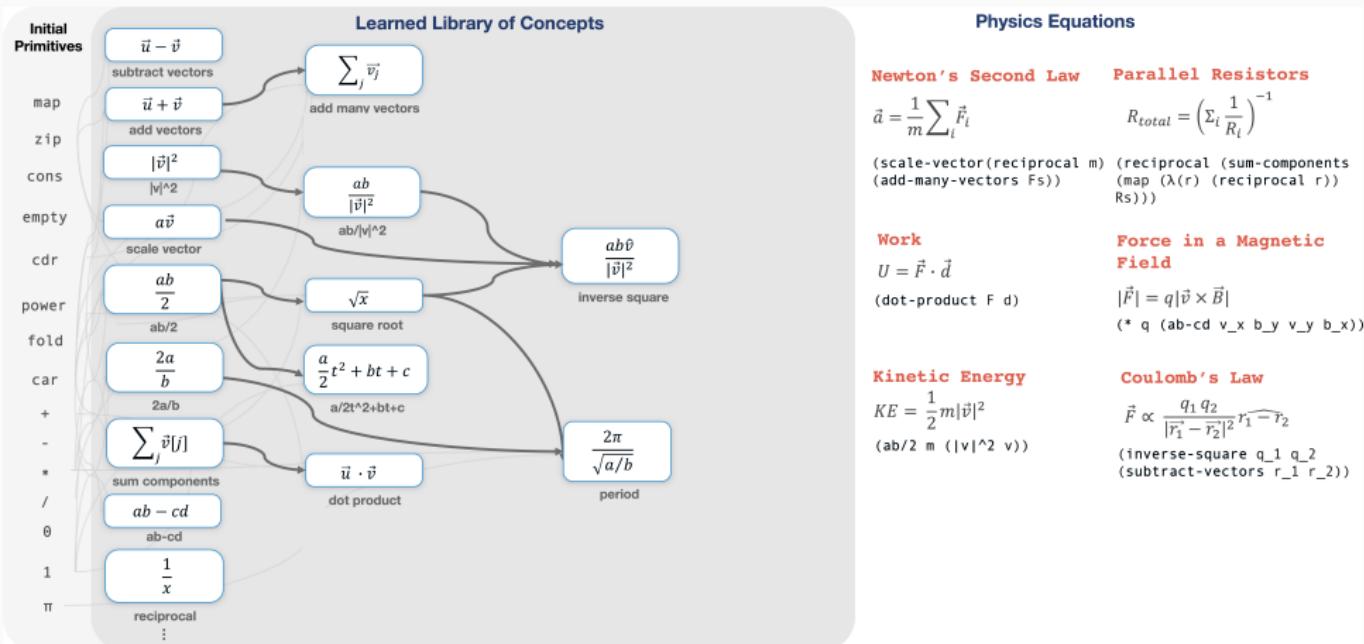
Growing languages for vector algebra and physics



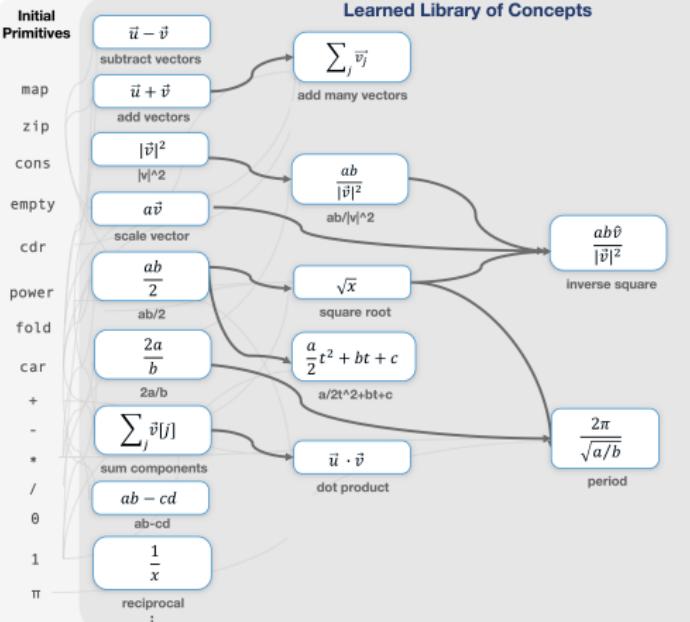
Growing languages for vector algebra and physics



Growing languages for vector algebra and physics



Growing languages for vector algebra and physics



Physics Equations

Newton's Second Law **Parallel Resistors**

$$\ddot{\vec{a}} = \frac{1}{m} \sum_l \vec{F}_l$$

$$R_{total} = \left(\sum_i \frac{1}{R_i} \right)^{-1}$$

(scale-vector(reciprocal m) (reciprocal (sum-components (add-many-vectors Fs))) (map (lambda(r) (reciprocal r)) Rs)))

Work

$$U = \vec{F} \cdot \vec{d}$$

(dot-product F d)

Force in a Magnetic Field

$$|\vec{F}| = q |\vec{v} \times \vec{B}|$$

(* q (ab-cd v_x b_y v_y b_x))

Kinetic Energy

$$KE = \frac{1}{2} m |\vec{v}|^2$$

(ab/2 m (|v|^2 v))

Coulomb's Law

$$\vec{F} \propto \frac{q_1 q_2}{|\vec{r}_1 - \vec{r}_2|^2} \hat{r}_1 - \hat{r}_2$$

(inverse-square q_1 q_2
(subtract-vectors r_1 r_2))

(lambda (x y z u) (map (lambda (v) (* (/ (* (power (/ (* x x) (fold (zip z u (lambda (w a) (- w a)))) theta (lambda (b c) (+ (* b b) c)))) (/ (* 1 1) (+ 1 1)))) y) (fold (zip z u (lambda (d e) (- d e)))) theta (lambda (f g) (+ (* f f) g)))) v)) (zip z u (lambda (h i) (- h i))))

Solution to Coulomb's Law if expressed in initial primitives

Growing a language for recursive programming

Initial Primitives

Y
combinator
cons
car
cdr
nil
if
nil?
+
-
0
1
=

Recursive Programming Algorithms

Stutter

[] → []
[] → []

Take every other

[] → []
[] → []

List lengths

[, []] → [3 1]
[[], [], []] → [2 0 1]

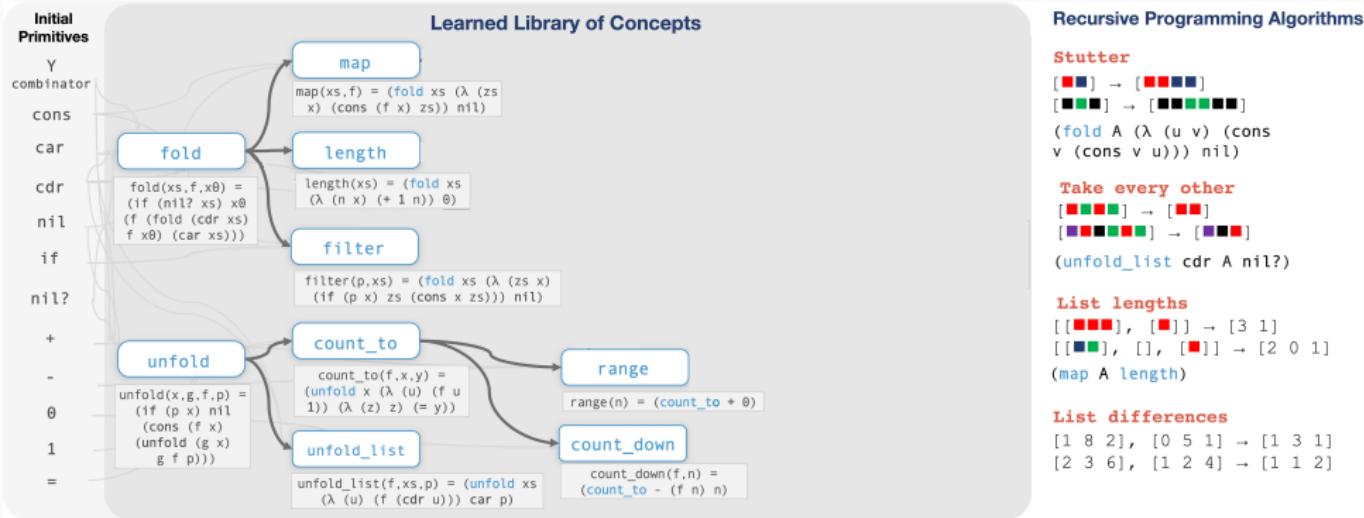
List differences

[1 8 2], [0 5 1] → [1 3 1]
[2 3 6], [1 2 4] → [1 1 2]

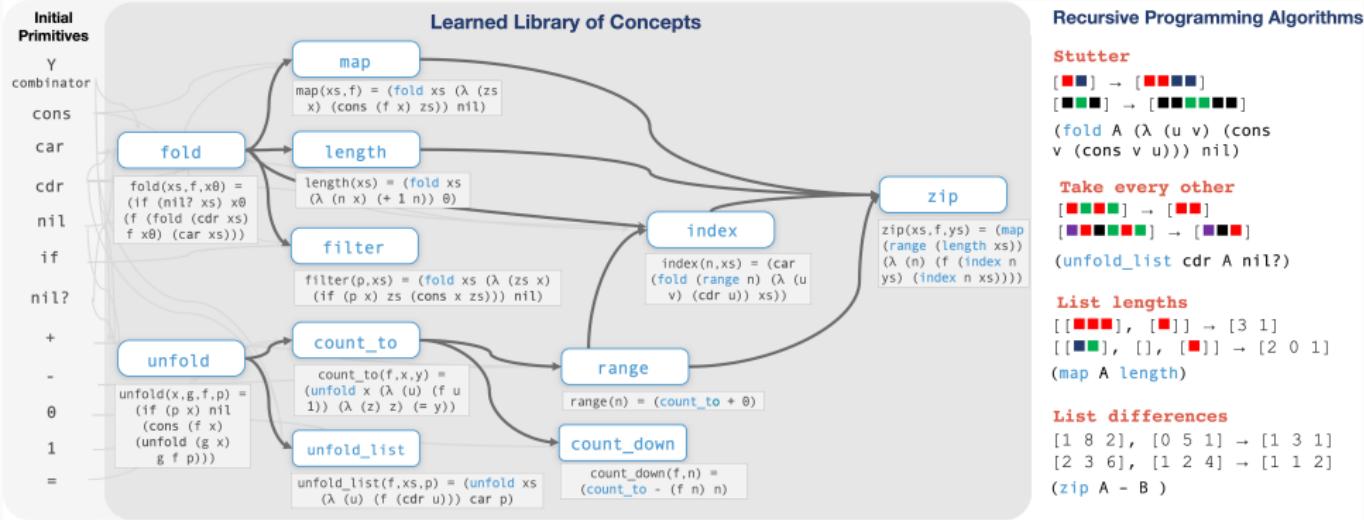
Growing a language for recursive programming



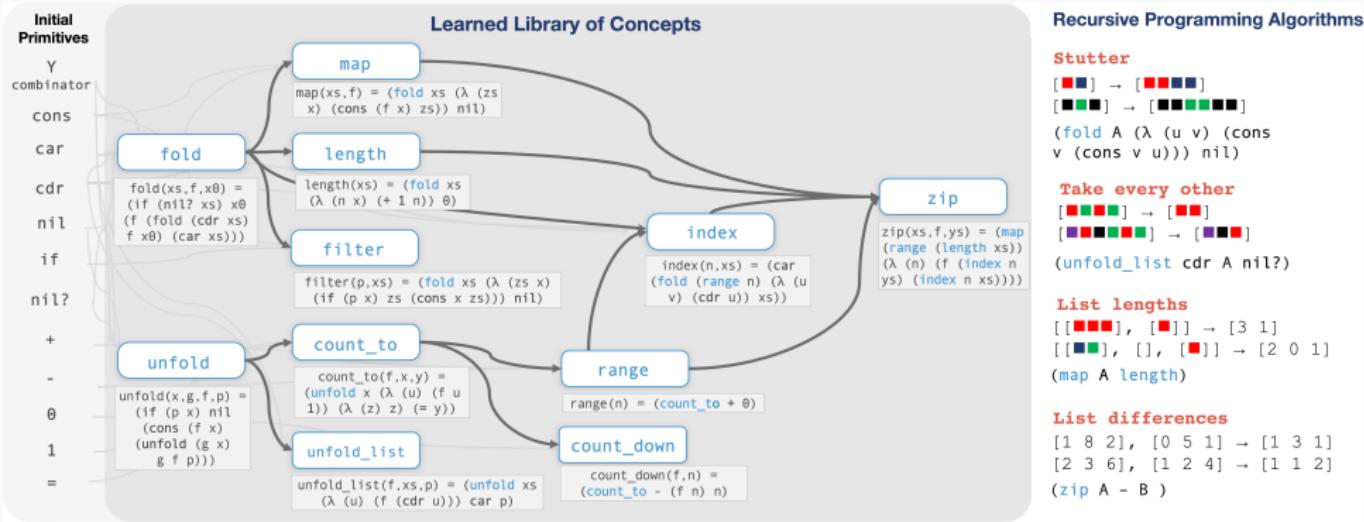
Growing a language for recursive programming



Growing a language for recursive programming

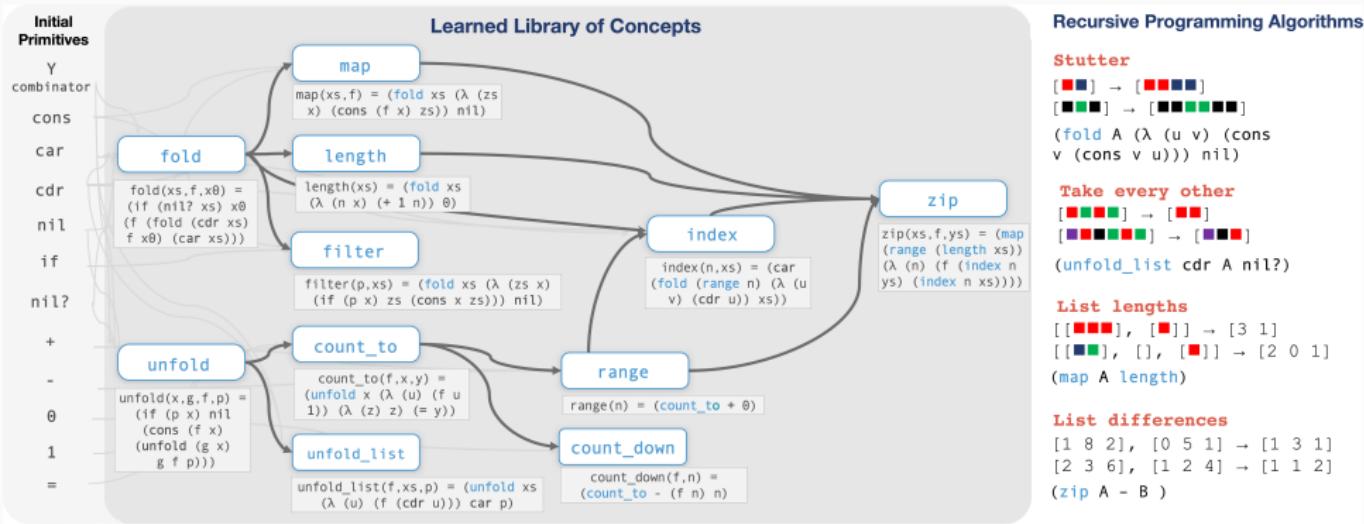


Growing a language for recursive programming



Origami Programming: Jeremy Gibbons, 2003

Growing a language for recursive programming



1 year of compute. 5 days on 64 CPUs.



Origami Programming: Jeremy Gibbons, 2003

Lessons

Symbols aren't necessarily interpretable. Flexibly grow the language based on experience to make it more powerful *and* more human understandable

Learning-from-scratch is possible in principle. Don't do it. But program induction makes it convenient to build in what we know how to build in, and then learn and adapt on top of that

Program Induction and perception
learning to learn
model discovery
the future

What we want for the future of machine learning

Strong generalization

Bootstrapping, learning-to-learn, representation learning

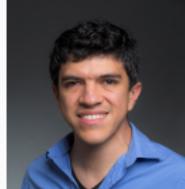
Discovering knowledge that humans can understand and build on

Collaborators

Josh
Tenenbaum



Armando
Solar-Lezama



Tim O'Donnell



Adam Albright



Max Nye



Cathy Wong



Yewen Pu



Dan Ritchie



Mathias Sable-Meyer



Lucas Morales



Tao Du



Collaborators

Josh Tenenbaum



Armando Solar-Lezama



Tim O'Donnell



Adam Albright



Max Nye



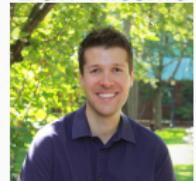
Cathy Wong



Yewen Pu



Dan Ritchie



Mathias Sable-Meyer



Lucas Morales



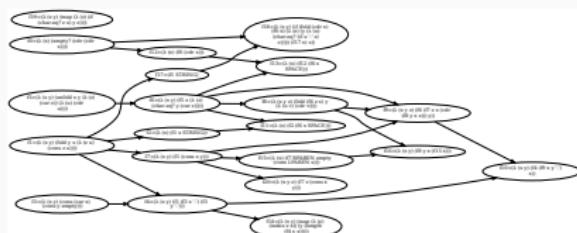
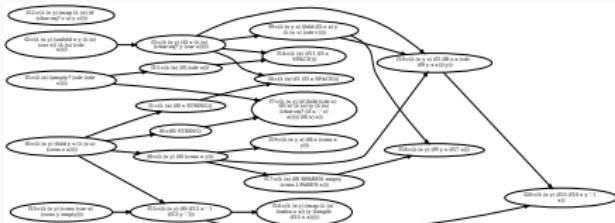
Tao Du



thank
you

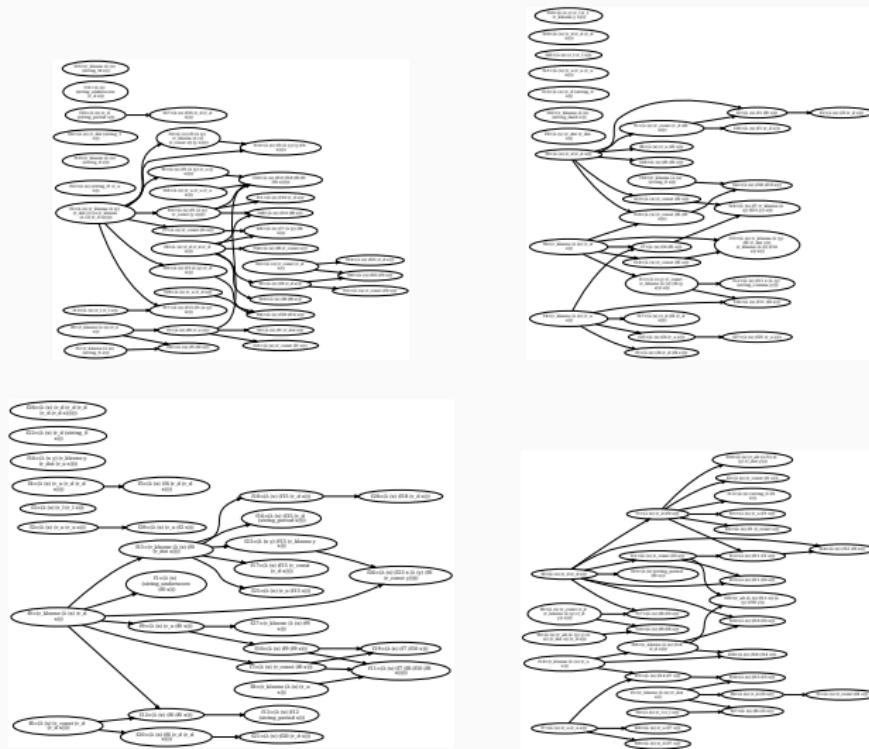
Library structure: Text Editing

DreamCoder learns libraries for FlashFill-style text editing [Gulwani 2012]

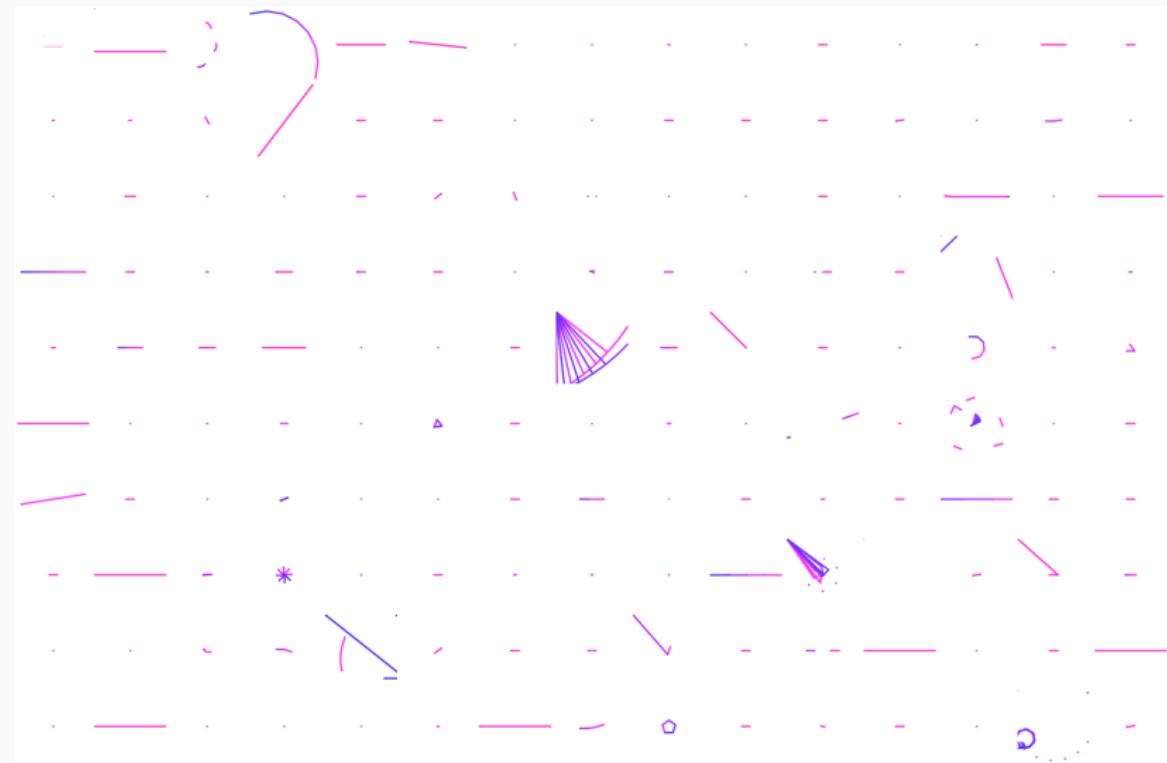


Library structure: Generating Text

Libraries for probabilistic generative models over text:
data from crawling web for CSV files



150 random dreams before learning



150 random dreams after learning

