DreamCoder: Growing generalizable, interpretable knowledge with wake-sleep program learning

Kevin Ellis
Collaborators: Catherine Wong, Maxwell Nye, Mathias Sablé-Meyer, Lucas Morales, Armando Solar-Lezama, Joshua B. Tenenbaum

2020

CAP NeurIPS workshop

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

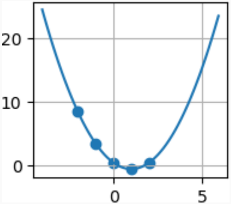
2. Learning=adding to that body of knowledge=
   making new programs=program synthesis

Why program induction?

Why program induction?

strong generalization

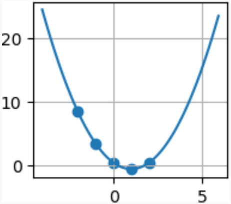
+data efficiency




```
f(x)=(x-1)**2 - 0.5
```

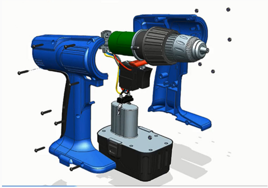
Why program induction?

strong generalization
+data efficiency

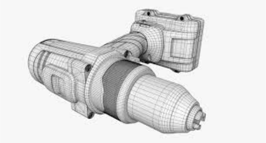


f(x)=(x-1)**2 - 0.5

interpretability

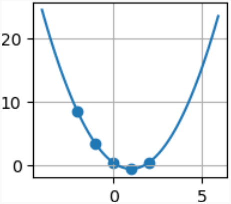


vs



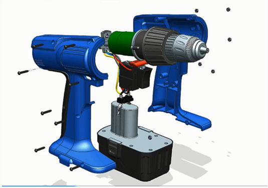
Why program induction?

strong generalization
+data efficiency

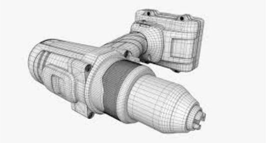


`f(x)=(x-1)**2 - 0.5`

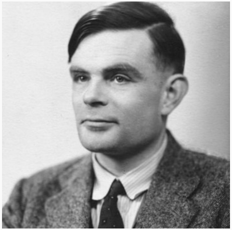
interpretability



vs



universal expressivity



FlashFill (Gulwani 2012)

EXAMPLE 3 (Directory Name Extraction). *Consider the following example taken from an excel online help forum.*

Input v_1	*Output*
Company\Code\index.html	*Company\Code*
Company\Docs\Spec\specs.doc	*Company\Docs\Spec*

String Program:

$\mathtt{SubStr}(v_1, \mathtt{CPos}(0), \mathtt{Pos}(SlashTok, \epsilon, -1))$

FlashFill (Gulwani 2012)

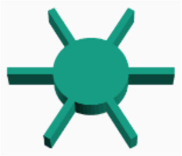
EXAMPLE 3 (Directory Name Extraction). *Consider the following example taken from an excel online help forum.*

Input v_1	*Output*
Company\Code\index.html	*Company\Code*
Company\Docs\Spec\specs.doc	*Company\Docs\Spec*

String Program:

$\mathtt{SubStr}(v_1, \mathtt{CPos}(0), \mathtt{Pos}(SlashTok, \epsilon, -1))$

Szalinski (Nandi 2020)



(a) CAD model of ship's wheel

```
(Union
 (Cylinder [1, 5, 5])
 (Fold Union
  (Tabulate (i 6)
   (Rotate [0, 0, 60i]
    (Translate [1, −0.5, 0]
     (Cuboid [10, 1, 1]))))))
```

(b) Caddy program

FlashFill (Gulwani 2012)

EXAMPLE 3 (Directory Name Extraction). *Consider the following example taken from an excel online help forum.*

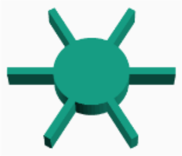
Input v_1	*Output*
Company\Code\index.html	*Company\Code*
Company\Docs\Spec\specs.doc	*Company\Docs\Spec*

String Program:

$\mathit{SubStr}(v_1, \mathit{CPos}(0), \mathit{Pos}(\mathit{SlashTok}, \epsilon, -1))$

$$
\begin{array}{rcl}
\text{String expr } P & := & \mathtt{Switch}((\mathrm{b}_1, \mathrm{e}_1), \cdot\cdot, (\mathrm{b}_n, \mathrm{e}_n)) \\
\text{Bool b} & := & \mathrm{d}_1 \vee \cdot\cdot \vee \mathrm{d}_n \\
\text{Conjunct d} & := & \pi_1 \wedge \cdot\cdot \wedge \pi_n \\
\text{Predicate } \pi & := & \mathtt{Match}(v_i, \mathrm{r}, k) \mid \neg\, \mathtt{Match}(v_i, \mathrm{r}, k) \\
\text{Trace expr e} & := & \mathtt{Concatenate}(\mathrm{f}_1, \cdot\cdot, \mathrm{f}_n) \\
\text{Atomic expr f} & := & \mathtt{SubStr}(v_i, \mathrm{p}_1, \mathrm{p}_2) \\
 & \mid & \mathtt{ConstStr}(s) \\
 & \mid & \mathtt{Loop}(\lambda w : \mathrm{e}) \\
\text{Position p} & := & \mathtt{CPos}(k) \mid \mathtt{Pos}(\mathrm{r}_1, \mathrm{r}_2, \mathrm{c}) \\
\text{Integer expr c} & := & k \mid k_1 w + k_2 \\
\text{Regular Expression r} & := & \mathtt{TokenSeq}(\mathrm{T}_1, \cdot\cdot, \mathrm{T}_m) \\
\text{Token T} & := & C+ \mid [\neg C]+ \\
 & \mid & \text{SpecialToken}
\end{array}
$$

Szalinski (Nandi 2020)



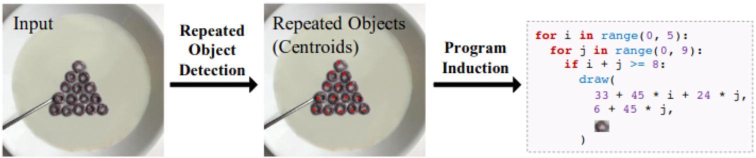
(a) CAD model of ship's wheel

```
(Union
 (Cylinder [1, 5, 5])
 (Fold Union
  (Tabulate (i 6)
   (Rotate [0, 0, 60i]
    (Translate [1, −0.5, 0]
     (Cuboid [10, 1, 1]))))))
```

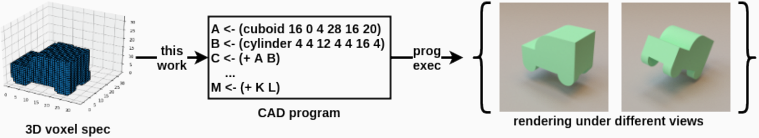
(b) Caddy program

$$
\begin{array}{lll}
\text{op} & ::= & + \mid - \mid \times \mid / \qquad \text{num} ::= \mathbb{R} \mid \langle \mathit{var} \rangle \mid \langle \mathit{num} \rangle\ \langle \mathit{op} \rangle\ \langle \mathit{num} \rangle \\
\text{vec2} & ::= & [\langle \mathit{num} \rangle, \langle \mathit{num} \rangle] \qquad \text{vec3} ::= [\langle \mathit{num} \rangle, \langle \mathit{num} \rangle, \langle \mathit{num} \rangle] \\
\text{affine} & ::= & \text{Translate} \mid \text{Rotate} \mid \text{Scale} \mid \textbf{TranslateSpherical} \\
\text{binop} & ::= & \text{Union} \mid \text{Difference} \mid \text{Intersection} \\
\text{cad} & ::= & (\text{Cuboid } \langle \mathit{vec3} \rangle) \mid (\text{Sphere } \langle \mathit{num} \rangle) \\
 & \mid & (\text{Cylinder } \langle \mathit{vec2} \rangle) \mid (\text{HexPrism } \langle \mathit{vec2} \rangle) \mid \ldots \\
 & \mid & (\langle \mathit{affine} \rangle\ \langle \mathit{vec3} \rangle\ \langle \mathit{cad} \rangle) \\
 & \mid & (\langle \mathit{binop} \rangle\ \langle \mathit{cad} \rangle\ \langle \mathit{cad} \rangle) \\
 & \mid & \textbf{(Fold } \langle \mathit{binop} \rangle\ \langle \mathit{cad\text{-}list} \rangle \textbf{)} \\
\text{cad-list} & ::= & (\text{List } \langle \mathit{cad} \rangle +) \\
 & \mid & (\text{Concat } \langle \mathit{cad\text{-}list} \rangle +) \\
 & \mid & (\text{Tabulate } (\langle \mathit{var} \rangle\ \ \mathbb{Z}^+)+\ \langle \mathit{cad} \rangle) \\
 & \mid & (\text{Map2 } \langle \mathit{affine} \rangle\ \langle \mathit{vec3\text{-}list} \rangle\ \langle \mathit{cad\text{-}list} \rangle) \\
\text{vec3-list} & ::= & (\text{List } \langle \mathit{vec3} \rangle +) \\
 & \mid & (\text{Concat } \langle \mathit{vec3\text{-}list} \rangle +) \\
 & \mid & (\text{Tabulate } (\langle \mathit{var} \rangle\ \ \mathbb{Z}^+)+\ \langle \mathit{vec3} \rangle)
\end{array}
$$

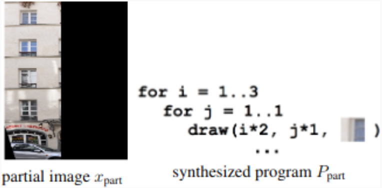
Visual programs

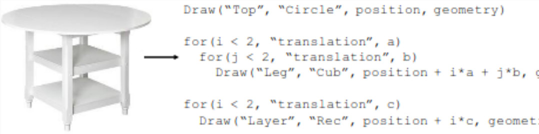


Mao*, Zhang*, et al 2019



Ellis*, Nye*, Pu*, Sosa*, et al 2019

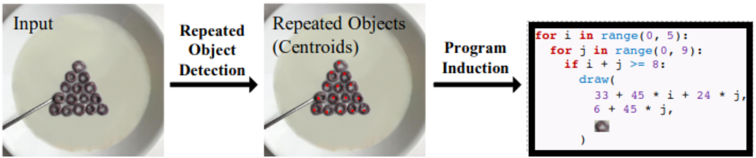




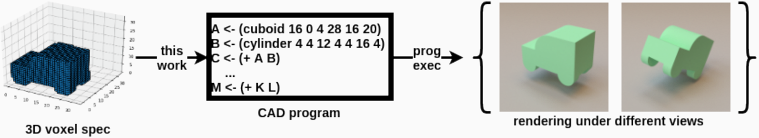
Young et al 2019

Tian et al 2019

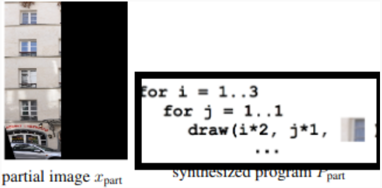
Where does this language come from?

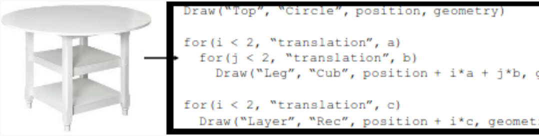


Mao*, Zhang*, et al 2019



Ellis*, Nye*, Pu*, Sosa*, et al 2019

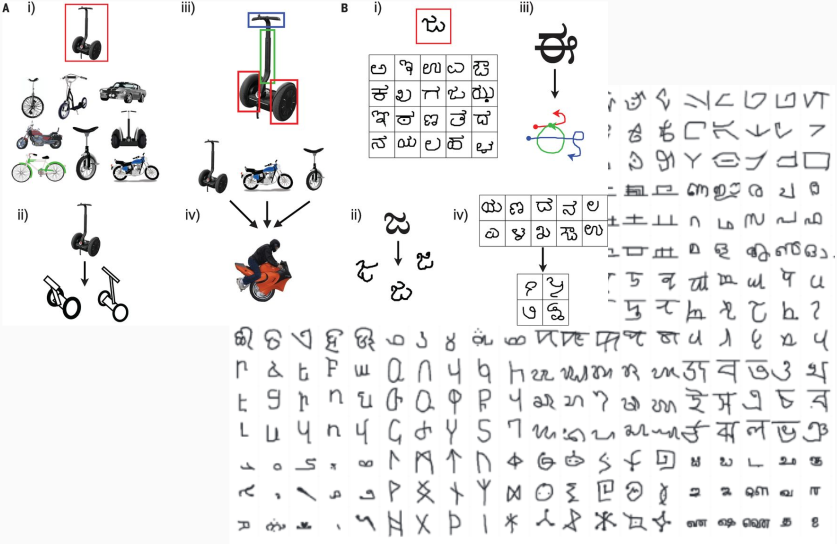




Young et al 2019

Tian et al 2019

Human-level Program induction



Lake et al 2015

Program Induction and learning to learn

learning a DSL

learning to synthesize

synergy between DSL+learned synthesizer

Learning to write code

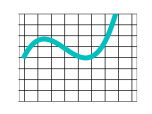
Goal: acquire domain-specific knowledge needed to induce a class of programs

- Library of abstractions (domain specific language)
- Inference strategy (synthesis algorithm)

Learning to write code

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

- Library of abstractions (domain specific language)
- Inference strategy (synthesis algorithm)



→ Learned program inducer → program: $f(x) = 0.3x^3 + 1.1x^2 - 2x + 0.6$

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]
...

Ellis, Morales, Sable-Meyer, Solar-Lezama, Tenenbaum. NeurIPS 2018.
Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Library learning

Initial Primitives

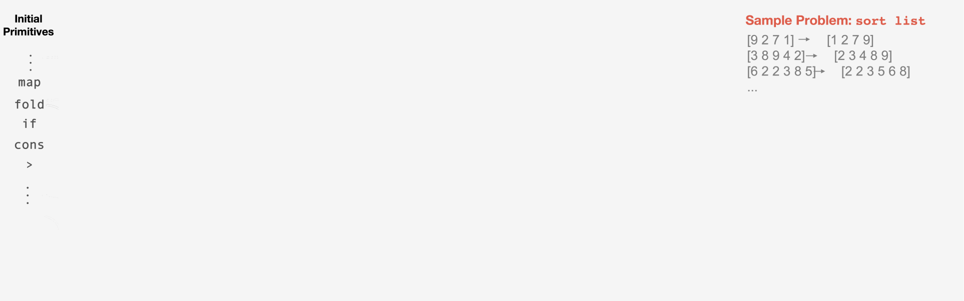
⋮
`map`
`fold`
`if`
`cons`
`>`
⋮

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]
...

Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Library learning



Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

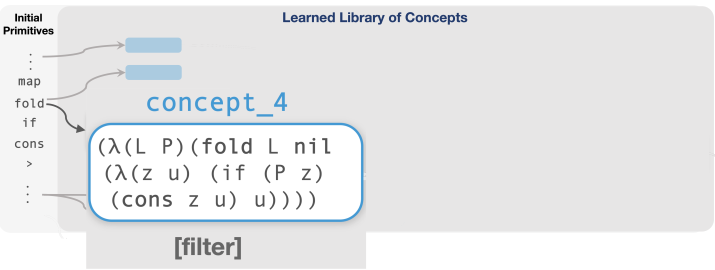
Library learning

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]
...

Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Library learning



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]
...

Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

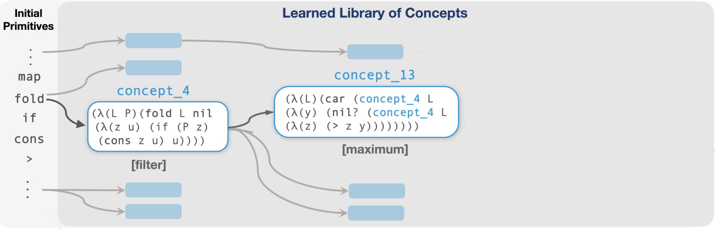
Library learning

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]
...

Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Library learning

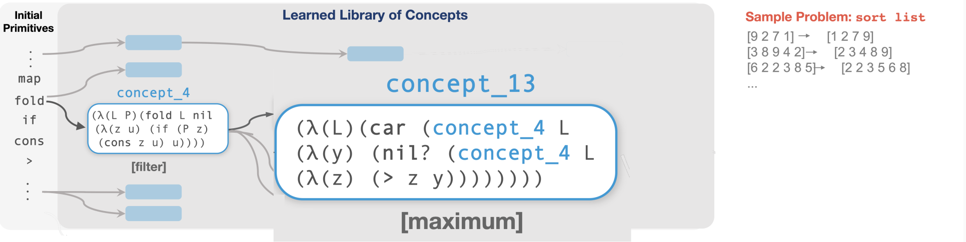


Sample Problem: `sort list`

[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]
...

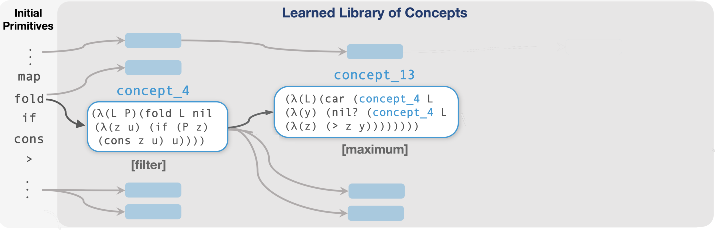
Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Library learning



Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Library learning

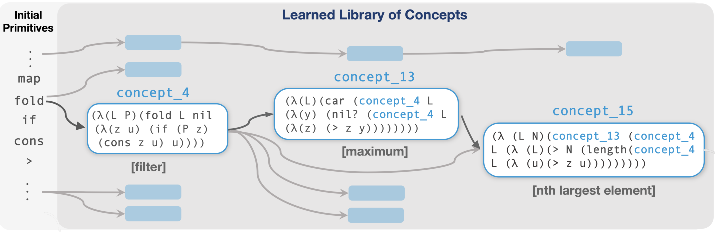


Sample Problem: `sort list`

[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]
...

Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Library learning

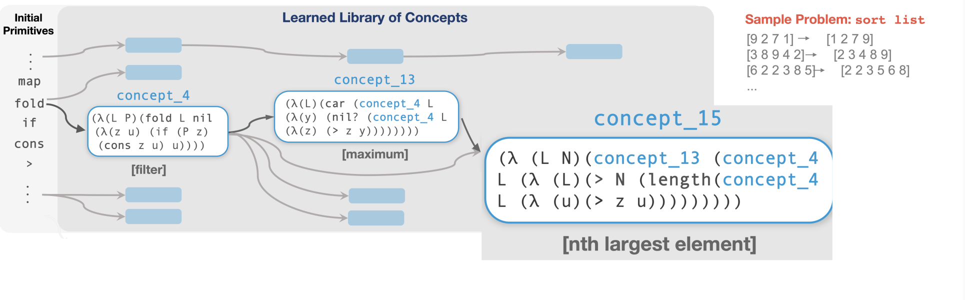


Sample Problem: `sort list`

[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]
...

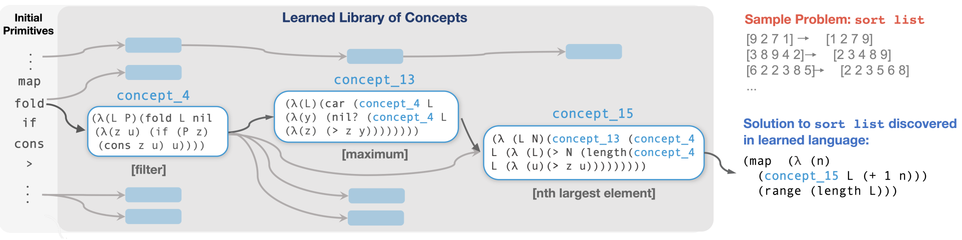
Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Library learning



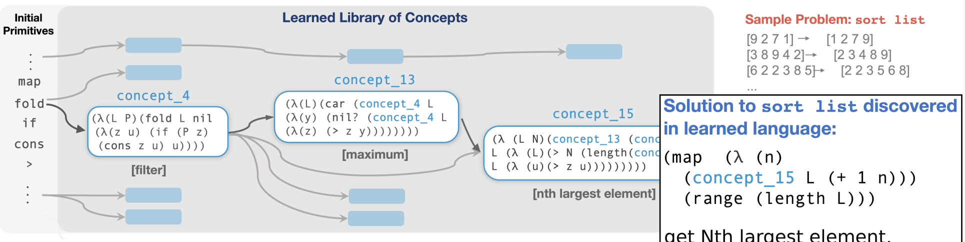
Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Library learning



Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Library learning



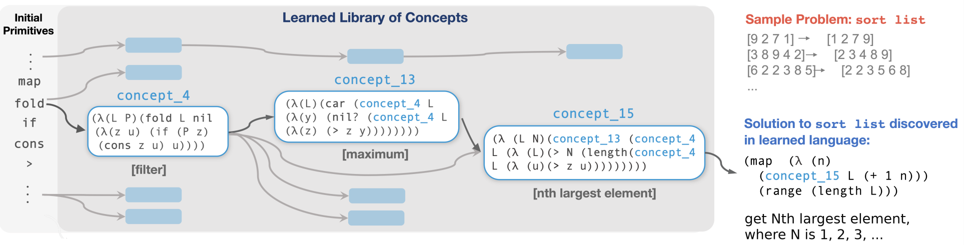
Solution to sort list discovered in learned language:

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

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

Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Library learning

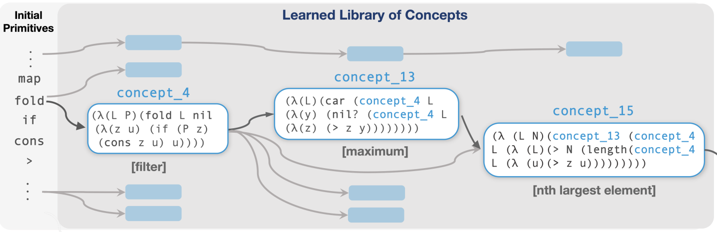


Solution rewritten in initial primitives:

```
(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))))
```

Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Library learning



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]
...

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))))
```

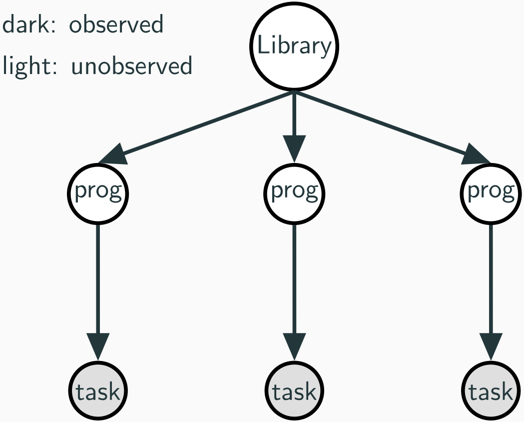
induced sort program found in $\leq$ 10min. Brute-force search without learned library would take $\approx 10^{73}$ years

Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

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

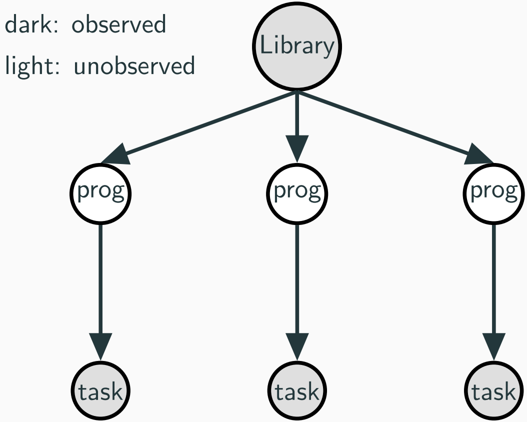
cf. Helmholtz machine, wake/sleep neural network training algorithms

Library learning as Bayesian inference



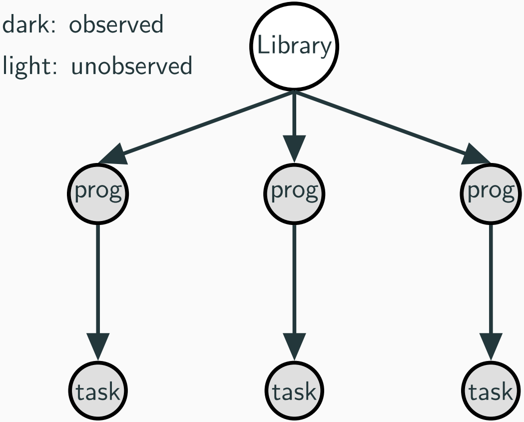
[Dechter et al, 2013] [Liang et al, 2010] [Lake et al, 2015]

Library learning as Bayesian inference



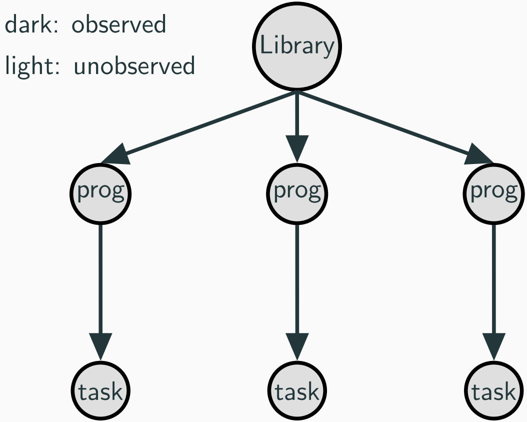
[Dechter et al, 2013] [Liang et al, 2010] [Lake et al, 2015]

Library learning as Bayesian inference



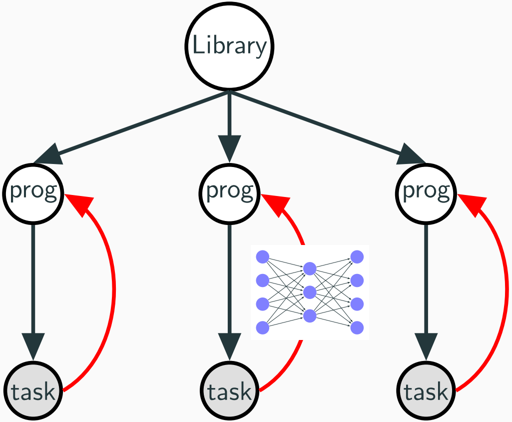
[Dechter et al, 2013] [Liang et al, 2010] [Lake et al, 2015]

Library learning as Bayesian inference



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

Library learning as neurally-guided Bayesian inference

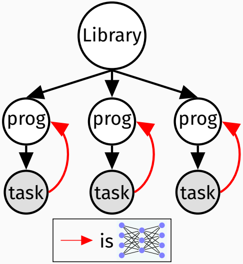


library learning via program analysis +

new neural inference network for program synthesis +

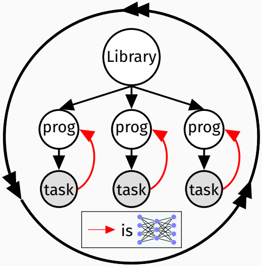
better program representation (Lisp+polymorphic types [Milner 1978])

Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.


Library
prog
prog
prog
task
task
task
is

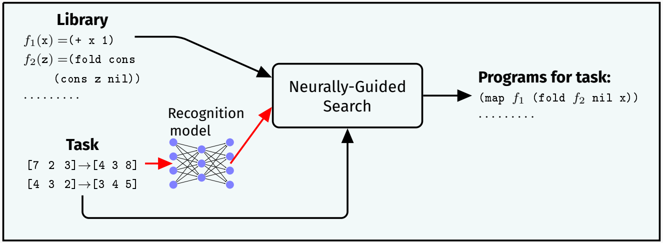
WAKE

SLEEP: ABSTRACTION

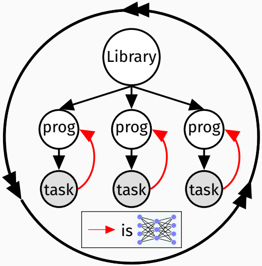


SLEEP: DREAMING

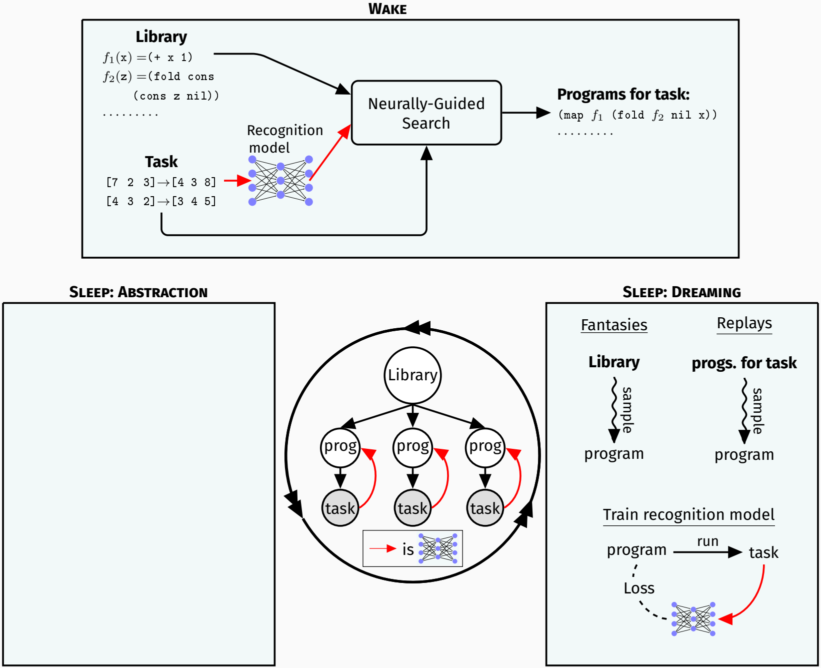
Wake

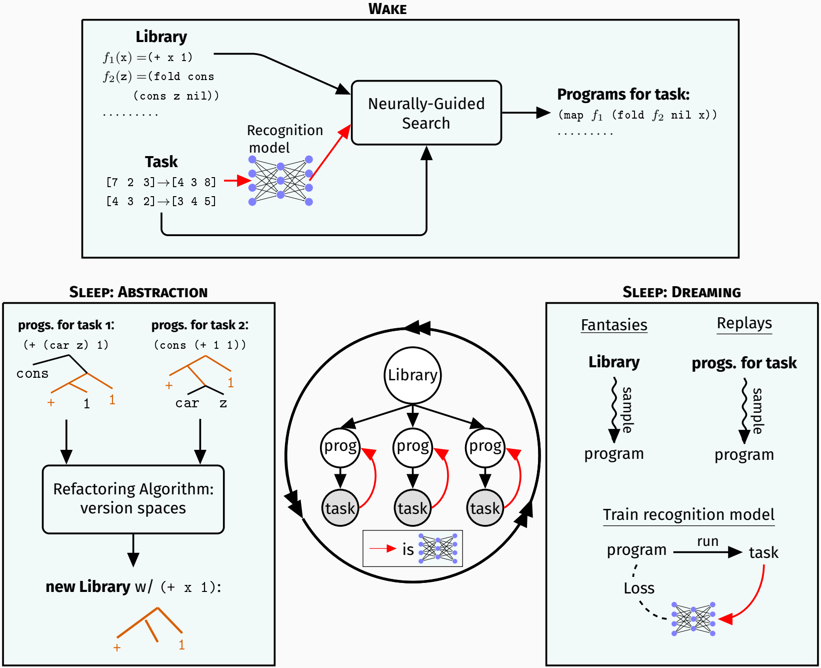


Sleep: Abstraction

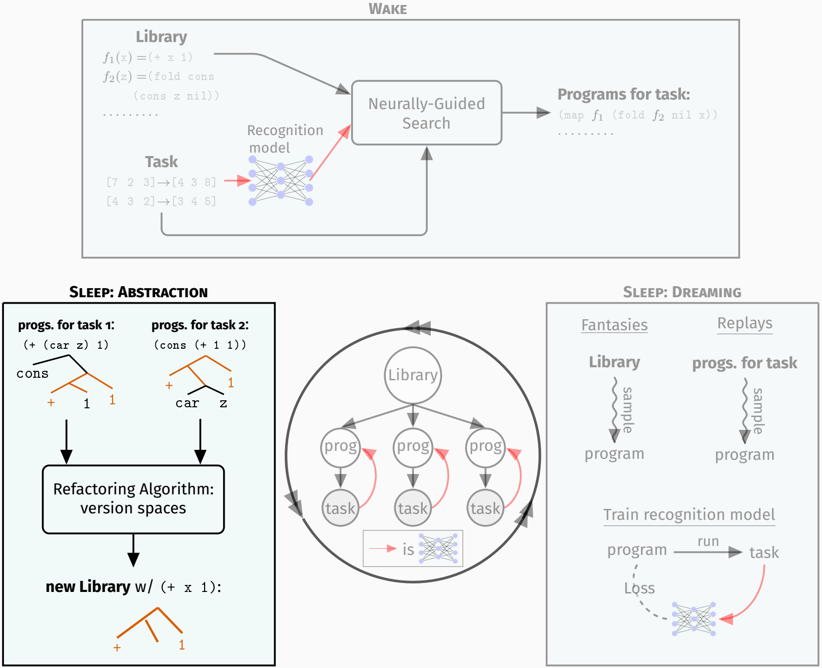


Sleep: Dreaming


Wake
Library
f_1(x) =(+ x 1)
f_2(z) =(fold cons (cons z nil))
....
Task
[7 2 3]→[4 3 8]
[4 3 2]→[3 4 5]
Recognition model
Neurally-Guided Search
Programs for task:
(map f_1 (fold f_2 nil x))
....
Sleep: Abstraction
Library
prog
prog
prog
task
task
task
is
Sleep: Dreaming
Fantasies
Replays
Library
sample
program
progs. for task
sample
program
Train recognition model
program
run
task
Loss



Wake
Library
f1(x) = (+ x 1)
f2(z) = (fold cons (cons z nil))
....
Recognition model
Neurally-Guided Search
Programs for task:
(map f1 (fold f2 nil x))
....
Task
[7 2 3]→[4 3 8]
[4 3 2]→[3 4 5]
Sleep: Abstraction
progs. for task 1:
(+ (car z) 1)
cons
+
1
1
progs. for task 2:
(cons (+ 1 1))
+
1
car
z
Refactoring Algorithm: version spaces
new Library w/ (+ x 1):
+
1
Library
prog
prog
prog
task
task
task
is
Sleep: Dreaming
Fantasies
Replays
Library
sample
program
progs. for task
sample
program
Train recognition model
program
run
task
Loss


WAKE
Library
f_1(x) =(+ x 1)
f_2(z) =(fold cons
(cons z nil))
....
Neurally-Guided
Search
Programs for task:
(map f_1 (fold f_2 nil x))
....
Recognition
model
Task
[7 2 3]→[4 3 8]
[4 3 2]→[3 4 5]
SLEEP: ABSTRACTION
progs. for task 1:
(+ (car z) 1)
cons
+
1
1
progs. for task 2:
(cons (+ 1 1))
+
1
car
z
Refactoring Algorithm:
version spaces
new Library w/ (+ x 1):
+
1
Library
prog
prog
prog
task
task
task
is
SLEEP: DREAMING
Fantasies
Replays
Library
sample
program
progs. for task
sample
program
Train recognition model
program
run
task
Loss

Program Induction and learning to learn

learning a DSL

learning to synthesize

synergy between DSL+learned synthesizer

Abstraction Sleep: Growing the library via refactoring

Task: [1 2 3]→[2 4 6]
[4 3 4]→[8 6 8]

Task: [1 2 3]→[0 1 2]
[4 3 4]→[3 2 3]

Abstraction Sleep: Growing the library via refactoring

Task: [1 2 3]→[2 4 6]
[4 3 4]→[8 6 8]

Wake: program search

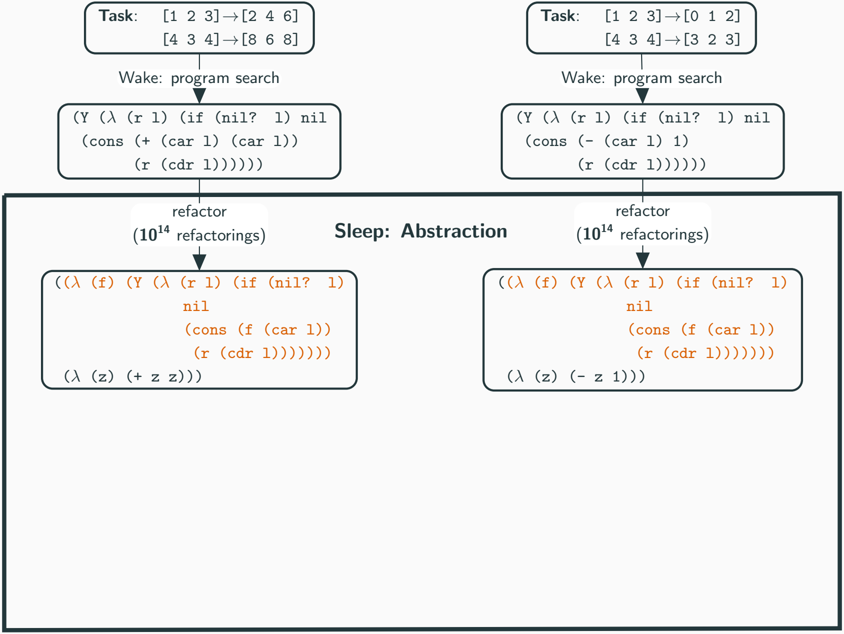
```
(Y (λ (r l) (if (nil? l) nil
 (cons (+ (car l) (car l))
       (r (cdr l))))))
```

Task: [1 2 3]→[0 1 2]
[4 3 4]→[3 2 3]

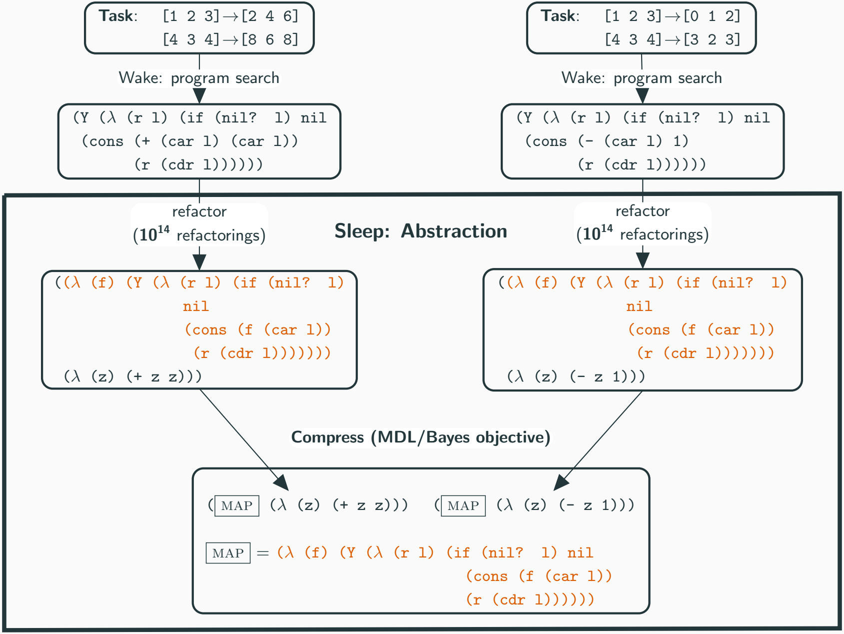
Wake: program search

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

Abstraction Sleep: Growing the library via refactoring



Abstraction Sleep: Growing the library via refactoring



Abstraction Sleep: Growing the library via refactoring

Task: [1 2 3]→[2 4 6]
[4 3 4]→[8 6 8]

Wake: program search

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

Task: [1 2 3]→[0 1 2]
[4 3 4]→[3 2 3]

Wake: program search

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

these $\mathbf{10^{14}}$ refactorings represented in exponentially more efficient refactoring data structure: equivalence graphs+version spaces using $\mathbf{10^{6}}$ nodes, calculated in under 5min

c.f. [Tate et al 2009], [Gulwani 2012]

Compress (MDL/Bayes objective)

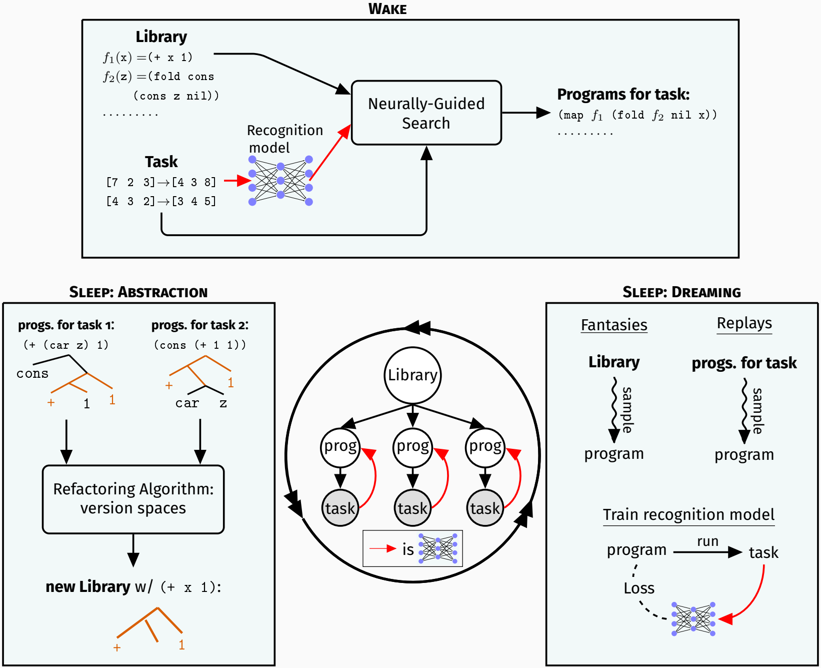
```
(MAP (λ (z) (+ z z)))   (MAP (λ (z) (- z 1)))

MAP = (λ (f) (Y (λ (r l) (if (nil? l) nil
                            (cons (f (car l))
                            (r (cdr l))))))
```

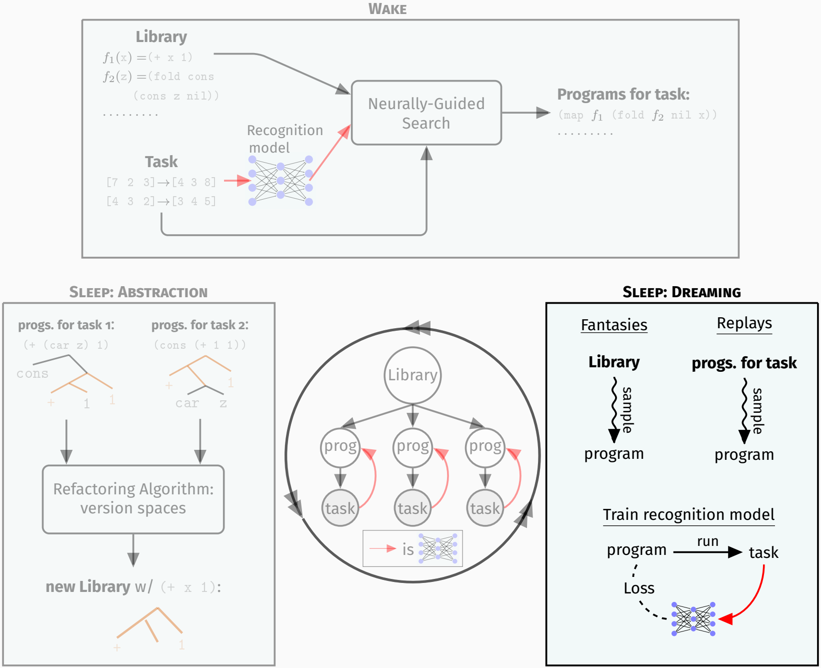
Program Induction and learning to learn

learning a DSL

learning to synthesize

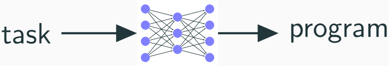
synergy between DSL+learned synthesizer


WAKE
Library
f1(x) =(+ x 1)
f2(z) =(fold cons
(cons z nil))
....
Recognition
model
Task
[7 2 3]→[4 3 8]
[4 3 2]→[3 4 5]
Neurally-Guided
Search
Programs for task:
(map f1 (fold f2 nil x))
....
SLEEP: ABSTRACTION
progs. for task 1:
(+ (car z) 1)
cons
+
1
1
progs. for task 2:
(cons (+ 1 1))
+
1
car
z
Refactoring Algorithm:
version spaces
new Library w/ (+ x 1):
+
1
Library
prog
prog
prog
task
task
task
is
SLEEP: DREAMING
Fantasies
Replays
Library
sample
program
progs. for task
sample
program
Train recognition model
program
run
task
Loss

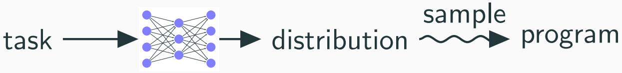


WAKE
Library
$f_1(x) =$ (+ x 1)
$f_2(z) =$ (fold cons (cons z nil))
....
Neurally-Guided Search
Programs for task:
(map f_1 (fold f_2 nil x))
....
Recognition model
Task
[7 2 3]→[4 3 8]
[4 3 2]→[3 4 5]
SLEEP: ABSTRACTION
progs. for task 1:
(+ (car z) 1)
cons
+
1
1
progs. for task 2:
(cons (+ 1 1))
+
1
car
z
Refactoring Algorithm: version spaces
new Library w/ (+ x 1):
+
1
Library
prog
prog
prog
task
task
task
is
SLEEP: DREAMING
Fantasies
Library
sample
program
Replays
progs. for task
sample
program
Train recognition model
program
run
task
Loss

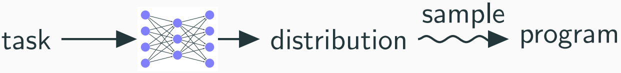
Neural recognition model guides search

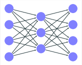


Neural recognition model guides search



Neural recognition model guides search

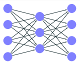


 is a...

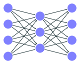
recurrent network (Devlin et al 2017)

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

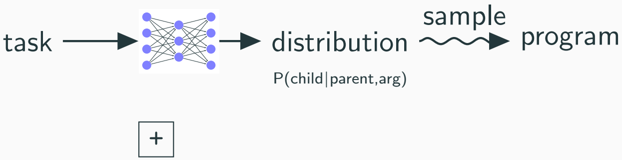
Neural recognition model guides search

task →  → distribution $\xrightarrow{\text{sample}}$ program

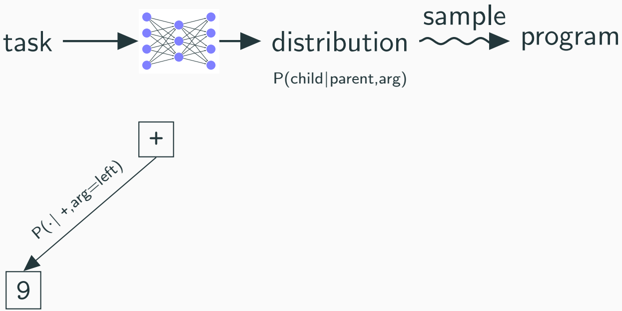
P(child|parent,arg)

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

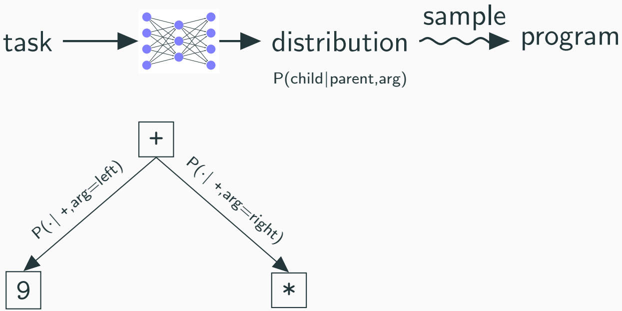
Neural recognition model guides search



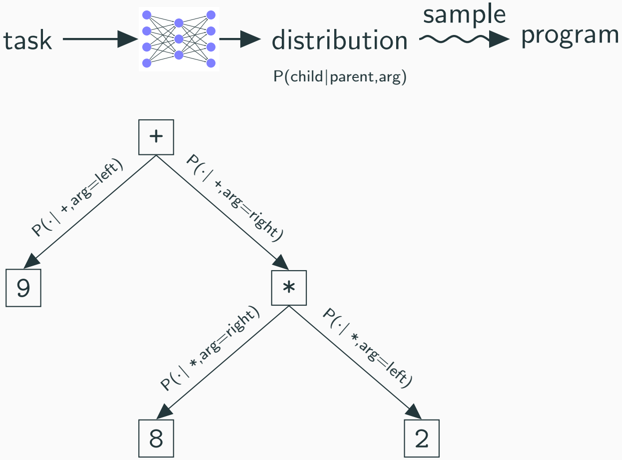
Neural recognition model guides search



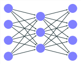
Neural recognition model guides search



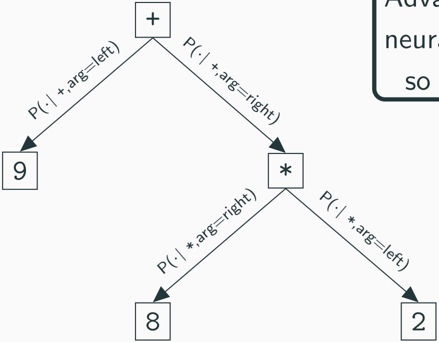
Neural recognition model guides search



Neural recognition model guides search

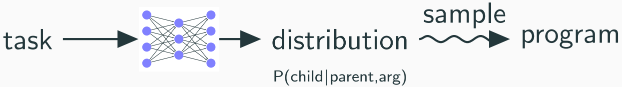
task →  → distribution $\xrightarrow{\text{sample}}$ program

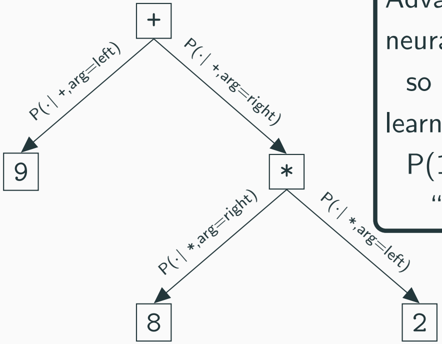
P(child|parent,arg)



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"

Program Induction and learning to learn

learning a DSL

learning to synthesize

synergy between DSL+learned synthesizer

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

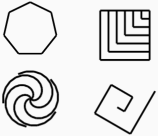
Phone numbers

`(555) 867-5309`
`(650) 555-2368`

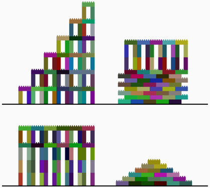
Currency

`$100.25`
`$4.50`

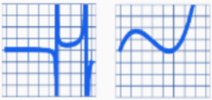
LOGO Graphics



Block Towers



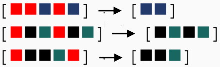
Symbolic Regression



$y = f(x)$

Recursive Programming

Filter Red



Physical Laws

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

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

Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

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

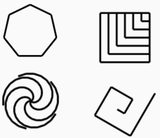
Phone numbers

(555) 867-5309
(650) 555-2368

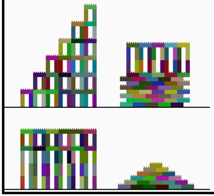
Currency

$100.25
$4.50

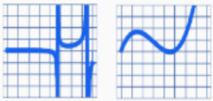
LOGO Graphics



Block Towers



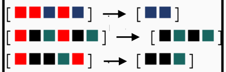
Symbolic Regression



$y = f(x)$

Recursive Programming

Filter Red



Physical Laws

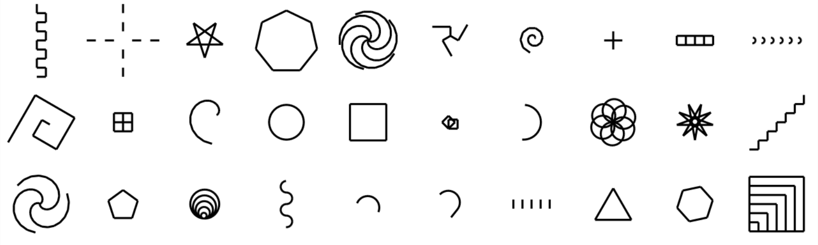
$$\vec{a} = \frac{1}{m}\sum_i \vec{F}_i$$

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

Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

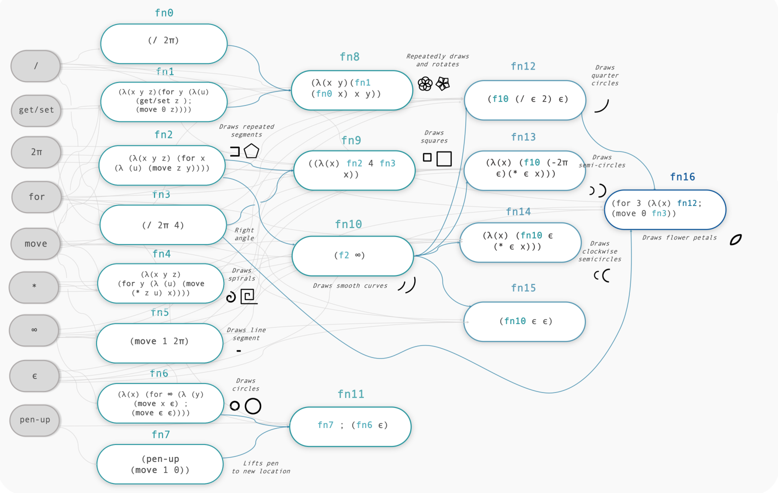
LOGO Turtle Graphics

30 out of 160 tasks



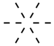
Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

LOGO Turtle Graphics – learning an interpretable library



(fn8 5 (fn4 (* ϵ 2) ∞ ϵ))

(for 7 (λ (x) (fn9 x)))

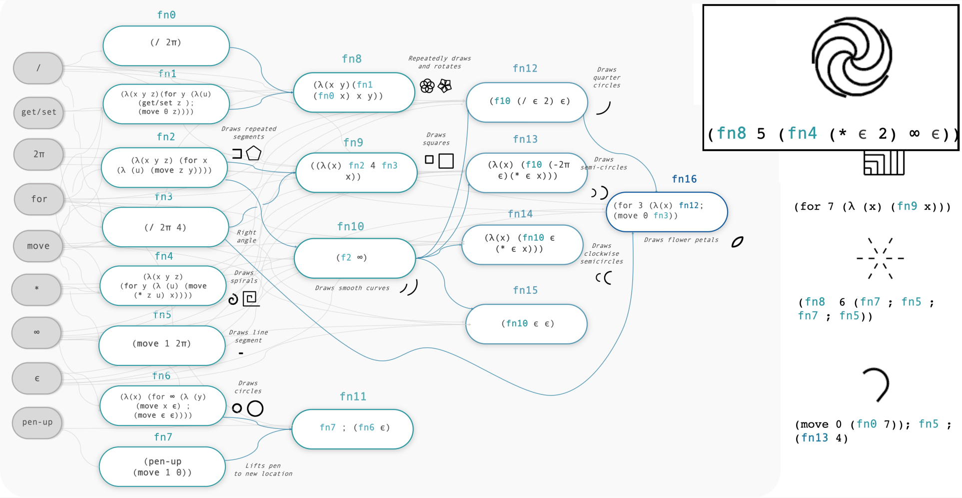


(fn8 6 (fn7 ; fn5 ; fn7 ; fn5))

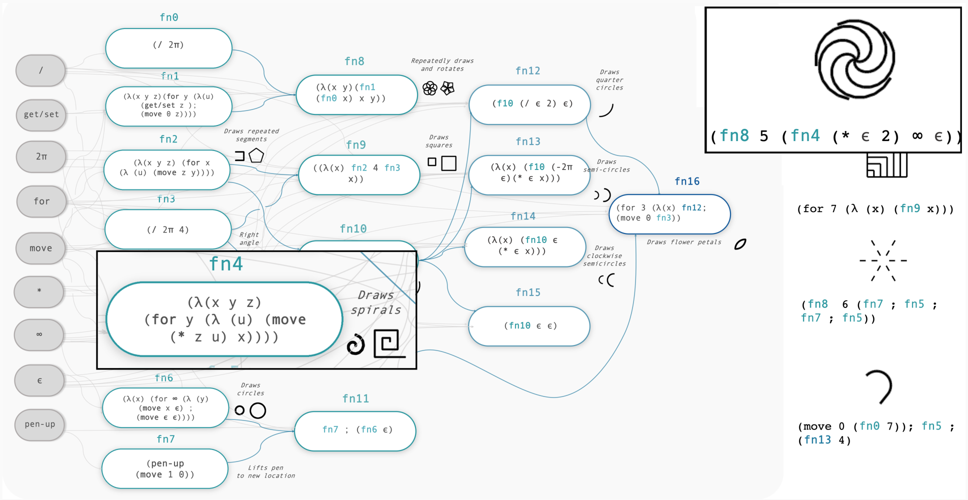
(move 0 (fn0 7)); fn5 ; (fn13 4)

Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

LOGO Turtle Graphics – learning an interpretable library

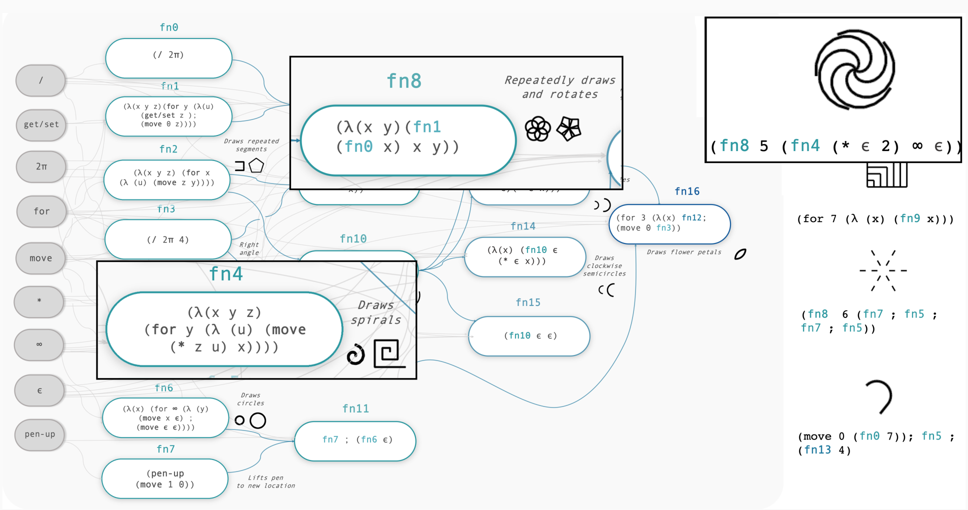


LOGO Turtle Graphics – learning an interpretable library



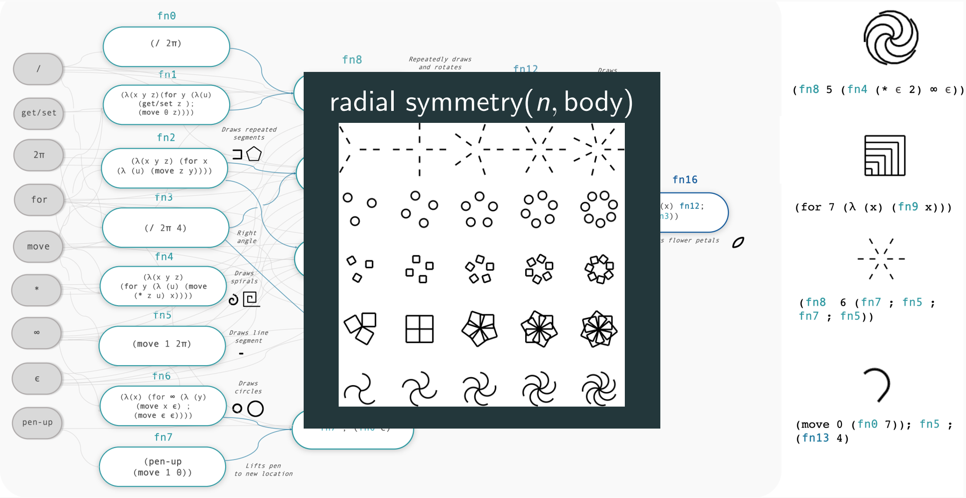
Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

LOGO Turtle Graphics – learning an interpretable library



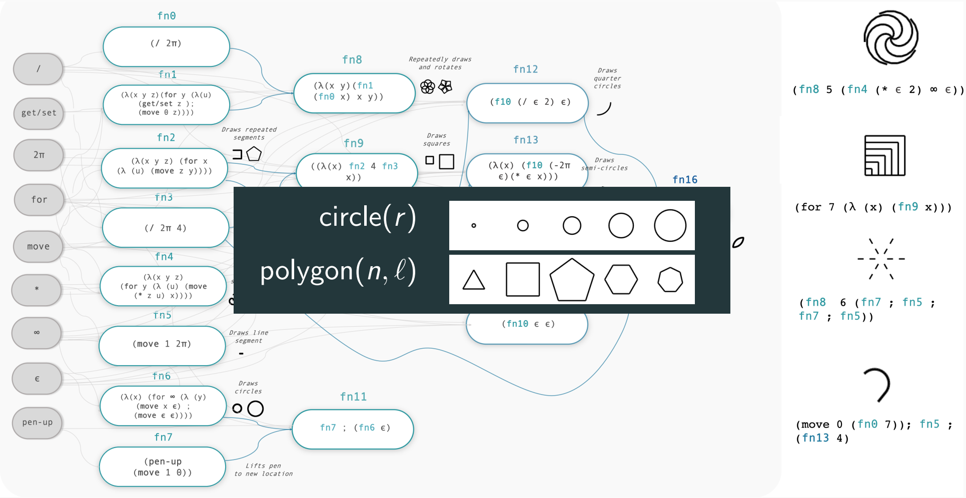
Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

LOGO Turtle Graphics – learning an interpretable library



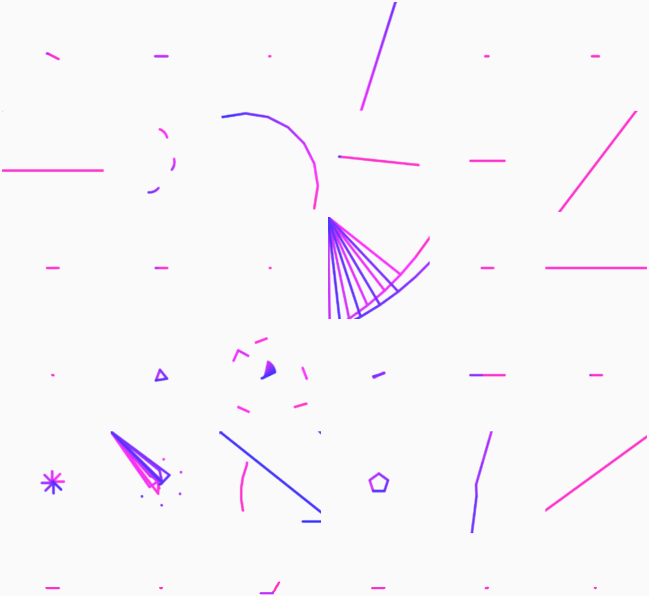
Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

LOGO Turtle Graphics – learning an interpretable library

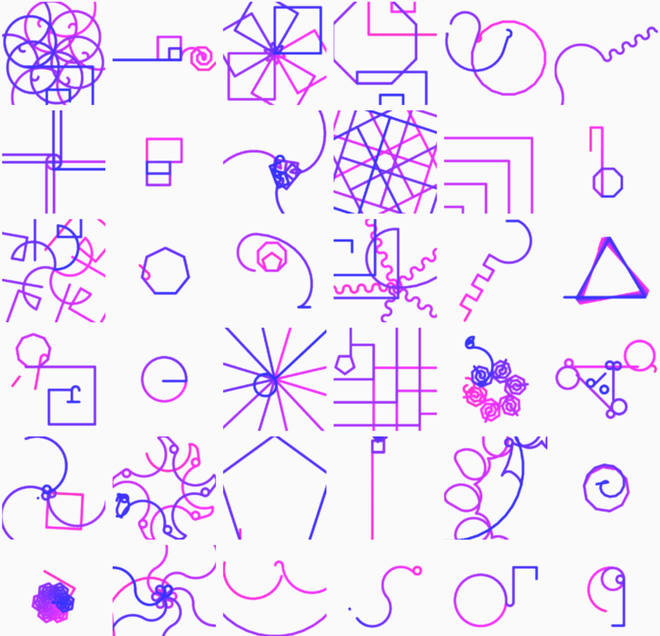


Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

What does DreamCoder dream of? (before learning)

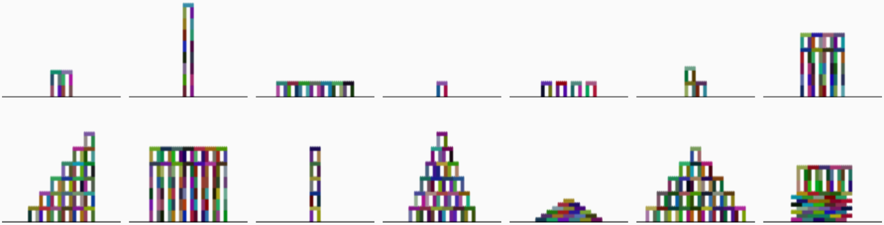


What does DreamCoder dream of? (after learning)



Planning to build towers

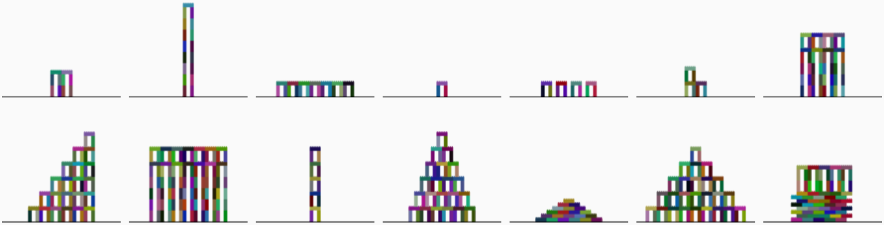
example tasks (112 total)



Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Planning to build towers

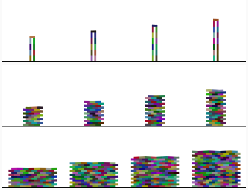
example tasks (112 total)



learned library routines ($\approx$ 20 total)

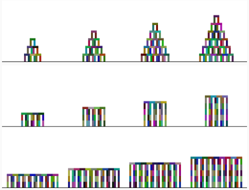
arch(h)

wall(w, h)



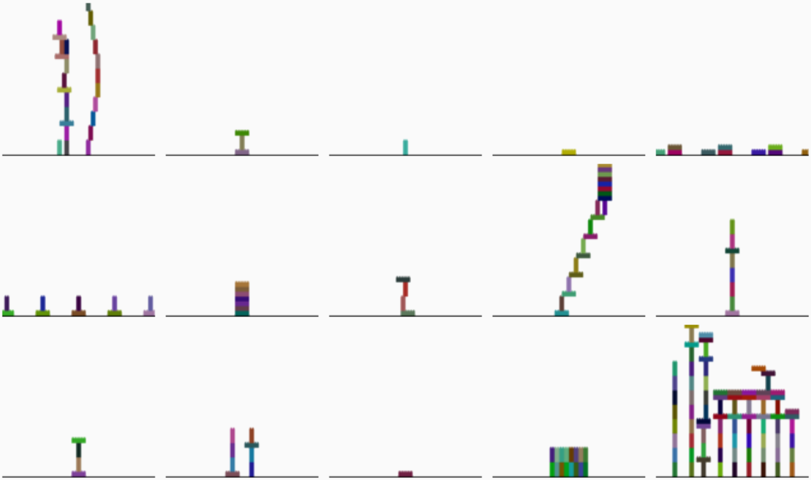
pyramid(h)

bridge(w, h)

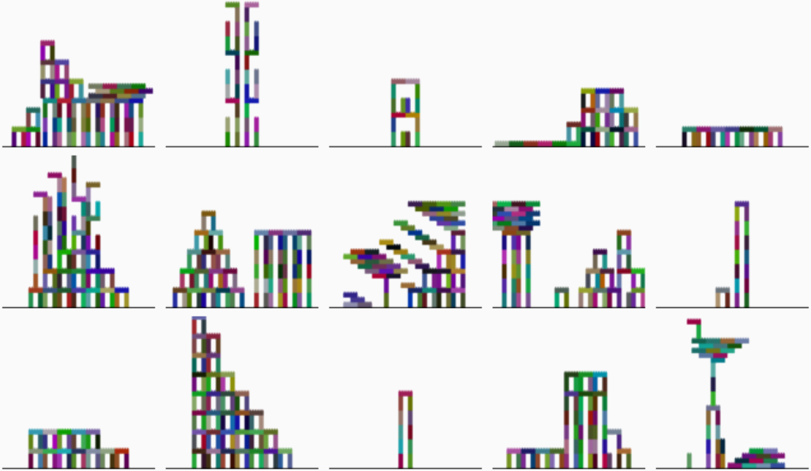


Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

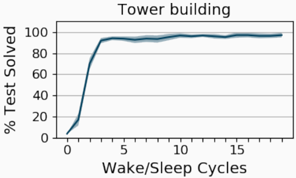
Dreams before learning



Dreams after learning

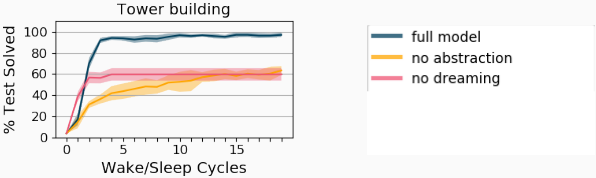


Learning dynamics



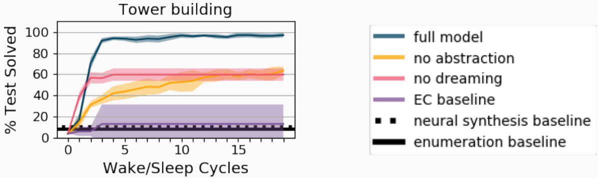
Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Learning dynamics



Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

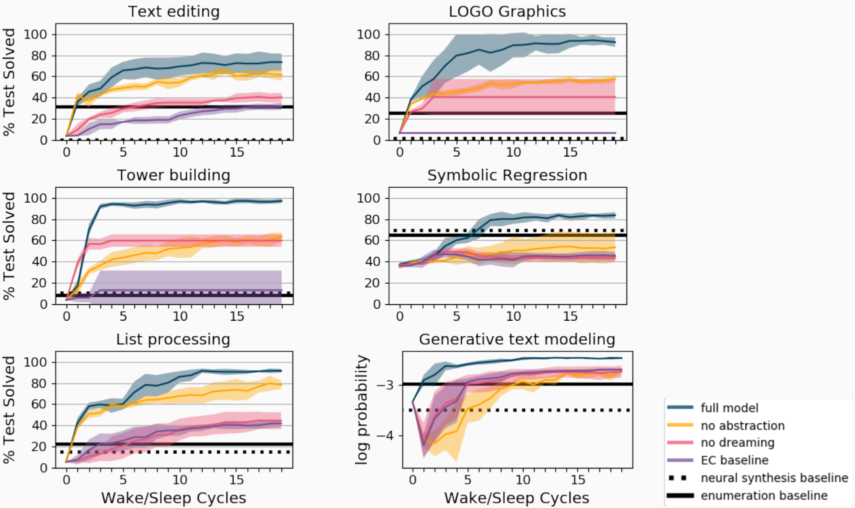
Learning dynamics



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

Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Learning dynamics



Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Synergy between recognition model and library learning

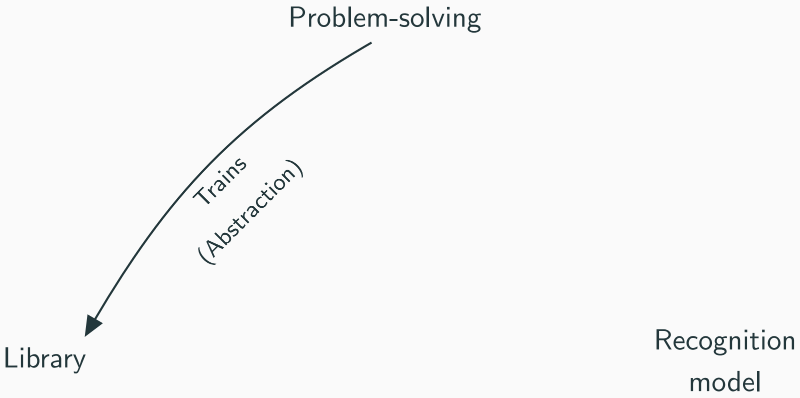
Problem-solving

Library

Recognition model

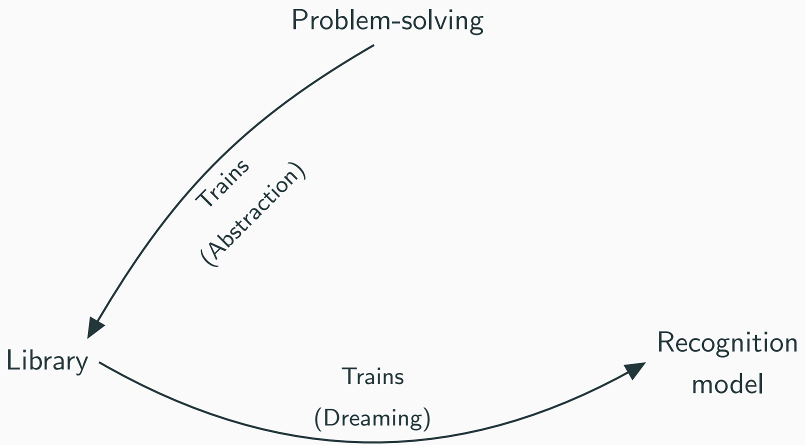
Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Synergy between recognition model and library learning



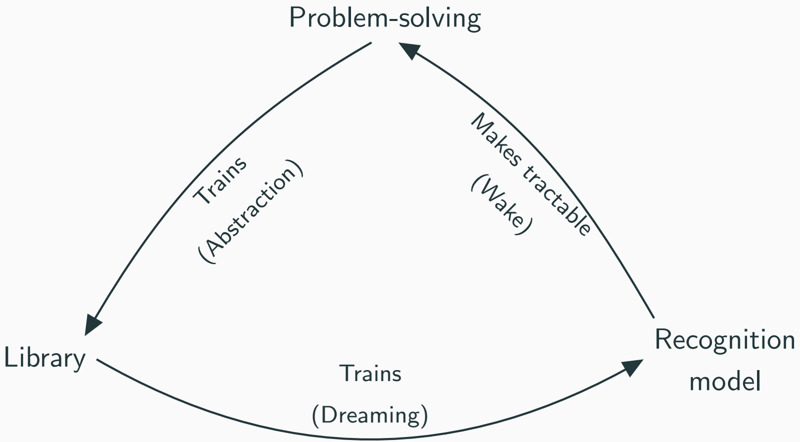
Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Synergy between recognition model and library learning



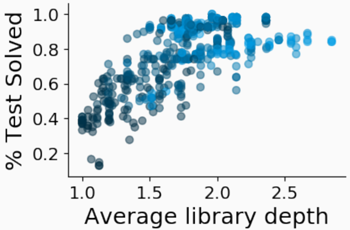
Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Synergy between recognition model and library learning



Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Evidence for dreaming bootstrapping better libraries

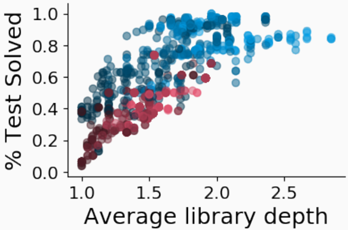


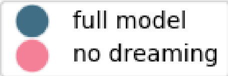
Darker: Early in learning

Brighter: Later in learning

Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Evidence for dreaming bootstrapping better libraries



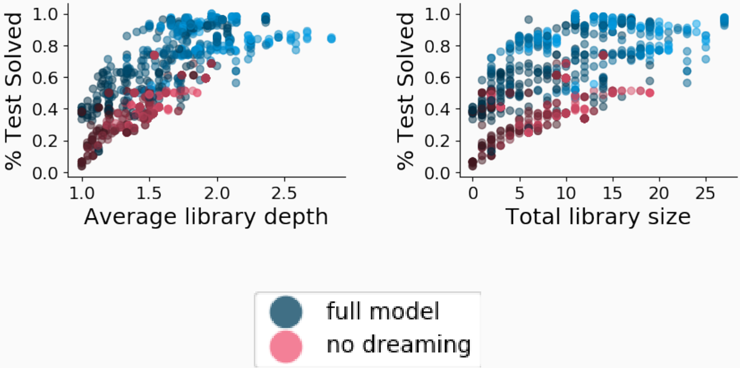


Darker: Early in learning

Brighter: Later in learning

Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Evidence for dreaming bootstrapping better libraries



Darker: Early in learning

Brighter: Later in learning

Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

From learning libraries, to learning languages

From learning libraries,
to learning languages

modern functional programming $\rightarrow$ physics

From learning libraries, to learning languages

1950's Lisp $\rightarrow$ modern functional programming $\rightarrow$ physics

Physics Formula Sheet

Mechanics

$x = x_0 + v_{x0}t + \frac{1}{2}a_x t^2$

$a_c = \frac{v^2}{r}$

$|\vec{F}_{spring}| = k|\vec{x}|$

$v = v_0 + at$

$\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t^2$

$PE_{spring} = \frac{1}{2}kx^2$

$v_x^2 - v_{x0}^2 = 2a(x - x_0)$

$\omega = \omega_0 + \alpha t$

$T_{spring} = 2\pi\sqrt{\frac{m}{k}}$

$\vec{a} = \frac{\Sigma\vec{F}}{m} = \frac{\vec{F}_{net}}{m}$

$T = \frac{2\pi}{\omega} = \frac{1}{f}$

$T_{pendulum} = 2\pi\sqrt{\frac{\ell}{g}}$

$|\vec{F}_{friction}| \le \mu|\vec{F}_{Normal}|$

$v = f\lambda$

$\vec{p} = m\vec{v}$

$x = A\cos(2\pi f t)$

$|\vec{F}_{gravity}| = G\frac{m_1 m_2}{r^2}$

$\Delta\vec{p} = \vec{F}\Delta t$

$\vec{\alpha} = \frac{\Sigma\vec{\tau}}{I} = \frac{\vec{\tau}_{net}}{I}$

$|\vec{F}_{gravity}| = m\vec{g}$

$KE = \frac{1}{2}mv^2$

$\vec{\tau} = r \times F$

$PE_{gravity} = -G\frac{m_1 m_2}{r}$

$\Delta PE = mg\Delta y$

$L = I\,\omega$

$\rho = \frac{m}{V}$

$\Delta E = W = Fd\cos\theta$

$\Delta L = \tau\Delta t$

$KE = \frac{1}{2}I\,\omega^2$

Electricity

$|\vec{F}_E| = k\left|\frac{q_1 q_2}{r^2}\right|$

$\Delta V = IR$

$R = \frac{\rho\ell}{A}$

$I = \frac{\Delta q}{\Delta t}$

$P = I\Delta V$

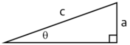
$R_{series} = R_1 + R_2 + \ldots + R_n$

$\frac{1}{R_{Parallel}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$

Geometry

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

Trigonometry



$c^2 = a^2 + b^2$

$\sin\theta = \frac{a}{c}$ $\cos\theta = \frac{b}{c}$ $\tan\theta = \frac{a}{b}$

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

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

Work

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

Force in a Magnetic Field

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

Kinetic Energy

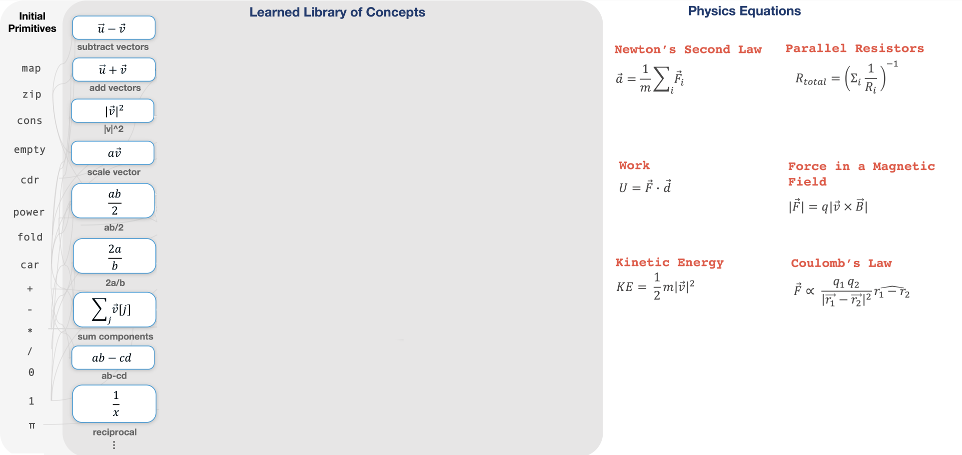
$KE = \frac{1}{2}m|\vec{v}|^2$

Coulomb's Law

$\vec{F} \propto \frac{q_1 q_2}{|\vec{r_1} - \vec{r_2}|^2}\widehat{r_1 - r_2}$

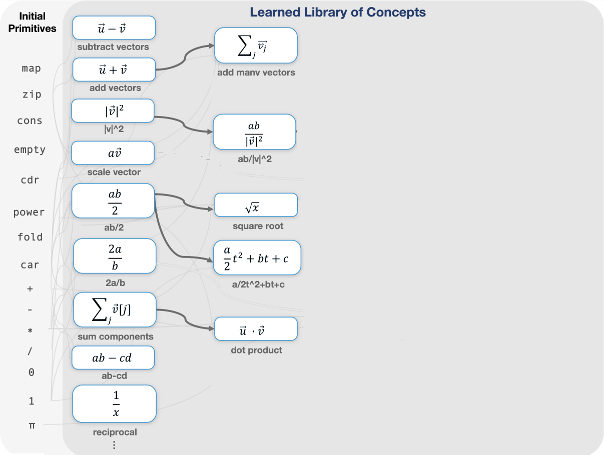
Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Growing languages for vector algebra and physics



Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Growing languages for vector algebra and physics



Physics Equations

Newton's Second Law

$$\vec{a} = \frac{1}{m}\sum_i \vec{F_i}$$

Parallel Resistors

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

Work

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

Force in a Magnetic Field

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

Kinetic Energy

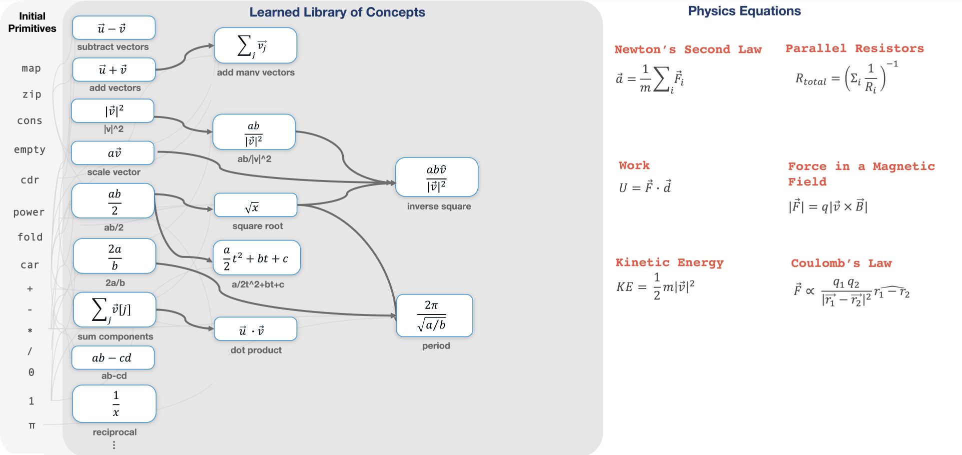
$$KE = \frac{1}{2} m |\vec{v}|^2$$

Coulomb's Law

$$\vec{F} \propto \frac{q_1 q_2}{|\vec{r_1} - \vec{r_2}|^2}\widehat{r_1 - r_2}$$

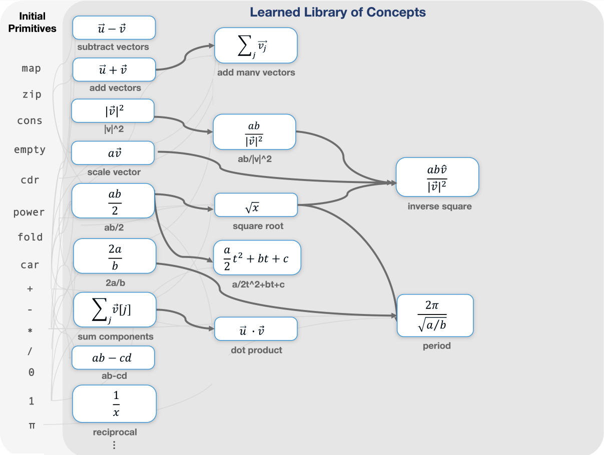
Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Growing languages for vector algebra and physics



Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Growing languages for vector algebra and physics



Physics Equations

Newton's Second Law

$$\vec{a} = \frac{1}{m}\sum_i \vec{F_i}$$

```
(scale-vector(reciprocal m)
(add-many-vectors Fs))
```

Parallel Resistors

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

```
(reciprocal (sum-components
(map (λ(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))
```

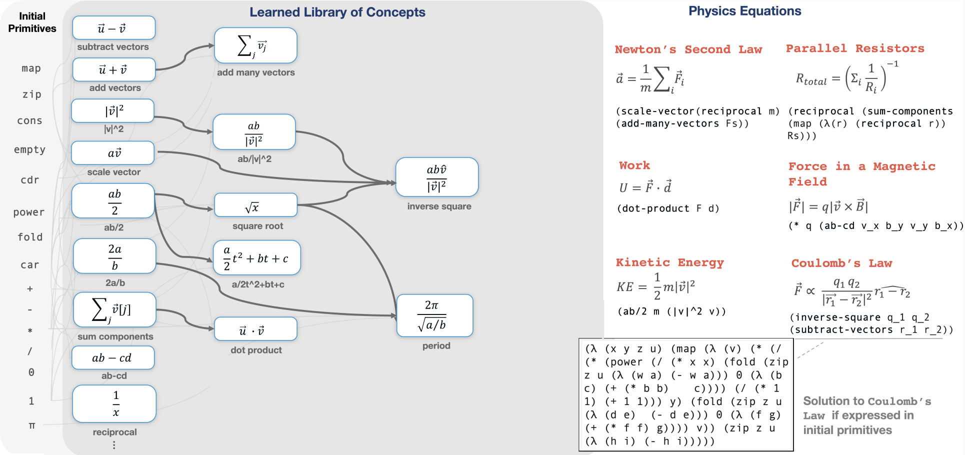
Coulomb's Law

$$\vec{F} \propto \frac{q_1 q_2}{|\vec{r_1} - \vec{r_2}|^2}\widehat{r_1 - r_2}$$

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

Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Growing languages for vector algebra and physics



Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

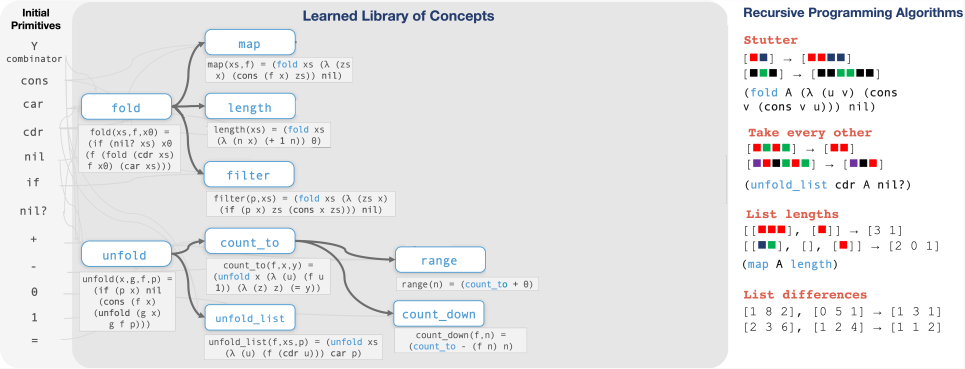
Growing a language for recursive programming

Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Growing a language for recursive programming

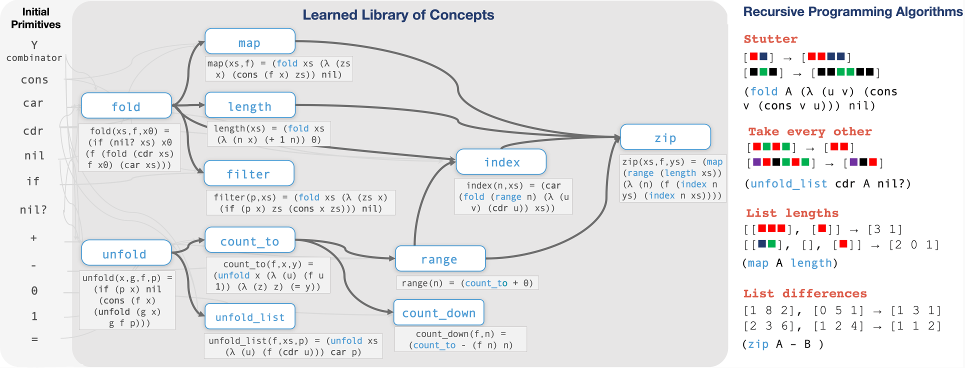
Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Growing a language for recursive programming



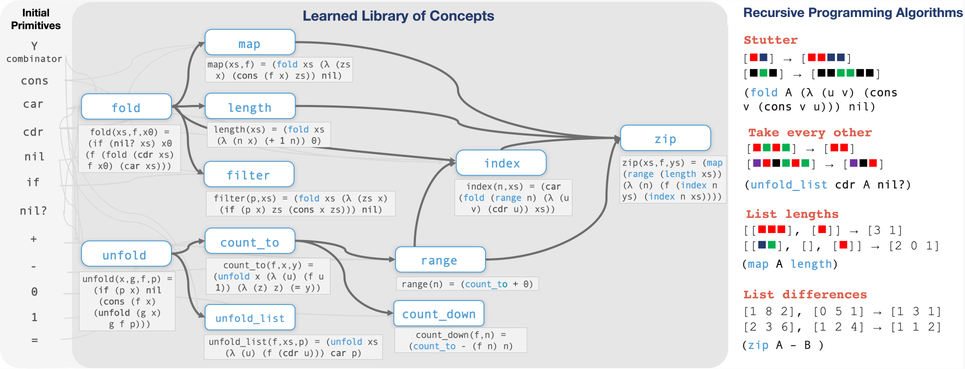
Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

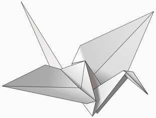
Growing a language for recursive programming



Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Growing a language for recursive programming

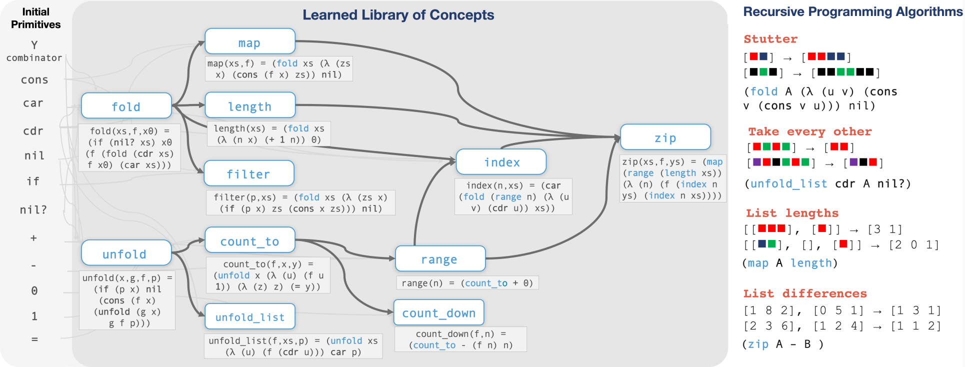




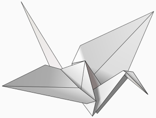
Origami Programming: Jeremy Gibbons, 2003

Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Growing a language for recursive programming



1 year of compute. 5 days on 64 CPUs.



Origami Programming: Jeremy Gibbons, 2003

Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Lessons

Library learning interacts synergistically with neural synthesis: bootstrapping, more than sum of parts

Lessons

Library learning interacts synergistically with neural synthesis: bootstrapping, more than sum of parts

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

Lessons

Library learning interacts synergistically with neural synthesis: bootstrapping, more than sum of parts

Symbols aren't necessarily interpretable. 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 on top of that

Program Induction and learning to learn

learning a DSL

learning to synthesize

next steps

Some unresolved questions

Not everything is crisp and symbolic. How do we learn DSLs for neurosymbolic hybrid programs?
(see Memoised Wake-Sleep, Hewitt et al 2020)

Some unresolved questions

Not everything is crisp and symbolic. How do we learn DSLs for neurosymbolic hybrid programs?
(see Memoised Wake-Sleep, Hewitt et al 2020)

Combinatorial search is still hard

Some unresolved questions

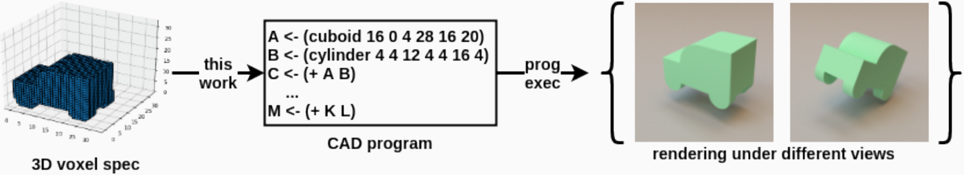
Not everything is crisp and symbolic. How do we learn DSLs for neurosymbolic hybrid programs?
(see Memoised Wake-Sleep, Hewitt et al 2020)

Combinatorial search is still hard

Library$\neq$Language:
How do we learn data structures, or discover new types, and thereby *actually* learn DSLs?

the end.

3D program induction



Challenge: combinatorial search!

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

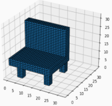
search space size: $(1.3 \text{ million})^{20} \approx 10^{122}$ programs

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

*equal contribution

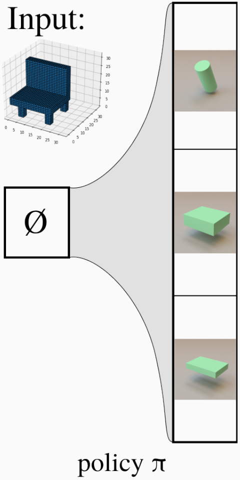
Solution: stochastic **tree search** + learn **policy** that writes code + learn **value** function that assesses execution of program so far; analogous to **AlphaGo** [Silver et al. 2016]

Input:

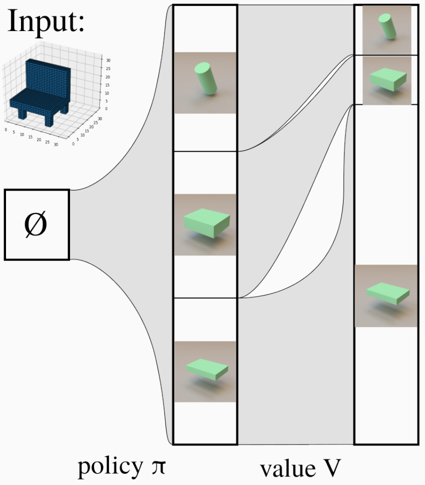


$\boxed{\varnothing}$

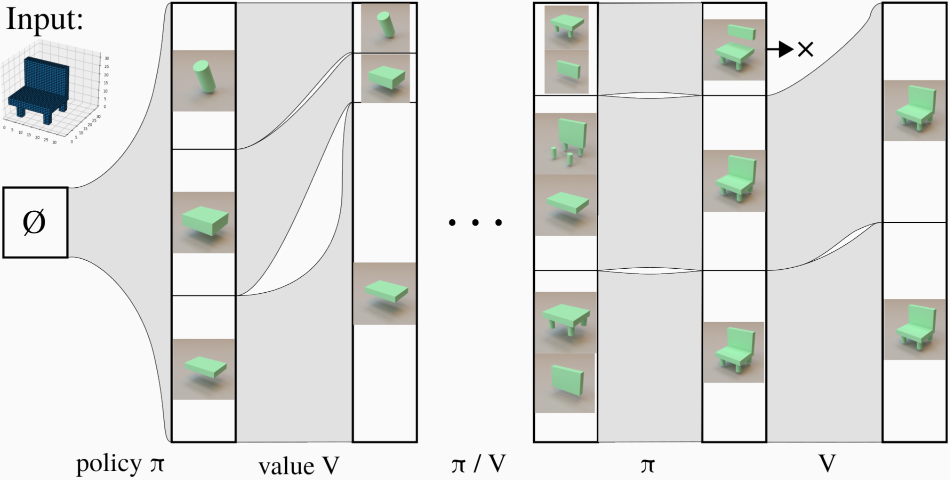
Solution: stochastic **tree search** + learn **policy** that writes code + learn **value** function that assesses execution of program so far; analogous to **AlphaGo** [Silver et al. 2016]



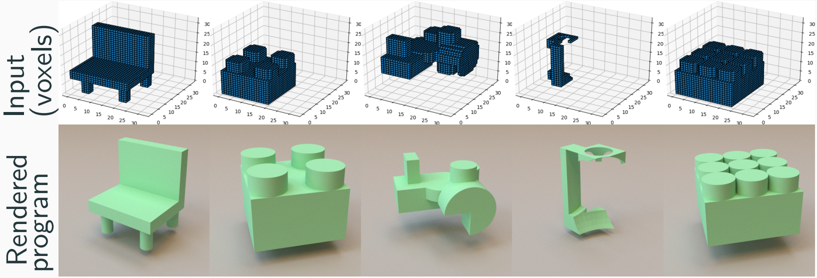
Solution: stochastic **tree search** + learn **policy** that writes code + learn **value** function that assesses execution of program so far; analogous to **AlphaGo** [Silver et al. 2016]



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]

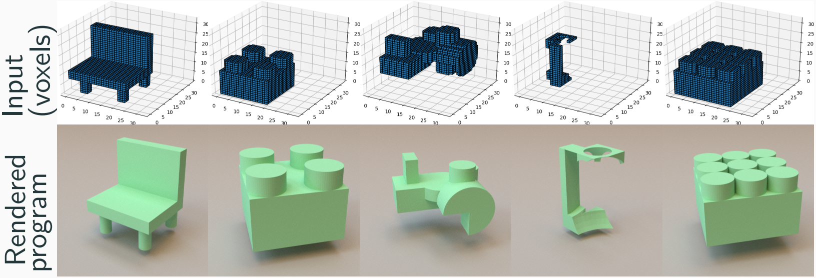


3D program induction



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

3D program induction

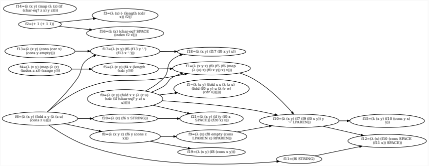


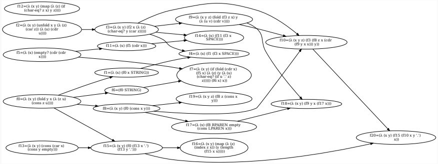
same architecture learns to synthesize text editing programs (FlashFill, Gulwani 2012)

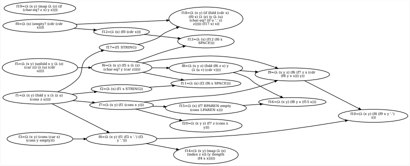
Ellis*, Nye*, Pu*, Sosa*, Tenenbaum, Solar-Lezama. NeurIPS 2019.
*equal contribution

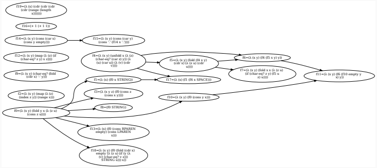
Library structure: Text Editing

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





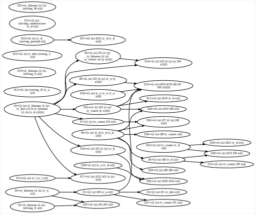


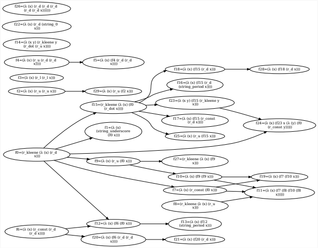


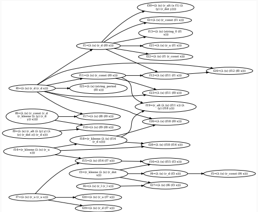
Ellis, Wong, Nye, ..., Solar-Lezama, Tenenbaum. arxiv 2020.

Library structure: Generating Text

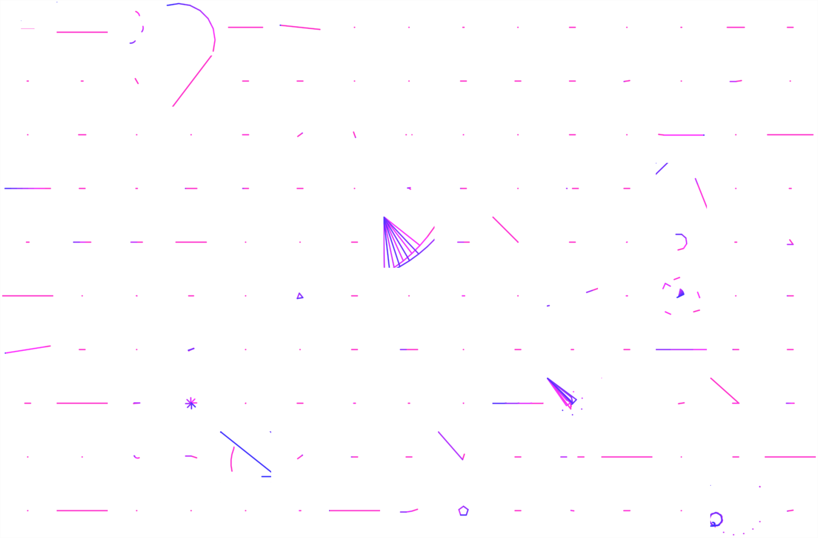
Libraries for probabilistic generative models over text:
data from crawling web for CSV files







150 random dreams before learning



150 random dreams after learning