Program Induction:
Bridging AI and program synthesis

Kevin Ellis

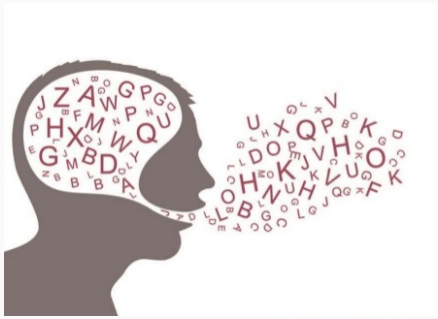
2020

MIT

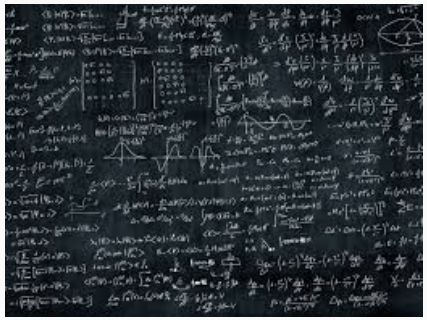
What computational problems are solved by intelligence?

an endless range of problems

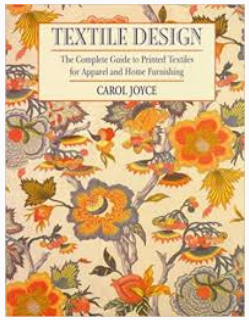
language



science

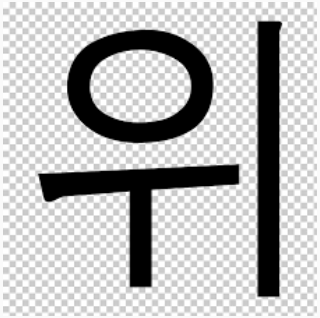


design



using new devices

writing new characters



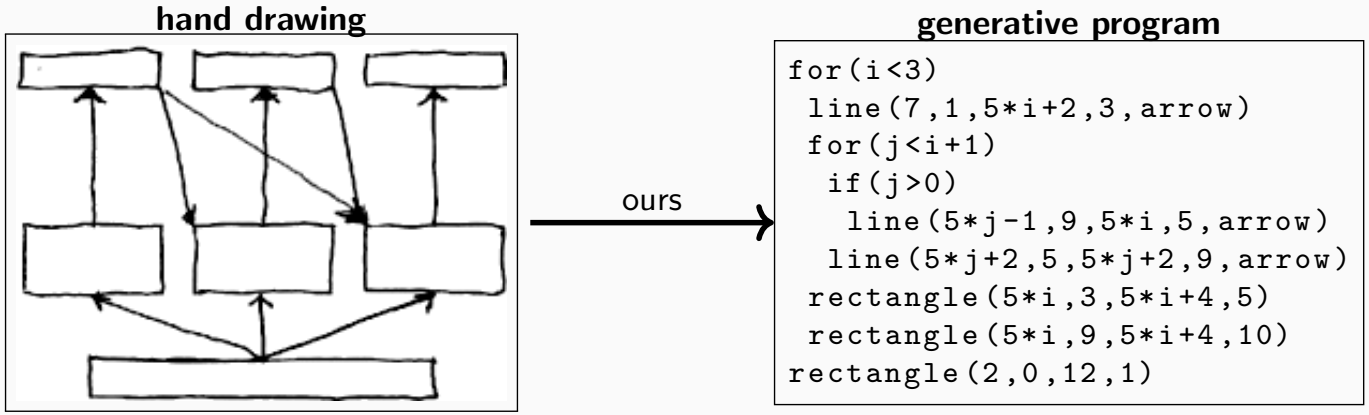
coding

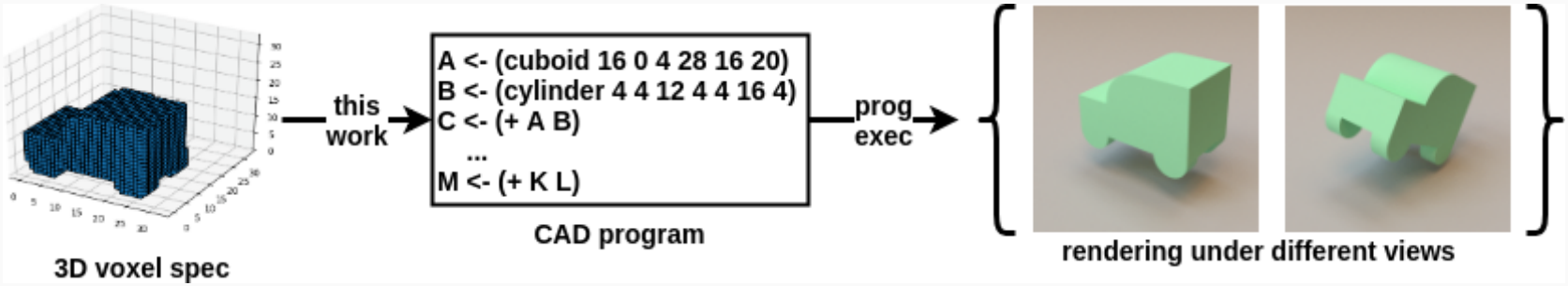
```
(MEMBER
 (LAMBDA (X L)
  (COND  ((NULL L) NIL)
         ((EQ X (FIRST L)) T)
         (T (MEMBER X (REST L))))))
```

Allen, Anatomy of Lisp, 1975

Perception, Learning-to-Learn, Synthesizing models

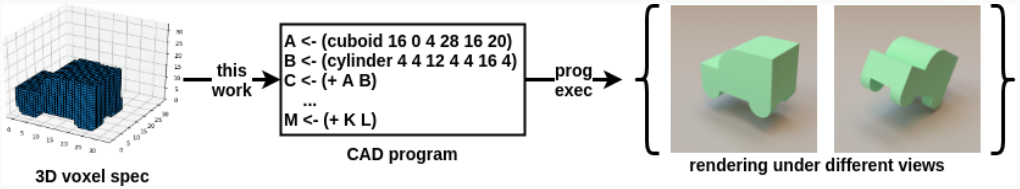
Theme #1: high-level scene understanding, pixels→programs





Perception, Learning-to-Learn, Synthesizing models

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



Theme #2: Learning to synthesize programs

List Processing

Sum List

```
[1 2 3] → 6
[4 6 8 1] → 17
```

Double

```
[1 2 3 4] → [2 4 6 8]
[6 5 1] → [12 10 2]
```

Check Evens

```
[0 2 3] → [T T F]
[2 4 9 6] → [T T F T]
```

Text Editing

Abbreviate

```
Allen Newell → A.N.
Herb Simon → H.S.
```

Drop Last Characters

```
jabberwocky → jabberw
copycat → cop
```

Extract

```
see spot(run) → run
a (bee) see → bee
```

Regexes

Phone Numbers

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

Currency

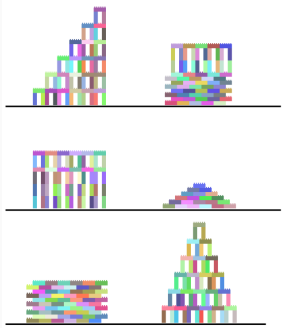
```
$100.25
$4.50
```

Dates

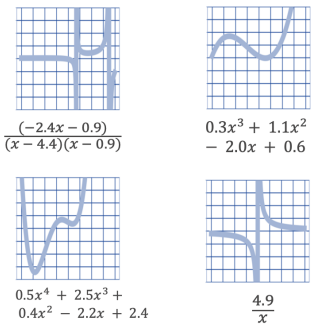
```
Y1775/0704
Y2000/0101
```

LOGO Graphics

Block Towers



Symbolic Regression



Recursive Programming

Filter

```
[■■■■] → [■■]
[■■■■■] → [■■■■]
[■■■■] → [■■■]
```

Index List

```
0, [■■■■■■] → ■
1, [■■■■■■] → ■
1, [■■■■■■] → ■
```

Length

```
[■■■■] → 4
[■■■■■] → 6
[■■■] → 3
```

Every Other

```
[■■■■] → [■■]
[■■■■■] → [■■■]
[■■■■■■] → [■■■]
```

Physics

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

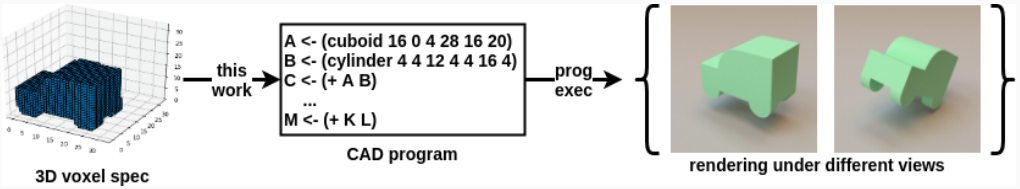
$$\vec{a} = \frac{1}{m}\sum_i \vec{F}_i$$

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

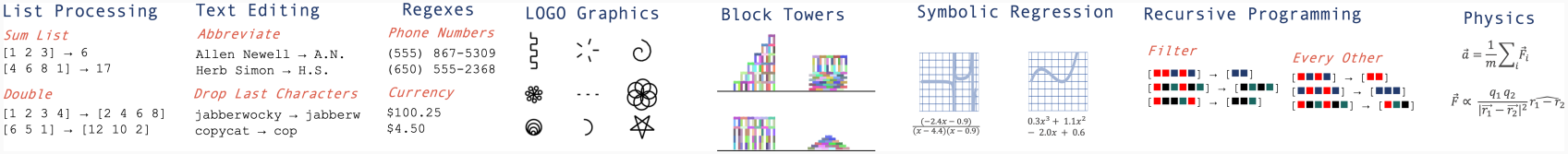
$$R_{total} = \left(\Sigma_i \frac{1}{R_i}\right)^{-1}$$

Perception, Learning-to-Learn, Synthesizing models

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



Theme #2: Learning to synthesize programs



Theme #3: Synthesizing human-understandable models

Language: Kerewe

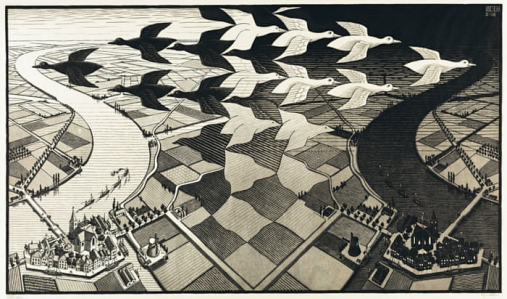
theory

INF→/ku/+stem+/a/, V e.o.→/ku/+stem+/ana/,
V for→/ku/+stem+/ila/, V for e.o.→/ku/+stem+/ilana/
V us→/kutú/+stem+/a/, V it→/kuki/+stem+/a/,
V for us→/kutú/+stem+/ila/, V it for us→/kukítú/+stem+/ila/

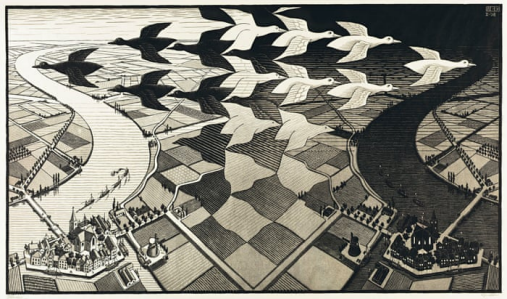
r_1: [ ] → [-hiTone] / [+hiTone] [-vowel]$_0$_
r_2: [+vowel] → [+hiTone] / [+hiTone] [-vowel]$_0$_[-vowel]

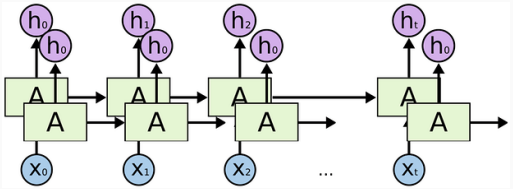
stems (unobserved)	observed data & unobserved derivation
⟨/gul/, BUY⟩	BUY US→/kutú/+/gul/+/a/→/kutúgula/$\xrightarrow{r_2}$[kutúgúla]
⟨/láb/, PASS⟩	PASS→/ku/+/láb/+/a/→[kulába]
⟨/sún/, PINCH⟩	PINCH IT FOR US→/kukítú/+/sún/+/ila/→ /kukítúsúnila/$\xrightarrow{r_1}$/kukítusunila/$\xrightarrow{r_2}$[kukítúsunila]
...	··· *total 56 words/8 inflections* ···

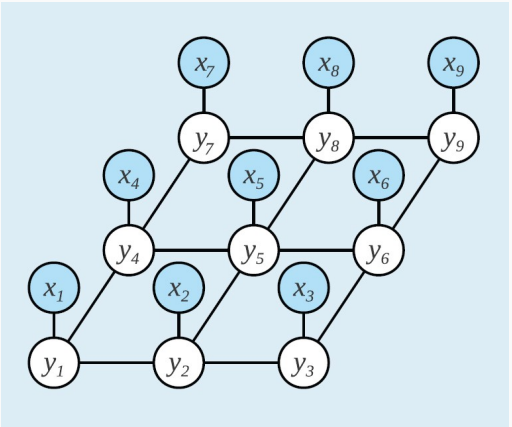
High-level, abstract visual abilities



High-level, abstract visual abilities







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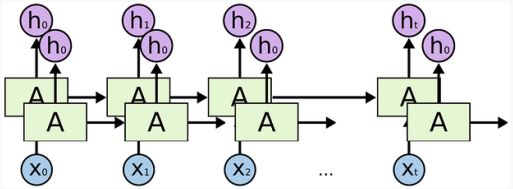

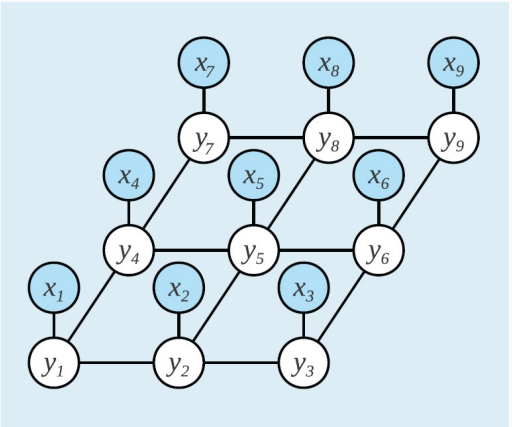

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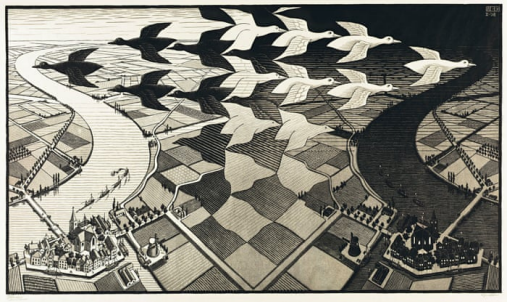

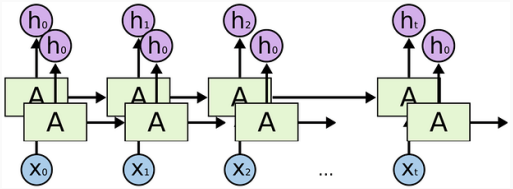

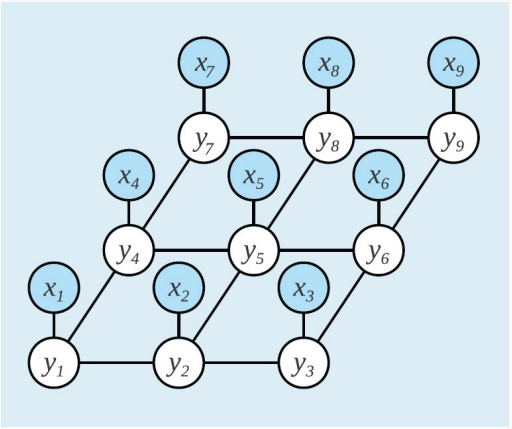

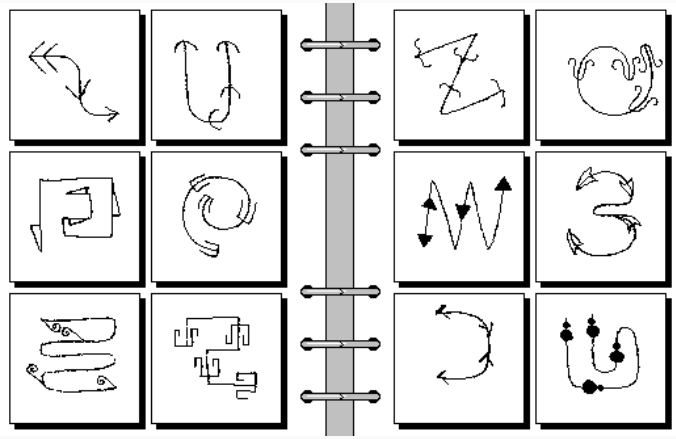

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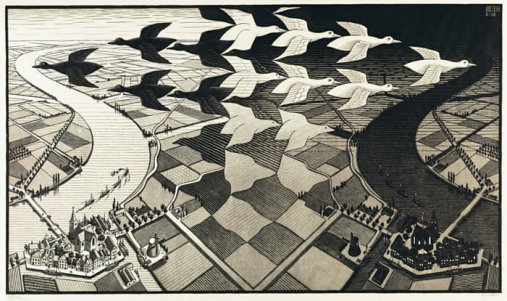

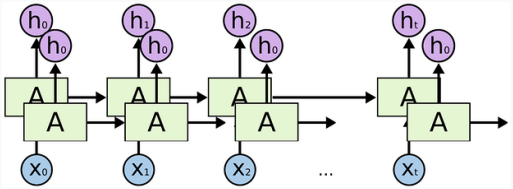

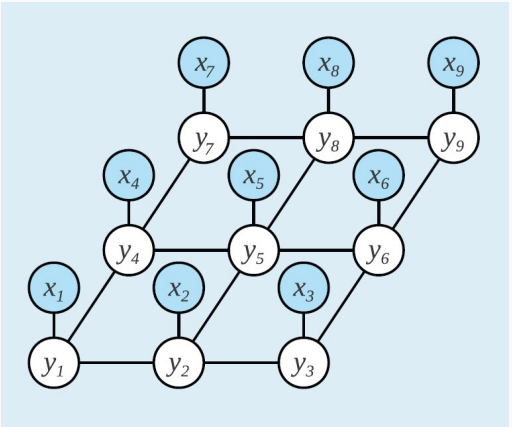

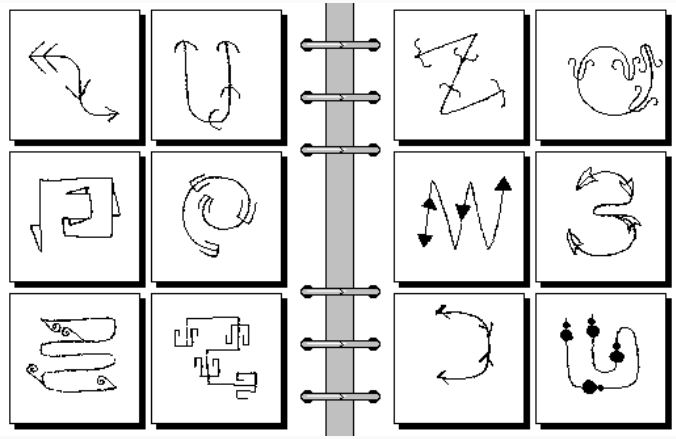

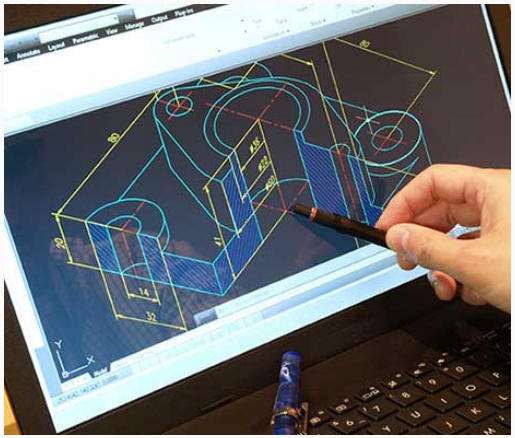

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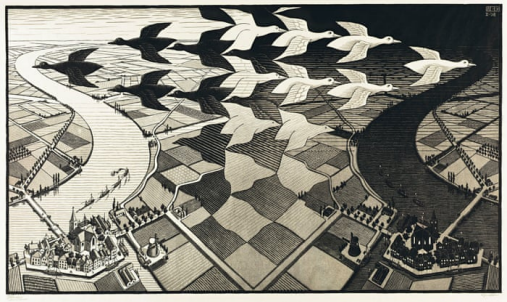
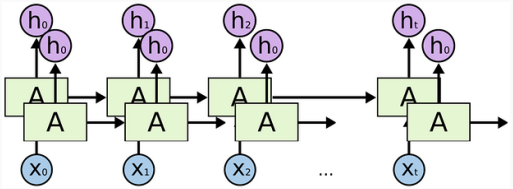
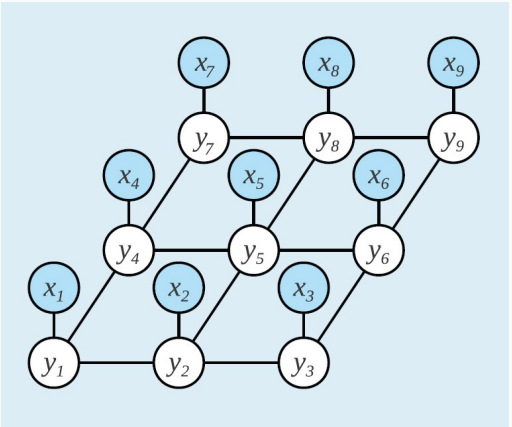
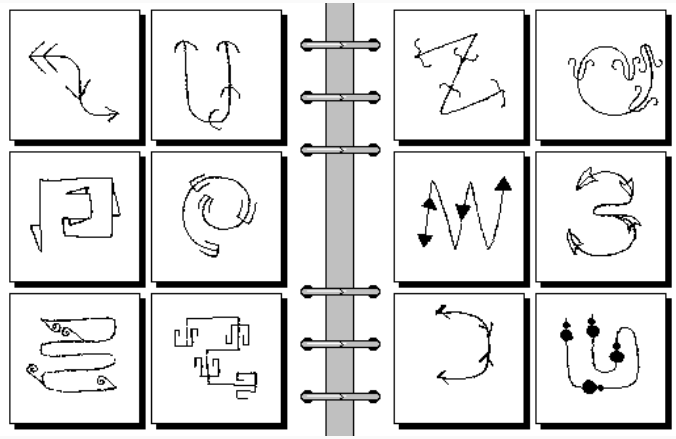
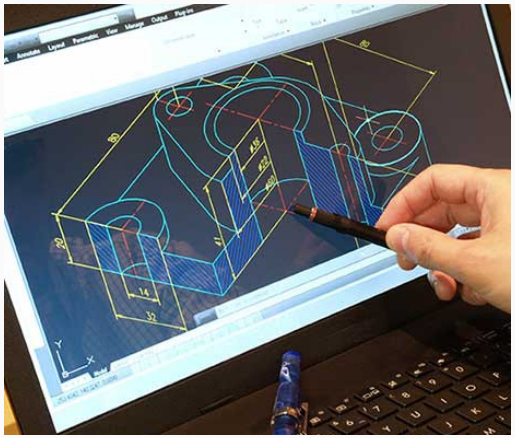


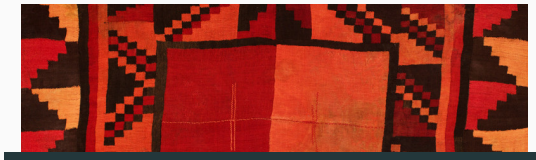


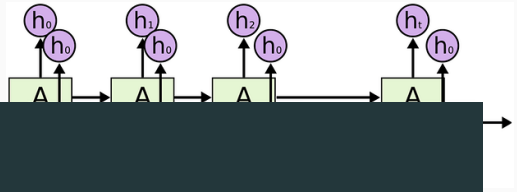






High-level, abstract visual abilities





why?

impute missing objects, extrapolate percepts,

learn visual concepts (‘arch’, ‘spiral’, HMM),

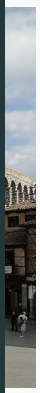
assist graphic design, assist 3D modeling

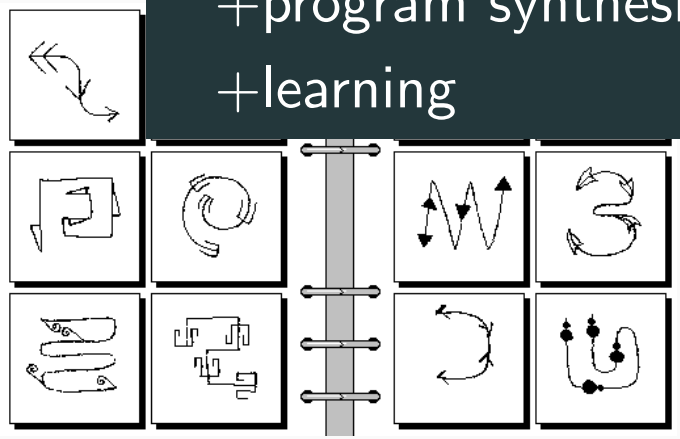
how?

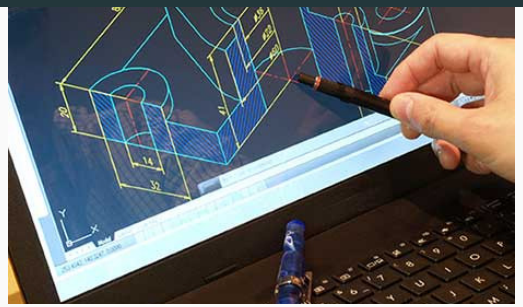
Bayesian inference of graphics program conditioned on image,

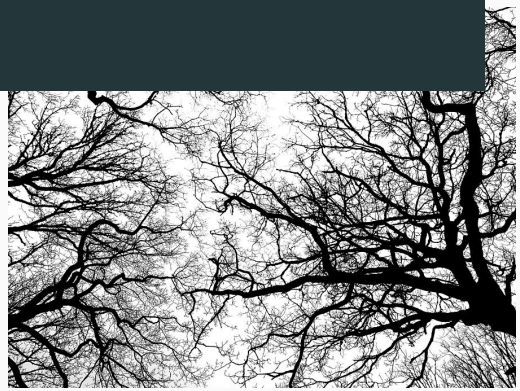
+program synthesis

+learning



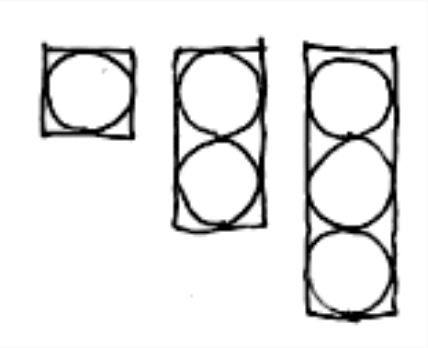






Learning to infer graphics programs from hand-drawn images

model infers program from drawing



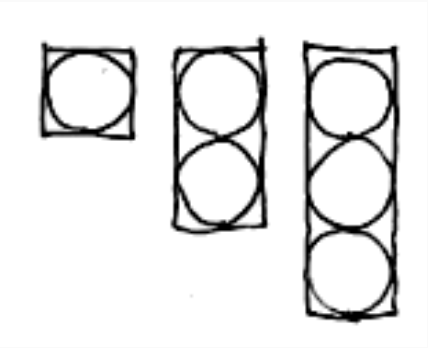
```
for (0 <= i < 3)
 rectangle(3*i,-2*i+4,
           3*i+2,6)
 for (0 <= j < i + 1)
  circle(3*i+1,-2*j+5)
```

Ellis, Ritchie, Solar-Lezama, Tenenbaum. NeurIPS 2018.

Learning to infer graphics programs from hand-drawn images

model infers program from drawing

zero-shot generalization / extrapolation



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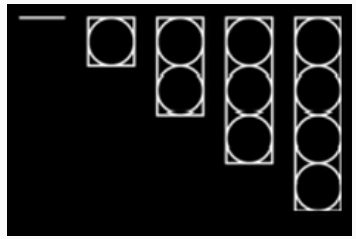

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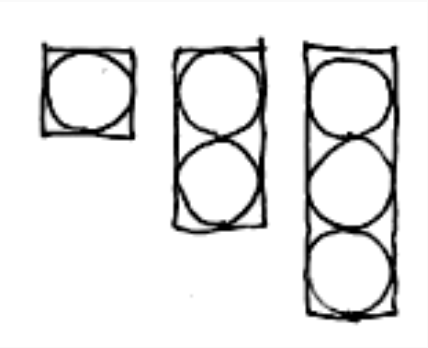

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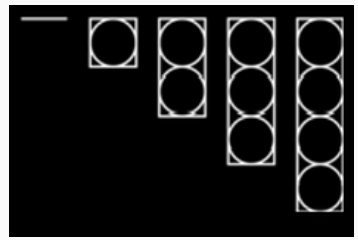
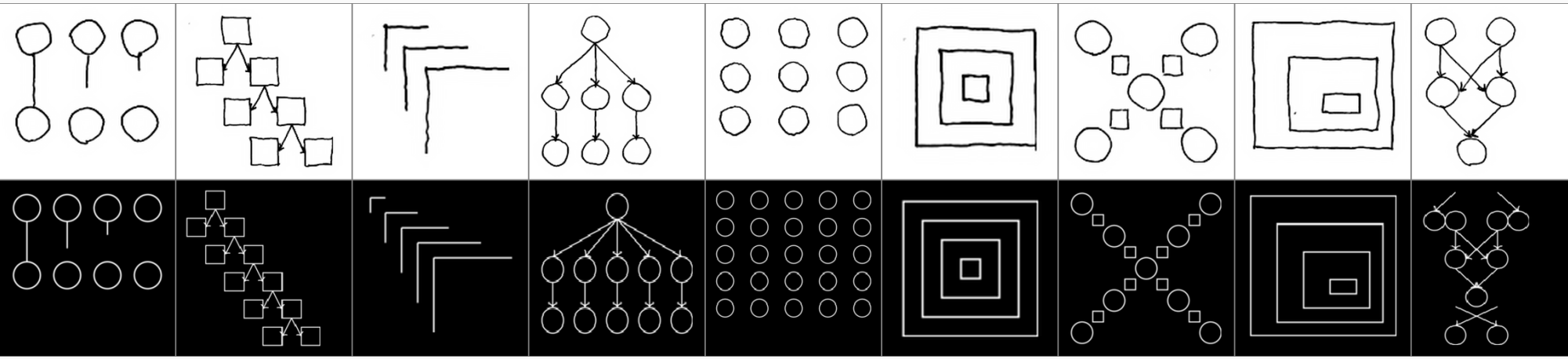
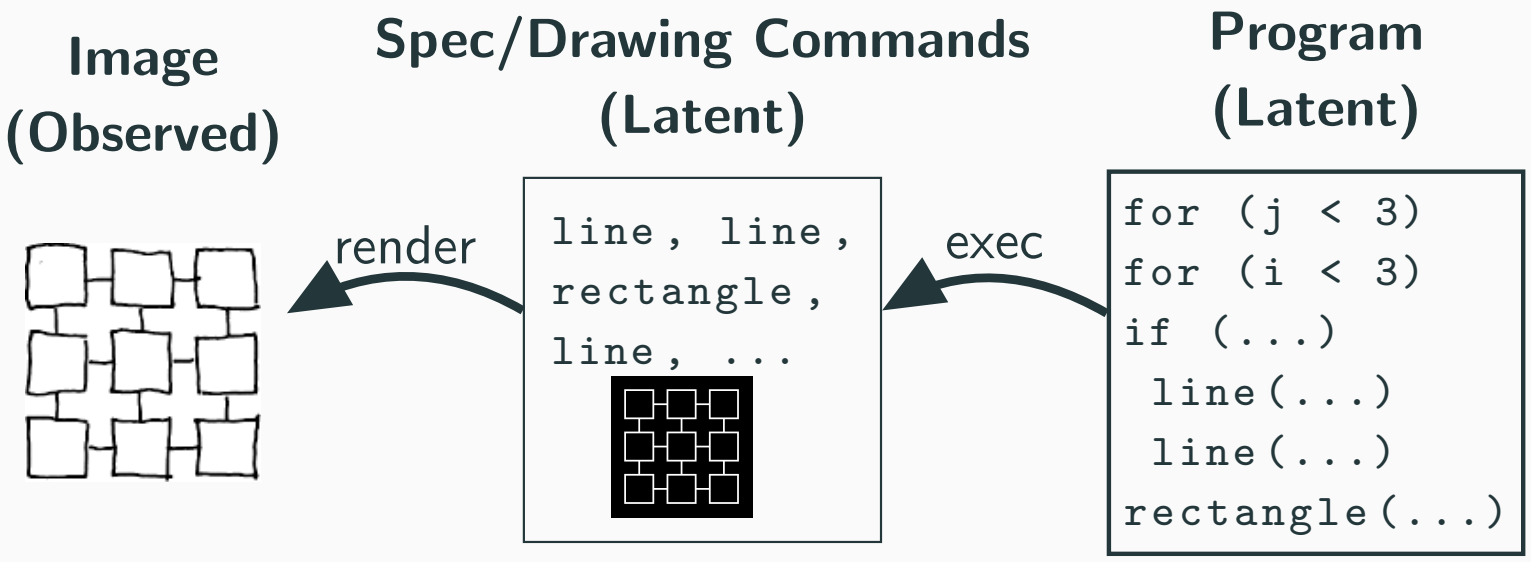




How to infer graphics programs from hand-drawn images



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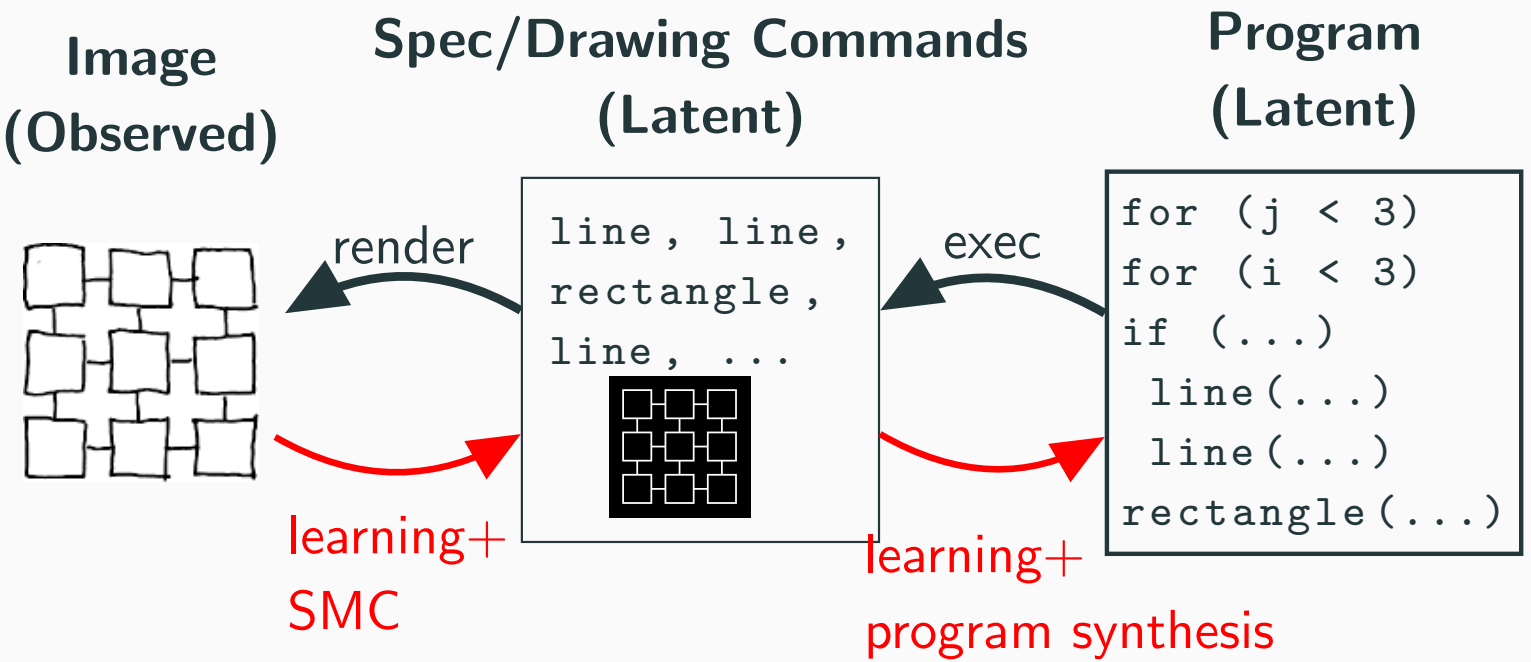

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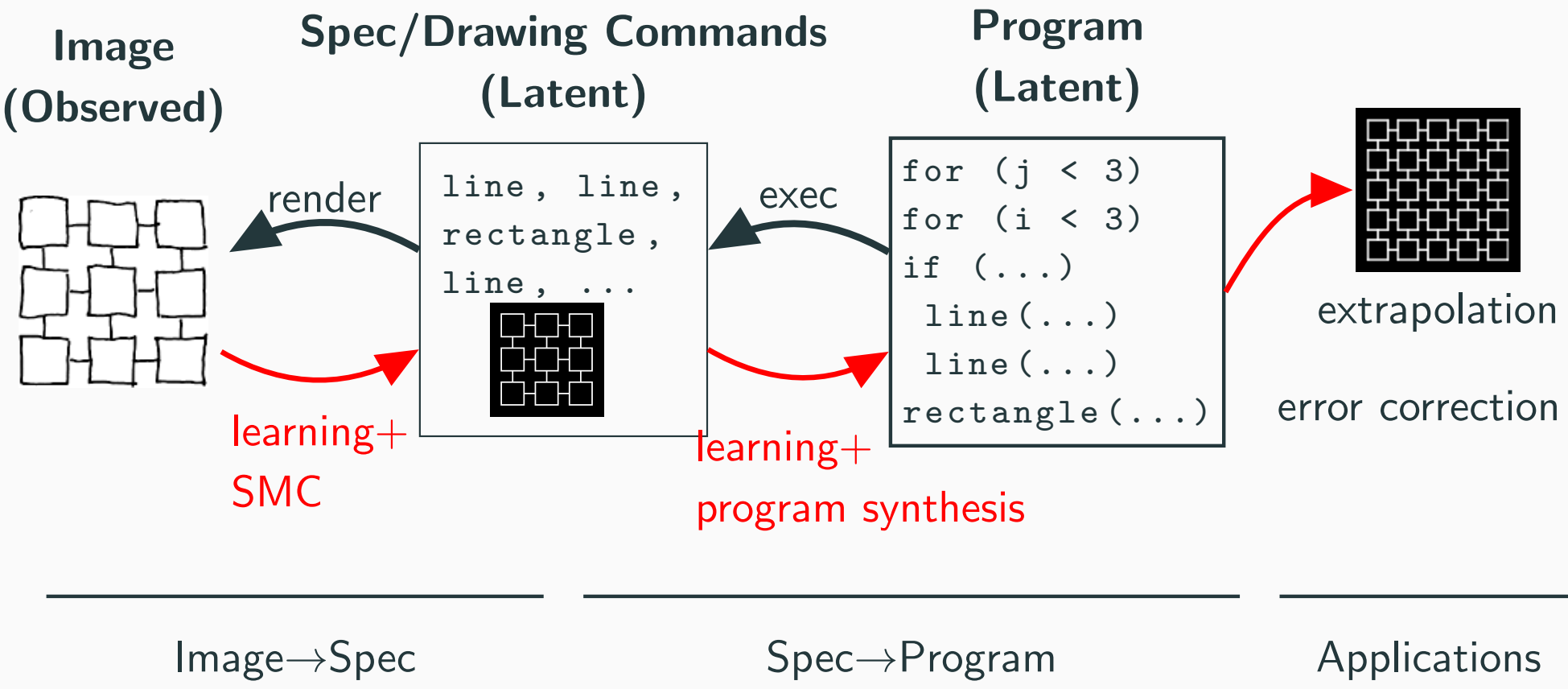
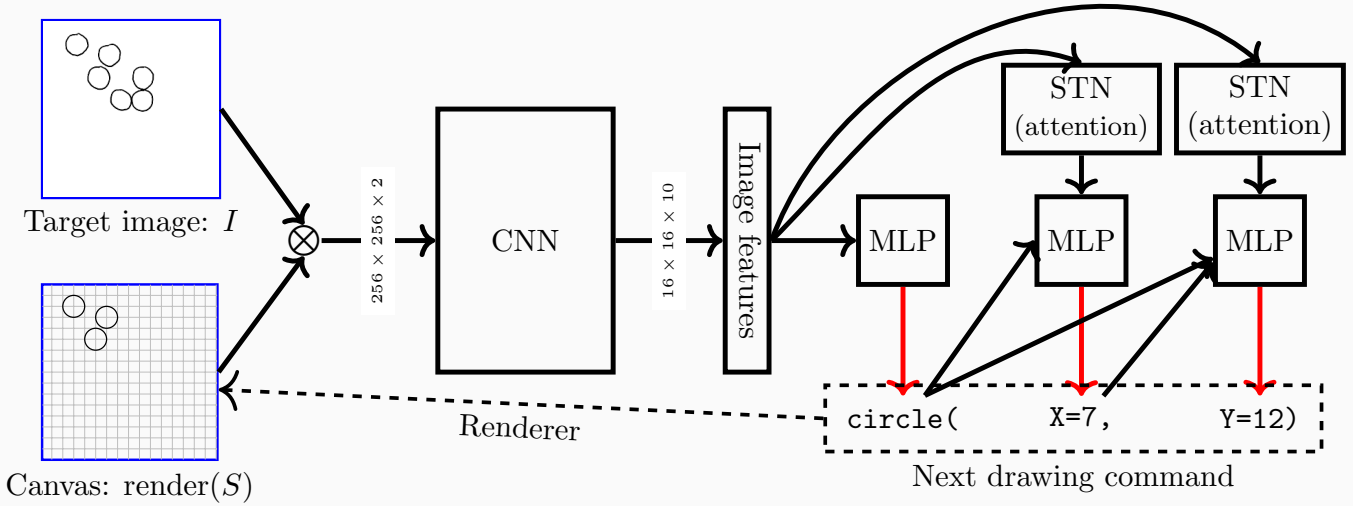


Parsing images into specs (LaTeX TikZ commands)

Neurally Guided Procedural Modeling (Ritchie et al 2016) +

Attend, Infer, Repeat (Eslami et al 2016)



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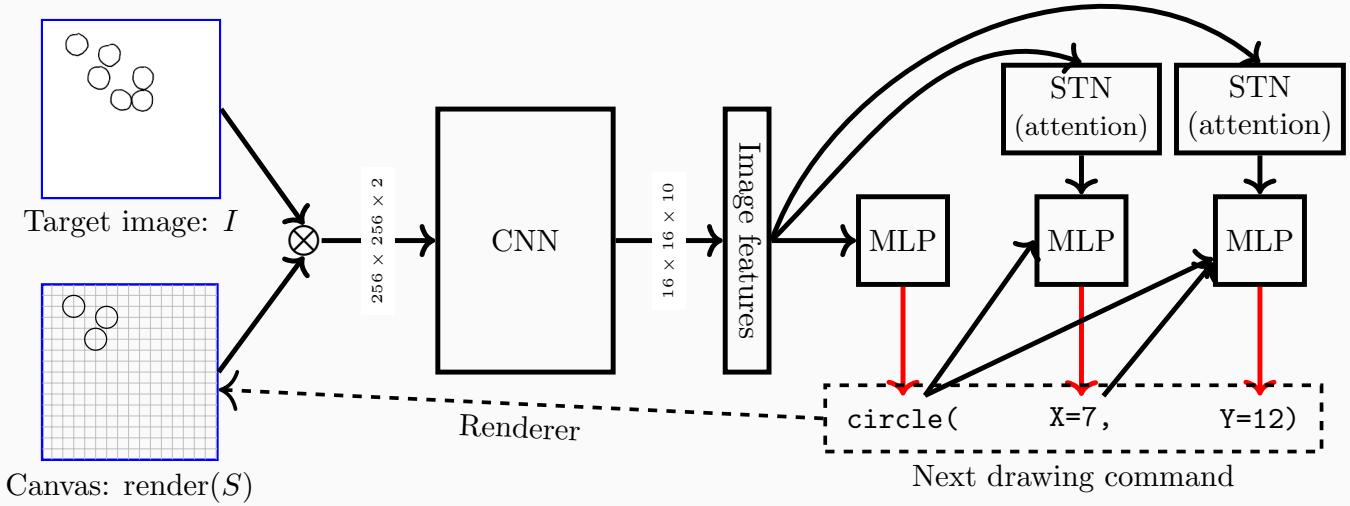
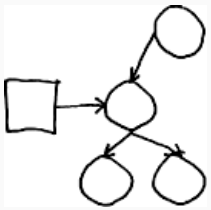
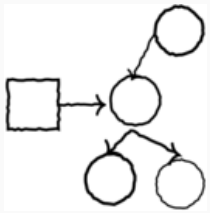




hand drawing



noisy rerender

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Neurally Guided Procedural Modeling (Ritchie et al 2016) +

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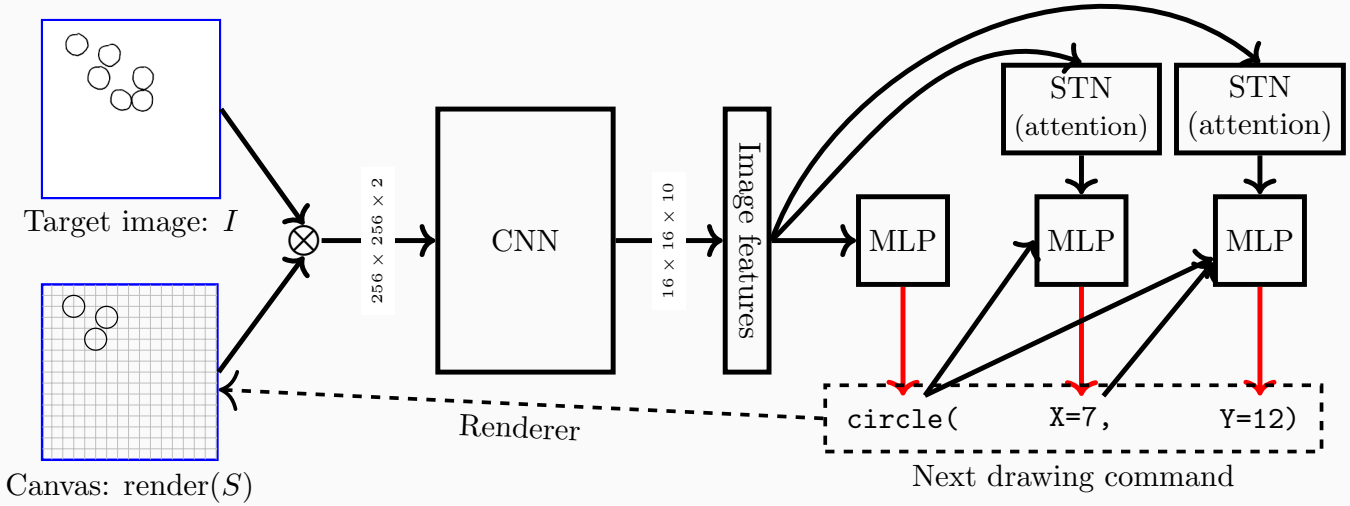
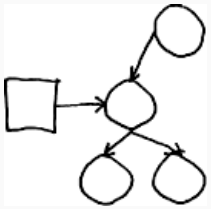
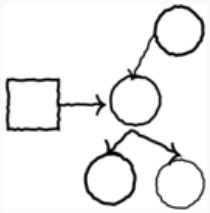
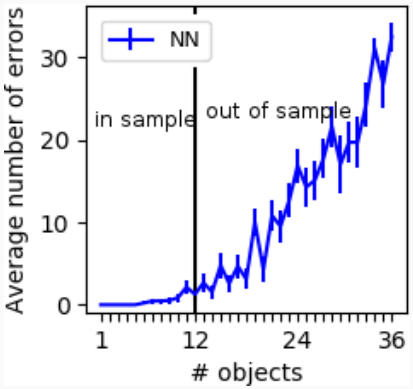




hand drawing



noisy rerender



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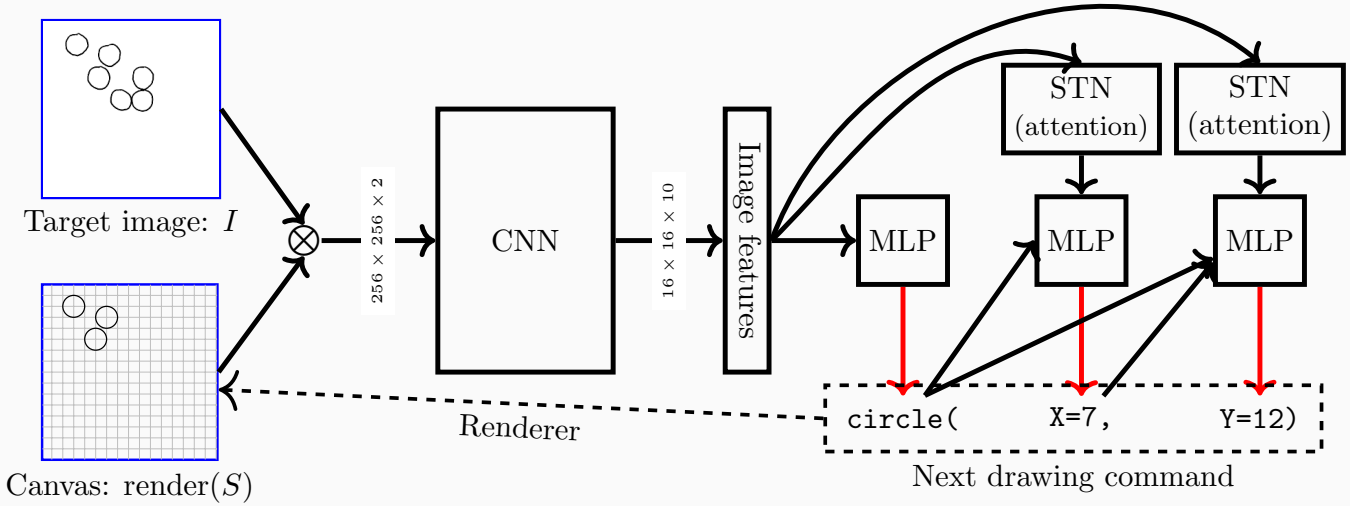
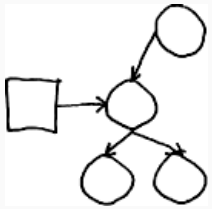
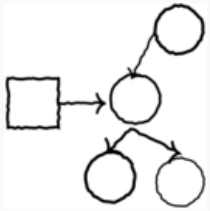
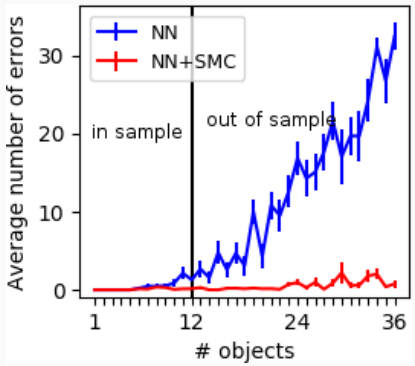




hand drawing

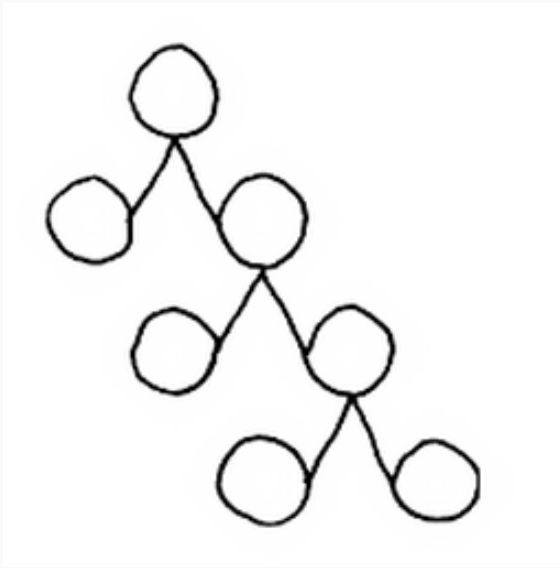


noisy rerender

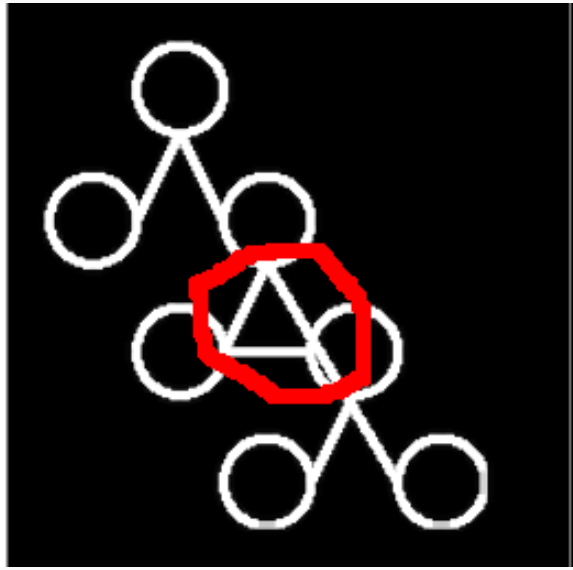


Top-down influences on perception

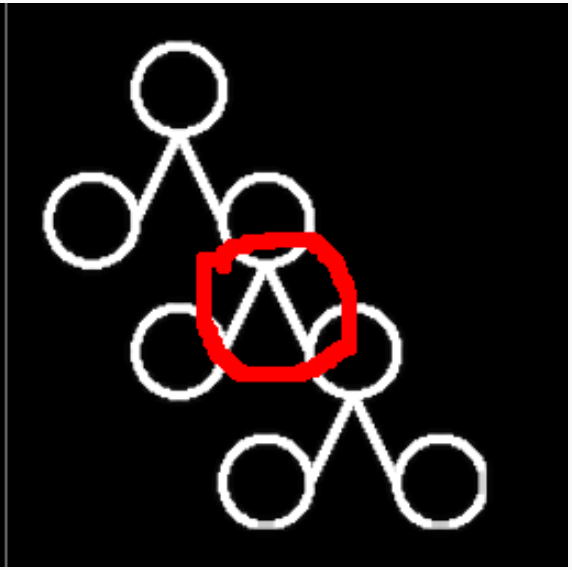
drawing



bottom-up neural net

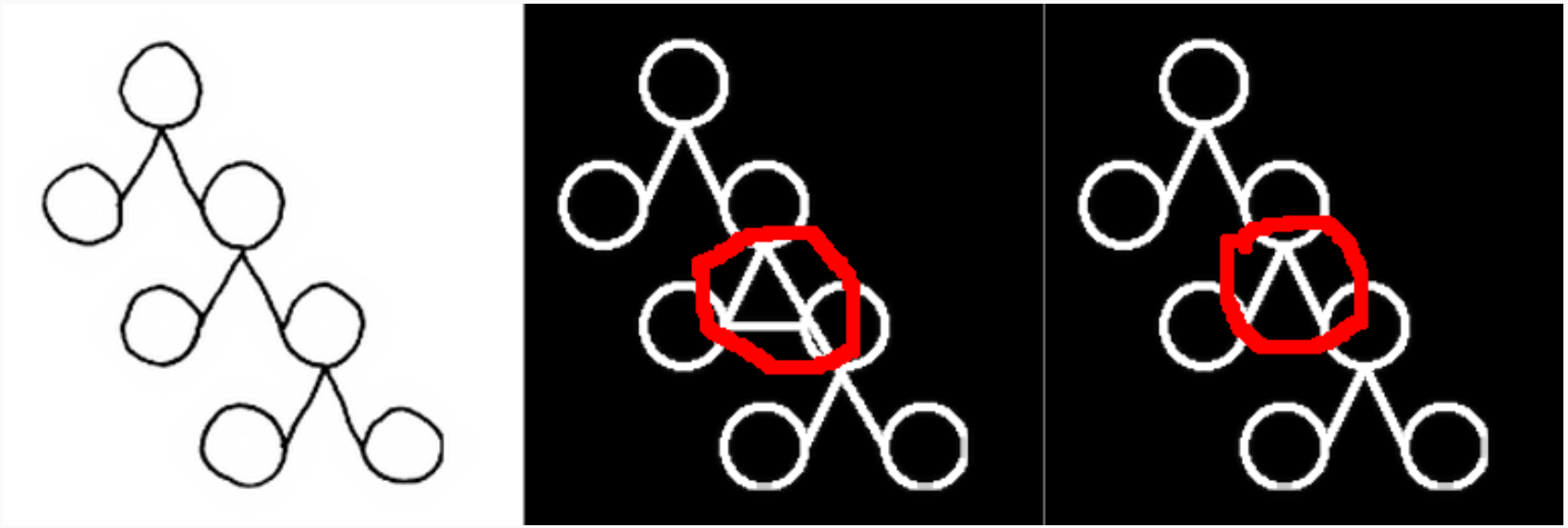


w/ top-down program bias



Top-down influences on perception

drawing | bottom-up neural net | w/ top-down program bias

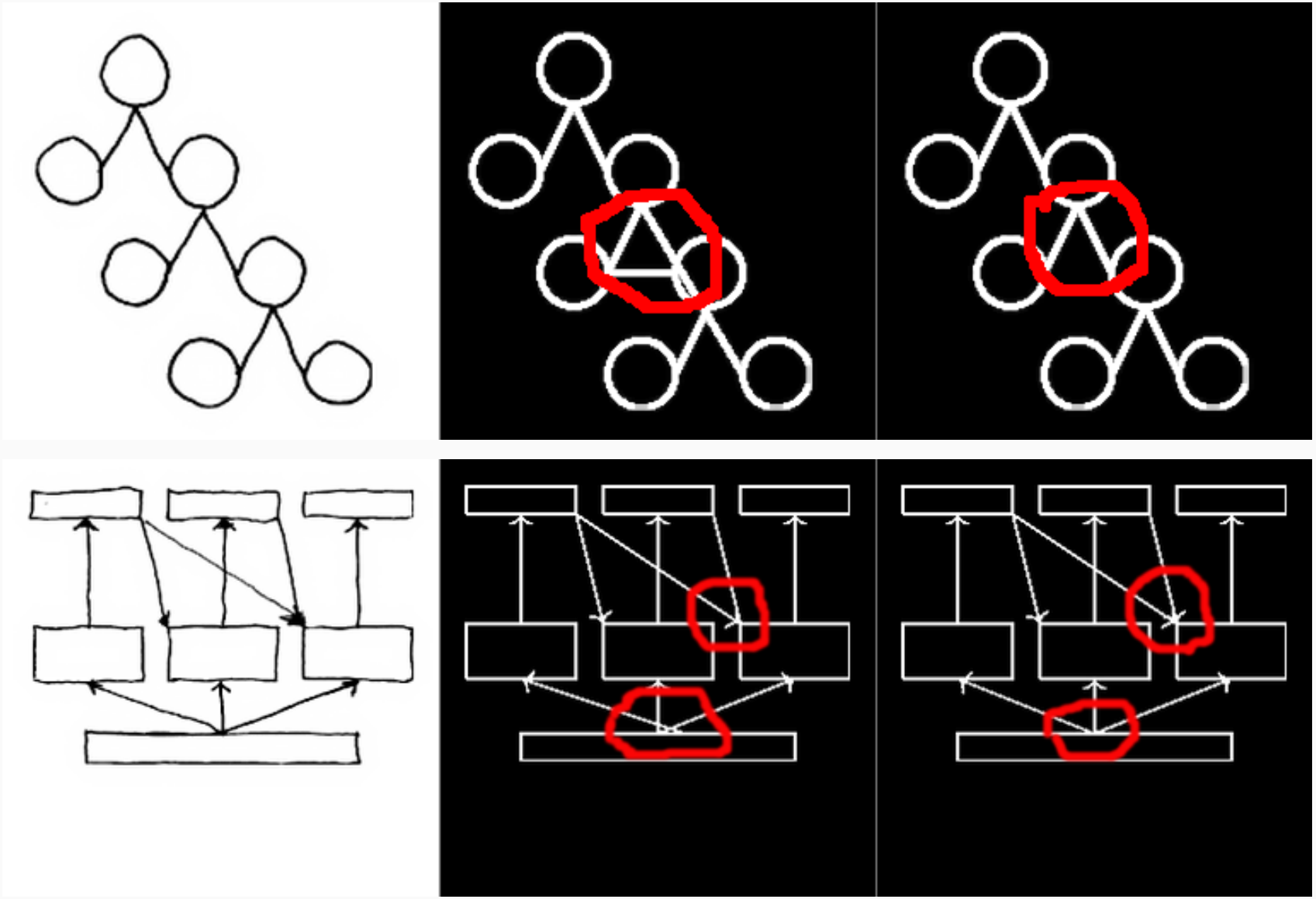


$$\hat{S}(I) = \arg\max_{S \in \mathcal{F}(I)} \mathbb{P}(I|\text{render}(S)) \times \mathbb{P}_\beta[\text{program}(S)]$$

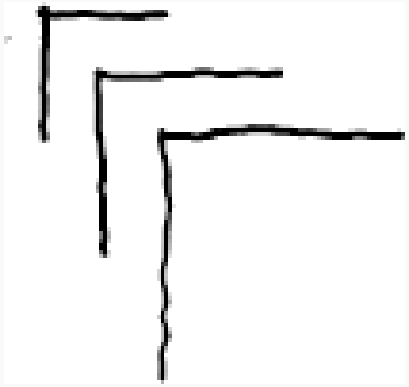
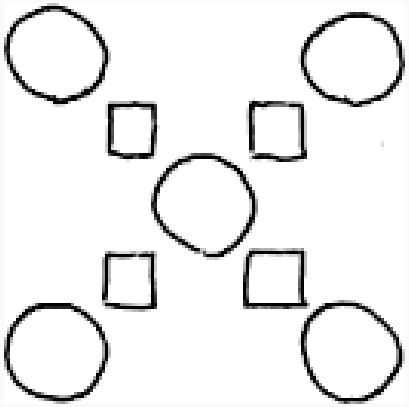
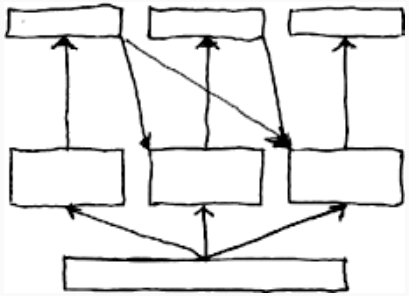
$$\beta^* = \arg\max_\beta \mathbb{E}\left[\log \frac{\mathbb{P}_\beta[\text{program}(S)] \times \mathbb{P}(I|\text{render}(S))}{\sum_{S' \in \mathcal{F}(I)} \mathbb{P}_\beta[\text{program}(S')] \times \mathbb{P}(I|\text{render}(S'))}\right]$$

Top-down influences on perception

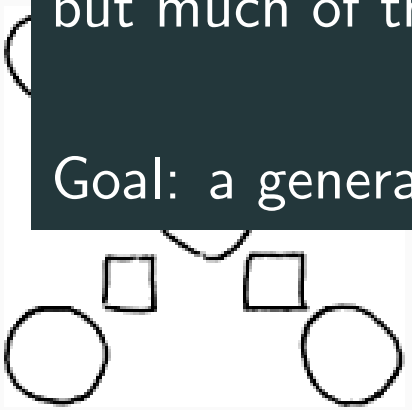
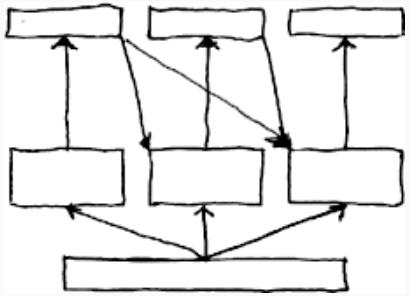
drawing | bottom-up neural net | w/ top-down program bias



Example programs

Drawing	Spec	Program
	`Line(2,15, 4,15)` `Line(4,9, 4,13)` `Line(3,11, 3,14)` `Line(2,13, 2,15)` `Line(3,14, 6,14)` `Line(4,13, 8,13)`	`for(i<3)` `  line(i,-1*i+6,` `  2*i+2,-1*i+6)` `  line(i,-2*i+4,i,-1*i+6)`
	`Circle(2,8)` `Rectangle(6,9, 7,10)` `Circle(8,8)` `Rectangle(6,12, 7,13)` `Rectangle(3,9, 4,10)` *... etc. ...; 9 lines*	`reflect(y=8)` `  for(i<3)` `  if(i>0)` `  rectangle(3*i-1,2,3*i,3)` `  circle(3*i+1,3*i+1)`
	`Line(3,10,3,14,arrow)` `Rectangle(11,8,15,10)` `Rectangle(11,14,15,15)` `Line(13,10,13,14,arrow)` *... etc. ...; 16 lines*	`for(i<3)` `  line(7,1,5*i+2,3,arrow)` `  for(j<i+1)` `  if(j>0)` `  line(5*j-1,9,5*i,5,arrow)` `  line(5*j+2,5,5*j+2,9,arrow)` `  rectangle(5*i,3,5*i+4,5)` `  rectangle(5*i,9,5*i+4,10)` `rectangle(2,0,12,1)`

Example programs

Drawing	Spec	Program
	`Line(2,15, 4,15)` `Line(4,9, 4,13)` `Line(3,11, 3,14)` `Line(2,13, 2,15)` `Line(3,14, 6,14)` `Line(4,13, 8,13)`	`for(i<3)` `line(i,-1*i+6,` `2*i+2,-1*i+6)` `line(i,-2*i+4,i,-1*i+6)`
	`Rectangle(3,9, 4,10)` *... etc. ...; 9 lines*	`rectangle(3*i-1,2,3*i,3)` `circle(3*i+1,3*i+1)`
	`Line(3,10,3,14,arrow)` `Rectangle(11,8,15,10)` `Rectangle(11,14,15,15)` `Line(13,10,13,14,arrow)` *... etc. ...; 16 lines*	`for(i<3)` `line(7,1,5*i+2,3,arrow)` `for(j<i+1)` `if(j>0)` `line(5*j-1,9,5*i,5,arrow)` `line(5*j+2,5,5*j+2,9,arrow)` `rectangle(5*i,3,5*i+4,5)` `rectangle(5*i,9,5*i+4,10)` `rectangle(2,0,12,1)`

Learning played a role...

but much of this system is specific to 2-D graphics

Goal: a general algorithm for learning to synthesize programs

Growing domain-specific knowledge

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

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

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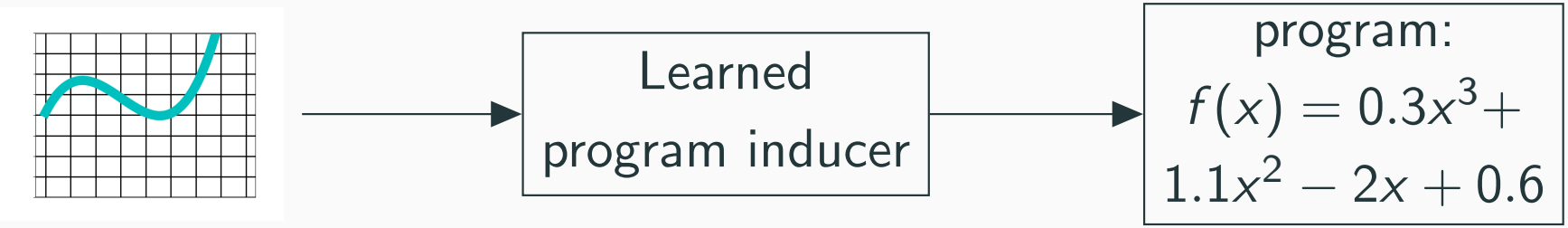

Concepts: x^3, $\alpha x + \beta$, etc

Inference strategy: neurosymbolic search for programs

Growing domain-specific knowledge

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

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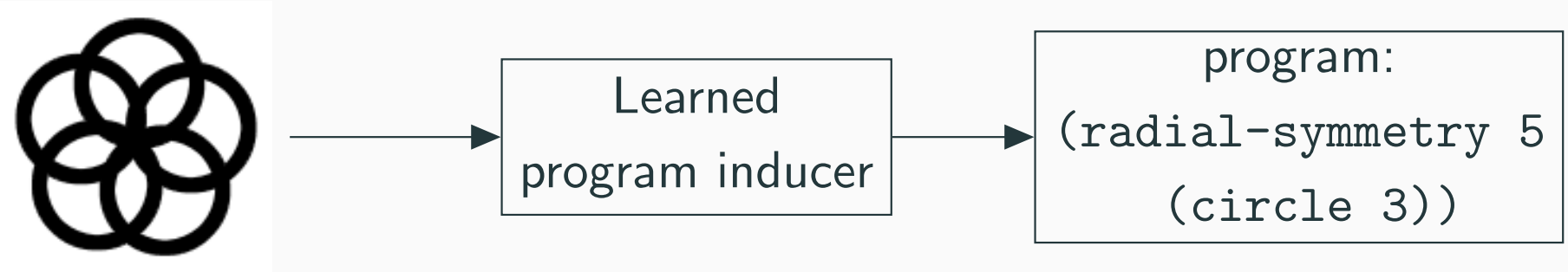
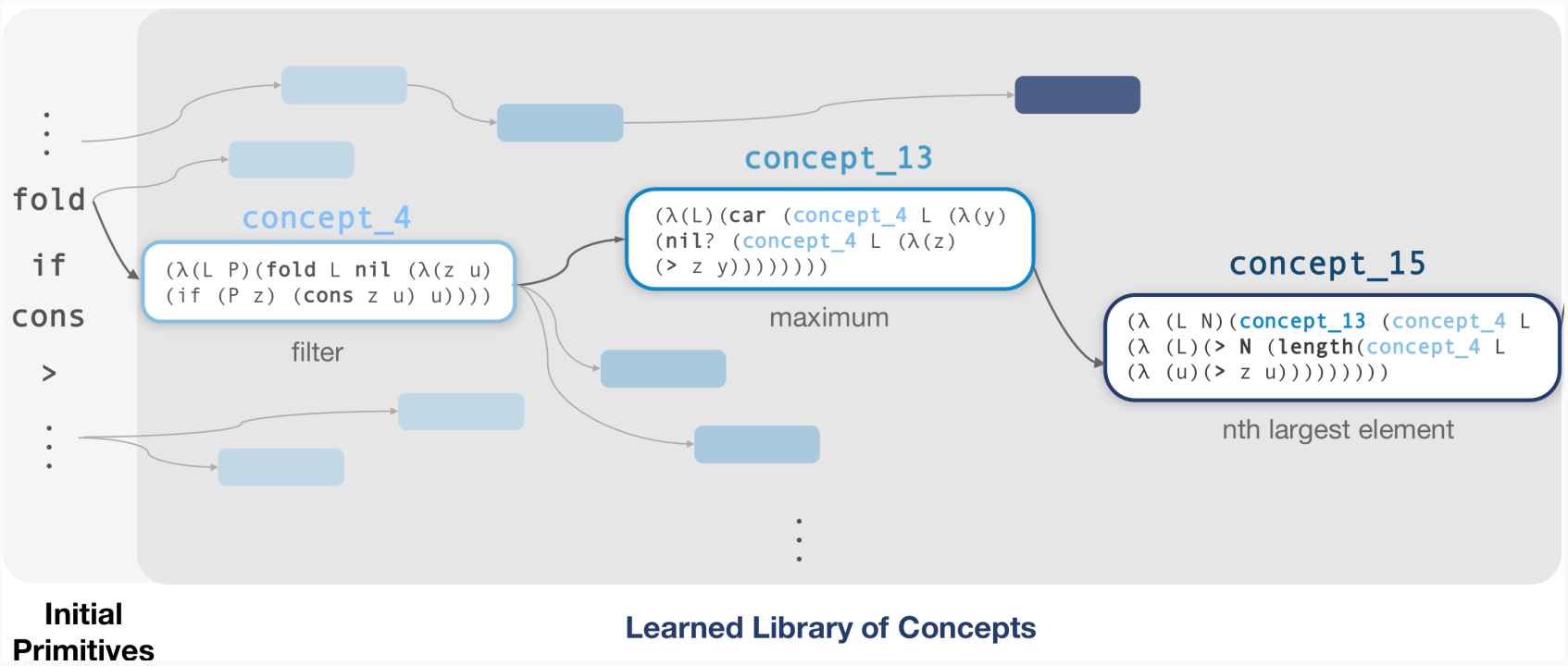


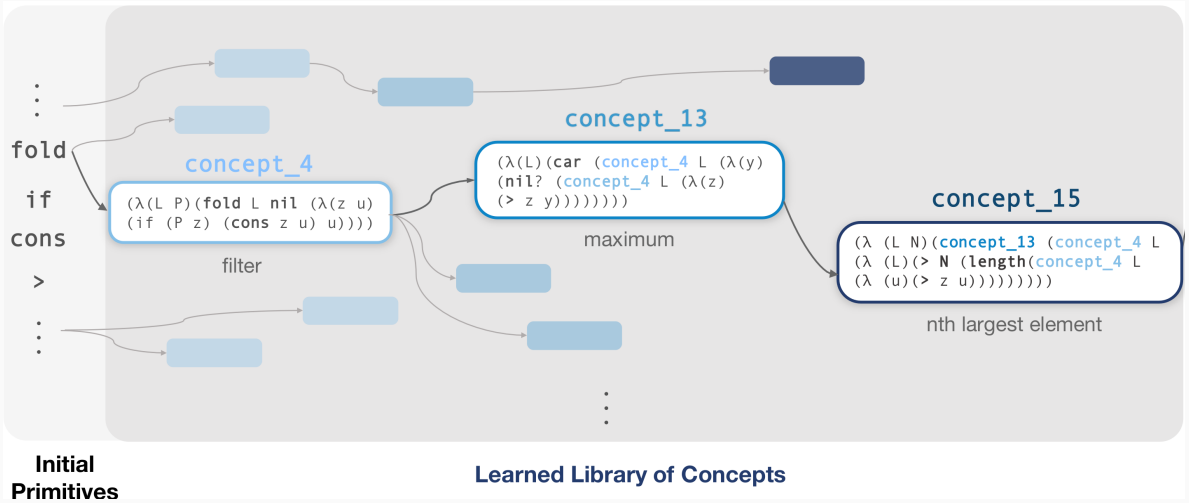
Concepts: `circle`, `radial-symmetry`, etc

Inference strategy: neurosymbolic search for programs

Library learning



Library learning



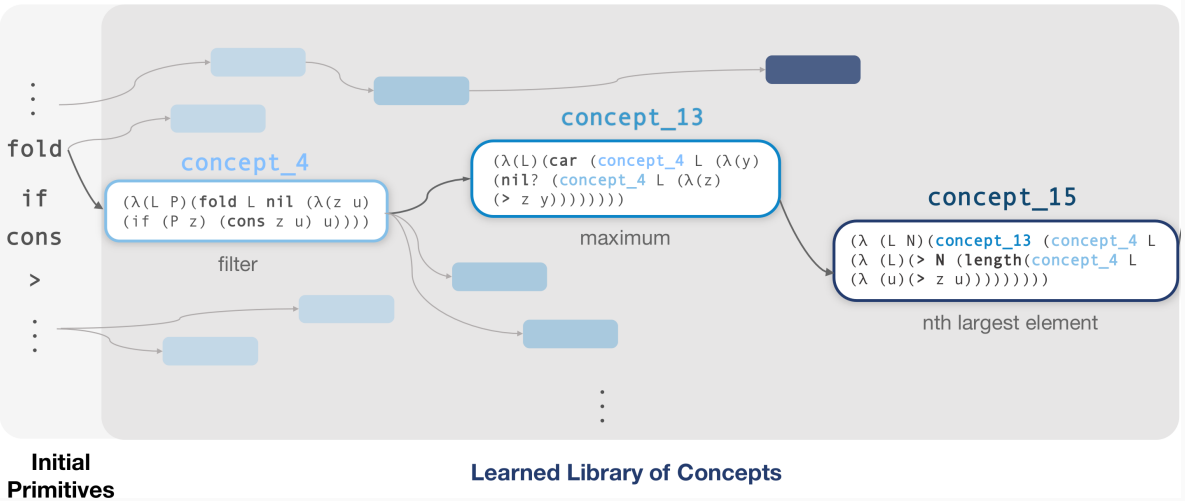
Problem: sort list

Solution:

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

get nth largest element where n = 1, 2, 3 ….length of list

Library learning



Problem: sort list

Solution:

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

get nth largest element where n = 1, 2, 3 ….length of list

Solution in initial primitives:

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

Discovered Problem Solutions

DreamCoder

- **Wake:** Solve problems by writing programs
- **Sleep:** Improve DSL and neural recognition model:
  - **Abstraction sleep:** Improve library
  - **Dream sleep:** Improve neural inference model
- Combines ideas from Wake-Sleep & Exploration-Compression

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List Processing

Sum List

[1 2 3] → 6
[4 6 8 1] → 17

Double

[1 2 3 4] → [2 4 6 8]
[6 5 1] → [12 10 2]

Check Evens

[0 2 3] → [T T F]
[2 4 9 6] → [T T F T]

Text Editing

Abbreviate

Allen Newell → A.N.
Herb Simon → H.S.

Drop Last Characters

jabberwocky → jabberw
copycat → cop

Extract

see spot(run) → run
a (bee) see → bee

Regexes

Phone Numbers

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

Currency

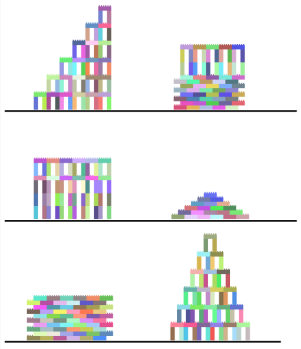
$100.25
$4.50

Dates

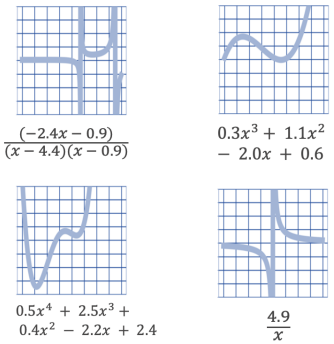
Y1775/0704
Y2000/0101

LOGO Graphics

Block Towers



Symbolic Regression



Recursive Programming

Filter

[■■■■■] → [■■]
[■■■■■■] → [■■■■]
[■■■■■] → [■■■]

Index List

0, [■■■■■■] → ■
1, [■■■■■■] → ■
1, [■■■■■■■] → ■

Length

[■■■■] → 4
[■■■■■■] → 6
[■■■] → 3

Every Other

[■■■■] → [■■]
[■■■■■] → [■■■]
[■■■■■■] → [■■■]

Physics

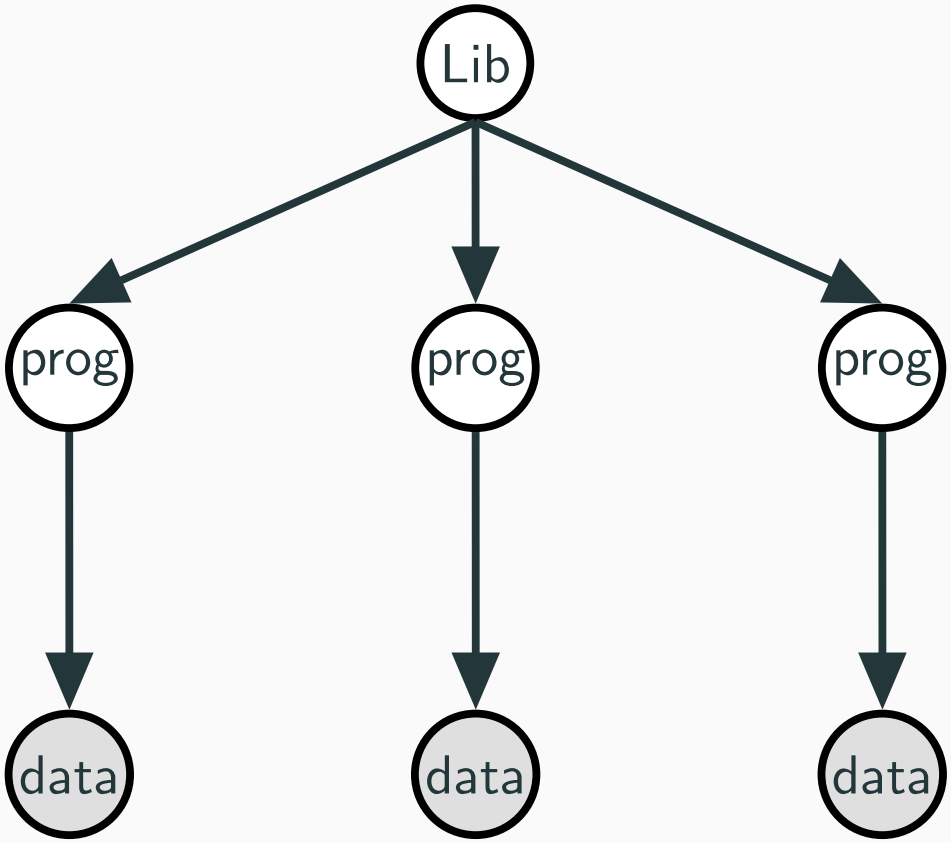
$$KE = \frac{1}{2}m|\vec{v}|^2$$

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

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

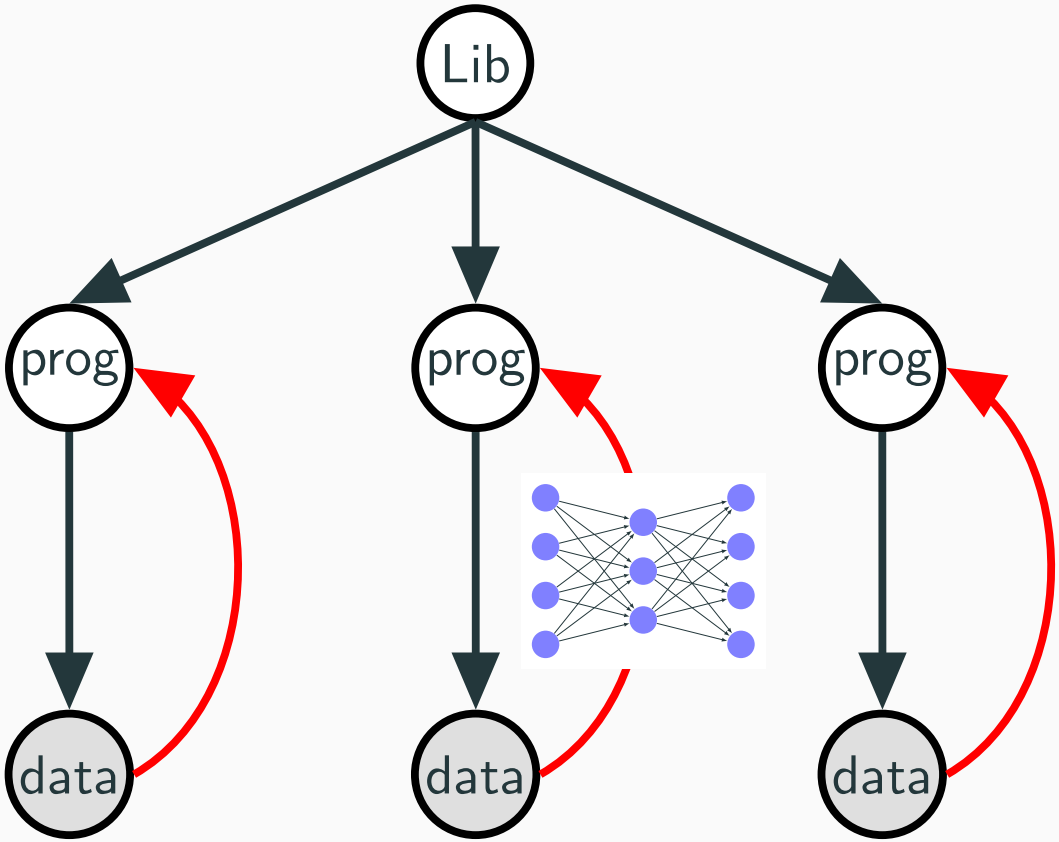
$$R_{total} = \left(\Sigma_i \frac{1}{R_i}\right)^{-1}$$

Library learning as Bayesian inference



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

Library learning as amortized Bayesian inference

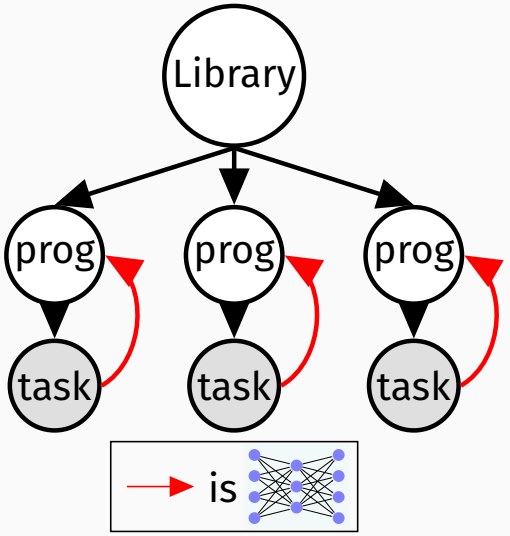


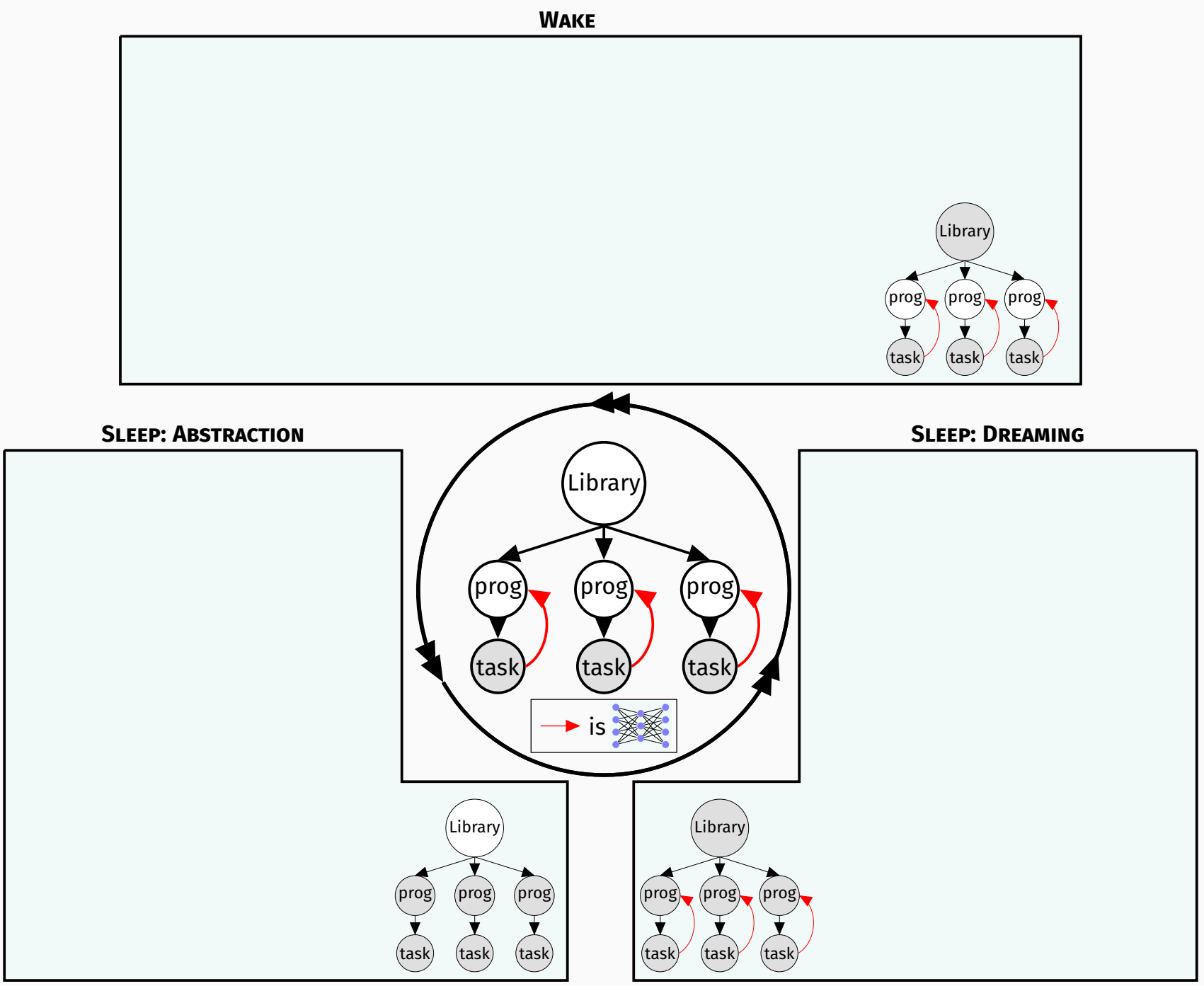
amortized inference +

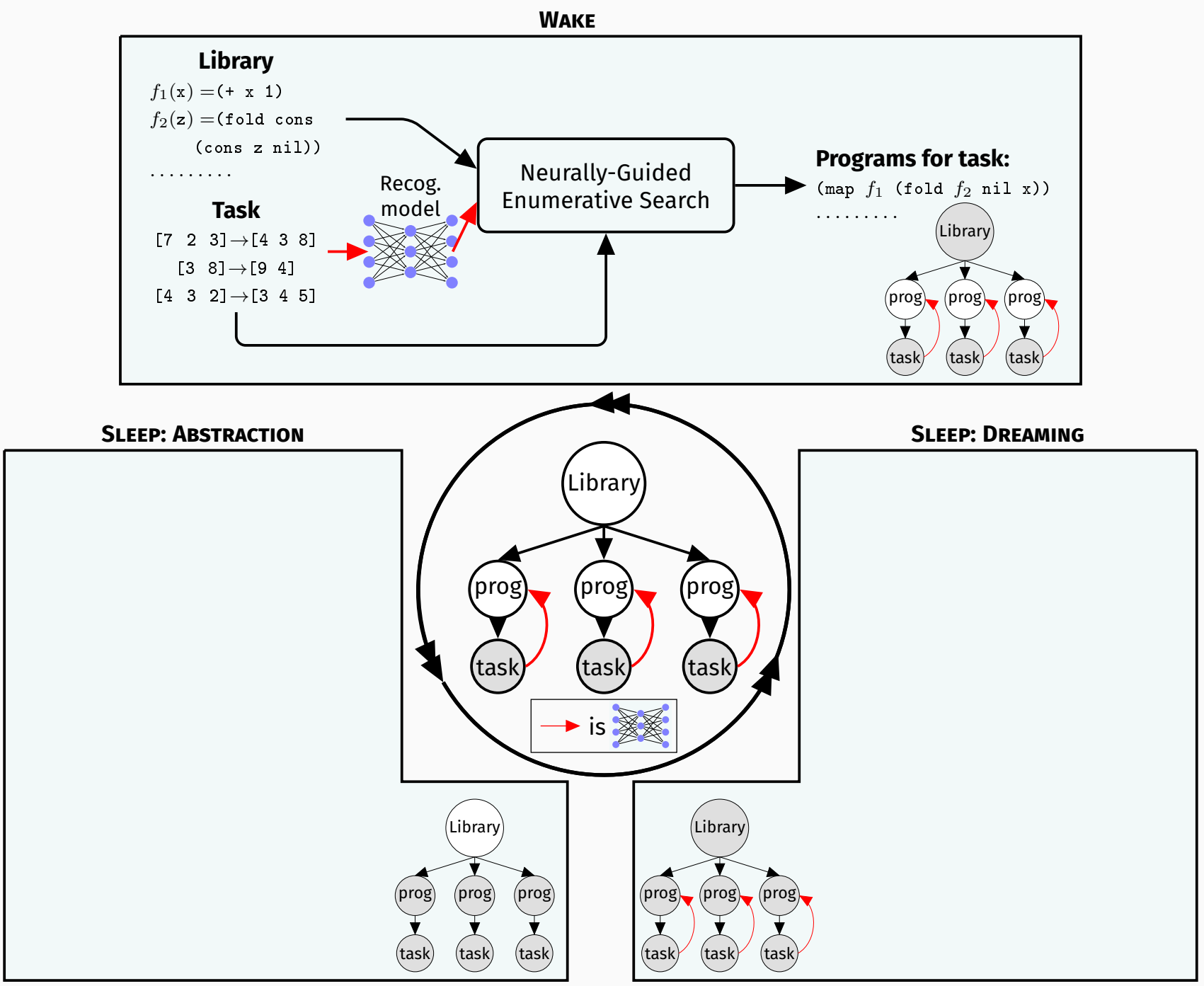
better program representation (Lisp) +

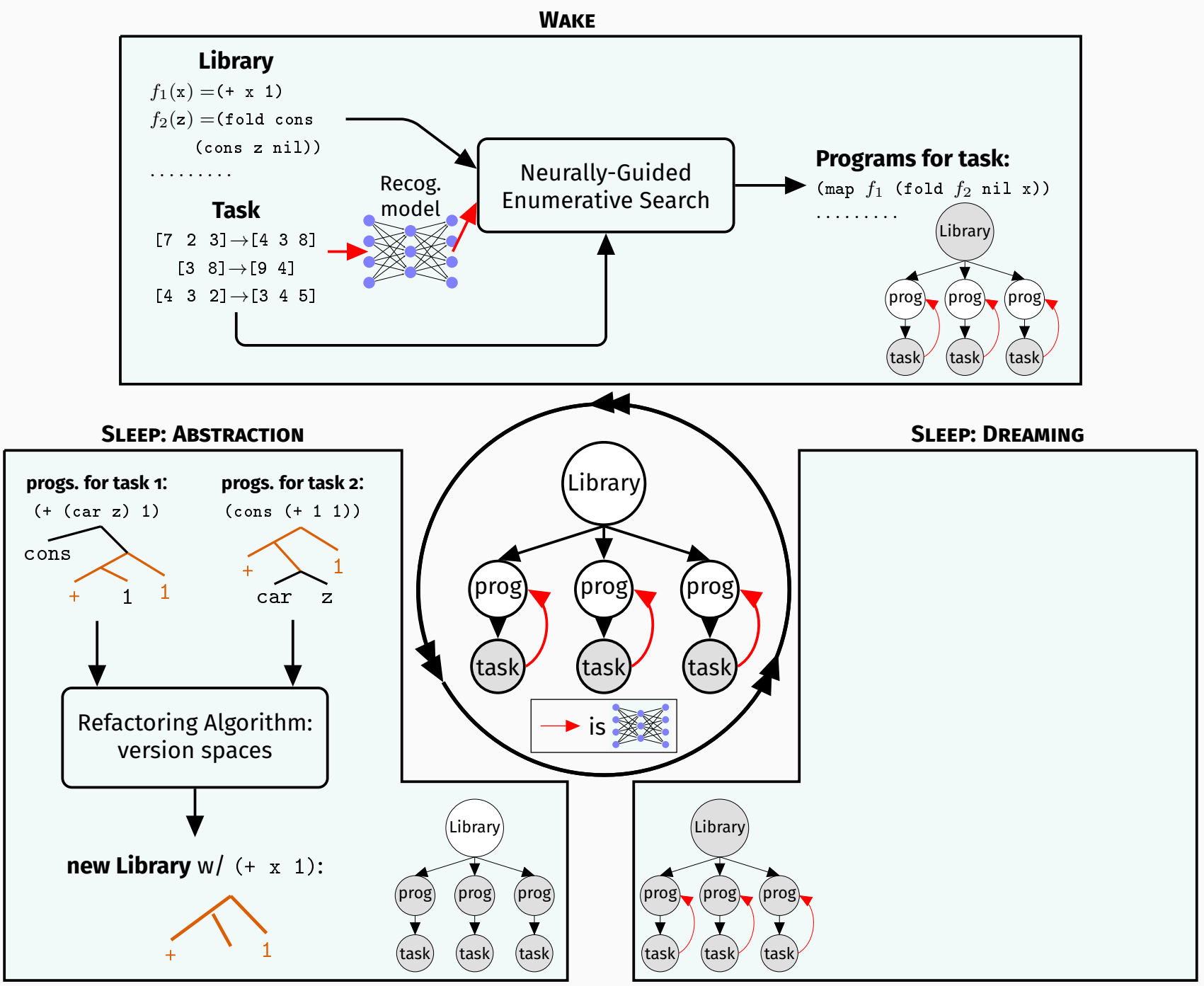
library learning via program analysis +

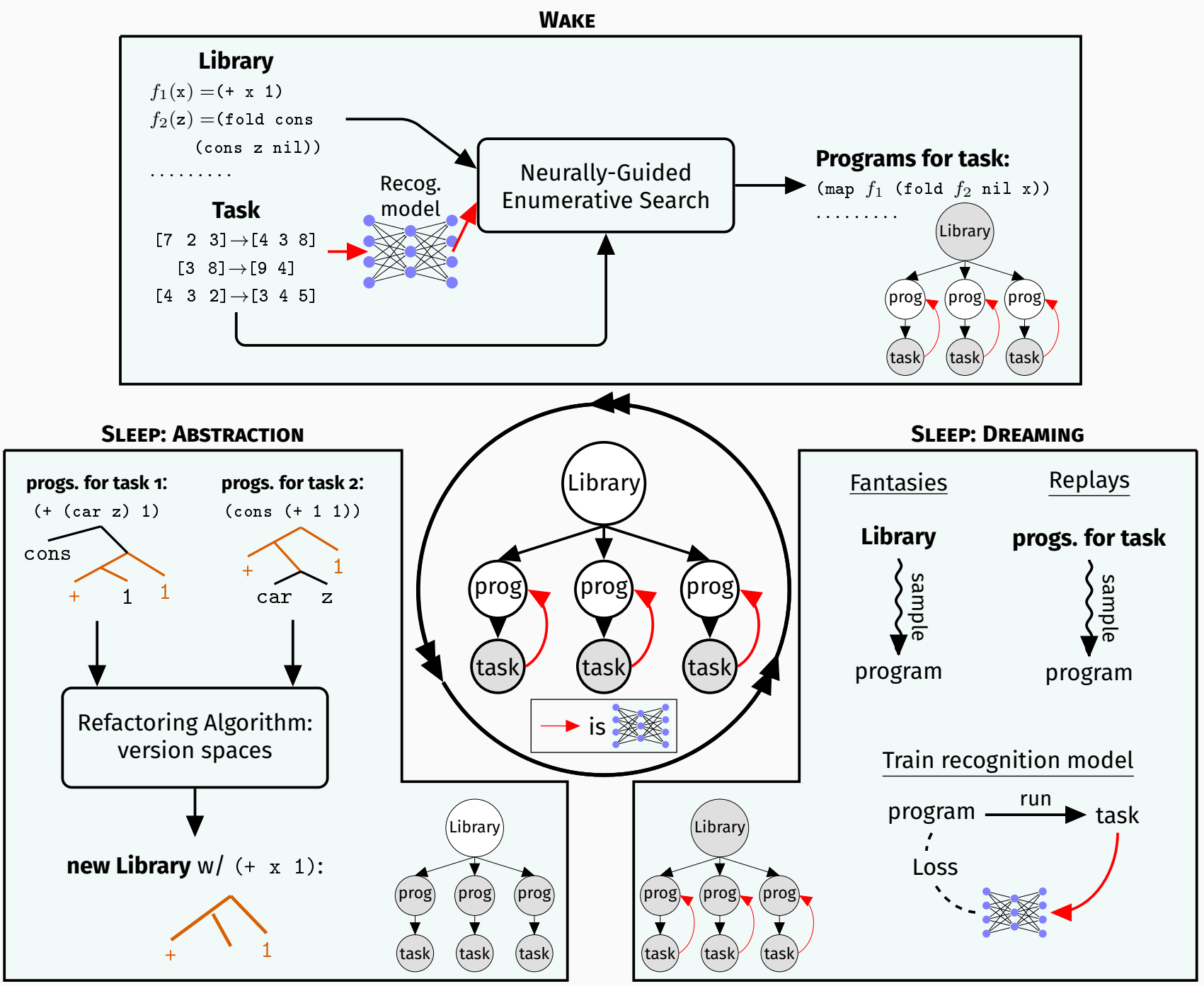
new neural inference network for program synthesis


Library
prog
prog
prog
task
task
task
is

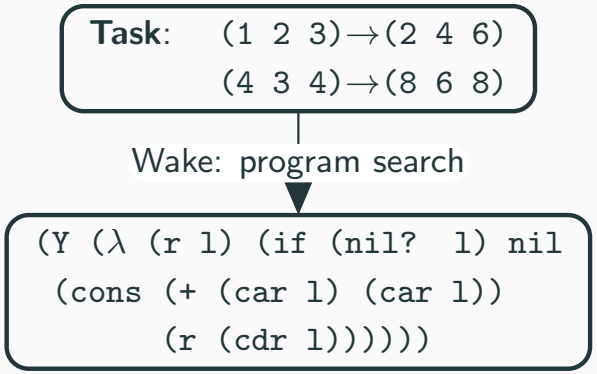

WAKE
Library
prog
prog
prog
task
task
task
SLEEP: ABSTRACTION
SLEEP: DREAMING
Library
prog
prog
prog
task
task
task
is
Library
prog
prog
prog
task
task
task
Library
prog
prog
prog
task
task
task

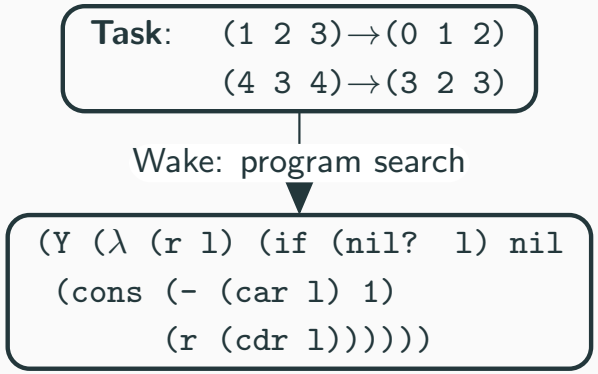

WAKE
Library
f_1(x) =(+ x 1)
f_2(z) =(fold cons
(cons z nil))
.....
Task
[7 2 3]→[4 3 8]
[3 8]→[9 4]
[4 3 2]→[3 4 5]
Recog. model
Neurally-Guided Enumerative Search
Programs for task:
(map f_1 (fold f_2 nil x))
.....
Library
prog
task
SLEEP: ABSTRACTION
SLEEP: DREAMING
is


WAKE
Library
f_1(x) =(+ x 1)
f_2(z) =(fold cons
(cons z nil))
.....
Task
[7 2 3]→[4 3 8]
[3 8]→[9 4]
[4 3 2]→[3 4 5]
Recog. model
Neurally-Guided Enumerative Search
Programs for task:
(map f_1 (fold f_2 nil x))
.....
Library
prog
task
SLEEP: ABSTRACTION
progs. for task 1:
(+ (car z) 1)
progs. for task 2:
(cons (+ 1 1))
cons
car z
Refactoring Algorithm: version spaces
new Library w/ (+ x 1):
SLEEP: DREAMING
is

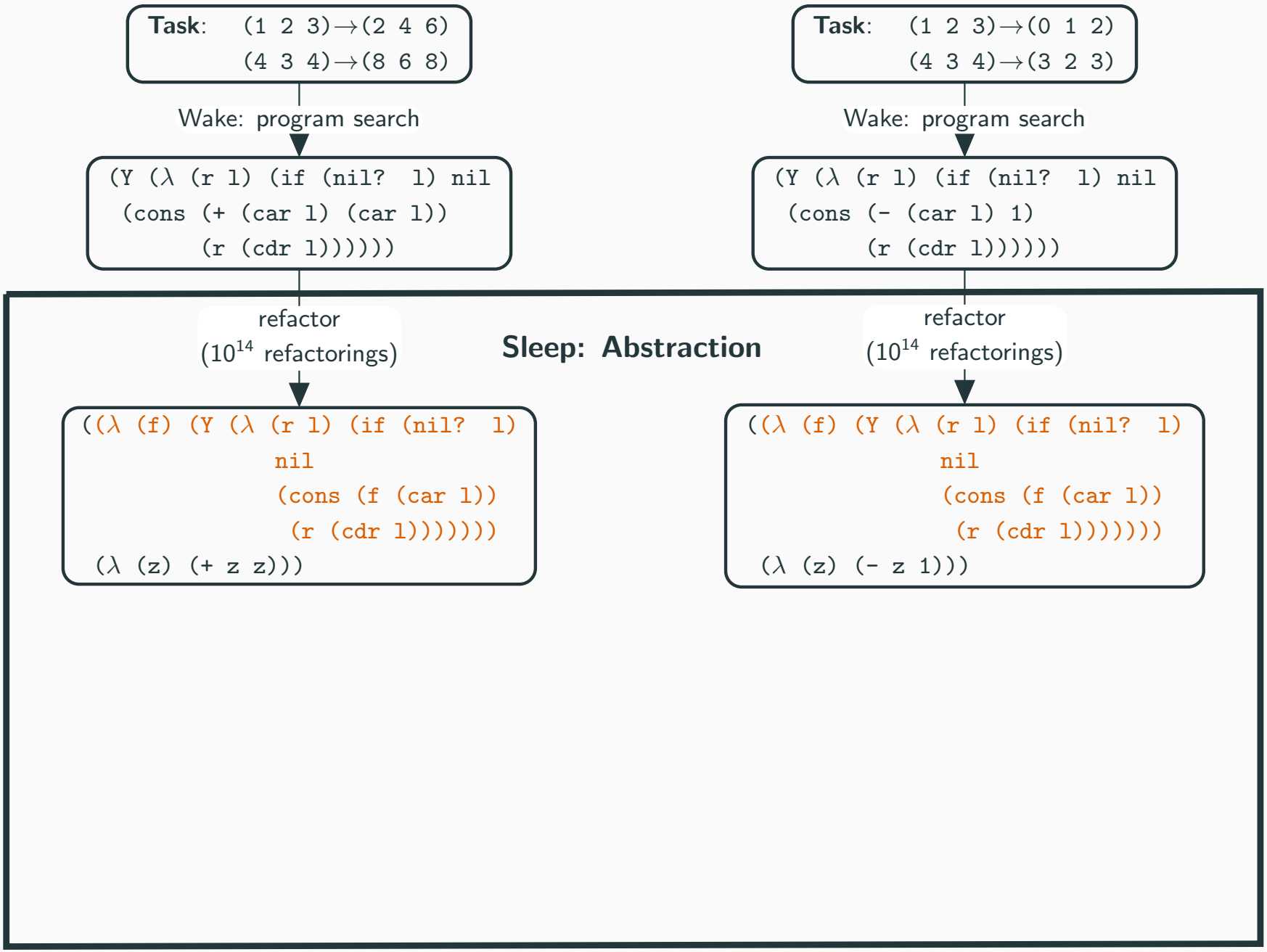

WAKE
Library
f_1(x) =(+ x 1)
f_2(z) =(fold cons
(cons z nil))
.....
Task
[7 2 3]→[4 3 8]
[3 8]→[9 4]
[4 3 2]→[3 4 5]
Recog. model
Neurally-Guided Enumerative Search
Programs for task:
(map f_1 (fold f_2 nil x))
.....
Library
prog
task
SLEEP: ABSTRACTION
progs. for task 1:
(+ (car z) 1)
cons
progs. for task 2:
(cons (+ 1 1))
car z
Refactoring Algorithm: version spaces
new Library w/ (+ x 1):
Library
is
SLEEP: DREAMING
Fantasies
Replays
Library
progs. for task
sample
program
Train recognition model
program
run
task
Loss

Abstraction Sleep: Growing the library via refactoring

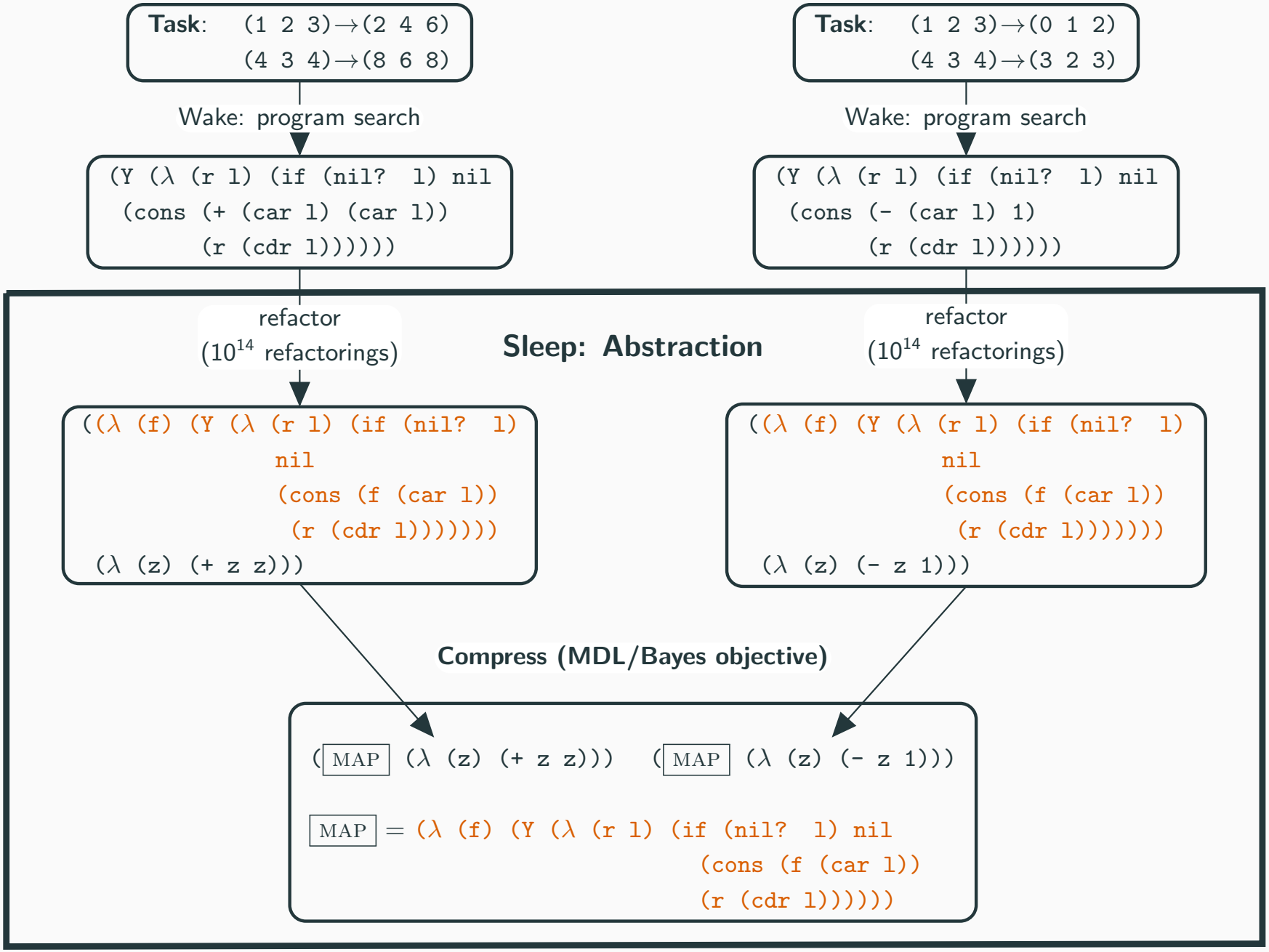




Abstraction Sleep: Growing the library via refactoring



Abstraction Sleep: Growing the library via refactoring



Version space algebra for refactoring

$$
\begin{aligned}
\text{Expr} \rightarrow\ & \text{var} \\
\mid\ & \lambda\text{var.Expr} \\
\mid\ & (\text{Expr Expr}) \\
\mid\ & \text{primitive}
\end{aligned}
$$

Version space algebra for refactoring

$$
\begin{array}{l}
\text{Expr} \rightarrow \text{var} \\
\quad \mid \lambda\text{var.Expr} \\
\quad \mid (\text{Expr Expr}) \\
\quad \mid \text{primitive}
\end{array}
\qquad
\begin{array}{ll}
\text{VS} \rightarrow \text{var} & \\
\quad \mid \lambda\text{var.VS} & \\
\quad \mid (\text{VS VS}) & \\
\quad \mid \text{primitive} & \\
\quad \mid \text{VS} \uplus \text{VS} & \textit{nondeterministic choice} \\
\quad \mid \Lambda & \textit{choose any expression} \\
\quad \mid \varnothing & \textit{choose no expression}
\end{array}
$$

Version space algebra for refactoring

$$
\begin{array}{lll}
\text{Expr} \to \text{var} & \text{VS} \to \text{var} & \\
\quad \mid \lambda\text{var.Expr} & \quad \mid \lambda\text{var.VS} & \\
\quad \mid (\text{Expr Expr}) & \quad \mid (\text{VS VS}) & \\
\quad \mid \text{primitive} & \quad \mid \text{primitive} & \\
 & \quad \mid \text{VS} \uplus \text{VS} & \textit{nondeterministic choice} \\
 & \quad \mid \Lambda & \textit{choose any expression} \\
 & \quad \mid \varnothing & \textit{choose no expression}
\end{array}
$$

what version spaces mean:

$$
\begin{array}{ll}
[\![\text{var}]\!] = \{\text{var}\} & [\![v_1 \uplus v_2]\!] = \{e : v \in \{v_1, v_2\}, e \in [\![v]\!]\} \\
[\![\lambda x.v]\!] = \{\lambda x.e : e \in [\![v]\!]\} & [\![(v_1\, v_2)]\!] = \{(e_1 e_2) : e_1 \in [\![v_1]\!], e_2 \in [\![v_2]\!]\} \\
[\![\varnothing]\!] = \varnothing & [\![\Lambda]\!] = \Lambda
\end{array}
$$

Using version spaces

$$
\begin{aligned}
\mathrm{VS} \rightarrow\ & \mathrm{var} \mid \lambda \mathrm{var}.\mathrm{VS} \mid (\mathrm{VS}\ \mathrm{VS}) \mid \mathrm{primitive} \\
\mid\ & \mathrm{VS} \uplus \mathrm{VS} && \textit{nondeterministic choice} \\
\mid\ & \Lambda && \textit{choose any expression} \\
\mid\ & \varnothing && \textit{choose no expression}
\end{aligned}
$$

Using version spaces

$$\begin{aligned}
\text{VS} \rightarrow\ & \text{var} \mid \lambda\text{var.VS} \mid (\text{VS VS}) \mid \text{primitive} \\
\mid\ & \text{VS} \uplus \text{VS} && \textit{nondeterministic choice} \\
\mid\ & \Lambda && \textit{choose any expression} \\
\mid\ & \varnothing && \textit{choose no expression}
\end{aligned}$$

exploit the fact that $e \in [\![v]\!]$ can be efficiently computed:

$$\textsc{refactor}(v|\text{Lib}) = \begin{cases} e, \text{ if } e \in \text{Lib and } e \in [\![v]\!] \\ \textsc{refactor}'(v|\text{Lib}), \text{ otherwise.} \end{cases}$$

$$\textsc{refactor}'(v|\text{Lib}) = v, \text{ if } v \text{ is a primitive or variable}$$

$$\textsc{refactor}'(\lambda x.b|\text{Lib}) = \lambda x.\textsc{refactor}(b|\text{Lib})$$

$$\textsc{refactor}'(v_1\, v_2|\text{Lib}) = (\textsc{refactor}(v_1|\text{Lib})\ \ \textsc{refactor}(v_2|\text{Lib}))$$

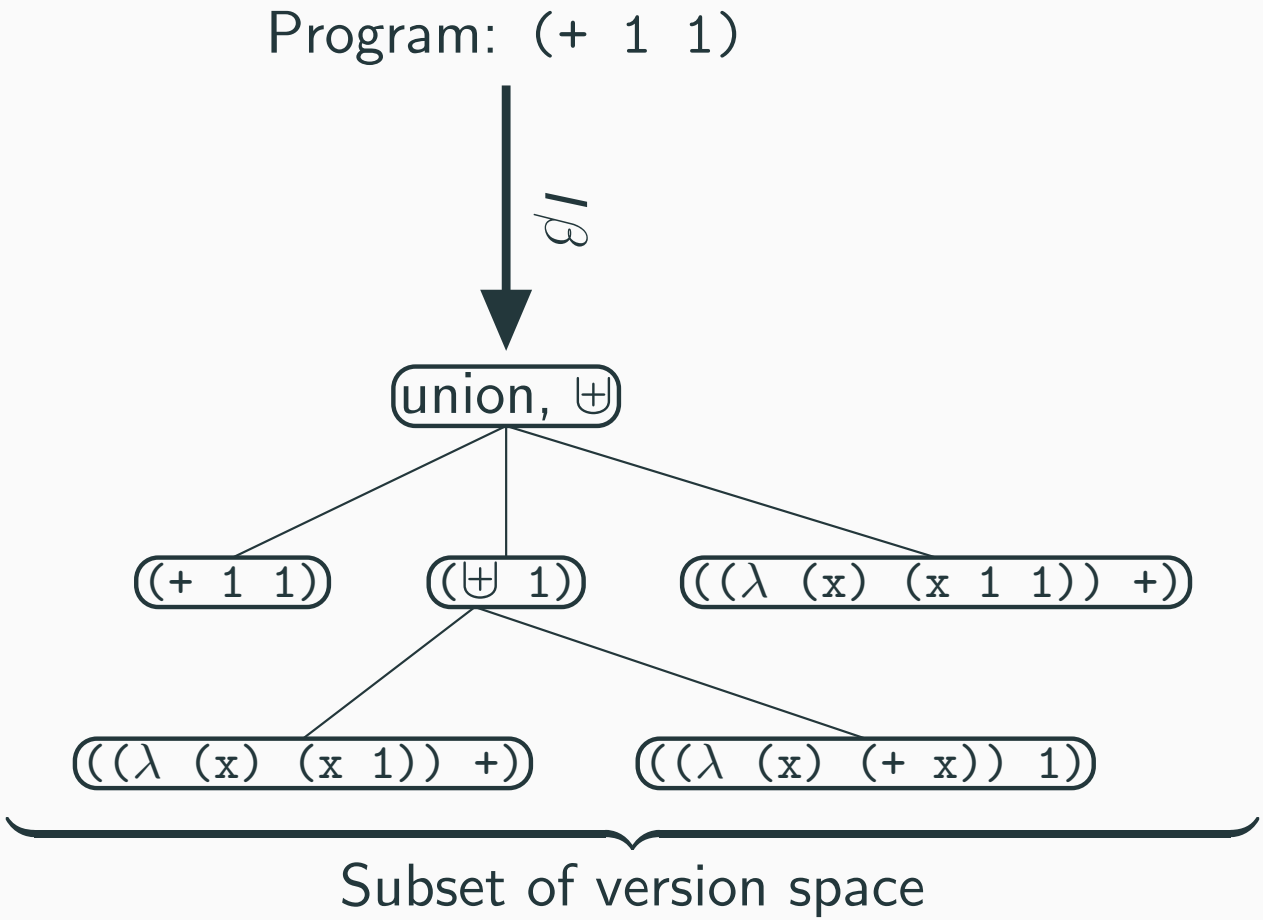
Using version spaces

VS $\rightarrow$ var | λvar.VS | (VS VS) | primitive

| VS$\uplus$VS *nondeterministic choice*

| Λ *choose any expression*

| $\varnothing$ *choose no expression*



Using version spaces

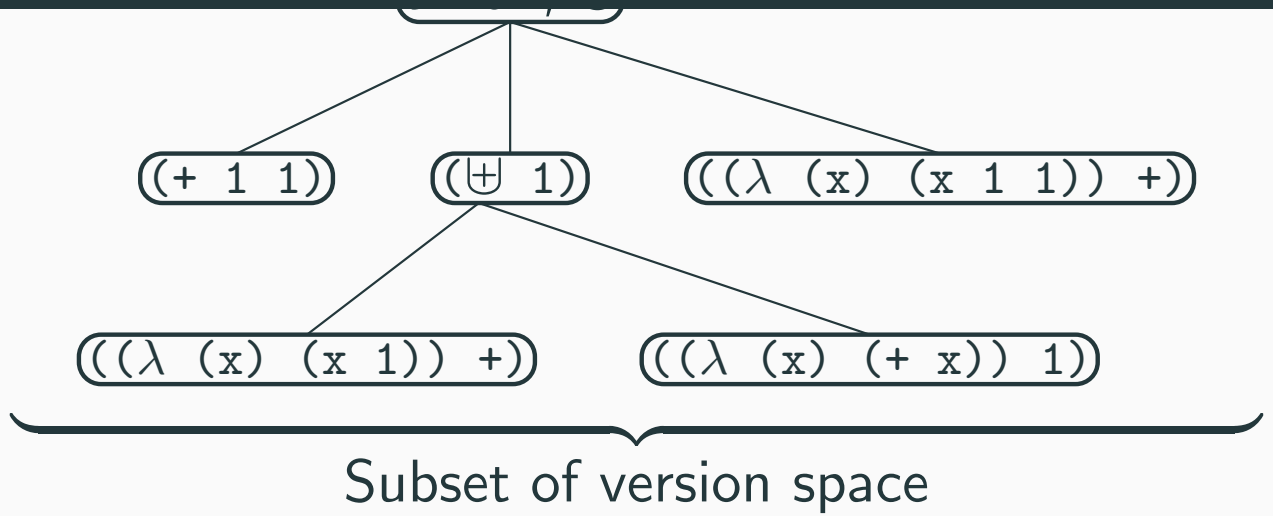
$$\begin{aligned} VS \rightarrow\ & \text{var} \mid \lambda\text{var}.VS \mid (VS\ VS) \mid \text{primitive} \\ \mid\ & VS \uplus VS && \textit{nondeterministic choice} \\ \mid\ & \Lambda && \textit{choose any expression} \\ \mid\ & \varnothing && \textit{choose no expression} \end{aligned}$$

completeness: $I\beta$ gets all the refactorings

let $v_2 = I\beta(v_1)$ and $e_1 \in [\![v_1]\!]$. for any $e_2 \longrightarrow e_1$ then $e_2 \in [\![v_2]\!]$

consistency: $I\beta$ only gets valid refactorings

let $v_2 = I\beta(v_1)$ and $e_2 \in [\![v_2]\!]$. then there is a $e_1 \in [\![v_1]\!]$ where $e_2 \longrightarrow e_1$



DreamCoder Domains

List Processing

Sum List

```
[1 2 3] → 6
[4 6 8 1] → 17
```

Double

```
[1 2 3 4] → [2 4 6 8]
[6 5 1] → [12 10 2]
```

Check Evens

```
[0 2 3] → [T T F]
[2 4 9 6] → [T T F T]
```

Text Editing

Abbreviate

```
Allen Newell → A.N.
Herb Simon → H.S.
```

Drop Last Characters

```
jabberwocky → jabberw
copycat → cop
```

Extract

```
see spot(run) → run
a (bee) see → bee
```

Regexes

Phone Numbers

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

Currency

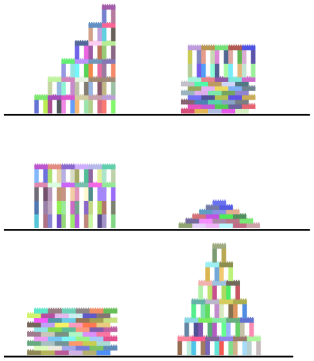
```
$100.25
$4.50
```

Dates

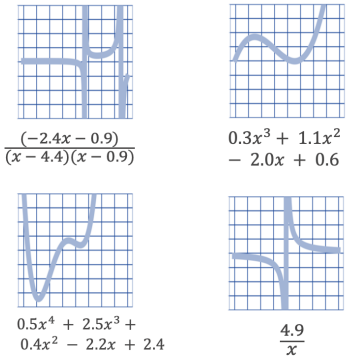
```
Y1775/0704
Y2000/0101
```

LOGO Graphics

Block Towers

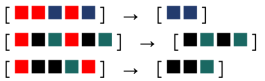


Symbolic Regression



Recursive Programming

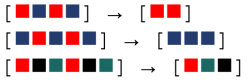
Filter



Length

Index List

Every Other



Physics

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

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

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

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

DreamCoder Domains

List Processing

Sum List

[1 2 3] → 6
[4 6 8 1] → 17

Double

[1 2 3 4] → [2 4 6 8]
[6 5 1] → [12 10 2]

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(650) 555-2368

Currency

$100.25
$4.50

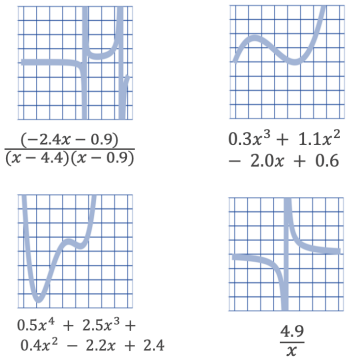
Dates

Y1775/0704
Y2000/0101

LOGO Graphics

Block Towers

Symbolic Regression



Recursive Programming

Filter

[■■■■■] → [■■■]
[■■■■■■] → [■■■■]
[■■■■■] → [■■■■]

Index List

0, [■■■■■■] → ■
1, [■■■■■■] → ■
1, [■■■■■■■] → ■

Length

[■■■■] → 4
[■■■■■■] → 6
[■■■] → 3

Every Other

[■■■■] → [■■]
[■■■■■] → [■■■■]
[■■■■■■] → [■■■]

Physics

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

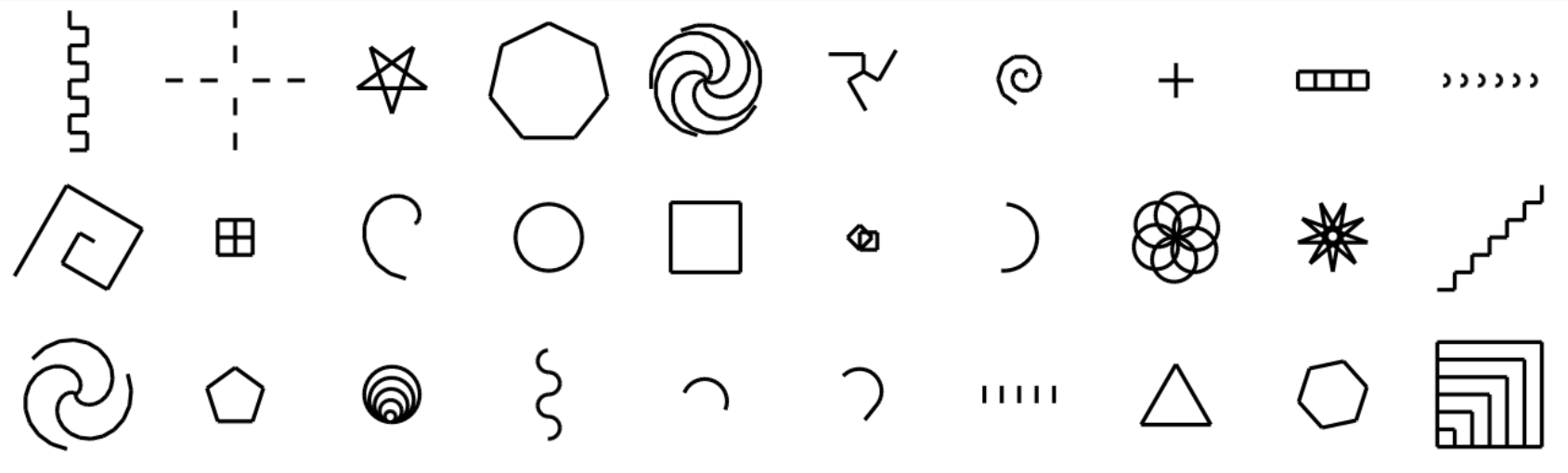
$$\vec{a} = \frac{1}{m}\sum_i \vec{F}_i$$

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

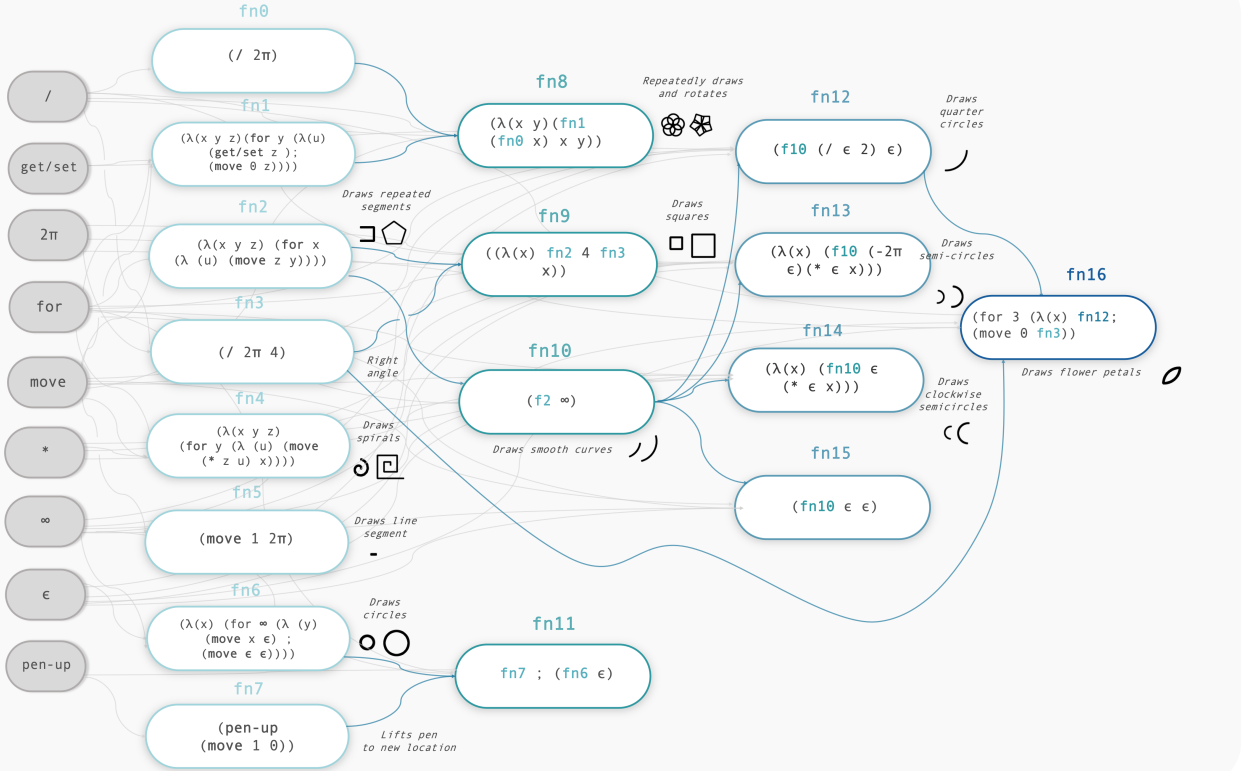
$$R_{total} = \left(\Sigma_i \frac{1}{R_i}\right)^{-1}$$

LOGO Graphics

30 out of 160 tasks



LOGO Graphics – learning interpretable library of concepts



```
(fn8 5 (fn4 (* ϵ 2) ∞ ϵ))
```

```
(for 2 (λ (x)
(fn14 2); (fn13 2)))
```

```
(for 7 (λ (x) (fn9 x)))
```

```
(fn10 (* (fn0 7) 3) 3)
```

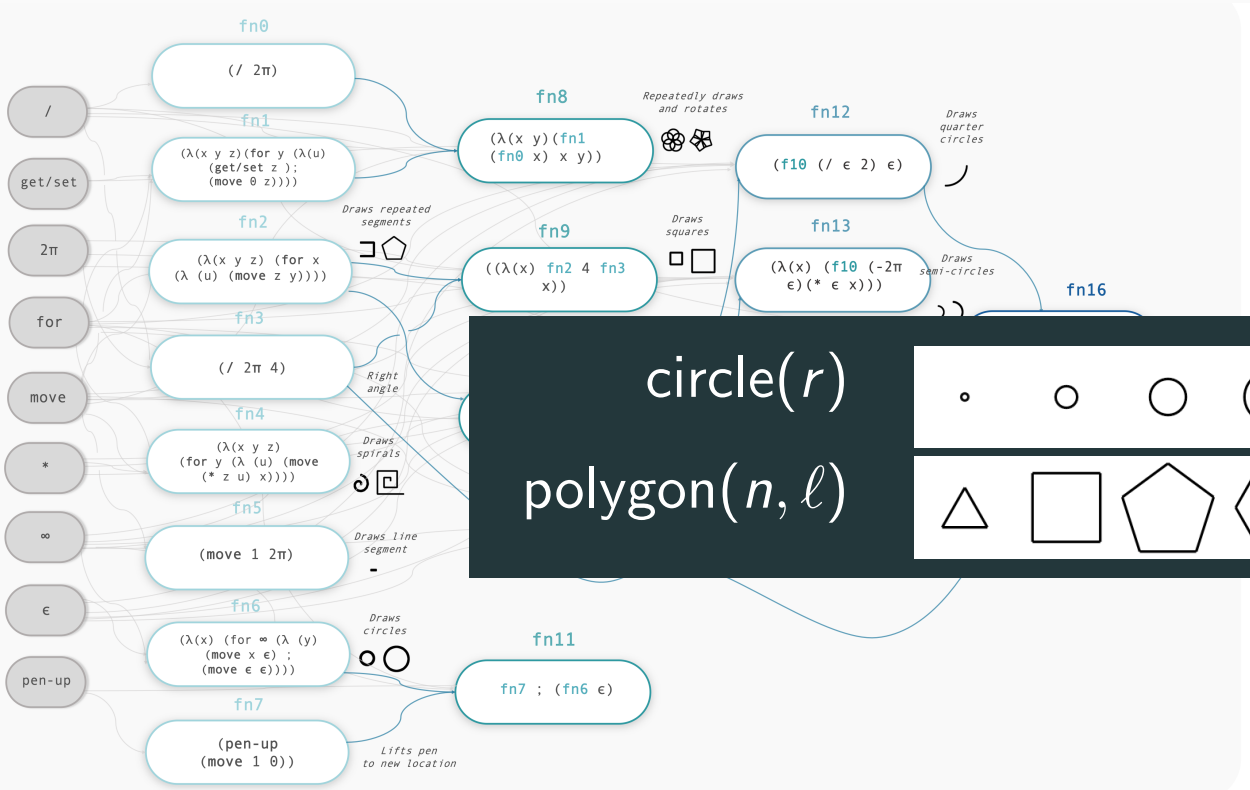
```
(fn8  6 (fn7 ; fn5 ;
fn7 ; fn5))
```

```
(fn8 5 fn16)
```

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

```
(fn4 fn3 9 1)
```

LOGO Graphics – learning interpretable library of concepts



(fn8 5 (fn4 (* ϵ 2) ∞ ϵ))

(for 2 (λ (x)
(fn14 2); (fn13 2)))

))

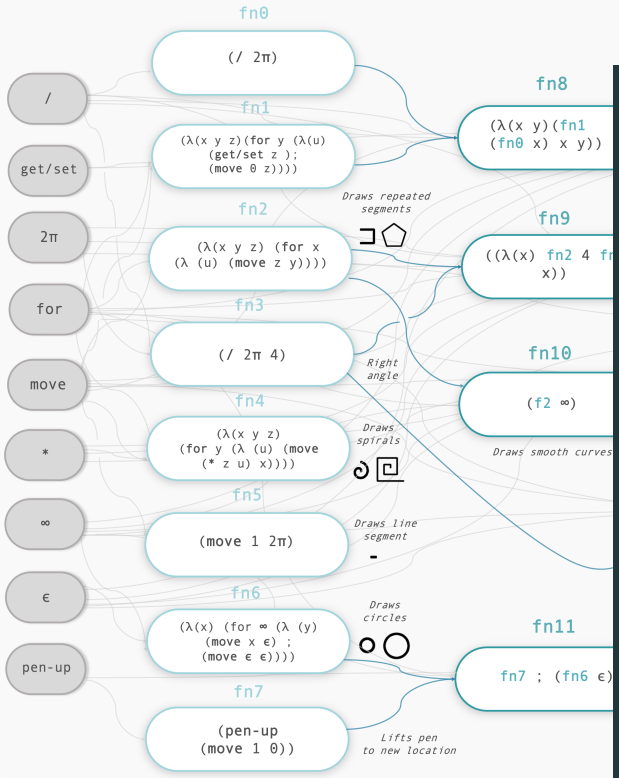
(fn10 (* (fn0 7) 3) 3)

(fn8 5 fn16)

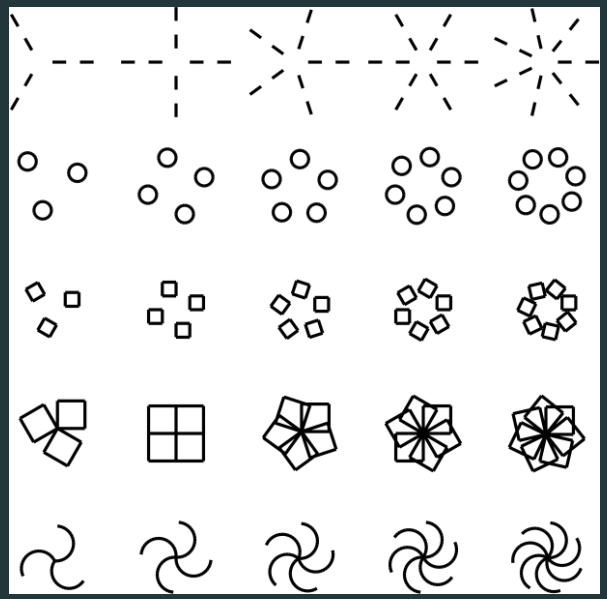
(move 0 (fn0 7)); fn5 ;
(fn13 4)

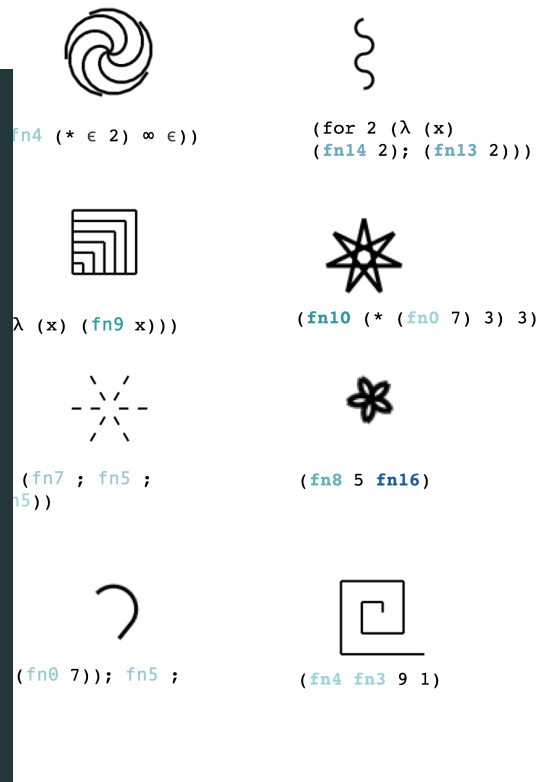
(fn4 fn3 9 1)

LOGO Graphics – learning interpretable library of concepts



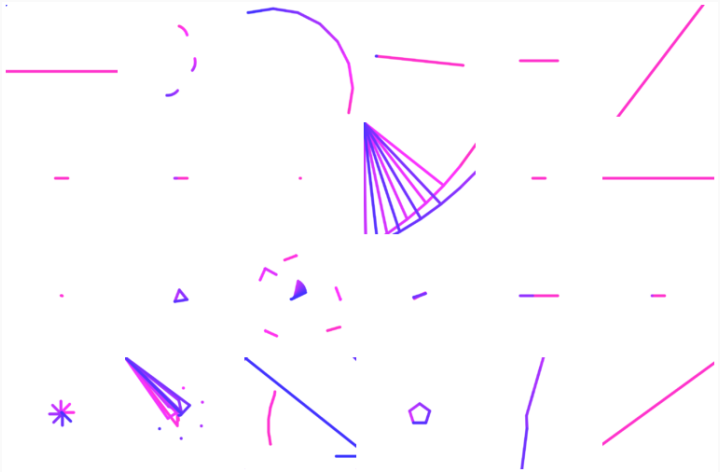
radial symmetry(n, body)



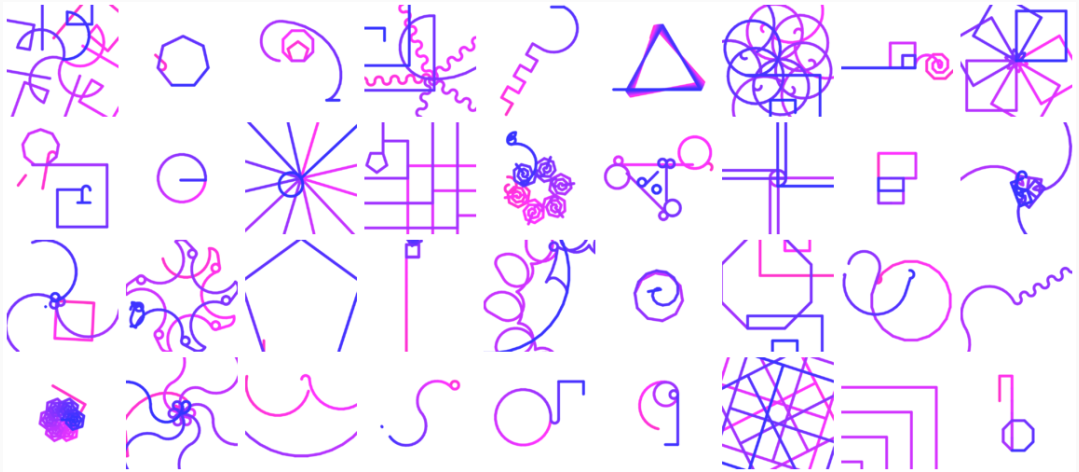


what does DreamCoder dream of?

before learning

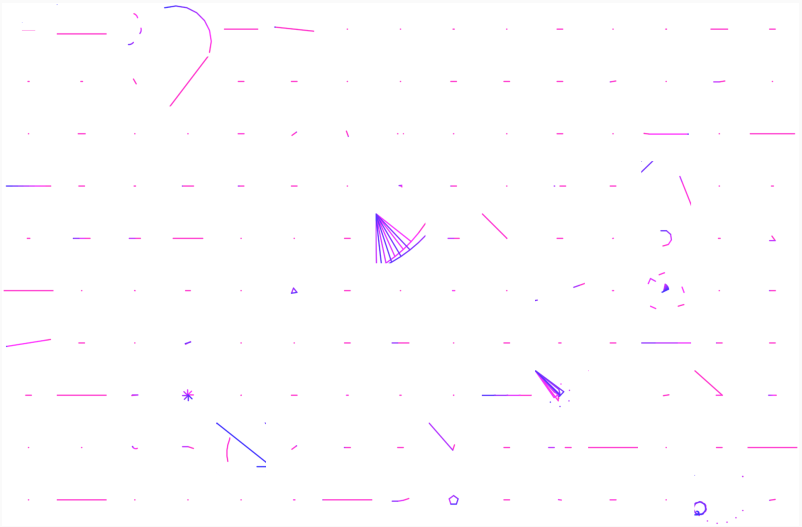


after learning

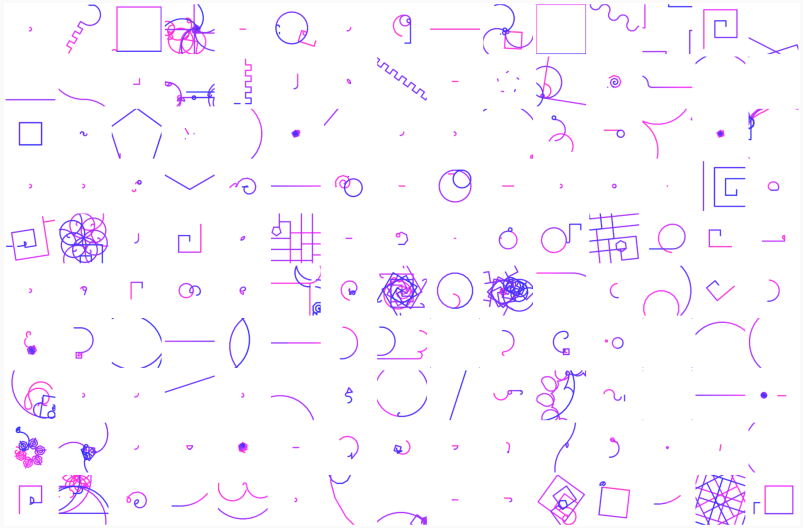


what does DreamCoder dream of?

before learning

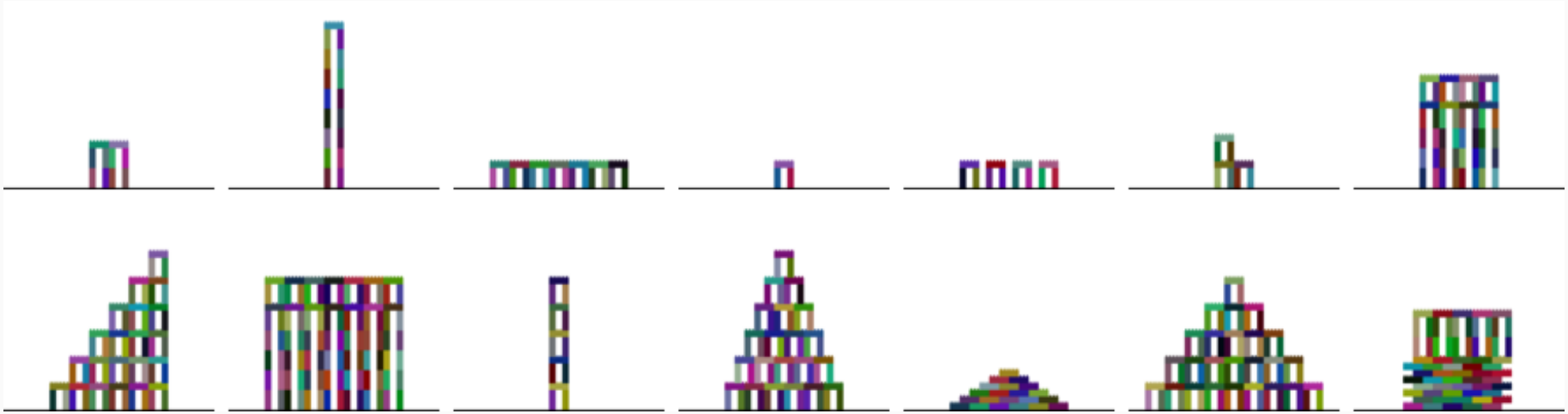


after learning



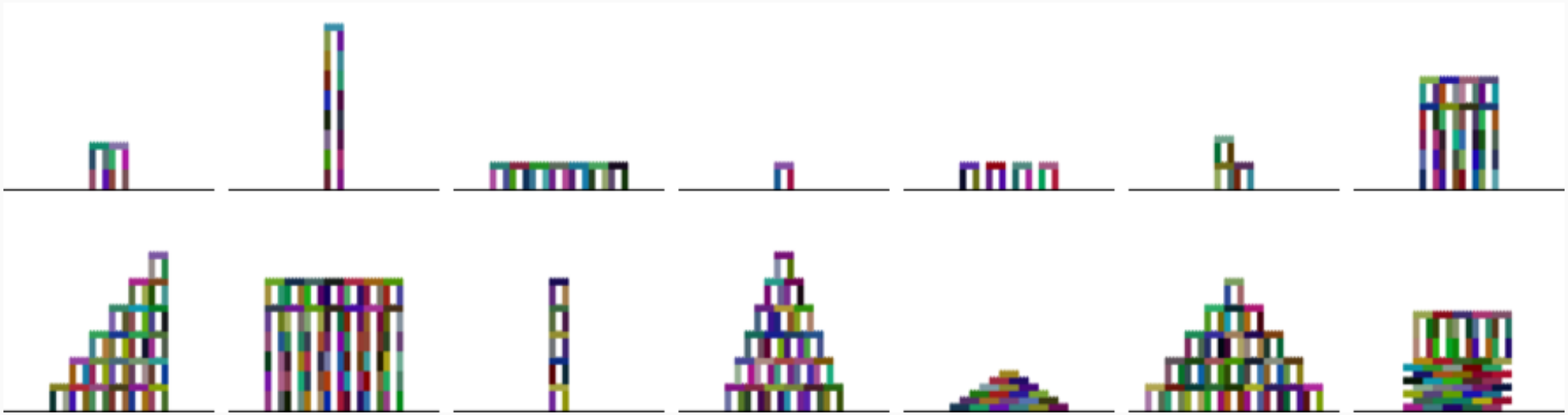
Planning to build towers

example tasks (112 total)



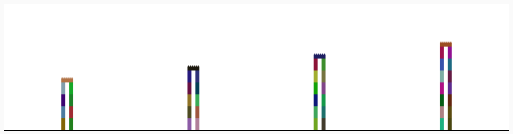
Planning to build towers

example tasks (112 total)

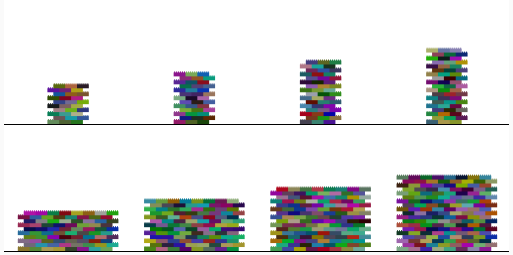


learned library routines ($\approx$ 20 total)

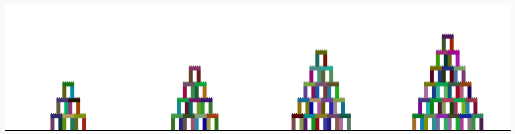
arch(h)



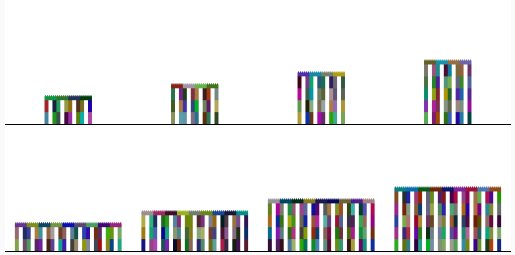
wall(w, h)



pyramid(h)

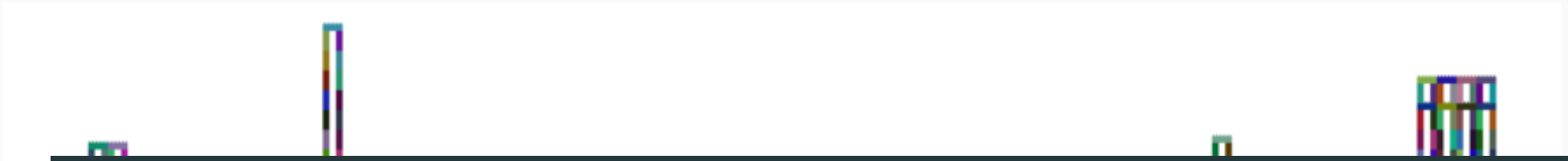


bridge(w, h)



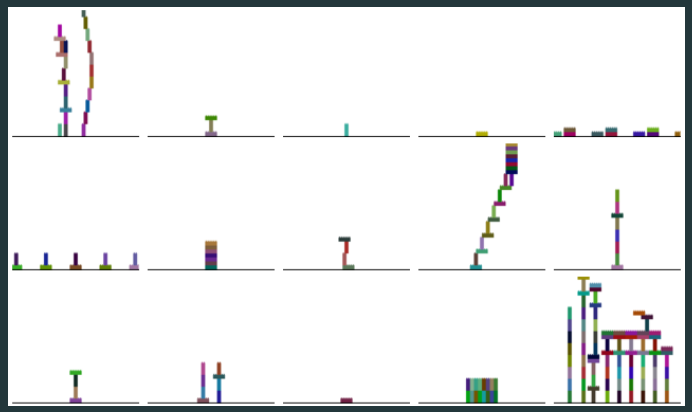
Planning to build towers

example tasks (112 total)

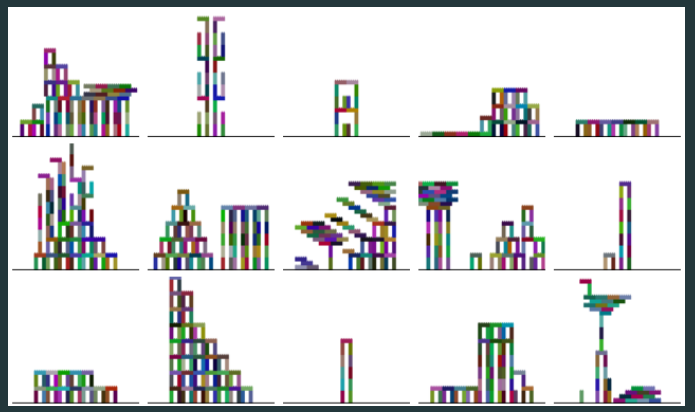


lea

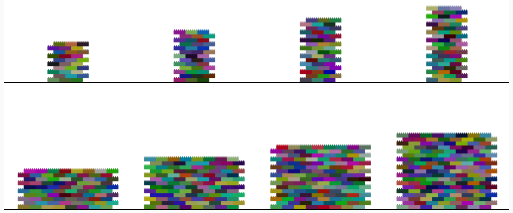
dreams before learning



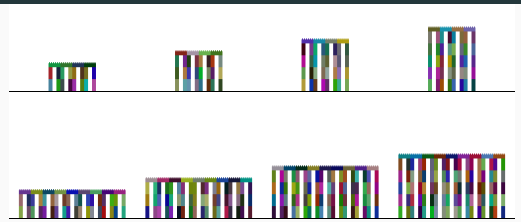
dreams after learning



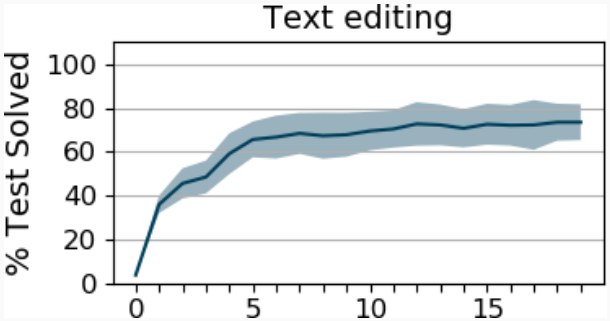
wall(w, h)

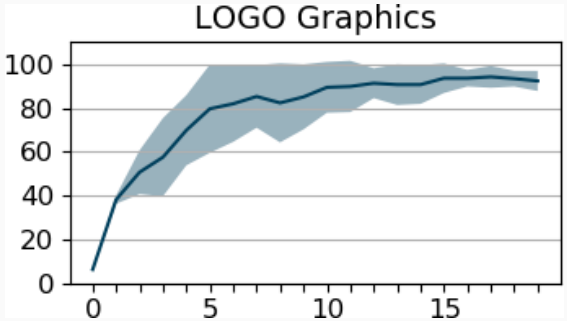


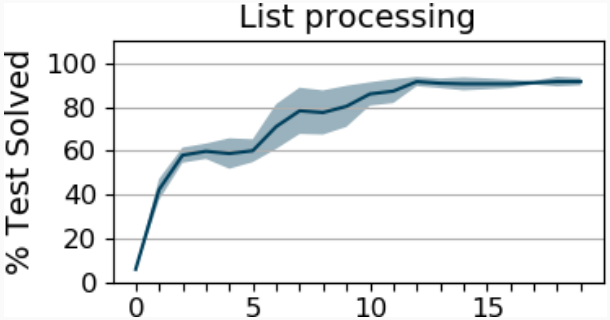
bridge(w, h)

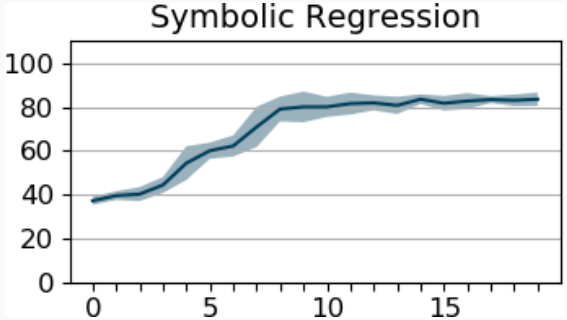


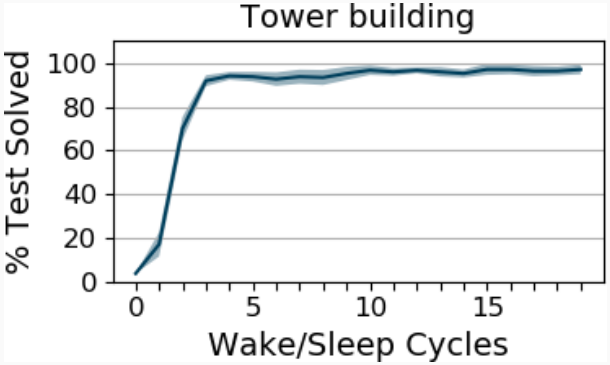
synergy between dreaming and library learning

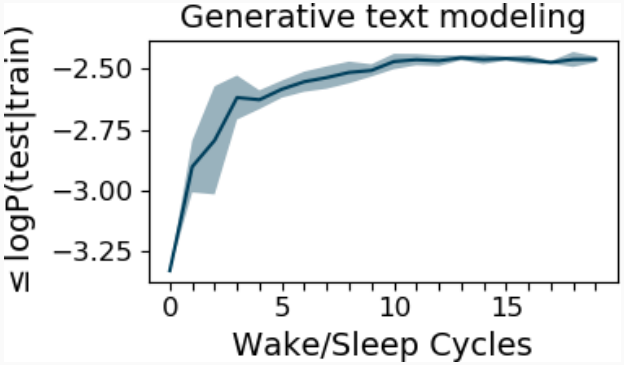


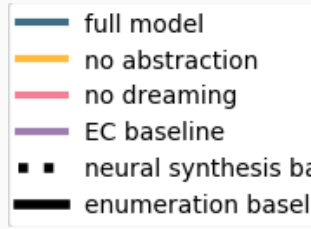




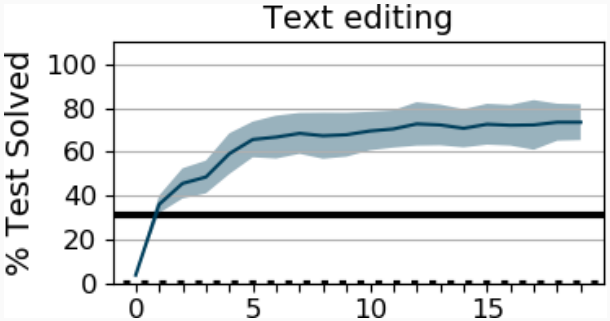


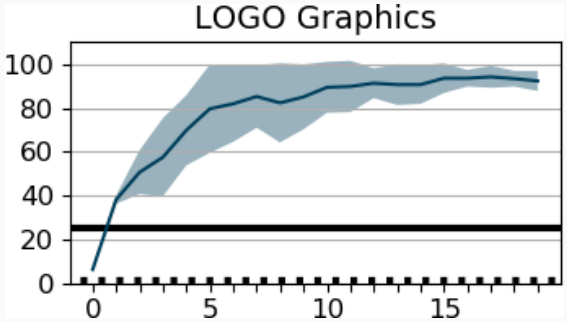


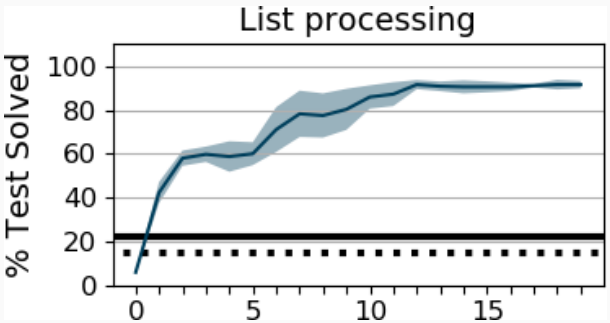


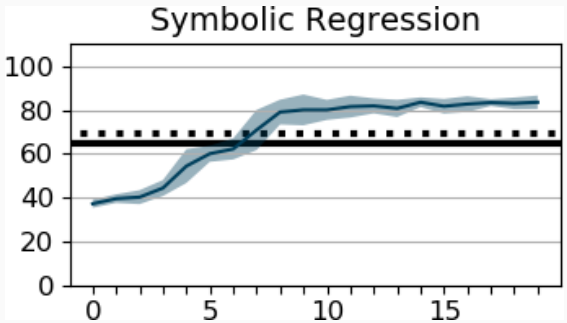


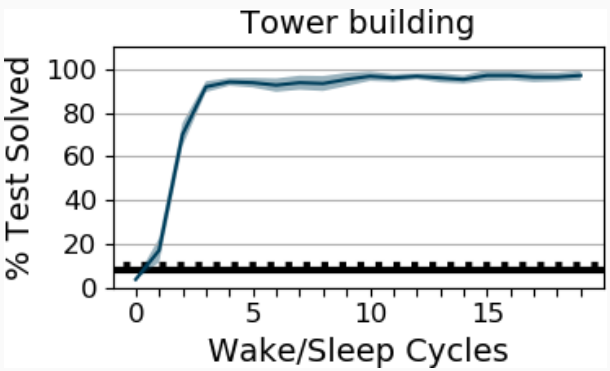
synergy between dreaming and library learning

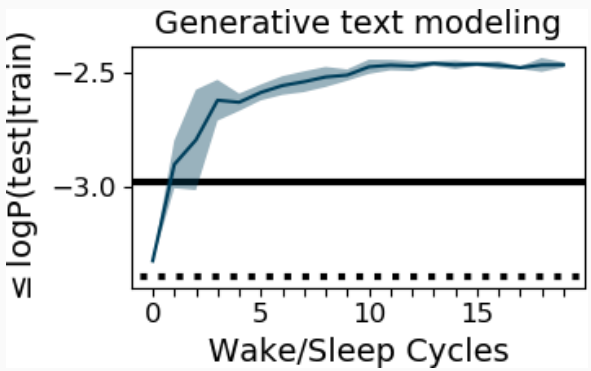


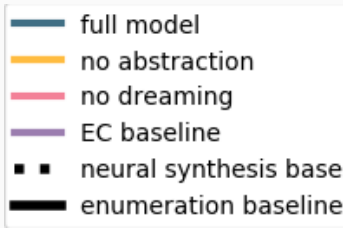




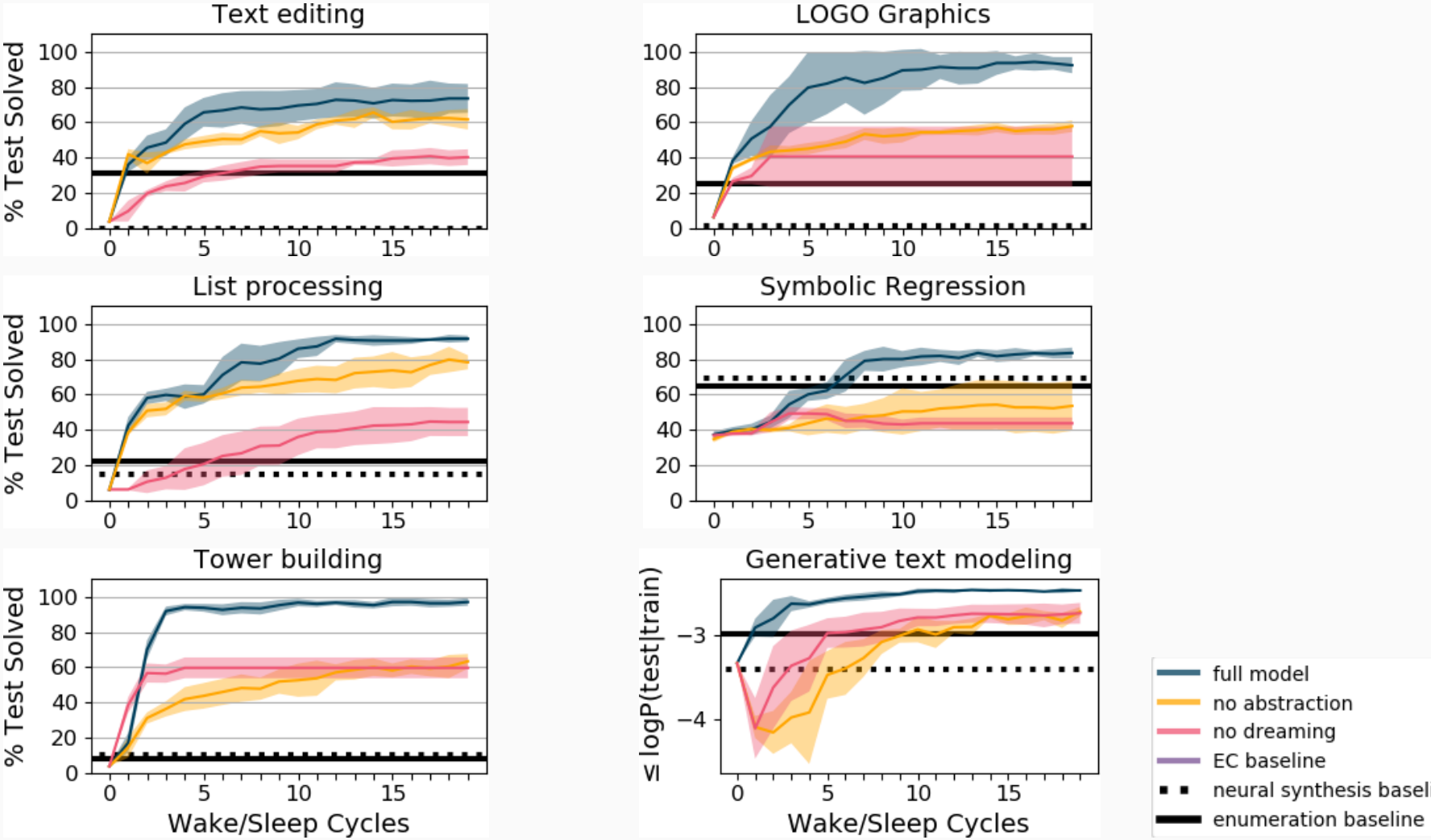




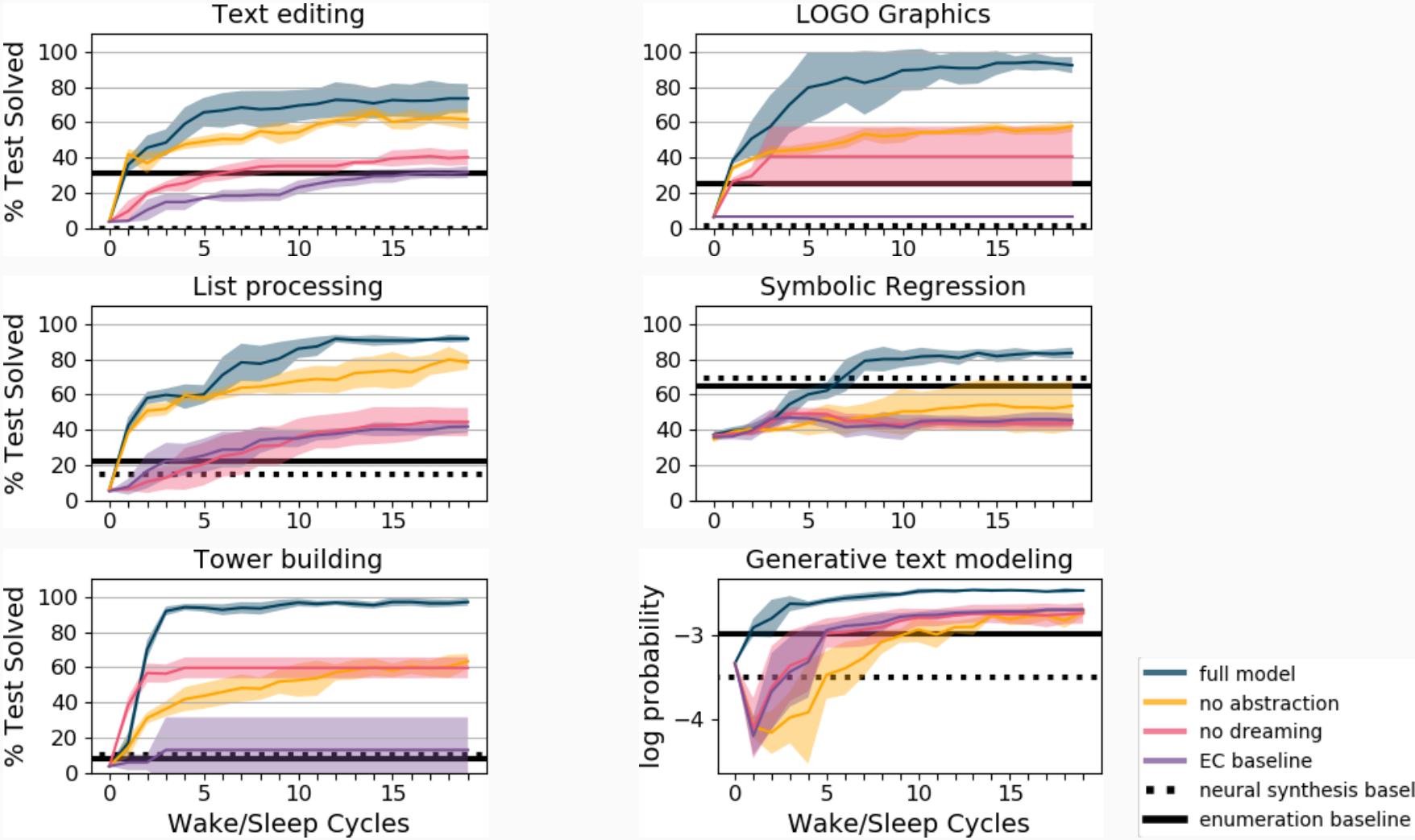




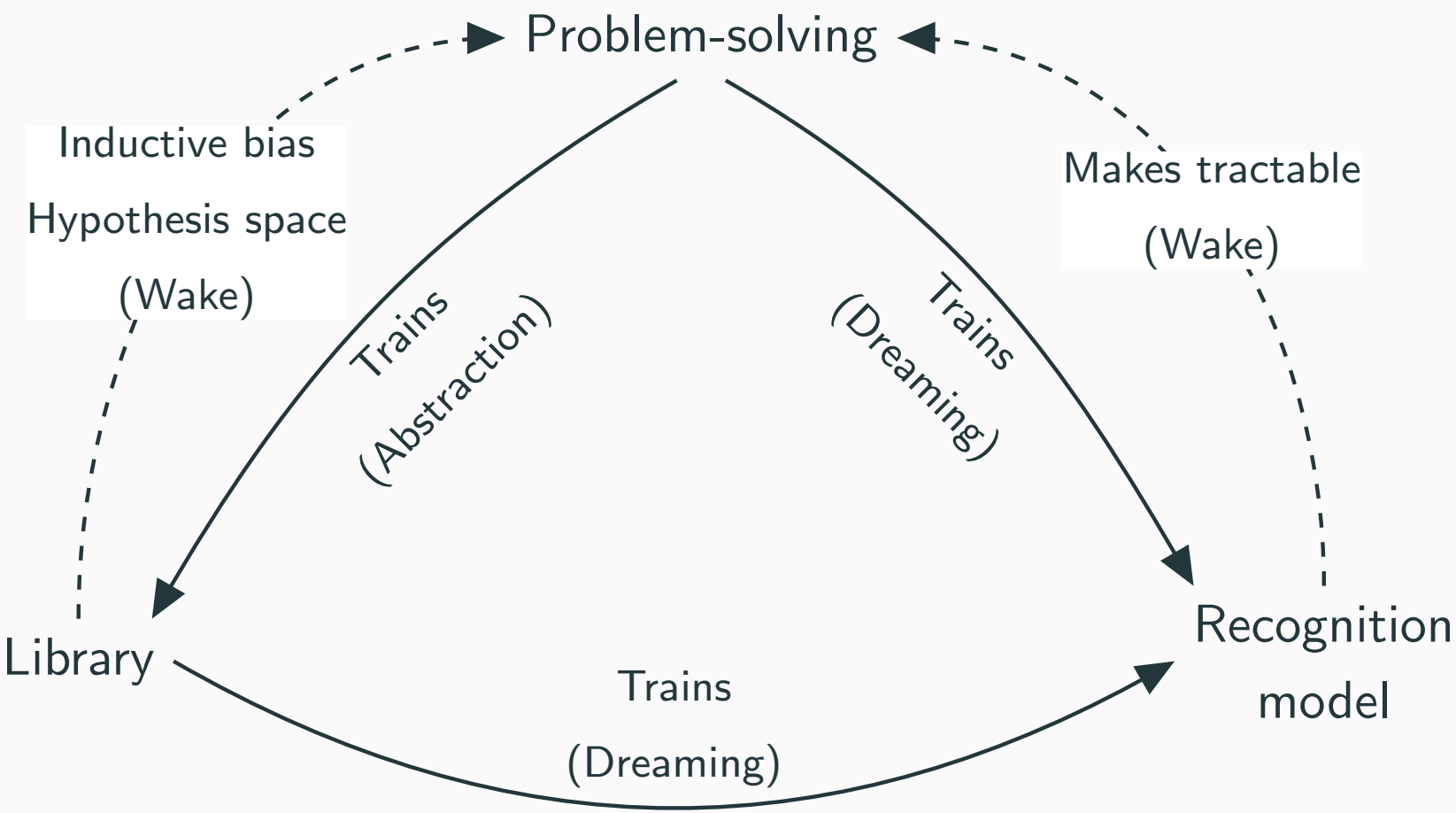
synergy between dreaming and library learning



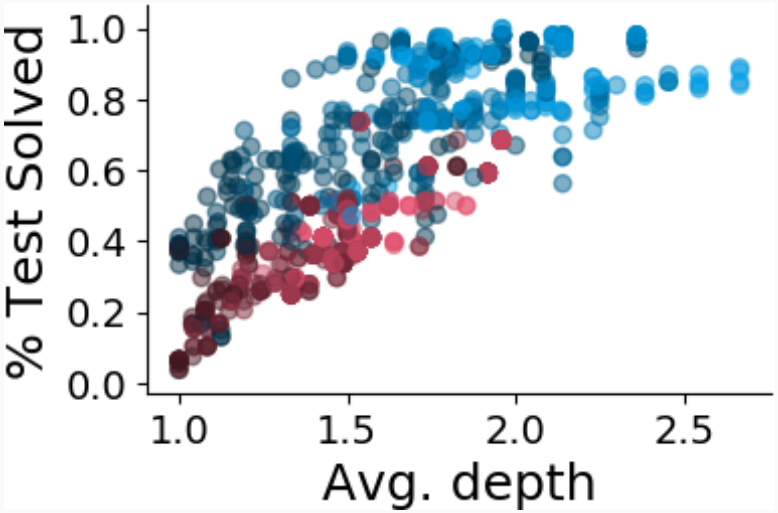
synergy between dreaming and library learning

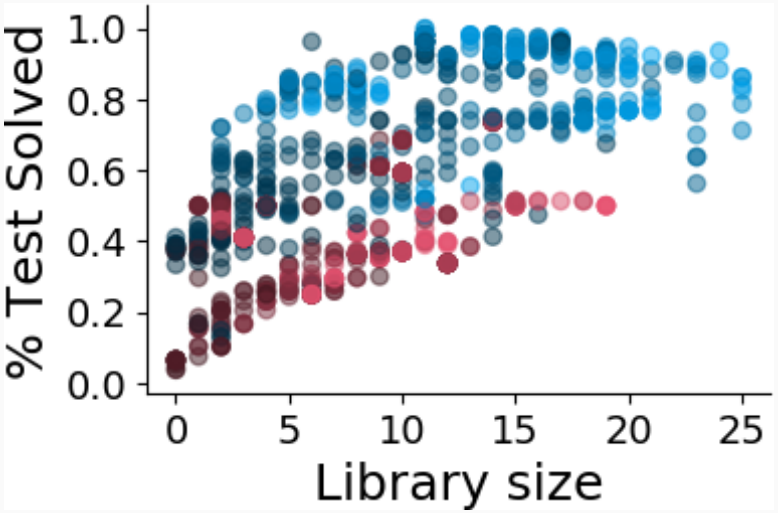


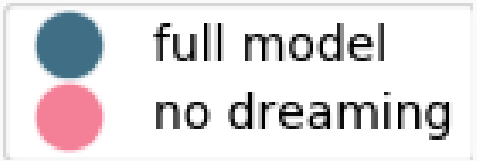
synergy between dreaming and library learning



Evidence for dreaming bootstrapping better libraries







Dark→Light: Early in learning→Later in learning

Vision

More human-like machine intelligence

- Acquiring a domain-specific representation (DSL)
- Learning to use that representation (recognition model)

DreamCoder: an algorithm for jointly realizing these goals

f_2(p,f,n,x) = (if (p x) nil
(cons (f x) (f_2 (n x))))
(f_2: *unfold*)
f_3(i,l) = (if (= i 0) (car l)
(f_3 (f_1 i) (cdr l))))
(f_3: *index*)
f_4(f,l,x) = (if (empty? l) x
(f (car l) (f_4 (cdr l))))
(f_4: *fold*)
f_5(f,l) = (if (empty? l) nil)
(cons (f (car l)) (f_5 (cdr l)))
(f_5: *map*)

Symbolic Regression

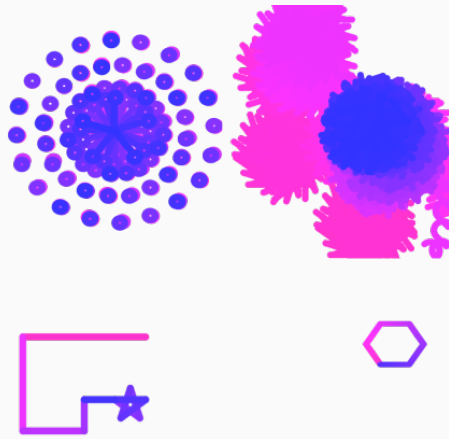

$f(x) = (f_1\ x)$


$f(x) = (f_6\ x)$


$f(x) = (f_4\ x)$


$f(x) = (f_3\ x)$

$f_0(x) = (+\ x\ \text{real})$
$f_1(x) = (f_0\ (*\ \text{real}\ x))$
$f_2(x) = (f_1\ (*\ x\ (f_0\ x)))$
$f_3(x) = (f_0\ (*\ x\ (f_2\ x)))$
$f_4(x) = (f_0\ (*\ x\ (f_3\ x)))$
(f_4: *4th order polynomial*)
$f_5(x) = (/\ \text{real}\ x)$
$f_6(x) = (f_5\ (f_0\ x))$
(f_6: *rational function*)



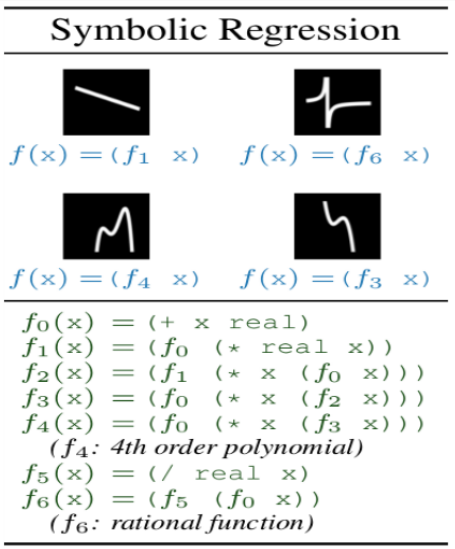
Vision

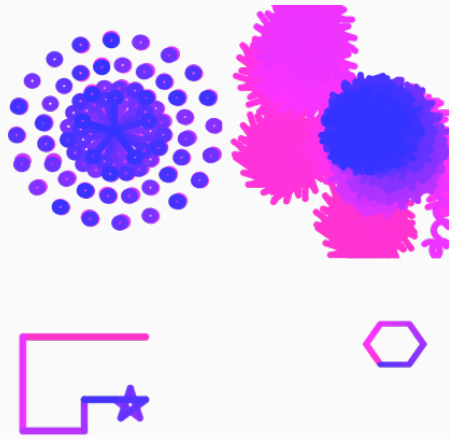
More human-like machine intelligence

- Acquiring a domain-specific representation (DSL)
- Learning to use that representation (recognition model)

DreamCoder: an algorithm for jointly realizing these goals

```
f2(p,f,n,x) = (if (p x) nil
                  (cons (f x) (f2 (n x))))
  (f2: unfold)
f3(i,l) = (if (= i 0) (car l)
              (f3 (f1 i) (cdr l))))
  (f3: index)
f4(f,l,x) = (if (empty? l) x
                (f (car l) (f4 (cdr l))))
  (f4: fold)
f5(f,l) = (if (empty? l) nil)
              (cons (f (car l)) (f5 (cdr l)))
  (f5: map)
```





The End.