Growing libraries of concepts with wake-sleep program induction

Kevin Ellis & Mathias Sablé Meyer
Joint with: Lucas Morales, Armando Solar-Lezama, Joshua B. Tenenbaum
Heavy inspiration from: Eyal Dechter

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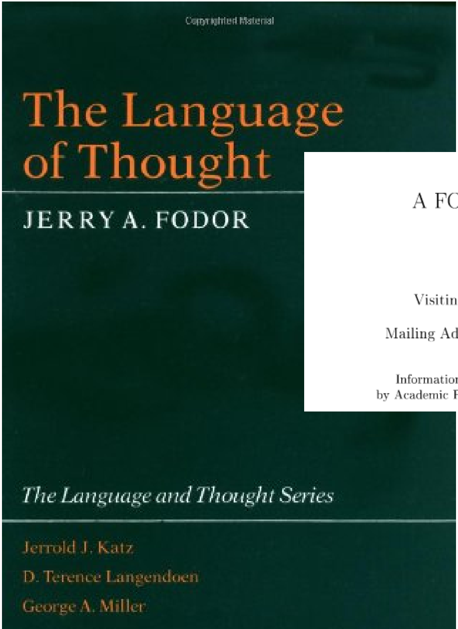
MIT

The Language of Thought



A FORMAL THEORY OF INDUCTIVE INFERENCE, Part 1*†

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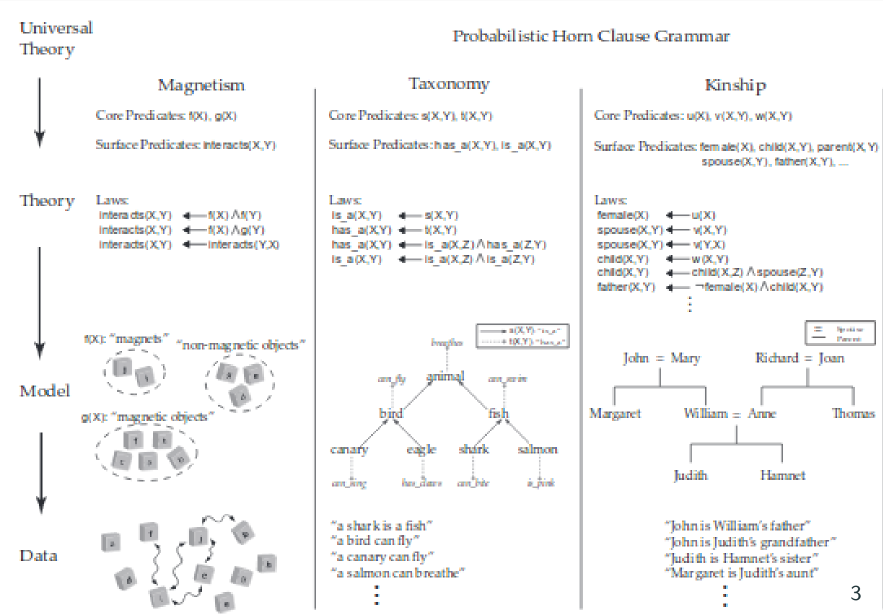
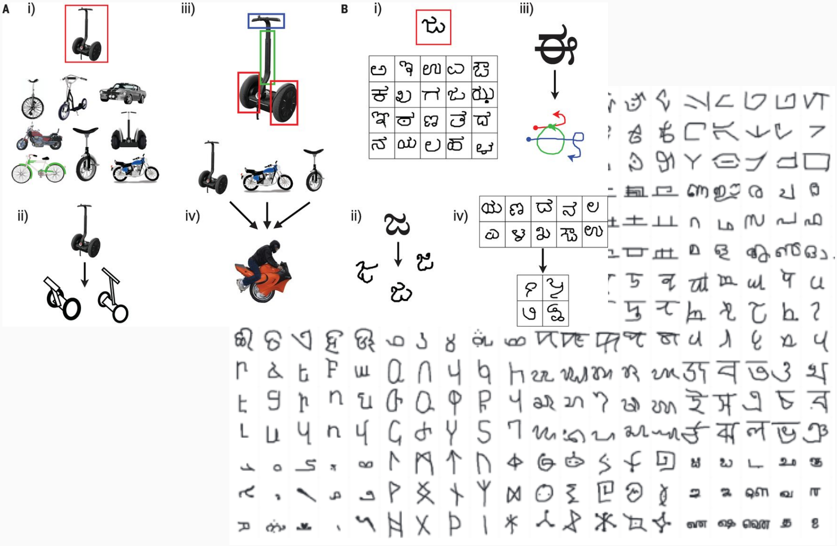
Engineering the language of thought



Ullman et al 2012

Engineering the language of thought



Lake et al 2015

Growing a domain-specific language of thought

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

Growing a domain-specific language of thought

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

- Library of concepts (declarative knowledge)
- Search strategy (procedural knowledge)

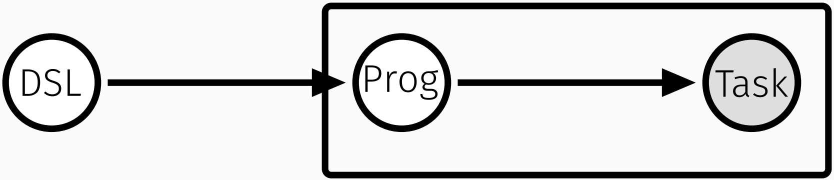
DSL: Library of concepts

Tasks and Programs		DSL
$[7\ 2\ 3] \to [7\ 3]$ $[1\ 2\ 3\ 4] \to [3\ 4]$ $[4\ 3\ 2\ 1] \to [4\ 3]$ $f(\ell) = (f_1\ \ell\ (\lambda\ (x)\ (>\ x\ 2)))$	$[7\ 3] \to$ False $[3] \to$ False $[9\ 0\ 0] \to$ True $[0] \to$ True $[0\ 7\ 3] \to$ True $f(\ell) = (f_3\ \ell\ 0)$	$f_0(\ell,r) = (\texttt{foldr r}\ \ell\ \texttt{cons})$ (f_0: *Append lists* r *and* ℓ) $f_1(\ell,p) = (\texttt{foldr}\ \ell\ \texttt{nil}\ (\lambda\ (\texttt{x a})\ (\texttt{if (p x) (cons x a) a})))$ (f_1: *Higher-order filter function*) $f_2(\ell) = (\texttt{foldr}\ \ell\ 0\ (\lambda\ (\texttt{x a})\ (\texttt{if (> a x) a x})))$ (f_2: *Maximum element in list* ℓ) $f_3(\ell,k) = (\texttt{foldr}\ \ell\ (\texttt{is-nil}\ \ell)\ (\lambda\ (\texttt{x a})\ (\texttt{if a a (= k x)})))$ (f_2: *Whether* ℓ *contains* k)
$[2\ 7\ 8\ 1] \to 8$ $[3\ 19\ 14] \to 19$ $f(\ell) = (f_2\ \ell)$		

- **Wake:** Solve problems by writing programs
- **Sleep:** Improve DSL and neural recognition model:
    - **Sleep-G:** Improve DSL (**G**enerative model)
    - **Sleep-R:** Improve **R**ecognition model

Combines ideas from Wake-Sleep & Exploration-Compression algorithm by Eyal Dechter

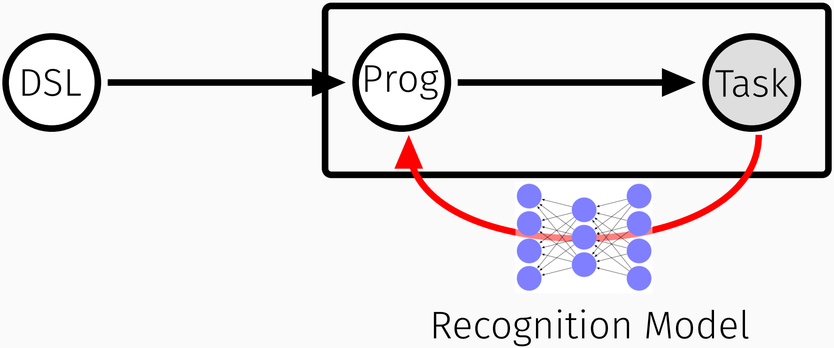
DSL learning as Bayesian inference



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

Gray: Observed.
White: Latent.
Boxed (plate): Repeated.

DSL learning as amortized Bayesian inference



Recognition model: Neural net.

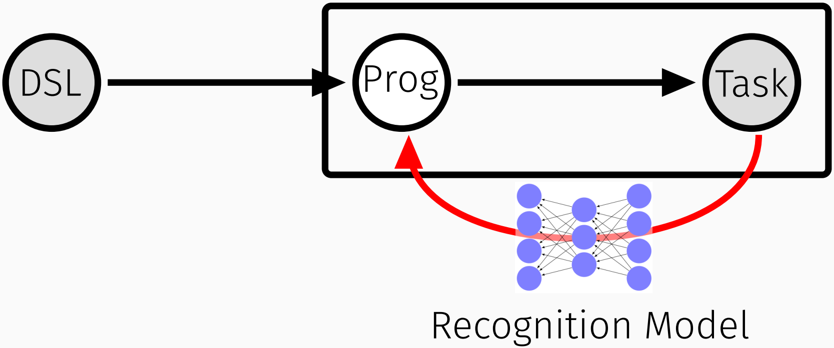
Red: Bottom-up inference.

Gray: Observed.

White: Latent.

Boxed (plate): Repeated.

Wake: Problem solving



Recognition model: Neural net.

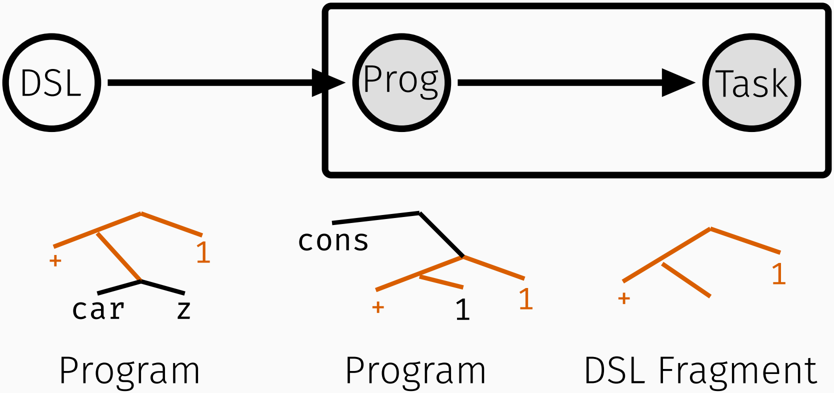
Red: Bottom-up inference.

Gray: Observed.

White: Latent.

Boxed (plate): Repeated.

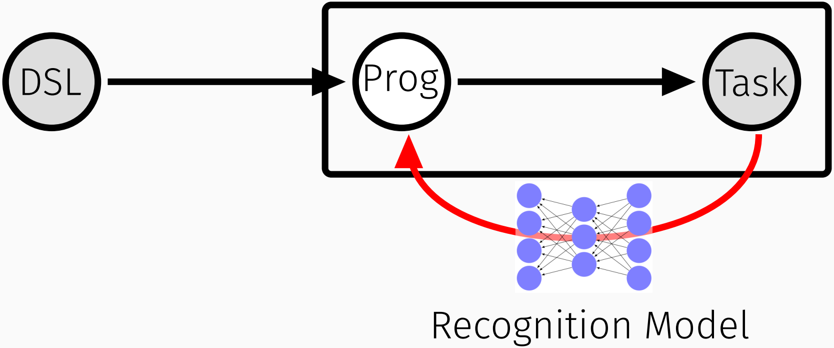
Sleep-G: Memory consolidation



Fragment Grammars: O'Donnell 2015.

Orange: Code fragments.

Sleep-R: Objective

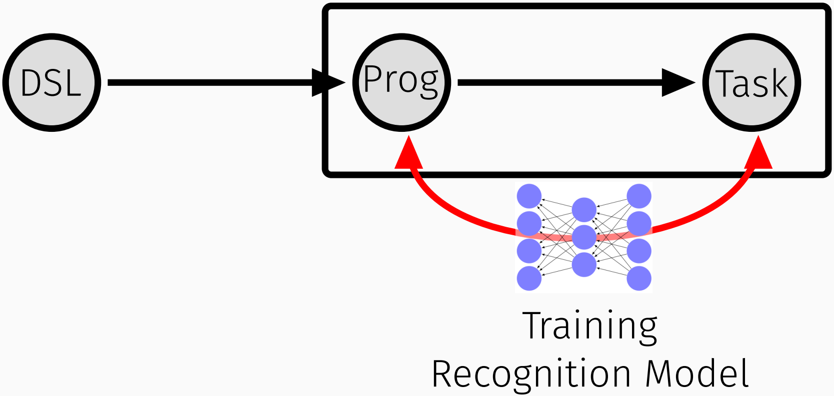


Recognition model predicts distribution over program, conditional on task.

Training: (program, task) pairs

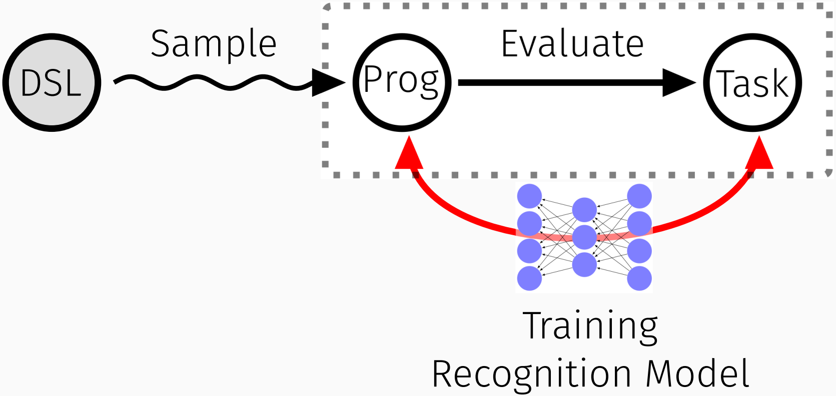
Objective: Predict program w/ (1) high prior under DSL & (2) high likelihood for task

Sleep-R: Experience replay



Train on (program, task) pairs found during waking

Sleep-R: Dreaming



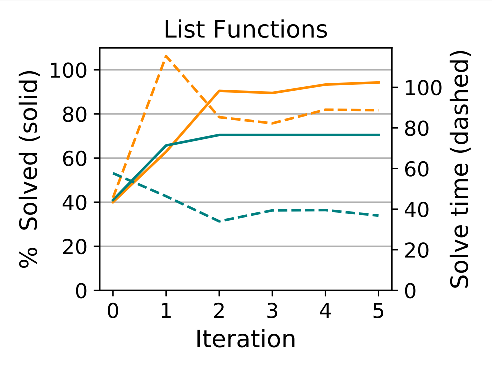
Train on (program, task) pairs sampled from DSL

List functions — Created & investigated by Lucas Morales

Name	Input	Output
repeat-3	[7 0]	[7 0 7 0 7 0]
drop-3	[0 3 8 6 4]	[6 4]
rotate-2	[8 14 1 9]	[1 9 8 14]
count-head-in-tail	[1 2 1 1 3]	2
keep-div-5	[5 9 14 6 3 0]	[5 0]
product	[7 1 6 2]	84

Discovers 38 concepts, including ‘filter’

List functions: Learning curves on hold out tasks



Learning curves for DreamCoder both with (in orange) and without (in teal) the recognition model. Solid lines: % holdout testing tasks solved w/ 10m timeout. Dashed lines: Average solve time, averaged only over tasks that are solved.

Turtle graphics — Created & investigated by Mathias Sablé–Meyer

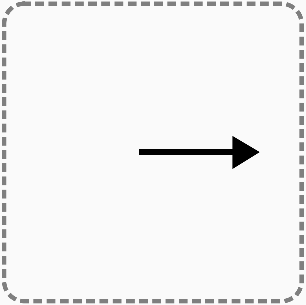
DSL

`OP ::= FW x | RT x | UP | DOWN | SET state`

Tasks

`task : unit -> image`

```
FW 1
```



Turtle graphics — Created & investigated by Mathias Sablé–Meyer

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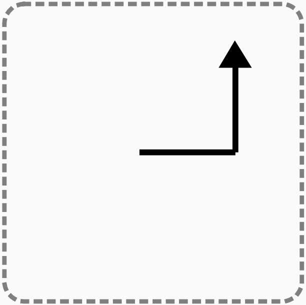
Tasks

`task : unit -> image`

FW 1

RT $\frac{\pi}{2}$

FW 1



DSL

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OP ::= FW x | RT x | UP | DOWN | SET state
```

Tasks

```
task : unit -> image
```

FW 1

RT $\frac{\pi}{2}$

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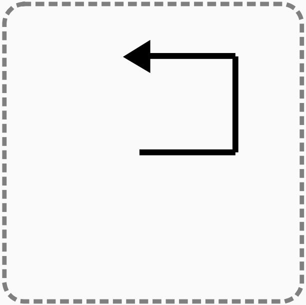
RT $\frac{\pi}{2}$

FW 1



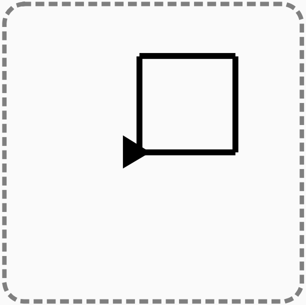
DSL

```
OP ::= FW x | RT x | UP | DOWN | SET state
```

Tasks

```
task :  unit -> image
```

```
for i in range(4)
> FW 1
> RT π/2
```



Turtle graphics — Created & investigated by Mathias Sablé–Meyer

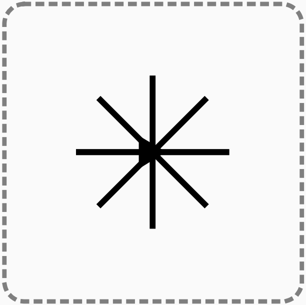
DSL

```
OP ::= FW x | RT x | UP | DOWN | SET state
```

Tasks

```
task :  unit -> image
```

```
for i in range(8)
> FW 1
> SET origin
> RT 2π/8
```



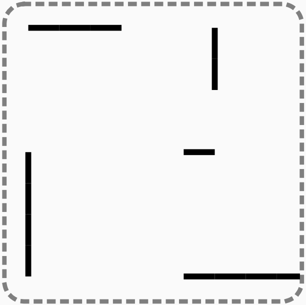
DSL

```
OP ::= FW x | RT x | UP | DOWN | SET state
```

Tasks

```
task :  unit -> image
```

for i in range(8)
> PU
> FW $\frac{i}{2}$
> PD
> FW $\frac{i}{2}$
> RT $\frac{\pi}{2}$



Turtle graphics — Created & investigated by Mathias Sablé–Meyer

DSL

```
OP ::= FW x | RT x | UP | DOWN | SET state
```

Tasks

```
task : unit -> image
```

```
for i in range(∞)
> FW ε
> RT ε
```

figures/teachLogo/circle-eps-

DSL

`OP ::= FW x | RT x | UP | DOWN | SET state`

Tasks

`task : unit -> image`

for i in range($5 \times \infty$)

> FW i $\times \varepsilon$

> RT ε

figures/teachLogo/sspiral-eps-

Turtle graphics — Created & investigated by Mathias Sablé–Meyer

DSL

`OP ::= FW x | RT x | UP | DOWN | SET state`

Tasks

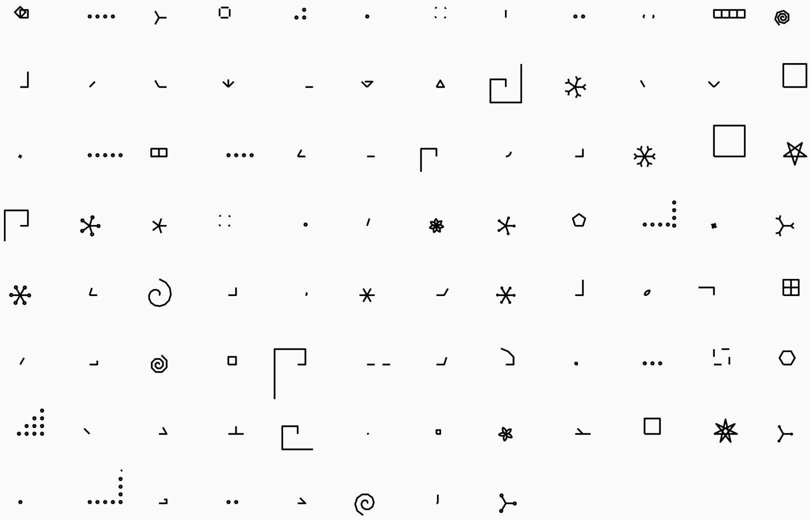
`task : unit -> image`

for i in range($5 \times \infty$)
> FW i $\times\ \varepsilon$
> RT ε

figures/teachLogo/sspiral-eps-

NUM ::= 1 | π | ∞ | ε | + | - | * | /

Turtle graphics — Training tasks



Contributions

Takeaway:

- Humans flexibly adapt to diverse sets of new problem domains
  — DreamCoder takes a step in this direction

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Future work

- More human-like learning: intelligently composing new tasks,

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Takeaway:

- Humans flexibly adapt to diverse sets of new problem domains — DreamCoder takes a step in this direction

Future work

- More human-like learning: intelligently composing new tasks,
- Theory learning
- Planning