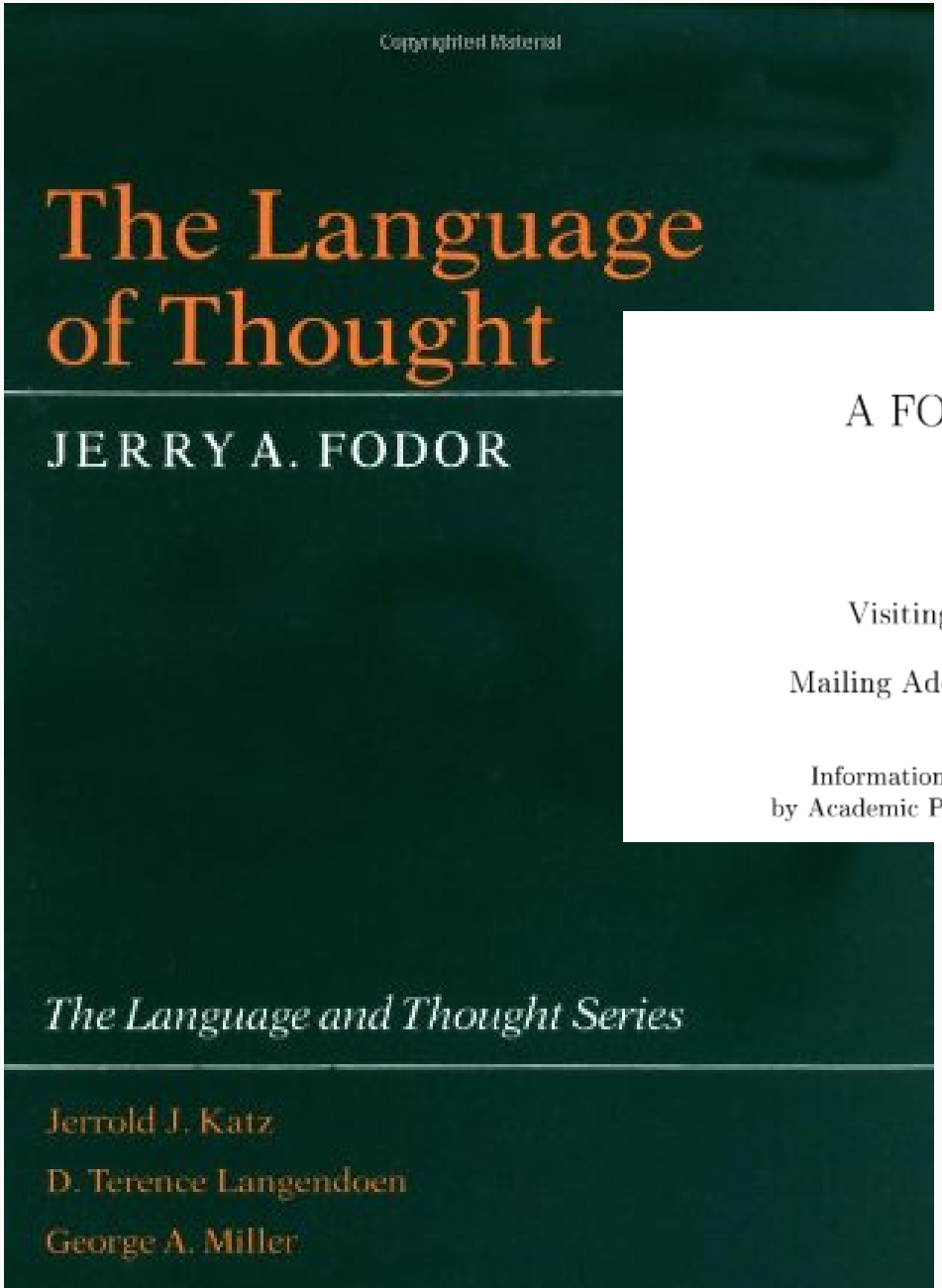
Growing libraries of concepts with wake-sleep program induction

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

July 25, 2018

MIT

The Language of Thought



A FORMAL THEORY OF INDUCTIVE INFERENCE, Part I*†

Ray J. Solomonoff

Visiting Professor, Computer Learning Research Center
Royal Holloway, University of London
Mailing Address: P.O.B. 400404, Cambridge, Ma. 02140, U.S.A.

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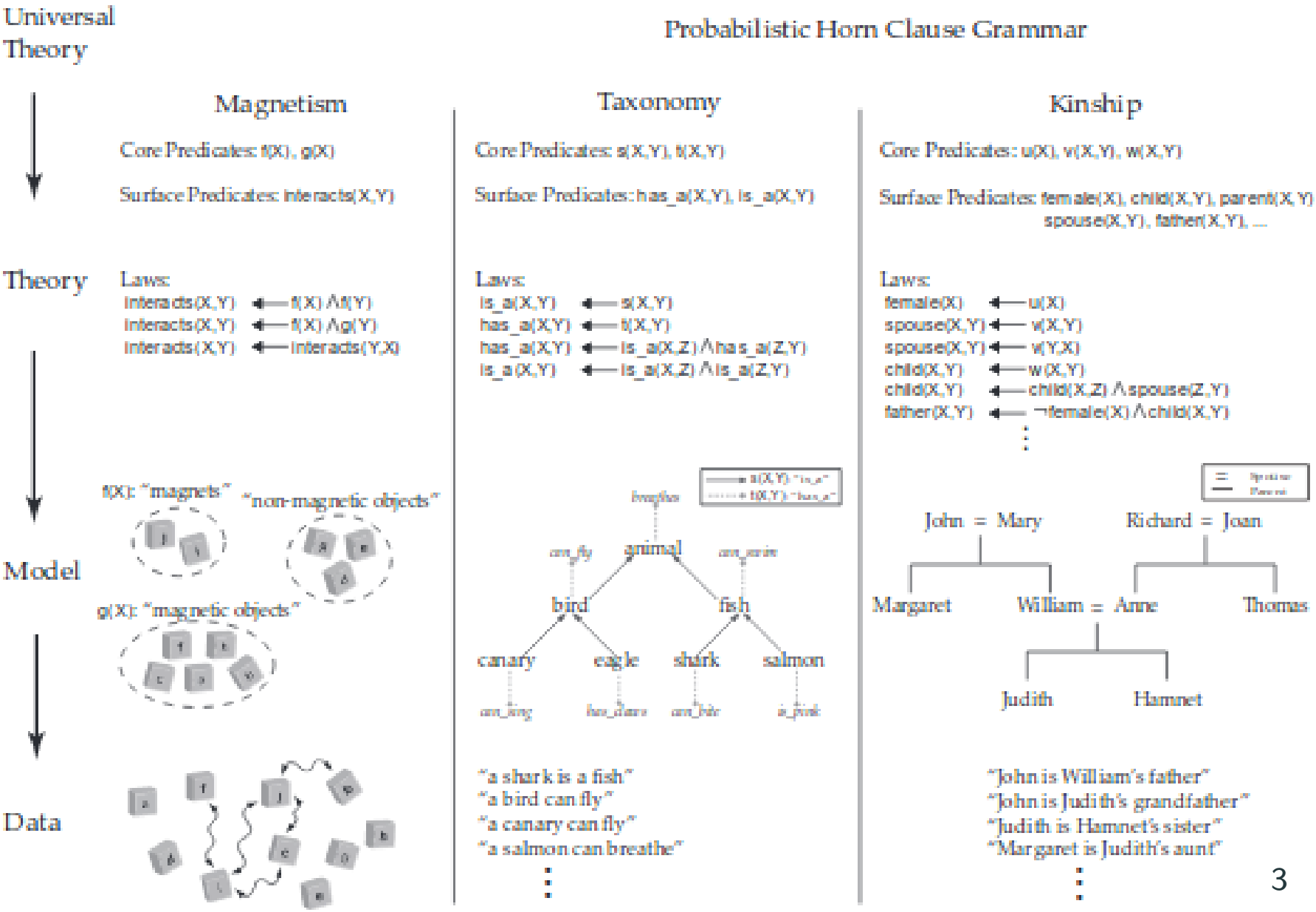
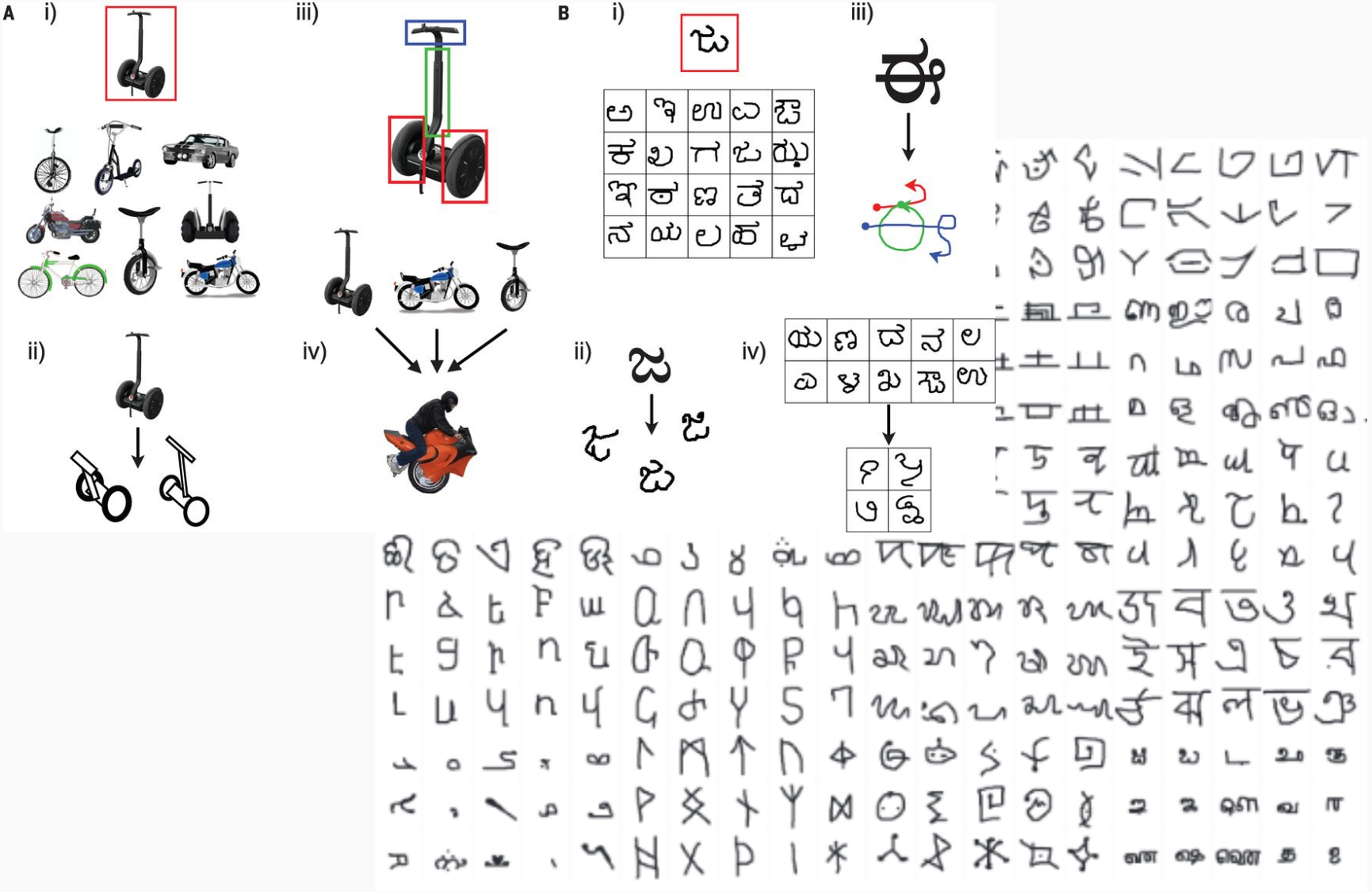
Engineering the language of thought



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

```
[7 2 3]→[7 3]
[1 2 3 4]→[3 4]
[4 3 2 1]→[4 3]
f(ℓ) = (f1 ℓ (λ (x) (> x 2)))
```

```
[7 3]→False
[3]→False
[9 0 0]→True
[0]→True
[0 7 3]→True
f(ℓ) = (f3 ℓ 0)
```

```
[2 7 8 1]→8
[3 19 14]→19
f(ℓ) = (f2 ℓ)
```

DSL

$f_0(\ell,\mathtt{r}) = (\mathtt{foldr\ r}\ \ell\ \mathtt{cons})$
(f_0: *Append lists* r *and* ℓ)

$f_1(\ell,\mathtt{p}) = (\mathtt{foldr}\ \ell\ \mathtt{nil}\ (\lambda\ (\mathtt{x\ a})\ (\mathtt{if\ (p\ x)\ (cons\ x\ a)\ a})))$
(f_1: *Higher-order filter function*)

$f_2(\ell) = (\mathtt{foldr}\ \ell\ 0\ (\lambda\ (\mathtt{x\ a})\ (\mathtt{if\ (>\ a\ x)\ a\ x})))$
(f_2: *Maximum element in list* ℓ)

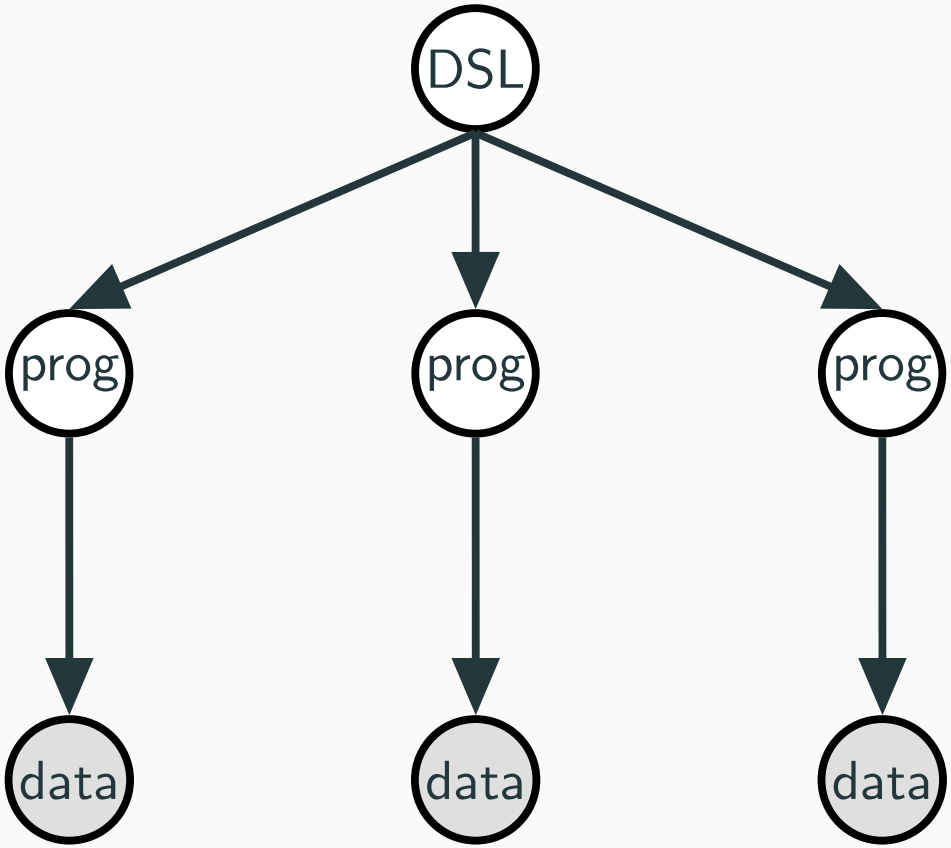
$f_3(\ell,\mathtt{k}) = (\mathtt{foldr}\ \ell\ (\mathtt{is\text{-}nil}\ \ell)\ (\lambda\ (\mathtt{x\ a})\ (\mathtt{if\ a\ a\ (=\ k\ x)}))))$
(f_2: *Whether* ℓ *contains* k)

DreamCoder

- **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

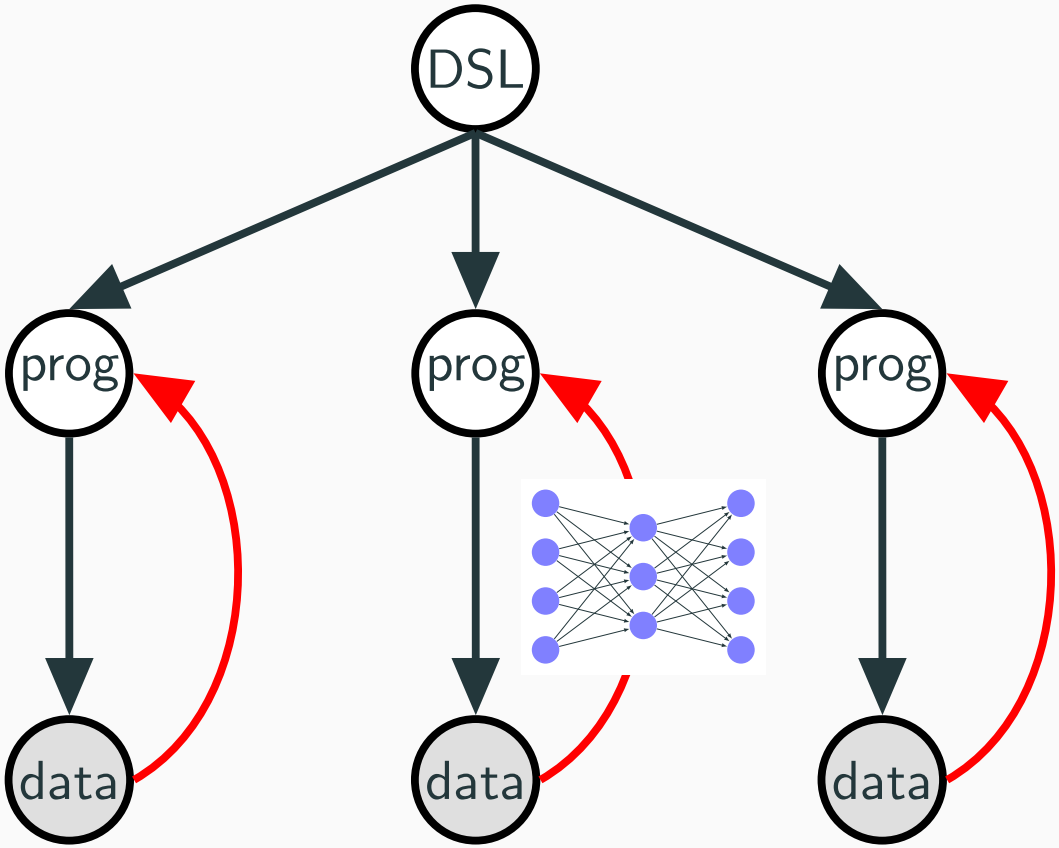
Combines ideas from Wake-Sleep & Exploration-Compression algorithm by Eyal Dechter

DSL learning as Bayesian inference

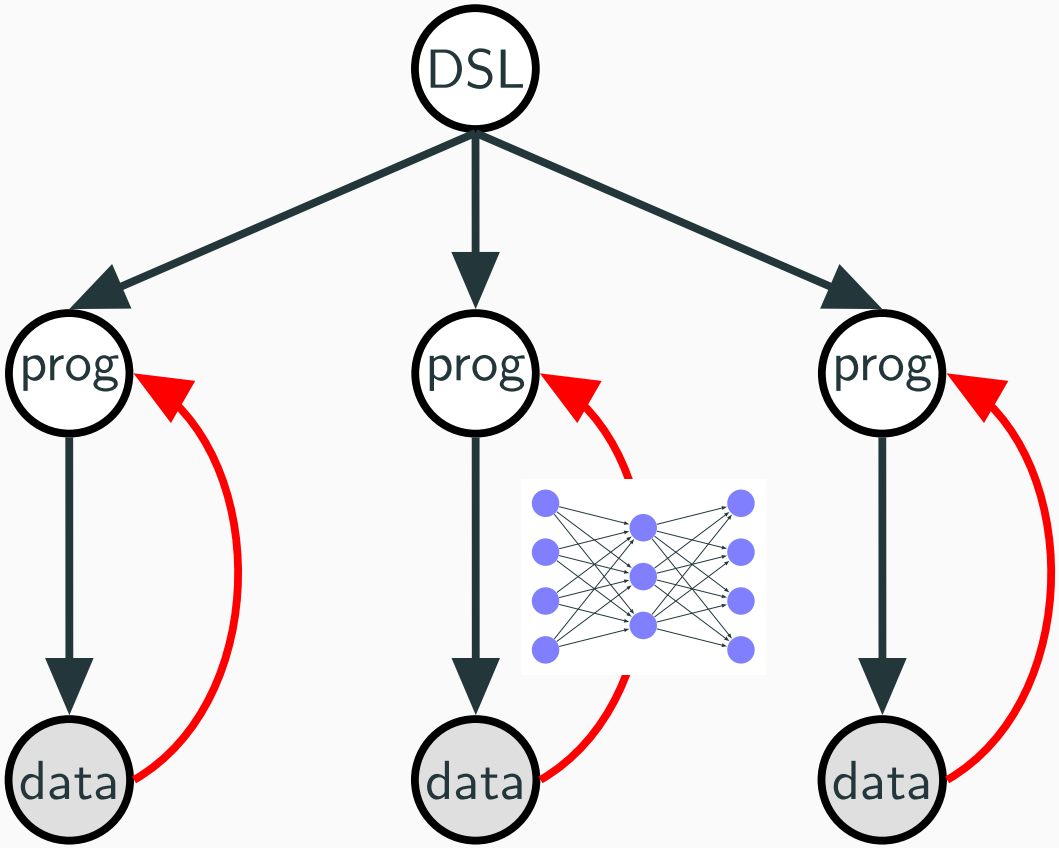


[Dechter et al., 2013] [Liang et al, 2010]; [Lake et al, 2015]

DSL learning as amortized Bayesian inference

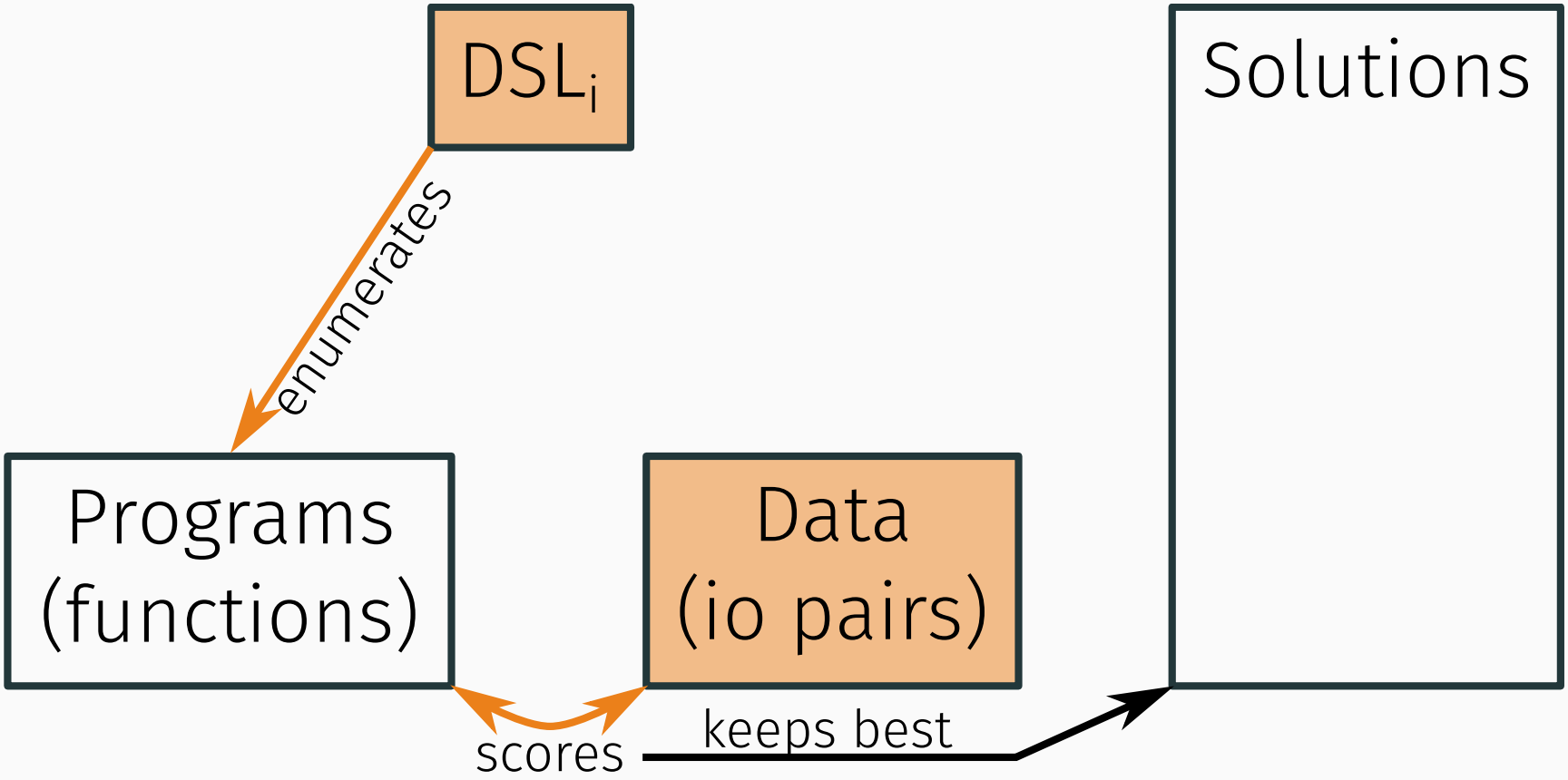


DSL learning as amortized Bayesian inference



New: amortized inference +
better program representation (Lisp) +
better DSL inference

Wake — as in Exploration/Compression Algorithm



DSL

```
f0(l,r) = foldr r l cons
f1(l,p) = foldr r nil
            (λ (x a)
              (if (p x)
                (cons x a)
                a))
```

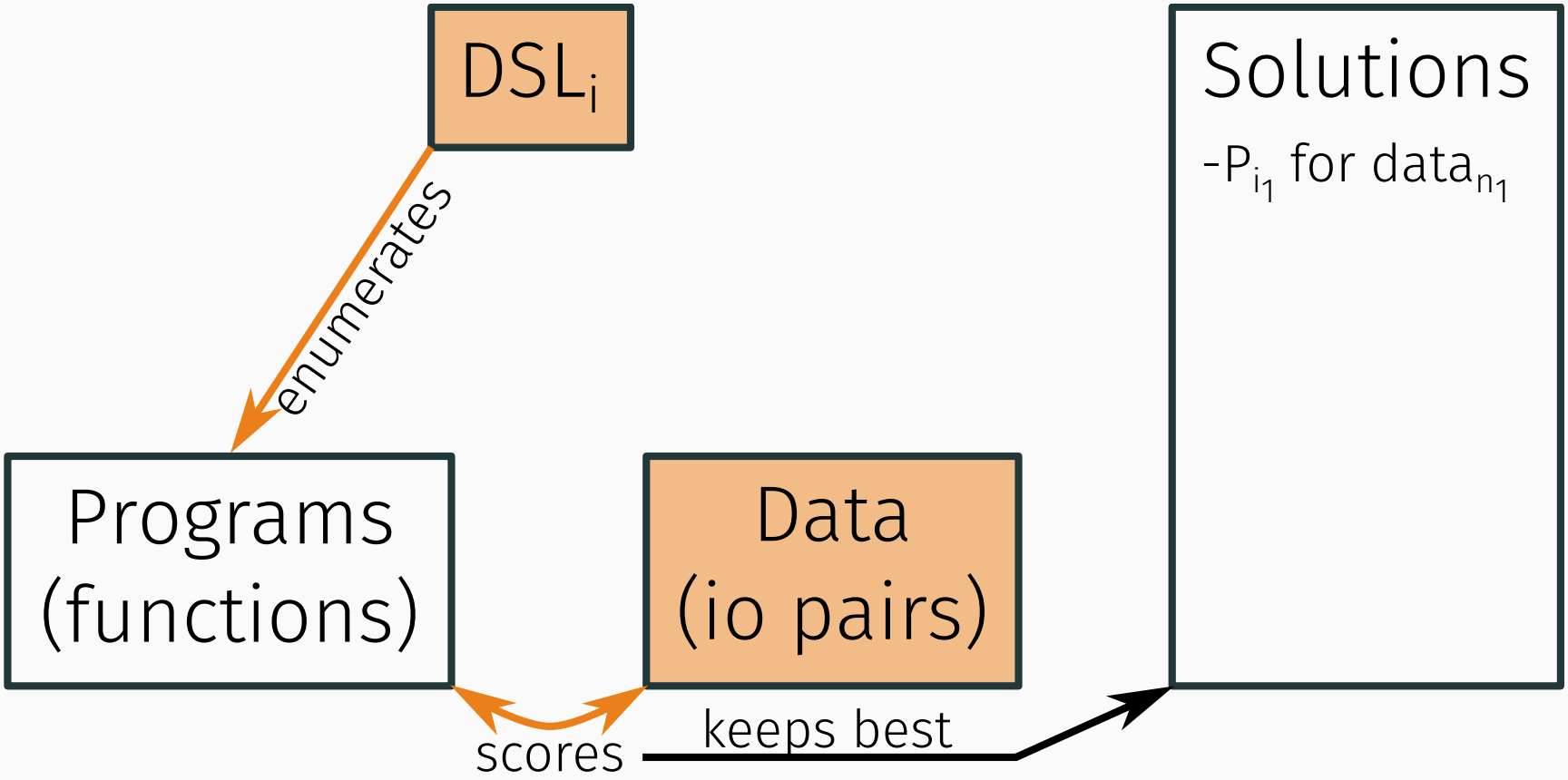
Programs

```
f(l) = (f0 l l)

f(l) = (f1 l (λx. > x 2))
```

Data

```
[7 2]→[7 2 7 2]
["a"]→["a" "a"]

[7 2 3]→[7 3]
[1 2 3 4]→[3 4]
[4 3 2 1]→[4 3]
```

Wake — as in Exploration/Compression Algorithm



DSL

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Programs

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f(l) = (f0 l l)

f(l) = (f1 l (λx. > x 2))
```

Data

```
[7 2]→[7 2 7 2]
["a"]→["a" "a"]

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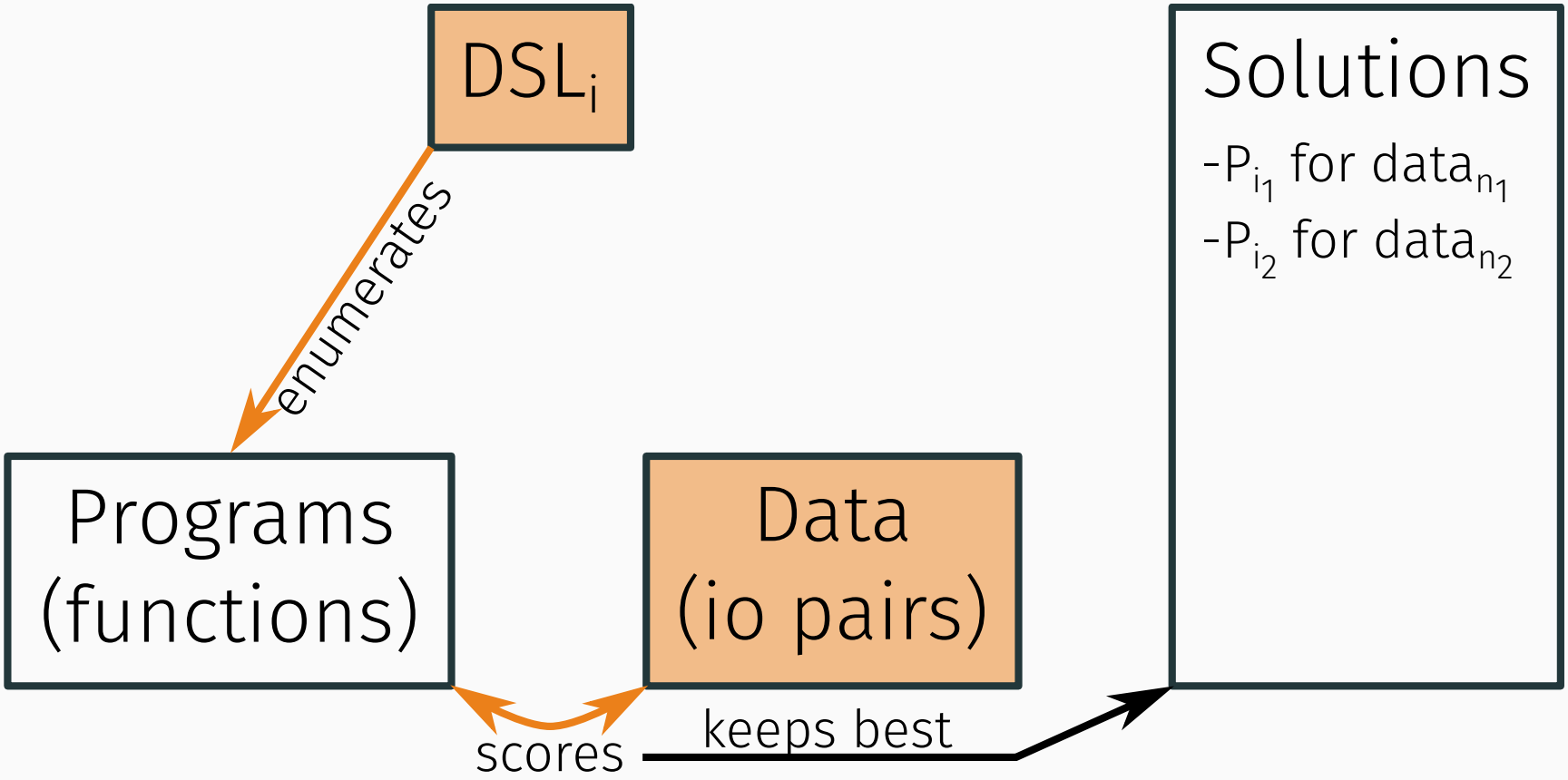
[1 2 3 4]→[3 4]
[4 3 2 1]→[4 3]
```

Wake — as in Exploration/Compression Algorithm



DSL

```
f₀(l,r) = foldr r l cons
f₁(l,p) = foldr r nil
            (λ (x a)
              (if (p x)
                (cons x a)
                a))
```

Programs

```
f(l) = (f₀ l l)

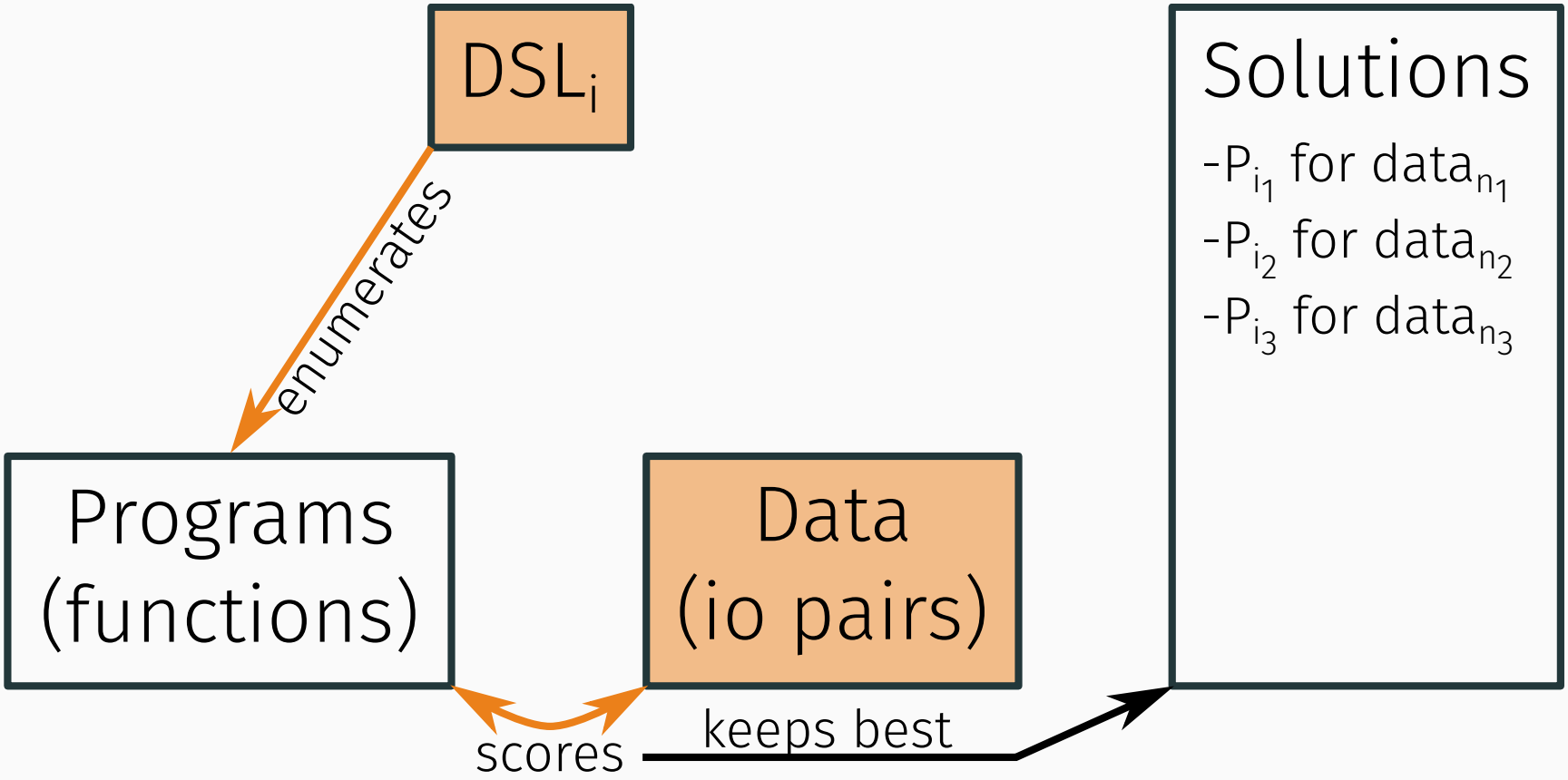
f(l) = (f₁ l (λx. > x 2))
```

Data

```
[7 2]→[7 2 7 2]
["a"]→["a" "a"]

[7 2 3]→[7 3]
[1 2 3 4]→[3 4]
[4 3 2 1]→[4 3]
```

Wake — as in Exploration/Compression Algorithm



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            (λ (x a)
              (if (p x)
                (cons x a)
                a))
```
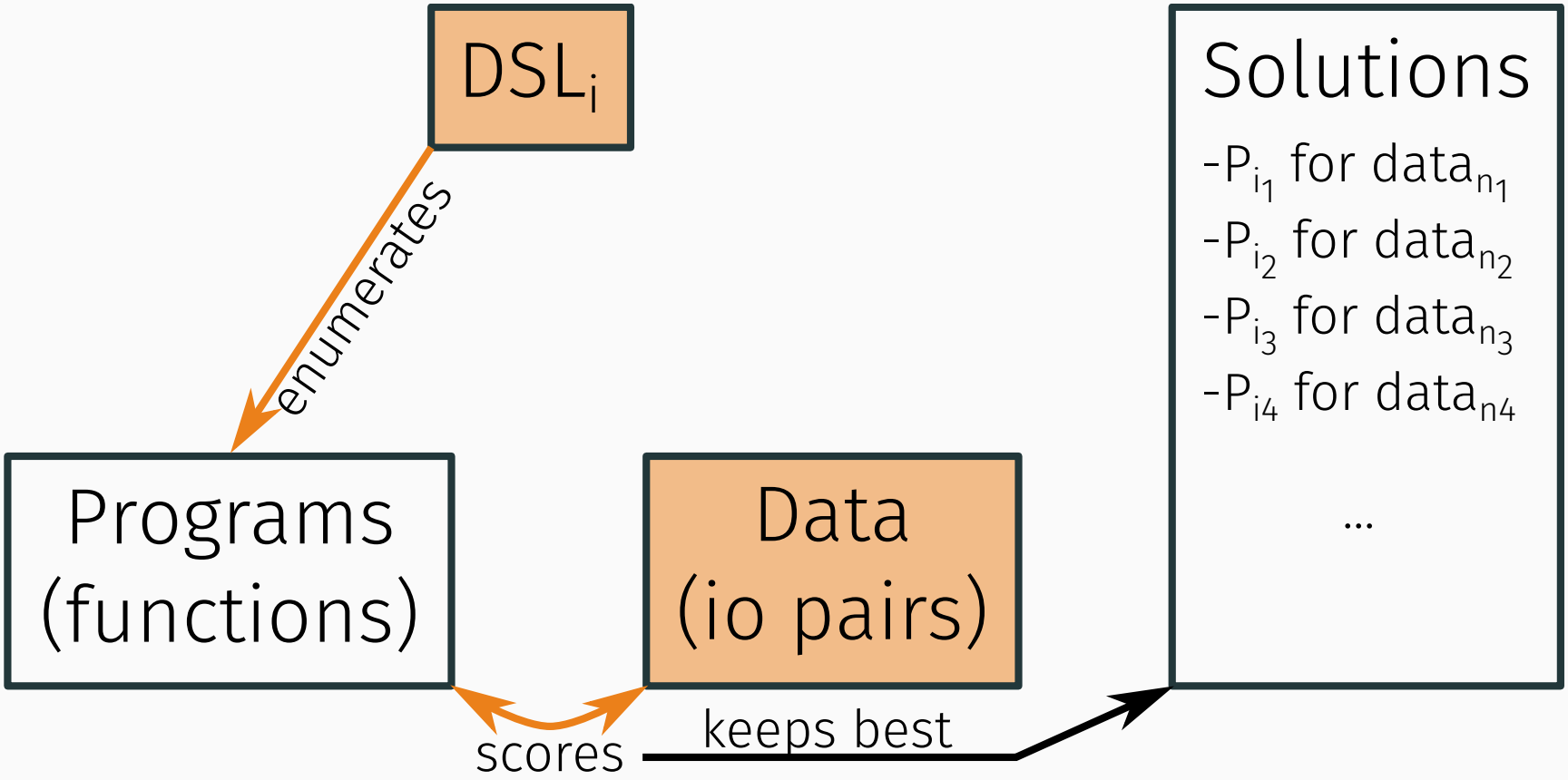

Programs

```
f(l) = (f0 l l)

f(l) = (f1 l (λx. > x 2))
```

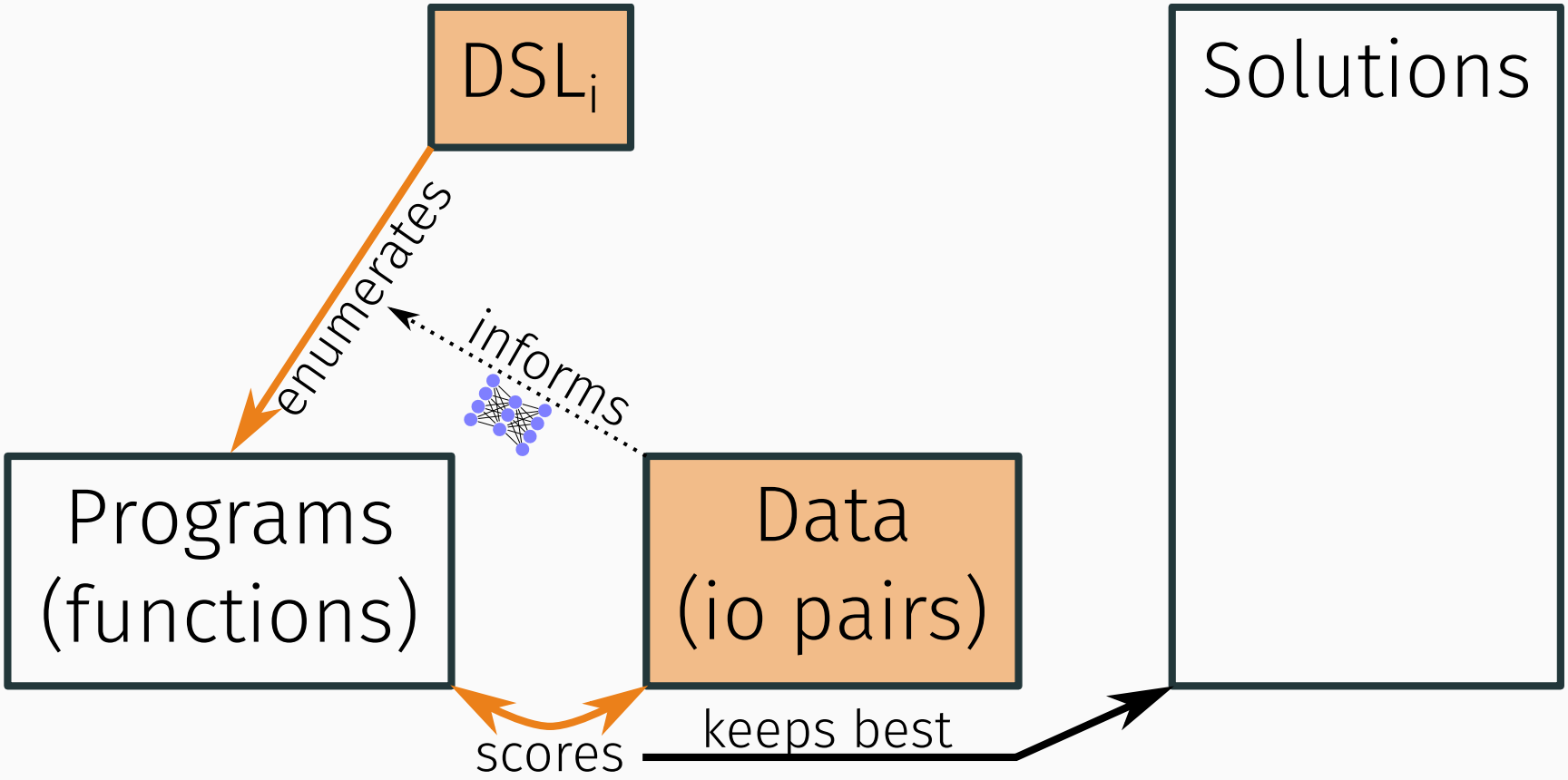
Data

```
[7 2]→[7 2 7 2]
["a"]→["a" "a"]

[7 2 3]→[7 3]
[1 2 3 4]→[3 4]
[4 3 2 1]→[4 3]
```

Wake — as in Exploration/Compression Algorithm



DreamCoder — Wake



DSL

```
f0(l,r) = foldr r l cons
f1(l,p) = foldr r nil
            (λ (x a)
              (if (p x)
                (cons x a)
                a))
```

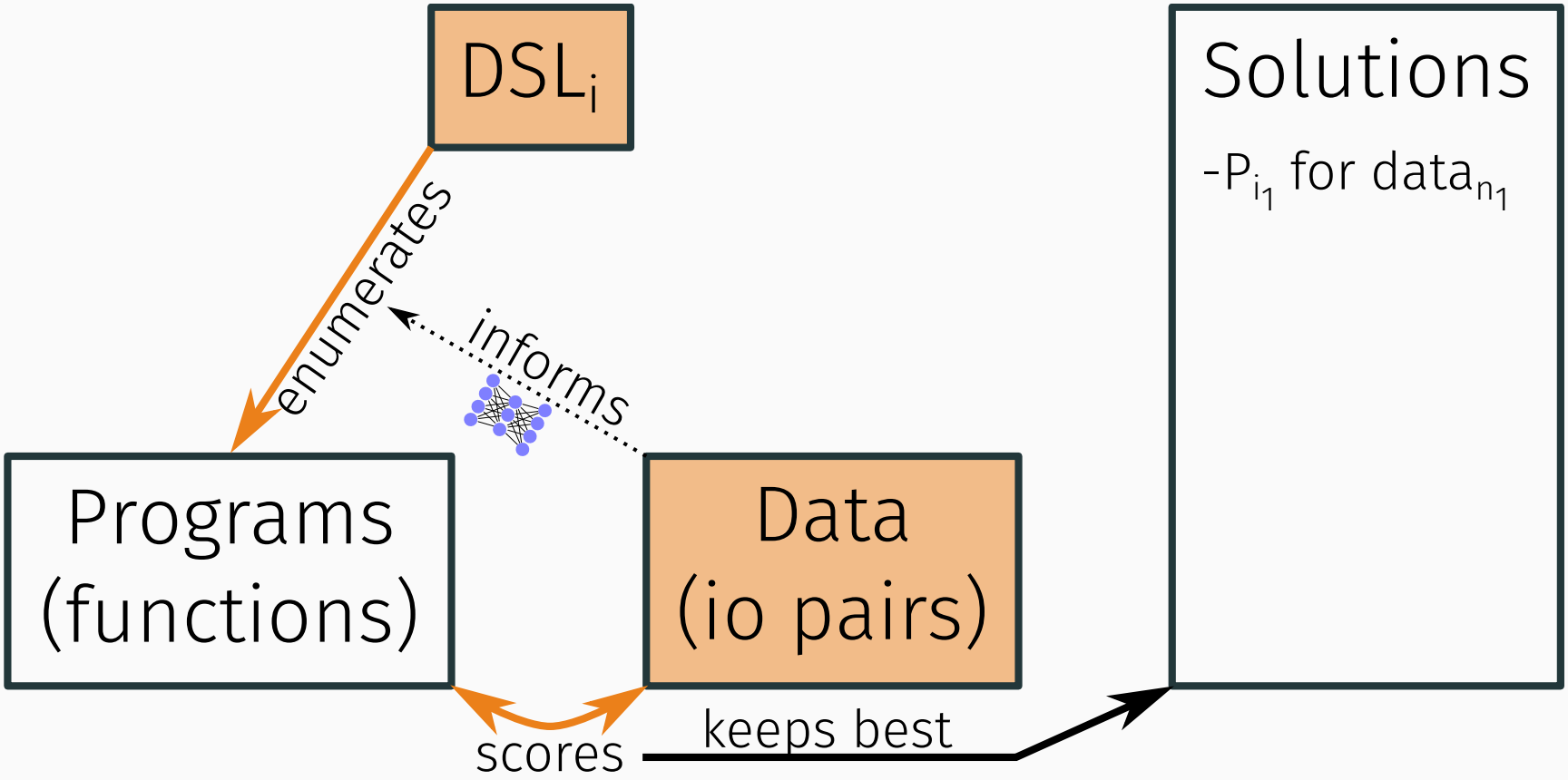
Programs

```
f(l) = (f0 l l)

f(l) = (f1 l (λx. > x 2))
```

Data

```
[7 2]→[7 2 7 2]
["a"]→["a" "a"]

[7 2 3]→[7 3]
[1 2 3 4]→[3 4]
[4 3 2 1]→[4 3]
```

DreamCoder — Wake



DSL

```
f0(l,r) = foldr r l cons
f1(l,p) = foldr r nil
            (λ (x a)
              (if (p x)
                (cons x a)
                a))
```

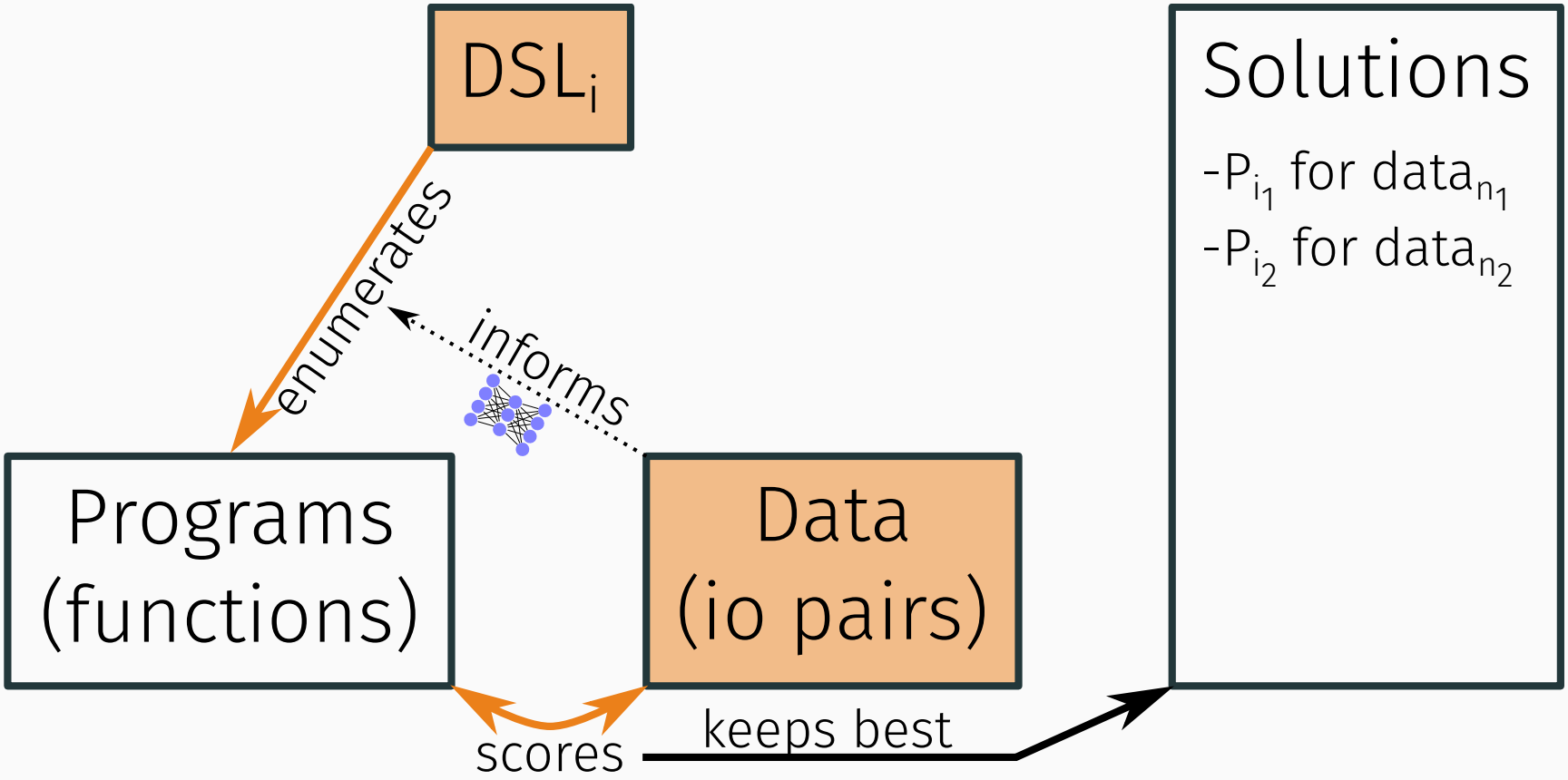
Programs

```
f(l) = (f0 l l)

f(l) = (f1 l (λx. > x 2))
```

Data

```
[7 2]→[7 2 7 2]
["a"]→["a" "a"]

[7 2 3]→[7 3]
[1 2 3 4]→[3 4]
[4 3 2 1]→[4 3]
```

DreamCoder — Wake



DSL

```
f₀(l,r) = foldr r l cons
f₁(l,p) = foldr r nil
            (λ (x a)
              (if (p x)
                (cons x a)
                a))
```

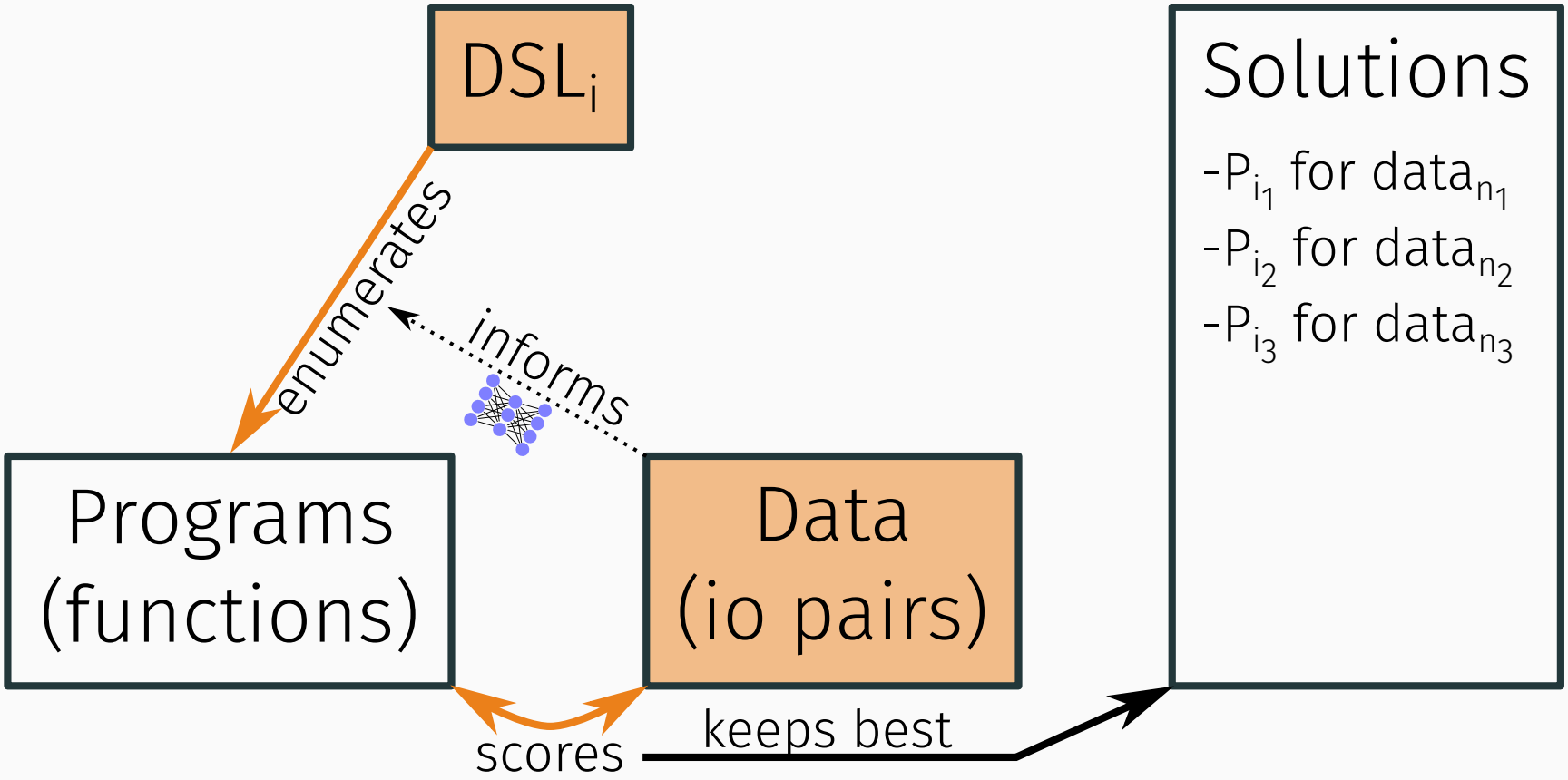
Programs

```
f(l) = (f₀ l l)

f(l) = (f₁ l (λx. > x 2))
```

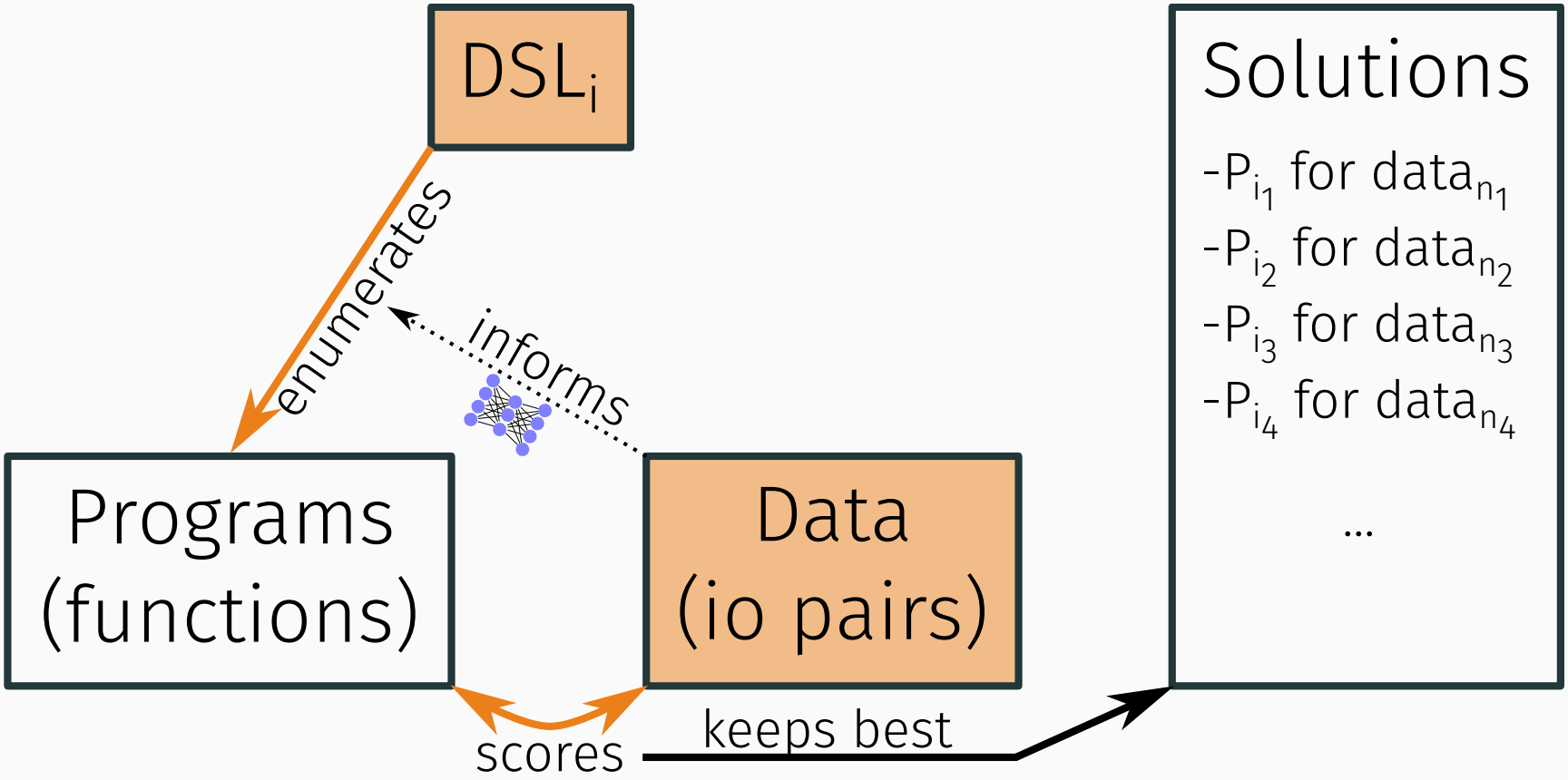
Data

```
[7 2]→[7 2 7 2]
["a"]→["a" "a"]

[7 2 3]→[7 3]
[1 2 3 4]→[3 4]
[4 3 2 1]→[4 3]
```

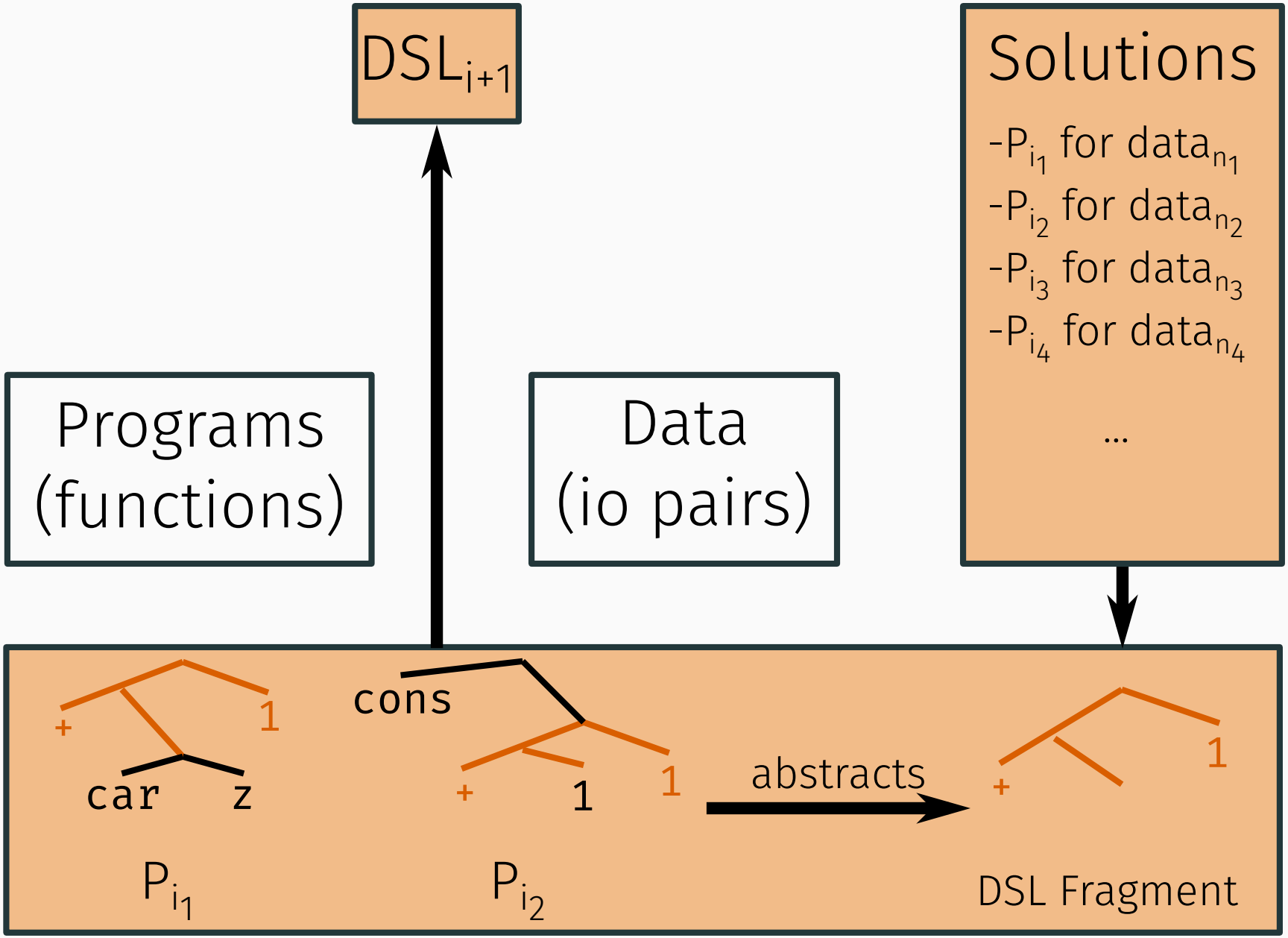
DreamCoder — Wake



DreamCoder — Wake



DreamCoder — Sleep-G



DreamCoder — Sleep-R (Experience Replay)

DSL_{i+1}

Solutions

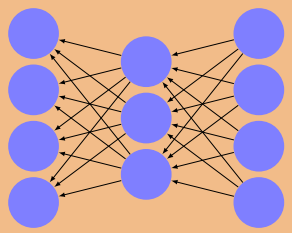
- P_{i_1} for $data_{n_1}$
- P_{i_2} for $data_{n_2}$
- P_{i_3} for $data_{n_3}$
- P_{i_4} for $data_{n_4}$

...

Programs (functions)

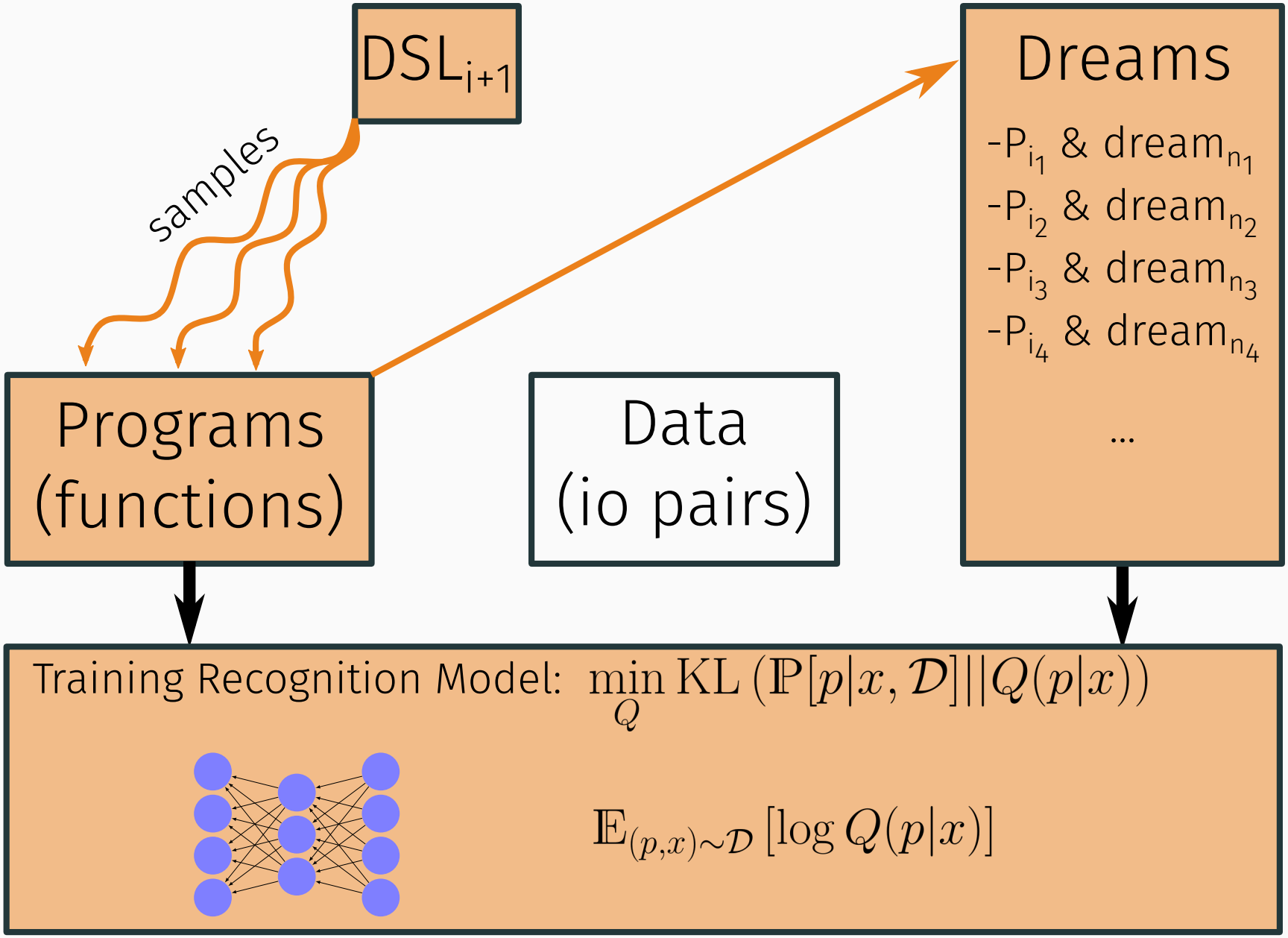
Data (io pairs)

Training Recognition Model: $\min_Q \mathrm{KL}\left(\mathbb{P}[p|x,\mathcal{D}]||Q(p|x)\right)$



$$\frac{\mathbb{P}\left[x_n, p_n|\mathcal{D}\right]}{\sum_{(x_n,p'_n)} \mathbb{P}\left[x_n, p_n|\mathcal{D}\right]} \log Q(p_n|x_n)$$

DreamCoder — Sleep-R (Dreaming)

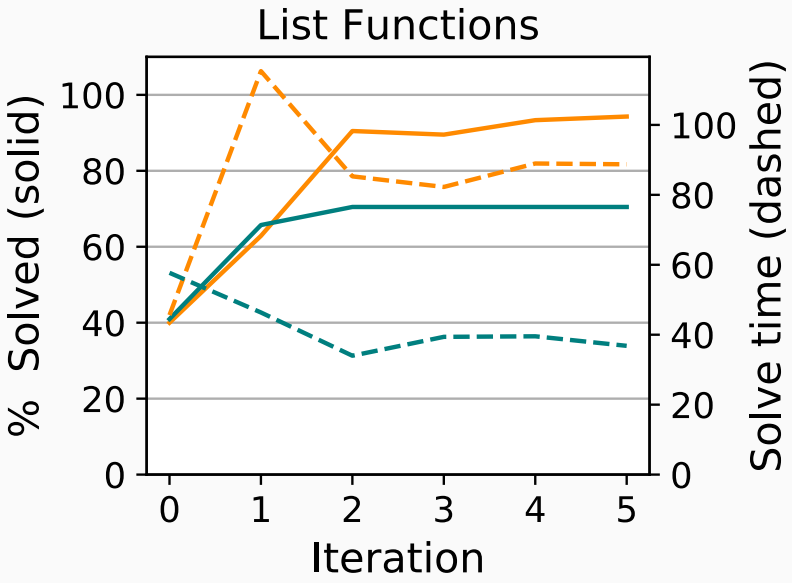


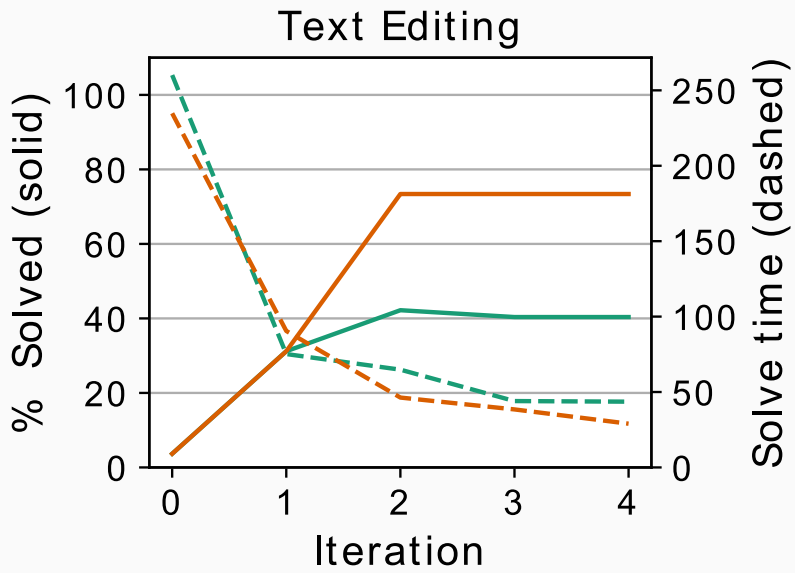
List functions — Created & investigated by Lucas Morales

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’. With suitable curriculum can also learn ‘map’, ‘fold’, etc.

List functions & Text editing: 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

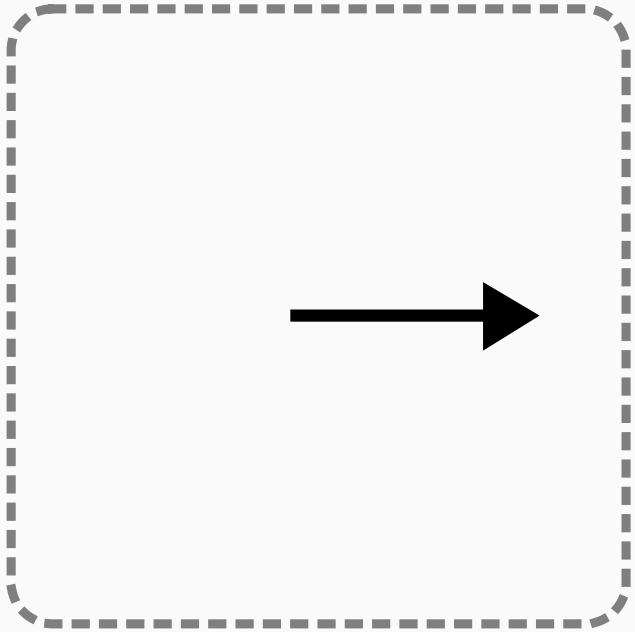
DSL

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

Tasks

```
task :  image
```

```
FW 1
```



Turtle graphics — Created & investigated by Mathias Sablé–Meyer

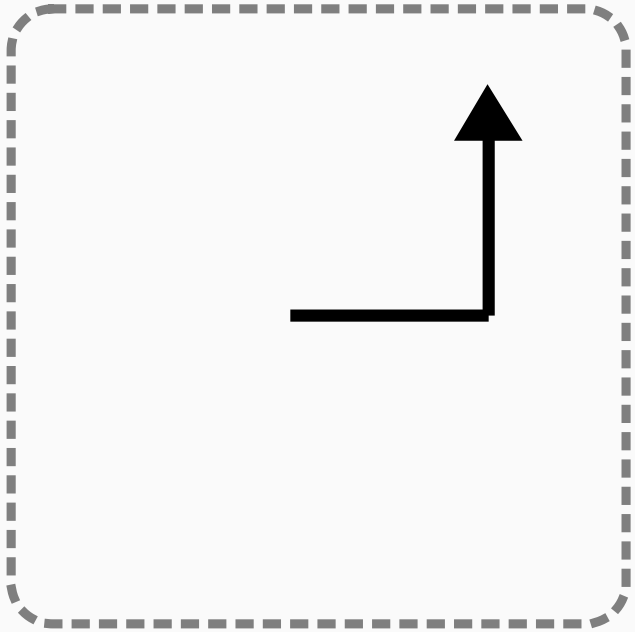
DSL

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

Tasks

```
task :  image
```

```
FW 1
RT π/2
FW 1
```



Turtle graphics — Created & investigated by Mathias Sablé–Meyer

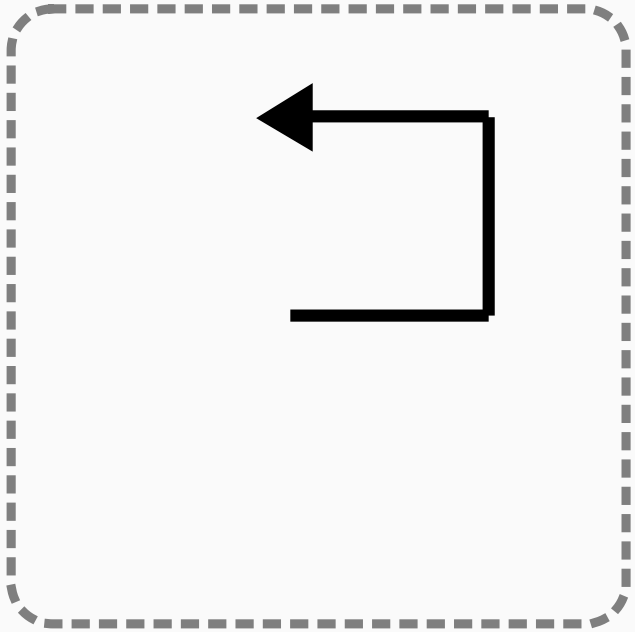
DSL

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

Tasks

```
task :  image
```

```
FW 1
RT π/2
FW 1
RT π/2
FW 1
```



Turtle graphics — Created & investigated by Mathias Sablé–Meyer

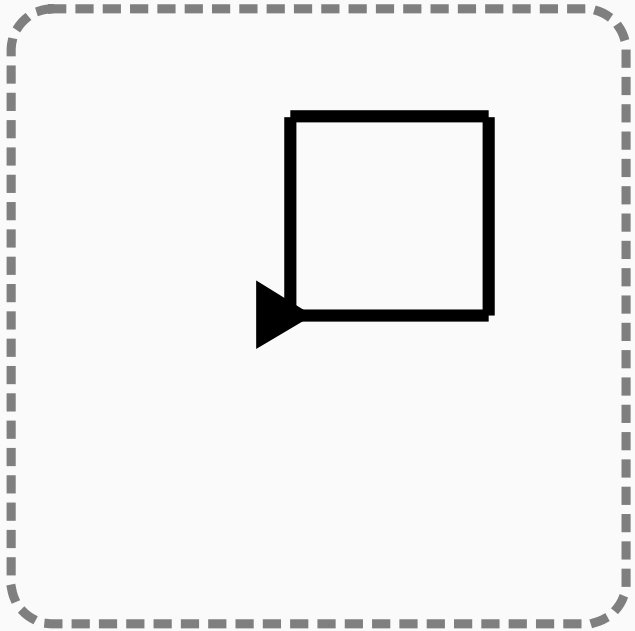
DSL

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

Tasks

```
task :  image
```

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



Turtle graphics — Created & investigated by Mathias Sablé–Meyer

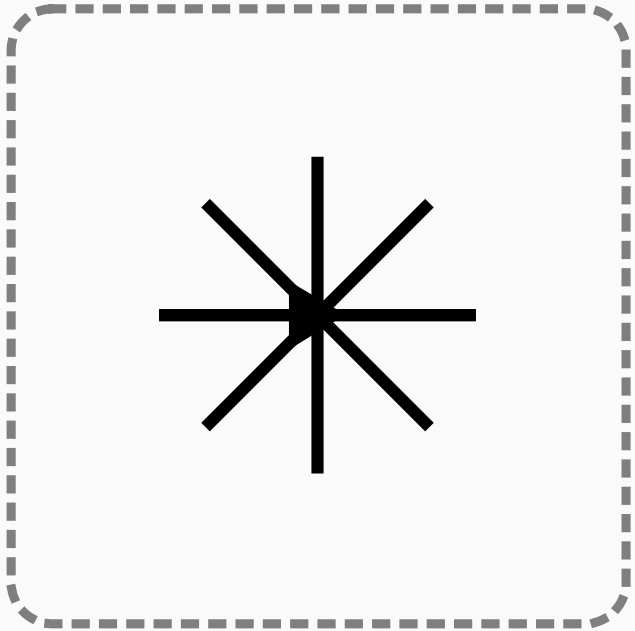
DSL

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

Tasks

```
task :  image
```

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



Turtle graphics — Created & investigated by Mathias Sablé–Meyer

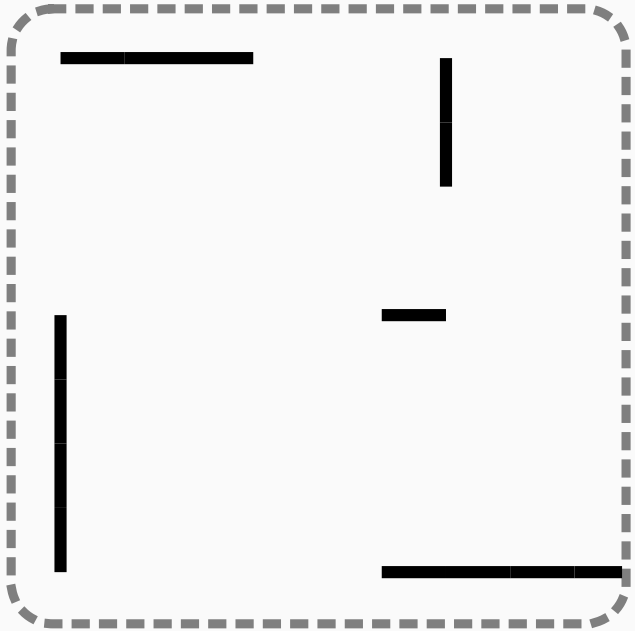
DSL

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

Tasks

```
task :  image
```

```
for i in range(8)
> PU
> FW i/2
> PD
> FW i/2
> RT π/2
```



Turtle graphics — Created & investigated by Mathias Sablé–Meyer

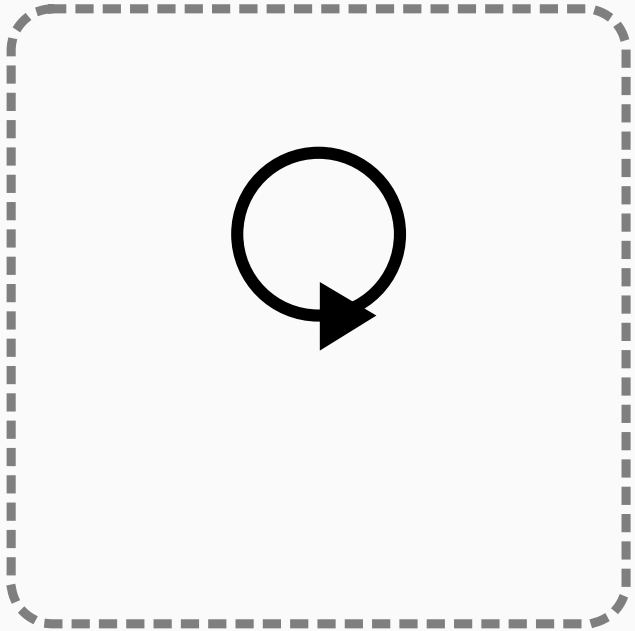
DSL

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

Tasks

```
task :  image
```

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



Turtle graphics — Created & investigated by Mathias Sablé–Meyer

DSL

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

Tasks

```
task :  image
```

```
for i in range(5 × ∞)
> FW i × ε
> RT ε
```

Turtle graphics — Created & investigated by Mathias Sablé–Meyer

DSL

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

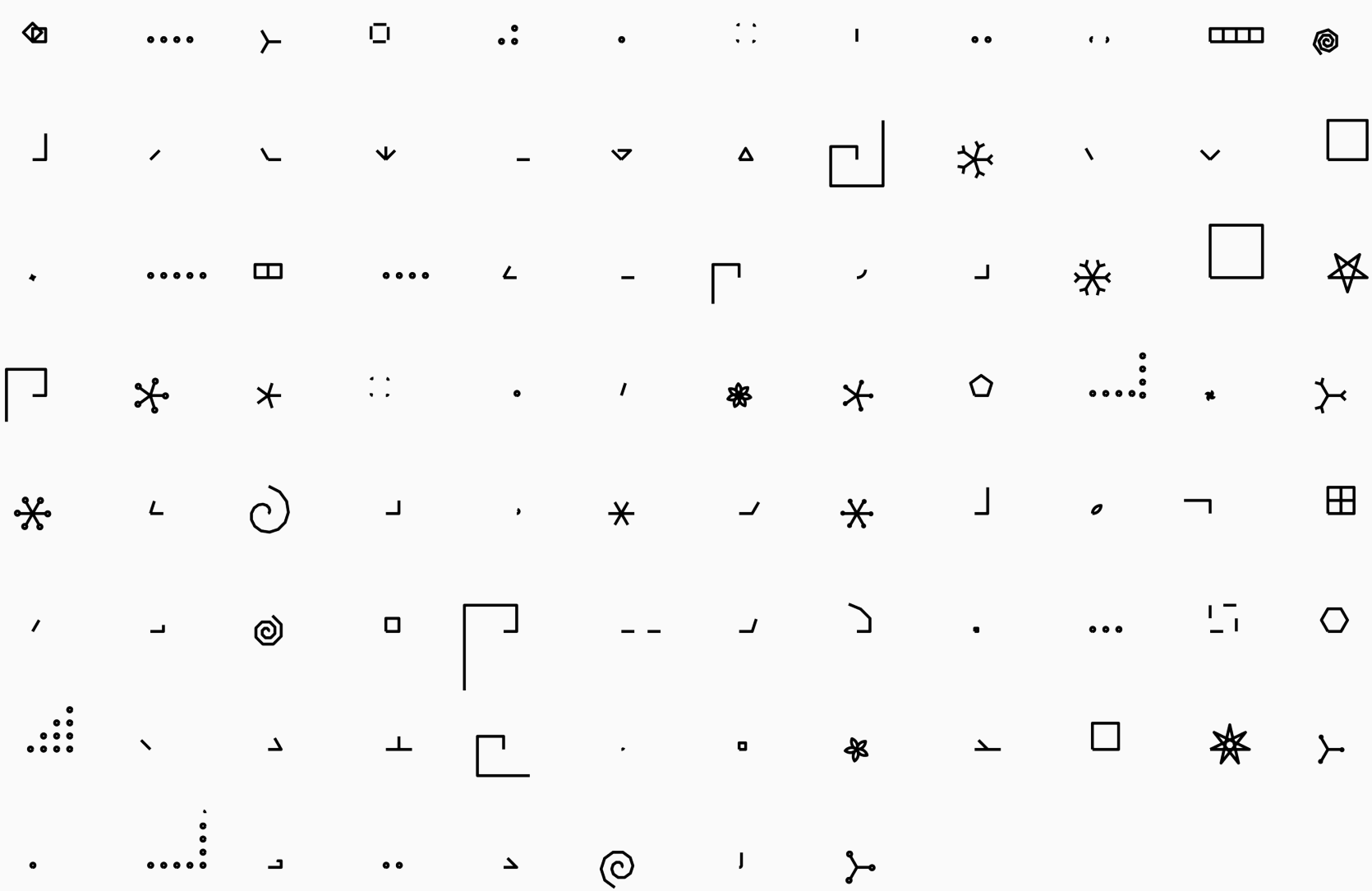
Tasks

```
task :  image
```

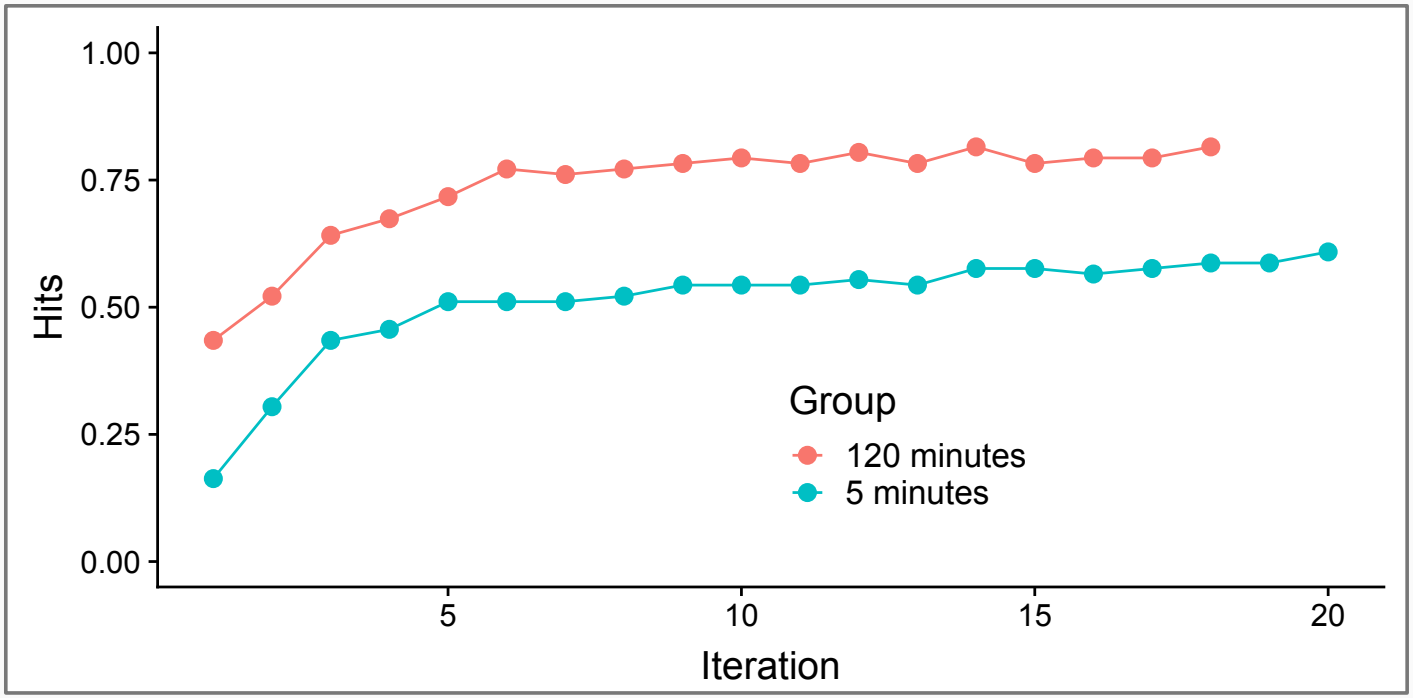
```
for i in range(5 × ∞)
> FW i × ε
> RT ε
```

```
NUM ::= 1 | π | ∞ | ε | + | - | * | /
```

Turtle graphics — Training tasks



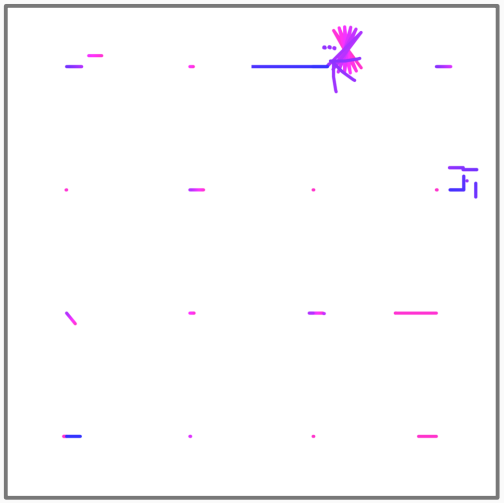
Turtle graphics — Learning curves

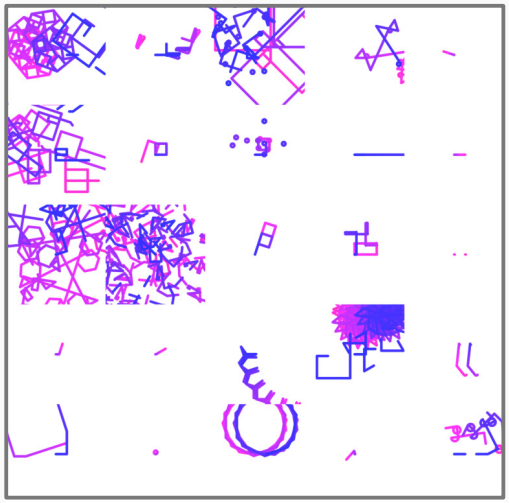


- $\frac{\pi}{2}$ and $\frac{\pi}{4}$ from π, 2, $+$ and $/$
- A line of length `n` followed with a right angle
- Loops of length `n` that uses the number `n` inside.
- Unit line then teleport back to origin
- ...

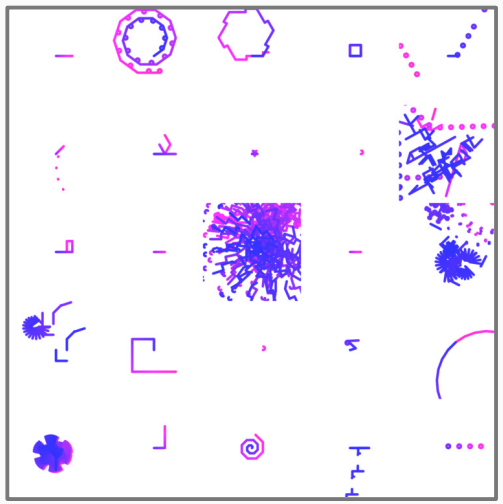
Turtle graphics — Dreams

Before training



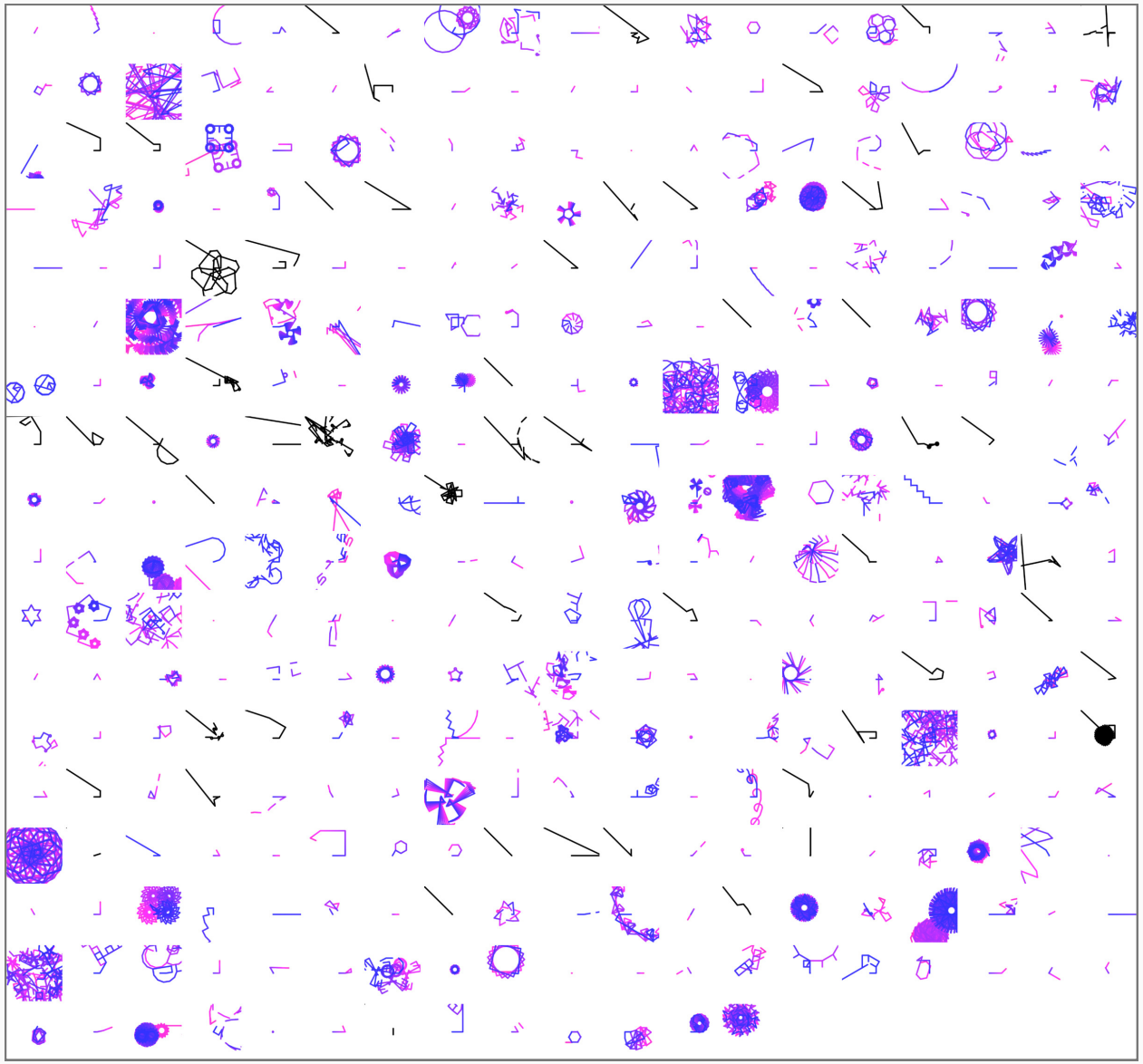


Plateau 5 minutes

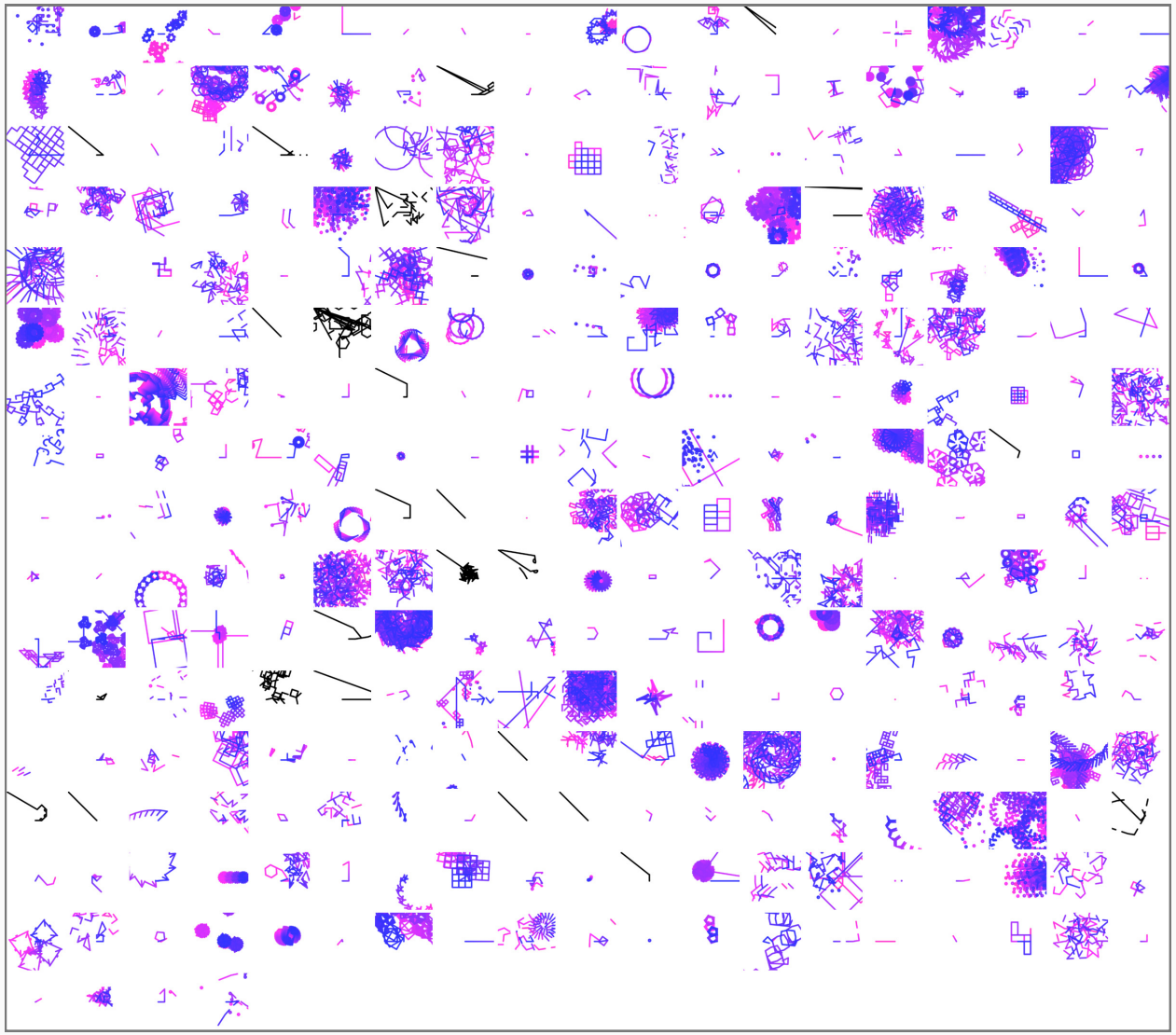


Plateau 2 hours

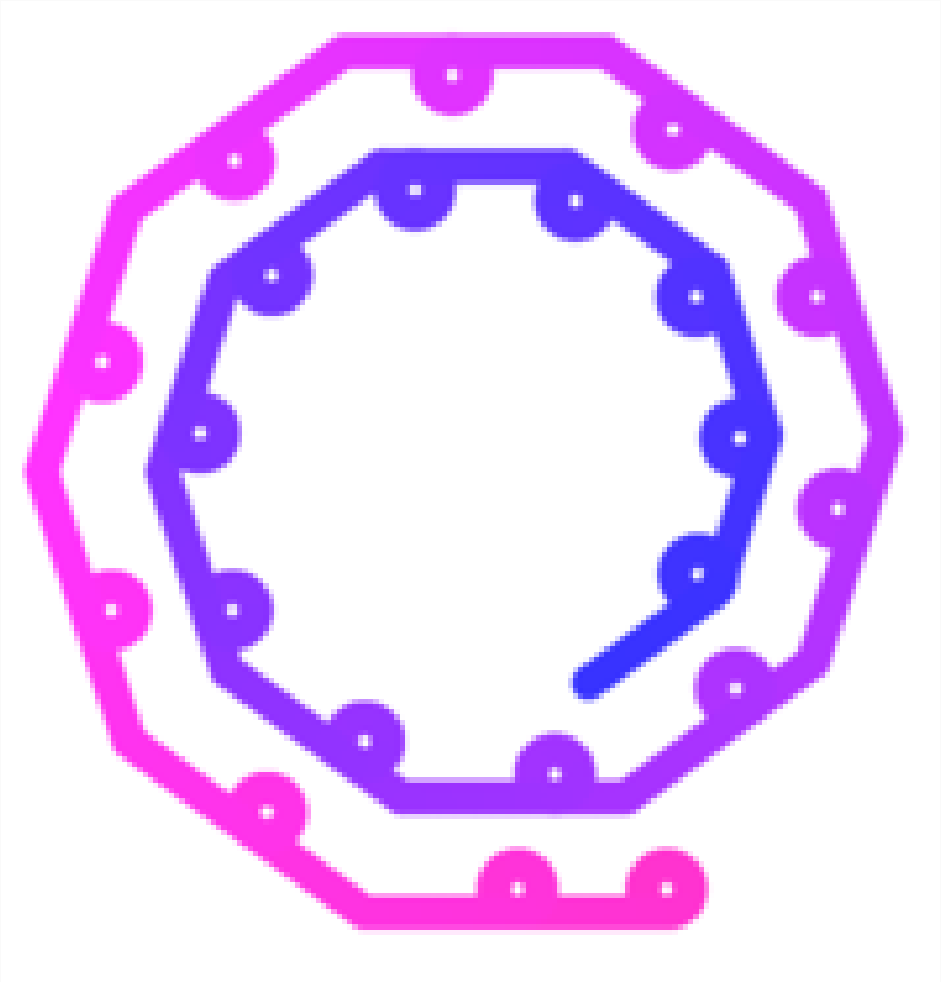
Turtle graphics — More dreams, 5 minutes, 1st iteration



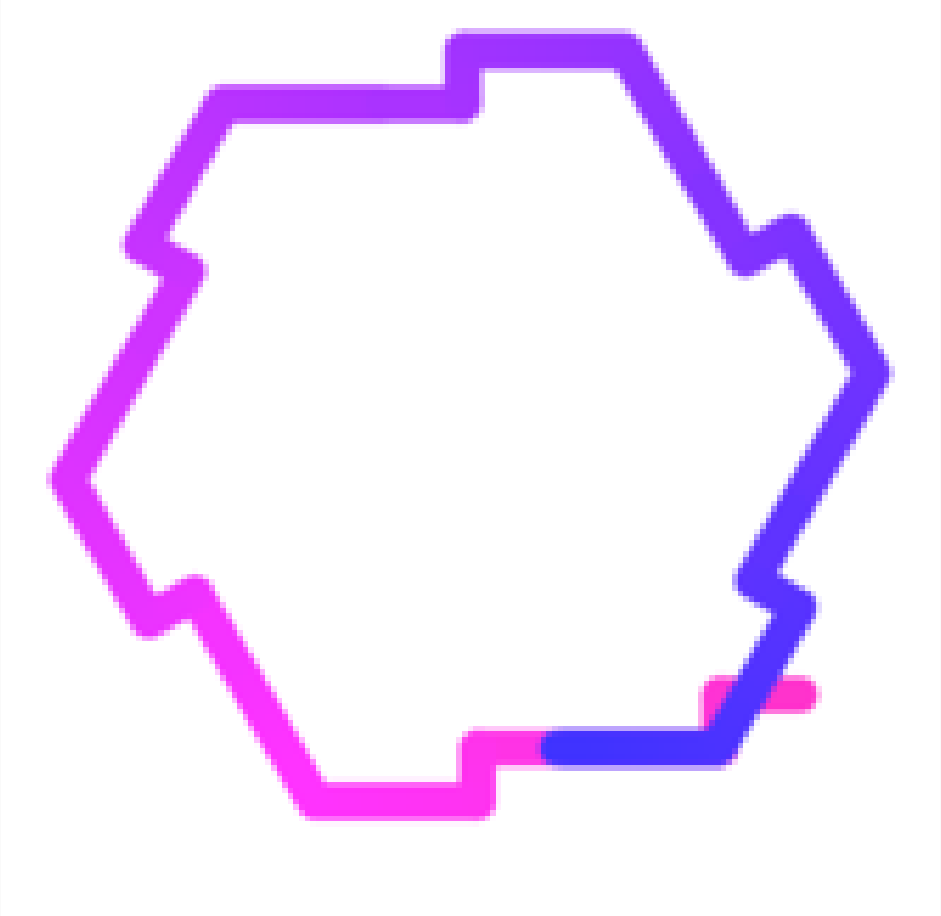
Turtle graphics — More dreams, 5 minutes, last iteration



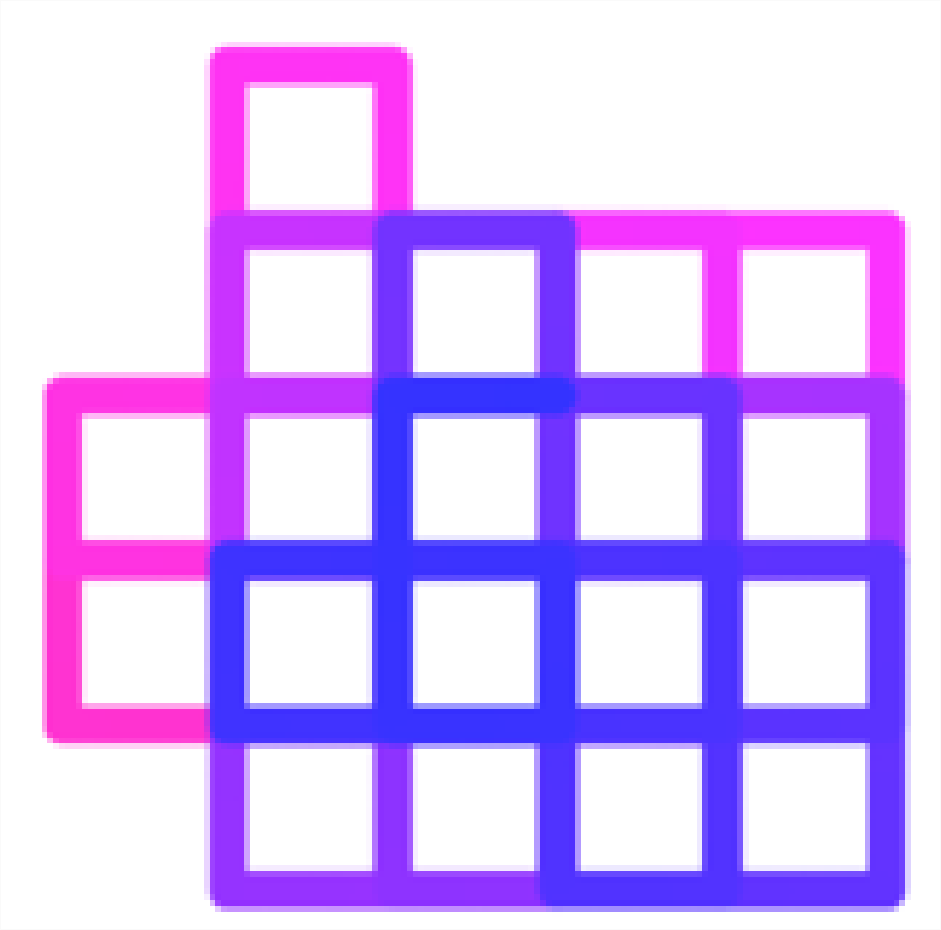
Turtle graphics — Generative model



Turtle graphics — Generative model

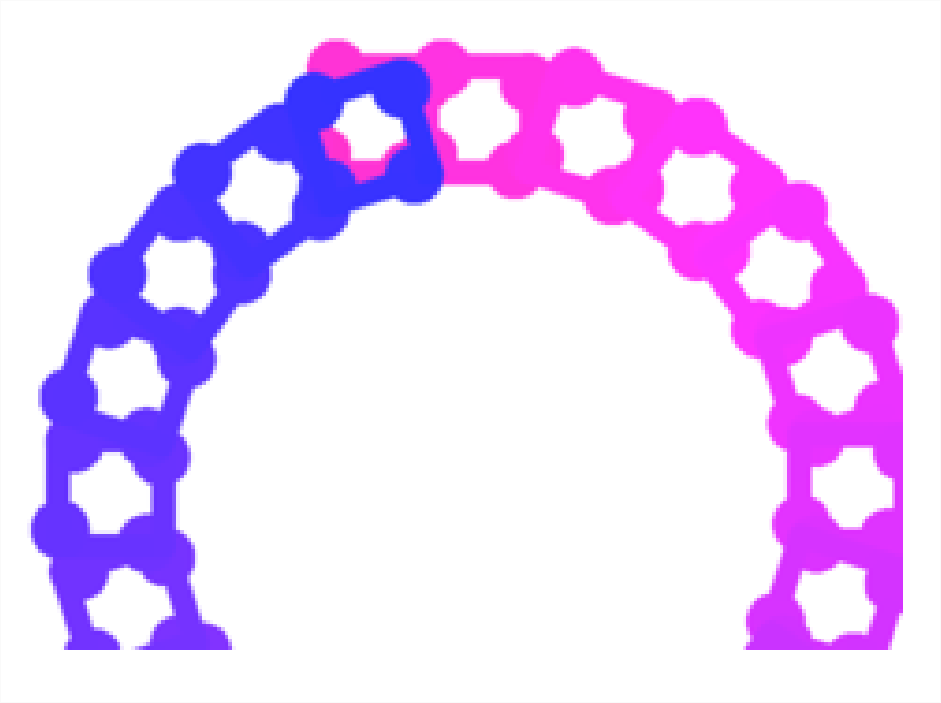


Turtle graphics — Generative model

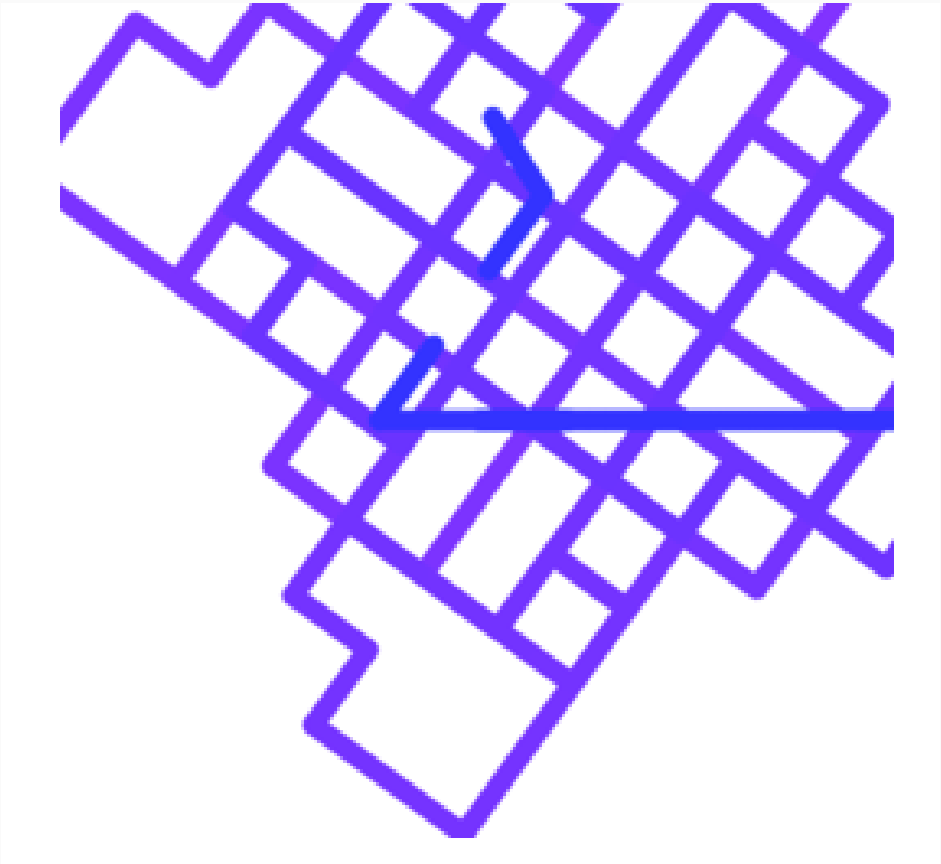


Turtle graphics — Generative model

Turtle graphics — Generative model



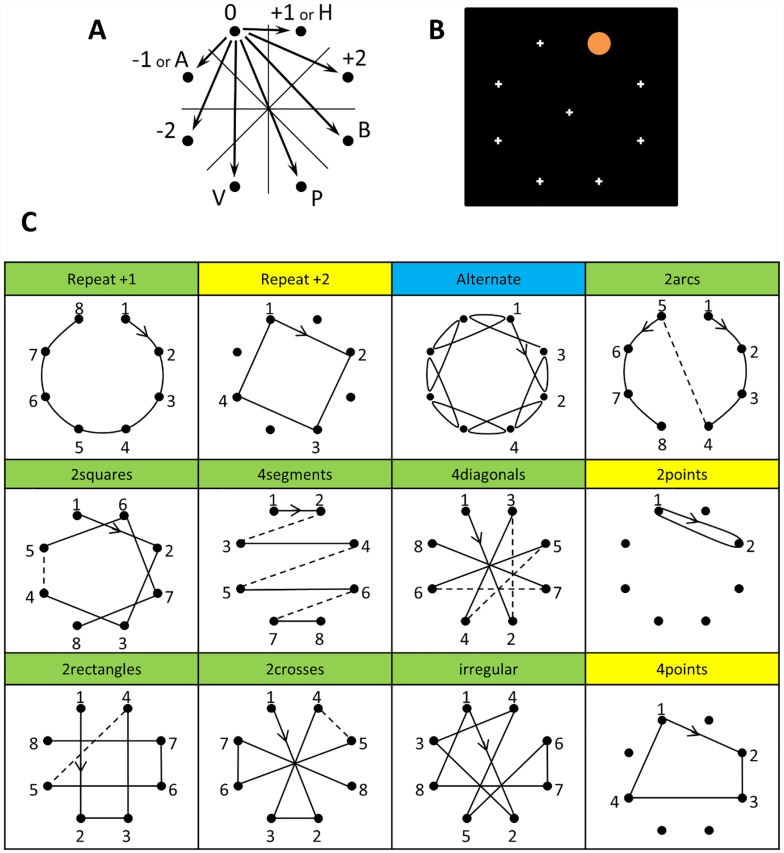
Turtle graphics — Generative model

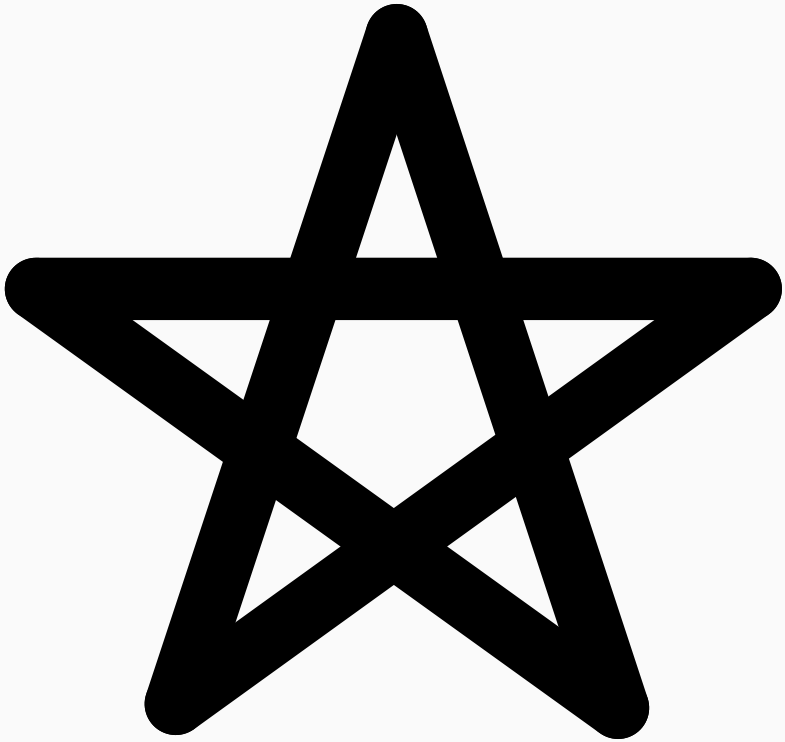


Turtle graphics — Generative model

Turtle graphics — Generative model

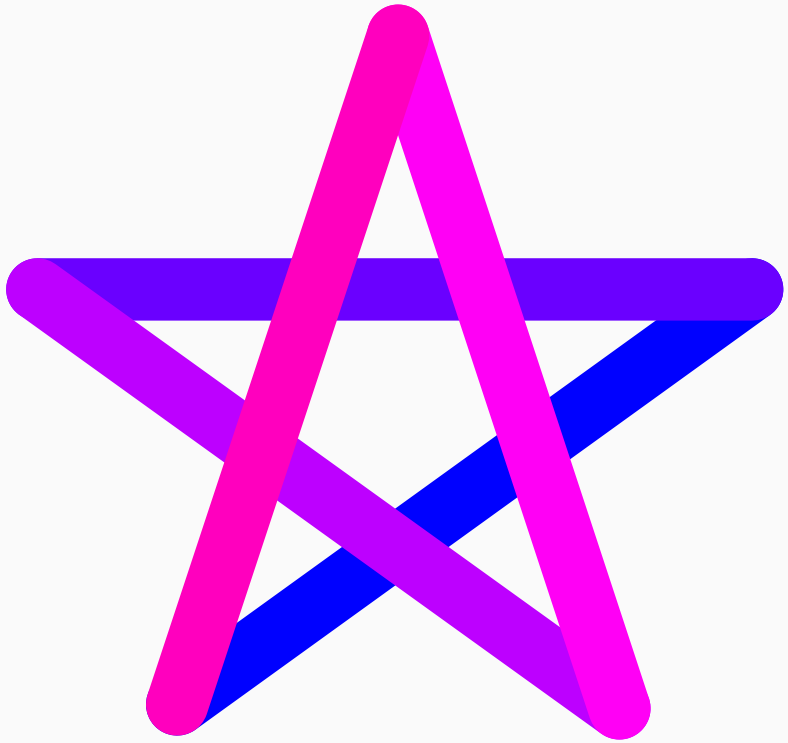
Turtle graphics — All the way down



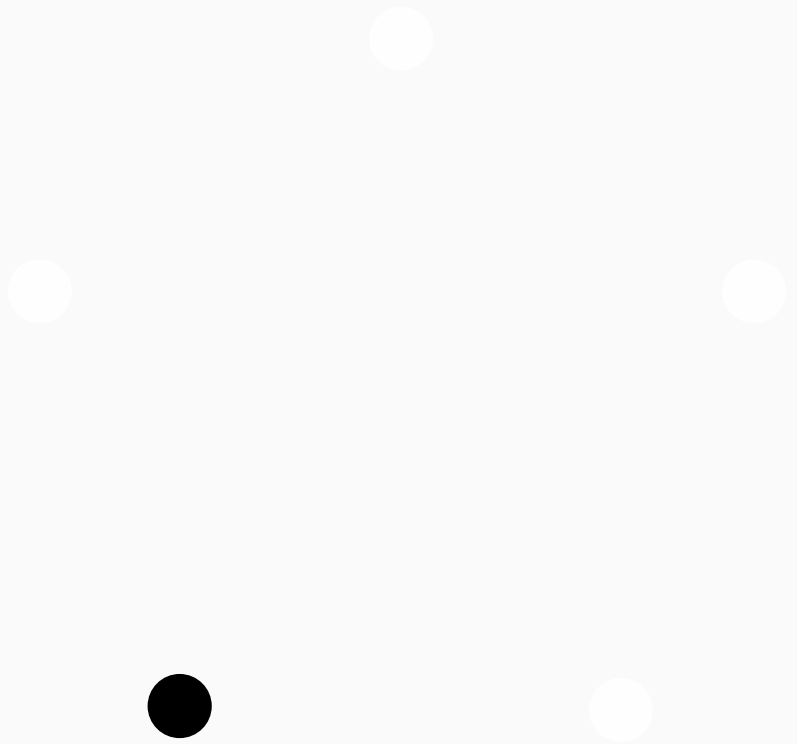


Marie Amalric, Stanislas Dehaene et al.

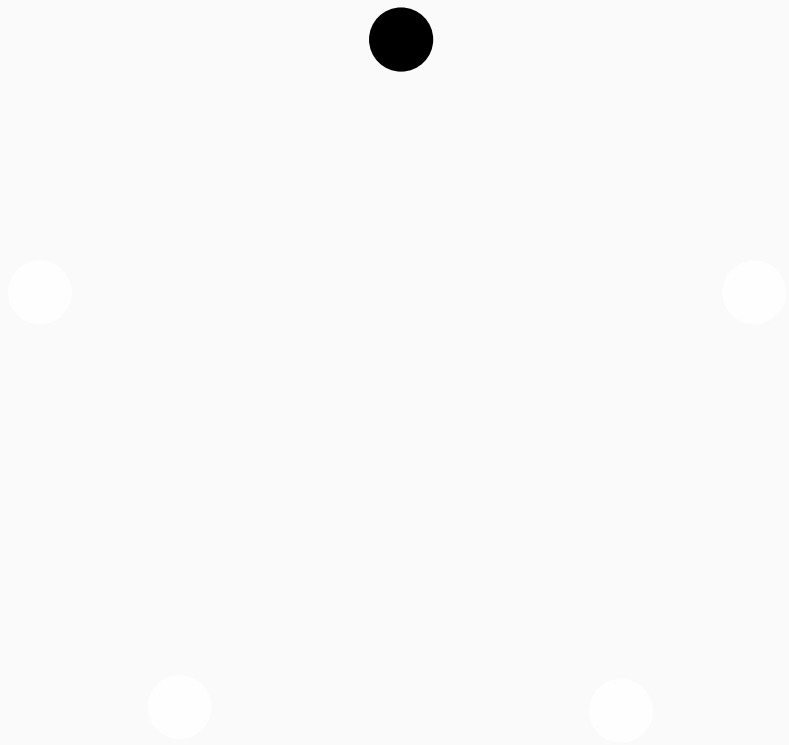
Turtle graphics — All the way down



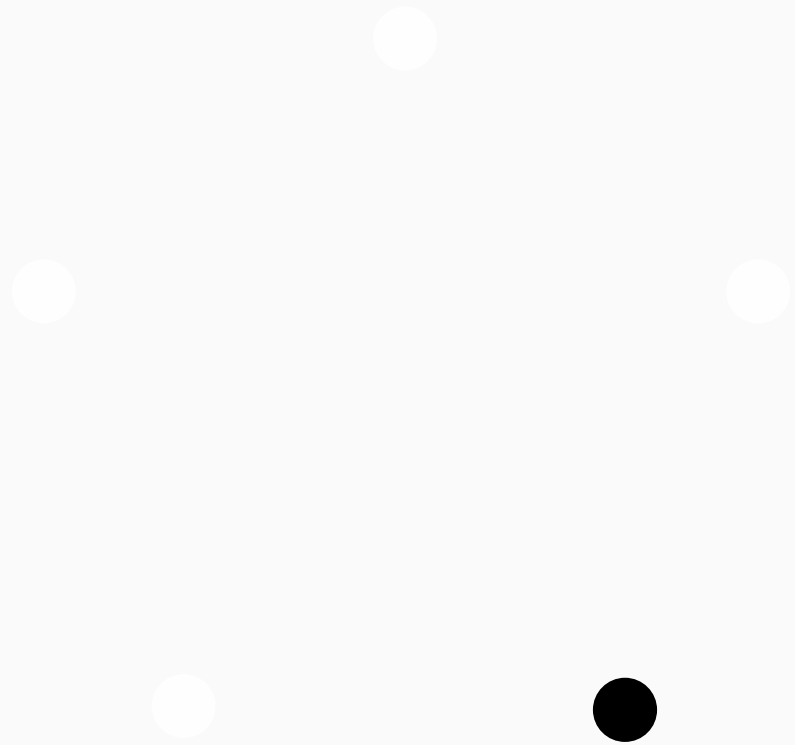
Turtle graphics — All the way down



Turtle graphics — All the way down



Turtle graphics — All the way down



Turtle graphics — All the way down

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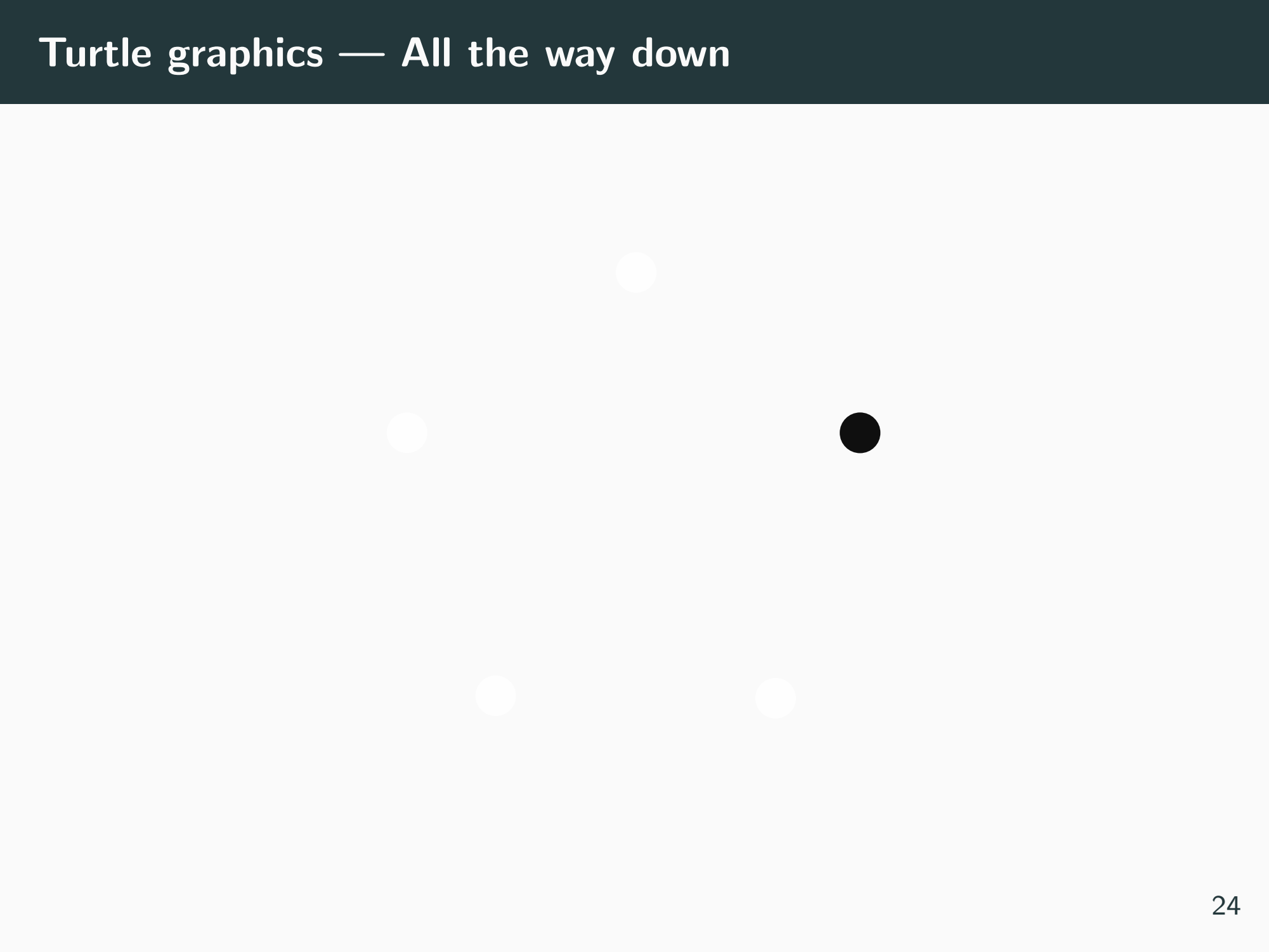
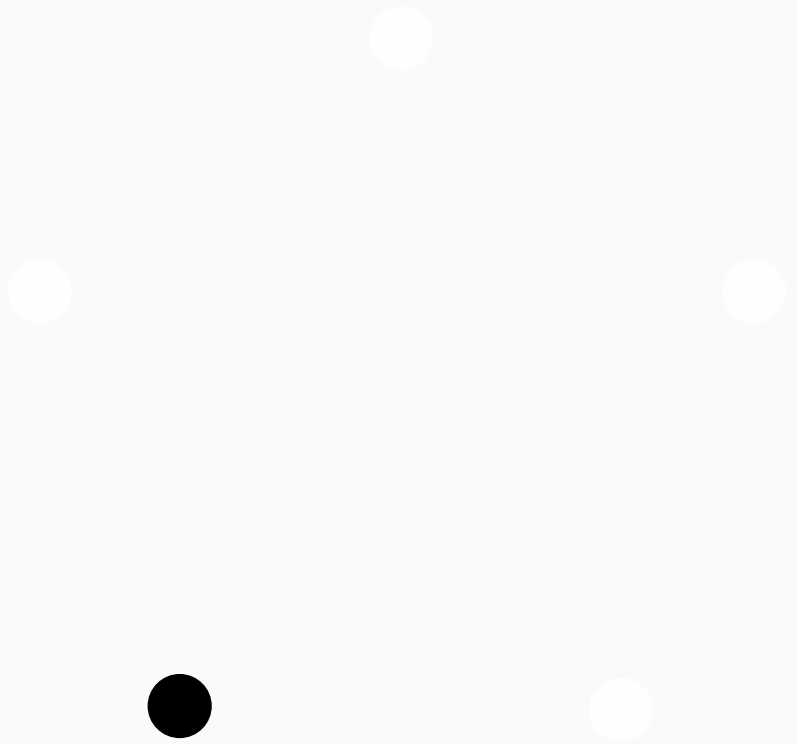
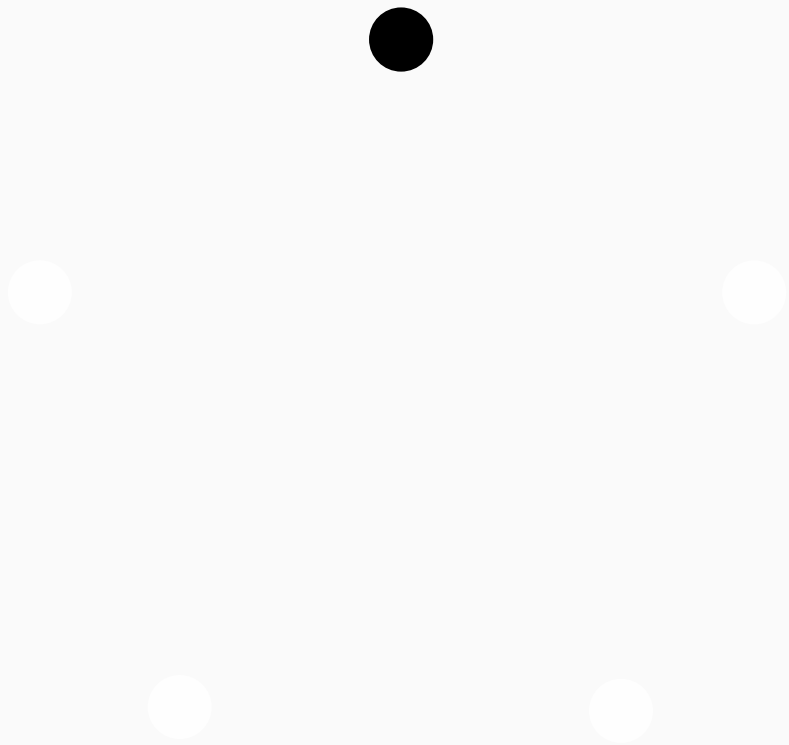


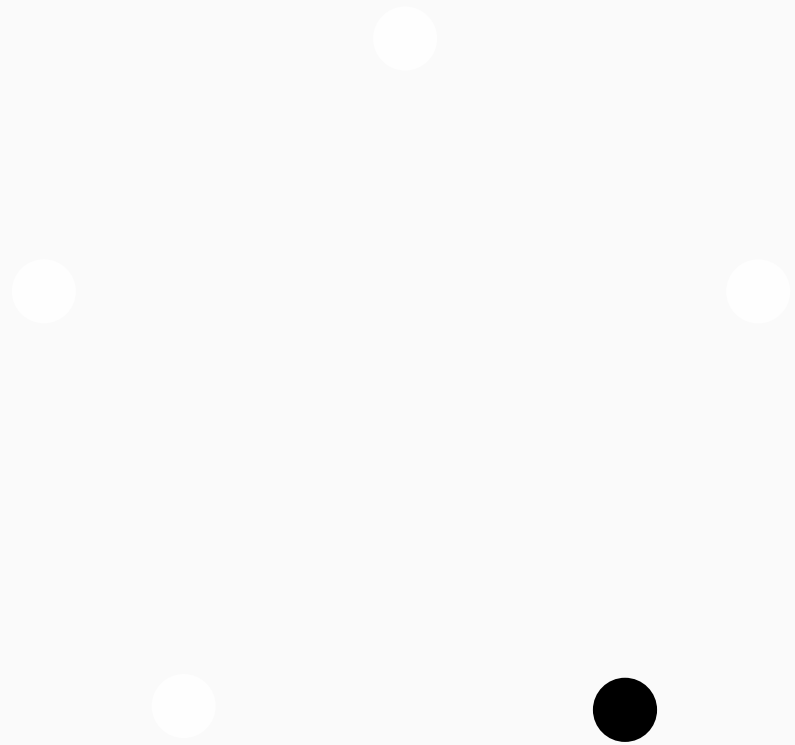
Turtle graphics — All the way down



Turtle graphics — All the way down



Turtle graphics — All the way down



Turtle graphics — All the way down

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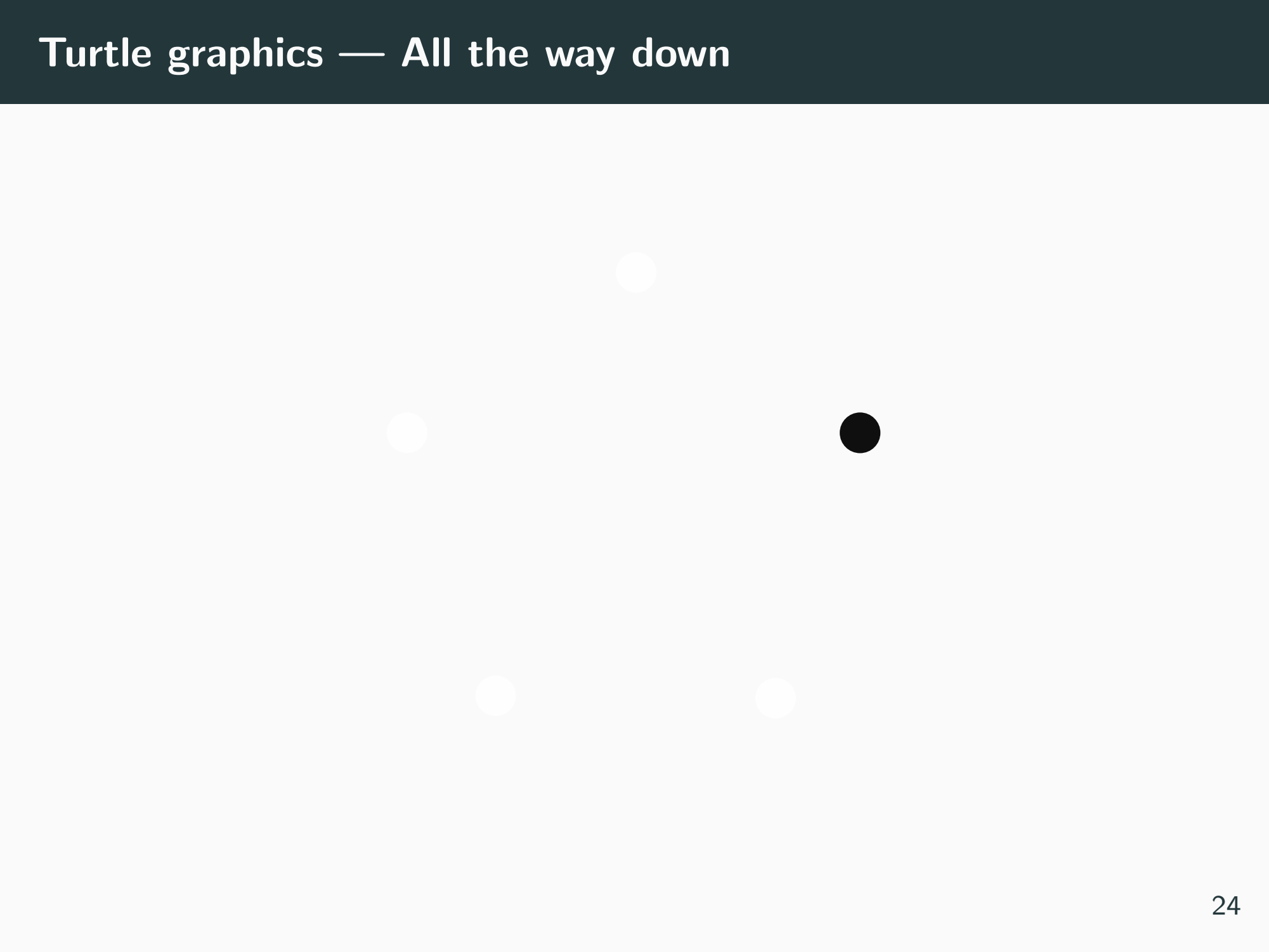
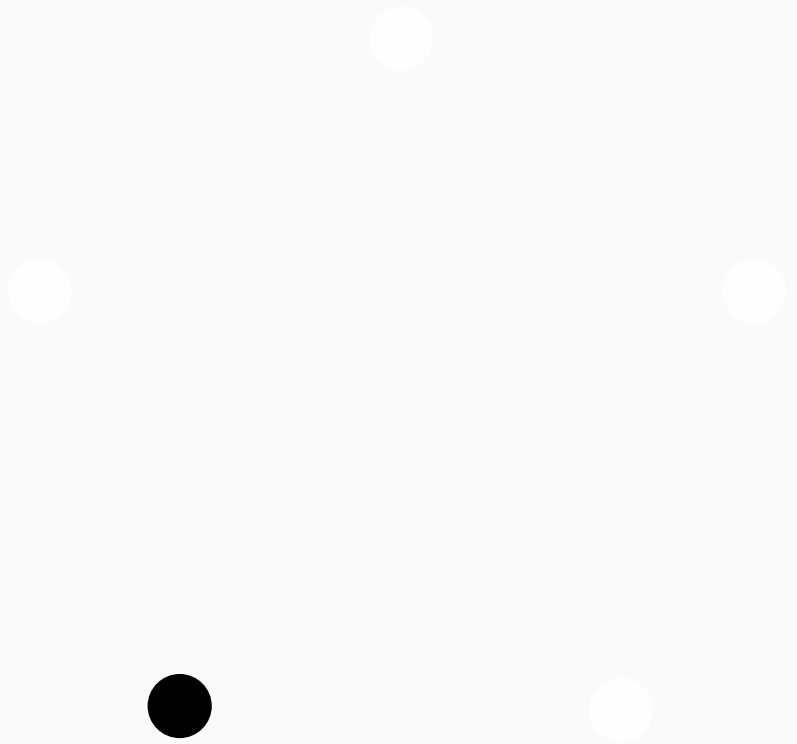


Turtle graphics — All the way down



Turtle graphics — All the way down

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Vision

More human-like machine intelligence:

Flexibly adapting to new problem domains by acquiring a domain-specific language-of-thought (DSL), while jointly learning how to use the language of thought (recognition model)

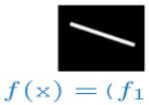
Vision

More human-like machine intelligence:

Flexibly adapting to new problem domains by acquiring a domain-specific language-of-thought (DSL), while jointly learning how to use the language of thought (recognition model)

```
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)
```

Symbolic Regression



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

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

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

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

```
f0(x) = (+ x real)
f1(x) = (f0 (* real x))
f2(x) = (f1 (* x (f0 x)))
f3(x) = (f0 (* x (f2 x)))
f4(x) = (f0 (* x (f3 x)))
  (f4: 4th order polynomial)
f5(x) = (/ real x)
f6(x) = (f5 (f0 x))
  (f6: rational function)
```