Learning to Infer Graphics Programs from Hand-Drawn Images

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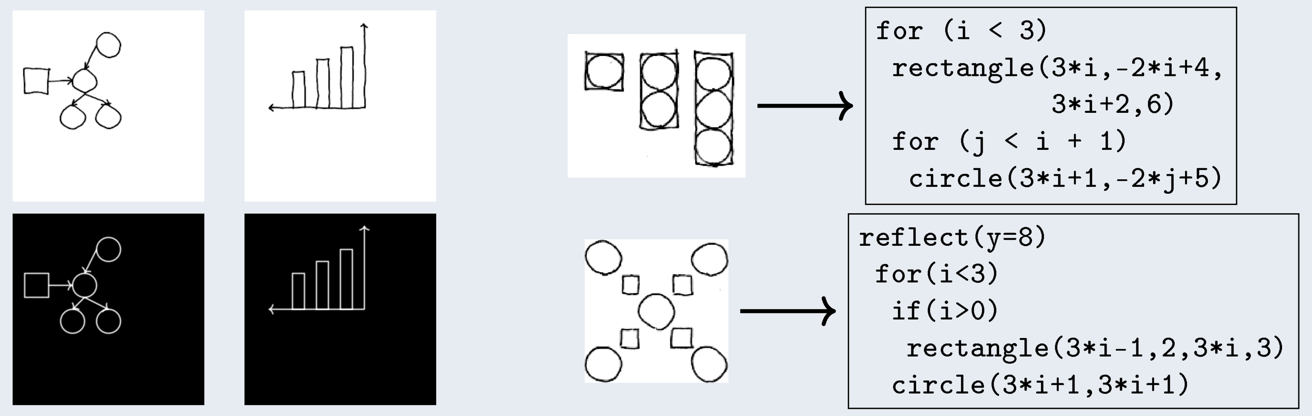
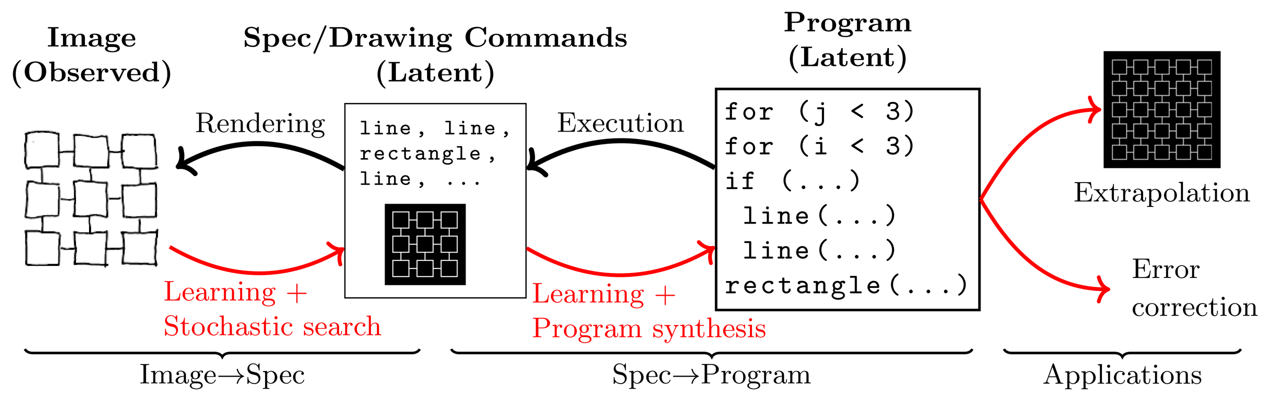
Hand drawings to high-level graphics procedures

Convert image of hand drawing into LaTeX (left pair: top white is drawing, bottom black is LaTeX render). Infer high-level graphics program from drawing: captures higher-order structure like repetition, motifs, symmetries.

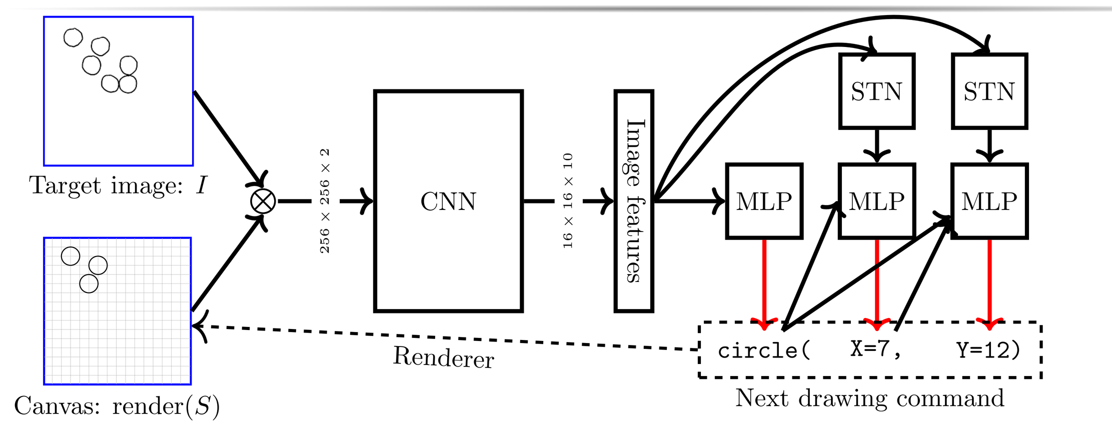


Two-Stage Pipeline

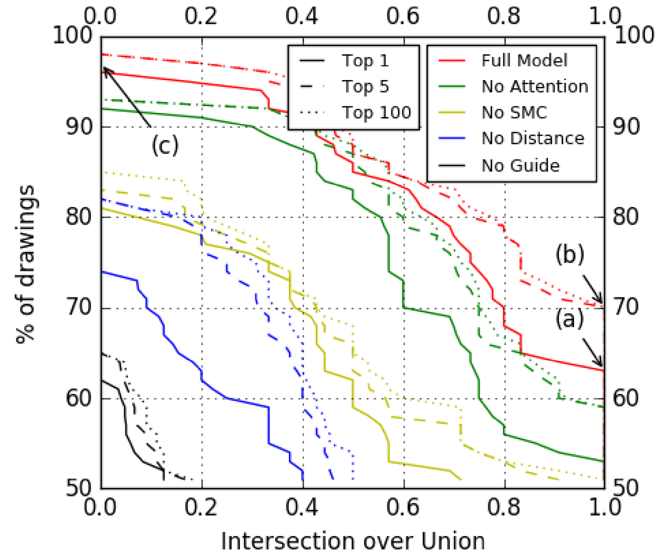


Black arrows: Top–down generative model; Program→Spec→Image. Red arrows: Bottom–up inference procedure. **Bold:** Random variables (image/spec/program)

Parsing Images into Drawing Commands (specs)



Blue: network inputs. Black: network operations. Red: draws from a multinomial. `Typewriter font`: network outputs. Renders on a 16×16 grid, shown in gray. STN: differentiable attention mechanism. **Combined with stochastic search (Sequential Monte Carlo)**



(Left) NN outputs vs ground truth on hand drawings (measured by IoU), as we consider larger sets of samples (1, 5, 100). (a) for 63% of drawings the model's top prediction is exactly correct; (b) for 70% of drawings the ground truth is in the top 5 model predictions; (c) for 4% of drawings all of the model outputs have no overlap with the ground truth. Red: the full model. Other colors: ablations. Model is at ceiling for synthetic LaTeX output.

Domain-Specific Language for Graphics Programs

We allow loops (`for`) with conditionals (`if`), vertical/horizontal reflections (`reflect`), variables (Var) and affine transformations ($\mathbb{Z}\times$Var+$\mathbb{Z}$).

Program→	Statement; $\cdots$; Statement
Statement→	`circle`(Expression,Expression)
Statement→	`rectangle`(Expression,Expression,Expression,Expression)
Statement→	`line`(Expression,Expression,Expression,Expression,Boolean,Boolean)
Statement→	`for`($0 \leq$ Var $<$ Expression) `{ if` (Var > 0) `{` Program `};` Program `}`
Statement→	`reflect`(Axis) `{` Program `}`
Expression→	$\mathbb{Z}\times$Var+$\mathbb{Z}$
Axis→	`X =` $\mathbb{Z}$ | `Y =` $\mathbb{Z}$
$\mathbb{Z}$ →	an integer

Learning & Constraint-Based Program Synthesis

Sketch: state-of-the-art program synthesizer. Solar-Lezama 2008.
Solves, for spec S & program p:

$$\text{program}(S) = \underset{p\in\text{DSL, s.t. } p \text{ consistent w/ } S}{\arg\min} \text{cost}(p)$$

Learn policy π_θ to accelerate program synthesizer's search.
$\pi_\theta(\cdot|S) \in \Delta^\Sigma$, where $\Sigma \ni \sigma$ a set of synthesis problem (i.e., $\sigma \in \Sigma$ is a sketch)
Inference strategy: Timeshare according to $\pi_\theta(\cdot|S)$, like in Levin Search

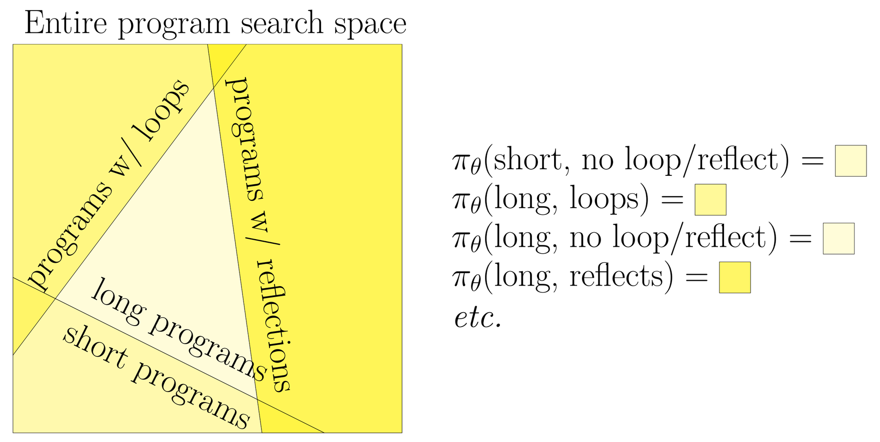
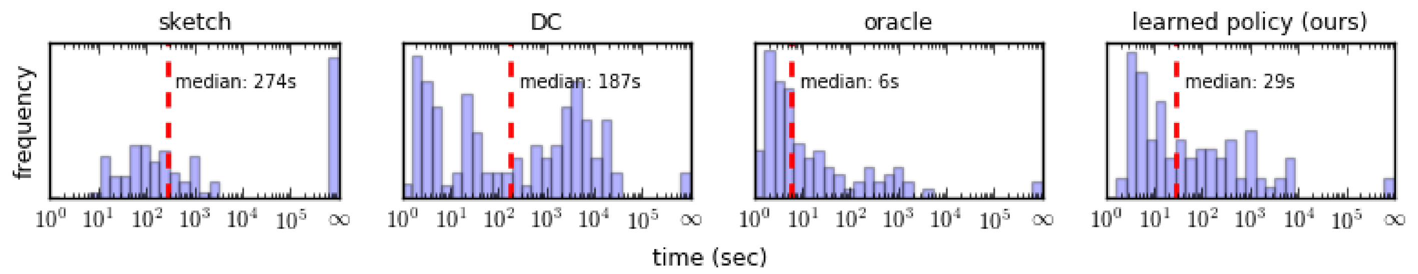


Figure 1: The bias-optimal search algorithm divides the entire (intractable) program search space in to (tractable) program subspaces (written σ), each of which contains a restricted set of programs. For example, one subspace might be short programs which don't loop. The policy π predicts a distribution over program subspaces: weight assigned by π indicated by shading

Differentiable loss ($\mathcal{D}$ a corpus of synthesis problems):

$$\textsc{Loss}(\theta;\mathcal{D}) = \mathbb{E}_{S\sim\mathcal{D}}\left[\min_{\sigma\in\textsc{Best}(S)} \frac{t(\sigma|S)}{\pi_\theta(\sigma|S)}\right] + \lambda\|\theta\|_2^2 \tag{1}$$

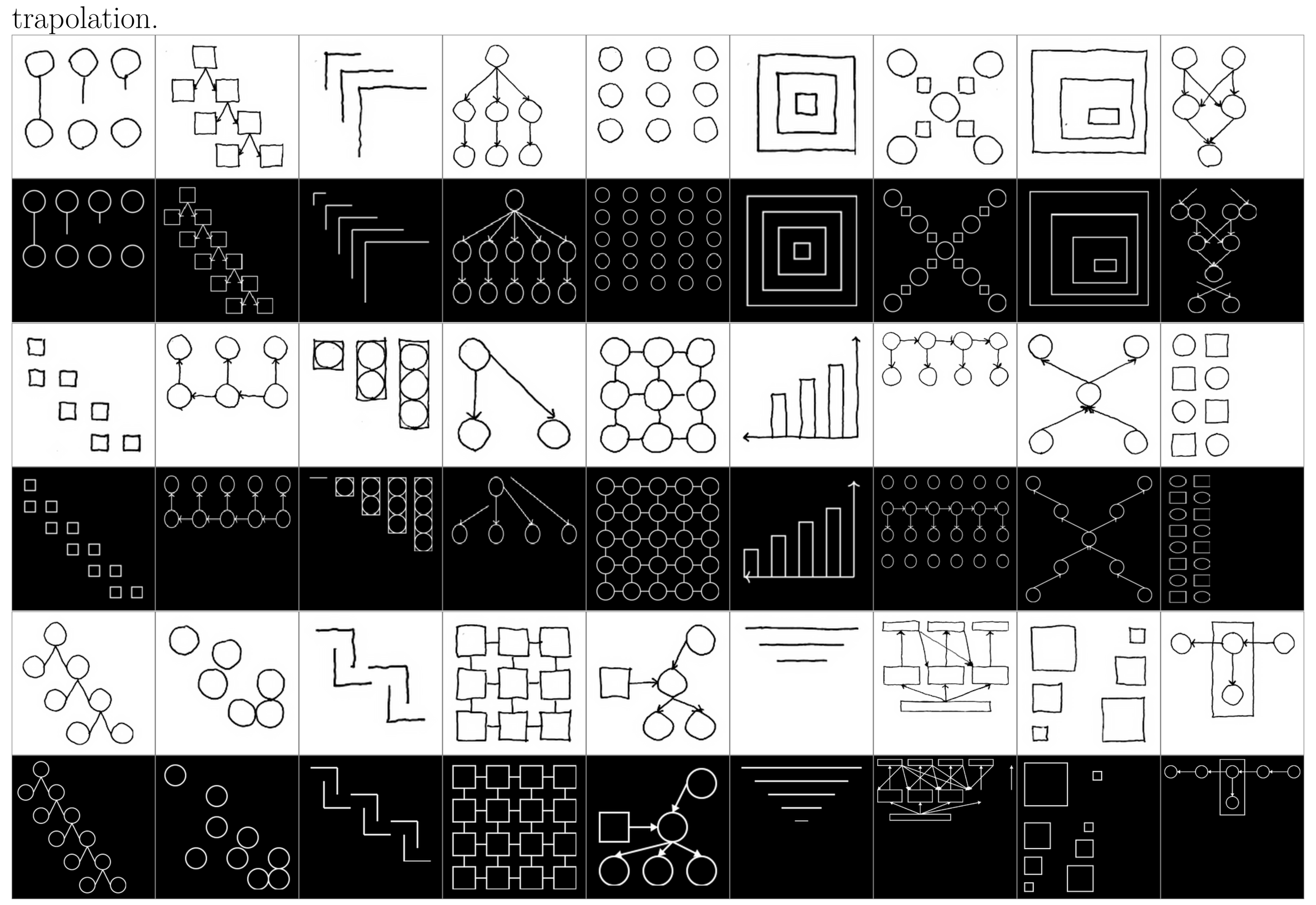
where $\sigma \in \textsc{Best}(S)$ if a minimum cost program for S is in σ.



Time to synthesize a minimum cost program. Sketch: out-of-the-box performance of Sketch. DC: Deep–Coder style baseline that predicts program components, trained like Balog 2016. Oracle: upper bounds the performance of any bias–optimal search policy. ∞ = timeout. Red dashed line is median time

Extrapolating Drawings

Automatically extrapolate by increasing loop bounds. Top white: Hand drawing. Bottom black: extrapolation.



Error correction

'Top down' influences upon perception: reasoning engine (program synthesizer) can influence agent's percept through higher-level considerations like symmetry and alignment.

$$\hat{S}(I) = \underset{S\in\mathcal{F}(I)}{\arg\max}\, L_{\text{learned}}(I|\text{render}(S)) \times \mathbb{P}_\theta[S|I] \times \mathbb{P}_\beta[\text{program}(S)]$$

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

where $\mathcal{F}(I)$ is set of parses output by neural net on image I; $\mathbb{P}_\beta[\cdot]$ is prior over programs parameterized by β; and expectation is taken over a corpus of program synthesis problems.

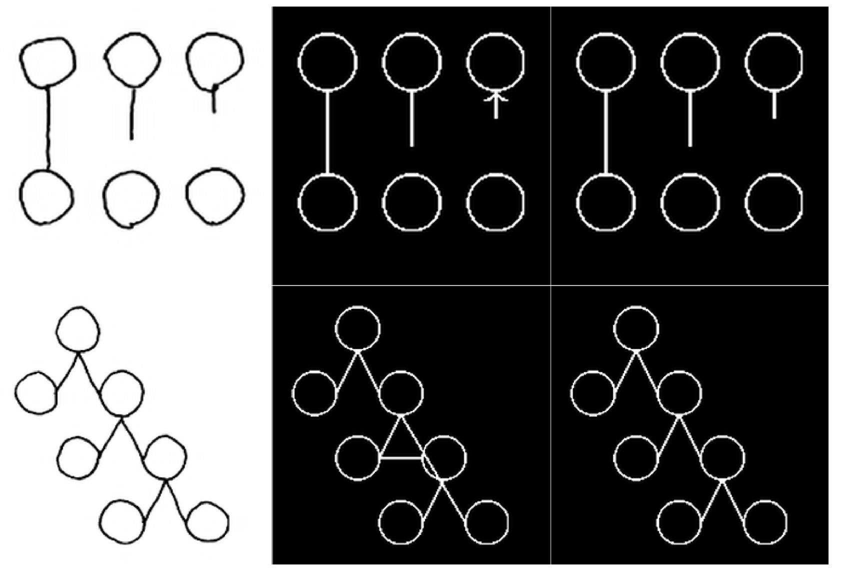
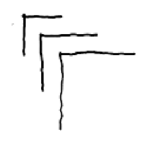
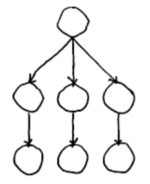
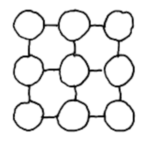
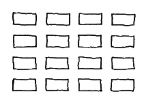
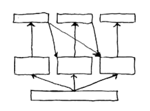
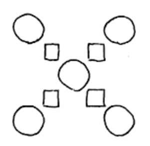


Figure 2: Left: hand drawings. Center: interpretations favored by the deep network. Right: interpretations favored after learning a prior over programs. The prior favors simpler programs, thus (top) continuing the pattern of not having an arrow is preferred, or (bottom) continuing the "binary search tree" is preferred.

Example System Outputs

Drawing	Spec	Program	Compression factor
	`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)`	$\frac{6}{3} = 2$x
	`Line(5,13,2,10,arrow)` `Circle(5,9)` `Circle(8,5)` `Line(2,8, 2,6,arrow)` `Circle(2,5)` *... etc. ...; 13 lines*	`circle(4,10)` `for(i<3)` ` circle(-3*i+7,5)` ` circle(-3*i+7,1)` ` line(-3*i+7,4,-3*i+7,2,arrow)` ` line(4,9,-3*i+7,6,arrow)`	$\frac{13}{6} = 2.2$x
	`Circle(5,8)` `Circle(2,8)` `Circle(8,11)` `Line(2,9, 2,10)` `Circle(8,8)` `Line(3,8, 4,8)` `Line(3,11, 4,11)` *... etc. ...; 21 lines*	`for(i<3)` ` for(j<3)` `  if(j>0)` `   line(-3*j+8,-3*i+7,` `        -3*j+9,-3*i+7)` `   line(-3*i+7,-3*j+8,` `        -3*i+7,-3*j+9)` `  circle(-3*j+7,-3*i+7)`	$\frac{21}{6} = 3.5$x
	`Rectangle(1,10,3,11)` `Rectangle(1,12,3,13)` `Rectangle(4,8,6,9)` `Rectangle(4,10,6,11)` *... etc. ...; 16 lines*	`for(i<4)` ` for(j<4)` `  rectangle(-3*i+9,-2*j+6,` `            -3*i+11,-2*j+7)`	$\frac{16}{3} = 5.3$x
	`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)`	$\frac{16}{9} = 1.8$x
	`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)`	$\frac{9}{5} = 1.8$x