Low-Rank Constraints for Fast Inference in Structured Models

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Structured Models

- ► Explicitly model output associations

  - ► Directly or through latent variables

- ► Focus on combinatorially large latent <u>discrete structures</u>

  - ► Complementary to continuous, distributed representations

Scaling Structured Models

- Prior work demonstrated: Size 🔼 Performance 🔼
  - Hidden Markov Models (HMM)
  - Probabilistic Context-Free Grammars (PCFG)

- Prior work scaled via
  - Sparsity for HMMs[1]
  - Low-rank tensor decompositions for PCFGs[2]

- This work: low-rank matrix constraints
  - More general
  - Less speedup

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[1]Chiu and Rush, *Scaling Hidden Markov Language Models*.
[2]Yang, Zhao, and Tu, 'PCFGs Can Do Better: Inducing Probabilistic Context-Free Grammars with Many Symbols'.

Inference as Matrix-Vector Products

- ▶ Inference: sequence of matrix-vector products

- ▶ Speed up via fast matvec methods

- ▶ Applies to a large family of structured models

Fast Matrix-Vector Products

▶ Matvecs take $O(L^2)$ computation

▶ Various fast methods
  ▶ Sparsity (nnz entries)
  ▶ Fast Fourier Transform ($L \log L$)
  ▶ Low-Rank factorization (LR)

▶ Connected to efficient attention and kernel approximations[3]

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[3]Choromanski et al., *Rethinking Attention with Performers*; Peng et al., *Random Feature Attention*; Blanc and Rendle, *Adaptive Sampled Softmax with Kernel Based Sampling*.
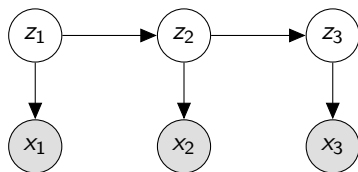
Roadmap

- ▶ Inference in HMMs and PCFGs as matvecs

- ▶ Low-rank matvec inference

- ▶ Generalization to hypergraph inference

- ▶ Experiments

Inference as Matvecs

Hidden Markov Models (HMMs)

For times t, model states $z_t \in [L] = \mathcal{L}$, and tokens $x_t \in [X] = \mathcal{X}$,

with joint distribution

$$p(x, z) = \prod_t p(x_t \mid z_t) p(z_t \mid z_{t-1})$$

Inference in HMMs

Given observed $x = (x_1, \ldots, x_T)$, we wish to maximize

$$p(x) = \sum_{z_1} \cdots \sum_{z_T} p(x, z) = \mathbf{1}^\top \Psi_1 \Psi_2 \cdots \Psi_T \mathbf{1},$$

where

$$[\Psi_t]_{z_t, z_{t+1}} = p(z_{t+1}, x_t \mid z_t)$$
$$[\Psi_1]_{z_1, z_2} = p(z_2, x_1 \mid z_1) p(z_1)$$

Matvec Inference in HMMs

Algorithm HMM Inference

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    for $t \leftarrow (t+1)$ in right-to-left order **do**

        $\beta_t \overset{+}{\leftarrow} \Psi_t \beta_{t+1}$

    return $\beta_0^\top \mathbf{1}$

Probabilistic Context-Free Grammars (PCFG)

A context-free grammar $\mathcal{G} = (\mathcal{L}, \mathcal{R})$ where

$$\mathcal{L}: \text{Label symbols}; \qquad \mathcal{X}: \text{Tokens}; \qquad \mathcal{R}: \text{Rules},$$

where rules take the form

$$
\begin{aligned}
A &\rightarrow B\ C, & A, B, C \in \mathcal{L} \\
P &\rightarrow x, & P \in \mathcal{L}, x \in \mathcal{X}
\end{aligned}
$$

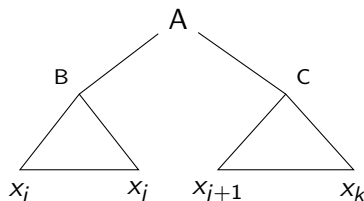In a PCFG, each rule has probability mass

$$p(r) = p(B, C \mid A)$$

The joint distribution over rules in a tree t

$$p(t) = \prod_{r \in t} p(r)$$

Inference in PCFGs

- For a given observation x, compute $p(x) = \sum_{t:\text{yield}(t)=x} p(t)$ via dynamic programming

- For each span (i, k), sum over split point $j \in (i, k)$:

- Similar to HMMs, define

$$[\Psi]_{z_u,(z_1,z_2)} = p(B = z_1, C = z_2 \mid A = z_u),$$

for each rule

Matvec Inference in PCFGs

Algorithm PCFG Inference

$\quad$ **for** $(i, k) \leftarrow (i, j), (j, k)$ in span-size order **do**
$\quad\quad$ **for** $z_1, z_2 \in \mathcal{L}_{i,j} \times \mathcal{L}_{j,k}$ **do**
$\quad\quad\quad$ $[\beta_{i,j,k}]_{(z_1, z_2)} = [\alpha_{i,j}]_{z_1} [\alpha_{j,k}]_{z_2}$
$\quad\quad$ $\alpha_{i,k} \overset{+}{\leftarrow} \Psi_{i,j,k} \beta_{i,j,k}$
$\quad$ **return** $\alpha_{1,T}^{\top} \mathbf{1}$

Speeding Up Inference

Low-Rank Factorization

▶ Factor matrices $\Psi \in \mathbb{R}^{L \times L}$ into product of $U, V \in \mathbb{R}^{L \times R}$

$$\boxed{\Psi} \times \boxed{\beta} = \boxed{U} \times \left(\boxed{V^\top} \times \boxed{\beta} \right)$$

▶ Two matrix-vector products of cost $O(LR)$ each

▶ Also holds for rectangular Ψ

Expressiveness and Generality

- Rank constraints limit expressivity

- Replace $\Psi = UV^\top$ for a subset of parameter matrices

  - Transition matrix for HMMs

  - Subset of the transition matrix for PCFGs

- An L-state HMM with rank R $(< L)$ is more expressive than an R-state HMM

- What other models does this work for?

Hypergraph Marginalization

▶ Models where exact inference is a directed acyclic hypergraph

▶ Hypergraph contains a node set and hyperedge set
  ▶ Nodes have label set $\mathcal{L}$
  ▶ Hyperedges join a single head node u and a list of tail nodes v
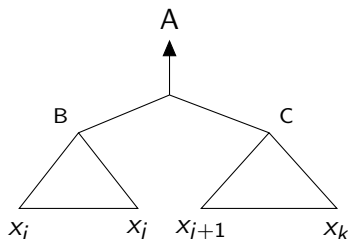
Hyperedge representations for HMMs and PCFGs

Hypergraph Marginalization Algorithms

Algorithm Hypergraph marginalization

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  for $u \leftarrow v$ hyperedge e topologically **do**

    $\beta_v \leftarrow \alpha_{v_1} \alpha_{v_2}^\top$ $\triangleright\ O(L^{|e|})$

    $\alpha_u \overset{+}{\leftarrow} \Psi_e \beta_v$ $\triangleright\ O(L^{|e|+1})$

  return $\alpha_S^\top \mathbf{1}$

Algorithm Low-rank marginalization

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  for $u \leftarrow v_1, v_2$ hyperedge e topologically **do**

    $\beta_v \leftarrow \alpha_{v_1} \alpha_{v_2}^\top$ $\triangleright\ O(L^{|e|})$

    $\gamma \leftarrow V_e^\top \beta_v$ $\triangleright\ O(L^{|e|} R)$

    $\alpha_u \overset{+}{\leftarrow} U_e \gamma$ $\triangleright\ O(LR)$

  return $\alpha_S^\top \mathbf{1}$
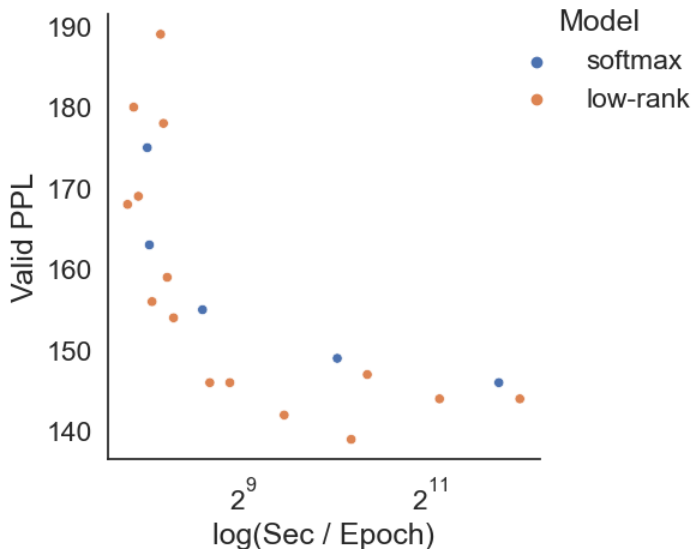

Experiments

Experiments

- ▶ Compare speed vs accuracy frontier

- ▶ Language modeling on Penn Treebank[4]

  - ▶ Softmax HMM and PCFG vs low-rank versions (LHMM, LPCFG)
  - ▶ Evaluate accuracy with perplexity, a function of likelihood

- ▶ Video modeling on CrossTask[5]

  - ▶ Softmax HSMM vs low-rank HSMM
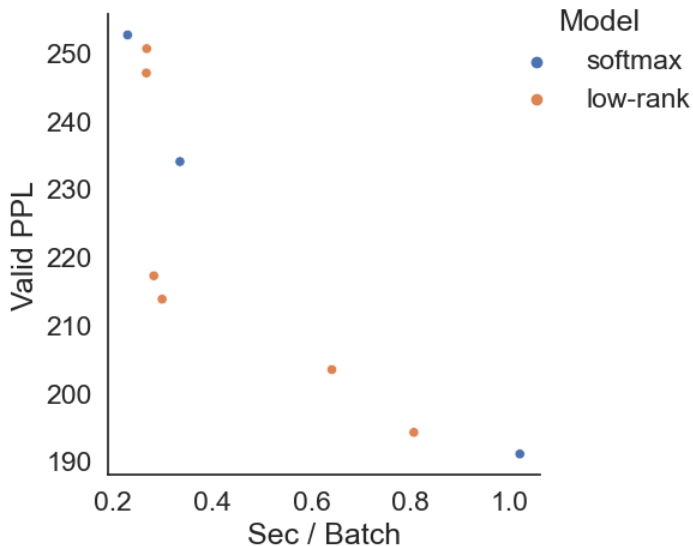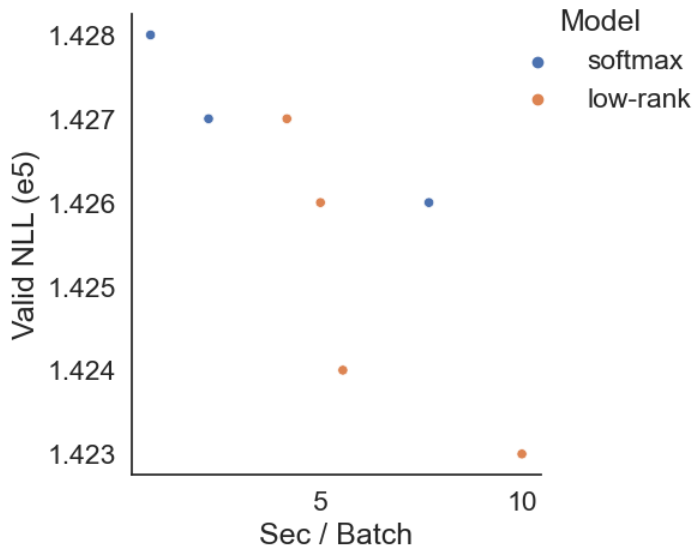 - ▶ Evaluate accuracy with negative log-likelihood

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[4].

[5].

HMM Speed vs Accuracy

PCFG Speed vs Accuracy

HSMM Speed vs Accuracy

HMM Music Results

Model	Nott	Piano	Muse	JSB
RNN-NADE	2.31	**7.05**	**5.6**	5.19
R-Transformer	**2.24**	7.44	7.00	8.26
LSTM	3.43	7.77	7.23	8.17
LV-RNN	2.72	7.61	6.89	**3.99**
SRNN	2.94	8.20	6.28	4.74
TSBN	3.67	7.89	6.81	7.48
HMM	2.43	8.51	7.34	5.74
LHMM	2.60	8.89	7.60	5.80

Citations

📄 Blanc, Guy and Steffen Rendle. *Adaptive Sampled Softmax with Kernel Based Sampling*. 2018. arXiv: 1712.00527 [cs.LG].

📄 Chiu, Justin T. and Alexander M. Rush. *Scaling Hidden Markov Language Models*. 2020. arXiv: 2011.04640 [cs.CL].

📄 Choromanski, Krzysztof et al. *Rethinking Attention with Performers*. 2021. arXiv: 2009.14794 [cs.LG].

📄 Peng, Hao et al. *Random Feature Attention*. 2021. arXiv: 2103.02143 [cs.CL].

📄 Yang, Songlin, Yanpeng Zhao, and Kewei Tu. 'PCFGs Can Do Better: Inducing Probabilistic Context-Free Grammars with Many Symbols'. In: *CoRR* abs/2104.13727 (2021). arXiv: 2104.13727. URL: https://arxiv.org/abs/2104.13727.