Optimizations and Extensions for Weighted CFG Parsers

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2021-06-21

Outline

Pruning

- Pruning for CKY parsing
- Pruning for deductive parsing

k-best parsing

A*-parsing

Pruning

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- During CKY or deductive parsing many items are explored which are not part of the best derivation
- Idea: avoid items that are not part of the best derivation to speed up parsing
- Problem: How can we know these items in advance?
- Practical solution: Use simple methods but take the risk of finding suboptimal derivation.

Pruning for CKY parsing

Consider this slightly modified (red) version of the CKY algorithm:

Require: weighted binary cfg (N, Σ, P, S, μ), word $t_1 \dots t_n$ where $t_1, \dots, t_n \in \Sigma$
Ensure: family $(c_{i,j,A} \in \mathbb{R} \mid 0 \le i < j \le n, A \in N)$ such that, for all i, j, A,
$c_{i,j,A} = \max\{\mu(d) \mid d \in D_G^A(t_{i+1} \dots t_j)\} \cup \{0\}$

function $\text{CKY}(P,\ \mu,\ t_1 \dots t_n)$
  $(c_{i,j,A} := 0 \mid 0 \le i < j \le n, A \in N)$
  for $1 \le i \le n$ **do**
    for $A \to t_i \in P$ **do**
      $c_{i-1,i,A} := \max\{c_{i-1,i,A}, \mu(A \to t_i)\}$
  for $2 \le r \le n$ **do**
    for $0 \le i \le n - r$ **do**
      $j := i + r$
      for $m \in \{i+1, i+2, \dots, j-1\}$ **do**
        for $B, C \in N$ **do**
          for $A \in N$ such that $A \to BC \in R$ **do**
            $c_{i,j,A} := \max\{c_{i,j,A}, \mu(A \to BC) \cdot c_{i,m,B} \cdot c_{m,j,C}\}$
  return c

Pruning for CKY parsing

An abstract "pruning operation" on the chart can be included (lines 6, 15).
We speed up the algorithm by skipping the application of cfg rules to chart cells with 0 probability (line 12).

Require: weighted binary cfg (N, Σ, P, S, μ), word $t_1 \dots t_n$ where $t_1, \dots, t_n \in \Sigma$
Ensure: family $(c_{i,j,A} \in \mathbb{R} \mid 0 \leq i < j \leq n, A \in N)$ such that, for all i, j, A, $c_{i,j,A} \leq \max\{\mu(d) \mid d \in D_G^A(t_{i+1} \dots t_j)\} \cup \{0\}$

1: **function** $\textsc{CKY}(P,\ \mu,\ t_1 \dots t_n)$
2: $\quad (c_{i,j,A} := 0 \mid 0 \leq i < j \leq n, A \in N)$
3: $\quad$ **for** $1 \leq i \leq n$ **do**
4: $\quad\quad$ **for** $A \to t_i \in P$ **do**
5: $\quad\quad\quad c_{i-1,i,A} := \max\{c_{i-1,i,A}, \mu(A \to t_i)\}$
6: $\quad\quad (c_{i-1,i,A} \mid A \in N) := \mathrm{prune}((c_{i-1,i,A} \mid A \in N))$
7: $\quad$ **for** $2 \leq r \leq n$ **do**
8: $\quad\quad$ **for** $0 \leq i \leq n - r$ **do**
9: $\quad\quad\quad j := i + r$
10: $\quad\quad\quad$ **for** $m \in \{i+1, i+2, \dots, j-1\}$ **do**
11: $\quad\quad\quad\quad$ **for** $B, C \in N$ **do**
12: $\quad\quad\quad\quad\quad$ **if** $c_{i,m,B} = 0$ or $c_{m,j,C} = 0$ **then** continue
13: $\quad\quad\quad\quad\quad$ **for** $A \in N$ such that $A \to BC \in R$ **do**
14: $\quad\quad\quad\quad\quad\quad c_{i,j,A} := \max\{c_{i,j,A}, \mu(A \to BC) \cdot c_{i,m,B} \cdot c_{m,j,C}\}$
15: $\quad\quad\quad (c_{i,j,A} \mid A \in N) := \mathrm{prune}((c_{i,j,A} \mid A \in N))$
16: $\quad$ **return** c

Pruning for CKY parsing

How can the pruning operation be implemented?

- Threshold beam (set all cell probabilities to 0 if worse than $\theta \cdot$ best cell probability)

Require: family $c = (c_{i,j,A} \in \mathbb{R} \mid A \in N)$, threshold $\theta \in [0, 1]$
Ensure: family $(c_{i,j,A} \in \mathbb{R} \mid A \in N)$

function $\textsc{Prune}(c)$
  $m = \max_{A \in N}\{c_{i,j,A} \mid A \in N\}$
  for $A \in N$ **do**
    if $c_{i,j,A} < m \cdot \theta$ **then**
      $c_{i,j,A} := 0$
  return c

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      $m = \max_{A \in N}\{c_{i,j,A} \mid A \in N\}$
      for $A \in N$ **do**
          if $c_{i,j,A} < m \cdot \theta$ **then**
              $c_{i,j,A} := 0$
      return c

- Fixed-sized beam (set all but n best cell probabilities to 0)

  Require: family $c = (c_{i,j,A} \in \mathbb{R} \mid A \in N)$, size $1 \leq n \leq |N|$
  Ensure: family $(c_{i,j,A} \in \mathbb{R} \mid A \in N)$

  function $\textsc{Prune}(c)$
      $[s_1, \ldots, s_n] = n\text{-best}\{c_{i,j,A} \mid A \in N\}$
      for $A \in N$ **do**
          if $c_{i,j,A} < s_n$ **then**
              $c_{i,j,A} := 0$
      return c

$n\text{-best}(C)$ returns list of the n highest values in C in descending order

Pruning for CKY parsing– implementation considerations

- No changes to data structures required.
- More speed-ups might be obtained by not adding items to chart which for sure would later be pruned:
  - Threshold beam: store weight m of currently best item. If new item has weight m below $\theta \cdot m$, it is save to prune immediately.
  - Fixed-size beam: store weights of the n best items. If the weight of new is below of worst item, prune immediately.

Pruning for deductive parsing

Original algorithm for deductive parsing.

Require: weighted binary cfg (N, Σ, P, S, μ), word $t_1 \ldots t_n$ where $t_1, \ldots, t_n \in \Sigma$
Ensure: family $(c_{i,j,A} \colon \mathbb{R} \mid 0 \leq i < j \leq n, A \in N)$ such that
$c_{i,j,A} = \max\{\mu(d) \mid d \in D_G^A(t_{i+1} \ldots t_j)\} \cup \{0\}$

function $\textsc{deduce}(P,\ \mu,\ t_1 \ldots t_n)$
  $\mathit{queue} := \{(i-1, A, i, \mu(A \to t_i)) \mid 1 \leq i \leq n, A \to t_i \in P\}$
  $(c_{i,j,A} := 0 \mid 0 \leq i < j \leq n, A \in N)$
  while $\mathit{queue} \neq \varnothing$ **do**
    $(i, A, j, w) := \operatorname{argmax}_{(i,A,j,w) \in \mathit{queue}}\ w$
    $\mathit{queue} \setminus= \{(i, A, j, w)\}$
    if $c_{i,j,A} = 0$ **then**
      $c_{i,j,A} := w$
      $\mathit{queue} \cup= \{(i, A', j', \mu(A' \to AC) \cdot w \cdot c_{j,j',C}) \mid A' \to AC \in P\}$
      $\mathit{queue} \cup= \{(i', A', j, \mu(A' \to BA) \cdot c_{i',i,B} \cdot w) \mid A' \to BA \in P\}$
      $\mathit{queue} \cup= \{(i, A', j, \mu(A' \to A) \cdot w) \mid A' \to A \in P\}$
  return c

Pruning for deductive parsing

Pruning operation on queue is added.

Require: weighted binary cfg (N, Σ, P, S, μ), word $t_1 \dots t_n$ where $t_1, \dots, t_n \in \Sigma$
Ensure: family $(c_{i,j,A} \colon \mathbb{R} \mid 0 \le i < j \le n, A \in N)$ such that
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function $\textsc{deduce}(P,\ \mu,\ t_1 \dots t_n)$
  $queue := \{(i-1, A, i, \mu(A \to t_i)) \mid 1 \le i \le n, A \to t_i \in P\}$
  $(c_{i,j,A} := 0 \mid 0 \le i < j \le n, A \in N)$
  while $queue \ne \emptyset$ **do**
    $(i, A, j, w) := \operatorname{argmax}_{(i,A,j,w) \in queue}\ w$
    $queue \setminus= \{(i, A, j, w)\}$
    if $c_{i,j,A} = 0$ **then**
      $c_{i,j,A} := w$
      $queue \cup= \{(i, A', j', \mu(A' \to AC) \cdot w \cdot c_{j,j',C}) \mid A' \to AC \in P\}$
      $queue \cup= \{(i', A', j, \mu(A' \to BA) \cdot c_{i',i,B} \cdot w) \mid A' \to BA \in P\}$
      $queue \cup= \{(i, A', j, \mu(A' \to A) \cdot w) \mid A' \to A \in P\}$
      $\mathrm{prune}(queue)$
  return c

Pruning for deductive parsing

Again two options for pruning:

- Threshold beam (remove each queue item if its probability is worse than $\theta \cdot$ prob. of best queue item)

Require: set *queue* $\subseteq \mathbb{N} \times N \times \mathbb{N} \times \mathbb{R}$, threshold $\theta \in [0, 1]$
Ensure: set *queue*$'$ $\subseteq \mathbb{N} \times N \times \mathbb{N} \times \mathbb{R}$

1: **function** PRUNE(*queue*)
2: $\quad m = \max_{(i,A,j,w) \in queue} w$
3: $\quad$ **return** $\{(i, A, j, w) \in queue \mid w > \theta \cdot m\}$

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  function PRUNE($queue$)
  $m = \max_{(i,A,j,w) \in queue} w$
  return $\{(i,A,j,w) \in queue \mid w > \theta \cdot m\}$

- Fixed-sized beam (only keep the n most probable queue items)

  Require: set $queue \subseteq \mathbb{N} \times N \times \mathbb{N} \times \mathbb{R}$, size $n \in \mathbb{N}$
  Ensure: set $queue' \subseteq \mathbb{N} \times N \times \mathbb{N} \times \mathbb{R}$

  function PRUNE($queue$)
  $[i_1, \ldots, i_n] = n\text{-best}(queue)$ w.r.t. 4th tuple component
  return $\{i_1, \ldots, i_n\}$

Pruning for deductive parsing – implementation considerations

- Best implement queue as Min-max heap [Atk+86], because access to best and worst elements is required.

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- Beware: Items for large spans are often more probable than items for small spans. Risk of pruning "good" large items in favour of "bad" small items.

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  Each reading has a different parse tree.
- Solution: return multiple parse trees per sentence.

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  Each reading has a different parse tree.
- Solution: return multiple parse trees per sentence.
- Goal: given a sentence w, a PCFG G, and a positive integer k, find the k most probable derivations of G for w

k-best parsing – naïve algorithm

Similar to CKY algorithm. Uses functions:

- $\mathrm{sort}(c)$ – sorts a set c of tuples (according to 2nd component)
- $\mathrm{take}(k, \ell)$ – returns first k elements of list ℓ

Require: $k \in \mathbb{N}$, weighted binary CFG (N, Σ, S, R, μ), word $t_1 \cdots t_n$
Ensure: k most probable parse trees of PCFG for $t_1 \cdots t_n$

function $\textsc{kbest}(k,\ R,\ \mu,\ t_1, \ldots, t_n)$
  $b[i,j,A] := [\,]$ for each cell (i,j,A)
  for $i \in \{0, \ldots, n-1\}$ and $A \in N$ **do**
    $c := \{(A(t_{i+1}), w) \mid A \to t_{i+1} \text{ in } R, w = \mu(A \to t_{i+1})\}$
    $b[i, i+1, A] = \mathrm{take}(k, \mathrm{sort}(c))$
  for $z \in \{2, \ldots, n\}$ **do**
    for $i \in \{0, \ldots, n-z\}$ **do**
      $j := i + z$
      for $A \in N$ **do**
        $c := \{(A(d_1, d_2), w) \mid A \to BC \text{ in } R, m \in \{i+1, \ldots, j-1\},$
          $(d_1, w_1) \in b[i, m, B], (d_2, w_2) \in b[m, j, C],$
          $w = \mu(A \to BC) \cdot w_1 \cdot w_2\}$
        $b[i,j,A] = \mathrm{take}(k, \mathrm{sort}(c))$
  return $b[0, n, S]$

k-best parsing – implementation of merging

$$
\begin{aligned}
& c := \{(A(d_1, d_2), w) \mid A \to BC, m \in \{i+1, \ldots, j-1\}, \\
& \qquad (d_1, w_1) \in b[i, m, B], (d_2, w_2) \in b[m, j, C], \\
& \qquad w = \mu(A \to BC) \cdot w_1 \cdot w_2\} \\
& b[i, j, A] = \mathrm{take}(k, \mathrm{sort}(c))
\end{aligned}
$$

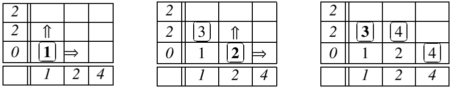
can be implemented as

$$
\begin{aligned}
& b[i, j, A] := [\,] \\
& \textbf{for } m \in \{i+1, \ldots, j-1\} \textbf{ do} \\
& \quad \textbf{for } A \to BC \text{ in } R \textbf{ do} \\
& \qquad c := \{(A(d_1, d_2), w) \mid (d_1, w_1) \in b[i, m, B], (d_2, w_2) \in b[m, j, C], \\
& \qquad\qquad w = \mu(A \to BC) \cdot w_1 \cdot w_2\} \\
& \qquad b[i, j, A] := \mathrm{mergeAndTakeK}(k, b[i, j, A], c)
\end{aligned}
$$

here $\mathrm{mergeAndTakeK}(k, \ell, c)$ returns the list of k-best items in the union of list ℓ and set c

k-best parsing – merging more efficiently [HC05]

- the set c can be computed lazily
  - avoid considering all k^2 items obtained by combining each of $b[i,m,B]$ with $b[m,j,C]$
  - instead, we only combine the best items of $b[i,m,B]$ with the best items of $b[m,j,C]$:
    - if the combination of the u-th best of $b[i,m,B]$ and v-th best of $b[m,j,C]$ was considered, then consider also the combinations $(u+1,v)$ and $(u,v+1)$



(a) (b) (c)

$b[i,j,A] := [\ ]$
for $m \in \{i+1,\dots,j-1\}$ **do**
  for $A \to BC$ in R **do**
    denote $w_{u,v} := \mu(A \to BC) \cdot w_u^1 \cdot w_v^2$ where
      $(d_u^1, w_u^1) := b[i,m,B][u]$ and
      $(d_v^2, w_v^2) := b[m,j,C][v]$
    $F := \{(1,1)\}$
    while $\max_{(u,v)\in F} w_{u,v} > \min_{(d,w)\in b[i,j,A]} w$ or $|b[i,j,A]| < k$ **do**
      $(u,v) = \operatorname{argmax}_{(u,v)\in F} w_{u,v}$
      $b[i,j,A] := \mathrm{insertAndTakeK}(k,\ \ b[i,j,A],\ \ \{(A(d_u^1,d_v^2), w_{u,v})\})$
      $F := (F \setminus \{(u,v)\}) \cup \{(u+1,v),(u,v+1)\}$

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- If future costs are taken into account, then maybe less items from the queue need to be processed.

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- Klein and Manning [KM03] propose several admissible heuristics.

- A heuristic may also be useful when pruning items during CKY parsing.

A*-parsing – Viterbi outside score

We use the admissible heuristic out:

$$\mathrm{out}(A) = \max_{d \in D_G, u,w \in \Sigma^* :\, S \overset{d}{\Rightarrow}_G uAw} \mathsf{weight}(d)$$

It can be computed by a variant of the inside/outside algorithm:

function INSIDE
  for $A \in N$ **do**
    $\mathrm{in}(A) := \max(\{\mu(A \to \alpha) \mid A \to \alpha \ \in R\} \cup \{0\})$
  while not converged **do**
    for $A \in N$ **do**
      $\mathrm{in}(A) = \max(\{\mathrm{in}(A)\} \cup \{\mu(A \to BC) \cdot \mathrm{in}(B) \cdot \mathrm{in}(C) \mid A \to BC \text{ in } R\}$
      $\cup \{\mu(A \to B) \cdot \mathrm{in}(B) \mid A \to B \text{ in } R\})$

function OUTSIDE
  set $\mathrm{out}(B) := \begin{cases} 1 & B = S \\ 0 & \text{otherwise} \end{cases}$ **for each** $B \in N$
  while not converged **do**
    for $B \in N$ **do**
      $\mathrm{out}(B) := \max(\{\mathrm{out}(B)\} \cup \{\mathrm{out}(A) \cdot \mu(A \to BC) \cdot \mathrm{in}(C) \mid A \to BC \text{ in } R\}$
      $\cup \{\mathrm{out}(A) \cdot \mu(A \to CB) \cdot \mathrm{in}(C) \mid A \to CB \text{ in } R\}$
      $\cup \{\mathrm{out}(A) \cdot \mu(A \to B) \mid A \to B \text{ in } R\})$

A*-parsing – parsing algorithm with heuristic

The out-value is now simply included when selecting the best item from the queue:

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Ensure: family $(c_{i,j,A} \colon \mathbb{R} \mid 0 \leq i < j \leq n, A \in N)$ such that

$c_{i,j,A} = \max\{\mu(d) \mid d \in D_G^A(t_{i+1} \dots t_j)\} \cup \{0\}$

function $\textsc{deduce}(P,\ \mu,\ t_1 \dots t_n)$

  $queue := \{(i-1, A, i, \mu(A \to t_i)) \mid 1 \leq i \leq n, A \to t_i \in P\}$

  $(c_{i,j,A} := 0 \mid 0 \leq i < j \leq n, A \in N)$

  while $queue \neq \varnothing$ **do**

    $(i, A, j, w) := \operatorname{argmax}_{(i,A,j,w) \in queue}\ w \cdot \mathrm{out(A)}$

    $queue \setminus= \{(i, A, j, w)\}$

    if $c_{i,j,A} = 0$ **then**

      $c_{i,j,A} := w$

      $queue \cup= \{(i, A', j', \mu(A' \to AC) \cdot w \cdot c_{j,j',C}) \mid A' \to AC \in P\}$

      $queue \cup= \{(i', A', j, \mu(A' \to BA) \cdot c_{i',i,B} \cdot w) \mid A' \to BA \in P\}$

      $queue \cup= \{(i, A', j, \mu(A' \to A) \cdot w) \mid A' \to A \in P\}$

  return c

Pruning for deductive parsing – in the context of CKY

Can A*-parsing be applied for CKY parsing?
Yes: in combination with pruning:

- Threshold beam

  Require: family $c = (c_{i,j,A} \in \mathbb{R} \mid A \in N)$, threshold $\theta \in [0, 1]$
  Ensure: family $(c_{i,j,A} \in \mathbb{R} \mid A \in N)$

  function $\textsc{Prune}(c)$
  $\quad m = \max_{A \in N}\{c_{i,j,A} \cdot \mathrm{out}(A) \mid A \in N\}$
  $\quad$ **for** $A \in N$ **do**
  $\quad\quad$ **if** $c_{i,j,A} \cdot \mathrm{out}(A) < m \cdot \theta$ **then**
  $\quad\quad\quad c_{i,j,A} := 0$
  $\quad$ **return** c

Pruning for deductive parsing – in the context of CKY

Can A*-parsing be applied for CKY parsing?
Yes: in combination with pruning:

- Threshold beam

  Require: family $c = (c_{i,j,A} \in \mathbb{R} \mid A \in N)$, threshold $\theta \in [0, 1]$
  Ensure: family $(c_{i,j,A} \in \mathbb{R} \mid A \in N)$

  function $\textsc{Prune}(c)$
      $m = \max_{A \in N}\{c_{i,j,A} \cdot \mathrm{out}(A) \mid A \in N\}$
      for $A \in N$ **do**
          if $c_{i,j,A} \cdot \mathrm{out}(A) < m \cdot \theta$ **then**
              $c_{i,j,A} := 0$
      return c

- Fixed-size beam

  Require: family $c = (c_{i,j,A} \in \mathbb{R} \mid A \in N)$, size $1 \leq n \leq |N|$
  Ensure: family $(c_{i,j,A} \in \mathbb{R} \mid A \in N)$

  function $\textsc{Prune}(c)$
      $[s_1, \ldots, s_n] = n\text{-best}\{c_{i,j,A} \cdot \mathrm{out}(A) \mid A \in N\}$
      for $A \in N$ **do**
          if $c_{i,j,A} \cdot \mathrm{out}(A) < s_n$ **then**
              $c_{i,j,A} := 0$
      return c

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