Implementation of weighted cfg parsers

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Outline

Overview

CKY parsing

Deductive parsing

Conclusion

Overview

read binary cfg from file

G

read word from `stdin`

G, w

weighted CKY parsing or deductive parsing

print best derivation tree

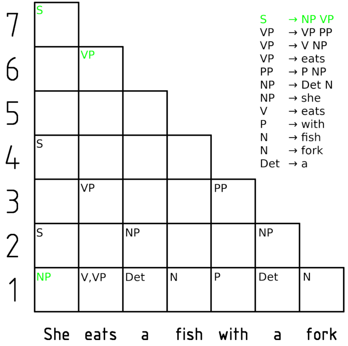
d

Outline

Weighted CKY parsing [CS70; Kas66; You67]

- requires cfg in Chomsky normal form
- fill chart from bottom to top
- each cell corresponds to span in word to parse
- add nonterminal to cell if partial derivation yields span

- store best weight along with nonterminals
- close each cell with chain rules
- store *backtrace* (rule, reference to predecessor cells)



Trougnouf, "CYK algorithm: animation showing every step of a sentence parsing", 15 January 2018, via wikimedia.org

The CKY parsing algorithm

Require: cfg $G = (N, \Sigma, P, S)$ in Cnf, word $t_1 ... t_n$ where $t_1, ..., t_n \in \Sigma$
Ensure: family of sets $(c_{i,j} \subseteq N \mid 0 \leq i < j \leq n)$ such that $A \in c_{i-1,j} \iff D_G^A(t_i ... t_j) \neq \emptyset$

function $\textsc{cky}(P, t_1 ... t_n)$
    for $1 \leq i \leq n$ **do**
        $c_{i-1,i} := \{A \mid A \to t_i \in P\}$
    for $2 \leq r \leq n$ **do**
        for $0 \leq i \leq n - r$ **do**
            $j := i + r$
            $c_{i,j} := \{A \mid i < m < j, A \to BC \in P \colon B \in c_{i,m}, C \in c_{m,j}\}$
    return $(c_{i,j} \mid 0 \leq i < j \leq n)$

The CKY parsing algorithm

Require: cfg $G = (N, \Sigma, P, S)$ in Cnf, word $t_1 ... t_n$ where $t_1, ..., t_n \in \Sigma$
Ensure: family of sets $(c_{i,j} \in N \mid 0 \leq i < j \leq n)$ such that $A \in c_{i-1,j} \iff D_G^A(t_i ... t_j) \neq \emptyset$

function $\textsc{cky}(P,\, t_1 ... t_n)$
  for $1 \leq i \leq n$ **do**
    $c_{i-1,i} := \emptyset$
    for $A \to t_i \in P$ **do**
      $c_{i-1,i} \cup= \{A\}$
  for $2 \leq r \leq n$ **do**
    for $0 \leq i \leq n - r$ **do**
      $j := i + r$
      $c_{i,j} := \emptyset$
      for $A \in N$ **do**
        for $m \in \{l+1, l+2, ..., r-1\}$ **do**
          for $A \to BC \in R$ **do**
            if $B \in c_{i,m}$ and $C \in c_{m,j}$ **then**
              $c_{i,j} \cup= \{A\}$
  return $(c_{i,j} \mid 0 \leq i < j \leq n)$

The CKY parsing algorithm + weights

Require: weighted cfg $G = (N, \Sigma, P, S, \mu)$ in Cnf, word $t_1 ... t_n$ where $t_1, ..., t_n \in \Sigma$
Ensure: family of mappings $(c_{i,j} \colon N \to \mathbb{R} \mid 0 \leq i < j \leq n)$ such that
$c_{i-1,j}(A) = \max\{\mu(d) \mid d \in D_G^A(t_i ... t_j)\} \cup \{0\}$

function CKY(P, μ, $t_1 ... t_n$)
  for $1 \leq i \leq n$ **do**
    $c_{i-1,i} := A \mapsto \max\{\mu(A \to t_i) \mid A \to t_i \in P\} \cup \{0\}$
  for $2 \leq r \leq n$ **do**
    for $0 \leq i \leq n - r$ **do**
      $j := i + r$
      $c_{i,j} := A \mapsto \max\{\mu(A \to BC) \cdot c_{i,m}(B) \cdot c_{m,j}(C) \mid i < m < j, A \to BC \in P\} \cup \{0\}$
  return $(c_{i,j} \mid 0 \leq i < j \leq n)$

The CKY parsing algorithm + weights

Require: weighted cfg (N, Σ, P, S, μ) in Cnf, word $t_1 \ldots t_n$ where $t_1, \ldots, t_n \in \Sigma$
Ensure: family of mappings $(c_{i,j} \colon N \to \mathbb{R} \mid 0 \leq i < j \leq n)$ such that

$$c_{i-1,j}(A) = \max\{\mu(d) \mid d \in D_G^A(t_i \ldots t_j)\} \cup \{0\}$$

function $\textsc{cky}(P, \mu, t_1 \ldots t_n)$
  $(c_{i,j,A} := 0 \mid 0 \leq i < j \leq n, A \in N)$
  for $1 \leq i \leq n$ **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 $2 \leq r \leq n$ **do**
    for $0 \leq i \leq n - r$ **do**
      $j := i + r$
      for $A \in N$ **do**
        for $m \in \{i+1, i+2, \ldots, j-1\}$ **do**
          for $A \to BC \in R$ **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 $(c_{i,j} := A \mapsto c_{i,j,A} \mid 0 \leq i < j \leq n)$

The CKY parsing algorithm + weights + chain rules

Require: weighted binary cfg (N, Σ, P, S, μ), word $t_1 ... t_n$ where $t_1, ..., t_n \in \Sigma$
Ensure: family of mappings $(c_{i,j} \colon N \to \mathbb{R} \mid 0 \le i < j \le n)$ such that

$$c_{i,j}(A) = \max\{\mu(d) \mid d \in D_G^A(t_i ... t_j)\} \cup \{0\}$$

function $\textsc{cky}(P,\ \mu,\ t_1 ... t_n)$
    $(c_{i,j,A} := 0 \mid 0 \le i < j \le n, A \in N)$
    for $1 \le i \le n$ **do**
        for $A \to t_i \in P$ **do**
            $c_{i-1,i,A} := \max\{c_{i-1,i,A}, \mu(A \to t_i)\}$
        $c' = \textsc{unary\_closure}(P, \mu, (c_{i-1,i,A} \mid A \in N))$
        $(c_{i-1,i,A} := c'_A \mid A \in N)$
    for $2 \le r \le n$ **do**
        for $0 \le i \le n - r$ **do**
            $j := i + r$
            for $A \in N$ **do**
                for $m \in \{i+1, i+2, ..., j-1\}$ **do**
                    for $A \to BC \in R$ **do**
                        $c_{i,j,A} := \max\{c_{i,j,A}, \mu(A \to BC) \cdot c_{i,m,B} \cdot c_{m,j,C}\}$
            $c' = \textsc{unary\_closure}(P, \mu, (c_{i,j,A} \mid A \in N))$
            $(c_{i,j,A} := c'_A \mid A \in N)$
    return $(c_{i,j} := A \mapsto c_{i,j,A} \mid 0 \le i < j \le n)$

The CKY parsing algorithm + weights + chain rules

function $\textsc{unary\_closure}(P,\ \mu,\ (c_A \in \mathbb{R} \mid A \in N))$

  $queue := \{(A, c_A) \in N \times \mathbb{R} \mid A \in N, c_A \neq 0\}$

  $(c_A := 0 \mid A \in N)$

  while $queue \neq \emptyset$ **do**

    $(B, w) := \operatorname{argmax}_{(B,w) \in queue}\ w$

    $queue \setminus= \{(B, w)\}$

    if $c_B < w$ **then**

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

      $c_B := w$

  return $(c_A \mid A \in N)$

About backtraces

- only best derivation:
  - store at most *one* backtrace per span and nonterminal
  - update when weight is updated
- recursively read trees from backtraces:

Require: family of backtraces $(b_{i,j,A} \mid 0 \leq i < j \leq n, A \in N)$, each otf. $\perp$, or $A \to t$, or $(A \to B, i, j)$ or $(A \to BC, i, m, m, j)$

function $\textsc{first\_tree}(b,\ i,\ j,\ A)$
  if $b_{i,j,A}$ otf. $A \to t$ **then return** $A \to t$
  else if $b_{i,j,A}$ otf. $(A \to B, i, j)$ **then return** $(A \to B)(\textsc{first\_tree}(b, i, j, B))$
  else if $b_{i,j,A}$ otf. $(A \to BC, i, m, m, j)$ **then**
    return $(A \to BC)(\textsc{first\_tree}(b, i, m, B), \textsc{first\_tree}(b, m, j, C))$

Let's talk about data structures

- access to grammar rules depends on loops:
  - access by first nonterminal on rhs `Map<Nt, Set<(Rule, Wt)>>`
  - for some, that be no concern `Set<(Rule, Wt)>`
- weights for each nonterminal and span:
  - usually in a $(\frac{|w|\cdot(|w|+1)}{2} \cdot |N|)$-dimensional vector (dense) `Vec<Wt>`
  - or hashmap (sparse) `Map<(Int, Nt, Int), Wt>`
- storing backtraces:
  - each backtrace: applied rule and references to cells
    `Bt = Bin(Rule, [Int; 4])+ Chain(Rule, [Int; 2])+ Term(Rule)`
  - backtraces for each chart cell and nonterminal `Vec<Set<Bt>>`
  - or do not store them at all

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Deduction systems [Ned03]

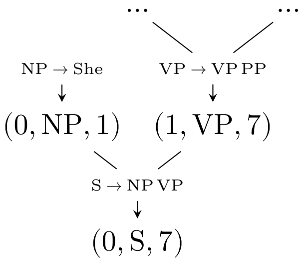
- rule-based system
- derive consequence (c) from antecedents ($a_1, ..., a_k$) for some $k \in \mathbb{N}$
- compute weight of consequence using weight of antecedents ($w_1, ..., w_k$)
- side condition b

$$\frac{a_1 : w_1, ..., a_k : w_k}{c\colon f(w_1,...,w_k)}\ b$$

Deduction system for parsing weighted cfg [Ned03]

- item (i, A, j) for each nonterminal A spanning $t_i \ldots t_j$
- predict initial items $\frac{}{(i-1,A,i)\colon\, \mu(A \longrightarrow t_i)}\ A \to t_i \in P \wedge w = t_1 \ldots t_i \ldots t_n$
- combine items $\frac{(i_0,B_1,i_1)\colon\, w_1,(i_1,B_2,i_2)\colon\, w_2,\ldots,(i_{k-1},B_k,i_k)\colon\, w_k}{(i_0,A,i_k)\colon\, \mu(A \to B_1 \ldots B_k) \cdot w_1 \cdots w_k}\ A \to B_1 \ldots B_k \in P$
- goal item: $(0, S, |w|)$

- deduction system $\rightsquigarrow$ weighted hypergraph
  - edge from antecedents to consequence
  - can be explored with respect weight
  - hyperpaths to goal item correspond to parse trees



Weighted deductive parsing algorithm

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 of mappings $(c_{i,j} \colon N \to \mathbb{R} \mid 0 \le i < j \le n)$ such that
$c_{i-1,j}(A) = \max\{\mu(d) \mid d \in D_G^A(t_i \ldots t_j)\} \cup \{0\}$

function DEDUCE(P, μ, $t_1 \ldots t_n$)
  $queue := \{(i-1, A, i, \mu(A \to t_i)) \mid 1 \le i \le n, A \to t_i \in P\}$
  $(c_{i,j,A} := 0 \mid 0 \le i < j \le n, A \in N)$
  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**
      $c_{i,j,A} := w$
      $queue \cup= \{(i, A', j', \mu(A' \to AC) \cdot w \cdot c_{j,j',C}) \mid A' \to AC \in P\}$
      $queue \cup= \{(i', A', j, \mu(A' \to BA) \cdot c_{i',i,B} \cdot w) \mid A' \to BA \in P\}$
      $queue \cup= \{(i, A', j, \mu(A' \to A) \cdot w) \mid A' \to A \in P\}$
  return $(c_{i,j} := A \mapsto c_{i,j,A} \mid 0 \le i < j \le n)$

Let's talk about data structures … again

- access of grammar from each rhs nonterminal `Map<Nt, Set<(Rule, Wt)>>`
- each item may need to sotre a backtrace `(Int, Nt, Int, Wt, Bt)`
- storing the found items and their weights:
  - access from left `Map<(Int, Nt), Set<(Int, Nt, Int, Wt)>>`
  - access from right `Map<(Nt, Int), Set<(Int, Nt, Int, Wt)>>`
- storing backtraces:
  - store applied rule and antecedent items
    `Bt = Bin(Rule, [Int; 4])+ Chain(Rule, [Int; 2])+ Term(Rule)`
  - set of backtraces for item `Map<(UInt, Nt, UInt), Set<Bt>>`
  - or do not store them at all

Outline

General Comments and Tips

- order of loops in CKY algorithm doesn't matter that much, *but*[1]:
  - may be used to cache-optimize,
  - may lead to other optimizations
- deductive parsers may not need to expand the whole search space
- try to think about efficient access in your data structures
  - don't search in lists
  - indexed access: maps
  - check if you *really* need sets/maps
  - flat data structures are faster than stacked heap allocations
- try not to over-engineer it

[1] Bodenstab [Bod09] discusses this in detail.

[Bod09] Nathan Bodenstab. "Efficient Implementation of the cky algorithm". In: *Computational Linguistics, Final Project Paper* (2009).

[CS70] John Cocke and J. T. Schwartz. *Programming languages and their compilers: Preliminary notes*. Tech. rep. Version 2nd. Courant Institute of Mathematical Sciences, New York University, Apr. 1970.

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[Kas66] T. Kasami. *An efficient recognition and syntax-analysis algorithm for context-free languages*. Tech. rep. R-257. AFCRL, Mar. 1966.

[Ned03] Mark-Jan Nederhof. "Weighted deductive parsing and Knuth's algorithm". In: *Computational Linguistics* 29.1 (2003), pp. 135–143.

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