Implementation of PCFG parsers

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Outline

1. Overview
2. CKY parsing
3. Deductive parsing
4. Conclusion

Overview

Parser invocation:

`./pcfg_tool parse grammar.rules grammar.lexicon < sentences`

Parser mainloop:

read PCFG G from files

G

read sentence w (1 line) from `stdin`

G, w

weighted CKY parsing or deductive parsing

print best derivation tree

d

Outline

The CKY parsing algorithm (formal notation)

Require: CFG $G = (N, \Sigma, R, S)$ in CNF, sentence $w = w_1 \ldots w_n$ where $w_1, \ldots, w_n \in \Sigma$
Ensure: family of sets $(c_{i,j} \subseteq N \mid 0 \leq i < j \leq n)$ such that $A \in c_{i,j} \iff D_G^A(w_{i+1} \ldots w_j) \neq \emptyset$

function CKY($R, w_1 \ldots w_n$)
  for $i := 1$ **to** n **do**
    $c_{i-1,i} := \{A \mid A \to w_i \in R\}$
  for $r := 2$ **to** n **do**
    for $i := 0$ **to** $n - r$ **do**
      $j := i + r$
      $c_{i,j} := \{A \mid i < m < j, A \to BC \in R \colon B \in c_{i,m}, C \in c_{m,j}\}$
  return $(c_{i,j} \mid 0 \leq i < j \leq n)$

where

- CNF = Chomsky normal form
- $D_G^A(w_i \ldots w_j)$ = set of (left) derivations of A in G that result in $w_i \ldots w_j$
- $c_{i,j}$ = set of all nonterminals that derive $w_{i+1} \ldots w_j$

The CKY parsing algorithm (imperative flavor)

Require: CFG $G = (N, \Sigma, R, S)$ in CNF, sentence $w = w_1 \ldots w_n$ where $w_1, \ldots, w_n \in \Sigma$
Ensure: family of sets $(c_{i,j} \subseteq N \mid 0 \le i < j \le n)$ such that $A \in c_{i,j} \iff D_G^A(w_{i+1} \ldots w_j) \neq \emptyset$

function CKY($R, w_1 \ldots w_n$)
    $(c_{i,j} := \emptyset \mid 0 \le i < j \le n)$
    for $i := 1$ **to** n **do**
        for $A \to w_i \in R$ **do**
            $c_{i-1,i} := c_{i-1,i} \cup \{A\}$

$c_{i-1,i} := \{A \mid A \to w_i \in R\}$

    for $r := 2$ **to** n **do** ▷ length of span
        for $i := 0$ **to** $n - r$ **do** ▷ start of span
            $j := i + r$ ▷ end of span
            for $A \in N$ **do**
                for $m := i + 1$ **to** $j - 1$ **do** ▷ partition position
                    for $A \to BC \in R$ **do**
                        if $B \in c_{i,m}$ and $C \in c_{m,j}$ **then**
                            $c_{i,j} := c_{i,j} \cup \{A\}$

$c_{i,j} := \{A \mid i < m < j, A \to BC \in R\colon B \in c_{i,m}, C \in c_{m,j}\}$

    return $(c_{i,j} \mid 0 \le i < j \le n)$

From unweighted to weighted CKY parsing

	Unweighted	Weighted
data structure for spans	set of nonterminals $(c_{i,j} \subseteq N \mid 0 \leq i < j \leq n)$	map nonterminals to real numbers $(c_{i,j} \colon N \to \mathbb{R} \mid 0 \leq i < j \leq n)$
update operation for rule $r = A \to \ldots$	$c_{i,j} := c_{i,j} \cup \{A\}$	$c_{i,j}(A) := \max\{c_{i,j}(A), p(r)\}$

Convention: we will write $c_{i,j,A}$ rather than $c_{i,j}(A)$

The CKY parsing algorithm + weights

Require: PCFG (N, Σ, R, S, p) in CNF, sentence $w = w_1 \ldots w_n$ where $w_1, \ldots, w_n \in \Sigma$
Ensure: family $(c_{i,j,A} \in \mathbb{R} \mid 0 \leq i < j \leq n, A \in N)$ such that

$$c_{i,j,A} = \max \left(\{p(d) \mid d \in D_G^A(w_{i+1} \ldots w_j)\} \cup \{0\}\right)$$

function CKY(R, p, $w_1 \ldots w_n$)
    $(c_{i,j,A} := 0 \mid 0 \leq i < j \leq n, A \in N)$
    for $i := 1$ **to** n **do**
        for $A \to w_i \in R$ **do**
            $c_{i-1,i,A} := \max\{c_{i-1,i,A}, p(A \to w_i)\}$
    for $r := 2$ **to** n **do**
        for $i := 0$ **to** $n - r$ **do**
            $j := i + r$
            for $A \in N$ **do**
                for $m := i + 1$ **to** $j - 1$ **do**
                    for $A \to BC \in R$ **do**
                        $c_{i,j,A} := \max\{c_{i,j,A}, p(A \to BC) \cdot c_{i,m,B} \cdot c_{m,j,C}\}$
    return $(c_{i,j,A} \mid 0 \leq i < j \leq n, A \in N)$

Adding chain rules

Types of rules accepted by classic CKY: (with $A, B, C \in N$ and $w \in \Sigma$)

$$A \to w \qquad\qquad A \to BC$$

What we also want: $A \to B$ (with $A, B \in N$)

Solution: two-phase procedure per cell $c_{i,j}$

1. perform classic CKY step
2. compute closure under unary rules

The CKY parsing algorithm + weights + chain rules

Require: binary PCFG (N, Σ, R, S, p), sentence $w = w_1 \ldots w_n$ where $w_1, \ldots, w_n \in \Sigma$
Ensure: family $(c_{i,j,A} \in \mathbb{R} \mid 0 \le i < j \le n, A \in N)$ such that

$$c_{i,j,A} = \max\big(\{p(d) \mid d \in D_G^A(w_{i+1} \ldots w_j)\} \cup \{0\}\big)$$

function CKY(R, μ, $w_1 \ldots w_n$)
  $(c_{i,j,A} := 0 \mid 0 \le i < j \le n, A \in N)$
  for $i := 1$ **to** n **do**
    for $A \to w_i \in R$ **do**
      $c_{i-1,i,A} := p(A \to w_i)$
    $(c_{i-1,i,A} \mid A \in N) = \text{UNARY\_CLOSURE}(R, p, (c_{i-1,i,A} \mid A \in N))$
  for $r := 2$ **to** n **do**
    for $i := 0$ **to** $n - r$ **do**
      $j := i + r$
      for $A \in N$ **do**
        for $m := i + 1$ **to** $j - 1$ **do**
          for $A \to BC \in R$ **do**
            $c_{i,j,A} := \max\{c_{i,j,A}, p(A \to BC) \cdot c_{i,m,B} \cdot c_{m,j,C}\}$
      $(c_{i,j,A} \mid A \in N) = \text{UNARY\_CLOSURE}(R, p, (c_{i,j,A} \mid A \in N))$
  return $(c_{i,j,A} \mid 0 \le i < j \le n, A \in N)$

The CKY parsing algorithm + weights + chain rules

function UNARY_CLOSURE($R, p, (c_A \mid A \in N)$)
    $queue := \{(A, c_A) \mid A \in N, c_A \neq 0\}$
    $(c_A := 0 \mid A \in N)$
    while $queue \neq \emptyset$ **do**
        $(B, q) := \operatorname{argmax}_{(\hat{B}, \hat{q}) \in queue} \hat{q}$
        $queue := queue \setminus \{(B, q)\}$
        if $c_B < q$ **then**
            $c_B := q$
            for $A \to B \in R$ **do**
                $queue := queue \cup \{(A, p(A \to B) \cdot q)\}$
    return $(c_A \mid A \in N)$

About backtraces

What we have: best weight $c_{i,j,A}$ for derivations in $D_G^A(w_{i+1}...w_j)$ for each $A \in N$, $0 \leq i < j \leq n$
What we want: the best derivation of S that results in $w = w_1 \ldots w_n$

During the CKY algorithm:

- store *backtraces* (indicators *how* a weight was computed)
- for best derivation: at most one backtrace per span and nonterminal
- update when weight is updated

After the CKY algorithm:

- recursively read trees from backtraces:

Require: family of backtraces b, each otf. $\bot$, or $A \to t$, or $(A \to B, i, j)$ or $(A \to BC, i, m, m, j)$

1: **function** BEST_TREE($(b_{i,j,A} \mid 0 \leq i < j \leq n, A \in N), i, j, A$)
2: **if** $b_{i,j,A}$ otf. $A \to t$ **then return** $A \to t$
3: **else if** $b_{i,j,A}$ otf. $(A \to B, i, j)$ **then return** $(A \to B)$(BEST_TREE(b, i, j, B))
4: **else if** $b_{i,j,A}$ otf. $(A \to BC, i, m, m, j)$ **then**
5: **return** $(A \to BC)$(BEST_TREE(b, i, m, B), BEST_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, (Rule, Wt)>`
  - for some, that be no concern `Set<(Rule, Wt)>`

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- weights for each span and nonterminal:
  - usually in a $(\frac{|w|\cdot(|w|+1)}{2} \cdot |N|)$-dimensional vector (dense) `Vec<Wt>`
  - or hashmap (sparse) `Map<(Int, Int, Nt), Wt>`

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  - or hashmap (sparse) `Map<(Int, Int, Nt), Wt>`
- storing backtraces:
  - each backtrace: rule and spans and nonterminals (on rule's right-hand side)
    `Bt = Bin(Rule, [Int; 4])+ Chain(Rule, [Int; 2])+ Term(Rule)`
  - one backtrace for each span and nonterminal (dense) `Vec<Bt>`
  - or in a hashmap (sparse) `Map<(Int, Int, Nt), Bt>`
  - or do not store them at all

Outline

Deduction systems [Ned03]

- rule-based system (derivation of *items*)
- derive consequence (c) from antecedents ($a_1, \ldots, a_k$) for some $k \in \mathbb{N}$

$$\frac{a_1 \qquad , \ldots, a_k}{c}$$

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- compute weight of consequence using weight of antecedents ($w_1, \ldots, w_k$)

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

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- side condition b

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

Deduction system for parsing weighted cfg [Ned03]

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- combine items $\frac{(i_0, B_1, i_1) \colon w_1, (i_1, B_2, i_2) \colon w_2, \ldots, (i_{k-1}, B_k, i_k) \colon w_k}{(i_0, A, i_k) \colon p(A \to B_1 \ldots B_k) \cdot w_1 \cdots w_k}$ $A \to B_1 \ldots B_k \in R$

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- goal item: $(0, S, |w|)$

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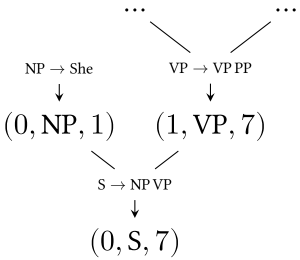
- deduction system $\rightsquigarrow$ weighted hypergraph
  - edge from antecedents to consequence
  - can be explored with respect weight
  - hyperpaths to goal item correspond to parse trees



Weighted deductive parsing algorithm

Require: weighted binary cfg (N, Σ, R, S, p), word $w_1 \ldots w_n$ where $w_1, \ldots, w_n \in \Sigma$
Ensure: family $(c_{i,j,A} \in \mathbb{R} \mid 0 \leq i < j \leq n, A \in N)$ such that
$c_{i,j,A} = \max \left(\{p(d) \mid d \in D_G^A(w_i \ldots w_j)\} \cup \{0\} \right)$

```
function DEDUCE(R, p, w_1…w_n)
    queue := {(i − 1, A, i, p(A → w_i)) | 1 ≤ i ≤ n, A → w_i ∈ R}
    (c_{i,j,A} := 0 | 0 ≤ i < j ≤ n, A ∈ N)
    while queue ≠ ∅ do
        (i, A, j, q) := argmax_{(î, Â, ĵ, q̂) ∈ queue} q̂
        queue := queue \ {(i, A, j, q)}
        if c_{i,j,A} = 0 then
            c_{i,j,A} := q
            queue := queue ∪ {(i, A′, j′, p(A′ → AC) · q · c_{j,j′,C}) | j < j′ ≤ n, A′ → AC ∈ R}
            queue := queue ∪ {(i′, A′, j, p(A′ → BA) · c_{i′,i,B} · q) | 0 ≤ i′ < i, A′ → BA ∈ R}
            queue := queue ∪ {(i, A′, j, p(A′ → A) · q) | A′ → A ∈ R}
    return (c_{i,j,A} | 0 ≤ i < j ≤ n, A ∈ N)
```

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- 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)>>`

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- storing backtraces:
  - store applied rule and antecedent items
    Bt = Bin(Rule, [Int; 4])+ Chain(Rule, [Int; 2])+ Term(Rule)
  - one backtrace for each item Map<(Int, Nt, Int), Bt>
  - or do not store them at all

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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

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

General Comments and Tips

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- 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

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- try not to over-engineer it

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