

# CS 6120/CS4120: Natural Language Processing

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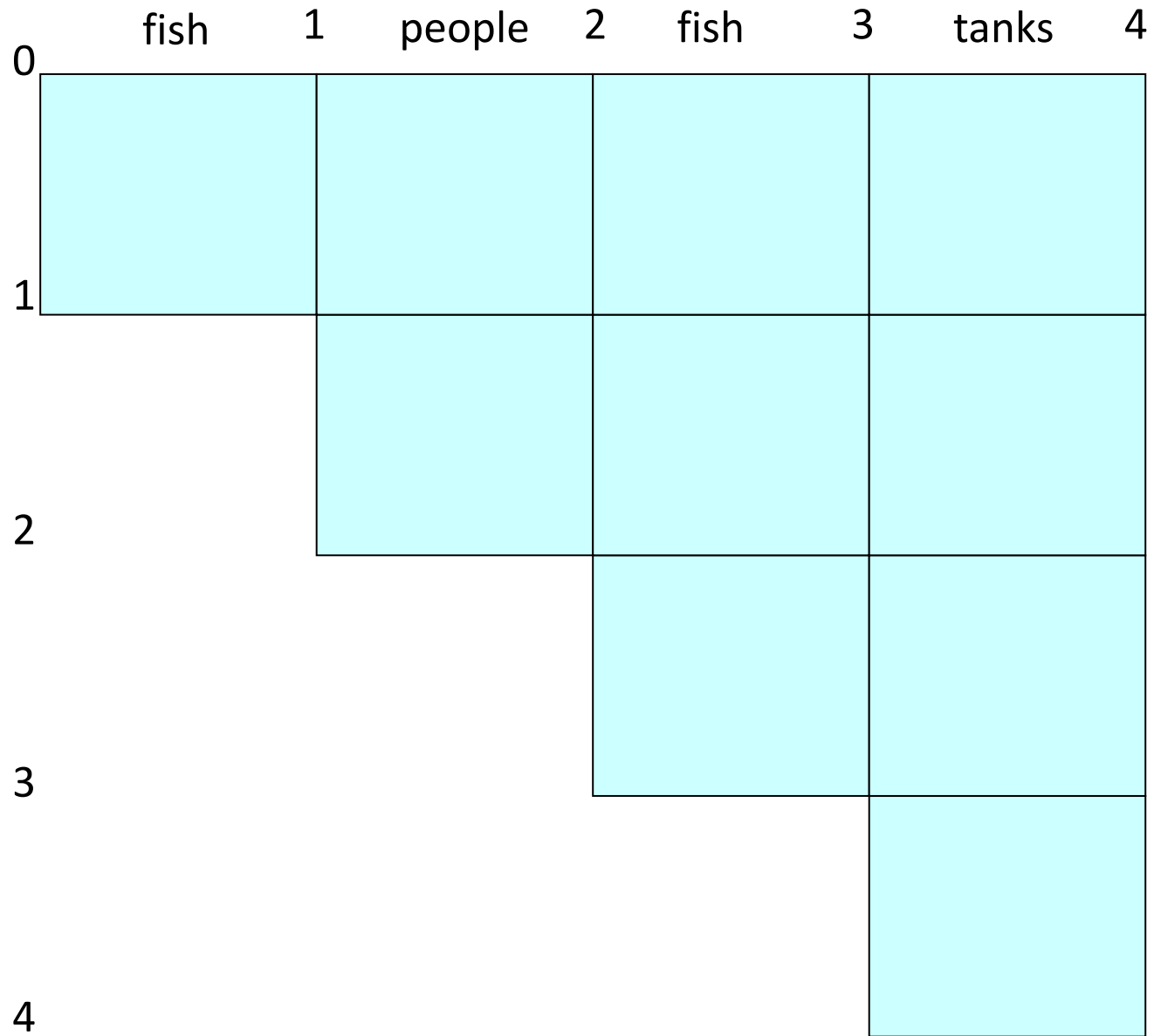
# The grammar

S → NP VP      0.9  
S → VP          0.1  
VP → V NP      0.5  
VP → V          0.1  
VP → V @VP\_V   0.3  
VP → V PP      0.1  
@VP\_V → NP PP 1.0  
NP → NP NP     0.1  
NP → NP PP     0.2  
NP → N          0.7  
PP → P NP      1.0

N → *people* 0.5  
N → *fish*    0.2  
N → *tanks*   0.2  
N → *rods*    0.1  
V → *people* 0.1  
V → *fish*    0.6  
V → *tanks*   0.3  
P → *with*    1.0

	fish	1	people	2	fish	3	tanks	4
0	score[0][1]	score[0][2]	score[0][3]	score[0][4]				
1		score[1][2]	score[1][3]	score[1][4]				
2			score[2][3]	score[2][4]				
3						score[3][4]		
4								

$S \rightarrow NP VP$	0.9
$S \rightarrow VP$	0.1
$VP \rightarrow V NP$	0.5
$VP \rightarrow V$	0.1
$VP \rightarrow V @VP\_V$	0.3
$VP \rightarrow V PP$	0.1
$@VP\_V \rightarrow NP PP$	1.0
$NP \rightarrow NP NP$	0.1
$NP \rightarrow NP PP$	0.2
$NP \rightarrow N$	0.7
$PP \rightarrow P NP$	1.0
$N \rightarrow \textit{people}$	0.5
$N \rightarrow \textit{fish}$	0.2
$N \rightarrow \textit{tanks}$	0.2
$N \rightarrow \textit{rods}$	0.1
$V \rightarrow \textit{people}$	0.1
$V \rightarrow \textit{fish}$	0.6
$V \rightarrow \textit{tanks}$	0.3
$P \rightarrow \textit{with}$	1.0



$S \rightarrow NP VP$  0.9  
 $S \rightarrow VP$  0.1  
 $VP \rightarrow V NP$  0.5  
 $VP \rightarrow V$  0.1  
 $VP \rightarrow V @VP\_V$  0.3  
 $VP \rightarrow V PP$  0.1  
 $@VP\_V \rightarrow NP PP$  1.0  
 $NP \rightarrow NP NP$  0.1  
 $NP \rightarrow NP PP$  0.2  
 $NP \rightarrow N$  0.7  
 $PP \rightarrow P NP$  1.0  
  
 $N \rightarrow \textit{people}$  0.5  
 $N \rightarrow \textit{fish}$  0.2  
 $N \rightarrow \textit{tanks}$  0.2  
 $N \rightarrow \textit{rods}$  0.1  
 $V \rightarrow \textit{people}$  0.1  
 $V \rightarrow \textit{fish}$  0.6  
 $V \rightarrow \textit{tanks}$  0.3  
 $P \rightarrow \textit{with}$  1.0

	fish	1	people	2	fish	3	tanks	4
0	$N \rightarrow \textit{fish}$ 0.2 $V \rightarrow \textit{fish}$ 0.6							
1			$N \rightarrow \textit{people}$ 0.5 $V \rightarrow \textit{people}$ 0.1					
2					$N \rightarrow \textit{fish}$ 0.2 $V \rightarrow \textit{fish}$ 0.6			
3							$N \rightarrow \textit{tanks}$ 0.2 $V \rightarrow \textit{tanks}$ 0.3	
4								

S → NP VP 0.9  
 S → VP 0.1  
 VP → V NP 0.5  
 VP → V 0.1  
 VP → V @VP\_V 0.3  
 VP → V PP 0.1  
 @VP\_V → NP PP 1.0  
 NP → NP NP 0.1  
 NP → NP PP 0.2  
 NP → N 0.7  
 PP → P NP 1.0  
  
 N → *people* 0.5  
 N → *fish* 0.2  
 N → *tanks* 0.2  
 N → *rods* 0.1  
 V → *people* 0.1  
 V → *fish* 0.6  
 V → *tanks* 0.3  
 P → *with* 1.0

	fish	1	people	2	fish	3	tanks	4
0								
1	N → fish 0.2 V → fish 0.6 NP → N 0.14 VP → V 0.06 S → VP 0.006							
2		N → people 0.5 V → people 0.1 NP → N 0.35 VP → V 0.01 S → VP 0.001						
3				N → fish 0.2 V → fish 0.6 NP → N 0.14 VP → V 0.06 S → VP 0.006				
4						N → tanks 0.2 V → tanks 0.3 NP → N 0.14 VP → V 0.03 S → VP 0.003		

$S \rightarrow NP VP$  0.9  
 $S \rightarrow VP$  0.1  
 $VP \rightarrow V NP$  0.5  
 $VP \rightarrow V$  0.1  
 $VP \rightarrow V @VP\_V$  0.3  
 $VP \rightarrow V PP$  0.1  
 $@VP\_V \rightarrow NP PP$  1.0  
 $NP \rightarrow NP NP$  0.1  
 $NP \rightarrow NP PP$  0.2  
 $NP \rightarrow N$  0.7  
 $PP \rightarrow P NP$  1.0  
  
 $N \rightarrow people$  0.5  
 $N \rightarrow fish$  0.2  
 $N \rightarrow tanks$  0.2  
 $N \rightarrow rods$  0.1  
 $V \rightarrow people$  0.1  
 $V \rightarrow fish$  0.6  
 $V \rightarrow tanks$  0.3  
 $P \rightarrow with$  1.0

	fish	1	people	2	fish	3	tanks	4
0								
1	$N \rightarrow fish$ 0.2 $V \rightarrow fish$ 0.6 $NP \rightarrow N$ 0.14 $VP \rightarrow V$ 0.06 $S \rightarrow VP$ 0.006	$NP \rightarrow NP NP$ 0.0049 $VP \rightarrow V NP$ 0.105 $S \rightarrow NP VP$ 0.00126						
2		$N \rightarrow people$ 0.5 $V \rightarrow people$ 0.1 $NP \rightarrow N$ 0.35 $VP \rightarrow V$ 0.01 $S \rightarrow VP$ 0.001	$NP \rightarrow NP NP$ 0.0049 $VP \rightarrow V NP$ 0.007 $S \rightarrow NP VP$ 0.0189					
3				$N \rightarrow fish$ 0.2 $V \rightarrow fish$ 0.6 $NP \rightarrow N$ 0.14 $VP \rightarrow V$ 0.06 $S \rightarrow VP$ 0.006	$NP \rightarrow NP NP$ 0.00196 $VP \rightarrow V NP$ 0.042 $S \rightarrow NP VP$ 0.00378			
4						$N \rightarrow tanks$ 0.2 $V \rightarrow tanks$ 0.3 $NP \rightarrow N$ 0.14 $VP \rightarrow V$ 0.03 $S \rightarrow VP$ 0.003		

$S \rightarrow NP VP$  0.9  
 $S \rightarrow VP$  0.1  
 $VP \rightarrow V NP$  0.5  
 $VP \rightarrow V$  0.1  
 $VP \rightarrow V @VP\_V$  0.3  
 $VP \rightarrow V PP$  0.1  
 $@VP\_V \rightarrow NP PP$  1.0  
 $NP \rightarrow NP NP$  0.1  
 $NP \rightarrow NP PP$  0.2  
 $NP \rightarrow N$  0.7  
 $PP \rightarrow P NP$  1.0  
  
 $N \rightarrow \textit{people}$  0.5  
 $N \rightarrow \textit{fish}$  0.2  
 $N \rightarrow \textit{tanks}$  0.2  
 $N \rightarrow \textit{rods}$  0.1  
 $V \rightarrow \textit{people}$  0.1  
 $V \rightarrow \textit{fish}$  0.6  
 $V \rightarrow \textit{tanks}$  0.3  
 $P \rightarrow \textit{with}$  1.0

	fish	1	people	2	fish	3	tanks	4
0								
1	$N \rightarrow \textit{fish}$ 0.2 $V \rightarrow \textit{fish}$ 0.6 $NP \rightarrow N$ 0.14 $VP \rightarrow V$ 0.06 $S \rightarrow VP$ 0.006	$NP \rightarrow NP NP$ 0.0049 $VP \rightarrow V NP$ 0.105 $S \rightarrow VP$ 0.0105						
2		$N \rightarrow \textit{people}$ 0.5 $V \rightarrow \textit{people}$ 0.1 $NP \rightarrow N$ 0.35 $VP \rightarrow V$ 0.01 $S \rightarrow VP$ 0.001	$NP \rightarrow NP NP$ 0.0049 $VP \rightarrow V NP$ 0.007 $S \rightarrow NP VP$ 0.0189					
3				$N \rightarrow \textit{fish}$ 0.2 $V \rightarrow \textit{fish}$ 0.6 $NP \rightarrow N$ 0.14 $VP \rightarrow V$ 0.06 $S \rightarrow VP$ 0.006	$NP \rightarrow NP NP$ 0.00196 $VP \rightarrow V NP$ 0.042 $S \rightarrow VP$ 0.0042			
4						$N \rightarrow \textit{tanks}$ 0.2 $V \rightarrow \textit{tanks}$ 0.3 $NP \rightarrow N$ 0.14 $VP \rightarrow V$ 0.03 $S \rightarrow VP$ 0.003		



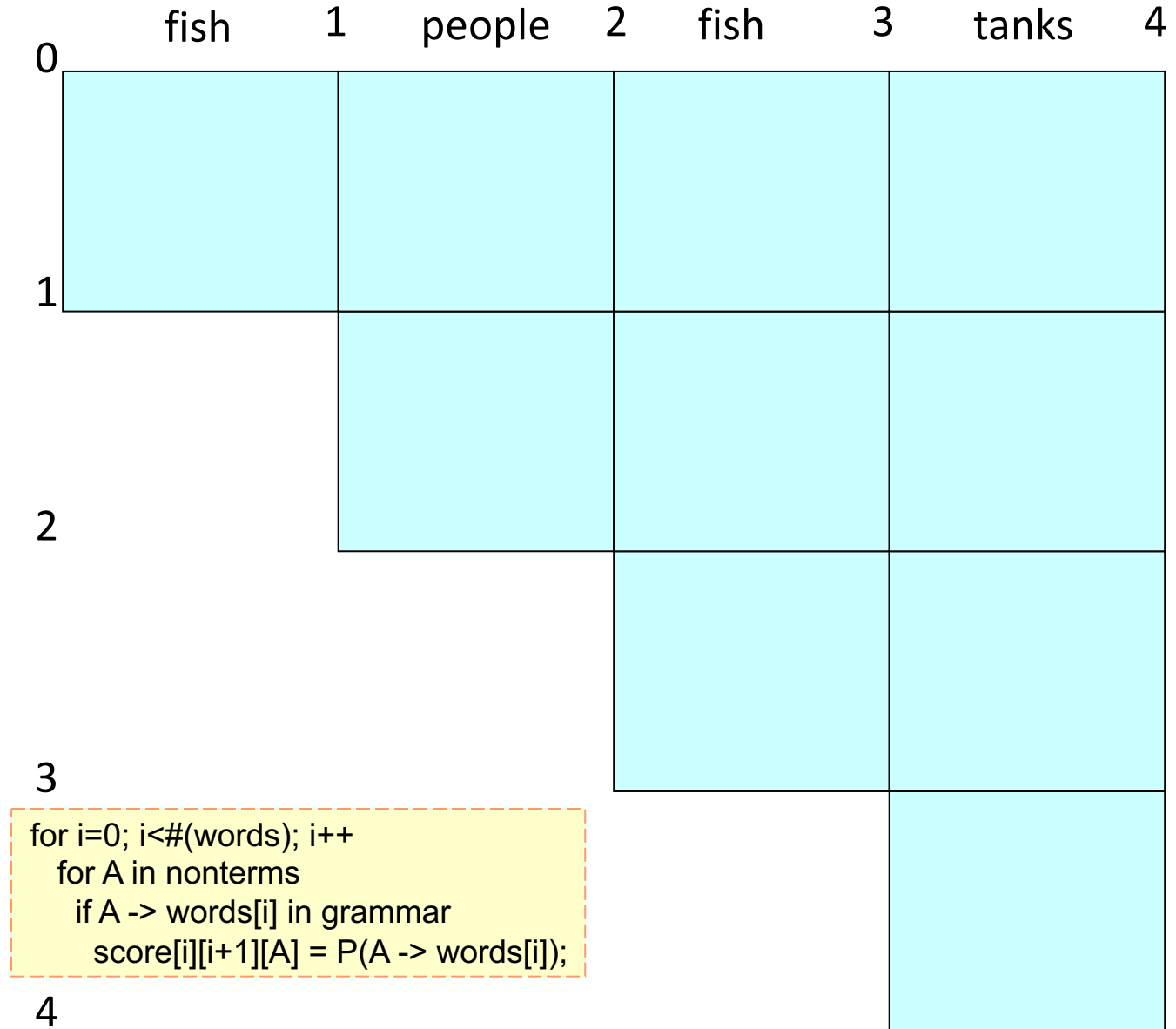
		0	1	2	3	4
S → NP VP	0.9					
S → VP	0.1					
VP → V NP	0.5					
VP → V	0.1					
VP → V @VP_V	0.3					
VP → V PP	0.1					
@VP_V → NP PP	1.0					
NP → NP NP	0.1					
NP → NP PP	0.2					
NP → N	0.7					
PP → P NP	1.0					
N → <i>people</i>	0.5					
N → <i>fish</i>	0.2					
N → <i>tanks</i>	0.2					
N → <i>rods</i>	0.1					
V → <i>people</i>	0.1					
V → <i>fish</i>	0.6					
V → <i>tanks</i>	0.3					
P → <i>with</i>	1.0					
		fish	people	fish	tanks	
		0	1	2	3	4
		N → fish 0.2 V → fish 0.6 NP → N 0.14 VP → V 0.06 S → VP 0.006	NP → NP NP 0.0049 VP → V NP 0.105 S → VP 0.0105	NP → NP NP 0.0000686 VP → V NP 0.00147 S → NP VP 0.000882		
		1	N → people 0.5 V → people 0.1 NP → N 0.35 VP → V 0.01 S → VP 0.001	NP → NP NP 0.0049 VP → V NP 0.007 S → NP VP 0.0189		
		2		N → fish 0.2 V → fish 0.6 NP → N 0.14 VP → V 0.06 S → VP 0.006	NP → NP NP 0.00196 VP → V NP 0.042 S → VP 0.0042	
		3			N → tanks 0.2 V → tanks 0.3 NP → N 0.14 VP → V 0.03 S → VP 0.003	
		4				

			fish	1	people	2	fish	3	tanks	4
S → NP VP	0.9	0								
S → VP	0.1		N → fish 0.2	NP → NP NP		NP → NP NP				
VP → V NP	0.5		V → fish 0.6	0.0049		0.0000686				
VP → V	0.1		NP → N 0.14	VP → V NP		VP → V NP				
VP → V @VP_V	0.3		VP → V 0.06	0.105		0.00147				
VP → V PP	0.1	1	S → VP	S → VP		S → NP VP				
@VP_V → NP PP	1.0		S → VP 0.006	0.0105		0.000882				
NP → NP NP	0.1			N → people 0.5	NP → NP NP	NP → NP NP	NP → NP NP			
NP → NP PP	0.2			V → people 0.1	0.0049	0.0000686				
NP → N	0.7	2		NP → N 0.35	VP → V NP	VP → V NP	VP → V NP			
PP → P NP	1.0			VP → V 0.01	0.007	0.000098				
				S → VP 0.001	S → NP VP	S → NP VP	S → NP VP			
N → <i>people</i>	0.5				0.0189	0.01323				
N → <i>fish</i>	0.2					N → fish 0.2	NP → NP NP			
N → <i>tanks</i>	0.2	3				V → fish 0.6	0.00196			
N → <i>rods</i>	0.1					NP → N 0.14	VP → V NP			
V → <i>people</i>	0.1					VP → V 0.06	0.042			
V → <i>fish</i>	0.6					S → VP 0.006	S → VP			
V → <i>tanks</i>	0.3	4					0.0042			
P → <i>with</i>	1.0							N → tanks 0.2		
								V → tanks 0.3		
								NP → N 0.14		
								VP → V 0.03		
								S → VP 0.003		

S → NP VP 0.9  
 S → VP 0.1  
 VP → V NP 0.5  
 VP → V 0.1  
 VP → V @VP\_V 0.3  
 VP → V PP 0.1  
 @VP\_V → NP PP 1.0  
 NP → NP NP 0.1  
 NP → NP PP 0.2  
 NP → N 0.7  
 PP → P NP 1.0  
  
 N → *people* 0.5  
 N → *fish* 0.2  
 N → *tanks* 0.2  
 N → *rods* 0.1  
 V → *people* 0.1  
 V → *fish* 0.6  
 V → *tanks* 0.3  
 P → *with* 1.0

	0	1	2	3	4
	fish	people	fish	tanks	
0	N → fish 0.2 V → fish 0.6 NP → N 0.14 VP → V 0.06 S → VP 0.006	NP → NP NP 0.0049 VP → V NP 0.105 S → VP 0.0105	NP → NP NP 0.0000686 VP → V NP 0.00147 S → NP VP 0.000882	NP → NP NP 0.0000009604 VP → V NP 0.00002058 S → NP VP 0.00018522	
1		N → people 0.5 V → people 0.1 NP → N 0.35 VP → V 0.01 S → VP 0.001	NP → NP NP 0.0049 VP → V NP 0.007 S → NP VP 0.0189	NP → NP NP 0.0000686 VP → V NP 0.000098 S → NP VP 0.01323	
2			N → fish 0.2 V → fish 0.6 NP → N 0.14 VP → V 0.06 S → VP 0.006	NP → NP NP 0.00196 VP → V NP 0.042 S → VP 0.0042	
3				N → tanks 0.2 V → tanks 0.3 NP → N 0.14 VP → V 0.03 S → VP 0.003	
4					

$S \rightarrow NP VP$  0.9  
 $S \rightarrow VP$  0.1  
 $VP \rightarrow V NP$  0.5  
 $VP \rightarrow V$  0.1  
 $VP \rightarrow V @VP\_V$  0.3  
 $VP \rightarrow V PP$  0.1  
 $@VP\_V \rightarrow NP PP$  1.0  
 $NP \rightarrow NP NP$  0.1  
 $NP \rightarrow NP PP$  0.2  
 $NP \rightarrow N$  0.7  
 $PP \rightarrow P NP$  1.0  
  
 $N \rightarrow \textit{people}$  0.5  
 $N \rightarrow \textit{fish}$  0.2  
 $N \rightarrow \textit{tanks}$  0.2  
 $N \rightarrow \textit{rods}$  0.1  
 $V \rightarrow \textit{people}$  0.1  
 $V \rightarrow \textit{fish}$  0.6  
 $V \rightarrow \textit{tanks}$  0.3  
 $P \rightarrow \textit{with}$  1.0



S → NP VP 0.9  
 S → VP 0.1  
 VP → V NP 0.5  
 VP → V 0.1  
 VP → V @VP\_V 0.3  
 VP → V PP 0.1  
 @VP\_V → NP PP 1.0  
 NP → NP NP 0.1  
 NP → NP PP 0.2  
 NP → N 0.7  
 PP → P NP 1.0  
  
 N → *people* 0.5  
 N → *fish* 0.2  
 N → *tanks* 0.2  
 N → *rods* 0.1  
 V → *people* 0.1  
 V → *fish* 0.6  
 V → *tanks* 0.3  
 P → *with* 1.0

	fish	1	people	2	fish	3	tanks	4
0	N → fish 0.2 V → fish 0.6							
1			N → people 0.5 V → people 0.1					
2				N → fish 0.2 V → fish 0.6				
							N → tanks 0.2 V → tanks 0.3	

```

// handle unaries
boolean added = true
while added
  added = false
  for A, B in nonterms
    if score[i][i+1][B] > 0 && A->B in grammar
      prob = P(A->B)*score[i][i+1][B]
      if(prob > score[i][i+1][A])
        score[i][i+1][A] = prob
        back[i][i+1][A] = B
        added = true
  
```

S → NP VP 0.9  
 S → VP 0.1  
 VP → V NP 0.5  
 VP → V 0.1  
 VP → V @VP\_V 0.3  
 VP → V PP 0.1  
 @VP\_V → NP PP 1.0  
 NP → NP NP 0.1  
 NP → NP PP 0.2  
 NP → N 0.7  
 PP → P NP 1.0  
  
 N → *people* 0.5  
 N → *fish* 0.2  
 N → *tanks* 0.2  
 N → *rods* 0.1  
 V → *people* 0.1  
 V → *fish* 0.6  
 V → *tanks* 0.3  
 P → *with* 1.0

	fish	1	people	2	fish	3	tanks	4
0								
1	N → fish 0.2 V → fish 0.6 NP → N 0.14 VP → V 0.06 S → VP 0.006							
2		N → people 0.5 V → people 0.1 NP → N 0.35 VP → V 0.01 S → VP 0.001						
3				N → fish 0.2 V → fish 0.6 NP → N 0.14 VP → V 0.06 S → VP 0.006				
4						N → tanks 0.2 V → tanks 0.3 NP → N 0.14 VP → V 0.03 S → VP 0.003		

prob=score[begin][split][B]\*score[split][end][C]\*P(A->BC)  
 if (prob > score[begin][end][A])  
   score[begin][end][A] = prob  
   back[begin][end][A] = new Triple(split,B,C)

S → NP VP 0.9  
 S → VP 0.1  
 VP → V NP 0.5  
 VP → V 0.1  
 VP → V @VP\_V 0.3  
 VP → V PP 0.1  
 @VP\_V → NP PP 1.0  
 NP → NP NP 0.1  
 NP → NP PP 0.2  
 NP → N 0.7  
 PP → P NP 1.0  
  
 N → *people* 0.5  
 N → *fish* 0.2  
 N → *tanks* 0.2  
 N → *rods* 0.1  
 V → *people* 0.1  
 V → *fish* 0.6  
 V → *tanks* 0.3  
 P → *with* 1.0

	fish	1	people	2	fish	3	tanks	4
0								
1	N → fish 0.2 V → fish 0.6 NP → N 0.14 VP → V 0.06 S → VP 0.006	NP → NP NP 0.0049 VP → V NP 0.105 S → NP VP 0.00126						
2		N → people 0.5 V → people 0.1 NP → N 0.35 VP → V 0.01 S → VP 0.001	NP → NP NP 0.0049 VP → V NP 0.007 S → NP VP 0.0189					
3				N → fish 0.2 V → fish 0.6 NP → N 0.14 VP → V 0.06 S → VP 0.006	NP → NP NP 0.00196 VP → V NP 0.042 S → NP VP 0.00378			
4						N → tanks 0.2 V → tanks 0.3 NP → N 0.14 VP → V 0.03 S → VP 0.003		

```

//handle unaries
boolean added = true
while added
  added = false
  for A, B in nonterms
    prob = P(A->B)*score[begin][end][B];
    if prob > score[begin][end][A]
      score[begin][end][A] = prob
      back[begin][end][A] = B
  added = true
  
```

S → NP VP 0.9  
 S → VP 0.1  
 VP → V NP 0.5  
 VP → V 0.1  
 VP → V @VP\_V 0.3  
 VP → V PP 0.1  
 @VP\_V → NP PP 1.0  
 NP → NP NP 0.1  
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 N → *people* 0.5  
 N → *fish* 0.2  
 N → *tanks* 0.2  
 N → *rods* 0.1  
 V → *people* 0.1  
 V → *fish* 0.6  
 V → *tanks* 0.3  
 P → *with* 1.0

	fish	1	people	2	fish	3	tanks	4
0								
1	N → fish 0.2 V → fish 0.6 NP → N 0.14 VP → V 0.06 S → VP 0.006	NP → NP NP 0.0049 VP → V NP 0.105 S → VP 0.0105						
2		N → people 0.5 V → people 0.1 NP → N 0.35 VP → V 0.01 S → VP 0.001	NP → NP NP 0.0049 VP → V NP 0.007 S → NP VP 0.0189					
3				N → fish 0.2 V → fish 0.6 NP → N 0.14 VP → V 0.06 S → VP 0.006	NP → NP NP 0.00196 VP → V NP 0.042 S → VP 0.0042			
4						N → tanks 0.2 V → tanks 0.3 NP → N 0.14 VP → V 0.03 S → VP 0.003		

```

for split = begin+1 to end-1
  for A,B,C in nonterms
    prob=score[begin][split][B]*score[split][end][C]*P(A->BC)
    if prob > score[begin][end][A]
      score[begin][end][A] = prob
      back[begin][end][A] = new Triple(split,B,C)
  
```



S → NP VP 0.9  
 S → VP 0.1  
 VP → V NP 0.5  
 VP → V 0.1  
 VP → V @VP\_V 0.3  
 VP → V PP 0.1  
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 NP → NP NP 0.1  
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 NP → N 0.7  
 PP → P NP 1.0  
  
 N → *people* 0.5  
 N → *fish* 0.2  
 N → *tanks* 0.2  
 N → *rods* 0.1  
 V → *people* 0.1  
 V → *fish* 0.6  
 V → *tanks* 0.3  
 P → *with* 1.0

	fish	1	people	2	fish	3	tanks	4
0								
1	N → fish 0.2 V → fish 0.6 NP → N 0.14 VP → V 0.06 S → VP 0.006	NP → NP NP 0.0049 VP → V NP 0.105 S → VP 0.0105	NP → NP NP 0.0000686 VP → V NP 0.00147 S → NP VP 0.000882					
2		N → people 0.5 V → people 0.1 NP → N 0.35 VP → V 0.01 S → VP 0.001	NP → NP NP 0.0049 VP → V NP 0.007 S → NP VP 0.0189					
3				N → fish 0.2 V → fish 0.6 NP → N 0.14 VP → V 0.06 S → VP 0.006	NP → NP NP 0.00196 VP → V NP 0.042 S → VP 0.0042			
4						N → tanks 0.2 V → tanks 0.3 NP → N 0.14 VP → V 0.03 S → VP 0.003		

```

for split = begin+1 to end-1
  for A,B,C in nonterms
    prob=score[begin][split][B]*score[split][end][C]*P(A->BC)
    if prob > score[begin][end][A]
      score[begin][end][A] = prob
      back[begin][end][A] = new Triple(split,B,C)
  
```

S → NP VP 0.9  
 S → VP 0.1  
 VP → V NP 0.5  
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 VP → V PP 0.1  
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 NP → NP NP 0.1  
 NP → NP PP 0.2  
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 PP → P NP 1.0  
  
 N → *people* 0.5  
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 N → *rods* 0.1  
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 V → *fish* 0.6  
 V → *tanks* 0.3  
 P → *with* 1.0

	fish	1	people	2	fish	3	tanks	4
0								
1	N → fish 0.2 V → fish 0.6 NP → N 0.14 VP → V 0.06 S → VP 0.006	NP → NP NP 0.0049 VP → V NP 0.105 S → VP 0.0105	NP → NP NP 0.0000686 VP → V NP 0.00147 S → NP VP 0.000882					
2		N → people 0.5 V → people 0.1 NP → N 0.35 VP → V 0.01 S → VP 0.001	NP → NP NP 0.0049 VP → V NP 0.007 S → NP VP 0.0189	NP → NP NP 0.0000686 VP → V NP 0.000098 S → NP VP 0.01323				
3				N → fish 0.2 V → fish 0.6 NP → N 0.14 VP → V 0.06 S → VP 0.006	NP → NP NP 0.00196 VP → V NP 0.042 S → VP 0.0042			
4						N → tanks 0.2 V → tanks 0.3 NP → N 0.14 VP → V 0.03 S → VP 0.003		

```

for split = begin+1 to end-1
  for A,B,C in nonterms
    prob=score[begin][split][B]*score[split][end][C]*P(A->BC)
    if prob > score[begin][end][A]
      score[begin][end][A] = prob
      back[begin][end][A] = new Triple(split,B,C)
  
```

S → NP VP 0.9  
 S → VP 0.1  
 VP → V NP 0.5  
 VP → V 0.1  
 VP → V @VP\_V 0.3  
 VP → V PP 0.1  
 @VP\_V → NP PP 1.0  
 NP → NP NP 0.1  
 NP → NP PP 0.2  
 NP → N 0.7  
 PP → P NP 1.0  
  
 N → *people* 0.5  
 N → *fish* 0.2  
 N → *tanks* 0.2  
 N → *rods* 0.1  
 V → *people* 0.1  
 V → *fish* 0.6  
 V → *tanks* 0.3  
 P → *with* 1.0

	0	1	2	3	4
	fish	people	fish	tanks	
0	N → fish 0.2 V → fish 0.6 NP → N 0.14 VP → V 0.06 S → VP 0.006	NP → NP NP 0.0049 VP → V NP 0.105 S → VP 0.0105	NP → NP NP 0.0000686 VP → V NP 0.00147 S → NP VP 0.000882	NP → NP NP 0.0000009604 VP → V NP 0.00002058 S → NP VP 0.00018522	
1		N → people 0.5 V → people 0.1 NP → N 0.35 VP → V 0.01 S → VP 0.001	NP → NP NP 0.0049 VP → V NP 0.007 S → NP VP 0.0189	NP → NP NP 0.0000686 VP → V NP 0.000098 S → NP VP 0.01323	
2			N → fish 0.2 V → fish 0.6 NP → N 0.14 VP → V 0.06 S → VP 0.006	NP → NP NP 0.00196 VP → V NP 0.042 S → VP 0.0042	
3				N → tanks 0.2 V → tanks 0.3 NP → N 0.14 VP → V 0.03 S → VP 0.003	
4					

Call buildTree(score, back) to get the best parse

# Extended CKY parsing

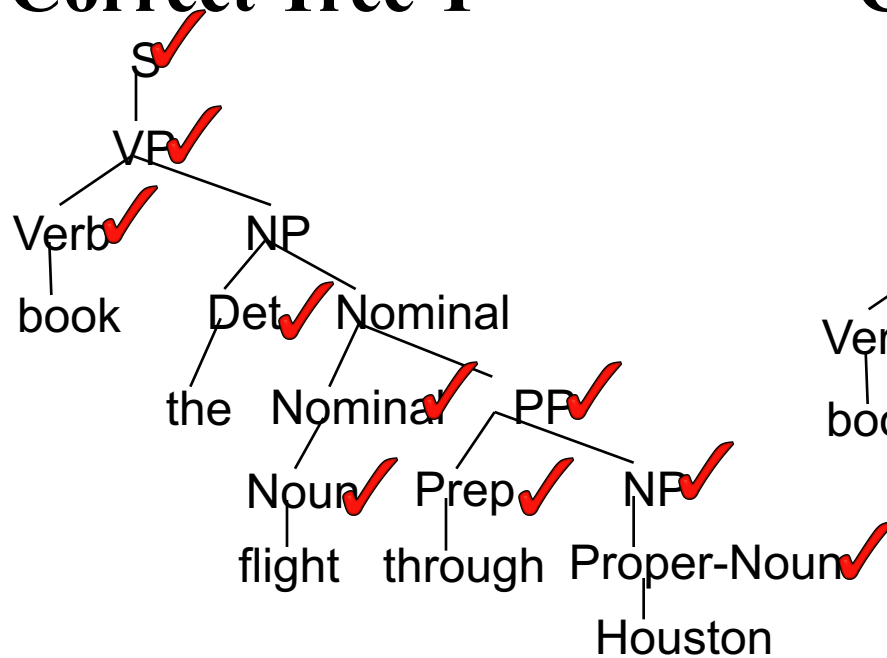
- CKY parsing is usually done **after binarization**
- Unaries can be incorporated into the algorithm
  - Messy, but doesn't increase algorithmic complexity
- Empties can be incorporated
  - Doesn't increase complexity; essentially like unaries
- Binarization is *vital*
  - Without binarization, you don't get parsing cubic in the length of the sentence and in the number of nonterminals in the grammar

# Where to learn the probabilities: Treebanks

- **English Penn Treebank**: Standard corpus for testing syntactic parsing consists of 1.2 M words of text from the Wall Street Journal (WSJ).
- Typical to train on about 40,000 parsed sentences and test on an additional standard disjoint test set of 2,416 sentences.
- **Chinese Penn Treebank**: 100K words from the Xinhua news service.
- Other corpora existing in many languages, see the Wikipedia article “Treebank”

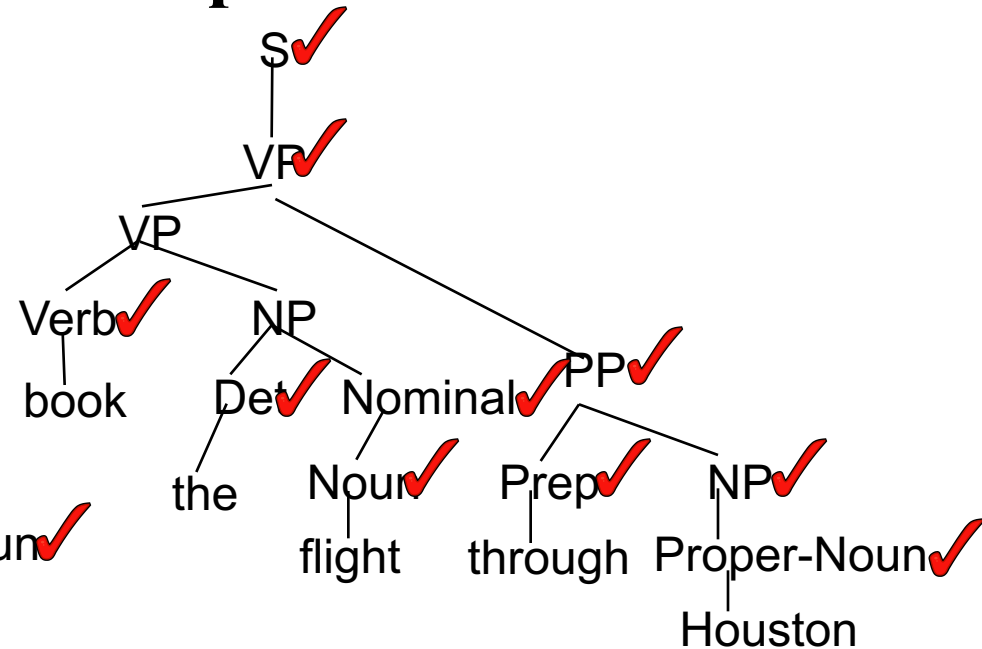
# Computing Evaluation Metrics

## Correct Tree T



# Constituents: 12

## Computed Tree P



# Constituents: 12

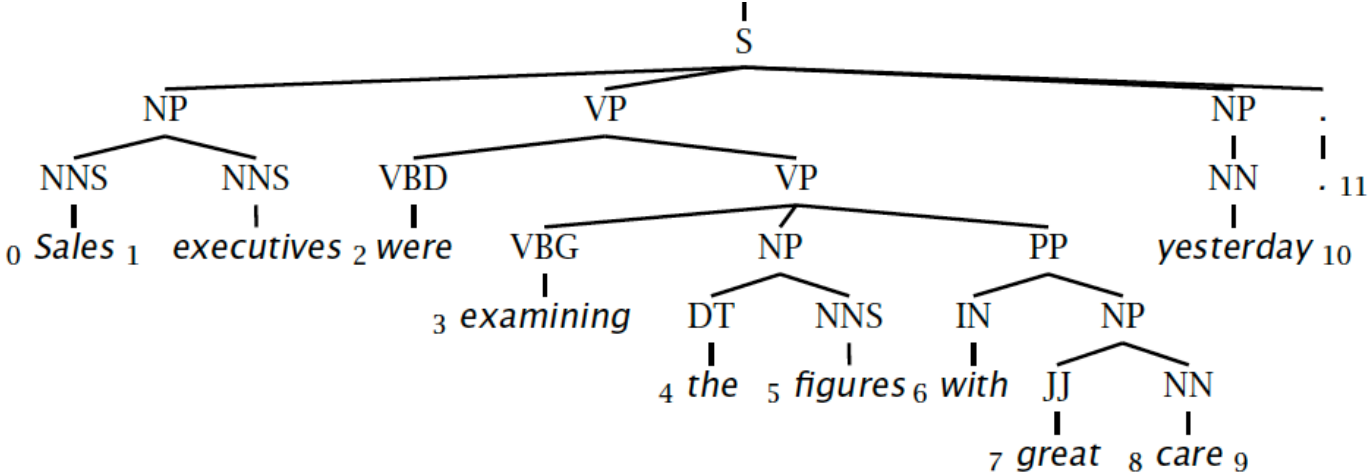
# Correct Constituents: 10

Recall =  $10/12 = 83.3\%$  Precision =  $10/12 = 83.3\%$

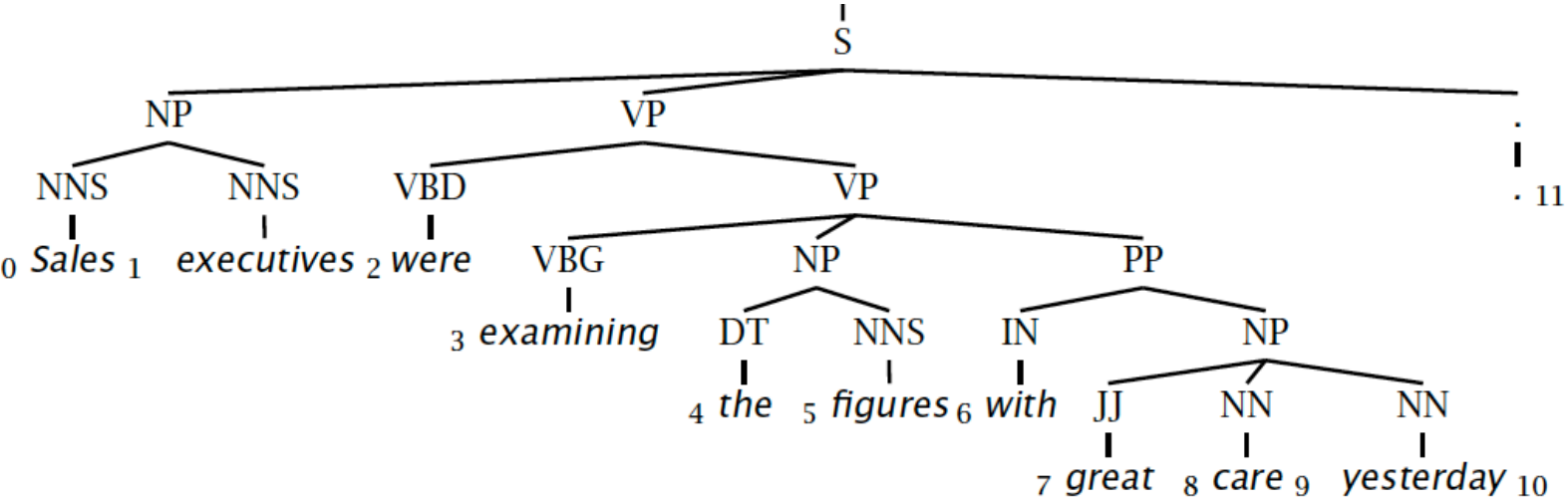
$F_1 = 83.3\%$

# Evaluating constituency parsing

Gold standard brackets: S-(0:11), NP-(0:2), VP-(2:9), VP-(3:9), NP-(4:6), PP-(6-9), NP-(7,9), NP-(9:10)



Candidate brackets: S-(0:11), NP-(0:2), VP-(2:10), VP-(3:10), NP-(4:6), PP-(6-10), NP-(7,10)



# Evaluating constituency parsing

## Gold standard brackets:

S-(0:11), NP-(0:2), VP-(2:9), VP-(3:9), NP-(4:6), PP-(6-9), NP-(7,9), NP-(9:10)

## Candidate brackets:

S-(0:11), NP-(0:2), VP-(2:10), VP-(3:10), NP-(4:6), PP-(6-10), NP-(7,10)

Labeled Precision             $3/7 = 42.9\%$

Labeled Recall               $3/8 = 37.5\%$

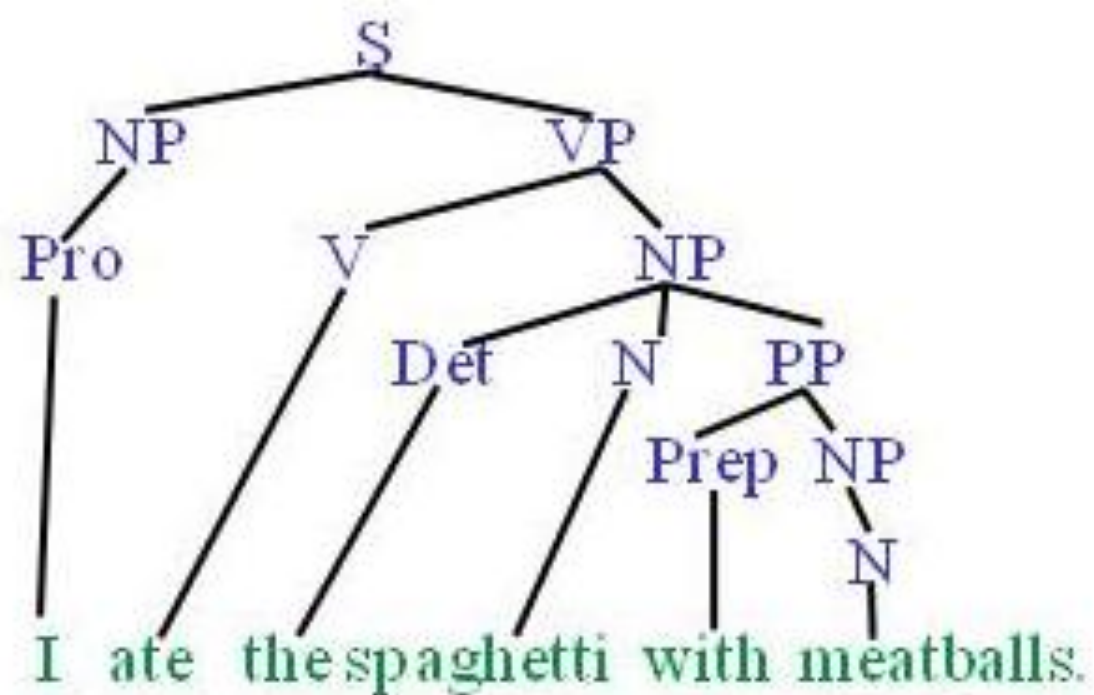
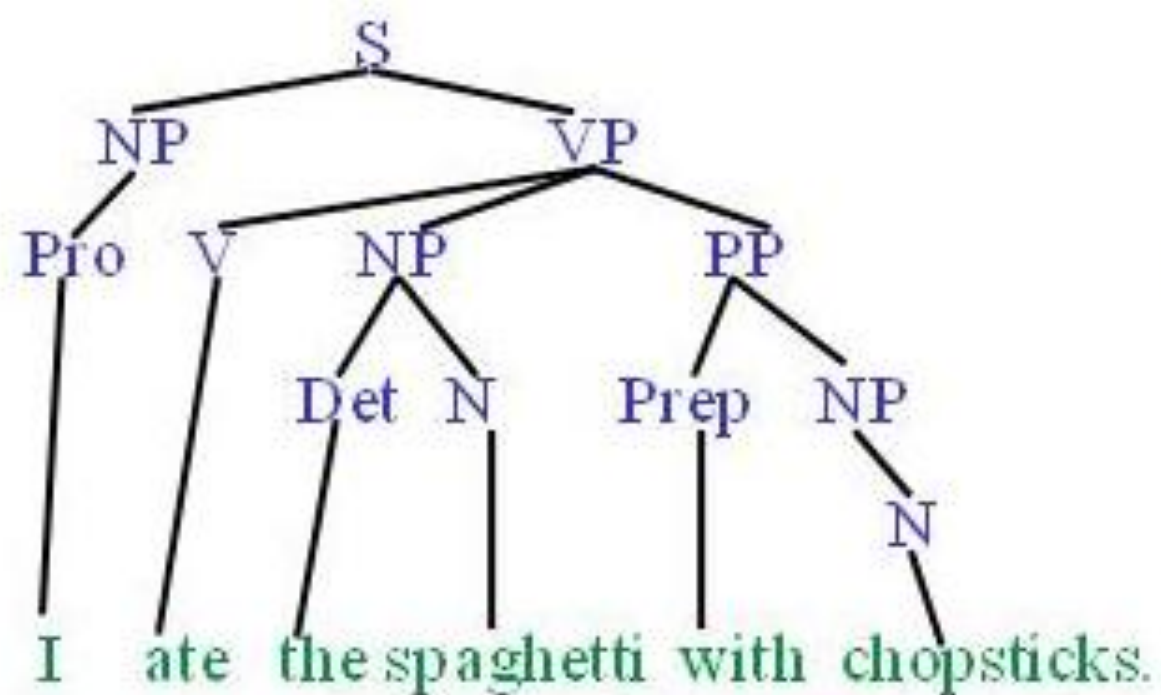
LP/LR F1                    40.0%

POS Tagging Accuracy       $11/11 = 100.0\%$



# How good are PCFGs?

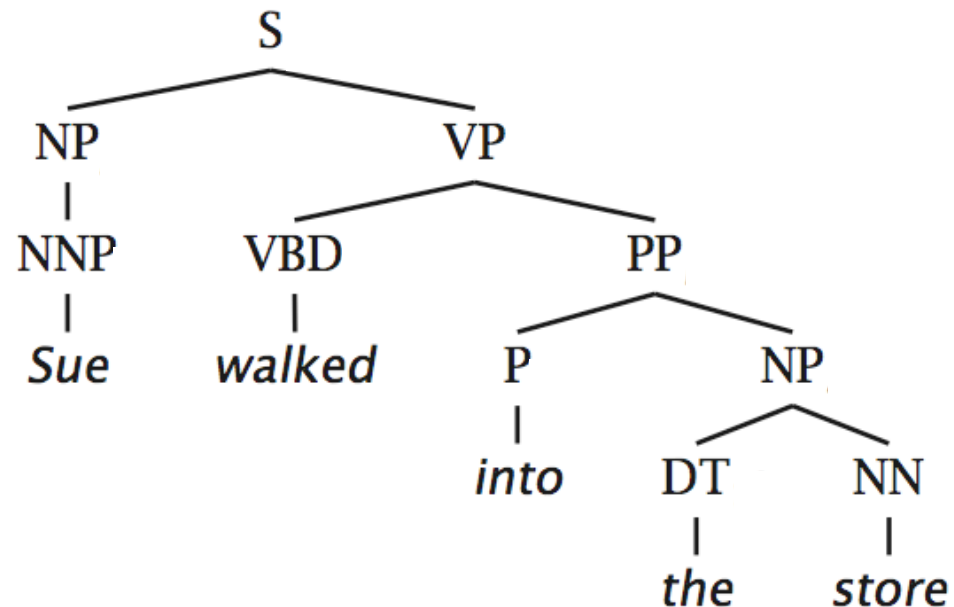
- Penn WSJ parsing accuracy: about 73% LP/LR F1 with feature-based models; state-of-the-art neural model is 91-92% F1



# (Head) Lexicalization of PCFGs

[Magerman 1995, Collins 1997; Charniak 1997]

- The **head word** of a phrase gives a good representation of the phrase's structure and meaning (*head words are decided by rules, the most important word in a constituent*)
- Puts the properties of words back into a PCFG



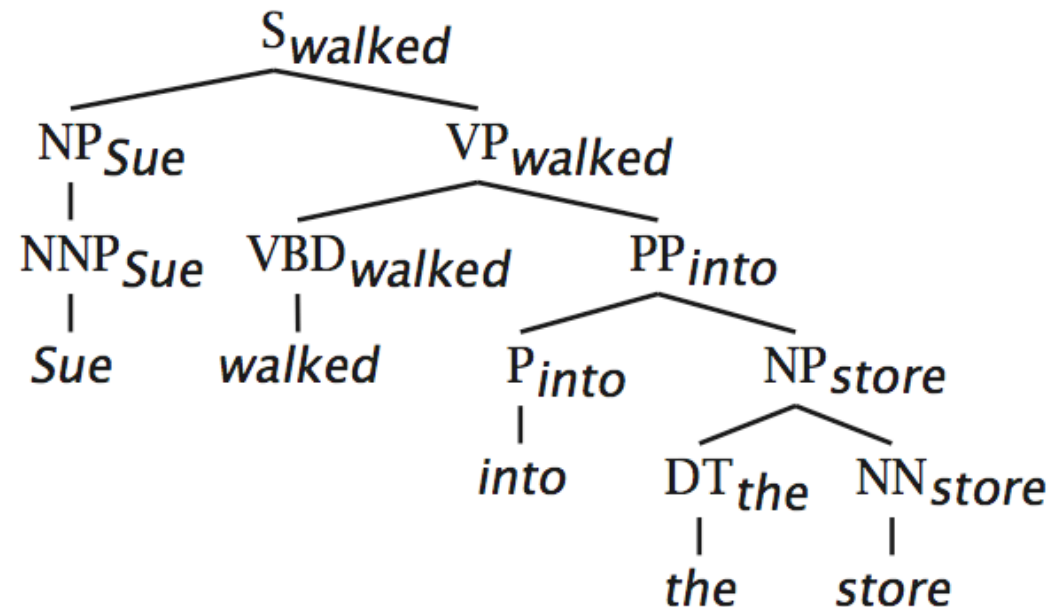
# Head Words

- Syntactic phrases usually have a word in them that is most “central” to the phrase.
- Linguists have defined the concept of a lexical **head** of a phrase.
- Simple rules can identify the head of any phrase by percolating head words up the parse tree.
  - Head of a VP is the main verb
  - Head of an NP is the main noun
  - Head of a PP is the preposition
  - Head of a sentence is the head of its VP

# (Head) Lexicalization of PCFGs

[Magerman 1995, Collins 1997; Charniak 1997]

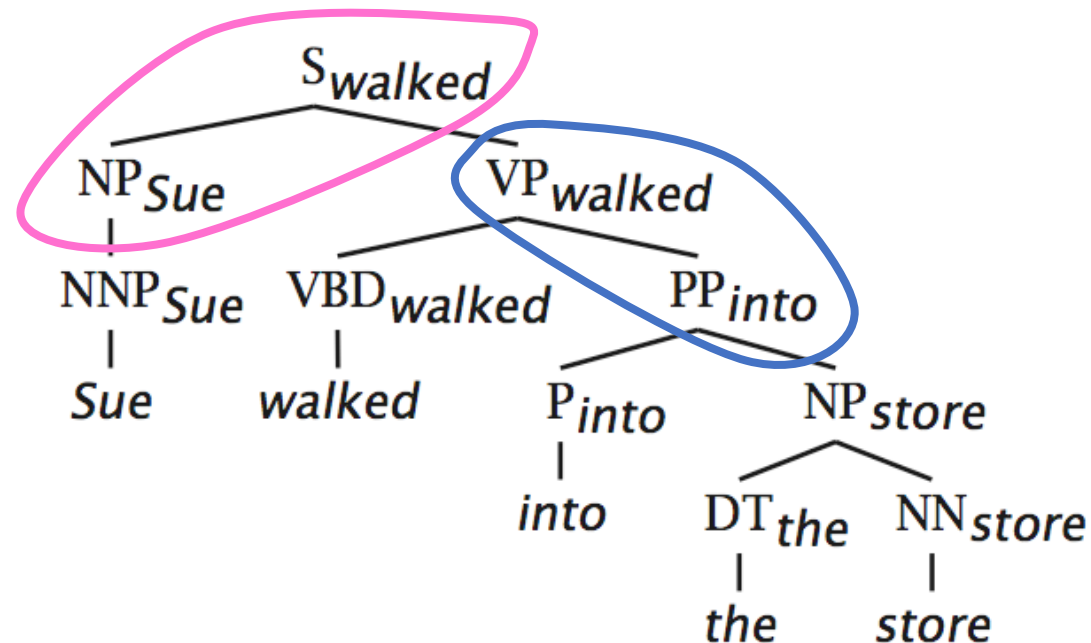
- The head word of a phrase gives a good representation of the phrase's structure and meaning
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# (Head) Lexicalization of PCFGs

[Magerman 1995, Collins 1997; Charniak 1997]

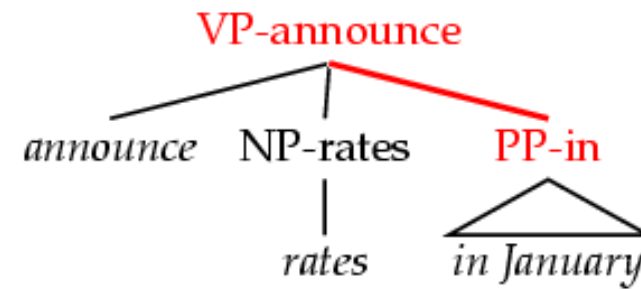
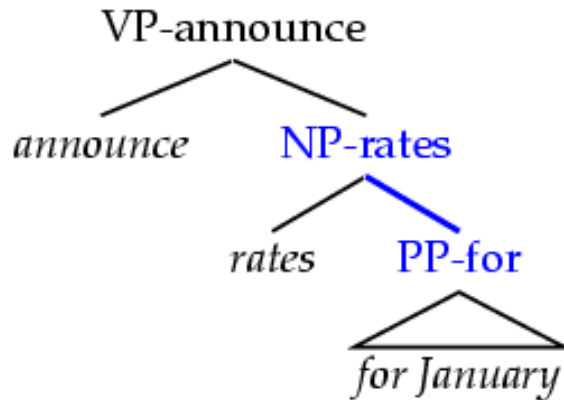
- The head word of a phrase gives a good representation of the phrase's structure and meaning
- Puts the properties of words back into a PCFG



# (Head) Lexicalization of PCFGs

[Magerman 1995, Collins 1997; Charniak 1997]

- Word-to-word affinities are useful for certain ambiguities
  - PP attachment is now (partly) captured in a local PCFG rule.



# Lexicalized parsing was seen as *the* parsing breakthrough of the late 1990s

- Eugene Charniak, 2000 JHU workshop: “To do better, it is necessary to condition probabilities on the actual words of the sentence. This makes the probabilities much tighter:
  - $p(\text{VP} \rightarrow \text{V NP NP}) = 0.00151$
  - $p(\text{VP} \rightarrow \text{V NP NP} \mid \text{said}) = 0.00001$
  - $p(\text{VP} \rightarrow \text{V NP NP} \mid \text{gave}) = 0.01980$      ”  $p(\text{rule} \mid \text{head word})$
- Michael Collins, 2003 COLT tutorial: “**Lexicalized Probabilistic Context-Free Grammars** ... perform vastly better than PCFGs (88% vs. 73% accuracy)”



# Lexicalization models argument selection by sharpening rule expansion probabilities

- The probability of different verbal complement frames (i.e., “subcategorizations”) depends on the verb:

<i>Local Tree</i>	<i>come</i>	<i>take</i>	<i>think</i>	<i>want</i>
VP → V	9.5%	2.6%	4.6%	5.7%
VP → V NP	1.1%	<b>32.1%</b>	0.2%	13.9%
VP → V PP	<b>34.5%</b>	3.1%	7.1%	0.3%
VP → V SBAR	6.6%	0.3%	<b>73.0%</b>	0.2%
VP → V S	2.2%	1.3%	4.8%	<b>70.8%</b>
VP → V NP S	0.1%	5.7%	0.0%	0.3%
VP → V PRT NP	0.3%	5.8%	0.0%	0.0%
VP → V PRT PP	6.1%	1.5%	0.2%	0.0%

# Human Parsing

- Computational parsers can be used to predict human reading time as measured by tracking the time taken to read each word in a sentence.
- Psycholinguistic studies show that words that are more probable given the preceding lexical and syntactic context are read faster.
  - John put the dog in the pen with a **lock**.
  - John put the dog in the pen with a **bone**.
- Modeling these effects requires an ***incremental*** statistical parser that incorporates one word at a time into a continuously growing parse tree.

# Garden Path Sentences

- People are confused by sentences that seem to have a particular syntactic structure but then suddenly violate this structure, so the listener is “lead down the garden path”.
  - The horse raced past the barn fell.
    - vs. The horse raced past the barn broke his leg.
  - The complex houses married students.
  - The old man the sea.
  - While Anna dressed the baby spit up on the bed.
- Incremental computational parsers can try to predict and explain the problems encountered parsing such sentences.

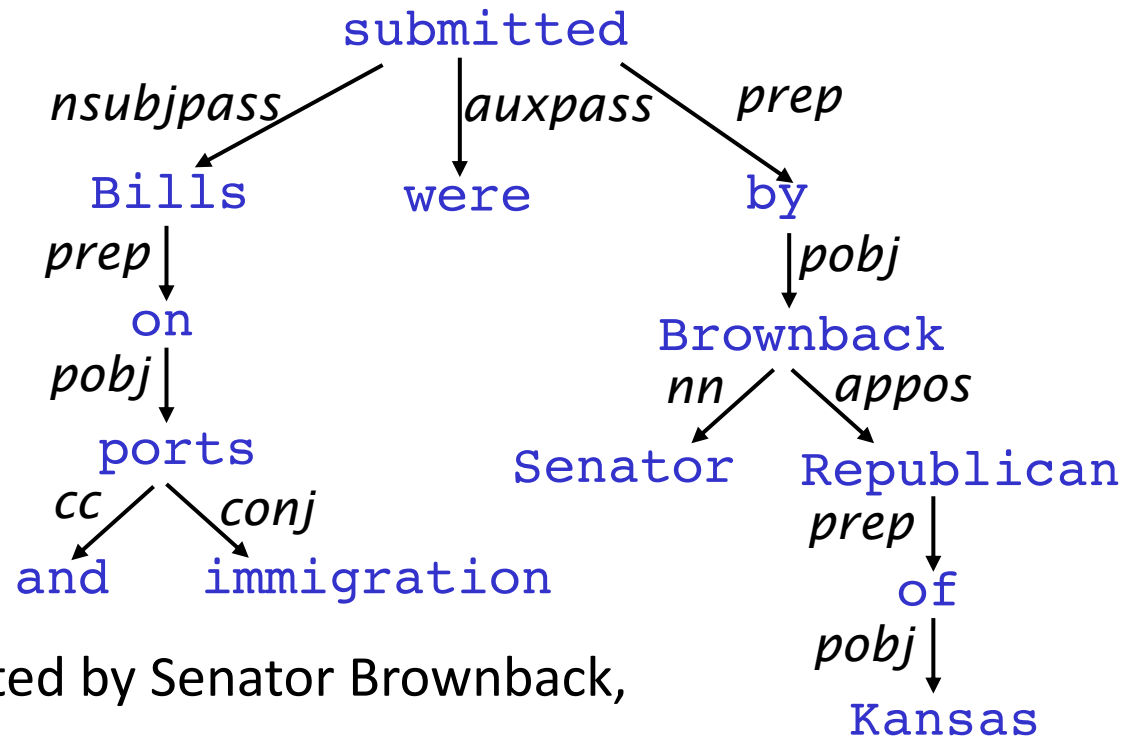
# Center Embedding

- Nested expressions are hard for humans to process beyond 1 or 2 levels of nesting.
  - The rat the cat chased died.
  - The rat the cat the dog bit chased died.
  - The rat the cat the dog the boy owned bit chased died.
- Requires remembering and popping incomplete constituents from a stack and strains human short-term memory.
- Equivalent “tail embedded” (tail recursive) versions are easier to understand since no stack is required.
  - The boy owned a dog that bit a cat that chased a rat that died.

# Dependency Grammar and Dependency Structure

Dependency syntax postulates that syntactic structure consists of lexical items linked by binary asymmetric relations (“arrows”) called dependencies

The arrows are commonly **typed** with the name of grammatical relations (subject, prepositional object, apposition, etc.)



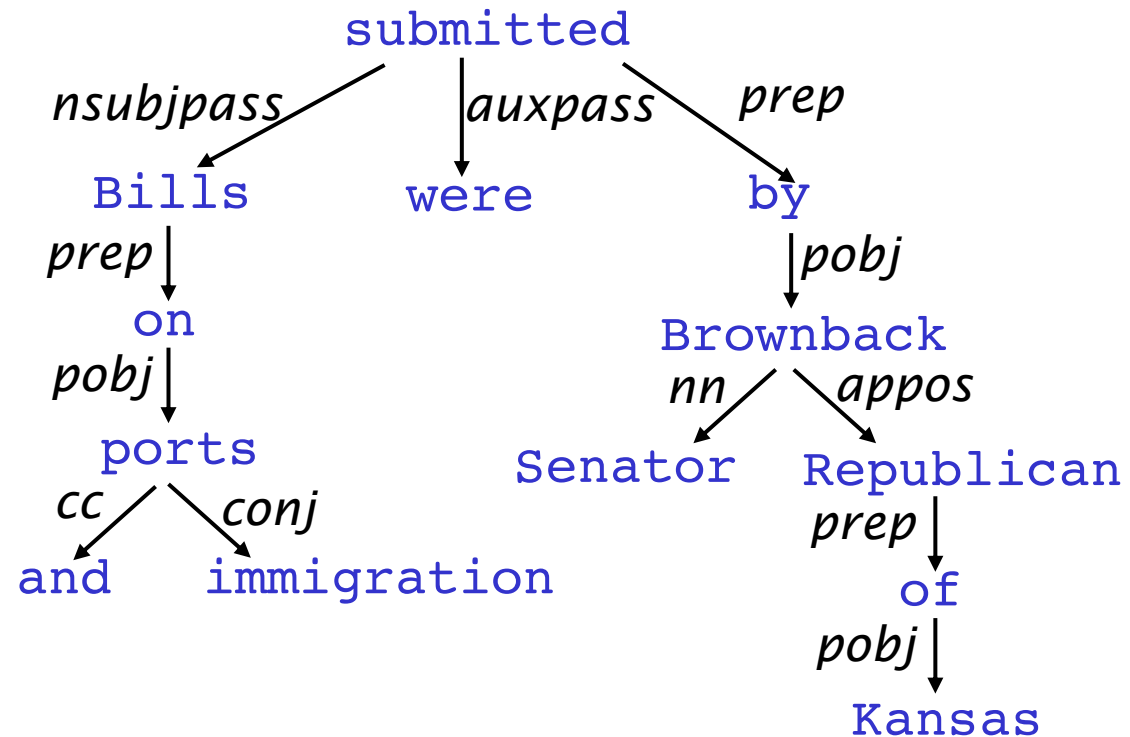
Bills on ports and immigration were submitted by Senator Brownback,  
Republican of Kansas.

# Dependency Grammar and Dependency Structure

Dependency syntax postulates that syntactic structure consists of lexical items linked by binary asymmetric relations (“arrows”) called dependencies

The arrow connects a **head** (governor, superior, regent) with a **dependent** (modifier, inferior, subordinate)

Usually, dependencies form a tree (connected, acyclic, single-head)

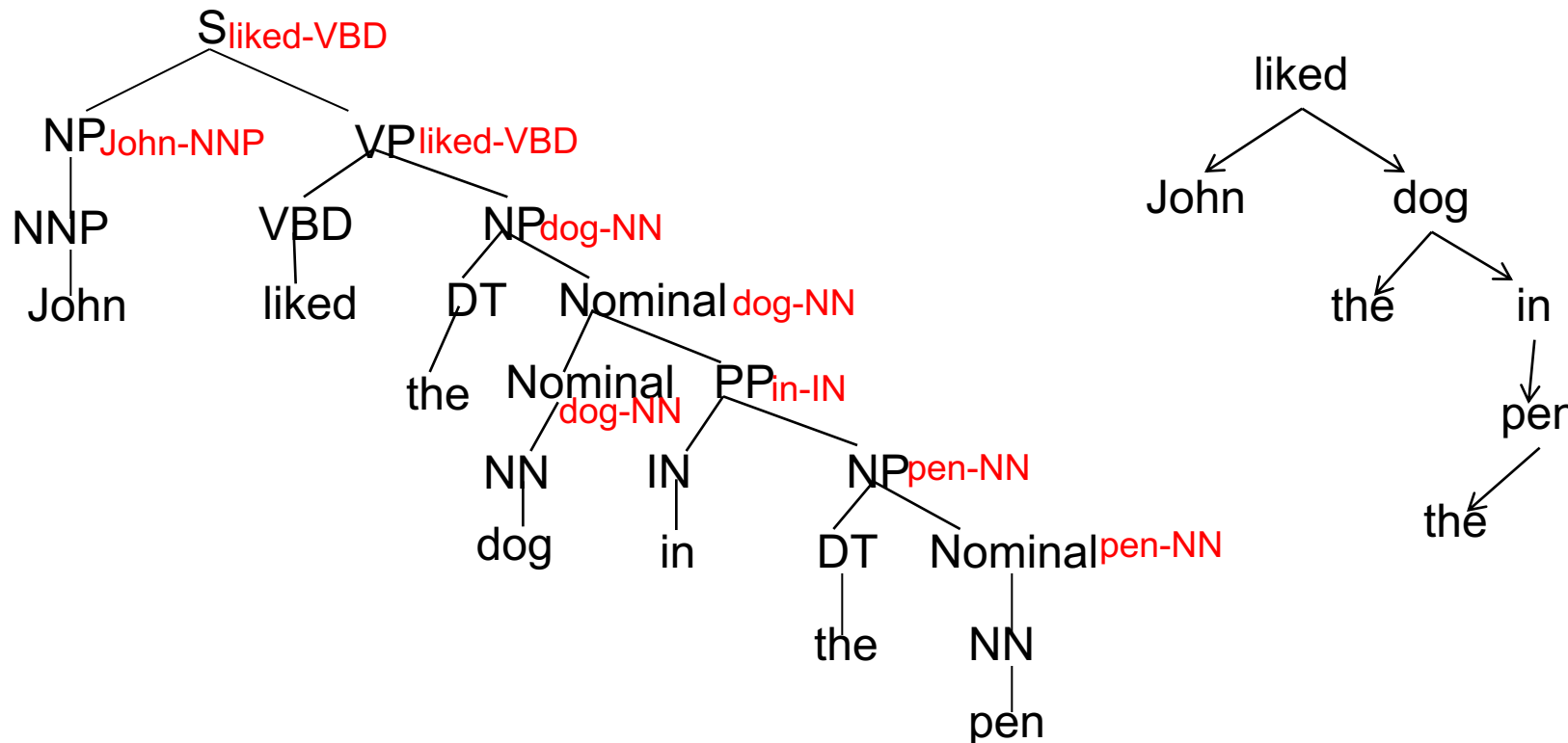


# Relation between phrase structure and dependency structure

- A dependency grammar has a notion of a head. Officially, CFGs don't.
- But modern linguistic theory and all modern statistical parsers (Charniak, Collins, Stanford, ...) do, via hand-written phrasal “head rules”:
  - The head of a Noun Phrase is a noun/number/adj/...
  - The head of a Verb Phrase is a verb/modal/....
- The head rules can be used to extract a dependency parse from a CFG parse

# Dependency Graph from Parse Tree

- Can convert a phrase structure parse to a dependency tree by making the head of each non-head child of a node depend on the head of the head child.



Like a depth first search