

Algoritmer og Datastrukturer 2

Gerth Stølting Brodal

Dynamisk Programmering
[CLRS 15]



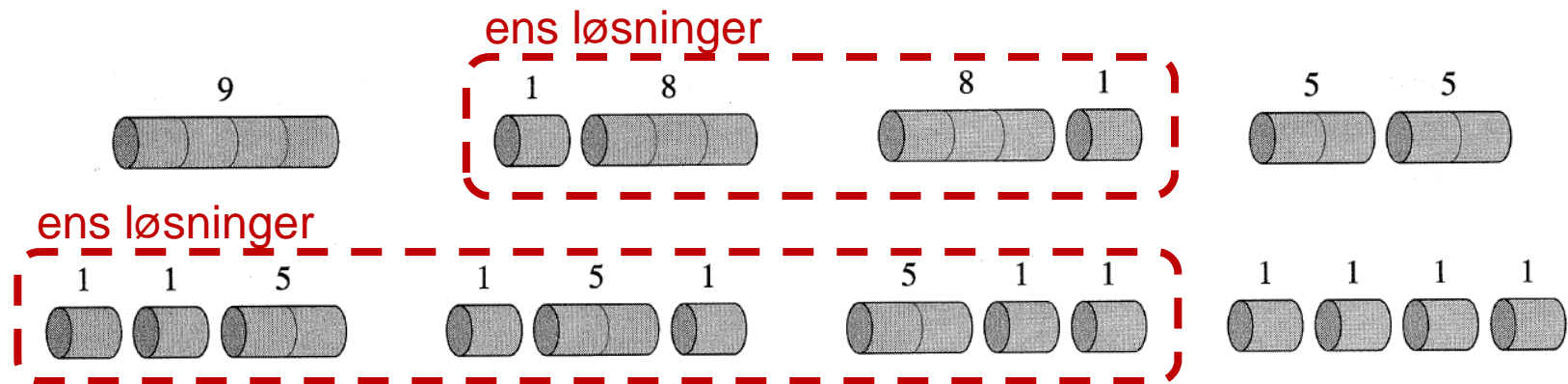
AARHUS UNIVERSITET

Dynamisk Programmering

- **Generel algoritmisk teknik** – virker for mange (men langt fra alle) problemer
- **Krav:** "Optimal delstruktur" – en løsning til problemet kan konstrueres ud fra optimale løsninger til "**delproblemer**"
- **Rekursive løsning:**
 - Typisk eksponentiel tid
- **Dynamisk Programmering:**
 - Beregn delløsninger systematisk
 - Typisk polynomiel tid

Dynamisk Programmering: Optimal opdeling af en stang

Problem: Opdel en stang i dele, hvor hver del har en pris, således at den resulterende sum er maksimereret



En stang af længde 4 kan opdeles 8 forskellige måder – dog kun 5 forskellige resultater

length i	1	2	3	4	5	6	7	8	9	10
price p_i	1	5	8	9	10	17	17	20	24	30

Optimal opdeling af stænger af længde 1..10

Bedste pris

Opdeling

$r_1 = 1$	$1 = 1$ (no cuts) ,
$r_2 = 5$	$2 = 2$ (no cuts) ,
$r_3 = 8$	$3 = 3$ (no cuts) ,
$r_4 = 10$	$4 = 2 + 2$,
$r_5 = 13$	$5 = 2 + 3$,
$r_6 = 17$	$6 = 6$ (no cuts) ,
$r_7 = 18$	$7 = 1 + 6$ or $7 = 2 + 2 + 3$,
$r_8 = 22$	$8 = 2 + 6$,
$r_9 = 25$	$9 = 3 + 6$,
$r_{10} = 30$	$10 = 10$ (no cuts) .

length i	1	2	3	4	5	6	7	8	9	10
price p_i	1	5	8	9	10	17	17	20	24	30

Optimal opdeling af en stang: Rekursiv løsning

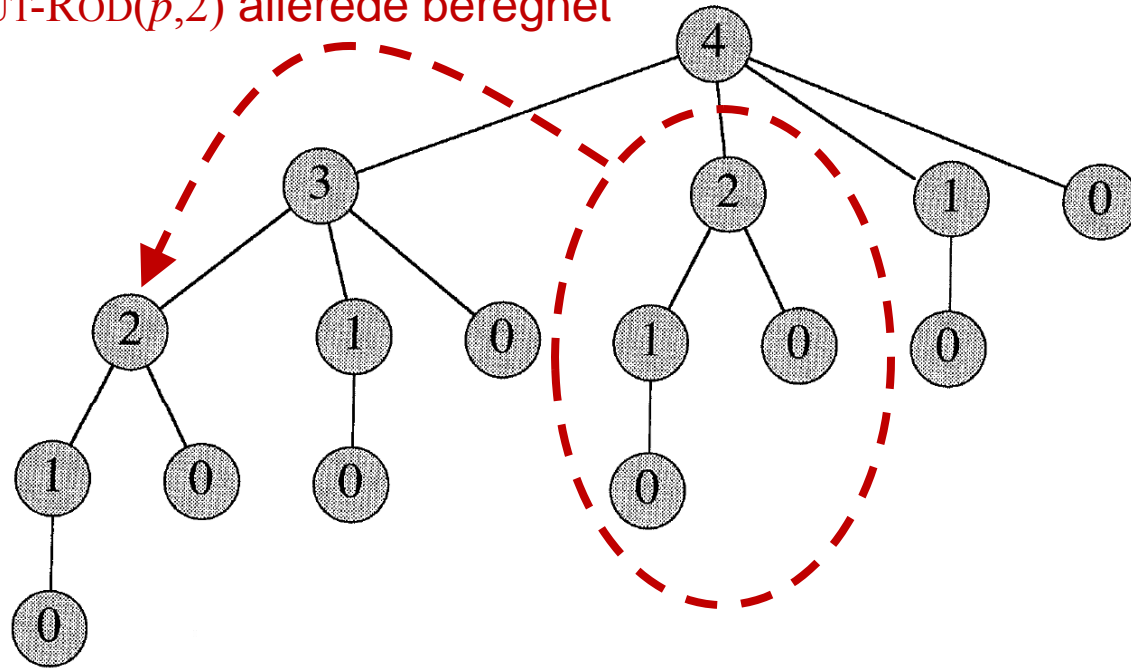
$$r_n = \begin{cases} 0 & \text{hvis } n = 0 \\ \max_{i=1..n} (p_i + r_{n-i}) & \text{ellers} \end{cases}$$

CUT-ROD(p, n)

```
1  if  $n == 0$ 
2      return 0
3   $q = -\infty$ 
4  for  $i = 1$  to  $n$ 
5       $q = \max(q, p[i] + \text{CUT-ROD}(p, n - i))$ 
6  return  $q$ 
```

Optimal opdeling af en stang: Rekursiv løsning

CUT-ROD($p, 2$) allerede beregnet

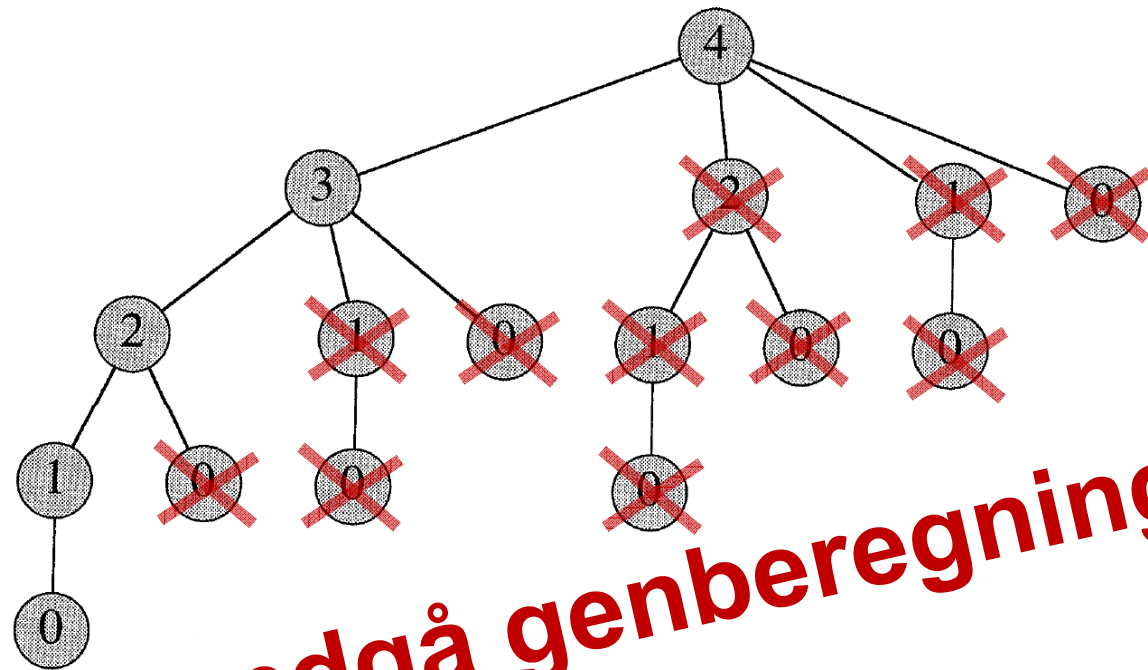


CUT-ROD(p, n)

```
1  if  $n == 0$ 
2      return 0
3   $q = -\infty$ 
4  for  $i = 1$  to  $n$ 
5       $q = \max(q, p[i] + \text{CUT-ROD}(p, n - i))$ 
6  return  $q$ 
```

Tid $O(2^n)$

Optimal opdeling af en stang: Rekursiv løsning



undgå genberegning?

CUT-ROD(p, n)

- 1 **if** $n == 0$
- 2 **return** 0
- 3 $q = -\infty$
- 4 **for** $i = 1$ **to** n
- 5 $q = \max(q, p[i] + \text{CUT-ROD}(p, n - i))$
- 6 **return** q

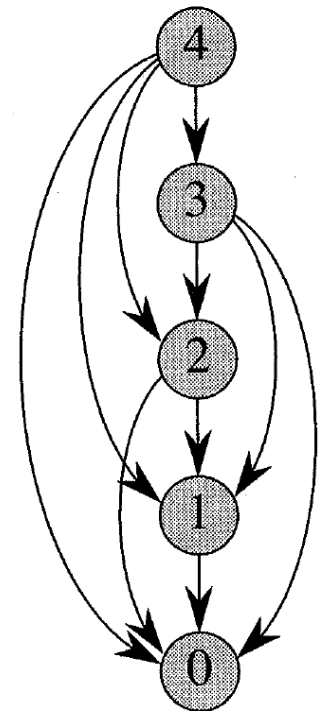
Optimal opdeling af en stang: Rekursiv løsning + Memoization

MEMOIZED-CUT-ROD(p, n)

```
1  let  $r[0..n]$  be a new array
2  for  $i = 0$  to  $n$ 
3       $r[i] = -\infty$ 
4  return MEMOIZED-CUT-ROD-AUX( $p, n, r$ )
```

MEMOIZED-CUT-ROD-AUX(p, n, r)

```
1  if  $r[n] \geq 0$ 
2      return  $r[n]$ 
3  if  $n == 0$ 
4       $q = 0$ 
5  else  $q = -\infty$ 
6      for  $i = 1$  to  $n$ 
7           $q = \max(q, p[i] + \text{MEMOIZED-CUT-ROD-AUX}(p, n - i, r))$ 
8   $r[n] = q$  ← - husk resultatet !
9  return  $q$ 
```

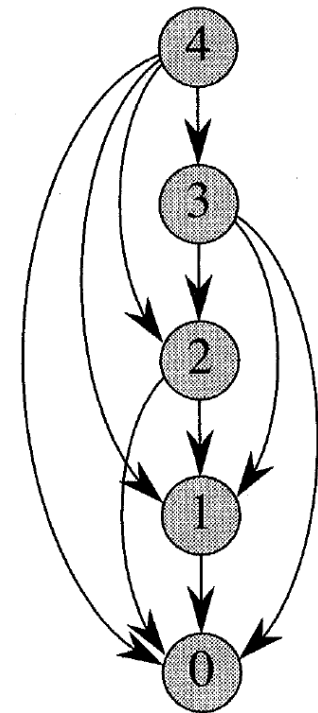


Tid $O(n^2)$

Optimal opdeling af en stang: Systematisk udfyldning

BOTTOM-UP-CUT-ROD(p, n)

```
1 let  $r[0..n]$  be a new array
2  $r[0] = 0$ 
3 for  $j = 1$  to  $n$  ← — rækkefølgen vigtig !
4      $q = -\infty$ 
5     for  $i = 1$  to  $j$ 
6          $q = \max(q, p[i] + r[j - i])$ 
7      $r[j] = q$ 
8 return  $r[n]$ 
```



Tid $O(n^2)$

Optimal opdeling af en stang: Udskrivning af løsningen

EXTENDED-BOTTOM-UP-CUT-ROD(p, n)

```
1  let  $r[0..n]$  and  $s[0..n]$  be new arrays
2   $r[0] = 0$ 
3  for  $j = 1$  to  $n$ 
4       $q = -\infty$ 
5      for  $i = 1$  to  $j$ 
6          if  $q < p[i] + r[j - i]$ 
7               $q = p[i] + r[j - i]$ 
8               $s[j] = i$ 
9       $r[j] = q$ 
10 return  $r$  and  $s$ 
```

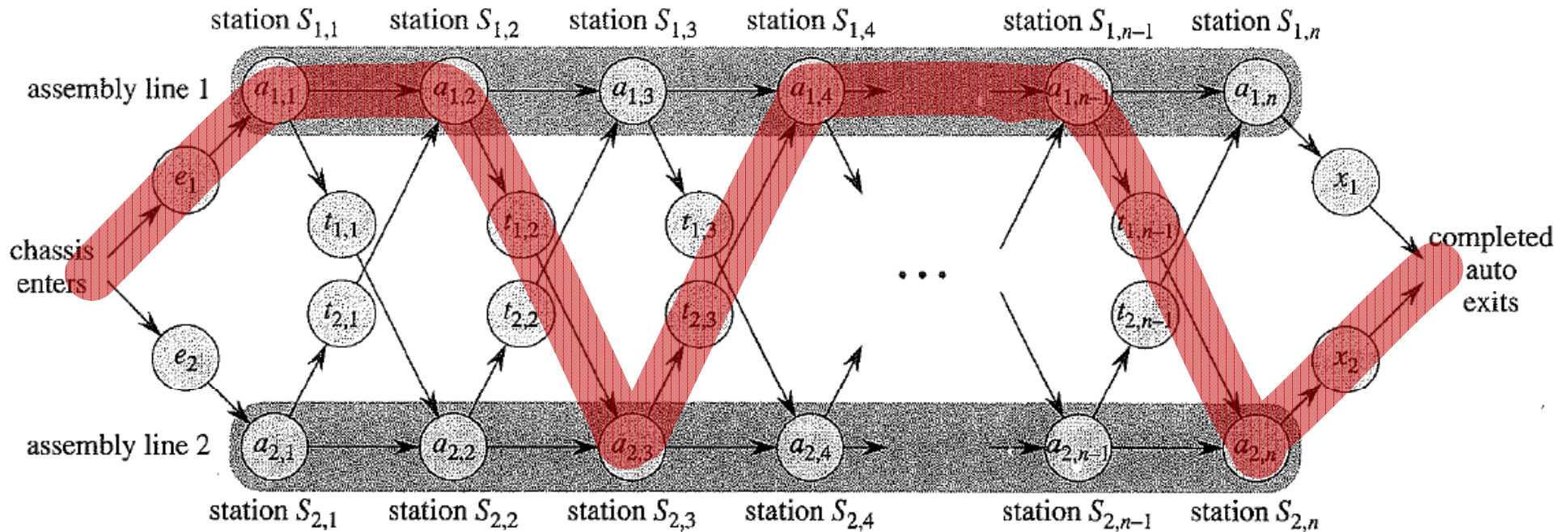
i	0	1	2	3	4	5	6	7	8	9	10
$r[i]$	0	1	5	8	10	13	17	18	22	25	30
$s[i]$	0	1	2	3	2	2	6	1	2	3	10

PRINT-CUT-ROD-SOLUTION(p, n)

```
1  ( $r, s$ ) = EXTENDED-BOTTOM-UP-CUT-ROD( $p, n$ )
2  while  $n > 0$ 
3      print  $s[n]$ 
4       $n = n - s[n]$ 
```

Tid $O(n^2+n)$

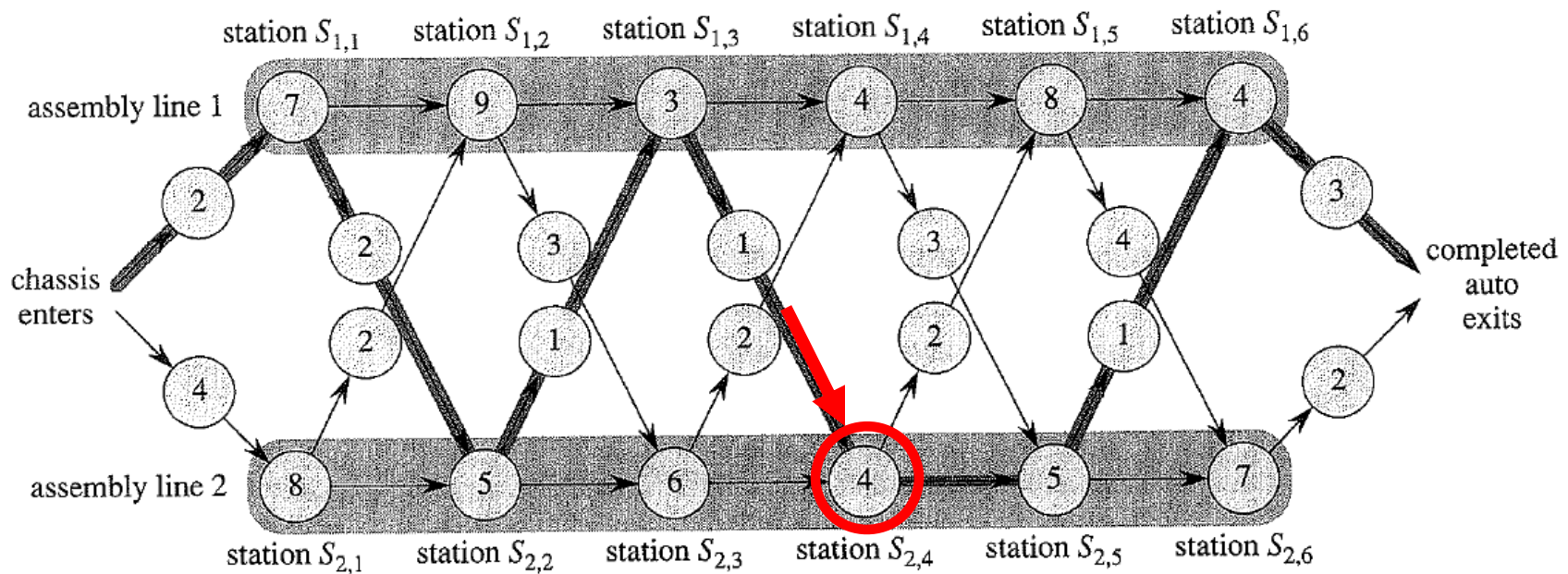
”Colonel Motors Corporation”



Mål Find en hurtigste vej fra ”Chassis enters” til ”completed auto” – knuderne angiver hvor lang tid de forskellige ting tager

Naive algoritme Prøv alle 2^n forskellige veje – tid $\Omega(2^n)$

”Colonel Motors Corporation”



(a)

j	1	2	3	4	5	6
$f_1[j]$	9	18	20	24	32	35
$f_2[j]$	12	16	22	25	30	37

$f^* = 38$

Korteste tid til og med stationerne

j	2	3	4	5	6
$l_1[j]$	1	2	1	1	2
$l_2[j]$	1	2	1	2	2

$l^* = 1$

(b)

Forrige station for hurtigste løsning

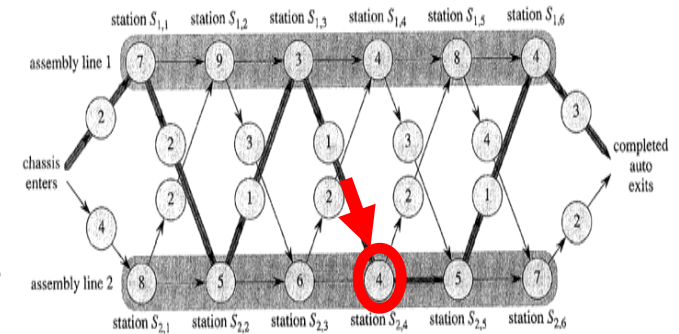
”Colonel Motors Corporation”

FASTEST-WAY (a, t, e, x, n)

```

1   $f_1[1] \leftarrow e_1 + a_{1,1}$ 
2   $f_2[1] \leftarrow e_2 + a_{2,1}$ 
3  for  $j \leftarrow 2$  to  $n$ 
4      do if  $f_1[j - 1] + a_{1,j} \leq f_2[j - 1] + t_{2,j-1} + a_{1,j}$ 
5          then  $f_1[j] \leftarrow f_1[j - 1] + a_{1,j}$ 
6               $l_1[j] \leftarrow 1$ 
7          else  $f_1[j] \leftarrow f_2[j - 1] + t_{2,j-1} + a_{1,j}$ 
8               $l_1[j] \leftarrow 2$ 
9      if  $f_2[j - 1] + a_{2,j} \leq f_1[j - 1] + t_{1,j-1} + a_{2,j}$ 
10         then  $f_2[j] \leftarrow f_2[j - 1] + a_{2,j}$ 
11              $l_2[j] \leftarrow 2$ 
12         else  $f_2[j] \leftarrow f_1[j - 1] + t_{1,j-1} + a_{2,j}$ 
13              $l_2[j] \leftarrow 1$ 
14 if  $f_1[n] + x_1 \leq f_2[n] + x_2$ 
15     then  $f^* = f_1[n] + x_1$ 
16          $l^* = 1$ 
17     else  $f^* = f_2[n] + x_2$ 
18          $l^* = 2$ 

```



(a)

j	1	2	3	4	5	6
$f_1[j]$	9	18	20	24	32	35
$f_2[j]$	12	16	22	25	31	37

$f^* = 38$

(b)

j	2	3	4	5	6
$l_1[j]$	1	2	1	1	2
$l_2[j]$	1	2	1	2	2

$l^* = 1$

Længden af den hurtigste vej findes i tid $O(n)$

”Colonel Motors Corporation”

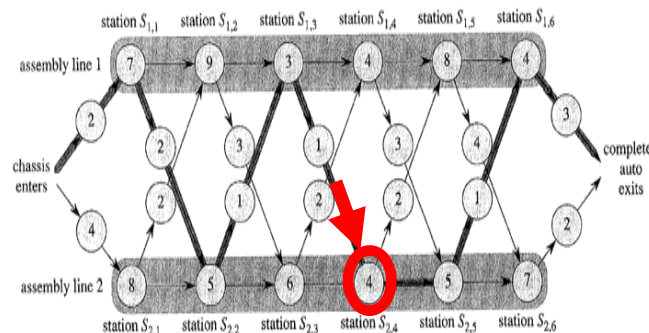
PRINT-STATIONS (l, n)

```

1   $i \leftarrow l^*$ 
2  print “line ”  $i$  “, station ”  $n$ 
3  for  $j \leftarrow n$  downto 2
4      do  $i \leftarrow l_i[j]$ 
5      print “line ”  $i$  “, station ”  $j - 1$ 

```

line 1, station 6
 line 2, station 5
 line 2, station 4
 line 1, station 3
 line 2, station 2
 line 1, station 1



(a)

j	1	2	3	4	5	6
$f_1(l)$	9	18	20	24	32	35
$f_2(l)$	12	16	22	25	31	37

$f^* = 38$

j	2	3	4	5	6
$l_1(l)$	1	2	1	1	2
$l_2(l)$	1	2	1	2	2

$f^* = 1$

(b)

Gå ”baglæns”
 igennem de
 beregnede
 værdier, og
 find løsningen

Matrix-kæde Multiplikation

MATRIX-MULTIPLY(A, B)

```
1  if  $A.columns \neq B.rows$ 
2      error "incompatible dimensions"
3  else let  $C$  be a new  $A.rows \times B.columns$  matrix
4      for  $i = 1$  to  $A.rows$ 
5          for  $j = 1$  to  $B.columns$ 
6               $c_{ij} = 0$ 
7              for  $k = 1$  to  $A.columns$ 
8                   $c_{ij} = c_{ij} + a_{ik} \cdot b_{kj}$ 
9      return  $C$ 
```

Multiplikation af to matricer A og B af størrelse

$p_1 \times p_2$ og $p_2 \times p_3$ tager tid $O(p_1 \cdot p_2 \cdot p_3)$

Matrix-kæde Multiplikation

$(A \cdot B) \cdot C$ eller $A \cdot (B \cdot C)$?

Matrix multiplikation er associativ (kan sætte paranteser som man vil) men ikke kommutative (kan ikke bytte rundt på rækkefølgen af matricerne)

Matrix-kæde Multiplikation

Problem: Find den bedste rækkefølge (paranteser) for at gange n matricer sammen

$$A_1 \cdot A_2 \cdot \dots \cdot A_n$$

hvor A_i er en $p_{i-1} \times p_i$ matrice

NB: Der er $\Omega(4^n/n^{3/2})$ mulige måder for paranteserne

Matrix-kæde Multiplikation

$m[i, j]$ = minimale antal (primitive) multiplikationer for at beregne $A_i \cdot \dots \cdot A_j$

$$m[i, j] = \begin{cases} 0 & \text{if } i = j, \\ \min_{i \leq k < j} \{m[i, k] + m[k + 1, j] + p_{i-1}p_kp_j\} & \text{if } i < j. \end{cases}$$

RECURSIVE-MATRIX-CHAIN(p, i, j)

```
1  if  $i == j$ 
2      return 0
3   $m[i, j] = \infty$ 
4  for  $k = i$  to  $j - 1$ 
5       $q =$  RECURSIVE-MATRIX-CHAIN( $p, i, k$ )
           + RECURSIVE-MATRIX-CHAIN( $p, k + 1, j$ )
           +  $p_{i-1}p_kp_j$ 
6      if  $q < m[i, j]$ 
7           $m[i, j] = q$ 
8  return  $m[i, j]$ 
```

Tid $\Omega(4^n/n^{3/2})$

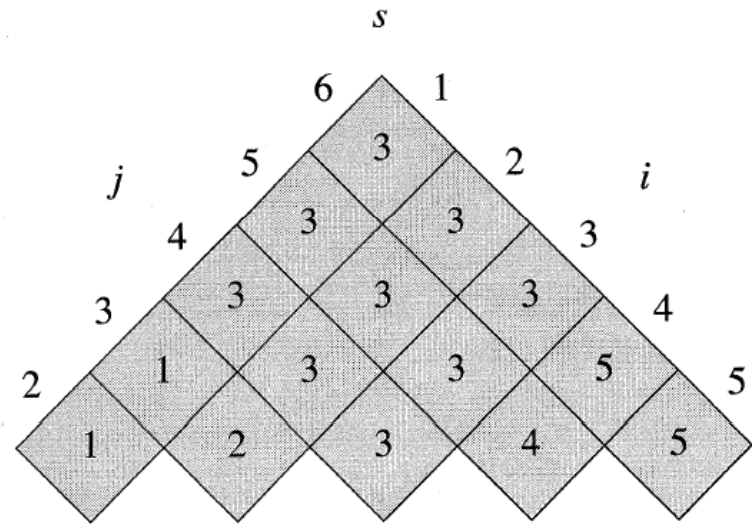
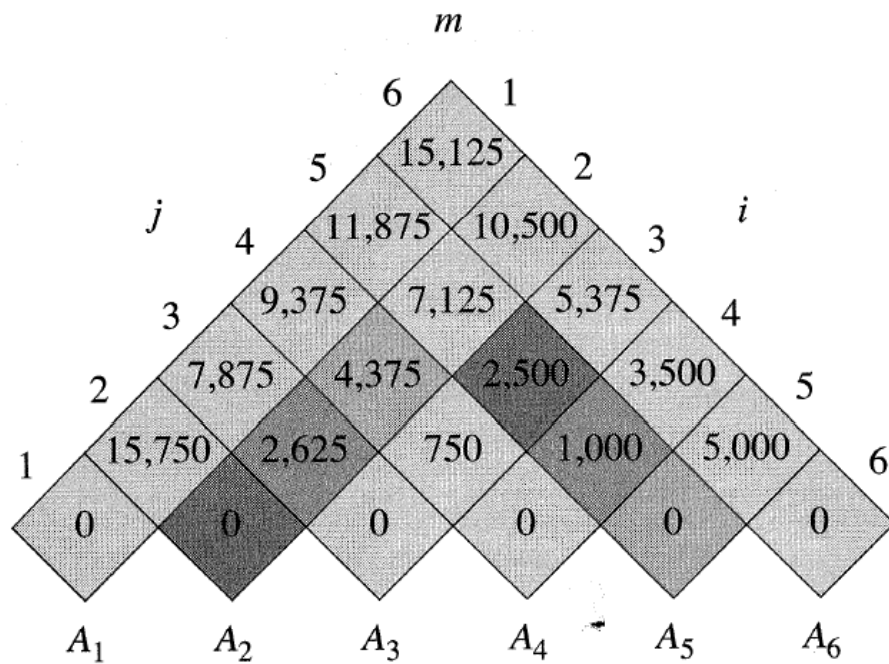
Matrix-kæde Multiplikation

MATRIX-CHAIN-ORDER(p)

```
1   $n = p.length - 1$ 
2  let  $m[1..n, 1..n]$  and  $s[1..n - 1, 2..n]$  be new tables
3  for  $i = 1$  to  $n$ 
4       $m[i, i] = 0$ 
5  for  $l = 2$  to  $n$            //  $l$  is the chain length
6      for  $i = 1$  to  $n - l + 1$ 
7           $j = i + l - 1$ 
8           $m[i, j] = \infty$ 
9          for  $k = i$  to  $j - 1$ 
10              $q = m[i, k] + m[k + 1, j] + p_{i-1}p_kp_j$ 
11             if  $q < m[i, j]$ 
12                  $m[i, j] = q$ 
13                  $s[i, j] = k$ 
14  return  $m$  and  $s$ 
```

Tid $O(n^3)$

Matrix-kæde Multiplikation



matrix	A_1	A_2	A_3	A_4	A_5	A_6
dimension	30×35	35×15	15×5	5×10	10×20	20×25

Matrix-kæde Multiplikation

PRINT-OPTIMAL-PARENS(s, i, j)

```
1  if  $i == j$ 
2      print " $A$ " $i$ 
3  else print "("
4      PRINT-OPTIMAL-PARENS( $s, i, s[i, j]$ )
5      PRINT-OPTIMAL-PARENS( $s, s[i, j] + 1, j$ )
6      print ")"
```

Tid $O(n)$

”Memoized” Matrix-kæde Multiplikation

MEMOIZED-MATRIX-CHAIN(p)

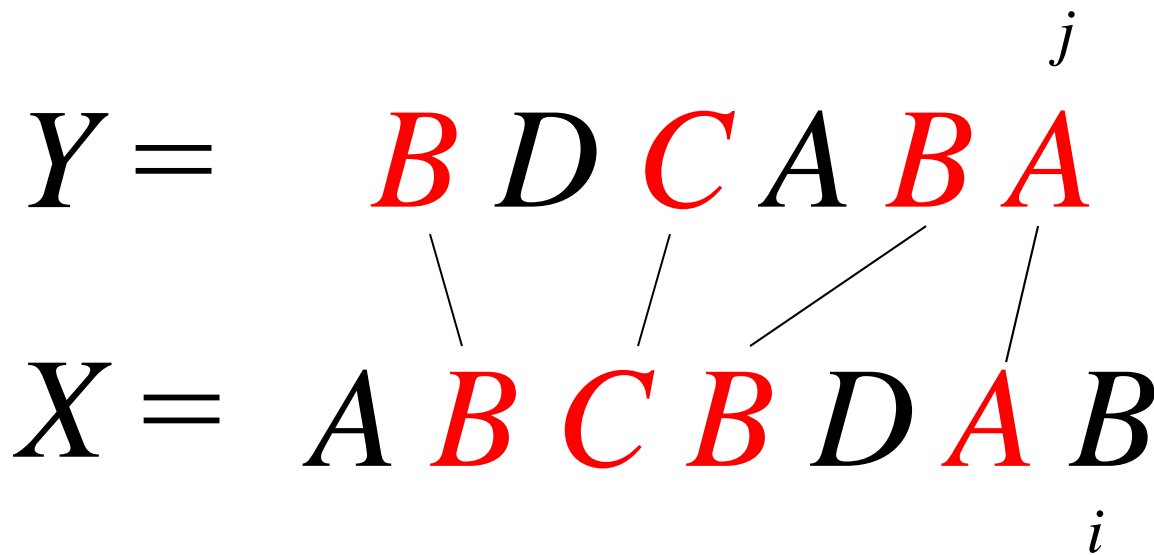
```
1   $n = p.length - 1$ 
2  let  $m[1..n, 1..n]$  be a new table
3  for  $i = 1$  to  $n$ 
4      for  $j = i$  to  $n$ 
5           $m[i, j] = \infty$ 
6  return LOOKUP-CHAIN( $m, p, 1, n$ )
```

LOOKUP-CHAIN(m, p, i, j)

```
1  if  $m[i, j] < \infty$ 
2      return  $m[i, j]$ 
3  if  $i == j$ 
4       $m[i, j] = 0$ 
5  else for  $k = i$  to  $j - 1$ 
6       $q = \text{LOOKUP-CHAIN}(m, p, i, k)$ 
           +  $\text{LOOKUP-CHAIN}(m, p, k + 1, j) + p_{i-1}p_kp_j$ 
7      if  $q < m[i, j]$ 
8           $m[i, j] = q$ 
9  return  $m[i, j]$ 
```

Tid $O(n^3)$

Længste Fælles Delsekvens



$$c[i, j] = \begin{cases} 0 & \text{if } i = 0 \text{ or } j = 0, \\ c[i - 1, j - 1] + 1 & \text{if } i, j > 0 \text{ and } x_i = y_j, \\ \max(c[i, j - 1], c[i - 1, j]) & \text{if } i, j > 0 \text{ and } x_i \neq y_j. \end{cases}$$

længden af en længste fælles delsekvens af $x_1x_2 \dots x_i$ og $y_1y_2 \dots y_j$

Længste Fælles Delsekvens

j	0	1	2	3	4	5	6
i	y_j	B	D	C	A	B	A
0	x_i	0	0	0	0	0	0
1	A	0	↑	↑	↑	↖1	↖1
2	B	0	↖1	↖1	↖1	↑1	↖2
3	C	0	↑1	↑1	↖2	↖2	↑2
4	B	0	↖1	↑1	↑2	↑2	↖3
5	D	0	↑1	↖2	↑2	↑2	↖3
6	A	0	↑1	↑2	↑2	↖3	↑3
7	B	0	↖1	↑2	↑2	↑3	↖4



$$c[i, j] = \begin{cases} 0 & \text{if } i = 0 \text{ or } j = 0, \\ c[i - 1, j - 1] + 1 & \text{if } i, j > 0 \text{ and } x_i = y_j, \\ \max(c[i, j - 1], c[i - 1, j]) & \text{if } i, j > 0 \text{ and } x_i \neq y_j. \end{cases}$$

Længste Fælles Delsekvens

LCS-LENGTH(X, Y)

```

1   $m = X.length$ 
2   $n = Y.length$ 
3  let  $b[1..m, 1..n]$  and  $c[0..m, 0..n]$  be new tables
4  for  $i = 1$  to  $m$ 
5       $c[i, 0] = 0$ 
6  for  $j = 0$  to  $n$ 
7       $c[0, j] = 0$ 
8  for  $i = 1$  to  $m$ 
9      for  $j = 1$  to  $n$ 
10         if  $x_i == y_j$ 
11              $c[i, j] = c[i - 1, j - 1] + 1$ 
12              $b[i, j] = \text{“}\nearrow\text{”}$ 
13         elseif  $c[i - 1, j] \geq c[i, j - 1]$ 
14              $c[i, j] = c[i - 1, j]$ 
15              $b[i, j] = \text{“}\uparrow\text{”}$ 
16         else  $c[i, j] = c[i, j - 1]$ 
17              $b[i, j] = \text{“}\leftarrow\text{”}$ 
18  return  $c$  and  $b$ 

```

		j	0	1	2	3	4	5	6
		y_j		B	D	C	A	B	A
i	x_i	0	0	0	0	0	0	0	0
1	A	0	↑	↑	↑	↖	1	←	1
2	B	0	↖	1	←	1	↑	2	←
3	C	0	↑	↑	↖	2	←	2	↑
4	B	0	↖	1	↑	↑	↑	3	←
5	D	0	↑	↖	2	↑	↑	3	↑
6	A	0	↑	↑	↑	↖	3	↑	4
7	B	0	↖	↑	↑	↑	↖	4	↑

Tid $O(nm)$

Længste Fælles Delsekvens

PRINT-LCS(b, X, i, j)

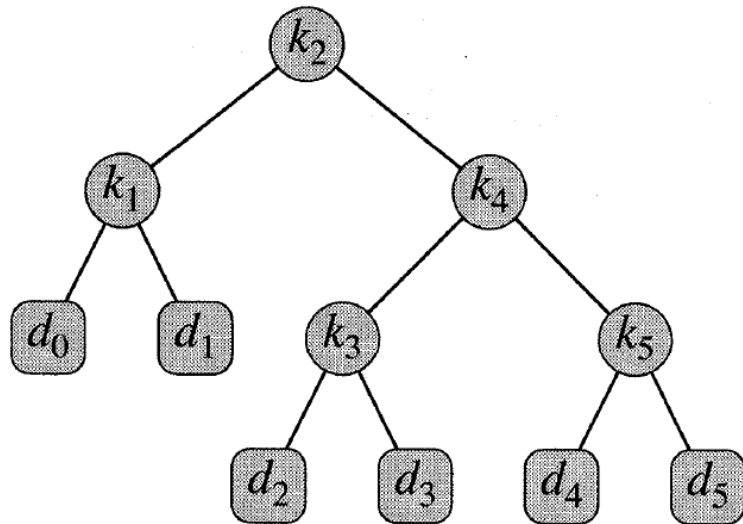
```

1  if  $i == 0$  or  $j == 0$ 
2      return
3  if  $b[i, j] == \swarrow$ 
4      PRINT-LCS( $b, X, i - 1, j - 1$ )
5      print  $x_i$ 
6  elseif  $b[i, j] == \uparrow$ 
7      PRINT-LCS( $b, X, i - 1, j$ )
8  else PRINT-LCS( $b, X, i, j - 1$ )
    
```

		j	0	1	2	3	4	5	6
i	y_j		B	D	C	A	B	A	
	x_i								
0		0	0	0	0	0	0	0	0
1	A	0	\uparrow	\uparrow	\uparrow	\swarrow	1	\leftarrow 1	\swarrow 1
2	B	0	\swarrow	1	\leftarrow 1	\leftarrow 1	\uparrow 1	\swarrow 2	\leftarrow 2
3	C	0	\uparrow 1	\uparrow 1	\swarrow 2	\leftarrow 2	\uparrow 2	\uparrow 2	\uparrow 2
4	B	0	\swarrow 1	\uparrow 1	\uparrow 2	\uparrow 2	\swarrow 3	3	\leftarrow 3
5	D	0	\uparrow 1	\swarrow 2	\uparrow 2	\uparrow 2	\uparrow 3	3	\uparrow 3
6	A	0	\uparrow 1	\uparrow 2	\uparrow 2	\swarrow 3	\uparrow 3	3	\swarrow 4
7	B	0	\swarrow 1	\uparrow 2	\uparrow 2	\uparrow 3	\swarrow 4	4	\uparrow 4

Tid $O(n+m)$

Optimale Binære Søgetræer



Forventet søgetid 2.80

node	depth	probability	contribution
k_1	1	0.15	0.30
k_2	0	0.10	0.10
k_3	2	0.05	0.15
k_4	1	0.10	0.20
k_5	2	0.20	0.60
d_0	2	0.05	0.15
d_1	$(2 + 1) \times$	0.10	$= 0.30$
d_2	3	0.05	0.20
d_3	3	0.05	0.20
d_4	3	0.05	0.20
d_5	3	0.10	0.40
Total			2.80

i	0	1	2	3	4	5
p_i		0.15	0.10	0.05	0.10	0.20
q_i	0.05	0.10	0.05	0.05	0.05	0.10

Optimale Binære Søgetræer

$$\sum_{i=1}^n p_i + \sum_{i=0}^n q_i = 1 \qquad w(i, j) = \sum_{l=i}^j p_l + \sum_{l=i-1}^j q_l$$

$$\begin{aligned} E[\text{search cost in } T] &= \sum_{i=1}^n (\text{depth}_T(k_i) + 1) \cdot p_i + \sum_{i=0}^n (\text{depth}_T(d_i) + 1) \cdot q_i \\ &= 1 + \sum_{i=1}^n \text{depth}_T(k_i) \cdot p_i + \sum_{i=0}^n \text{depth}_T(d_i) \cdot q_i \end{aligned}$$

$$e[i, j] = \begin{cases} q_{i-1} & \text{if } j = i - 1, \\ \min_{i \leq r \leq j} \{e[i, r-1] + e[r+1, j] + w(i, j)\} & \text{if } i \leq j. \end{cases}$$

Optimale Binære Søgetræer

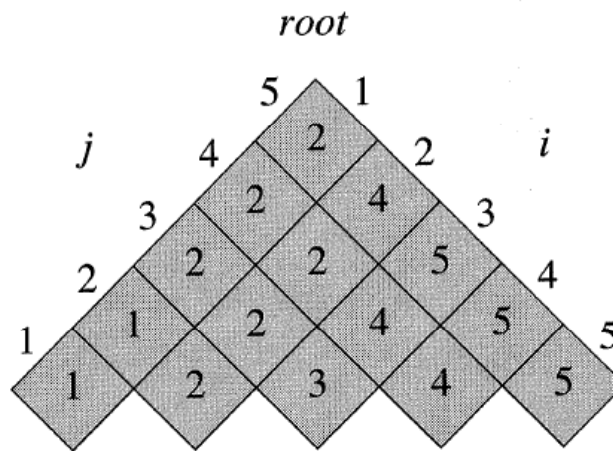
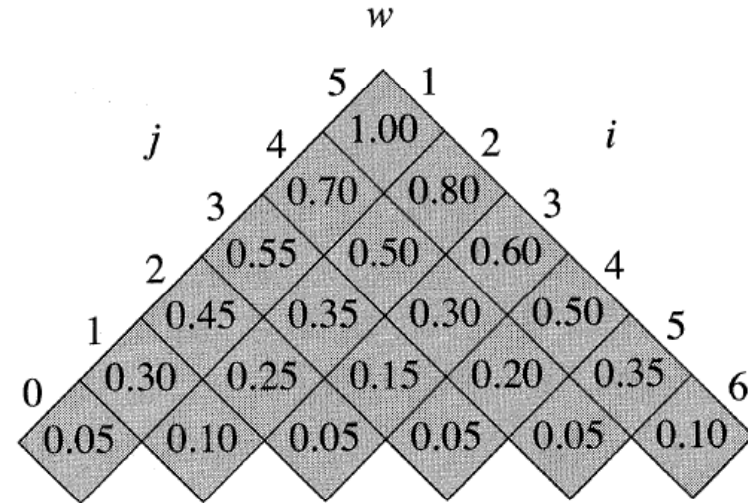
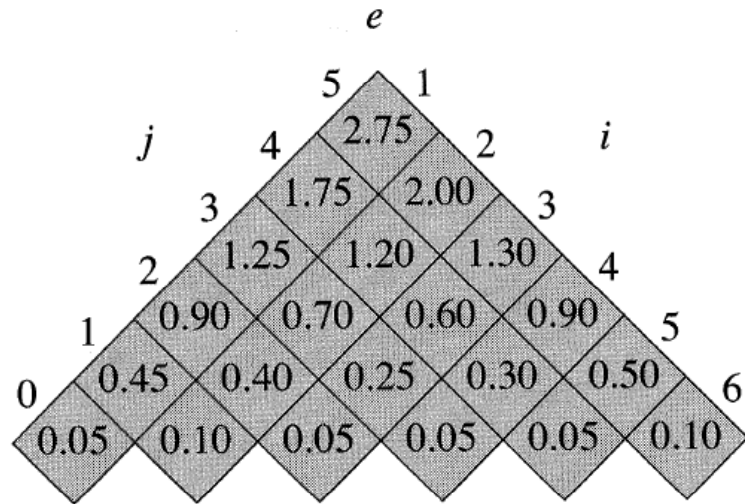
$$e[i, j] = \begin{cases} q_{i-1} & \text{if } j = i - 1, \\ \min_{(r \in E)} \{e[i, r - 1] + e[r + 1, j] + w(i, j)\} & \text{if } i \leq j. \end{cases}$$

OPTIMAL-BST(p, q, n)

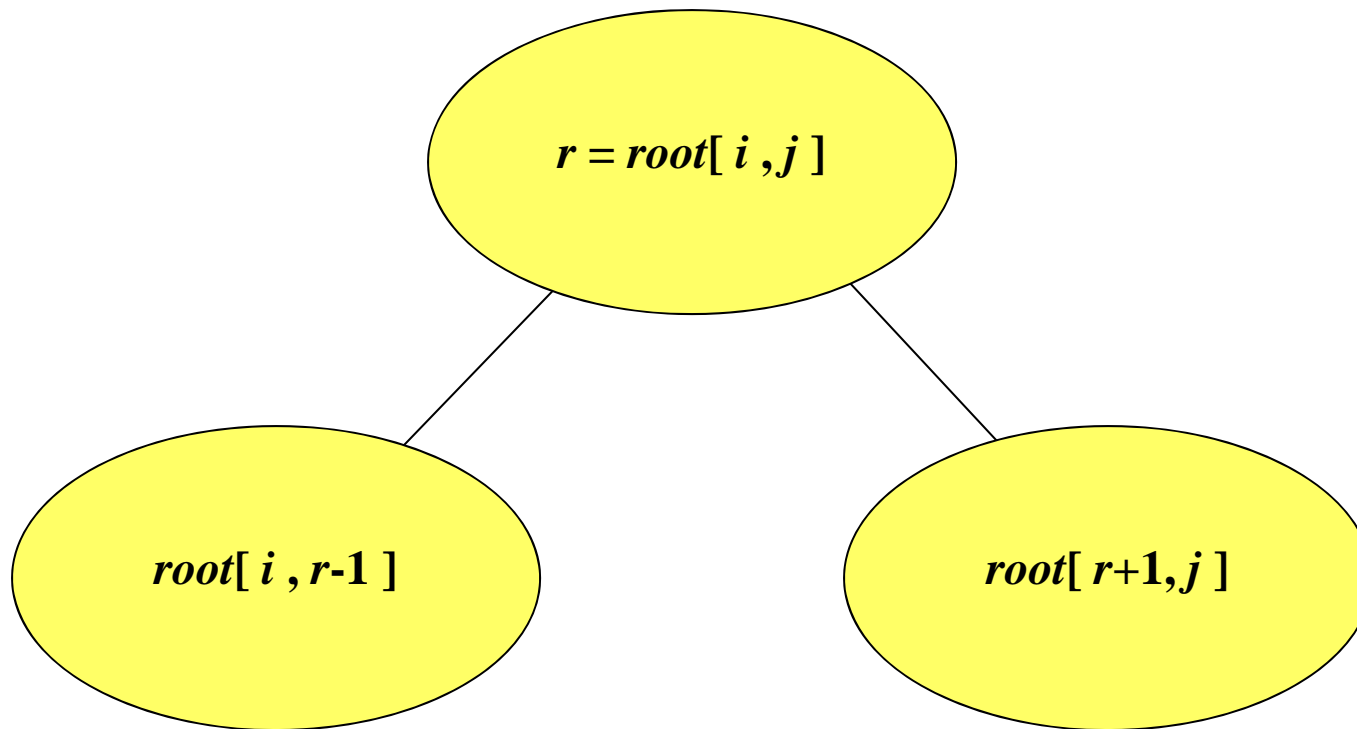
```
1  let  $e[1..n + 1, 0..n]$ ,  $w[1..n + 1, 0..n]$ ,  
    and  $root[1..n, 1..n]$  be new tables  
2  for  $i = 1$  to  $n + 1$   
3       $e[i, i - 1] = q_{i-1}$   
4       $w[i, i - 1] = q_{i-1}$   
5  for  $l = 1$  to  $n$   
6      for  $i = 1$  to  $n - l + 1$   
7           $j = i + l - 1$   
8           $e[i, j] = \infty$   
9           $w[i, j] = w[i, j - 1] + p_j + q_j$   
10         for  $r = i$  to  $j$   
11              $t = e[i, r - 1] + e[r + 1, j] + w[i, j]$   
12             if  $t < e[i, j]$   
13                  $e[i, j] = t$   
14                  $root[i, j] = r$   
15  return  $e$  and  $root$ 
```

Tid $O(n^3)$

Optimale Binære Søgetræer



Konstruktion af Optimalt Binært Søgetræ



Dynamisk Programmering

- **Generel algoritmisk teknik**
- ***Krav:*** "Optimal delstruktur" – en løsning til problemet kan konstrueres ud fra optimale løsninger til "**delproblemer**"
- **Rekursionsligning**
- **Eksempler**
 - Stang opdeling
 - Matrix-kæde multiplikation
 - Længste fælles delsekvens
 - Optimale søgetræer