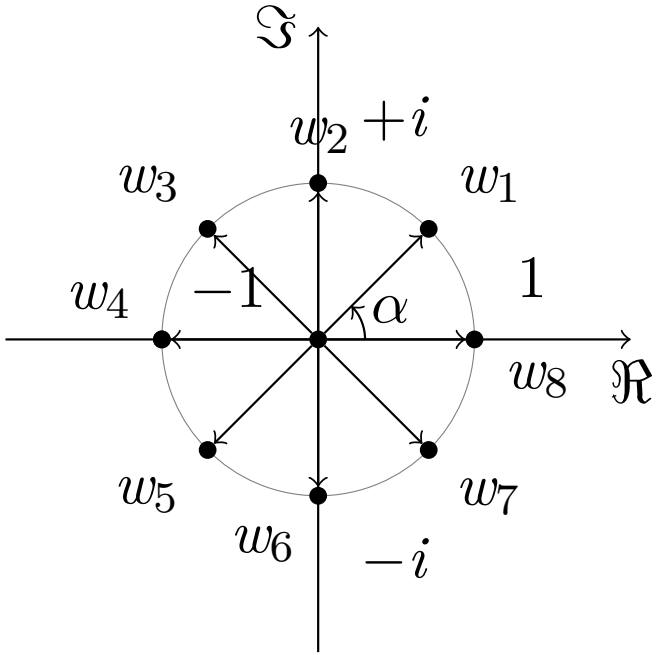
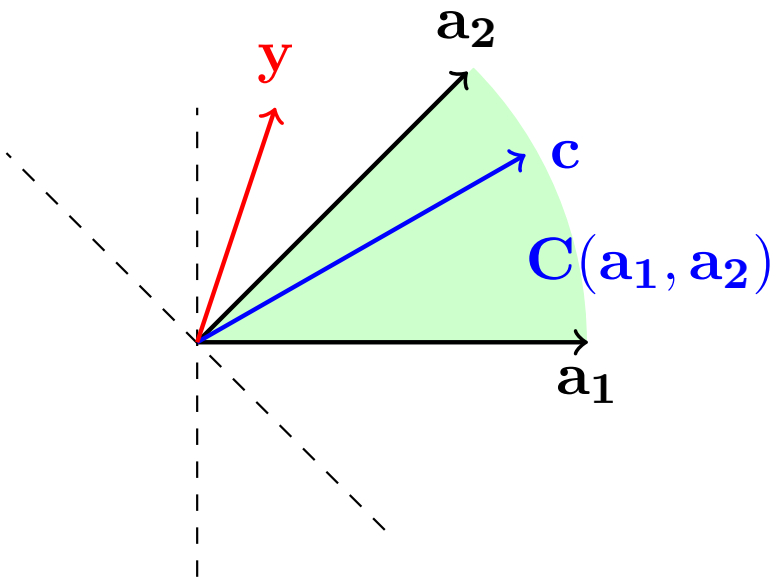
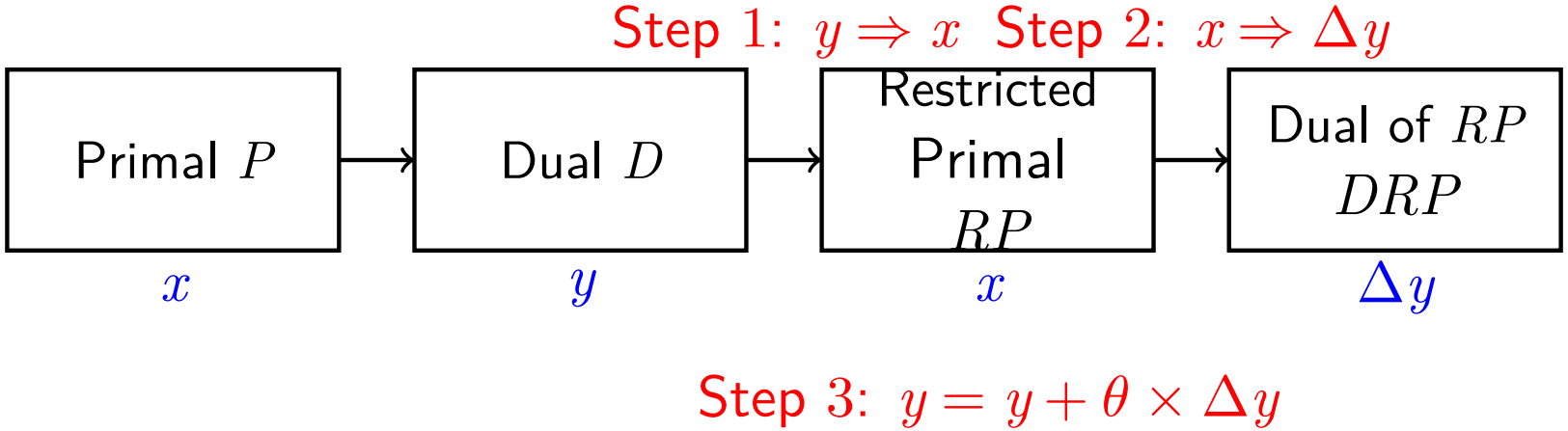
Root of unity



Farkas lemma

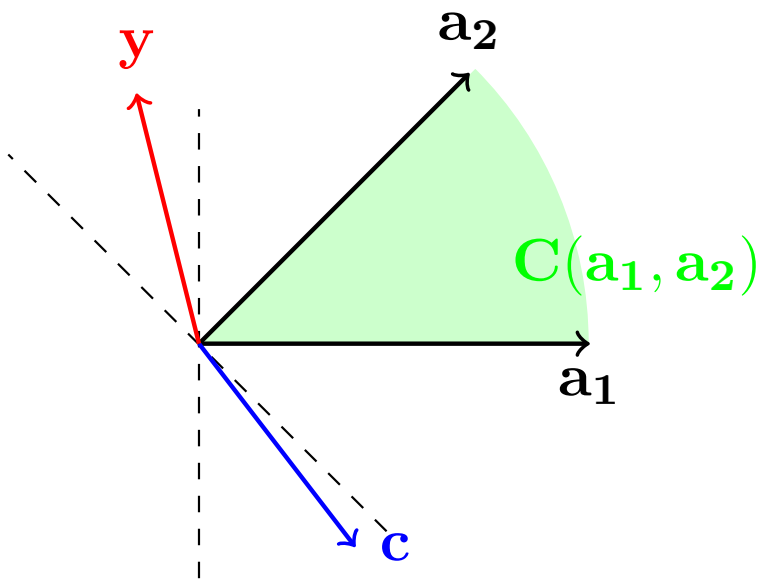


DRP

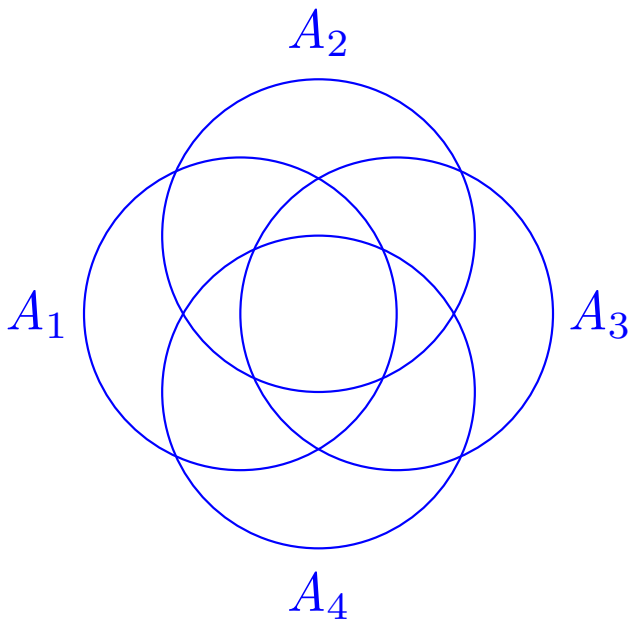


Step 3: $y = y + \theta \times \Delta y$

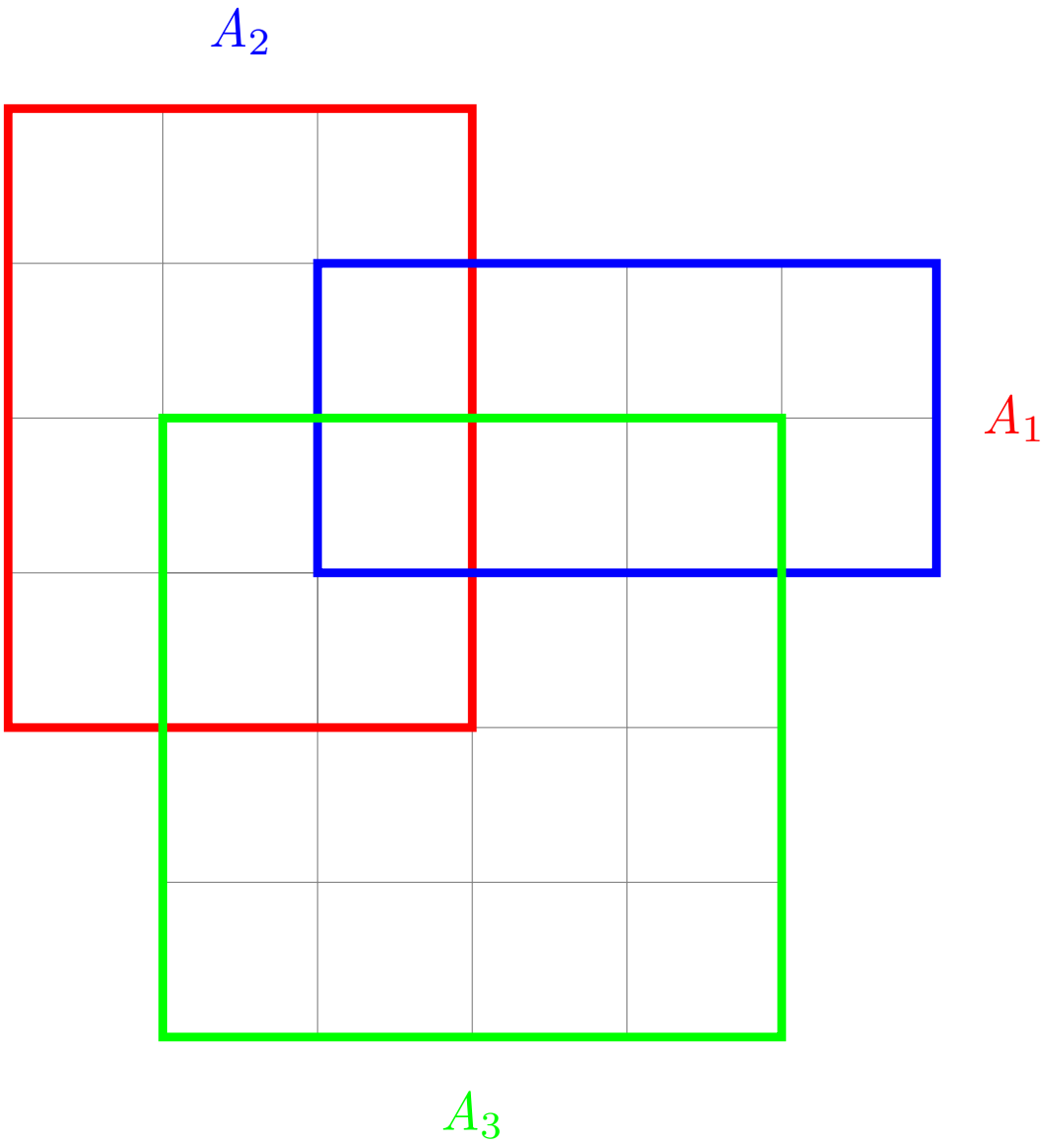
Farkas lemma



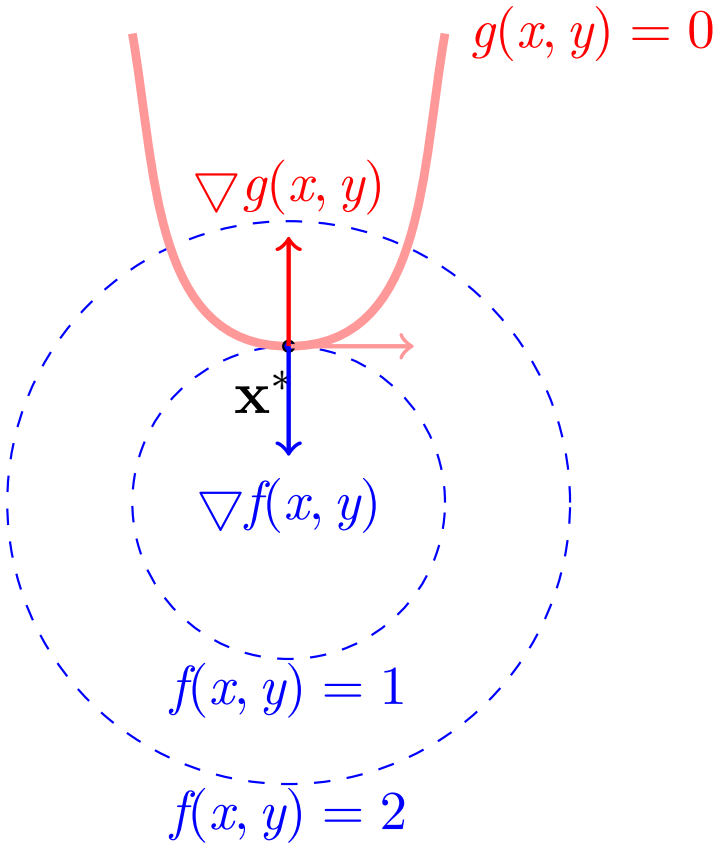
Max Coverage Problem



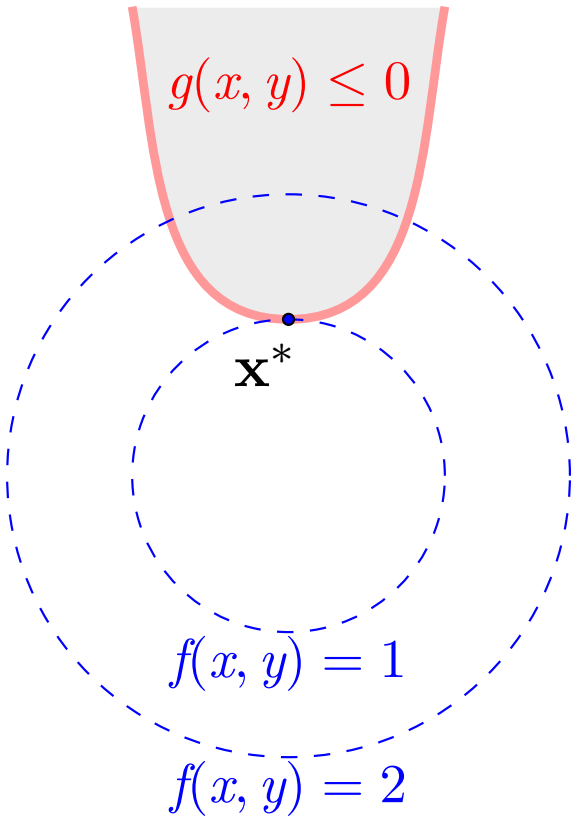
Max Coverage Problem2



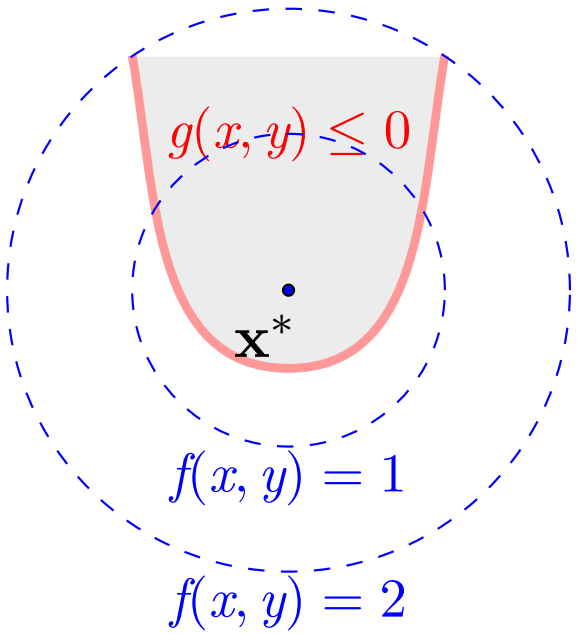
Lagrangian

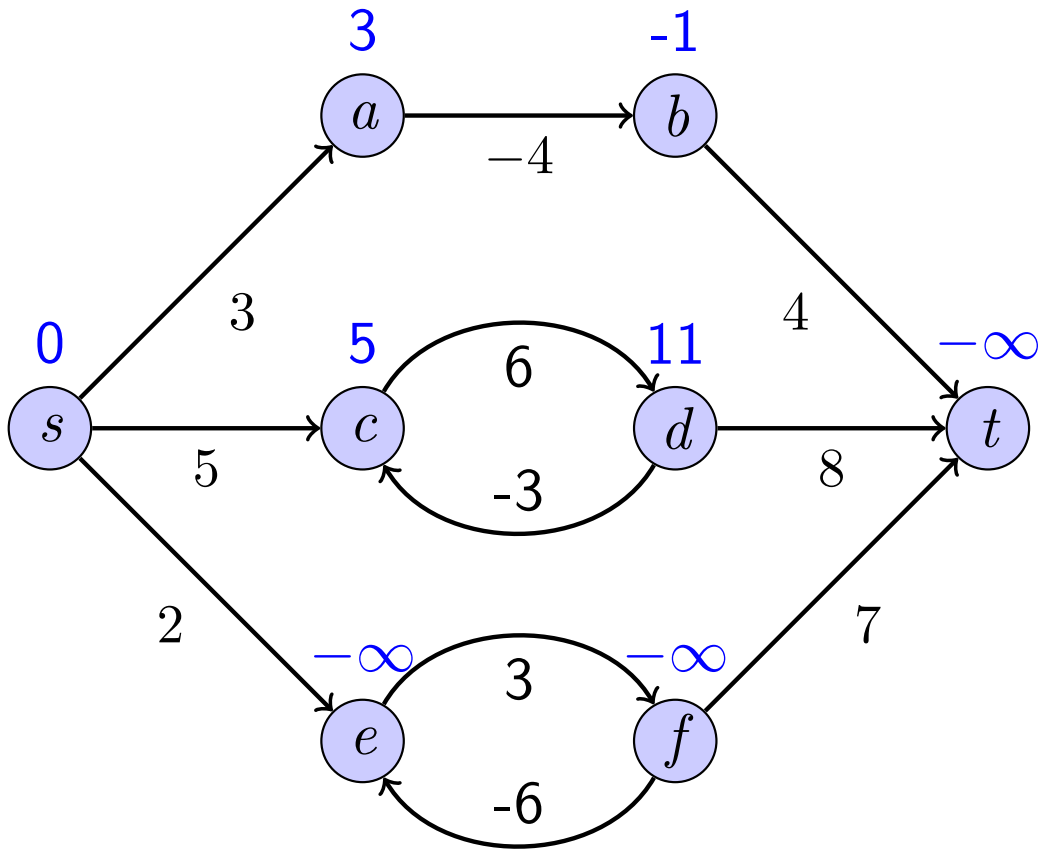


Lagrangian



Lagrangian




3
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a
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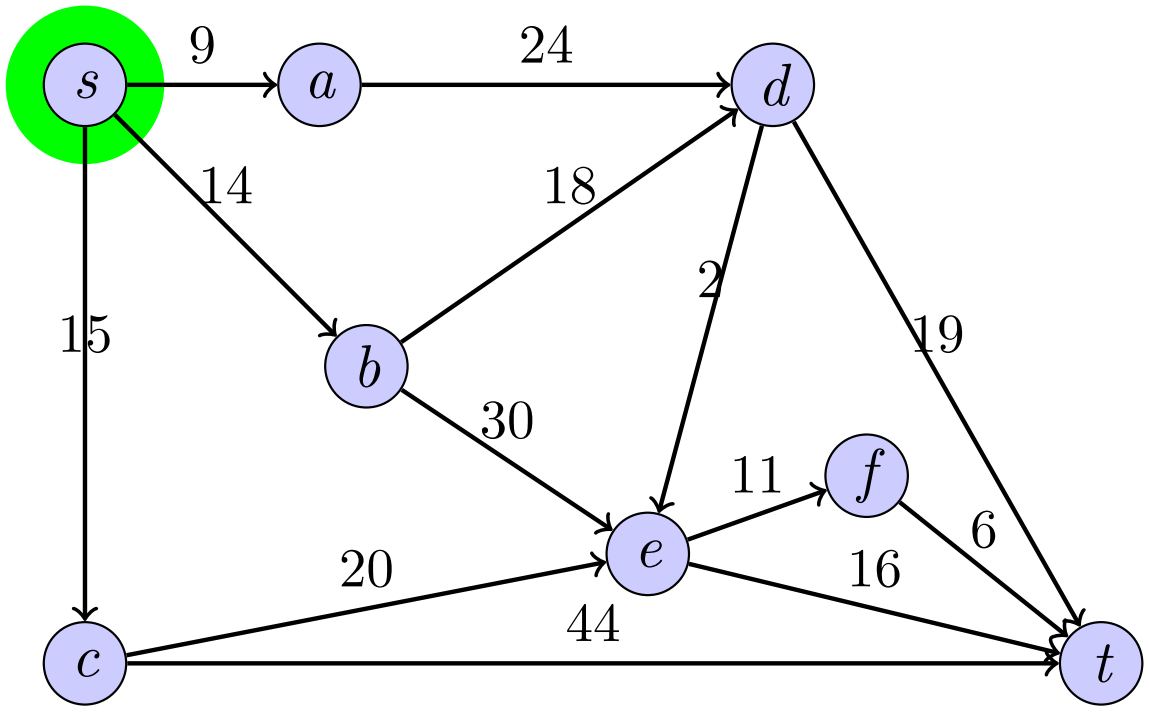
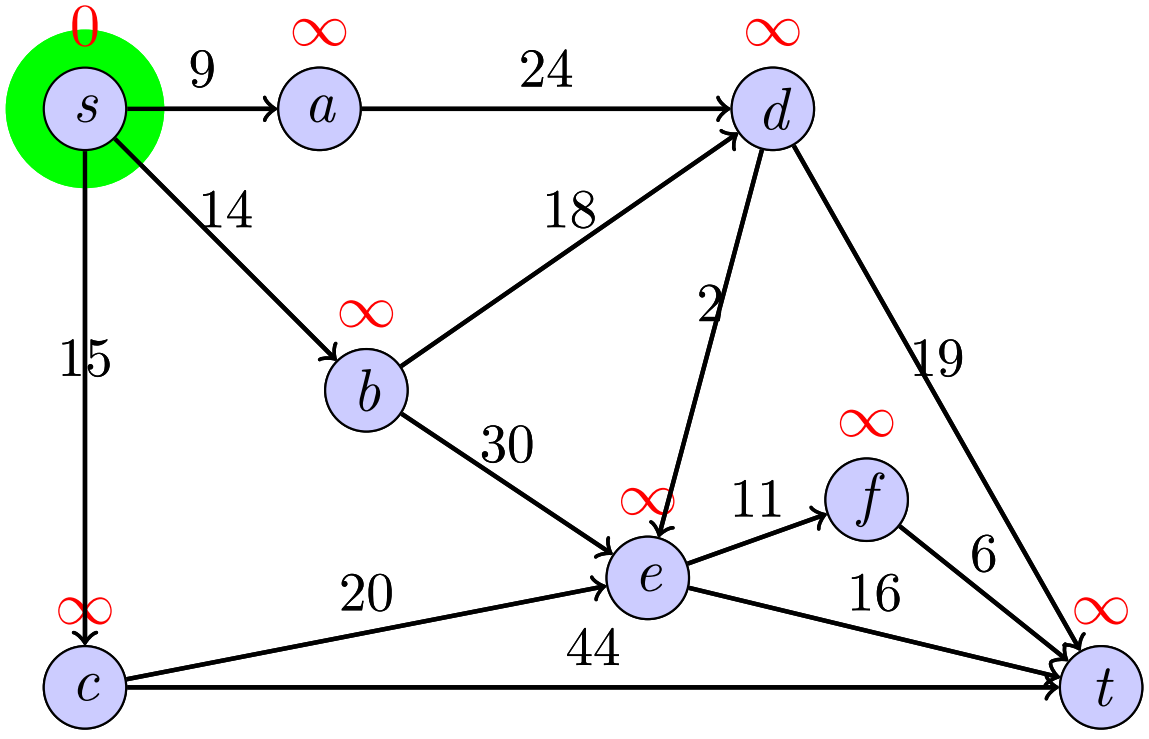
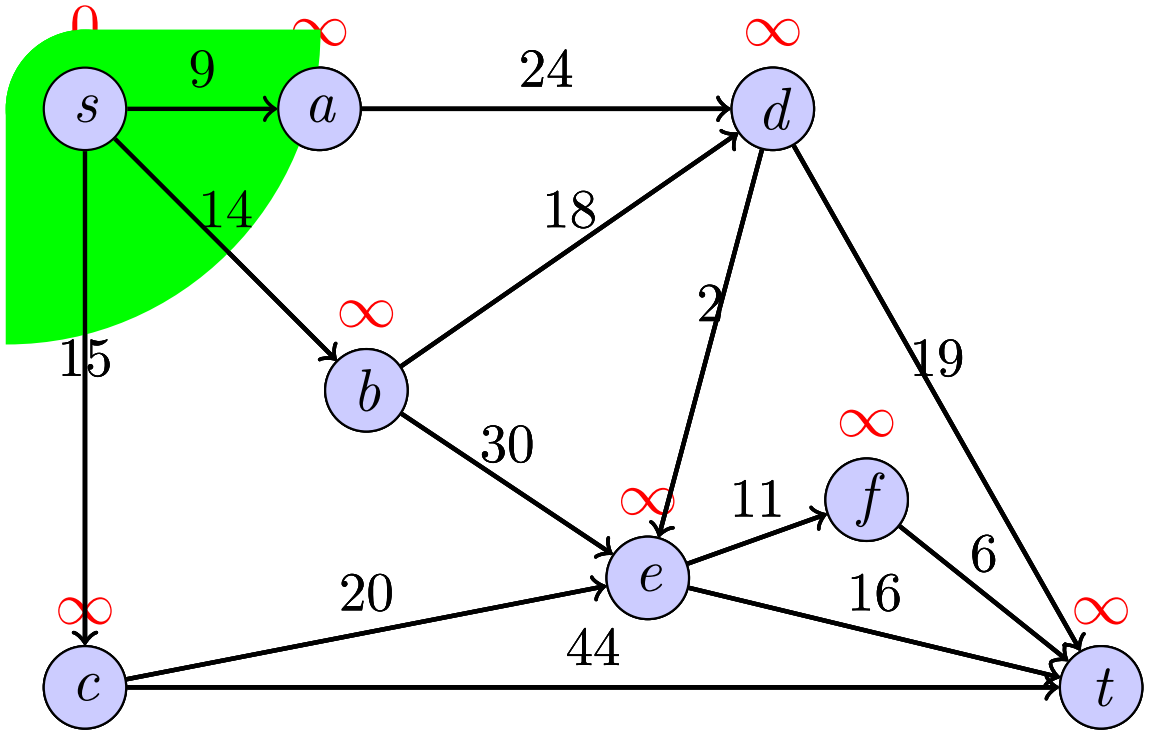
e
f
-6

EEE2



EEE2




0
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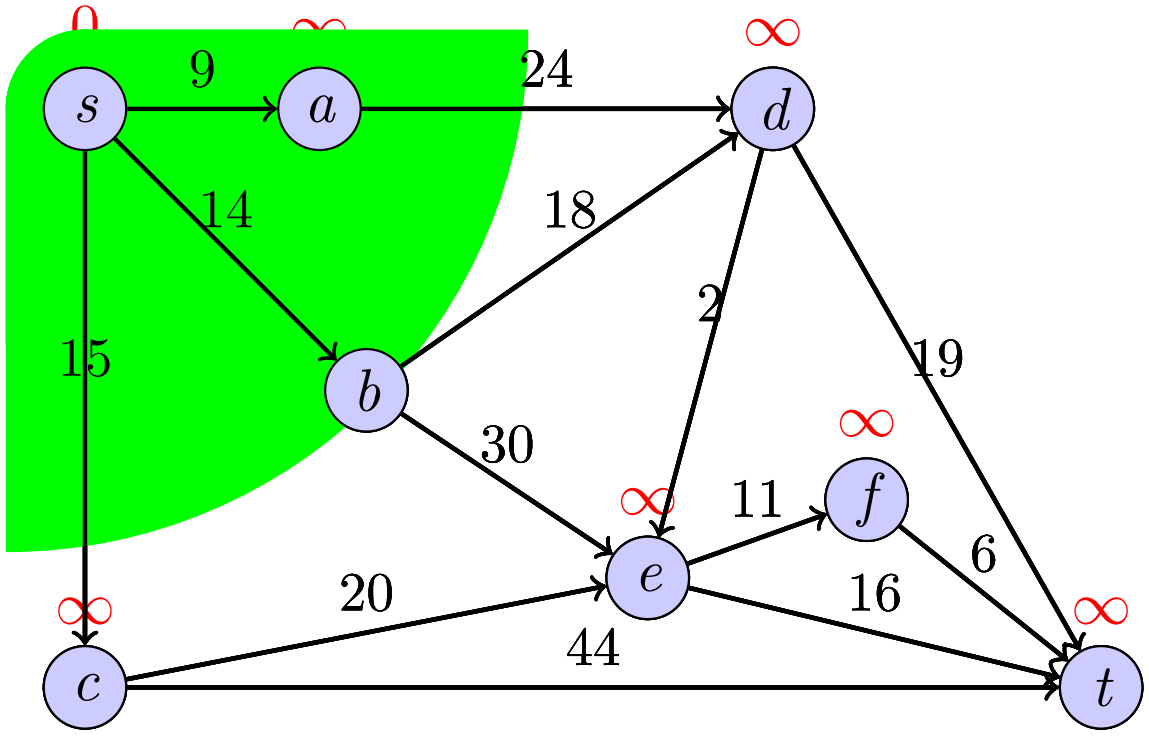
16
44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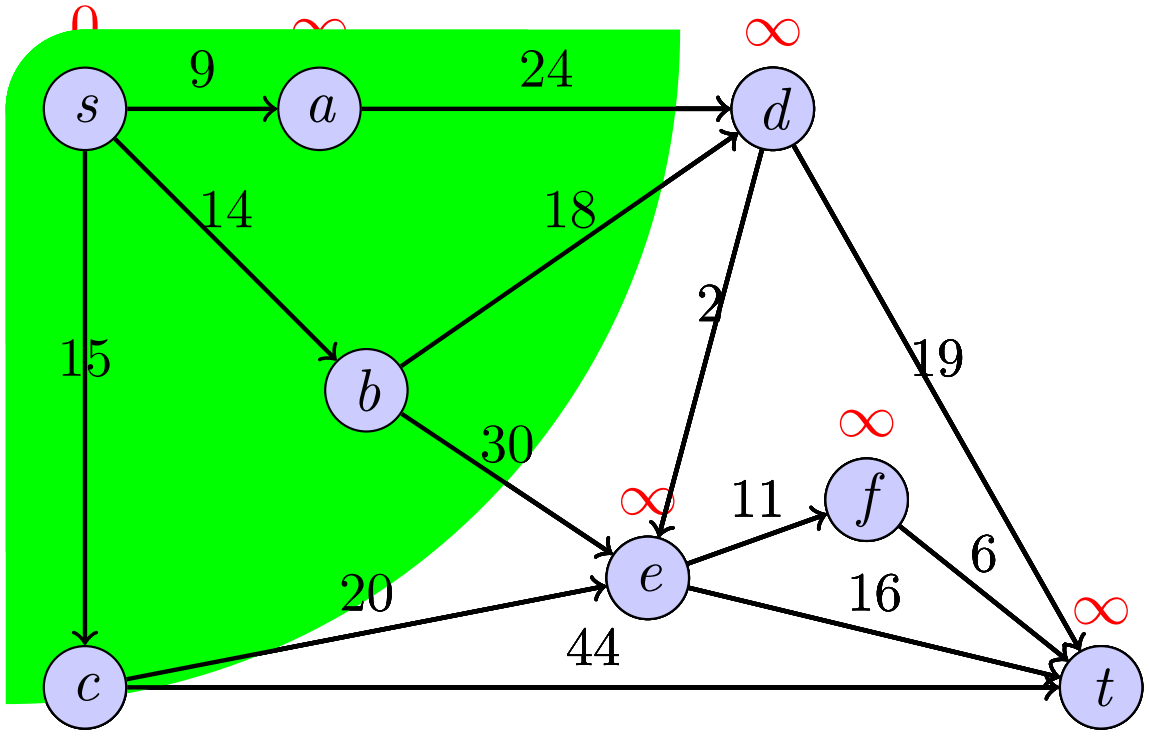
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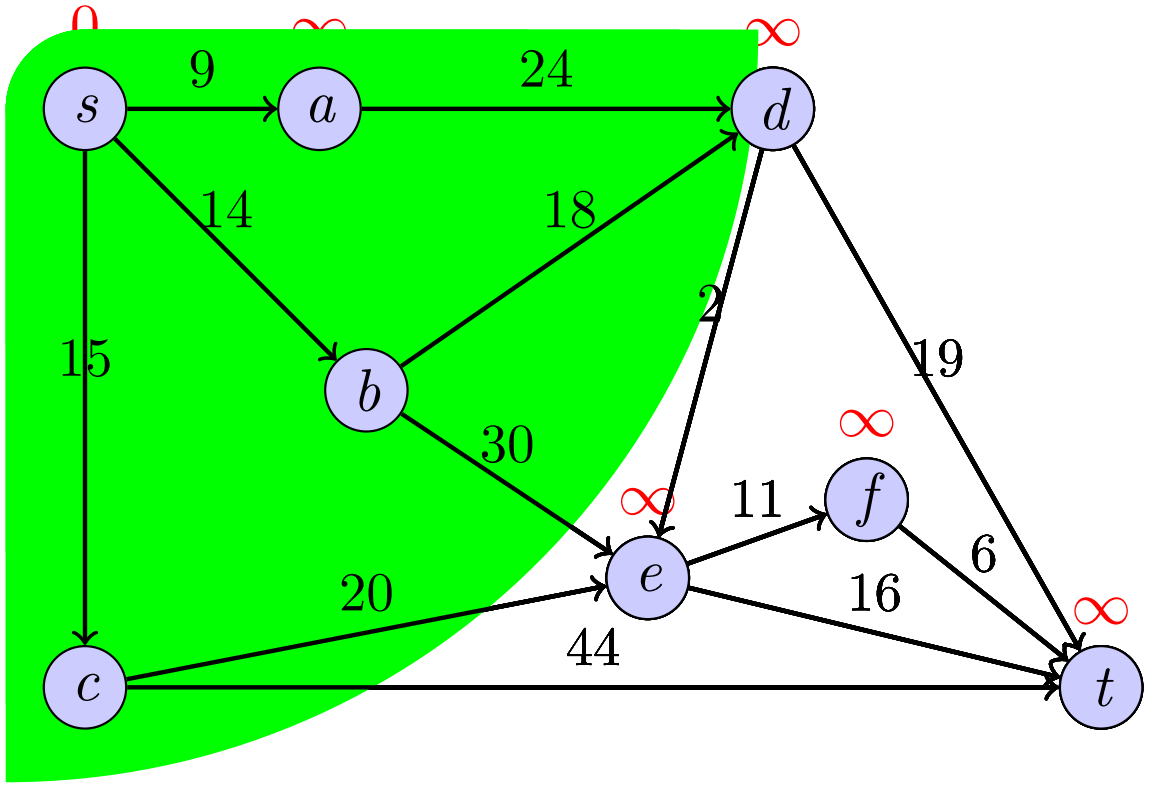
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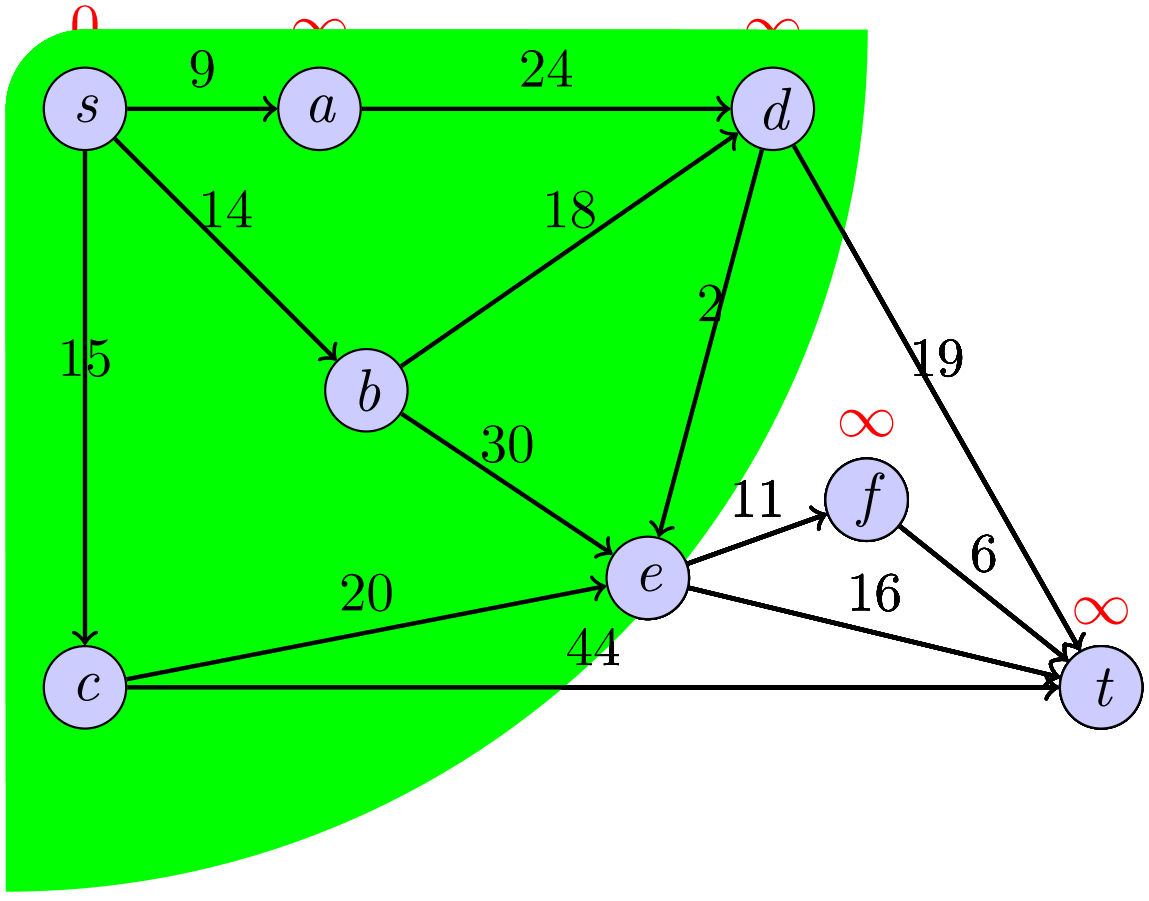
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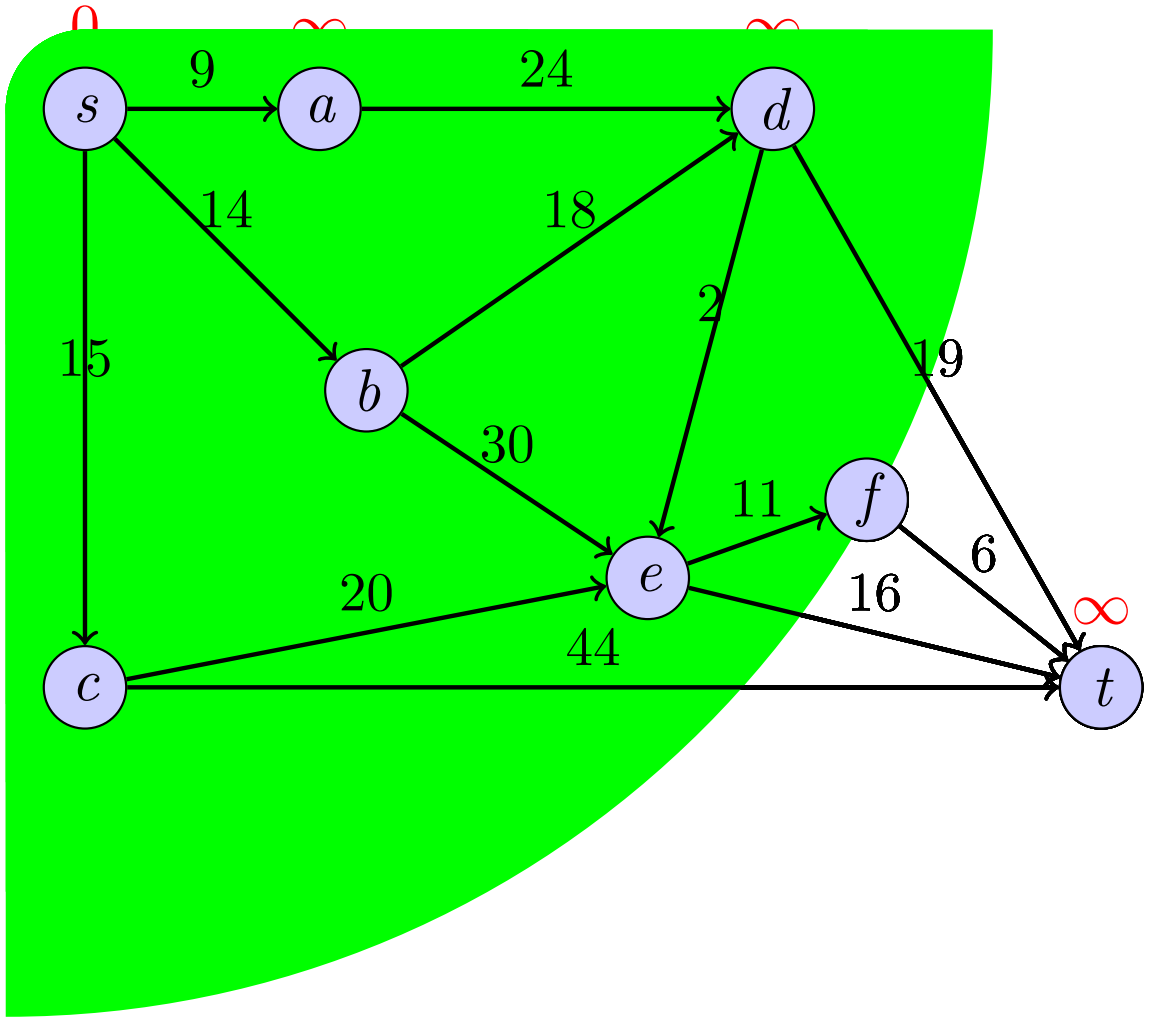
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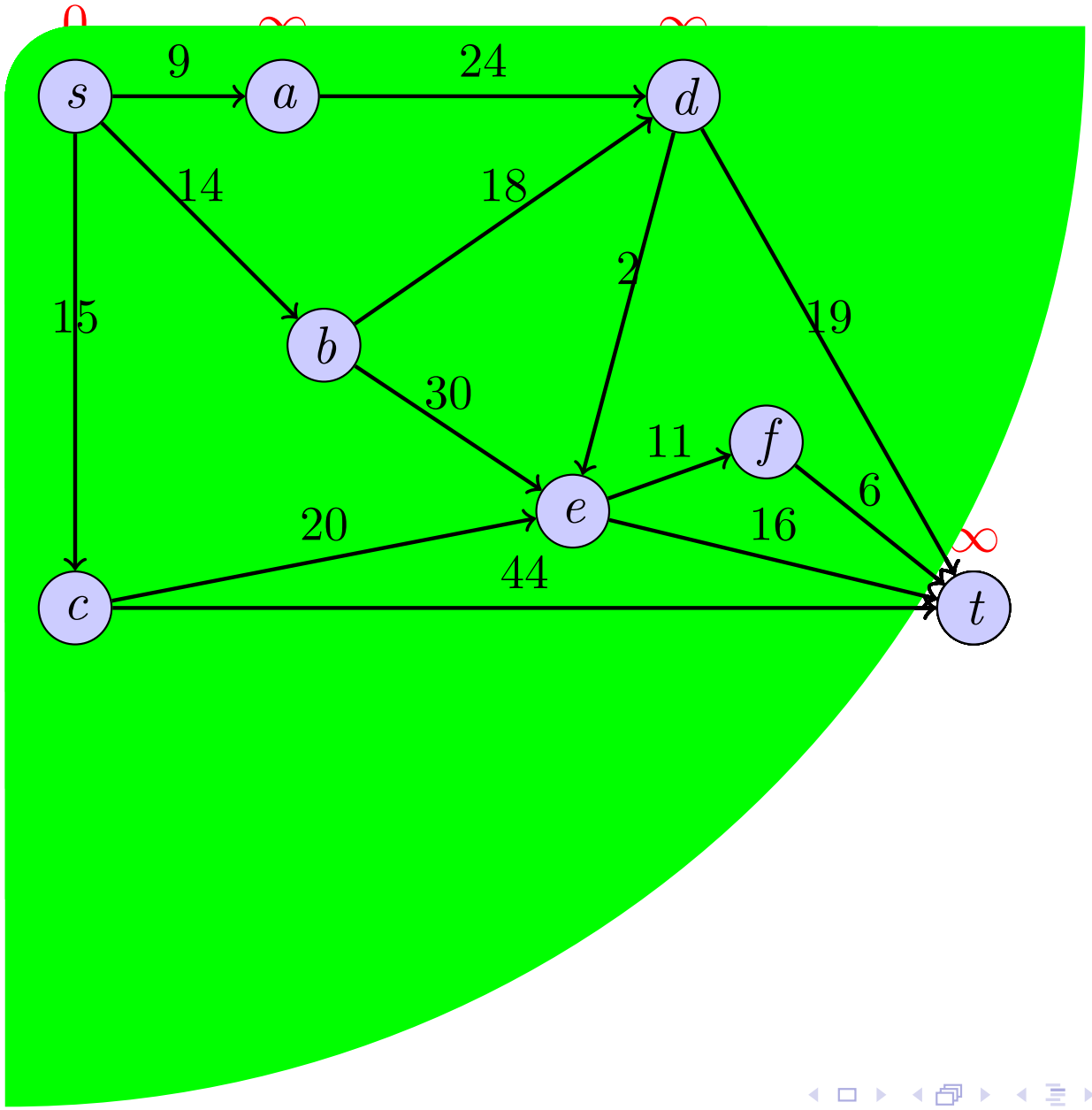
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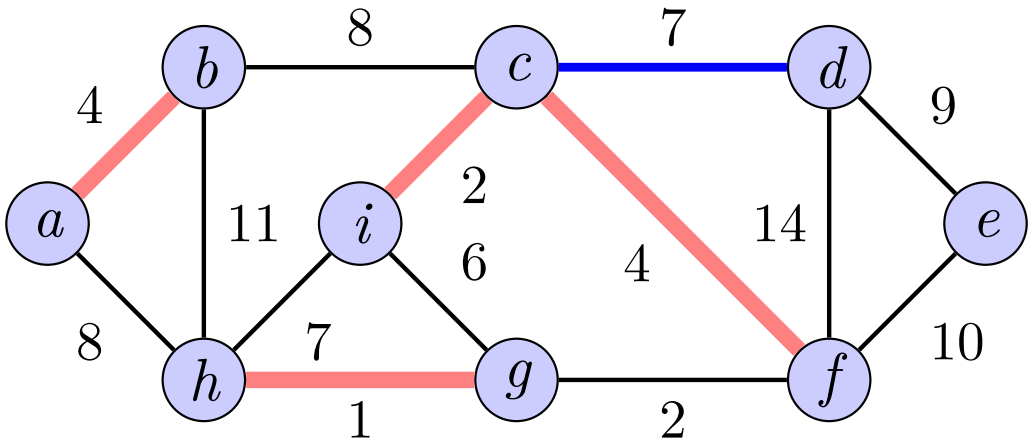
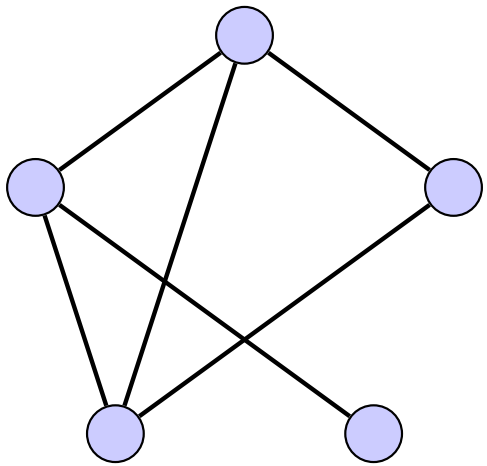
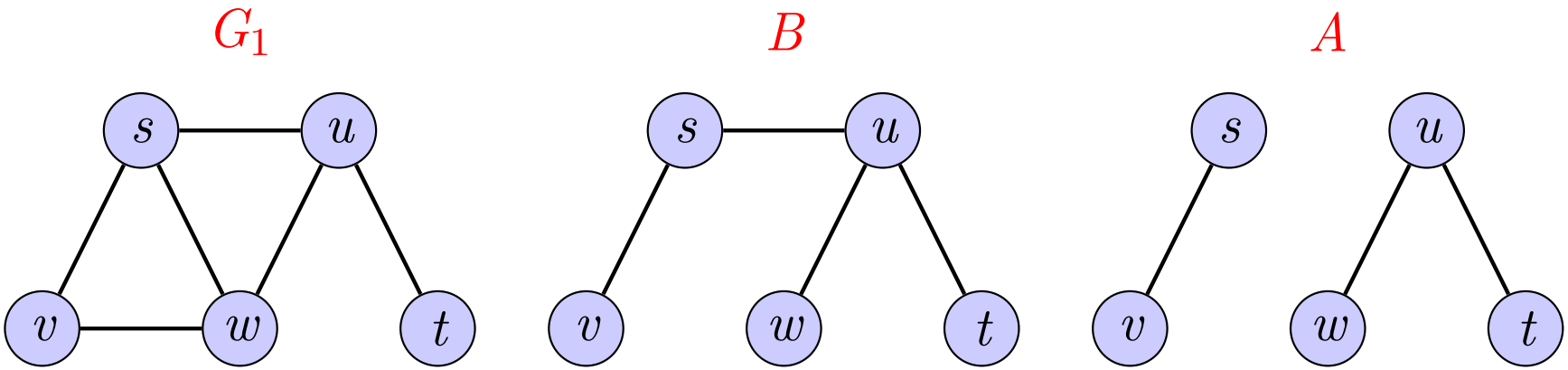
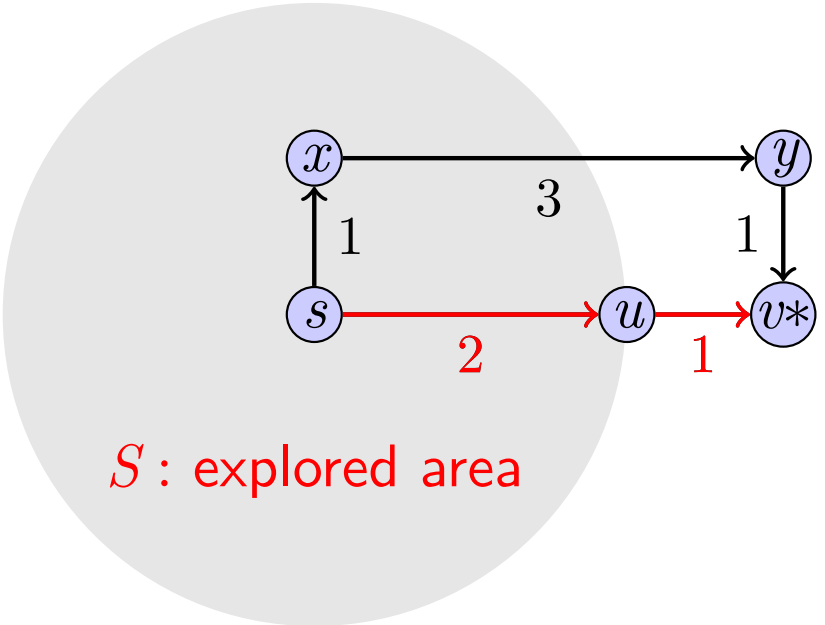
DDD

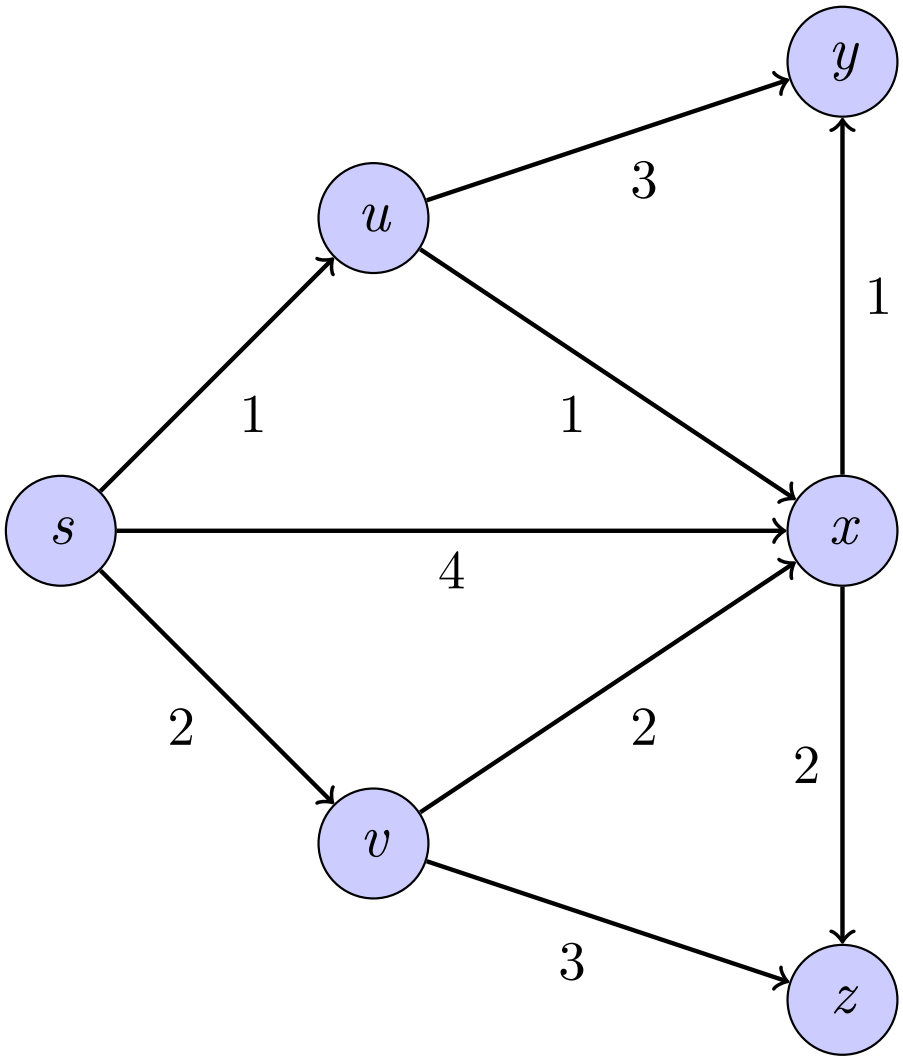


Pentagon

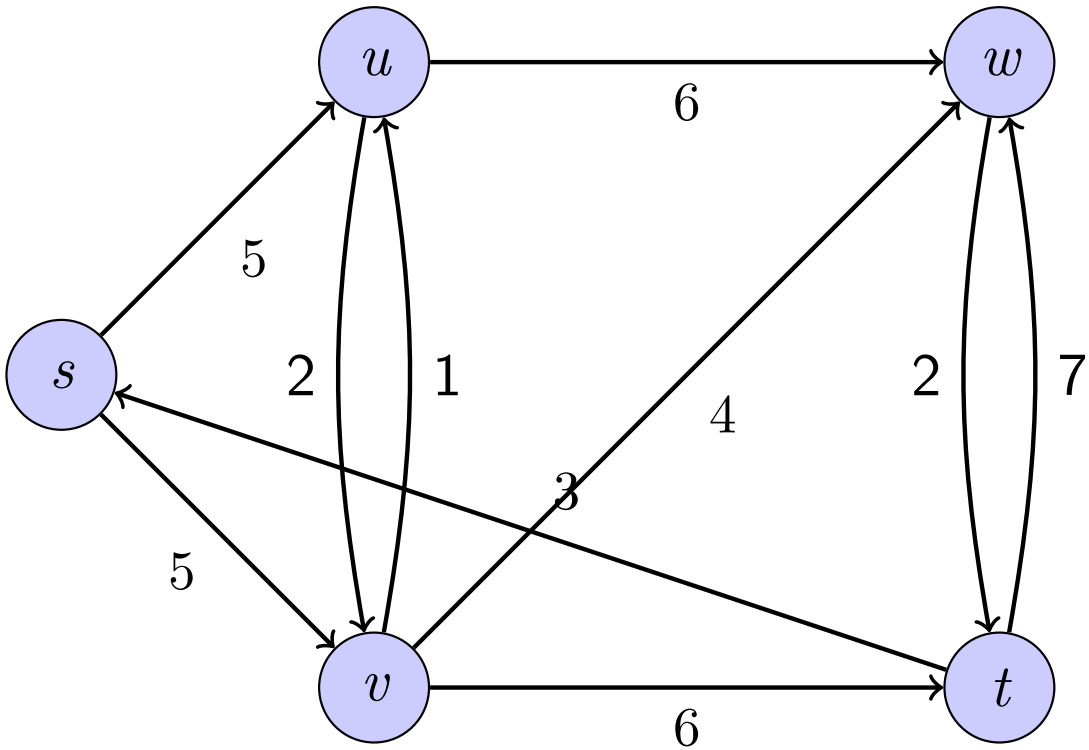



G_1
s
u
v
w
t
B
s
u
v
w
t
A
s
u
v
w
t


x
y
3
1
1
s
u
v*
2
1
S : explored area


y
u
3
1
1
1
s
x
4
2
2
2
v
3
z

AAAA



Lec6 Alignment matrix Suffix FULL

4	0	−4	−10	−12	−16	−18	−22	−26	−30	E
5	3	−1	−7	−9	−13	−15	−19	−23	−27	C
3	6	2	−4	−6	−10	−12	−16	−20	−24	N
−1	2	5	−1	−3	−7	−9	−13	−17	−21	E
−5	−2	1	4	0	−4	−6	−10	−14	−18	R
−9	−6	−3	0	3	−1	−3	−7	−11	−15	R
−13	−10	−7	−4	−1	2	0	−4	−8	−12	U
−15	−12	−9	−6	−3	0	3	−1	−5	−9	C
−19	−16	−13	−10	−7	−4	−1	2	−2	−6	C
−23	−20	−17	−14	−11	−8	−5	−2	1	−3	O
−27	−24	−21	−18	−15	−12	−9	−6	−3	0	''
E	C	N	A	R	R	U	C	O	''	S T

Lec6 Alignment matrix Prefix FULL

	S: ''	O	C	U	R	R	A	N	C	E
T: ''	0	−3	−6	−9	−12	−15	−18	−21	−24	−27
O	−3	1	−2	−5	−8	−11	−14	−17	−20	−23
C	−6	−2	2	−1	−4	−7	−10	−13	−16	−19
C	−9	−5	−1	1	−2	−5	−8	−11	−12	−15
U	−12	−8	−4	0	0	−3	−6	−9	−12	13
R	−15	−11	−7	−3	1	1	−2	−5	−8	−11
R	−18	−14	−10	−6	−2	2	−	−3	−6	−9
E	−21	−17	−13	−9	−5	−1	1	−1	−4	−5
N	−24	−20	−16	−12	−8	−4	−2	2	−1	−4
C	−27	−23	−19	−15	−11	−7	−5	−1	3	0
E	−30	−26	−22	−18	−14	−10	−8	−4	0	4

Lec7 Shortest Path example FULL

	k=0	1	2	3	4	5
S	0	0	0	0	0	0
U	–	1	1	1	1	1
V	–	2	2	2	2	2
X	–	4	2	2	2	2
Y	–	–	4	3	3	3
Z	–	–	5	4	4	4

Lec6 Alignment matrix Prefix

	S: ''	O	C	U	R	R	A	N	C	E
T:''	0	−3	−6	−9	−12	−15	−18	−21	−24	−27
O	−3									
C	−6									
C	−9									
U	−12									
R	−15									
R	−18									
E	−21									
N	−24									
C	−27									
E	−30									

OPT

1	2	3	4	
0	6			1
	0	24		2
		0	60	3
			0	4

SPLITTER

1	2	3	4	
	1			1
		2		2
			3	3
				4

OPT

1	2	3	4	
0	6	18		1
	0	24	64	2
		0	60	3
			0	4

SPLITTER

1	2	3	4	
	1	2		1
		2	3	2
			3	3
				4

OPT

1	2	3	4	
0	6	18	38	1
	0	24	64	2
		0	60	3
			0	4

SPLITTER

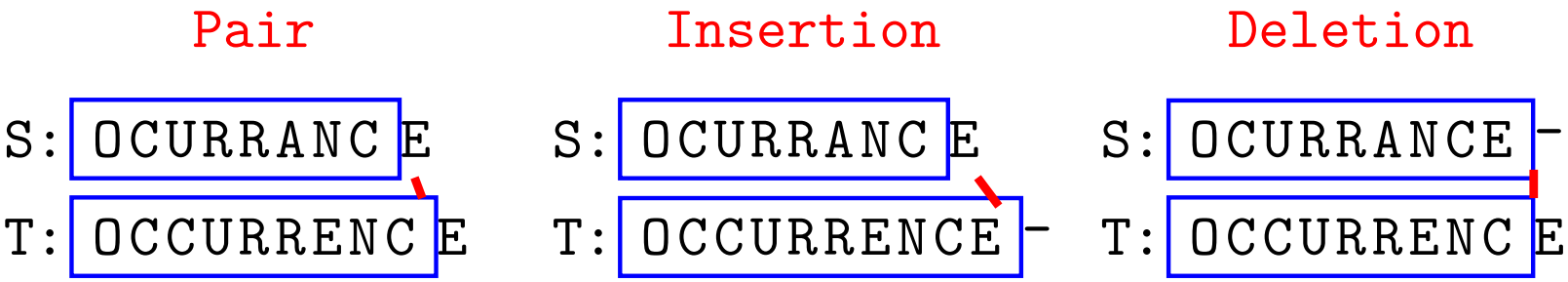
1	2	3	4	
	1	2	3	1
		2	3	2
			3	3
				4

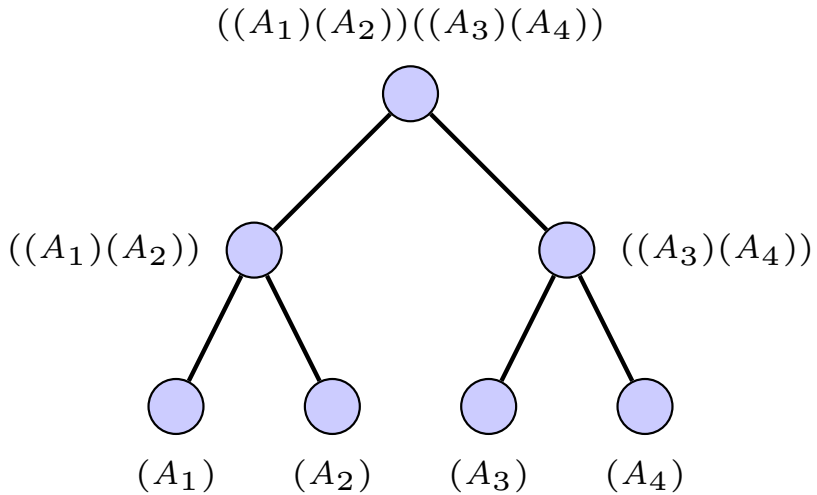
$$\frac{n}{2}$$

S: OCUR | RANCE

T: OCCUR | RENCE

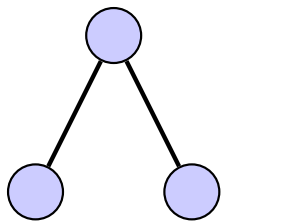
$$1 \leq q \leq n$$


Pair
S: OCURRANC E
T: OCCURRENC E
Insertion
S: OCURRANC E
T: OCCURRENCE -
Deletion
S: OCURRANCE -
T: OCCURRENC E


$((A_1)(A_2))((A_3)(A_4))$
$((A_1)(A_2))$
$((A_3)(A_4))$
(A_1)
(A_2)
(A_3)
(A_4)

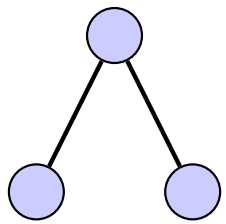
$k = 1$

$(A_1)(A_2 A_3 A_4)$



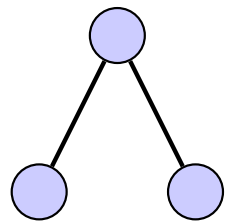
$k = 2$

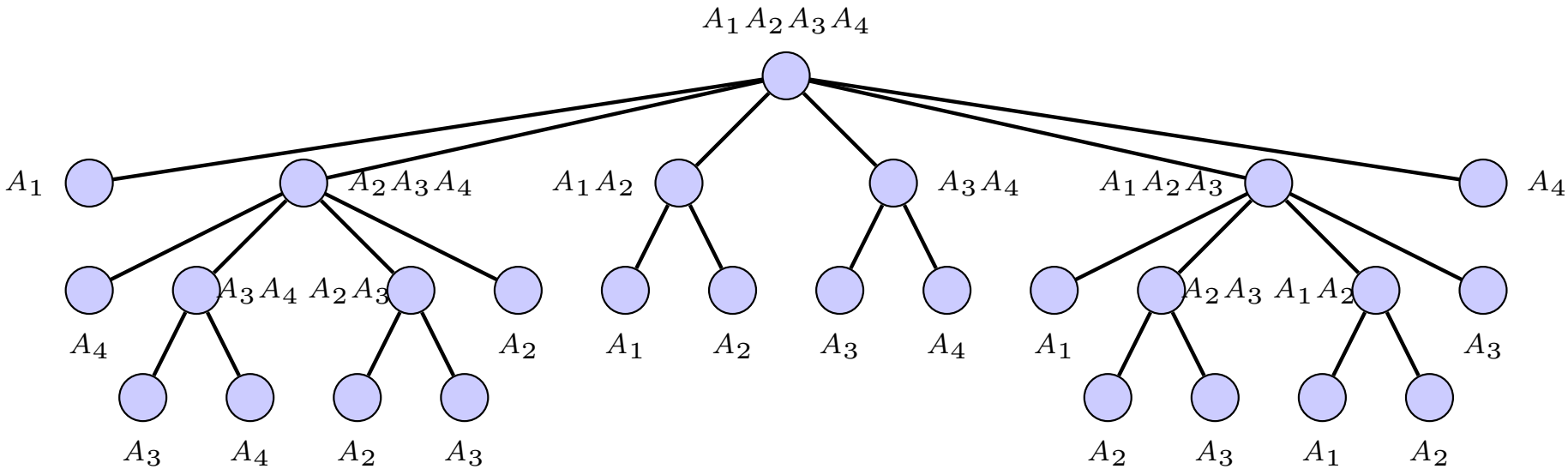
$(A_1 A_2)(A_3 A_4)$

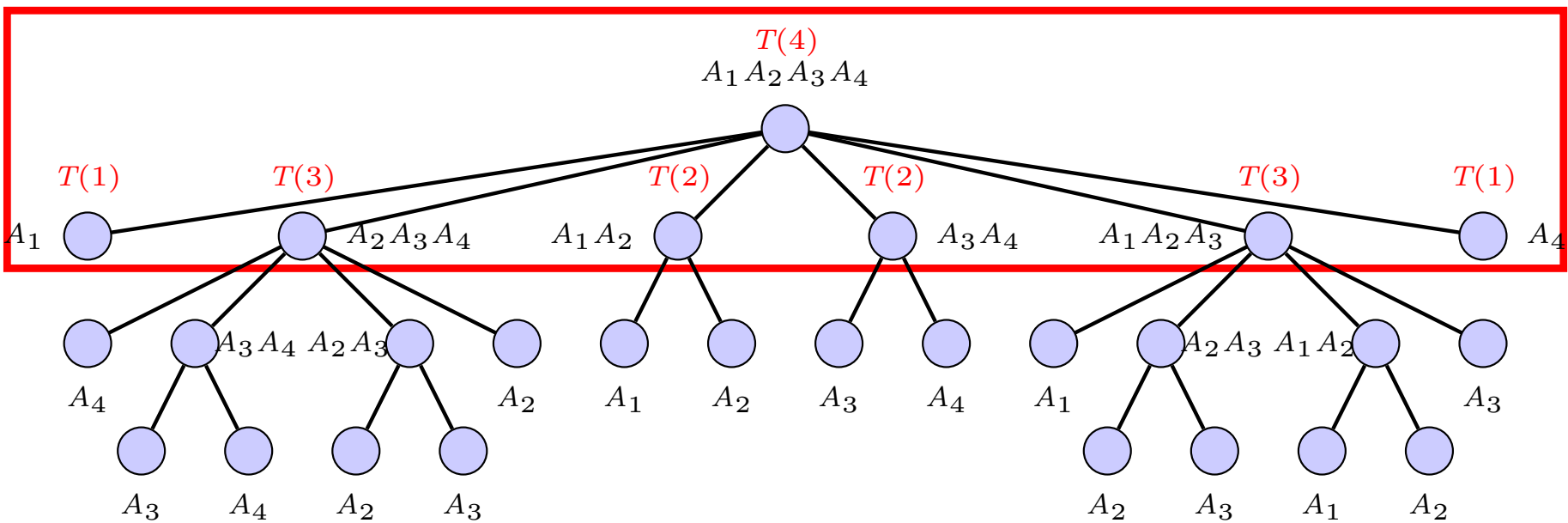


$k = 3$

$(A_1 A_2 A_3)(A_4)$




$A_1 A_2 A_3 A_4$
A_1
$A_2 A_3 A_4$
$A_1 A_2$
$A_3 A_4$
$A_1 A_2 A_3$
A_4
A_4
$A_3 A_4$
$A_2 A_3$
A_2
A_1
A_2
A_3
A_4
A_1
$A_2 A_3$
$A_1 A_2$
A_3
A_3
A_4
A_2
A_3
A_2
A_3
A_1
A_2


$T(4)$
$A_1\,A_2\,A_3\,A_4$
$T(1)$
$T(3)$
$T(2)$
$T(2)$
$T(3)$
$T(1)$
A_1
$A_2\,A_3\,A_4$
$A_1\,A_2$
$A_3\,A_4$
$A_1\,A_2\,A_3$
A_4
$A_3\,A_4$
$A_2\,A_3$
A_2
A_1
A_2
A_3
A_4
A_1
$A_2\,A_3$
$A_1\,A_2$
A_3
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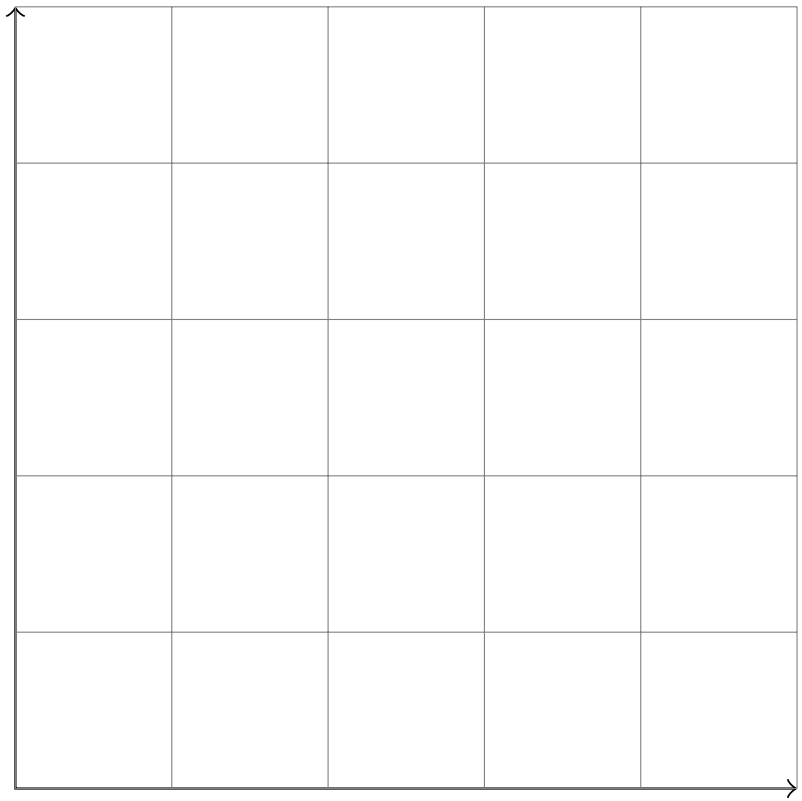
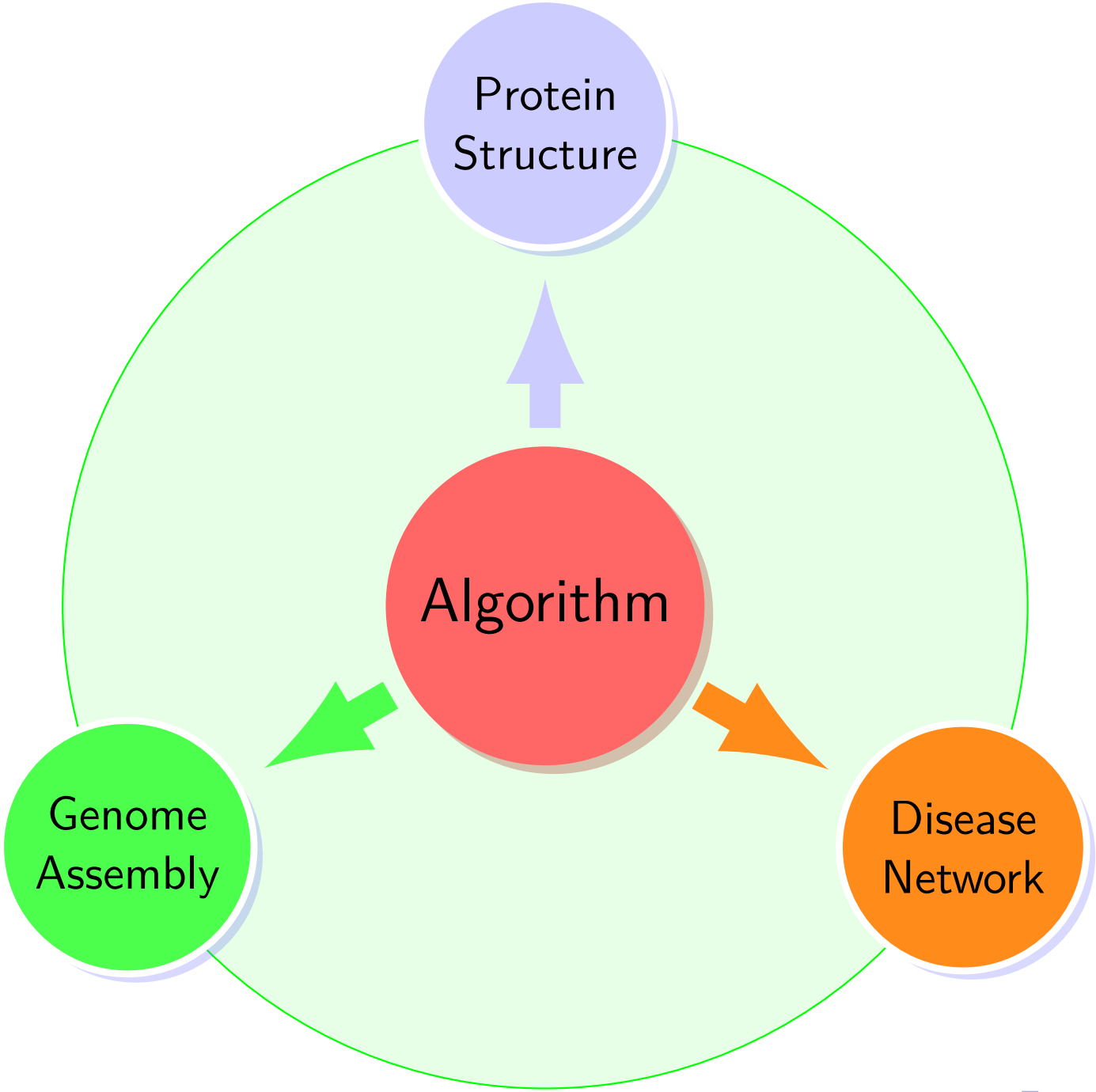
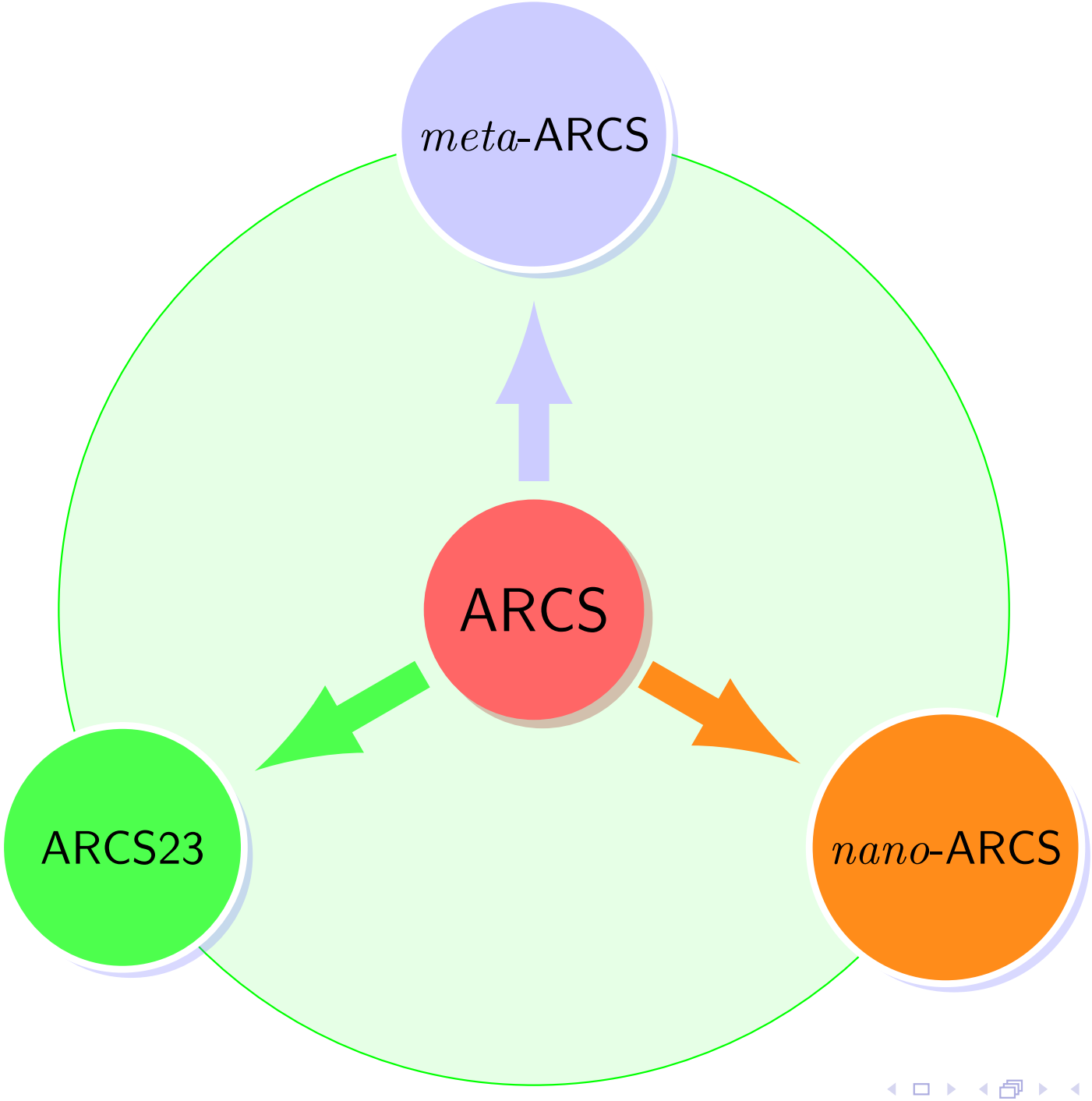
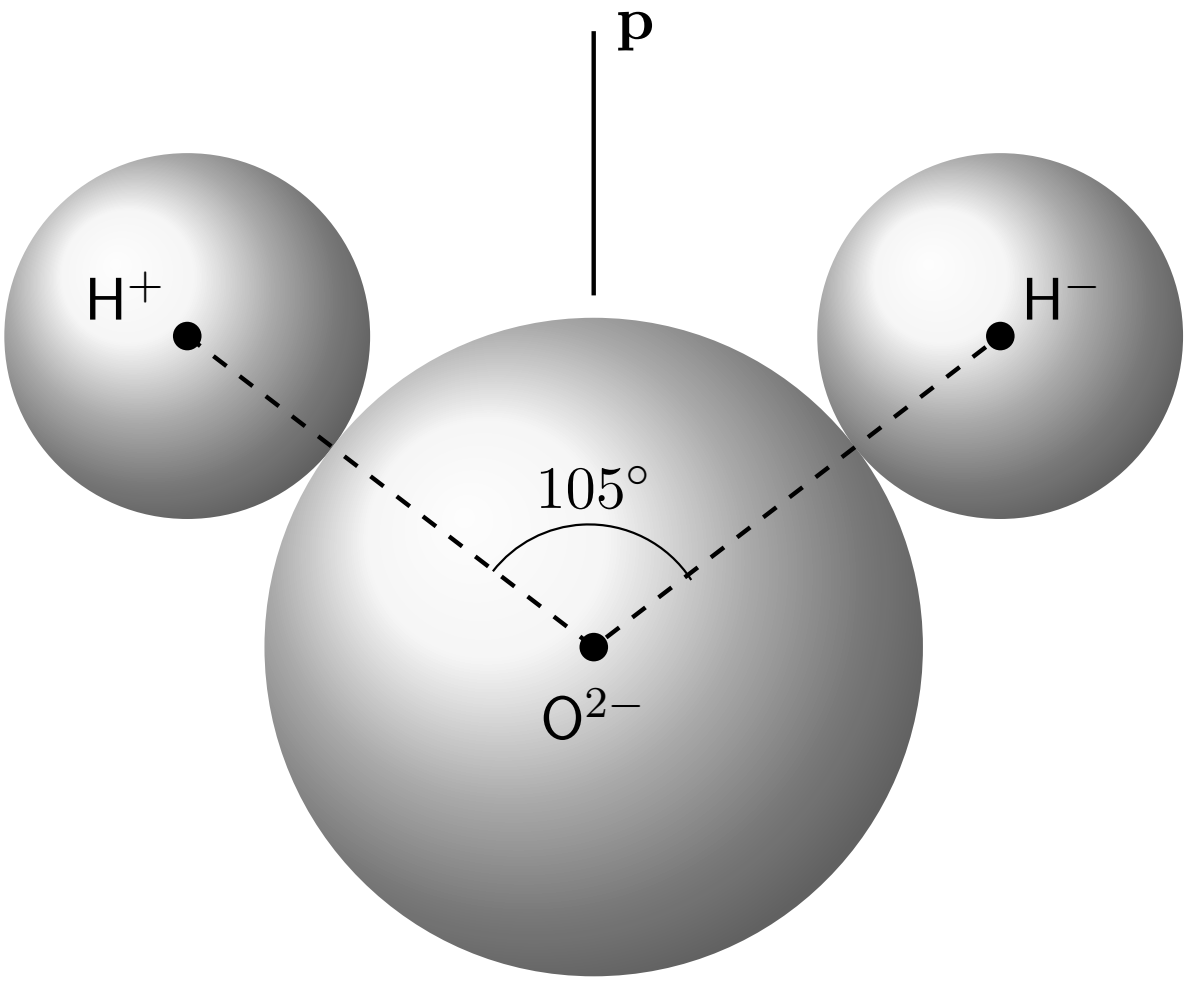
A_1
A_2



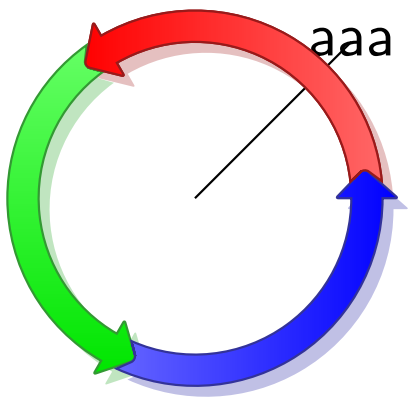
$$
\begin{array}{cccc}
 & 1\times 2 & 2\times 3 & 3\times 4 \qquad\qquad 4\times 5 \\
A_1 = \begin{bmatrix} 1 & 2 \end{bmatrix} & A_2 = \begin{bmatrix} 1 & 2 & 3 \\ 1 & 2 & 3 \end{bmatrix} & A_3 = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 1 & 2 & 3 & 4 \\ 1 & 2 & 3 & 4 \end{bmatrix} & A_4 = \begin{bmatrix} 1 & 2 & 3 & 4 & 5 \\ 1 & 2 & 3 & 4 & 5 \\ 1 & 2 & 3 & 4 & 5 \\ 1 & 2 & 3 & 4 & 5 \end{bmatrix}
\end{array}
$$

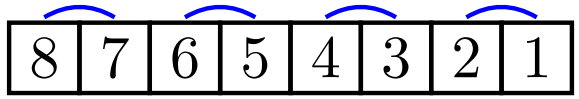

Protein
Structure
Algorithm
Genome
Assembly
Disease
Network


meta-ARCS
ARCS
ARCS23
nano-ARCS

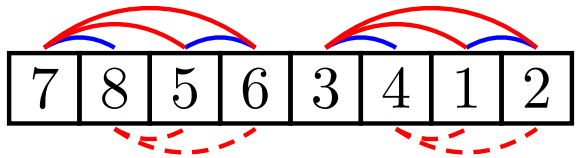

p
H+
H−
105°
O2−

arrow

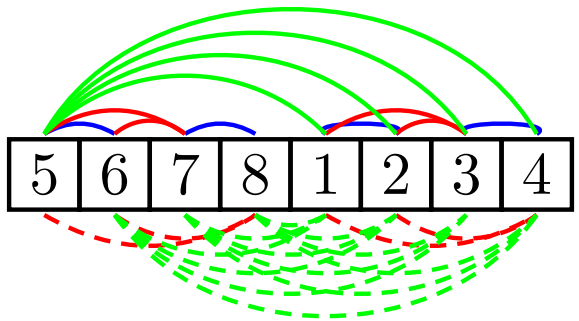




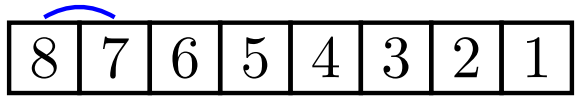
MergeSort step 1: 4 ops

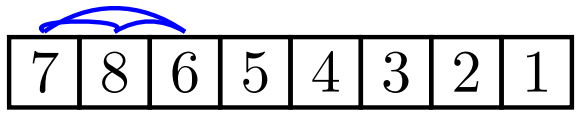


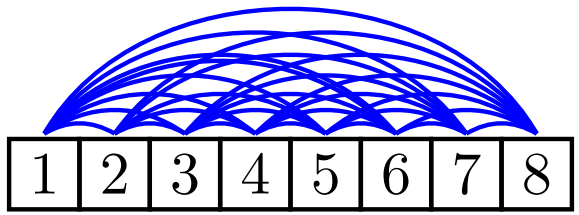
MergeSort step 2: 4 ops, save: 4 ops



MergeSort step 3: 4 ops, save: 12 ops

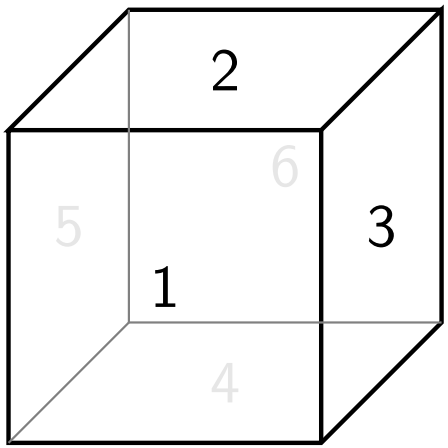




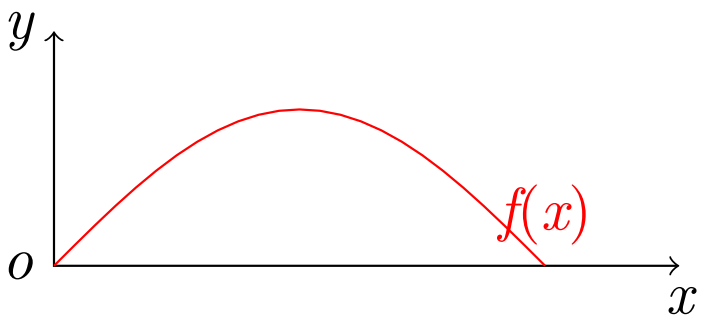


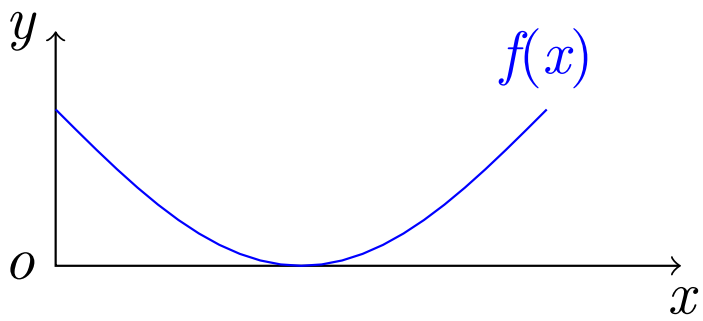
InsertSort: 28 ops

cube

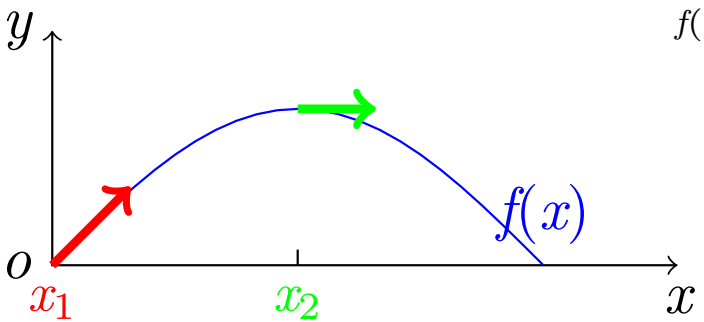


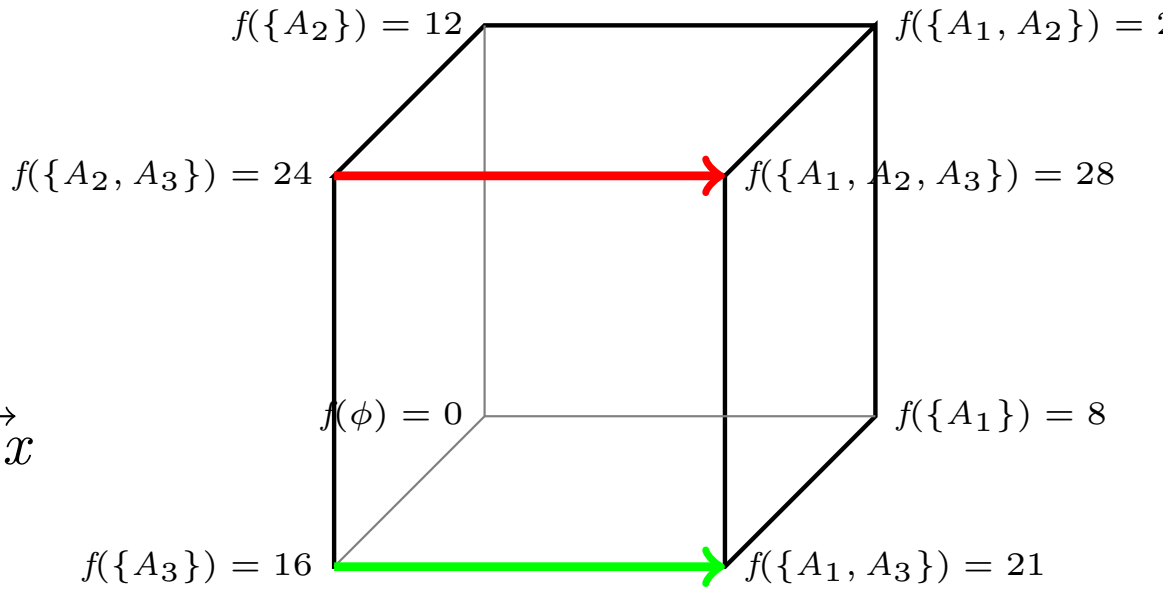
f(x) convex



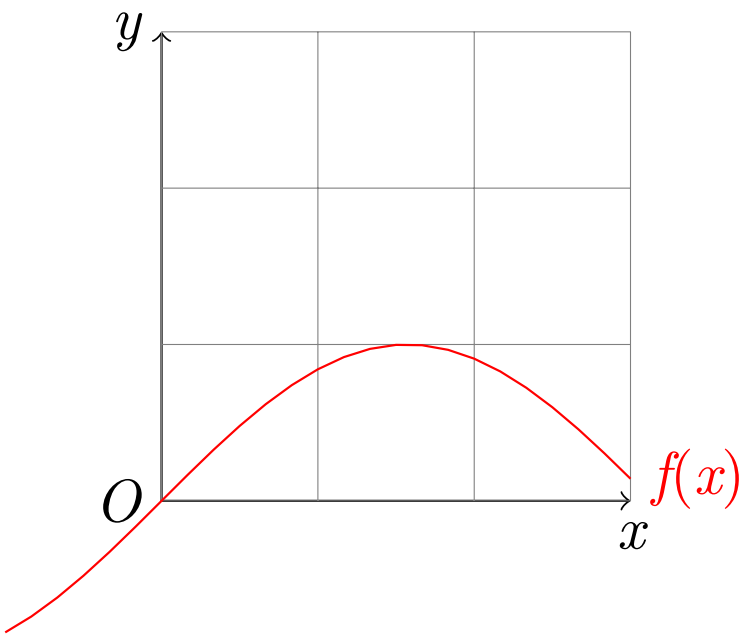


f(x) convex

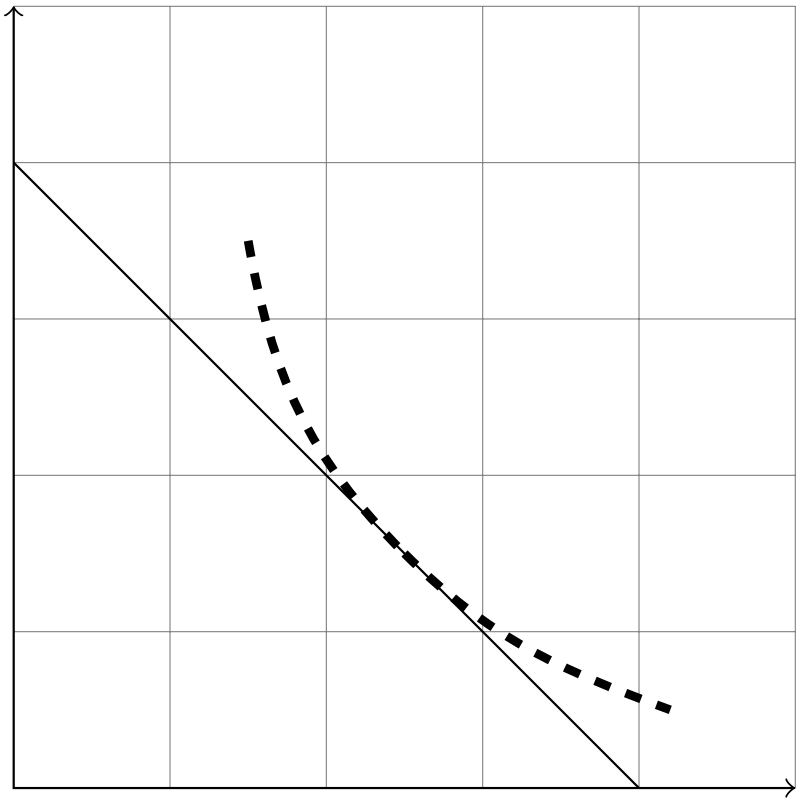

y
o
x_1
x_2
x
$f(x)$

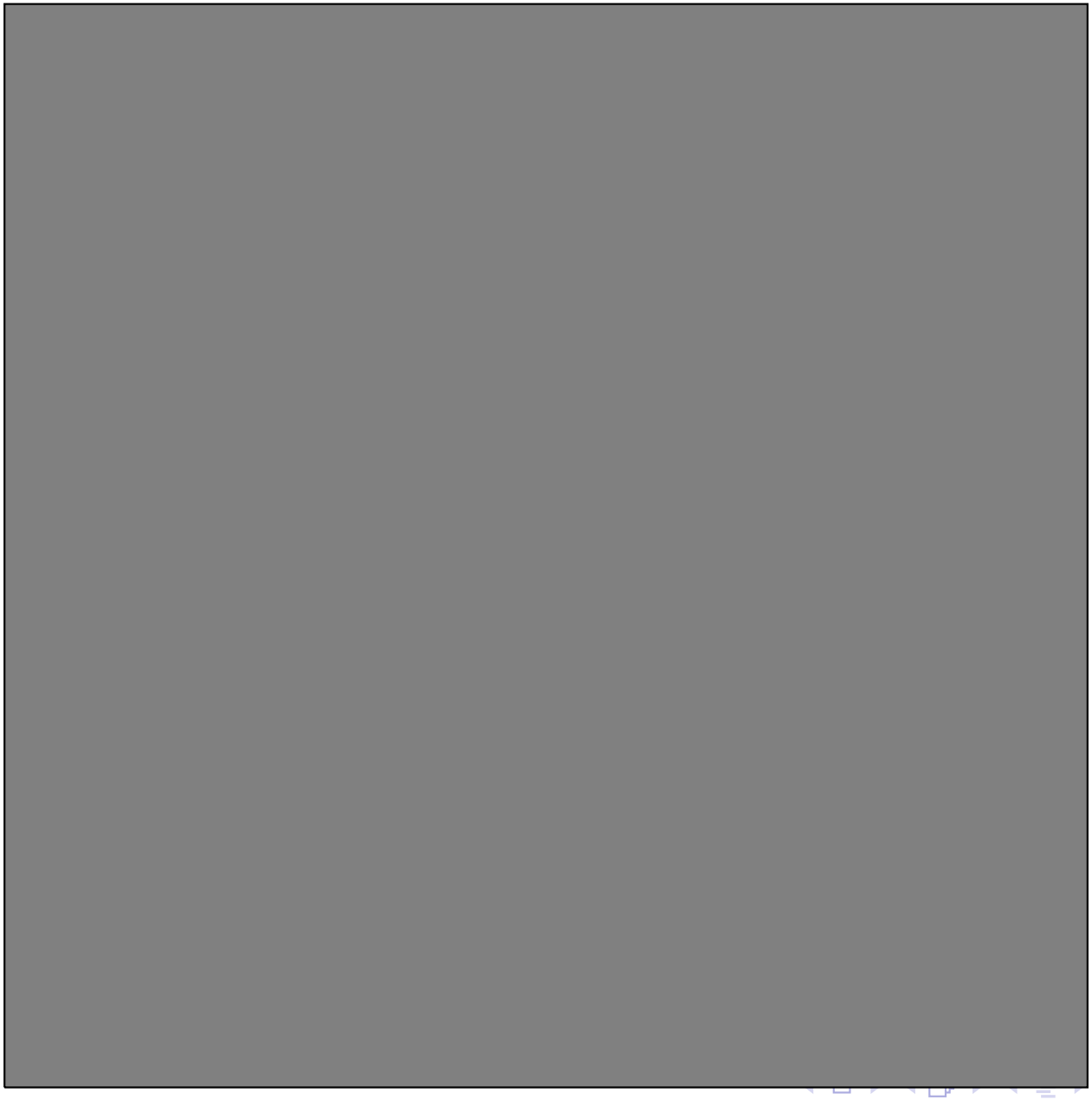

$f(\{A_2\}) = 12$
$f(\{A_1, A_2\}) =$
$f(\{A_2, A_3\}) = 24$
$f(\{A_1, A_2, A_3\}) = 28$
$f(\phi) = 0$
$f(\{A_1\}) = 8$
$f(\{A_3\}) = 16$
$f(\{A_1, A_3\}) = 21$

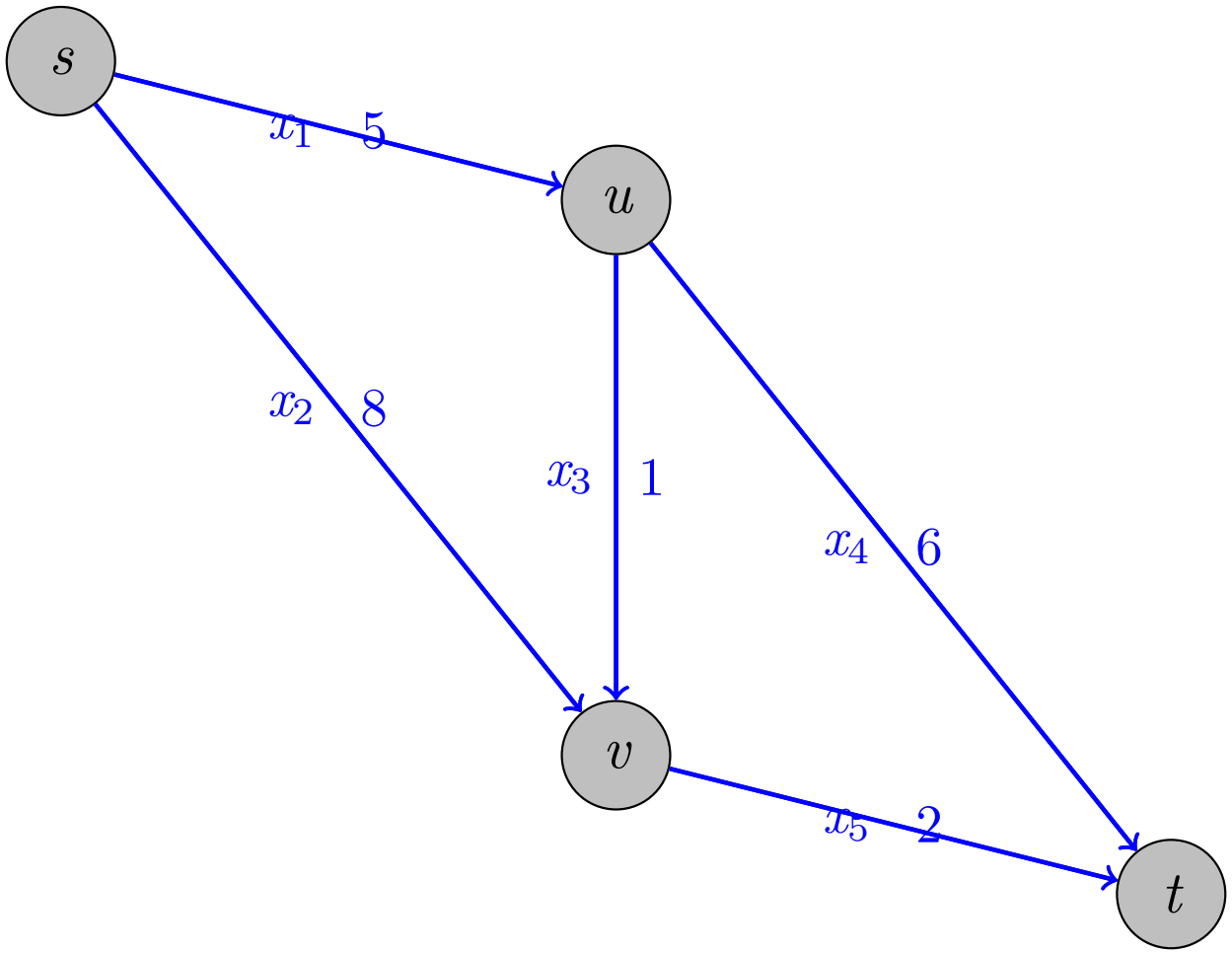
f(x)



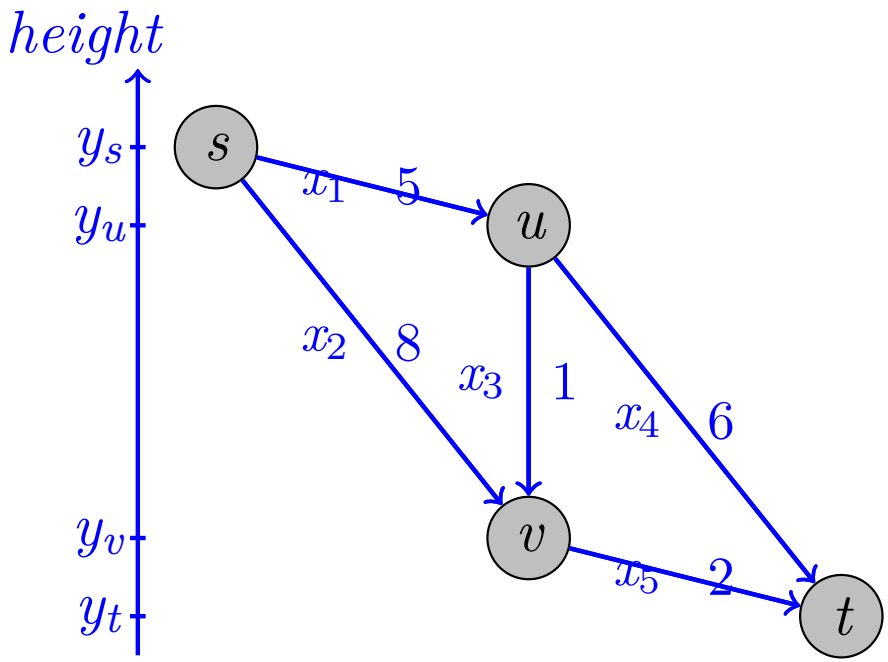
f(x)





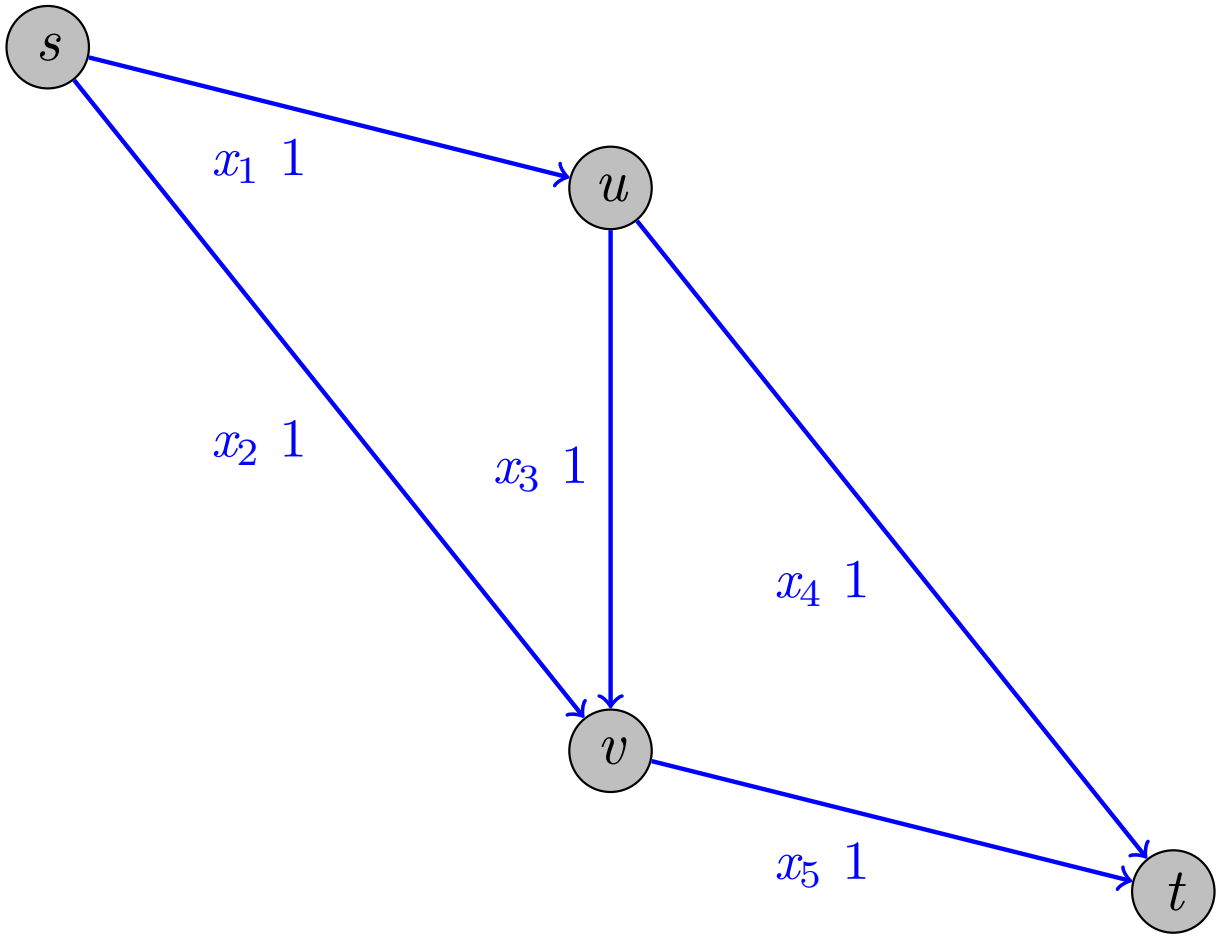

s
u
v
t
x_1 5
x_2 8
x_3 1
x_4 6
x_5 2

Shortest path

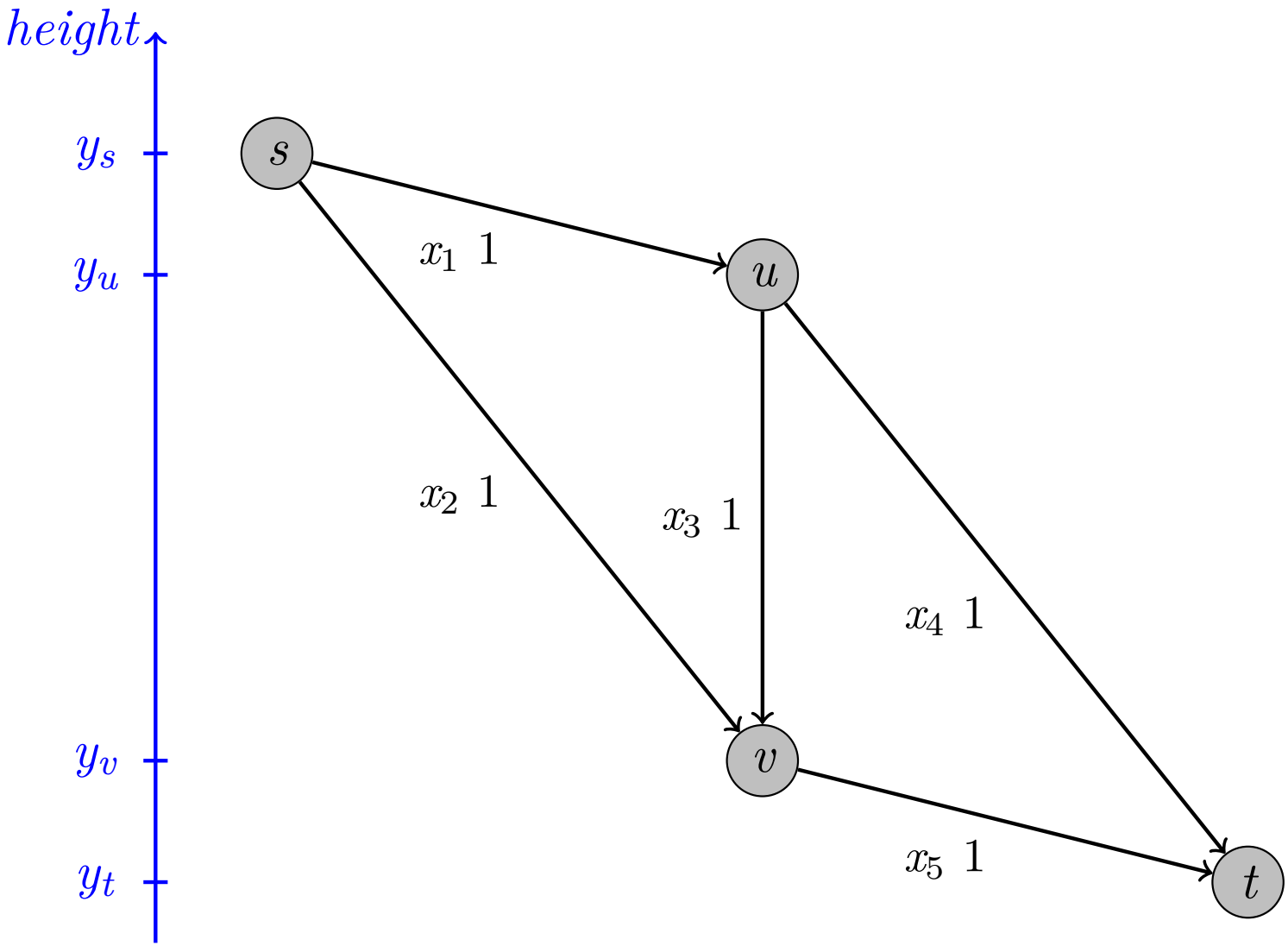


Dual

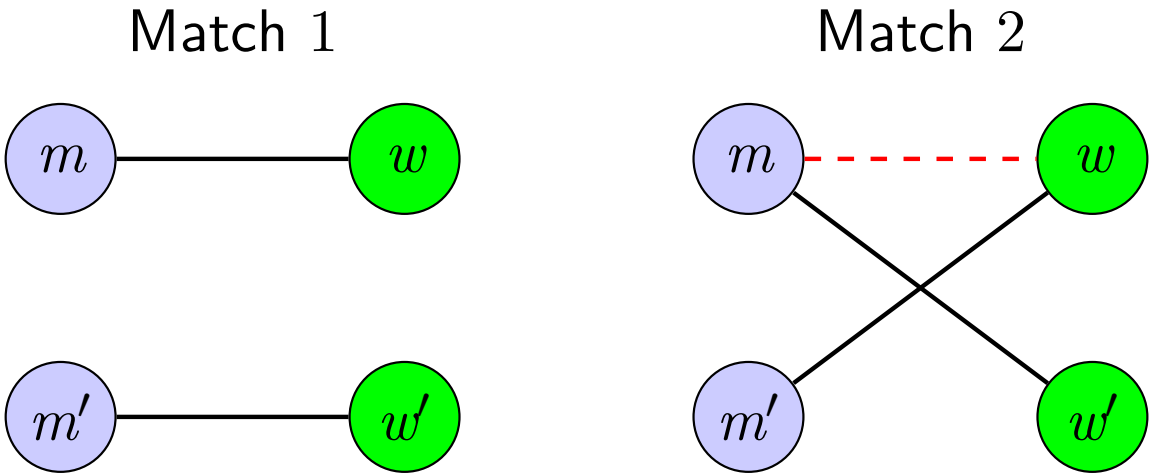
$$
\begin{array}{ccccc}
 & & & x_n = 0 & \\
 & & & \Uparrow & \\
c_1 & c_2 & \dots & c_n & \\
\| & \| & & \vee & \max \\
y_1\, a_{11} & y_1\, a_{12} & \dots & y_1\, a_{1n} & y_1\, b_1 \\
+ & + & & + & + \\
y_2\, a_{21} & y_2\, a_{22} & \dots & y_2\, a_{2n} & y_2\, b_2 \\
+ & + & & + & + \\
\vdots & \vdots & \dots & \vdots & \vdots \\
+ & + & & + & + \\
y_m\, a_{m1} & y_m\, a_{m2} & \dots & y_m\, a_{mn} & y_m\, b_m
\end{array}
$$


s
u
v
t
x_1 1
x_2 1
x_3 1
x_4 1
x_5 1

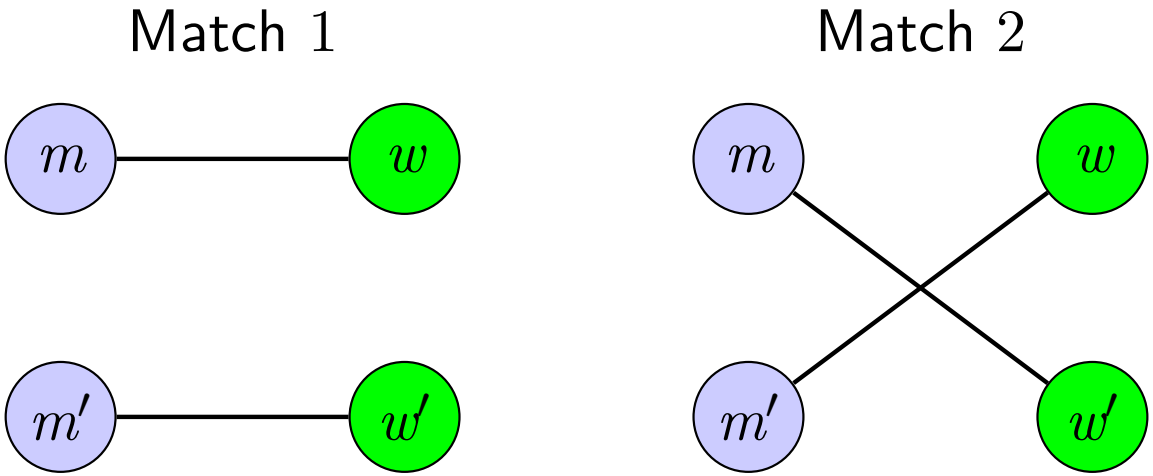
dual of shortest path



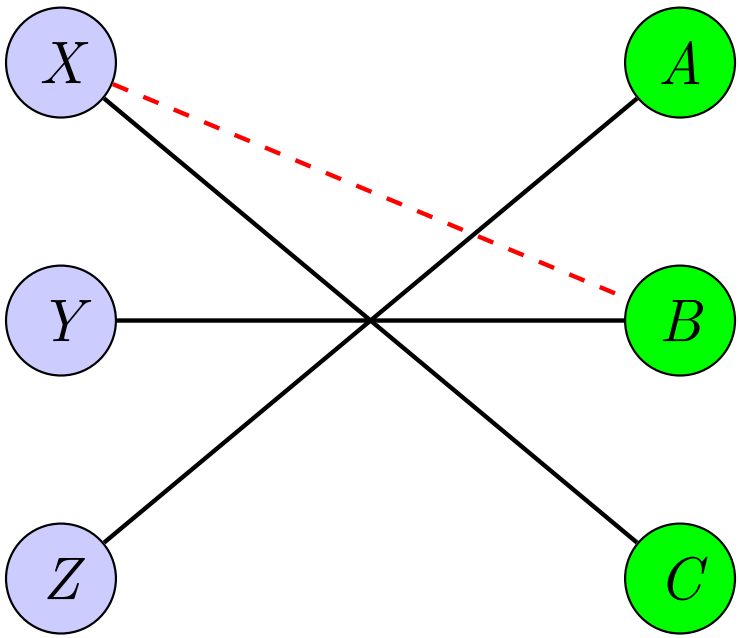
Stable 1



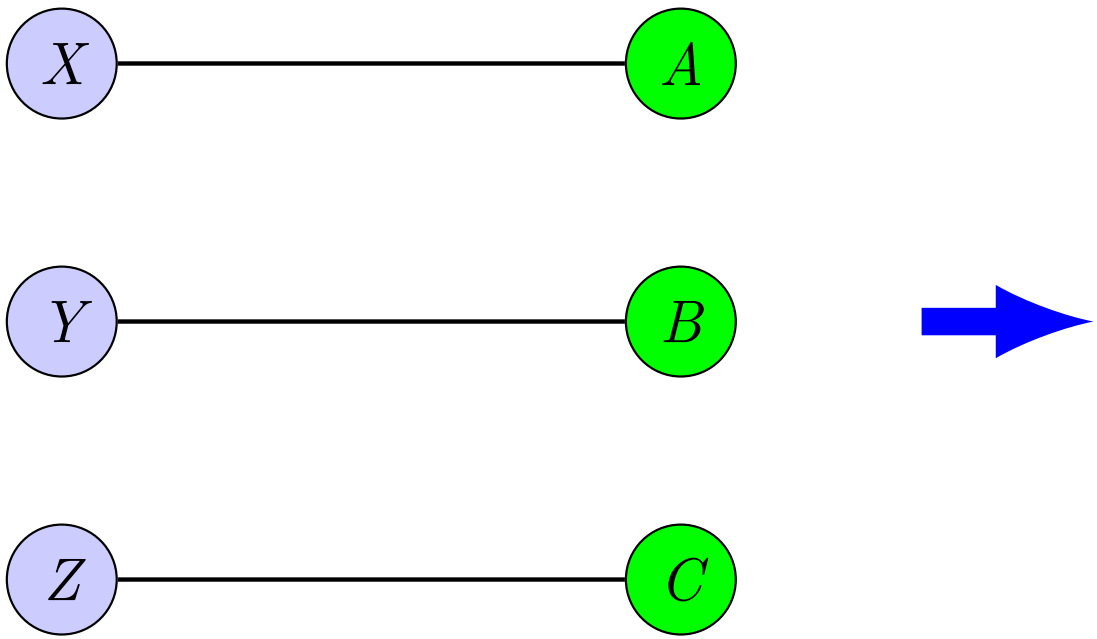
Stable 2



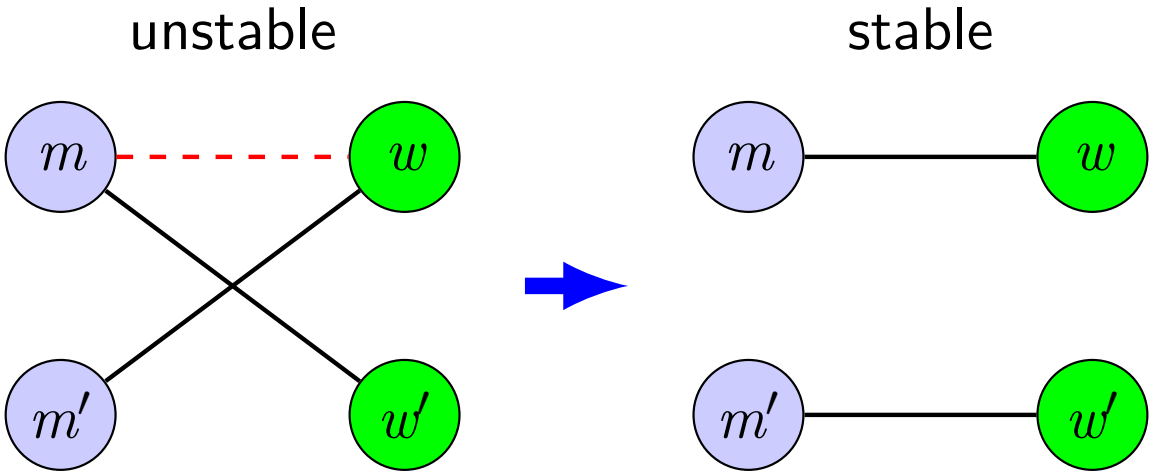
Stable 4



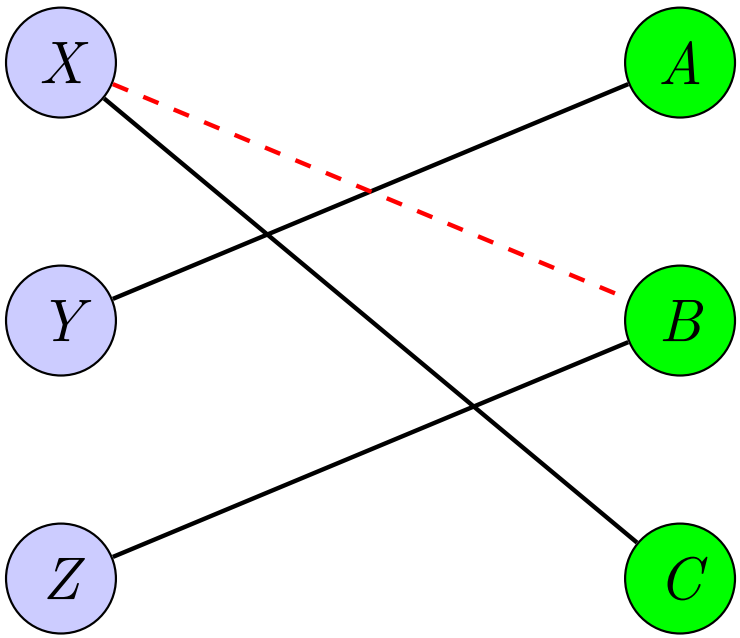
Stable 5



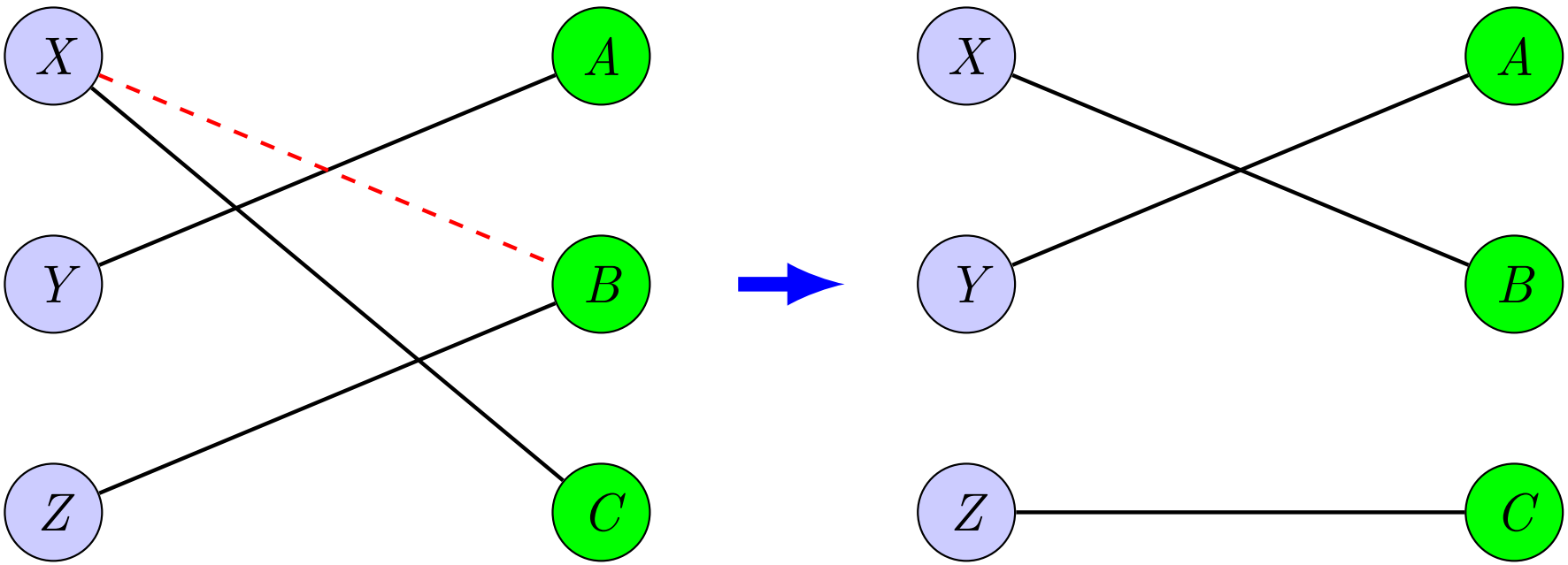
Stable 6



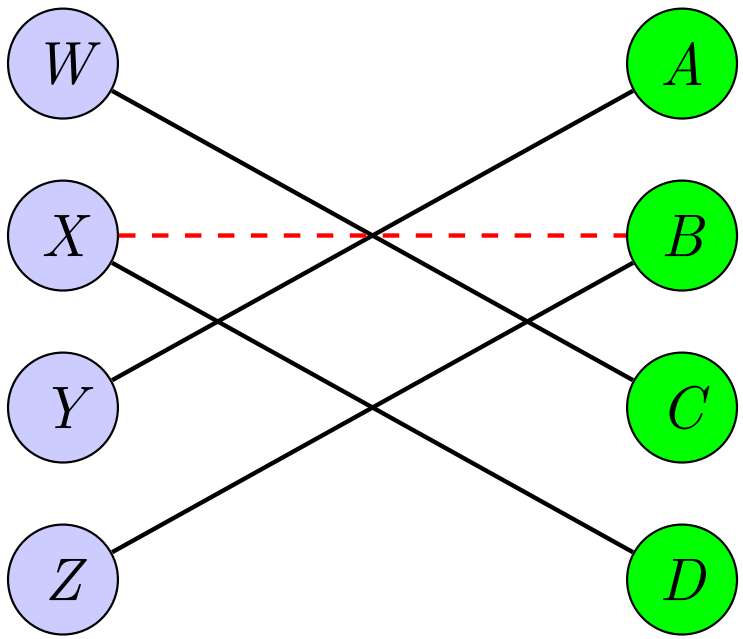
Stable 7



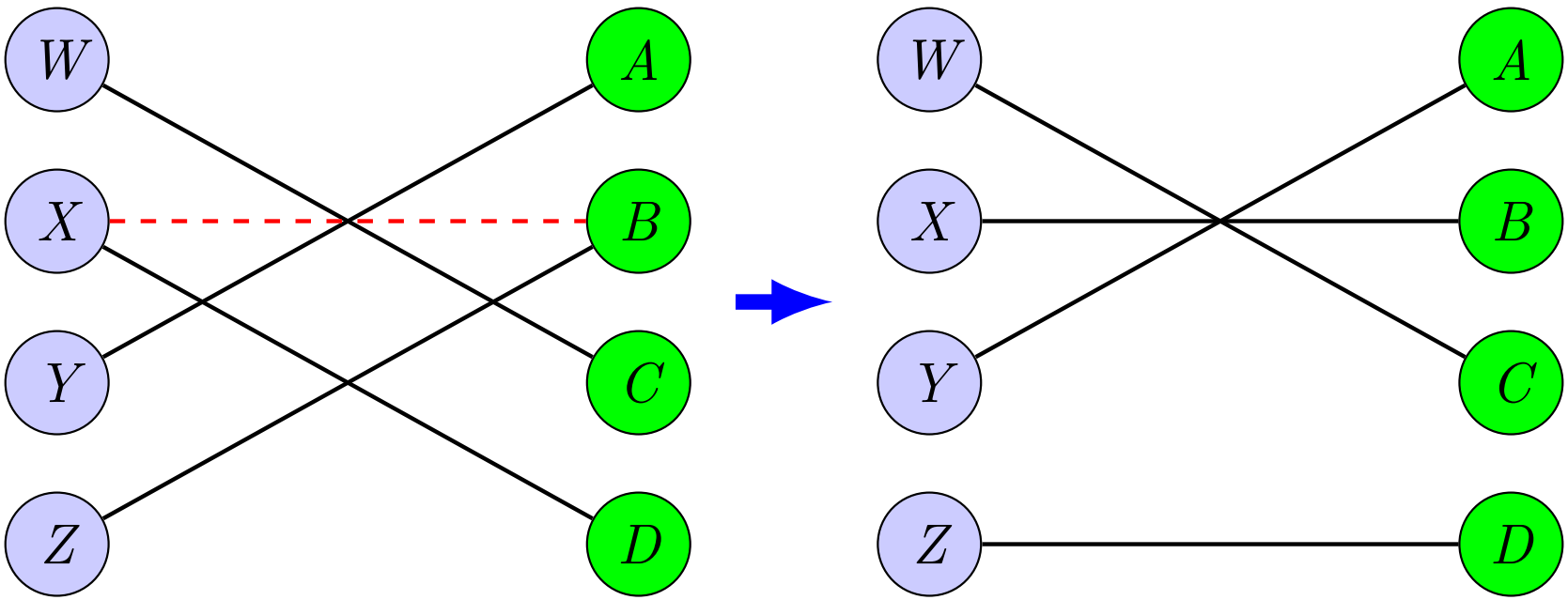
Stable 8



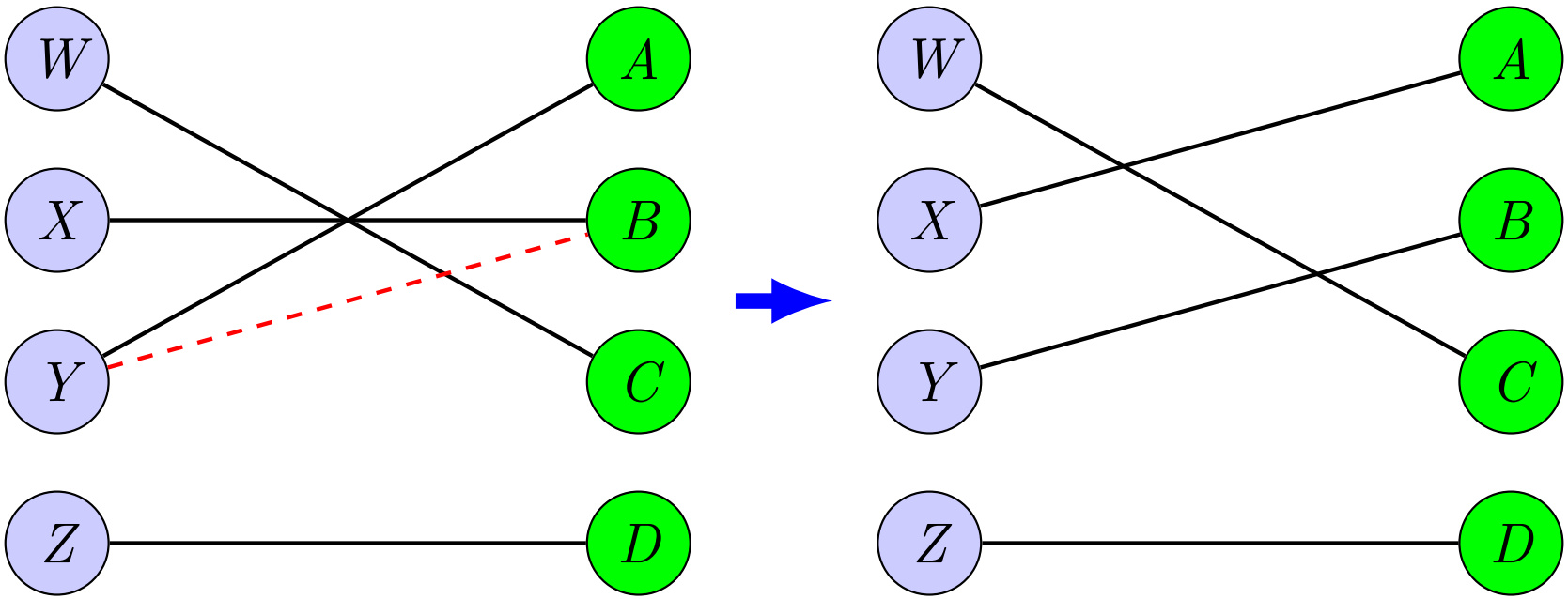
Stable 9



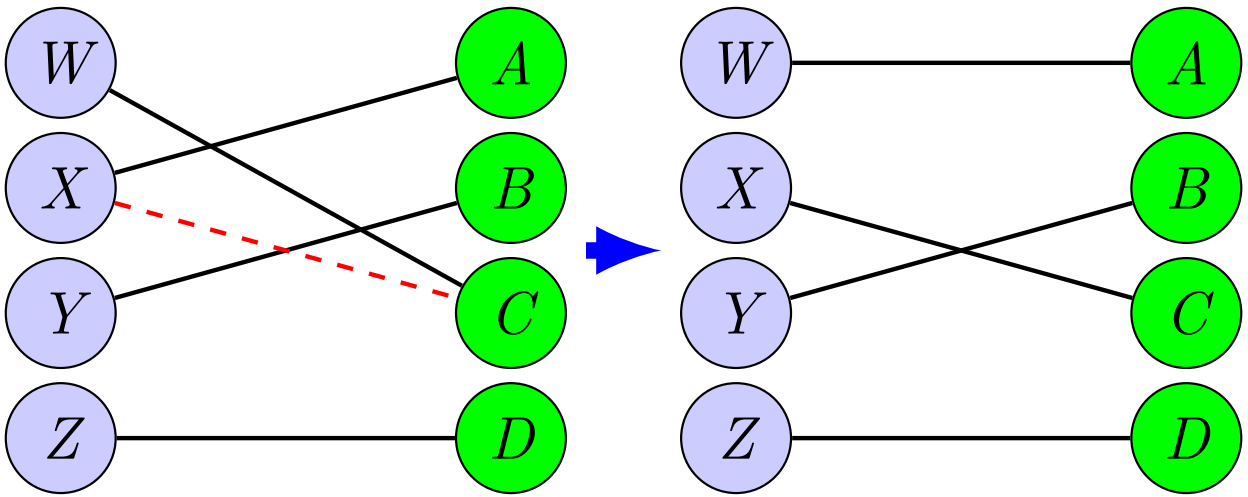
Stable 10



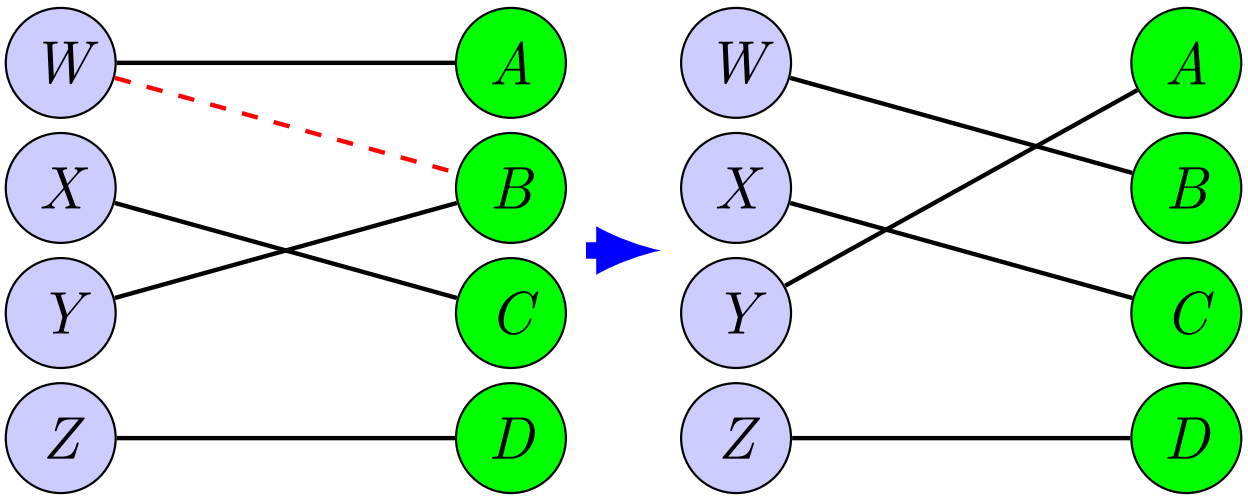
Stable 11



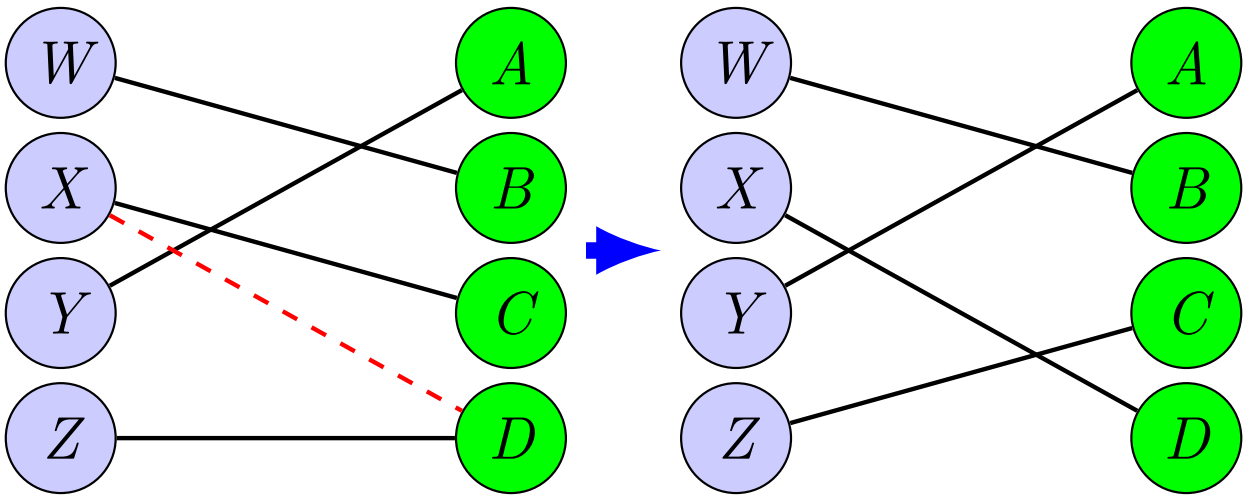
Stable 12



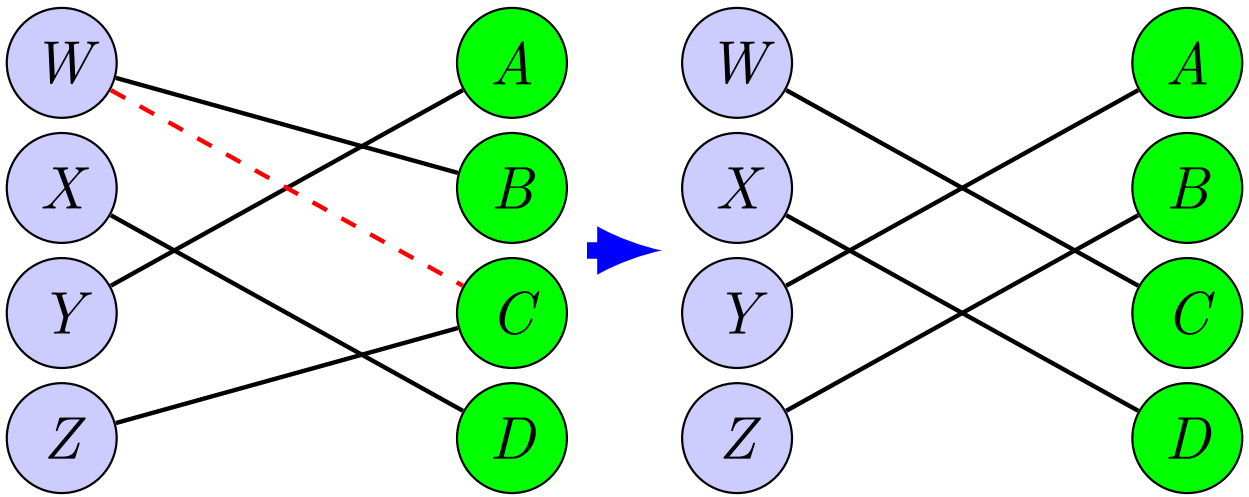
Stable 13



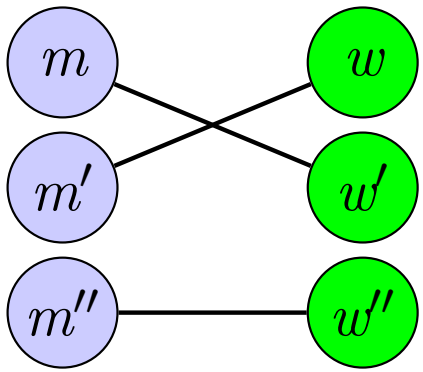
Stable 14



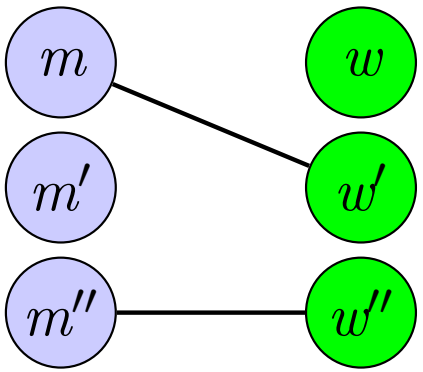
Stable 15



Stable Proof 1

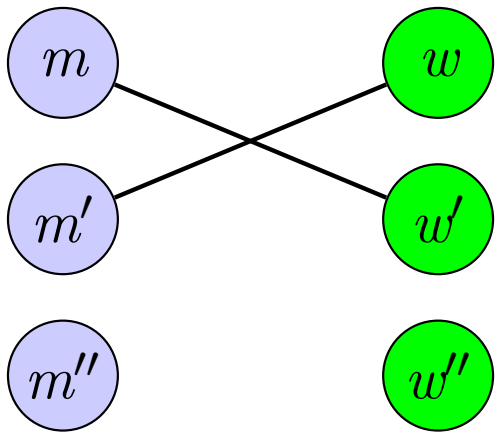


complete solution

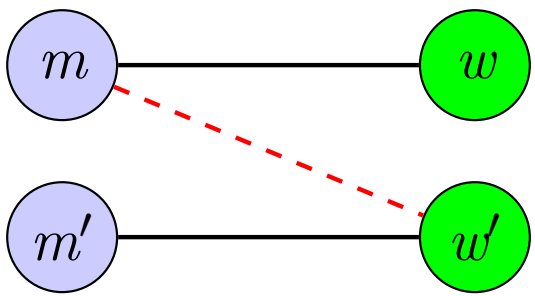


partial solution

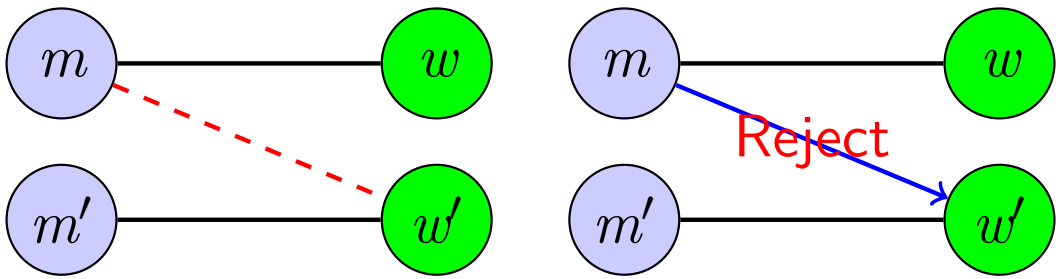
Stable Proof 2



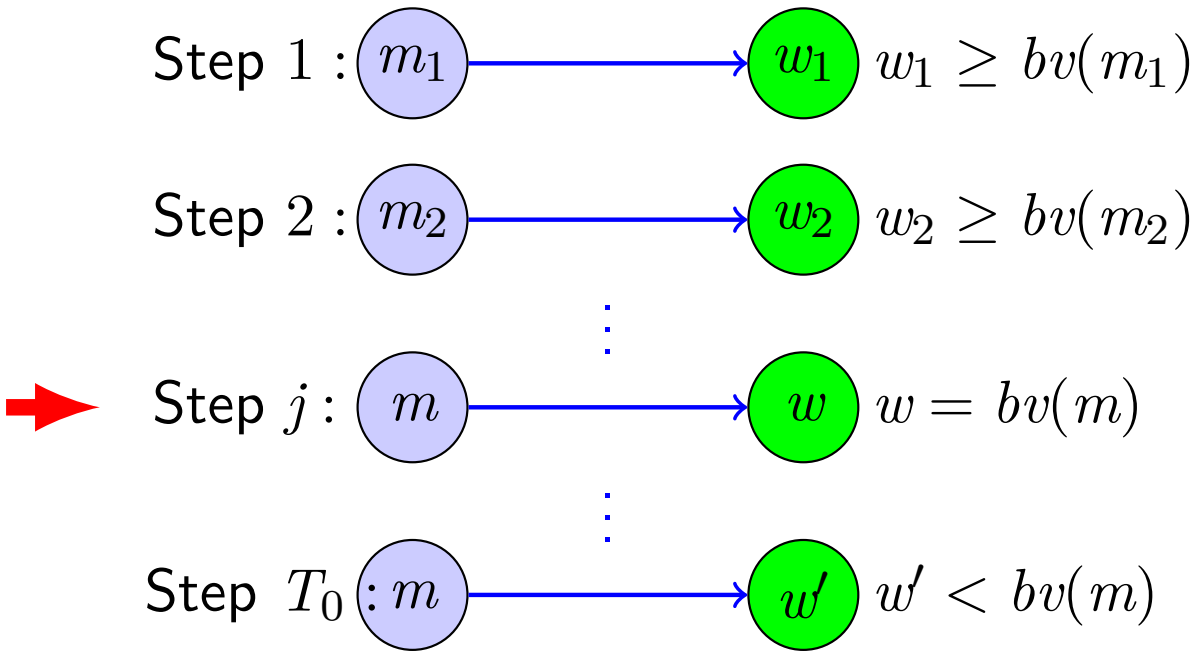
Stable Proof 3



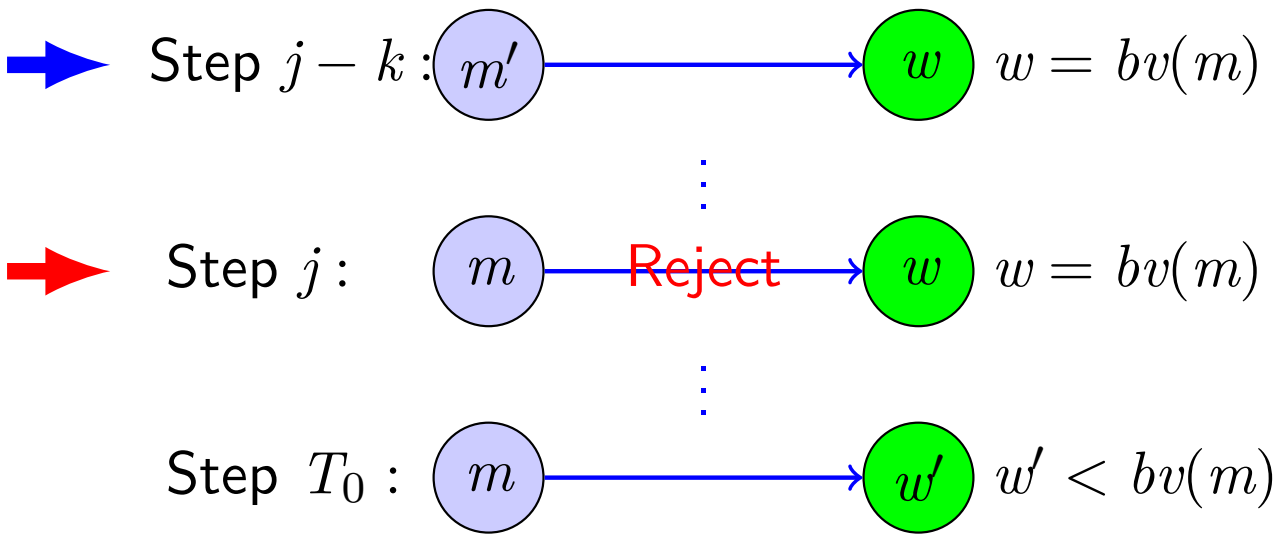
Stable Proof 4



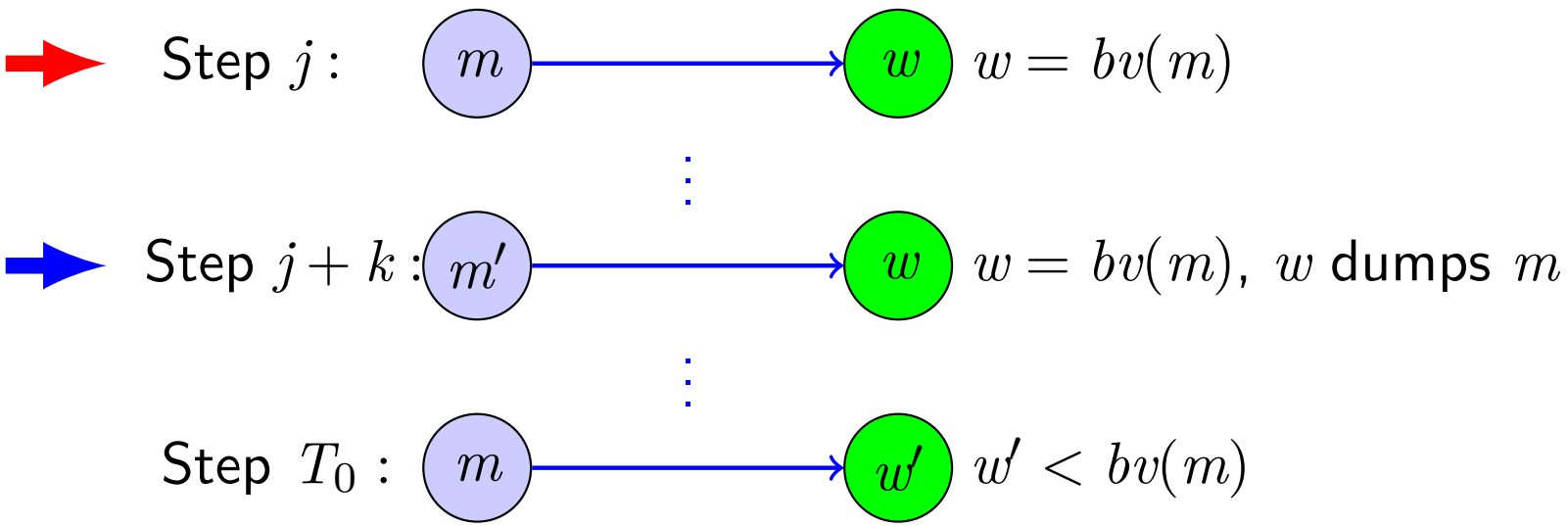
Stable Proof 5



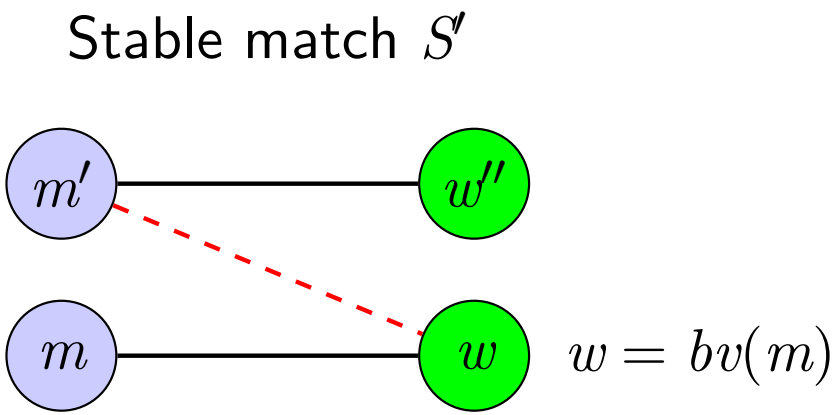
Stable Proof 6



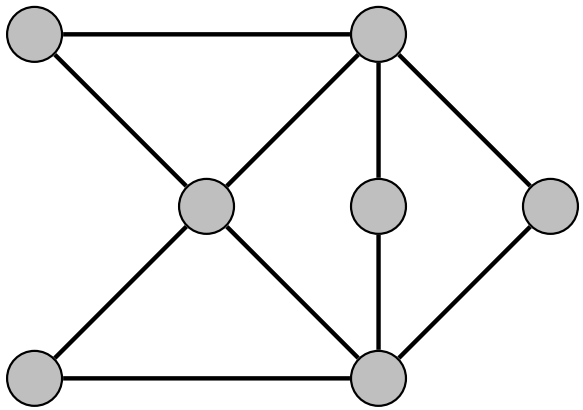
Stable Proof 7

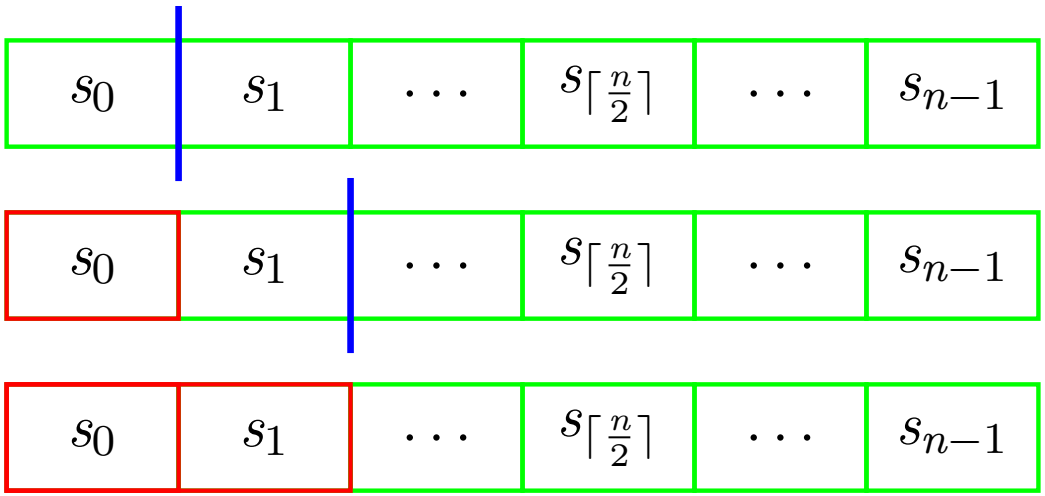


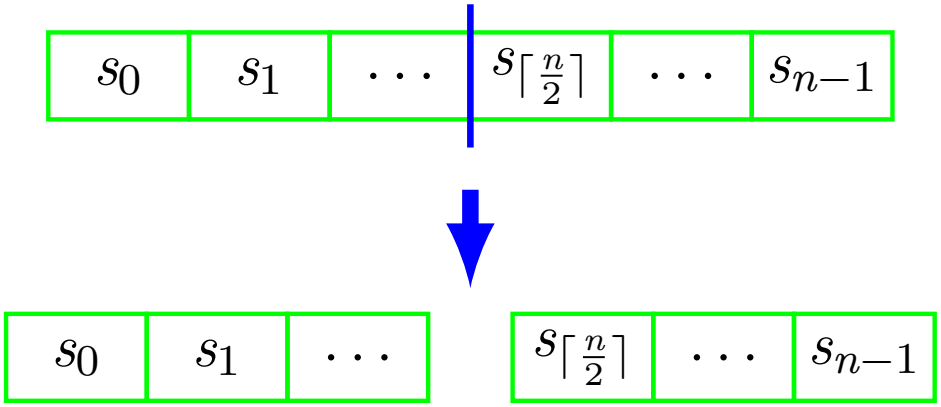
Stable Proof 8



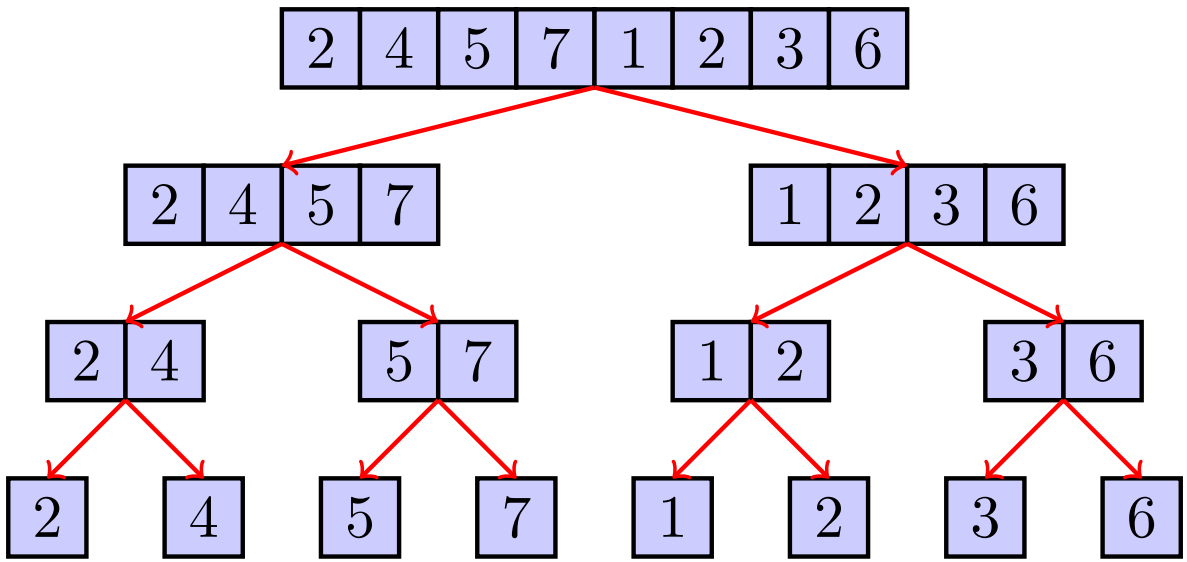
network example



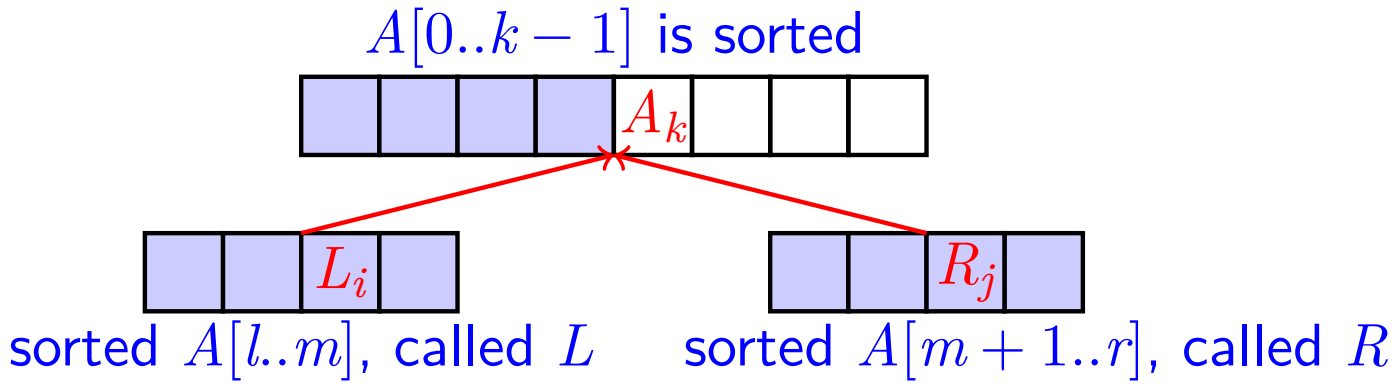

s_0 s_1 $\cdots$ $s_{\lceil \frac{n}{2} \rceil}$ $\cdots$ s_{n-1}
s_0 s_1 $\cdots$ $s_{\lceil \frac{n}{2} \rceil}$ $\cdots$ s_{n-1}
s_0 s_1 $\cdots$ $s_{\lceil \frac{n}{2} \rceil}$ $\cdots$ s_{n-1}


s_0
s_1
$\cdots$
$s_{\lceil \frac{n}{2} \rceil}$
$\cdots$
s_{n-1}
s_0
s_1
$\cdots$
$s_{\lceil \frac{n}{2} \rceil}$
$\cdots$
s_{n-1}

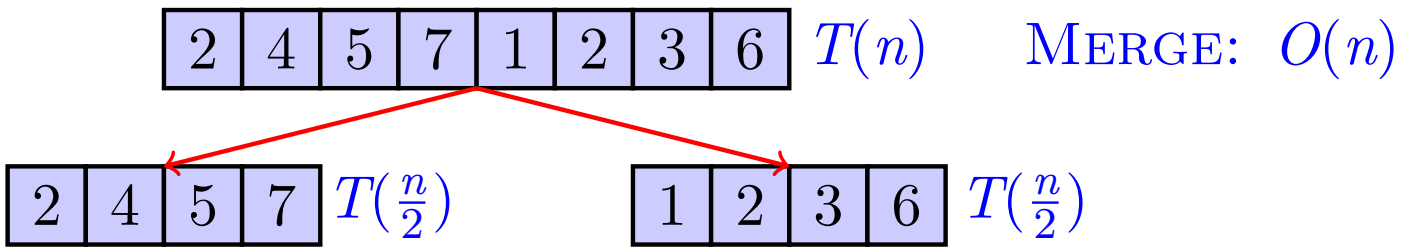
Lec5 how to divide?

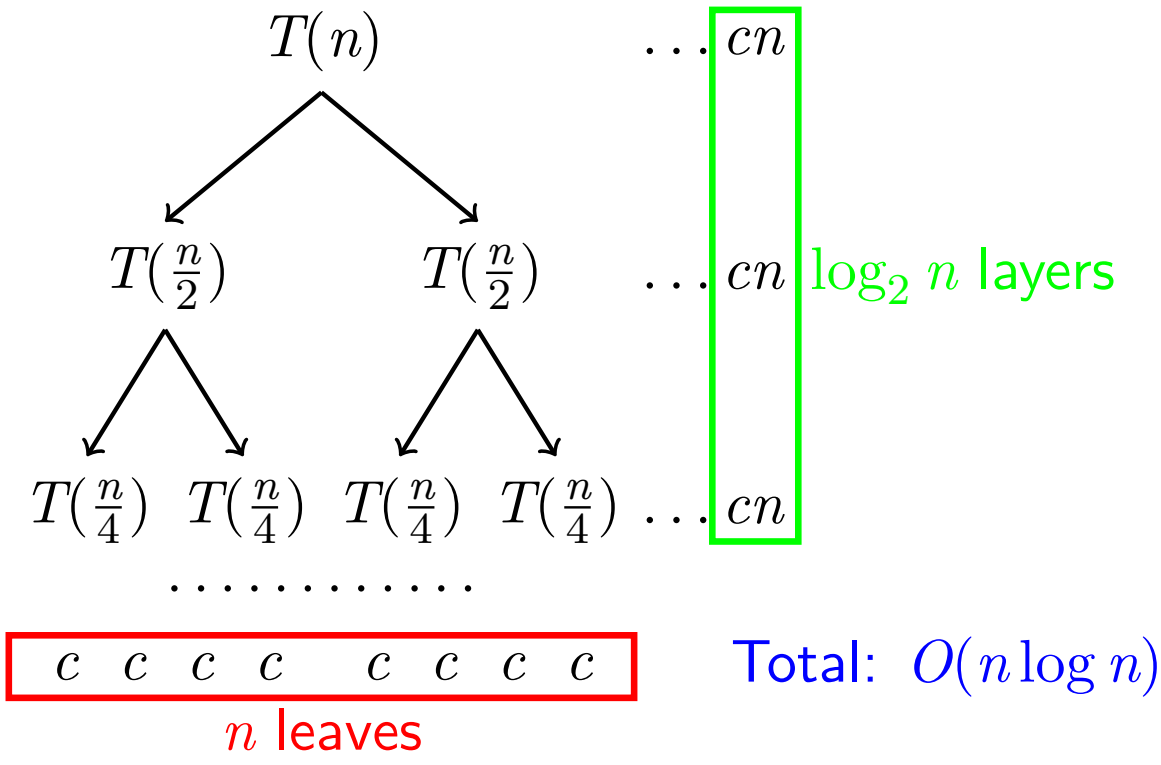


Lec5 how to combine?

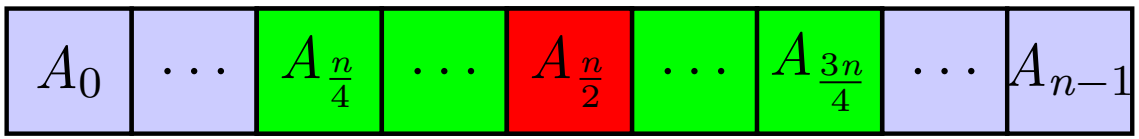


Lec5 time complexity?

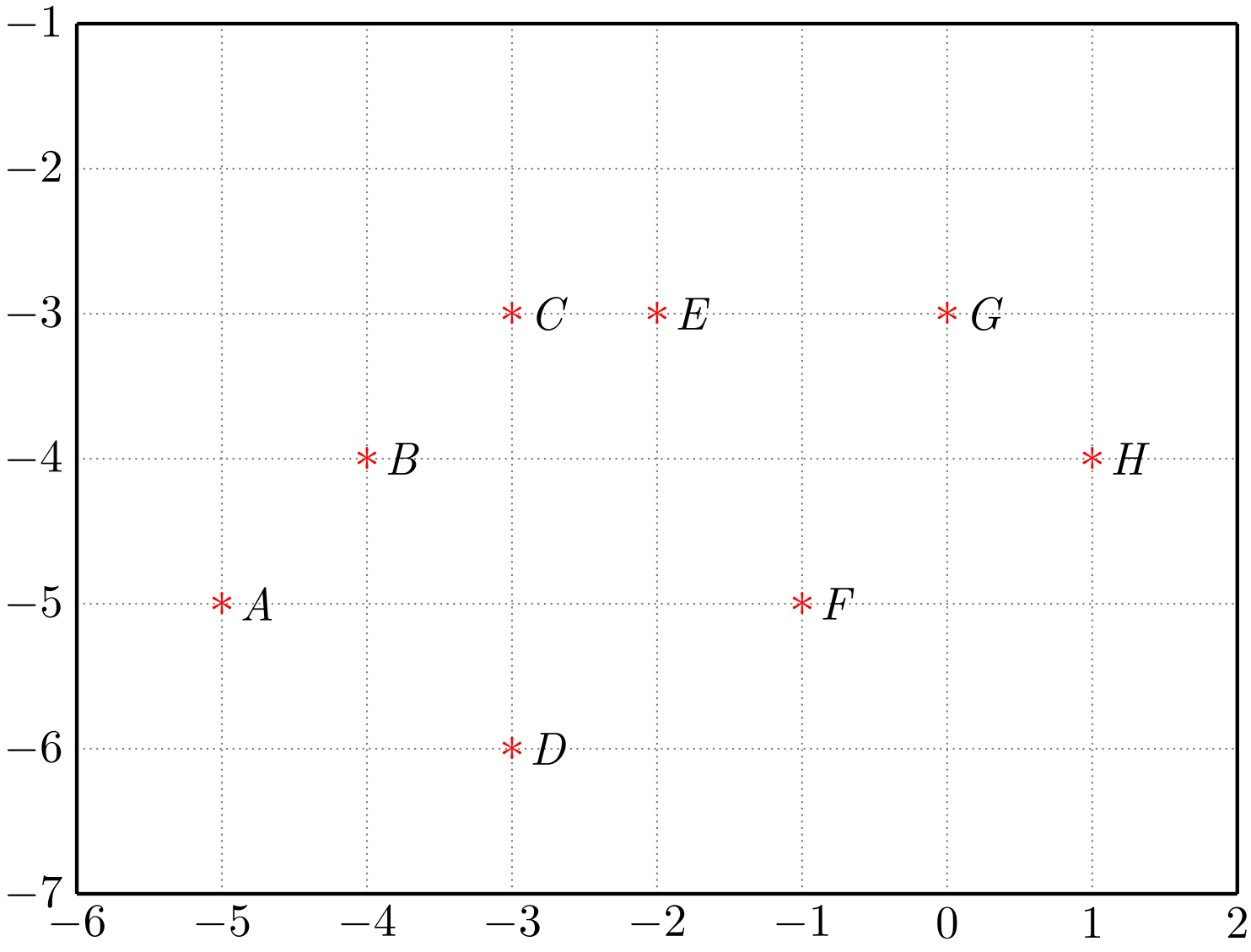


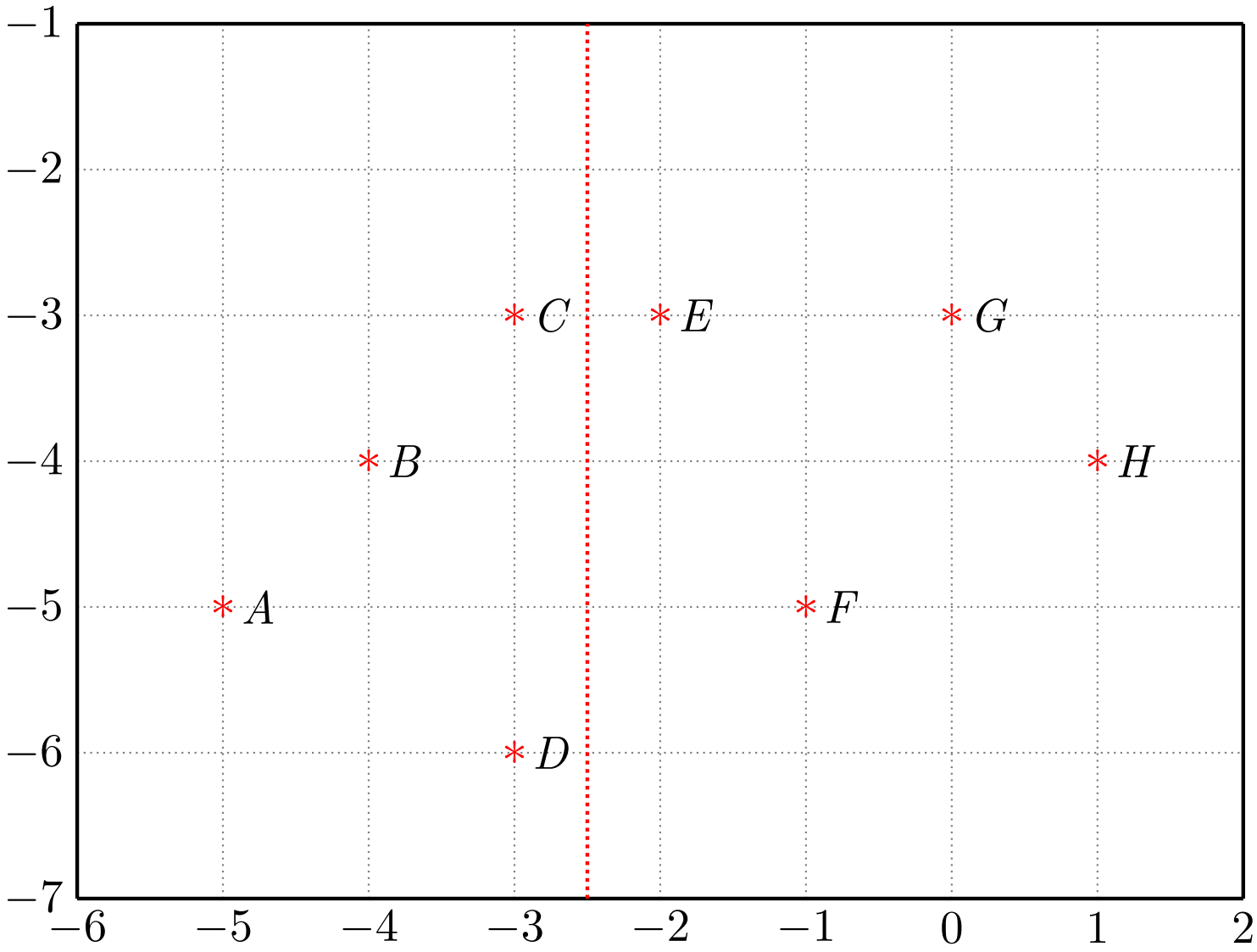

$T(n)$
$T(\frac{n}{2})$ $T(\frac{n}{2})$
$T(\frac{n}{4})$ $T(\frac{n}{4})$ $T(\frac{n}{4})$ $T(\frac{n}{4})$
$\ldots cn$
$\ldots cn$
$\ldots cn$
$\log_2 n$ layers
c c c c c c c c
n leaves
Total: $O(n \log n)$

best splitter



good splitters


−1
−2
−3
−4
−5
−6
−7
−6
−5
−4
−3
−2
−1
0
1
2
A
B
C
D
E
F
G
H


−1
−2
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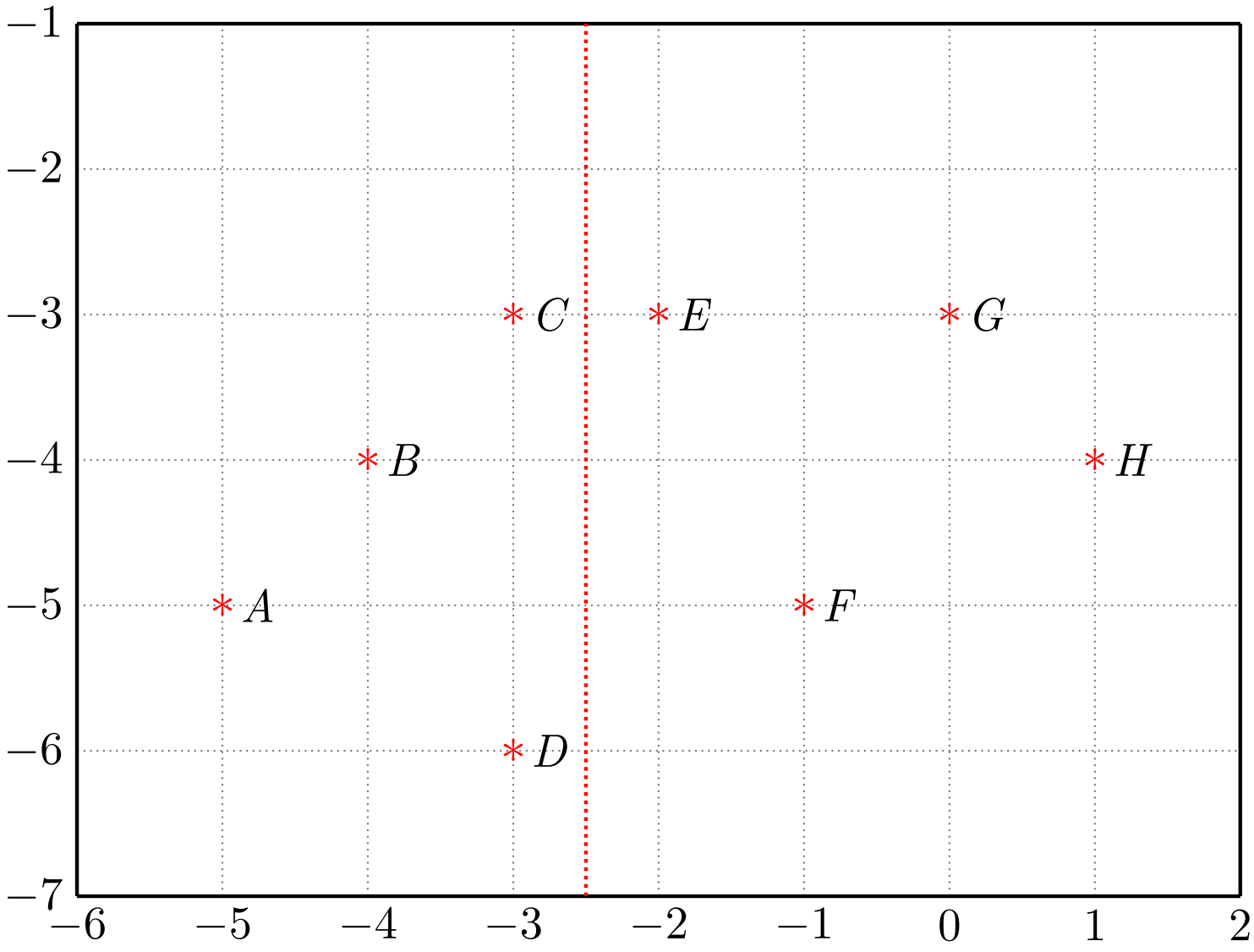
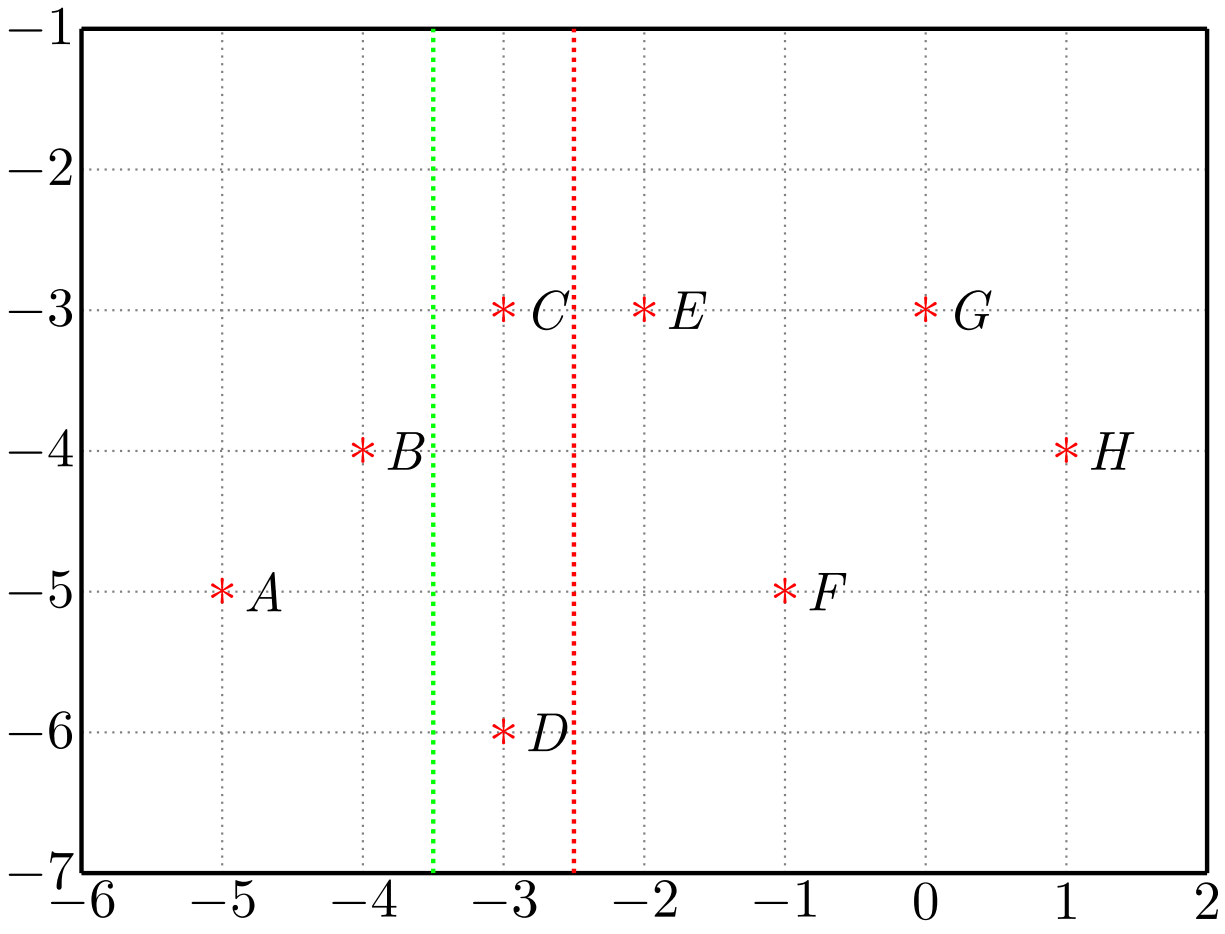
−6
−7
−6
−5
−4
−3
−2
−1
0
1
2
A
B
C
D
E
F
G
H

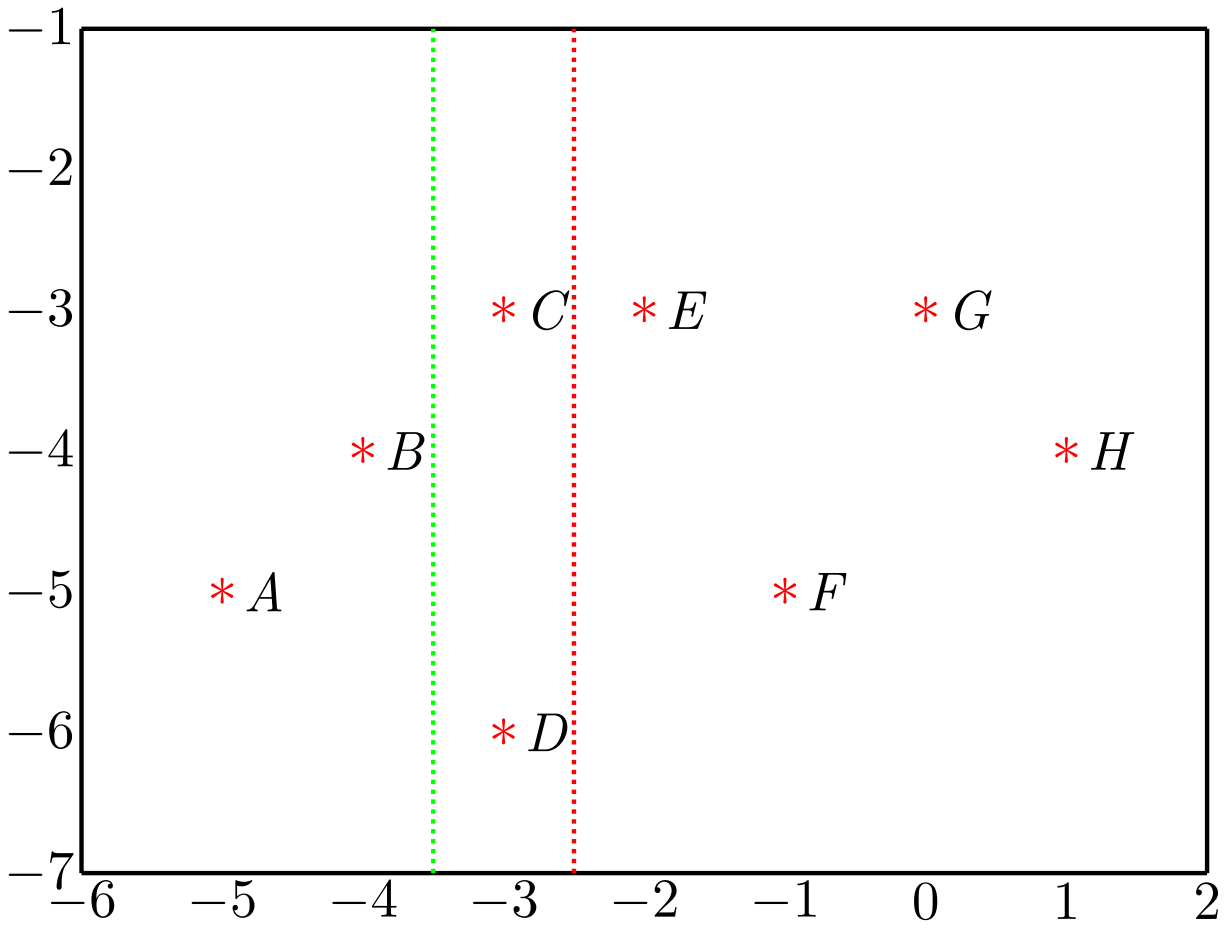
Lec5 Closest Pairs Middle Red Line



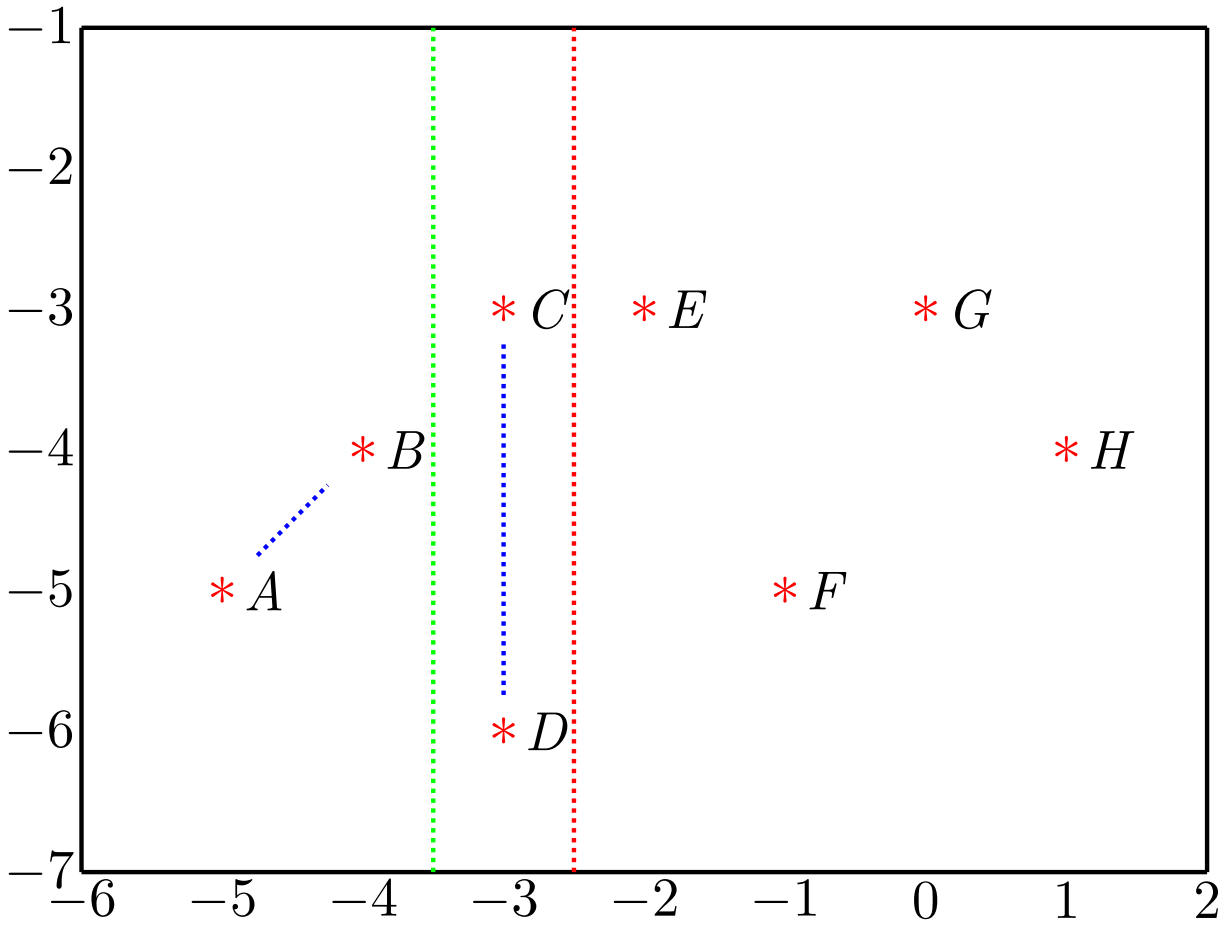
Leech Closest Pairs Left



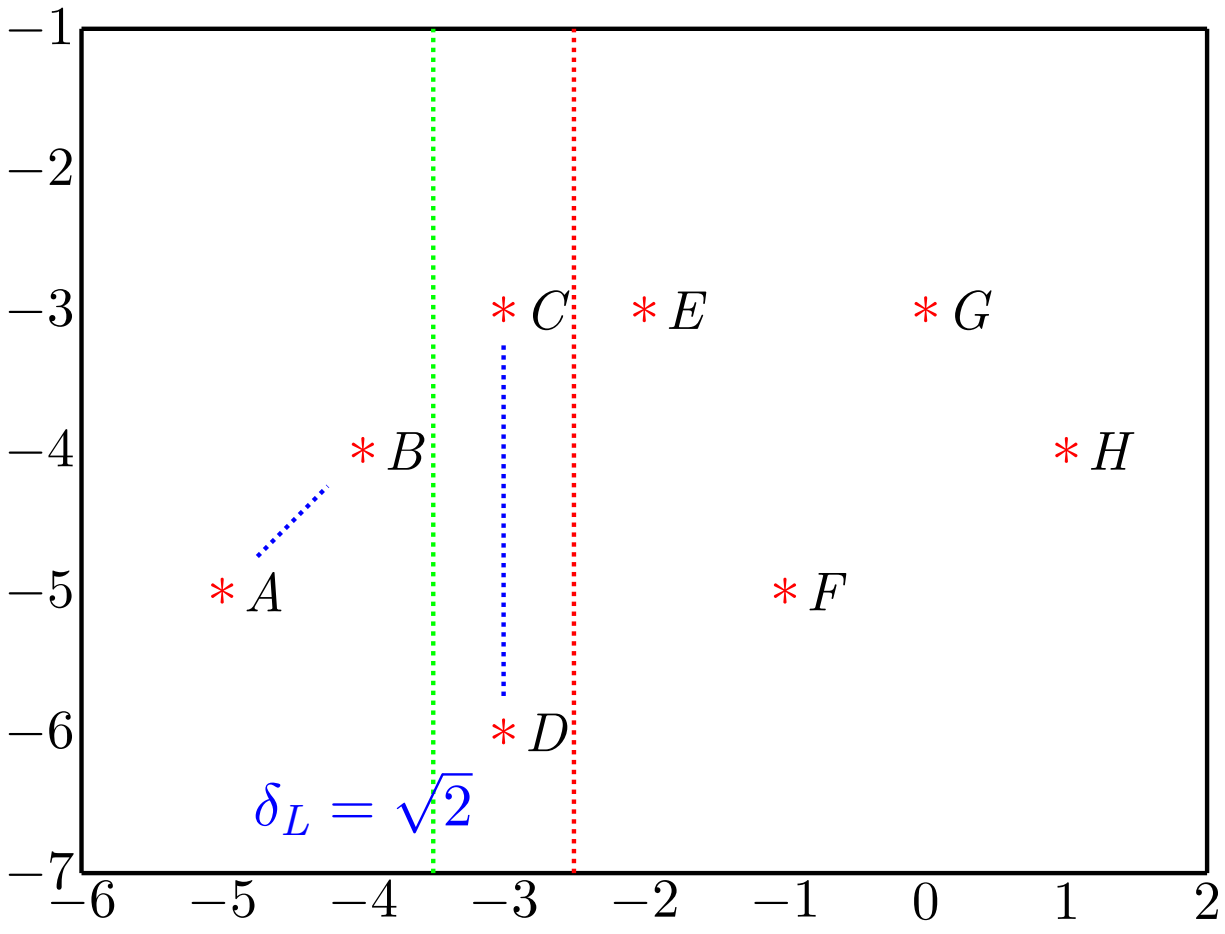
Lec5 Closest Pairs Left Grids



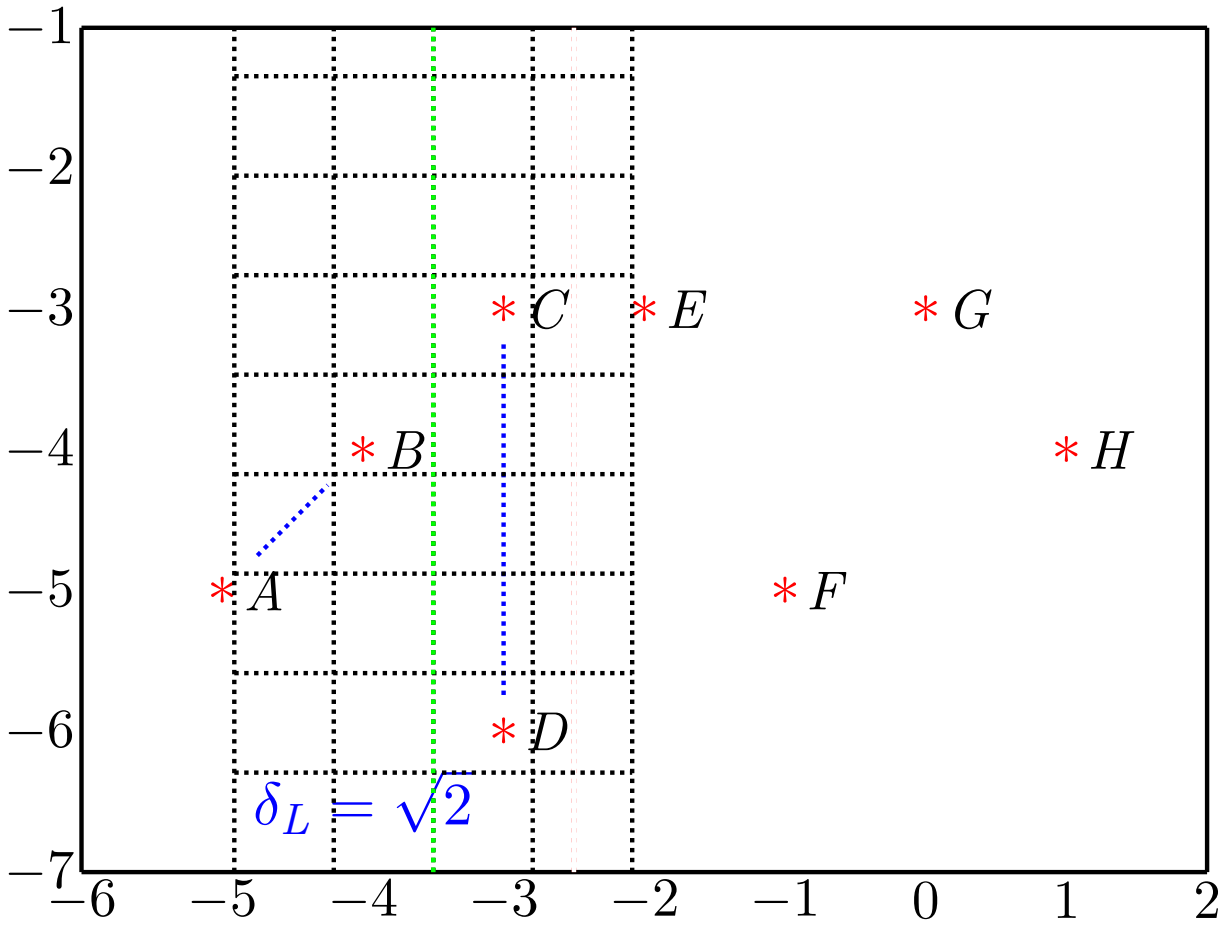
Lec5 Closest Pairs Left Grids

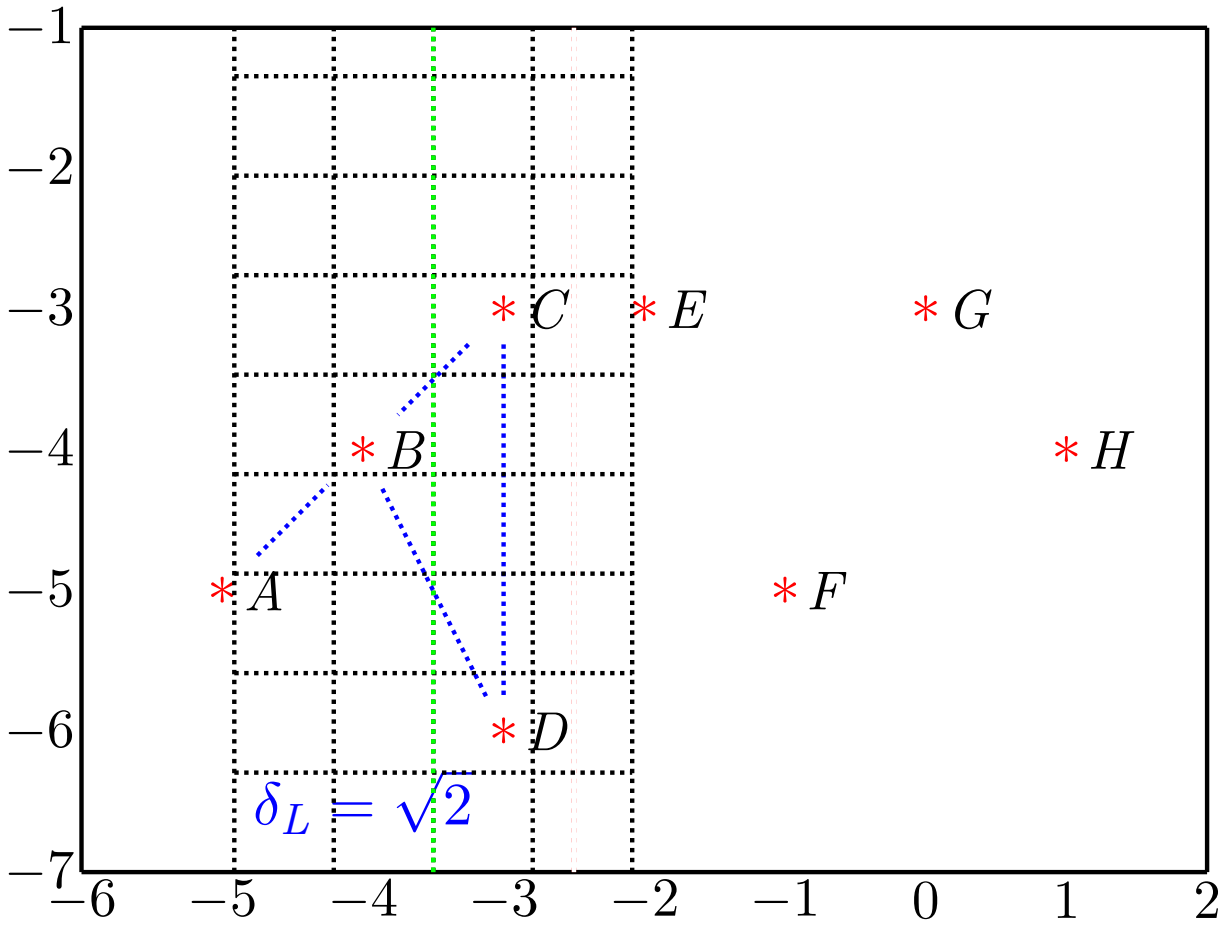


Lec5 Closest Pairs Left Grids

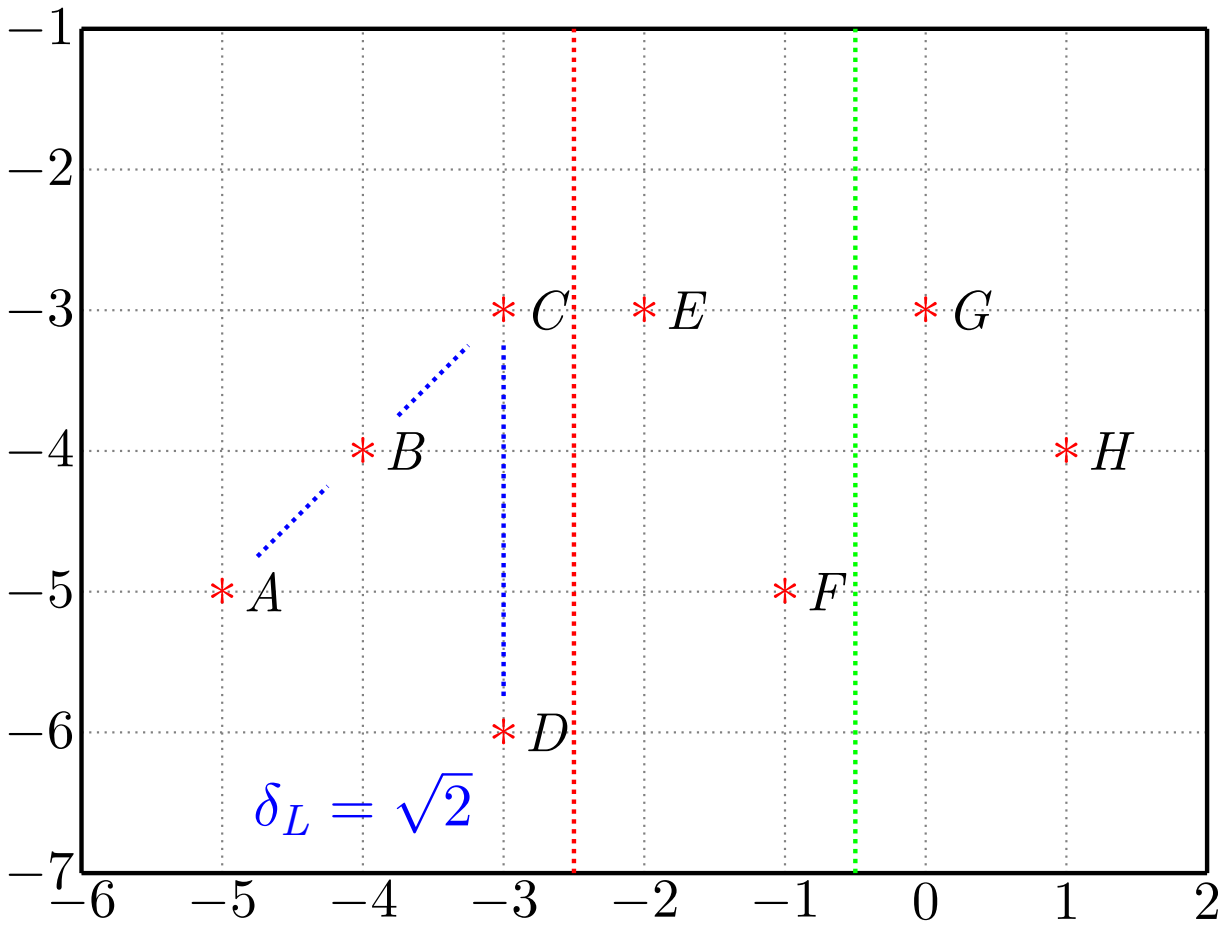


Lec5 Closest Pairs Left Grids

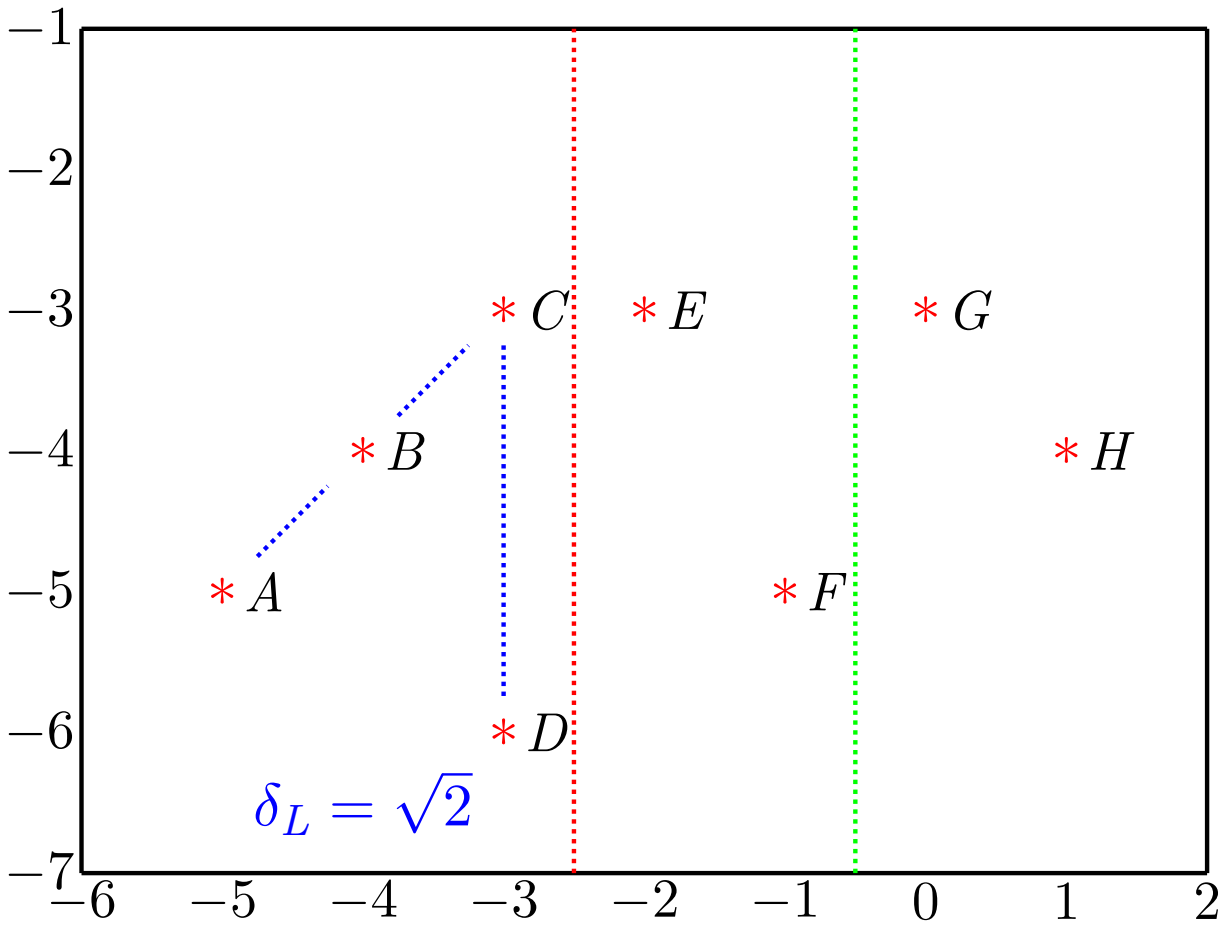


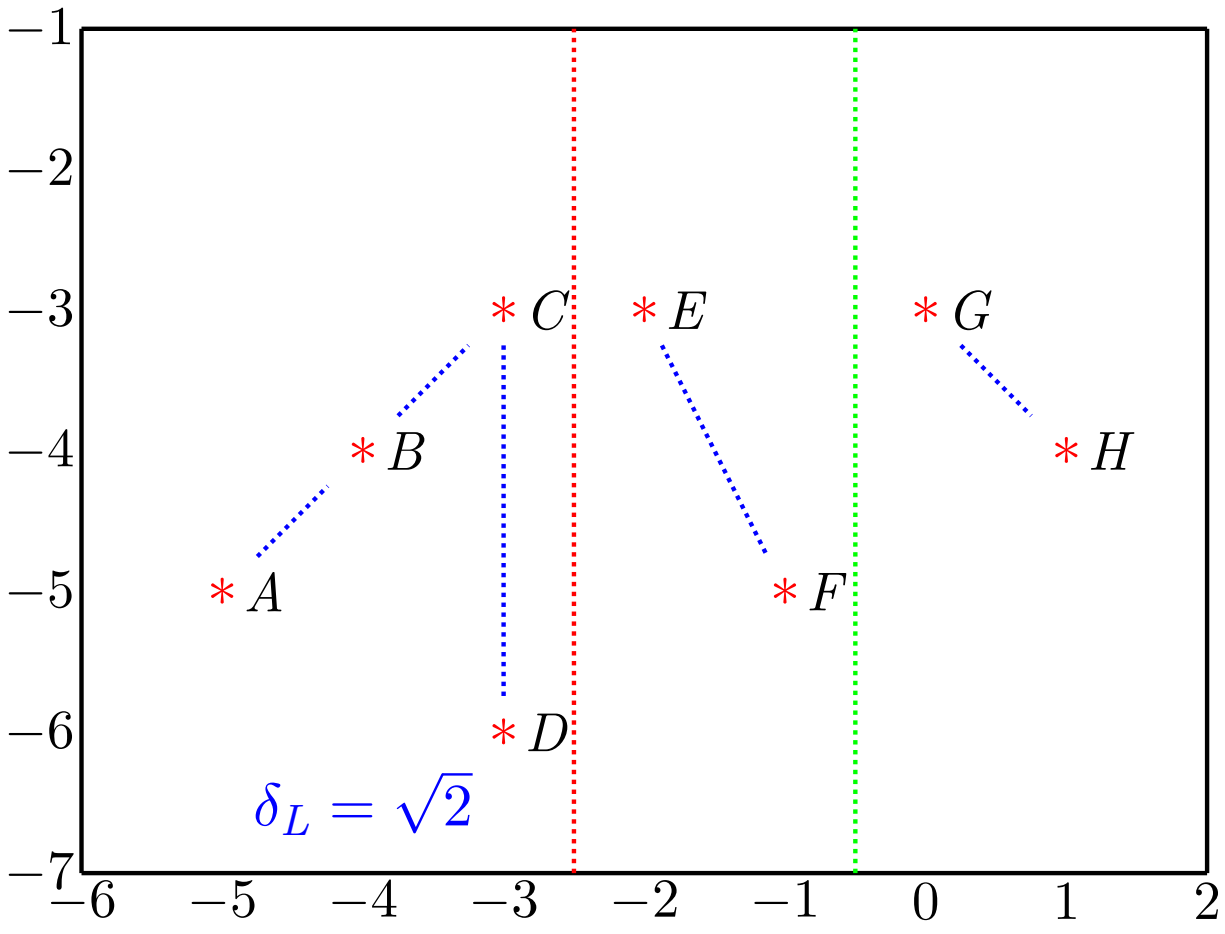

−1
−2
−3
−4
−5
−6
−7
−6
−5
−4
−3
−2
−1
0
1
2
A
B
C
D
E
F
G
H
$\delta_L = \sqrt{2}$

Lec5 Closest Pair Right

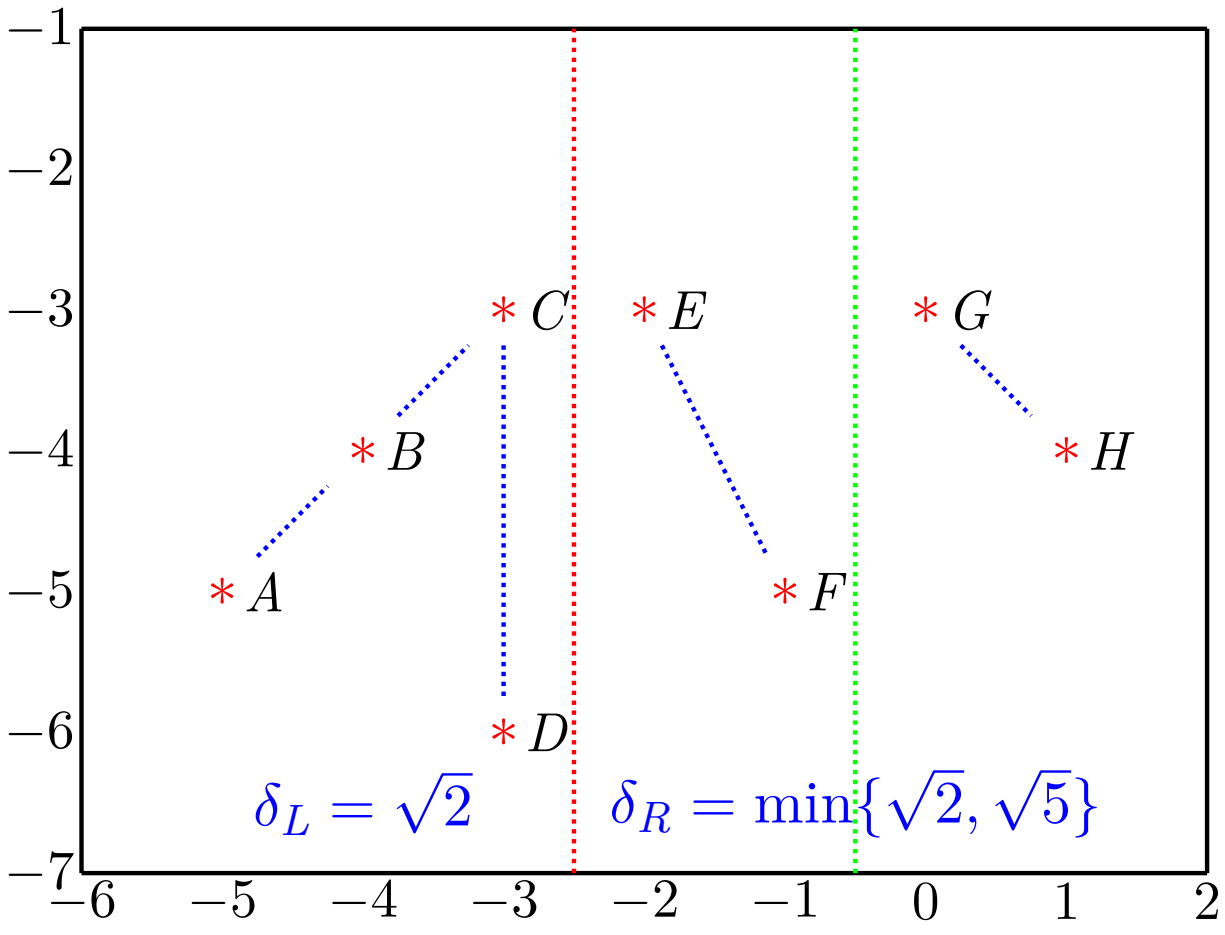


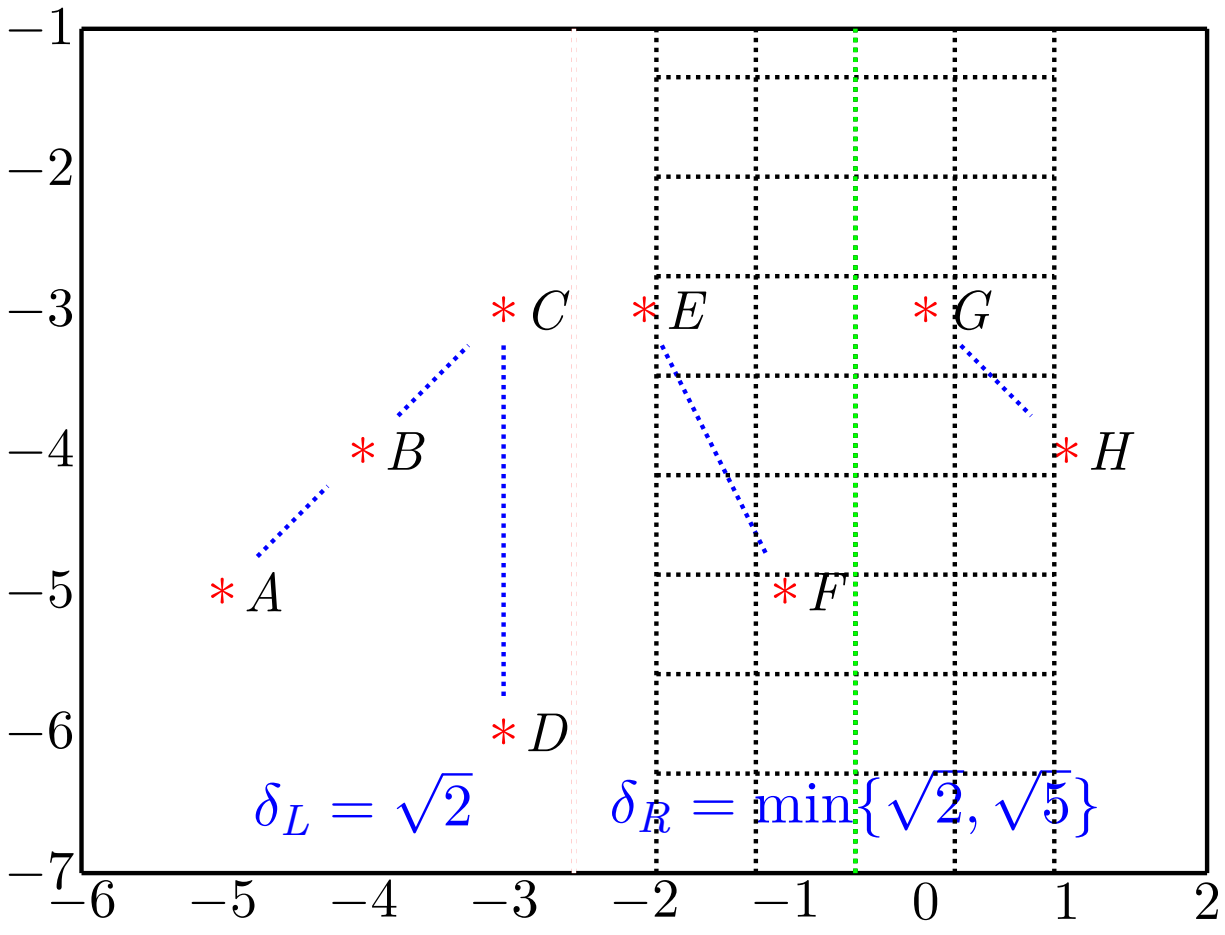
Lec5 Closest Pairs Right Grids

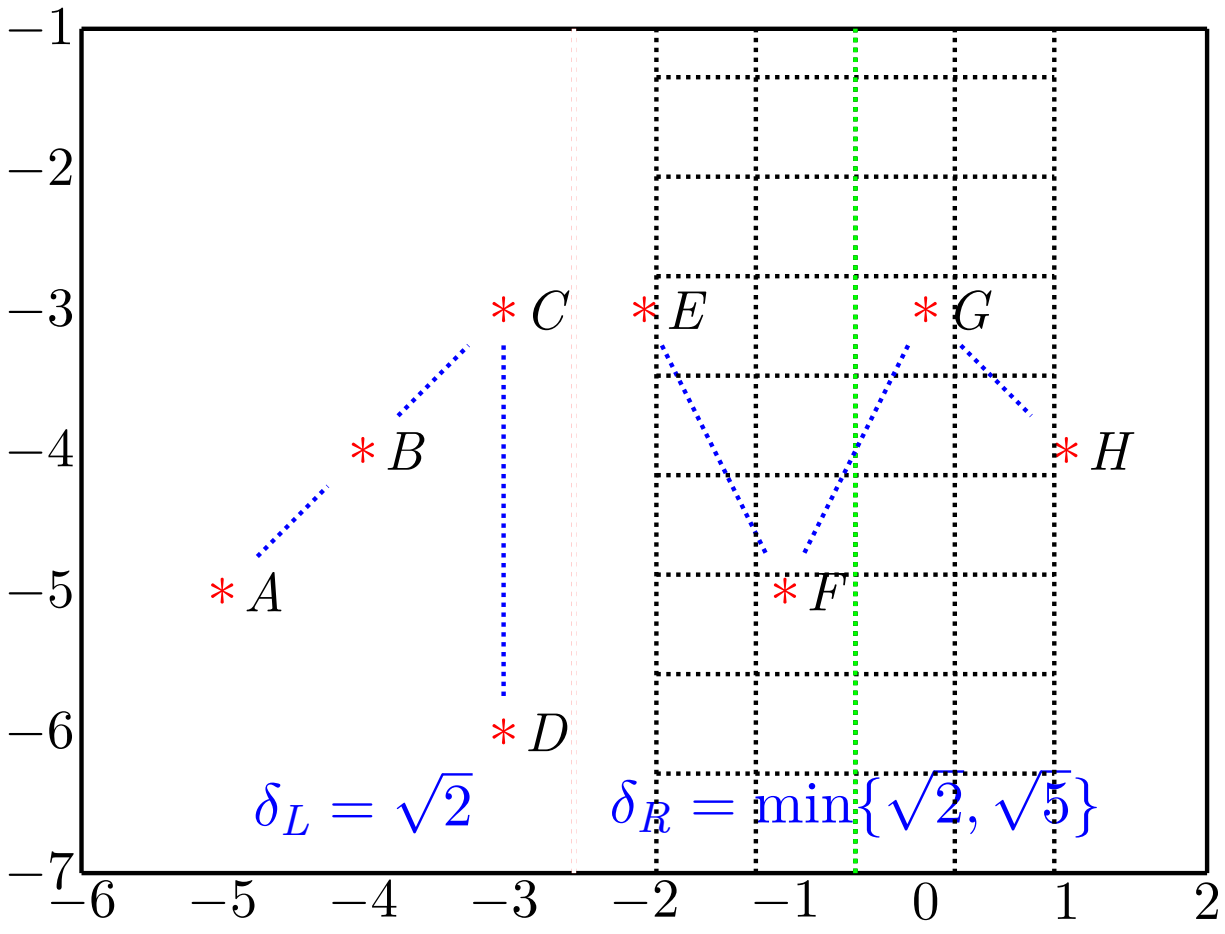



−1
−2
−3
−4
−5
−6
−7
−6
−5
−4
−3
−2
−1
0
1
2
A
B
C
D
E
F
G
H
$\delta_L = \sqrt{2}$

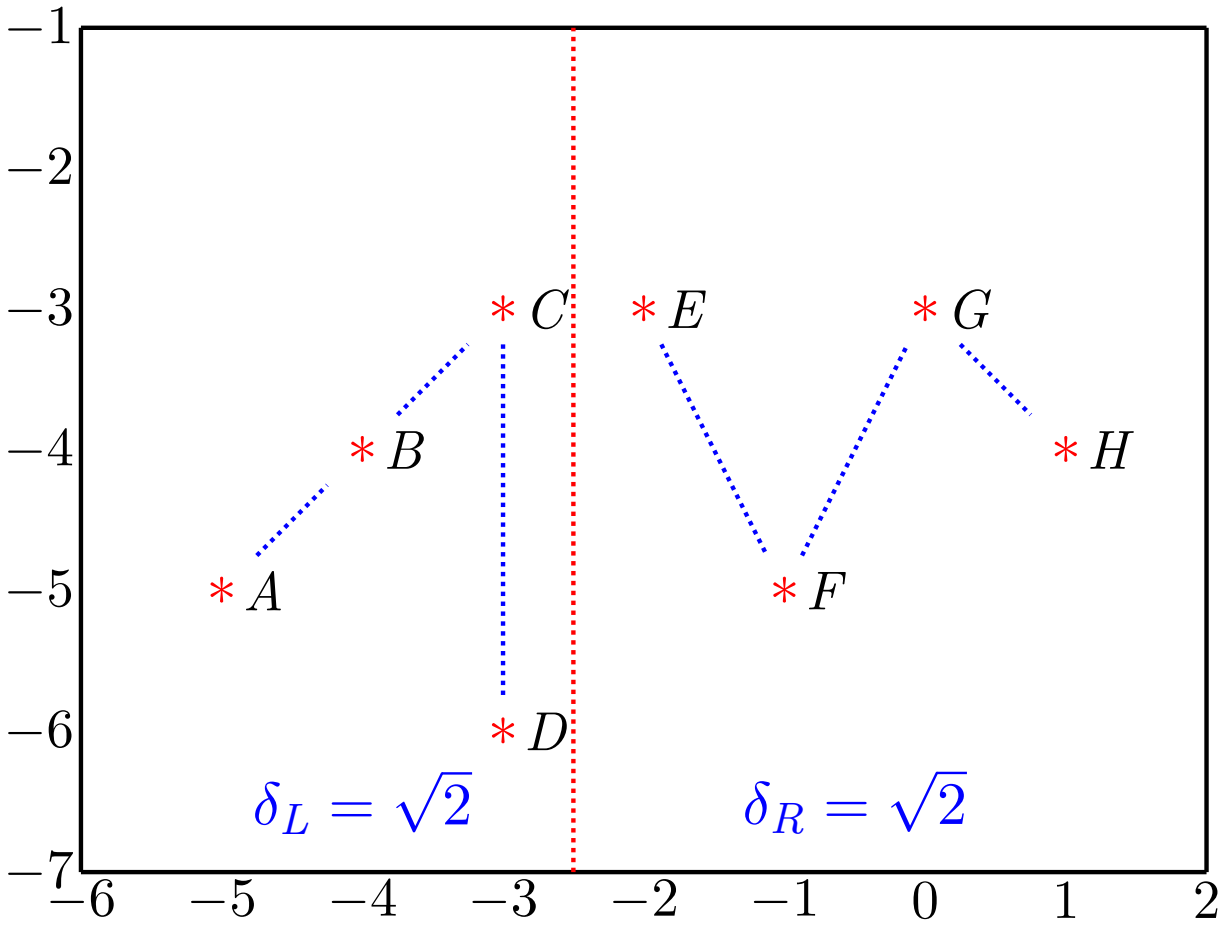
Lec5 Closest Pairs Right Grids

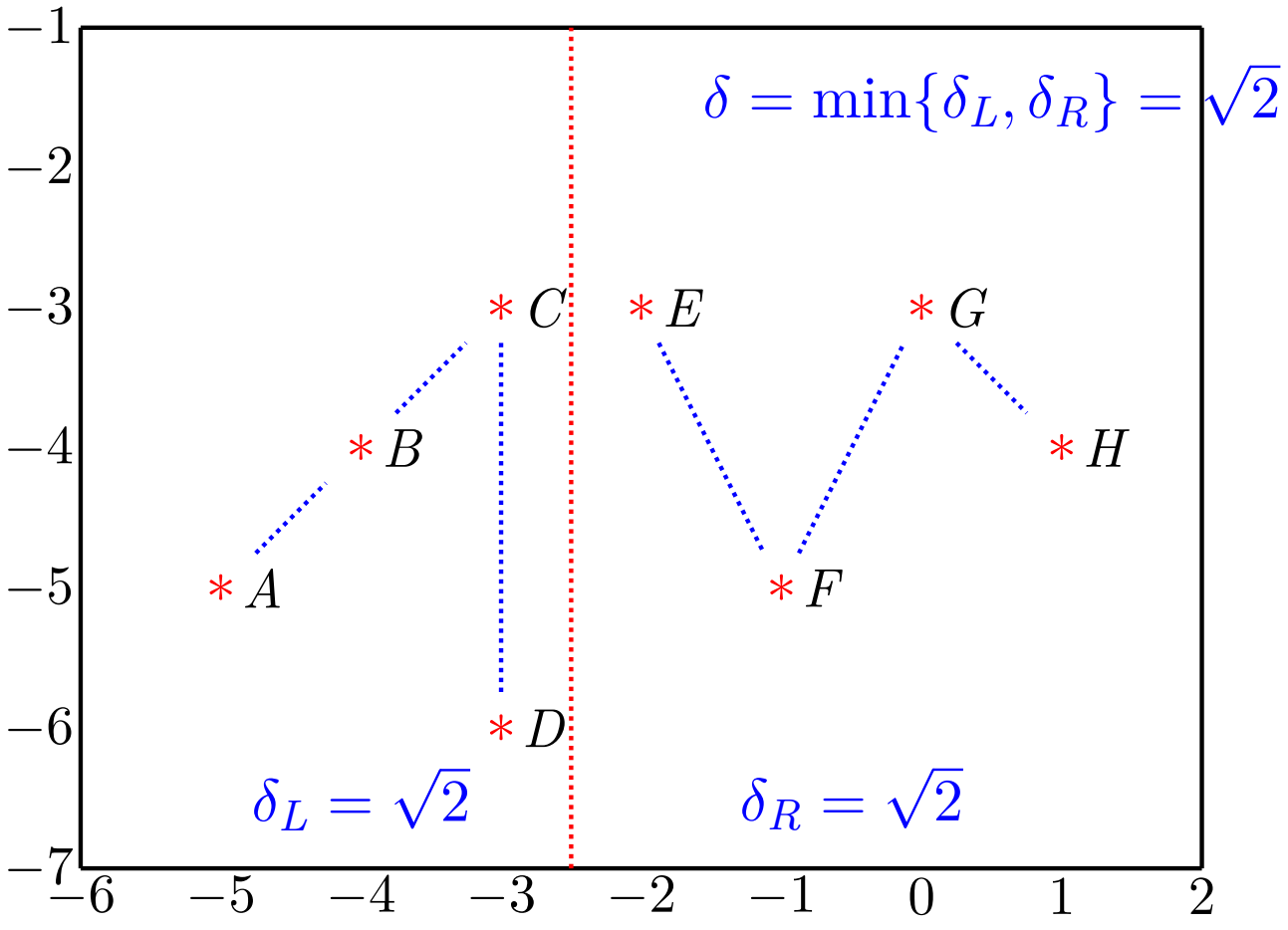


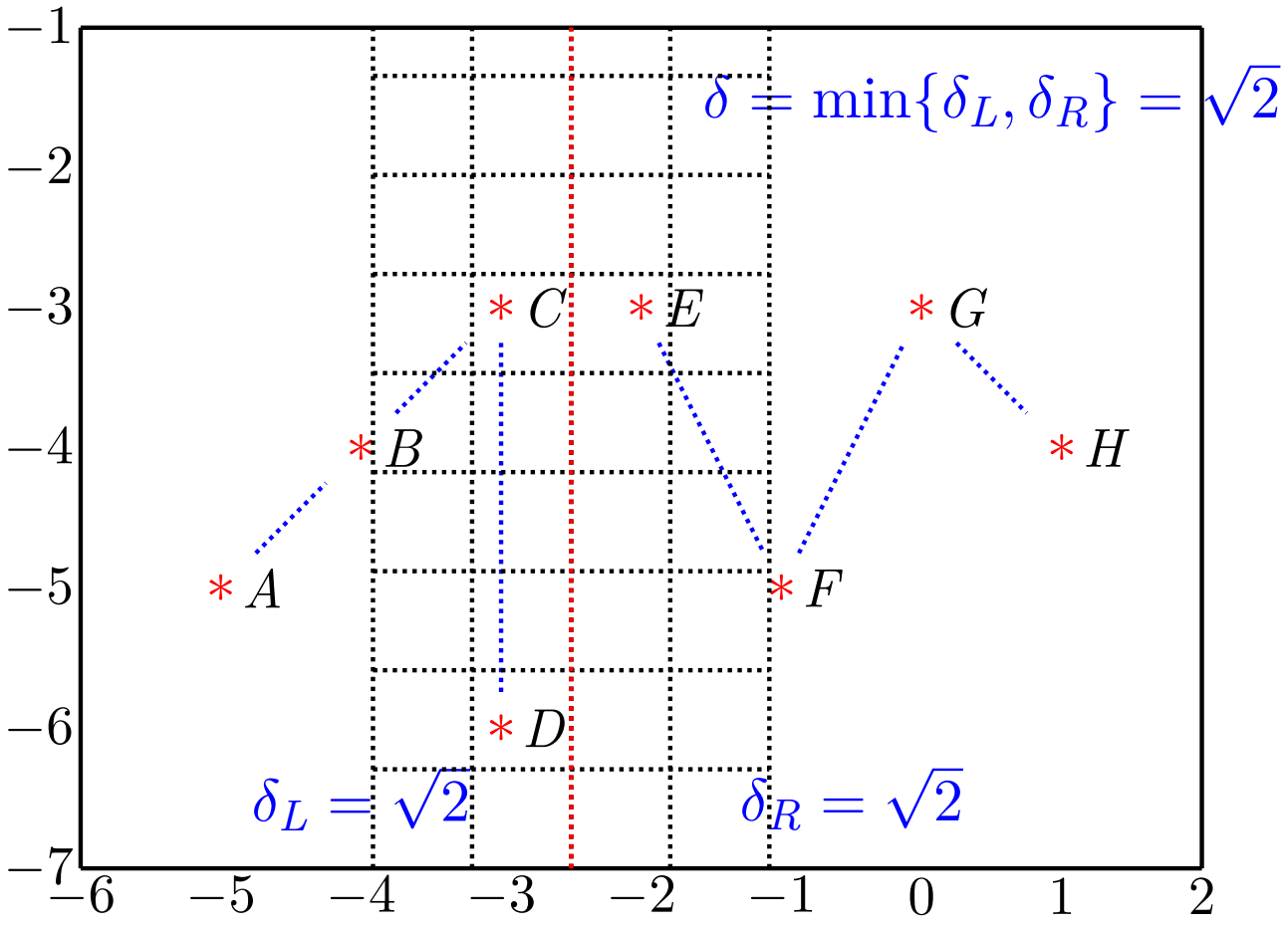

−1
−2
−3
−4
−5
−6
−7
−6
−5
−4
−3
−2
−1
0
1
2
A
B
C
D
E
F
G
H
$\delta_L = \sqrt{2}$
$\delta_R = \min\{\sqrt{2}, \sqrt{5}\}$

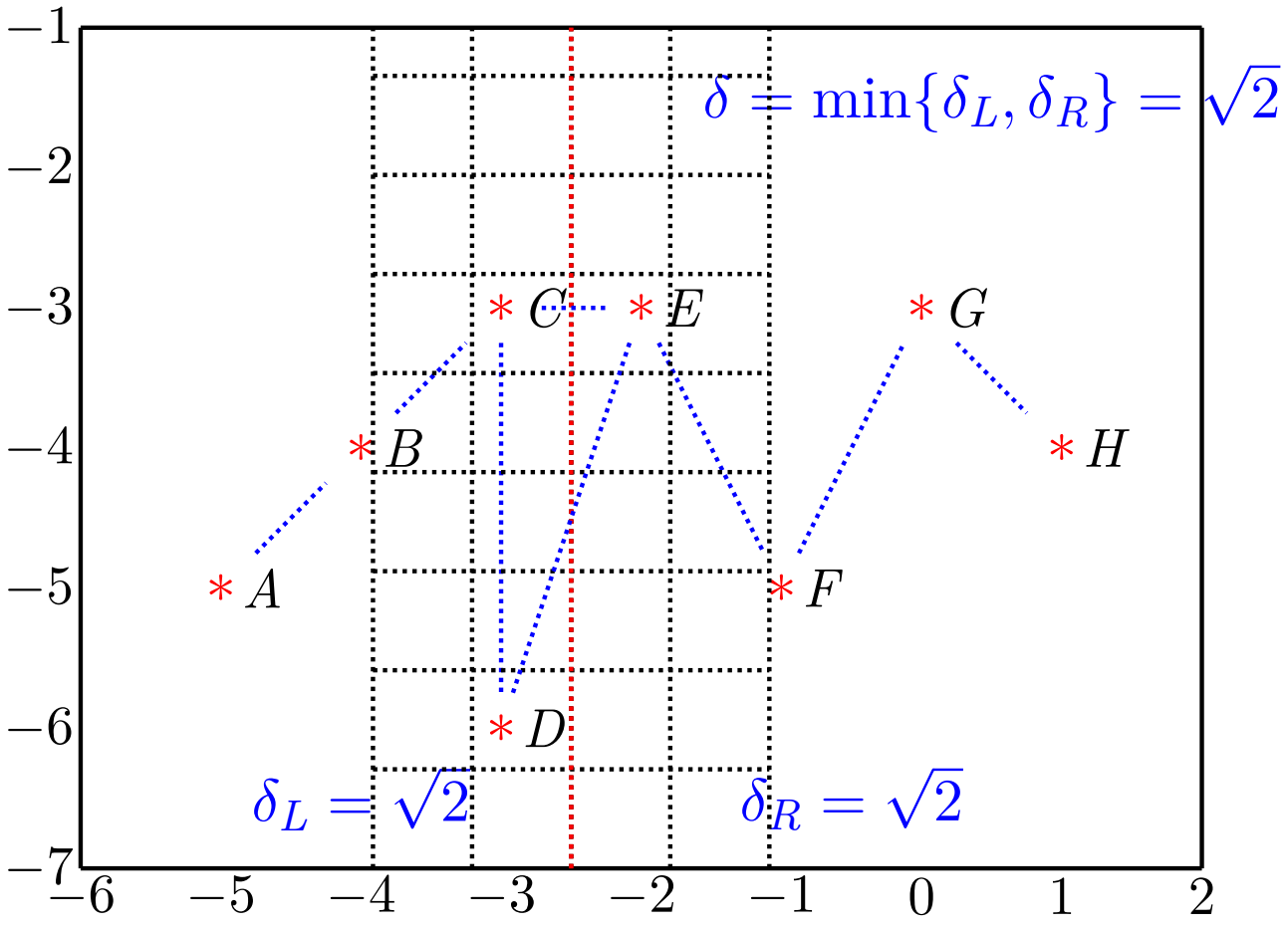

−1
−2
−3
−4
−5
−6
−7
−6
−5
−4
−3
−2
−1
0
1
2
A
B
C
D
E
F
G
H
$\delta_L = \sqrt{2}$
$\delta_R = \min\{\sqrt{2}, \sqrt{5}\}$

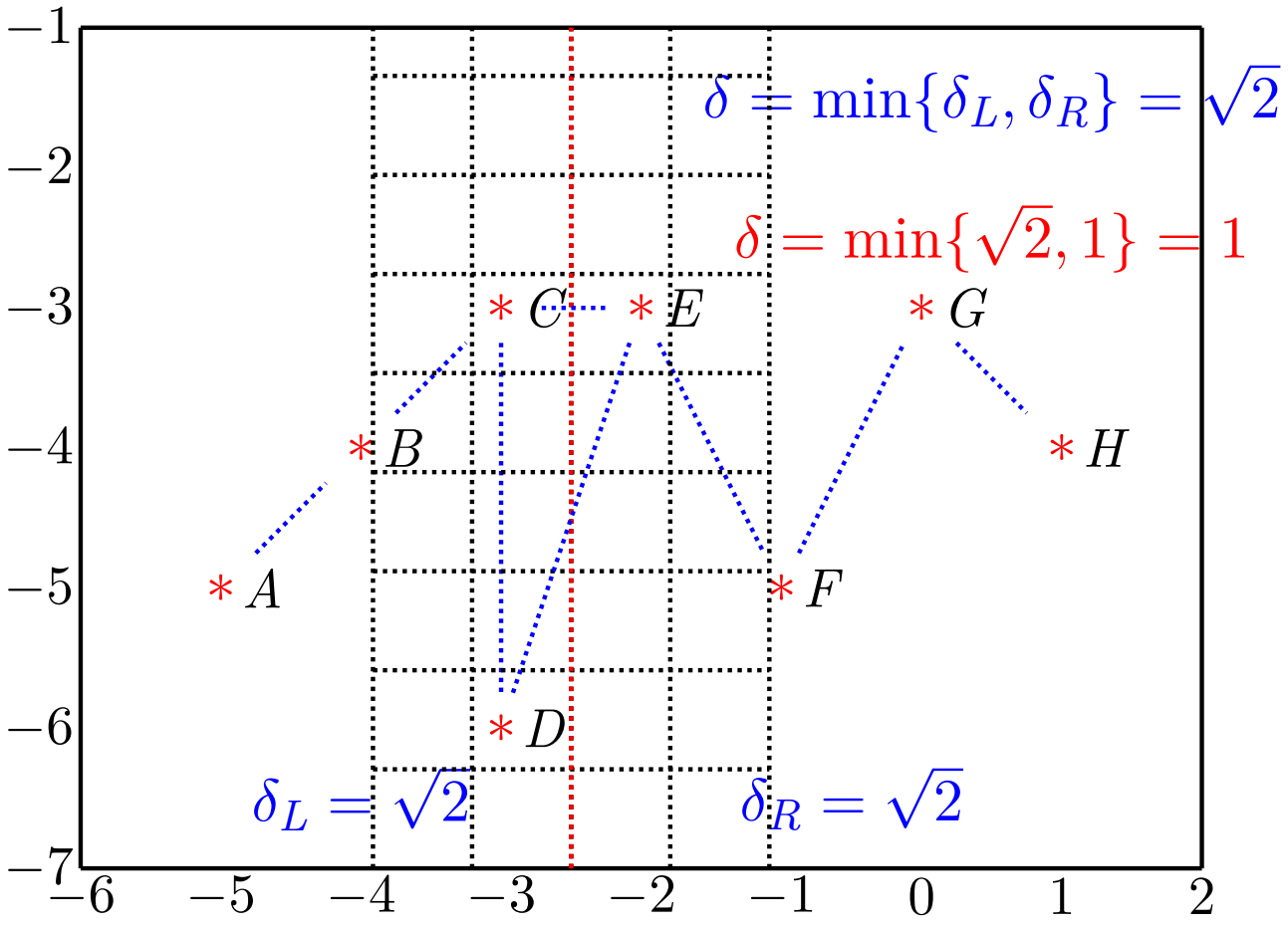
Lec5 Closest Pairs Final



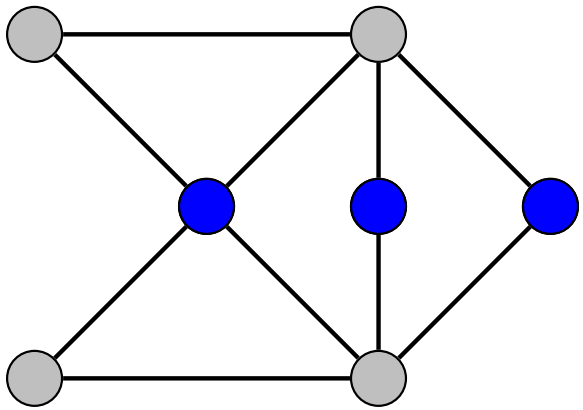

$\delta = \min\{\delta_L, \delta_R\} = \sqrt{2}$
A
B
C
D
E
F
G
H
$\delta_L = \sqrt{2}$
$\delta_R = \sqrt{2}$
−1
−2
−3
−4
−5
−6
−7
−6
−5
−4
−3
−2
−1
0
1
2

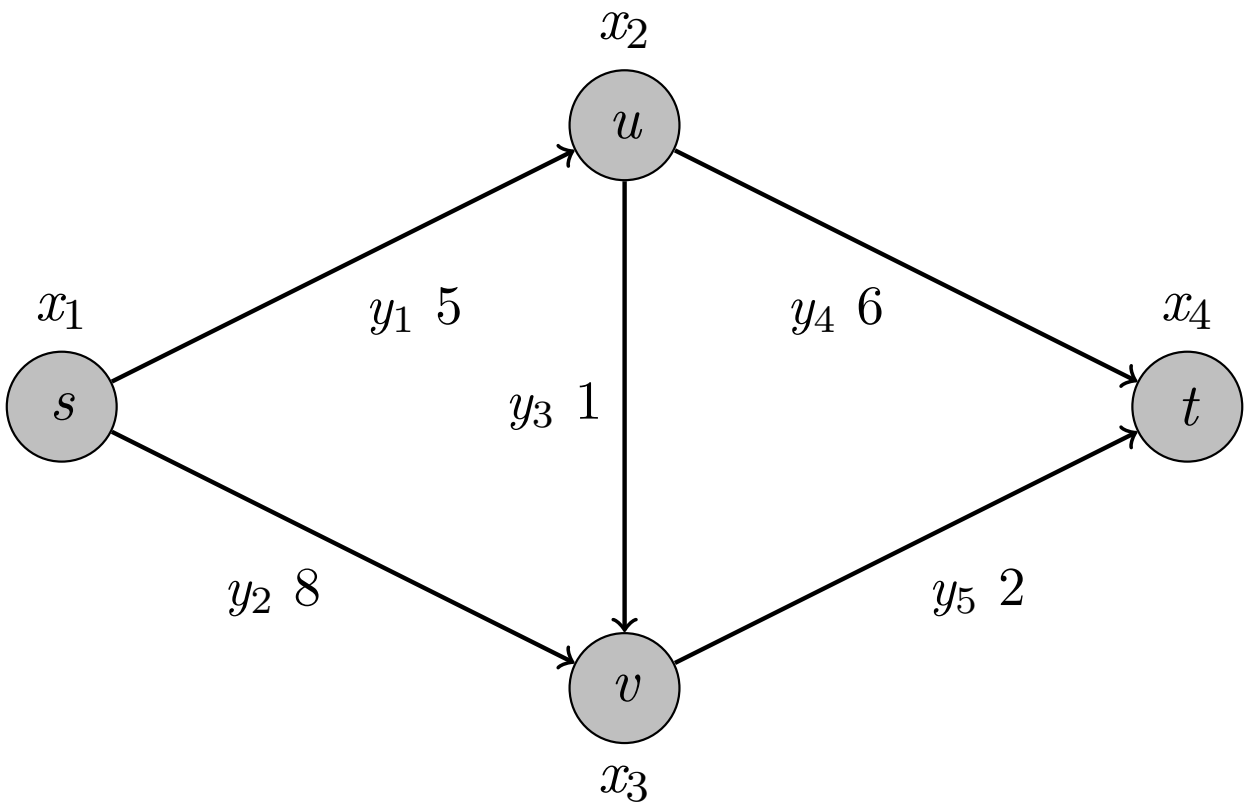

$\delta = \min\{\delta_L, \delta_R\} = \sqrt{2}$
$\delta_L = \sqrt{2}$
$\delta_R = \sqrt{2}$
A
B
C
D
E
F
G
H
−1
−2
−3
−4
−5
−6
−7
−6
−5
−4
−3
−2
−1
0
1
2


$\delta = \min\{\delta_L, \delta_R\} = \sqrt{2}$
$\delta_L = \sqrt{2}$
$\delta_R = \sqrt{2}$
A
B
C
D
E
F
G
H
−1
−2
−3
−4
−5
−6
−7
−6
−5
−4
−3
−2
−1
0
1
2


$\delta = \min\{\delta_L, \delta_R\} = \sqrt{2}$
$\delta = \min\{\sqrt{2}, 1\} = 1$
C
E
G
B
H
A
F
D
$\delta_L = \sqrt{2}$
$\delta_R = \sqrt{2}$
−1
−2
−3
−4
−5
−6
−7
−6
−5
−4
−3
−2
−1
0
1
2

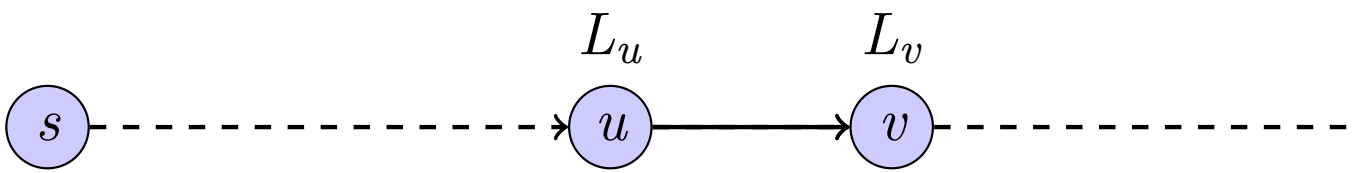
Examples



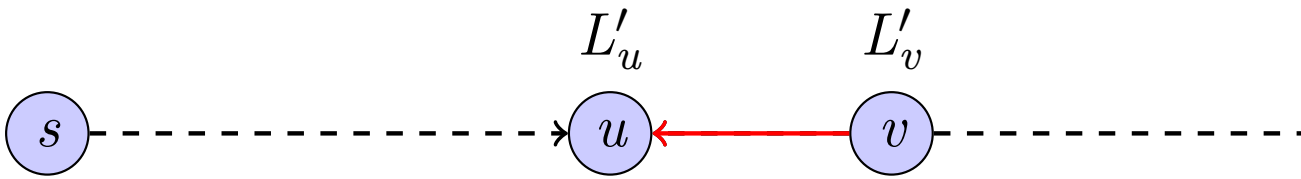

x_2
u
x_1
y_1 5
y_4 6
x_4
s
y_3 1
t
y_2 8
y_5 2
v
x_3

Edmonds Karp

Step k :

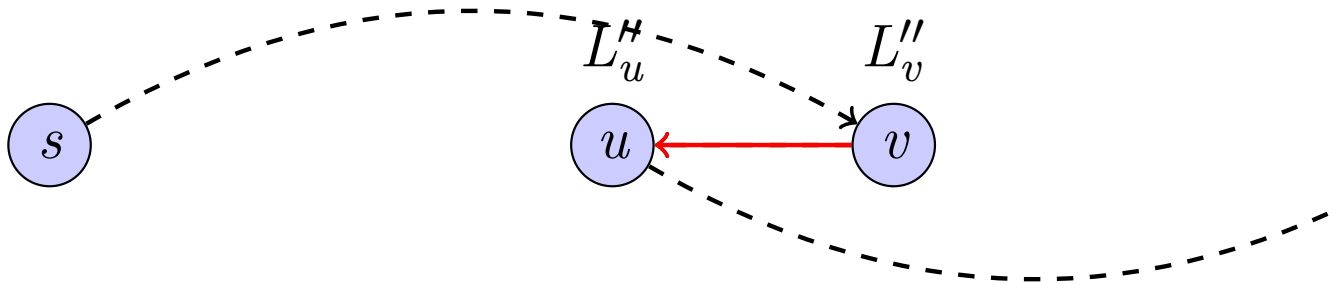


Step $k+1$:

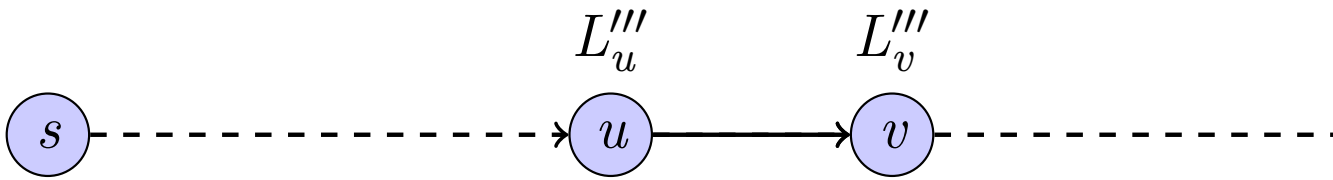


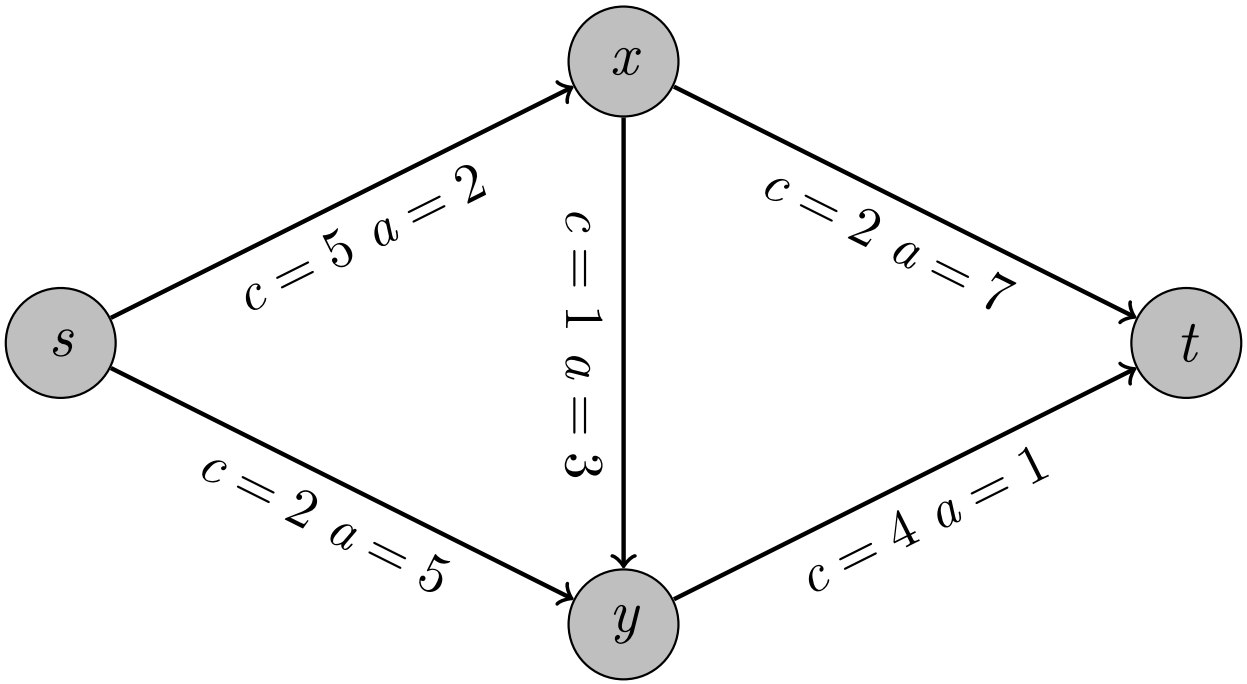
Primal and dual

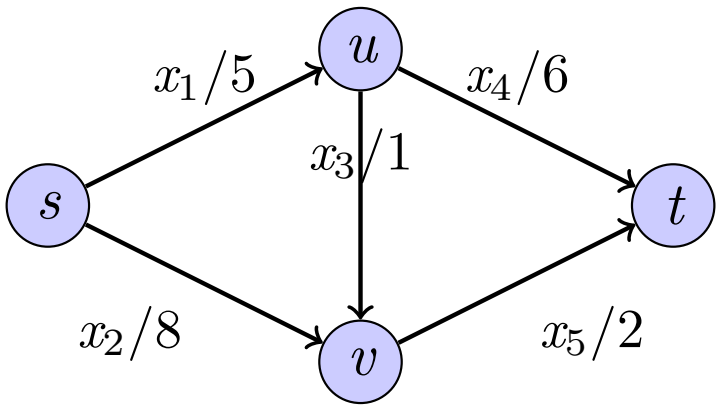
Step k'' :

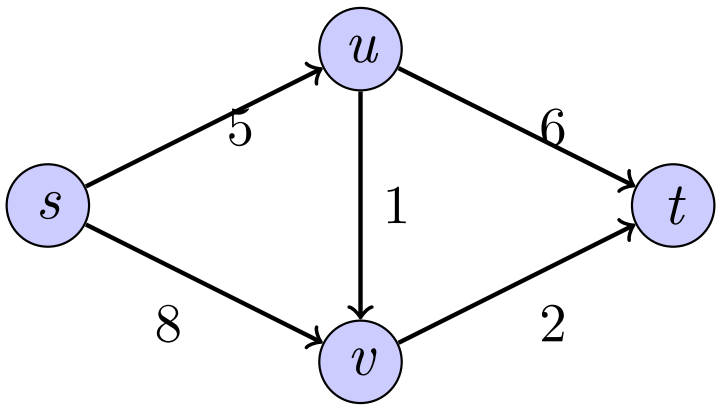


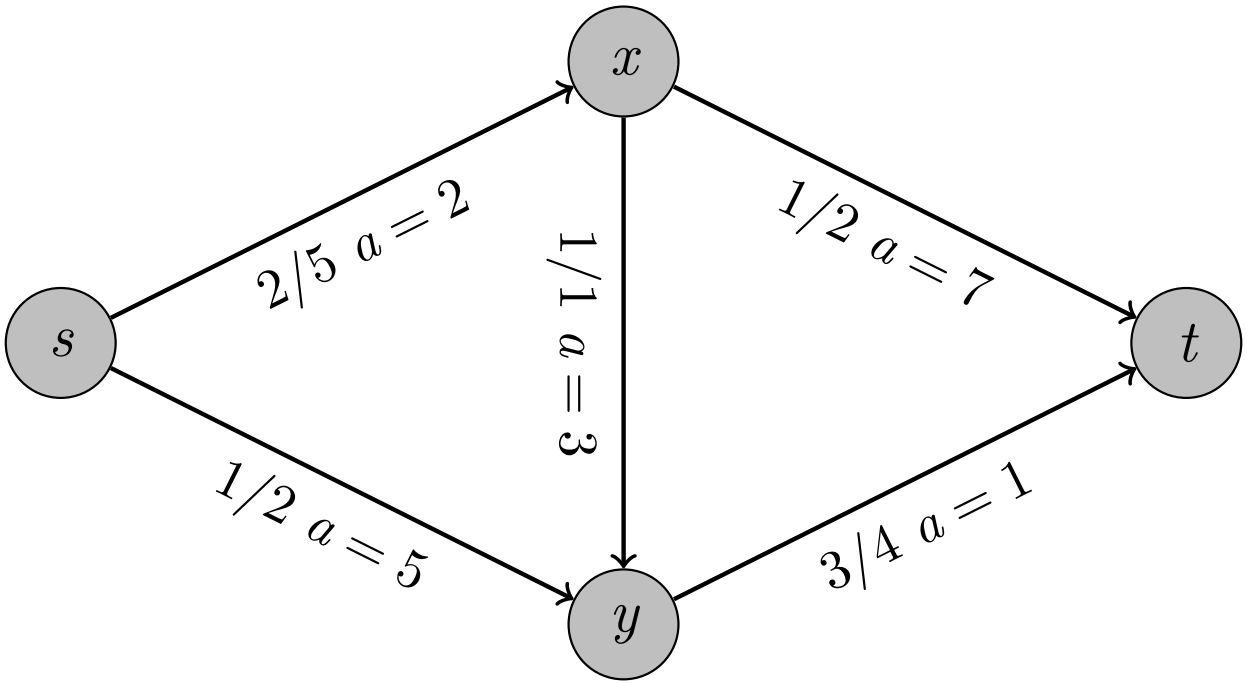
Step k''' :

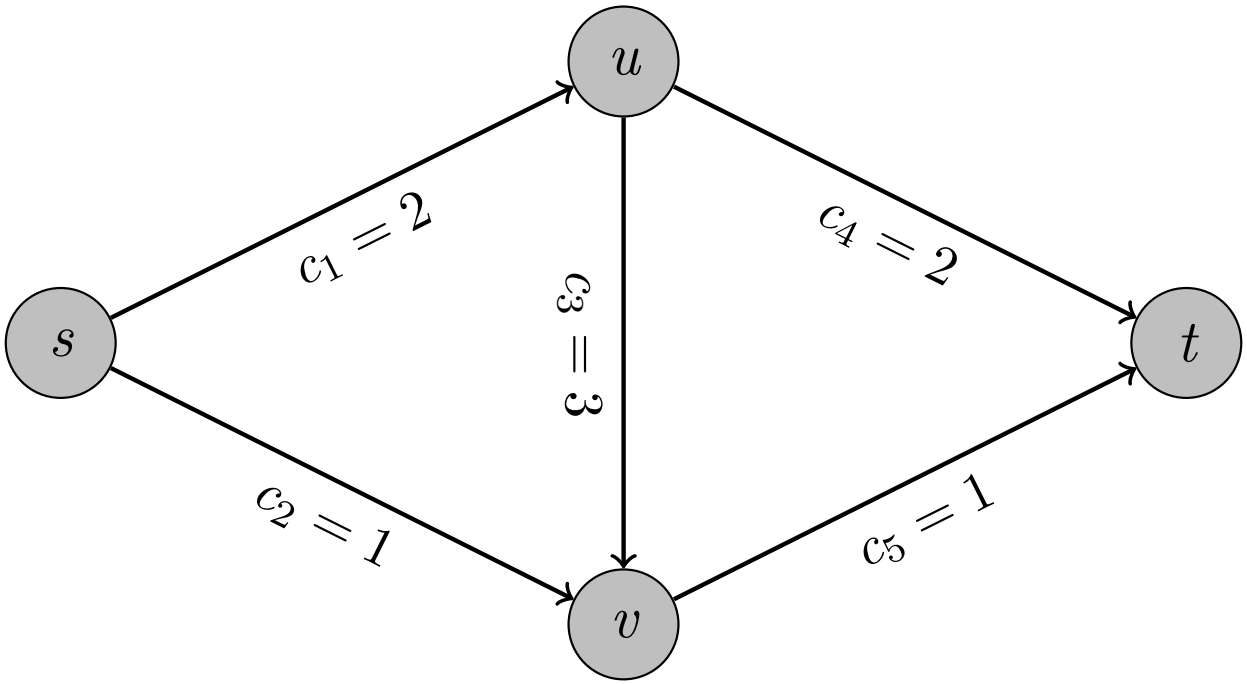


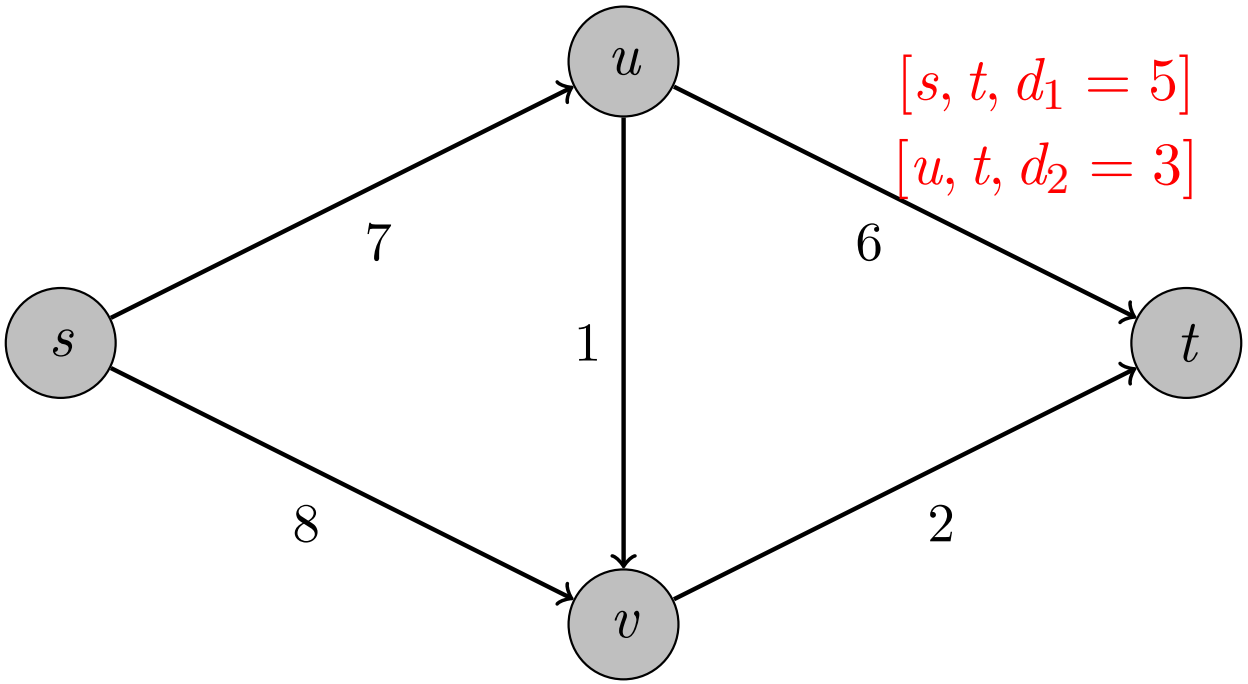

x
s
t
y
c = 5 a = 2
c = 1 a = 3
c = 2 a = 7
c = 2 a = 5
c = 4 a = 1

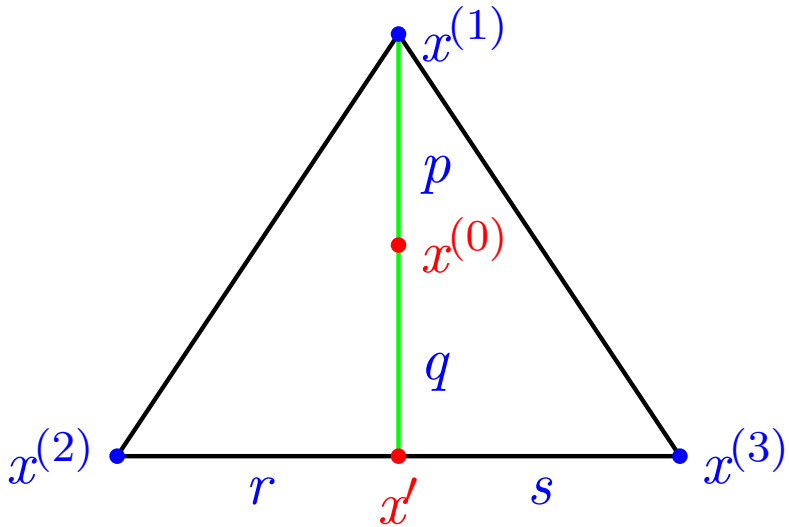

u
$x_1/5$
$x_4/6$
$x_3/1$
s
t
$x_2/8$
v
$x_5/2$


u
5
6
s
1
t
8
2
v

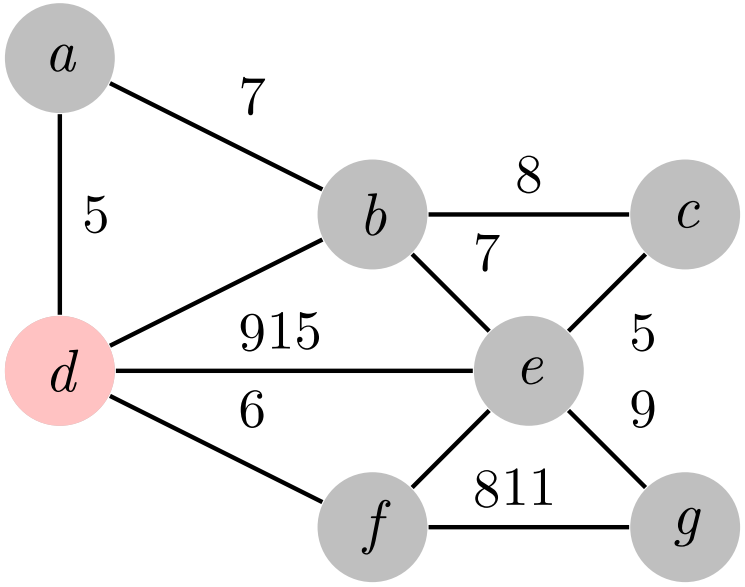

x
s
t
y
2/5 a = 2
1/1 a = 3
1/2 a = 7
1/2 a = 5
3/4 a = 1


u
s
t
v
$c_1 = 2$
$c_2 = 1$
$c_3 = 3$
$c_4 = 2$
$c_5 = 1$

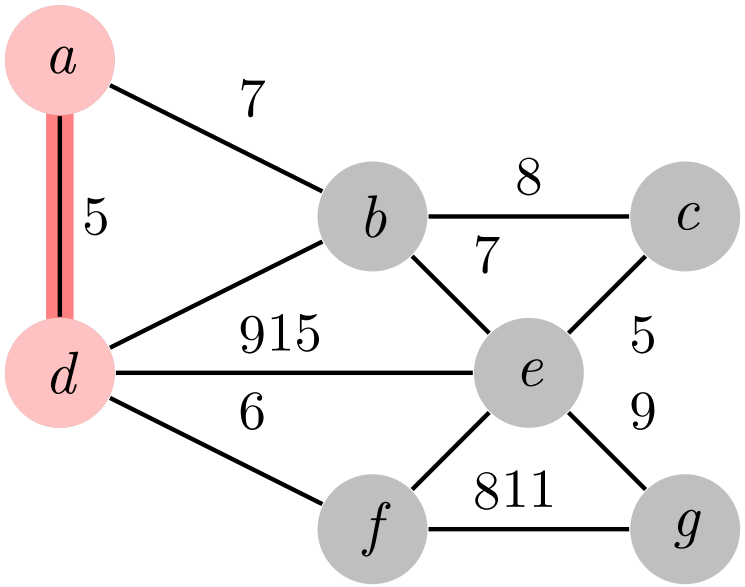

u
s
t
v
7
1
6
8
2
$[s, t, d_1 = 5]$
$[u, t, d_2 = 3]$


$x^{(1)}$
p
$x^{(0)}$
q
$x^{(2)}$
r
x'
s
$x^{(3)}$

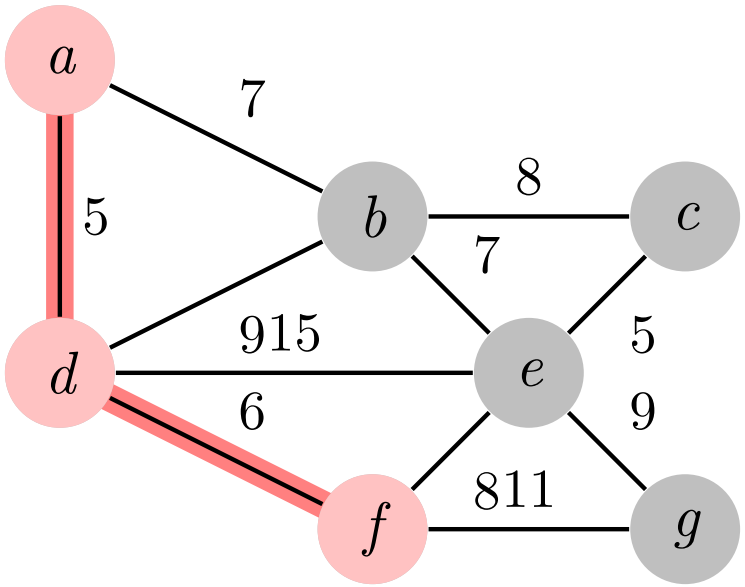
Prim's algorithm



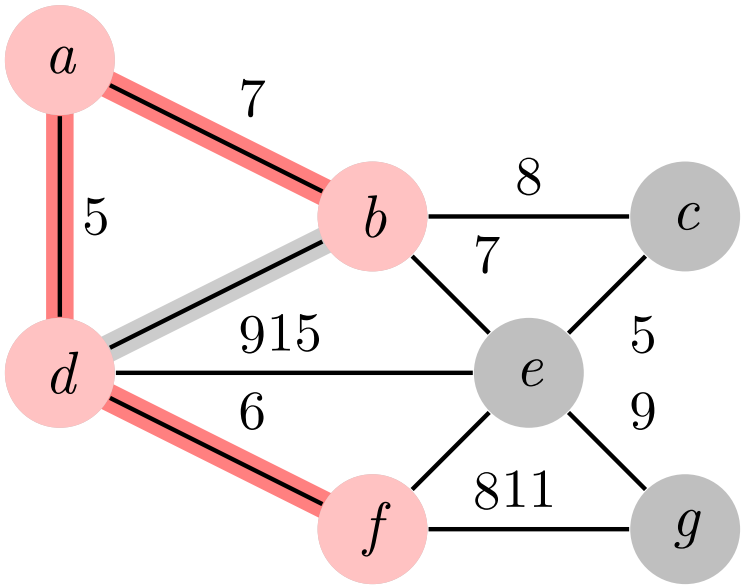
Prim's algorithm



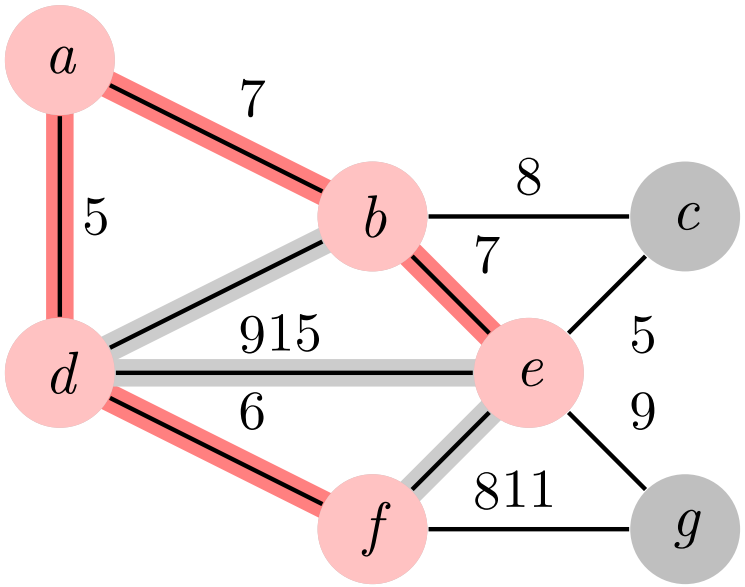
Prim's algorithm



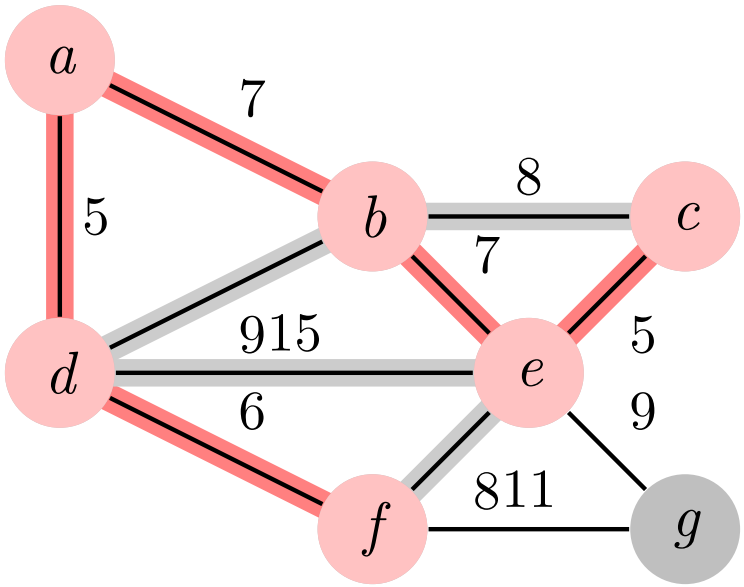
Prim's algorithm



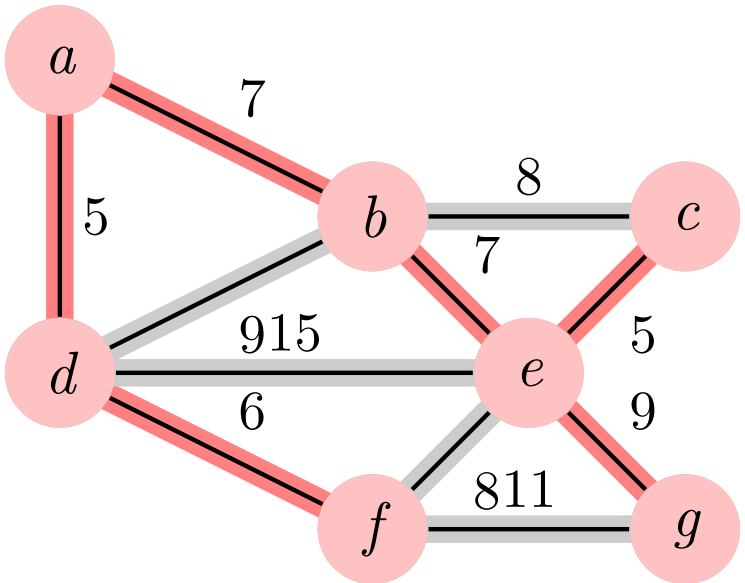
Prim's algorithm



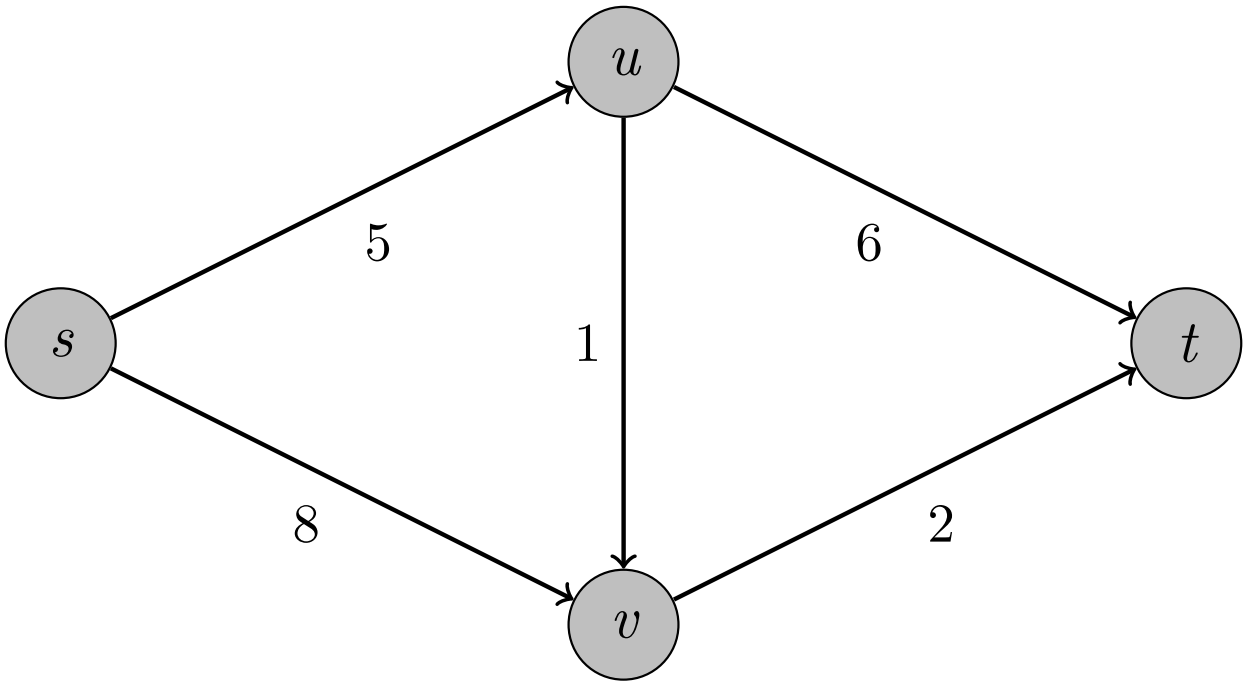
Prim's algorithm



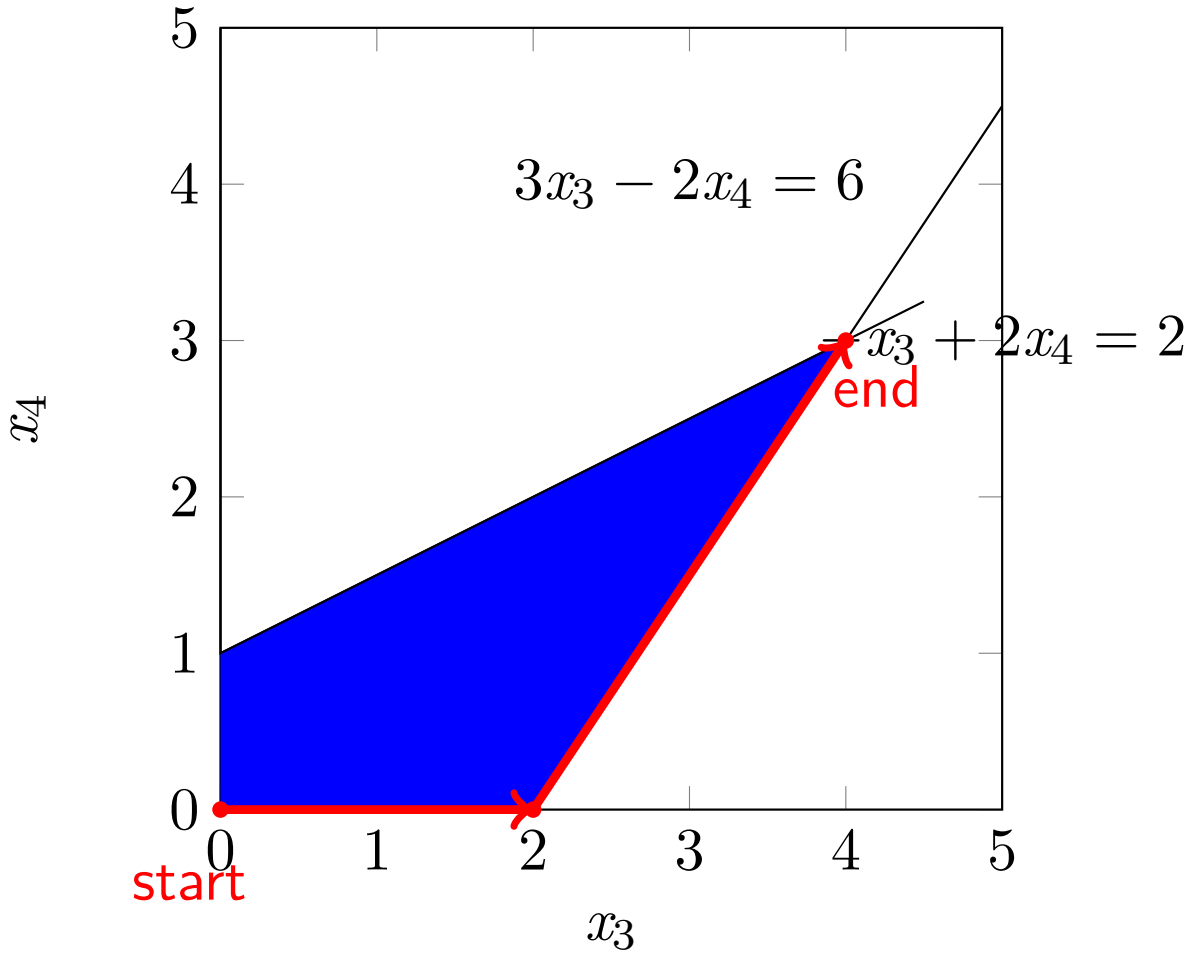
Prim's algorithm

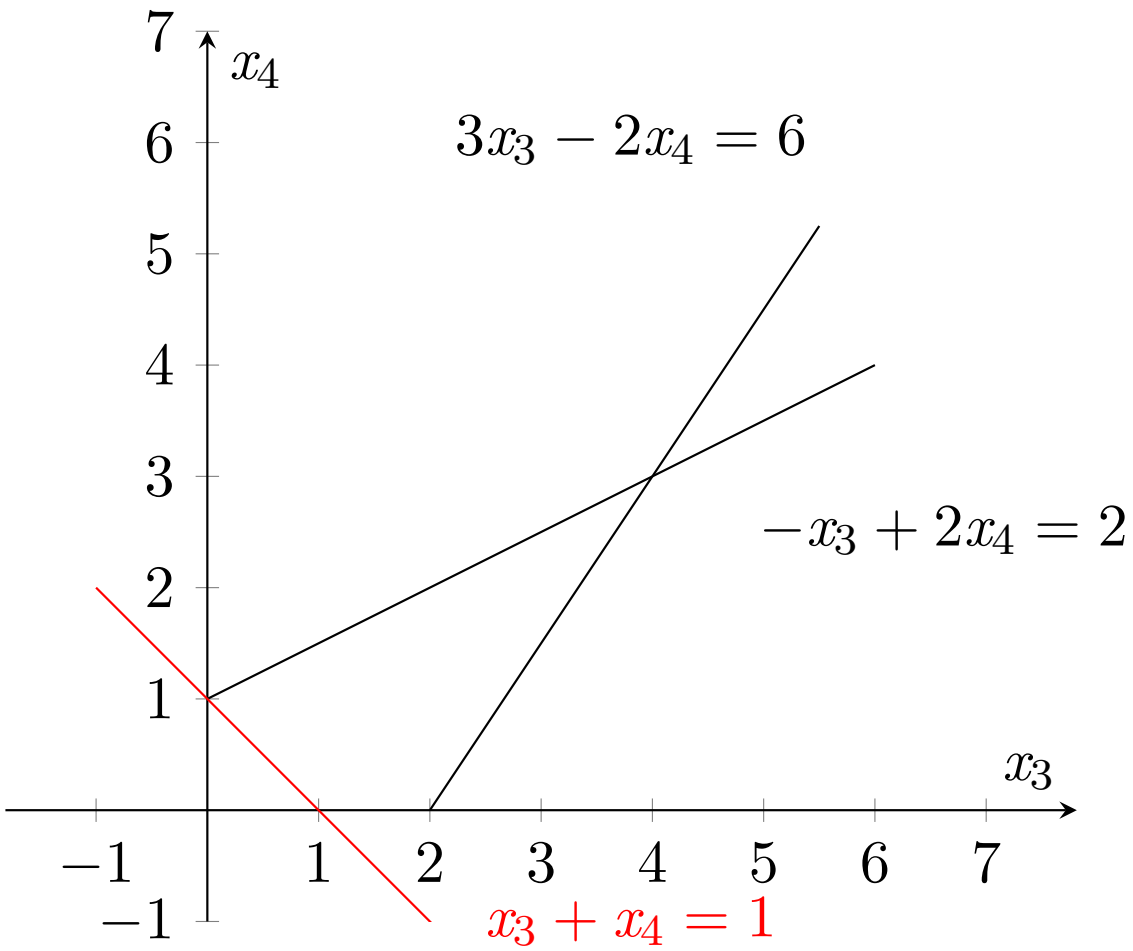


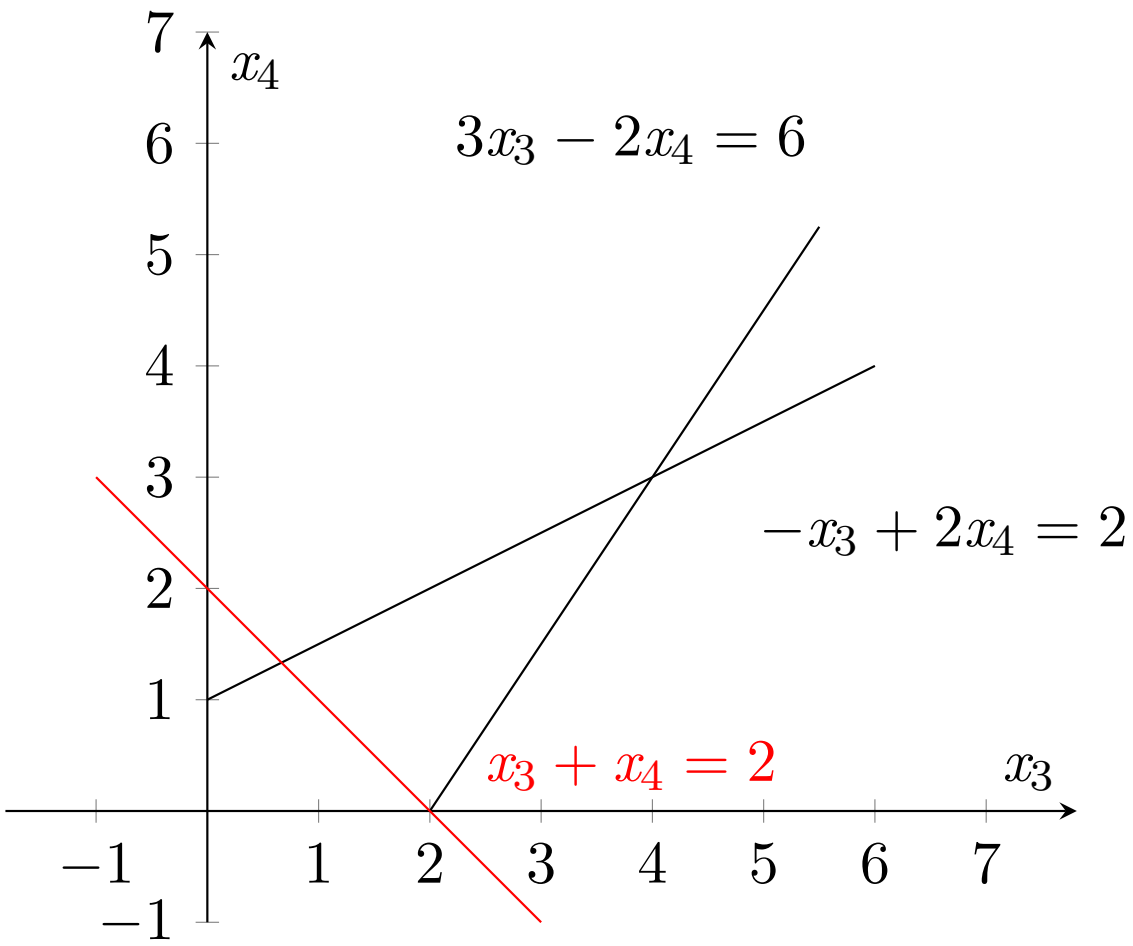
Max Flow

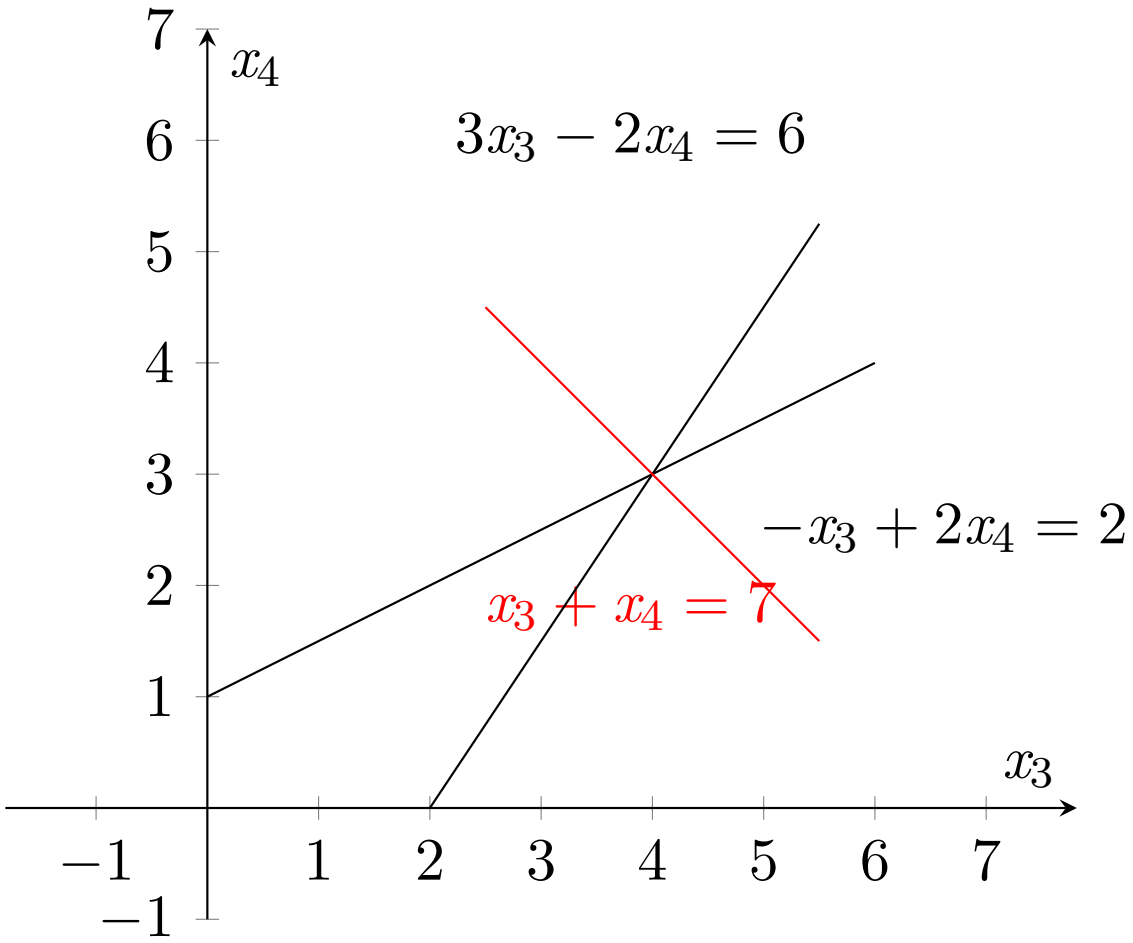


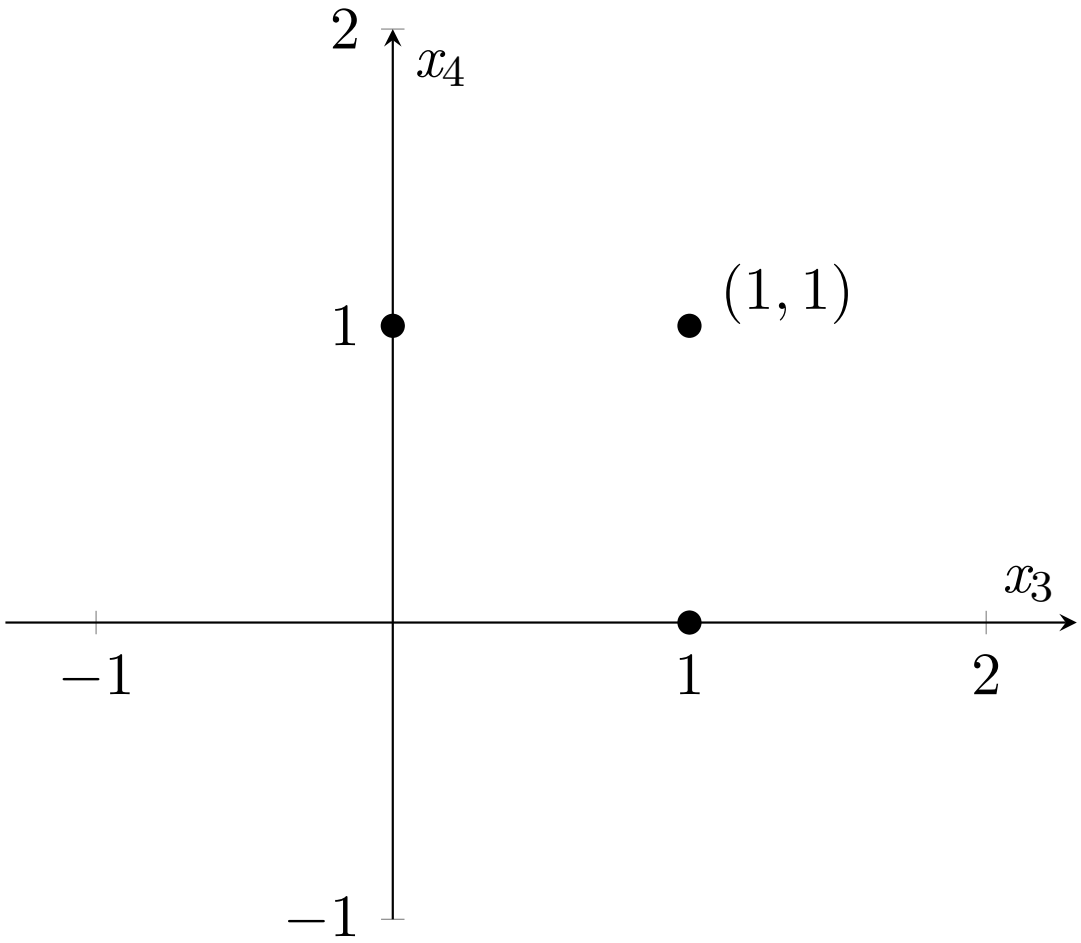
LP example

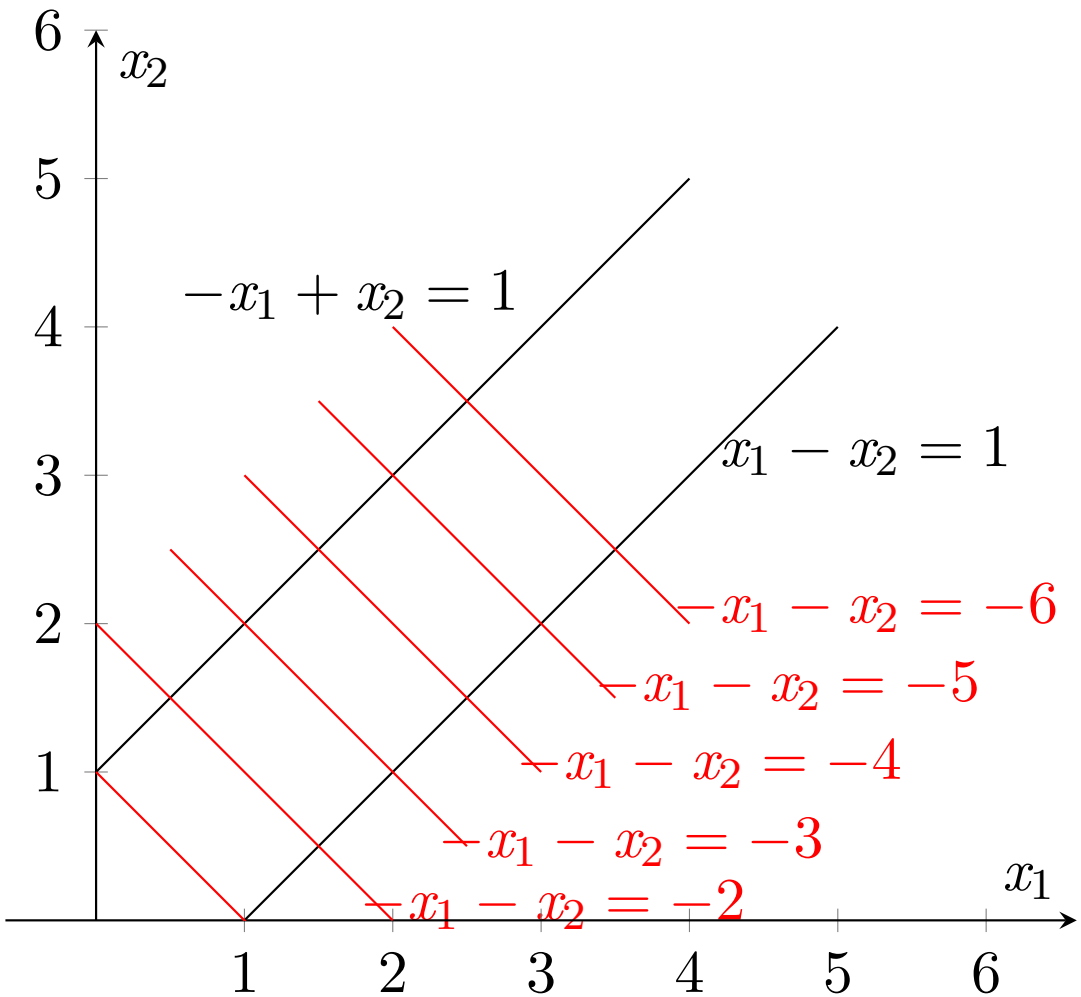


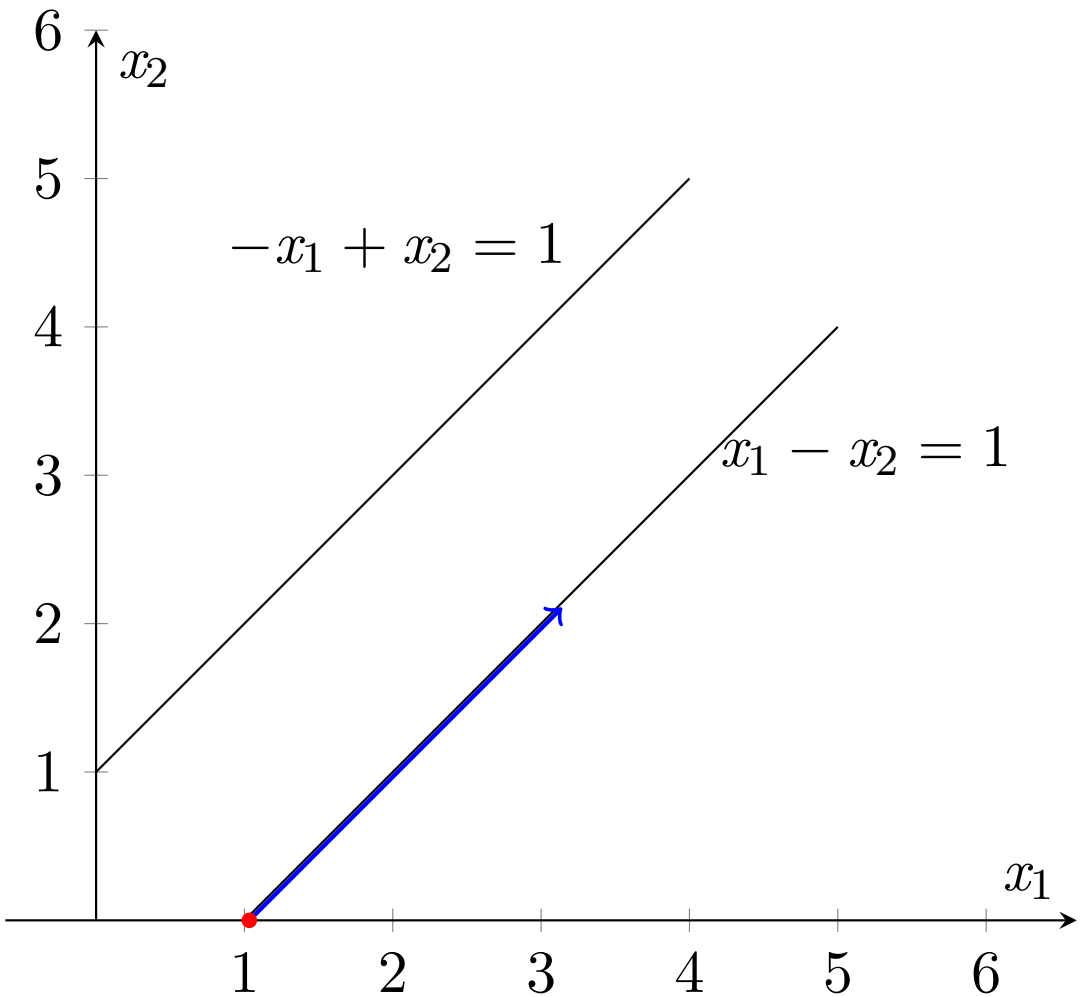

7
6
5
4
3
2
1
−1
−1
1
2
3
4
5
6
7
x_4
x_3
$3x_3 - 2x_4 = 6$
$-x_3 + 2x_4 = 2$
$x_3 + x_4 = 1$

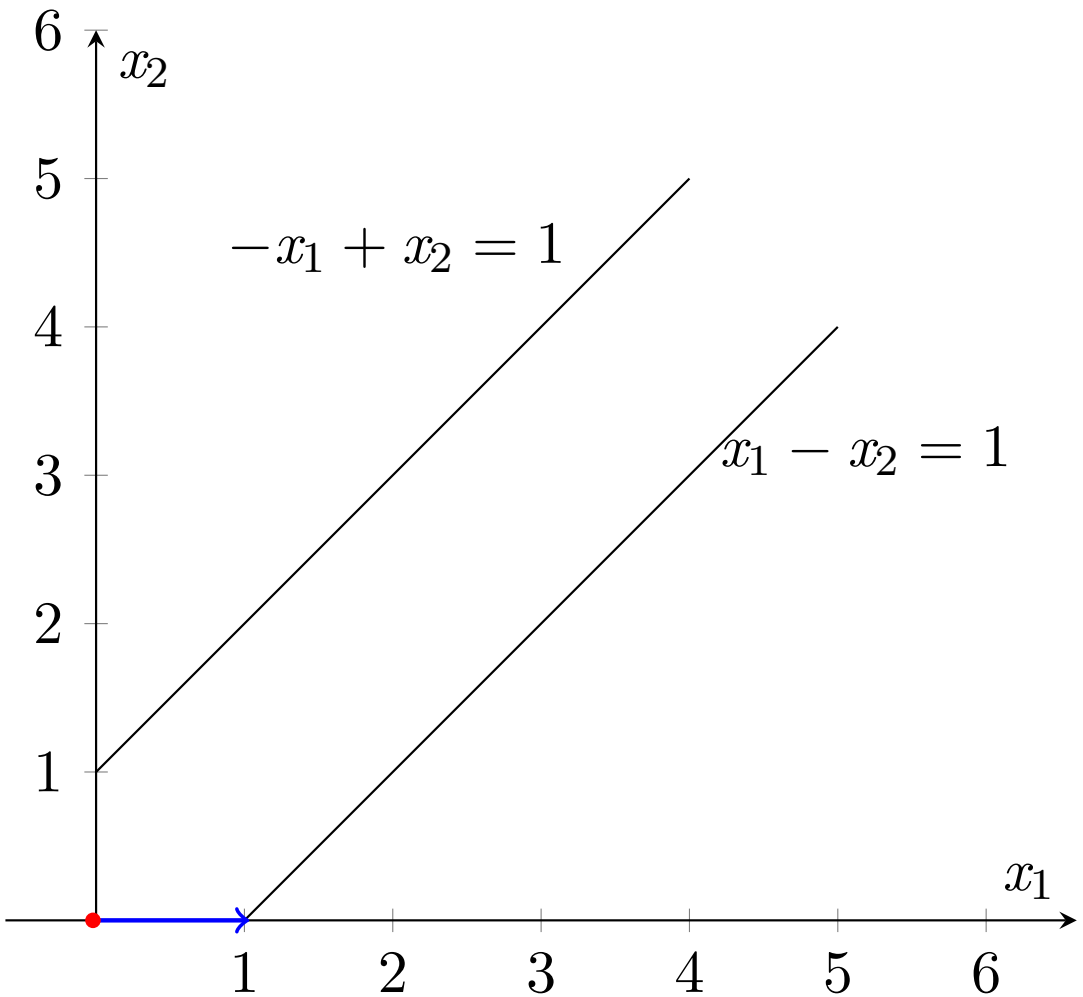

7
6
5
4
3
2
1
−1
−1
1
2
3
4
5
6
7
x_4
x_3
$3x_3 - 2x_4 = 6$
$-x_3 + 2x_4 = 2$
$x_3 + x_4 = 2$


7
6
5
4
3
2
1
−1
−1
1
2
3
4
5
6
7
x_4
x_3
$3x_3 - 2x_4 = 6$
$-x_3 + 2x_4 = 2$
$x_3 + x_4 = 7$


2
x_4
1
$(1, 1)$
x_3
-1
1
2
-1


6
5
4
3
2
1
x_2
x_1
1
2
3
4
5
6
$-x_1 + x_2 = 1$
$x_1 - x_2 = 1$
$-x_1 - x_2 = -6$
$-x_1 - x_2 = -5$
$-x_1 - x_2 = -4$
$-x_1 - x_2 = -3$
$-x_1 - x_2 = -2$

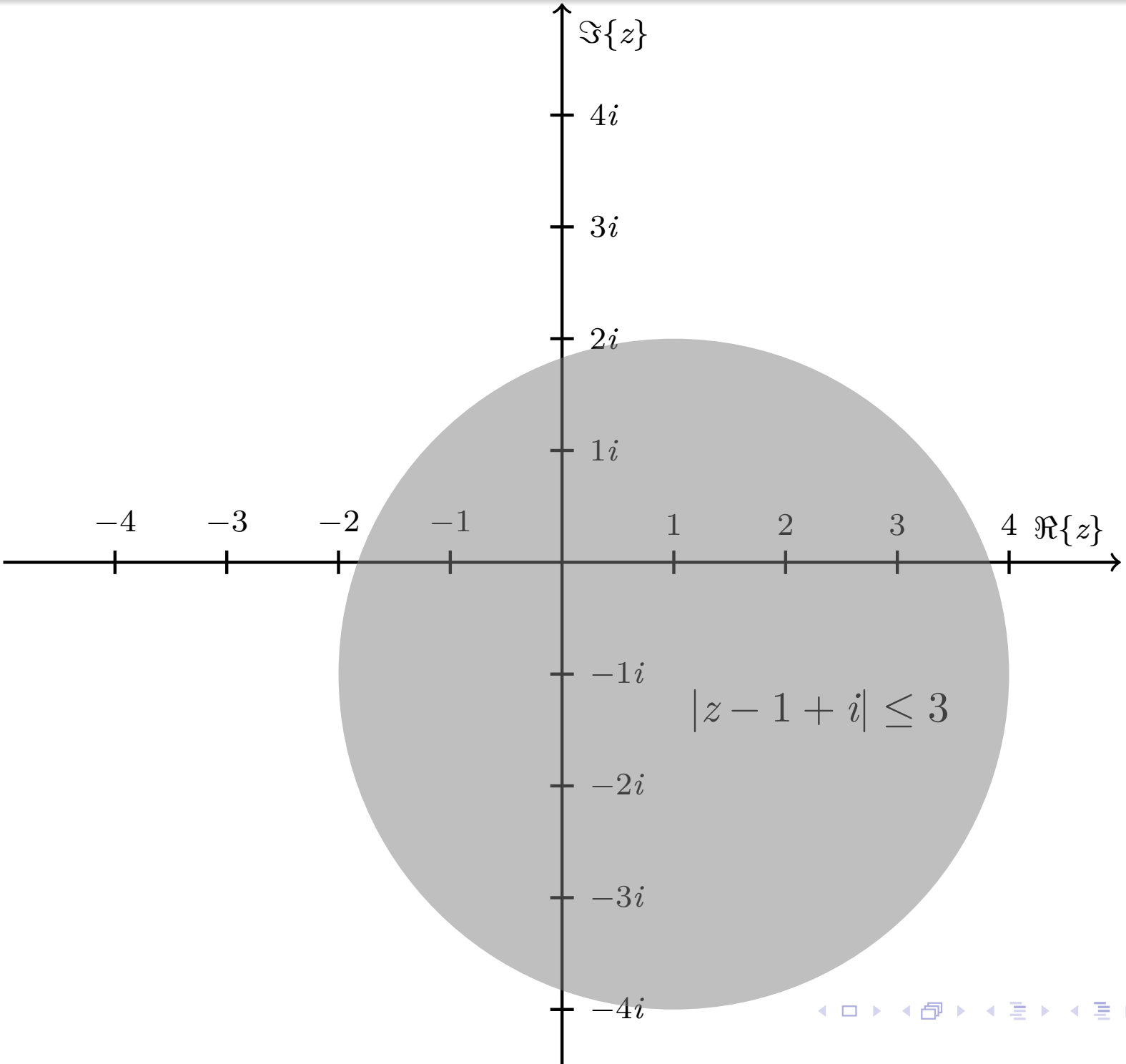

6
5
4
3
2
1
x_2
$-x_1 + x_2 = 1$
$x_1 - x_2 = 1$
x_1
1
2
3
4
5
6


6
5
4
3
2
1
x_2
$-x_1 + x_2 = 1$
$x_1 - x_2 = 1$
x_1
1
2
3
4
5
6

$$
\begin{array}{ccccc}
c_1 & c_2 & \dots & c_n & \\
a_{11} & a_{12} & \dots & a_{1n} & b_1 \\
a_{21} & a_{22} & \dots & a_{2n} & b_2 \\
 & & \dots & & \\
a_{m1} & a_{m2} & \dots & a_{mn} & b_m
\end{array}
$$

$$
\begin{array}{lrcrcrcrcl}
\min & c_1 x_1 & + & c_2 x_2 & + & \ldots & + & c_n x_n & & \\
 & a_{11} x_1 & + & a_{12} x_2 & + & \ldots & + & a_{1n} x_n & \geq & b_1 \\
 & a_{21} x_1 & + & a_{22} x_2 & + & \ldots & + & a_{2n} x_n & \geq & b_2 \\
 & & & & & \ldots & & & & \\
 & a_{m1} x_1 & + & a_{m2} x_2 & + & \ldots & + & a_{mn} x_n & \geq & b_m \\
 & & & & & & & x_i & \geq & 0 \quad \text{for each } i
\end{array}
$$

$$
\begin{array}{rrcrcl}
c_1 & c_2 & \cdots & c_n & & \\
\vee| & \vee| & & \vee| & & \max \\
y_1\, a_{11} & y_1\, a_{12} & \cdots & y_1\, a_{1n} & & y_1\, b_1 \\
+ & + & & + & & + \\
y_2\, a_{21} & y_2\, a_{22} & \cdots & y_2\, a_{2n} & & y_2\, b_2 \\
+ & + & & + & & + \\
 & & \cdots & & & \\
+ & + & & + & & + \\
y_m\, a_{m1} & y_m\, a_{m2} & \cdots & y_m\, a_{mn} & & y_m\, b_m \\
 & & & y_j & \geq & 0 \quad \text{for each } j
\end{array}
$$


$\Im\{z\}$
$4i$
$3i$
$2i$
$1i$
-4
-3
-2
-1
1
2
3
4
$\Re\{z\}$
$-1i$
$-2i$
$-3i$
$-4i$
$|z-1+i| \leq 3$

$$\begin{pmatrix} 0 & c_1 & c_2 & \cdots & c_m & \cdots & c_n \\ b_1 & a_{11} & a_{12} & \cdots & a_{1m} & \cdots & a_{1n} \\ b_2 & a_{21} & a_{22} & \cdots & a_{2m} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ b_m & a_{m1} & a_{m2} & \cdots & a_{mm} & \cdots & a_{mn} \end{pmatrix}$$

$\Longrightarrow \times \mathbf{B^{-1}}$

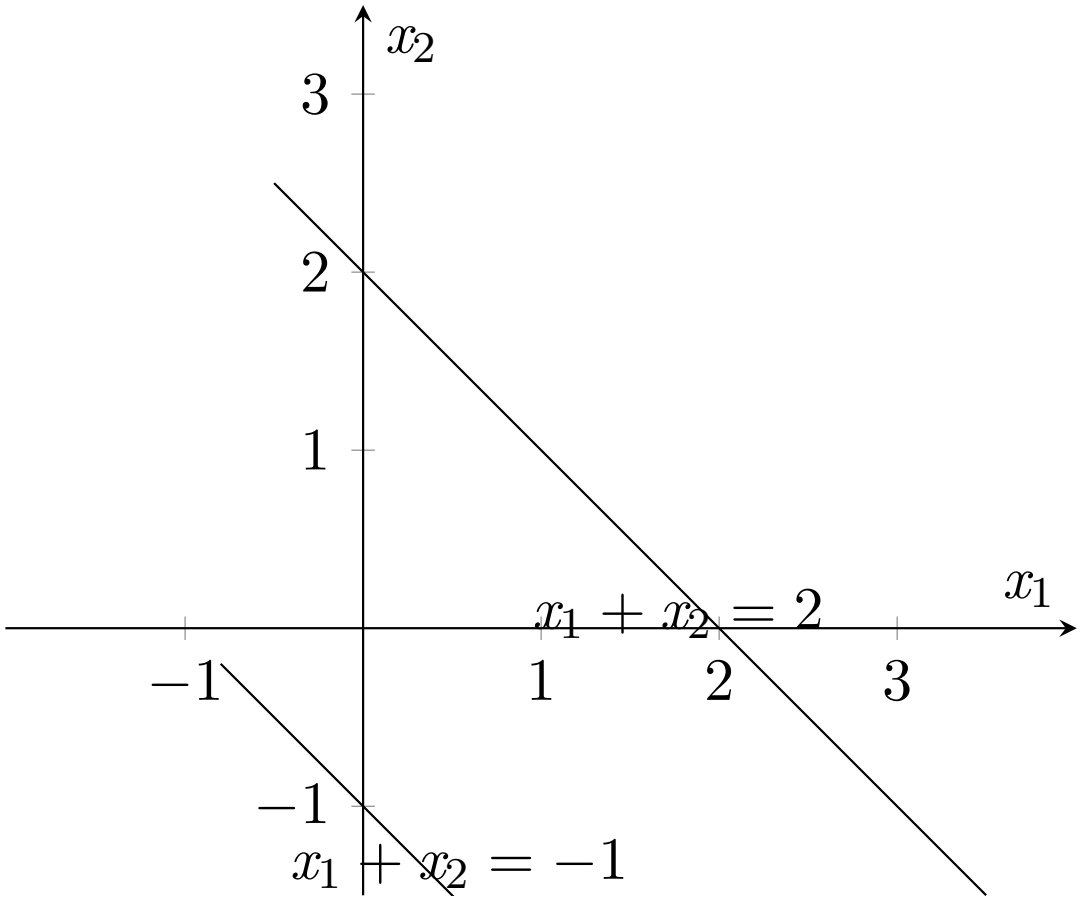
$$\begin{pmatrix} \mathbf{c_B^T B^{-1} b} & 0 & 0 & \cdots & 0 & \mathbf{c_N^T - c_B^T B^{-1} N} \\ & 1 & 0 & \cdots & 0 & \\ \mathbf{B^{-1} b} & 0 & 1 & \cdots & 0 & \mathbf{B^{-1} N} \\ & \vdots & \vdots & \ddots & \vdots & \\ & 0 & 0 & \cdots & 1 & \end{pmatrix}$$

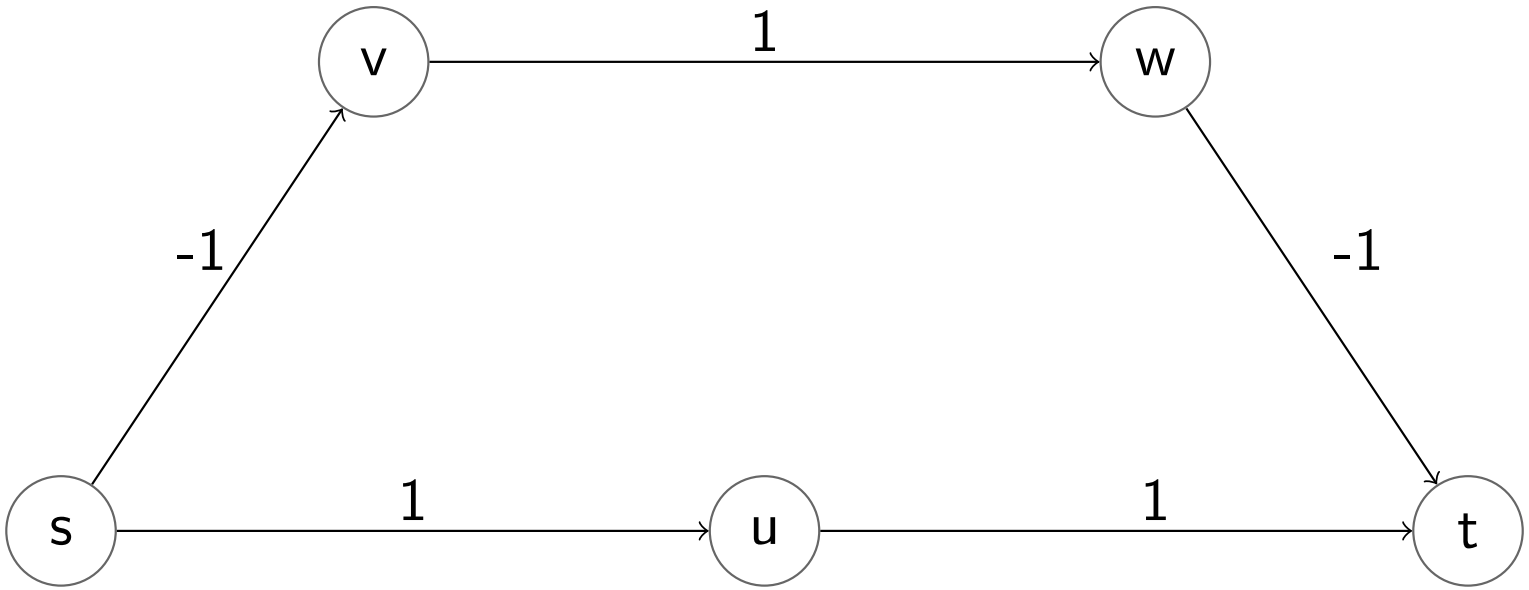
$$\begin{pmatrix} 0 & \dots & 0 & \cdots & c_e & \cdots \\ b_1 & \dots & 0 & \cdots & a_{1e} & \cdots \\ b_2 & \dots & 0 & \cdots & a_{2e} & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ b_l & \dots & 1 & \cdots & a_{le} & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ b_m & \dots & 0 & \cdots & a_{me} & \cdots \end{pmatrix}$$

$\Rightarrow$

$$\begin{pmatrix} -\frac{a_{me}}{a_{le}} b_l & \dots & -\frac{c_e}{a_{le}} & \cdots & 0 & \cdots \\ b_1 - \frac{a_{1e}}{a_{le}} b_l & \dots & -\frac{a_{1e}}{a_{le}} & \cdots & 0 & \cdots \\ b_2 - \frac{a_{2e}}{a_{le}} b_l & \dots & -\frac{a_{2e}}{a_{le}} & \cdots & 0 & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \frac{1}{a_{le}} b_l & \dots & \frac{1}{a_{le}} & \cdots & 1 & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ b_m - \frac{a_{me}}{a_{le}} b_l & \dots & -\frac{a_{me}}{a_{le}} & \cdots & 0 & \cdots \end{pmatrix}$$

LP x1x2-1

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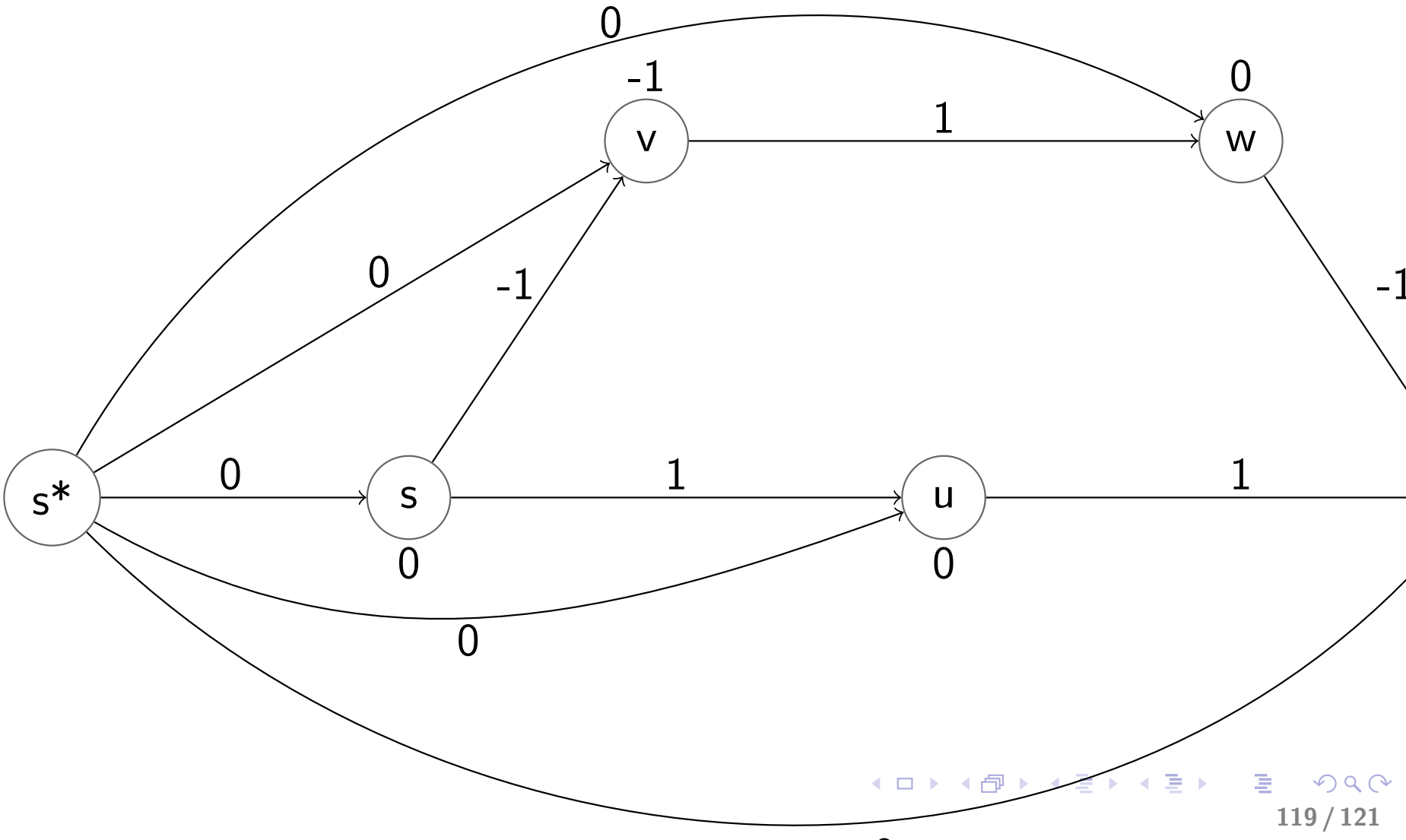
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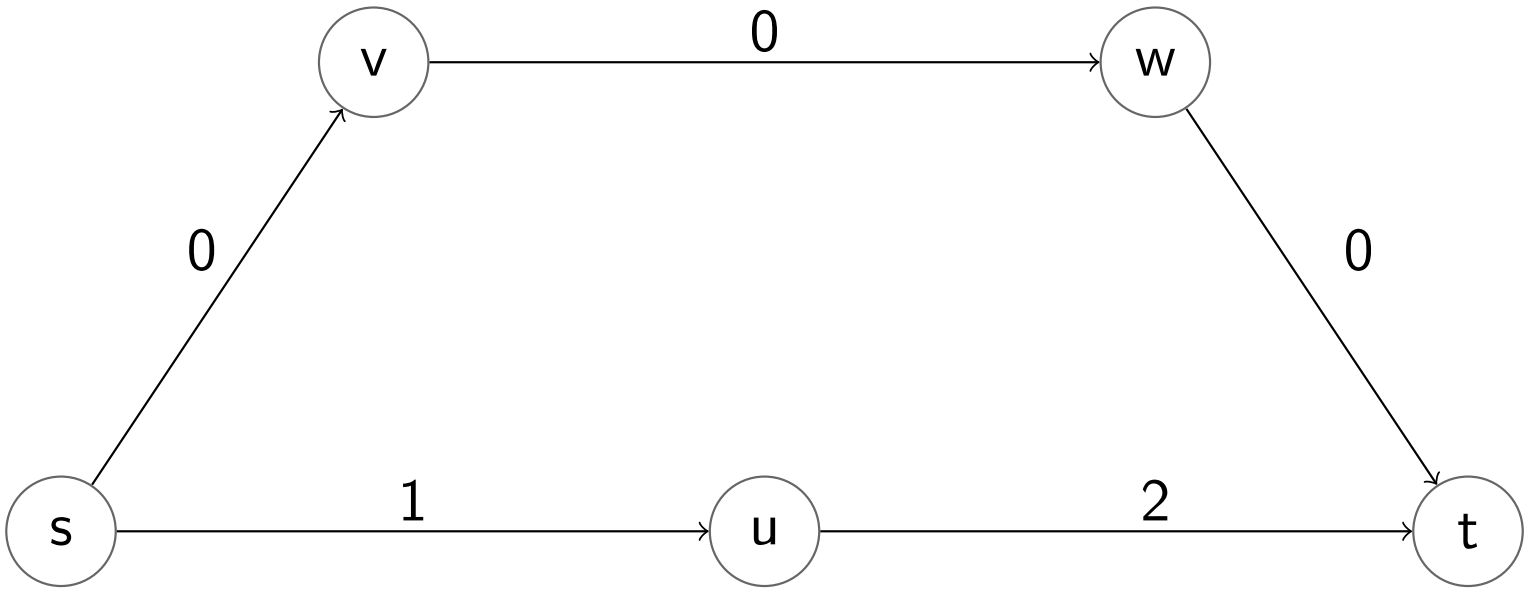
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