4 Simplex Algorithm

Enumerating all basic feasible solutions (BFS), in order to find the optimum is slow.

Simplex Algorithm [George Dantzig 1947]
Move from BFS to adjacent BFS, without decreasing objective function.

Two BFSs are called adjacent if the bases just differ in one variable.

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Two BFSs are called adjacent if the bases just differ in one variable.

4 Simplex Algorithm

$$\begin{array}{llllllll} \text{max} & 13a + 23b \\ \text{s.t.} & 5a + 15b + s_c & & & = 480 \\ & 4a + 4b & + s_h & & = 160 \\ & 35a + 20b & & + s_m & = 1190 \\ & a\ ,\ b\ ,\ s_c\ ,\ s_h\ ,\ s_m & & & \geq 0 \end{array}$$

$$\begin{array}{lllll} \text{max } Z \\ 13a + 23b & & & - Z & = 0 \\ 5a + 15b + s_c & & & & = 480 \\ 4a + 4b & + s_h & & & = 160 \\ 35a + 20b & & + s_m & & = 1190 \\ a\ ,\ b\ ,\ s_c\ ,\ s_h\ ,\ s_m & & & & \geq 0 \end{array}$$

basis = $\{s_c, s_h, s_m\}$
$A = B = 0$
$Z = 0$

$s_c = 480$
$s_h = 160$
$s_m = 1190$

4 Simplex Algorithm

$$
\begin{array}{lrcrcrcrcrcl}
\text{max} & 13a & + & 23b & & & & & & & & \\
\text{s.t.} & 5a & + & 15b & + & s_c & & & & & = & 480 \\
 & 4a & + & 4b & & & + & s_h & & & = & 160 \\
 & 35a & + & 20b & & & & & + & s_m & = & 1190 \\
 & a & , & b & , & s_c & , & s_h & , & s_m & \geq & 0
\end{array}
$$

$$
\begin{array}{lrcrcrcrcrcrl}
\text{max } Z & & & & & & & & & & & & \\
 & 13a & + & 23b & & & & & & & - & Z & = 0 \\
 & 5a & + & 15b & + & s_c & & & & & & & = 480 \\
 & 4a & + & 4b & & & + & s_h & & & & & = 160 \\
 & 35a & + & 20b & & & & & + & s_m & & & = 1190 \\
 & a & , & b & , & s_c & , & s_h & , & s_m & & & \geq 0
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$$

basis $= \{s_c, s_h, s_m\}$

$A = B = 0$

$Z = 0$

$s_c = 480$

$s_h = 160$

$s_m = 1190$

Pivoting Step

max Z

$$\begin{aligned}
13a + 23b - Z &= 0 \\
5a + 15b + s_c &= 480 \\
4a + 4b + s_h &= 160 \\
35a + 20b + s_m &= 1190 \\
a \;,\; b \;,\; s_c \;,\; s_h \;,\; s_m &\geq 0
\end{aligned}$$

basis = $\{s_c, s_h, s_m\}$

$a = b = 0$

$Z = 0$

$s_c = 480$

$s_h = 160$

$s_m = 1190$

- choose variable to bring into the basis
- chosen variable should have positive coefficient in objective function
- apply test to find out by how much the variable can be increased
- pivot on row found by min ratio test
- the existing basis variable in this row leaves the basis

Pivoting Step

max Z

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\begin{aligned}
13a + 23b \qquad\qquad\qquad\qquad - Z &= 0 \\
5a + 15b + s_c \qquad\qquad\qquad &= 480 \\
4a + 4b \qquad + s_h \qquad\qquad &= 160 \\
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a \;,\; b \;,\; s_c \;,\; s_h \;,\; s_m \qquad &\geq 0
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\text{basis} = \{s_c, s_h, s_m\} \\
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a, \; b, \; s_c, \; s_h, \; s_m &\geq 0
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basis $= \{s_c, s_h, s_m\}$

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$s_c = 480$

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max Z

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\begin{aligned}
13a + 23\mathbf{b} \qquad\qquad\qquad\qquad - Z &= 0 \\
5a + 15\mathbf{b} + s_c \qquad\qquad\qquad &= 480 \\
4a + 4\mathbf{b} \qquad + s_h \qquad\qquad &= 160 \\
35a + 20\mathbf{b} \qquad\qquad + s_m \quad &= 1190 \\
a\ ,\quad \mathbf{b}\ ,\ s_c\ ,\ s_h\ ,\ s_m \quad &\geq 0
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basis $= \{s_c, s_h, s_m\}$

$a = b = 0$

$Z = 0$

$s_c = 480$

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- Choose variable with coefficient ≥ 0 as entering variable.

$$
\begin{array}{l}
\max Z \\
\quad 13a + 23\mathbf{b} \qquad\qquad\qquad - Z = 0 \\
\quad 5a + 15\mathbf{b} + s_c \qquad\qquad\qquad = 480 \\
\quad 4a + 4\mathbf{b} \qquad + s_h \qquad\qquad = 160 \\
\quad 35a + 20\mathbf{b} \qquad\qquad + s_m \quad = 1190 \\
\quad a\ ,\ \mathbf{b}\ ,\ s_c\ ,\ s_h\ ,\ s_m \qquad \geq 0
\end{array}
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$$
\begin{array}{l}
\text{basis} = \{s_c, s_h, s_m\} \\
a = b = 0 \\
Z = 0 \\
s_c = 480 \\
s_h = 160 \\
s_m = 1190
\end{array}
$$

- Choose variable with coefficient ≥ 0 as entering variable.
- If we keep $a = 0$ and increase b from 0 to $\theta > 0$ s.t. all constraints ($Ax = b, x \geq 0$) are still fulfilled the objective value Z will strictly increase.

max Z

$$
\begin{array}{rcrcccccl}
13a & + & 23\boldsymbol{b} & & & & & -Z & = 0 \\
5a & + & 15\boldsymbol{b} & + s_c & & & & & = 480 \\
4a & + & 4\boldsymbol{b} & & + s_h & & & & = 160 \\
35a & + & 20\boldsymbol{b} & & & + s_m & & & = 1190 \\
a & , & \boldsymbol{b} & , s_c & , s_h & , s_m & & & \geq 0
\end{array}
$$

basis $= \{s_c, s_h, s_m\}$

$a = b = 0$

$Z = 0$

$s_c = 480$

$s_h = 160$

$s_m = 1190$

- Choose variable with coefficient ≥ 0 as entering variable.
- If we keep $a = 0$ and increase b from 0 to $\theta > 0$ s.t. all constraints ($Ax = b, x \geq 0$) are still fulfilled the objective value Z will strictly increase.
- For maintaining $Ax = b$ we need e.g. to set $s_c = 480 - 15\theta$.

$$\begin{array}{l} \max Z \\ \quad 13a + 23b \qquad\qquad\qquad\qquad - Z = 0 \\ \quad 5a + 15\mathbf{b} + s_c \qquad\qquad\qquad = 480 \\ \quad 4a + \ \ 4b \qquad + s_h \qquad\qquad = 160 \\ \quad 35a + 20b \qquad\qquad + s_m \quad = 1190 \\ \quad a\ ,\quad b\ ,\ s_c\ ,\ s_h\ ,\ s_m \qquad \geq 0 \end{array}$$

$$\begin{array}{l} \text{basis} = \{s_c, s_h, s_m\} \\ a = b = 0 \\ Z = 0 \\ s_c = 480 \\ s_h = 160 \\ s_m = 1190 \end{array}$$

- Choose variable with coefficient ≥ 0 as entering variable.
- If we keep $a = 0$ and increase b from 0 to $\theta > 0$ s.t. all constraints ($Ax = b, x \geq 0$) are still fulfilled the objective value Z will strictly increase.
- For maintaining $Ax = b$ we need e.g. to set $s_c = 480 - 15\theta$.
- Choosing $\theta = \min\{480/15, 160/4, 1190/20\}$ ensures that in the new solution one current basic variable becomes 0, and no variable goes negative.

$$\begin{array}{l} \max Z \\ \begin{array}{rrrrrrl} 13a & + 23b & & & & -Z & = 0 \\ 5a & + 15\mathbf{b} & + s_c & & & & = 480 \\ 4a & + 4b & & + s_h & & & = 160 \\ 35a & + 20b & & & + s_m & & = 1190 \\ a & , \; b & , s_c & , s_h & , s_m & & \geq 0 \end{array} \end{array}$$

$$\begin{array}{l} \text{basis} = \{s_c, s_h, s_m\} \\ a = b = 0 \\ Z = 0 \\ s_c = 480 \\ s_h = 160 \\ s_m = 1190 \end{array}$$

- Choose variable with coefficient ≥ 0 as entering variable.
- If we keep $a = 0$ and increase b from 0 to $\theta > 0$ s.t. all constraints ($Ax = b, x \geq 0$) are still fulfilled the objective value Z will strictly increase.
- For maintaining $Ax = b$ we need e.g. to set $s_c = 480 - 15\theta$.
- Choosing $\theta = \min\{480/15, 160/4, 1190/20\}$ ensures that in the new solution one current basic variable becomes 0, and no variable goes negative.
- The basic variable in the row that gives $\min\{480/15, 160/4, 1190/20\}$ becomes the leaving variable.

$$\begin{aligned}
&\max Z\\
&13a + 23b - Z = 0\\
&5a + 15b + s_c = 480\\
&4a + 4b + s_h = 160\\
&35a + 20b + s_m = 1190\\
&a, b, s_c, s_h, s_m \ge 0
\end{aligned}$$

basis = $\{s_c, s_h, s_m\}$

$a = b = 0$

$Z = 0$

$s_c = 480$

$s_h = 160$

$s_m = 1190$

Substitute $b = \frac{1}{15}(480 - 5a - s_c)$.

$$\begin{aligned}
&\max Z\\
&\tfrac{16}{3}a - \tfrac{23}{15}s_c - Z = -736\\
&\tfrac{1}{3}a + b + \tfrac{1}{15}s_c = 32\\
&\tfrac{8}{3}a - \tfrac{4}{15}s_c + s_h = 32\\
&\tfrac{85}{3}a - \tfrac{4}{3}s_c + s_m = 550\\
&a, b, s_c, s_h, s_m \ge 0
\end{aligned}$$

basis = $\{b, s_h, s_m\}$

$a = s_c = 0$

$Z = 736$

$b = 32$

$s_h = 32$

$s_m = 550$

$$\begin{array}{l} \max Z \\ 13a + 23b \qquad\qquad - Z = 0 \\ 5a + 15\mathbf{b} + s_c = 480 \\ 4a + 4b + s_h = 160 \\ 35a + 20b + s_m = 1190 \\ a,\ b,\ s_c,\ s_h,\ s_m \geq 0 \end{array}$$

basis = $\{s_c, s_h, s_m\}$

$a = b = 0$

$Z = 0$

$s_c = 480$

$s_h = 160$

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Substitute $b = \frac{1}{15}(480 - 5a - s_c)$.

$$\begin{array}{l} \max Z \\ \frac{16}{3}a - \frac{23}{15}s_c \qquad - Z = -736 \\ \frac{1}{3}a + b + \frac{1}{15}s_c = 32 \\ \frac{8}{3}a - \frac{4}{15}s_c + s_h = 32 \\ \frac{85}{3}a - \frac{4}{3}s_c + s_m = 550 \\ a,\ b,\ s_c,\ s_h,\ s_m \geq 0 \end{array}$$

basis = $\{b, s_h, s_m\}$

$a = s_c = 0$

$Z = 736$

$b = 32$

$s_h = 32$

$s_m = 550$

$$\max Z$$

$$\begin{aligned}
13a + 23b \quad & - Z = 0 \\
5a + 15\mathbf{b} + s_c \quad & = 480 \\
4a + 4b \quad + s_h \quad & = 160 \\
35a + 20b \quad + s_m & = 1190 \\
a, \; b, \; s_c, \; s_h, \; s_m & \geq 0
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Substitute $b = \frac{1}{15}(480 - 5a - s_c)$.

$$\max Z$$

$$\begin{aligned}
\tfrac{16}{3}a \quad - \tfrac{23}{15}s_c \quad & - Z = -736 \\
\tfrac{1}{3}a + b + \tfrac{1}{15}s_c \quad & = 32 \\
\tfrac{8}{3}a \quad - \tfrac{4}{15}s_c + s_h \quad & = 32 \\
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a, \; b, \; s_c, \; s_h, \; s_m & \geq 0
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basis = $\{b, s_h, s_m\}$

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$Z = 736$

$b = 32$

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max Z

$$\begin{array}{rcl} \frac{16}{3}a - \frac{23}{15}s_c - Z &=& -736 \\ \frac{1}{3}a + b + \frac{1}{15}s_c &=& 32 \\ \frac{8}{3}a - \frac{4}{15}s_c + s_h &=& 32 \\ \frac{85}{3}a - \frac{4}{3}s_c + s_m &=& 550 \\ a, b, s_c, s_h, s_m &\geq& 0 \end{array}$$

basis = $\{b, s_h, s_m\}$

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max Z

$$
\begin{aligned}
\tfrac{16}{3}a \quad - \tfrac{23}{15}s_c \quad - Z &= -736 \\
\tfrac{1}{3}a + b + \tfrac{1}{15}s_c &= 32 \\
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a\ ,\ b\ ,\ s_c\ ,\ s_h\ ,\ s_m &\geq 0
\end{aligned}
$$

basis = $\{b, s_h, s_m\}$

$a = s_c = 0$

$Z = 736$

$b = 32$

$s_h = 32$

$s_m = 550$

Choose variable a to bring into basis.

$$\max Z$$

$$\begin{array}{lllllll}
\frac{16}{3}\boldsymbol{a} & & -\ \frac{23}{15}s_c & & & -\ Z & = -736 \\
\frac{1}{3}\boldsymbol{a} & +\ b & +\ \frac{1}{15}s_c & & & & = 32 \\
\frac{8}{3}\boldsymbol{a} & & -\ \frac{4}{15}s_c & +\ s_h & & & = 32 \\
\frac{85}{3}\boldsymbol{a} & & -\ \frac{4}{3}s_c & & +\ s_m & & = 550 \\
\boldsymbol{a}\ , & b\ , & s_c\ , & s_h\ , & s_m & & \geq 0
\end{array}$$

basis = $\{b, s_h, s_m\}$
$a = s_c = 0$
$Z = 736$

$b = 32$
$s_h = 32$
$s_m = 550$

Choose variable a to bring into basis.

Computing $\min\{3 \cdot 32, {}^{3\cdot 32}/_{8}, {}^{3\cdot 550}/_{85}\}$ means pivot on line 2.

$$\max Z$$

$$\begin{array}{l}
\frac{16}{3}a - \frac{23}{15}s_c - Z = -736 \\
\frac{1}{3}a + b + \frac{1}{15}s_c = 32 \\
\frac{8}{3}\mathbf{a} - \frac{4}{15}s_c + s_h = 32 \\
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\end{array}$$

basis $= \{b, s_h, s_m\}$
$a = s_c = 0$
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$b = 32$
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Choose variable a to bring into basis.

Computing $\min\{3 \cdot 32, {}^{3\cdot 32}/8, {}^{3\cdot 550}/85\}$ means pivot on line 2.

Substitute $a = \frac{3}{8}(32 + \frac{4}{15}s_c - s_h)$.

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\begin{array}{l}
\max Z \\
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a, b, s_c, s_h, s_m \geq 0
\end{array}
$$

basis = $\{b, s_h, s_m\}$
$a = s_c = 0$
$Z = 736$
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Substitute $a = \frac{3}{8}(32 + \frac{4}{15}s_c - s_h)$.

$$
\begin{array}{l}
\max Z \\
\quad - s_c - 2s_h \quad - Z = -800 \\
b + \frac{1}{10}s_c - \frac{1}{8}s_h \quad = 28 \\
a \quad - \frac{1}{10}s_c + \frac{3}{8}s_h \quad = 12 \\
\frac{3}{2}s_c - \frac{85}{8}s_h + s_m \quad = 210 \\
a, b, s_c, s_h, s_m \geq 0
\end{array}
$$

basis = $\{a, b, s_m\}$
$s_c = s_h = 0$
$Z = 800$
$b = 28$
$a = 12$
$s_m = 210$

4 Simplex Algorithm

Pivoting stops when all coefficients in the objective function are non-positive.

Solution is optimal:

- any feasible solution satisfies all equations in the tableaux
- in particular: $Z = 800 - s_c - 2s_h$, $s_c \ge 0$, $s_h \ge 0$
- hence optimum solution value is at most 800
- the current solution has value 800

4 Simplex Algorithm

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Matrix View

Let our linear program be

$$\begin{array}{rcrcl} c_B^t x_B & + & c_N^t x_N & = & Z \\ A_B x_B & + & A_N x_N & = & b \\ x_B & , & x_N & \geq & 0 \end{array}$$

The simplex tableaux for basis B is

$$\begin{array}{rcrcl} & & (c_N^t - c_B^t A_B^{-1} A_N) x_N & = & Z - c_B^t A_B^{-1} b \\ I x_B & + & A_B^{-1} A_N x_N & = & A_B^{-1} b \\ x_B & , & x_N & \geq & 0 \end{array}$$

The BFS is given by $x_N = 0, x_B = A_B^{-1} b$.

If $(c_N^t - c_B^t A_B^{-1} A_N) \leq 0$ we know that we have an optimum solution.

Matrix View

Let our linear program be

$$\begin{array}{rcrcl} c_B^t x_B & + & c_N^t x_N & = & Z \\ A_B x_B & + & A_N x_N & = & b \\ x_B & , & x_N & \geq & 0 \end{array}$$

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The BFS is given by $x_N = 0, x_B = A_B^{-1} b$.

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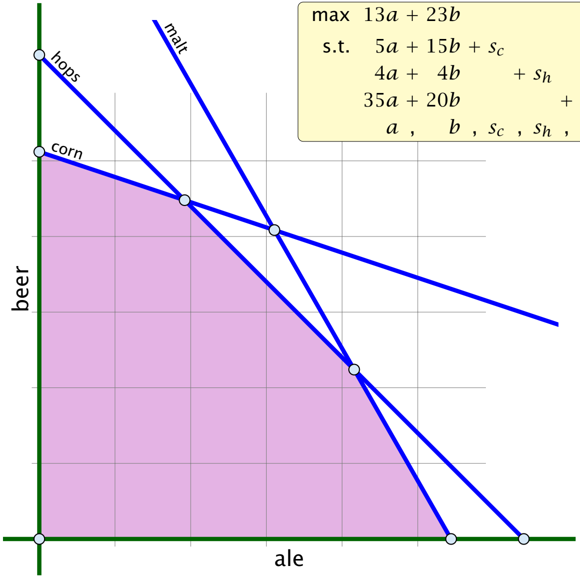

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\begin{array}{lrcrcccccl}
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\text{s.t.} & 5a & + & 15b & + s_c & & & & = & 480 \\
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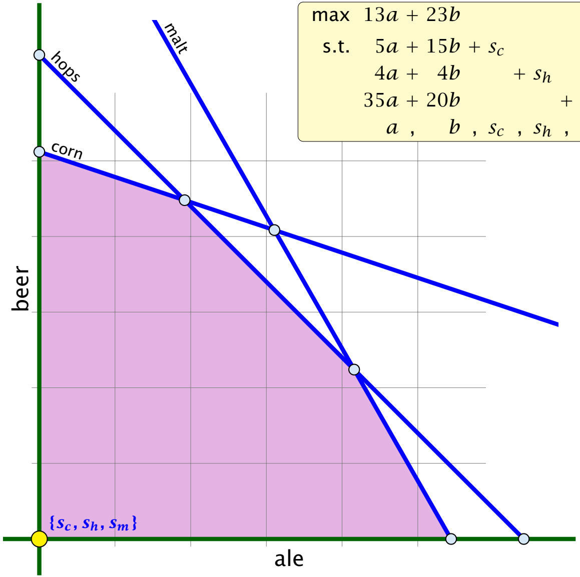

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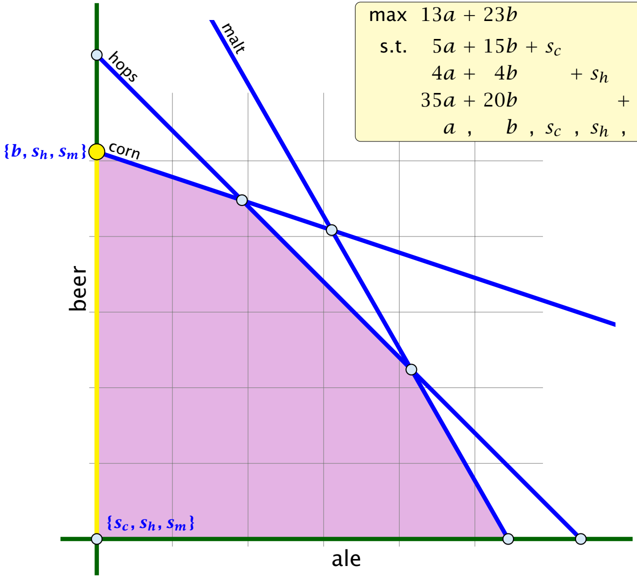

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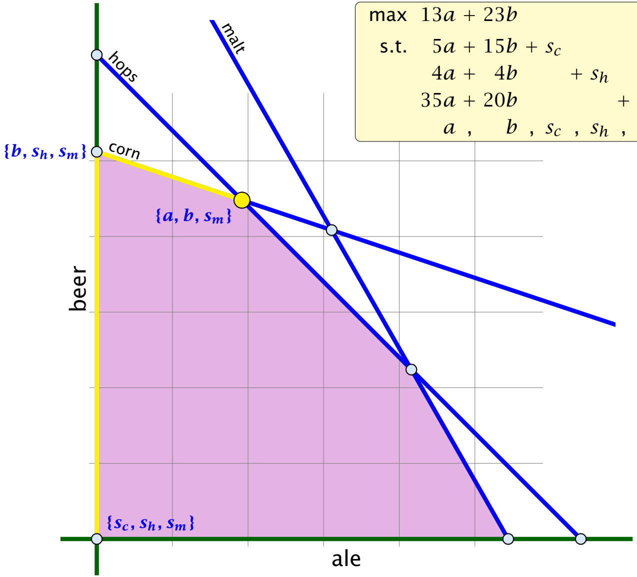

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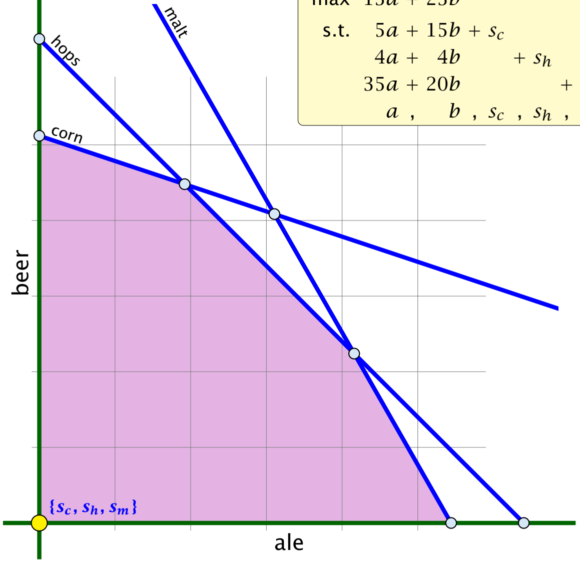

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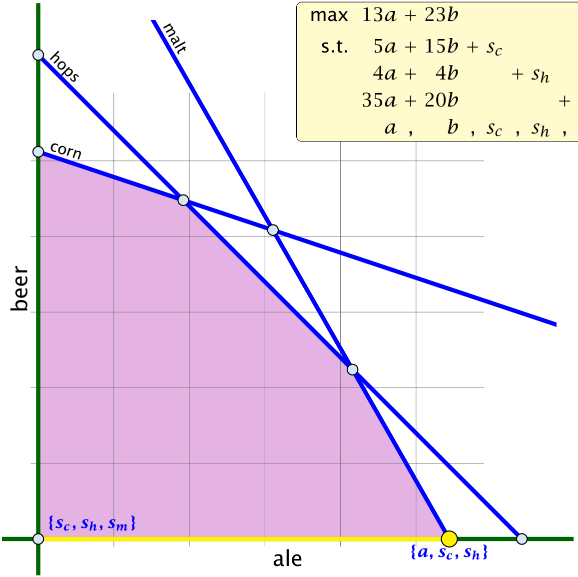

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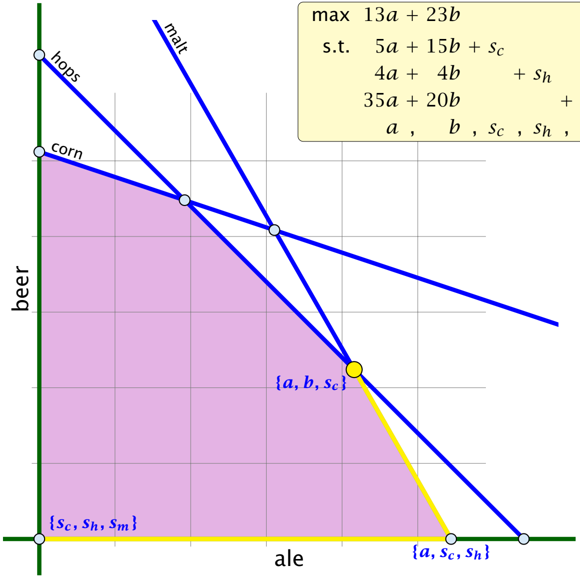

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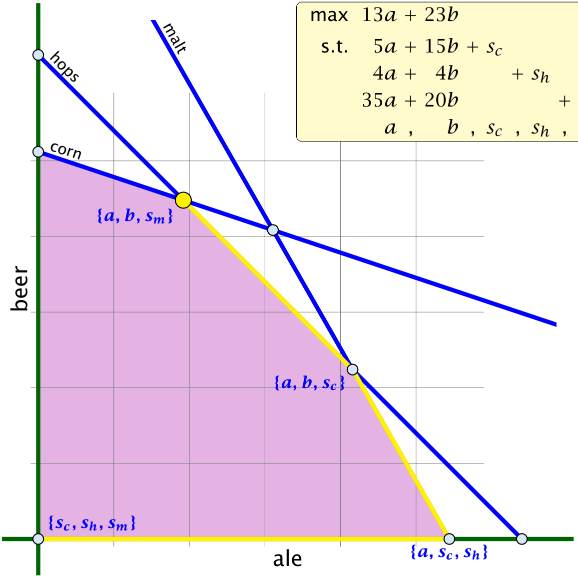

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- Given basis B with BFS x^*.
- Choose index $j \notin B$ in order to increase x_j^* from 0 to $\theta > 0$.
  - Other non-basis variables should stay at 0.
  - Basis variables change to maintain feasibility.
- Go from x^* to $x^* + \theta \cdot d$.

Requirements for d:

- $d_j = 1$ (normalization)
- $d_\ell = 0$, $\ell \notin B$, $\ell \neq j$
- $A(x^* + \theta d) = b$ must hold. Hence $Ad = 0$.
- Altogether: $A_B d_B + A_{*j} = Ad = 0$, which gives $d_B = -A_B^{-1} A_{*j}$.

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Algebraic Definition of Pivoting

Definition 2 (j-th basis direction)

Let B be a basis, and let $j \notin B$. The vector d with $d_j = 1$ and $d_\ell = 0, \ell \notin B, \ell \neq j$ and $d_B = -A_B^{-1}A_{*j}$ is called the j-th basis direction for B.

Going from x^* to $x^* + \theta \cdot d$ the objective function changes by

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Definition 3 (Reduced Cost)

For a basis B the value

$$\tilde{c}_j = c_j - c_B^t A_B^{-1} A_{*j}$$

is called the reduced cost for variable x_j.

Note that this is defined for every j. If $j \in B$ then the above term is 0.

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Let our linear program be

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4 Simplex Algorithm

Questions:

- What happens if the min ratio test fails to give us a value by which we can safely increase the entering variable?
- How do we find the initial basic feasible solution?
- Is there always a basis B such that

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Then we can terminate because we know that the solution is optimal.

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The min ratio test computes a value $\theta \geq 0$ such that after setting the entering variable to θ the leaving variable becomes 0 and all other variables stay non-negative.

For this one computes b_i/A_{ie} for all constraints i and calculates the minimum positive value.

What does it mean that the ratio b_i/A_{ie} (and hence A_{ie}) is negative for a constraint?

This means that the corresponding basic variable will increase if we increase b. Hence, there is no danger of this basic variable becoming negative

What happens if **all** b_i/A_{ie} are negative? Then we do not have a leaving variable. Then the LP is unbounded!

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Because a variable x_ℓ with $\ell \in B$ is already 0.

The set of inequalities is degenerate (also the basis is degenerate).

Definition 4 (Degeneracy)

A BFS x^* is called degenerate if the set $J = \{j \mid x_j^* > 0\}$ fulfills $|J| < m$.

It is possible that the algorithm cycles, i.e., it cycles through a sequence of different bases without ever terminating. Happens, very rarely in practise.

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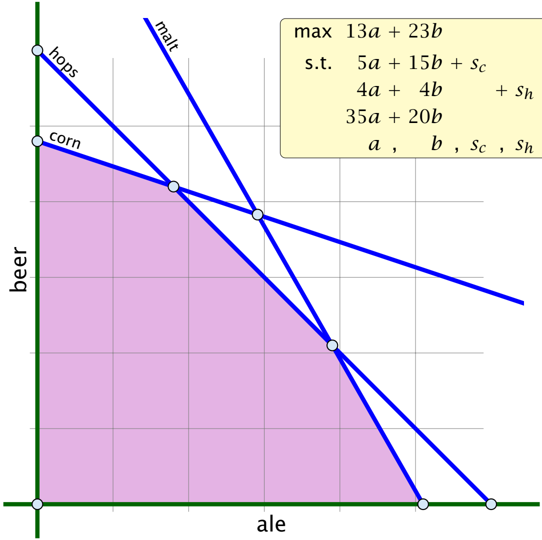
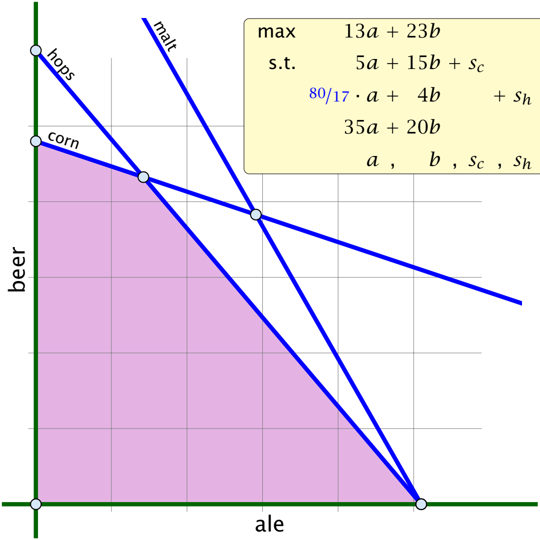
Non Degenerate Example



$$
\begin{array}{lrcrcccccl}
\text{max} & 13a & + & 23b & & & & & & \\
\text{s.t.} & 5a & + & 15b & + & s_c & & & = & 480 \\
 & 4a & + & 4b & & & + s_h & & = & 160 \\
 & 35a & + & 20b & & & & + s_m & = & 1190 \\
 & a & , & b & , & s_c & , s_h & , s_m & \geq & 0
\end{array}
$$

Degenerate Example



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\begin{array}{llllllll}
\text{max} & 13a & + 23b & & & & & \\
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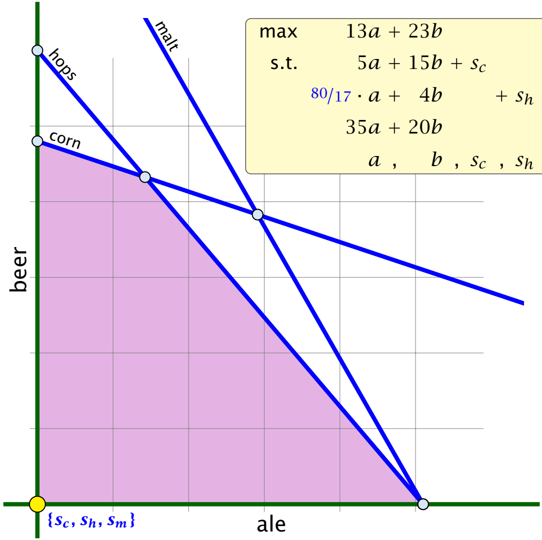

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\begin{array}{llcl}
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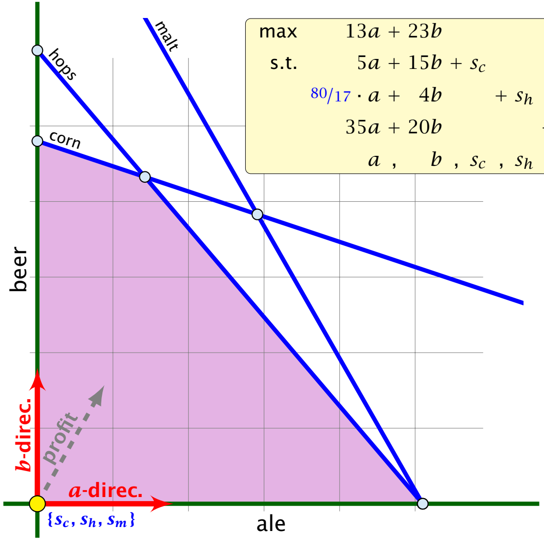

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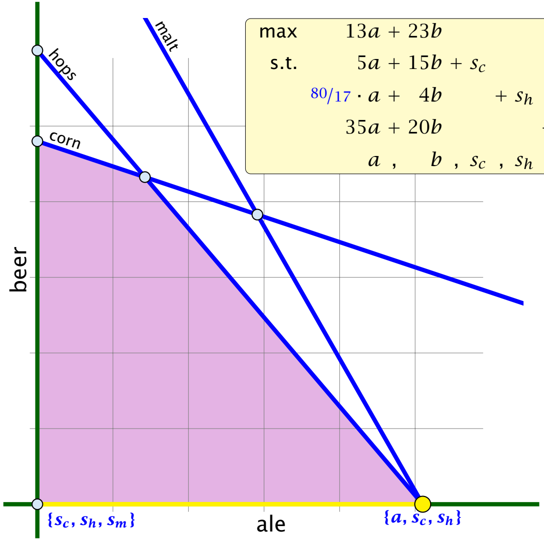

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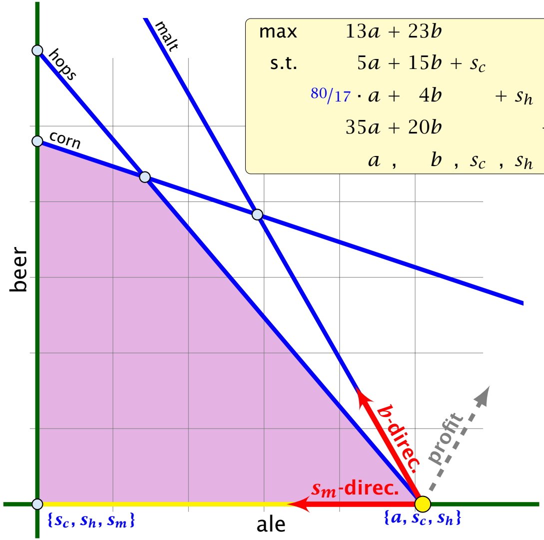

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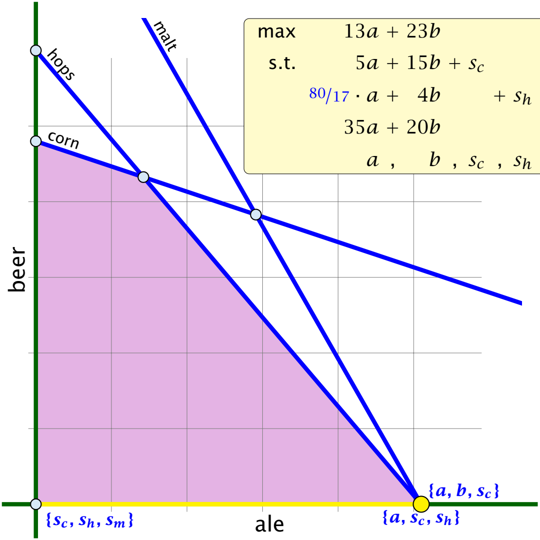

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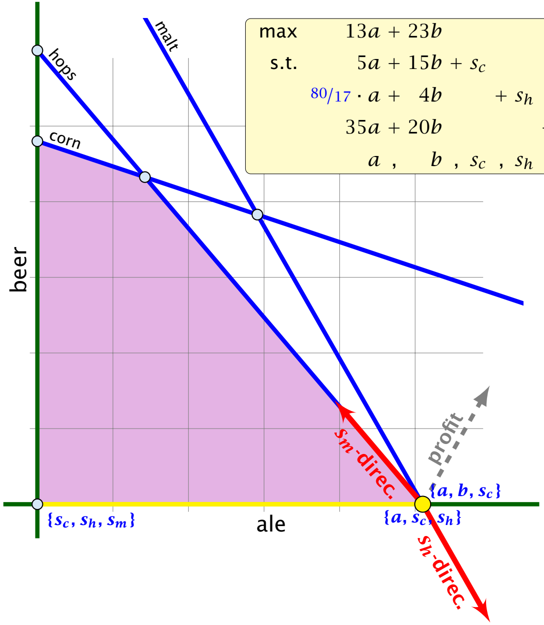

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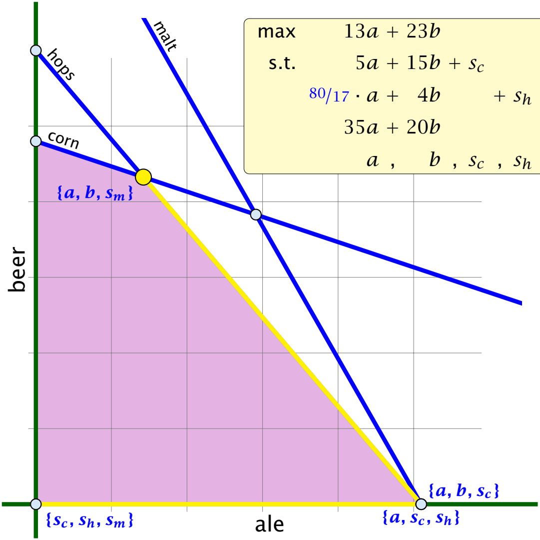

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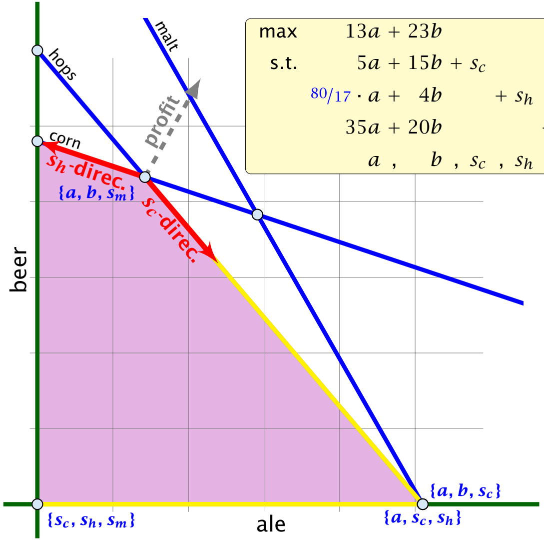

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Summary: How to choose pivot-elements

- We can choose a column e as an entering variable if $\tilde{c}_e > 0$ ($\tilde{c}_e$ is reduced cost for x_e).
- The standard choice is the column that maximizes $\tilde{c}_e$.
- If $A_{ie} \leq 0$ for all $i \in \{1, \ldots, m\}$ then the maximum is not bounded.
- Otw. choose a leaving variable ℓ such that $b_\ell / A_{\ell e}$ is minimal among all variables i with $A_{ie} > 0$.
- If several variables have minimum $b_\ell / A_{\ell e}$ you reach a degenerate basis.
- Depending on the choice of ℓ it may happen that the algorithm runs into a cycle where it does not escape from a degenerate vertex.

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Termination

What do we have so far?

Suppose we are given an initial feasible solution to an LP. If the LP is non-degenerate then Simplex will terminate.

Note that we either terminate because the min-ratio test fails and we can conclude that the LP is unbounded, or we terminate because the vector of reduced cost is non-positive. In the latter case we have an optimum solution.

How do we come up with an initial solution?

- $Ax \le b, x \ge 0$, and $\boldsymbol{b \ge 0}$.
- The standard slack from for this problem is $Ax + Is = b, x \ge 0, s \ge 0$, where s denotes the vector of slack variables.
- Then $s = b$, $x = 0$ is a basic feasible solution (how?).
- We directly can start the simplex algorithm.

How do we find an initial basic feasible solution for an arbitrary problem?

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How do we find an initial basic feasible solution for an arbitrary problem?

Two phase algorithm

Suppose we want to maximize c^tx s.t. $Ax = b, x \geq 0$.

1. Multiply all rows with $b_i < 0$ by -1.
2. maximize $-\sum_i v_i$ s.t. $Ax + Iv = b, x \geq 0, v \geq 0$ using Simplex. $x = 0, v = b$ is initial feasible.
3. If $\sum_i v_i > 0$ then the original problem is infeasible.
4. Otw. you have $x \geq 0$ with $Ax = b$.
5. From this you can get basic feasible solution.
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Two phase algorithm

Suppose we want to maximize $c^t x$ s.t. $Ax = b, x \geq 0$.

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Optimality

Lemma 5
Let B be a basis and x^* a BFS corresponding to basis B. $\tilde{c} \leq 0$ implies that x^* is an optimum solution to the LP.