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

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

4 Simplex Algorithm

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

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

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

$A = B = 0$

$Z = 0$

$s_c = 480$

$s_h = 160$

$s_m = 1190$

4 Simplex Algorithm

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

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

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

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

Pivoting Step

max Z

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

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

$a = b = 0$

$Z = 0$

$s_c = 480$

$s_h = 160$

$s_m = 1190$

- choose variable to bring into the basis
- chosen variable should have positive coefficient in objective function
- apply min ratio 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

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

basis $= \{s_c, s_h, s_m\}$
$a = b = 0$
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Pivoting Step

$$\begin{aligned}
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&13a + 23b - Z = 0\\
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&35a + 20b + s_m = 1190\\
&a, b, s_c, s_h, s_m \geq 0
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Pivoting Step

max Z

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

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

$a = b = 0$

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\begin{array}{l}
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\quad a \ , \quad 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}
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max Z

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

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- Choose variable with coefficient ≥ 0 as entering variable.

max Z

$$
\begin{array}{rcl}
13a + 23\boldsymbol{b} & - Z & = 0 \\
5a + 15\boldsymbol{b} + s_c & & = 480 \\
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a \; , \; \boldsymbol{b} \; , \; s_c \; , \; s_h \; , \; s_m & & \geq 0
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basis = $\{s_c, s_h, s_m\}$
$a = b = 0$
$Z = 0$
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- 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.

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

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

$a = b = 0$

$Z = 0$

$s_c = 480$

$s_h = 160$

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- 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 $s_c = 480 - 15\theta$.

max Z

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

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

$s_c = 480$
$s_h = 160$
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- Choose variable with coefficient ≥ 0 as entering variable.
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- 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.

$$\max Z$$

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

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 $s_c = 480 - 15\theta$.
- 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.

max Z

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

$a = b = 0$

$Z = 0$

$s_c = 480$

$s_h = 160$

$s_m = 1190$

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

max Z

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

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

$a = s_c = 0$

$Z = 736$

$b = 32$

$s_h = 32$

$s_m = 550$

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

$$
\begin{array}{l}
\text{basis} = \{s_c, s_h, s_m\} \\
a = b = 0 \\
Z = 0 \\
s_c = 480 \\
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s_m = 1190
\end{array}
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Substitute $b = \frac{1}{15}(480 - 5a - s_c)$.

$$
\begin{array}{l}
\max Z \\
\begin{array}{rcccccl}
\frac{16}{3}a & & - \frac{23}{15}s_c & & & - Z & = -736 \\
\frac{1}{3}a & + b & + \frac{1}{15}s_c & & & & = 32 \\
\frac{8}{3}a & & - \frac{4}{15}s_c & + s_h & & & = 32 \\
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a & , b & , s_c & , s_h & , s_m & & \geq 0
\end{array}
\end{array}
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$$
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\text{basis} = \{b, s_h, s_m\} \\
a = s_c = 0 \\
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\end{array}
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$$\begin{array}{l}\max Z\\ 13a + 23b - Z = 0\\ 5a + 15\mathbf{b} + s_c = 480\\ 4a + 4b + s_h = 160\\ 35a + 20b + s_m = 1190\\ a, b, s_c, s_h, s_m \geq 0\end{array}$$

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

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

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

$$\begin{array}{l}\text{basis} = \{b, s_h, s_m\}\\ a = s_c = 0\\ Z = 736\\ b = 32\\ s_h = 32\\ s_m = 550\end{array}$$

$$\max Z$$

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

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

$a = s_c = 0$

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$b = 32$

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a\ ,\ b\ ,\ s_c\ ,\ s_h\ ,\ s_m &\geq 0
\end{aligned}
$$

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

$a = s_c = 0$

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Choose variable a to bring into basis.

max Z

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

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.

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

$$
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&\tfrac{1}{3}a + b + \tfrac{1}{15}s_c \qquad\qquad\qquad\qquad\quad\ = 32\\
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$$\max Z$$

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a\,,\ b\,,\ s_c\,,\ s_h\,,\ s_m &\geq 0
\end{aligned}$$

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

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

$$\max Z$$

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

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

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- hence optimum solution value is at most 800
- the current solution has value 800

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.

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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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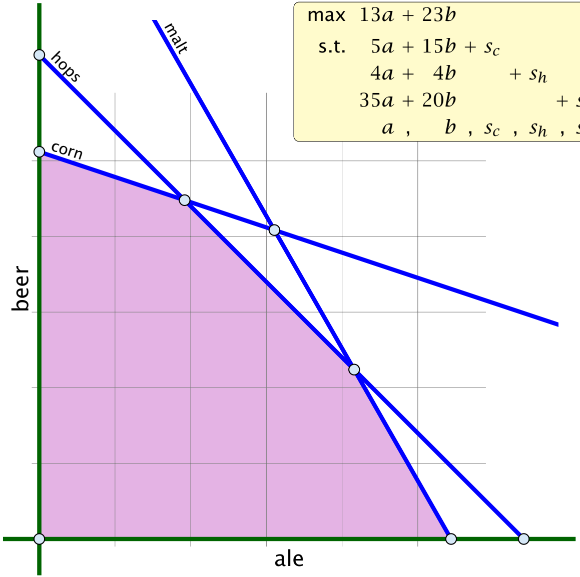
Geometric View of Pivoting



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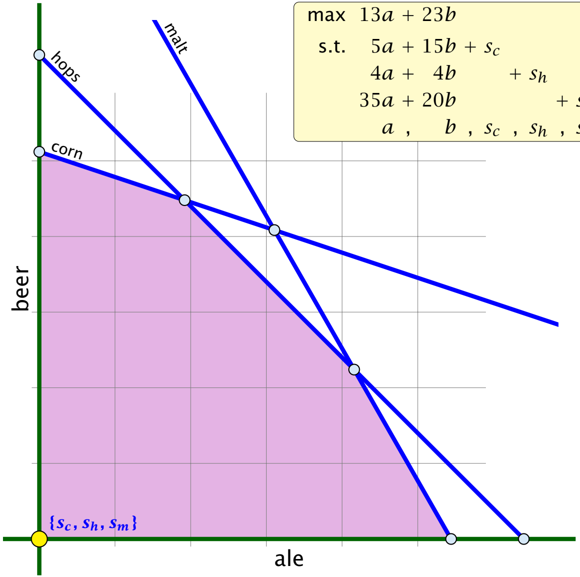

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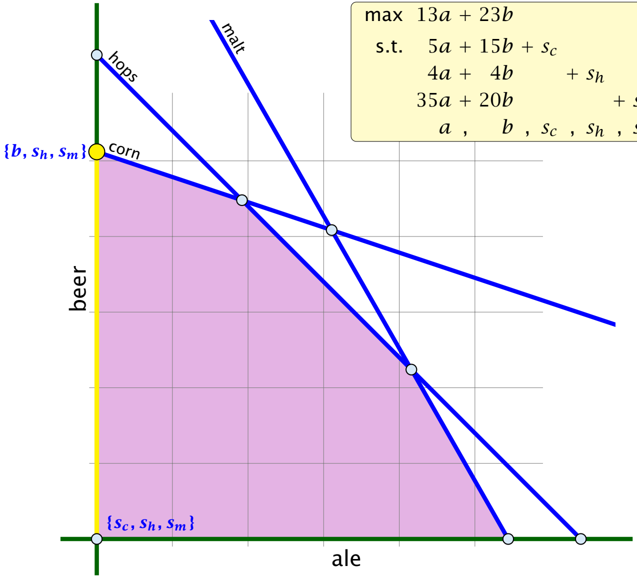

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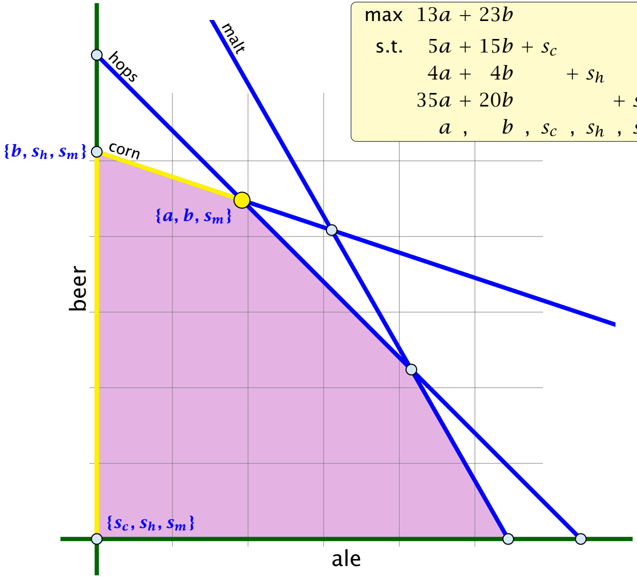

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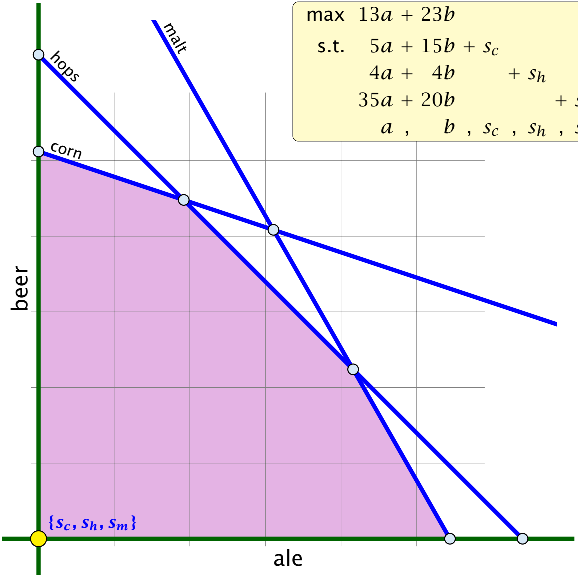

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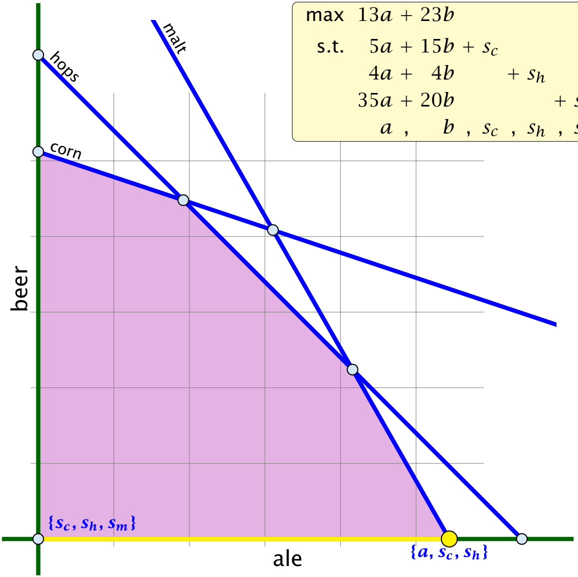

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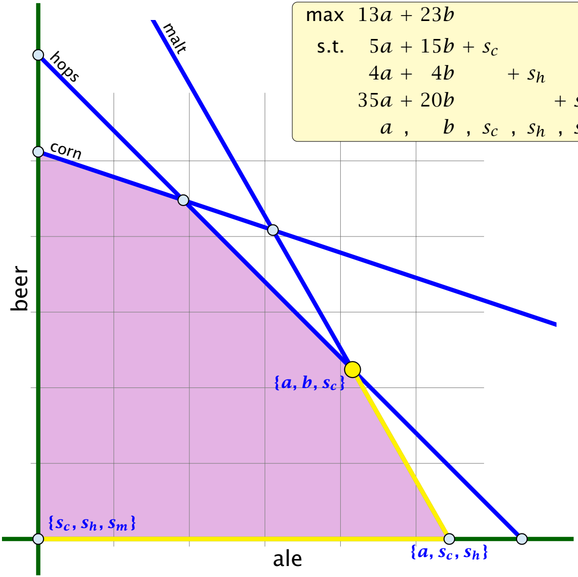

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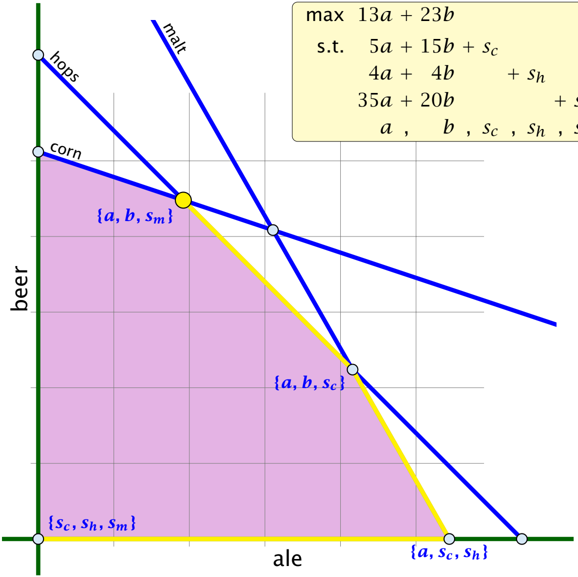

Algebraic Definition of Pivoting

- Given basis B with BFS x^*.
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- $d_j = 1$ (normalization)
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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.

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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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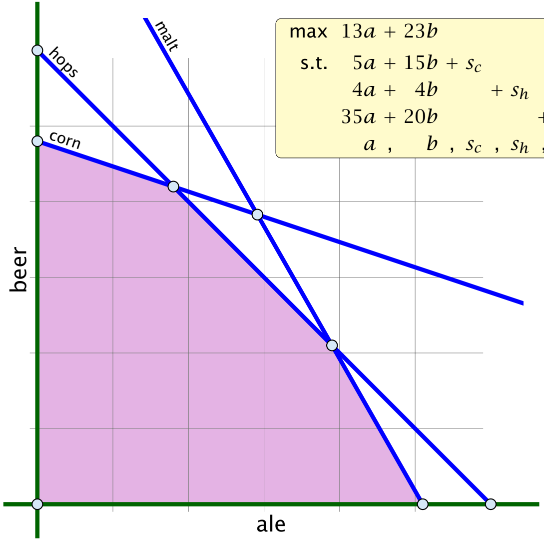
Non Degenerate Example



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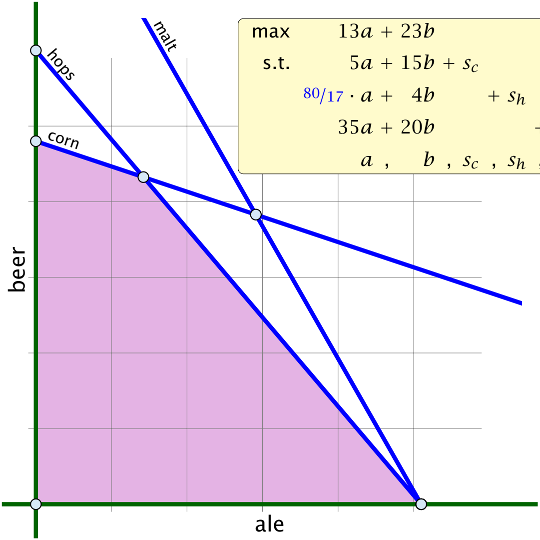

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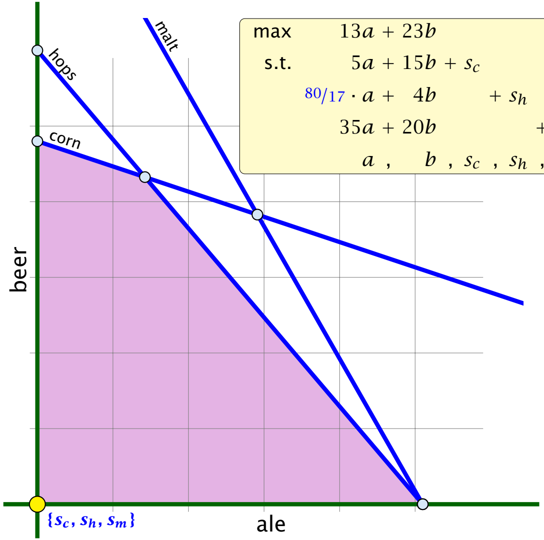

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& \frac{80}{17} \cdot a & + \ \ 4b & & + s_h & & = & 160 \\
& 35a & + 20b & & & + s_m & = & 1190 \\
& a \ , & b & , s_c & , s_h & , s_m & \geq & 0
\end{array}
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Degenerate Example

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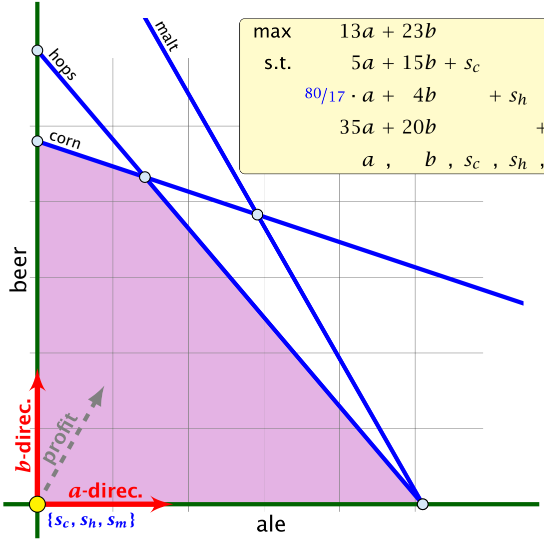

Degenerate Example

$$\begin{array}{lrl}
\text{max} & 13a + 23b & \\
\text{s.t.} & 5a + 15b + s_c & = 480 \\
 & {}^{80}/_{17} \cdot a + 4b + s_h & = 160 \\
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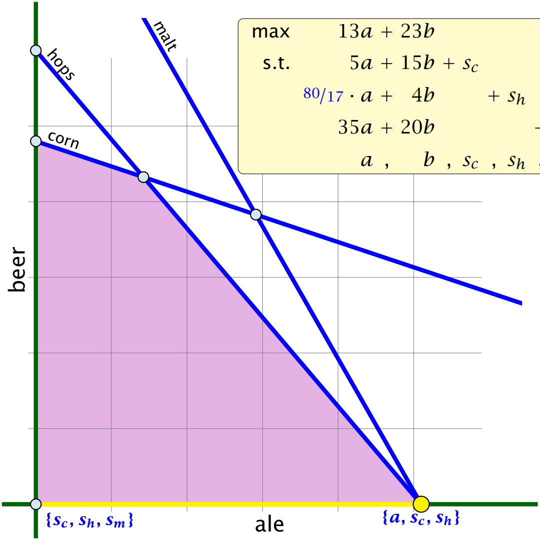

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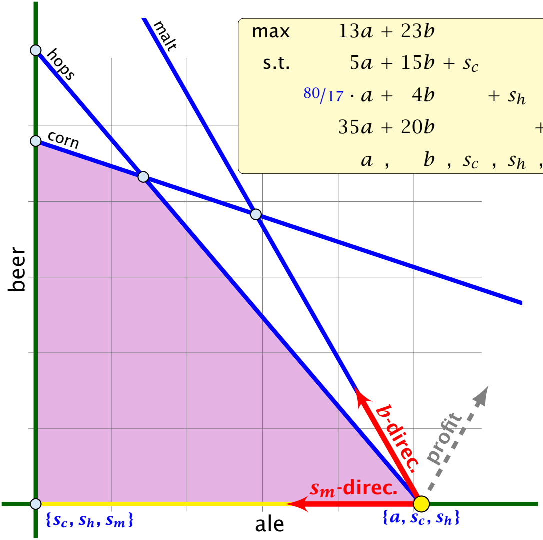

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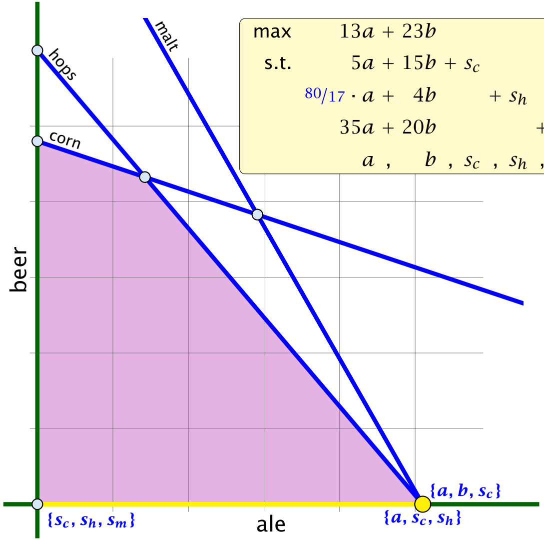

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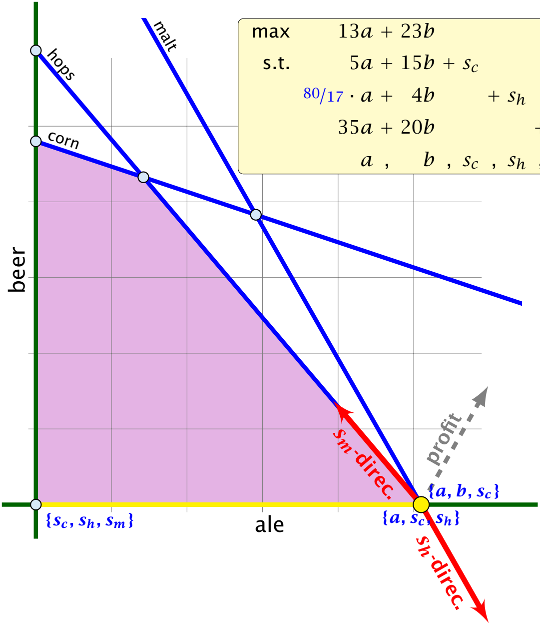

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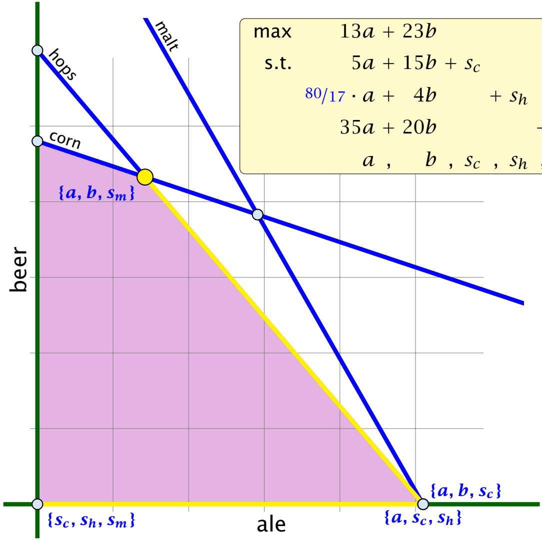

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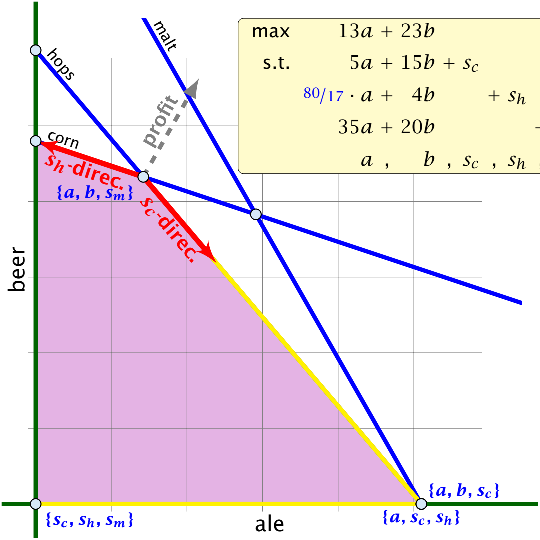

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Summary: How to choose pivot-elements

- 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 $\boldsymbol{b} \ge \boldsymbol{0}$.
- 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 $c^T x$ 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.
6. Now you can start the Simplex for the original problem.

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Optimality

Lemma 5

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