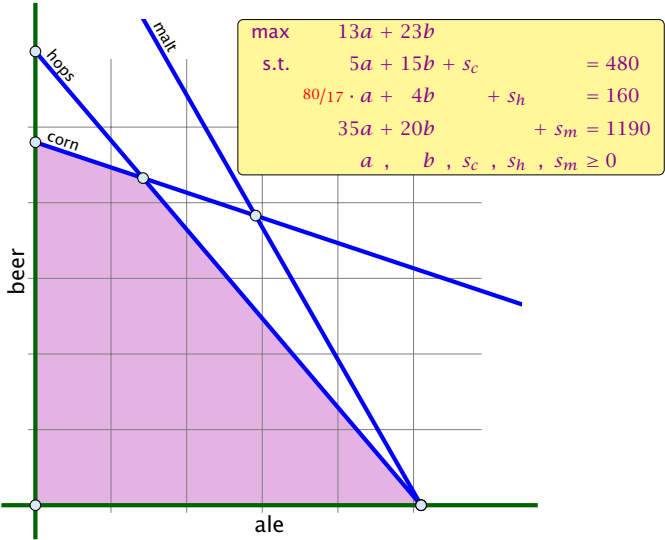


Degeneracy Revisited

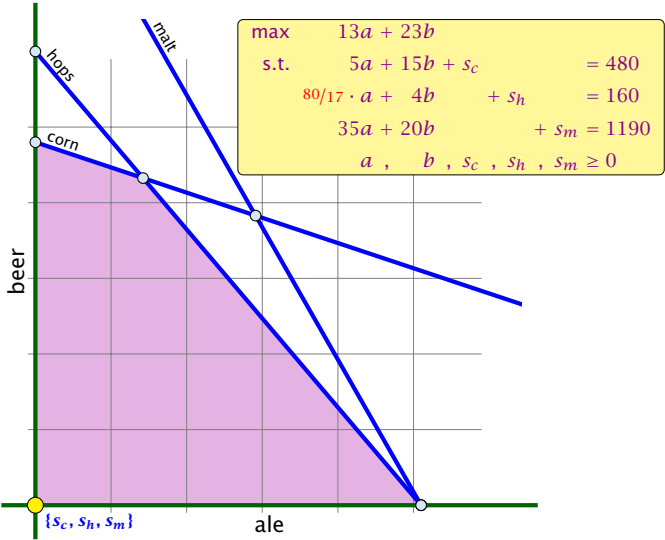
Degeneracy Revisited

If a basis variable is 0 in the basic feasible solution then we may not make progress during an iteration of simplex.

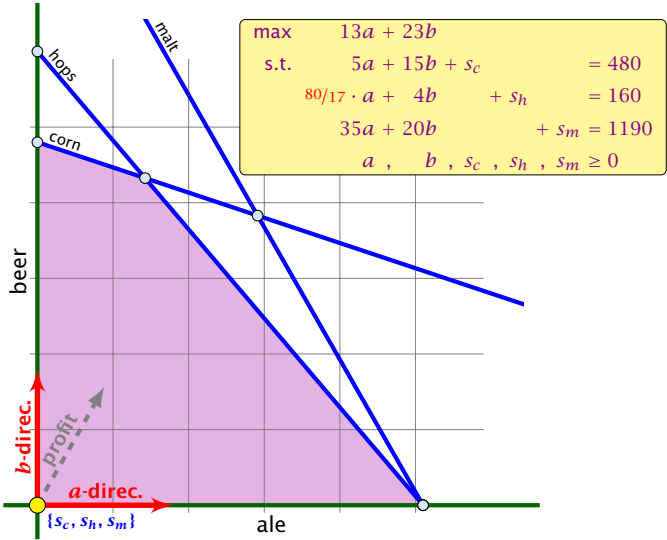
Degenerate Example



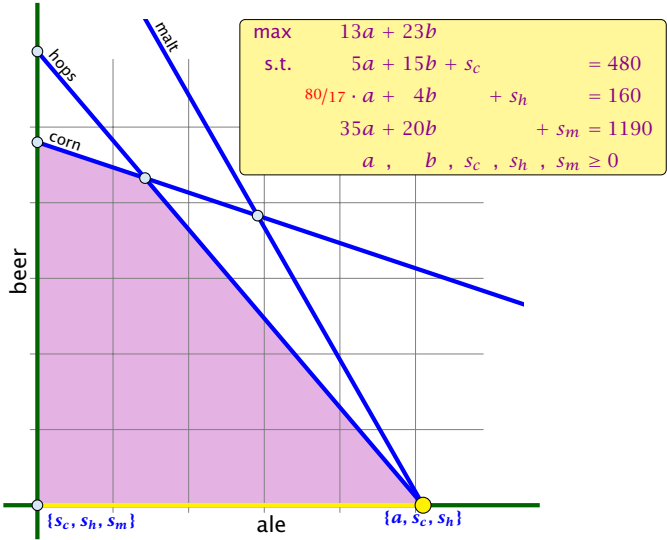
Degenerate Example



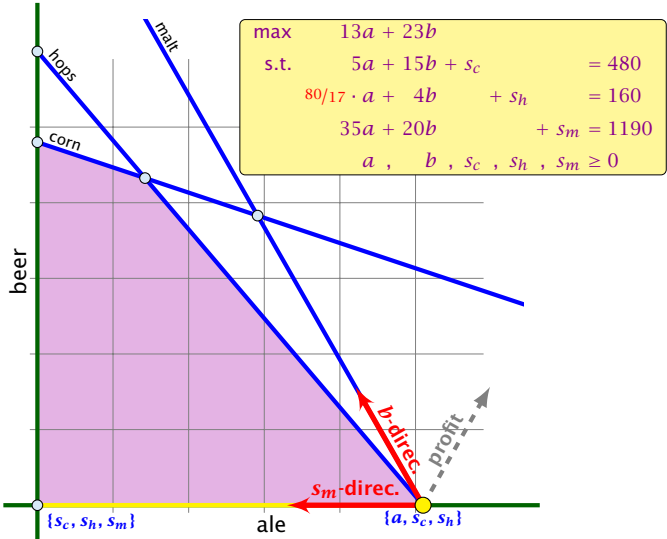
Degenerate Example



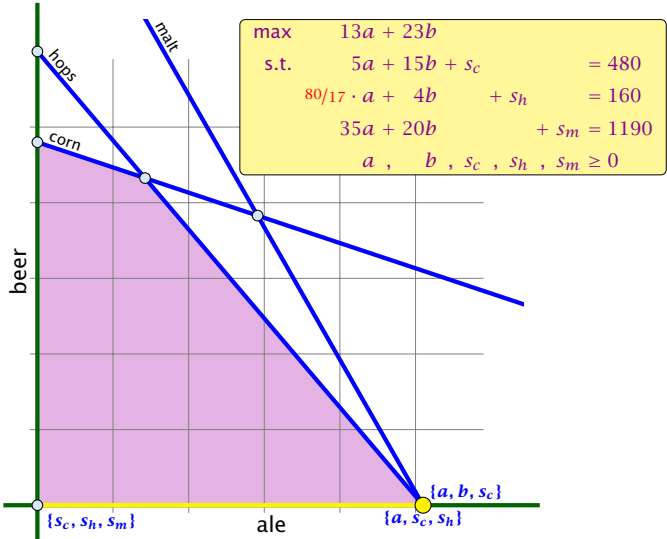
Degenerate Example



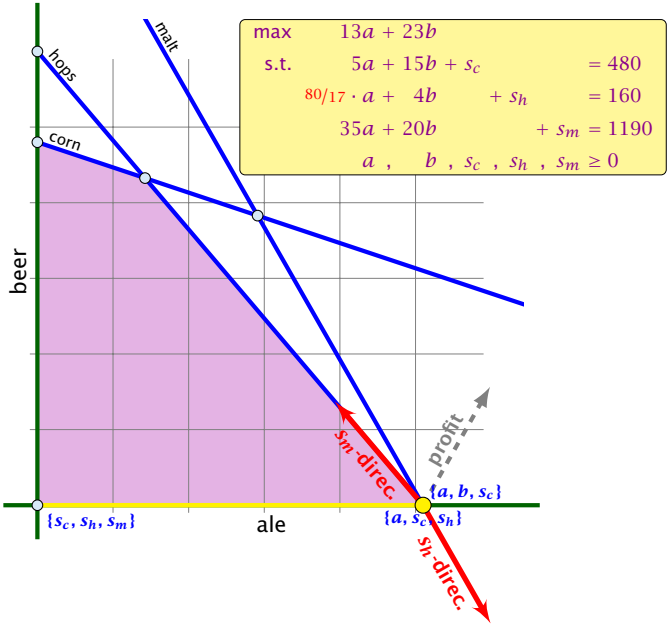
Degenerate Example



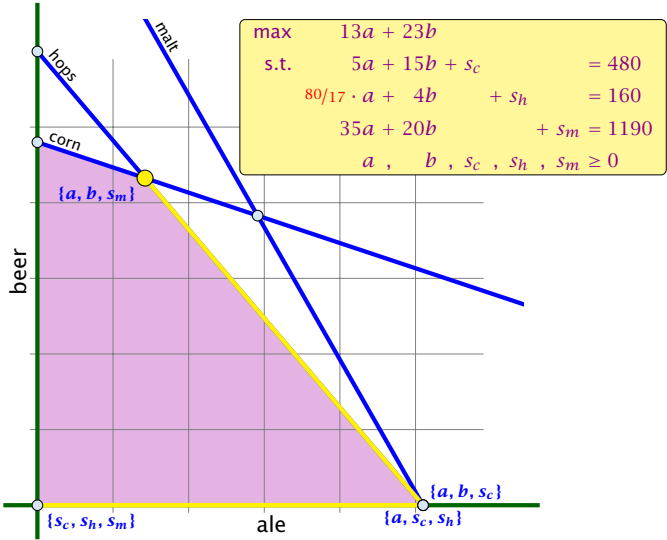
Degenerate Example



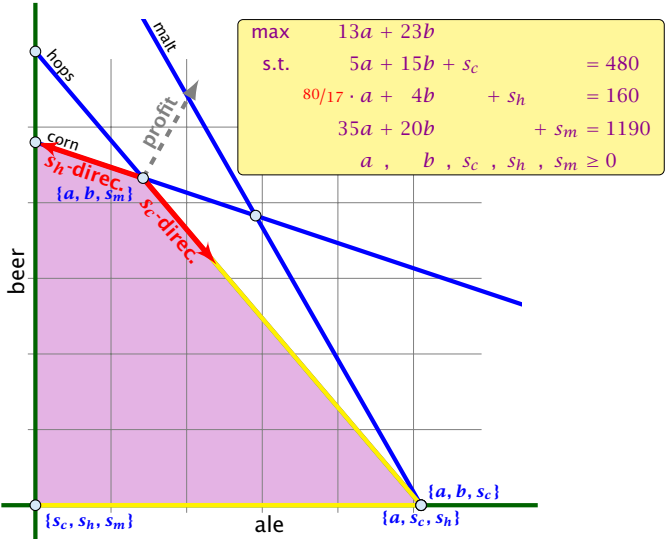
Degenerate Example



Degenerate Example



Degenerate Example



Degeneracy Revisited

If a basis variable is 0 in the basic feasible solution then we may not make progress during an iteration of simplex.

Idea:

Given feasible LP := $\max\{c^T x, Ax = b; x \geq 0\}$. Change it into LP' := $\max\{c^T x, Ax = b', x \geq 0\}$ such that

is feasible

and a set of m nonvariables corresponds to an optimal solution. This set of nonvariables is $\{0\}$. This corresponds to an optimal basis for

LP' (which should be linearly independent)

and the original LP is solved.

Degeneracy Revisited

If a basis variable is 0 in the basic feasible solution then we may not make progress during an iteration of simplex.

Idea:

Given feasible $LP := \max\{c^T x, Ax = b; x \geq 0\}$. Change it into $LP' := \max\{c^T x, Ax = b', x \geq 0\}$ such that

Degeneracy Revisited

If a basis variable is 0 in the basic feasible solution then we may not make progress during an iteration of simplex.

Idea:

Given feasible $LP := \max\{c^T x, Ax = b; x \geq 0\}$. Change it into $LP' := \max\{c^T x, Ax = b', x \geq 0\}$ such that

- I. LP' is feasible
- II. If a set B of basis variables corresponds to an infeasible basis (i.e. $A_B^{-1}b \not\geq 0$) then B corresponds to an infeasible basis in LP' (note that columns in A_B are linearly independent).
- III. LP' has no degenerate basic solutions

Degeneracy Revisited

If a basis variable is 0 in the basic feasible solution then we may not make progress during an iteration of simplex.

Idea:

Given feasible $LP := \max\{c^T x, Ax = b; x \geq 0\}$. Change it into $LP' := \max\{c^T x, Ax = b', x \geq 0\}$ such that

- I. LP' is feasible
- II. If a set B of basis variables corresponds to an **infeasible** basis (i.e. $A_B^{-1}b \not\geq 0$) then B corresponds to an infeasible basis in LP' (note that columns in A_B are linearly independent).
- III. LP' has no degenerate basic solutions

Degeneracy Revisited

If a basis variable is 0 in the basic feasible solution then we may not make progress during an iteration of simplex.

Idea:

Given feasible $LP := \max\{c^T x, Ax = b; x \geq 0\}$. Change it into $LP' := \max\{c^T x, Ax = b', x \geq 0\}$ such that

- I. LP' is feasible
- II. If a set B of basis variables corresponds to an **infeasible** basis (i.e. $A_B^{-1}b \not\geq 0$) then B corresponds to an infeasible basis in LP' (note that columns in A_B are linearly independent).
- III. LP' has no degenerate basic solutions

Perturbation

Let B be index set of **some** basis with basic solution

$$x_B^* = A_B^{-1}b \geq 0, x_N^* = 0 \quad (\text{i.e. } B \text{ is feasible})$$

Fix

$$b' := b + A_B \begin{pmatrix} \varepsilon \\ \vdots \\ \varepsilon^m \end{pmatrix} \quad \text{for } \varepsilon > 0 .$$

This is the perturbation that we are using.

Perturbation

Let B be index set of **some** basis with basic solution

$$x_B^* = A_B^{-1}b \geq 0, x_N^* = 0 \quad (\text{i.e. } B \text{ is feasible})$$

Fix

$$b' := b + A_B \begin{pmatrix} \varepsilon \\ \vdots \\ \varepsilon^m \end{pmatrix} \quad \text{for } \varepsilon > 0 .$$

This is the perturbation that we are using.

Property I

The new LP is feasible because the set B of basis variables provides a feasible basis:

$$A_B^{-1} \left(b + A_B \begin{pmatrix} \varepsilon \\ \vdots \\ \varepsilon^m \end{pmatrix} \right) = x_B^* + \begin{pmatrix} \varepsilon \\ \vdots \\ \varepsilon^m \end{pmatrix} \geq 0 .$$

Property I

The new LP is feasible because the set B of basis variables provides a feasible basis:

$$A_B^{-1} \left(b + A_B \begin{pmatrix} \varepsilon \\ \vdots \\ \varepsilon^m \end{pmatrix} \right) = x_B^* + \begin{pmatrix} \varepsilon \\ \vdots \\ \varepsilon^m \end{pmatrix} \geq 0 .$$

Property II

Let \tilde{B} be a non-feasible basis. This means $(A_{\tilde{B}}^{-1}b)_i < 0$ for some row i .

Property II

Let \tilde{B} be a non-feasible basis. This means $(A_{\tilde{B}}^{-1}b)_i < 0$ for some row i .

Then for small enough $\epsilon > 0$

$$\left(A_{\tilde{B}}^{-1} \left(b + A_B \begin{pmatrix} \epsilon \\ \vdots \\ \epsilon^m \end{pmatrix} \right) \right)_i$$

Property II

Let \tilde{B} be a non-feasible basis. This means $(A_{\tilde{B}}^{-1}b)_i < 0$ for some row i .

Then for small enough $\epsilon > 0$

$$\left(A_{\tilde{B}}^{-1} \left(b + A_B \begin{pmatrix} \epsilon \\ \vdots \\ \epsilon^m \end{pmatrix} \right) \right)_i = (A_{\tilde{B}}^{-1}b)_i + \left(A_{\tilde{B}}^{-1}A_B \begin{pmatrix} \epsilon \\ \vdots \\ \epsilon^m \end{pmatrix} \right)_i < 0$$

Property II

Let \tilde{B} be a non-feasible basis. This means $(A_{\tilde{B}}^{-1}b)_i < 0$ for some row i .

Then for small enough $\epsilon > 0$

$$\left(A_{\tilde{B}}^{-1} \left(b + A_B \begin{pmatrix} \epsilon \\ \vdots \\ \epsilon^m \end{pmatrix} \right) \right)_i = (A_{\tilde{B}}^{-1}b)_i + \left(A_{\tilde{B}}^{-1}A_B \begin{pmatrix} \epsilon \\ \vdots \\ \epsilon^m \end{pmatrix} \right)_i < 0$$

Hence, \tilde{B} is not feasible.

Property III

Let \tilde{B} be a basis. It has an associated solution

$$x_{\tilde{B}}^* = A_{\tilde{B}}^{-1}b + A_{\tilde{B}}^{-1}A_B \begin{pmatrix} \varepsilon \\ \vdots \\ \varepsilon^m \end{pmatrix}$$

in the perturbed instance.

We can view each component of the vector as a polynomial with variable ε of degree at most m .

$A_{\tilde{B}}^{-1}A_B$ has rank m . Therefore no polynomial is 0.

A polynomial of degree at most m has at most m roots (Nullstellen).

Hence, $\varepsilon > 0$ small enough gives that no component of the above vector is 0. Hence, no degeneracies.

Property III

Let \tilde{B} be a basis. It has an associated solution

$$x_{\tilde{B}}^* = A_{\tilde{B}}^{-1}b + A_{\tilde{B}}^{-1}A_B \begin{pmatrix} \varepsilon \\ \vdots \\ \varepsilon^m \end{pmatrix}$$

in the perturbed instance.

We can view each component of the vector as a polynomial with variable ε of degree at most m .

$A_{\tilde{B}}^{-1}A_B$ has rank m . Therefore no polynomial is 0.

A polynomial of degree at most m has at most m roots (Nullstellen).

Hence, $\varepsilon > 0$ small enough gives that no component of the above vector is 0. Hence, no degeneracies.

Property III

Let \tilde{B} be a basis. It has an associated solution

$$x_{\tilde{B}}^* = A_{\tilde{B}}^{-1}b + A_{\tilde{B}}^{-1}A_B \begin{pmatrix} \varepsilon \\ \vdots \\ \varepsilon^m \end{pmatrix}$$

in the perturbed instance.

We can view each component of the vector as a polynomial with variable ε of degree at most m .

$A_{\tilde{B}}^{-1}A_B$ has rank m . Therefore no polynomial is 0.

A polynomial of degree at most m has at most m roots (Nullstellen).

Hence, $\varepsilon > 0$ small enough gives that no component of the above vector is 0. Hence, no degeneracies.

Property III

Let \tilde{B} be a basis. It has an associated solution

$$x_{\tilde{B}}^* = A_{\tilde{B}}^{-1}b + A_{\tilde{B}}^{-1}A_B \begin{pmatrix} \varepsilon \\ \vdots \\ \varepsilon^m \end{pmatrix}$$

in the perturbed instance.

We can view each component of the vector as a polynomial with variable ε of degree at most m .

$A_{\tilde{B}}^{-1}A_B$ has rank m . Therefore no polynomial is 0.

A polynomial of degree at most m has at most m roots (Nullstellen).

Hence, $\varepsilon > 0$ small enough gives that no component of the above vector is 0. Hence, no degeneracies.

Property III

Let \tilde{B} be a basis. It has an associated solution

$$x_{\tilde{B}}^* = A_{\tilde{B}}^{-1}b + A_{\tilde{B}}^{-1}A_B \begin{pmatrix} \varepsilon \\ \vdots \\ \varepsilon^m \end{pmatrix}$$

in the perturbed instance.

We can view each component of the vector as a polynomial with variable ε of degree at most m .

$A_{\tilde{B}}^{-1}A_B$ has rank m . Therefore no polynomial is 0.

A polynomial of degree at most m has at most m roots (Nullstellen).

Hence, $\varepsilon > 0$ small enough gives that no component of the above vector is 0. Hence, no degeneracies.

Property III

Let \tilde{B} be a basis. It has an associated solution

$$x_{\tilde{B}}^* = A_{\tilde{B}}^{-1}b + A_{\tilde{B}}^{-1}A_B \begin{pmatrix} \varepsilon \\ \vdots \\ \varepsilon^m \end{pmatrix}$$

in the perturbed instance.

We can view each component of the vector as a polynomial with variable ε of degree at most m .

$A_{\tilde{B}}^{-1}A_B$ has rank m . Therefore no polynomial is 0.

A polynomial of degree at most m has at most m roots (Nullstellen).

Hence, $\varepsilon > 0$ small enough gives that no component of the above vector is 0. Hence, no degeneracies.

Since, there are no degeneracies Simplex will terminate when run on LP' .

Since, there are no degeneracies Simplex will terminate when run on LP' .

- ▶ If it terminates because the reduced cost vector fulfills

$$\tilde{c} = (c^T - c_B^T A_B^{-1} A) \leq 0$$

then we have found an optimal basis.

Since, there are no degeneracies Simplex will terminate when run on LP' .

- ▶ If it terminates because the reduced cost vector fulfills

$$\tilde{c} = (c^T - c_B^T A_B^{-1} A) \leq 0$$

then we have found an optimal basis. **Note that this basis is also optimal for LP , as the above constraint does not depend on b .**

Since, there are no degeneracies Simplex will terminate when run on LP' .

- ▶ If it terminates because the reduced cost vector fulfills

$$\tilde{c} = (c^T - c_B^T A_B^{-1} A) \leq 0$$

then we have found an optimal basis. **Note that this basis is also optimal for LP, as the above constraint does not depend on b .**

- ▶ If it terminates because it finds a variable x_j with $\tilde{c}_j > 0$ for which the j -th basis direction d , fulfills $d \geq 0$ we know that LP' is unbounded. The basis direction **does not depend on b .** Hence, we also know that LP is unbounded.

Lexicographic Pivoting

Doing calculations with perturbed instances may be costly. Also the right choice of ε is difficult.

Idea:

Simulate behaviour of LP' without explicitly doing a perturbation.

Lexicographic Pivoting

Doing calculations with perturbed instances may be costly. Also the right choice of ε is difficult.

Idea:

Simulate behaviour of LP' without explicitly doing a perturbation.

Lexicographic Pivoting

Doing calculations with perturbed instances may be costly. Also the right choice of ε is difficult.

Idea:

Simulate behaviour of LP' without explicitly doing a perturbation.

Lexicographic Pivoting

We choose the entering variable arbitrarily as before ($\tilde{c}_e > 0$, of course).

If we do not have a choice for the leaving variable then LP' and LP do the same (i.e., choose the same variable).

Otherwise we have to be careful.

Lexicographic Pivoting

We choose the entering variable arbitrarily as before ($\tilde{c}_e > 0$, of course).

If we do not have a choice for the leaving variable then LP' and LP do the same (i.e., choose the same variable).

Otherwise we have to be careful.

Lexicographic Pivoting

We choose the entering variable arbitrarily as before ($\tilde{c}_e > 0$, of course).

If we do not have a choice for the leaving variable then LP' and LP do the same (i.e., choose the same variable).

Otherwise we have to be careful.

Lexicographic Pivoting

We choose the entering variable arbitrarily as before ($\tilde{c}_e > 0$, of course).

If we do not have a choice for the leaving variable then LP' and LP do the same (i.e., choose the same variable).

Otherwise we have to be careful.

Lexicographic Pivoting

In the following we assume that $b \geq 0$. This can be obtained by replacing the initial system $(A \mid b)$ by $(A_B^{-1}A \mid A_B^{-1}b)$ where B is the index set of a feasible basis (found e.g. by the first phase of the Two-phase algorithm).

Then the perturbed instance is

$$b' = b + \begin{pmatrix} \varepsilon \\ \vdots \\ \varepsilon^m \end{pmatrix}$$

Lexicographic Pivoting

In the following we assume that $b \geq 0$. This can be obtained by replacing the initial system $(A \mid b)$ by $(A_B^{-1}A \mid A_B^{-1}b)$ where B is the index set of a feasible basis (found e.g. by the first phase of the Two-phase algorithm).

Then the perturbed instance is

$$b' = b + \begin{pmatrix} \varepsilon \\ \vdots \\ \varepsilon^m \end{pmatrix}$$

Matrix View

Let our linear program be

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

The simplex tableaux for basis B is

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

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.

Lexicographic Pivoting

LP chooses an arbitrary leaving variable that has $\hat{A}_{\ell e} > 0$ and minimizes

$$\theta_{\ell} = \frac{\hat{b}_{\ell}}{\hat{A}_{\ell e}} = \frac{(A_B^{-1}b)_{\ell}}{(A_B^{-1}A_{*e})_{\ell}}.$$

ℓ is the index of a leaving variable within B . This means if e.g. $B = \{1, 3, 7, 14\}$ and leaving variable is 3 then $\ell = 2$.

Lexicographic Pivoting

LP chooses an arbitrary leaving variable that has $\hat{A}_{\ell e} > 0$ and minimizes

$$\theta_{\ell} = \frac{\hat{b}_{\ell}}{\hat{A}_{\ell e}} = \frac{(A_B^{-1}b)_{\ell}}{(A_B^{-1}A_{*e})_{\ell}}.$$

ℓ is the index of a leaving variable within B . This means if e.g. $B = \{1, 3, 7, 14\}$ and leaving variable is 3 then $\ell = 2$.

Lexicographic Pivoting

LP chooses an arbitrary leaving variable that has $\hat{A}_{\ell e} > 0$ and minimizes

$$\theta_{\ell} = \frac{\hat{b}_{\ell}}{\hat{A}_{\ell e}} = \frac{(A_B^{-1}b)_{\ell}}{(A_B^{-1}A_{*e})_{\ell}} .$$

ℓ is the index of a leaving variable within B . This means if e.g. $B = \{1, 3, 7, 14\}$ and leaving variable is 3 then $\ell = 2$.

Lexicographic Pivoting

LP chooses an arbitrary leaving variable that has $\hat{A}_{\ell e} > 0$ and minimizes

$$\theta_{\ell} = \frac{\hat{b}_{\ell}}{\hat{A}_{\ell e}} = \frac{(A_B^{-1}b)_{\ell}}{(A_B^{-1}A_{*e})_{\ell}} .$$

ℓ is the index of a leaving variable within B . This means if e.g. $B = \{1, 3, 7, 14\}$ and leaving variable is 3 then $\ell = 2$.

Lexicographic Pivoting

Definition 44

$u \leq_{\text{lex}} v$ if and only if the first component in which u and v differ fulfills $u_i \leq v_i$.

Lexicographic Pivoting

LP' chooses an index that minimizes

θ_ℓ

Lexicographic Pivoting

LP' chooses an index that minimizes

$$\theta_\ell = \frac{\left(A_B^{-1} \left(b + \begin{pmatrix} \varepsilon \\ \vdots \\ \varepsilon^m \end{pmatrix} \right) \right)_\ell}{(A_B^{-1} A_* e)_\ell}$$

Lexicographic Pivoting

LP' chooses an index that minimizes

$$\theta_\ell = \frac{\left(A_B^{-1} \left(b + \begin{pmatrix} \varepsilon \\ \vdots \\ \varepsilon^m \end{pmatrix} \right) \right)_\ell}{(A_B^{-1} A_{*e})_\ell} = \frac{\left(A_B^{-1} (b \mid I) \begin{pmatrix} 1 \\ \varepsilon \\ \vdots \\ \varepsilon^m \end{pmatrix} \right)_\ell}{(A_B^{-1} A_{*e})_\ell}$$

Lexicographic Pivoting

LP' chooses an index that minimizes

$$\begin{aligned}\theta_\ell &= \frac{\left(A_B^{-1} \left(b + \begin{pmatrix} \varepsilon \\ \vdots \\ \varepsilon^m \end{pmatrix} \right) \right)_\ell}{(A_B^{-1} A_{*e})_\ell} = \frac{\left(A_B^{-1}(b | I) \begin{pmatrix} 1 \\ \varepsilon \\ \vdots \\ \varepsilon^m \end{pmatrix} \right)_\ell}{(A_B^{-1} A_{*e})_\ell} \\ &= \frac{\ell\text{-th row of } A_B^{-1}(b | I)}{(A_B^{-1} A_{*e})_\ell} \begin{pmatrix} 1 \\ \varepsilon \\ \vdots \\ \varepsilon^m \end{pmatrix}\end{aligned}$$

Lexicographic Pivoting

This means you can choose the variable/row ℓ for which the vector

$$\frac{\ell\text{-th row of } A_B^{-1}(b \mid I)}{(A_B^{-1}A_{*e})_\ell}$$

is lexicographically minimal.

Of course only including rows with $(A_B^{-1}A_{*e})_\ell > 0$.

This technique guarantees that your pivoting is the same as in the perturbed case. This guarantees that cycling does not occur.

Lexicographic Pivoting

This means you can choose the variable/row ℓ for which the vector

$$\frac{\ell\text{-th row of } A_B^{-1}(b \mid I)}{(A_B^{-1}A_{*e})_\ell}$$

is lexicographically minimal.

Of course only including rows with $(A_B^{-1}A_{*e})_\ell > 0$.

This technique guarantees that your pivoting is the same as in the perturbed case. This guarantees that cycling does not occur.

Lexicographic Pivoting

This means you can choose the variable/row ℓ for which the vector

$$\frac{\ell\text{-th row of } A_B^{-1}(b \mid I)}{(A_B^{-1}A_{*e})_\ell}$$

is lexicographically minimal.

Of course only including rows with $(A_B^{-1}A_{*e})_\ell > 0$.

This technique guarantees that your pivoting is the same as in the perturbed case. This guarantees that cycling does not occur.