CSC373

Week 7:
Linear Programming

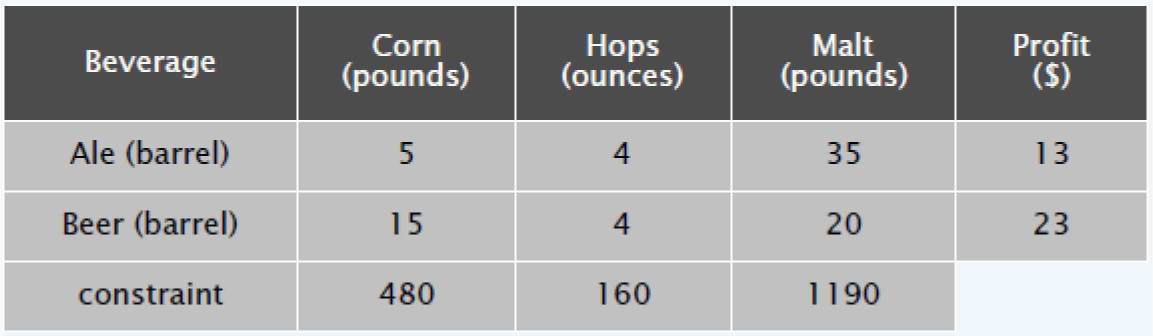
Illustration Courtesy:
Kevin Wayne & Denis Pankratov

Recap

- Network flow
  - Ford-Fulkerson algorithm
    - Ways to make the running time polynomial
  - Correctness using max-flow, min-cut
  - Applications:
    - Edge-disjoint paths
    - Multiple sources/sinks
    - Circulation
    - Circulation with lower bounds
    - Survey design
    - Image segmentation
    - Profit maximization

Brewery Example

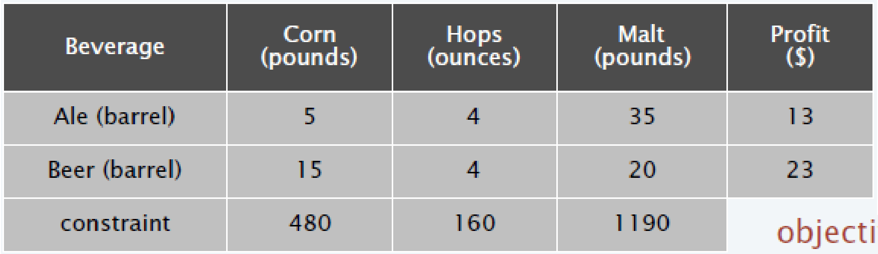
- A brewery can invest its inventory of corn, hops and malt into producing some amount of ale and some amount of beer
  - Per unit resource requirement and profit of the two items are as given below



Beverage	Corn (pounds)	Hops (ounces)	Malt (pounds)	Profit ($)
Ale (barrel)	5	4	35	13
Beer (barrel)	15	4	20	23
constraint	480	160	1190	

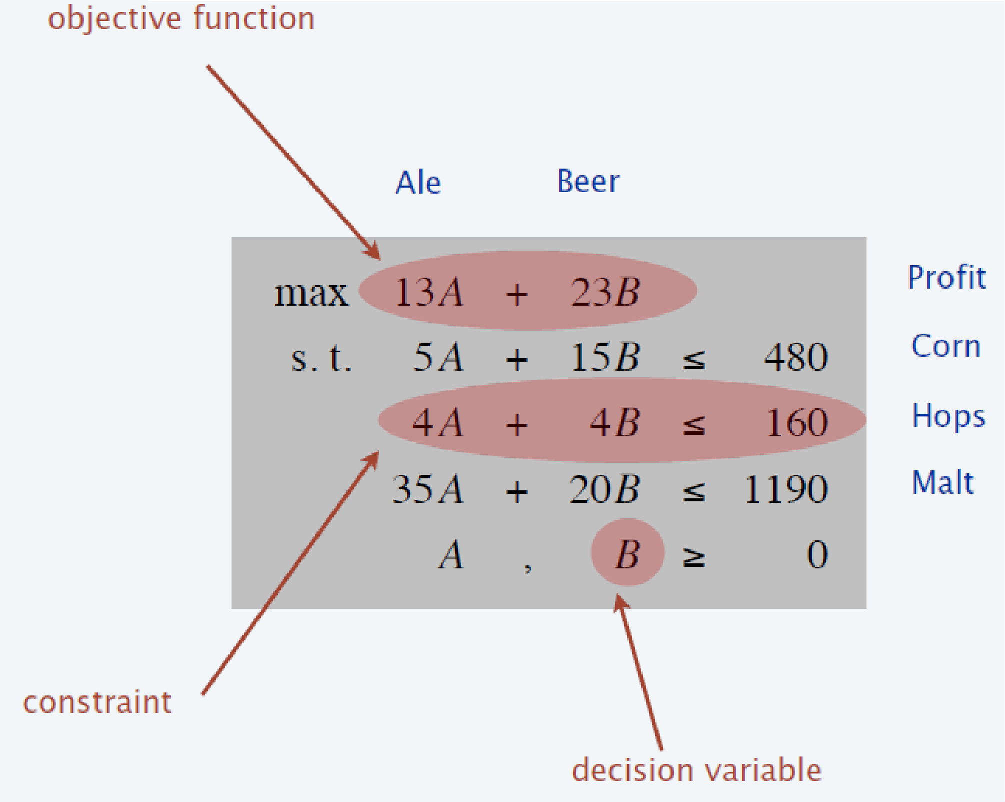
Example Courtesy: Kevin Wayne

Brewery Example



Beverage	Corn (pounds)	Hops (ounces)	Malt (pounds)	Profit ($)
Ale (barrel)	5	4	35	13
Beer (barrel)	15	4	20	23
constraint	480	160	1190	

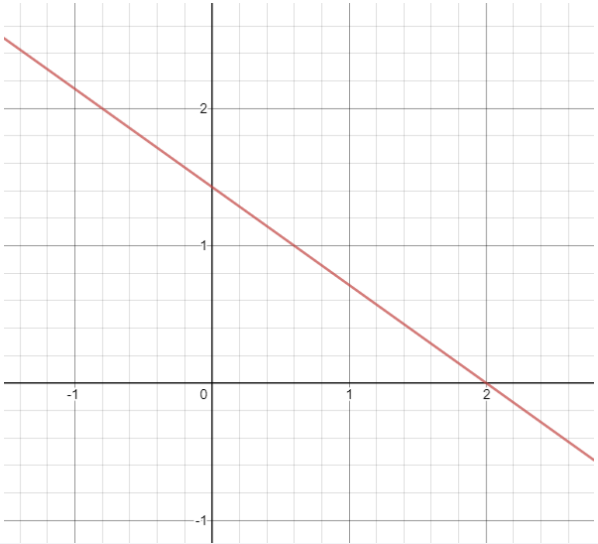
- Suppose it produces A units of ale and B units of beer
- Then we want to solve this program:



$$\begin{array}{lrcrcr} \max & 13A & + & 23B & & \\ \text{s. t.} & 5A & + & 15B & \le & 480 \\ & 4A & + & 4B & \le & 160 \\ & 35A & + & 20B & \le & 1190 \\ & A & , & B & \ge & 0 \end{array}$$

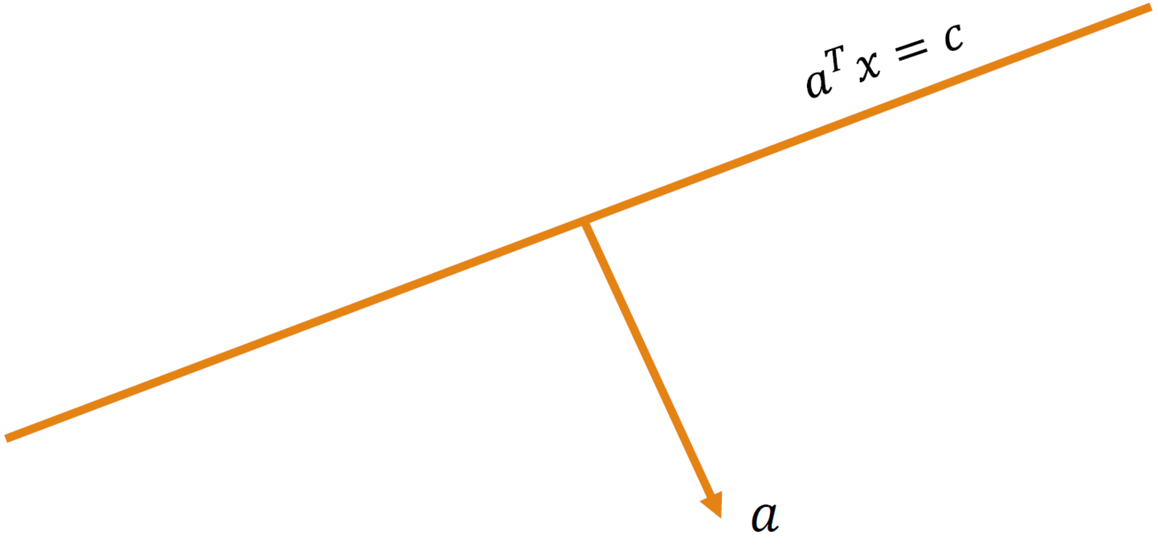
Linear Function

- $f: \mathbb{R}^n \to \mathbb{R}$ is a linear function if $f(x) = a^T x$ for some $a \in \mathbb{R}^n$
  - Example: $f(x_1, x_2) = 3x_1 - 5x_2 = \binom{3}{-5}^T \binom{x_1}{x_2}$
- Linear objective: f
- Linear constraints:
  - $g(x) = c$, where $g: \mathbb{R}^n \to \mathbb{R}$ is a linear function and $c \in \mathbb{R}$
  - Line in the plane (or a hyperplane in $\mathbb{R}^n$)
  - Example: $5x_1 + 7x_2 = 10$



Linear Function

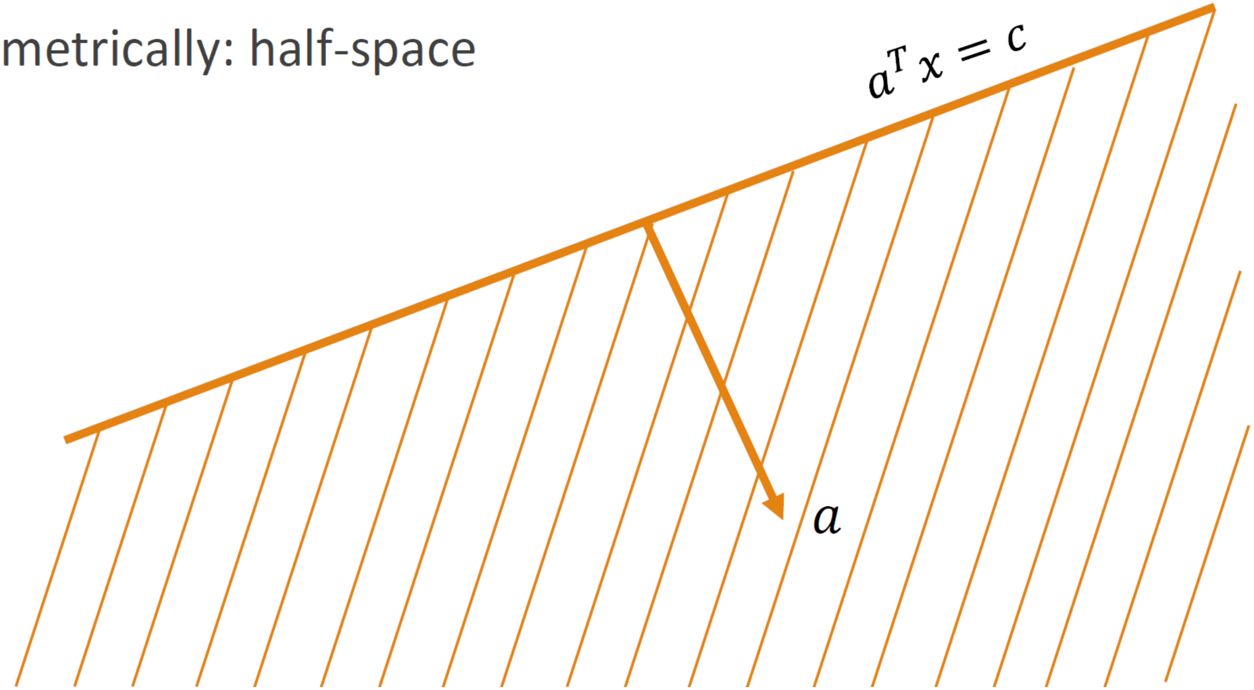
- Geometrically, a is the normal vector of the line(or hyperplane) represented by $a^T x = c$



Linear Inequality

- $a^T x \leq c$ represents a "half-space"

Geometrically: half-space



Linear Programming

- Maximize/minimize a linear function subject to linear equality/inequality constraints

Could be min

Linear objective!

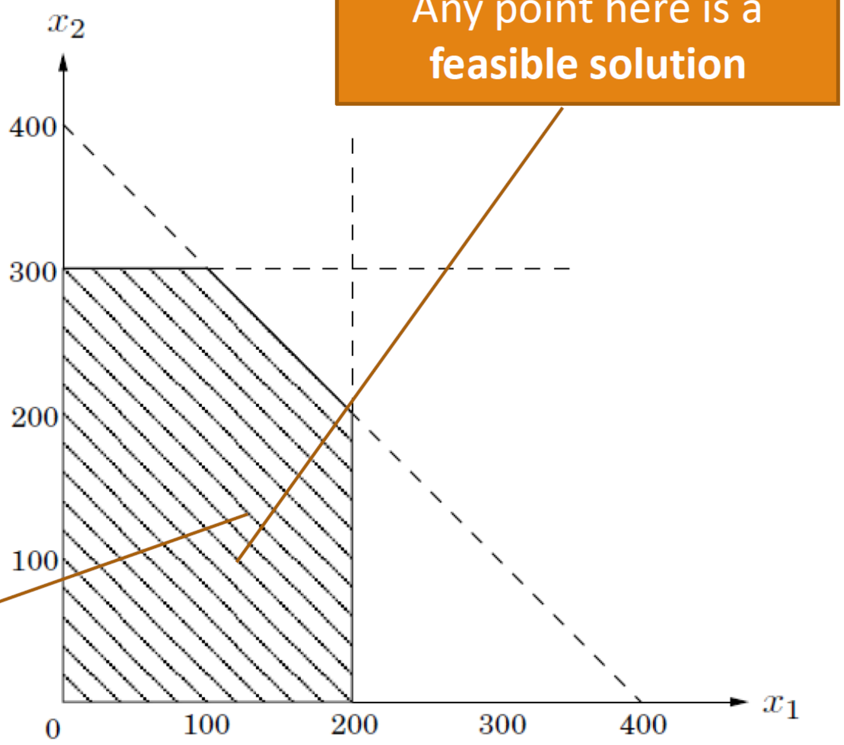
$$\begin{array}{ll} \text{Objective function} & \max x_1 + 6x_2 \\ \text{Constraints} & x_1 \leq 200 \\ & x_2 \leq 300 \\ & x_1 + x_2 \leq 400 \\ & x_1, x_2 \geq 0 \end{array}$$

Linear constraints: inequalities/equalities

Geometrically…

Objective function $\max x_1 + 6x_2$

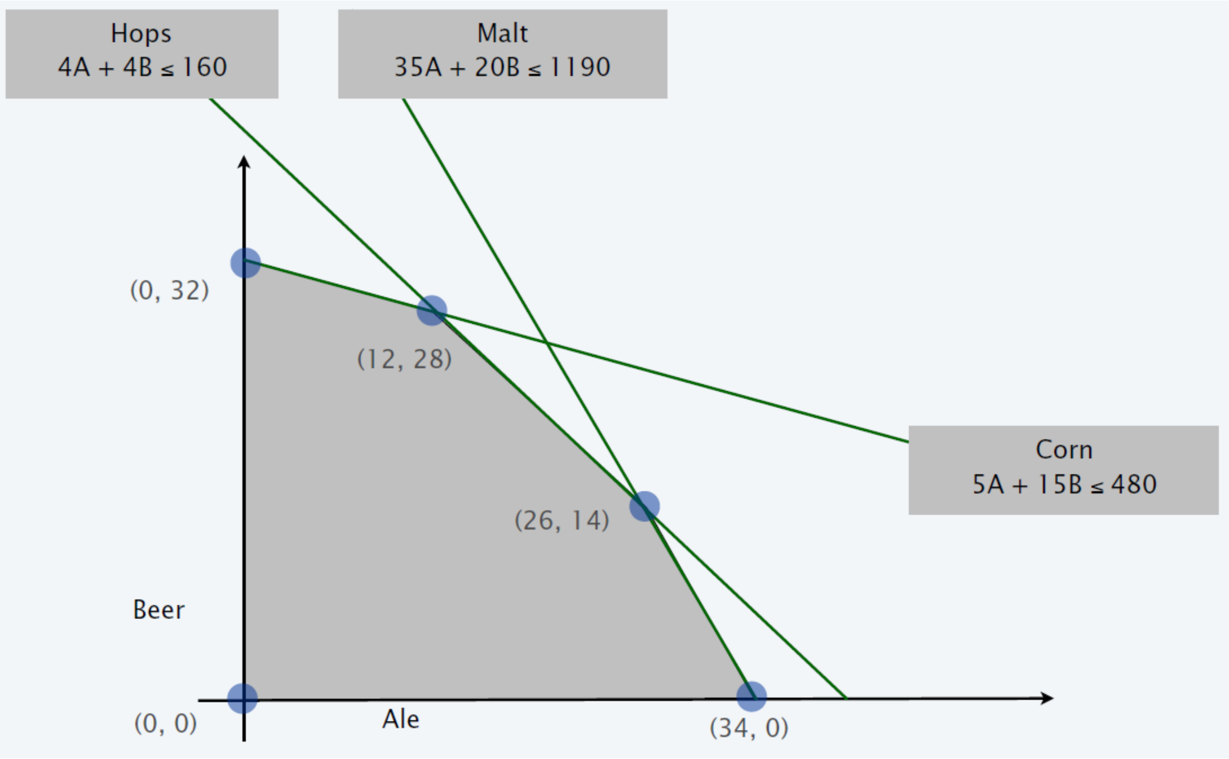
Constraints
$$x_1 \leq 200$$
$$x_2 \leq 300$$
$$x_1 + x_2 \leq 400$$
$$x_1, x_2 \geq 0$$



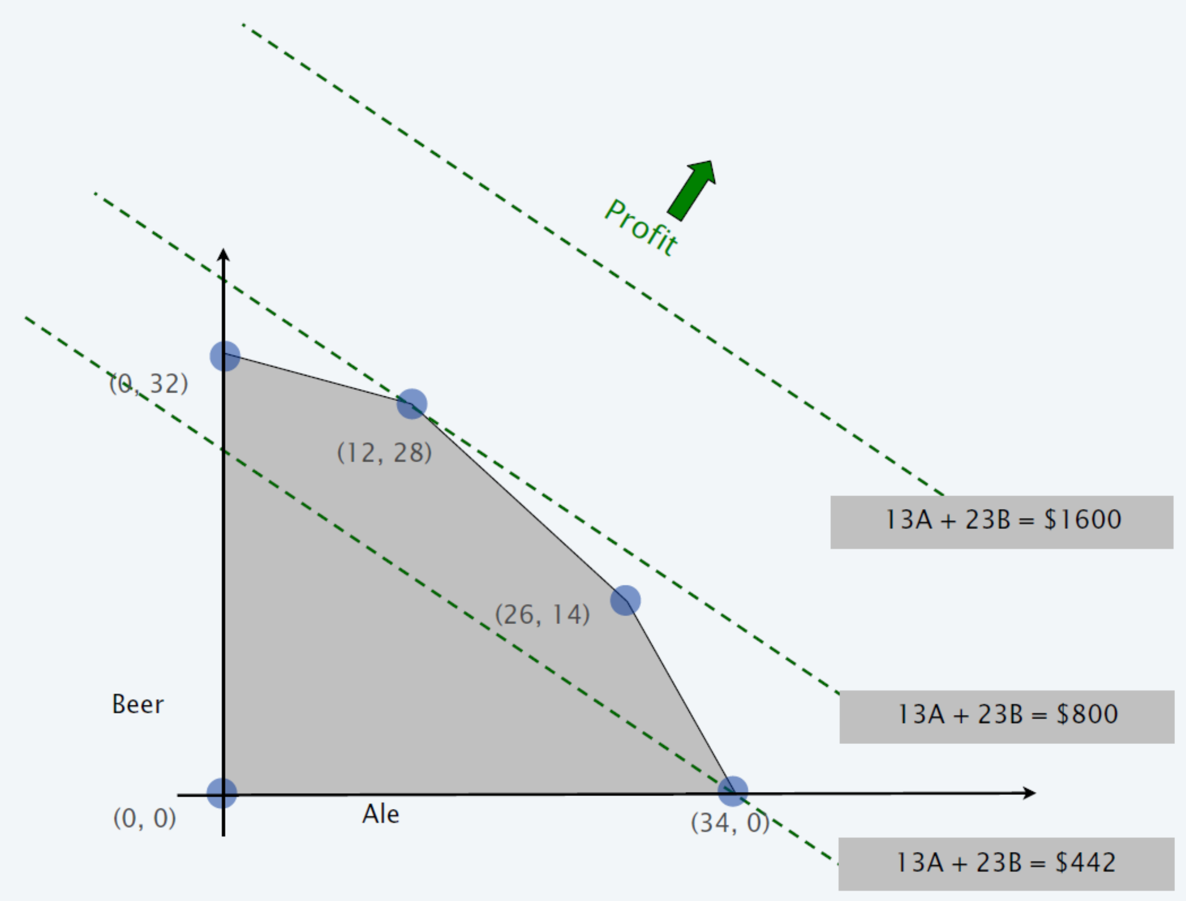
Any point here is a **feasible solution**

Feasible region – polytope, aka intersection of half-spaces!

Back to Brewery Example

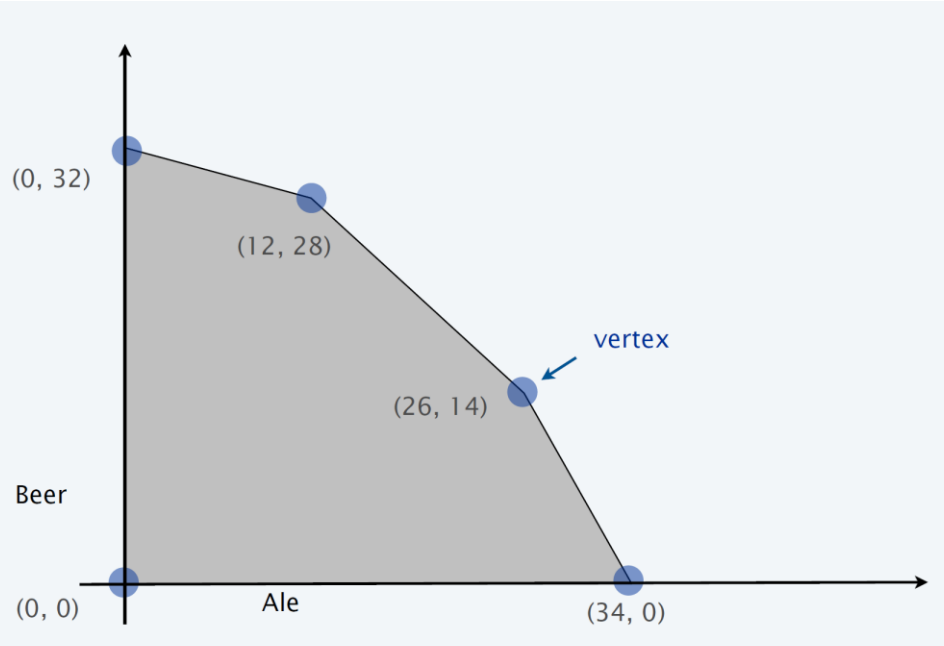


Back to Brewery Example



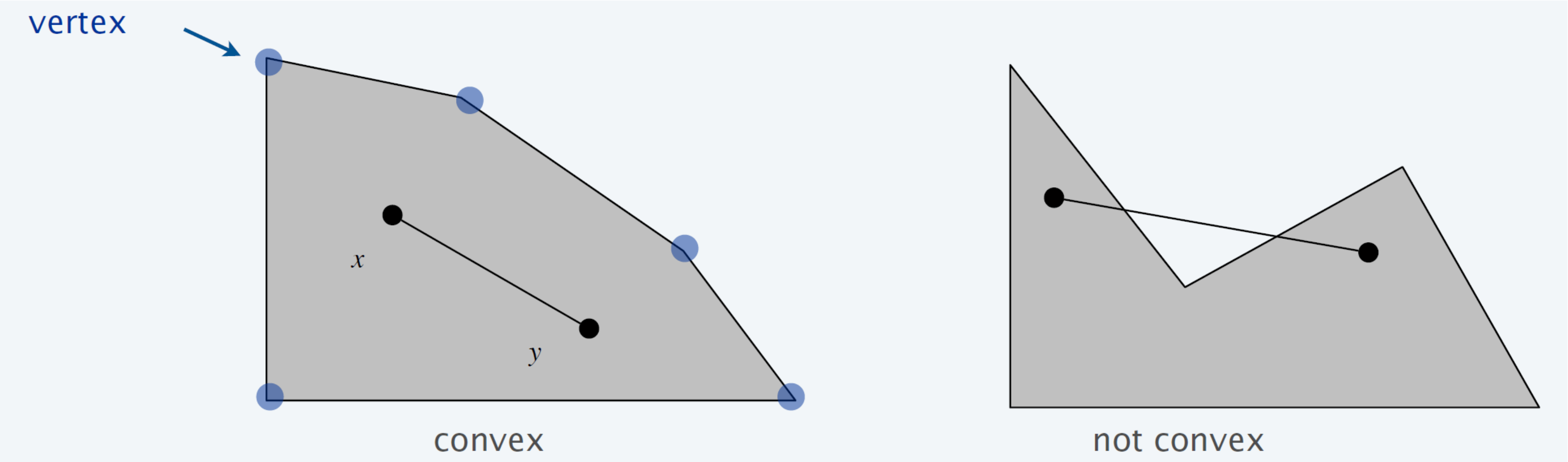
Optimal Solution At A Vertex

- Claim: Regardless of the objective function, there must be a vertex that is an optimal solution



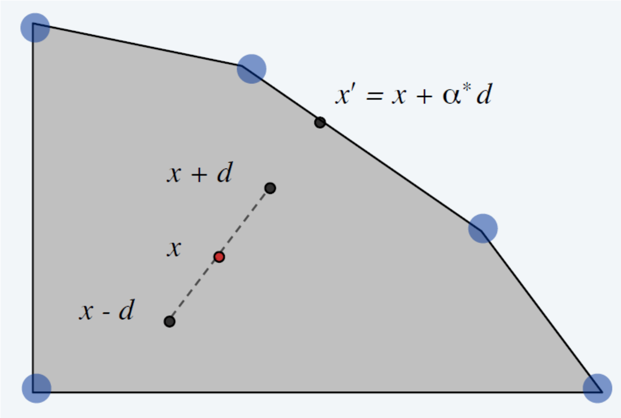
Convexity

- **Convex set**: S is convex if
$$x, y \in S, \lambda \in [0,1] \Rightarrow \lambda x + (1-\lambda) y \in S$$
- **Vertex**: A point which cannot be written as a strict convex combination of any two points in the set
- **Observation**: Feasible region of an LP is a convex set



Optimal Solution At A Vertex

- Intuitive proof of the claim:
  - Start at some point x in the feasible region
  - If x is not a vertex:
    - Find a direction d such that points within a positive distance of ϵ from x in both d and $-d$ directions are within the feasible region
    - Objective must *not decrease* in at least one of the two directions
    - Follow that direction until you reach a new point x for which at least one more constraint is "tight"
  - Repeat until we are at a vertex



LP, Standard Formulation

- Input: $c, a_1, a_2, \dots, a_m \in \mathbb{R}^n, b \in \mathbb{R}^m$
  - There are n variables and m constraints
- Goal:

$$\begin{aligned} &\text{Maximize } c^T x \\ &\text{Subject to } a_1^T x \le b_1 \\ &a_2^T x \le b_2 \\ &\vdots \\ &a_m^T x \le b_m \\ &x \ge 0 \end{aligned}$$

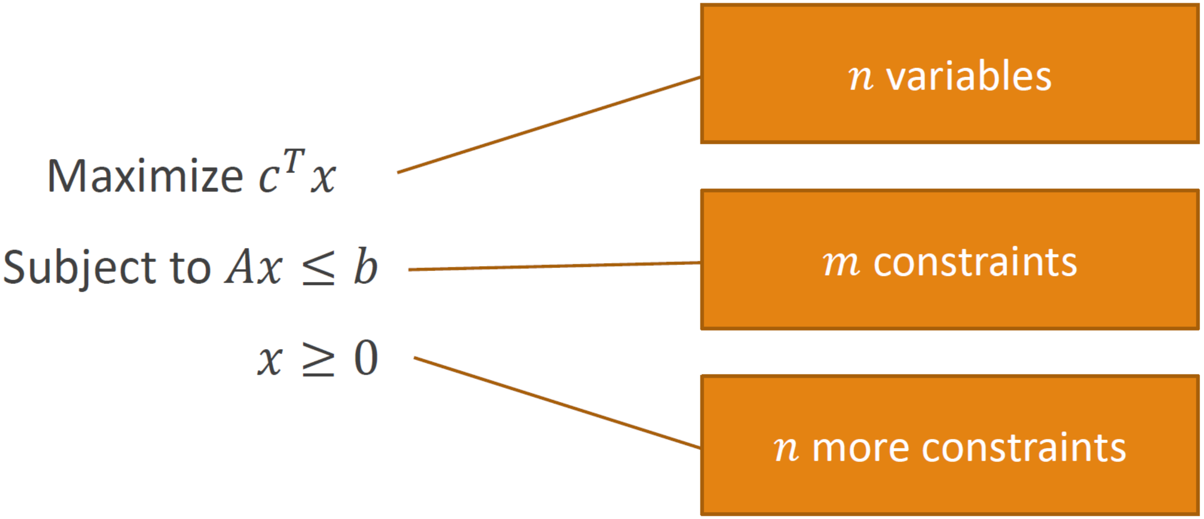
n variables

m constraints

n more constraints

LP, Standard Matrix Form

- Input: $c, a_1, a_2, \ldots, a_m \in \mathbb{R}^n, b \in \mathbb{R}^m$
  - There are n variables and m constraints
- Goal:



Maximize $c^T x$

Subject to $Ax \leq b$

$x \geq 0$

Convert to Standard Form

- What if the LP is not in standard form?
  - Constraints that use $\geq$
    - $a^T x \geq b \iff -a^T x \leq -b$
  - Constraints that use equality
    - $a^T x = b \iff a^T x \leq b,\ a^T x \geq b$
  - Objective function is a minimization
    - Minimize $c^T x \iff$ Maximize $-c^T x$
  - Variable is unconstrained
    - x with no constraint $\iff$ Replace x by two variables $x'$and x'', replace every occurrence of x with $x' - x''$, and add constraints $x' \geq 0,\ x'' \geq 0$

LP Transformation Example

$$
\begin{array}{lrcrcl}
\text{minimize} & -2x_1 & + & 3x_2 & & \\
\text{subject to} & & & & & \\
& x_1 & + & x_2 & = & 7 \\
& x_1 & - & 2x_2 & \leq & 4 \\
& x_1 & & & \geq & 0 \;,
\end{array}
$$

$$
\begin{array}{lrcrcl}
\text{maximize} & 2x_1 & - & 3x_2 & & \\
\text{subject to} & & & & & \\
& x_1 & + & x_2 & = & 7 \\
& x_1 & - & 2x_2 & \leq & 4 \\
& x_1 & & & \geq & 0 \;.
\end{array}
$$

$$
\begin{array}{lrcrcrcl}
\text{maximize} & 2x_1 & - & 3x_2' & + & 3x_2'' & & \\
\text{subject to} & & & & & & & \\
& x_1 & + & x_2' & - & x_2'' & = & 7 \\
& x_1 & - & 2x_2' & + & 2x_2'' & \leq & 4 \\
& & & x_1, x_2', x_2'' & & & \geq & 0 \;.
\end{array}
$$

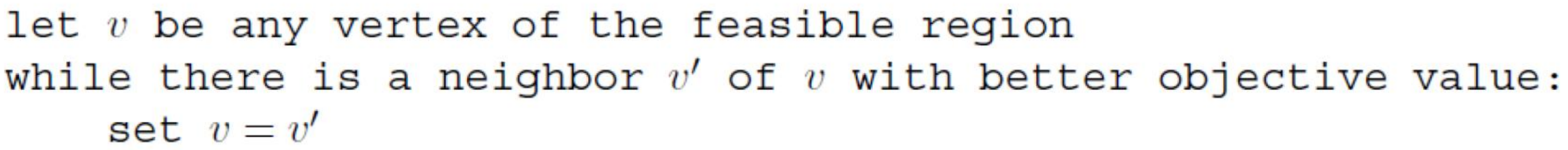
Optimal Solution

- Does an LP always have an optimal solution?

- No! The LP can "fail" for two reasons:
  1. It is *infeasible*, i.e., $\{x \mid Ax \leq b\} = \emptyset$
     - E.g., the set of constraints is $\{x_1 \leq 1, -x_1 \leq -2\}$
  2. It is *unbounded*, i.e., the objective function can be made arbitrarily large (for maximization) or small (for minimization)
     - E.g., "maximize x_1 subject to $x_1 \geq 0$"

- But if the LP has an optimal solution, we know that there must be a vertex which is optimal

Simplex Algorithm



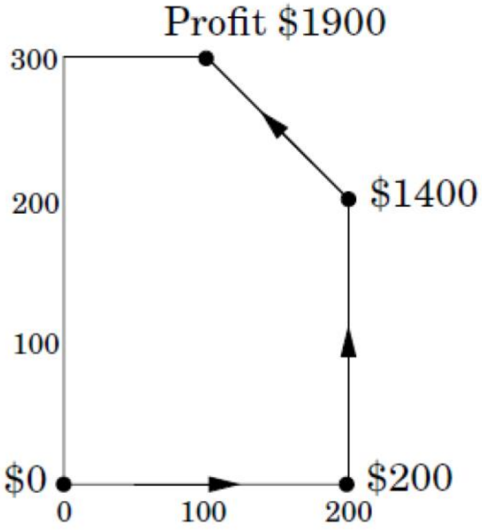
```
let $v$ be any vertex of the feasible region
while there is a neighbor $v'$ of $v$ with better objective value:
    set $v = v'$
```

- Simple algorithm, easy to specify geometrically
- Worst-case running time is exponential
- Excellent performance in practice

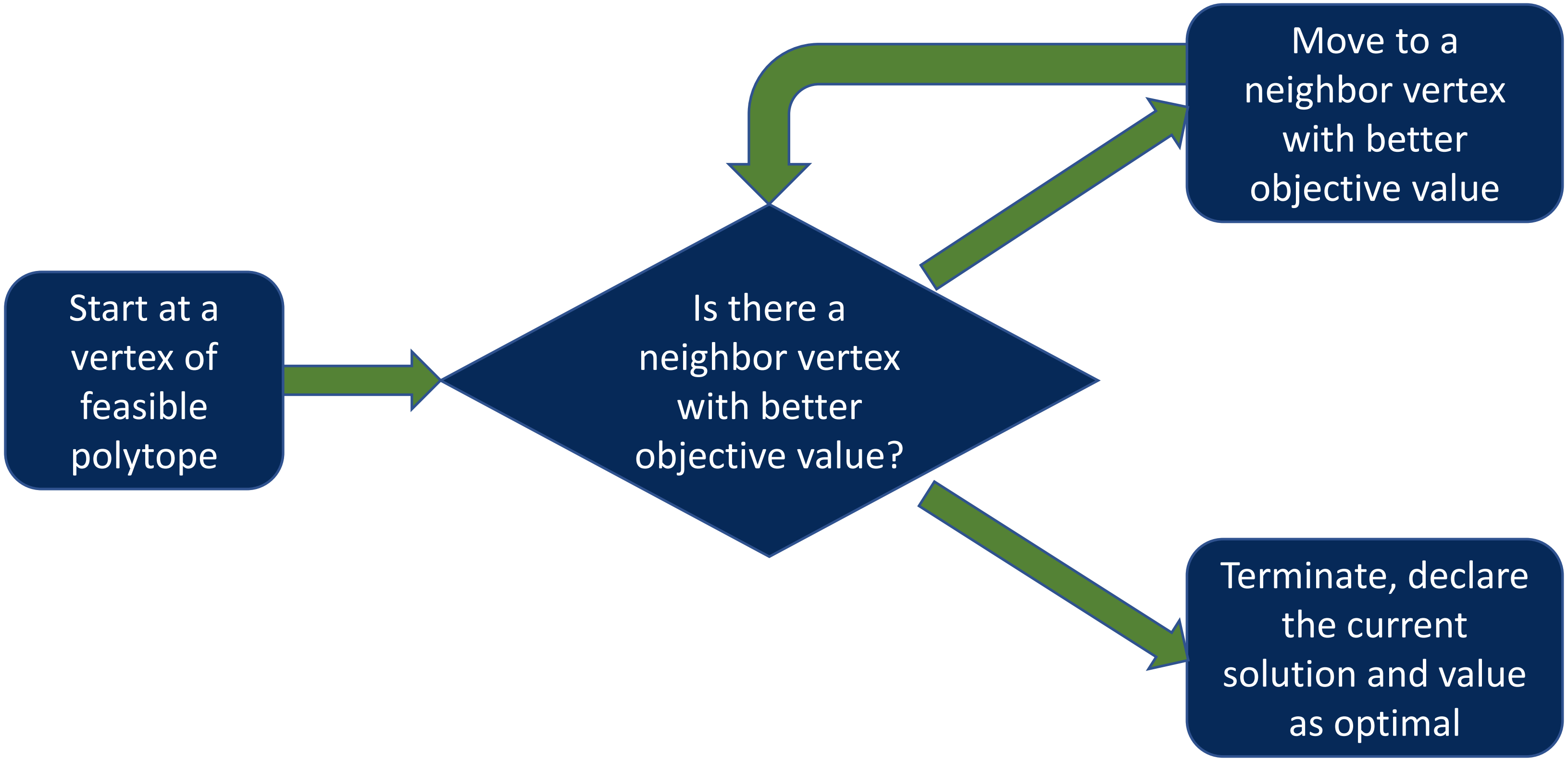
Simplex: Geometric View

```
let $v$ be any vertex of the feasible region
while there is a neighbor $v'$ of $v$ with better objective value:
    set $v = v'$
```

$$\begin{aligned} \max\ x_1 + 6x_2 \\ x_1 \leq 200 \\ x_2 \leq 300 \\ x_1 + x_2 \leq 400 \\ x_1, x_2 \geq 0 \end{aligned}$$



Algorithmic Implementation



Start at a vertex of feasible polytope

Is there a neighbor vertex with better objective value?

Move to a neighbor vertex with better objective value

Terminate, declare the current solution and value as optimal

How Do We Implement This?

- We'll work with the slack form of LP
  - Convenient for implementing simplex operations
  - We want to maximize z in the slack form, but for now, forget about the maximization objective

Standard form:

Maximize $c^T x$
Subject to $Ax \leq b$
$x \geq 0$

Slack form:

$$\mathrm{z} = c^T x$$
$$s = b - Ax$$
$$s, x \geq 0$$

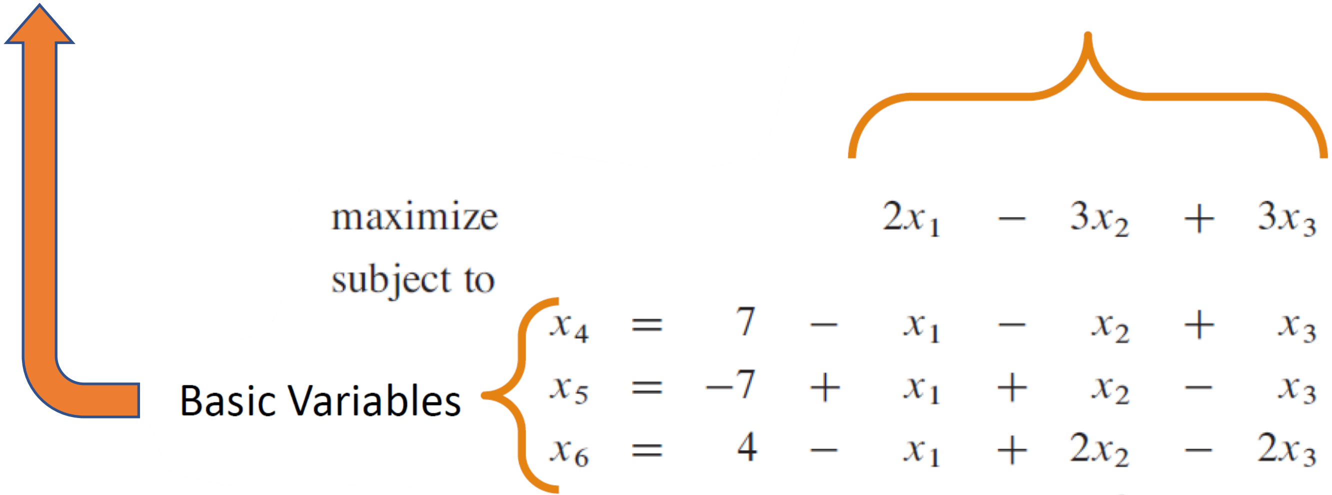
Slack Form

$$\begin{array}{lrcrcrcr}
\text{maximize} & 2x_1 & - & 3x_2 & + & 3x_3 & & \\
\text{subject to} & & & & & & & \\
& x_1 & + & x_2 & - & x_3 & \leq & 7 \\
& -x_1 & - & x_2 & + & x_3 & \leq & -7 \\
& x_1 & - & 2x_2 & + & 2x_3 & \leq & 4 \\
& x_1, x_2, x_3 & & & & & \geq & 0 \; .
\end{array}$$

$$\begin{array}{ll}
\text{maximize} & \overbrace{2x_1 - 3x_2 + 3x_3}^{\text{Nonbasic Variables}} \\
\text{subject to} & \\
\text{Basic Variables} & \left\{\begin{array}{rcrcrcrcr}
x_4 & = & 7 & - & x_1 & - & x_2 & + & x_3 \\
x_5 & = & -7 & + & x_1 & + & x_2 & - & x_3 \\
x_6 & = & 4 & - & x_1 & + & 2x_2 & - & 2x_3
\end{array}\right. \\
& x_1, x_2, x_3, x_4, x_5, x_6 \geq 0 \; .
\end{array}$$

Slack Form

$$\begin{array}{rcrcrcrcr}
z & = & & & 2x_1 & - & 3x_2 & + & 3x_3 \\
x_4 & = & 7 & - & x_1 & - & x_2 & + & x_3 \\
x_5 & = & -7 & + & x_1 & + & x_2 & - & x_3 \\
x_6 & = & 4 & - & x_1 & + & 2x_2 & - & 2x_3 \\
\multicolumn{3}{l}{x_1, x_2, x_3, x_4, x_5, x_6} & \geq & 0 & & & &
\end{array}$$



Nonbasic Variables

Basic Variables

$$\begin{array}{lrcrcrcrcr}
\text{maximize} & & & & & 2x_1 & - & 3x_2 & + & 3x_3 \\
\text{subject to} & & & & & & & & & \\
& x_4 & = & 7 & - & x_1 & - & x_2 & + & x_3 \\
& x_5 & = & -7 & + & x_1 & + & x_2 & - & x_3 \\
& x_6 & = & 4 & - & x_1 & + & 2x_2 & - & 2x_3 \\
& \multicolumn{3}{l}{x_1, x_2, x_3, x_4, x_5, x_6} & \geq & 0 & . & & &
\end{array}$$

Simplex: Step 1

- Start at a feasible vertex
  - How do we find a feasible vertex?
  - For now, assume $b \geq 0$ (that is, each $b_i \geq 0$)
    - In this case, $x = 0$ is a feasible vertex.
    - In the slack form, this means setting the nonbasic variables to 0
  - We'll later see what to do in the general case

Standard form:	Slack form:
Maximize $c^T x$	$z = c^T x$
Subject to $Ax \leq b$	$s = b - Ax$
$x \geq 0$	$s, x \geq 0$

Simple: Step 2

- What next? Let's look at an example

$$\begin{array}{rcrcrcrcr}
z & = & & & 3x_1 & + & x_2 & + & 2x_3 \\
x_4 & = & 30 & - & x_1 & - & x_2 & - & 3x_3 \\
x_5 & = & 24 & - & 2x_1 & - & 2x_2 & - & 5x_3 \\
x_6 & = & 36 & - & 4x_1 & - & x_2 & - & 2x_3 \\
\multicolumn{5}{l}{x_1, x_2, x_3, x_4, x_5, x_6} & \geq & 0 & &
\end{array}$$

- To increase the value of z:
  - Find a nonbasic variable with a positive coefficient
    - This is called an *entering variable*
  - See how much you can increase its value without violating any constraints

Simple: Step 2

Try to increase!

$$\begin{array}{rcrcrcrcr} z & = & & & 3x_1 & + & x_2 & + & 2x_3 \\ x_4 & = & 30 & - & x_1 & - & x_2 & - & 3x_3 \\ x_5 & = & 24 & - & 2x_1 & - & 2x_2 & - & 5x_3 \\ x_6 & = & 36 & - & 4x_1 & - & x_2 & - & 2x_3 \\ \multicolumn{5}{l}{x_1, x_2, x_3, x_4, x_5, x_6} & \geq & 0 & & \end{array}$$

Obstacles!

$x_1 \leq 30$

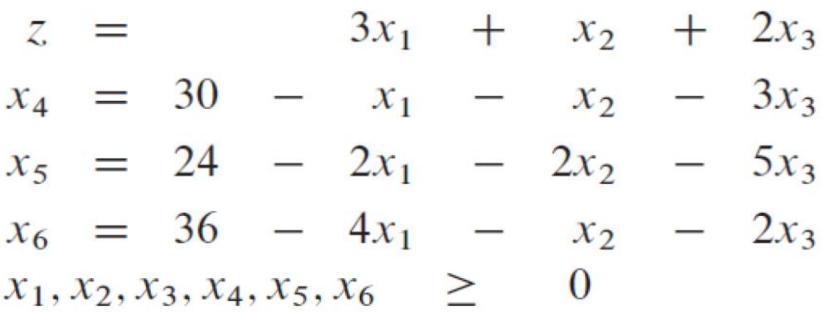
$x_1 \leq 24/2 = 12$

$x_1 \leq 36/4 = 9$

Tightest obstacle!

This is because the current values of x_2 and x_3 are 0, and we need $x_4, x_5, x_6 \geq 0$

Simple: Step 2



$$\begin{array}{rcrcrcrcr} z & = & & & 3x_1 & + & x_2 & + & 2x_3 \\ x_4 & = & 30 & - & x_1 & - & x_2 & - & 3x_3 \\ x_5 & = & 24 & - & 2x_1 & - & 2x_2 & - & 5x_3 \\ x_6 & = & 36 & - & 4x_1 & - & x_2 & - & 2x_3 \\ \multicolumn{5}{l}{x_1, x_2, x_3, x_4, x_5, x_6} & \geq & 0 & & \end{array}$$

Tightest obstacle

- Solve the tightest obstacle for the nonbasic variable

$$x_1 = 9 - \frac{x_2}{4} - \frac{x_3}{2} - \frac{x_6}{4}$$

- Substitute the entering variable (called pivot) in other equations
- Now x_1 becomes basic and x_6 becomes non-basic
- x_6 is called the *leaving variable*

Simplex: Step 2

$$
\begin{array}{rcrcrcrcr}
z & = & & & 3x_1 & + & x_2 & + & 2x_3 \\
x_4 & = & 30 & - & x_1 & - & x_2 & - & 3x_3 \\
x_5 & = & 24 & - & 2x_1 & - & 2x_2 & - & 5x_3 \\
x_6 & = & 36 & - & 4x_1 & - & x_2 & - & 2x_3 \\
\multicolumn{3}{l}{x_1, x_2, x_3, x_4, x_5, x_6} & \geq & 0 & & & &
\end{array}
$$

$$
\begin{array}{rcrcrcrcr}
z & = & 27 & + & \frac{x_2}{4} & + & \frac{x_3}{2} & - & \frac{3x_6}{4} \\
x_1 & = & 9 & - & \frac{x_2}{4} & - & \frac{x_3}{2} & - & \frac{x_6}{4} \\
x_4 & = & 21 & - & \frac{3x_2}{4} & - & \frac{5x_3}{2} & + & \frac{x_6}{4} \\
x_5 & = & 6 & - & \frac{3x_2}{2} & - & 4x_3 & + & \frac{x_6}{2} \\
\multicolumn{5}{l}{x_1, x_2, x_3, x_4, x_5, x_6} & \geq & 0 & &
\end{array}
$$

- After one iteration of this step:
  - The basic feasible solution (i.e., substituting 0 for all nonbasic variables) improves from $z = 0$ to $z = 27$
- Repeat!

Simplex: Step 2

Entering variable
Try to increase!

$$
\begin{aligned}
z &= 27 + \frac{x_2}{4} + \frac{x_3}{2} - \frac{3x_6}{4} \\
x_1 &= 9 - \frac{x_2}{4} - \frac{x_3}{2} - \frac{x_6}{4} \\
x_4 &= 21 - \frac{3x_2}{4} - \frac{5x_3}{2} + \frac{x_6}{4} \\
x_5 &= 6 - \frac{3x_2}{2} - 4x_3 + \frac{x_6}{2} . \\
x_1, x_2, x_3, x_4, x_5, x_6 &\geq 0
\end{aligned}
$$

Leaving variable
Tightest obstacle!

Pivot!

$$
\begin{aligned}
z &= \frac{111}{4} + \frac{x_2}{16} - \frac{x_5}{8} - \frac{11x_6}{16} \\
x_1 &= \frac{33}{4} - \frac{x_2}{16} + \frac{x_5}{8} - \frac{5x_6}{16} \\
x_3 &= \frac{3}{2} - \frac{3x_2}{8} - \frac{x_5}{4} + \frac{x_6}{8} \\
x_4 &= \frac{69}{4} + \frac{3x_2}{16} + \frac{5x_5}{8} - \frac{x_6}{16} \\
x_1, x_2, x_3, x_4, x_5, x_6 &\geq 0
\end{aligned}
$$

Simplex: Step 2

Entering variable
Try to increase!

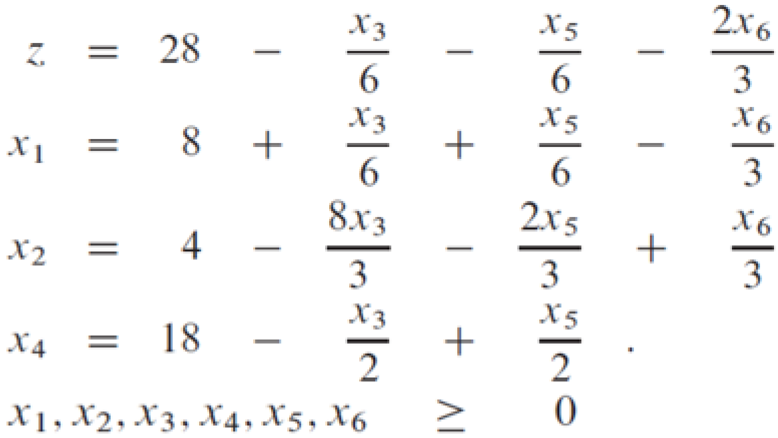
$$\begin{aligned} z &= \frac{111}{4} + \frac{x_2}{16} - \frac{x_5}{8} - \frac{11x_6}{16} \\ x_1 &= \frac{33}{4} - \frac{x_2}{16} + \frac{x_5}{8} - \frac{5x_6}{16} \\ x_3 &= \frac{3}{2} - \frac{3x_2}{8} - \frac{x_5}{4} + \frac{x_6}{8} \\ x_4 &= \frac{69}{4} + \frac{3x_2}{16} + \frac{5x_5}{8} - \frac{x_6}{16} . \\ x_1, x_2, x_3, x_4, x_5, x_6 &\geq 0 \end{aligned}$$

Leaving variable
Tightest obstacle!

Pivot!

$$\begin{aligned} z &= 28 - \frac{x_3}{6} - \frac{x_5}{6} - \frac{2x_6}{3} \\ x_1 &= 8 + \frac{x_3}{6} + \frac{x_5}{6} - \frac{x_6}{3} \\ x_2 &= 4 - \frac{8x_3}{3} - \frac{2x_5}{3} + \frac{x_6}{3} \\ x_4 &= 18 - \frac{x_3}{2} + \frac{x_5}{2} . \\ x_1, x_2, x_3, x_4, x_5, x_6 &\geq 0 \end{aligned}$$

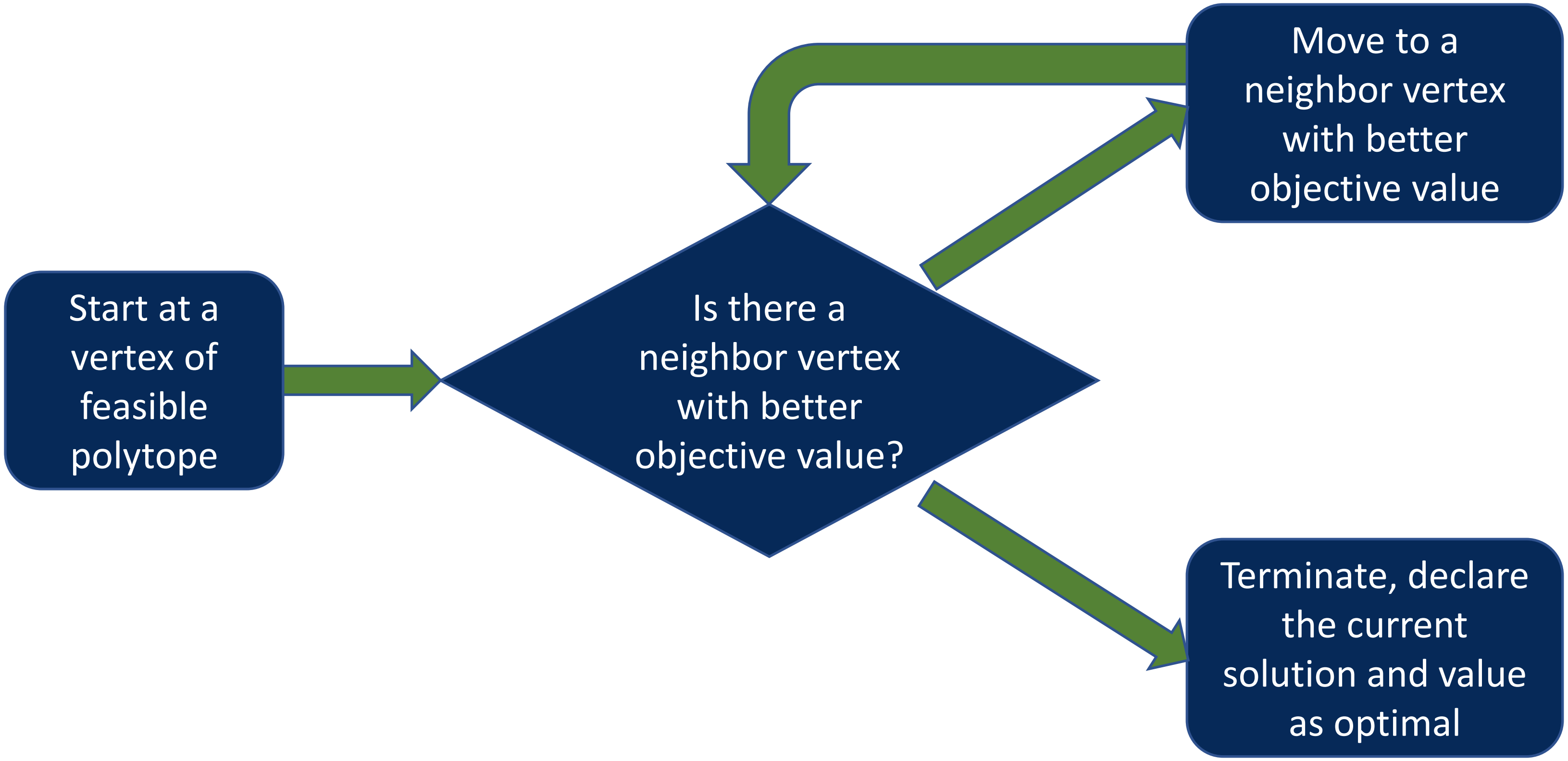
Simplex: Step 2



$$\begin{aligned} z &= 28 - \frac{x_3}{6} - \frac{x_5}{6} - \frac{2x_6}{3} \\ x_1 &= 8 + \frac{x_3}{6} + \frac{x_5}{6} - \frac{x_6}{3} \\ x_2 &= 4 - \frac{8x_3}{3} - \frac{2x_5}{3} + \frac{x_6}{3} \\ x_4 &= 18 - \frac{x_3}{2} + \frac{x_5}{2} . \\ x_1, x_2, x_3, x_4, x_5, x_6 &\geq 0 \end{aligned}$$

- There is no entering variable (nonbasic variable with positive coefficient)
- What now? Nothing! We are done.
- Take the basic feasible solution ($x_3 = x_5 = x_6 = 0$).
- Gives the optimal value $z = 28$
- In the optimal solution, $x_1 = 8$, $x_2 = 4$, $x_3 = 0$

Simplex Overview



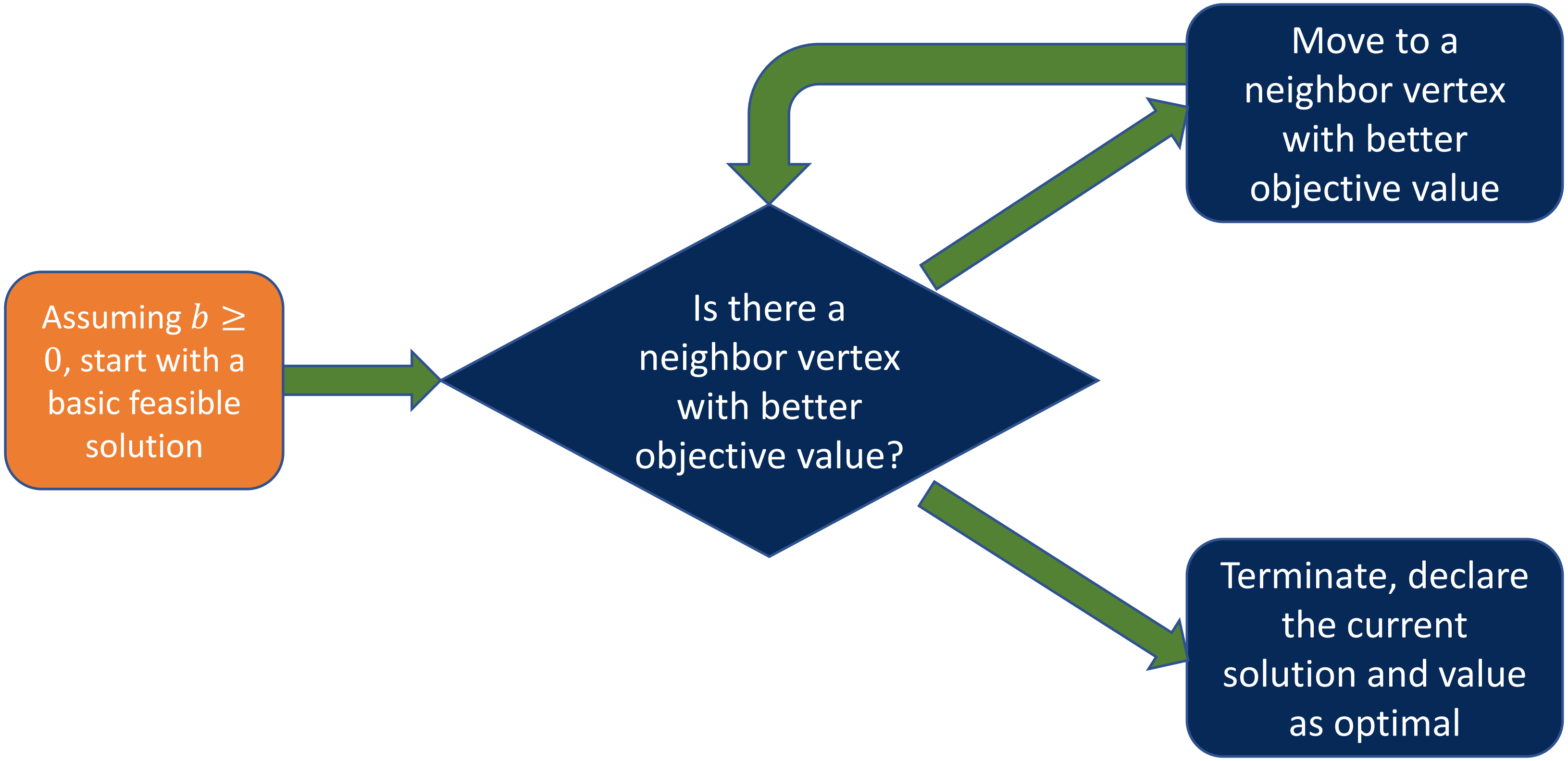
Start at a vertex of feasible polytope

Is there a neighbor vertex with better objective value?

Move to a neighbor vertex with better objective value

Terminate, declare the current solution and value as optimal

Simplex Overview



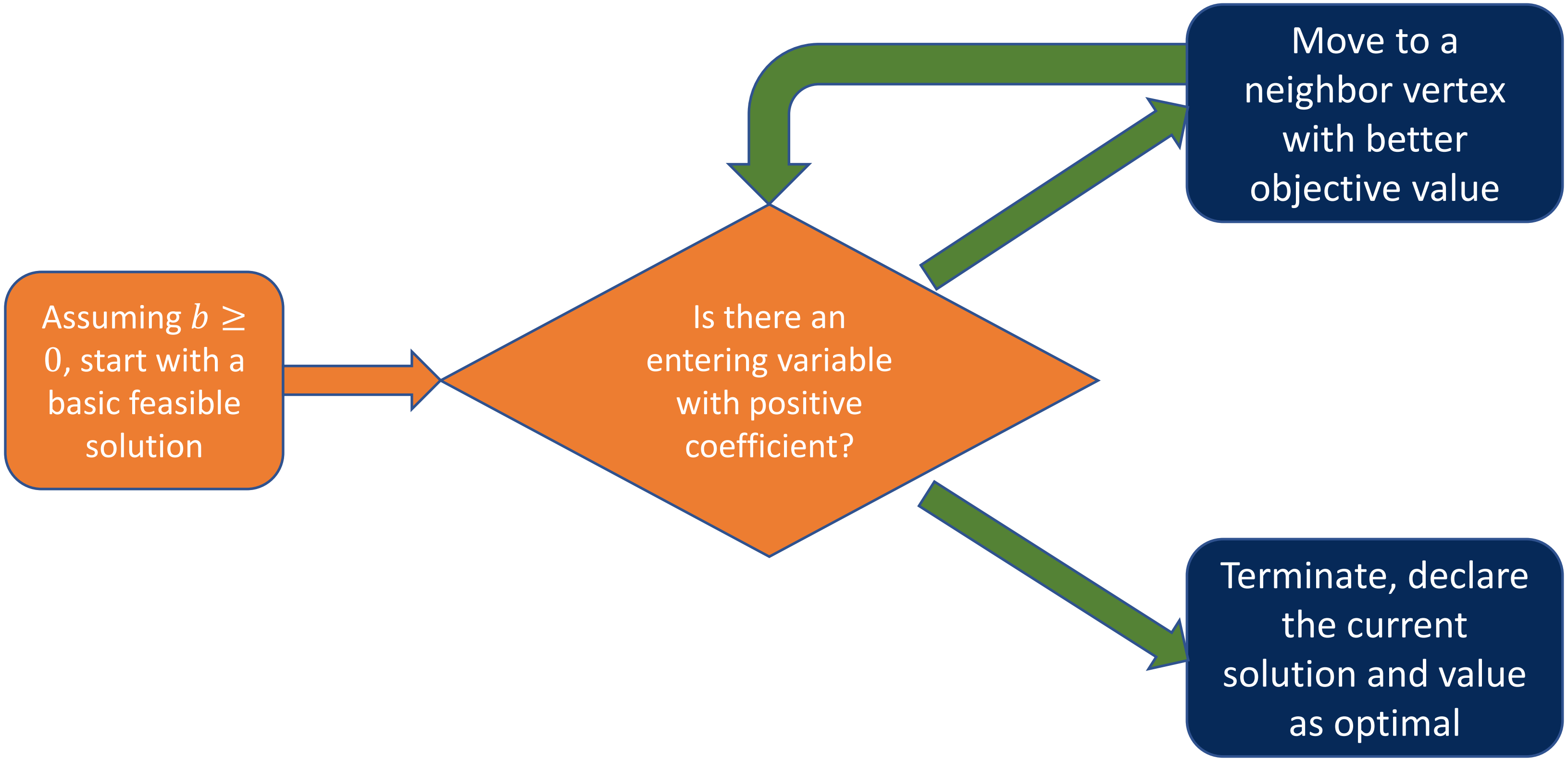
Assuming $b \geq 0$, start with a basic feasible solution

Is there a neighbor vertex with better objective value?

Move to a neighbor vertex with better objective value

Terminate, declare the current solution and value as optimal

Simplex Overview



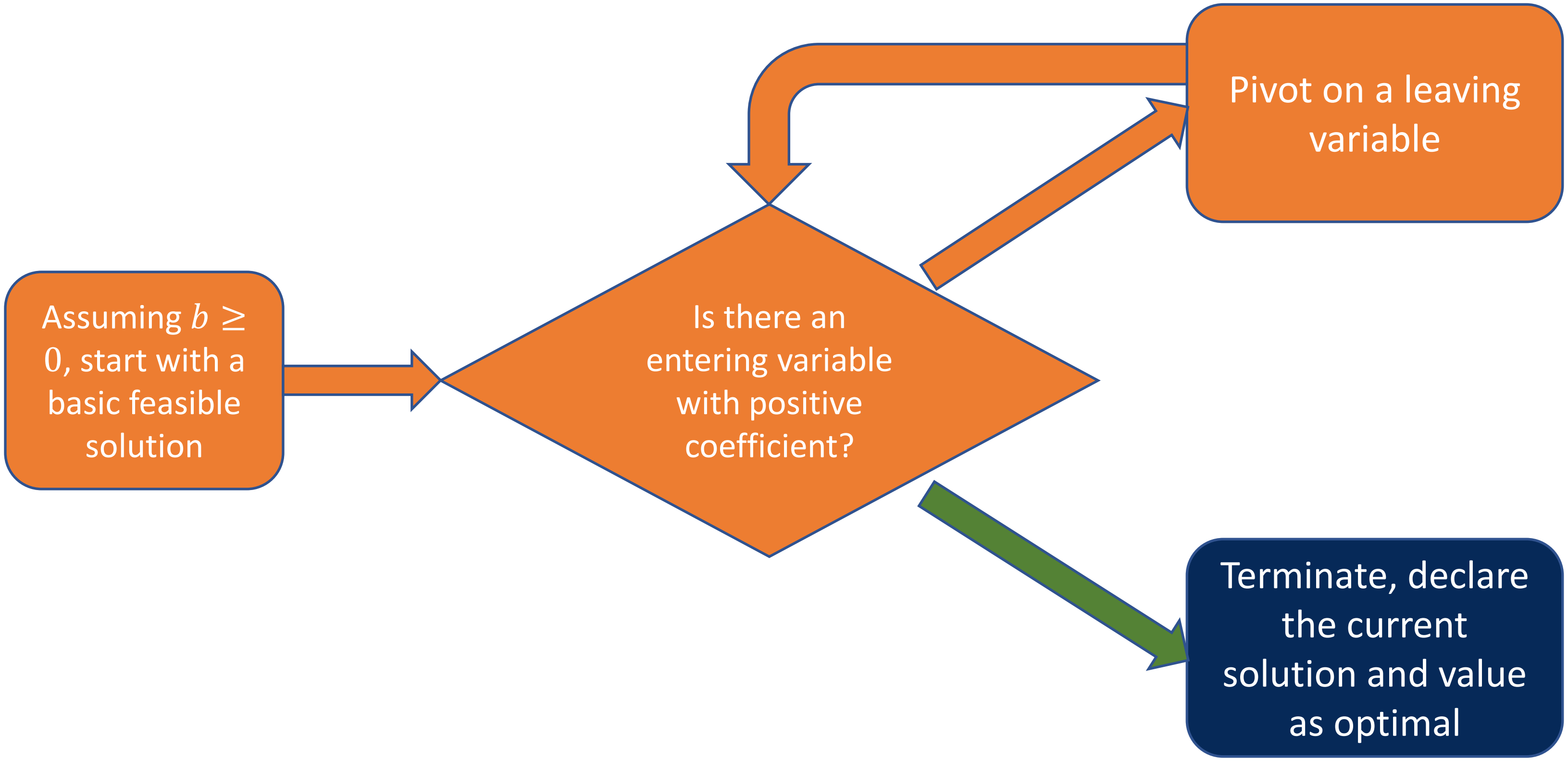
Assuming $b \geq 0$, start with a basic feasible solution

Is there an entering variable with positive coefficient?

Move to a neighbor vertex with better objective value

Terminate, declare the current solution and value as optimal

Simplex Overview



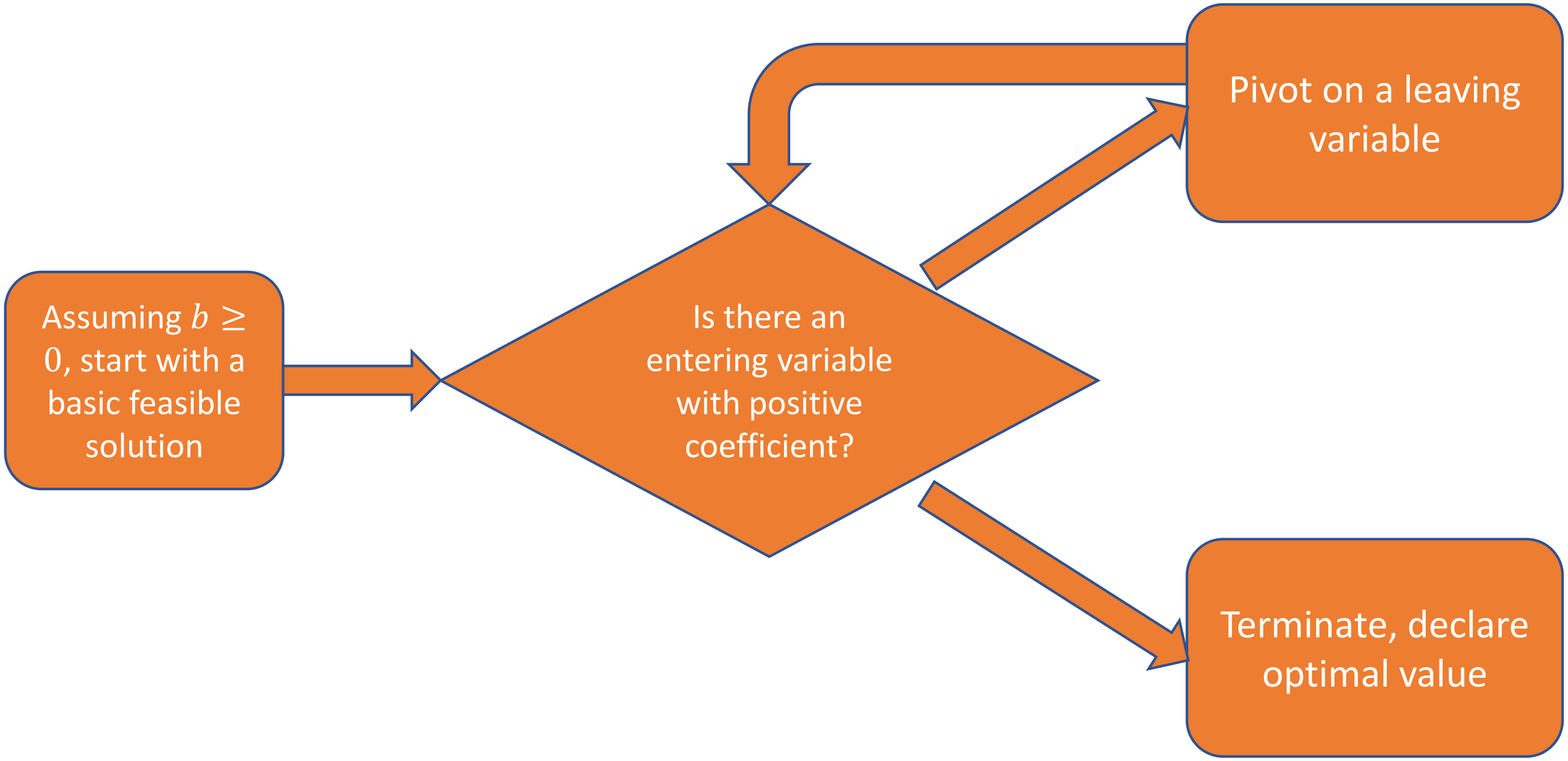
Assuming $b \geq 0$, start with a basic feasible solution

Is there an entering variable with positive coefficient?

Pivot on a leaving variable

Terminate, declare the current solution and value as optimal

Simplex Overview



Assuming $b \geq 0$, start with a basic feasible solution

Is there an entering variable with positive coefficient?

Pivot on a leaving variable

Terminate, declare optimal value

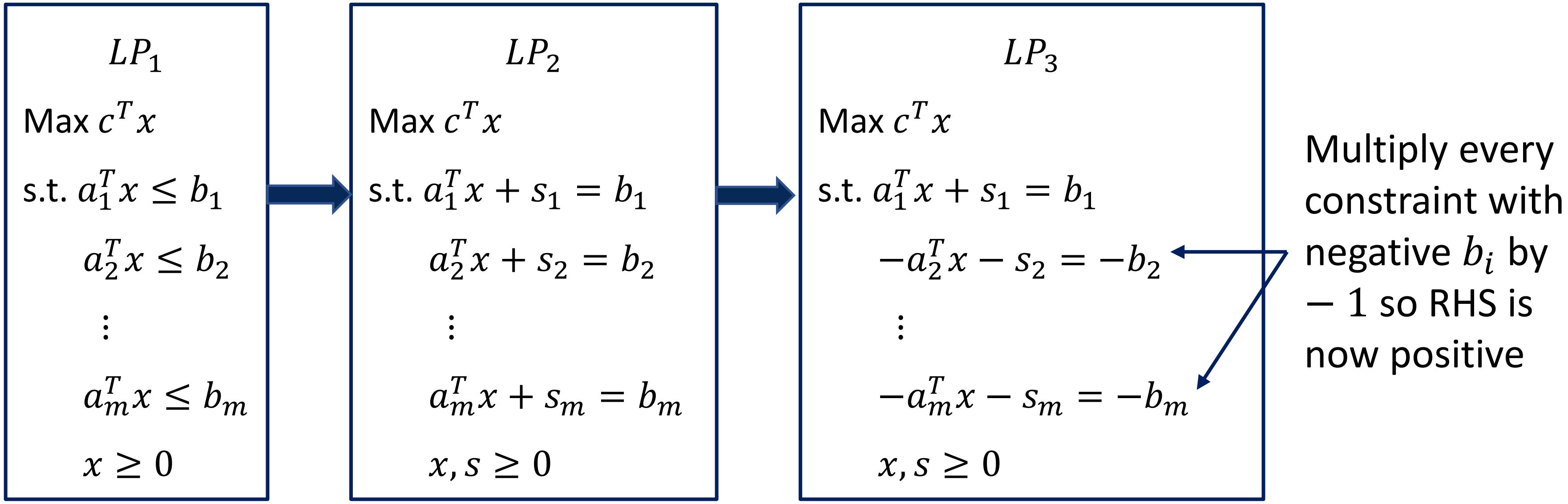
Some Outstanding Issues

- What if the entering variable has no upper bound?
  - If it doesn't appear in any constraints, or only appears in constraints where it can go to ∞
  - Then z can also go to ∞, so declare that LP is unbounded

- What if pivoting doesn't change the constant in z?
  - Known as *degeneracy*, and can lead to infinite loops
  - Can be prevented by "perturbing" b by a small random amount in each coordinate
  - Or by carefully breaking ties among entering and leaving variables, e.g., by smallest index (known as *Bland's rule*)

Some Outstanding Issues

- We assumed $b \geq 0$, and then started with the vertex $x = 0$
- What if this assumption does not hold?



$$
\begin{aligned}
&LP_1\\
&\text{Max } c^T x\\
&\text{s.t. } a_1^T x \leq b_1\\
&\quad a_2^T x \leq b_2\\
&\quad \vdots\\
&\quad a_m^T x \leq b_m\\
&\quad x \geq 0
\end{aligned}
$$

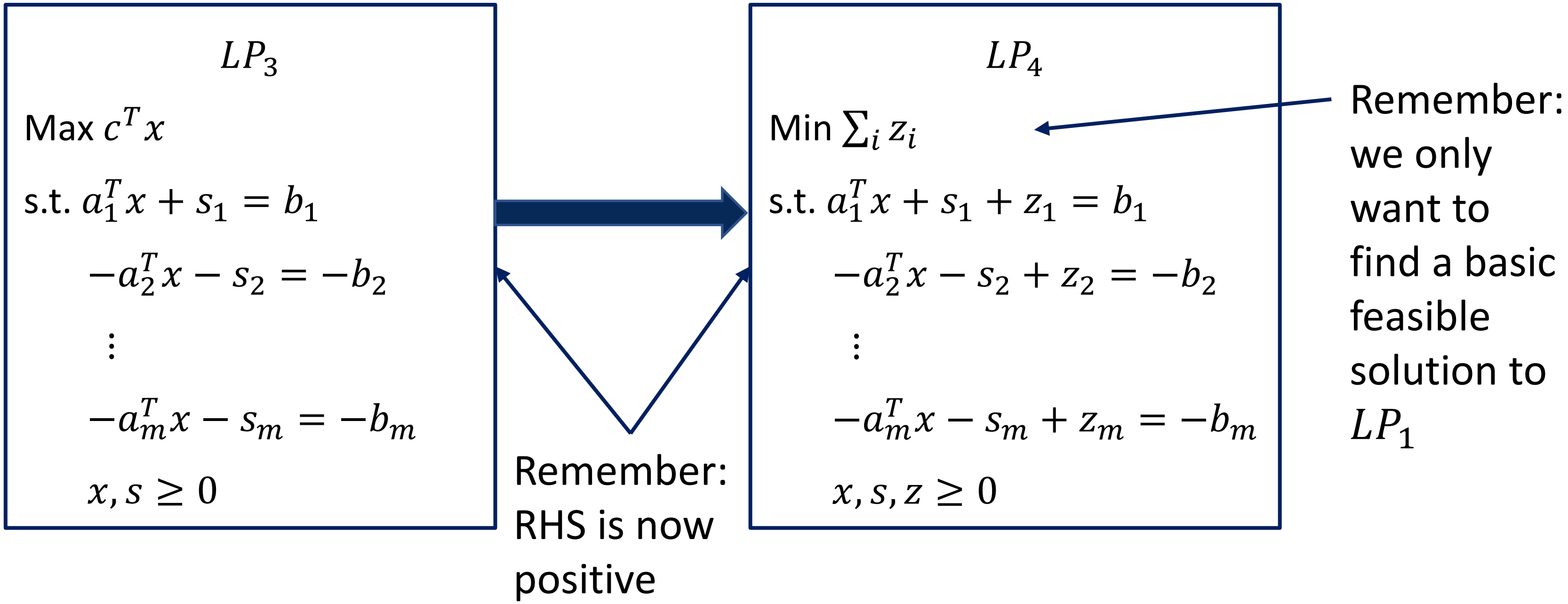
$$
\begin{aligned}
&LP_2\\
&\text{Max } c^T x\\
&\text{s.t. } a_1^T x + s_1 = b_1\\
&\quad a_2^T x + s_2 = b_2\\
&\quad \vdots\\
&\quad a_m^T x + s_m = b_m\\
&\quad x, s \geq 0
\end{aligned}
$$

$$
\begin{aligned}
&LP_3\\
&\text{Max } c^T x\\
&\text{s.t. } a_1^T x + s_1 = b_1\\
&\quad -a_2^T x - s_2 = -b_2\\
&\quad \vdots\\
&\quad -a_m^T x - s_m = -b_m\\
&\quad x, s \geq 0
\end{aligned}
$$

Multiply every constraint with negative b_i by -1 so RHS is now positive

Some Outstanding Issues

- We assumed $b \geq 0$, and then started with the vertex $x = 0$
- What if this assumption does not hold?



LP_3

Max $c^T x$

$$\begin{aligned} \text{s.t. } & a_1^T x + s_1 = b_1 \\ & -a_2^T x - s_2 = -b_2 \\ & \vdots \\ & -a_m^T x - s_m = -b_m \\ & x, s \geq 0 \end{aligned}$$

LP_4

Min $\sum_i z_i$

$$\begin{aligned} \text{s.t. } & a_1^T x + s_1 + z_1 = b_1 \\ & -a_2^T x - s_2 + z_2 = -b_2 \\ & \vdots \\ & -a_m^T x - s_m + z_m = -b_m \\ & x, s, z \geq 0 \end{aligned}$$

Remember: RHS is now positive

Remember: we only want to find a basic feasible solution to LP_1

Some Outstanding Issues

- We assumed $b \geq 0$, and then started with the vertex $x = 0$
- What if this assumption does not hold?

$$LP_4$$

Min $\sum_i z_i$

s.t. $a_1^T x + s_1 + z_1 = b_1$

$$-a_2^T x - s_2 + z_2 = -b_2$$

$$\vdots$$

$$-a_m^T x - s_m + z_m = -b_m$$

$$x, s, z \geq 0$$

Remember:
the RHS is now
positive

What now?

- Solve LP_4 using simplex with the initial basic solution being $x = s = 0, z = |b|$
- If its optimum value is 0, extract a basic feasible solution x^* from it, use it to solve LP_1 using simplex
- If optimum value for LP_4 is greater than 0, then LP_1 is infeasible

Some Outstanding Issues

- Curious about pseudocode? Proof of correctness? Running time analysis?

- See textbook for details, but this is NOT in syllabus!

Running Time

- Notes
  - #vertices of a polytope can be exponential in the #constraints
    - There are examples where simplex takes exponential time if you choose your pivots arbitrarily
    - No pivot rule known which guarantees polynomial running time
  - Other algorithms known which run in polynomial time
    - Ellipsoid method, interior point method, …
    - Ellipsoid uses $O(mn^3L)$ arithmetic operations
      - L = length of input in binary
    - But no known *strongly polynomial time* algorithm
      - Number of arithmetic operations = poly(m,n)
      - We know how to avoid dependence on length(b), but not for length(A)

Certificate of Optimality

- Suppose you design a state-of-the-art LP solver that can solve very large problem instances

- You want to convince someone that you have this new technology without showing them the code
    - Idea: They can give you very large LPs and you can quickly return the optimal solutions
    - Question: But how would they know that your solutions are optimal, if they don't have the technology to solve those LPs?

Certificate of Optimality

$$\begin{aligned} \max\ x_1 + 6x_2 & \\ x_1 &\leq 200 \\ x_2 &\leq 300 \\ x_1 + x_2 &\leq 400 \\ x_1, x_2 &\geq 0 \end{aligned}$$

- Suppose I tell you that $(x_1, x_2) = (100{,}300)$ is optimal with objective value 1900
- How can you check this?
  - Note: Can easily substitute (x_1, x_2), and verify that it is feasible, and its objective value is indeed 1900

Certificate of Optimality

$$\begin{aligned} \max\ x_1 + 6x_2 & \\ x_1 &\le 200 \\ x_2 &\le 300 \\ x_1 + x_2 &\le 400 \\ x_1, x_2 &\ge 0 \end{aligned}$$

- Claim: $(x_1, x_2) = (100{,}300)$ is optimal with objective value 1900

- Any solution that satisfies these inequalities also satisfies their positive combinations
  - E.g. 2*first_constraint + 5*second_constraint + 3*third_constraint
  - Try to take combinations which give you $x_1 + 6x_2$ on LHS

Certificate of Optimality

$$\begin{aligned} \max \;\; x_1 + 6x_2 & \\ x_1 &\le 200 \\ x_2 &\le 300 \\ x_1 + x_2 &\le 400 \\ x_1, x_2 &\ge 0 \end{aligned}$$

- Claim: $(x_1, x_2) = (100{,}300)$ is optimal with objective value 1900

- first_constraint + 6*second_constraint
  - $x_1 + 6x_2 \le 200 + 6 * 300 = 2000$
  - This shows that no feasible solution can beat 2000

Certificate of Optimality

$$\begin{aligned} \max \ x_1 + 6x_2 & \\ x_1 &\leq 200 \\ x_2 &\leq 300 \\ x_1 + x_2 &\leq 400 \\ x_1, x_2 &\geq 0 \end{aligned}$$

- Claim: $(x_1, x_2) = (100{,}300)$ is optimal with objective value 1900

- 5*second_constraint + third_constraint
  - $5x_2 + (x_1 + x_2) \leq 5 * 300 + 400 = 1900$
  - This shows that no feasible solution can beat 1900
    - No need to proceed further
    - We already know one solution that achieves 1900, so it must be optimal!

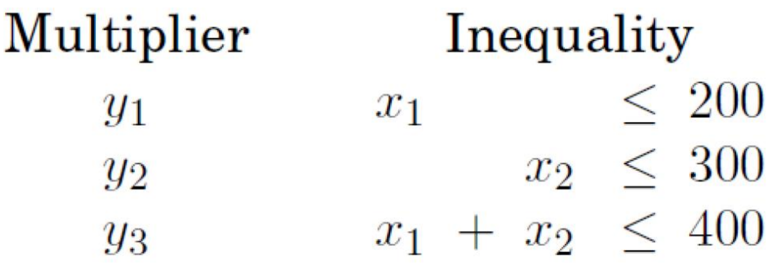
Is There a General Algorithm?

- Introduce variables y_1, y_2, y_3 by which we will be multiplying the three constraints
    - Note: These need not be integers. They can be reals.

Multiplier	Inequality
y_1	$x_1 \leq 200$
y_2	$x_2 \leq 300$
y_3	$x_1 + x_2 \leq 400$

- After multiplying and adding constraints, we get: $(y_1 + y_3)x_1 + (y_2 + y_3)x_2 \leq 200y_1 + 300y_2 + 400y_3$

Is There a General Algorithm?



Multiplier	Inequality
y_1	$x_1 \leq 200$
y_2	$x_2 \leq 300$
y_3	$x_1 + x_2 \leq 400$

- We have:

  $$(y_1 + y_3)x_1 + (y_2 + y_3)x_2 \leq 200y_1 + 300y_2 + 400y_3$$

- What do we want?
  - $y_1, y_2, y_3 \geq 0$ because otherwise direction of inequality flips
  - LHS to look like objective $x_1 + 6x_2$
    - In fact, it is sufficient for LHS to be an upper bound on objective
    - So, we want $y_1 + y_3 \geq 1$ and $y_2 + y_3 \geq 6$

Is There a General Algorithm?

Multiplier	Inequality
y_1	$x_1 \leq 200$
y_2	$x_2 \leq 300$
y_3	$x_1 + x_2 \leq 400$

- We have:

  $$(y_1 + y_3)x_1 + (y_2 + y_3)x_2 \leq 200y_1 + 300y_2 + 400y_3$$

- What do we want?
  - $y_1, y_2, y_3 \geq 0$
  - $y_1 + y_3 \geq 1,\ \ y_2 + y_3 \geq 6$
  - Subject to these, we want to minimize the upper bound $200y_1 + 300y_2 + 400y_3$

Is There a General Algorithm?

Multiplier	Inequality
y_1	$x_1 \leq 200$
y_2	$x_2 \leq 300$
y_3	$x_1 + x_2 \leq 400$

- We have:

  $$(y_1 + y_3)x_1 + (y_2 + y_3)x_2 \leq 200y_1 + 300y_2 + 400y_3$$

- What do we want?
  - This is just another LP!
  - Called the dual
  - Original LP is called the primal

$$\begin{aligned} \min\ 200y_1 + 300y_2 + 400y_3 \\ y_1 + y_3 \geq 1 \\ y_2 + y_3 \geq 6 \\ y_1, y_2, y_3 \geq 0 \end{aligned}$$

Is There a General Algorithm?

PRIMAL

$$\begin{aligned} \max\ x_1 + 6x_2 & \\ x_1 &\le 200 \\ x_2 &\le 300 \\ x_1 + x_2 &\le 400 \\ x_1, x_2 &\ge 0 \end{aligned}$$

DUAL

$$\begin{aligned} \min\ 200y_1 + 300y_2 + 400y_3 & \\ y_1 + y_3 &\ge 1 \\ y_2 + y_3 &\ge 6 \\ y_1, y_2, y_3 &\ge 0 \end{aligned}$$

- The problem of verifying optimality is another LP
  - For any (y_1, y_2, y_3) that you can find, the objective value of the dual is an upper bound on the objective value of the primal
  - If you found a specific (y_1, y_2, y_3) for which this dual objective becomes equal to the primal objective for the (x_1, x_2) given to you, then you would know that the given (x_1, x_2) is optimal for primal (and your (y_1, y_2, y_3) is optimal for dual)

Is There a General Algorithm?

PRIMAL

$$\begin{aligned} \max\ x_1 + 6x_2 & \\ x_1 &\leq 200 \\ x_2 &\leq 300 \\ x_1 + x_2 &\leq 400 \\ x_1, x_2 &\geq 0 \end{aligned}$$

DUAL

$$\begin{aligned} \min\ 200y_1 + 300y_2 + 400y_3 & \\ y_1 + y_3 &\geq 1 \\ y_2 + y_3 &\geq 6 \\ y_1, y_2, y_3 &\geq 0 \end{aligned}$$

- The problem of verifying optimality is another LP
  - Issue 1: But…but…if I can't solve large LPs, how will I solve the dual to verify if optimality of (x_1, x_2) given to me?
    - You don't. Ask the other party to give you both (x_1, x_2) and the corresponding (y_1, y_2, y_3) for proof of optimality
  - Issue 2: What if there are no (y_1, y_2, y_3) for which dual objective matches primal objective under optimal solution (x_1, x_2)?
    - As we will see, this can't happen!

Is There a General Algorithm?

Primal LP	**Dual LP**
$\max\ \mathbf{c}^T\mathbf{x}$	$\min\ \mathbf{y}^T\mathbf{b}$
$\mathbf{A}\mathbf{x} \leq \mathbf{b}$	$\mathbf{y}^T\mathbf{A} \geq \mathbf{c}^T$
$\mathbf{x} \geq 0$	$\mathbf{y} \geq 0$

- General version, in our standard form for LPs

Is There a General Algorithm?

Primal LP	**Dual LP**
$\max\ \mathbf{c}^T\mathbf{x}$	$\min\ \mathbf{y}^T\mathbf{b}$
$\mathbf{A}\mathbf{x} \leq \mathbf{b}$	$\mathbf{y}^T\mathbf{A} \geq \mathbf{c}^T$
$\mathbf{x} \geq 0$	$\mathbf{y} \geq 0$

- ○ $c^T x$ for any feasible $x \ \leq\ y^T b$ for any feasible y
- ○ $\max\limits_{\text{primal feasible } x} c^T x \ \leq \min\limits_{\text{dual feasible } y} y^T b$
- ○ If there is (x^*, y^*) with $c^T x^* = (y^*)^T b$, then both must be optimal
- ○ In fact, for optimal (x^*, y^*), we claim that this must happen!
  - Does this remind you of something? Max-flow, min-cut…

Weak Duality

Primal LP	**Dual LP**
$\max\ \mathbf{c}^T\mathbf{x}$	$\min\ \mathbf{y}^T\mathbf{b}$
$\mathbf{A}\mathbf{x} \leq \mathbf{b}$	$\mathbf{y}^T\mathbf{A} \geq \mathbf{c}^T$
$\mathbf{x} \geq 0$	$\mathbf{y} \geq 0$

- From here on, assume primal LP is feasible and bounded
- Weak duality theorem:
  - For any primal feasible x and dual feasible y, $c^T x \leq y^T b$
- Proof:

$$c^T x \leq (y^T A)x = y^T(Ax) \leq y^T b$$

Strong Duality

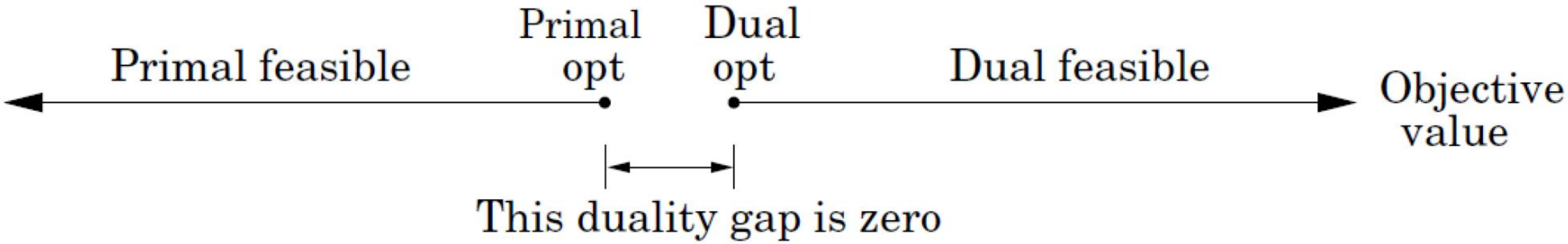
Primal LP

$$\max\ \mathbf{c}^T\mathbf{x}$$
$$\mathbf{A}\mathbf{x} \le \mathbf{b}$$
$$\mathbf{x} \ge 0$$

Dual LP

$$\min\ \mathbf{y}^T\mathbf{b}$$
$$\mathbf{y}^T\mathbf{A} \ge \mathbf{c}^T$$
$$\mathbf{y} \ge 0$$

- Strong duality theorem:
  - For any primal optimal x^* and dual optimal y^*, $c^T x^* = (y^*)^T b$



Strong Duality Proof

This slide is not in the scope of the course

- Farkas' lemma (one of many, many versions):
  - Exactly one of the following holds:

1) There exists x such that $Ax \leq b$
2) There exists y such that $y^T A = 0,\ y \geq 0,\ y^T b < 0$

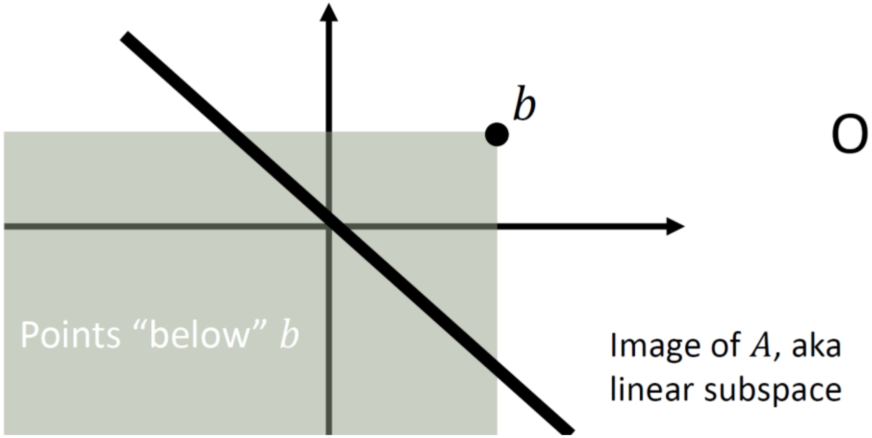
- Geometric intuition:
  - Define image of A = set of all possible values of Ax
  - It is known that this is a "linear subspace" (e.g., a line in a plane, a line or plane in 3D, etc)

Strong Duality Proof

This slide is not in the scope of the course

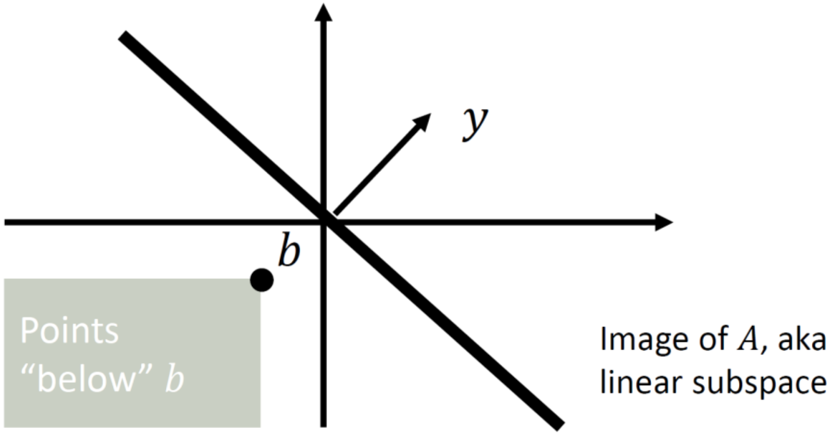
- Farkas' lemma: Exactly one of the following holds:
  1) There exists x such that $Ax \leq b$
  2) There exists y such that $y^T A = 0,\ y \geq 0,\ y^T b < 0$

1) Image of A contains a point "below" b



OR

2) The region "below" b doesn't intersect image of A this is witnessed by normal vector to the image of A



Strong Duality

This slide is not in the scope of the course

Primal LP	**Dual LP**
$\max\ \mathbf{c}^T\mathbf{x}$	$\min\ \mathbf{y}^T\mathbf{b}$
$\mathbf{Ax} \leq \mathbf{b}$	$\mathbf{y}^T\mathbf{A} \geq \mathbf{c}^T$
$\mathbf{x} \geq 0$	$\mathbf{y} \geq 0$

- Strong duality theorem:
  - ➢ For any primal optimal x^* and dual optimal y^*, $c^T x^* = (y^*)^T b$
  - ➢ Proof (by contradiction):
    - ○ Let $z^* = c^T x^*$ be the optimal primal value.
    - ○ Suppose optimal dual objective value $> z^*$
    - ○ So, there is no y such that $y^T A \geq c^T$ and $y^T b \leq z^*$, i.e.,

$$\begin{pmatrix} -A^T \\ b^T \end{pmatrix} y \leq \begin{pmatrix} c \\ z^* \end{pmatrix}$$

Strong Duality

This slide is not in the scope of the course

- There is no y such that $\begin{pmatrix} -A^T \\ b^T \end{pmatrix} y \le \begin{pmatrix} c \\ z^* \end{pmatrix}$
- By Farkas' lemma, there is x and λ such that

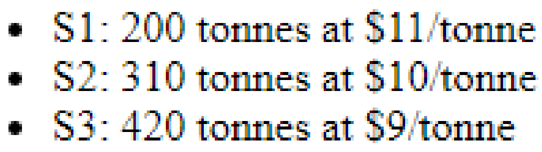
$$\begin{pmatrix} x^T & \lambda \end{pmatrix} \begin{pmatrix} -A^T \\ b^T \end{pmatrix} = 0, x \ge 0, \lambda \ge 0, -x^T c + \lambda z^* < 0$$

- Case 1: $\lambda > 0$
  - Note: $c^T x > \lambda z^*$ and $Ax = 0 = \lambda b$.
  - Divide both by λ to get $A \left(\frac{x}{\lambda}\right) = b$ and $c^T \left(\frac{x}{\lambda}\right) > z^*$
    - Contradicts optimality of z^*

- Case 2: $\lambda = 0$
  - We have $Ax = 0$ and $c^T x > 0$
  - Adding x to optimal x^* of primal improves objective value beyond $z^* \Rightarrow$ contradiction

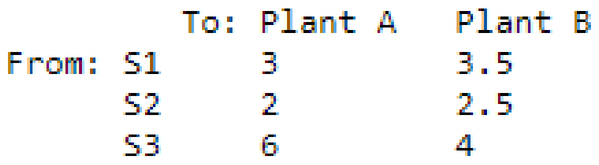
Exercise: Formulating LPs

- A canning company operates two canning plants (A and B).
- Three suppliers of fresh fruits:



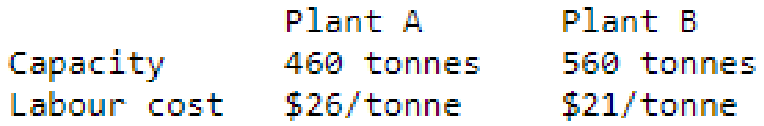
- S1: 200 tonnes at $11/tonne
- S2: 310 tonnes at $10/tonne
- S3: 420 tonnes at $9/tonne

- Shipping costs in $/tonne:



To:	Plant A	Plant B
From: S1	3	3.5
S2	2	2.5
S3	6	4

- Plant capacities and labour costs:



	Plant A	Plant B
Capacity	460 tonnes	560 tonnes
Labour cost	$26/tonne	$21/tonne

- Selling price: $50/tonne, no limit
- Objective: Find which plant should get how much supply from each grower to maximize profit

Exercise: Formulating LPs

- Similarly to the brewery example from earlier:
  - A brewery can invest its inventory of corn, hops and malt into producing three types of beer
  - Per unit resource requirement and profit are as given below
  - The brewery cannot produce positive amounts of *both* A and B
  - Goal: maximize profit

Beverage	Corn (kg)	Hops (kg)	Malt (kg)	Profit ($)
A	5	4	35	13
B	15	4	20	23
C	10	7	25	15
Limit	500	300	1000	

Exercise: Formulating LPs

- Similarly to the brewery example from the beginning:
  - A brewery can invest its inventory of corn, hops and malt into producing three types of beer
  - Per unit resource requirement and profit are as given below
  - The brewery can only produce C in integral quantities up to 100
  - Goal: maximize profit

Beverage	Corn (kg)	Hops (kg)	Malt (kg)	Profit ($)
A	5	4	35	13
B	15	4	20	23
C	10	7	25	15
Limit	500	300	1000	

Exercise: Formulating LPs

- Similarly to the brewery example from the beginning:
  - A brewery can invest its inventory of corn, hops and malt into producing three types of beer
  - Per unit resource requirement and profit are as given below
  - Goal: maximize profit, but if there are multiple profit-maximizing solutions, then…
    - Break ties to choose those with the largest quantity of A
    - Break any further ties to choose those with the largest quantity of B

Beverage	Corn (kg)	Hops (kg)	Malt (kg)	Profit ($)
A	5	4	35	13
B	15	4	20	23
C	10	7	25	15
Limit	500	300	1000	

More Tricks

- Constraint: $|x| \leq 3$
  - Replace with constraints $x \leq 3$ and $-x \leq 3$
  - What if the constraint is $|x| \geq 3$?
- Objective: minimize $3|x| + y$
  - Add a variable t
  - Add the constraints $t \geq x$ and $t \geq -x$ (so $t \geq |x|$)
  - Change the objective to minimize $3t + y$
  - What if the objective is to *maximize* $3|x| + y$?
- Objective: minimize $\max(3x + y, x + 2y)$
  - Hint: minimizing $3|x| + y$ in the earlier bullet was equivalent to minimizing $\max(3x + y, -3x + y)$
- …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