3. Linear programs

- Review: linear algebra
- Geometrical intuition
- Standard form for LPs
- Example: transformation to standard form

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Matrix basics

A matrix is an array of numbers. $A \in \mathbb{R}^{m \times n}$ means that:

$$A = \begin{bmatrix} a_{11} & \dots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{m1} & \dots & a_{mn} \end{bmatrix} \qquad (m \text{ rows and } n \text{ columns})$$

Two matrices can be multiplied if inner dimensions agree:

$$\underset{(m \times p)}{C} = \underset{(m \times n)}{A} \underset{(n \times p)}{B} \quad \text{where} \quad c_{ij} = \sum_{k=1}^{n} a_{ik} b_{kj}$$

Example:

$$\begin{bmatrix} 1 & 2 \\ 3 & 4 \\ 5 & 6 \end{bmatrix} \begin{bmatrix} 4 & 3 \\ 8 & 9 \end{bmatrix} = \begin{bmatrix} 1 \cdot 4 + 2 \cdot 8 & 1 \cdot 3 + 2 \cdot 9 \\ 3 \cdot 4 + 4 \cdot 8 & 3 \cdot 3 + 4 \cdot 9 \\ 5 \cdot 4 + 6 \cdot 8 & 5 \cdot 3 + 6 \cdot 9 \end{bmatrix} = \begin{bmatrix} 20 & 21 \\ 44 & 45 \\ 68 & 69 \end{bmatrix}$$

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Matrix basics

Transpose: The transpose operator A^T swaps rows and columns. If $A \in \mathbb{R}^{m\times n}$ then $A^\mathsf{T} \in \mathbb{R}^{n\times m}$ and $(A^\mathsf{T})_{ij} = A_{ji}$.

- $(A^\mathsf{T})^\mathsf{T} = A$
- $(AB)^\mathsf{T} = B^\mathsf{T} A^\mathsf{T}$

A vector is a column matrix. We write $x \in \mathbb{R}^n$ to mean that:

$$x = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} \qquad \text{(a vector } x \in \mathbb{R}^n \text{ is an } n \times 1 \text{ matrix)}$$

The transpose of a column vector is a row vector:

$$x^\mathsf{T} = \begin{bmatrix} x_1 & \cdots & x_n \end{bmatrix} \qquad \text{(i.e. a } 1 \times n \text{ matrix)}$$

Matrix basics

Two vectors $x, y \in \mathbb{R}^n$ can be multiplied together in two ways. Both are valid matrix multiplications:

- **inner product**: produces a scalar.

$$x^\mathsf{T} y = \begin{bmatrix} x_1 & \cdots & x_n \end{bmatrix} \begin{bmatrix} y_1 \\ \vdots \\ y_n \end{bmatrix} = x_1 y_1 + \cdots + x_n y_n$$

  Also called "dot product". Often written $x \cdot y$ or $\langle x, y \rangle$.

- **outer product**: produces an $n \times n$ matrix.

$$x y^\mathsf{T} = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} \begin{bmatrix} y_1 & \cdots & y_n \end{bmatrix} = \begin{bmatrix} x_1 y_1 & \dots & x_1 y_n \\ \vdots & \ddots & \vdots \\ x_n y_1 & \dots & x_n y_n \end{bmatrix}$$

Matrix basics

- Matrices and vectors can be stacked and combined to form bigger matrices as long as the dimensions agree. e.g. If $x_1, \dots, x_m \in \mathbb{R}^n$, then $X = \begin{bmatrix} x_1 & x_2 & \dots & x_m \end{bmatrix} \in \mathbb{R}^{m \times n}$.

- Matrices can also be concatenated in blocks. For example:

$$Y = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \qquad \begin{array}{l} \text{if } A,\ C \text{ have same number of columns,} \\ A,\ B \text{ have same number of rows, etc.} \end{array}$$

- Matrix multiplication also works with block matrices!

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} AP + BQ \\ CP + DQ \end{bmatrix}$$

as long as A has as many columns as P has rows, etc.

Linear and affine functions

- A function $f(x_1, \dots, x_m)$ is **linear** in the variables $x_1, \dots, x_m$ if there exist constants $a_1, \dots, a_m$ such that

$$f(x_1, \dots, x_m) = a_1 x_1 + \cdots + a_m x_m = a^\mathsf{T} x$$

- A function $f(x_1, \dots, x_m)$ is **affine** in the variables $x_1, \dots, x_m$ if there exist constants $b, a_1, \dots, a_m$ such that

$$f(x_1, \dots, x_m) = a_0 + a_1 x_1 + \cdots + a_m x_m = a^\mathsf{T} x + b$$

Examples:

Some texts use "linear" to mean either one!

1. $3x - y$ is linear in (x, y).
2. $2xy + 1$ is affine in x and y but not in (x, y).
3. $x^2 + y^2$ is not linear or affine.

Linear and affine functions

Several linear or affine functions can be combined:

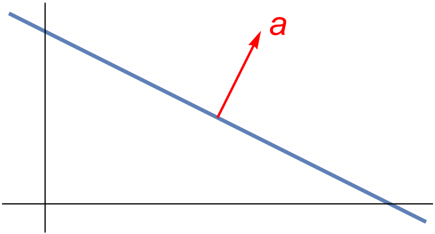
$$
\begin{matrix}
a_{11}x_1 + \cdots + a_{1n}x_n + b_1 \\
a_{21}x_1 + \cdots + a_{2n}x_n + b_2 \\
\vdots \qquad \vdots \qquad \vdots \\
a_{m1}x_1 + \cdots + a_{mn}x_n + b_m
\end{matrix}
\implies
\begin{bmatrix} a_{11} & \dots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{m1} & \dots & a_{mn} \end{bmatrix}
\begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix}
+
\begin{bmatrix} b_1 \\ \vdots \\ b_m \end{bmatrix}
$$

which can be written simply as $Ax + b$. Same definitions apply:

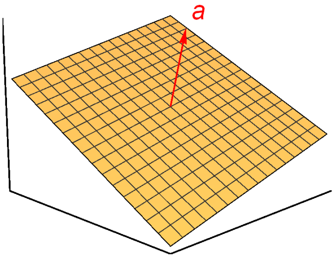
- A vector-valued function $F(x)$ is **linear** in x if there exists a constant matrix A such that $F(x) = Ax$.
- A vector-valued function $F(x)$ is **affine** in x if there exists a constant matrix A and vector b such that $F(x) = Ax + b$.

Geometry of affine equations

- The set of points $x \in \mathbb{R}^n$ that satisfies a linear equation $a_1 x_1 + \cdots + a_n x_n = 0$ (or $a^\mathsf{T} x = 0$) is called a **hyperplane**. The vector a is *normal* to the hyperplane.
- If the right-hand side is nonzero: $a^\mathsf{T} x = b$, the solution set is called an **affine hyperplane**, (it's a shifted hyperplane).



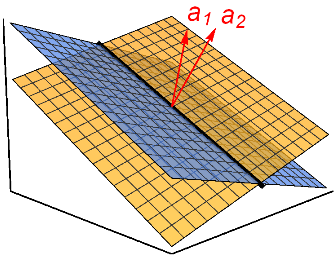
Affine hyperplane in 2D



Affine hyperplane in 3D

Geometry of affine equations

- The set of points $x \in \mathbb{R}^n$ satisfying many linear equations $a_{i1}x_1 + \cdots + a_{im}x_n = 0$ for $i = 1, \ldots, m$ (or $Ax = 0$) is called a **subspace** (the intersection of many hyperplanes).
- If the right-hand side is nonzero: $Ax = b$, the solution set is called an **affine subspace**, (it's a shifted subspace).



Intersections of affine hyperplanes are affine subspaces.

Geometry of affine equations

The **dimension** of a subspace is the number of independent directions it contains. A line has dimension 1, a plane has dimension 2, and so on.

Hyperplanes are subspaces!

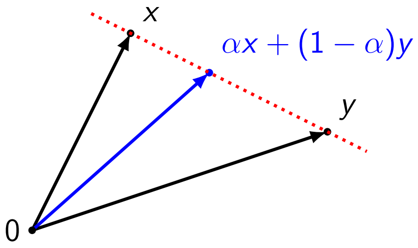
- A hyperplane in $\mathbb{R}^n$ is a subspace of dimension $n-1$.
- The intersection of k hyperplanes has dimension at least $n-k$ ("at least" because of potential redundancy).

Affine combinations

If $x, y \in \mathbb{R}^n$, then the combination

$$w = \alpha x + (1-\alpha) y \quad \text{for some } \alpha \in \mathbb{R}$$

is called an **affine combination**.



If $Ax = b$ and $Ay = b$, then $Aw = b$. So affine combinations of points in an (affine) subspace also belong to the subspace.

Affine combinations

If $x, y \in \mathbb{R}^n$, then the combination

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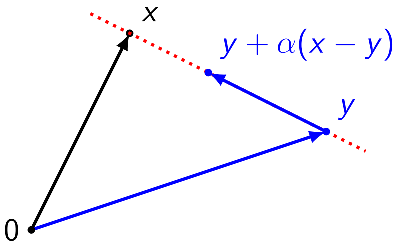


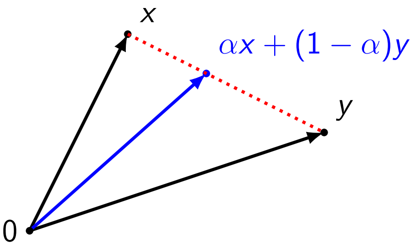
If $Ax = b$ and $Ay = b$, then $Aw = b$. So affine combinations of points in an (affine) subspace also belong to the subspace.

Convex combinations

If $x, y \in \mathbb{R}^n$, then the combination

$$w = \alpha x + (1-\alpha)y \quad \text{for some } 0 \le \alpha \le 1$$

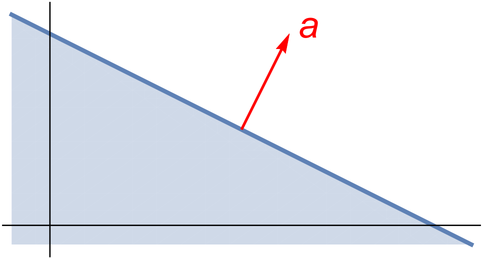
is called a **convex combination** (for reasons we will learn later). It's the line segment that connects x and y.



Geometry of affine inequalities

- The set of points $x \in \mathbb{R}^n$ that satisfies a linear inequality $a_1 x_1 + \cdots + a_n x_n \leq b$ (or $a^\mathsf{T} x \leq b$) is called a **halfspace**. The vector a is *normal* to the halfspace and b shifts it.

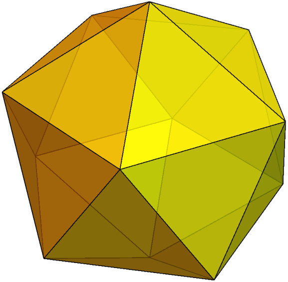
- Define $w = \alpha x + (1 - \alpha) y$ where $0 \leq \alpha \leq 1$. If $a^\mathsf{T} x \leq b$ and $a^\mathsf{T} y \leq b$, then $a^\mathsf{T} w \leq b$.



Halfspace

Geometry of affine inequalities

- The set of points $x \in \mathbb{R}^n$ satisfying many linear inequalities $a_{i1}x_1 + \cdots + a_{in}x_n \leq b_i$ for $i = 1, \ldots, m$ (or $Ax \leq b$) is called a **polyhedron** (the intersection of many halfspaces). Some sources use the term **polytope** instead.
- As before: let $w = \alpha x + (1 - \alpha)y$ where $0 \leq \alpha \leq 1$. If $Ax \leq b$ and $Ay \leq b$, then $Aw \leq b$.



Intersections of halfspaces are polyhedra.

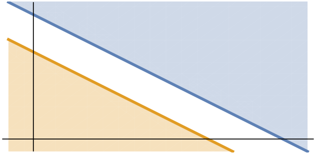
Solutions of an LP

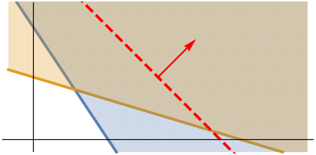
There are exactly three possible cases:

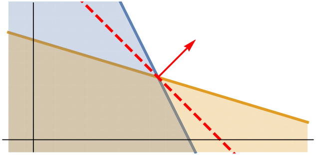
1. Model is **infeasible**: there is no x that satisfies all the constraints. (is the model correct?)

2. Model is feasible, but **unbounded**: the cost function can be arbitrarily improved. (forgot a constraint?)

3. Model has a solution which occurs **on the boundary** of the set. (there may be many solutions!)


infeasible


unbounded


boundary

The linear program

A linear program is an optimization model with:

- real-valued variables ($x \in \mathbb{R}^n$)
- affine objective function ($c^\mathsf{T}x + d$), can be min or max.
- constraints may be:
  - affine equations ($Ax = b$)
  - affine inequalities ($Ax \leq b$ or $Ax \geq b$)
  - combinations of the above
- individual variables may have:
  - box constraints ($p \leq x_i$, or $x_i \leq q$, or $p \leq x_i \leq q$)
  - no constraints (x_i is unconstrained)

There are many equivalent ways to express the same LP

Standard form

- Every LP can be put in the form:

$$\begin{aligned} \underset{x \in \mathbb{R}^n}{\text{maximize}} \quad & c^\mathsf{T} x \\ \text{subject to:} \quad & Ax \le b \\ & x \ge 0 \end{aligned}$$

- This is called the **standard form** of a LP.

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$$\begin{aligned} \max_{f,s} \quad & 12f + 9s \\ \text{s.t.} \quad & 4f + 2s \le 4800 \\ & f + s \le 1750 \\ & 0 \le f \le 1000 \\ & 0 \le s \le 1500 \end{aligned}$$

$\Longrightarrow$

$$\begin{aligned} \max_{f,s} \quad & \begin{bmatrix} 12 \\ 9 \end{bmatrix}^{\mathsf{T}} \begin{bmatrix} f \\ s \end{bmatrix} \\ \text{s.t.} \quad & \begin{bmatrix} 4 & 2 \\ 1 & 1 \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} f \\ s \end{bmatrix} \le \begin{bmatrix} 4800 \\ 1750 \\ 1000 \\ 1500 \end{bmatrix} \\ & \begin{bmatrix} f \\ s \end{bmatrix} \ge 0 \end{aligned}$$

This is in standard form, with:

$$A = \begin{bmatrix} 4 & 2 \\ 1 & 1 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad b = \begin{bmatrix} 4800 \\ 1750 \\ 1000 \\ 1500 \end{bmatrix}, \quad c = \begin{bmatrix} 12 \\ 9 \end{bmatrix}, \quad x = \begin{bmatrix} f \\ s \end{bmatrix}$$

Transformation tricks

1. converting min to max or vice versa (take the negative):

$$\min_x f(x) = -\max_x (-f(x))$$

2. reversing inequalities (flip the sign):

$$Ax \leq b \quad \iff \quad (-A)x \geq (-b)$$

3. equalities to inequalities (double up):

$$f(x) = 0 \quad \iff \quad f(x) \geq 0 \quad \text{and} \quad f(x) \leq 0$$

4. inequalities to equalities (add slack):

$$f(x) \leq 0 \quad \iff \quad f(x) + s = 0 \quad \text{and} \quad s \geq 0$$

Transformation tricks

5. unbounded to bounded (add difference):

$$x \in \mathbb{R} \quad \iff \quad u \geq 0, \quad v \geq 0, \quad \text{and} \quad x = u - v$$

6. bounded to unbounded (convert to inequality):

$$p \leq x \leq q \quad \iff \quad \begin{bmatrix} 1 \\ -1 \end{bmatrix} x \leq \begin{bmatrix} q \\ -p \end{bmatrix}$$

7. bounded to nonnegative (shift the variable)

$$p \leq x \leq q \quad \iff \quad 0 \leq (x - p) \quad \text{and} \quad (x - p) \leq (q - p)$$

More complicated example

Convert the following LP to standard form:

$$\begin{aligned} \underset{p,q}{\text{minimize}} \quad & p + q \\ \text{subject to:} \quad & 5p - 3q = 7 \\ & 2p + q \geq 2 \\ & 1 \leq q \leq 4 \end{aligned}$$

notebook: Standard Form.ipynb

More complicated example

Equivalent LP (standard form):

$$
\begin{aligned}
\underset{u,v,w}{\text{maximize}} \quad & -u + v - w \\
\text{subject to:} \quad & -5u + 5v + 3w \le -10 \\
& 5u - 5v - 3w \le 10 \\
& -2u + 2v - w \le -1 \\
& w \le 3 \\
& u, v, w \ge 0
\end{aligned}
$$

where: $p := u - v, \quad q := w + 1$

and: (original cost) $= -$(new cost) $+ 1$

Exercise

Write the following LP in standard form:

$$\begin{aligned} \underset{p,q}{\text{maximize}} \quad & 3p - 4q \\ \text{subject to} \quad & p \ge 0 \\ & p + q \ge 4 \\ & p \le q \end{aligned}$$