

# Introduction to Evolutionary Computation

Inteligencia Artificial en los Sistemas de Control Autónomo  
Máster en Ciencia y Tecnología desde el Espacio

Departamento de Automática

## Objectives

- Introduce artificial evolution
- Justify the utility of artificial evolution from an engineering perspective
- Overview the components of an Evolutionary Algorithm

## Bibliography

- Russell, S., Norvig, P. Artificial Intelligence: A modern approach, chapter 4. 3rd edition. Ed. Prentice-Hall. 2009
- Luke, S. Essentials of Metaheuristics. 2nd edition. Ed. Lulu, 2010. ([Link](#))

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## Biological background

## Historical review (I)

## Anaximander of Miletus (610 – 546 BC)

- First animals come from water
  - Man come from fishes

Plato (428/427 – 348/347 BC)

- Demiurgo created the cosmos
  - Theory of Ideas

## Aristotle (384 – 322 BC)

- Spontaneous generation
  - Strong influence in Europe



## Biological background

## Historical review (II)



## Creationism: God created all the species

- Literal interpretation of the Genesis
  - Species are hierarchical
  - Man has a superior position

## Main school in Europe for centuries

## Biological background

## Historical review (III)

## Georges Louis Leclerc (1707 - 1788)

- Speculated that species change
  - Noticed the similarities between men and apes
  - Could not provide a theory

Jean-Baptiste Lamarck (1744 - 1829)

- First to propose a theory of evolution
  - Transmutation of Species
  - Use strengthens/weakens organs
  - Heritability of acquired characteristics

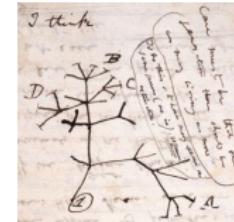


# Biological background

## Historical review (IV)

Charles Darwin (1809-1882)

- Published in “On the Origin of the Species” in 1859  
("On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life")
- Introduced natural selection ... and applies it to human being
  - Natural selection = Variability + selection
- Darwin did not explain the source of variation



# Biological background

## Historical review (V)

Gregor Mendel (1822 - 1884)

- Mendelian inheritance
- Recessive and dominant traits



August Weismann (1834 - 1914)

- Germ plasm theory
- Germ and somatic cells
- End of Lamarckism



J. Watson (1928) and F. Crick (1916 - 2004)

- Discovery of DNA
- Central Dogma of molecular biology



James Watson

Francis Crick

# Biological background

## Theory of Evolution

Neo-Darwinism: Darwin + Mendel + Weismann

- ... also called Theory of Evolution
- Variability + selection = evolution

There is variation among individuals

- Sexual reproduction, mutation and gene flow

There is a selection of those individuals

- Natural selection
- Artificial selection
- Sexual selection
- Genetic drift (deriva genética) (Link)

The fittest is the one that survives (not the strongest!)

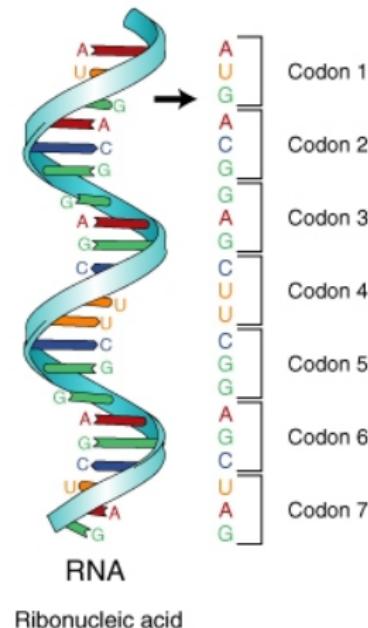
# Biological background

## Molecular Genetics (I)

Organisms are made by **proteins**

- Proteins are sequences of **aminoacids**
- They folder in a 3D structure
- 20 aminoacids

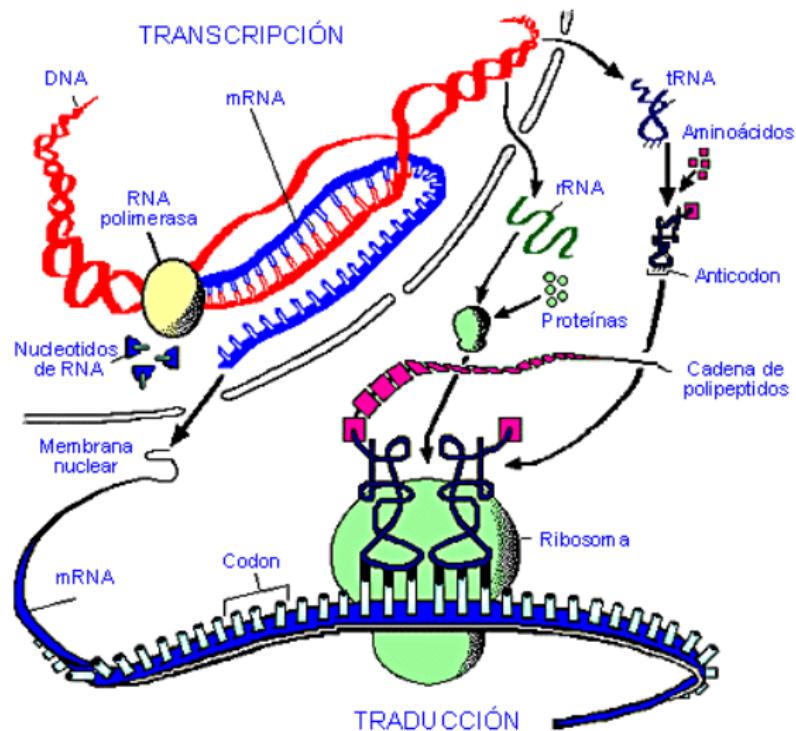
DNA codifies all the proteins in an organism



# Biological background

## Molecular Genetics (II)

### Protein synthesis: Creation of proteins from DNA (video)



# Biological background

## Molecular Genetics (III)

### Useful biological terms

Gene ADN fragment that codifies one protein

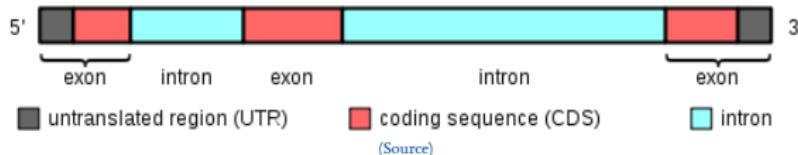
Allele The variant form of a gene

Genotype The sequence of DNA

Phenotype Characteristics of an individual

Exon Part of a gene that is transcribed

Intron Part of a gene that is not transcribed



# Biological background

## Theory of Evolution from an algorithmic perspective

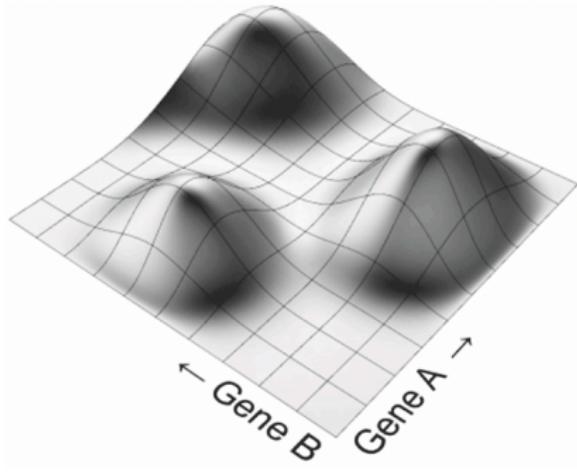
Given a population ...

1. There are differences among individuals
2. Fittest individuals more likely to reproduce
3. Go to 1

We are interested in applying this to Engineering

# Evolutionary Algorithms

## Evolution as optimization



Biological evolution is, in essence, an optimization algorithm

- ... it optimizes the survival probability
- Optimizing is to search the maximum

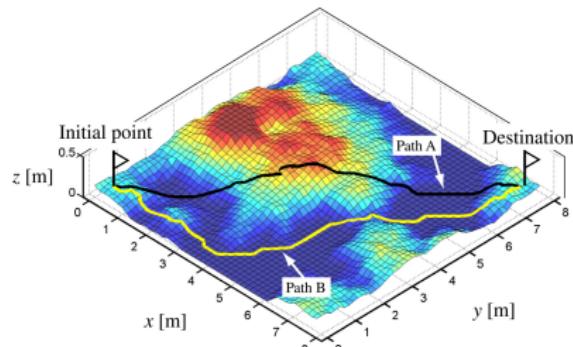
# Evolutionary Algorithms

## AI, search and optimization (I)

AI is much related to search a solution for a problem

- Search space
- Solution space

Almost any computational problem can be expressed as a search problem



(Source)

# Evolutionary Algorithms

## AI, search and optimization (II)

In AI, potential solutions are assessed

- Cost function
- Objective: Maximize cost function

The solution to any problem: **exhaustive search**

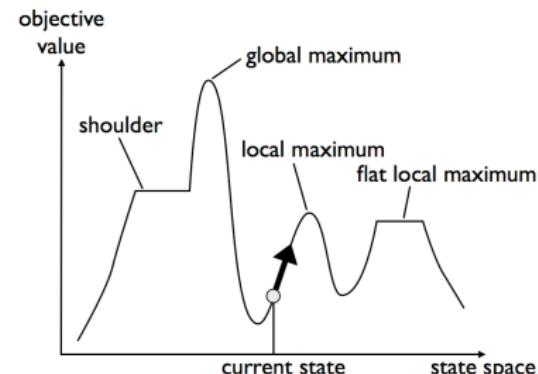
- Inviable in practice

A little less obvious solution: **hill-climbing**

- Cost function may be deceptive or incomplete

How to find a solution efficiently?

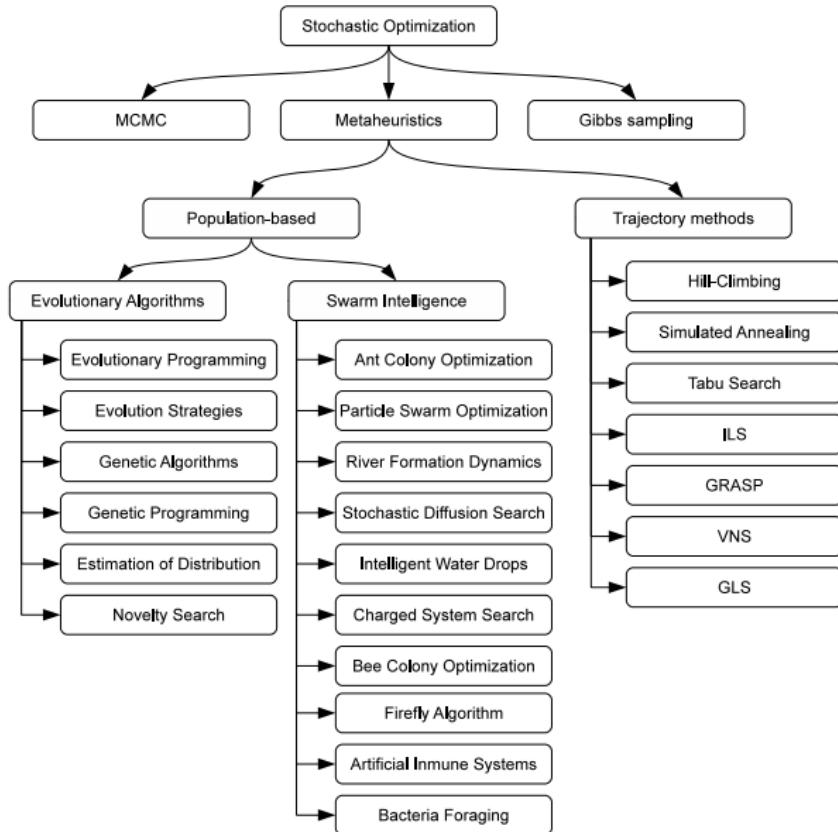
- With domain knowledge
- With randomness: **Metaheuristics**



(Source)

# Evolutionary Algorithms

## Metaheuristics



How can we apply biological evolution to solve engineering problems?

- Microstrip antenna layout design
- Wing shape design
- Artificial Neural Network
- Orbit transfer

# Evolutionary Algorithms

## Basics (I)

Large number of Evolutionary Algorithms

- There is no “canonical” algorithm
- They all imitate biological evolution

They use a population

- Each individual represents a (potential) solution
- Multiple **representations**

Population is modified

- Mutation ( $1$  individual)
- Crossover ( $>1$  individuals)
- Multiple **genetic operators**

Selection that imitates natural selection

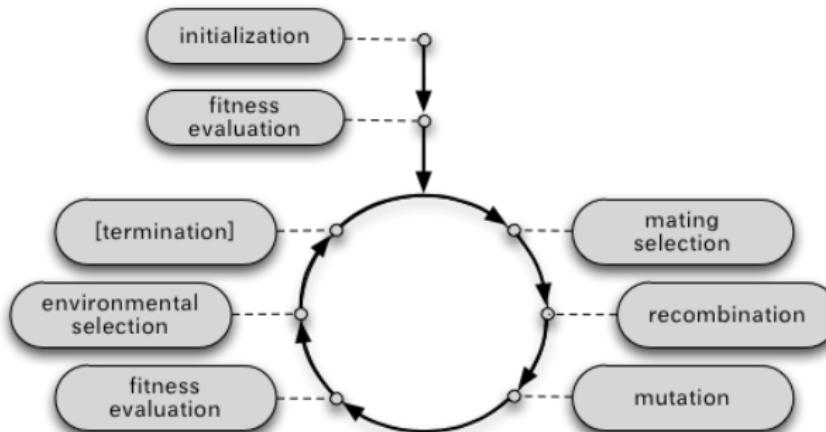
- Based on a **fitness** function

Iterative process

# Evolutionary Algorithms

## Basics (II)

### Possible basic algorithm



# Evolutionary Algorithms

## Basics (III)

Initialization is usually random

- Random population
- Domain-dependent heuristics may be used
- Known solutions might be injected into the initial population

Termination criteria

- Get a desired fitness
- Maximum number of iterations (or generations)
- Loss of genetic diversity
- Lack of fitness improvement

# Evolutionary Algorithms

## Exploration and exploitation

### Balance between exploitation and exploration

- These are opposite objectives ⇒ Need of trade-off

#### Exploration: Search of new regions

- Explore the search space
- Performed, mostly, by mutation

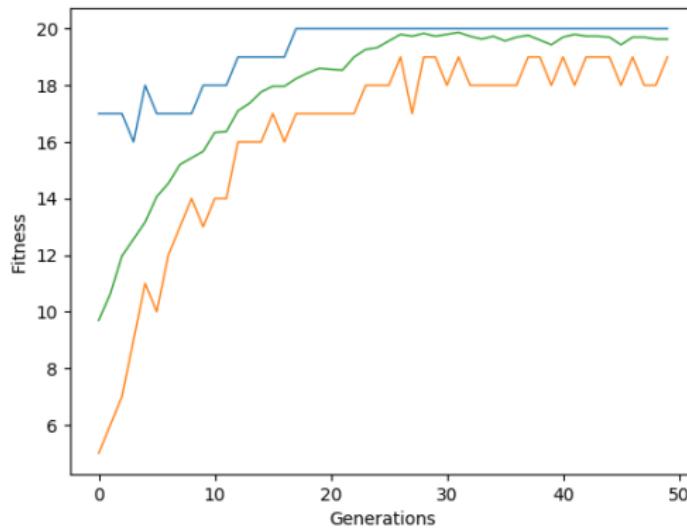
#### Exploitation: Search of local (or global) maxima

- Exploit the acquired knowledge
- Performed, mostly, by crossover

# Evolutionary Algorithms

## Fitness evolution

### Typical fitness behaviour



(Car design)

# EAs components

## Components of an EA

### Common components in any EA

- Representation
- Evaluation
- Selection
- Genetic operators

# EAs components

## Representation (I)

Main difference among EAs is the representation

- Strings: **Genetic Algorithms (GA)**
- Real vectors: **Evolution Strategies (ES)**
- State machine: **Evolutive Programming (EP)**
- Trees: **Genetic Programming (GP)**

These differences are, mostly, irrelevant

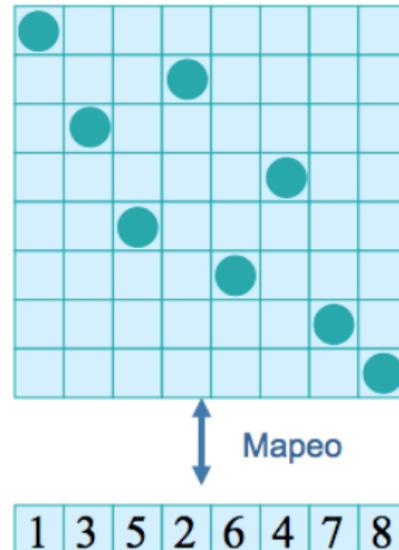
- Use the most natural representation
- Use the most natural genetic operators according to the representation

# EAs components

## Representation (II)

Example: 8 queens with a Genetic Algorithm

**Phenotype:** Board position  
**Genotype:** Integer vector

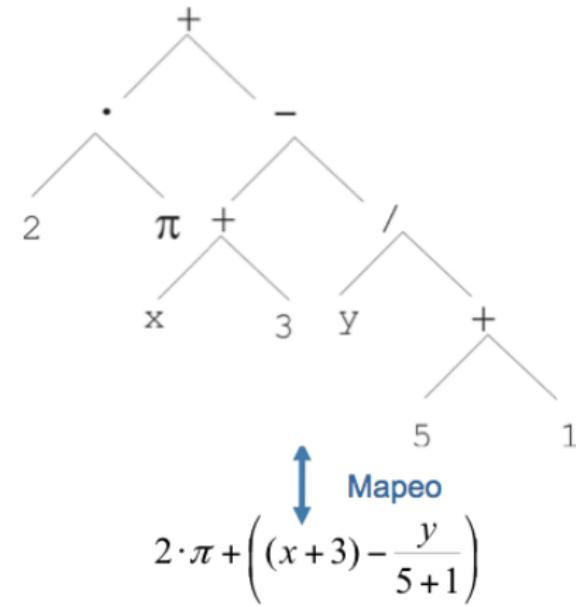


# EAs components

## Representation (III)

Example: Regression in Genetic Programming

**Phenotype:** Tree  
**Genotype:** Formula



# EAs components

## Evaluation (I)

Individuals quality is assessed by a **fitness function**

- Individual = Potential solution

The fitness assigns a numerical value to a phenotype

- Caution, phenotype, not genotype
- Multiobjective algorithms use several fitnesses

Evaluation used to be a bottleneck

- Many times it involves simulating a system

Minimize number of evaluations

# EAs components

## Evaluation (II)

### Example: 8 queens

- The fitness may be the number of threaded pieces
- Objective: Minimize fitness (minimation problem)

### Example: Regression

- The fitness may be the quadratic average error
- Objective: Minimize fitness (minimation problem)

# EAs components

## Selection (I)

Selection operator “selects” individuals for reproduction

- Imitates natural selection
- Higher reproduction probability for high fitness individuals
  - Randomness helps avoiding local minima
- Selection is done in phenotypic space!
  - Selection does not take into account how representation is

Introduces selective pressure

# EAs components

## Selection (II)

High selective pressure reduces genetic diversity

- Faster evolution, higher probability of local maxima
- Eliminates low fitness individuals
  - Potentially valuable genetic material can be lost
- Selection operators: Tournament size  $n$ , roulette-wheel, rank-based, ...

### Tournament size $n$

1. Take randomly  $n$  individuals
2. Compute their fitness
3. Select the highest fitness

Variable selective pressure depending on  $n$

# EAs components

## Selection (III)

### Replacement strategy

- Select which individual replace

### Two basic strategies

- Generational algorithms: Replace all the offspring
  - Iterations are named **generations**
  - Time is usually measured in generations
- Steady-state: Replace part of the offscript
  - Criteria: Age, fitness, selection, etc
  - Lower memory consumption

### Hybrid strategy: Elitism

- Replace the population, except the  $n$  fittest individuals
- $n$  fittest individuals guaranteed to survive

# EAs components

## Genetic operators (I)

Genetic operators build new individuals

- Two basic operators: **mutation** and **crossover**

Open discussion (=research) about the role of mutation and crossover

- Mutation enhances exploration
- Crossover enhances exploitation

Both are used

- Historical constraints

# EAs components

## Genetic operators (II)

### Mutation operator

- It takes a genotype and returns another one
  - It has a stochastic behavior
  - Used to maintain genetic diversity
- Guarantees search space connectivity
- Mutation plays a disruptive role
  - Moves population to new regions

Example: 8 queens permutation operator



# EAs components

## Genetic operators (III)

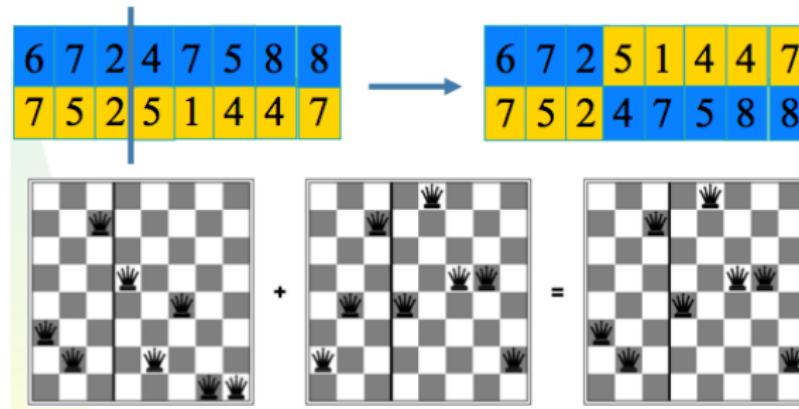
### Crossover operator

- Fuse information from the parents (sexual reproduction)
  - Randomness has a place
- Offspring uses to be worse than its parents
  - With luck, good components of the parents are joined ...
  - ... and this is something that happens
- Crossover has a constructive role
  - Join preexistent components
  - Does not generate new genetic material
  - Encourages exploitation

# EAs components

## Genetic operators (IV)

Example: 8 queens with one-point crossover



# EAs examples

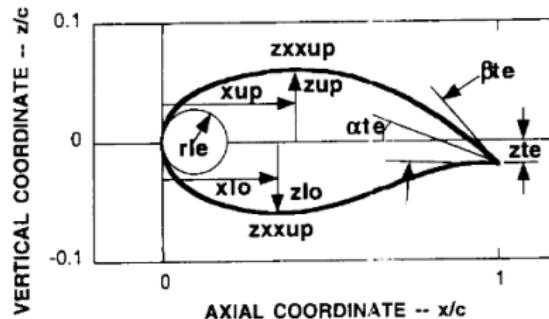
- (Genetic Algorithm Walkers)
- (Smart rockets)
- (Learn to walk)
- (Flexible Muscle-Based Locomotion for Bipedal Creatures)
- (MarI/O - Machine Learning for Video Games)
- (A genetic algorithm learns how to fight!)
- (Evolved Electrophysiological Soft Robots)

# Study case

## Case study I: Transonic wing shape optimization

Problem: Design a wing shape for transonic flight

- Maximize lift



Holst T.L., Pulliam T.H. (2003) Transonic Wing Shape Optimization Using a Genetic Algorithm. In: IUTAM Symposium Transsonicum IV. Fluid Mechanics and its Applications, vol 73. Springer.

# Study case

## Case study II: Mars orbital insertion

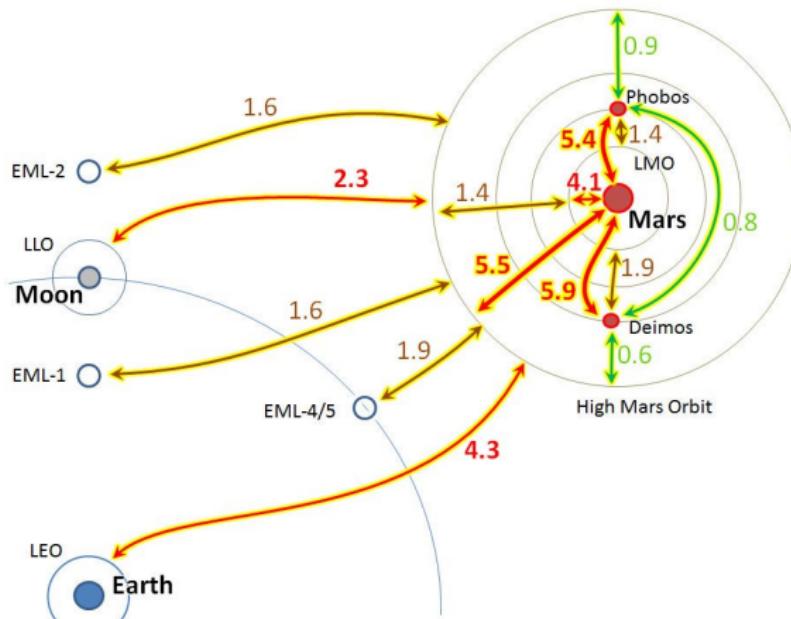


Chart by Richard Penn CC-BY, data from David Hollister [hopsblog-hop.blogspot.co.uk](http://hopsblog-hop.blogspot.co.uk)

# Study case

## Case study III: 9<sup>th</sup> Global Trajectory Optimization Competition

### GTOC: Global Trajectory Optimization Competition

- Proposed by ESA Advanced Concepts Team
- Difficult trajectory optimization problems

#### GTOC 9: The Kesser Run

- 123 orbiting debris
- Remove debris
- Design multiple missions

(Video) (Solution)