# Genetic Algorithms

CSc355

Alan Dix
dixa@comp.lancs.ac.uk

Manolis Sifalakis
mjs@comp.lancs.ac.uk

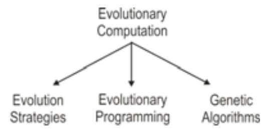
## Lecture Overview


- Evolutionary Computation (EC) and Genetic Algorithms (GA)
- A Brief History
- Terminology from Biology
- Computational Model
- Search space and fitness landscapes (an example)
- GAs versus other search methods
- Why evolution
- Applications of GAs
- Sample Application: Genetic Programming (GP)
- Performance Tuning of GAs
- Reference material (for GAs and GP)


## Evolutionary Computation

- Computational systems that use natural evolution (universal Darwinism) as an optimisation mechanism for solving engineering problems

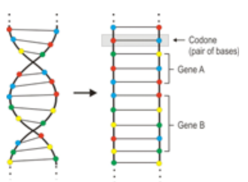

## A Brief History




- Evolution strategies: Real value parameter optimisation for device models [Rechenberg 1965, Schwefel 1975]
- Evolutionary programming: Evolvable state-transition diagrams (FSM) to produce fit solutions for specific tasks [Fogel, Owens, Walsh 1966]
- Genetic Algorithms: Abstraction and formalisation of natural-adaptation mechanisms for general purpose computations [Holand 1962]
  *... as opposed to problem-specific algorithm development*
- Other independent efforts for evolution-inspired algorithms

## Biological Systems: A rough guide

- Living organisms consist of cells
- Each cell contains one or more chromosomes (DNAs & RNAs)
- A set of chromosomes provide the organism blueprint
- A chromosome is divided conceptually in genes (functional blocks of DNA)
- A (set of) gene(s) encodes a protein – a trait (e.g. eye color)
- Alleles are the possible encodings of a gene (blue, green, red, yellow)
- Locus is the position of a gene in the chromosome

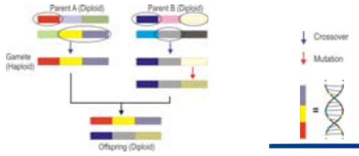



## Biological Systems: A rough guide

- Genome: Complete collection of chromosomes (genetic material)
- Genotype is a particular set of genes (encoded in chromosomes) in the genome that represent the genetic material of an individual
- Phenotype are the physical an mental characteristics related to a genotype (eye color, intelligence, height, hair type, etc) of an individual

## Biological Systems: A rough guide

- Organisms whose chromosomes appear in pairs (most sexually reproducing species) are called diploid, if not they are called haploid
- During sexual reproduction genetic recombination (crossover) occurs whereby chromosomes exchange sets of genes to produce a gamete (haploid)
- Mutation is the product of copying errors in the recombination process (biochem action, ext radiation, etc)
- Genetic fitness refers to the probability that a new organism will survive to reproduce (viability) or the number of offspring an organism has (fertility)




## Computational Model

- A chromosome is a string representation of a candidate solution to a problem

Bin: 0110110101110101011
Alpha: AABCAABCCDGGABCD
Hex: 937ff4539acc27d4bb92

- The genes are single digits or subsets of digits at specific locations in the chromosome string

Bin: 0110110101110101011

- An allele is the possible values a gene can take (0/1 if binary, a-z if alpha, 0-9 if decimal)

## Computational Model

- Crossover exchanges substrings between chromosomes

Crossover point
Chromo A: 01101 10101110101011
Chromo A: 11100 00011010110011
Offspring: 01101 00011010110011

- Mutation replaces a gene value with another from its allele

Offspring: 01101000110101100011
Offspring: 01101000000101100011

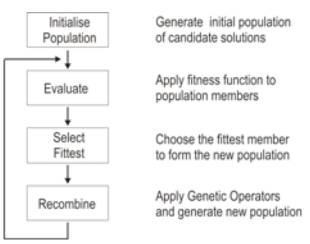
- Inversion swaps the head with the tail of the chromosome at a locus

Parent: 0110100010101100011
Offspring: 0101011000110110100

## Questionnaire 1

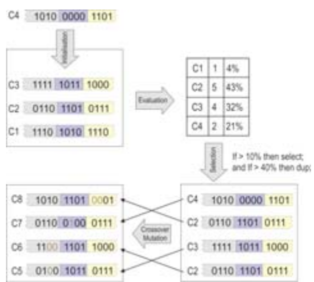
## Computational Model

### Main GA algorithm




## The computational equivalent

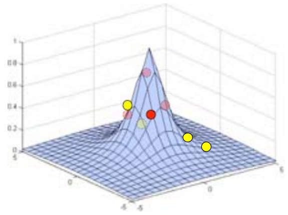
### A sample iteration



## Example: Search space & fitness landscapes

$$F(x,y) = \frac{1}{1 + x^2 + y^2}$$

| | X | Y |
|---|---|---|
| C1 | -1 | 2 |
| C2 | -2 | 3 |
| C3 | 1.5 | 0 |
| C4 | 0.5 | -1 |



Chromosome Encoding: Cartesian Coords — X coord, Y coord

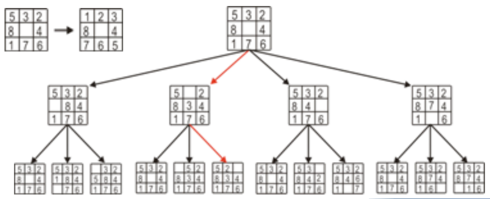
## GAs versus other search methods

"Search" for what?

- Data - Efficiently retrieve a piece of information, (Data mining) → Not AI
- Paths to solutions - Sequence of actions/steps from an initial state to a given goal, (AI-tree/graph search)
- Solutions - Find a good solution to a problem in a large space (search space) of candidate solutions
  - Aggressive methods (e.g. Simulated Annealing, Hill Climbing)
  - Non-aggressive methods (e.g. GAs)

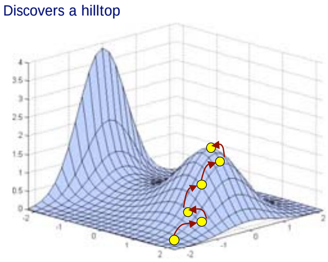
## Tree (Graph) Search

- Solution: Sequence of steps/Path through graph
- Solution "built" gradually (during graph traversal)
- Exhaustive search (constraints-assisted by heuristics)
- E.g. Depth-first, Breadth-first, Branch-&-Bound, ...

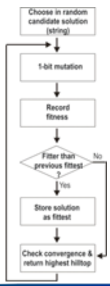


## Search for solutions aggressively

- Solution discovered gradually
- Problem: Can be trapped in local maximum
- Discovers a hilltop

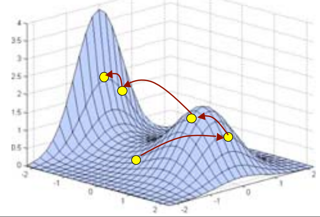


E.g. Steepest Ascend

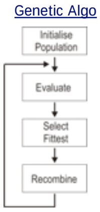



## Search for solutions with GAs

- Solution discovered probabilistically
- Problem: Can not guarantee discovery of hilltop
- Traces global maxima (wanders in whole search space)
- Combined w/ aggressive algorithm can find global maximum



Genetic Algo




## Why evolution?

- Evolution is a massively parallel search method
  - Many computational problems require searching through a huge number of possibilities for solutions
- Evolution use continually changing fitness criteria as creatures evolve
  - Many computational problems require adaptive solutions that perform well in changing environments
- Evolution is remarkably simple, yet responsible for extraordinary variety and complexity
  - Many computational problems require complex solutions that are difficult to program by hand

Computing

# Questionnaire 2

Computing

## Applications of GAs

- Numerical and Combinatorial Optimisation
  - Job-Shop Scheduling, Traveling salesman
- Automatic Programming
  - Genetic Programming
- Machine Learning
  - Classification, NNet training, Prediction
- Economic
  - Biding strategies, stock trends
- Ecology
  - host-parasite coevolution, resource flow, biological arm races
- Population Genetics
  - Viability of gene propagation
- Social systems
  - Evolution of social behavior in insect colonies

Computing

## Application: Genetic Programming (GP)

- Automatic programming implies the existence of computer programs that write … computer programs
- Early work on Evolutionary Computation (Evolutionary programming) aimed at automatic programming
- GP [Koza '92,'94] used GAs for automatic programming
  - Evolve computer programs rather than write them

Computing

## Genetic Programming: Overview

- Problem: We want to develop a system that builds programs that solve math equations
- Consider an instruction set for a zero-address VM (only stack, no registers)
- Solution encoding using byte strings for instruction strings:
  - Solution: OVER,ADD,MUL,ADD
  - Chromosome: 5 4 3 4

| Code | Operator | Description |
|---|---|---|
| 1 | DUP | X => A A |
| 2 | SWAP | X Y => Y X |
| 3 | MUL | X Y => (X*Y) |
| 4 | ADD | X Y => (X+Y) |
| 5 | OVER | X Y => X Y X |
| 6 | NOP | Null |

Computing

## Genetic Programming: Overview

- Fitness Evaluation: for random args calculate

  E = Expected value – Executed instr stream

- Recombination operators:
  - Crossover: break parent instruction streams at random point and exchange tails

    Parent 1 Chromo: 4 6 3 2 1<br>Parent 2 Chromo: 5 4 2 3 4 → Child 1 Chromo: 4 6 3 3 4<br>Child 2 Chromo: 5 4 2 2 1

  - Mutation: choose random position, replace instruction (gene) with another from the instruction set

    Solution: OVER,ADD,SWAP,MUL,ADD<br>Chromo: 5 4 2 3 4 → Solution: OVER,ADD,NOP,MUL,ADD<br>Chromo: 5 4 6 3 4

Computing

## GP: The (pseudo-) code

```
Main ( )
   InitPopulation ( )
   max_fitness := 0
   foreach member chromosome
      fitness := EvaluateFitness (chomosome)
      if fitness > max_fitness
         max_fitness := fitness
         fittest_solution = chromosome
   while generation < MAX_GENERATIONS
      offspring := SelectAndRecombine (parents)
      fitness := EvaluateFitness (offspring)
      if fitness > max_fitness
         max_fitness := fitness
         fittest_solution = offspring
   print fittest_solution
```

## GP: The (pseudo-) code

```
InitPopulation ( )
   while num_of_programs < MAX_PROG
      command_list := RandomSelectCommands ( )
      new_member := Concatenate (commands_list)

SelectAndRecombine ( )
   while num of programs < MAX_PROG/2
      parent_1 := RouletteWheelSelection ( )
      parent_2 := RouletteWheelSelection ( )
      randomly choose x-over point
      child_1 := parent_1 [head] ^ parent_2 [tail]
      child_2 := parent_2 [head] ^ parent_1 [tail]
      foreach child
         mutation_pt := RandomlyChooseMutationPoint (child)
         new_instr := RandomlyChooseNewInstruction ( )
         ReplaceInstruction (mutation_pt, new_instr)
```

## GP: The (pseudo-) code

```
Evaluate_fitness ( )
   forall chromosomes in population
      repeat COUNT times
         args := GenerateRandomArgs ( )
         expected_result := SolveEquation (args)
         InterpetFSM (chromosome, args)
         if  STACK_OVERFLOWN
            fitness += TIER1
         else if  stack[0] != expected_result
            fitness += TIER2
         else  // stack[0] == expected_result
            fitness += TIER3
         avg_fitness := fittness of all chromosomes / MAX_PROG
```

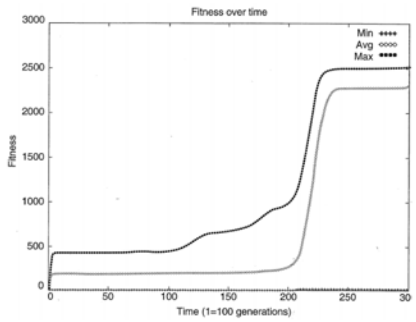
## GP: The (pseudo-) code

```
InterpretFSM ( )
   push args in stack and increase stack ptr
   while program counter < program_length
      pop args from stack
      result := ExecuteCommand (args)
      push result in stack
```

## Genetic Programming: Results

- Results of a few runs
  - $x^8$ :
    DUP, MUL, DUP, MUL, DUP, MUL → ((x∗x)∗(x∗x))∗((x∗x)∗(x∗x))
  - 2x + 2y + z :
    ADD, DUP, ADD, SWAP, ADD → ((x+y)+(x+y))+z
  - xy + $y^2$ + z :
    OVER, ADD, MUL, ADD → ((x+y)∗y)+z
  - $x^3$ + $y^2$ + z :
    DUP, DUP, MUL, MUL, SWAP, DUP, MUL, SWAP, ADD, SWAP, SWAP, ADD → ((x∗x∗x)+(y∗y))+z

## Genetic Programming: Performance




## Performance of GAs

- Chromosome representation must capture the dependencies of genes
- Initial population must be diverse
- Selection must make sure the fittest chromosomes are propagated to the next population and at the same time maintain diversity
- Recombination should not destroy good genes
- Mutation must guarantee seeding of new genetic material

## Some References – GA/GP

- GA Seminal paper
  - Holland J.H., Adaptation in natural and artificial system, Ann Arbor, The University of Michigan Press, 1975
- GA/GP Books
  - M. Mitchell. 1998: An Introduction to Genetic Algorithms. MIT Press
  - J. Koza. 1992: Genetic Programming: On the Programming of Computers by Means of Natural Selection. MIT Press
  - *Chapter*: M. Tim Jones. 2003: AI Application Programming. Charles River Media, Inc
  - *Chapter*: D. H. Ballard. 1999: An Introduction to Natural computation. MIT Press
- Artificial Intelligence course textbooks
- GAs on-line tutorial
  - Darell Whitley, An Introduction to Genetic Algorithms. http://samizdat.mines.edu/ga_tutorial/ga_tutorial.ps
- GP on-line resources
  - http://www.genetic-programming.com/

## Some References – GA/GP

- Something different !
  - R. Dawkins, 1976: The Selfish Gene. Oxford University Press.
  - S. Blackmoore, 1999: The Meme Machine. Oxford University Press.

## Questions ...

## TSP with GAs