Search

• for what?
  – the solution
  – the best possible (approximate?) solution

• from where?
  – search space (all valid solutions or paths)

• under which conditions?
  – compute time, space, ...
  – constraints, ...
Objective function

• An optimal solution
  – what is the measure that we optimise?
    • Any solution (satisfiability /SAT/ problem)
      – does the task have a solution?
      – is there a solution with objective measure better than X?
    • Minimal/maximal cost solution
    • A winning move in a game
    • A (feasible) solution with smallest nr of constraint violations (e.g. course time scheduling)

Search space

• Linear (list, binary search, …)

• Trees, Graphs

• Real nr in \([x,y)\)
  – Integers

• A point in high-dimensional space
Constraints

- **Time, space...**
  - if optimal cannot be found, approximate

- **All kinds of secondary characteristics**

- **Constraints**
  - sometimes finding even a point in the valid search space is hard
### Types of games

<table>
<thead>
<tr>
<th></th>
<th>deterministic</th>
<th>chance</th>
</tr>
</thead>
<tbody>
<tr>
<td>perfect information</td>
<td>chess, checkers, go, othello</td>
<td>backgammon monopoly</td>
</tr>
<tr>
<td>imperfect information</td>
<td>battleships, blind tictactoe</td>
<td>bridge, poker, scrabble nuclear war</td>
</tr>
</tbody>
</table>

An interesting constrained numerical optimization test case emerged recently; the problem (Keane, 1994) is to maximize a function:

\[ G2(\mathbf{x}) = \frac{\sum_{i=1}^{n} \cos^4(x_i) - 2 \prod \cos^2(x_i)}{\sqrt{\sum_{i=1}^{n} x_i}}. \]

subject to

\[ \prod_{i=1}^{n} x_i \geq 0.75, \quad \sum_{i=1}^{n} x_i \leq 7.5n, \quad \text{and bounds} \quad 0 \leq x_i \leq 10 \quad \text{for} \quad 1 \leq i \leq n. \]

Function \( G2 \) is nonlinear and its global maximum is unknown, lying somewhere near the origin. The problem has one nonlinear constraint and one linear constraint; the latter one is inactive around the origin and will be forgotten in the following.

\[ G2(\mathbf{x}) = (\sum \cos^4(x_i) - 2 \prod \cos^2(x_i))/\sqrt{\sum i x_i^2}, \]

where \( 0 \leq x_i \leq 10 \) and

\[ \prod x_i \geq 0.75 \]
The graph of function $G_2$ for $n = 2$. Infeasible solutions were as...
Classes of Search Techniques

- Search techniques
  - Calculus-based techniques
    - Direct methods
      - Fibonacci
    - Indirect methods
      - Newton
  - Evolutionary strategies
    - Genetic algorithms
      - Parallel
      - Sequential
      - Centralized
      - Distributed
      - Steady-state
      - Generational
  - Guided random search techniques
  - Enumerative techniques
    - Simulated annealing
    - Dynamic programming

Local Search
Local search algorithms

• In many optimization problems, the path to the goal is irrelevant; the goal state itself is the solution

• State space = set of "complete" configurations
• Find configuration satisfying constraints, e.g., n-queens

• In such cases, we can use local search algorithms
• keep a single "current" state, try to improve it

Example: $n$-queens

• Put $n$ queens on an $n \times n$ board with no two queens on the same row, column, or diagonal

• may get stuck...
Problems

• Cycles
  – Memorize; Tabu search

• How to transfer valleys with bad choices only...

Tree/Graph search

• order defined by picking a node for expansion

• BFS, DFS

• Random, Best First, ...
  – Best – an evaluation function
• Idea: use an evaluation function \( f(n) \) for each node
  – estimate of "desirability"
  – Expand most desirable unexpanded node

• Implementation:
  Order the nodes in fringe in decreasing order of desirability
  Priority queue

• Special cases:
  – greedy best-first search \( f(n) = h(n) \) heuristic, e.g. estimate to goal
  – A* search

\[ A^* \]

• \( f(n) = g(n) + h(n) \)

  – \( g(n) \) – path covered so far in graph
  – \( h(n) \) – estimated distance from \( n \) to goal
Admissible heuristics

- A heuristic $h(n)$ is **admissible** if for every node $n$, $h(n) \leq h^*(n)$, where $h^*(n)$ is the true cost to reach the goal state from $n$.

- An admissible heuristic **never overestimates** the cost to reach the goal, i.e., it is **optimistic**

- Example: $h_{SLD}(n)$ (never overestimates the actual road distance) (SLD – shortest linear distance)

- Theorem: If $h(n)$ is admissible, $A^*$ using TREE-SEARCH is optimal

Optimality of $A^*$ (proof)

- Suppose some suboptimal goal $G_2$ has been generated and is in the fringe. Let $n$ be an unexpanded node in the fringe such that $n$ is on a shortest path to an optimal goal $G$.

  ![Diagram showing the path from the start node to the goal nodes](image)

- $f(G_2) = g(G_2)$ since $h(G_2) = 0$
- $g(G_2) > g(G)$ since $G_2$ is suboptimal
- $f(G) = g(G)$ since $h(G) = 0$
- $f(G_2) > f(G)$ from above
Optimality of A* (proof)

• Suppose some suboptimal goal $G_2$ has been generated and is in the fringe. Let $n$ be an unexpanded node in the fringe such that $n$ is on a shortest path to an optimal goal $G$.

\[
\begin{align*}
\text{• } f(G_2) &= g(G_2) \quad \text{since } h(G_2) = 0 \\
\text{• } g(G_2) > g(G) \quad \text{since } G_2 \text{ is suboptimal} \\
\text{• } f(G) &= g(G) \quad \text{since } h(G) = 0 \\
\text{• } f(G_2) > f(G) \quad \text{from above} \\
\text{• Hence } f(G_2) > f(n), \text{ and A* will never select } G_2 \text{ for expansion}
\end{align*}
\]

Graph

• A Virtual graph/search space
  – valid states of Fifteen-game
  – Rubik’s cube

\[
\begin{array}{cccc}
1 & 2 & 3 & 4 \\
5 & 6 & 7 & 8 \\
9 & 10 & 11 & 12 \\
13 & 14 & 15 & 16
\end{array}
\]
Solve

- Which move takes us closer to the solution?
- Estimate the goodness of the state

How many are misplaced? (7)

How far have they been misplaced? Sum of theoretical shortest paths to the correct place

A* search towards a final goal
The Traveling Salesperson Problem (TSP)

- TSP – optimization variant:
  - For a given weighted graph $G = (V, E, w)$, find a Hamiltonian cycle in $G$ with minimal weight,
  - i.e., find the shortest round-trip visiting each vertex exactly once.

- TSP – decision variant:
  - For a given weighted graph $G = (V, E, w)$, decide whether a Hamiltonian cycle with minimal weight $\leq b$ exists in $G$.

TSP instance: shortest round trip through 532 US cities
Search Methods

• **Types of search methods:**
  • systematic $\leftrightarrow$ local search
  • deterministic $\leftrightarrow$ stochastic
  • sequential $\leftrightarrow$ parallel

Local Search (LS) Algorithms

• **search space** $S$
  (SAT: set of all complete truth assignments to propositional variables)
• **solution set** $S' \subseteq S$
  (SAT: models of given formula)
• **neighborhood relation** $N \subseteq S \times S$
  (SAT: neighboring variable assignments differ in the truth value of exactly one variable)
• **evaluation function** $g : S \rightarrow \mathbb{R}^+$
  (SAT: number of clauses unsatisfied under given assignment)
Local Search:

- start from initial position
- iteratively move from current position to neighboring position
- use evaluation function for guidance

**Two main classes:**
- local search on *partial solutions*
- local search on *complete solutions*

local search on partial solutions
Local search for partial solutions

- Order the variables in some order.
- Span a tree such that at each level a given value is assigned a value.
- Perform a depth-first search.
- But, use heuristics to guide the search. Choose the best child according to some heuristics. *(DFS with node ordering)*

Construction Heuristics for partial solutions

- **search space**: space of partial solutions
- **search steps**: extend partial solutions with assignment for the next element
- **solution elements** are often ranked according to a greedy evaluation function
**Nearest Neighbor heuristic for the TSP:**

- at any city, choose the closest yet unvisited city

  choose an arbitrary initial city $\pi(1)$

  at the $i$th step choose city $\pi(i-1)$ to be the city $j$

  that minimises $d(\pi(i), j); j \neq \pi(k), 1 < k < i$

- running time: $O(n^2)$

- worst case performance:

  $NN(x)/OPT(x) \leq 0.5(\lceil \log_2 n \rceil + 1)$

- other construction heuristics for TSP are available

---

**Nearest neighbor tour through 532 US cities**

![Graph showing the nearest neighbor tour through 532 US cities]
**DFS**

- Once a solution has been found (with the first dive into the tree) we can continue search the tree with DFS and backtracking.
- In fact, this is what we did with DFBnB.
- DFBnB with node ordering.

**local search on complete solutions**
**Iterative Improvement (Greedy Search):**

- initialize search at some point of search space
- in each step, move from the current search position to a neighboring position with better evaluation function value

**Iterative Improvement for SAT**

- **initialization**: randomly chosen, complete truth assignment
- **neighborhood**: variable assignments are neighbors iff they differ in truth value of one variable
- **neighborhood size**: $O(n)$ where $n =$ number of variables
- **evaluation function**: number of clauses unsatisfied under given assignment
Hill climbing

- Choose the neighbor with the largest improvement as the next state

\[ f-value = \text{evaluation}(\text{state}) \]

\[
\text{while } f-value(\text{state}) > f-value(\text{next-best}(\text{state})) \\
\text{state} := \text{next-best}(\text{state})
\]

Hill climbing

\[
\text{function Hill-Climbing(} \text{problem} \text{) returns a solution state}
\]

\[
current \leftarrow \text{Make-Node}(\text{Initial-State}[\text{problem}])
\]

\[
\text{loop do}
\]

\[
next \leftarrow \text{a highest-valued successor of } current
\]

\[
\text{if } \text{Value}[next] < \text{Value}[current] \text{ then return current}
\]

\[
current \leftarrow next
\]

\[
\text{end} \]
Problems with local search

Typical problems with local search (with hill climbing in particular)

• getting stuck in local optima
• being misguided by evaluation/objective function

Stochastic Local Search

• randomize initialization step
• randomize search steps such that suboptimal/worsening steps are allowed
• improved performance & robustness
• typically, degree of randomization controlled by noise parameter
**Stochastic Local Search**

**Pros:**
- for many combinatorial problems more efficient than systematic search
- easy to implement
- easy to parallelize

**Cons:**
- often incomplete (no guarantees for finding existing solutions)
- highly stochastic behavior
- often difficult to analyze theoretically/empirically

**Simple SLS methods**

- Random Search (Blind Guessing):
  - *In each step, randomly select one element of the search space.*

- (Uninformed) RandomWalk:
  - *In each step, randomly select one of the neighbouring positions of the search space and move there.*
Random restart hill climbing

Randomized Iterative Improvement:

• initialize search at some point of search space search steps:
• with probability $p$, move from current search position to a randomly selected neighboring position
• otherwise, move from current search position to neighboring position with better evaluation function value.
• Has many variations of how to choose the randomly neighbor, and how many of them
• Example: Take 100 steps in one direction (Army mistake correction) – to escape from local optima.
Search space

- Problem: depending on initial state, can get stuck in local maxima

General iterative Algorithms

- general and “easy” to implement
- approximation algorithms
- must be told when to stop
- hill-climbing
- convergence
General iterative search

- Algorithm
  - Initialize parameters and data structures
  - construct initial solution(s)
  - Repeat
    - Repeat
      - Generate new solution(s)
      - Select solution(s)
    - Until time to adapt parameters
    - Update parameters
  - Until time to stop
- End

Iterative search

- Most popular algorithms of this class
  - Genetic Algorithms
    - Probabilistic algorithm inspired by evolutionary mechanisms
  - Simulated Annealing
    - Probabilistic algorithm inspired by the annealing of metals
  - Tabu Search
    - Meta-heuristic which is a generalization of local search
Hill-climbing search

- Problem: depending on initial state, can get stuck in local maxima
  - Objective function
  - Global maximum
  - Shoulder
  - Local maximum
  - “Flat” local maximum

Simulated annealing

Combinatorial search technique inspired by the physical process of annealing [Kirkpatrick et al. 1983, Cerny 1985]

Outline
- Select a neighbor at random.
- If better than current state go there.
- Otherwise, go there with some probability.
- Probability goes down with time (similar to temperature cooling)
Simulated annealing

Acceptance criterion

- Metropolis acceptance criterion
  - better solutions are always accepted
  - worse solutions are accepted with probability

\[ e^{\Delta E / T} \sim \exp \left( \frac{g(s) - g(s')}{T} \right) \]

Annealing

- parameter \( T \), called temperature, is slowly decreased

\[ \text{delta} = -10 \]
\[ T = 0.1 \ldots 10,000 \]
Generic choices for annealing schedule

- initial temperature $T_0$
  (example: based on statistics of evaluation function)
- cooling schedule — how to change temperature over time
  (example: geometric cooling, $T_{n+1} = \alpha \cdot T_n$, $n = 0, 1, \ldots$)
- number of iterations at each temperature
  (example: multiple of the neighbourhood size)
- stopping criterion
  (example: no improved solution found for a number of temperature values)

Simulated Annealing
**Pseudo code**

```
function Simulated-Annealing(problem, schedule) returns solution state

current ← Make-Node(Initial-State[problem])

for t ← 1 to infinity

    T ← schedule[t]  // T goes downwards.

    if T = 0 then return current

    next ← Random-Successor(current)

    ΔE ← f-Value[next] - f-Value[current]

    if ΔE > 0 then current ← next
    else current ← next with probability e^{ΔE/T}

end
```

**Example application to the TSP [Johnson & McGeoch 1997]**

baseline implementation:
- start with random initial solution
- use 2-exchange neighborhood
- simple annealing schedule;
  $\Rightarrow$ relatively poor performance

improvements:
- look-up table for acceptance probabilities
- neighborhood pruning
- low-temperature starts
**Summary-Simulated Annealing**

**Simulated Annealing . . .**
- is historically important
- is easy to implement
- has interesting theoretical properties (convergence), but these are of very limited practical relevance
- achieves good performance often at the cost of substantial run-times

**Examples for combinatorial problems:**
- finding shortest/cheapest round trips (TSP)
- finding models of propositional formulae (SAT)
- planning, scheduling, time-tableing
- resource allocation
- protein structure prediction
- genome sequence assembly
**SAT**

**SAT Problem – decision variant:**
For a given propositional formula \( \Phi \),
decide whether \( \Phi \) has at least one model.

**SAT Problem – search variant:**
For a given propositional formula \( \Phi \), if \( \Phi \) is satisfiable,
find a model, otherwise declare \( \Phi \) unsatisfiable.

---

**The Propositional Satisfiability Problem (SAT)**

**Simple SAT instance (in CNF):**

\[(a \lor b) \land (\neg a \lor \neg b)\]

\(\sim\) satisfiable, two models:

- \(a = \text{true}, b = \text{false}\)
- \(a = \text{false}, b = \text{true}\)
Tabu Search

- Combinatorial search technique which heavily relies on the use of an explicit memory of the search process [Glover 1989, 1990] to guide search process
- memory typically contains only specific attributes of previously seen solutions
- simple tabu search strategies exploit only short term memory
- more complex tabu search strategies exploit long term memory

Tabu search – exploiting short term memory

- in each step, move to best neighboring solution although it may be worse than current one
- to avoid cycles, tabu search tries to avoid revisiting previously seen solutions by basing the memory on attributes of recently seen solutions
- tabu list stores attributes of the $tl$ most recently visited
- solutions; parameter $tl$ is called tabu list length or tabu tenure
- solutions which contain tabu attributes are forbidden
Example: Tabu Search for SAT / MAX-SAT

- **Neighborhood**: assignments which differ in exactly one variable instantiation
- **Tabu attributes**: variables
- **Tabu criterion**: flipping a variable is forbidden for a given number of iterations
- **Aspiration criterion**: if flipping a tabu variable leads to a better solution, the variable’s tabu status is overridden

[Hansen & Jaumard 1990; Selman & Kautz 1994]

- Bart Selman, Cornell
  
  [www-verimag.imag.fr/~maler/TCC/selman-tcc.ppt](http://www-verimag.imag.fr/~maler/TCC/selman-tcc.ppt)

  *Ideas from physics, statistics, combinatorics, algorithmics …*
Fundamental challenge: Combinatorial Search Spaces

• *Significant progress in the last decade.*

• How much?

  • For propositional reasoning:
    • -- We went from 100 variables, 200 clauses (early 90’s)
    • to 1,000,000 vars. and 5,000,000 constraints in
    • 10 years. Search space: from $10^30$ to $10^300,000$.

  • -- Applications: Hardware and Software Verification,
    • Test pattern generation, Planning, Protocol Design,
    • Routers, Timetabling, E-Commerce (combinatorial
    • auctions), etc.
    •
    •

• How can deal with such large combinatorial spaces and
  still do a decent job?

• I’ll discuss recent formal insights into
  combinatorial search spaces and their
  practical implications that makes searching
  such ultra-large spaces possible.

• Brings together ideas from physics of disordered systems
  (spin glasses), combinatorics of random structures, and
  algorithms.

  • *But first, what is BIG?*
What is BIG?
Consider a real-world Boolean Satisfiability (SAT) problem

The instance bac-1bm-6.cnf, IBM LSU 1997:

```
p cnf
-1 7 0
-1 6 0
-1 5 0
-1 -4 0
-1 3 0
-1 2 0
-1 -8 0
-9 15 0
-9 14 0
-9 13 0
-9 -12 0
-9 11 0
-9 10 0
-9 -16 0
-17 25 0
-17 22 0
```

I.e., ((not x_1) or x_7)
((not x_1) or x_6)

etc.

x_1, x_2, x_3, etc. our Boolean variables
(set to True or False)

Set x_1 to False ??

10 pages later:

```
185 -9 0
185 -1 0
177 169 161 153 145 137 129 121 113 105 97
89 81 73 65 57 49 41
33 25 17 9 1 -135 0
186 -187 0
186 -188 0
...
```

I.e., (x_177 or x_169 or x_161 or x_153 ...
x_33 or x_25 or x_17 or x_9 or x_1 or (not x_185))

clauses / constraints are getting more interesting…

Note x_1 …
4000 pages later:

10236 -10050 0
10236 -10051 0
10236 -10236 0
10008 10009 10010 10011 10012 10013 10014
10015 10016 10017 10018 10019 10020 10021
10022 10023 10024 10025 10026 10027 10028
10029 10030 10031 10032 10033 10034 10035
10036 10037 10038 10039 10040 10041 10042
10043 10044 10045 10046 10047 10048 10049
10050 10051 10235 -10236 0
10237 -10008 0
10237 -10009 0
10237 -10010 0

...

Finally, 15,000 pages later:

-7 260 0
7 -260 0
1072 1070 0
-15 -14 -13 -12 -11 -10 0
-15 -14 -13 -12 -11 10 0
-15 -14 -13 -12 11 -10 0
-15 -14 -13 -12 11 10 0
-7 -6 -5 -4 -3 -2 0
-7 -6 -5 -4 -3 2 0
-7 -6 -5 -4 3 -2 0
-7 -6 -5 -4 3 2 0
185 0

Combinatorial search space of truth assignments: HOW?

$2^{15000} \approx 3.16 \times 10^{15001}$

Current SAT solvers solve this instance in approx. 1 minute!
### Progress SAT Solvers

<table>
<thead>
<tr>
<th>Instance</th>
<th>Posit' 94</th>
<th>Grasp' 96</th>
<th>Sato' 98</th>
<th>Chaff' 01</th>
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</thead>
<tbody>
<tr>
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<td>0,95s</td>
<td>0,02s</td>
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<tr>
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<td>0,11s</td>
<td>0,04s</td>
<td>0,01s</td>
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<tr>
<td>pret150_25</td>
<td>&gt;3000s</td>
<td>0,21s</td>
<td>0,09s</td>
<td>0,01s</td>
</tr>
<tr>
<td>dubois100</td>
<td>&gt;3000s</td>
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<td>0,08s</td>
<td>0,01s</td>
</tr>
<tr>
<td>aim200-2_0-no-1</td>
<td>&gt;3000s</td>
<td>0,01s</td>
<td>0s</td>
<td>0s</td>
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<td>&gt;3000s</td>
<td>&gt;3000s</td>
<td>&gt;3000s</td>
</tr>
</tbody>
</table>

Source: Marques Silva 2002

---

- From academically interesting to practically relevant.
- We now have regular SAT solver competitions.
  - Germany '89, Dimacs '93, China '96, SAT-02, SAT-03, SAT-04, SAT05.
  - E.g. at SAT-2004 (Vancouver, May 04):
    - 35+ solvers submitted
    - 500+ industrial benchmarks
    - 50,000+ instances available on the WWW.
Real-World Reasoning
Tackling inherent computational complexity

DARPA Research Program

Example domains cast in propositional reasoning system (variables, rules).

A Journey from Random to Structured Instances

1 --- Random Instances
   - phase transitions and algorithms
   - from physics to computer science

II --- Capturing Problem Structure
   - problem mixtures (tractable / intractable)
   - backdoor variables, restarts, and heavy tails

III --- Beyond Satisfaction
   - sampling, counting, and probabilities
   - quantification
Genetic Algorithms: A Tutorial

“Genetic Algorithms are good at taking large, potentially huge search spaces and navigating them, looking for optimal combinations of things, solutions you might not otherwise find in a lifetime.”

- Salvatore Mangano
  Computer Design, May 1995

The Genetic Algorithm

- Directed search algorithms based on the mechanics of biological evolution
- Developed by John Holland, University of Michigan (1970’s)
  - To understand the adaptive processes of natural systems
  - To design artificial systems software that retains the robustness of natural systems
The Genetic Algorithm (cont.)

- Provide efficient, effective techniques for optimization and machine learning applications
- Widely-used today in business, scientific and engineering circles

Components of a GA

A problem to solve, and ...

- Encoding technique (gene, chromosome)
- Initialization procedure (creation)
- Evaluation function (environment)
- Selection of parents (reproduction)
- Genetic operators (mutation, recombination)
- Parameter settings (practice and art)
Simple Genetic Algorithm

```java
{ initialize population;
  evaluate population;
  while TerminationCriteriaNotSatisfied
    { select parents for reproduction;
      perform recombination and mutation;
      evaluate population;
    }
}
```

The GA Cycle of Reproduction

```
reproduction -> children
parents
population
deleted members
evaluation
modified children
modified children
```
Genetic algorithms

• How to generate the next generation.
• **1) Selection:** we select a number of states from the current generation. (we can use the fitness function in any reasonable way)
• **2) crossover:** select 2 states and reproduce a child.
• **3) mutation:** change some of the genues.

---

Example

= stochastic local beam search — generate successors from pairs of states

<table>
<thead>
<tr>
<th>Fitness</th>
<th>Selection</th>
<th>Pairs</th>
<th>Cross-Over</th>
<th>Mutation</th>
</tr>
</thead>
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<td>24415124</td>
<td>24415124</td>
<td>24415124</td>
<td></td>
</tr>
</tbody>
</table>
8-queen example

GAs require states encoded as strings (GPs use programs)
Crossover helps iff substrings are meaningful components

Summary: Genetic Algorithms

Genetic Algorithms
- use populations, which leads to increased search space exploration
- allow for a large number of different implementation choices
- typically reach best performance when using operators that are based on problem characteristics
- achieve good performance on a wide range of problems
Classes of Search Techniques

Search techniques
- Calculus-based techniques
  - Direct methods
  - Indirect methods
- Evolutionary strategies
  - Genetic algorithms
    - Parallel
    - Sequential
- Guided random search techniques
- Enumerative techniques
- Dynamic programming
- Evolutionary algorithms
- Simulated annealing

The GA Cycle of Reproduction

reproduction → children
parents
population
modified children
evaluation
evaluated children
discard
deleted members
Population

Chromosomes could be:

- Bit strings (0101 ... 1100)
- Real numbers (43.2 -33.1 ... 0.0 89.2)
- Permutations of elements (E11 E3 E7 ... E1 E15)
- Lists of rules (R1 R2 R3 ... R22 R23)
- Program elements (genetic programming)
- ... any data structure ...

Reproduction

Parents are selected at random with selection chances biased in relation to chromosome evaluations.
Chromosome Modification

- Modifications are stochastically triggered
- Operator types are:
  - Mutation
  - Crossover (recombination)

Mutation: Local Modification

Before: \((1\ 0\ 1\ 1\ 0\ 1\ 1\ 0)\)
After: \((0\ 1\ 1\ 0\ 0\ 1\ 1\ 0)\)

Before: \((1.38\ -69.4\ 326.44\ 0.1)\)
After: \((1.38\ -67.5\ 326.44\ 0.1)\)

- Causes movement in the search space (local or global)
- Restores lost information to the population
Crossover: Recombination

\[
P_1 \quad (0 \ 1 \ 1 \ 0 \ 1 \ 0 \ 0 \ 0) \quad (0 \ 1 \ 0 \ 0 \ 1 \ 0 \ 0 \ 0) \quad C_1
\]

\[
P_2 \quad (1 \ 1 \ 0 \ 1 \ 1 \ 0 \ 1 \ 0) \quad (1 \ 1 \ 1 \ 1 \ 1 \ 0 \ 1 \ 0) \quad C_2
\]

Crossover is a critical feature of genetic algorithms:

- It greatly accelerates search early in evolution of a population
- It leads to effective combination of schemata (subsolutions on different chromosomes)

Evaluation

- The evaluator decodes a chromosome and assigns it a fitness measure
- The evaluator is the only link between a classical GA and the problem it is solving
Deletion

- *Generational GA*: entire populations replaced with each iteration
- *Steady-state GA*: a few members replaced each generation
A Simple Example

“The Gene is by far the most sophisticated program around.”

- Bill Gates, Business Week, June 27, 1994

The Traveling Salesman Problem:

Find a tour of a given set of cities so that

- each city is visited only once
- the total distance traveled is minimized
Representation

Representation is an ordered list of city numbers known as an order-based GA.

1) London   3) Dunedin   5) Beijing   7) Tokyo
2) Venice    4) Singapore 6) Phoenix  8) Victoria

CityList1   (3 5 7 2 1 6 4 8)
CityList2   (2 5 7 6 8 1 3 4)

Crossover

Crossover combines inversion and recombination:

*         *

Parent1   (3 5 7 2 1 6 4 8)
Parent2   (2 5 7 6 8 1 3 4)
Child     (5 8 7 2 1 6 3 4)

This operator is called the Order1 crossover.
**Mutation**

Mutation involves reordering of the list:

Before: \((5\ 8\ 7\ 2\ 1\ 6\ 3\ 4)\)

After: \((5\ 8\ 6\ 2\ 1\ 7\ 3\ 4)\)

---

**TSP Example: 30 Cities**

![TSP Example Graph](image-url)
Solution \textsubscript{i} (Distance = 941)

Solution \textsubscript{j} (Distance = 800)
Solution \( k (\text{Distance} = 652) \)

**Best Solution (Distance = 420)**
Considering the GA Technology

“Almost eight years ago ... people at Microsoft wrote a program [that] uses some genetic things for finding short code sequences. Windows 2.0 and 3.2, NT, and almost all Microsoft applications products have shipped with pieces of code created by that system.”

- Nathan Myhrvold, Microsoft Advanced Technology Group, Wired, September 1995
Issues for GA Practitioners

- Choosing basic implementation issues:
  - representation
  - population size, mutation rate, ...
  - selection, deletion policies
  - crossover, mutation operators
- Termination Criteria
- Performance, scalability
- Solution is only as good as the evaluation function (often hardest part)

Benefits of Genetic Algorithms

- Concept is easy to understand
- Modular, separate from application
- Supports multi-objective optimization
- Good for “noisy” environments
- Always an answer; answer gets better with time
- Inherently parallel; easily distributed
Benefits of Genetic Algorithms (cont.)

- Many ways to speed up and improve a GA-based application as knowledge about problem domain is gained
- Easy to exploit previous or alternate solutions
- Flexible building blocks for hybrid applications
- Substantial history and range of use

When to Use a GA

- Alternate solutions are too slow or overly complicated
- Need an exploratory tool to examine new approaches
- Problem is similar to one that has already been successfully solved by using a GA
- Want to hybridize with an existing solution
- Benefits of the GA technology meet key problem requirements
Some GA Application Types

<table>
<thead>
<tr>
<th>Domain</th>
<th>Application Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>gas pipeline, pole balancing, missile evasion, pursuit</td>
</tr>
<tr>
<td>Design</td>
<td>semiconductor layout, aircraft design, keyboard</td>
</tr>
<tr>
<td>Scheduling</td>
<td>manufacturing, facility scheduling, resource allocation</td>
</tr>
<tr>
<td>Robotics</td>
<td>trajectory planning</td>
</tr>
<tr>
<td>Machine Learning</td>
<td>designing neural networks, improving classification</td>
</tr>
<tr>
<td>Signal Processing</td>
<td>algorithms, classifier systems</td>
</tr>
<tr>
<td>Game Playing</td>
<td>filter design</td>
</tr>
<tr>
<td>Combinatorial</td>
<td>poker, checkers, prisoner’s dilemma</td>
</tr>
<tr>
<td>Optimization</td>
<td>set covering, travelling salesman, routing, bin packing,</td>
</tr>
<tr>
<td></td>
<td>graph colouring and partitioning</td>
</tr>
</tbody>
</table>

Conclusions

Question: ‘If GAs are so smart, why ain’t they rich?’

Answer: ‘Genetic algorithms are rich - rich in application across a large and growing number of disciplines.’

- David E. Goldberg, Genetic Algorithms in Search, Optimization and Machine Learning