Advanced Algorithmics (6EAP)
Search and meta-heuristics

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2011 Spring

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
- A subset of a larger set
- An assignment of variables (in SAT)
- ...

The Propositional Satisfiability Problem (SAT)

Simple SAT instance (in CNF):

$$(a \lor b) \land (\neg a \lor \neg b)$$

$\neg \text{satisfiable, two models:}$

- $a = \text{true}, b = \text{false}$
- $a = \text{false}, b = \text{true}$

Search

- for what?
  - a solution
  - the (best possible (approximate?)) solution
- from where?
  - search space (all valid solutions or paths)
- under which conditions?
  - compute time, space, ...
  - constraints, ...

Tic-Tac-Toe

Consider the game of tic-tac-toe. Even if we use symmetry to reduce the search space of redundant moves, the number of possible paths through the search space is something like $12 \times 7! = 60480$. That is a measure of the amount of work that would have to be done by a brute-force search.

Initial State

State Space Search

$X(0)$ $X(1)$ $X(0)$ $X(1)$ $X(0)$ $X(1)$ $X(0)$ $X(1)$
TSP, nearest neighbour search

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

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

\[
G_2(x) = \prod_{i=1}^{n} \cos^2(x_i) - 2 \prod_{i=1}^{n} \cos(x_i) / \sqrt{\sum_i x_i^2},
\]

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

\[
\prod x_i \geq 0.75
\]
Outline

- Best-first search
- Greedy best-first search
- A* search
- Heuristics
- Local search algorithms
- Hill-climbing search
- Simulated annealing search
- Local beam search
- Genetic algorithms

Greedy

- Set Cover
  - Greedy Approximation Algorithm
  - polynomial-time \( p(n) \)-approximation algorithm
    * \( p(n) \) is a logarithmic function of set size

Greedy Set Covering Algorithm

```
Greedy-Set-Cover(X, F)
1 U = X
2 C = Ø
3 while U ≠ Ø
4   do select an S ∈ F that maximizes |S ∩ U|
5   U = U - S.
6 C = C ∪ {S}
7 return C
```

Set Cover Problem

Instance \((X, F)\):
- finite set \(X\) (e.g. of points)
- family \(F\) of subsets of \(X\)
- \(X = \bigcup S\)

Problem: Find a minimum-sized subset \(C \subseteq F\) whose members cover all of \(X\): \(X = \bigcup S\)

NP-Complete

source: 91.503 textbook Cormen et al.

Set Cover

**Theorem:** \textsc{Greedy-Set-Cover} is a polynomial-time \( p(n) \)-approximation algorithm for \( p(n) = H(\max\{|S| : S \in F\}) \)

**Proof:** 
1. 1th harmonic number \( H_n = \sum_{k=1}^{n} \frac{1}{k} = H(n) \) \( \forall n \geq 0 \)
2. Algorithm runs in time polynomial in \( n \).
3. \( S_i \) is the subset selected
4. selecting \( S_i \) costs \( 1 \)
5. \( c_i = \text{cost of element } x \in X \)
6. \( c_i = \text{cost of element } x \in X \) paid only when it is covered for the first time
7. \( c_i = \frac{1}{|S_i|} \) number of elements covered for the first time by \( S_i \)

source: 91.503 textbook Cormen et al.
Set Cover (proof continued)

\[\text{Theorem:} \ \text{GREEDY-SET-COVER is a polynomial-time} \ \rho(n)\text{-approximation algorithm for} \ \max_{S \in F} |S| \]

\[\text{Proof:} \ \begin{align*}
\rho(n) &= H(\max |S| : S \in F) \\
\text{Let } C^* \text{ be an optimal cover} \\
\text{Let } C \text{ be a cover from GREEDY-SET-COVER} \\
\sum_{x \in C} c_x &= \sum_{S \in F} \sum_{x \in S} c_x \\
|C| &\leq \sum_{S \in F} \sum_{x \in S} c_x
\end{align*}\]

Classes of Search Techniques

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

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 \( G_s \) 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 \( G \).

- \( f(G_s) = g(G_s) \) since \( h(G_s) = 0 \)
- \( g(G_s) > g(G) \) since \( G_s \) is suboptimal
- \( f(G) = g(G) \) since \( h(G) = 0 \)
- \( f(G_s) > f(G) \) from above
5.5.2011

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 $G$.

  - $f(G_2) = g(G_2)$ 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
  - Hence $f(G_2) > f(n)$, and A* will never select $G_2$ for expansion

A* path-finder

Graph

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

Solve

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

Search space

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 $G$. 

The Traveling Salesperson Problem (TSP)

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Search space

• 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

1 2 3 4
5 6 7 8
9 10 11 12
13 14 15

4 14 13 3
5 6 7 8
9 10 12
1 2 15 11
### TSP instance: shortest round trip through 532 US cities

![TSP instance image]

### 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 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)*
DFS

- Once a solution has been found (with the first dive into the tree) we can continue search the tree with DFS and backtracking.

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 \( d(\pi(i), j); j \neq \pi(k), 1 \leq k \leq i \)
- running time: \( O(n^2) \)
- worst case performance:
  \[ NN(x) / OPT(x) \leq 0.5(\lfloor \log_2 n \rfloor + 1) \]
- other construction heuristics for TSP are available

My current best is 27486.199404966355 (nn gives 27766.484757657887)

All the best,
Polina

My best is 24839,308924381 (Jaak S)
5.5.2011

My new best is 23474 (Oleg)

23297.72476804589
Probably some local minimum near Jaak Sarv's solution

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

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

\[
\text{states}
\]

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

\[
state := \text{next-best(state)}
\]

Hill climbing

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

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

\[
\text{loop do}
\]

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

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

\[
current := next
\]

\[
\text{end}
\]

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
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

Simulated annealing (SA) is a generic probabilistic metaheuristic for the global optimization problem of locating a good approximation to a global optimum in a large search space. It is often used when the search space is discrete (e.g., all tours that visit a given set of cities). For certain problems, simulated annealing may be more effective than exhaustive search (which is guaranteed to locate the optimal solution, given enough time). The method was independently described by Scott Kirkpatrick, C. Daniel Gelatt and Mario P. Vecchi in 1983 and by Vlado Černý in 1985. The method is an adaptation of the Metropolis–Hastings algorithm, a Monte Carlo method to generate sample states of a thermodynamic system, invented by M.N. Rosenbluth in a paper by N. Metropolis et al. in 1953.

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

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, $T_{n+1} = \alpha \cdot T_n$, $0 < \alpha < 1, \ldots$)
- 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;
  - relatively poor performance

improvements:

- look-up table for acceptance probabilities
- neighborhood pruning
- low-temperature starts

Diameter of the search graph

- Simulated annealing may be modeled as a random walk on a search graph, whose vertices are all possible states, and whose edges are the candidate moves. An essential requirement for the neighbour() function is that it must provide a sufficiently short path on this graph from the initial state to any state which may be the global optimum. (In other words, the diameter of the search graph must be small.) In the traveling salesman example above, for instance, the search space for $n = 20$ cities has $n! = 2432902008176640000$ (2.4 quintillion) states; yet the neighbour generator function that swaps two consecutive cities can get from any state (tour) to any other state in maximum $n(n − 1)/2 = 190$ steps.

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):**

$$ (a \lor b) \land (\neg a \lor \neg b) $$

$\leadsto$ 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]
Fundamental challenge: Combinatorial Search Spaces

- Significant progress in the last decade.

- How much?
  - For propositional reasoning:
    - We went from 120 variables, 200 clauses (early 90's)
    - to 1,000,000 vars. and 5,000,000 constraints in
    - 10 years. Search space: from $10^{18}$ to $10^{300,000}$.
  - Applications: Hardware and Software Verification, Test pattern generation, Planning, Protocol Design, Routers, Timetabling, E-Commerce (combinatorial auctions), etc.

What is BIG?
Consider a real-world Boolean Satisfiability (SAT) problem

The instance bsimp6-true-6.cnf, DIMACS LBF.

\[
\begin{align*}
\text{i.e., } &\neg x_1 \lor x_7 \\
&\neg x_1 \lor x_6 \\
&\vdots \\
\end{align*}
\]

I.e., \((\neg x_1) \lor x_7\)
\((\neg x_1) \lor x_6\)

etc.

\[
\begin{align*}
x_1, x_2, x_3, \text{etc. our Boolean variables} \\
\text{(set to True or False)} \\
\end{align*}
\]

Set \(x_1\) to False ??

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 make 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?

10 pages later:

\[
\begin{align*}
\text{i.e., } &\neg x_{177} \lor x_{169} \lor x_{161} \lor x_{153} \lor \ldots \\
&x_{33} \lor x_{25} \lor x_{17} \lor x_9 \lor x_1 \lor \neg x_{185} \\
\end{align*}
\]

clauses / constraints are getting more interesting...

Note \(x_1\) ...
Finally, 15,000 pages later:

Combinatorial search space of truth assignments:

\[
\begin{align*}
\text{SAT} & : 2^{15,000} = 3.16 \times 10^{4500} \\
\text{Brute Force} & : 10^{20,000}
\end{align*}
\]

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

\textbf{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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<td>1.2s</td>
<td>0.95s</td>
<td>0.02s</td>
</tr>
<tr>
<td>b1355-638</td>
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<td>0.04s</td>
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<td>0.09s</td>
<td>0.01s</td>
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<td>0.08s</td>
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<tr>
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<td>0.01s</td>
<td>0s</td>
<td>0s</td>
</tr>
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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.

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

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

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

The GA Cycle of Reproduction

```
reproduction  children
parents  modification
postulation  evaluated children

modified
children
discard
deleted
members
```

gene 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

```
Fitness  Selection  Parents  Cross-Over  Mutation
24748552  32%  32543213  24451524  24451524
32752411  23%  24548552  32752411  24756911
24451524  20%  32752411  24756911  24756911
32452413  11%  24451524  24451524  24451524
```
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### 8-queen example

GAs require states encoded as strings (GP's 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**
  - Randomized techniques
  - Derived from nature and evolution
  - Stochastic techniques
- **Evolutionary strategies**
  - Centralized
  - Distributed
  - Parallel
  - Steady-state
  - Generational
  - Sequential
- **Guided random search techniques**
  - Evolutionary algorithms
  - Simulated annealing
  - Dynamic programming
- **Enumerative techniques**
  - Search techniques

---

**Example application: evolving checkers players (Fogel'02)**

- Neural nets for evaluating future values of moves are evolved
- NNs have fixed structure with 5046 weights, these are evolved + one weight for “kings”
- Representation:
  - vector of 5046 real numbers for object variables (weights)
  - vector of 5046 real numbers for \( \sigma \)
- Mutation:
  - Gaussian, lognormal scheme with \( \sigma \)-first
  - Plus special mechanism for the kings’ weight
- Population size 15

---

**The GA Cycle of Reproduction**

![GA cycle diagram]

- Population
  - Parents
  - Evaluation
  - Modified children
  - Reproduction
- Discard
- Evaluated children
- Children
- New population

---

- **Example application: evolving checkers players (Fogel'02)**

  - Tournament size \( q = 5 \)
  - Programs (with NN inside) play against other programs, no human trainer or hard-wired intelligence
  - After 840 generation (6 months!) best strategy was tested against humans via Internet
  - Program earned “expert class” ranking outperforming 99.61% of all rated players
### 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 0 0 1 0 0 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

P1 (0 1 1 0 0 0 0 0)
P2 (1 1 1 1 0 1 0 0)

C1 (0 1 0 1 0 0 0 0)
C2 (1 1 1 1 0 1 0 0)

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

An Abstract Example

Distribution of Individuals in Generation 0

Distribution of Individuals in Generation N

A Simple Example

"The Gene is by far the most sophisticated program around."
- Bill Gates, Business Week, June 27, 1994

A Simple Example

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:

\[
\begin{array}{cccccccc}
\text{Parent1} & 3 & 5 & 7 & 2 & 1 & 6 & 4 & 8 \\
\text{Parent2} & 2 & 5 & 7 & 6 & 8 & 1 & 3 & 4 \\
\text{Child} & 5 & 8 & 7 & 2 & 1 & 6 & 3 & 4 \\
\end{array}
\]

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

Solution (Distance = 941)

Solution (Distance = 800)

Solution (Distance = 652)

Best Solution (Distance = 420)
Overview of Performance

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>filter design</td>
</tr>
<tr>
<td>Game Playing</td>
<td>poker, checkers, prisoner’s dilemma</td>
</tr>
<tr>
<td>Combinatorial</td>
<td>set covering, travelling salesman, routing, bin packing,</td>
</tr>
<tr>
<td>Optimization</td>
<td>graph colouring and partitioning</td>
</tr>
</tbody>
</table>

Review

4 main types of Evolutionary Algorithms

- Genetic Algorithm - John Holland
- Genetic Programming - John Koza
- Evolutionary Programming - Lawrence Fogel
- Evolutionary Strategies - Ingo Rechenberg

Genetic Algorithms

- Most widely used
- Robust
- uses 2 separate spaces
  - search space - coded solution (genotype)
  - solution space - actual solutions (phenotypes)
- Genotypes must be mapped to phenotypes before the quality or fitness of each solution can be evaluated

Genetic Programming

- Specialized form of GA
- Manipulates a very specific type of solution using modified genetic operators
- Original application was to design computer program
- Now applied in alternative areas eg. Analog Circuits
- Does not make distinction between search and solution space.
- Solution represented in very specific hierarchical manner

Evolutionary Strategies

- Like GP no distinction between search and solution space
- Individuals are represented as real-valued vectors.
- Simple ES
  - one parent and one child
  - Child solution generated by randomly mutating the problem parameters of the parent.
- Susceptible to stagnation at local optima

Evolutionary Strategies (cont’d)

- Slow to converge to optimal solution
- More advanced ES
  - have pools of parents and children
- Unlike GA and GP, ES
  - Separates parent individuals from child individuals
  - Selects its parent solutions deterministically
Evolutionary Programming

- Resembles ES, developed independently
- Early versions of EP applied to the evolution of transition table of finite state machines
- One population of solutions, reproduction is by mutation only
- Like ES operates on the decision variable of the problem directly (ie Genotype = Phenotype)
- Tournament selection of parents
  - better fitness more likely a parent
  - children generated until population doubled in size
  - everyone evaluated and the half of population with lowest fitness deleted.

Genetic Programming

- Evolves more complex structures - programs, Lisp code, neural networks
- Start with random programs of functions and terminals (data structures)
- Execute programs and give each a fitness measure
- Use crossover to create new programs, no mutation
- Keep best programs
- For example, place lisp code in a tree structure, functions at internal nodes, terminals at leaves, and do crossover at sub-trees - always legal in Lisp

Summary

<table>
<thead>
<tr>
<th></th>
<th>ES</th>
<th>EP</th>
<th>GA</th>
<th>GP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Representation</td>
<td>Real-valued</td>
<td>Real-valued</td>
<td>Binary-Valued</td>
<td>Genes</td>
</tr>
<tr>
<td>Self-Adaptation</td>
<td>Standard deviations and covariances</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Fitness</td>
<td>Objective function values</td>
<td>Scaled objective function value</td>
<td>Scaled objective function value</td>
<td>Scaled objective function value</td>
</tr>
<tr>
<td>Mutation</td>
<td>Main operator</td>
<td>Only operator</td>
<td>Background operator</td>
<td>Main operator</td>
</tr>
<tr>
<td>Recombination</td>
<td>Different variants, important for self-adaptation</td>
<td>None</td>
<td>Main Operator</td>
<td>Main Operator</td>
</tr>
<tr>
<td>Selection</td>
<td>Deterministic</td>
<td>Probabilistic</td>
<td>Probabilistic</td>
<td>Probabilistic</td>
</tr>
</tbody>
</table>

Evolutionary design

- Karl Sims Evolved Virtual Creatures (1994)
  - http://www.youtube.com/watch?v=XOHjycpg5iI
    - course work - 2005
- http://vimeo.com/7074089
structure expression:  
  head  
  neck (gene1)  
  grow (gene2)  
  stick (gene3)  
  bend (gene4)  
  twist (gene5)  

corresponding gene vector: <gene1, gene2, gene3, gene4, gene5>  

Figure 9.5 An example of a structure expression (created by the artist) and its corresponding gene vector (to be evolved by Maasor).

Figure 9.6 A frame of nine mutations. The parent is in the centre, surrounded by offspring.
Figure 9.14 Extract from an evolutionary tree. The tree has become too large to display clearly, so the artist has restricted the display to include only frames between one level above and one level below the current frame. Conus frames are not displayed.

Figure 9.24 The forms listed in a checklist. Mosaic version each as they would be in an arrangement as in the film ‘Mosaic’. 
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

• Games: Spore (2007)
  
  http://www.ted.com/talks/will_wright_makes_toys_that_make_worlds.html

• http://www.gametrailers.com/user-movie/spore-14min-2007-demonstration/86368
• http://eu.spore.com/home.cfm?lang=en