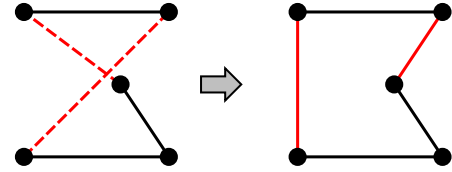


Example: Travelling Salesperson Problem

Start with any complete tour, perform pairwise exchanges



Variants of this approach get within 1% of optimal very quickly with thousands of cities

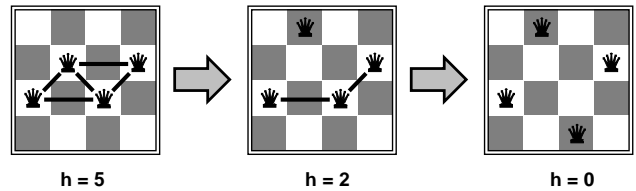
Outline

- ◇ Hill-climbing
- ◇ Simulated annealing
- ◇ Genetic algorithms (briefly)
- ◇ Local search in continuous spaces (very briefly)

Example: *n*-queens

Put *n* queens on an *n* × *n* board with no two queens on the same row, column, or diagonal

Move a queen to reduce number of conflicts



Almost always solves *n*-queens problems almost instantaneously for very large *n*, e.g., *n* = 1million

Iterative improvement algorithms

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

Then state space = set of "complete" configurations;
 find **optimal** configuration, e.g., TSP
 or, find configuration satisfying constraints, e.g., timetable

In such cases, can use **iterative improvement** algorithms; keep a single "current" state, try to improve it

Constant space, suitable for online as well as offline search

Hill-climbing (or gradient ascent/descent)

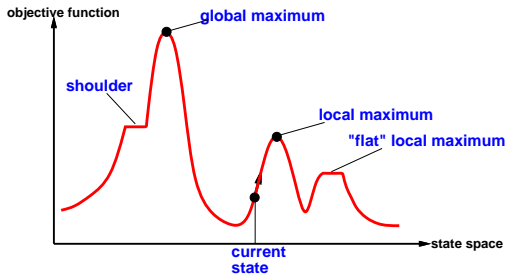
"Like climbing Everest in thick fog with amnesia"

```

function HILL-CLIMBING(problem) returns a state that is a local maximum
inputs: problem, a problem
local variables: current, a node
                  neighbor, a node
current ← MAKE-NODE(INITIAL-STATE[problem])
loop do
    neighbor ← a highest-valued successor of current
    if VALUE[neighbor] ≤ VALUE[current] then return STATE[current]
    current ← neighbor
end
    
```

Hill-climbing contd.

Useful to consider state space landscape



Random-restart hill climbing overcomes local maxima—trivially complete

Random sideways moves 🤪 escape from shoulders 🌀 loop on flat maxima

Local beam search

Idea: keep k states instead of 1; choose top k of all their successors

Not the same as k searches run in parallel!

Searches that find good states recruit other searches to join them

Problem: quite often, all k states end up on same local hill

Idea: choose k successors randomly, biased towards good ones

Observe the close analogy to natural selection!

Simulated annealing

Idea: escape local maxima by allowing some “bad” moves
but gradually decrease their size and frequency

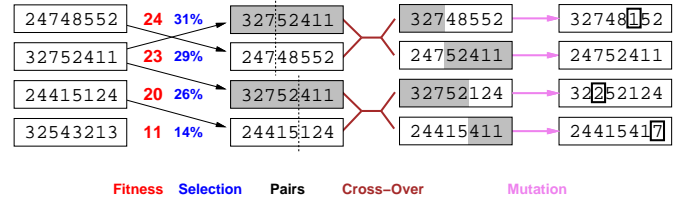
```

function SIMULATED-ANNEALING(problem, schedule) returns a solution state
  inputs: problem, a problem
         schedule, a mapping from time to “temperature”
  local variables: current, a node
                 next, a node
                 T, a “temperature” controlling prob. of downward steps

  current ← MAKE-NODE(INITIAL-STATE[problem])
  for t ← 1 to ∞ do
    T ← schedule[t]
    if T = 0 then return current
    next ← a randomly selected successor of current
    ΔE ← VALUE[next] − VALUE[current]
    if ΔE > 0 then current ← next
    else current ← next only with probability  $e^{\Delta E/T}$ 
    
```

Genetic algorithms

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



Fitness Selection Pairs Cross-Over Mutation

Properties of simulated annealing

At fixed “temperature” T , state occupation probability reaches Boltzman distribution

$$p(x) = \alpha e^{\frac{E(x)}{kT}}$$

T decreased slowly enough \implies always reach best state x^*

because $e^{\frac{E(x^*)}{kT}} / e^{\frac{E(x)}{kT}} = e^{\frac{E(x^*) - E(x)}{kT}} \gg 1$ for small T

Is this necessarily an interesting guarantee??

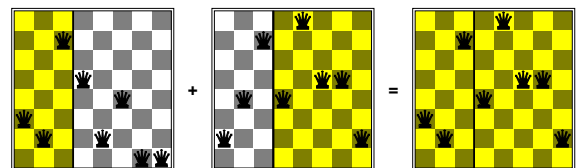
Devised by Metropolis et al., 1953, for physical process modelling

Widely used in VLSI layout, airline scheduling, etc.

Genetic algorithms contd.

GAs require states encoded as strings (GPs use programs)

Crossover helps iff substrings are meaningful components



GAs \neq evolution: e.g., real genes encode replication machinery!

Continuous state spaces

Suppose we want to site three airports in Romania:

- 6-D state space defined by $(x_1, y_1), (x_2, y_2), (x_3, y_3)$
- objective function $f(x_1, y_1, x_2, y_2, x_3, y_3) =$
sum of squared distances from each city to nearest airport

Discretization methods turn continuous space into discrete space,
e.g., empirical gradient considers $\pm\delta$ change in each coordinate

Gradient methods compute

$$\nabla f = \left(\frac{\partial f}{\partial x_1}, \frac{\partial f}{\partial y_1}, \frac{\partial f}{\partial x_2}, \frac{\partial f}{\partial y_2}, \frac{\partial f}{\partial x_3}, \frac{\partial f}{\partial y_3} \right)$$

to increase/reduce f , e.g., by $\mathbf{x} \leftarrow \mathbf{x} + \alpha \nabla f(\mathbf{x})$

Sometimes can solve for $\nabla f(\mathbf{x}) = 0$ exactly (e.g., with one city).

Newton–Raphson (1664, 1690) iterates $\mathbf{x} \leftarrow \mathbf{x} - \mathbf{H}_f^{-1}(\mathbf{x}) \nabla f(\mathbf{x})$

to solve $\nabla f(\mathbf{x}) = 0$, where $\mathbf{H}_{ij} = \partial^2 f / \partial x_i \partial x_j$