

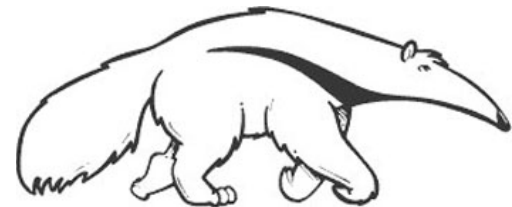
Local search algorithms

CS171, Fall 2017

Introduction to Artificial Intelligence

Prof. Richard Lathrop

Reading: R&N 4.1-4.2



Local search algorithms

- In many optimization problems, the **path** to the goal is irrelevant; **the goal state itself is the solution**
 - Local search: widely used for *very big* problems
 - Returns good but *not optimal* solutions
 - *Usually very slow*, but can yield good solutions if you wait
- State space = set of "complete" configurations
- Find a complete configuration satisfying constraints
 - Examples: n-Queens, VLSI layout, airline flight schedules
- **Local search algorithms**
 - Keep a single "current" state, or small set of states
 - Iteratively try to improve it / them
 - Very memory efficient
 - keeps only one or a few states
 - You control how much memory you use

Basic idea of local search (many variations)

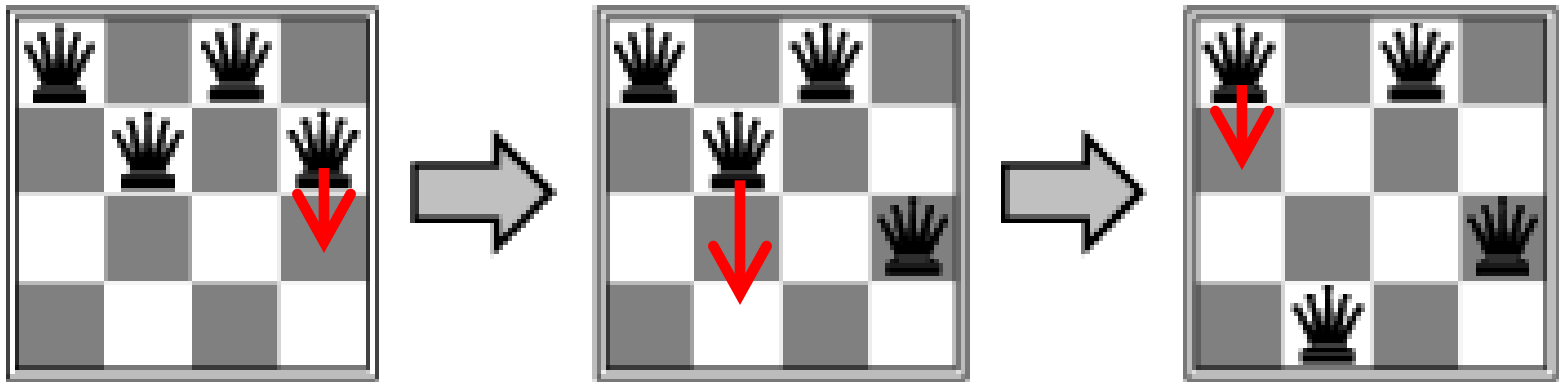
```
// initialize to something, usually a random initial state
// alternatively, might pass in a human-generated initial state
best_found  $\leftarrow$  current_state  $\leftarrow$  RandomState()
// now do local search
loop do
  if (tired of doing it) then return best_found
  else
    current_state  $\leftarrow$  MakeNeighbor( current_state )
    if ( Cost(current_state) < Cost(best_found) ) then
      // keep best result found so far
      best_found  $\leftarrow$  current_state
```

You, as algorithm designer, write the functions named in red.

Typically, “tired of doing it” means that some resource limit is exceeded, e.g., number of iterations, wall clock time, CPU time, etc. It may also mean that result improvements are small and infrequent, e.g., less than 0.1% result improvement in the last week of run time.

Example: n -queens

- Goal: Put n queens on an $n \times n$ board with no two queens on the same row, column, or diagonal
- Neighbor: move one queen to another row
- Search: go from one neighbor to the next...



Algorithm design considerations

- How do you represent your problem?
- What is a “complete state”?
- What is your objective function?
 - How do you measure cost or value of a state?
 - Stand on your head: **cost = -value, value = -cost**
- What is a “neighbor” of a state?
 - Or, what is a “step” from one state to another?
 - How can you compute a neighbor or a step?
- Are there any constraints you can exploit?

Random restart wrapper

- We'll use stochastic local search methods
 - Return different solution for each trial & initial state
- Almost every trial hits difficulties (see sequel)
 - Most trials will not yield a good result (sad!)
- Using many random restarts improves your chances
 - Many “shots at goal” may finally get a good one
- Restart a random initial state, *many times*
 - Report the best result found across *many* trials

Random restart wrapper

```
best_found ← RandomState() // initialize to something
```

```
// now do repeated local search
```

```
loop do
```

```
  if (tired of doing it)
```

```
    then return best_found
```

```
else
```

```
  result ← LocalSearch( RandomState() )
```

```
  if ( Cost(result) < Cost(best_found) )
```

```
    // keep best result found so far
```

```
    then best_found ← result
```

You, as algorithm designer, write the functions named in red.

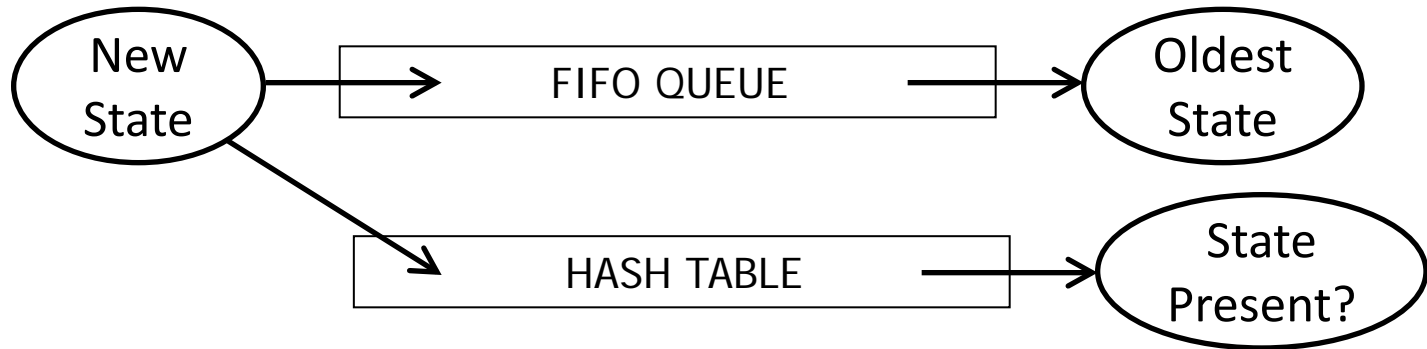
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It may also mean that result improvements are small and infrequent, e.g., less than 0.1% result improvement in the last week of run time.

Tabu search wrapper

- Add recently visited states to a tabu-list
 - Temporarily excluded from being visited again
 - Forces solver away from explored regions
 - Less likely to get stuck in local minima (hope, in principle)
- Implemented as a hash table + FIFO queue
 - Unit time cost per step; constant memory cost
 - You control how much memory is used
- `RandomRestart(TabuSearch (LocalSearch()))`

Tabu search wrapper (inside random restart!)



```
best_found  $\leftarrow$  current_state  $\leftarrow$  RandomState() // initialize
loop do // now do local search
  if (tired of doing it) then return best_found else
    neighbor  $\leftarrow$  MakeNeighbor( current_state )
    if ( neighbor is in hash_table ) then discard neighbor
  else push neighbor onto fifo, pop oldest_state
    remove oldest_state from hash_table, insert neighbor
    current_state  $\leftarrow$  neighbor;
    if ( Cost(current_state) < Cost(best_found) )
      then best_found  $\leftarrow$  current_state
```

Local search algorithms

- Hill-climbing search
 - Gradient descent in continuous state spaces
 - Can use, e.g., Newton's method to find roots
- Simulated annealing search
- Local beam search
- Genetic algorithms
- Linear Programming (for specialized problems)

Hill-climbing search

“...like trying to find the top of Mount Everest in a thick fog while suffering from 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
```

Ex: Hill-climbing, 8-queens

h = # of pairs of queens that are attacking each other, either directly or indirectly

$h=17$ for this state

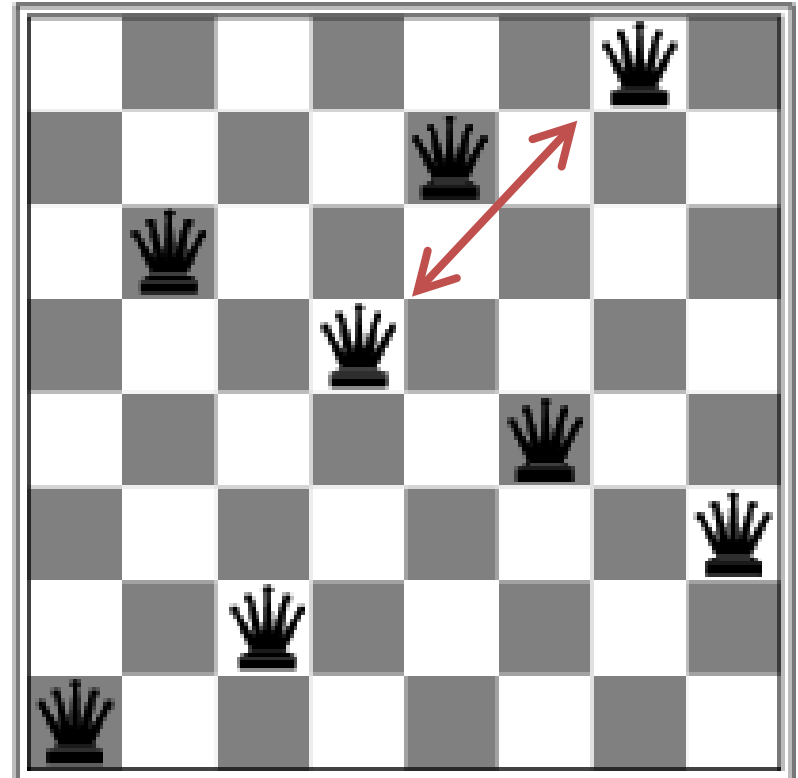
18	12	14	13	13	12	14	14
14	16	13	15	12	14	12	16
14	12	18	13	15	12	14	14
15	14	14		13	16	13	16
	14	17	15		14	16	16
17		16	18	15		15	
18	14		15	15	14		16
14	14	13	17	12	14	12	18

Each number indicates h if we move a queen in its column to that square

12 (boxed) = best h among all neighbors;
select one randomly

Ex: Hill-climbing, 8-queens

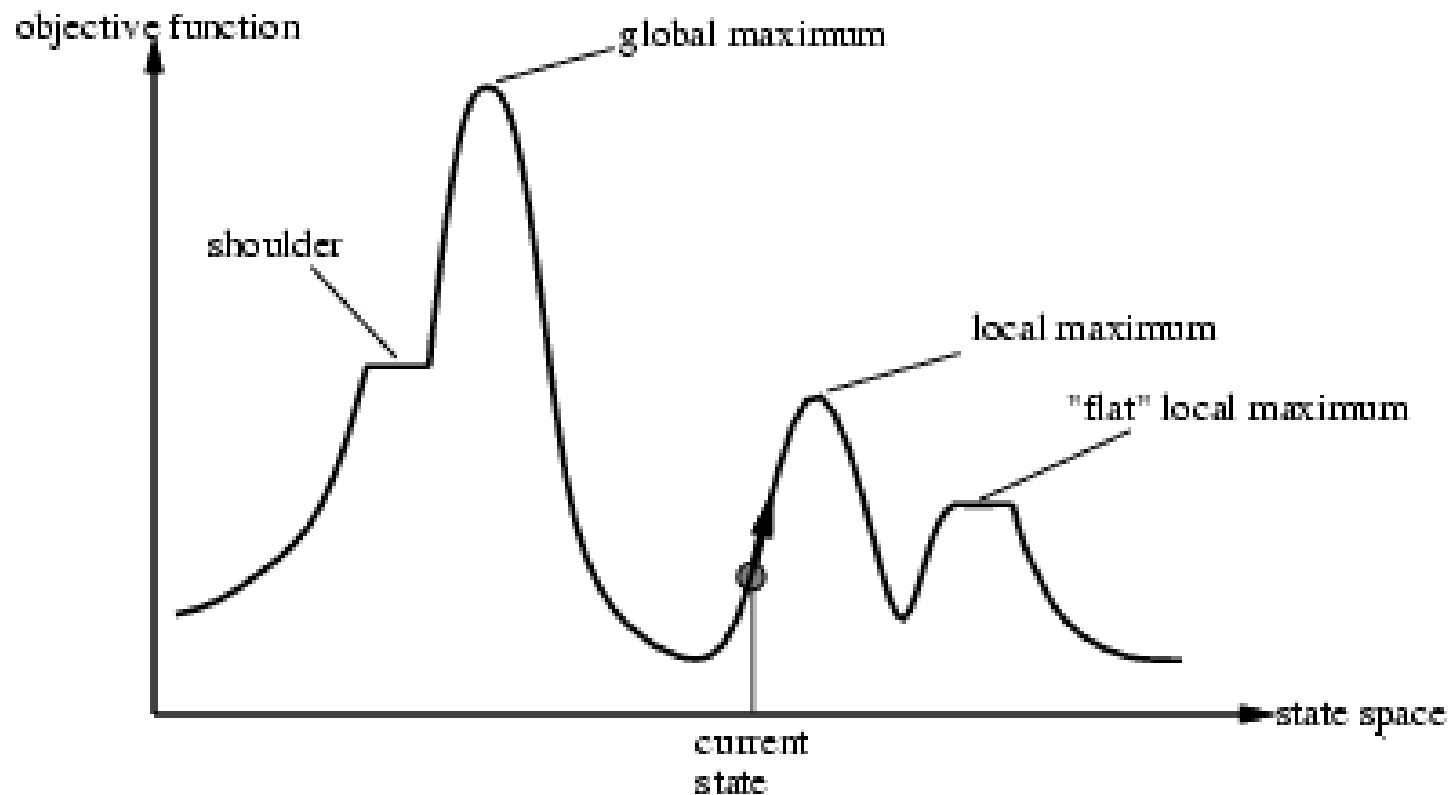
- A local minimum with $h=1$
- All one-step neighbors have higher h values
- What can you do to get out of this local minimum?



Hill-climbing difficulties

Note: these difficulties apply to all local search algorithms, and usually become much worse as the search space becomes higher dimensional

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



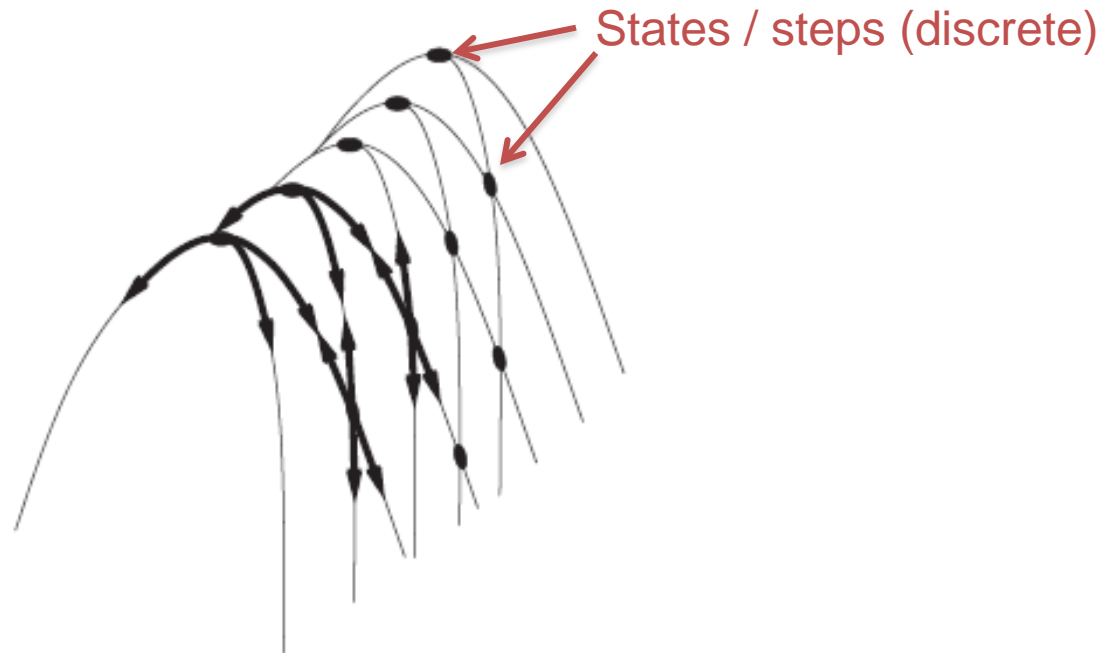
Hill-climbing difficulties

Note: these difficulties apply to all local search algorithms, and usually become much worse as the search space becomes higher dimensional

- Ridge problem: every neighbor appears to be downhill
 - But, search space has an uphill (just not in neighbors)
 -

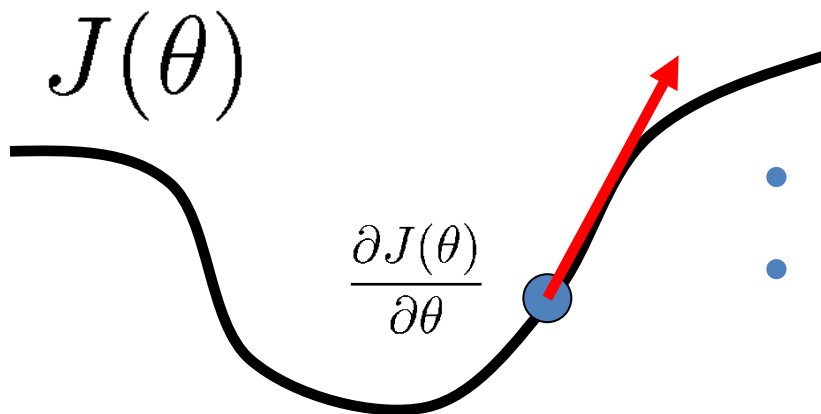
Ridge:

Fold a piece of paper and hold it tilted up at an unfavorable angle to every possible search space step. Every step leads downhill; but the ridge leads uphill.



Gradient descent

- Hill-climbing in continuous state spaces
- Denote “state” as θ , a vector of parameters
- Denote cost as $J(\theta)$



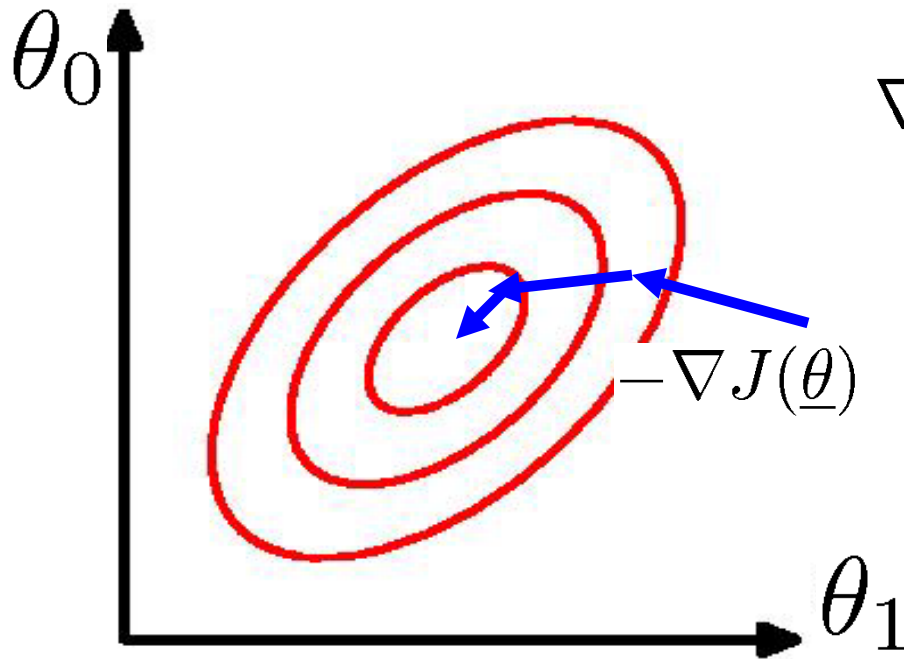
- How to change θ to improve $J(\theta)$?
- Choose a direction in which $J(\theta)$ is decreasing
- Derivative $\frac{\partial J(\theta)}{\partial \theta}$

The curly D means to take a derivative while holding all other variables constant. You are not responsible for multivariate calculus, but gradient descent is a very important method, so it is presented.

- Positive \Rightarrow increasing cost
- Negative \Rightarrow decreasing cost

Gradient descent

Hill-climbing in continuous spaces



- Gradient vector

$$\nabla J(\underline{\theta}) = \left[\frac{\partial J(\underline{\theta})}{\partial \theta_0} \quad \frac{\partial J(\underline{\theta})}{\partial \theta_1} \quad \dots \right]$$

Gradient = direction of steepest ascent

Negative gradient = steepest descent

Gradient descent

Hill-climbing in continuous spaces

Gradient = the most direct direction up-hill in the objective (cost) function, so its negative minimizes the cost function.

* Assume we have some cost-function: $J(x_1, x_2, \dots, x_n)$ and we want minimize over continuous variables x_1, x_2, \dots, x_n

1. Compute the *gradient* : $\frac{\partial}{\partial x_i} J(x_1, \dots, x_n) \quad \forall i$

2. Take a small step downhill in the direction of the gradient:

$$x'_i = x_i - \lambda \frac{\partial}{\partial x_i} J(x_1, \dots, x_n)$$

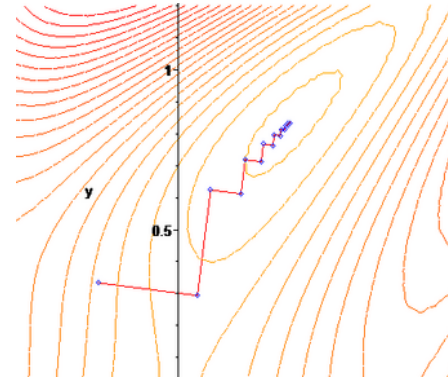
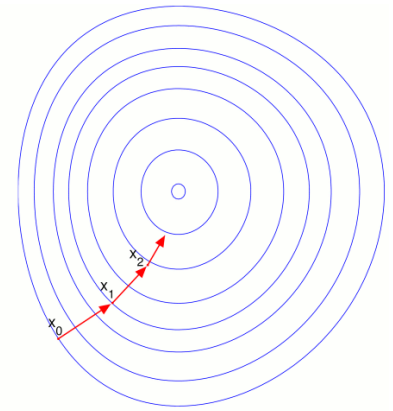
3. Check if $J(x'_1, \dots, x'_n) < J(x_1, \dots, x_n)$

(or, Armijo rule, etc.)

4. If true then accept move, if not "reject".

(decrease step size, etc.)

5. Repeat.



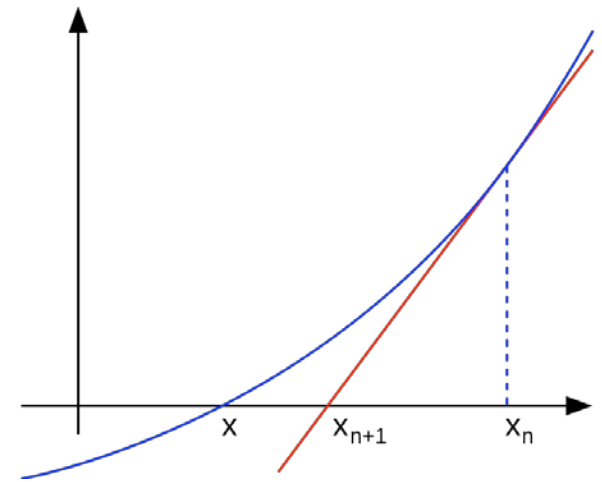
Gradient descent

Hill-climbing in continuous spaces

- How do I determine the gradient?
 - Derive formula using multivariate calculus.
 - Ask a mathematician or a domain expert.
 - Do a literature search.
- Variations of gradient descent can improve performance for this or that special case.
 - See Numerical Recipes in C (and in other languages) by Press, Teukolsky, Vetterling, and Flannery.
 - Simulated Annealing, Linear Programming too
- Works well in smooth spaces; poorly in rough.

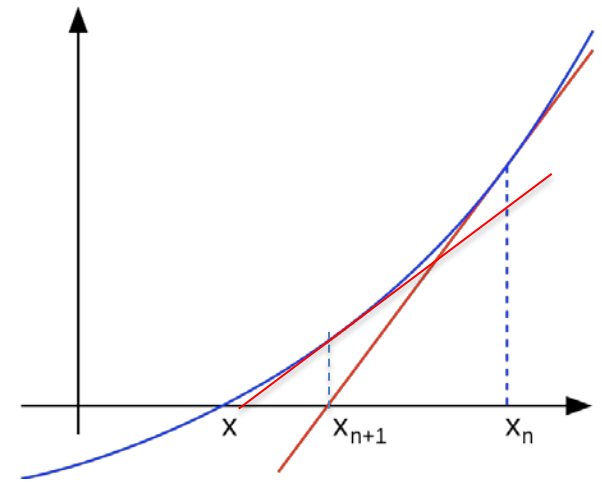
Newton's method

- Want to find the roots of $f(x)$
 - “Root”: value of x for which $f(x)=0$
- Initialize to *some* point x_n
- Compute the tangent at x_n & compute x_{n+1} = where it crosses x-axis



Newton's method

- Want to find the roots of $f(x)$
 - “Root”: value of x for which $f(x)=0$
- Initialize to *some* point x_n
- Compute the tangent at x_n & compute x_{n+1} = where it crosses x-axis
- Repeat for x_{n+1}
 - Does not always converge; sometimes unstable
 - If converges, usually very fast
 - Works well for smooth, non-pathological functions; accurate linearization
 - Works poorly for wiggly, ill-behaved functions; tangent is a poor guide to root



Simulated annealing (Physics!)

- Idea: escape local maxima by allowing some "bad" moves but **gradually decrease** their 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
     $\Delta E \leftarrow \text{VALUE}[\textit{next}] - \text{VALUE}[\textit{current}]$ 
    if  $\Delta E > 0$  then current ← next
    else current ← next only with probability  $e^{\Delta E/T}$ 
```

Improvement: Track the BestResultFoundSoFar. Here, this slide follows Fig. 4.5 of the textbook, which is simplified.

Typical annealing schedule

- Usually use a decaying exponential
- Axis values scaled to fit problem characteristics



Probability(accept worse successor)

- Decreases as temperature T decreases (accept bad moves early on)
- Increases as $|\Delta E|$ decreases (accept not “much” worse)
- Sometimes, step size also decreases with T

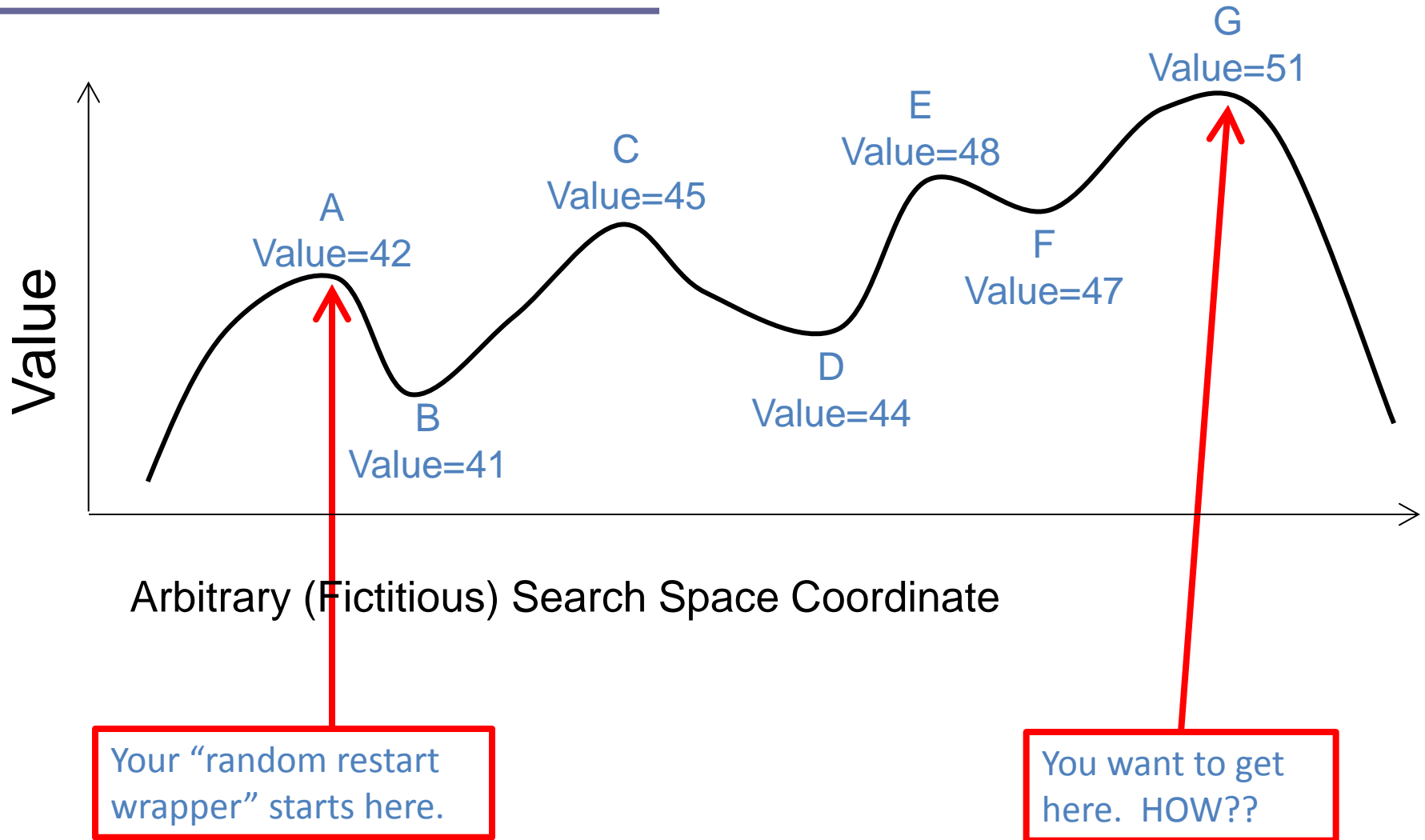
Temperature

$e^{\Delta E / T}$		Temperature T	
		High	Low
$ \Delta E $	High	Medium	Low
	Low	High	Medium

$next \leftarrow$ a randomly selected successor of $current$
 $\Delta E \leftarrow \text{VALUE}[next] - \text{VALUE}[current]$
 if $\Delta E > 0$ then $current \leftarrow next$
 else $current \leftarrow next$ only with probability $e^{\Delta E / T}$

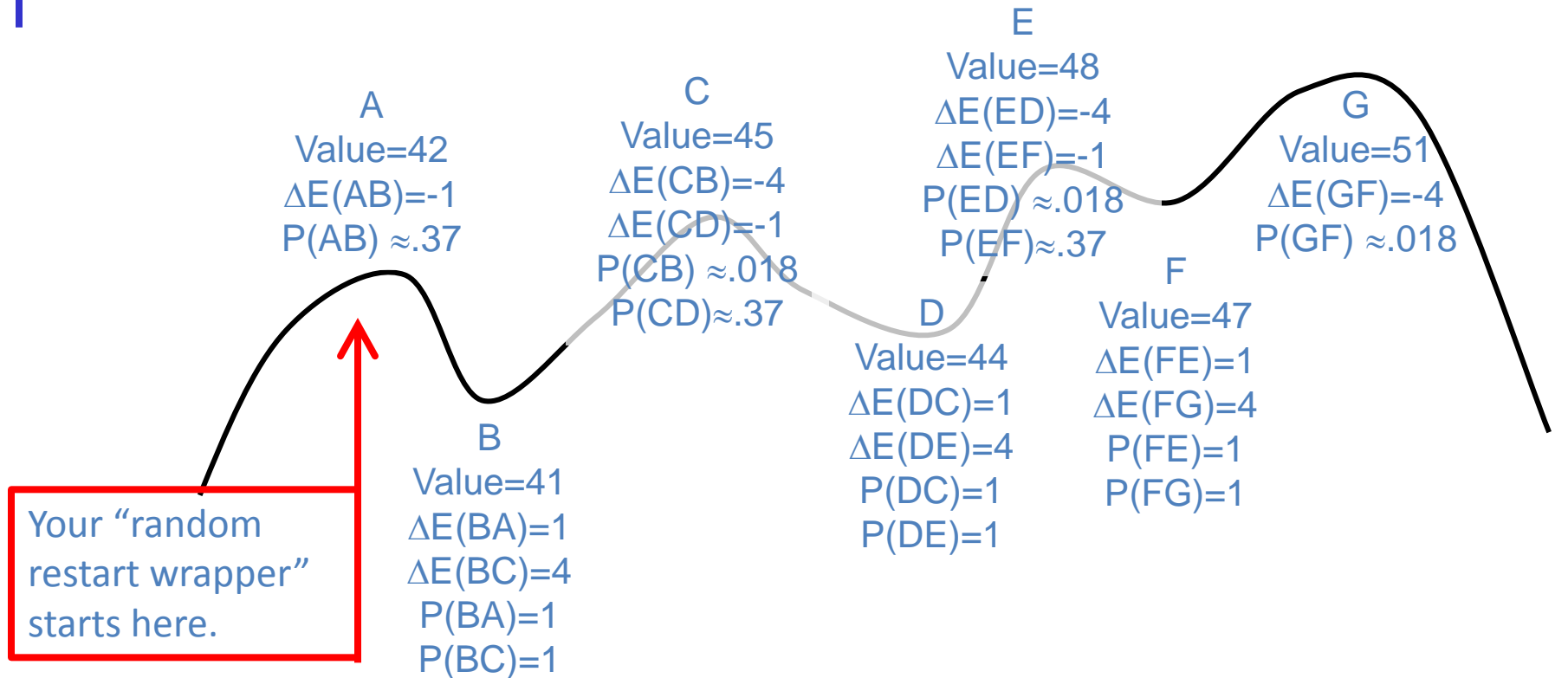
time \longrightarrow

Goal: “ratchet up” a jagged slope



This is an illustrative *cartoon*...

Goal: “ratchet up” a jagged slope



x	-1	-4
e ^x	≈.37	≈.018

From A you will accept a move to B with $P(AB) \approx .37$.
From B you are equally likely to go to A or to C.
From C you are $\approx 20X$ more likely to go to D than to B.
From D you are equally likely to go to C or to E.
From E you are $\approx 20X$ more likely to go to F than to D.
From F you are equally likely to go to E or to G.
Remember best point you ever found (G or neighbor?).

This is an illustrative *cartoon*...

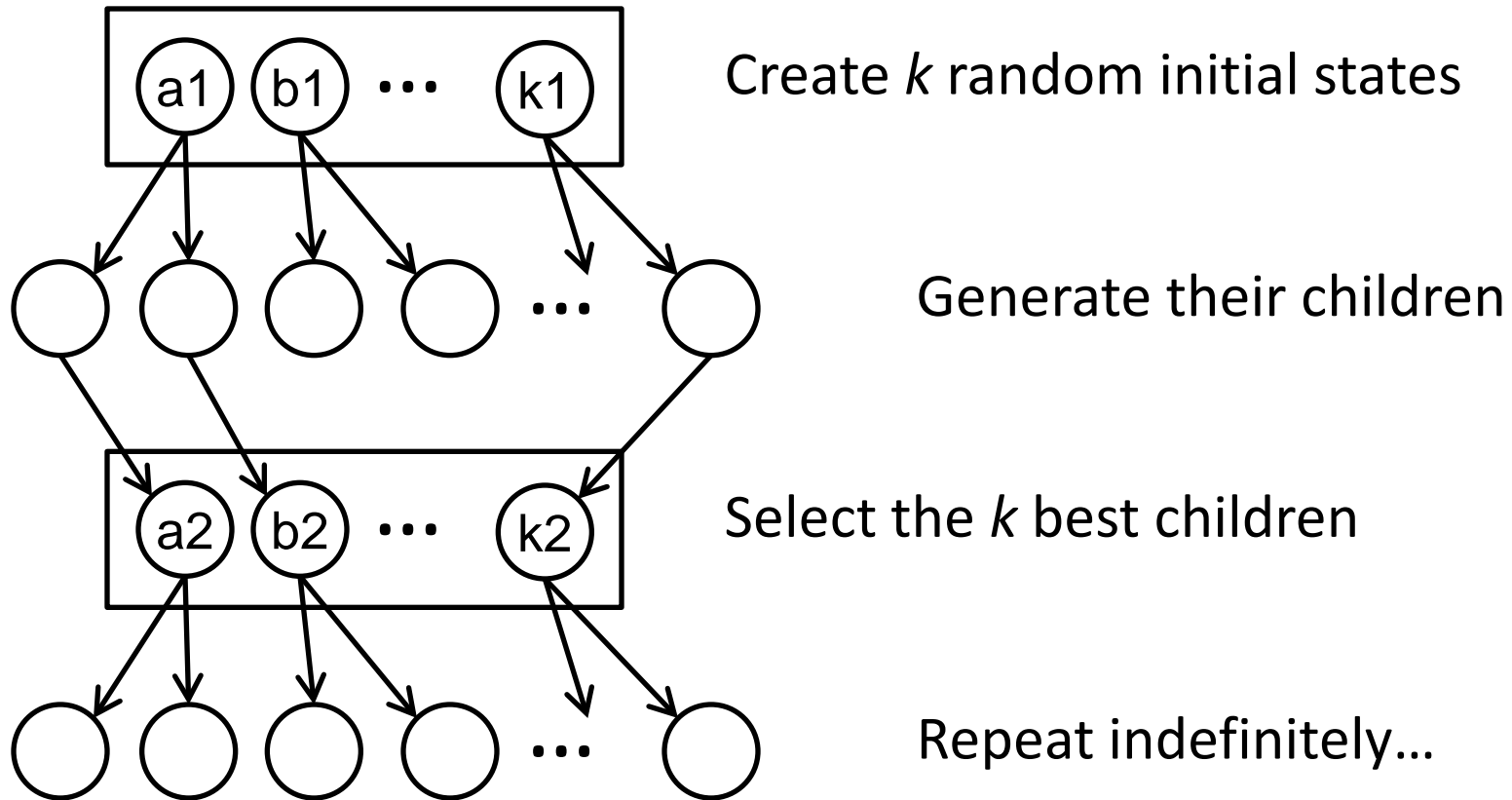
Properties of simulated annealing

- One can prove:
 - If T decreases slowly enough, then simulated annealing search will find a global optimum with probability approaching 1
 - Unfortunately this can take a VERY VERY long time
 - Note: in any finite search space, random guessing also will find a global optimum with probability approaching 1
 - So, ultimately this is a very weak claim
- Often works very well in practice
 - But usually VERY VERY slow
- Widely used in VLSI layout, airline scheduling, etc.

Local beam search

- Keep track of k states rather than just one
- Start with k randomly generated states
- At each iteration, all the successors of all k states are generated
- If any one is a goal state, stop; else select the k best successors from the complete list and repeat.
- Concentrates search effort in areas believed to be fruitful
 - May lose diversity as search progresses, resulting in wasted effort

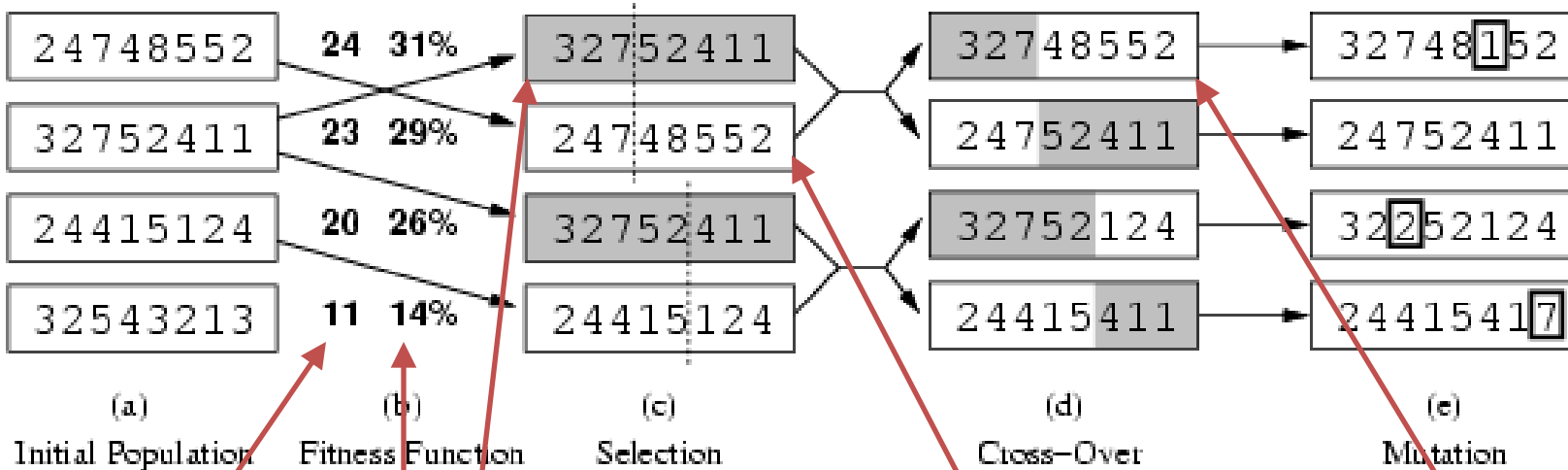
Local beam search



Is it better than simply running k searches?
Maybe...??

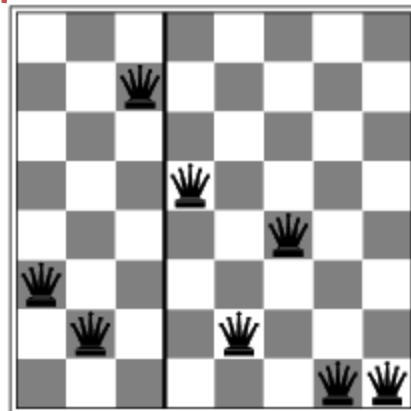
Genetic algorithms (Darwin!)

- State = a string over a finite alphabet (an **individual**)
 - A successor state is generated by combining two parent states
- Start with k randomly generated states (**population**)
- Evaluation function (**fitness function**).
 - Higher values for better states.
- **Select** individuals for next generation based on fitness
 - $P(\text{indiv. in next gen}) = \text{indiv. fitness} / \text{total population fitness}$
- **Crossover**: fit parents to yield next generation (offspring)
- **Mutate** the offspring randomly with some low probability

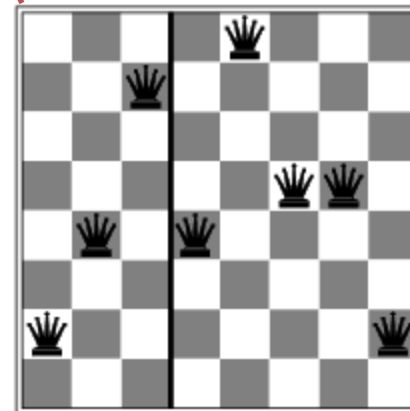


fitness =
#non-attacking
queens

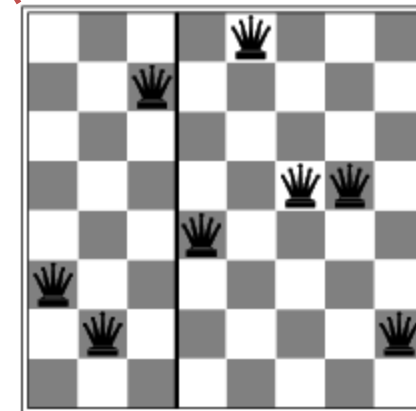
probability of being
in next generation =
 $\text{fitness} / (\sum_i \text{fitness}_i)$



+



=



- Fitness function: #non-attacking queen pairs
 - min = 0, max = $8 \times 7/2 = 28$
- $\sum_i \text{fitness}_i = 24 + 23 + 20 + 11 = 78$
- $P(\text{pick child}_1 \text{ for next gen.}) = \text{fitness}_1 / (\sum_i \text{fitness}_i) = 24/78 = 31\%$
- $P(\text{pick child}_2 \text{ for next gen.}) = \text{fitness}_2 / (\sum_i \text{fitness}_i) = 23/78 = 29\%$; etc

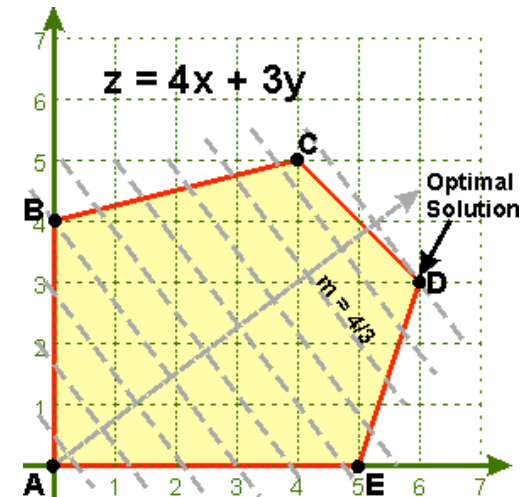
How to convert a
fitness value into a
probability of being in
the next generation.

Linear Programming

- Maximize: $z = c_1 x_1 + c_2 x_2 + \dots + c_n x_n$
- Primary constraints: $x_1 \geq 0, x_2 \geq 0, \dots, x_n \geq 0$
- Arbitrary additional linear constraints:
$$a_{i1} x_1 + a_{i2} x_2 + \dots + a_{in} x_n \leq a_i, (a_i \geq 0)$$
$$a_{j1} x_1 + a_{j2} x_2 + \dots + a_{jn} x_n \geq a_j \geq 0$$
$$b_{k1} x_1 + b_{k2} x_2 + \dots + b_{kn} x_n = b_k \geq 0$$
- Restricted class of linear problems.
 - Efficient for very large problems(!!) in this class.

Linear Programming Efficient Optimal Solution For a Restricted Class of Problems

- Very efficient “off-the-shelf” solvers are available for LPs.
- They quickly solve large problems with thousands of variables.



Summary

- Local search maintains a complete solution
 - Maintains a complete solution, seeks consistent (or at least good)
 - vs: Path search maintains a consistent solution; seeks complete
 - Goal of both: consistent & complete solution
- Types:
 - hill climbing, gradient ascent
 - simulated annealing, other Monte Carlo methods
 - Population methods: beam search; genetic / evolutionary algorithms
 - Wrappers: random restart; tabu search
- Local search often works well on very large problems
 - Abandons optimality
 - Always has some answer available (best found so far)
 - Often requires a very long time to achieve a good result