Informed search methods: IDA*
Constraint satisfaction search.

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Announcements

• Assignment 2 is up
  – Due date: Thursday, September 23, 2010

Course web page:
http://www.cs.pitt.edu/~milos/courses/cs1571/
Evaluation-function driven search

- A search strategy can be defined in terms of a node evaluation function
- **Evaluation function**
  - Denoted $f(n)$
  - Defines the desirability of a node to be expanded next

- **Evaluation-function driven search**: expand the node (state) with the best evaluation-function value
- **Implementation**: priority queue with nodes in the decreasing order of their evaluation function value

Best-first search

**Best-first search**

- incorporates a heuristic function, $h(n)$, into the evaluation function $f(n)$ to guide the search.
- **heuristic function**: measures a potential of a state (node) to reach a goal

**Special cases** (differ in the design of evaluation function):
- **Greedy search**
  
  $f(n) = h(n)$
- **A* algorithm**
  
  $f(n) = g(n) + h(n)$

+ **iterative deepening** version of A*: **IDA***
Properties of greedy search

- **Completeness:** *No.*
  We can loop forever. Nodes that seem to be the best choices can lead to cycles. Elimination of state repeats can solve the problem.
- **Optimality:** *No.*
  Even if we reach the goal, we may be biased by a bad heuristic estimate. Evaluation function disregards the cost of the path built so far.
- **Time complexity:** $O(b^m)$
  Worst case !!! But often better!
- **Memory (space) complexity:** $O(b^m)$
  Often better!

A* search

- The problem with the **greedy search** is that it can keep expanding paths that are already very expensive.
- The problem with the **uniform-cost search** is that it uses only past exploration information (path cost), no additional information is utilized
- **A* search**
  
  $f(n) = g(n) + h(n)$

  $g(n)$ - cost of reaching the state
  $h(n)$ - estimate of the cost from the current state to a goal
  $f(n)$ - estimate of the path length
- **Additional A*condition:** admissible heuristic
  
  $h(n) \leq h^*(n)$ for all $n$
Properties of A* search

- Completeness: Yes.
- Optimality: Yes (with the admissible heuristic)
- Time complexity:
  - Order roughly the number of nodes with $f(n)$ smaller than the cost of the optimal path $g^*$
- Memory (space) complexity:
  - Same as time complexity (all nodes in the memory)

Admissible heuristics

- Heuristics are designed based on relaxed version of problems
- Example: the 8-puzzle problem

<table>
<thead>
<tr>
<th>Initial position</th>
<th>Goal position</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 5 6</td>
<td>1 2 3</td>
</tr>
<tr>
<td>1 3 8</td>
<td>4 5 6</td>
</tr>
<tr>
<td>7 3 2</td>
<td>7 8</td>
</tr>
</tbody>
</table>

- Admissible heuristics:
  1. number of misplaced tiles
  2. Sum of distances of all tiles from their goal positions (Manhattan distance)
IDA*

Iterative deepening version of A*

- Progressively increases the evaluation function limit (instead of the depth limit)

- Performs limited-cost depth-first search for the current evaluation function limit
  - Keeps expanding nodes in the depth first manner up to the evaluation function limit

- **Problem:** the amount by which the evaluation limit should be progressively increased

Solutions:

1. **peak over the previous step boundary** to guarantee that in the next cycle some number of nodes are expanded
2. **Increase the limit by a fixed cost increment** – say $\varepsilon$

Cost limit = $k \varepsilon$
IDA* 

Solution 1: peak over the previous step boundary to guarantee that in the next cycle more nodes are expanded

Properties:
• the choice of the new cost limit influences how many nodes are expanded in each iteration
• Assume I choose a limit such that at least 5 new nodes are examined in the next DFS run
• What is the problem here?

---

IDA* 

Solution 1: peak over the previous step boundary to guarantee that in the next cycle more nodes are expanded

Properties:
• the choice of the new cost limit influences how many nodes are expanded in each iteration
• Assume I choose a limit such that at least 5 new nodes are examined in the next DFS run
• What is the problem here?
  
  We may find a sub-optimal solution
  
  – Fix: ?
**IDA***

**Solution 1:** peak over the previous step boundary to guarantee that in the next cycle more nodes are expanded

**Properties:**
- the choice of the new cost limit influences how many nodes are expanded in each iteration
- Assume I choose a limit such that at least 5 new nodes are examined in the next DFS run
- What is the problem here?
  - **Fix:** complete the search up to the limit to find the best

**IDA***

**Solution 2:** Increase the limit by a fixed cost increment ($\varepsilon$)

**Properties:**
- What is bad?

Cost limit = $k \varepsilon$
IDA*

Solution 2: Increase the limit by a fixed cost increment ($\varepsilon$)

Properties:
What is bad? Too many or too few nodes expanded – no control of the number of nodes
What is the quality of the solution?
The solution differs by $< \varepsilon$
Constraint satisfaction search

Search problem

A search problem:
- **Search space (or state space):** a set of objects among which we conduct the search;
- **Initial state:** an object we start to search from;
- **Operators (actions):** transform one state in the search space to the other;
- **Goal condition:** describes the object we search for

- **Possible metric on a search space:**
  - measures the quality of the object with respect to the goal

Search problems occur in planning, optimizations, learning
Constraint satisfaction problem (CSP)

Two types of search:
• path search (a path from the initial state to a state satisfying the goal condition)
• configuration search (a configuration satisfying goal conditions)

**Constraint satisfaction problem (CSP)** is a configuration search problem where:
• A state is defined by a set of variables
• Goal condition is represented by a set constraints on possible variable values

Special properties of the CSP lead to special procedures to be designed and applied for solving them

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Example of a CSP: N-queens

**Goal:** n queens placed in non-attacking positions on the board

**Variables:**
• Represent queens, one for each column: $Q_1, Q_2, Q_3, Q_4$
• Values:
  - Row placement of each queen on the board $\{1, 2, 3, 4\}$

**Constraints:** $Q_i \neq Q_j$ Two queens not in the same row
$|Q_i - Q_j| \neq |i - j|$ Two queens not on the same diagonal
Satisfiability (SAT) problem

Determine whether a sentence in the conjunctive normal form (CNF) is satisfiable (can evaluate to true)
- Used in the propositional logic (covered later)

\[(P \lor Q \lor \neg R) \land (\neg P \lor \neg R \lor S) \land (\neg P \lor Q \lor \neg T)\ldots\]

Variables:
- Propositional symbols (P, R, T, S)
- Values: True, False

Constraints:
- Every conjunct must evaluate to true, at least one of the literals must evaluate to true

\[(P \lor Q \lor \neg R) \equiv True, (\neg P \lor \neg R \lor S) \equiv True,\ldots\]

Other real world CSP problems

Scheduling problems:
- E.g. telescope scheduling
- High-school class schedule

Design problems:
- Hardware configurations
- VLSI design

More complex problems may involve:
- real-valued variables
- additional preferences on variable assignments – the optimal configuration is sought
Map coloring

Color a map using k different colors such that no adjacent countries have the same color

Variables: ?

• Variable values: ?

Constraints: ?

Map coloring

Color a map using k different colors such that no adjacent countries have the same color

Variables:
• Represent countries
  – A, B, C, D, E
• Values:
  – K -different colors
    {Red, Blue, Green,..}

Constraints: ?
Map coloring

Color a map using k different colors such that no adjacent countries have the same color

Variables:
• Represent countries
  – A, B, C, D, E
• Values:
  – K -different colors
  {Red, Blue, Green,..}

Constraints: A ≠ B, A ≠ C, C ≠ E, etc
An example of a problem with binary constraints

Constraint satisfaction as a search problem

Formulation of a CSP as a search problem:
• States. Assignment (partial, complete) of values to variables.
• Initial state. No variable is assigned a value.
• Operators. Assign a value to one of the unassigned variables.
• Goal condition. All variables are assigned, no constraints are violated.

• Constraints can be represented:
  – Explicitly by a set of allowable values
  – Implicitly by a function that tests for the satisfaction of constraints
Solving CSP as a standard search

Unassigned: $Q_1, Q_2, Q_3, Q_4$
Assigned:

Unassigned: $Q_2, Q_3, Q_4$
Assigned: $Q_1 = 1$

Unassigned: $Q_2, Q_3, Q_4$
Assigned: $Q_1 = 2$

Unassigned: $Q_3, Q_4$
Assigned: $Q_1 = 2, Q_2 = 4$

Solving a CSP through standard search

- Maximum depth of the tree (m): ?
- Depth of the solution (d) : ?
- Branching factor (b) : ?
Solving a CSP through standard search

- **Maximum depth of the tree:** Number of variables in the CSP
- **Depth of the solution:** Number of variables in the CSP
- **Branching factor:** if we fix the order of variable assignments, the branch factor depends on the number of their values

Depth of the tree = Depth of the solution = number of vars

```
Unassigned: Q_1, Q_2, Q_3, Q_4
Assigned:

Unassigned: Q_2, Q_3, Q_4
Assigned: Q_1 = 1

Unassigned: Q_2, Q_3, Q_4
Assigned: Q_1 = 2

Unassigned: Q_1, Q_4
Assigned: Q_1 = 2, Q_2 = 4

... ...
```

Solving a CSP through standard search

- **What search algorithm to use:** ?

Depth of the tree = Depth of the solution = number of vars

```
Unassigned: Q_1, Q_2, Q_3, Q_4
Assigned:

Unassigned: Q_2, Q_3, Q_4
Assigned: Q_1 = 1

Unassigned: Q_2, Q_3, Q_4
Assigned: Q_1 = 2

Unassigned: Q_3, Q_4
Assigned: Q_1 = 2, Q_2 = 4

... ...
```
Solving a CSP through standard search

• What search algorithm to use: Depth first search !!!
  • Since we know the depth of the solution
  • We do not have to keep large number of nodes in queues
Backtracking

Depth-first search for CSP is also referred to as backtracking.

The violation of constraints needs to be checked for each node, either during its generation or before its expansion.

Consistency of constraints:

- Current variable assignments together with constraints restrict remaining legal values of unassigned variables.
- The remaining legal and illegal values of variables may be inferred (effect of constraints propagates).
- To prevent “blind” exploration it is necessary to keep track of the remaining legal values, so we know when the constraints are violated and when to terminate the search.

Constraint propagation

A state (more broadly) is defined by a set of variables, their values and a list of legal and illegal assignments for unassigned variables.

Legal and illegal assignments can be represented via: equations (value assignments) and disequations (list of invalid assignments).

Example: map coloring

Equation $A = \text{Red}$

Disequation $C \neq \text{Red}$

Constraints + assignments can entail new equations and disequations

$A = \text{Red} \rightarrow B \neq \text{Red}$

Constraint propagation: the process of inferring of new equations and disequations from existing equations and disequations.
Constraint propagation

• Assign A=Red

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<tr>
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✓ - equations  ✗ - disequations

Constraint propagation

• Assign A=Red

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✓ - equations  ✗ - disequations
Constraint propagation

• Assign E=Blue

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Constraint propagation

• Assign E=Blue

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Constraint propagation

- Assign F=Green

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Constraint propagation

- Assign F=Green

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Constraint propagation

- Assign F=Green

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Conflict !!! No legal assignments available for B and C

Constraint propagation

- We can derive remaining legal values through propagation

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B=Green
C=Green
Constraint propagation

- We can derive remaining legal values through propagation

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B=Green  C=Green  ➔  F=Red
Constraint propagation

Three known techniques for propagating the effects of past assignments and constraints:

• Value propagation
• Arc consistency
• Forward checking

• Difference:
  – Completeness of inferences
  – Time complexity of inferences.

1. Value propagation. Infers:
   – equations from the set of equations defining the partial assignment, and a constraint

2. Arc consistency. Infers:
   – disequations from the set of equations and disequations defining the partial assignment, and a constraint
   – equations through the exhaustion of alternatives

3. Forward checking. Infers:
   – disequations from a set of equations defining the partial assignment, and a constraint
   – Equations through the exhaustion of alternatives

Restricted forward checking:
   – uses only active constraints (active constraint – only one variable unassigned in the constraint)
Example

Map coloring of Australia territories

Example: forward checking

Map coloring

Set: WA=Red

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<th>vars</th>
<th>WA</th>
<th>NT</th>
<th>Q</th>
<th>NSW</th>
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Example: forward checking

Map coloring

Set: WA=Red

<table>
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Example: forward checking

Map coloring

Set: Q=Green

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<th>NT</th>
<th>Q</th>
<th>NSW</th>
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Example: forward checking

Map coloring

Set: Q=Green

<table>
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Infer: Exhaustions of alternatives

Example: forward checking

Map coloring

Infer: Exhaustions of alternatives
Example: forward checking

Map coloring

Infer: Exhaustions of alternatives

<table>
<thead>
<tr>
<th>vars</th>
<th>WA</th>
<th>NT</th>
<th>Q</th>
<th>NSW</th>
<th>V</th>
<th>SA</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>domain</td>
<td>R R B</td>
<td>R R B</td>
<td>R R B</td>
<td>R R B</td>
<td>R R B</td>
<td>R R B</td>
<td>R R B</td>
</tr>
<tr>
<td>WA=Red</td>
<td>R</td>
<td>G B</td>
<td>R R B</td>
<td>R R B</td>
<td>R R B</td>
<td>G B</td>
<td>R R B</td>
</tr>
<tr>
<td>Q=Green</td>
<td>R</td>
<td>B</td>
<td>G</td>
<td>R B</td>
<td>R R B</td>
<td>B</td>
<td>R R B</td>
</tr>
<tr>
<td>Infer NT</td>
<td>R</td>
<td>B</td>
<td>G</td>
<td>R B</td>
<td>R R B</td>
<td>!</td>
<td>R R B</td>
</tr>
</tbody>
</table>

Example: arc consistency

Map coloring

Set: WA=Red
Set: Q=Green
### Example: arc consistency

**Map coloring**

Set: **WA=Red**
Set: **Q=Green**

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<tr>
<th>vars</th>
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<tr>
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<td>R G B</td>
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Consistent assignment

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### Example: arc consistency

**Map coloring**

Set: **WA=Red**
Set: **Q=Green**

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SA=B
NSW=R
Consistent assignment
Example: arc consistency

Map coloring

Set: WA=Red
Set: Q=Green

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NSW=B
SA=! 
Inconsistent assignment
Heuristics for CSPs

CSP searches the space in the depth-first manner. But we still can choose:
• Which variable to assign next?
• Which value to choose first?

Heuristics
• Most constrained variable
  – Which variable is likely to become a bottleneck?
• Least constraining value
  – Which value gives us more flexibility later?

Examples: map coloring

Heuristics
• Most constrained variable
  – ?
• Least constraining value
  – ?
Heuristics for CSP

Examples: map coloring

Heuristics

• Most constrained variable
  – Country E is the most constrained one (cannot use Red, Green)

• Least constraining value
  – ?

Heuristics for CSP

Examples: map coloring

Heuristics

• Most constrained variable
  – Country E is the most constrained one (cannot use Red, Green)

• Least constraining value
  – Assume we have chosen variable C
  – What color is the least constraining color?
Heuristics for CSP

Examples: map coloring

Heuristics

• Most constrained variable
  – Country E is the most constrained one (cannot use Red, Green)

• Least constraining value
  – Assume we have chosen variable C
  – Red is the least constraining valid color for the future