Cooperative Heuristic Search with Software Agents

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April 24, 2014
Outline

Cooperation and heuristic search

The A! algorithm

Solving $n$-puzzles with A!

Conclusion
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Cooperation

**cooperate**

- to work together
- to work with another person or group to do something
- to be helpful by doing what someone asks or tells you to do
- to act in a way that makes something possible or likely
- to produce the right conditions for something to happen

*(Merriam-Webster)*
Heuristic Search

- Searching is a fundamental computing task
- A heuristic provides focus to searching efforts
- The most well-known heuristic search algorithm is the $A^*$
A* search¹

- Informed best-first graph search algorithm
- Single-source shortest path problem (SSSP)
- Fringe nodes ranked by a cost estimate

\[ f(n) = g(n) + h(n) \]

- Admissible heuristics never overestimate, \( h(n) \leq h^*(n) \)
- Consistent heuristics guarantee optimality

\[ h(n) \leq d(n, n') + h(n') \]

- Optimally efficient on given heuristic
  - No algorithm can expand fewer nodes, except in tie-breaks

Constructing cooperative search

- **The goal**
  - Search faster as a collective, leverage parallel hardware

- **The hypothesis**
  - Cooperating search agents outperform agents in isolation

- **The idea**
  - Cooperation is communication
  - Agents share and make good use of progress information

- **The method**
  - A secondary ranking heuristic, a dynamic tiebreaker

- **The mechanism**
  - Asynchronous messaging, natural concurrency, implicit randomness, nondeterministic exploration

*Unus pro omnibus, omnes pro uno.*
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Overview of A!

- $A^* +$ cooperation + concurrency = A! (a-bang)
- A cooperative heuristic search algorithm for the SSSP
- Search agents run an upgraded version of $A^*$
- Shared information included as a secondary heuristic, $\hat{h}$
- Simplest case: share best encountered $(n, h(n))$-pair

- Vanilla $A^*$ maintains a node priority queue sorted by

$$f(n) = g(n) + h(n),$$

A! takes $k$ equal-valued nodes from the top, ranks by $\hat{h}$
A! search on a grid graph with two agents, A and B. Between nodes t and u, of equal distance to G (1st heuristic), agent A chooses u, because its closer (2nd heuristic) to best node marked with star, discovered by B.
Optimality of A!

- Proof sketch based on an argument for A* itself\(^2\)
- Cost estimates, \(f\)-values, are nondecreasing for all paths
  - Consistent heuristic
- Optimal path to a node is found before the node is opened
  - Expansion from the fringe, edge connection
- Let \(S\) be a subset of all equally good candidate nodes, \(E_S\)
  all explored nodes with a successor in \(S\)

1. \(f(n')\) is the same for all \(n' \in S\), so for \(n \in E_S\)
   \[
   f(n') = g(n') + h(n') = g(n) + d(n, n') + h(n') \geq g(n) + h(n) = f(n)
   \]

2. For a node to be opened before an optimal path there is found, another fringe node \(m\) with a better \(f\)-value is implied, but then \(f(n) < f(m)\) and \(f(n) > f(m)\).

A! cooperation architecture

- Agents process async messages at their own pace
  - Concurrency, nondeterminism; implicit randomness
- Best-effort notion of a globally superior reference node

- A *message broker* entity can facilitate communication
  - Instantaneous diffusion is *not* the goal
  - Publish/subscribe-topology (*cf. web chat*)
- Short-circuiting best-update leads to a **momentum effect**
  - Prefer nodes near the previously explored ones
  - Manifest already with a single agent

- Actor abstraction, fast termination, diversification, ...
Algorithm 1: A!Search

Require:  \( N > 0 \), NODE start, PREDICATE isGoal, HEURISTIC \( h \), HEURISTIC \( \hat{h} \)
Ensure:  path from start to nearest node satisfying isGoal is shortest possible

\[
\begin{align*}
mb & \leftarrow \text{MsgBroker}() \\
\text{for } i = 0 \text{ to } N & \text{ do} \\
\quad \text{workers}[i] & \leftarrow \text{A!Solver}(mb.portOut, mb.portIn, s, isGoal, h, \hat{h}) \\
\text{end for} \\
\text{for each worker in workers in parallel do} \\
\quad \text{worker.launch()} \\
\text{end for} \\
\text{wait for termination} \\
\text{return } \text{path} \leftarrow \text{getPath(workers)}
\end{align*}
\]
Algorithm 2: A!Solver

Require: PORT portIn, portOut, NODE start, PRED isGoal, HEUR h,  \hat{h}

1: openHeap ← FibonacciHeap\langle INTEGER, NODE\rangle
2: closedSet ← Set\langle NODE\rangle
3: pathMap ← Map\langle NODE, NODE\rangle
4: current ← start
5: repeat
6: if isGoal(current) then terminate(current, start, pathMap) end if
7: closedSet.add(current)
8: for each n in current.getNeighbors() do
9: if closedSet.contains(n) then continue end if
10: g ← current.g + dist(current, n)
11: f ← g + h(n)
12: improved ← openHeap.update(n, f)
13: if improved then pathMap.update(n, current) end if
14: end for
15: peekList ← openHeap.getPeekList()
16: if isEmpty(peekList) then terminate() end if
17: current ← A!Select(peekList, portIn, portOut, h,  \hat{h})
18: openHeap.remove(current)
19: until termination
Algorithm 3: A!Select

Require: \textsc{LIST} \textit{peekList}, \textsc{PORT} \textit{portIn}, \textit{portOut}, \textsc{HEURISTIC} \textit{h}, \hat{h}  

Ensure: \textit{select} is the most promising node in \textit{peekList} according to \hat{h} on \textit{best}  

1: \textit{update}, updateH \leftarrow \text{asyncRecv}(\textit{portIn})  
2: \textbf{if} updateH < bestH \textbf{then}  
3: \hspace{1em} best, bestH \leftarrow \textit{update}, updateH  
4: \textbf{end if}  
5: \textit{select} \leftarrow \textit{peekList}.pop()  
6: selectD \leftarrow \hat{h} (\textit{select}, \textit{best})  
7: \textbf{for each} \textit{node} in \textit{peekList} \textbf{do}  
8: \hspace{1em} d \leftarrow \hat{h}(\textit{node}, \textit{best})  
9: \hspace{1em} \textbf{if} d < selectD \textbf{then} \textit{select}, selectD \leftarrow \textit{node}, d \textbf{end if}  
10: \textbf{end for}  
11: \textbf{if} \textit{h(\textit{select})} < bestH \textbf{then}  
12: \hspace{1em} best, bestH \leftarrow \textit{select}, selectH  
13: \hspace{1em} \text{asyncSend}(\textit{portOut}, \{\textit{best}, bestH\})  
14: \textbf{end if}  
15: \textbf{return} \textit{select}
A! tradeoffs and challenges

- Shared memory vs. distributed
- Cooperation details: what to share and how, usage
- Maintaining diversity: partitioning, hashing, ...
- IDA* and maintaining memory-efficiency
- Clean, fast termination
- Priority queue bottleneck
- Agent abstraction: actors, coroutines, ...
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The $n$-puzzle

A start state

A standard goal state
The \( n \)-puzzle

- Classic sliding tile puzzle with a long history\(^3\)
- Turn the start state into the target state by sliding tiles
- Literally a toy problem
  - Finding \( k \)-bound sequence for general \( m \times m \) is NP-C\(^4\)
- 8-puzzle avg branching factor \( \sim 3 \), avg solution 22 steps
  - \( 3^{22} \) tree states, \( \frac{9!}{2} \approx 180k \) graph
  - 15-puzzle \( 1.3 \times 10^{12} \), 24-puzzle \( \sim 10^{25} \)
- Hardest 8-p on 31 steps, 15-p 80, 24-p 152–208
  - cf. God’s Number for the Rubik’s Cube is 20 (Rokicki et al., 2010)

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Heuristics for $n$-puzzle

- Misplaced tile count
- **Manhattan distance**
  - The sum of distances the tiles are from their target positions, counted as moves along the grid
- **Manhattan distance with linear collisions**
  - Two tiles on the right row, but in the wrong order must pass each other to reach their targets
- Walking distance
- Pattern databases
- **Additive/disjoint pattern databases**
  - Store precomputed solutions to sub-problems; disjoint sets ensure combination heuristic remains admissible
- Learned heuristics
Computational setting

- Randomly generated 8- and 15-puzzle instances
- Grouped by optimal path length
  - Substantial variance within each group
- Simple A! implementation based on A* by Brian Borowski
- Focus on **nodes opened by winning agent**
  - Correlates with runtime, total opened count
- Comparison with A* and non-coop randomized A*, A?
  - A!Select → A*Select, A?Select
- Test execution on Aalto SCI Science-IT project resources
  - **Triton** cluster of mixed multi-core blade servers
    - 2.6GHz Opteron 2435, 2.67GHz Xeon X5650, and 2.8GHz Xeon E5 2680 v2
Results: Cooperation benefit and scalability

15–puzzle runs, length groups 40–59, 1–8 agents, PDB heuristic.

Relative performance of $A^*$ (x-axis) and $A!$ (y-axis). The black line is par, so data points below it represent instances for which $A!$ performs better than $A^*$. Agent count is evaluated in five batches – 1, 2, 4, 6, and 8 agents – with the respective trend lines showing how the methods compare.
Results: Cooperation benefit and scalability

15-puzzle runs, length groups 40–59, 1–8 agents, PDB heuristic.

Relative performance of A? and A!. As before, the data points and trend lines below par-line reflect the benefit from cooperation. The slopes vary from around $\frac{7}{10}$ to $\frac{8}{10}$, reflecting a 25 – 40% performance difference in favor of A!. 
Results: Cooperation benefit and scalability

General A*, A? and A! performance trends. 100 inst./group. 1, 2, 4, 6, and 8 agents. Cooperation appears to be more beneficial with harder instances.
A*-normalized length groups
Scaling benefit from more agents
Overlapping trend lines
Rudimentary asymptotics
Results: Heuristic impact

Heuristic comparison with data grouped by agent configuration. The trend lines being essentially the same indicates that the number of agents is not strongly correlated with heuristic impact: regardless of method, two agents benefit from a better heuristic as much (or little) as eight agents.
Heuristic comparison with data grouped by method. The now more visible difference in trend lines suggests that A! benefits more from the improved heuristic than A?. The slope is about $\frac{1}{8}$ for A?, and around $\frac{1}{10}$ for A!.
Results: Path diversity

Visualization of $A^*$, $A?$ and $A!$ on 8-puzzle [8 6 7 2 5 4 3 0 1]. The heat-maps are derived from a $9 \times 9$ self-organizing map trained on an optimal solution path of 31 steps, shown top left in the codomain.

<table>
<thead>
<tr>
<th>METHOD</th>
<th>$A^*$</th>
<th>$A?$</th>
<th>$A!$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FREQ.</td>
<td>1  2  3 4</td>
<td>1  2  3 4</td>
<td>1  2  3 4</td>
</tr>
<tr>
<td>MEAN</td>
<td>648 414 269 4780</td>
<td>3290 1147 903 5245</td>
<td>562 600 1006 4544</td>
</tr>
<tr>
<td>RATIO</td>
<td>0.11 0.07 0.04 0.78</td>
<td>0.31 0.11 0.09 0.50</td>
<td>0.08 0.09 0.15 0.68</td>
</tr>
<tr>
<td>STD</td>
<td>476 363 235 525</td>
<td>1345 559 327 716</td>
<td>233 254 372 656</td>
</tr>
</tbody>
</table>

State visits for $A^*$, $A?$ and $A!$. The table gives the mean, ratio and standard deviation of state visit frequencies from ten iterations of $A^*$ on four agents with Manhattan heuristic.
Results: Path diversity

16 × 16 SOM visualization of A*, A? and A! on 54-optimal 15-puzzle \[12 \ 8 \ 6 \ 3 \ 13 \ 4 \ 2 \ 7 \ 0 \ 9 \ 15 \ 5 \ 14 \ 10 \ 11 \ 1\].

<table>
<thead>
<tr>
<th>METHOD</th>
<th>A*</th>
<th>A?</th>
<th>A!</th>
</tr>
</thead>
<tbody>
<tr>
<td>FREQ.</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>MEAN</td>
<td>661</td>
<td>862</td>
<td>346</td>
</tr>
<tr>
<td>RATIO</td>
<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>STD</td>
<td>352</td>
<td>1573</td>
<td>379</td>
</tr>
</tbody>
</table>

State visits for A*, A? and A! on 15-puzzle \[12 \ 8 \ 6 \ 3 \ 13 \ 4 \ 2 \ 7 \ 0 \ 9 \ 15 \ 5 \ 14 \ 10 \ 11 \ 1\]. The table gives the mean, ratio and standard deviation of state visit frequencies from ten iterations of A* on four agents with a 6-6-3 disjoint pattern database heuristic.
Results: Hybrid performance

- Diminishing returns from simply adding more agents
  - Search overhead, new agents mostly tread on old paths
- Path diversity is essential
  - Secondary heuristic performance depends on it
- Ideally, one would like to have the focused search performance of A! and the diversity apparent in A?
  - A! + A? = A''

- Simple threshold combination does not appear to work
  - A! seems to skip past the very states that A? wastes time on
Hybrid $A''$ performance over multiple $p$-thresholds

Three iterations per instance per group in the 45–54 range

$A!$ likelihood over $A?$ grows with $p$ to the right

- The downward trending slopes suggest that adding some $A?$ elements into $A!$ does not improve overall performance
Results: Discussion

- A! outperforms both vanilla A* and the non-cooperative random parallel search A*-variant A?
- Nondeterministic cooperation emerging from async message exchange was shown to be beneficial
- With more agents, A! was shown to work better
  - Rapidly diminishing returns
  - Search overhead appeared to be an issue
- Adding simple explicit randomization did not help
  - More robust diversity increasing mechanisms are needed
- A! demonstrated extra sensitivity for heuristic improvement
  - The reason for this is unclear
- SOM visualization proved thought-provoking, but lo-fi
  - More appropriate visualizations worth exploring
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Thesis summary

- Cooperation approach to parallel computing
- Heuristic search context, parallel A*
  - Cooperation as a secondary heuristic
- Cooperation is communication
  - Asynchronity, concurrency and nondeterminism
  - Ripple effects, implicit randomness
- The A! algorithm
- Empirical study, computational experiments
  - Performance, scalability
  - Path diversity, heuristic sensitivity
  - Hybrid algorithm
Related work