

PARA*: Parallel Anytime Repairing A*

AAAI 2015 Submission X

Abstract

PARA* is an anytime parallel heuristic search algorithm based on ARA* and PA*SE, which are in turn based on A*.

Fancy Stuff

Algorithm 1 Auxiliary Functions

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FUNCTION  $f(s)$ 
  return  $g(s) + wh(s, s_{goal})$ 
FUNCTION  $g_{back}(s', s)$ 
  if  $w \leq \epsilon$  then
    return  $g(s) + f(s') - f(s) + (2\epsilon - w - 1)c_l$ 
  else
    return  $\frac{\epsilon}{w}(g(s) + f(s') - f(s)) + (\epsilon - 1)c_l$ 
  end if
FUNCTION  $bound(s)$ 
   $g_{front} := g_p(s)$ 
   $s' := \text{first node in } OPEN \cup BE$ 
  while  $g_{back}(s', s) < g(s) \leq g_{front}$  do
     $g_{front} := \min(g_{front}, g_p(s') + \epsilon h(s', s))$ 
     $s' := \text{node following } s' \text{ in } OPEN \cup BE$ 
  end while
  return  $\min(g_{front}, g_{back}(s', s))$ 

```

We assume all edge costs are bounded below by c_l . h must be consistent: $h(s, s') \leq c(s, s')$ and $h(s, s') \leq h(s, s'') + h(s'', s')$ for all s, s', s'' . For most applications, we recommend using $w = \epsilon$. However, our analysis will show that using small w yields strong parallelism guarantees. All operations on the data structures *OPEN*, *BE*, *CLOSED*, *FROZEN* are assumed to be atomic, i.e. they are implicitly preceded and succeeded by synchronous locks and unlocks to the data structure, respectively. $v(s)$ is included to aid the analysis but is never used in the algorithm.

Lemma 1. *At all times, the following invariants hold:*

- $OPEN \cap CLOSED = \emptyset$
- $BE \cup FROZEN \subset CLOSED$

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Algorithm 2 $expand(s, g_{bound})$

```

for all  $s' \in successors(s)$  do
  LOCK  $s'$ 
  if  $s'$  was not yet seen in this main() iteration then
    if  $s'$  has not been generated yet then
       $g(s') := v(s') := \infty$ 
    end if
     $g_p(s') := g(s') + 2(\epsilon - 1)c_l$ 
  end if
   $g_p(s') = \min(g_p(s'), g_{bound} + \epsilon c(s, s'))$ 
  if  $g(s') > g(s) + c(s, s')$  then
     $g(s') = g(s) + c(s, s')$ 
     $bp(s') = s$ 
    if  $s' \in CLOSED$  then
      insert  $s'$  in FROZEN
    else
      insert/update  $s'$  in OPEN with key  $f(s')$ 
    end if
  end if
  UNLOCK  $s'$ 
end for

```

Algorithm 3 PARA*

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while  $g(s_{goal}) > bound(s_{goal})$  do
  among  $s \in OPEN$  such that  $g(s) \leq bound(s)$ , re-
  move one with the smallest  $f(s)$  and LOCK  $s$ 
  if such an  $s$  does not exist then
    wait until OPEN or BE change
    continue
  end if
   $v_{expand} := g(s)$ 
  insert  $s$  into CLOSED
  insert  $s$  into BE with key  $f(s)$ 
  UNLOCK  $s$ 
   $expand(s, bound(s))$ 
   $v(s) := v_{expand}$ 
  remove  $s$  from BE
end while

```

Algorithm 4 main()

```

OPEN := BE := CLOSED := FROZEN := ∅
g(s_start) := v(s_start) := 0
expand(s_start, 0)
repeat
  choose  $\epsilon \in [1, \infty]$  and  $w \in [0, \infty]$ 
  OPEN := OPEN  $\cup$  FROZEN with keys  $f(s)$ 
  CLOSED := FROZEN := ∅
  for all  $s \in OPEN$  do
     $g_p(s) := g(s) + (\epsilon - 1) \min(g(s), 2c_l)$ 
  end for
  run PARA* on multiple threads in parallel
until path is good enough or planning time runs out

```

- $s \in OPEN \cup BE \cup FROZEN \Rightarrow g(s) < v(s)$
- $s \notin OPEN \cup BE \cup FROZEN \Rightarrow g(s) = v(s)$
- $g(bp(s)) + c(bp(s), s) \leq g(s) \leq \min_{s'} \{v(s') + c(s', s)\}$
- Following $bp(\cdot)$ from s yields a path costing at most $g(s)$
- $s \in OPEN \cup CLOSED \Rightarrow g(s) + (\epsilon - 1)c_l \leq g_p(s) \leq \epsilon g(s)$
- $s \in OPEN \cup CLOSED$ iff we had $g(s) < v(s)$ some-time during the current main() loop iteration

Proof. Induction on time. \square

Lemma 2. At all times, for all states s and $s' \notin \{s_{start}, s\}$:

$$g_{back}(s', s) \leq g_p(s') + \epsilon h(s', s).$$

Proof. If $w \leq \epsilon$, then

$$\begin{aligned}
& g(s) + f(s') - f(s) + (2\epsilon - w - 1)c_l \\
&= g(s') + w(h(s', s_{goal}) - h(s, s_{goal})) + (2\epsilon - w - 1)c_l \\
&\leq g(s') + wh(s', s) + (2\epsilon - w - 1)c_l \\
&\leq g(s') + \epsilon h(s', s) + (w - \epsilon)c_l + (2\epsilon - w - 1)c_l \\
&= g(s') + (\epsilon - 1)c_l + \epsilon h(s', s) \\
&\leq g_p(s') + \epsilon h(s', s)
\end{aligned}$$

On the other hand, if $w > \epsilon$, then

$$\begin{aligned}
& \frac{\epsilon}{w} (g(s) + f(s') - f(s)) + (\epsilon - 1)c_l \\
&= \frac{\epsilon}{w} (g(s') + w(h(s', s_{goal}) - h(s, s_{goal}))) + (\epsilon - 1)c_l \\
&\leq g(s') + \epsilon(h(s', s_{goal}) - h(s, s_{goal})) + (\epsilon - 1)c_l \\
&\leq g(s') + (\epsilon - 1)c_l + \epsilon h(s', s) \\
&\leq g_p(s') + \epsilon h(s', s)
\end{aligned}$$

\square

TODO: since Lemma 2 fails when $s' = s_{start}$, if $s_{start} \in OPEN \cup BE$, then g_{front} will have to be initialized to $\epsilon h(s_{start}, s)$ instead of ∞ in order for Lemma 3 to hold.

Lemma 3. For all $s \in OPEN \cup BE$, $bound(s) \leq \min_{s' \in OPEN \cup BE} g_p(s') + \epsilon h(s', s)$. Furthermore, $g(s) \leq bound(s)$ iff $g(s) \leq \min_{s' \in OPEN \cup BE} g_p(s') + \epsilon h(s', s)$.

Proof. By construction, $bound(s)$ is bounded above by $g_p(s') + \epsilon h(s', s)$ for $s' = s$ as well as for the other states s' which are checked in the loop. As for the remaining states $s' \in OPEN \cup BE$, the algorithm ensures that $bound(s) \leq g_{back}(s', s)$ for these by using a minimum representative. By Lemma 2, it follows that

$$bound(s) \leq \min_{s' \in OPEN \cup BE} g_p(s') + \epsilon h(s', s).$$

To prove the second claim, note that the loop in $bound(s)$ terminates under only two conditions. Either $g(s) > g_{front}$, in which case we have $g(s) > g_p(s') + \epsilon h(s', s) \geq bound(s)$ for the s' which began the final iteration; or $g(s) \leq g_{back}(s', s)$, in which case $g(s) \leq bound(s)$ iff $g(s) \leq g_{front}$ iff $g(s) \leq g_p(s') + \epsilon h(s', s)$ for all $s' \in OPEN \cup BE$. \square

Theorem 1. For all $s \in OPEN \cup BE$, $bound(s) \leq \epsilon g^*(s)$. Hence, for all $s \in CLOSED$, $g(s) \leq v(s) \leq \epsilon g^*(s)$.

Proof. We proceed by induction on the order in which states are expanded.

Let $\pi = \langle s_0, s_1, \dots, s_N \rangle$ be a minimum-cost path from $s_0 = s_{start}$ to $s_N = s \in OPEN \cup BE$. Choose the minimum i such that $s_i \in OPEN \cup BE$. If $i = 1$, then

$$g_p(s_i) \leq \epsilon g(s_i) = g^*(s_i)$$

If $i \geq 2$, there are two cases to consider, depending on whether $s_{i-1} \in CLOSED$.

If so, then $expand(s_{i-1})$ has assigned to $g_p(s_i)$. Hence by the induction hypothesis,

$$\begin{aligned}
g_p(s_i) &\leq v(s_{i-1}) + \epsilon c(s_{i-1}, s_i) \\
&\leq \epsilon g^*(s_{i-1}) + \epsilon c(s_{i-1}, s_i) \\
&= \epsilon g^*(s_i)
\end{aligned}$$

On the other hand, suppose $s_{i-1} \notin CLOSED$. Choose the maximum $j < i$ such that $s_j \in CLOSED$, or $j = 0$ if there is no such j . Then $j \leq i - 2$ and, by the induction hypothesis, $g(s_j) \leq \epsilon g^*(s_j)$. Furthermore, $g(s_k) = v(s_k)$ for all $j < k < i$. Let $g_{old}(s_i)$ denote the value of $g(s_i)$ at the start of the current main() loop iteration. Then,

$$\begin{aligned}
g_p(s_i) &\leq g_{old}(s_i) + 2(\epsilon - 1)c_l \\
&\leq v(s_j) + c^*(s_j, s_i) + 2(\epsilon - 1)c_l \\
&\leq \epsilon g^*(s_j) + c^*(s_j, s_i) + 2(\epsilon - 1)c_l \\
&= \epsilon(g^*(s_j) + c^*(s_j, s_i)) + (\epsilon - 1)(2c_l - c^*(s_j, s_i)) \\
&\leq \epsilon g^*(s_i)
\end{aligned}$$

In all three cases, we found that

$$g_p(s_i) + \epsilon h(s_i, s) \leq \epsilon g^*(s_i) + \epsilon c^*(s_i, s) = \epsilon g^*(s).$$

Therefore, by Lemma 3,

$$bound(s) \leq \min_{s' \in OPEN \cup BE} g_p(s') + \epsilon h(s', s) \leq \epsilon g^*(s).$$

\square

Corollary 1. At the end of a main() loop iteration, the path obtained by following the back-pointers $bp(\cdot)$ from s_{goal} to s_{start} is ϵ -suboptimal.

Proof. The termination condition of PARA* implies $g(s_{goal}) \leq bound(s_{goal})$. By construction, the path given by following back-pointers costs at most $g(s_{goal})$. The claim now follows from Theorem 1. \square

Performance Guarantees

Consider a simplified version of PARA* which ignores the loop in $\text{bound}(s)$: we call it blind PARA*. In this case, no g_p values need be computed nor stored, and $\text{bound}(s)$ is simply $g(s) + f_{\min} - f(s) + (2\epsilon - w - 1)c_l$ where f_{\min} is the minimum f -value in $\text{OPEN} \cup \text{BE}$. Blind PARA* can only expand states which would be proved safe with zero iterations of the $\text{bound}(s)$ loop in ordinary PARA*. Thus, all of the performance guarantees we prove for blind PARA* also hold for PARA*.

Theorem 2. *If $w \leq 1$, the parallel depth of blind PARA* is bounded above by*

$$\min \left(\frac{\epsilon g^*(s_{\text{goal}})}{(1-w)c_l}, \frac{(\epsilon g^*(s_{\text{goal}}))^2}{(4\epsilon - 2w - 2)c_l^2} \right).$$

Proof. We prove the two bounds separately. For the first, note that if the lowest f -value is f_{\min} , every state with f -value up to $f_{\min} + (2\epsilon - w - 1)c_l$ can simultaneously be expanded. Since h is consistent, the successors' f -values is at least $f_{\min} + (1-w)c_l$. Therefore, the depth is at most

$$\frac{\epsilon g^*(s_{\text{goal}})}{(1-w)c_l}$$

For the other bound, notice that since f -values never decrease along paths, once the minimum f -value in OPEN surpasses f_{\min} , from then on all nodes with f -value up to $f_{\min} + (2\epsilon - w - 1)c_l$ are always safe to expand. And during each iteration of the simultaneous expansions, the g -value of all such nodes increases by at least c_l . Since g cannot exceed f , this continues for at most $(f_{\min} + (2\epsilon - w - 1)c_l)/c_l = f_{\min}/c_l + 2\epsilon - w - 1$ iterations, after which every node in OPEN has f -value $\geq f_{\min} + (2\epsilon - w - 1)c_l$. Continuing this process until f_{\min} exceeds $\epsilon g^*(s_{\text{goal}})$, a bound on the total iteration count is:

$$2\epsilon - w - 1 + 2(2\epsilon - w - 1) + 3(2\epsilon - w - 1) + \dots + \epsilon g^*(s_{\text{goal}})/c_l \cong (\epsilon g^*(s_{\text{goal}})/c_l)^2 / (4\epsilon - 2w - 2). \quad \square$$

Edgewise Supoptimality

Let $k(s)$ be the least number of edges used in a minimum-cost path to s and fix $\delta > 0$. If g_{front} and g_{back} are each increased by 2δ , then by similar arguments to the proofs earlier in the paper, we find that, upon expanding s , $g(s) \leq \epsilon g^*(s) + \delta k(s)$.

Here's an extension inspired by (Klein and Subramanian 1997): suppose the mean edge cost c_m along the optimal path is known to be much greater than the lower bound c_l . In such a case, the bound in Theorem 2 scales poorly. To remedy the situation, we "grow" the small edges, effectively running PARA* with $c'_l = c_l + \delta$ and $c'(s, s') = \max(c(s, s'), c'_l)$.

Theorem 3. *If the mean cost of the edges along the minimum-cost path to s is at least c_m , then upon expansion, $g(s) \leq \epsilon(1 + \delta/c_m)g^*(s)$. Therefore, to get the same optimality factor as ϵ , we can set $\delta = (\epsilon - 1)c_m$.*

Proof. We assumed $c_m \leq g^*(s)/k(s)$, so $k(s) \leq g^*(s)/c_m$. It follows from Lemma 1 that $g'(s) \leq \epsilon g^*(s) \leq \epsilon(g^*(s) + \delta k(s)) \leq \epsilon(1 + \delta/c_m)g^*(s)$. \square

Corollary 2. *If $w \leq 1$, the parallel depth of blind PARA* can be improved to*

$$\frac{\epsilon g^*(s_{\text{goal}})}{(1-w)(c_l + (\epsilon - 1)c_m)}.$$

References

Klein, P. N., and Subramanian, S. 1997. A randomized parallel algorithm for single-source shortest paths. *Journal of Algorithms* 25(2):205–220.