

# Foundations of Artificial Intelligence

## 18. State-Space Search: Properties of A\*, Part I

Malte Helmert

University of Basel

March 31, 2021

# Foundations of Artificial Intelligence

## March 31, 2021 — 18. State-Space Search: Properties of A\*, Part I

18.1 Introduction

18.2 Optimal Continuation Lemma

18.3  $f$ -Bound Lemma

18.4 Optimality of A\* with Reopening

18.5 Summary

## State-Space Search: Overview

Chapter overview: state-space search

- ▶ 5.–7. Foundations
- ▶ 8.–12. Basic Algorithms
- ▶ 13.–19. Heuristic Algorithms
  - ▶ 13. Heuristics
  - ▶ 14. Analysis of Heuristics
  - ▶ 15. Best-first Graph Search
  - ▶ 16. Greedy Best-first Search, A\*, Weighted A\*
  - ▶ 17. IDA\*
  - ▶ 18. Properties of A\*, Part I
  - ▶ 19. Properties of A\*, Part II

## 18.1 Introduction

## Optimality of A\*

- ▶ advantage of A\* over greedy search:  
optimal for heuristics with suitable properties
- ▶ very important result!

↪ next chapters: a closer look at A\*

- ▶ A\* with reopening ↪ this chapter
- ▶ A\* without reopening ↪ next chapter

## Optimality of A\* with Reopening

In this chapter, we prove that A\* with reopening is optimal when using admissible heuristics.

For this purpose, we

- ▶ give some basic definitions
- ▶ prove two lemmas regarding the behaviour of A\*
- ▶ use these to prove the main result

## Reminder: A\* with Reopening

reminder: A\* with reopening

### A\* with Reopening

```

open := new MinHeap ordered by ⟨f, h⟩
if h(init()) < ∞:
    open.insert(make_root_node())
distances := new HashTable
while not open.is_empty():
    n := open.pop_min()
    if distances.lookup(n.state) = none or g(n) < distances[n.state]:
        distances[n.state] := g(n)
        if is_goal(n.state):
            return extract_path(n)
        for each ⟨a, s'⟩ ∈ succ(n.state):
            if h(s') < ∞:
                n' := make_node(n, a, s')
                open.insert(n')
return unsolvable
  
```

## Solvable States

### Definition (solvable)

A state  $s$  of a state space is called solvable if  $h^*(s) < \infty$ .

German: lösbar

## Optimal Paths to States

### Definition ( $g^*$ )

Let  $s$  be a state of a state space with initial state  $s_0$ .

We write  $g^*(s)$  for the cost of the optimal (cheapest) path from  $s_0$  to  $s$  ( $\infty$  if  $s$  is unreachable).

### Remarks:

- ▶  $g$  is defined for nodes,  $g^*$  for states (Why?)
- ▶  $g^*(n.state) \leq g(n)$  for all nodes  $n$  generated by a search algorithm (Why?)

## Settled States in A\*

### Definition (settled)

A state  $s$  is called **settled** at a given point during the execution of A\* (with or without reopening) if  $s$  is included in *distances* and  $distances[s] = g^*(s)$ .

German: erledigt

## 18.2 Optimal Continuation Lemma

## Optimal Continuation Lemma

We now show the first important result for A\* with reopening:

### Lemma (optimal continuation lemma)

Consider A\* with reopening using a *safe* heuristic at the beginning of any iteration of the **while** loop.

If

- ▶ state  $s$  is settled,
- ▶ state  $s'$  is a solvable successor of  $s$ , and
- ▶ an optimal path from  $s_0$  to  $s'$  of the form  $\langle s_0, \dots, s, s' \rangle$  exists,

then

- ▶  $s'$  is settled or
- ▶ open contains a node  $n'$  with  $n'.state = s'$  and  $g(n') = g^*(s')$ .

German: Optimale-Fortsetzungs-Lemma

## Optimal Continuation Lemma: Intuition

(Proof follows on the next slides.)

Intuitively, the lemma states:

*If no optimal path to a given state has been found yet, open must contain a “good” node that contributes to finding an optimal path to that state.*

(This potentially requires multiple applications of the lemma along an optimal path to the state.)

## Optimal Continuation Lemma: Proof (1)

**Proof.**

Consider states  $s$  and  $s'$  with the given properties at the start of some iteration (“iteration A”) of A\*.

Because  $s$  is settled, an earlier iteration (“iteration B”) set  $distances[s] := g^*(s)$ .

Thus iteration B removed a node  $n$  with  $n.state = s$  and  $g(n) = g^*(s)$  from *open*.

A\* did not terminate in iteration B.  
(Otherwise iteration A would not exist.)

Hence  $n$  was expanded in iteration B. ...

## Optimal Continuation Lemma: Proof (2)

**Proof (continued).**

This expansion considered the successor  $s'$  of  $s$ .

Because  $s'$  is solvable, we have  $h^*(s') < \infty$ .

Because  $h$  is safe, this implies  $h(s') < \infty$ .

Hence a successor node  $n'$  was generated for  $s'$ .

This node  $n'$  satisfies the consequence of the lemma.

Hence the criteria of the lemma were satisfied for  $s$  and  $s'$  after iteration B.

To complete the proof, we show: if the consequence of the lemma is satisfied at the beginning of an iteration, it is also satisfied at the beginning of the next iteration. ...

## Optimal Continuation Lemma: Proof (3)

**Proof (continued).**

- ▶ If  $s'$  is settled at the beginning of an iteration, it remains settled until termination.
- ▶ If  $s'$  is not yet settled and *open* contains a node  $n'$  with  $n'.state = s'$  and  $g(n') = g^*(s')$  at the beginning of an iteration, then either the node remains in *open* during the iteration, or  $n'$  is removed during the iteration and  $s'$  becomes settled. □

## 18.3 f-Bound Lemma

## f-Bound Lemma

We need a second lemma:

### Lemma (f-bound lemma)

Consider  $A^*$  with reopening and an *admissible* heuristic applied to a *solvable* state space with optimal solution cost  $c^*$ .

Then *open* contains a node  $n$  with  $f(n) \leq c^*$  at the beginning of each iteration of the **while** loop.

German: f-Schranken-Lemma

## f-Bound Lemma: Proof (1)

### Proof.

Consider the situation at the beginning of any iteration of the **while** loop.

Let  $\langle s_0, \dots, s_n \rangle$  be an optimal solution.

(Here we use that the state space is solvable.)

Let  $s_i$  be the first state in the sequence that is not settled.

(Not all states in the sequence can be settled:  $s_n$  is a goal state, and when a goal state is inserted into *distances*,  $A^*$  terminates.)

...

## f-Bound Lemma: Proof (2)

### Proof (continued).

#### Case 1: $i = 0$

Because  $s_0$  is not settled yet, we are at the first iteration of the **while** loop.

Because the state space is solvable and  $h$  is admissible, we have  $h(s_0) < \infty$ .

Hence *open* contains the root  $n_0$ .

We obtain:  $f(n_0) = g(n_0) + h(s_0) = 0 + h(s_0) \leq h^*(s_0) = c^*$ , where " $\leq$ " uses the admissibility of  $h$ .

This concludes the proof for this case.

...

## f-Bound Lemma: Proof (3)

Proof (continued).

Case 2:  $i > 0$

Then  $s_{i-1}$  is settled and  $s_i$  is not settled.

Moreover,  $s_i$  is a solvable successor of  $s_{i-1}$  and  $\langle s_0, \dots, s_{i-1}, s_i \rangle$  is an optimal path from  $s_0$  to  $s_i$ .

We can hence apply the optimal continuation lemma (with  $s = s_{i-1}$  and  $s' = s_i$ ) and obtain:

(A)  $s_i$  is settled, or

(B) *open* contains  $n'$  with  $n'.state = s_i$  and  $g(n') = g^*(s_i)$ .

Because (A) is false, (B) must be true.

We conclude: *open* contains  $n'$  with  $f(n') = g(n') + h(s_i) = g^*(s_i) + h(s_i) \leq g^*(s_i) + h^*(s_i) = c^*$ , where " $\leq$ " uses the admissibility of  $h$ .  $\square$

## 18.4 Optimality of A\* with Reopening

## Optimality of A\* with Reopening

We can now show the main result of this chapter:

**Theorem (optimality of A\* with reopening)**

*A\* with reopening is optimal when using an admissible heuristic.*

## Optimality of A\* with Reopening: Proof

Proof.

By contradiction: assume that the theorem is wrong.

Hence there is a state space with optimal solution cost  $c^*$  where A\* with reopening and an admissible heuristic returns a solution with cost  $c > c^*$ .

This means that in the last iteration, the algorithm removes a node  $n$  with  $g(n) = c > c^*$  from *open*.

With  $h(n.state) = 0$  (because  $h$  is admissible and hence goal-aware), this implies:

$$f(n) = g(n) + h(n.state) = g(n) + 0 = g(n) = c > c^*.$$

A\* always removes a node  $n$  with minimal  $f$  value from *open*.

With  $f(n) > c^*$ , we get a contradiction to the  $f$ -bound lemma, which completes the proof.  $\square$

## 18.5 Summary

## Summary

- ▶ A\* with reopening using an admissible heuristic is optimal.
- ▶ The proof is based on the following lemmas that hold for solvable state spaces and admissible heuristics:
  - ▶ optimal continuation lemma: The open list always contains nodes that make progress towards an optimal solution.
  - ▶ f-bound lemma: The minimum  $f$  value in the open list at the beginning of each A\* iteration is a lower bound on the optimal solution cost.