Chapter S:V

V. Search Theory

- Properties of Search Space Graphs
- Auxiliary Concepts
- Roadmap
- Completeness of A*
- Admissibility of A*
- Efficiency of A*
- Monotone Heuristic Functions
Efficiency of A*
Efficiency of Search Algorithms

The basic steps in the loop of a search algorithm are:

1. Select a most promising solution base.
2. Select a node in that solution base.
3. Expand that node.

Efficiency is related to the number of node expansions.

Heuristics influence efficiency by

1. excluding nodes from expansion entirely (pruning), and by
2. preventing nodes from being expanded more than once (no reopening)
Efficiency of A*
Efficiency of Search Algorithms

**Definition 49 (Dominance, Optimality)**

1. A search algorithm $A_1$ dominates a search algorithm $A_2$ if each node that is expanded by $A_1$ is also expanded by $A_2$.

2. $A_1$ strictly dominates $A_2$ if $A_1$ dominates $A_2$ and $A_2$ does not dominate $A_1$.

3. A search algorithm is optimum regarding a class of search algorithms if it dominates all members of this class.
Remarks:

- Dominance defines a *partial* ordering on search algorithms.
- Dominance relations are often proved with regard to some fixed tie breaking rule.
- Instead of the term “dominates” we may also use the phrase “is more efficient than”.
Efficiency of A*
Efficiency of Search Algorithms

By not-expanding nodes, parts of the search space graph are pruned. The efficiency of A* depends on the accuracy of the heuristic estimate $h$.

Consider two extreme cases:

1. If estimates are perfect ($h = h^*$), A* will follow cheapest paths to goal nodes. In this case $f(n) = C^*$ holds for each expanded node $n$.

2. If no heuristic is used ($h = 0$), A* degenerates to a uniform cost search. In this case each node $n$ reachable from $s$ with path cost of at most $C^*$ will be expanded, i.e., $f(n) = g(n) \leq C^*$.

Hypothesis:

The closer $h$ is to $h^*$ (as long as $h \leq h^*$), the more powerful it is with respect to pruning.
Efficiency of A*
Conditions for Node Expansion I

Theorem 50 (Necessary Condition for Node Expansion I)
Let A* process a search space graph $G$ with $Prop(G)$, using an admissible heuristic function $h$. For each node $n$ expanded by A* holds:

$$f(n) \leq C^*$$
Efficiency of A*  
Conditions for Node Expansion I

**Theorem 50 (Necessary Condition for Node Expansion I)**

Let A* process a search space graph $G$ with $Prop(G)$, using an admissible heuristic function $h$. For each node $n$ expanded by A* holds:

$$f(n) \leq C^*$$

**Proof (sketch)**

1. If there is no solution path in $G$, then $C^* = \infty$ and this theorem is obviously true.

2. If there is a solution path in $G$, then there is also an optimum solution path with cost $C^*$.  
   [Corollary “Solution Existence Entails Optimum”]

3. At any time before A* terminates, there exists an OPEN node $n'$ with $f(n') \leq C^*$.  
   [Lemma “$C^*$-bounded OPEN Node”]

4. Since A* expands $n$, its $f$-value is less or equal to the $f$-value of all nodes on OPEN. Thus we have $f(n) \leq f(n')$ and therefore $f(n) \leq C^*$. 


Remarks:

- **Theorem 50** defines a set $S$ of nodes that will not be expanded: $S = \{n \mid f(n) > C^*\}$.
  
  Q. Why might this knowledge be helpful and how could it be applied?

- The application of **Theorem 50** requires knowledge on $C^*$.
  
  Q. Is this a problem?
  
  Q. If yes, how to solve it?

- In the book of Pearl this theorem is denoted as Theorem 3 and Nilsson Result 5 respectively. [Pearl 1984]
Efficiency of A*  
Conditions for Node Expansion I

**Theorem 51 (Sufficient Condition for Node Expansion I)**

Let A* process a search space graph $G$ with $Prop(G)$, using an admissible heuristic function $h$. A* will expand each node $n$ on OPEN with $f(n) < C^*$. 
Efficiency of A*  
Conditions for Node Expansion I

**Theorem 51 (Sufficient Condition for Node Expansion I)**

Let A* process a search space graph $G$ with $Prop(G)$, using an admissible heuristic function $h$. A* will expand each node $n$ on OPEN with $f(n) < C^\ast$.

**Proof (sketch)**

1. Let OPEN contain a node $n$ with $f(n) < C^\ast$.
2. If there is no solution path in $G$, then $g$-values determined for newly generated nodes are higher over time (because of lower bound $\delta$ on edge cost values). Therefore, $n$ will be expanded at some point in time, even if $G$ is an infinite graph.
3. Let A* terminate with goal node $\gamma$.
4. Due to the admissibility of A*, $f(\gamma) = C^\ast$.
5. From $f(n) < C^\ast$ and $C^\ast = f(\gamma)$ follows that $f(n) < f(\gamma)$.
6. The value of $f(n)$ can only decrease ($f(\gamma)$ remains constant).
7. A* expands the node $n$ before it terminates with solution $\gamma$. 
Remarks:

- In the book of Pearl this theorem is denoted as Theorem 4. [Pearl 1984]
Efficiency of A*  

Conditions for Node Expansion I \([\text{Conditions II, Conditions III}]\)

Let \(n \in \text{OPEN}\). For admissible heuristic functions \(h\) hold:

\[
\text{node expansion by A*} \quad \Rightarrow \quad f(n) \leq C^* \\
\begin{array}{c}
\text{necessary} \\
\end{array}
\]

\[
f(n) < C^* \quad \Rightarrow \quad \text{node expansion by A*} \\
\begin{array}{c}
\text{sufficient} \\
\end{array}
\]

Observe that the Theorems 50 and 51 do not give a condition for node expansion that is both necessary and sufficient:

In particular, for OPEN nodes with \(f(n) = C^*\) some tie breaking rule has to determine which of these nodes are expanded or not.
Efficiency of A*
Conditions for Node Expansion I

**Corollary 52 (Re-Expansion of Expanded Nodes)**
Let A* process a search space graph $G$ with $\text{Prop}(G)$, using an admissible heuristic function $h$. If a node $n$ on CLOSED is reopened, then A* will expand node $n$ again.

**Proof (sketch)**

1. For each node $n$ on CLOSED, $f(n) \leq C^*$ is true (Theorem 50).
2. Due to reopening, the value of $f(n)$ decreases, $f(n) < C^*$.
3. Hence, A* expands the node $n$ (Theorem 51).

Even worse, any node $n'$ in CLOSED, which has $n$ in its backpointer path, i.e. $n \in PP_{s-n'}$, when $n$ is reopened, will be reopened and expanded as well.
Efficiency of A*
Conditions for Node Expansion II

The expansion conditions I are *algorithm-centered*:

- The value of $g(n)$ is no property of node $n$ but depends on the path to $n$ that A* has discovered.

- **Theorem 51** requires that $n$ resides on OPEN before it is selected for expansion. Whether a given node enters OPEN depends not on $n$ itself but on the behavior of A* while exploring the paths leading to $n$.

Instead of arguing about algorithmic concepts (discovered paths, OPEN list), expansion conditions should be formulated with regard to the search space graph $G$ only.
Efficiency of A*  
Conditions for Node Expansion II

**Definition 53 (Cost-Bounded Paths)**

A path $P$ is called $C$-bounded iff ($\leftrightarrow$) for each node $n$ on $P$ holds

$$g_P(n) + h(n) \leq C.$$ 

$P$ is called strictly $C$-bounded iff ($\leftrightarrow$) for each node $n$ on $P$ holds

$$g_P(n) + h(n) < C.$$ 

$C$-boundedness can be checked for each finite path in $G$—not only for paths considered by A*. 
Efficiency of A*
Conditions for Node Expansion II

Theorem 54 (Necessary Condition for Node Expansion II)
Let A* process a search space graph $G$ with $Prop(G)$, using an admissible heuristic function $h$. For each node $n$ expanded by A* we have a $C^*$-bounded path from $s$ to $n$ in $G$. 
Efficiency of A*

Conditions for Node Expansion II

Theorem 54 (Necessary Condition for Node Expansion II)

Let A* process a search space graph $G$ with $Prop(G)$, using an admissible heuristic function $h$. For each node $n$ expanded by A* we have a $C^*$-bounded path from $s$ to $n$ in $G$.

Proof (sketch)

1. Since A* expands $n$, the equation $f(n) = g(n) + h(n) \leq C^*$ holds. [Theorem 50]

2. When $n$ is on OPEN, all predecessors $n'$ of $n$ on the current backpointer path $PP_{s-n}$ are on CLOSED.

3. At time of expansion of such a node $n'$ we also had $g'(n') + h(n') \leq C^*$, where $g'$ denotes the path cost at the time when $n'$ was expanded.

4. Pointer-paths are only changed when a cheaper path is found, i.e., $g$-values can only decrease.

5. Thus we have $f(n') = g(n') + h(n') \leq g'(n') + h(n') \leq C^*$. 
Efficiency of A*
Conditions for Node Expansion II

Theorem 55 (Sufficient Condition for Node Expansion II)
Let A* process a search space graph $G$ with $Prop(G)$, using an admissible heuristic function $h$. A* will expand each node $n$ for which we have a strictly $C^*$-bounded path from $s$ to $n$ in $G$. 
Efficiency of A*
Conditions for Node Expansion II

Theorem 55 (Sufficient Condition for Node Expansion II)
Let A* process a search space graph $G$ with $Prop(G)$, using an admissible heuristic function $h$. A* will expand each node $n$ for which we have a strictly $C^*$-bounded path from $s$ to $n$ in $G$.

Proof (sketch)
1. Let $P$ be a strictly $C^*$-bounded path from $s$ to $n$ in $G$.
2. Let A* terminate with goal node $\gamma$.
3. Due to admissibility of A*, $f(\gamma) = C^*$.
4. Let $n'$ be the shallowest OPEN node on $P$ when A* terminates.
5. Since all predecessors of $n'$ on $P$ are on CLOSED, the path cost $g(n')$ currently maintained by A* cannot be higher than $g_P(n')$: $f(n') = g(n') + h(n') \leq g_P(n') + h(n')$
6. Since $P$ is strictly $C^*$-bounded, we have $g_P(n') + h(n') < C^*$ and thus $f(n') < f(\gamma)$.
7. A* expands the node $n'$ and all nodes on $P$ before it terminates with solution $\gamma$. 
Remarks:

- If there is no solution path in $G$, we have $C^* = \infty$ and any node reachable from $s$ will be expanded by A* using $h$.

- An optimum path to a node $n$ may be $C^*$-bounded only, although a strictly $C^*$-bounded path exists.

- In the book of Pearl, the two previous theorems are denoted as Theorem 6 and Theorem 5 respectively. [Pearl 1984]
Efficiency of A*

Conditions for Node Expansion II  [Conditions I, Conditions III]

For admissible heuristic functions \( h \) hold:

\[
\text{node expansion by A* } \Rightarrow \exists C^*-\text{bounded path } P_{s-n}
\]

\[
\exists \text{ strictly } C^*-\text{bounded path } P_{s-n} \Rightarrow \text{ node expansion by A*}
\]

Again, none of the Theorems 54 and 55 gives a condition for node expansion that is both necessary and sufficient:

The theorems do not treat \( C^* \)-bounded paths with \( f(n') = C^* \) for some intermediate node \( n' \).
Efficiency of A*
Informedness and Dominance

**Definition 56 (Informedness)**
A heuristic function $h_2$ is called more informed than a heuristic function $h_1$ iff (↔) both functions are admissible and if holds

$$h_2(n) > h_1(n), \quad \forall n \in G, n \notin \Gamma$$

An A* algorithm that uses such a heuristic function $h_2$ is called more informed than an A* algorithm that uses $h_1$. 
Corollary 57 (Dominance)

Let $G$ be a search space graph with $\text{Prop}(G)$. If $h_2(n) > h_1(n)$ holds for any $n$ in $G$ with $n \notin \Gamma$, and if $h_2(n)$ and $h_1(n)$ both are admissible, then $A^*_2$ ($A^*$ informed by $h_2(n)$) dominates $A^*_1$ ($A^*$ informed by $h_1(n)$).
Corollary 57 (Dominance)

Let $G$ be a search space graph with $\text{Prop}(G)$. If $h_2(n) > h_1(n)$ holds for any $n$ in $G$ with $n \notin \Gamma$, and if $h_2(n)$ and $h_1(n)$ both are admissible, then $A^*_2$ ($A^*$ informed by $h_2(n)$) dominates $A^*_1$ ($A^*$ informed by $h_1(n)$).

Proof (sketch)

1. Let $A^*_2$ expand a node $n$ in $G$ with $n \notin \Gamma$.
2. Thus the current backpointer path $P$ of $n$ is a $C^*$-bounded path $P$ from $s$ to $n$ with respect to $h_2$, i.e., $g_P(n') + h_2(n') \leq C^*$ for each $n'$ on $P$. [Theorem 51]
3. Since no goal node is contained in $P$ and $h_2$ is more informed than $h_1$, for each node $n'$ on $P$ holds $h_2(n') > h_1(n')$.
4. Hence $g_P(n') + h_1(n') < C^*$ for each $n'$ on $P$.
5. Thus $P$ is strictly $C^*$-bounded with respect to $h_1$.
6. $A^*_1$ will expand $n$. [Theorem 55]
Remarks:

- The requirement of Definition 56 (Informedness), namely, the strict inequality between \( h_2 \) and \( h_1 \), is rarely satisfied—even in situations where \( h_2 \) is clearly superior to \( h_1 \).

  Example 8-Puzzle: \( h_1 \) (number of misplaced tiles) often equals \( h_2 \) (sum of Manhattan distances of misplaced tiles).

- In the book of Pearl this theorem is denoted as Theorem 7 and Nilsson Result 6 respectively. [Pearl 1984]
Efficiency of A*
Informedness and Dominance: Discussion

Q. If $h_2 > h_1$ cannot be satisfied in practice, then under which conditions does $A^*_2$ (using $h_2$) dominate $A^*_1$ (using $h_1$) when $h_2 \geq h_1$?

A1: If both algorithms use the same tie breaking rule and if the rule is purely structural (i.e., independent of the values of $g$ and $h$).

A2: In situations where we want to find all goal nodes that can be reached with cheapest cost, Theorem 54 gives both a necessary and sufficient condition for node expansion.
In this case, Definition 56 (Informedness) can permit equalities without affecting Theorem 57.

A3: Theorem 64 demonstrates that under reasonable assumptions equalities between $h_1$ and $h_2$ only violate the dominance of $A^*_2$ on a small set of nodes for which $g^*(n) + h_2(n) = C^*$ holds.
Remarks:

- For search space graphs $G$ with $Prop(G)$ it is possible to find all goal nodes that can be reached with cheapest cost. But for search space graphs $G$ with $Prop(G)$ it is in general not possible to find all optimum cost solution paths (path discarding for multiple optimum cost paths to the same node).
Monotone Heuristic Functions

Motivation

Previous consideration:

The efficiency of A* can be measured by the number of nodes it manages to exclude from expansion.

\[
\text{maximize } \left\{ n \mid f(n) > C^* \right\}_{S}
\]

More reasonable:

The number of expansion operations should be analyzed. Why?
Monotone Heuristic Functions

Motivation

Previous consideration:

The efficiency of A* can be measured by the number of nodes it manages to exclude from expansion.

\[
\text{maximize} \quad \left| \left\{ n \mid f(n) > C^* \right\} \right| \quad S
\]

More reasonable:

The number of expansion operations should be analyzed. Why?

Starting point:

Under certain conditions A* will never reopen a node from CLOSED. What does that mean?
Monotone Heuristic Functions

Motivation

Recap: Cheapest paths to a goal, which are constrained to pass through a node \( n \), cannot be cheaper than unrestricted cheapest paths to a goal.

Formally:

\[
\forall n : h^*(s) \leq g^*(n) + h^*(n)
\]

or:

\[
h^*(s) \leq k(s, n) + h^*(n), \quad \text{since } g^*(n) = k(s, n)
\]
Monotone Heuristic Functions

Motivation

Recap: Cheapest paths to a goal, which are constrained to pass through a node $n$, cannot be cheaper than unrestricted cheapest paths to a goal.

Formally:

$$\forall n : h^*(s) \leq g^*(n) + h^*(n)$$

or:

$$h^*(s) \leq k(s,n) + h^*(n), \text{ since } g^*(n) = k(s,n)$$

In general, the following “triangle inequality” holds:

$$\forall n, n' : h^*(n) \leq k(n, n') + h^*(n')$$

It is reasonable to expect that if the process of estimating $h(n)$ is “consistent”, it should inherit the triangle inequality from $h^*$. 
Monotone Heuristic Functions

Illustration of the Global Triangle Inequality

\[ \forall n, n': \quad h^*(n) \leq k(n, n') + h^*(n') \]
Monotone Heuristic Functions
Illustration of the Local Triangle Inequality

\[ \forall n, n' : h^*(n) \leq c(n, n') + h^*(n') \]

Different paths:

Identical paths:
Monotone Heuristic Functions

**Definition 58 (Consistency Condition)**

Let $G$ be a search space graph with $Prop(G)$. A heuristic function $h$ is called consistent, iff $(\leftrightarrow)$ for all nodes $n, n'$ in $G$ holds:

$$h(n) \leq k(n, n') + h(n')$$
Monotone Heuristic Functions

**Definition 58 (Consistency Condition)**

Let $G$ be a search space graph with $Prop(G)$.
A heuristic function $h$ is called consistent, iff (↔) for all nodes $n, n'$ in $G$ holds:

$$h(n) \leq k(n, n') + h(n')$$

**Definition 59 (Monotonicity Condition)**

Let $G$ be a search space graph with $Prop(G)$.
A heuristic function $h$ is called monotone, iff (↔) for all nodes $n, n'$ in $G$ with $n' \in succ(n)$ holds:

$$h(n) \leq c(n, n') + h(n')$$
Remarks:

- The consistency condition corresponds to the fulfillment of the global triangle inequality.
- The monotonicity condition corresponds to the fulfillment of the local triangle inequality.
- The global triangle inequality is obviously fulfilled for nodes $n, n'$ where $n'$ is not reachable from $n$ in $G$. Recall that we defined $k(n, n')$ as $\infty$ for such nodes.
- If $c(n, n') = \infty$ for nodes $n, n'$ with $n' \notin \text{succ}(n)$, the local triangle inequality holds for all nodes $n, n'$ in $G$. 

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Monotone Heuristic Functions

**Theorem 60 (Consistency Equivalent to Monotonicity)**

Let $G$ be a search space graph with $Prop(G)$. A heuristic function $h$ is consistent iff ($\leftrightarrow$) $h$ is monotone.

$$h(n) \leq k(n,n') + h(n') \quad h(n) \leq c(n,n') + h(n')$$
Monotone Heuristic Functions

**Theorem 60 (Consistency Equivalent to Monotonicity)**

Let $G$ be a search space graph with $Prop(G')$. A heuristic function $h$ is consistent iff ($\leftrightarrow$) $h$ is monotone.

Consistency $\iff$ Monotonicity

$$h(n) \leq k(n, n') + h(n') \quad h(n) \leq c(n, n') + h(n')$$

**Proof (sketch)**

1. "$\Rightarrow$"
   
   Monotonicity follows from consistency, since consistency states the triangle inequality for any pair of nodes $n, n'$ with $n'$ reachable from $n$ considering cost of a cheapest path. Monotonicity considers special pairs of nodes $n' \in succ(n)$, and per definition holds: $k(n, n') \leq c(n, n')$

2. "$\Leftarrow$"

   Let $n_l$ be reachable from $n_0$ and let $P = (n_0, n_1, \ldots, n_l)$ be a cheapest path from $n_0$ to $n_l$. Using the monotonicity of $h$ it can be proven by induction over the path length that

   $$h(n_0) \leq \sum_{i=1}^{l} c(n_{i-1}, n_i) + h(n_l)$$

   Since a cheapest path $P$ was considered, we have $k(n_0, n_l) = \sum_{i=1}^{l} c(n_{i-1}, n_i)$. 
Monotone Heuristic Functions

Illustration of a Monotone $h$ [non-monotone]

Monotonicity defines a restriction on $h(n')$: When moving from $n$ to $n'$ along the edge $(n, n')$, the $h$-value decreases at most by $c(n, n')$.

- For an edge:

![Diagram](image-url)
Monotone Heuristic Functions

Illustration of a Monotone $h$ [non-monotone]

Monotonicity defines a restriction on $h(n')$: When moving from $n$ to $n'$ along the edge $(n, n')$, the $h$-value decreases at most by $c(n, n')$.

- For an edge:
  
  ![Diagram of an edge](image_url)

- For a solution path:
  
  ![Diagram of a solution path](image_url)
Monotone Heuristic Functions

Theorem 61 (Monotone Heuristic Functions)
Let $G'$ be a search space graph with $Prop(G')$. A consistent heuristic function $h$ is admissible.
Monotone Heuristic Functions

**Theorem 61 (Monotone Heuristic Functions)**

Let $G$ be a search space graph with $Prop(G')$. A consistent heuristic function $h$ is admissible.

**Proof (sketch)**

1. Let $h$ be consistent, i.e., $h(n) \leq k(n, n') + h(n')$ for all nodes $n, n'$ in $G$.

2. Consider an arbitrary node $n$.

3. If no goal node is reachable from $n$, then $h^*(n) = \infty$ and thus $h(n) \leq h^*(n)$.

4. If some goal node is reachable from $n$, there is also a goal node $\gamma$ reachable from $n$ with cheapest cost. [Corollary “Solution Existence Entails Optimum”]

5. Using $n' = \gamma$, we have $h(n) \leq k(n, \gamma) + h(\gamma)$.

6. Since $n$ is arbitrary chosen, $h(n) \leq h^*(n)$ holds for all nodes. Hence $h$ is admissible.
Remarks:

- Consider the special case $h(n) = 0$. For a graph with positive edge cost $h(n) = 0$ is monotone.

- Q. Compare A* with $h(n) = 0$ to the shortest-path algorithm of Dijkstra. Does Dijkstra’s shortest-path algorithm reopen nodes?
Monotone Heuristic Functions

**Theorem 62 (No Reopening)**

Let $G$ be a search space graph with $Prop(G)$. An A* algorithm that uses a monotone heuristic function $h$ will expand only nodes to which it has found cheapest paths:

$$g(n) = g^*(n), \forall n \in \text{CLOSED}$$
Monotone Heuristic Functions

Theorem 62 (No Reopening)

Let $G$ be a search space graph with $\text{Prop}(G)$. An A* algorithm that uses a monotone heuristic function $h$ will expand only nodes to which it has found cheapest paths:

$$g(n) = g^*(n), \quad \forall \ n \in \text{CLOSED}$$

Proof (sketch)

1. Assume that A* selects a node $n$ for expansion with $g(n) > g^*(n)$.
2. Let $P^*_{s-n}$ be a cheapest path from $s$ to $n$.
3. If $P^*_{s-n} \cap \text{OPEN} = \{n\}$, then all predecessors of $n$ on $P^*_{s-n}$ have been expanded and $g(n) = g^*(n)$, contradicting the assumption. [Lemma “Shallowest OPEN Node on Optimum Path”]
4. If $P^*_{s-n} \cap \text{OPEN} \neq \{n\}$, let $n'$ be the shallowest OPEN node on $P^*_{s-n}$.
5. Using $g(n') = g^*(n')$ [Lemma “Shallowest OPEN Node on Optimum Path”] and the monotonicity of $h$ we have $f(n') = g(n') + h(n') = g^*(n') + h(n') \leq g^*(n') + k(n',n) + h(n)$.
6. Since $n' \in P^*_{s-n}$, we have $g^*(n') + k(n',n) = g^*(n)$ and thus $f(n') \leq g^*(n) + h(n)$.
7. According to the assumption $g(n) > g^*(n)$ we have $f(n') < g(n) + h(n)$ and thus $f(n') < f(n)$.
8. A* selects $n'$ for expansion instead of $n$, contradicting the assumption.
Remarks:

- Note that a heuristic function can be admissible without being monotone: admissibility is necessary for monotonicity.

- In the book of Pearl this theorem is denoted as Theorem 10 and Nilsson Result 7 respectively. [Pearl 1984]
Monotone Heuristic Functions
Illustration of a Non-Monotone $h$ [monotone]

$f = g + h = 10 + 20 = 30$
Monotone Heuristic Functions

Illustration of a Non-Monotone $h$ [monotone]

- $f = g + h = 10 + 20 = 30$
- $f = g + h = 15 + 20 = 35$
- $f = g + h = 15 + 40 = 55$

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Monotone Heuristic Functions

Illustration of a Non-Monotone $h$

$\gamma$

\[ f = g + h = 10 + 20 = 30 \]

$\gamma$

\[ f = g + h = 15 + 20 = 35 \]

\[ f = g + h = 15 + 40 = 55 \]

$t_1 : f = g + h = 25 + 15 = 40$
Monotone Heuristic Functions
Illustration of a Non-Monotone $h$ [monotone]

$$f = g + h = 10 + 20 = 30$$

$$f = g + h = 15 + 20 = 35$$
$$f = g + h = 15 + 40 = 55$$

$t_1 : f = g + h = 25 + 15 = 40$
$t_2 : f = g + h = 20 + 15 = 35$
Monotone Heuristic Functions

Illustration of a Non-Monotone $h$

The monotonicity condition, $h(n_2) \leq c(n_2, n) + h(n)$, is not satisfied for $n_2$: $40 > 5 + 15$

Sequence of node expansions: $n_0, n_1, n, \ldots, n_2, n$
Monotone Heuristic Functions

**Theorem 63 (Non-Decreasing \( f \)-Values)**

Let \( G \) be a search space graph with \( \text{Prop}(G) \). When using a monotone heuristic function \( h \) the \( f \)-values of the sequence of nodes expanded by an A* algorithm will be non-decreasing.
Monotone Heuristic Functions

Theorem 63 (Non-Decreasing $f$-Values)
Let $G$ be a search space graph with $\text{Prop}(G)$. When using a monotone heuristic function $h$ the $f$-values of the sequence of nodes expanded by an A* algorithm will be non-decreasing.

Proof (sketch)

1. Let $n_2$ be expanded directly after $n_1$ in the sequence of node expansions.
2. If $n_2$ is no successor of $n_1$ in $G$, then $n_2$ is on OPEN as well and $f(n_2) \geq f(n_1)$.
3. If $n_2$ is successor of $n_1$ in $G$, then a new path to $n_2$ was found when $n_1$ was expanded.

For the $f$-value of $n_2$ holds:

(a) If $n_2$ was newly generated, then, since $h$ is monotone,
$$f_{\text{new}}(n_2) = g(n_1) + c(n_1, n_2) + h(n_2) \geq g(n_1) + h(n_1) = f(n_1).$$  [Illustration]

(b) If $n_2$ was already on OPEN then holds:
- If $f(n_2)$ was improved, then Case (a) defines the new $f$-value of $n_2$.
- If $f(n_2)$ was not improved, then $f(n_2) \geq f(n_1)$ must still have hold.

Finally, $n_2$ was not on CLOSED, since it was expanded. [Theorem 62]
Remarks:

- In the book of Pearl this theorem is denoted as Theorem 11 and Nilsson Result 8 respectively. [Pearl 1984]
Monotone Heuristic Functions
Illustration of Non-Decreasing $f$-Values

1. Along a solution path (in the search space graph):
   - Path cost values $g(n)$ are (strictly) increasing since $c(n, n') > 0$.

   ![Graph showing increasing path cost values]

   - Usually, estimated cheapest remaining cost values $h(n)$ are decreasing. The monotonicity condition $h(n) \leq c(n, n') + h(n')$ restricts the possible changes in $h(n)$.

   ![Graph showing decreasing estimated remaining cost values]

   → This ensures that the estimated cheapest total cost values $f(n)$ are non-decreasing.
Monotone Heuristic Functions
Illustration of Non-Decreasing $f$-Values (continued)

2. In the sequence of nodes expanded by A* (in order of expansion):

- Again we have: Estimated cheapest total cost values $f(n)$ of nodes expanded by A* are non-decreasing. [Theorem 63]

- But: For the sequences of path cost values $g(n)$ or estimated cheapest remaining cost values $h(n)$ for node expanded by A* no monotonicity can be stated.
  Q. Why not?
Monotone Heuristic Functions

Example: Knight Moves (revisited)

\[ h = \left\lceil \frac{\text{#rows}}{2} \right\rceil \]

- OPEN \{c, e, l, n, \ f, g, h, i, j, k, o, p}\}
- CLOSED \{m, b, d, a, s}\}

<table>
<thead>
<tr>
<th>( n )</th>
<th>( g(n) )</th>
<th>( h_1(n) )</th>
<th>( f(n) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( s )</td>
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<td>2</td>
</tr>
<tr>
<td>( a )</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>( b )</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>( c )</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>( d )</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>( e )</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>( f )</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>( g )</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>( h )</td>
<td>3</td>
<td>1</td>
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</tr>
<tr>
<td>( i )</td>
<td>3</td>
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<td>( j )</td>
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<td>( m )</td>
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<td>( l )</td>
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<td>( n )</td>
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<tr>
<td>( k )</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>( o )</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>( p )</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

f-values never decrease.
Monotone Heuristic Functions

Example: Knight Moves (revisited)

Analyzed part of the search space graph:

- **f**-values never decrease.
- Q. Is \( h \) monotone—i.e., does \( h(n) \leq c(n, n') + h(n') \) hold?
Monotone Heuristic Functions

Example: Knight Moves (revisited)

Analyzed part of the search space graph:

- $h_1 = 1, f = 4$
- Solved rest problem

$f$-values never decrease.

Q. Is $h$ monotone—i.e., does $h(n) \leq c(n, n') + h(n')$ hold?
Monotone Heuristic Functions

Coping with non-monotonicity [Martelli 77]

Starting point: Decreasing \( f \)-values indicate non-monotonicity in estimations.

Martelli suggests algorithm B with a node selection strategy based on storing a value \( F \) that is the biggest \( f \)-value of nodes expanded so far:

- Initially, assign \( F \leftarrow 0 \).
- When entering the main loop:
  - If there is a node \( n' \) on OPEN with \( f(n') < F \), then select a node \( n \) from OPEN with \( f(n) < F \) and minimum \( g \)-value.
  - Otherwise, select a node \( n \) with minimum \( f \)-value from OPEN and let \( F \leftarrow f(n) \).

Algorithm B is A* with a different node selection strategy.

→ Algorithm B is admissible. B dominates A*.

The exponential number of node expansions example problem for A* will be solved with a quadratic number by algorithm B.
Monotone Heuristic Functions

Coping with non-monotonicity  [Mero 84]

Starting point: Non-monotone behavior of \( h \) is observed in node expansions.

Mero suggests algorithm B’ with an additional adaption of \( h \)-values in node expansions in Martelli’s algorithm:

- Initially, assign \( h'(s) \leftarrow h(s) \) for the start node \( s \).
- When entering the main loop:
  - Select a node \( n \) with minimum value \( g(n) + h'(n) \) from OPEN.
  - If \( n \) is expanded, then let
    \[
    h'(n') \leftarrow \begin{cases} 
    \max\{h(n'), (h'(n) - c(n, n'))\} & \text{for all successor nodes } n' \text{ of } n \\
    \max\{h'(n'), (h'(n) - c(n, n'))\} & \text{for all other successor nodes } n' \text{ of } n.
    \end{cases}
    \]

Algorithm B’ is A* with heuristic values \( h' \) changing during runtime.

→ Algorithm B’ is admissible. B’ dominates B and A*.
Remarks:

- If only the adaption of $h$-values for successor nodes is used, the resulting method is known as pathmax:

\[ h'(n') = \max\{h(n'), h'(n) - c(n, n')\} \]

for all successors $n'$ of $n$.

Let A* use $h'$-values in the node selection step instead of $h$-values.

In this way, $f$-values in backpointer paths increase along the path. However, using this method does not prevent CLOSED nodes from being reopened. The following example, which shows this behavior, is based on an idea of Holte [Holte 2010]:

Remarks on Mero's full method can be found in [Zhang 2009].
Theorem 64 (Necessary and Sufficient Conditions for Node Expansion III)

Let $G$ be a search space graph with $Prop(G)$ and let A* use a monotone heuristic function $h$. The condition $g^*(n) + h(n) \leq C^*$ is a necessary condition for expanding node $n$. A sufficient condition for expanding $n$ is $g^*(n) + h(n) < C^*$. 

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**Theorem 64 (Necessary and Sufficient Conditions for Node Expansion III)**

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Monotone Heuristic Functions
Conditions for Node Expansion III

**Theorem 64 (Necessary and Sufficient Conditions for Node Expansion III)**

Let $G$ be a search space graph with $\text{Prop}(G)$ and let $A^*$ use a monotone heuristic function $h$. The condition $g^*(n) + h(n) \leq C^*$ is a necessary condition for expanding node $n$. A sufficient condition for expanding $n$ is $g^*(n) + h(n) < C^*$.

**Proof (sketch)**

1. The necessary condition follows by combining [Theorem 50](#) and [Theorem 62](#).
2. The sufficient condition follows from the non-decreasing behavior of $f$-values along optimum paths, i.e.,
   \[
   g^*(n_1) + h(n_1) \leq g^*(n_1) + c(n_1, n_2) + h(n_2) = g^*(n_2) + h(n_2)
   \]
   for nodes $n_1, n_2$ on an optimum path $P_{s-n}^*$ to a node $n$ with $n_2$ being a successor of $n_1$.
3. $\Rightarrow$ From condition $g^*(n) + h(n) < C^*$ then follows that $P_{s-n}^*$ is strictly $C^*$-bounded.
4. $\Rightarrow$ Hence, $n$ will be expanded. [Theorem 55](#)
For monotone heuristic functions $h$ hold:

$$\text{node expansion by } A^* \implies g^*(n) + h(n) \leq C^*$$

necessary

$$g^*(n) + h(n) < C^* \implies \text{node expansion by } A^*$$

sufficient

Again, Theorem 64 does not give a condition for node expansion that is both necessary and sufficient:

The theorem does not treat nodes with $g^*(n) + h(n) = C^*$. 
Remarks:

- If monotone heuristic functions are used, then the condition \( g^*(n) + h(n) < C^* \) has to be tested only for a node \( n \)—but the computation of \( g^*(n) \) may be costly. If searching a strictly \( C^* \)-bounded path to \( n \), any node on that path has to be considered.

- Since \( f \)-values for the sequence of expanded nodes are non-decreasing, the advantage of using different tie breaking rules along with the same monotone heuristic \( h \) is limited to the number of nodes with \( g^*(n) + h(n) = C^* \). Recall that such nodes may occur on any path, not only on solution paths. An inferior tie breaking rule may select a node with \( g^*(n) + h(n) = C^* \) that is not on an optimum solution path.

Nodes with \( g^*(n) + h(n) < C^* \) may be expanded at different points in time due to different tie breaking rules but they will be expanded before termination.

- **Theorem 64** gives an explanation why the difference between the relation \( f(n) \leq C^* \) and \( f(n) < C^* \) is often insignificant: If \( f(n) \) can be modeled as a continuous random variable, the equality \( f(n) = C^* \) becomes a rare event.

- In the book of Pearl this theorem is denoted as Theorem 12. [Pearl 1984]
Monotone Heuristic Functions

**Definition 65 (Largely Dominating Algorithms)**

An algorithm $A_1$ (informed by $h_1$) largely dominates $A_2$ (informed by $h_2$) if every node expanded by $A_1$ is also expanded by $A_2$ except, perhaps, some nodes for which $h_1(n) = h_2(n) = C^* - g^*(n)$ holds.

**Corollary 66 (of Theorem 64)**

Let $G$ be a search space graph with $Prop(G)$. If $h_1(n) \geq h_2(n)$ holds for any $n$ and if $h_1(n)$ and $h_2(n)$ both are monotone, then $A^*_1$ ($A^*$ informed by $h_1(n)$) largely dominates $A^*_2$ ($A^*$ informed by $h_2(n)$).
Monotone Heuristic Functions

Definition 65 (Largely Dominating Algorithms)
An algorithm $A_1$ (informed by $h_1$) largely dominates $A_2$ (informed by $h_2$) if every node expanded by $A_1$ is also expanded by $A_2$ except, perhaps, some nodes for which $h_1(n) = h_2(n) = C^* - g^*(n)$ holds.

Corollary 66 (of Theorem 64)
Let $G$ be a search space graph with $\text{Prop}(G)$. If $h_1(n) \geq h_2(n)$ holds for any $n$ and if $h_1(n)$ and $h_2(n)$ both are monotone, then $A^*_1$ ($A^*$ informed by $h_1(n)$ ) largely dominates $A^*_2$ ($A^*$ informed by $h_2(n)$ ).

Proof (sketch)
1. Let $n$ be a node expanded by $A^*_1$ but not by $A^*_2$.
2. It holds: $g^*(n) + h_1(n) \leq C^*$ and $C^* \leq g^*(n) + h_2(n)$ [Theorem 64]
3. Since $h_1(n) \geq h_2(n)$ holds: $C^* \leq g^*(n) + h_2(n) \leq g^*(n) + h_1(n) \leq C^*$
4. $\Rightarrow h_1(n) = h_2(n) = C^* - g^*(n)$
Remarks:

- Note that in the absence of monotonicity, the advantage of A\(^*\)\(_1\) over A\(^*\)\(_2\) would be much less certain: every descendant of \(n\) that is reachable from \(n\) by a—wrt. \(h_1\) strictly \(C^*\)-bounded path—will also be expanded by A\(^*\)\(_1\) and possibly not by A\(^*\)\(_2\).

- If \(h\) is monotone (or consistent), then A\(^*\) largely dominates every admissible algorithm having access to the same \(h\). [Dechter/Pearl 1983]

- If \(h\) is admissible but not monotone (or consistent), then there are admissible algorithms that, using the same \(h\), will grossly outperform A\(^*\) in some problem instances, regardless of what tie breaking rule A\(^*\) invokes. [Pearl 1984]

- Monotonicity is not an exceptional property but can be often established for an admissible heuristic. For instance, all the heuristic functions discussed in the introduction are monotone.