

Exercises: Artificial Intelligence

A^*

A*

A* ALGORITHM

A* Algorithm

- **Input:**
 - **QUEUE:** Path only containing root
- **Algorithm:**
 - **WHILE** (QUEUE not empty && first path not reach goal) **DO**
 - Remove **first path** from QUEUE
 - Create paths to all children
 - Reject paths with loops
 - Add paths and sort QUEUE (by $f = \text{cost} + \text{heuristic}$)
 - **IF** QUEUE contains paths: P, Q
 - AND** P ends in node N_i && Q contains node N_i
 - AND** $\text{cost } P \geq \text{cost } Q$
 - THEN** remove P
 - **IF** goal reached **THEN** success **ELSE** failure

A^*

FIRST EXAMPLE ON A^*

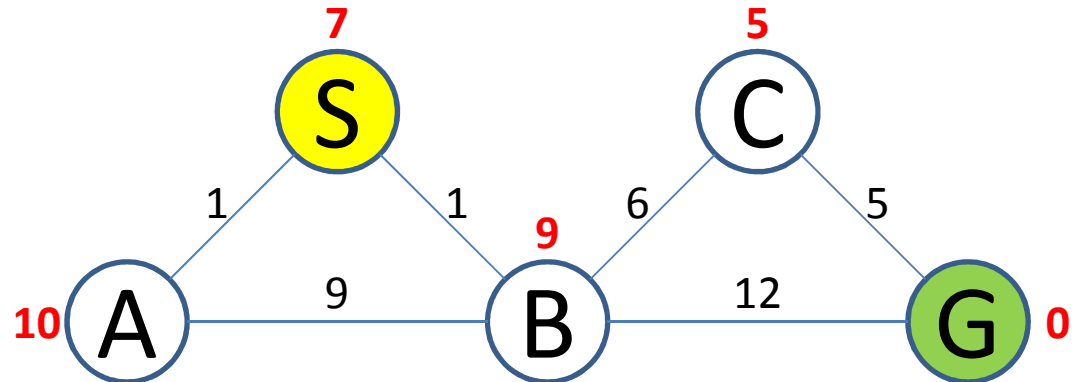
A* algorithm by Example



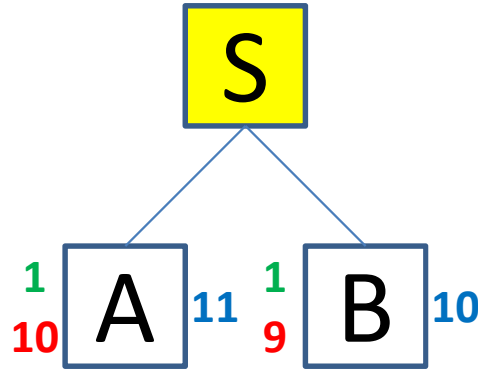
$f = \text{accumulated path cost} + \text{heuristic}$

QUEUE = *path containing root*

QUEUE: <S>



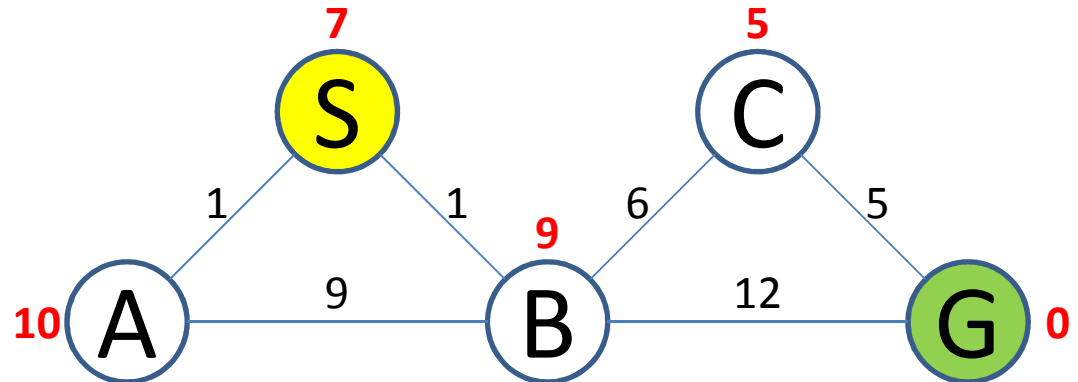
A* algorithm by Example



$f = \text{accumulated path cost} + \text{heuristic}$

Remove first path, Create paths to all children, Reject loops and Add paths.
Sort QUEUE by f

QUEUE: <SB,SA>

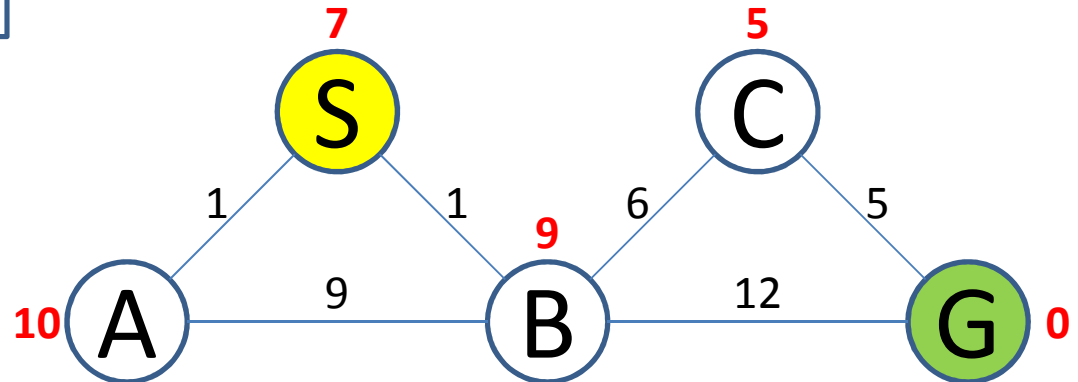
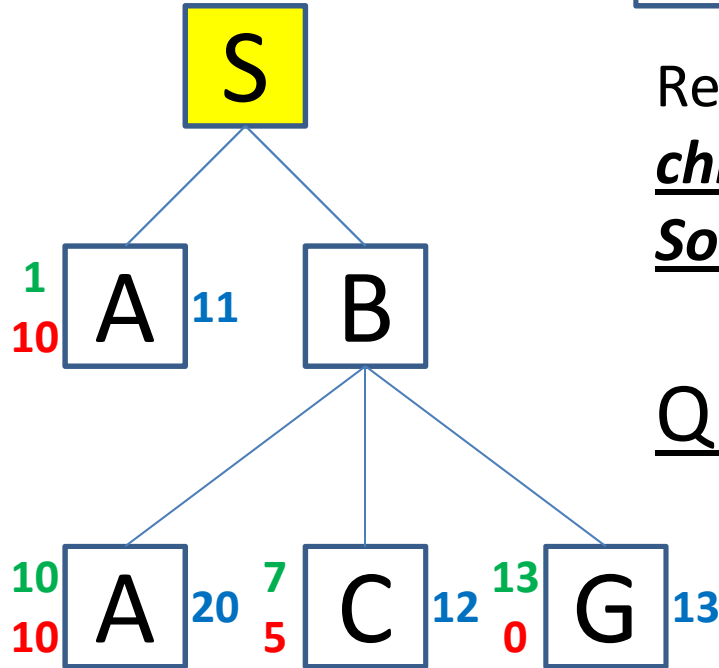


A* algorithm by Example

$f = \text{accumulated path cost} + \text{heuristic}$

Remove first path, Create paths to all children, Reject loops and Add paths.
Sort QUEUE by f

QUEUE: <SA,SBC,SBG,SBA>

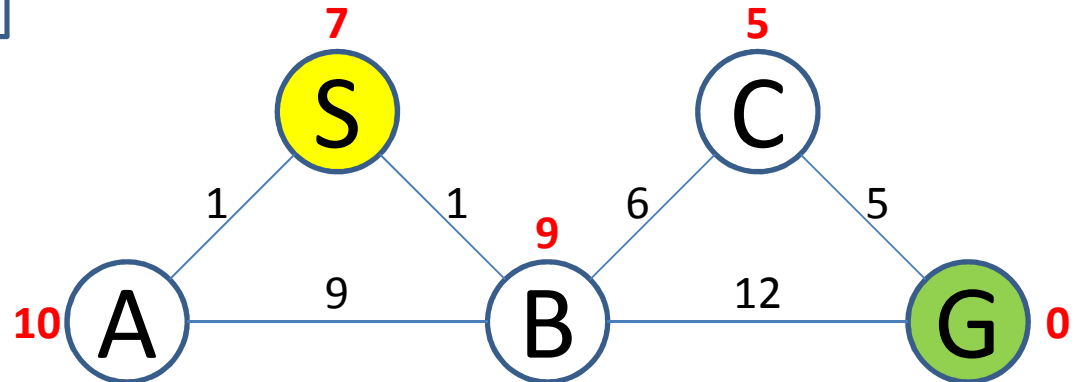
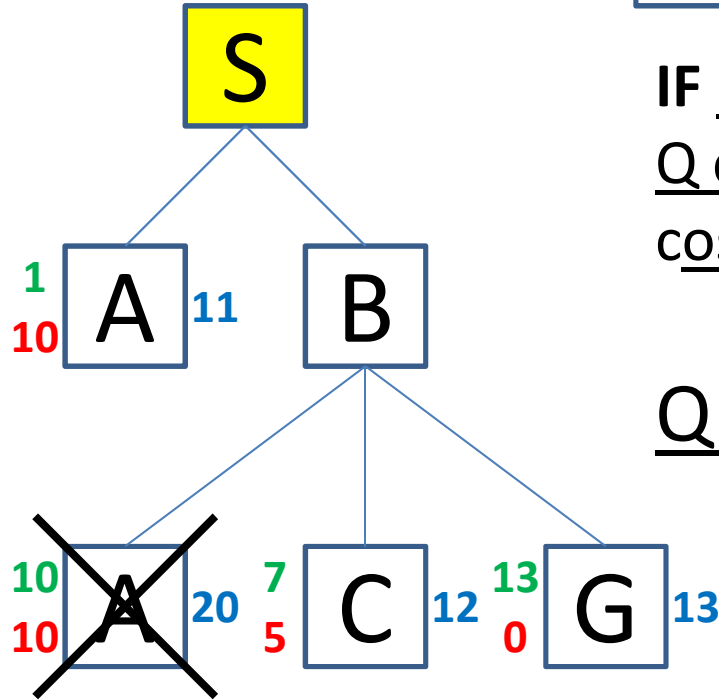


A* algorithm by Example

$f = \text{accumulated path cost} + \text{heuristic}$

IF P terminating in I with cost P &&
Q containing I with cost Q **AND**
cost P \geq cost Q **THEN** remove P

QUEUE: <SA, SBC, SBG, **SBA**>

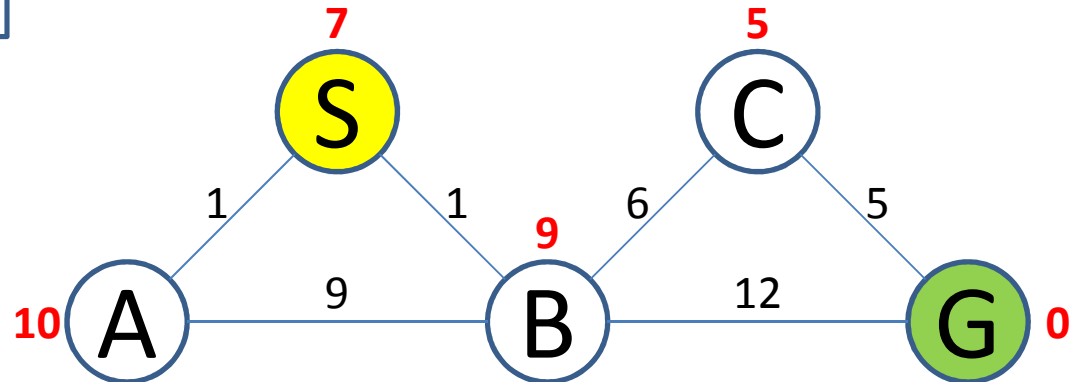
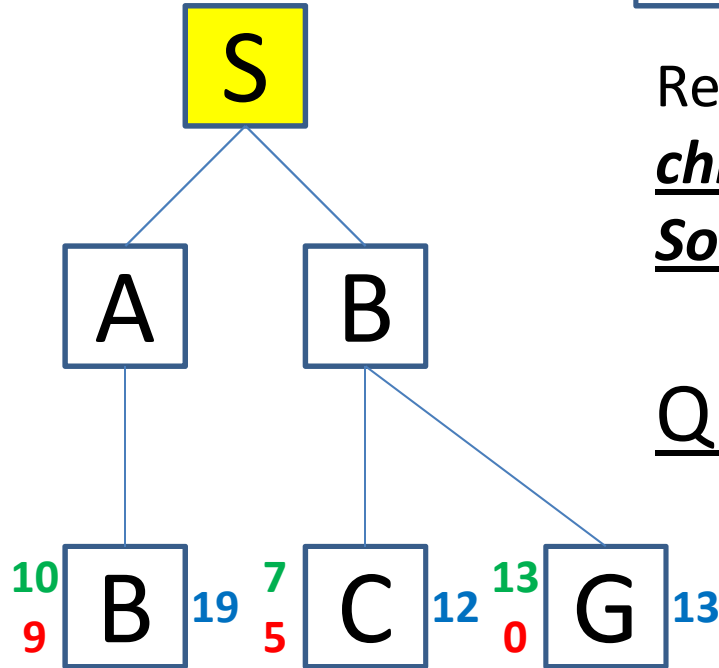


A* algorithm by Example

$f = \text{accumulated path cost} + \text{heuristic}$

Remove first path, Create paths to all children, Reject loops and Add paths.
Sort QUEUE by f

QUEUE: <SBC,SBG,SAB>

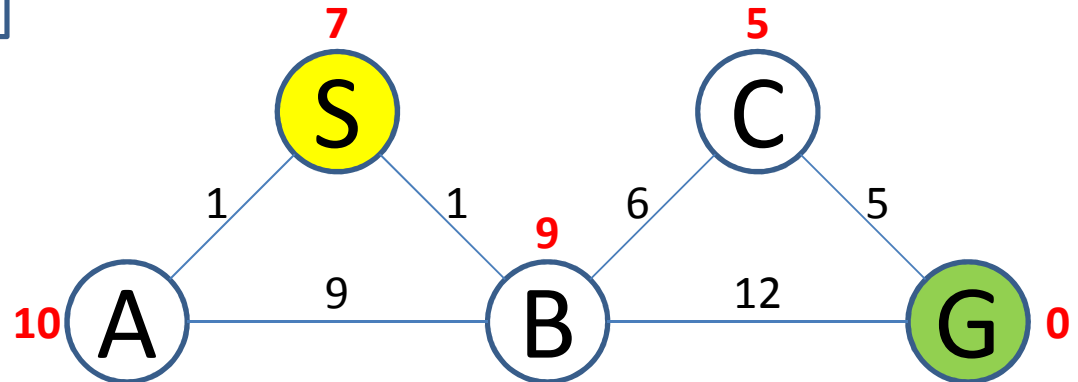
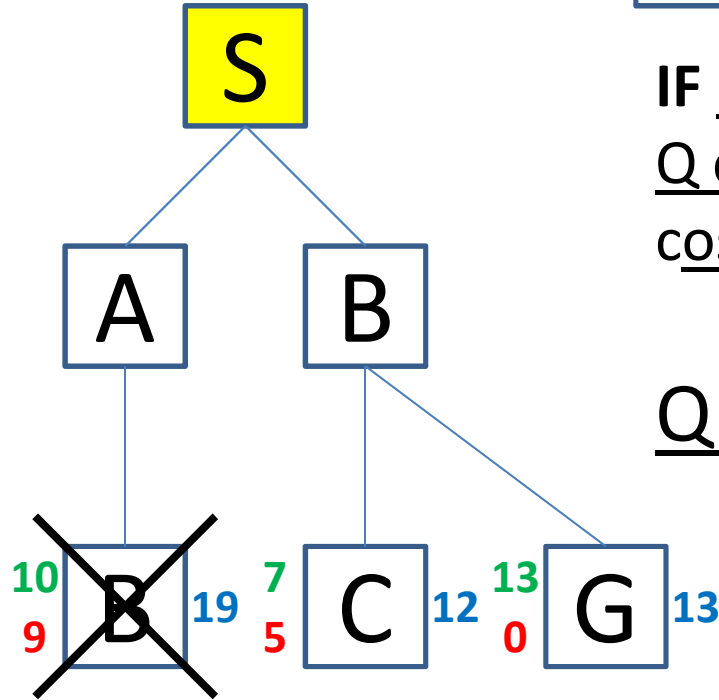


A* algorithm by Example

$f = \text{accumulated path cost} + \text{heuristic}$

IF P terminating in I with cost P &&
Q containing I with cost Q **AND**
cost P \geq cost Q **THEN** remove P

QUEUE: <SBC,SBG,SAB>

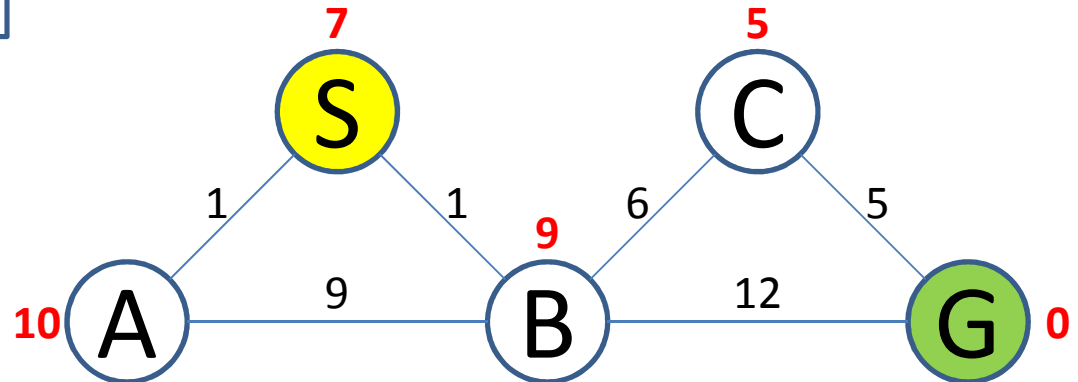
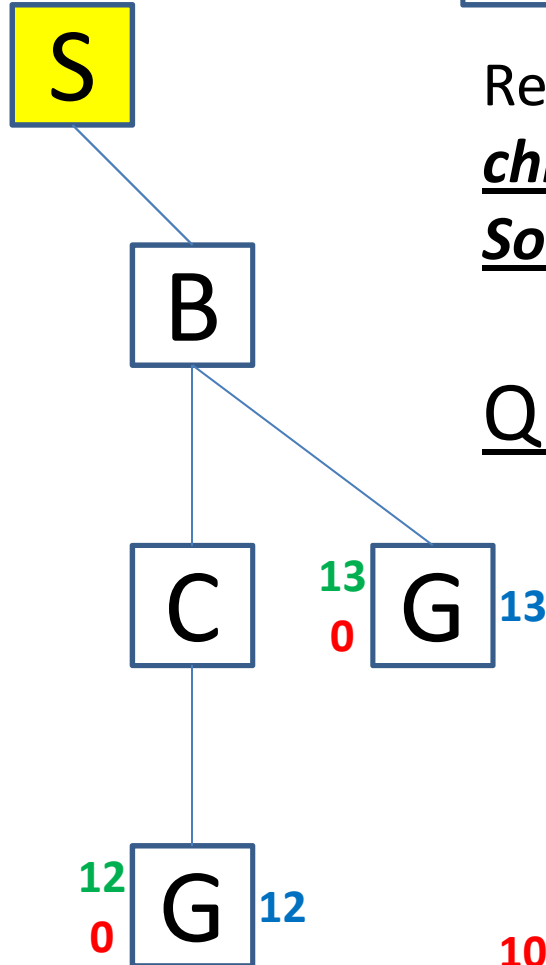


A* algorithm by Example

$f = \text{accumulated path cost} + \text{heuristic}$

Remove first path, Create paths to all children, Reject loops and Add paths.
Sort QUEUE by f

QUEUE: <SBCG, SBG>

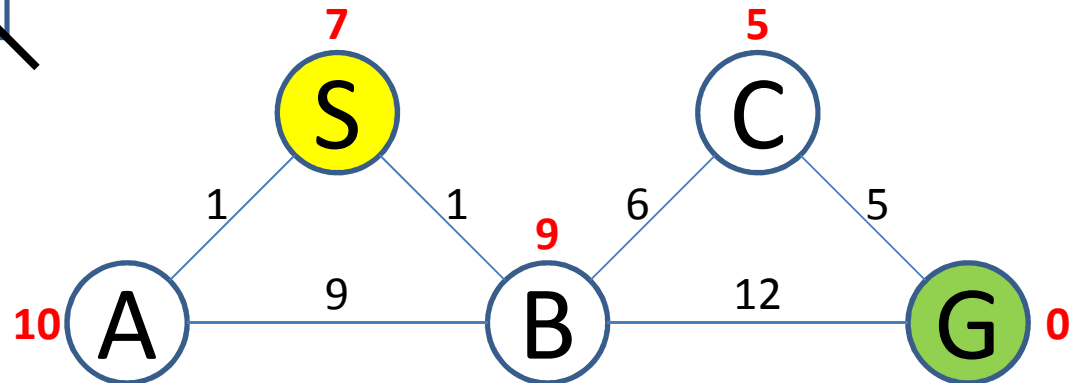
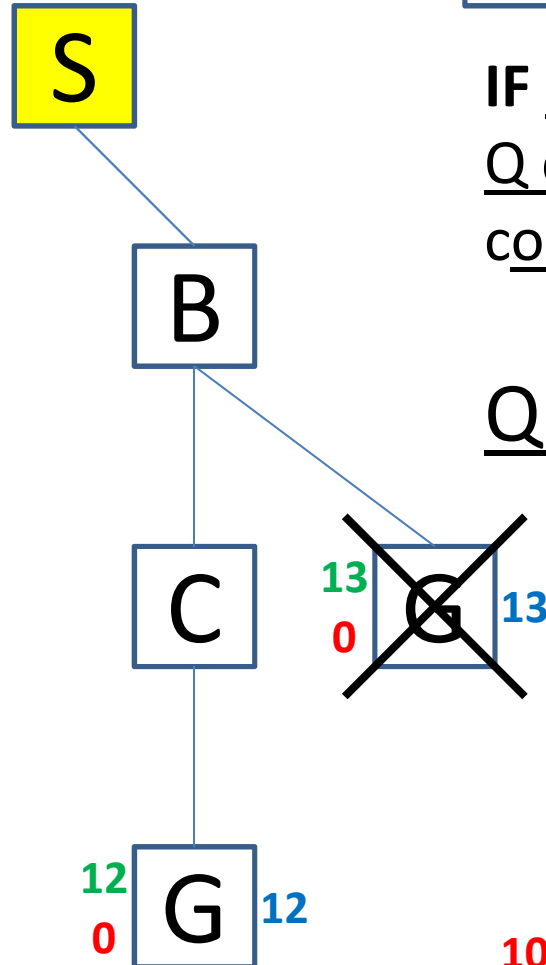


A* algorithm by Example

$f = \text{accumulated path cost} + \text{heuristic}$

IF P terminating in I with cost P &&
Q containing I with cost Q **AND**
cost P \geq cost Q **THEN** remove P

QUEUE: <SBCG, **SBG**>

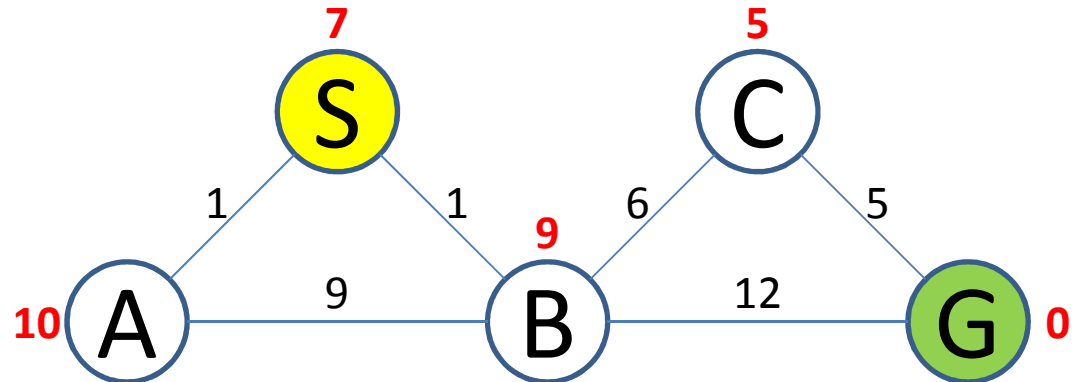
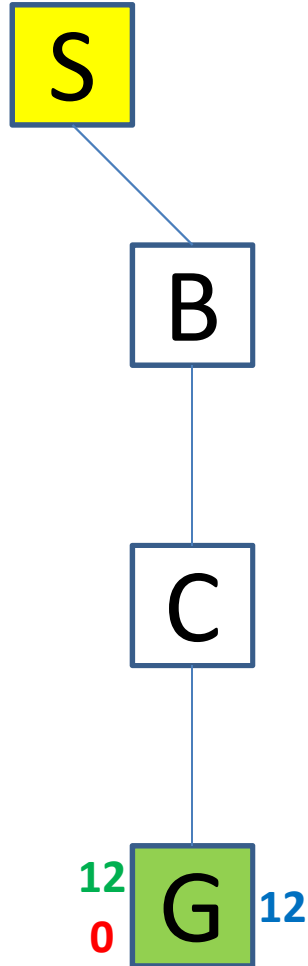


A* algorithm by Example

$f = \text{accumulated path cost} + \text{heuristic}$

SUCCESS

QUEUE: <SBCG>

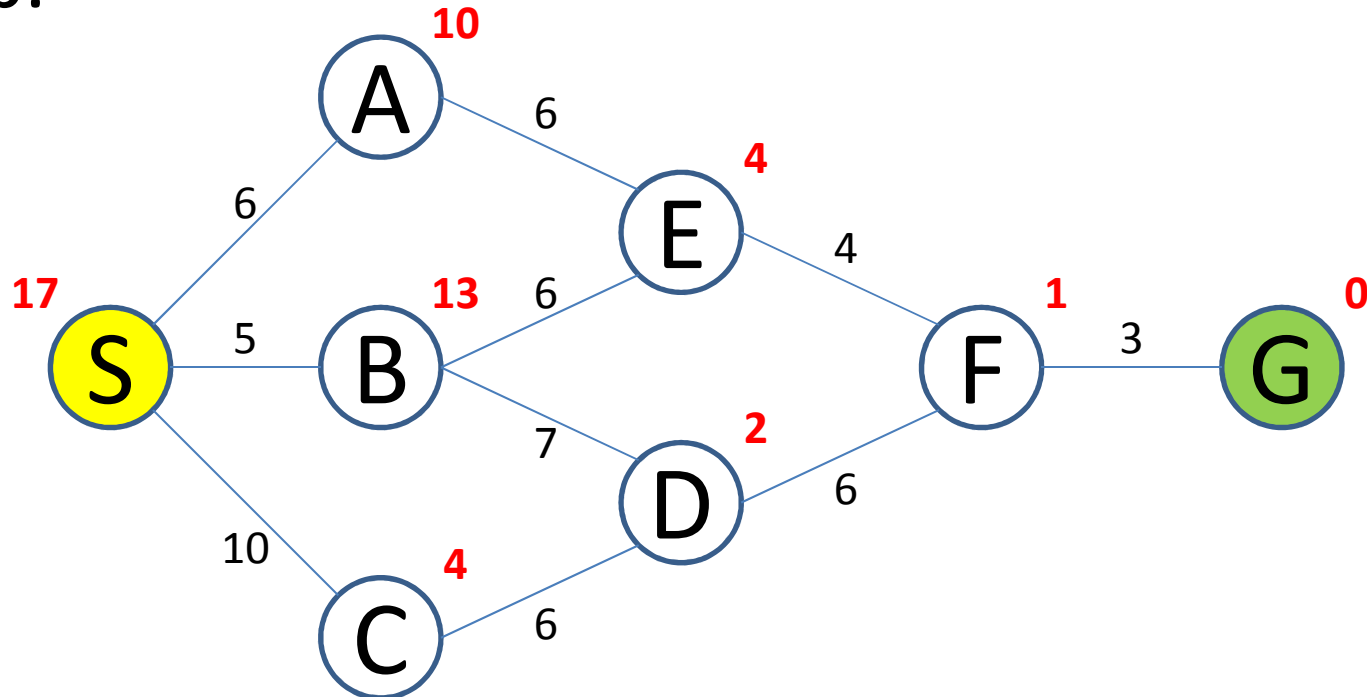


A*

PROBLEM

Problem

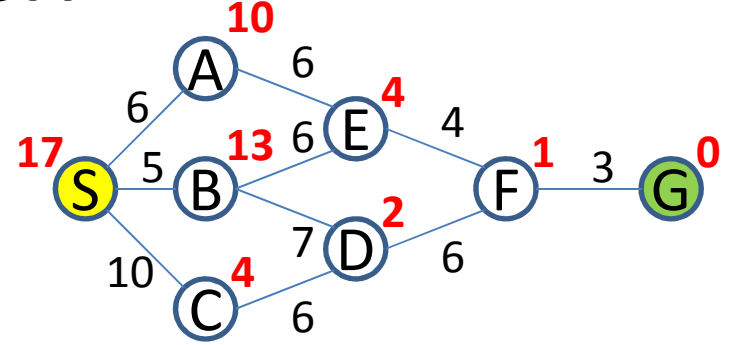
- Perform the A* Algorithm on the following figure. Explicitly write down the queue at each step.



A*

A* SEARCH

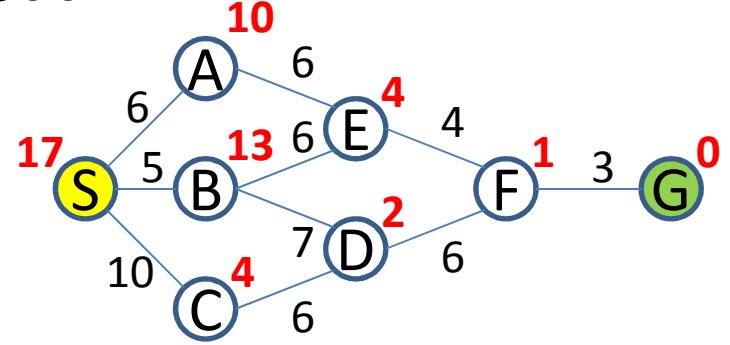
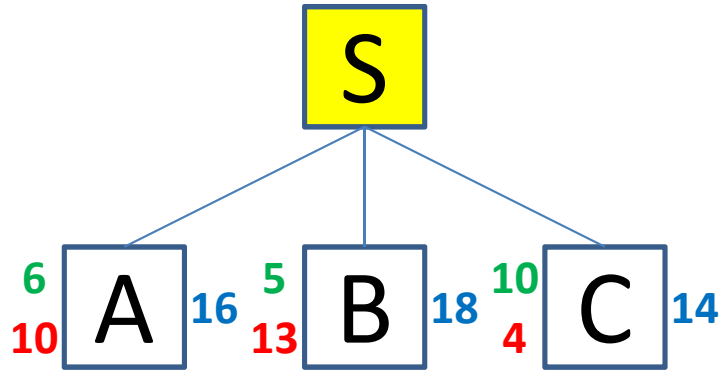
A* Search



QUEUE:

S

A* Search



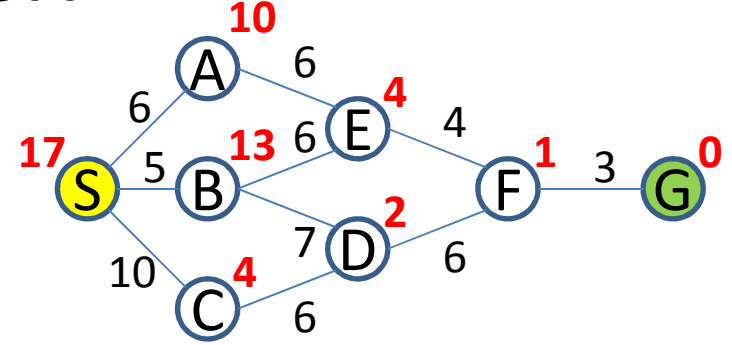
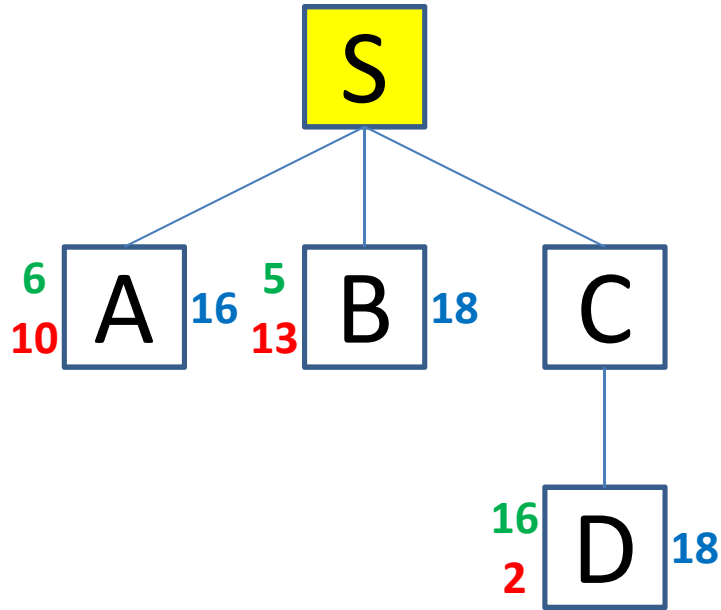
QUEUE:

SC

SA

SB

A* Search



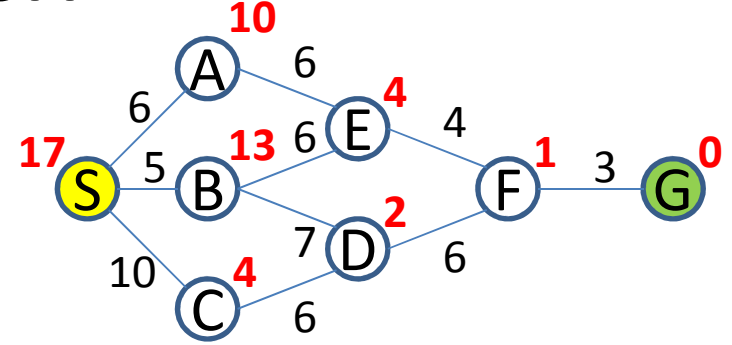
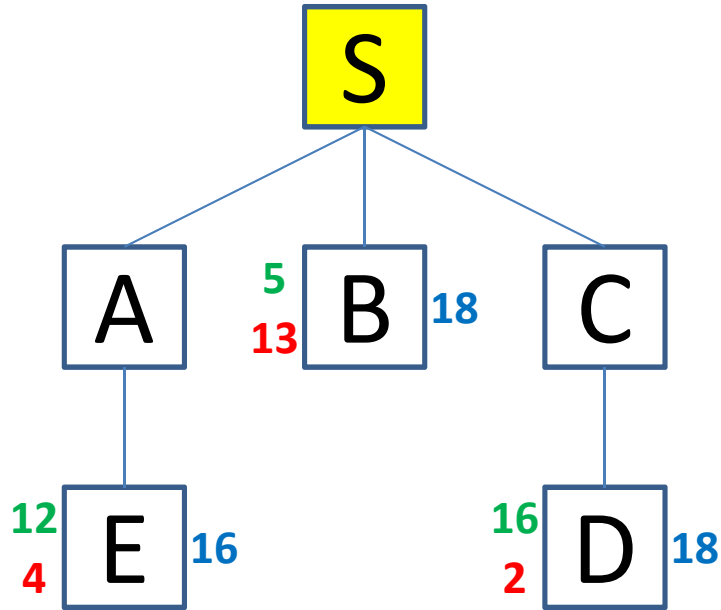
QUEUE:

SA

SCD

SB

A* Search



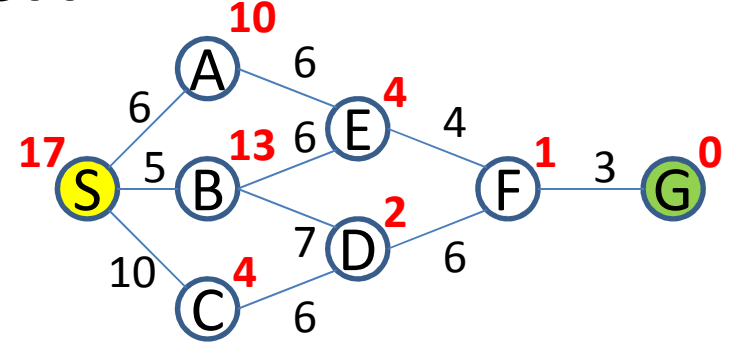
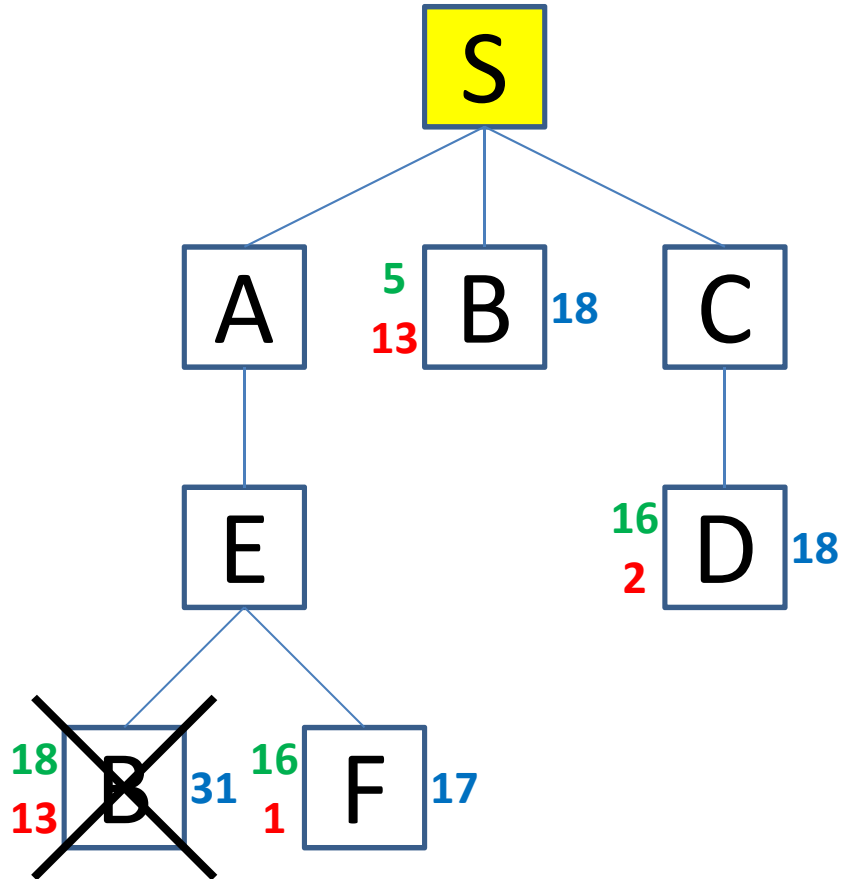
QUEUE:

SAE

SCD

SB

A* Search



QUEUE:

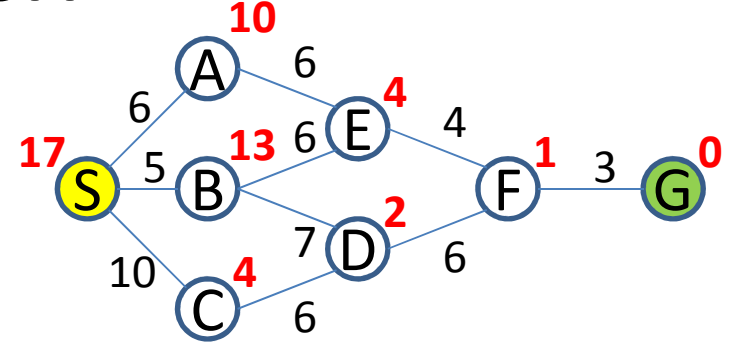
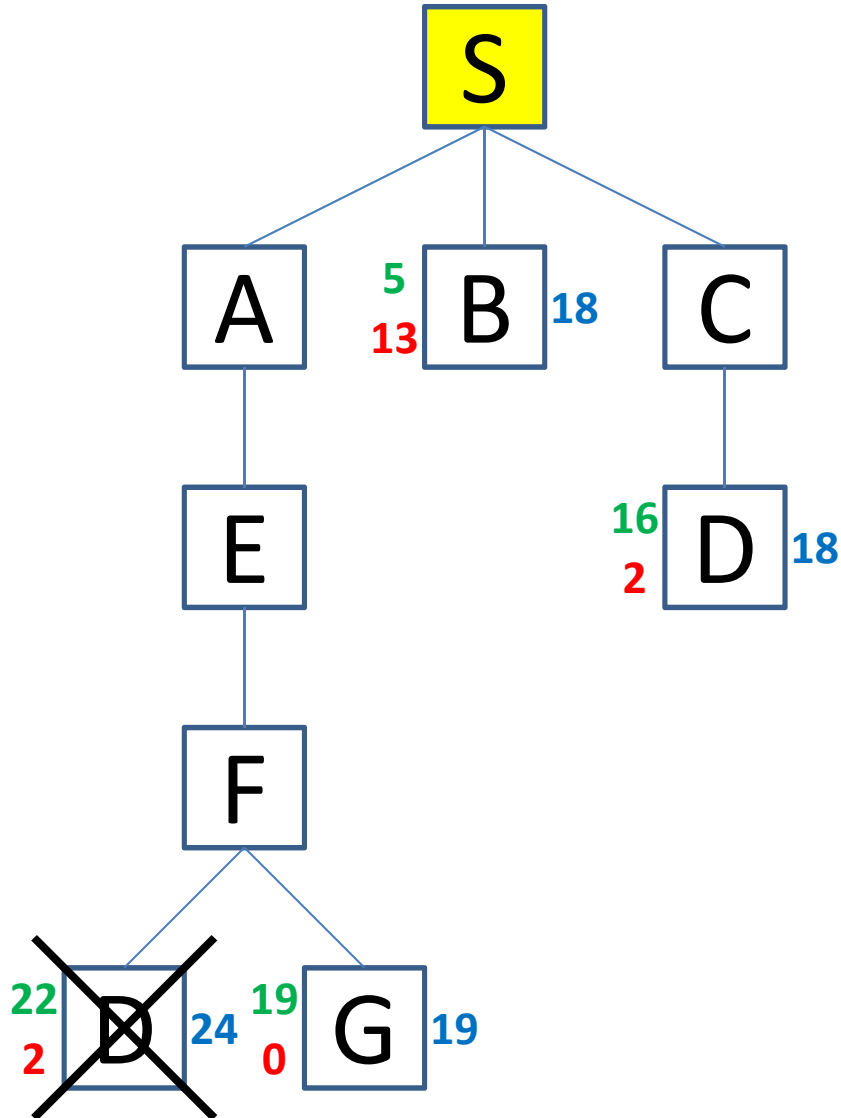
SAEF

SCD

SB

SAEB

A* Search



QUEUE:

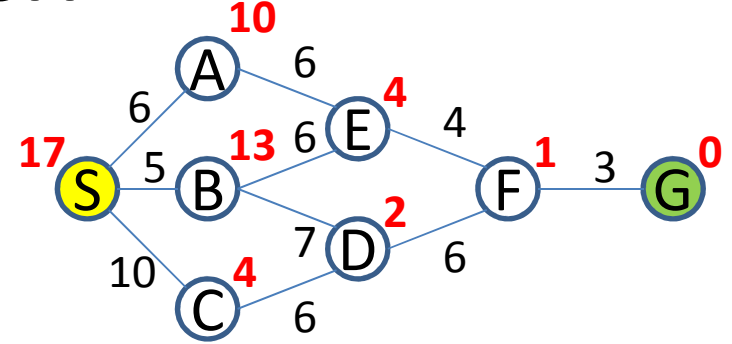
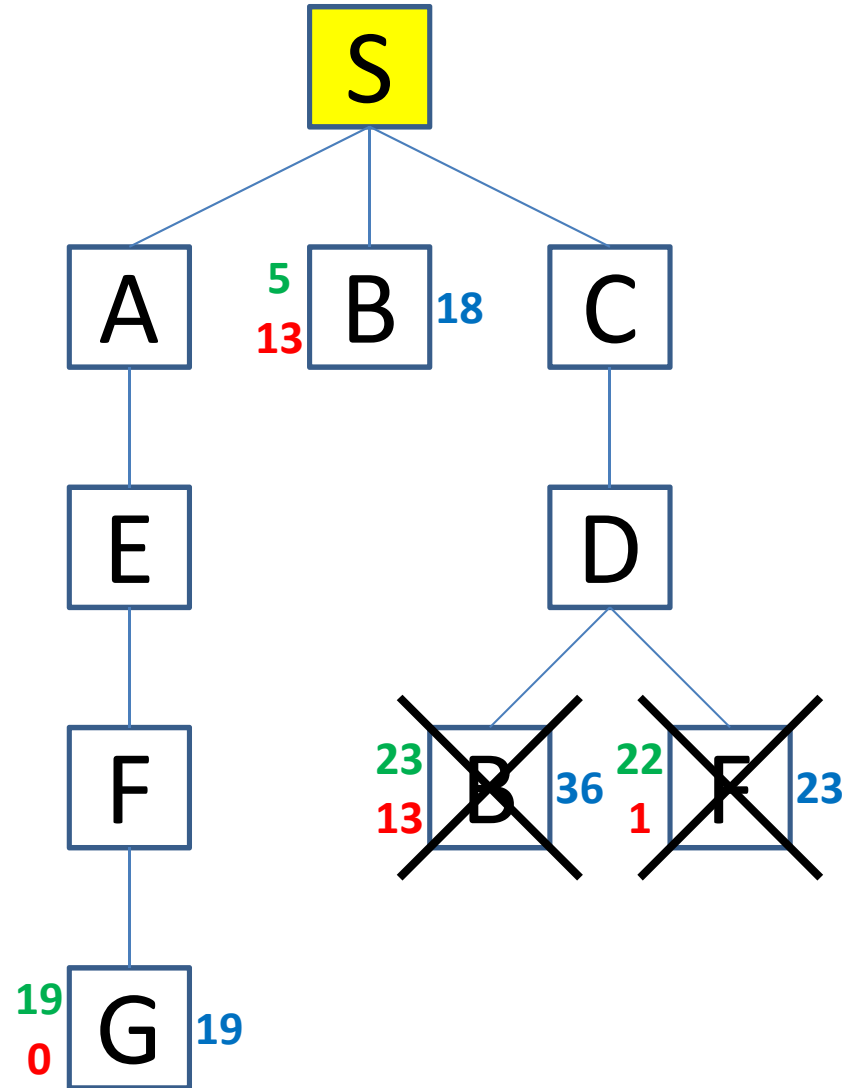
SCD

SB

SAEFG

SAEFD

A* Search



QUEUE:

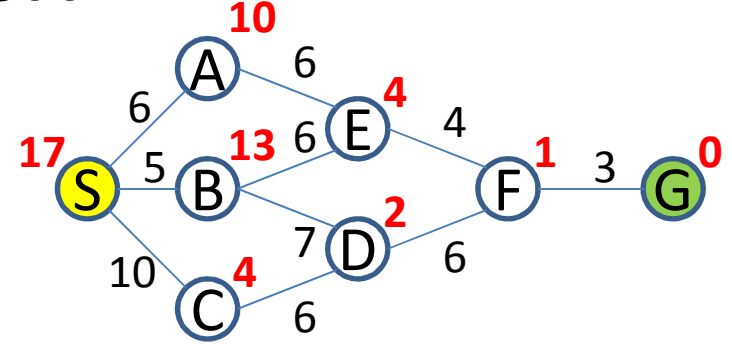
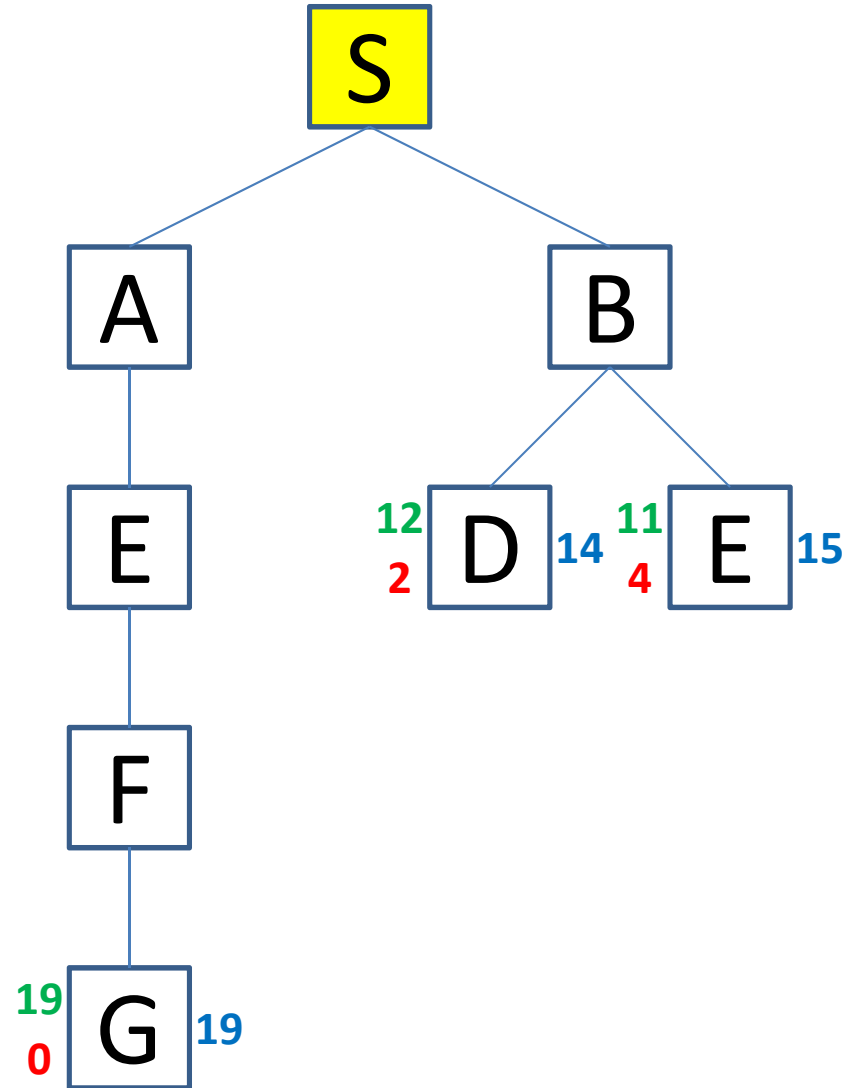
SB

SAEFG

SCDF

SCDB

A* Search



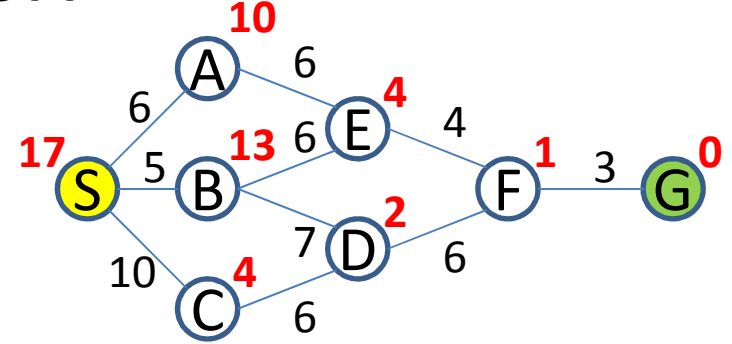
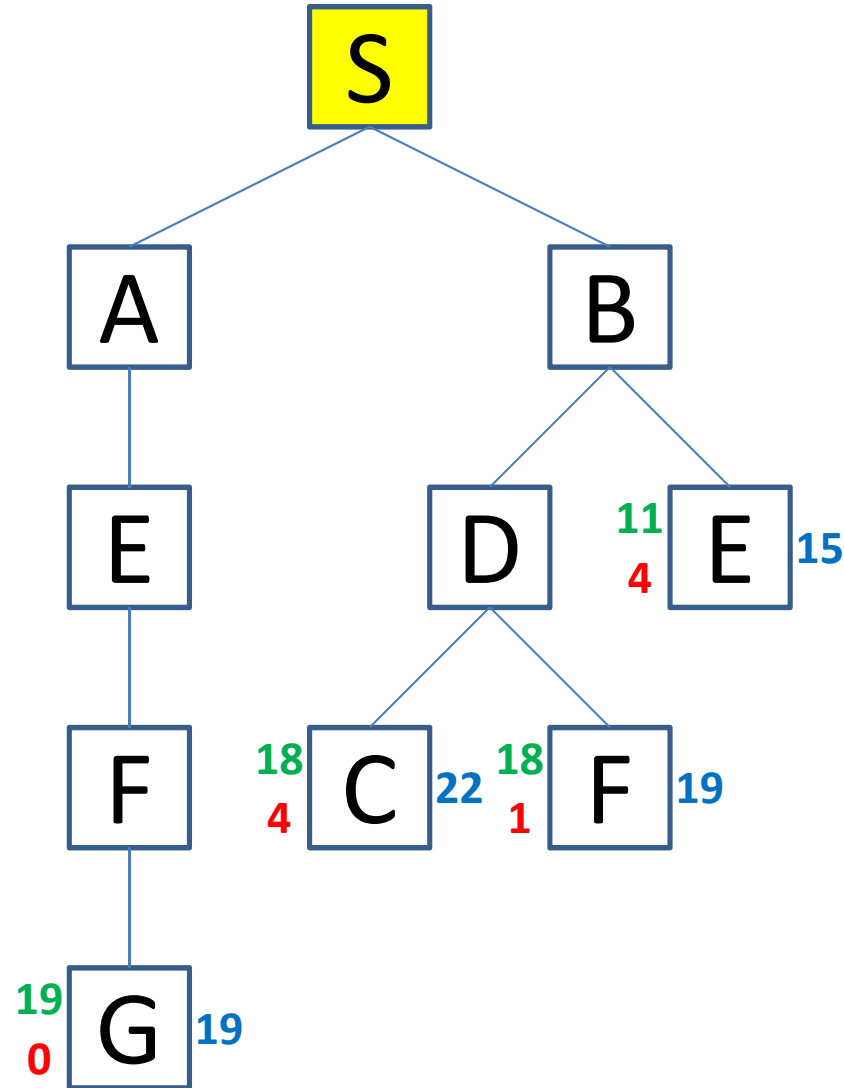
QUEUE:

SBD

SBE

SAEFG

A* Search



QUEUE:

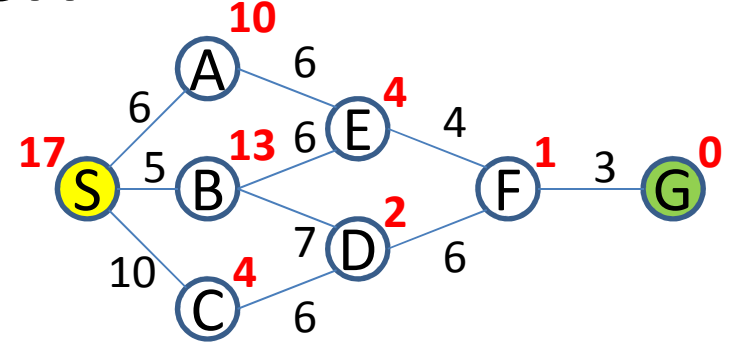
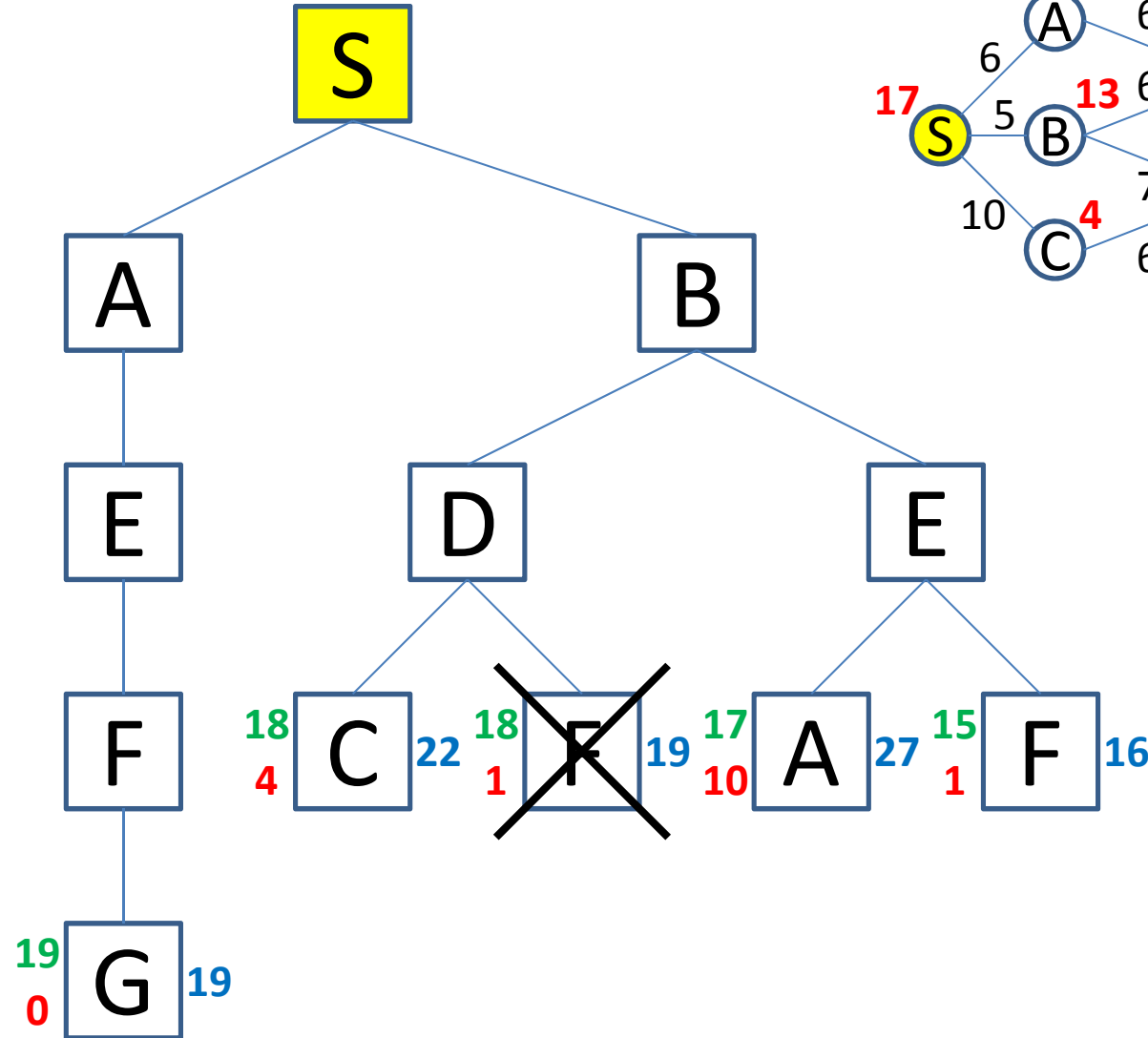
SBE

SBDF

SAEFG

SBDC

A* Search



QUEUE:

SBEF

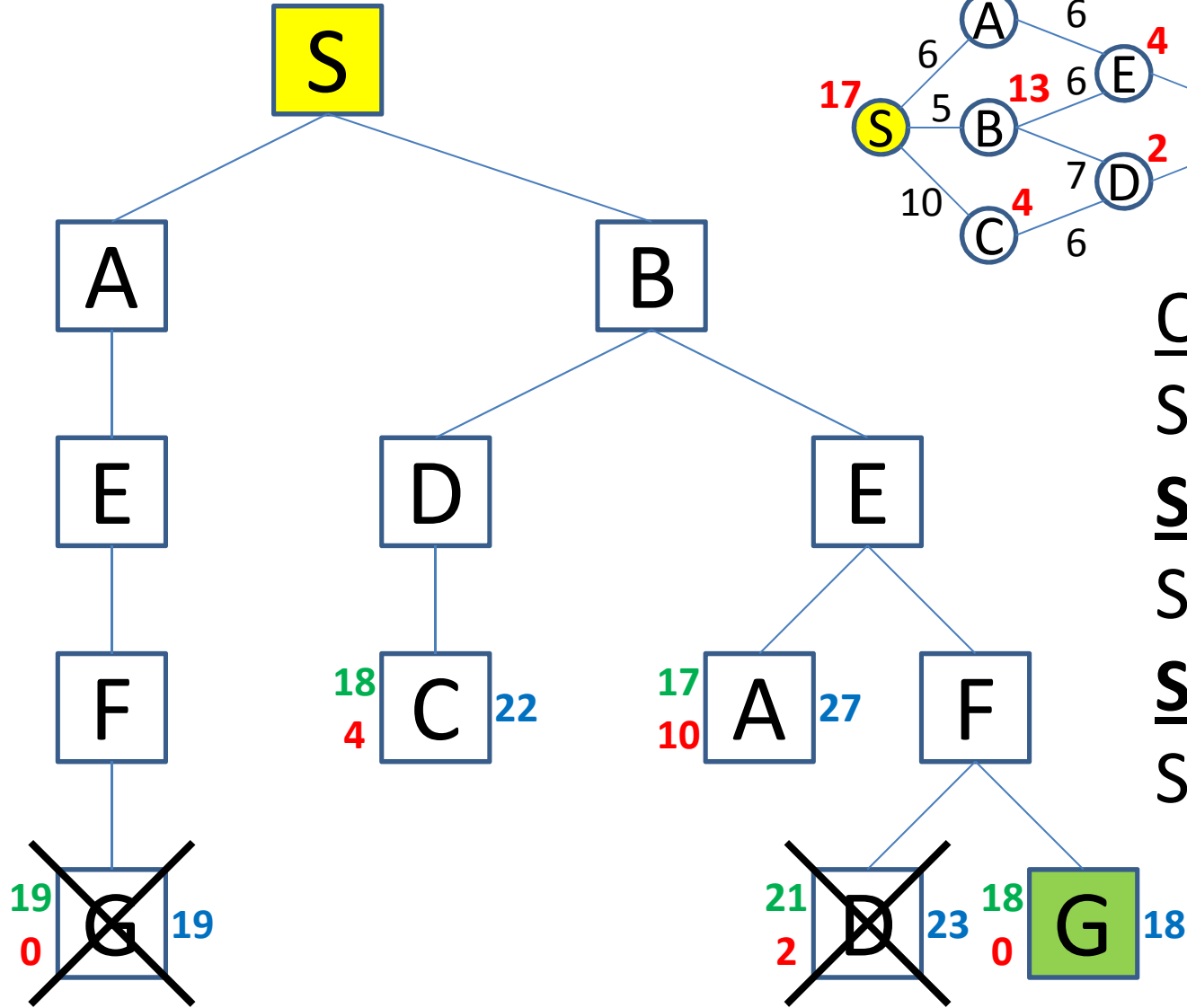
SAEFG

SBDF

SBDC

SBEA

A* Search



QUEUE:

SBEFG

SAEFG

SBDC

SBEFD

SBEA

Exercises: Artificial Intelligence

Iterated Deepening A*

Iterated Deepening A*

IDA* ALGORITHM

IDA* Algorithm

- $f\text{-bound} \leftarrow f(S)$
- **Algorithm:**
 - **WHILE** (goal is not reached) **DO**
 - $f\text{-bound} \leftarrow f\text{-limited_search}(f\text{-bound})$
 - Perform **f-limited search** with $f\text{-bound}$
(See next slide)

f-limited Search Algorithm

- ***Input:***

- QUEUE \leftarrow Path only containing root
- f-bound \leftarrow Natural number
- f-new $\leftarrow \infty$

- ***Algorithm:***

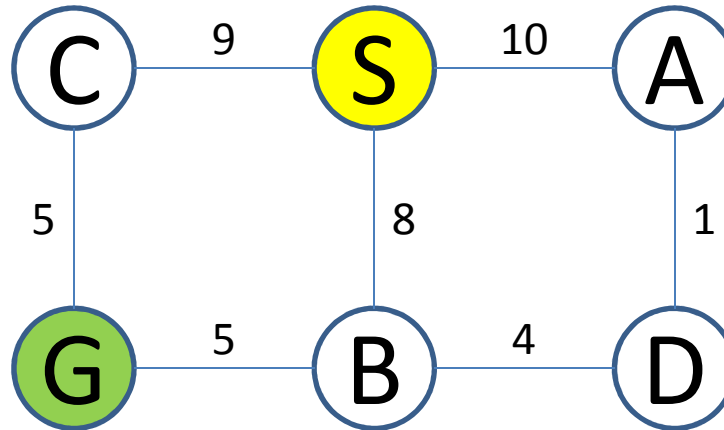
- **WHILE** (QUEUE not empty && goal not reached) **DO**
 - Remove **first path** from QUEUE
 - Create paths to children
 - Reject paths with loops
 - Add paths with **f(path) \leq f-bound** to **front** of QUEUE (*depth-first*)
 - f-new \leftarrow minimum({f-new} \cup {f(P) | P is rejected path})
- **IF** goal reached **THEN** success **ELSE** report f-new

Iterated Deepening A*

PROBLEM

Problem

- Perform the IDA* Algorithm on the following figure.

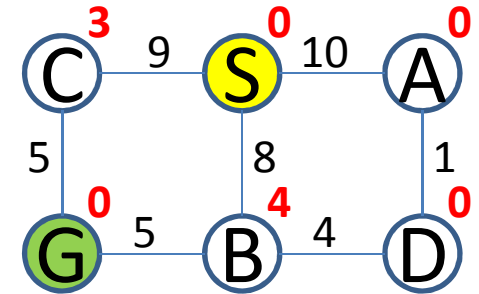


	S	A	B	C	D	G
heuristic	0	0	4	3	0	0

Iterated Deepening A*

IDA* SEARCH

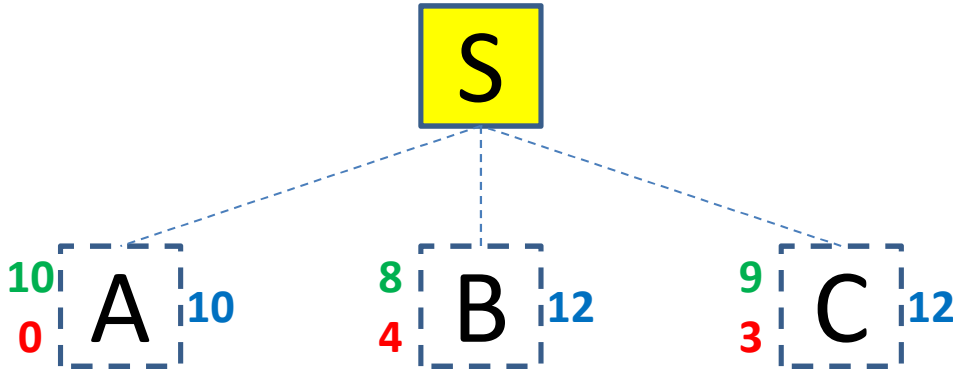
IDA* Search



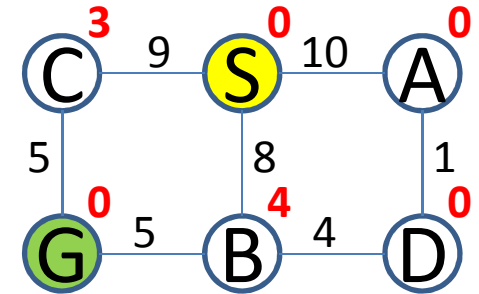
f-bound = 0

f-new = ∞

IDA* Search

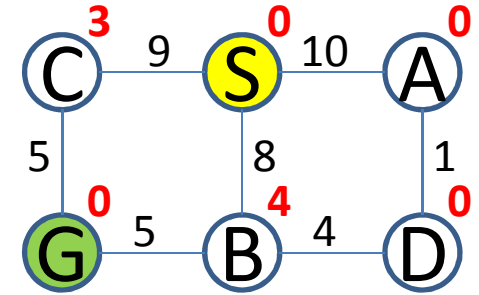


Children are explored
depth-first!



f-bound = 0
f-new = 10

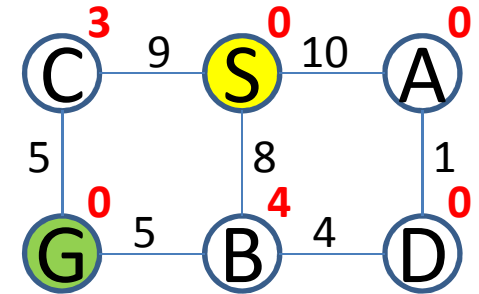
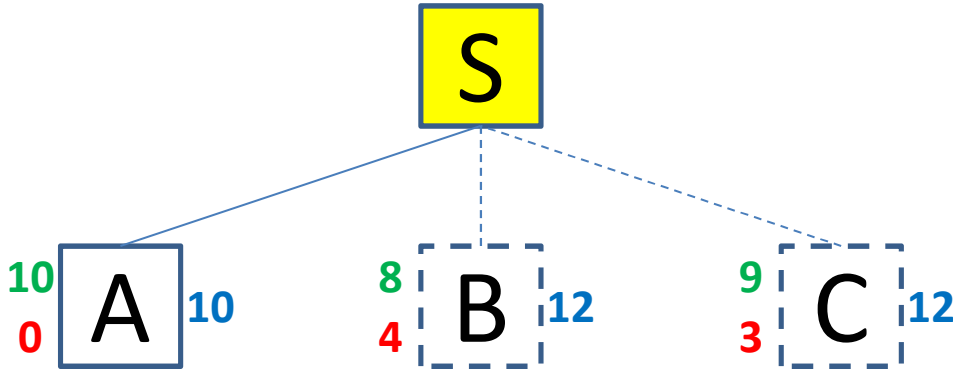
IDA* Search



f-bound = 10

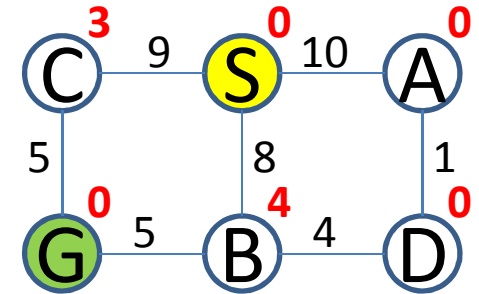
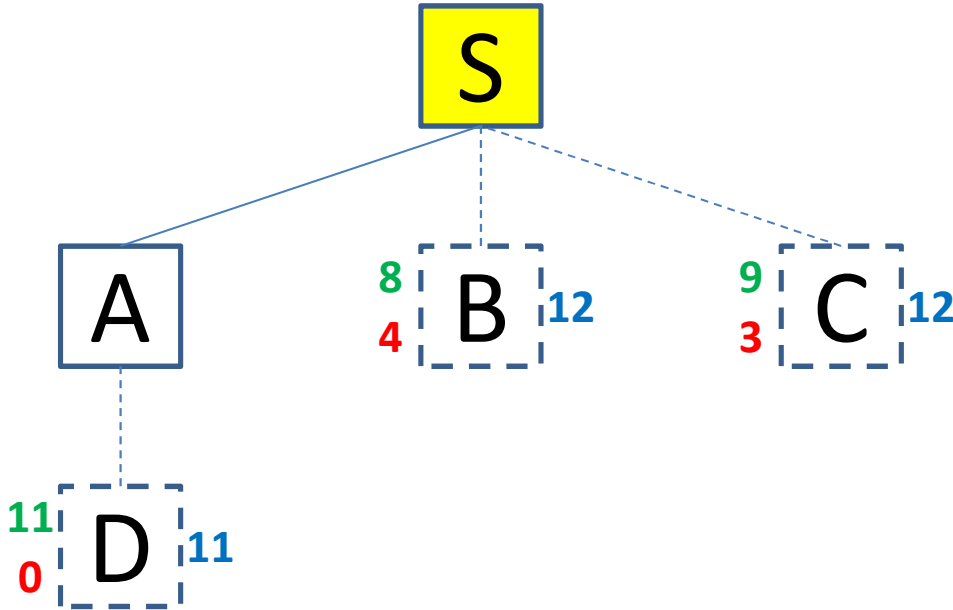
f-new = ∞

IDA* Search



f-bound = 10
f-new = 12

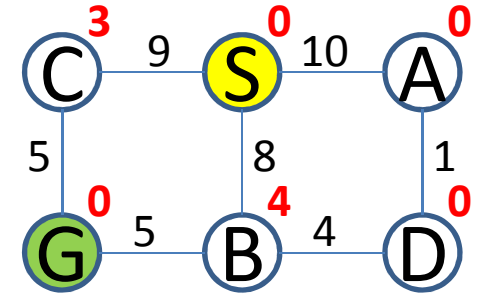
IDA* Search



f-bound = 10

f-new = 11

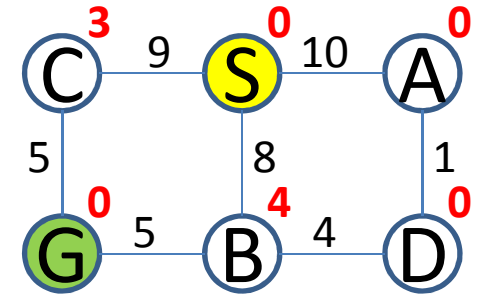
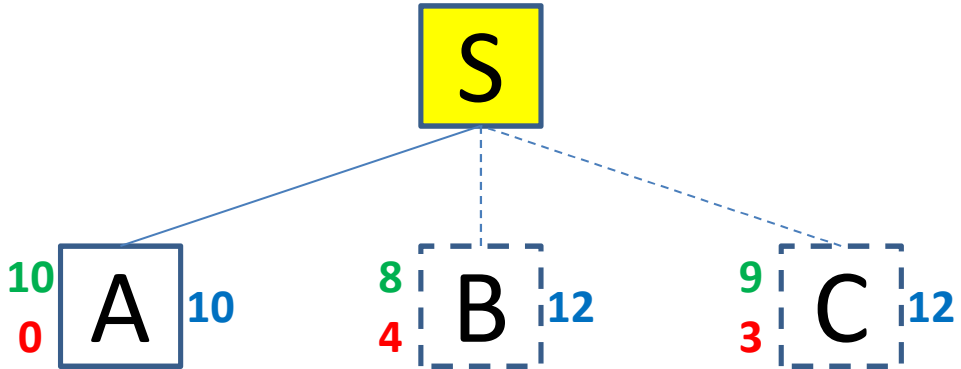
IDA* Search



f-bound = 11

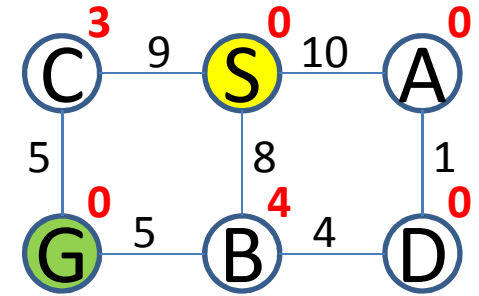
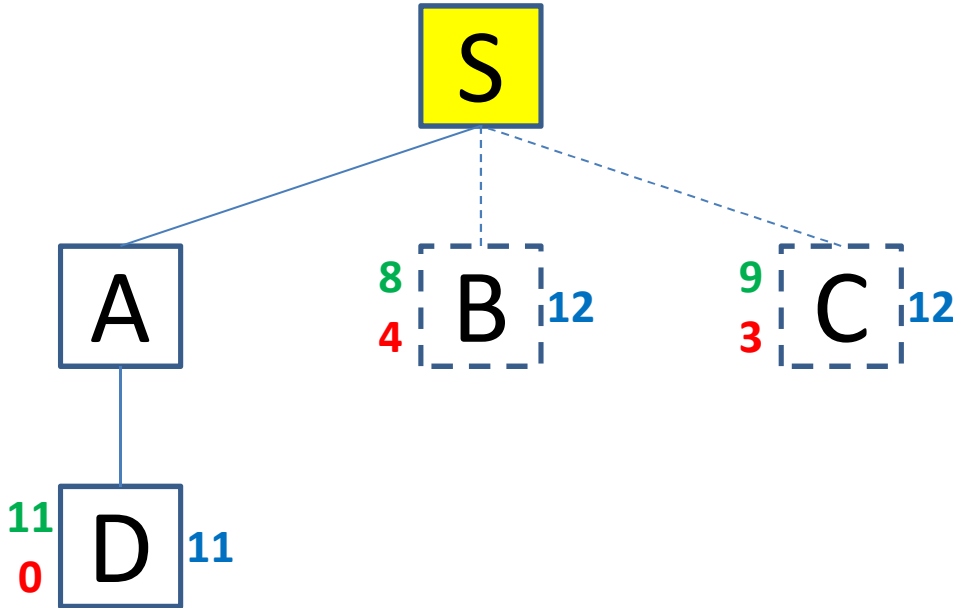
f-new = ∞

IDA* Search



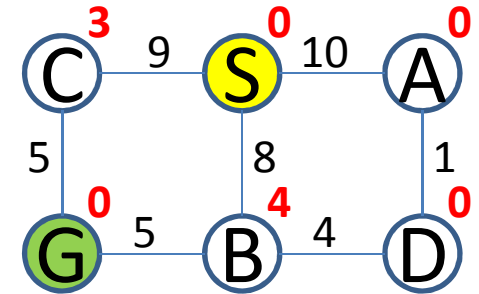
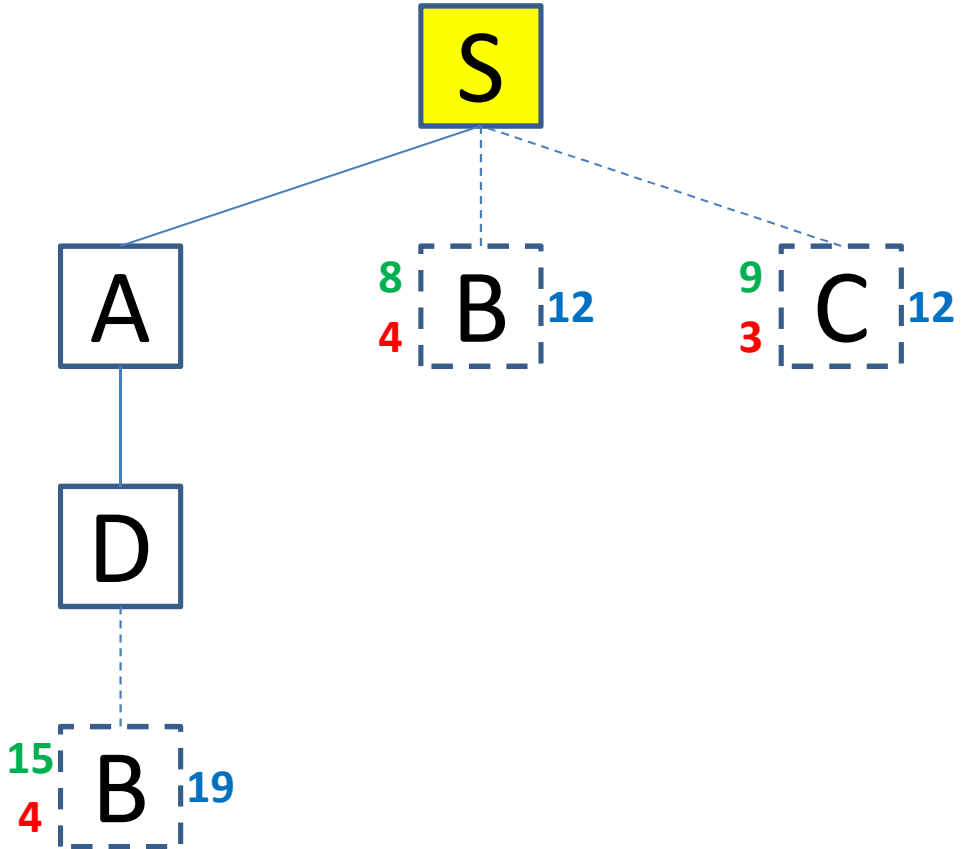
f-bound = 11
f-new = 12

IDA* Search



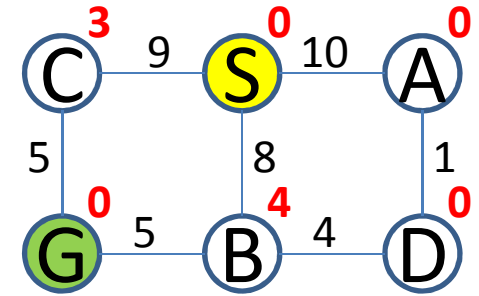
f-bound = 11
f-new = 12

IDA* Search



f-bound = 11
f-new = 12

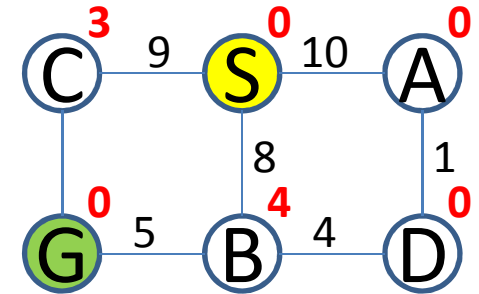
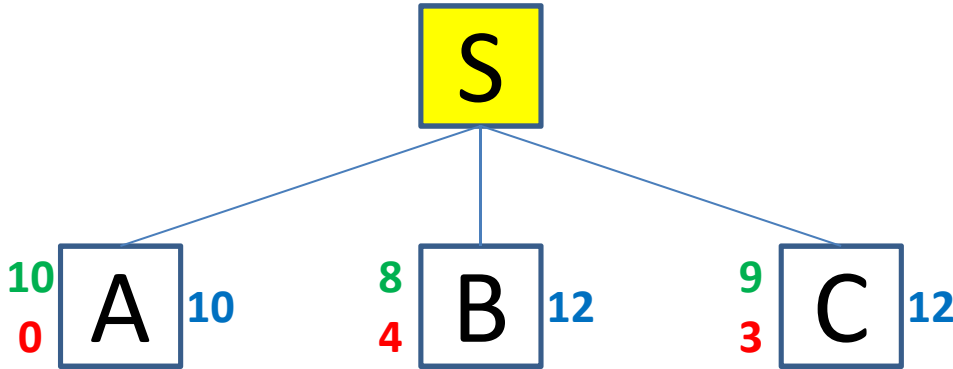
IDA* Search



f-bound = 12

f-new = ∞

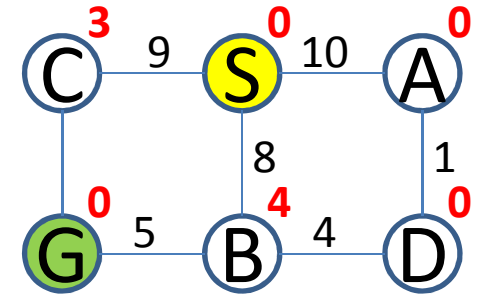
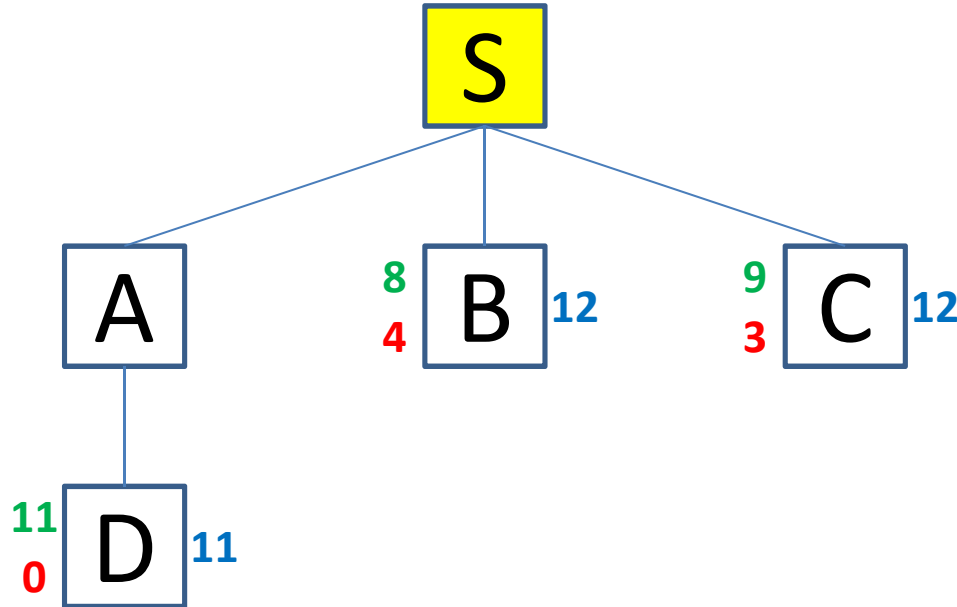
IDA* Search



f-bound = 12

f-new = ∞

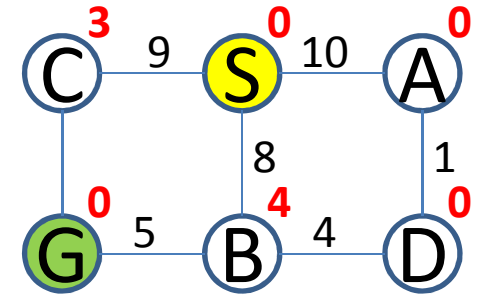
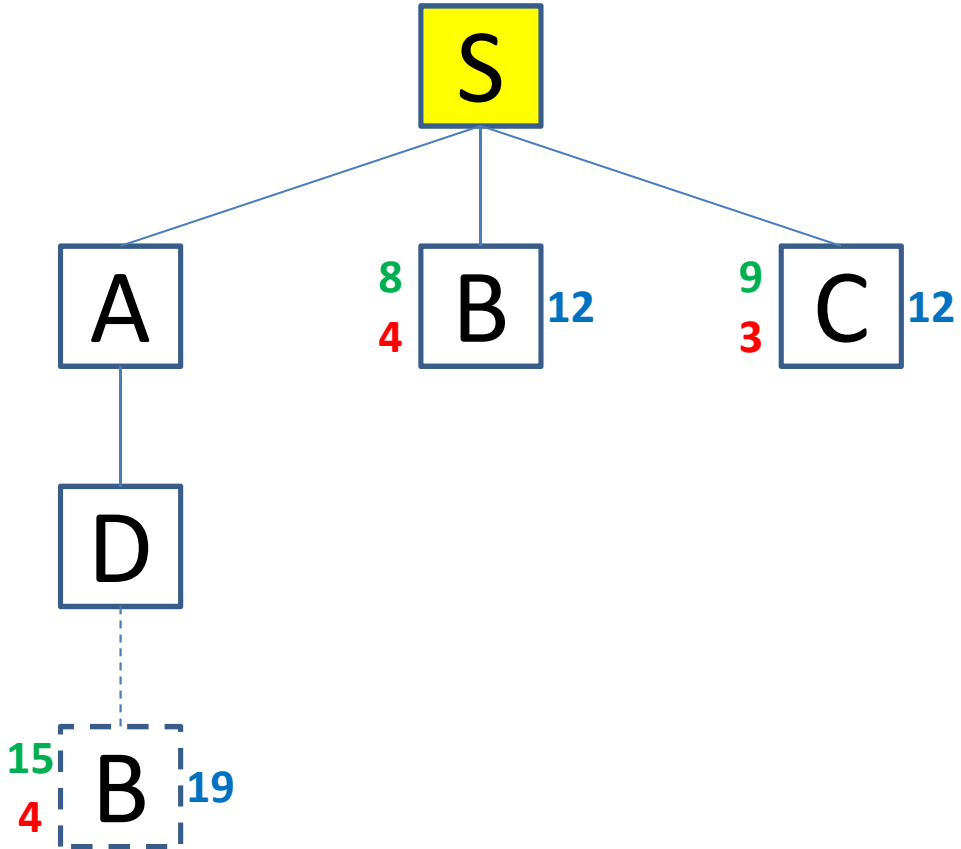
IDA* Search



f-bound = 12

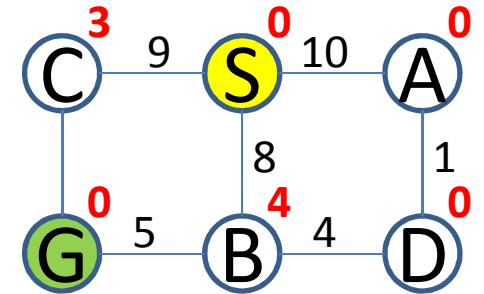
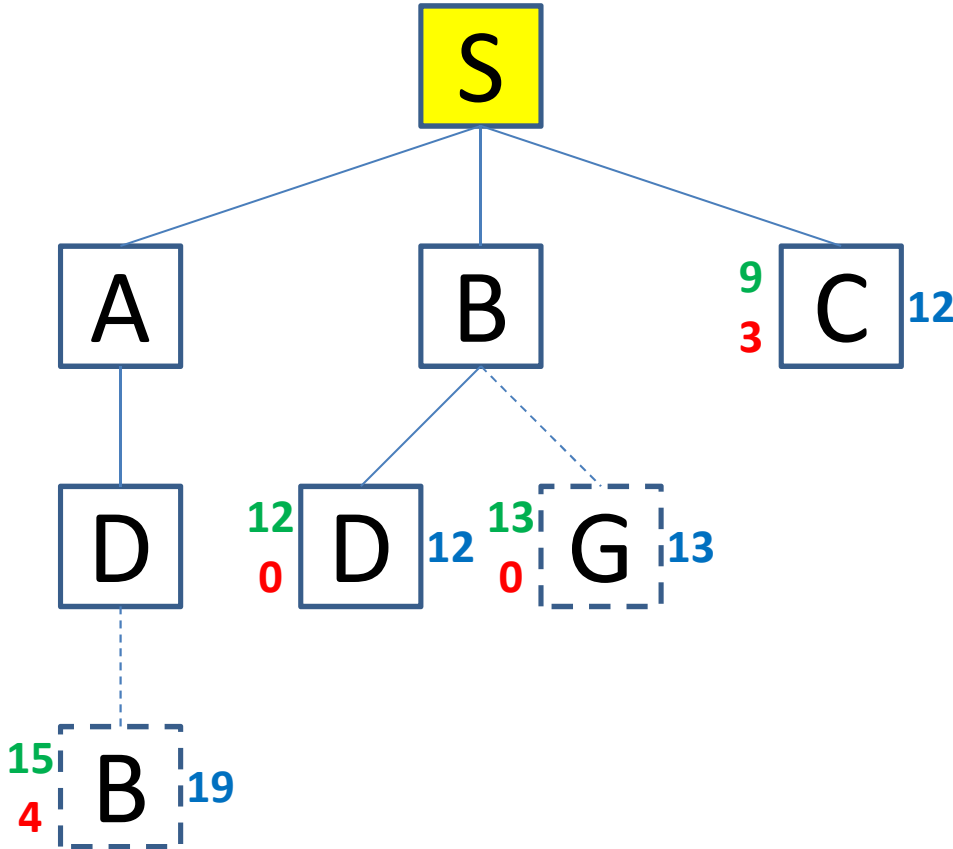
f-new = ∞

IDA* Search



f-bound = 12
f-new = 19

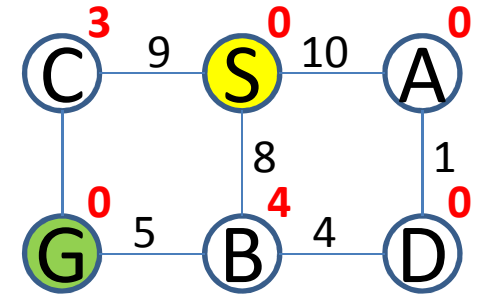
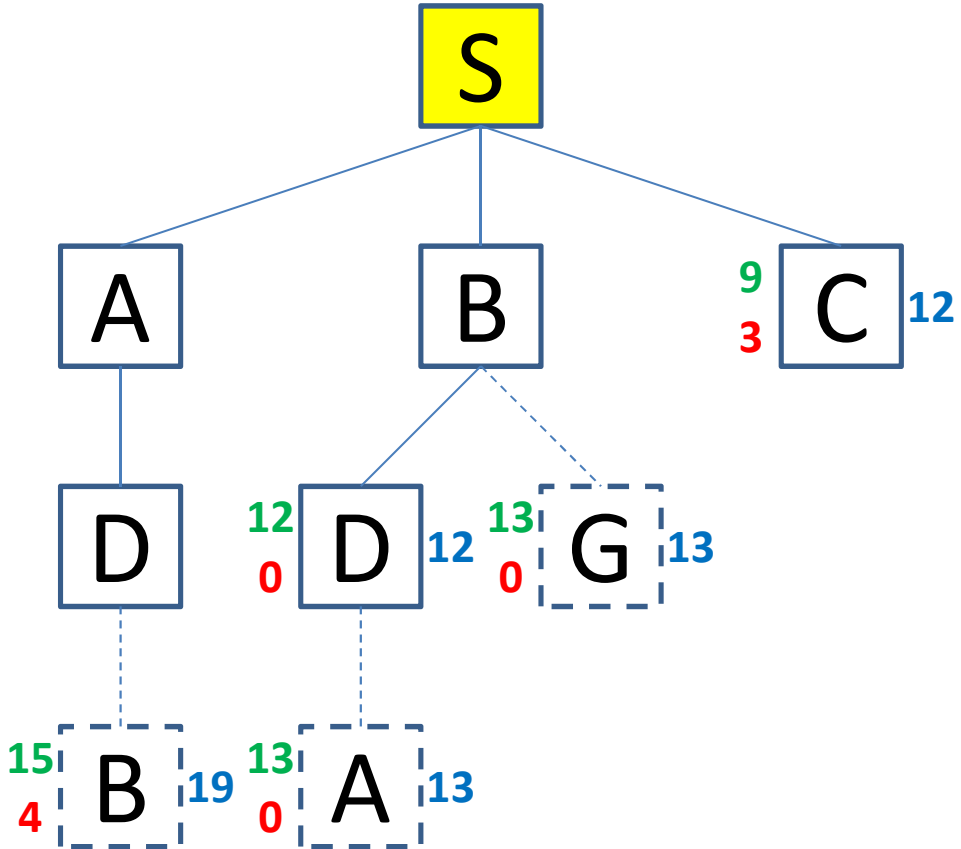
IDA* Search



f-bound = 12

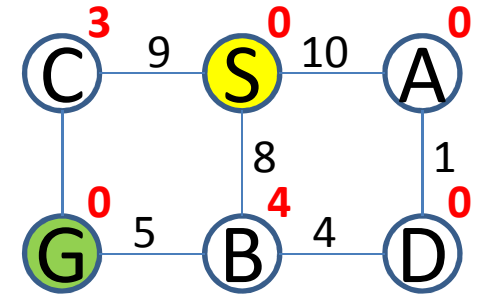
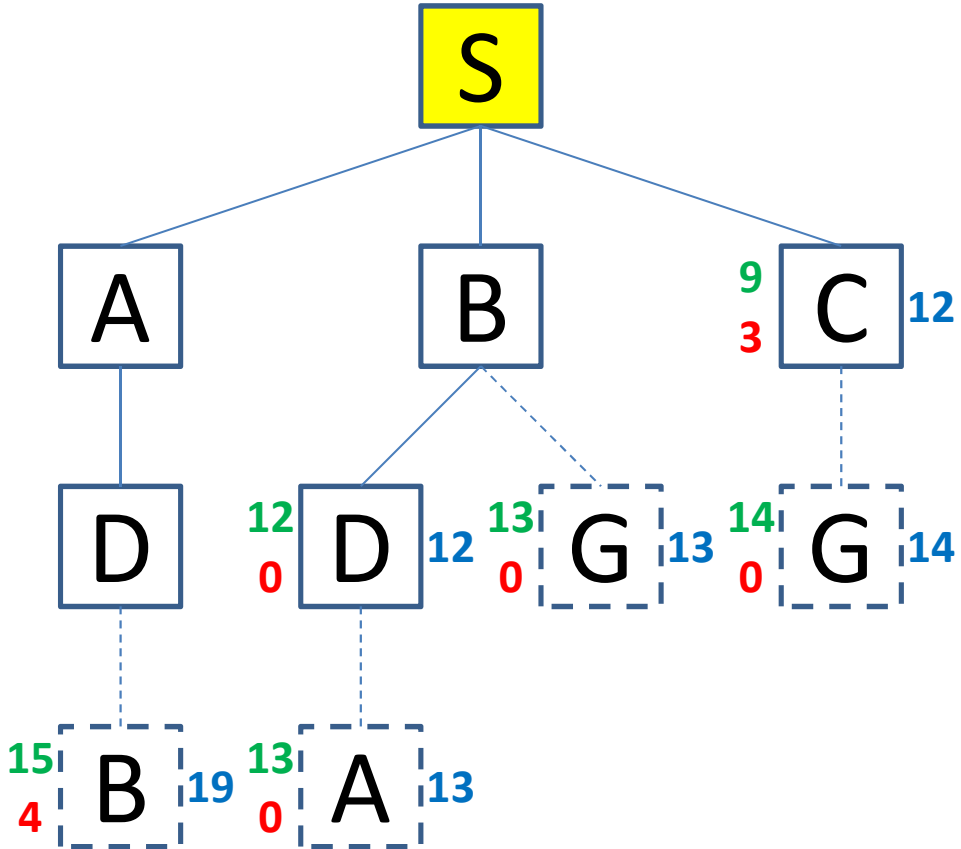
f-new = 13

IDA* Search



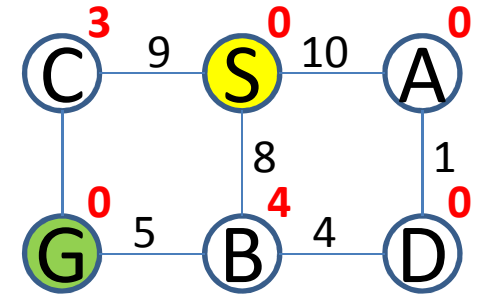
f-bound = 12
f-new = 13

IDA* Search



f-bound = 12
f-new = 13

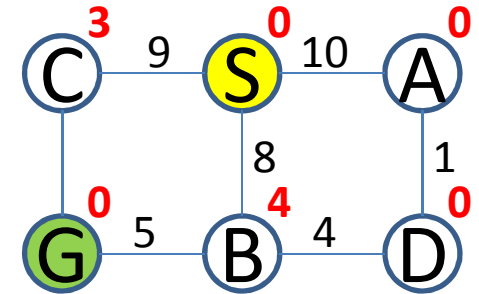
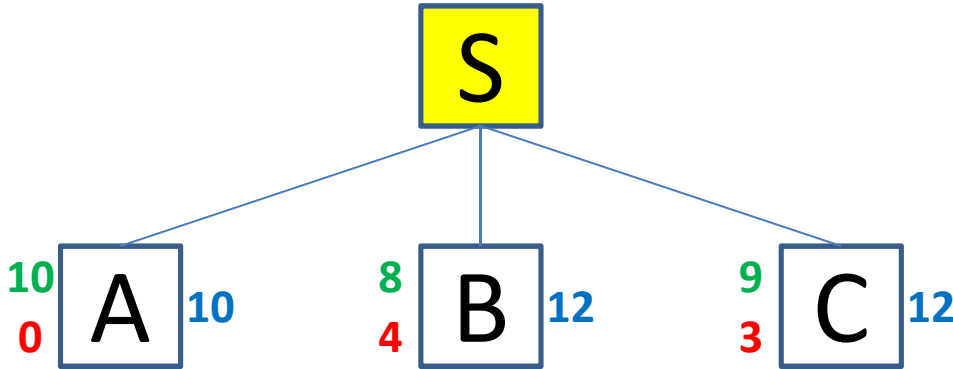
IDA* Search



f-bound = 13

f-new = ∞

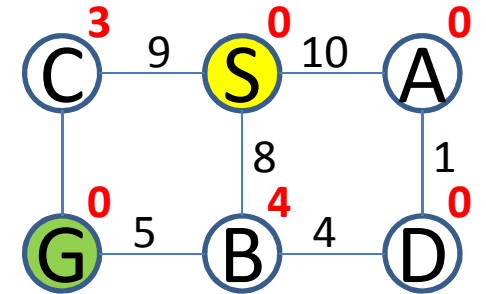
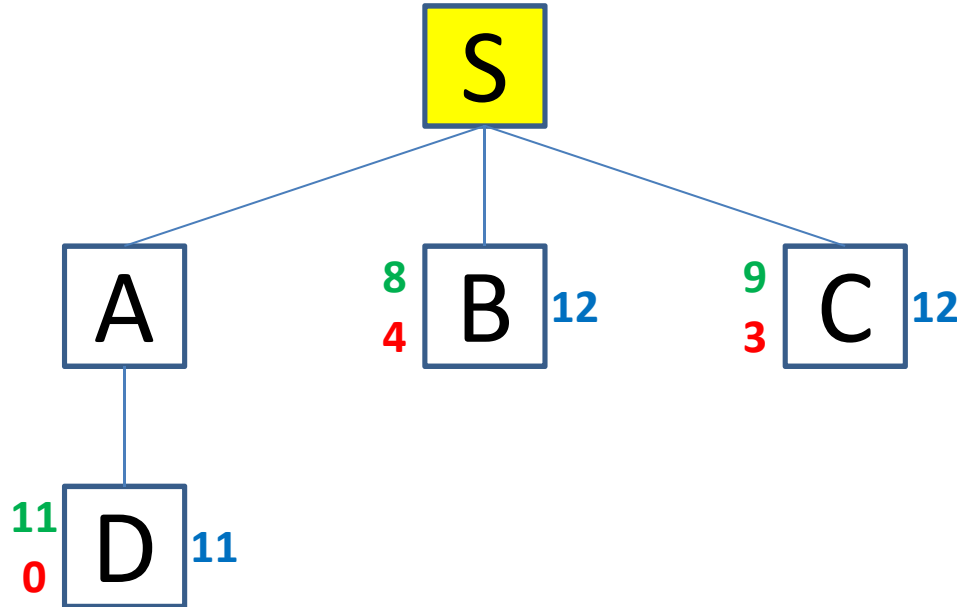
IDA* Search



f-bound = 13

f-new = ∞

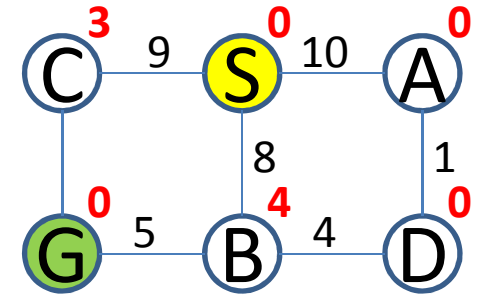
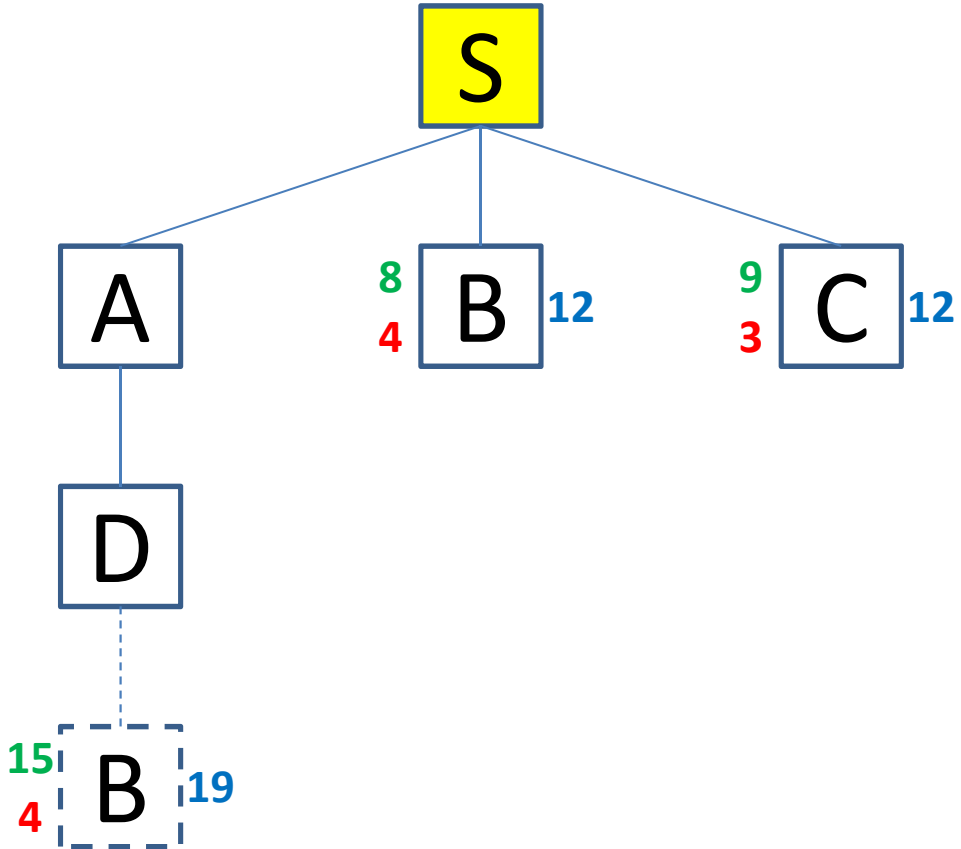
IDA* Search



f-bound = 13

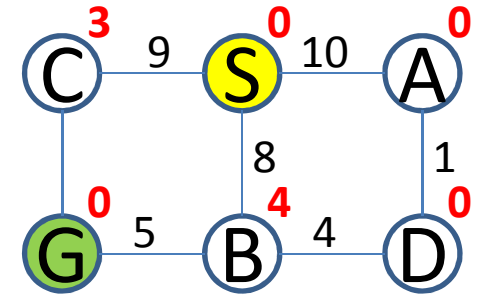
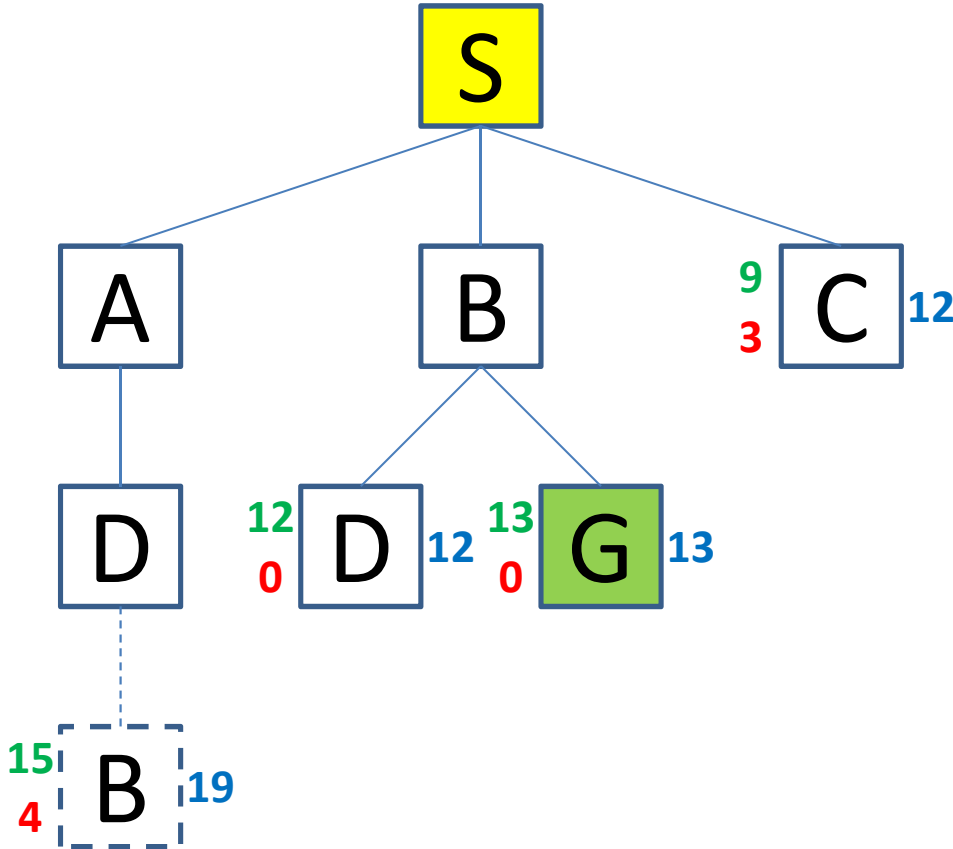
f-new = ∞

IDA* Search



f-bound = 13
f-new = 19

IDA* Search



f-bound = 13
f-new = 19

Exercises: Artificial Intelligence

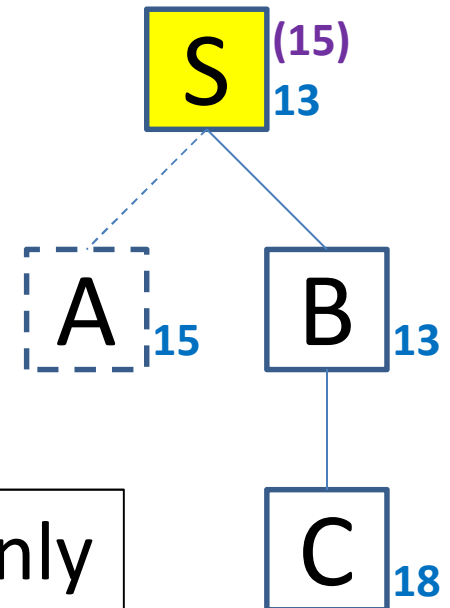
Simplified Memory-bounded A*

Simplified Memory-bounded A*

SMA* ALGORITHM

SMA* Algorithm

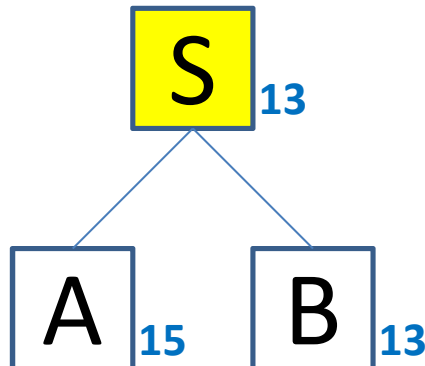
- Optimizes A* to work within reduced memory
- **Key Idea:**
 - IF memory full for extra node (C)
 - Remove highest f-value leaf (A)
 - Remember best-forgotten child in each parent node (15 in S)



E.g. Memory of 3 nodes only

SMA* Algorithm

- **Generate Children 1 by 1**
 - **Expanding:** add 1 child at the time to QUEUE
 - Avoids **memory overflow**
 - **Allows monitoring** if nodes need deletion

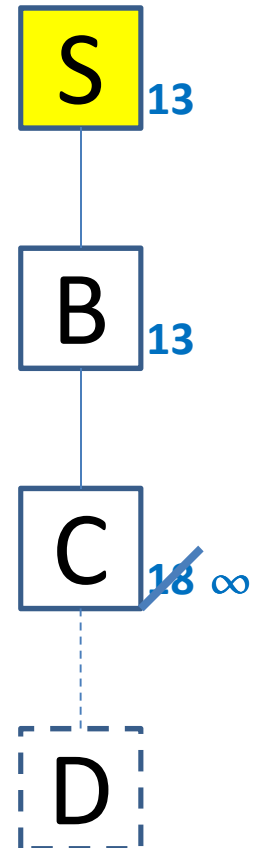


First add A later B

SMA* Algorithm

- **Too long paths: Give up**
 - **Extending path cannot fit in memory**
 - give up (C)
 - Set **f-value** node (C) to ∞
 - **Remembers:**
path cannot be found here

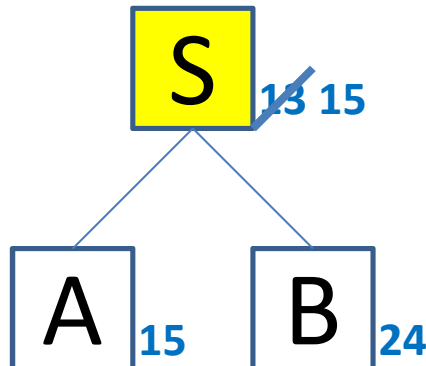
E.g. Memory of 3 nodes only



SMA* Algorithm

- **Adjust f-values**

- **IF** all children M_i of node N have been explored
- **AND** $\forall i: f(S...M_i) > f(S...N)$
- **THEN reset** (through $N \implies$ through children)
 - $f(S...N) = \min\{f(S...M_i) \mid M_i \text{ child of } N\}$



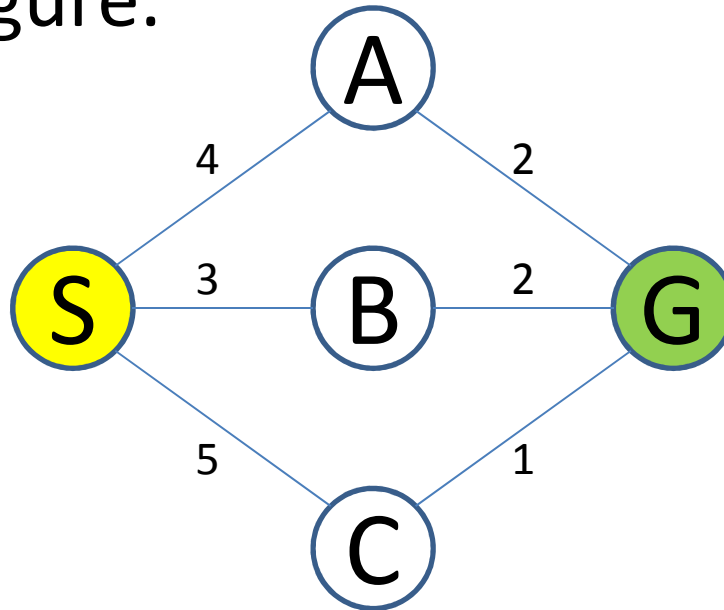
Better estimate for $f(S)$

Simplified Memory-bounded A*

SMA* BY EXAMPLE

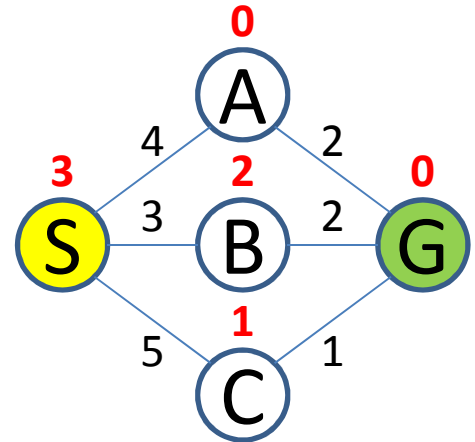
SMA* by Example

- Perform SMA* (memory: 3 nodes) on the following figure.

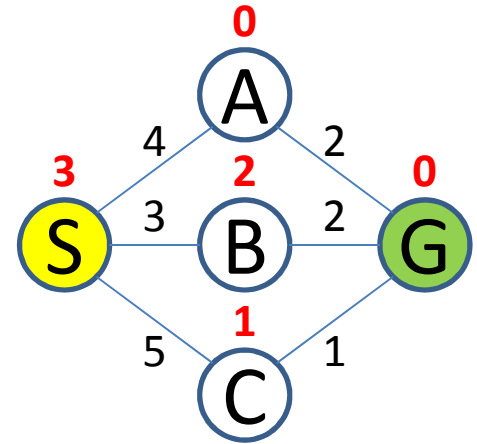
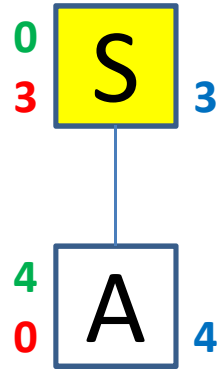


	S	A	B	C	G
heuristic	3	0	2	1	0

SMA* by Example

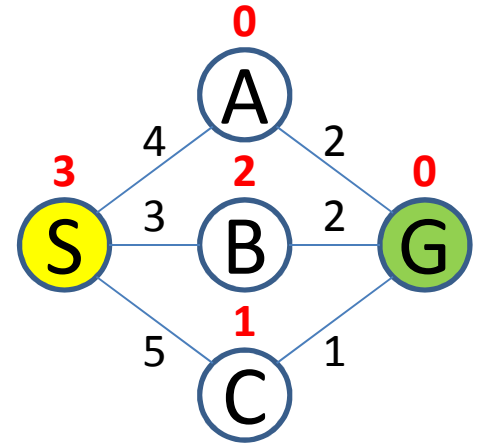
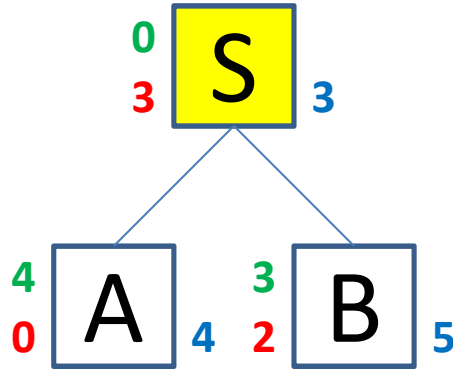


SMA* by Example



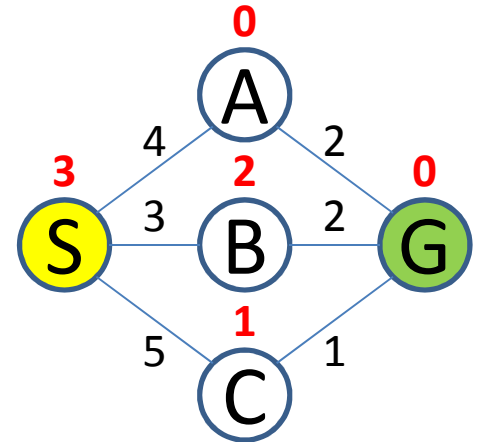
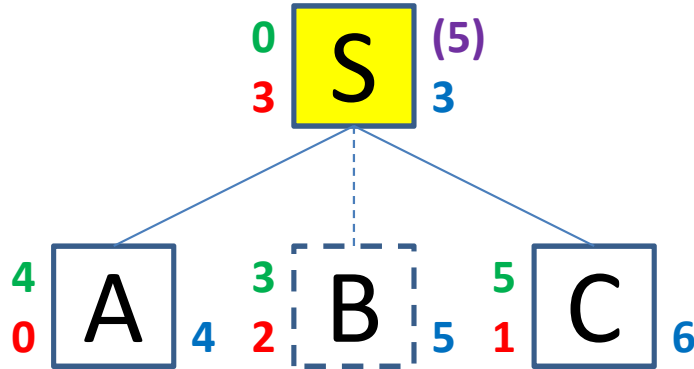
**Generate children
(One by one)**

SMA* by Example



Generate children
(One by one)

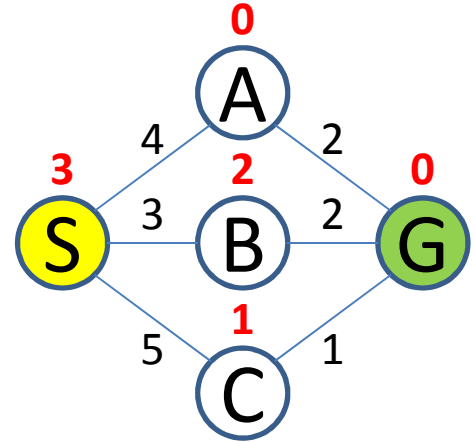
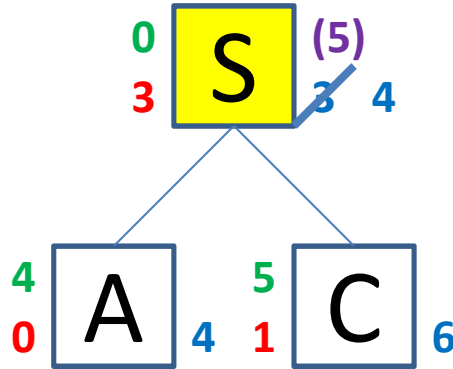
SMA* by Example



Generate children
(One by one)

Memory full

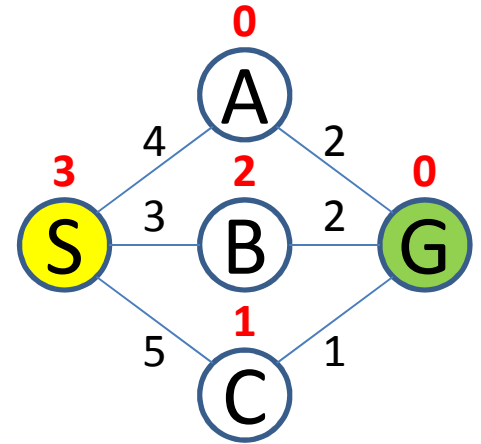
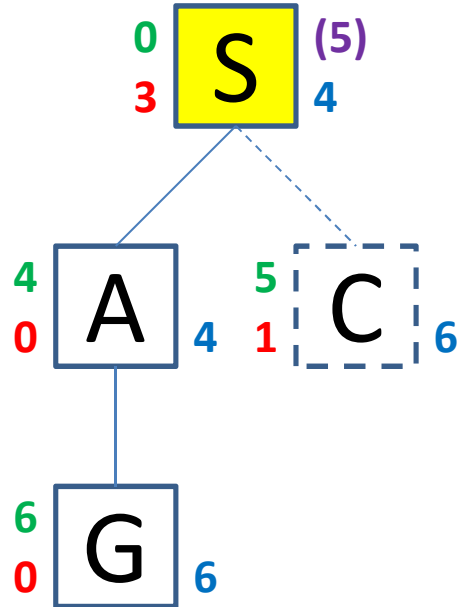
SMA* by Example



All children are explored

Adjust f-values

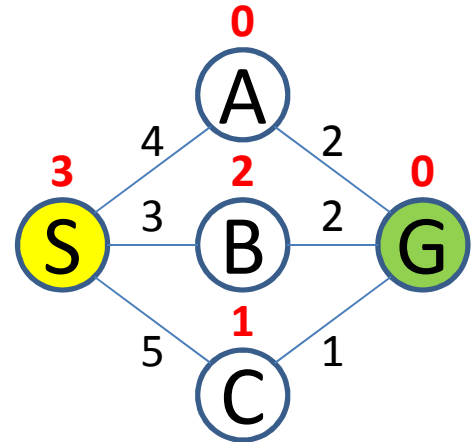
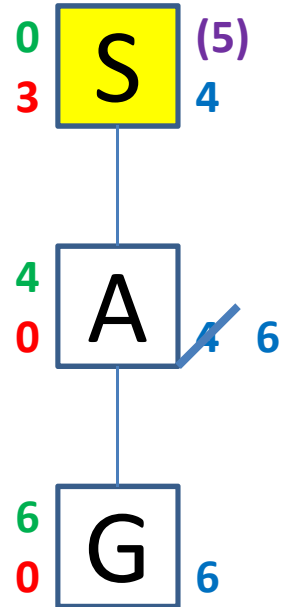
SMA* by Example



Generate children
(One by one)

Memory full

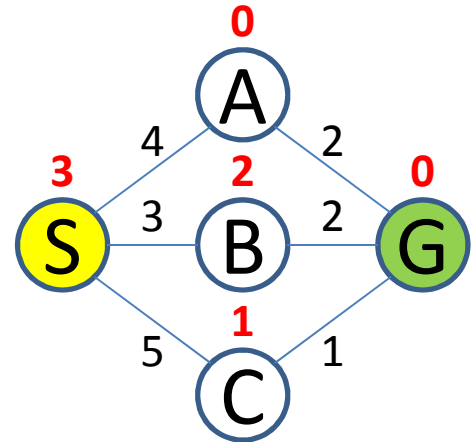
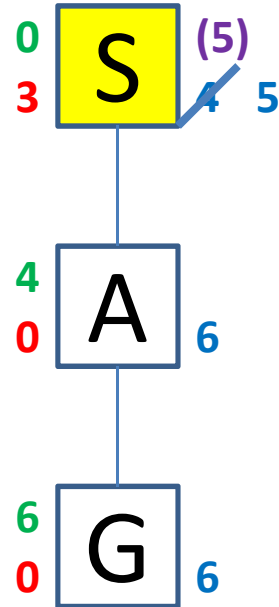
SMA* by Example



All children are explored

Adjust f-values

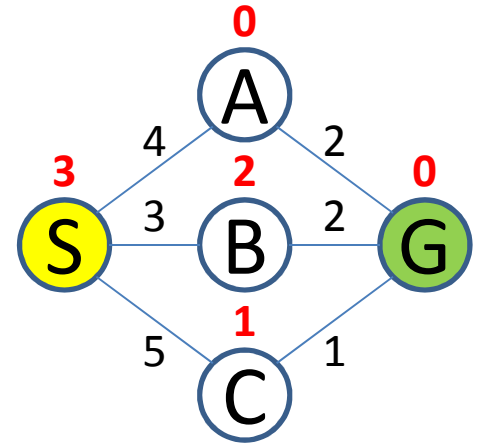
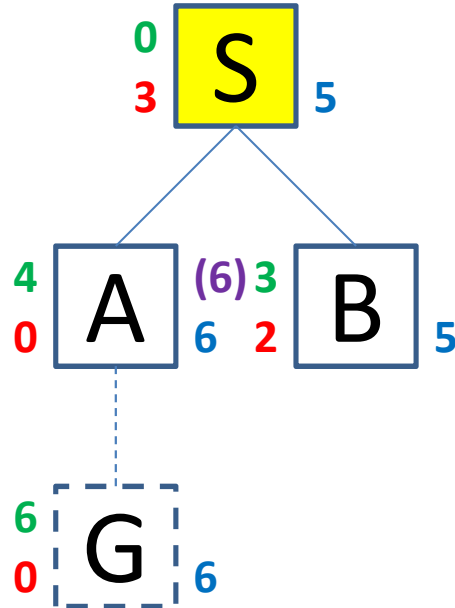
SMA* by Example



All children are explored (update)

Adjust f-values

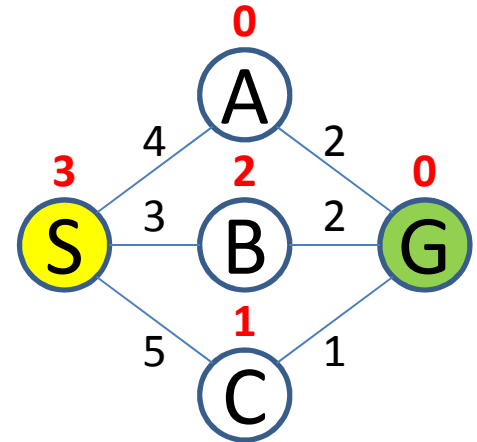
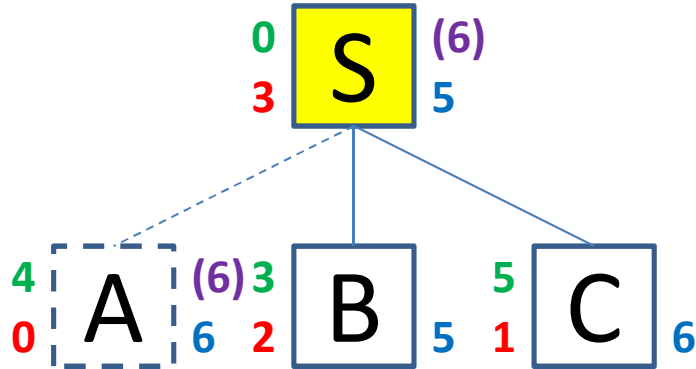
SMA* by Example



Generate children
(One by one)

Memory full

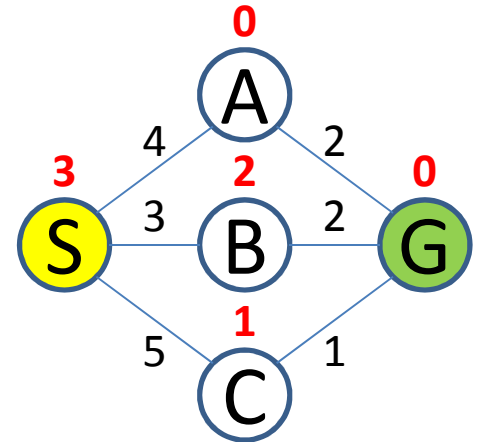
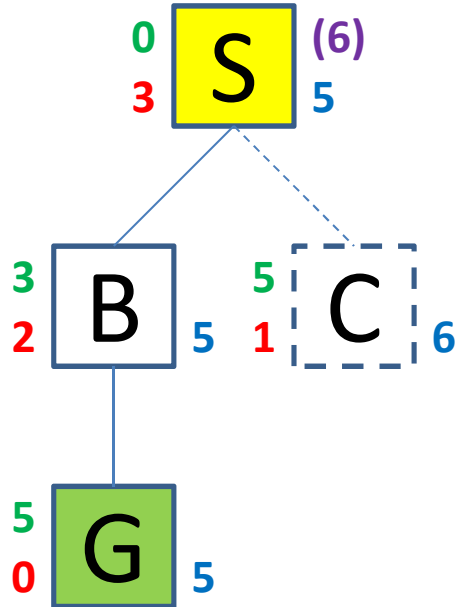
SMA* by Example



**Generate children
(One by one)**

Memory full

SMA* by Example



Generate children
(One by one)

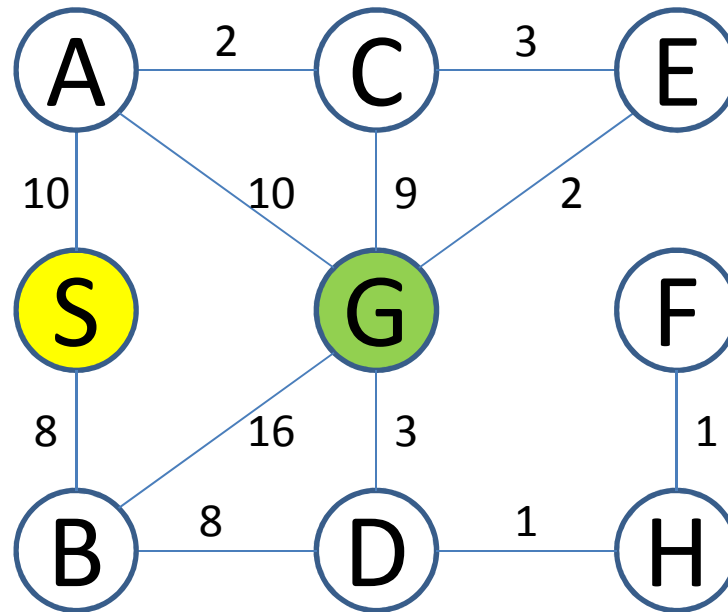
Memory full

Simplified Memory-bounded A*

PROBLEM

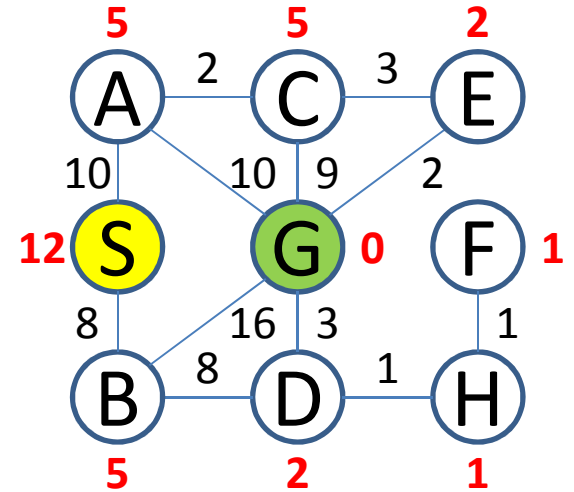
Problem

- Perform SMA* (memory: 4 nodes) on the following figure.

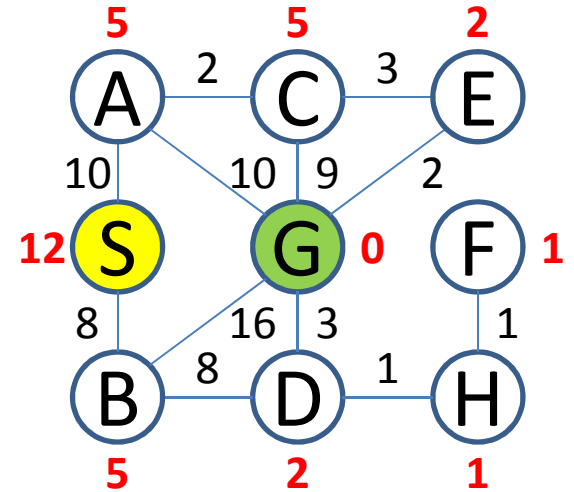
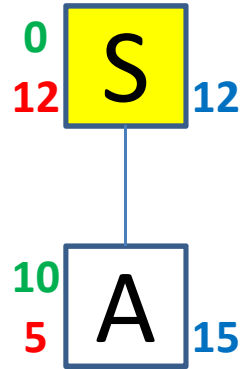


	S	A	B	C	D	E	F	H	G
heuristic	12	5	5	5	2	2	1	1	0

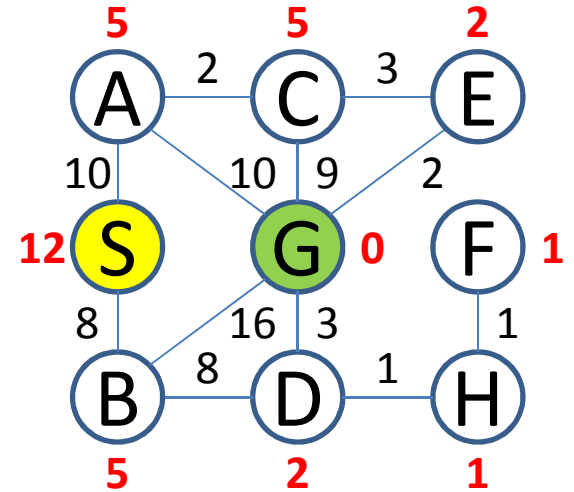
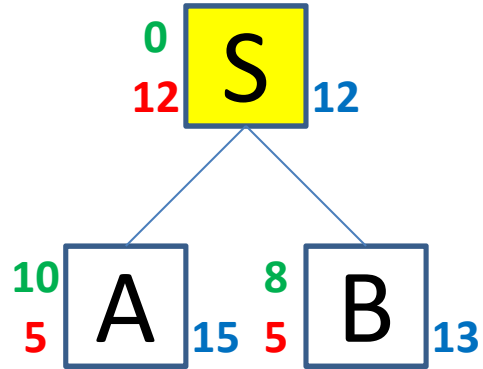
Problem



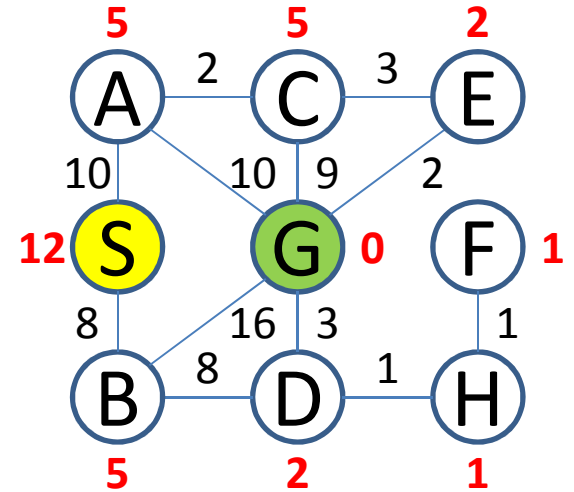
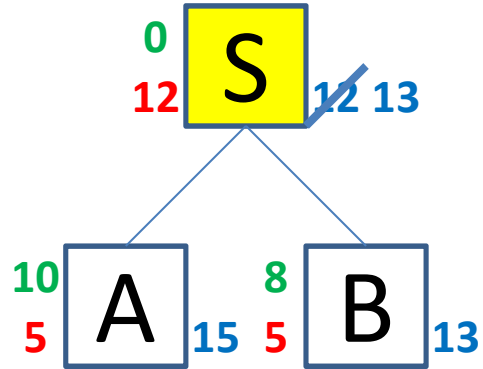
Problem



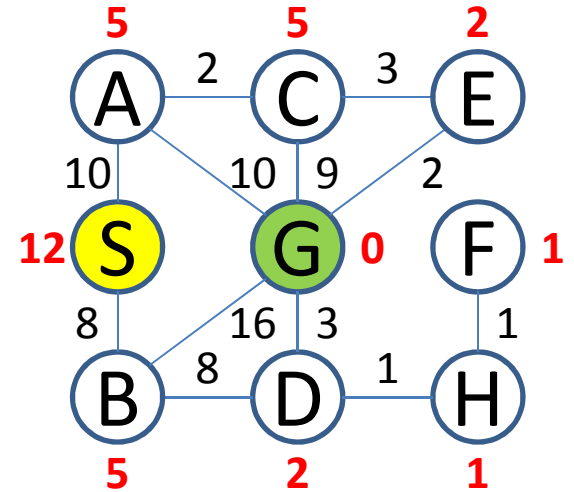
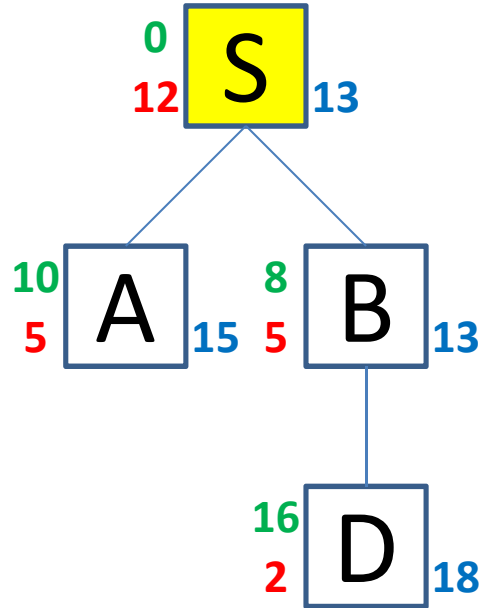
Problem



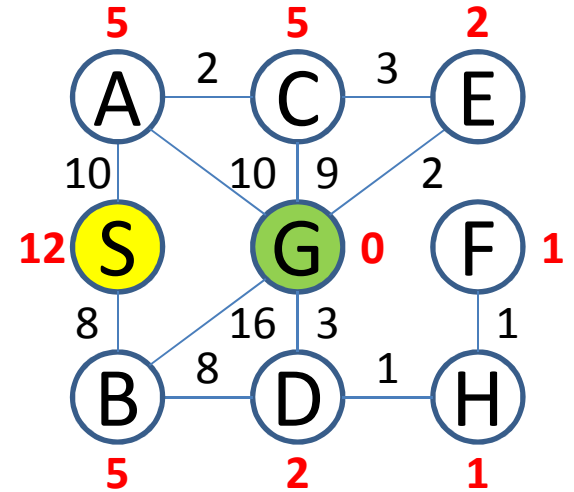
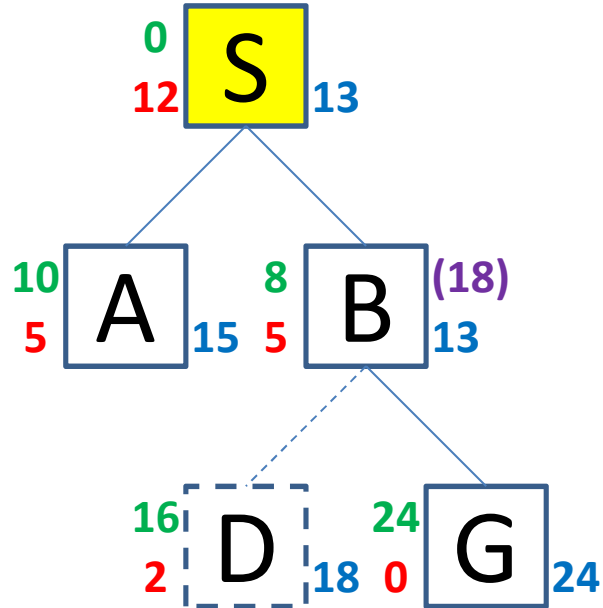
Problem



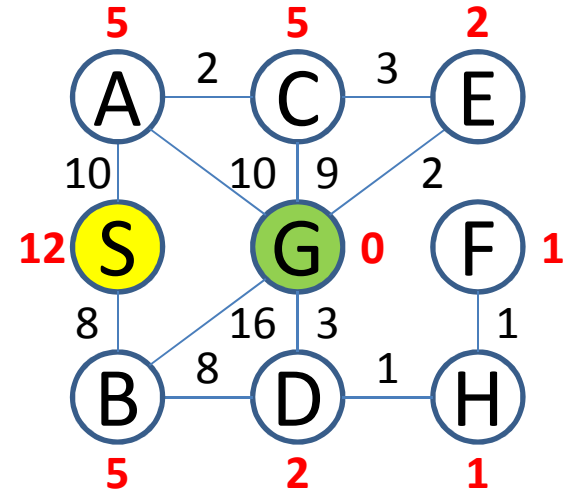
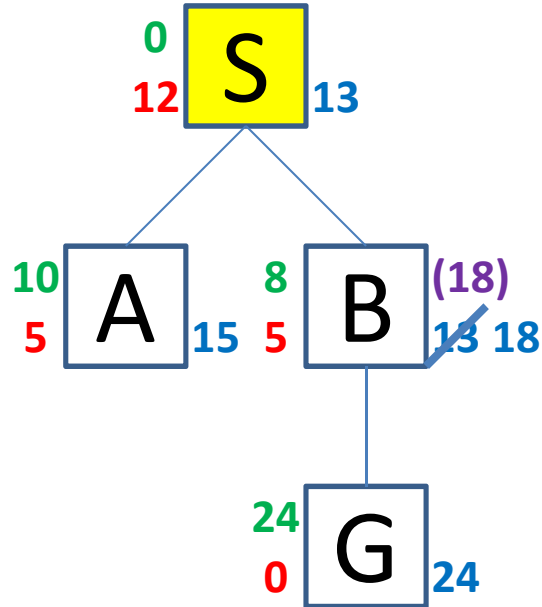
Problem



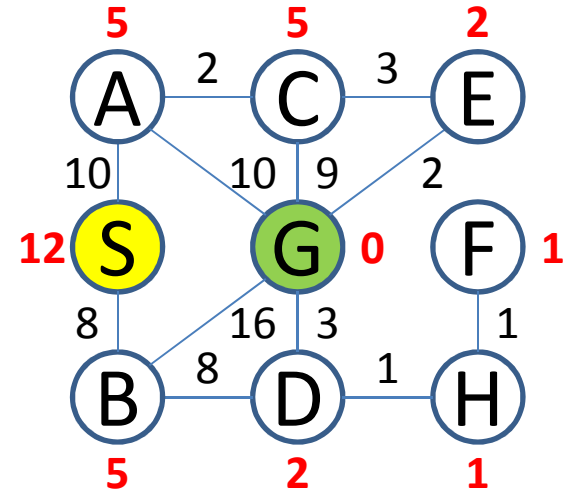
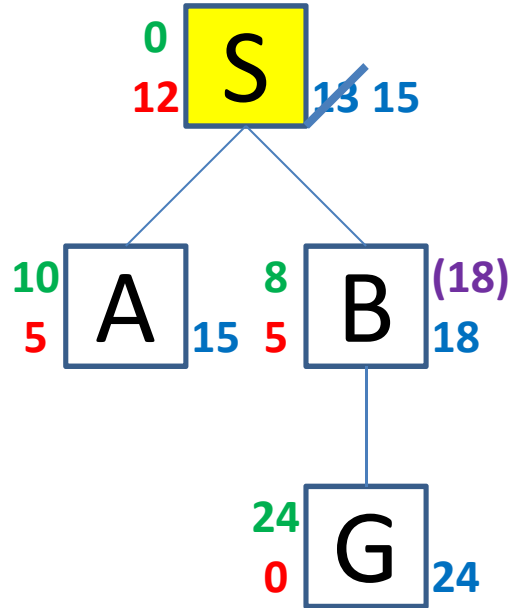
Problem



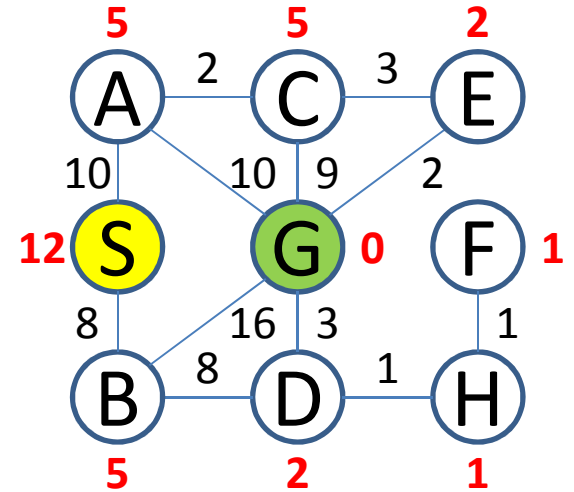
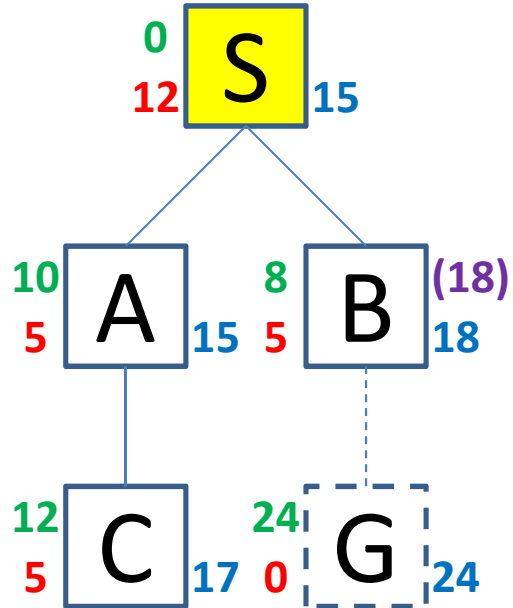
Problem



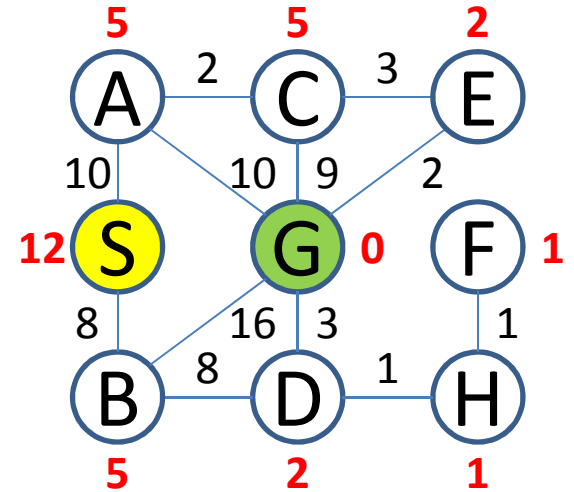
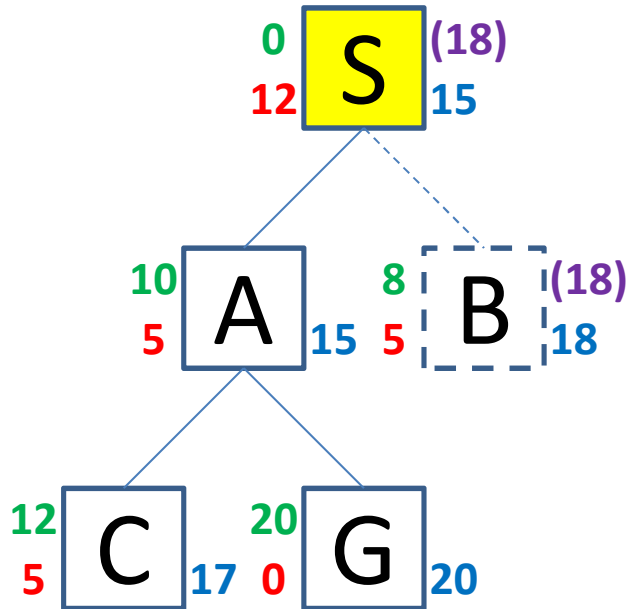
Problem



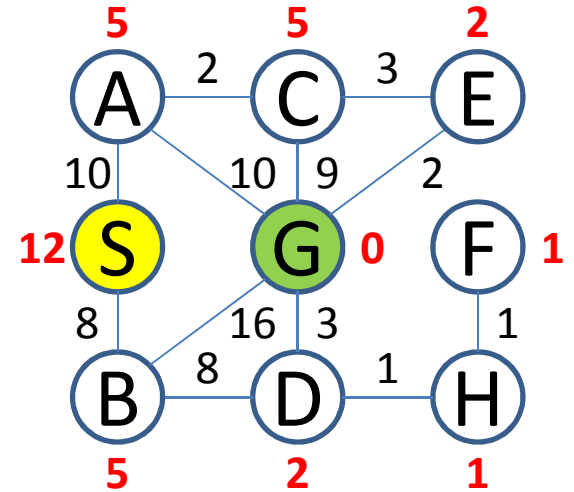
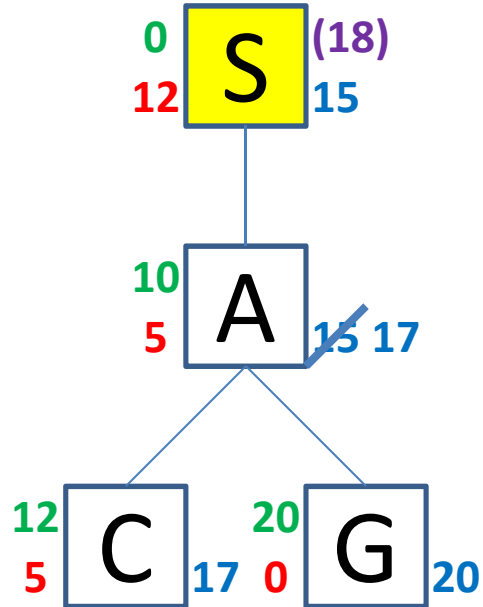
Problem



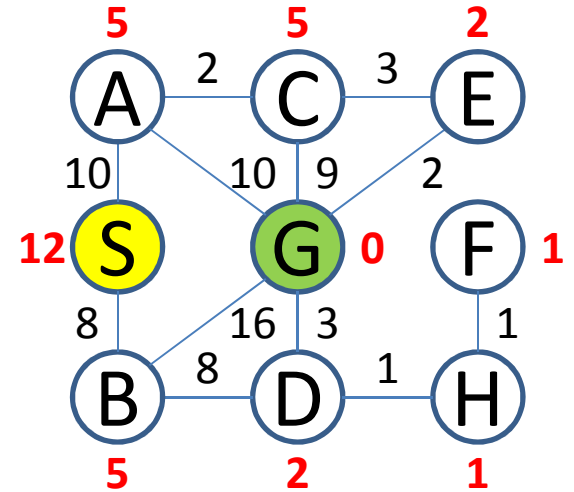
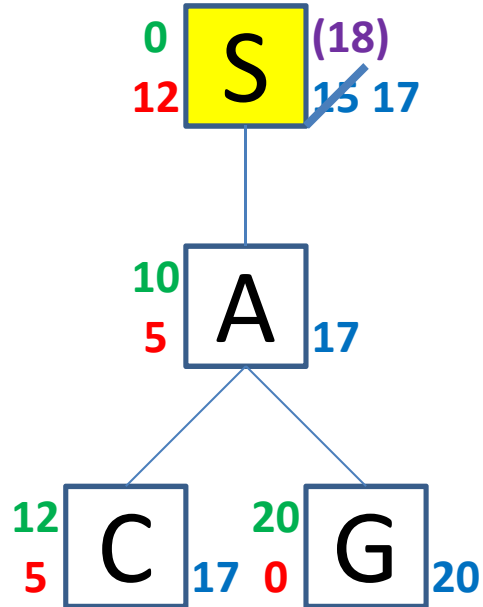
Problem



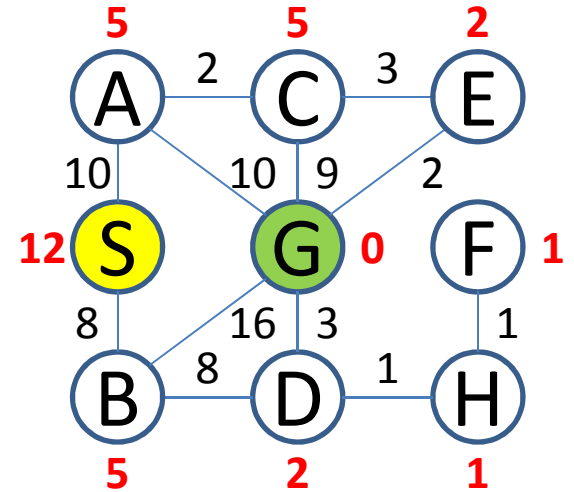
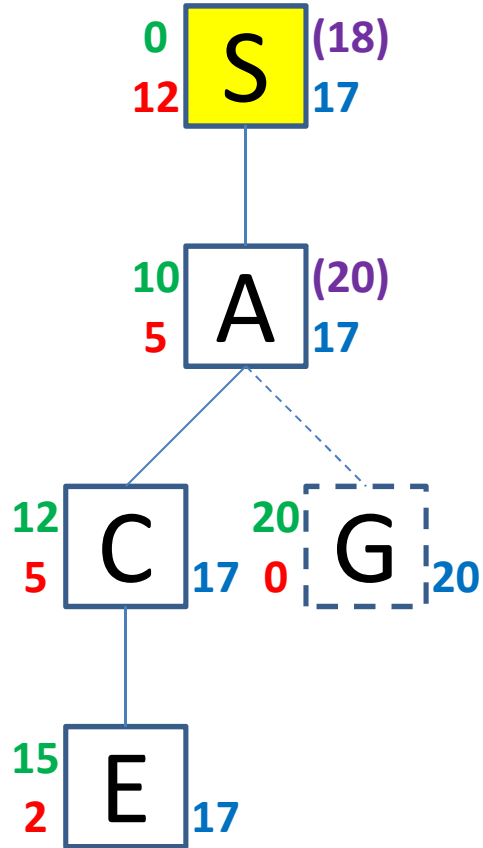
Problem



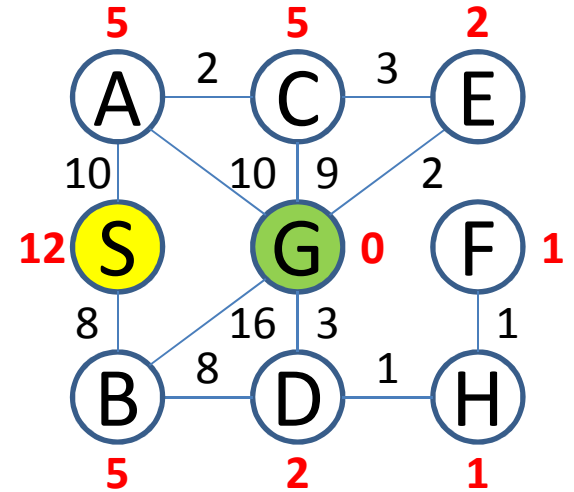
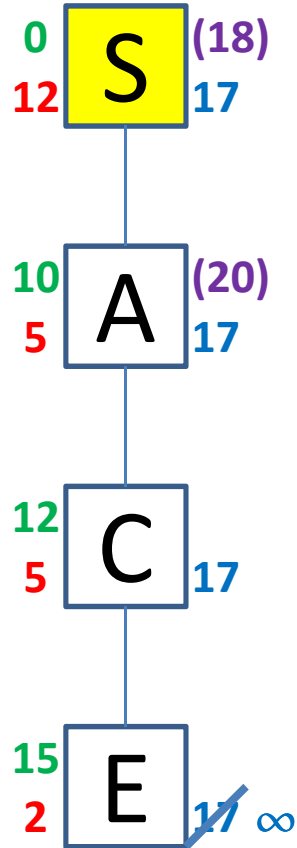
Problem



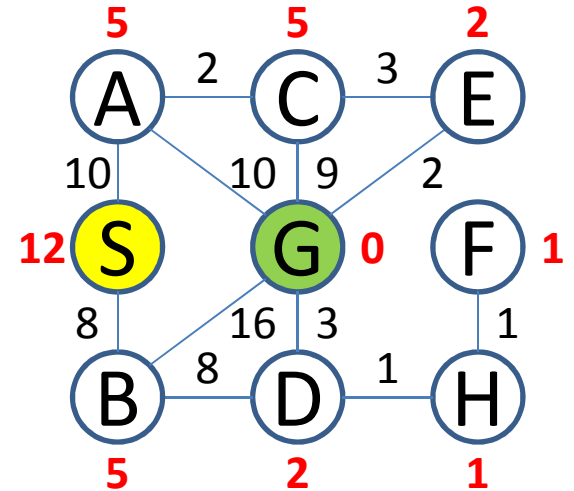
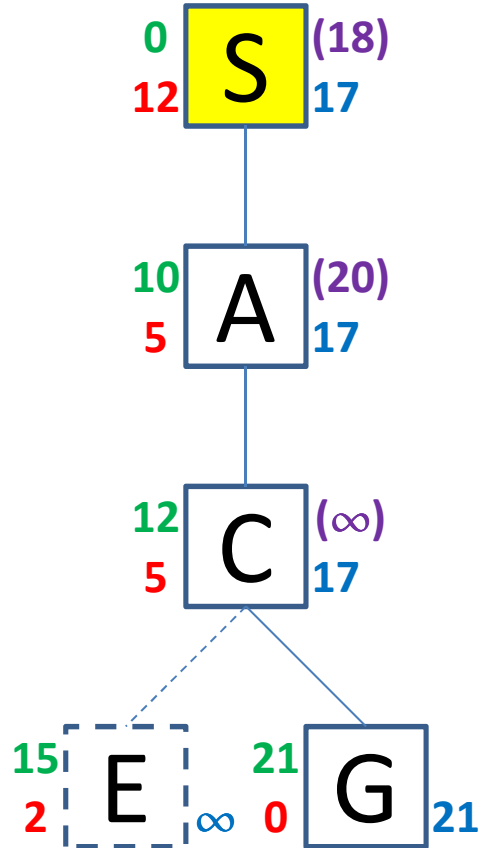
Problem



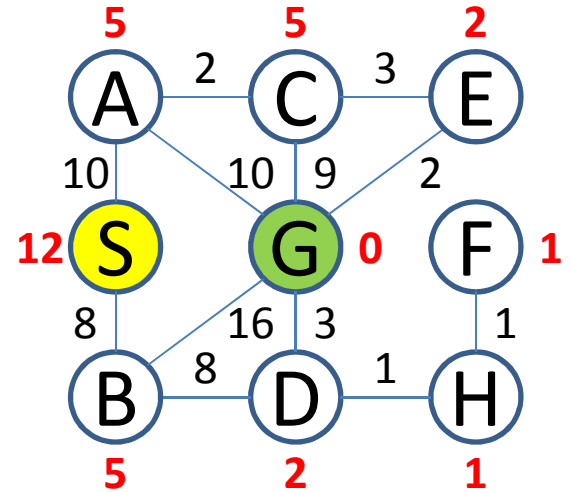
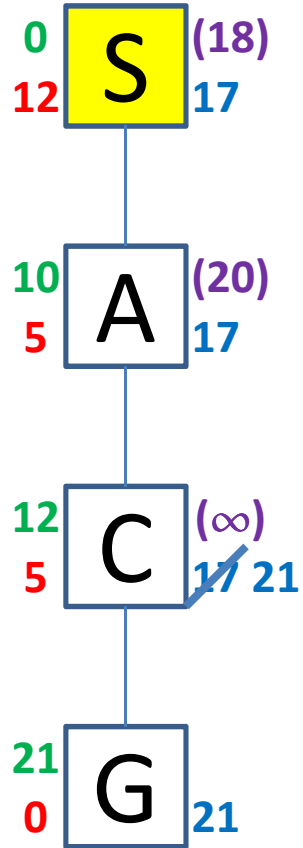
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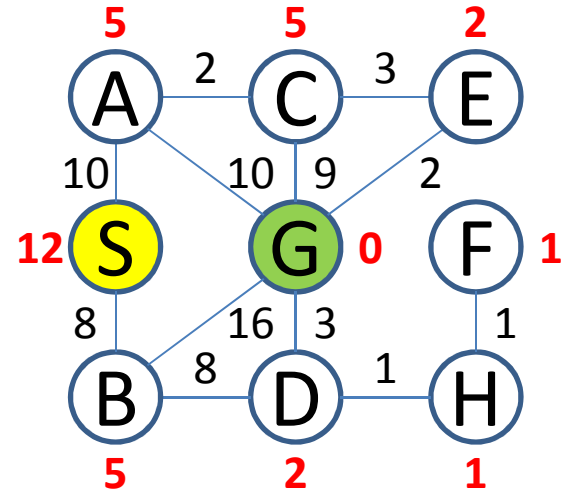
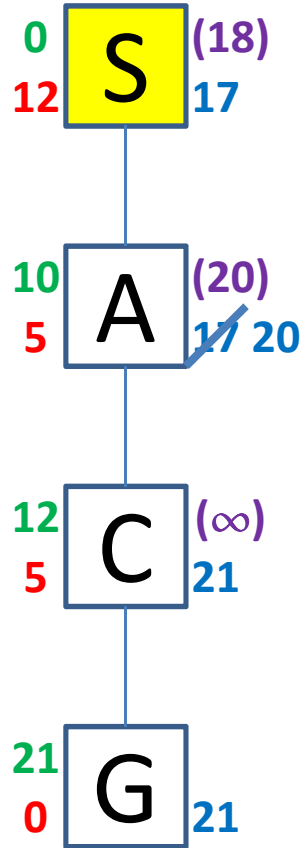
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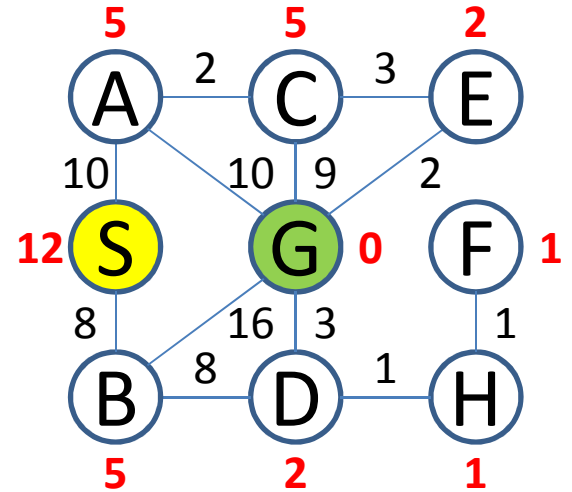
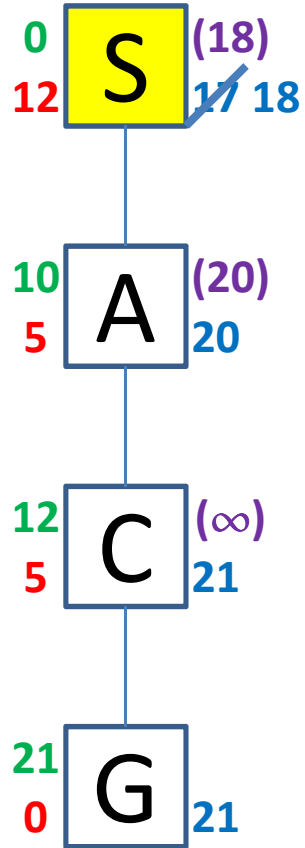
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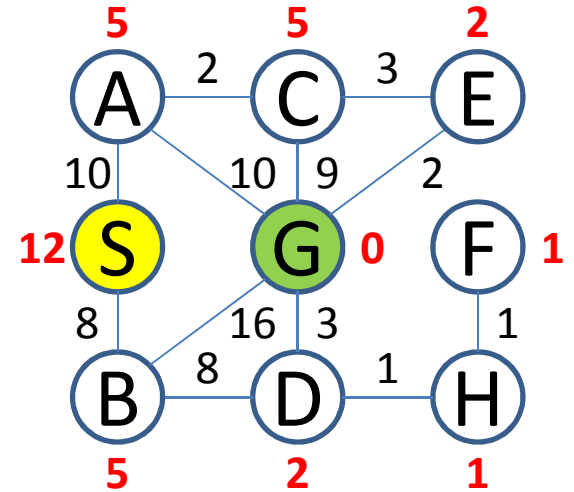
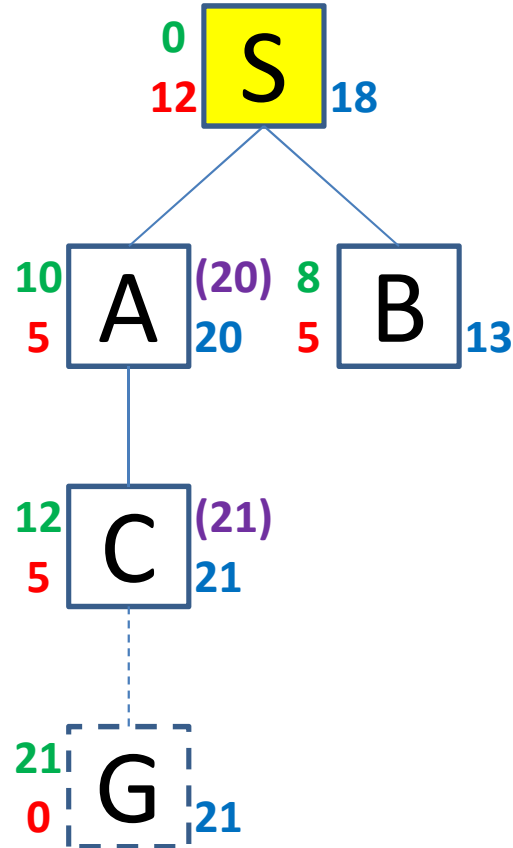
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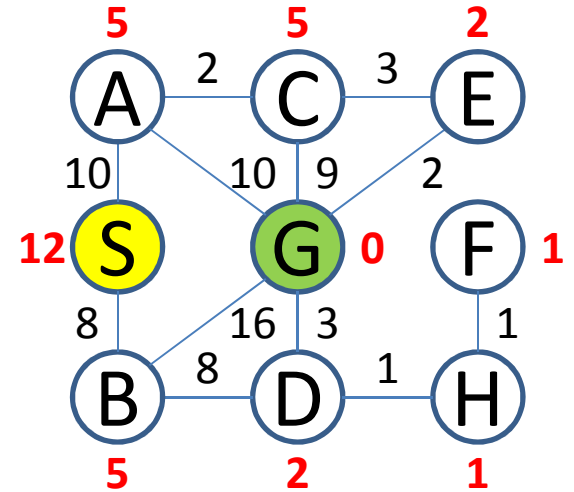
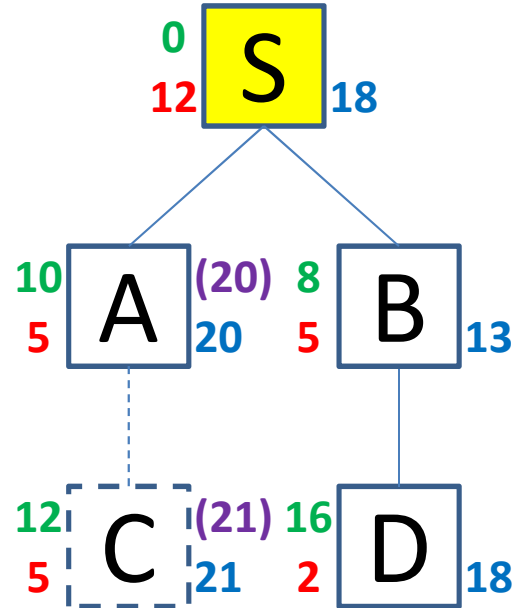
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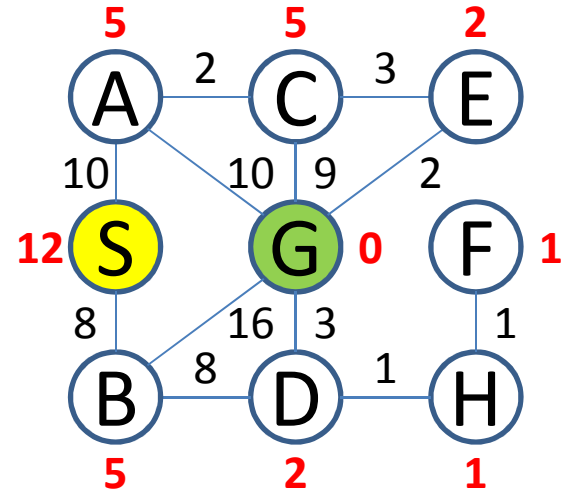
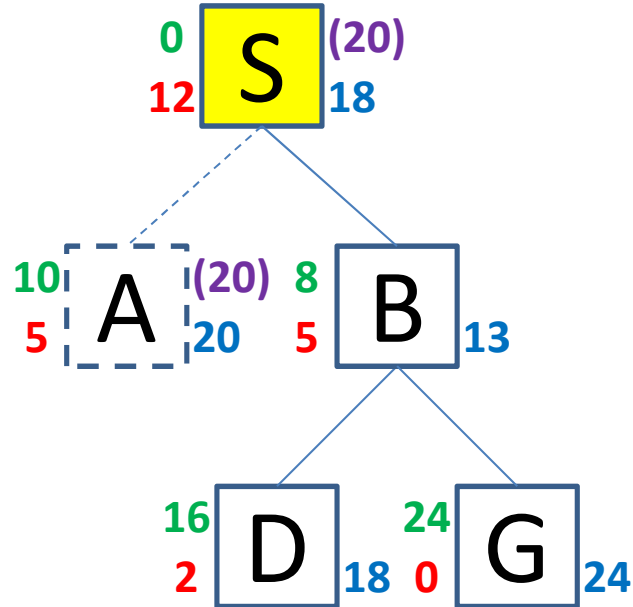
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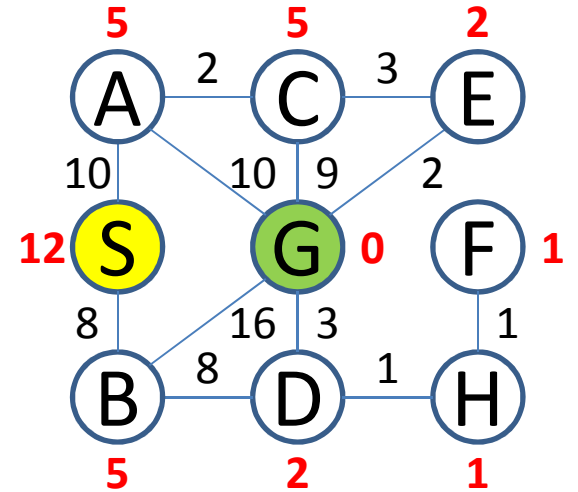
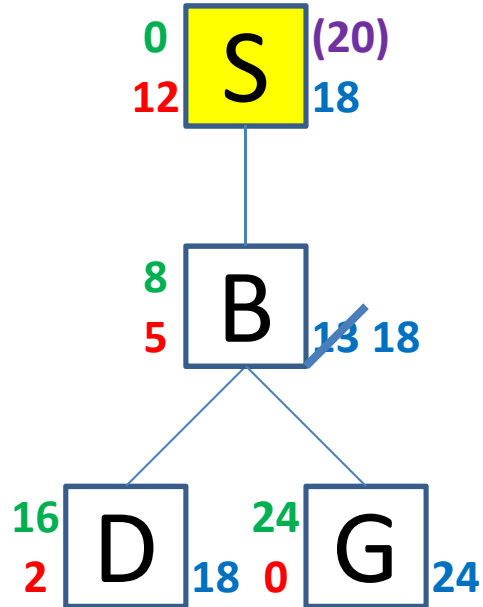
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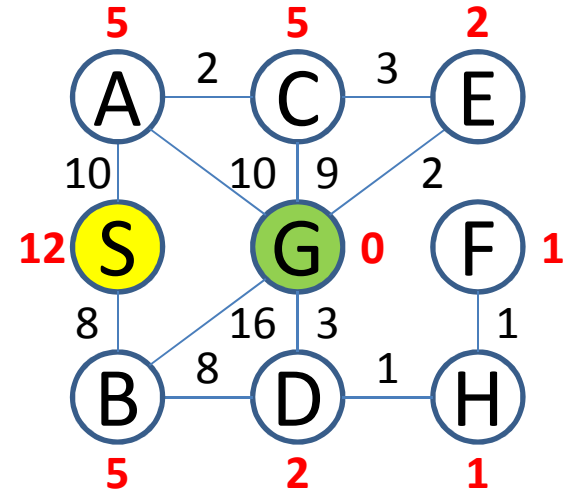
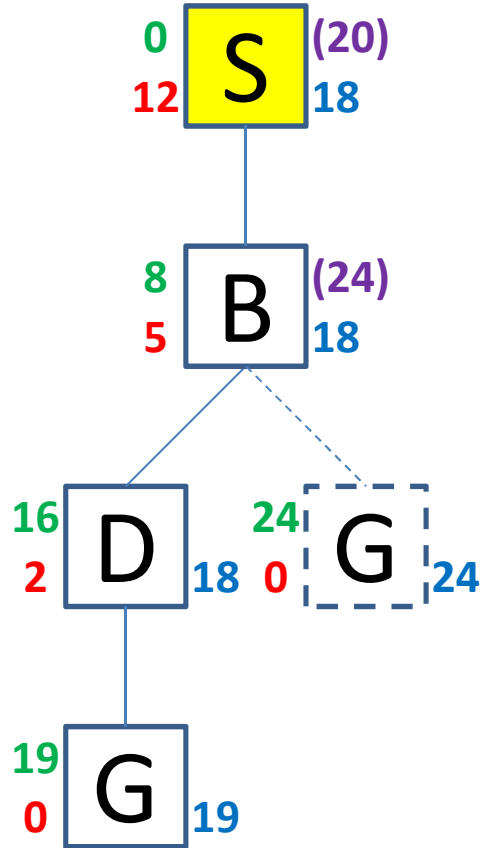
Problem



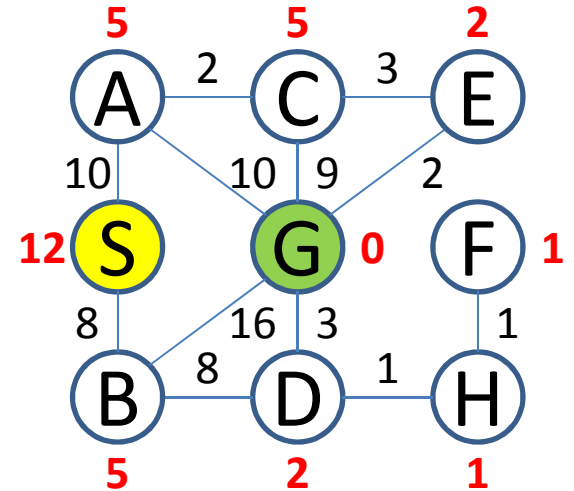
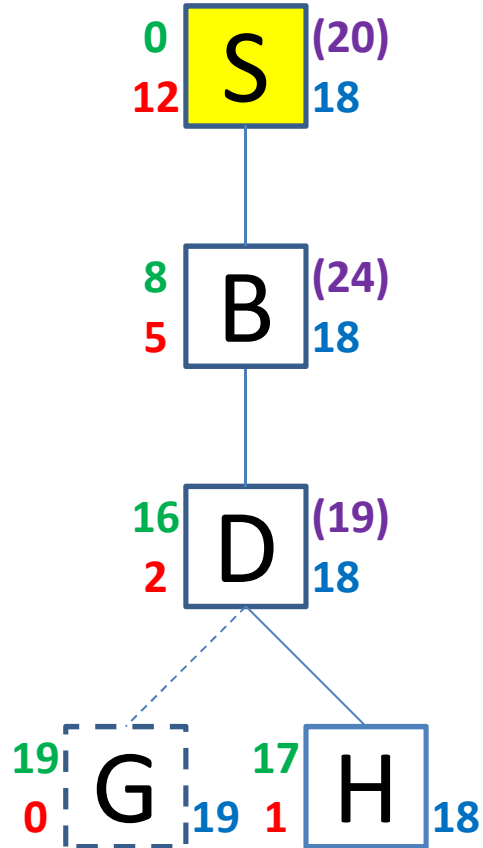
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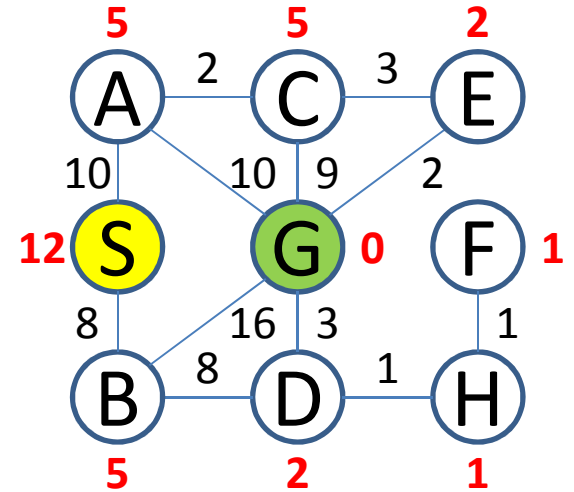
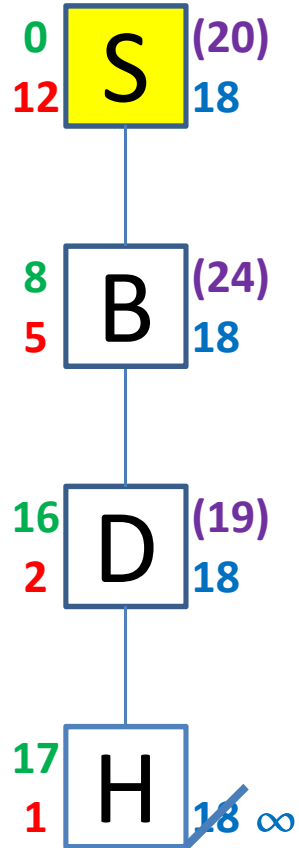
Problem



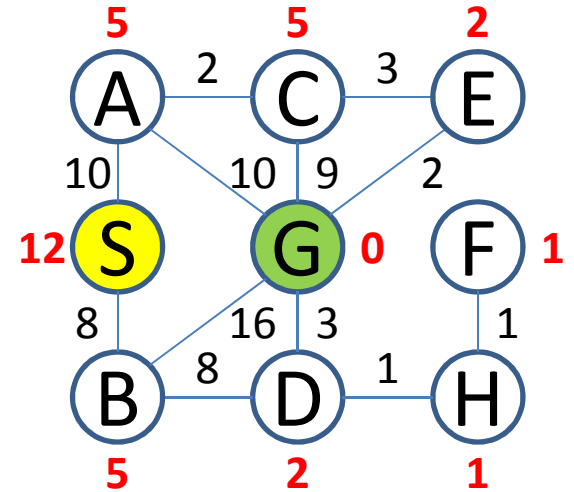
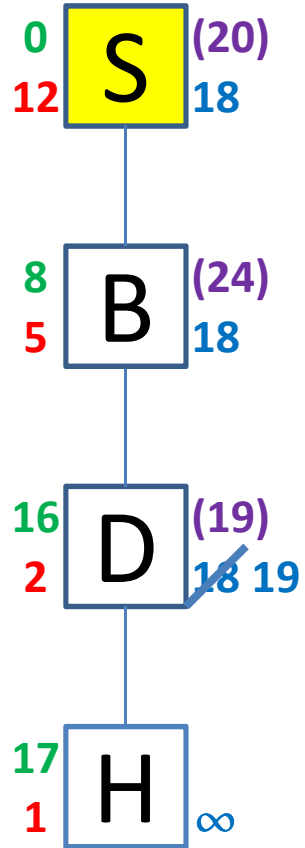
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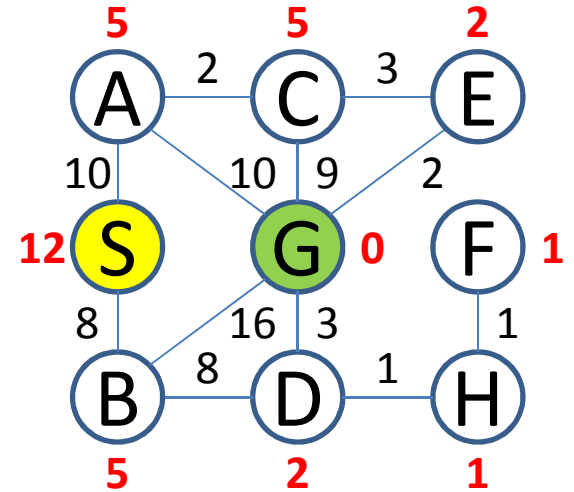
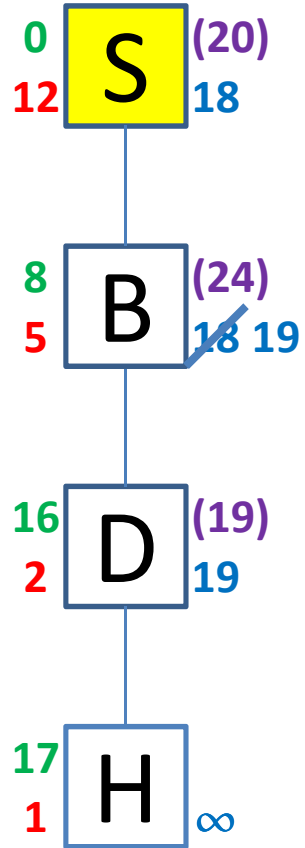
Problem



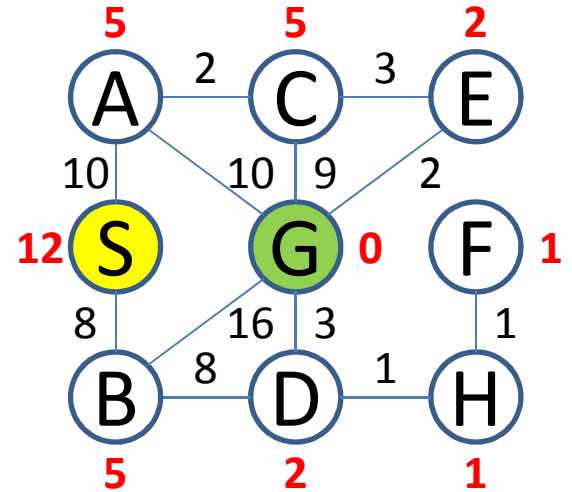
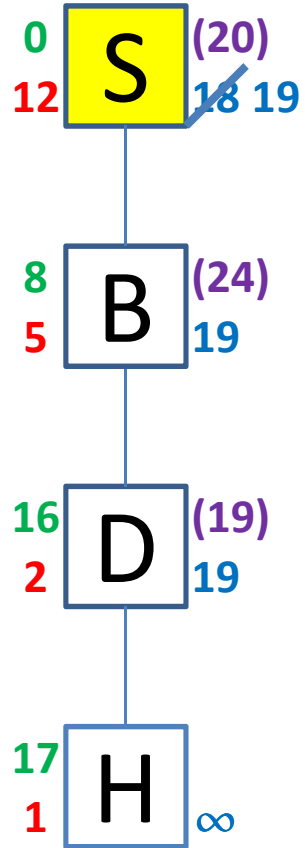
Problem



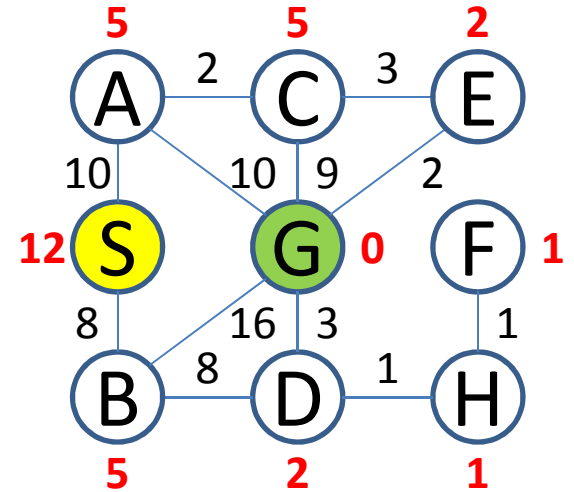
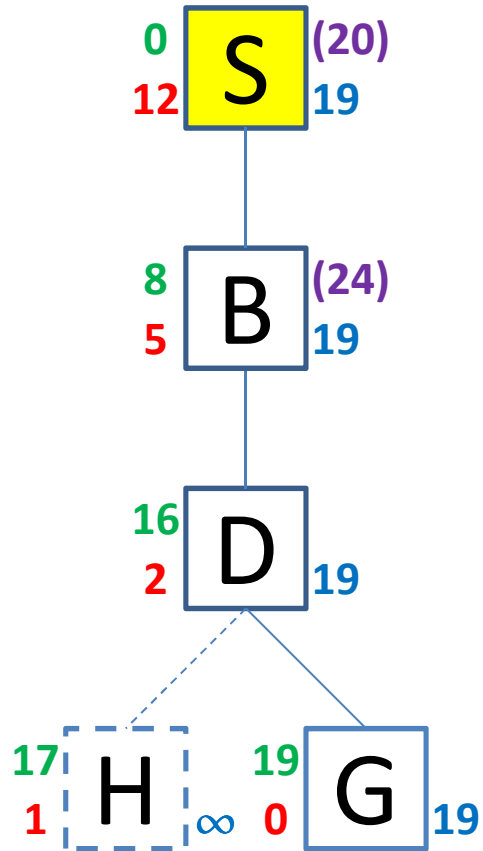
Problem



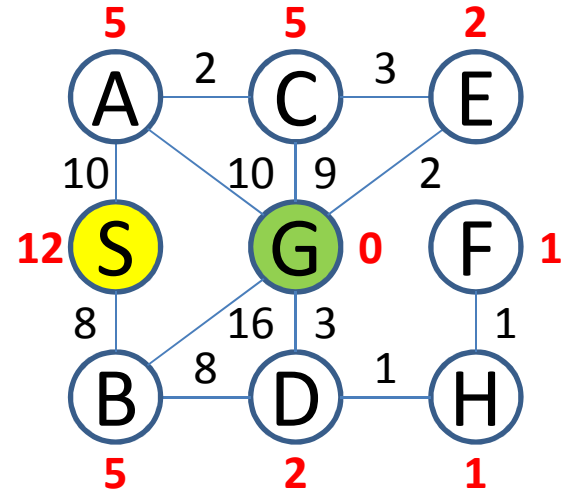
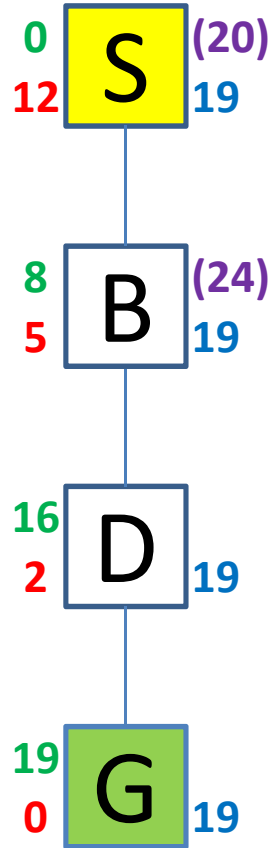
Problem



Problem



Problem



Exercises: Artificial Intelligence

Monotonicity 1

Monotonicity 1

PROBLEM

Problem

- Prove that:
 - **IF** a heuristic function h satisfies the *monotonicity restriction*
 - $h(x) \leq \text{cost}(x...y) + h(y)$
 - **THEN** f is *monotonously non-decreasing*
 - $f(s...x) \leq f(s...x...y)$

Monotonicity 1

- *Given:*
 - *h* satisfies the *monotonicity restriction*
- *Proof:*
$$f(S...A) = \text{cost}(S...A) + h(A)$$

Monotonicity 1

- *Given:*
 - *h* satisfies the **monotonicity restriction**
- *Proof:*
$$\begin{aligned} f(S...A) &= \text{cost}(S...A) + h(A) \\ &\leq \text{cost}(S...A) + \text{cost}(A...B) + h(B) \end{aligned}$$

Monotonicity 1

- *Given:*
 - *h* satisfies the ***monotonicity restriction***
- *Proof:*
$$\begin{aligned}f(S...A) &= \text{cost}(S...A) + h(A) \\ &\leq \text{cost}(S...A) + \mathbf{\text{cost}(A...B)} + h(B) \\ &\leq \text{cost}(S...A...B) + h(B)\end{aligned}$$

Monotonicity 1

- *Given:*
 - *h* satisfies the **monotonicity restriction**

- *Proof:*

$$\begin{aligned} f(S...A) &= \text{cost}(S...A) + h(A) \\ &\leq \text{cost}(S...A) + \mathbf{\text{cost}(A...B)} + h(B) \\ &\leq \text{cost}(S...A...B) + h(B) \\ &\leq \mathbf{f(S...A...B)} \end{aligned}$$

Exercises: Artificial Intelligence

Monotonicity 2

Monotonicity 2

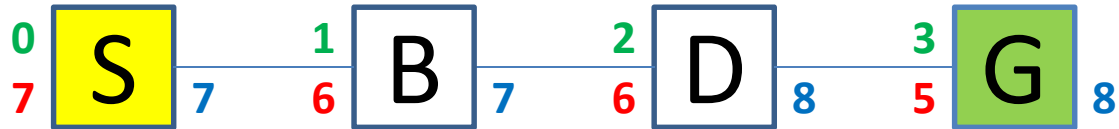
PROBLEM

Problem

- Prove or refute:
 - **IF** f is *monotonously non-decreasing*
 - $f(s...x) \leq f(s...xy)$
 - **THEN** h is an *admissable heuristic*
 - h is an underestimate of the remaining path to the goal with the smallest cost
- Can an extra constraint on h change this?

Monotonicity 2

- *Given:*
 - f is monotonously non-decreasing
- *Proof (Counter-example):*



f is monotonously non-decreasing,
yet h is not an admissible heuristic.

Monotonicity 2

- *Given:*
 - f is monotonously non-decreasing
 - Extra constraint: $h(G) = 0$
- *Proof:*
 - $f(S...A) \leq f(S...AB) \leq \dots \leq f(S...AB...G)$

Monotonicity 2

- *Given:*
 - f is *monotonously non-decreasing*
 - Extra constraint: $h(G) = 0$
- *Proof:*
 - $f(S...A) \leq f(S...AB) \leq \dots \leq f(S...AB...G)$ \Leftrightarrow
 $f(S...A) \leq f(S...G)$

Monotonicity 2

- *Given:*
 - f is *monotonously non-decreasing*
 - Extra constraint: $h(G) = 0$
- *Proof:*
 - $f(S...A) \leq f(S...AB) \leq \dots \leq f(S...AB...G)$ \Leftrightarrow
 - $f(S...A) \leq f(S...G) \Leftrightarrow$
 - $\text{cost}(S...A) + h(A) \leq \text{cost}(S...G) + h(G)$

Monotonicity 2

- *Given:*

- f is *monotonously non-decreasing*

- Extra constraint: $h(G) = 0$

- *Proof:*

$$\underline{f(S...A) \leq f(S...AB) \leq \dots \leq f(S...AB...G)} \Leftrightarrow$$

$$f(S...A) \leq f(S...G) \Leftrightarrow$$

$$\text{cost}(S...A) + h(A) \leq \text{cost}(S...G) + h(G) \Leftrightarrow$$

$$\underline{\text{cost}(S...A)} + h(A) \leq \underline{\text{cost}(S...A)} + \text{cost}(A...G) + h(G)$$

Monotonicity 2

- *Given:*

- f is *monotonously non-decreasing*

- Extra constraint: $h(G) = 0$

- *Proof:*

$$\underline{f(S...A) \leq f(S...AB) \leq \dots \leq f(S...AB...G)} \Leftrightarrow$$

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$$\underline{\text{cost}(S...A)} + h(A) \leq \underline{\text{cost}(S...A)} + \text{cost}(A...G) + h(G) \Leftrightarrow$$

$$h(A) \leq \text{cost}(A...G) + \mathbf{h(G)}$$

Monotonicity 2

- *Given:*

- f is monotonously non-decreasing

- Extra constraint: $h(G) = 0$

- *Proof:*

$$\underline{f(S...A) \leq f(S...AB) \leq \dots \leq f(S...AB...G)} \Leftrightarrow$$

$$f(S...A) \leq f(S...G) \Leftrightarrow$$

$$\text{cost}(S...A) + h(A) \leq \text{cost}(S...G) + h(G) \Leftrightarrow$$

$$\underline{\text{cost}(S...A)} + h(A) \leq \underline{\text{cost}(S...A)} + \text{cost}(A...G) + h(G) \Leftrightarrow$$

$$h(A) \leq \text{cost}(A...G) + \underline{h(G)} \Leftrightarrow$$

$$h(A) \leq \text{cost}(A...G)$$