Innovative Teaching Approaches in development of Software Designed Instrumentation and its application in real-time systems

Theory of Robotics Systems

Planning – getting from A to B

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Innovative Teaching Approaches in development of Software Designed Instrumentation and its application in real-time systems

Faculty of Technical Sciences

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Šta znači planiranje?

- Generalno, naš fokus će biti na **planiranju kretanja** u robotici. Određivaćemo set akcija koje će robota odvesti iz poznate pozicije u neku drugu takođe poznatu poziciju.
- Takođe posmatraćemo koja su to **ograničenja** koja mogu uticati na planiranje i od čega potiču kako bismo znali da li je naše planiranje kretanja **izvodljivo**.

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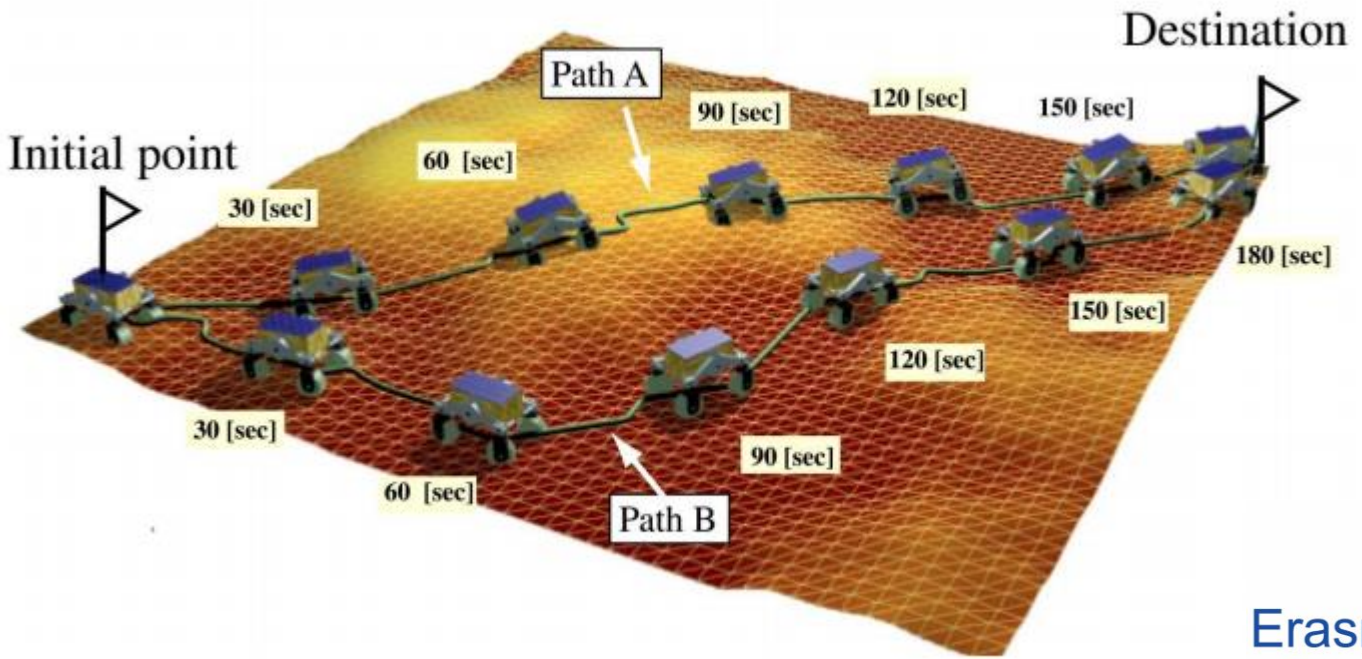
Šta je planiranje u mobilnoj robotici?



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Povezane teme

- Upravljanje:
  - Generalni zadatak dohvatanja (dolaženja) do željenog stanja.
  - Najčešće koristimo **feedback** upravljanje.
  - Uspešnost upravljanja merimo pomoću stabilnosti, robusnosti i otpornosti na poremećaj.
- Planiranje u Veštačkoj Inteligenciji:
  - Bavi se diskretnim problemima.
  - Klasični algoritmi u VI (pretraga grafova, problem trgovačkog putnika, orijentiring) se često primenjuju kao algoritmi za planiranje u robotici.

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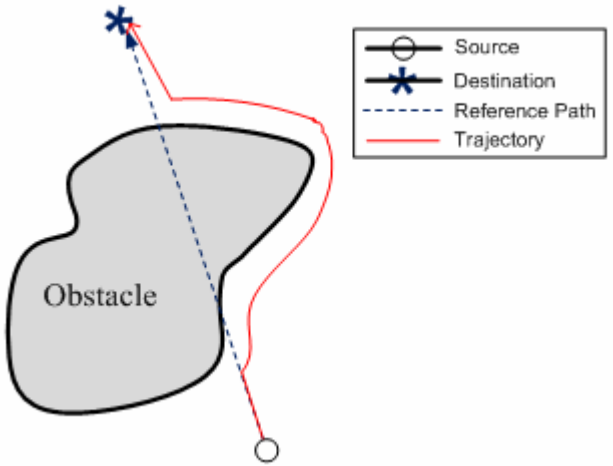
Istorija planiranja kretanja u robotici

- Klasična robotika (sredina 70-ih)
  - Tačan model, bez senzora
- Reaktivno planiranje trajektorije (sredina 80-ih)
  - Bez modela, oslanja se isključivo na senzoriku



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Istorija planiranja kretanja u robotici

- Hibridno / hijerarhijsko planiranje (početak 90-ih)
  - Model za globalno planiranje, viši nivo
  - Reaktivno (zaobilaženje prepreka), niži nivo
- Probabalističko planiranje (sredina 90-ih)
  - Uključuje nesigurnost modela i senzora u sve nivoi planiranja

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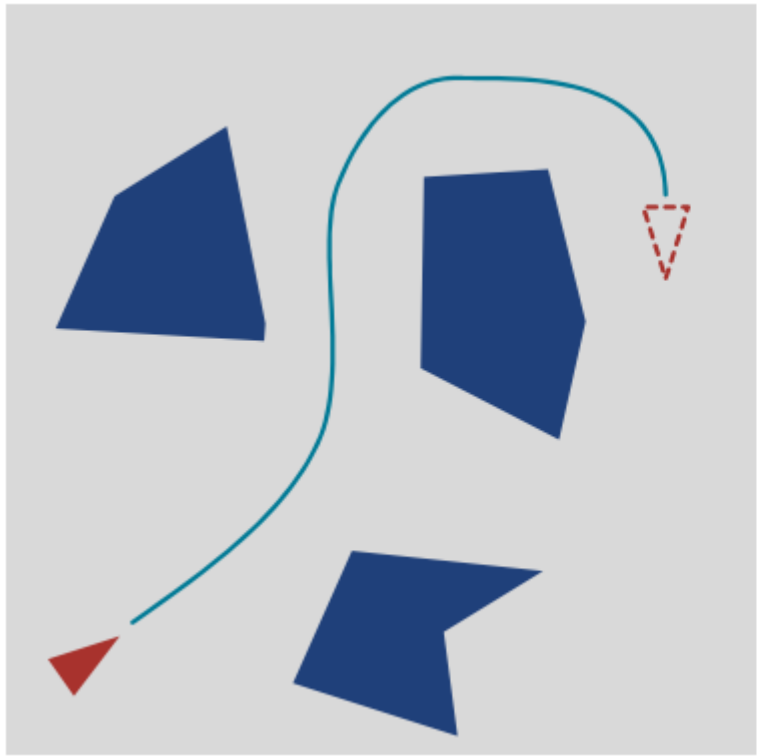
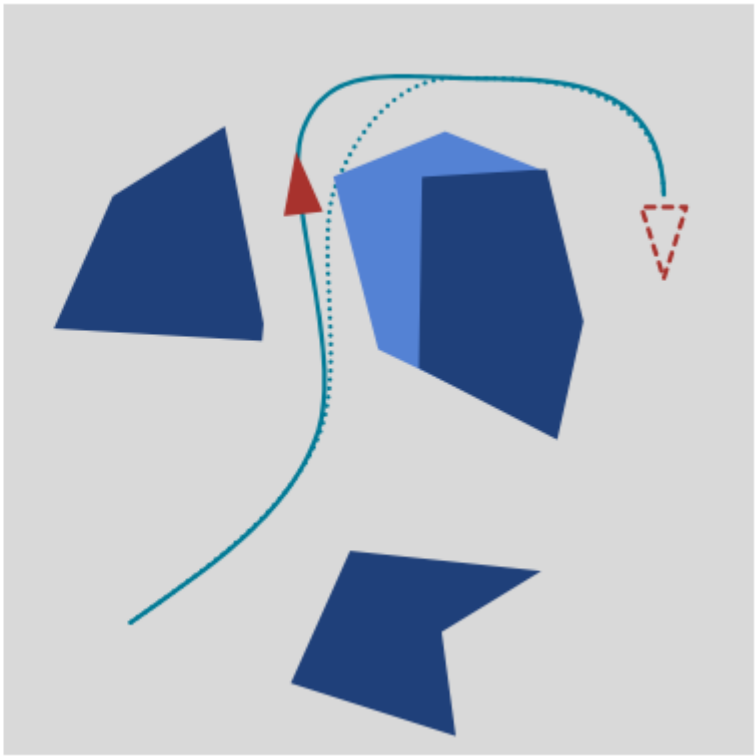


Planirano



Izvršeno

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Uloga navigacije

- Ukratko, naći način kako robot može da se pomeri sa jednog mesta na drugo, poštujući sva ograničenja.
- Neke od pretpostavki:
  - Dovoljno dobro možemo da **predstavimo** okolinu i robota
  - Znamo gde se robot **nalazi** i gde **treba da dođe**
  - Posedujemo **model kretanja** robota
- Obično se predstavlja kao problem optimizacije – minimizacija cene (vreme, udaljenost, energija), poštujući ograničenja.

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Planiranje

- Robot se nalazi na startnoj poziciji S, treba da dođe do tačke G:
  - Potrebno je pronaći put koji vodi robota od S do G.
- Izazovi:
  - Prepreke?
  - Dinamika?
  - Izvodljivost?
- Optimizacion problem !

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Reprezentacija

- Veoma je bitno na koji način robot predstavlja i razume svet.
- Uglavnom se moraju primeniti određene metode pojednostavljivanja.
- Odabirom odgovarajuće reprezentacije sveta, određeni algoritmi se mogu primeniti kako bi rešili problem planiranja.

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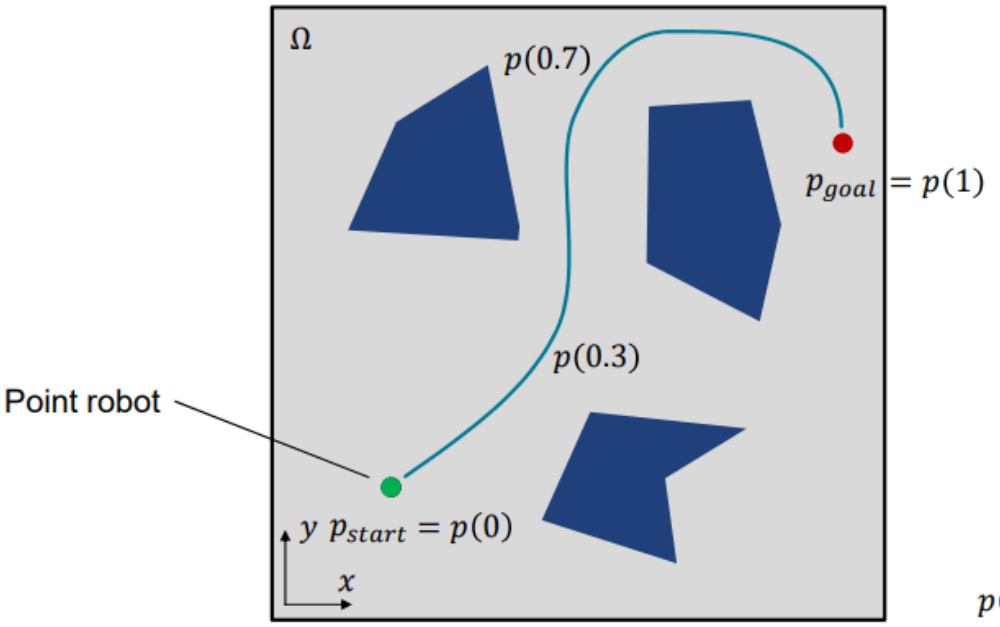
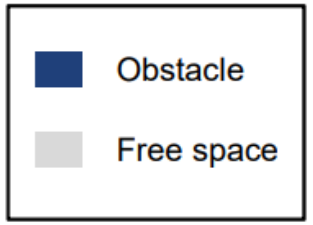
Reprezentacija – radni prostor i putanja





$$\omega_{free} = \Omega - \omega_{obs}$$

$$p: [0,1] \rightarrow \omega_{free}$$

$$p(t): \forall t \in [0,1], \; p(t) \in \omega_{free}$$

$$p(0) = p_{start}$$

$$p(1) = p_{goal}$$

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Reprezentacija – radni prostor i putanja

- Radni prostor uglavnom predstavlja sam svet (mapu), po mogućstvu nezavisno od robota. Uglavnom na određeni način predstavlja koje su oblasti slobodne a koje ne.
- Konfiguracijski prostor opisuje sva stanja u kojima se robot u datom prostoru može naći.
- Od sad smatramo da naš robot nije tačka u prostoru već sam zauzima određeni prostor.

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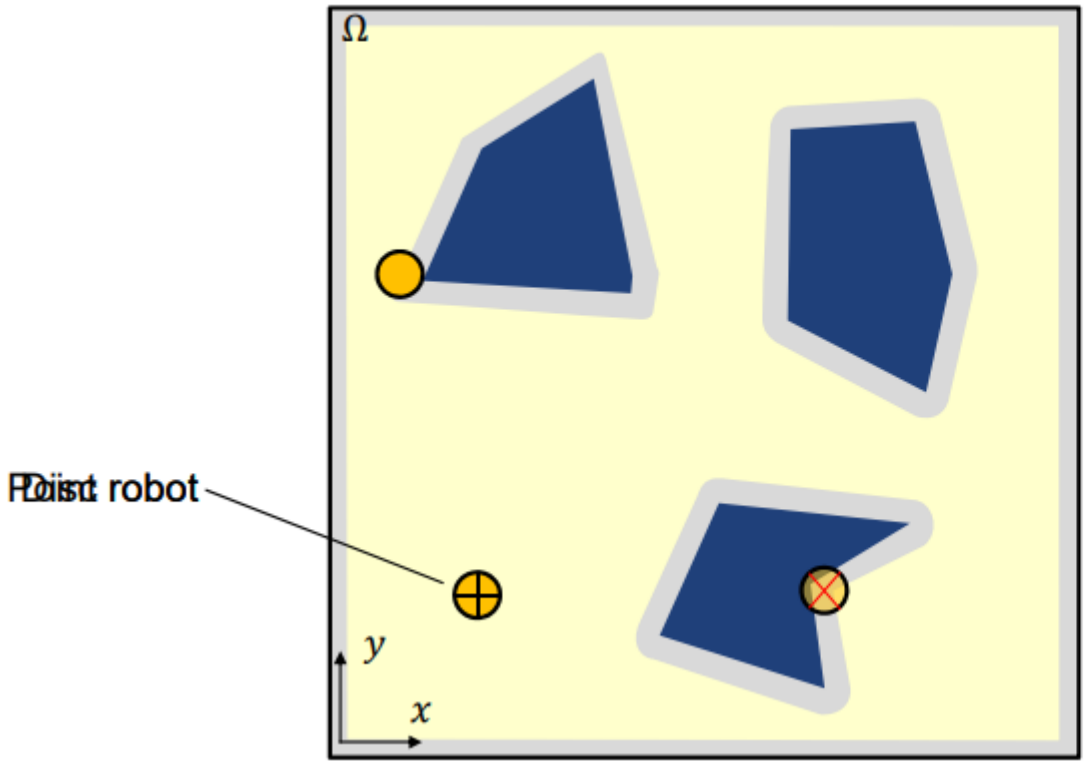
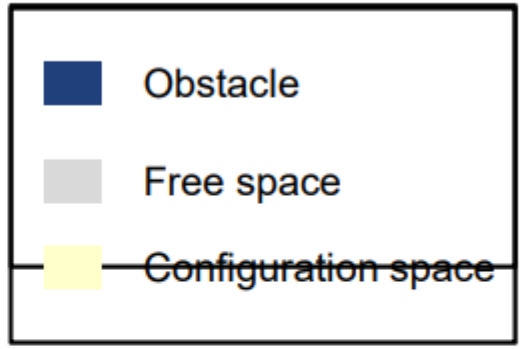
Konfiguracijski prostor





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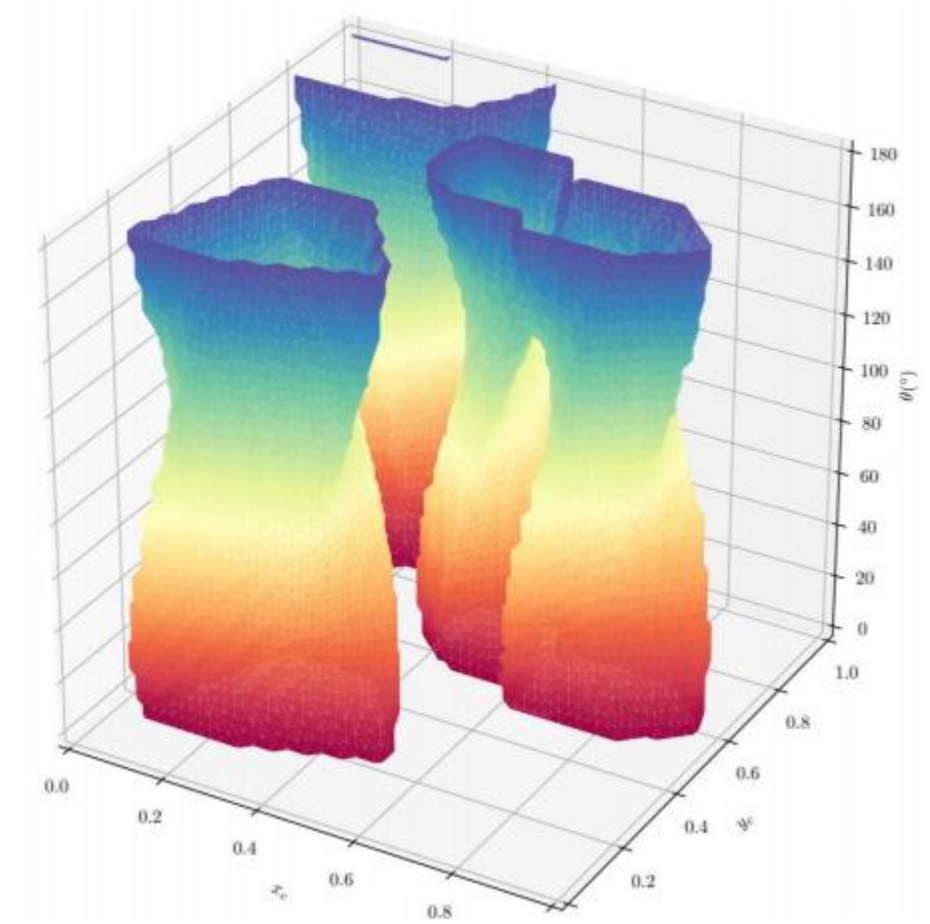
Konfiguracijski prostor



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Kontinualna vs Diskretna reprezentacija

- Iako za kontinualnu reprezentaciju posedujemo dobar matematički alat, uglavnom nam takva predstava nije zgodna.
- Kako računari čuvaju podatke digitalno, potrebno je naći pametan i efikasan način za kreiranje (aproksimacije) diskretne reprezentacije.
- Veoma je uobičajeno da problem planiranja predstavimo kao problem pretrage grafa, jer za pretragu grafova postoji dosta već razrađenih algoritama.

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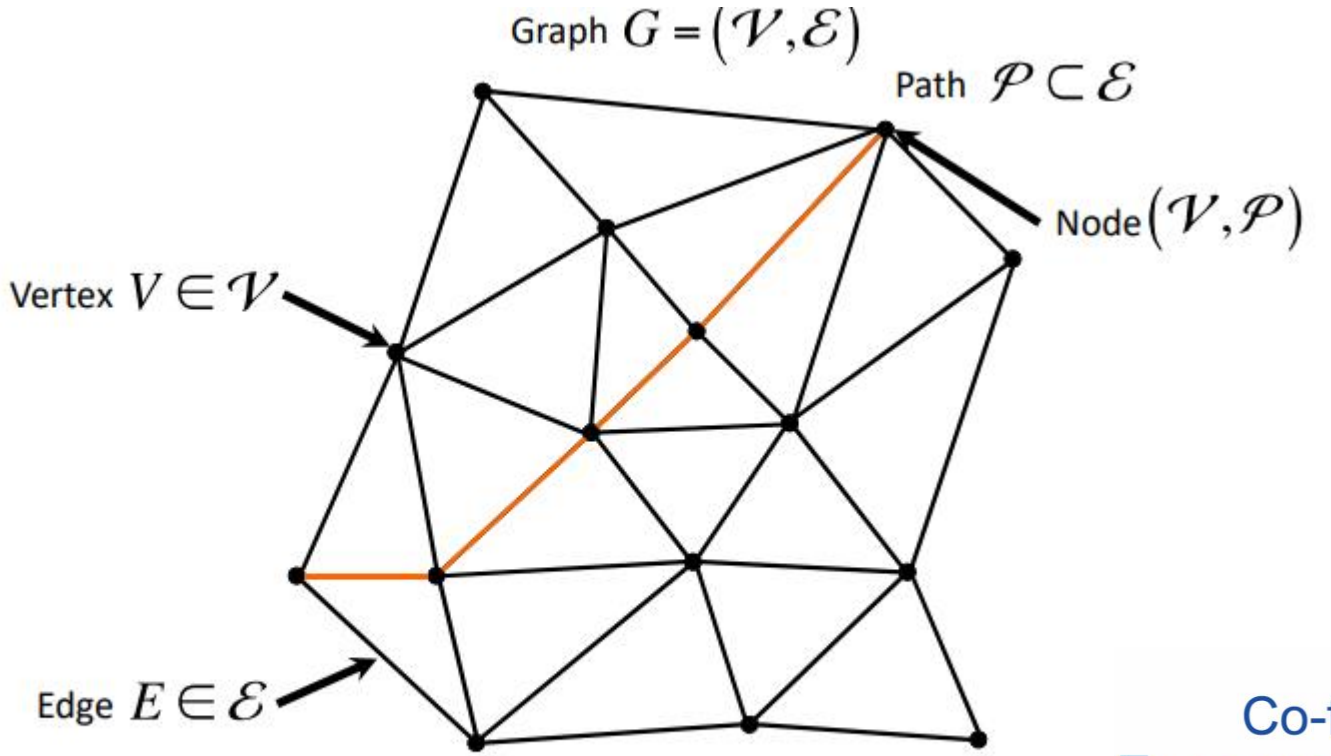
Terminlogija



Directed graph: edges have direction
Weighted graph: edges have costs

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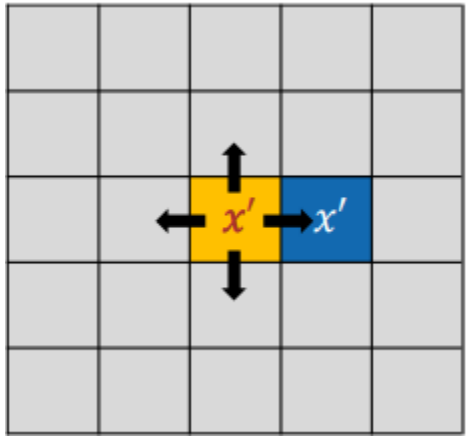
Diskretna reprezentacija prostora stanja

- Redukujemo kontinualna stanja na skup konačnih diskretnih stanja.
  - $x \in X$
- Definišemo izvodljiv skup akcija za svako stanje
  - $A(x) = \{a_0, a_1, \ldots, a_n\}$
- I svakoj od akcija pridružujemo funkciju tranzicije
  - $f(x, a) = x'$



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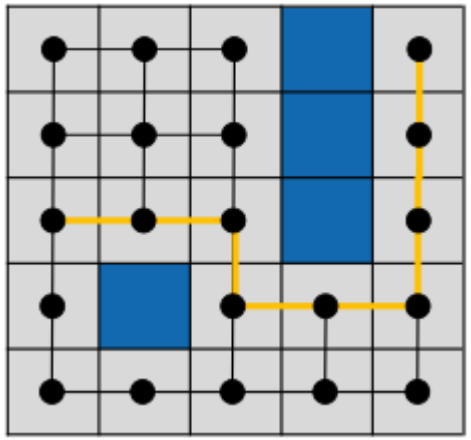
Grid → Graf

- Primeniti:
  - Stanja se uzimaju kao vrhovi
  - Prelazi kao usmerene ivice
- Rezultat je graf
- Dodajemo:
  - Početni nod, x_s
  - Završni nod, x_g
  - Funkcija cene $C: X \times A \rightarrow \mathbb{R}^+$
- Traženje najkraćeg puta možemo tretirati kao problem pretrage grafa.



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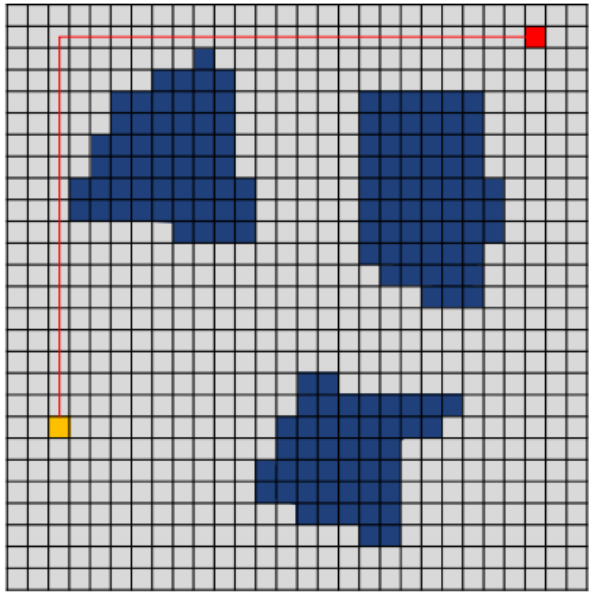
Problemi sa reprezentacijom pomoću grid-a

- Uglavnom se neki sitni detalji i preciznost mogu izgubiti.
- Odabir prave rezolucije može

da bude veoma izazovan zadatak

(mapiranje multi-rezolucijom)

- Izlazna putanja može biti ograničena.
- Loša rezolucija za mape velikih dimenzija.



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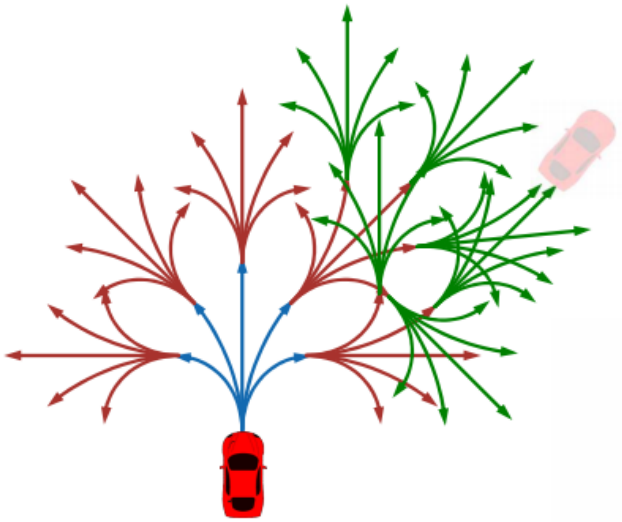
Grid rešetka

- Kreira set mogućih primitivnih kretanja,

i konstruiše drvo (graf) koje sadrži određena kretanja u sekvenci (putanja)



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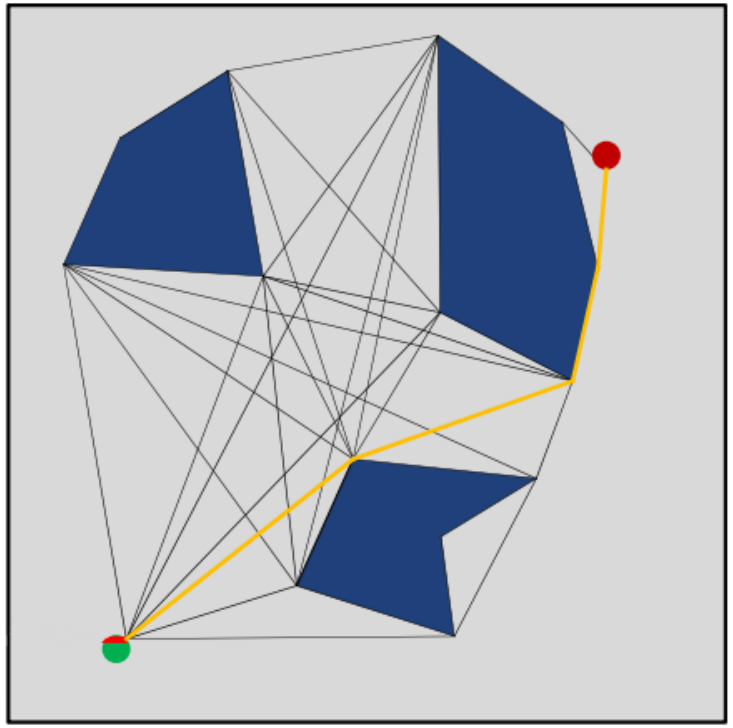
Grafikon vidljivosti

- Kreira ivice grafa između svih parova vidljivih čvorova.
- Pretraga se vrši prema dobijenom grafu.
- Optimalan put je putanja kretanja.
- Ograničeno kretanje na prave putanje.



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Planiranje kretanja

- Planiranje kretanja: deljenje zadatka kretanja na diskretna kretanja:
  - Robot mora da stigne od početne lokacija na cilj.
  - Robot mora da zaobiđe zidove, da uspešno izbegne stepenice, …
  - Idealno, putanja mora da bude najefikasnija (najkraća)
- Ulazi algoritma:
  - Opis zadatka (početna i krajnja pozicija)
  - Ograničenja (fizička ograničenja robota, prepreke, …)
  - Nesigurnosti robota i okruženja
- Izlaz algoritma:
  - Putanja robota
    - Set tačaka koje treba da poseti kako bi otišao od tačke A do tačke B

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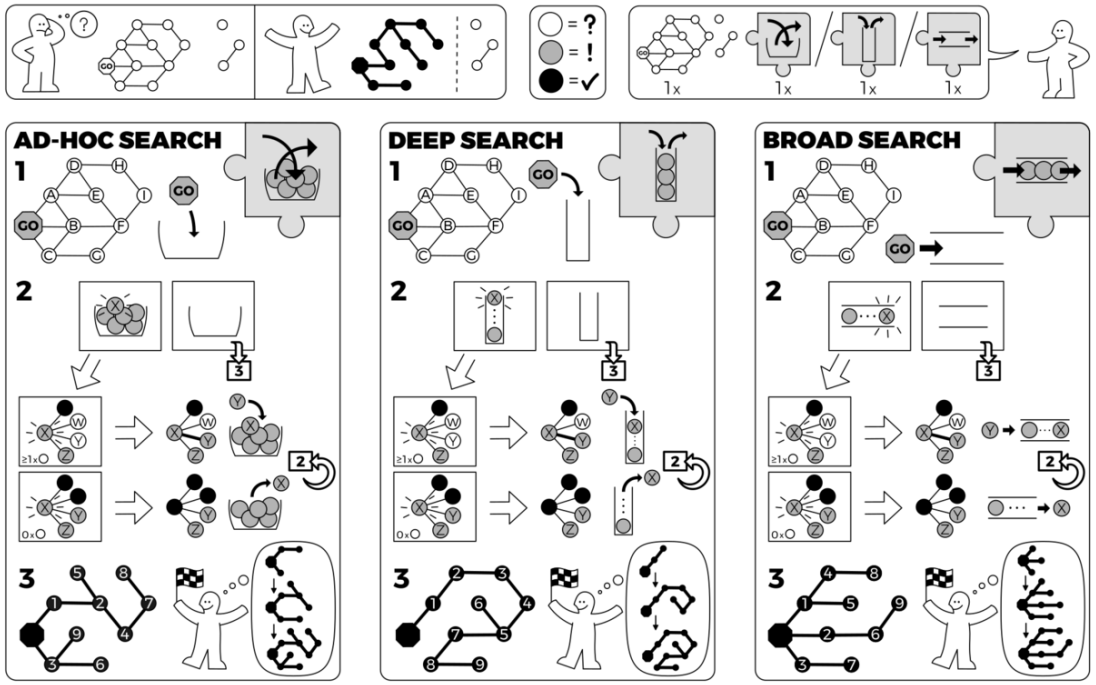
Metode pretrage grafova



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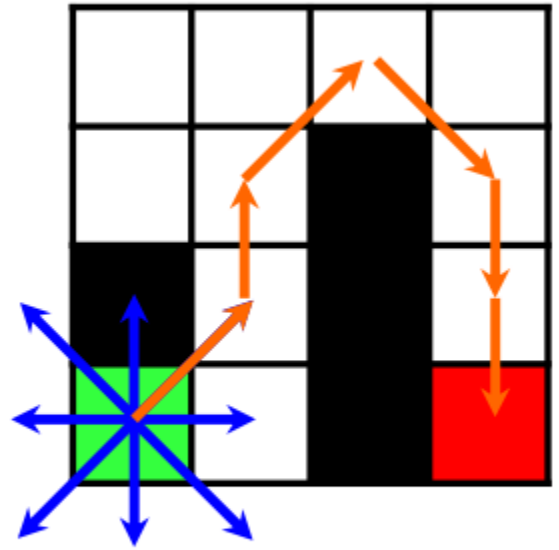
Primer 1

- Putanja od zelene ćelije do crvene
- 8 koraka iz jedne ćelije
- Koja je najkraća putanja?
- Šta ako imamo 4 moguća koraka iz ćelije.



Assumptions about robot motion

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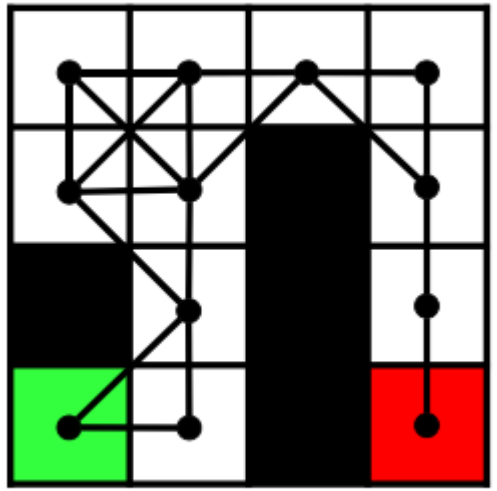
Primer 1

- Pretražimo dobijeni graf.
- Pretpostavljamo da sve ivice grafa mogu kreirati putanju.
- Rešimo problem tako što nađemo putanju od A do B.



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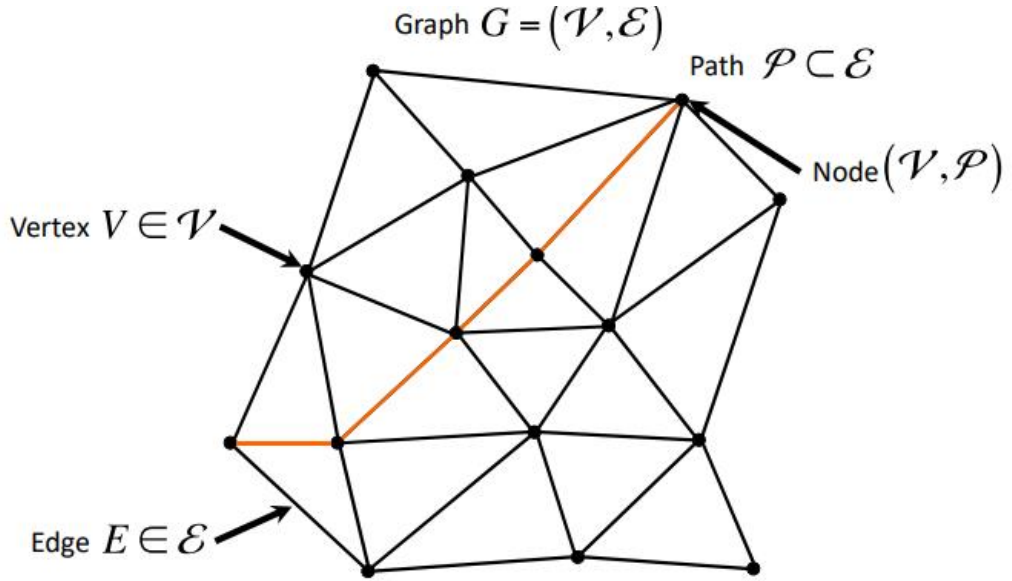
Pretraga grafova

- Ivice grafa mogu imati pridružene **težine**
  - Cena putanje
- Ima smisla da se razmatraju samo pozitivne težine.
- Algoritmi sa minimalnom cenom nikad ne posećuju isti čvor dva puta.
- Najpoznatije pretrage:
  - Pretraga u širinu (BFS)
  - Pretraga u dubinu (DFS)
  - Dijkstra's Algoritam
  - A*



Directed graph: edges have direction
Weighted graph: edges have costs

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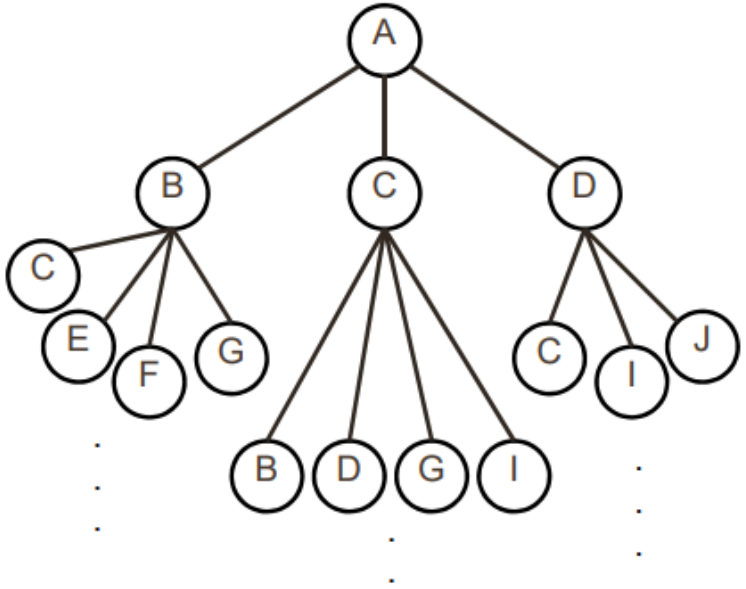
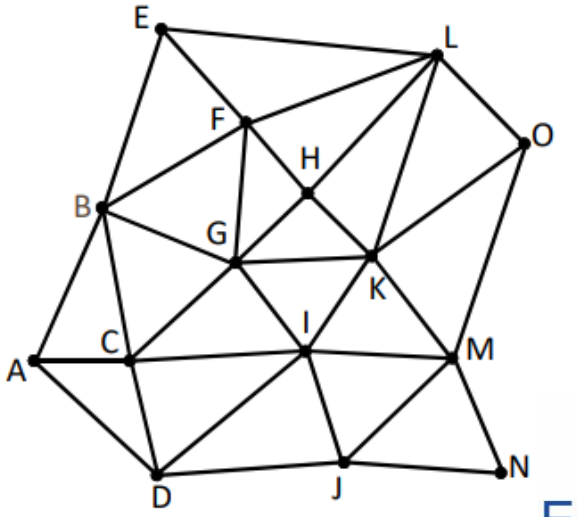
Drvo pretrage

- Konstruišemo „drvo“ pomoću kojeg vršimo pretragu.





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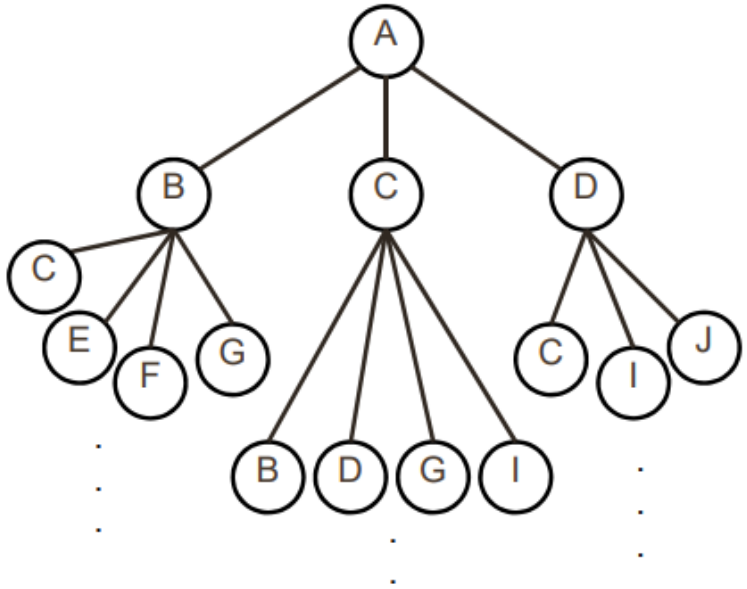
Drvo pretrage

- Drvo pretrage:
  - Početno stanje se uzima kao koren
  - Naslednici – skup svih mogućih akcija
  - Uglavnom želimo da izbegnemo konstrukciju kompletnog stabla



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Osnove pravolinijske pretrage

- Počnemo od korena (početno stanje), širimo drvo sve dok ne dođemo do cilja.
- Proširivanje nodova znači dodavanje njihovih naslednika.
- Treba probati da se nađe rešenje sa što manje proširivanja.
- Otvoren set – čvorovi iz kojih se mogu vršiti proširivanja
- Zatvoren set – svi oni čvorovi koje je algoritam posetio

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Osnove pravolinijske pretrage

```
FORWARD_SEARCH
1   Q.Insert(x_I) and mark x_I as visited
2   while Q not empty do
3       x ← Q.GetFirst()
4       if x ∈ X_G
5           return SUCCESS
6       forall u ∈ U(x)
7           x' ← f(x, u)
8           if x' not visited
9               Mark x' as visited
10              Q.Insert(x')
11          else
12              Resolve duplicate x'
13  return FAILURE
```

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Pretraga po širini

```
FORWARD SEARCH
1   Q.Insert(x_I) and mark x_I as visited
2   while Q not empty do
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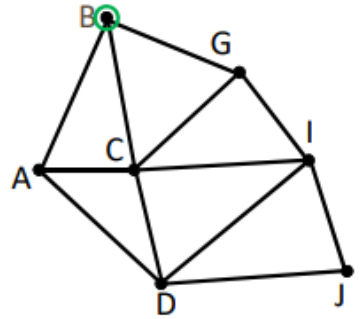

Open (Q): {B}

Closed: {}

Our (BFS) queue will be FIFO:
- push (*Q.Insert*) onto the end
- pop (*Q.GetFirst*) from the front

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Pretraga po širini

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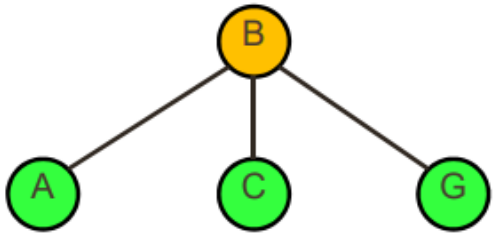

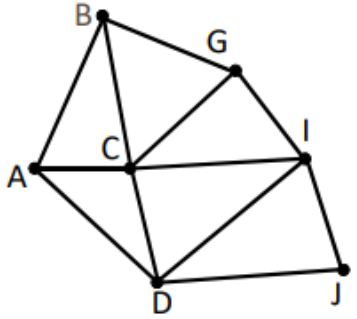

Open (Q): {A,C,G}

Closed: {B,A,C,G}

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Pretraga po širini

```
FORWARD_SEARCH
1   Q.Insert(x_I) and mark x_I as visited
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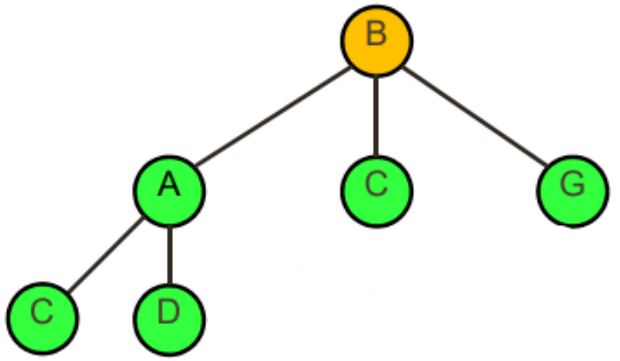

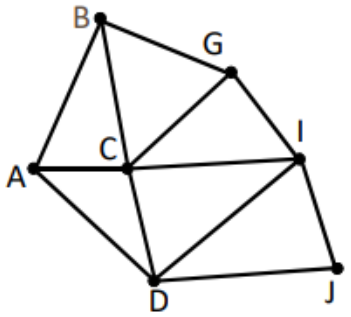

Open (Q): {C,G,D}

Closed: {B,A,C,G,D}

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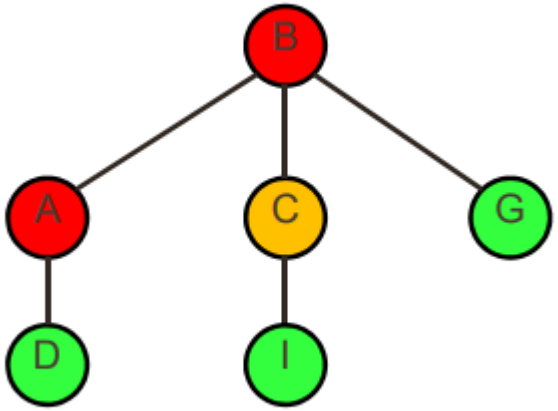
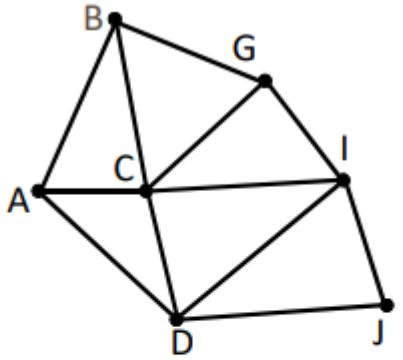
Pretraga po širini





Open (Q): {G,D,I}

Closed: {B,A,C,G,D,I}

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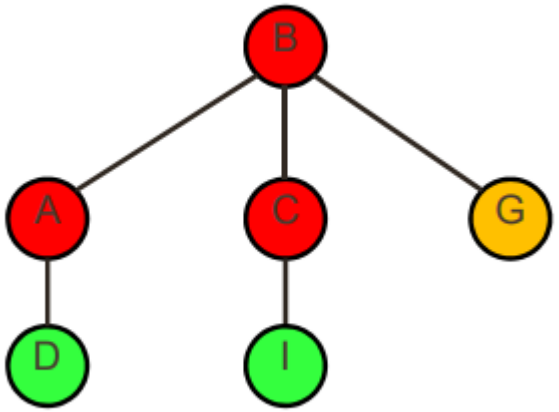
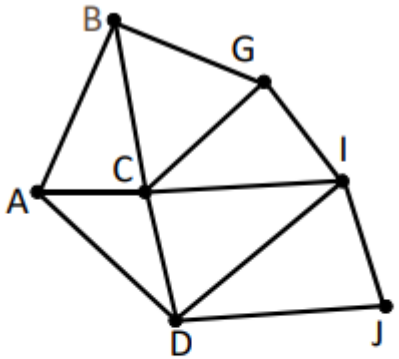
Pretraga po širini





Open (Q): {D,I}

Closed: {B,A,C,G,D,I}

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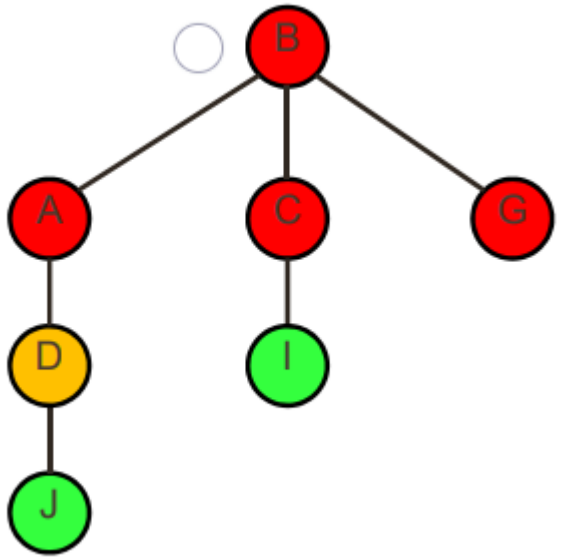
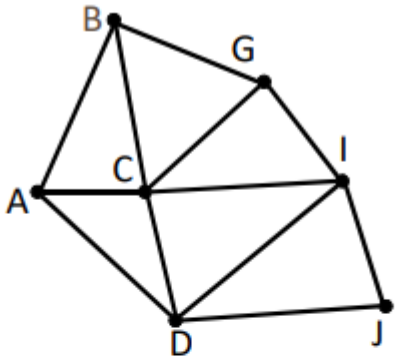
Itasdi

Pretraga po širini





Open (Q): {I,J}

Closed: {B,A,C,G,D,I,J}

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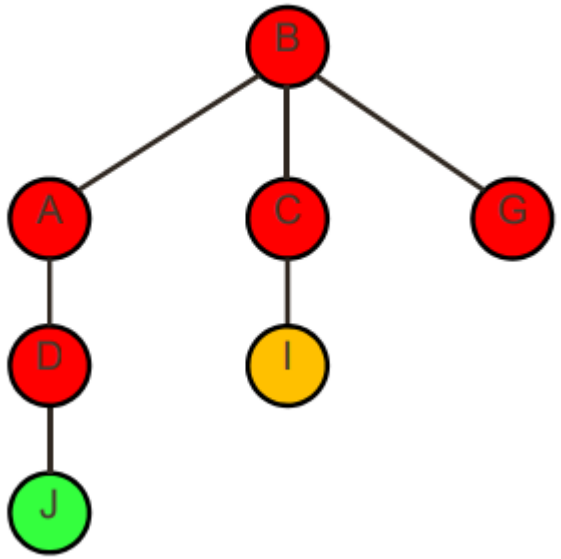
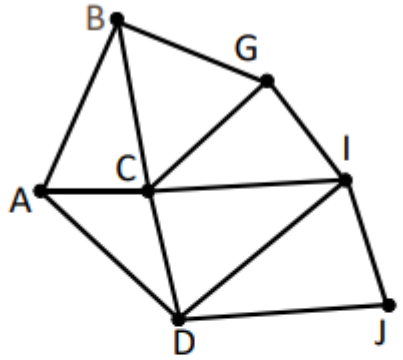
Pretraga po širini





Open (Q):	Closed:
{J}	{B,A,C,G,D,I,J}

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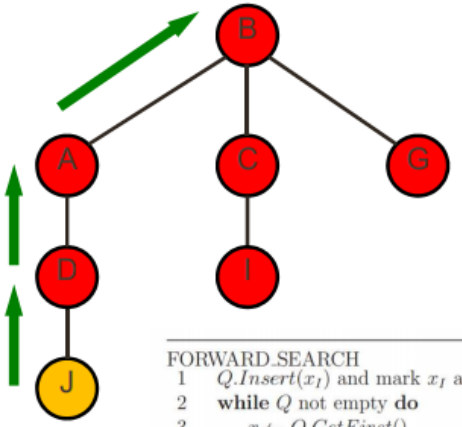
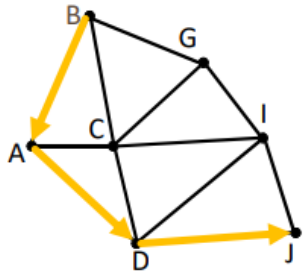
Itasdi

Pretraga po širini




```
FORWARD_SEARCH
1   Q.Insert(x_I) and mark x_I as visited
2   while Q not empty do
3       x ← Q.GetFirst()
4       if x ∈ X_G
5           return SUCCESS
6       forall u ∈ U(x)
7           x' ← f(x, u)
8           if x' not visited
9               Mark x' as visited
10              Q.Insert(x')
11          else
12              Resolve duplicate x'
13  return FAILURE
```



Open (Q): {}

Closed: {B,A,C,G,D,I,J}

Final path solution: B→A→D→J

Other solutions may exist but have the same number or more transitions

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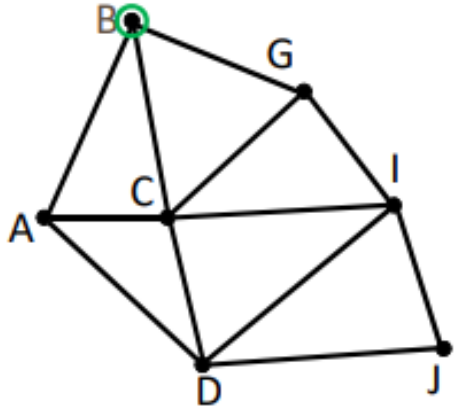
Itasdi

Pretraga po dubini

```
FORWARD SEARCH
1   Q.Insert(x_I) and mark x_I as visited
2   while Q not empty do
3       x ← Q.GetFirst()
4       if x ∈ X_G
5           return SUCCESS
6       forall u ∈ U(x)
7           x' ← f(x, u)
8           if x' not visited
9               Mark x' as visited
10              Q.Insert(x')
11          else
12              Resolve duplicate x'
13  return FAILURE
```



Open (Q): {B}

Closed: {}

Our (DFS) queue will be LIFO:
- push (*Q.Insert*) onto the front
- pop (*Q.GetFirst*) from the front

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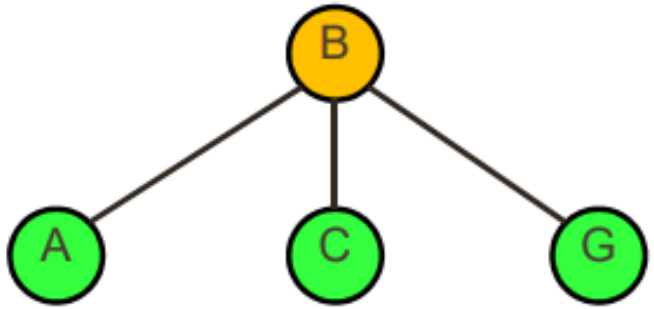
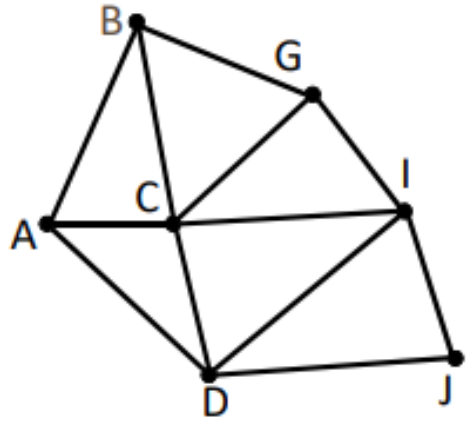
Pretraga po dubini

```
FORWARD_SEARCH
1   Q.Insert(x_I) and mark x_I as visited
2   while Q not empty do
3       x ← Q.GetFirst()
4       if x ∈ X_G
5           return SUCCESS
6       forall u ∈ U(x)
7           x' ← f(x, u)
8           if x' not visited
9               Mark x' as visited
10              Q.Insert(x')
11          else
12              Resolve duplicate x'
13  return FAILURE
```





Open (Q): {A,C,G}

Closed: {B,A,C,G}

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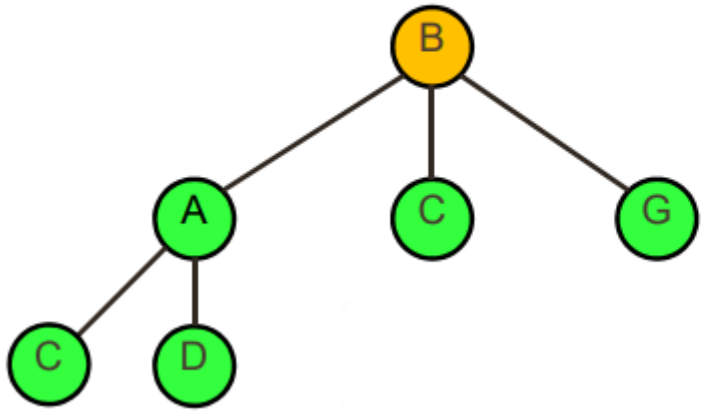
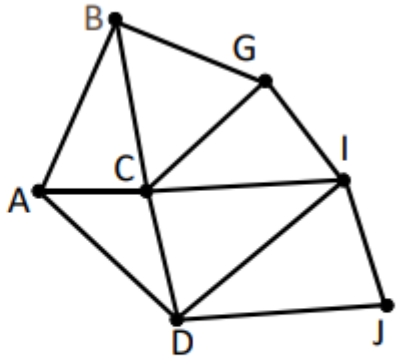
Pretraga po dubini

```
FORWARD_SEARCH
1   Q.Insert(x_I) and mark x_I as visited
2   while Q not empty do
3       x ← Q.GetFirst()
4       if x ∈ X_G
5           return SUCCESS
6       forall u ∈ U(x)
7           x' ← f(x, u)
8           if x' not visited
9               Mark x' as visited
10              Q.Insert(x')
11          else
12              Resolve duplicate x'
13  return FAILURE
```





Open (Q): {D,C,G}

Closed: {B,A,C,G,D}

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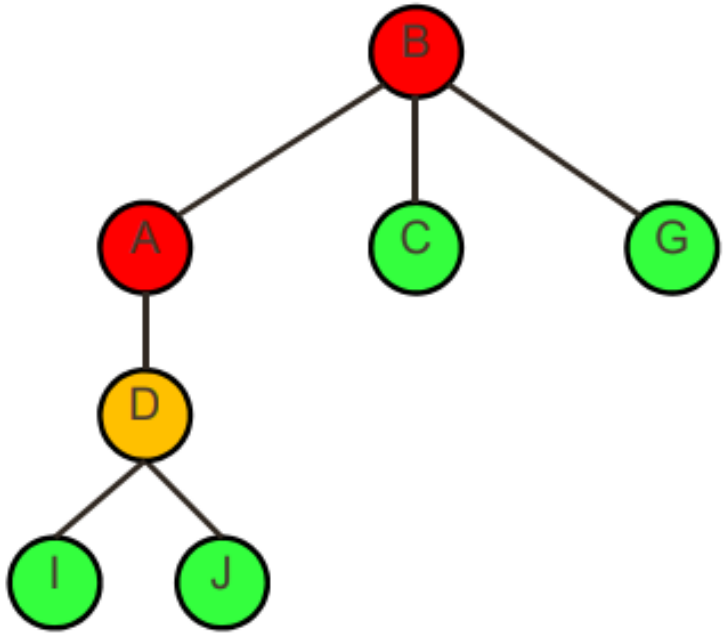
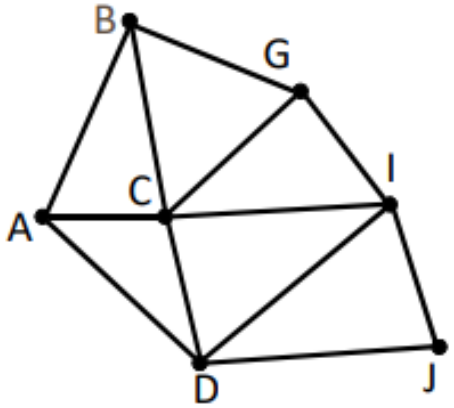
Pretraga po dubini





Open (Q): {I,J,C,G}

Closed: {B,A,C,G,D,I,J}

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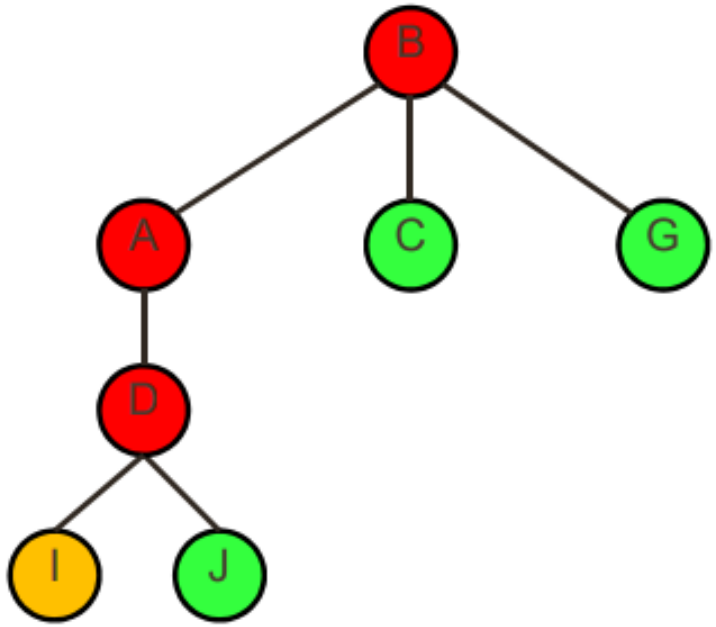
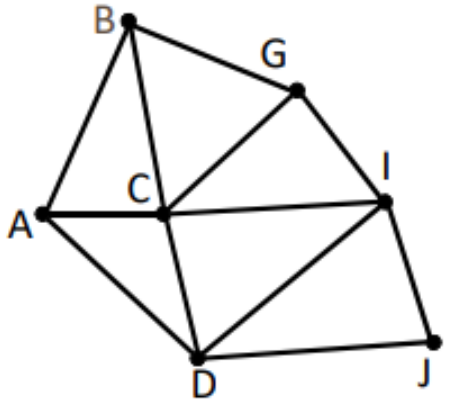
Pretraga po dubini





Open (Q): {J,C,G}

Closed: {B,A,C,G,D,I,J}

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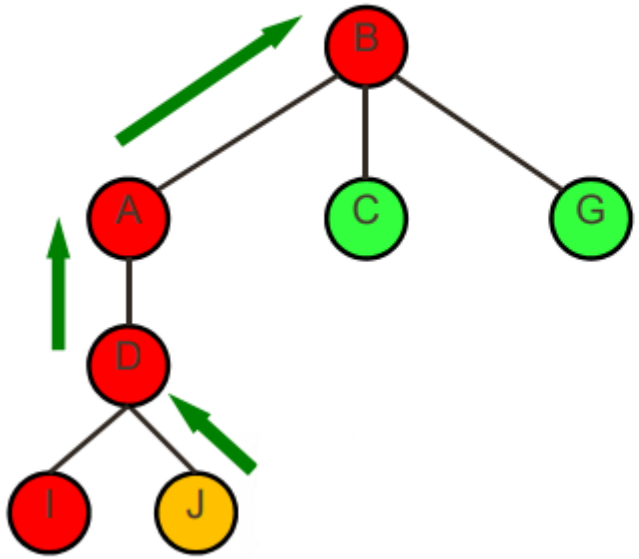
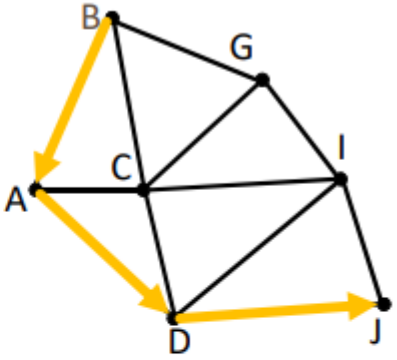
Pretraga po dubini

```
FORWARD_SEARCH
1   Q.Insert(x_I) and mark x_I as visited
2   while Q not empty do
3       x ← Q.GetFirst()
4       if x ∈ X_G
5           return SUCCESS
6       forall u ∈ U(x)
7           x' ← f(x, u)
8           if x' not visited
9               Mark x' as visited
10              Q.Insert(x')
11          else
12              Resolve duplicate x'
13  return FAILURE
```





Open (Q): {}

Closed: {B,A,C,G,D,I,J}

Final path solution: B→A→D→J

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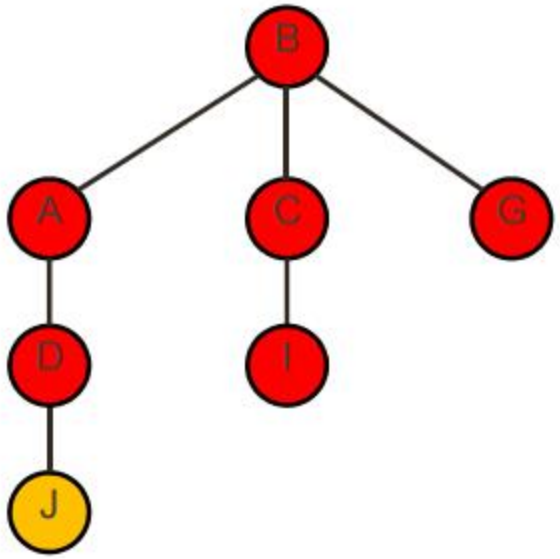
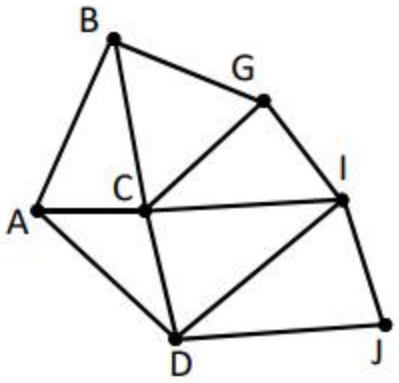
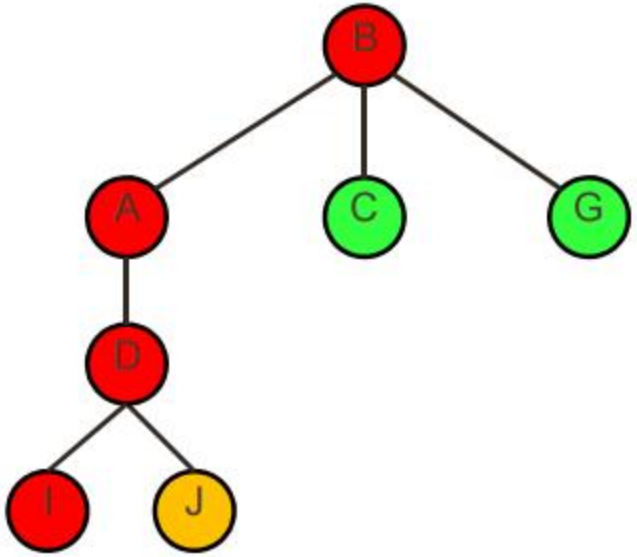
Uporedna analiza



BFS





DFS

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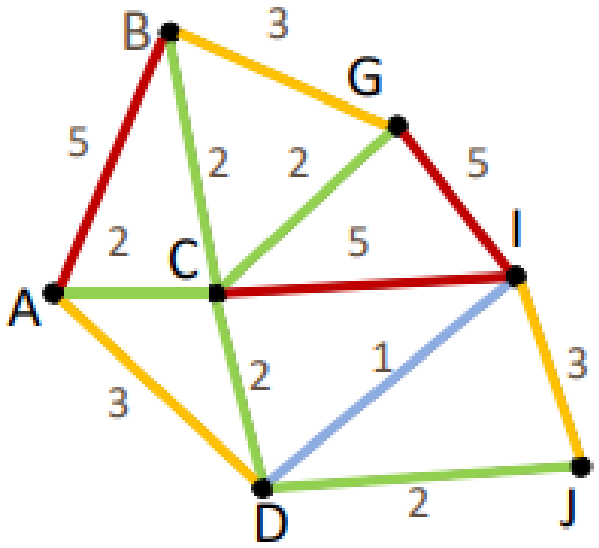
Akcije sa cenom

- Kako rešiti slučaj ako određena putanja ima veću cenu nego neka druga?
- Najpopularniji algoritmi Dijkstra's i A*



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Dijkstra's algoritam

- Objavljen od strane Edsger Dijsktra 1959.
- Otvara čvorove sa najmanjom cenom najbliže od korena grafa.
- Najkorišćeniji algoritam za rešavanje problema trgovačkog putnika.

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Dijkstra's algoritam

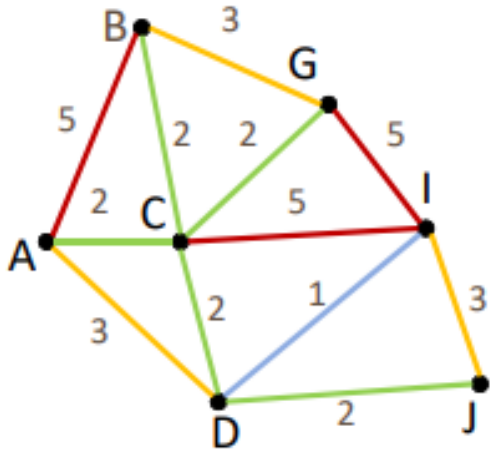
```
FORWARD SEARCH
1   Q.Insert(x_I) and mark x_I as visited
2   while Q not empty do
3       x ← Q.GetFirst()
4       if x ∈ X_G
5           return SUCCESS
6       forall u ∈ U(x)
7           x' ← f(x, u)
8           if x' not visited
9               Mark x' as visited
10              Q.Insert(x')
11          else
12              Resolve duplicate x'
13  return FAILURE
```

B(0)

Open (Q):	Closed:
{B(0)}	{B(0)}

Our Dijkstra queue will be ordered by cost to arrive:

- push (*Q.Insert*) by cost
- pop (*Q.GetFirst*) from the front, and add it to the closed list



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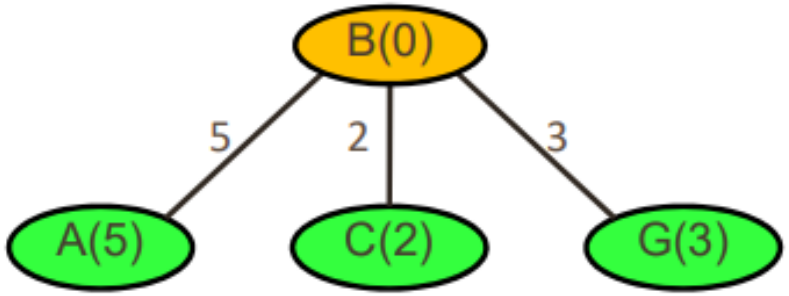
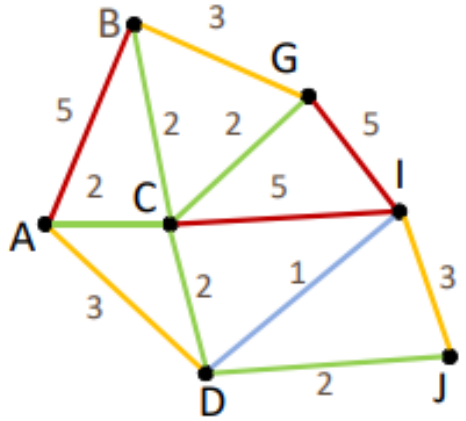
Dijkstra's algoritam

```
FORWARD_SEARCH
1   Q.Insert(x_I) and mark x_I as visited
2   while Q not empty do
3       x ← Q.GetFirst()
4       if x ∈ X_G
5           return SUCCESS
6       forall u ∈ U(x)
7           x' ← f(x, u)
8           if x' not visited
9               Mark x' as visited
10              Q.Insert(x')
11          else
12              Resolve duplicate x'
13  return FAILURE
```





Open (Q):
{ C (2),
G (3),
A (5) }

Closed:
{ B (0) }

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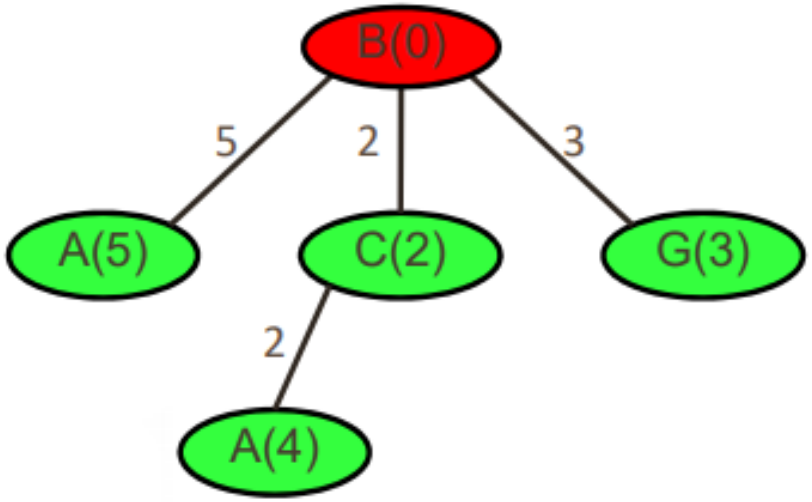
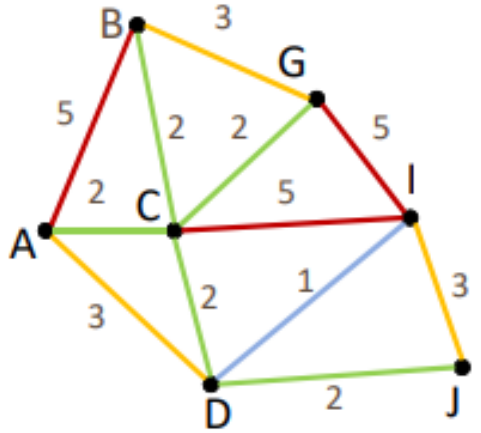
Dijkstra's algoritam

```
FORWARD_SEARCH
1   Q.Insert(x_I) and mark x_I as visited
2   while Q not empty do
3       x ← Q.GetFirst()
4       if x ∈ X_G
5           return SUCCESS
6       forall u ∈ U(x)
7           x' ← f(x, u)
8           if x' not visited
9               Mark x' as visited
10              Q.Insert(x')
11          else
12              Resolve duplicate x'
13  return FAILURE
```





Open (Q):
{ G (3),
A (4) }

Closed:
{ B (0),
C (2) }

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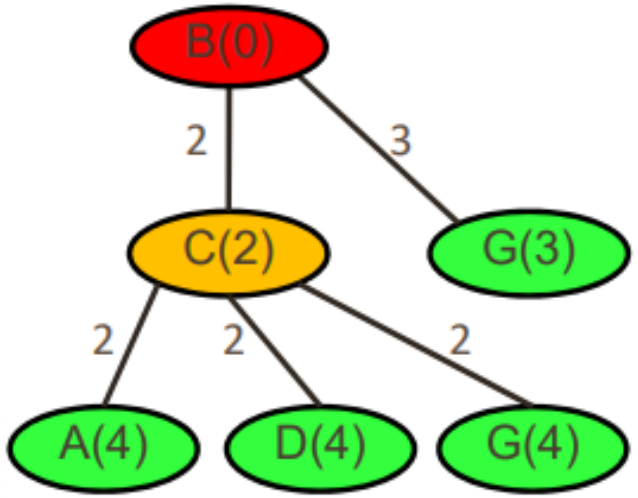
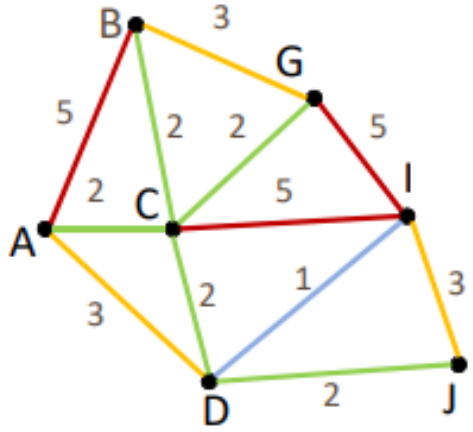
Dijkstra's algoritam

```
FORWARD_SEARCH
1   Q.Insert(x_I) and mark x_I as visited
2   while Q not empty do
3       x ← Q.GetFirst()
4       if x ∈ X_G
5           return SUCCESS
6       forall u ∈ U(x)
7           x' ← f(x, u)
8           if x' not visited
9               Mark x' as visited
10              Q.Insert(x')
11          else
12              Resolve duplicate x'
13  return FAILURE
```





Open (Q):
{ G (3),
A (4),
D (4) }

Closed:
{ B (0),
C (2) }

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Dijkstra's algoritam

```
FORWARD_SEARCH
1   Q.Insert(x_I) and mark x_I as visited
2   while Q not empty do
3       x ← Q.GetFirst()
4       if x ∈ X_G
5           return SUCCESS
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7           x' ← f(x, u)
8           if x' not visited
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10              Q.Insert(x')
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12              Resolve duplicate x'
13  return FAILURE
```

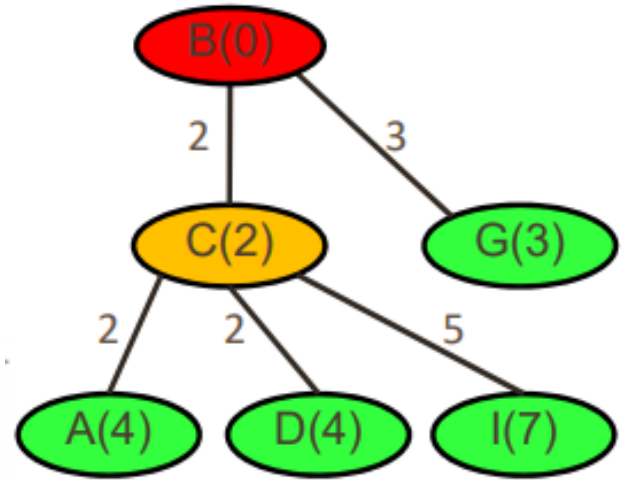

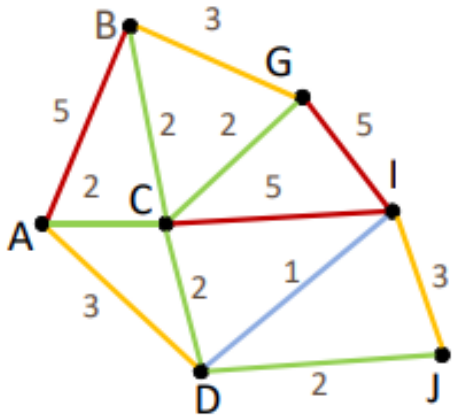

Open (Q):
{ G (3),
A (4),
D (4),
I (7) }

Closed:
{ B (0),
C (2) }

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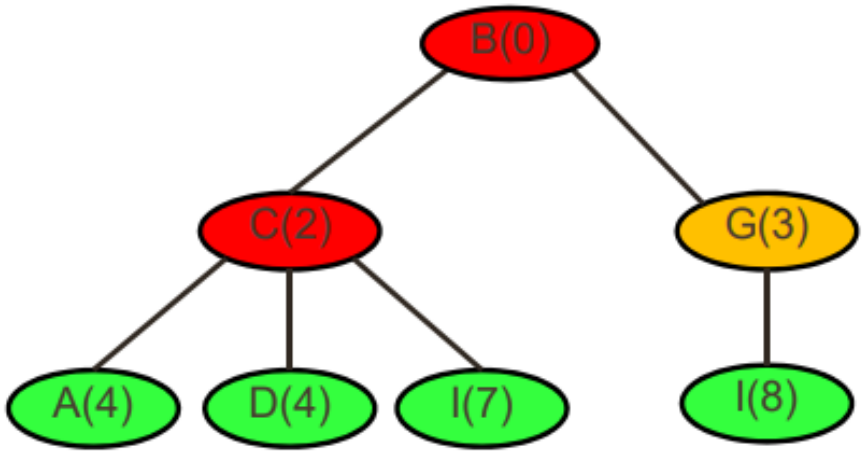
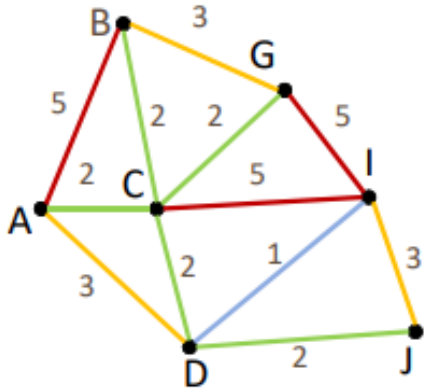
Dijkstra's algoritam





Open (Q):	Closed:
{ A (4),	{ B (0),
D (4),	C (2),
I (7) }	G (3) }

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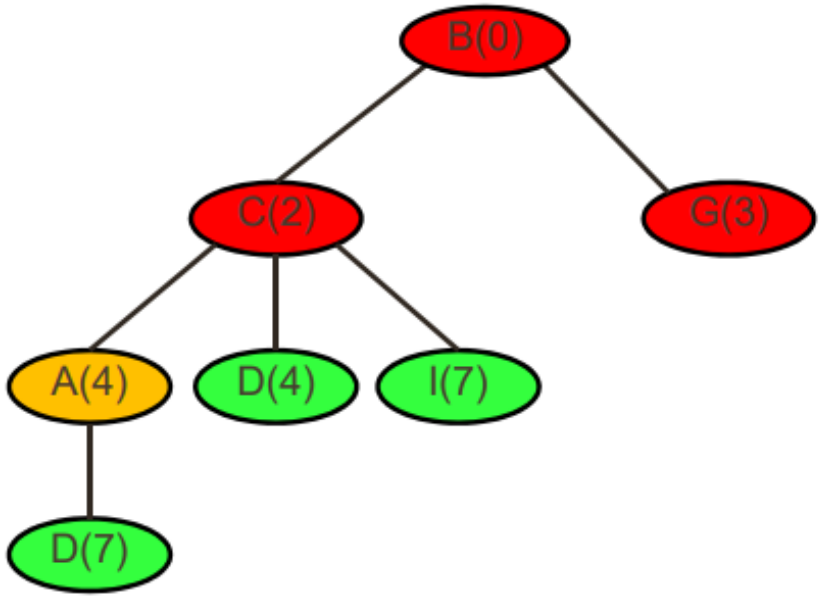
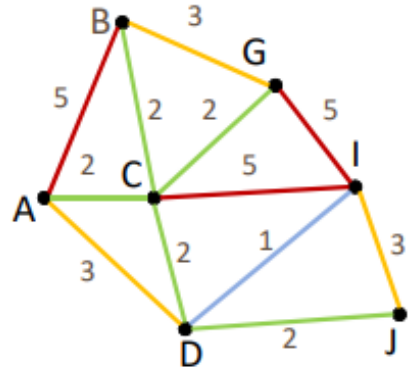
Dijkstra's algoritam





Open (Q):
{ D (4),
I (7) }

Closed:
{ B (0),
C (2),
G (3),
A (4) }

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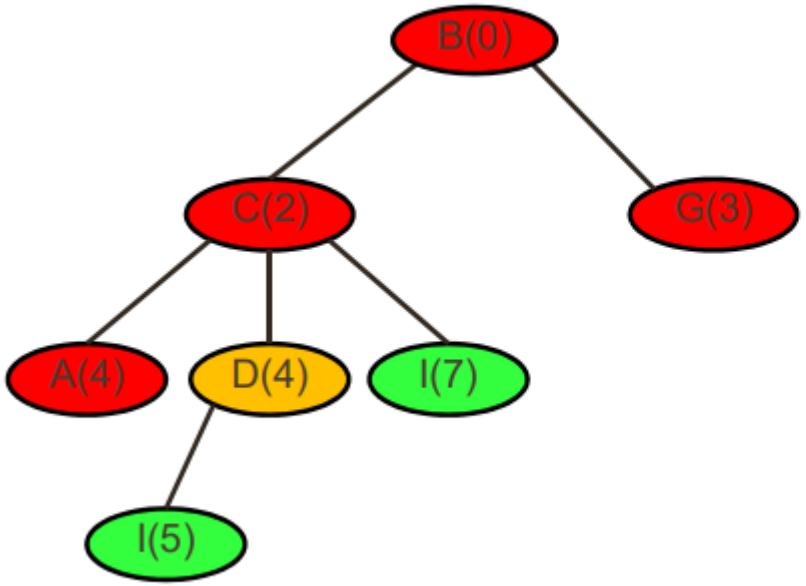
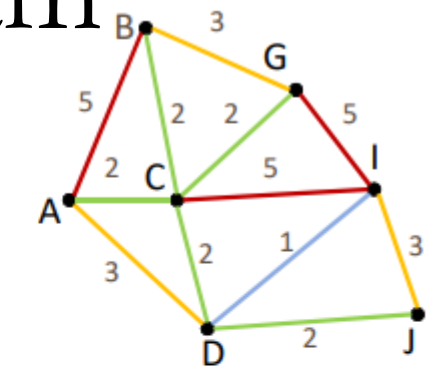
Dijkstra's algoritam





Open (Q):
{ I (5) }

Closed:
{ B (0),
C (2),
G (3),
A (4),
D (4) }

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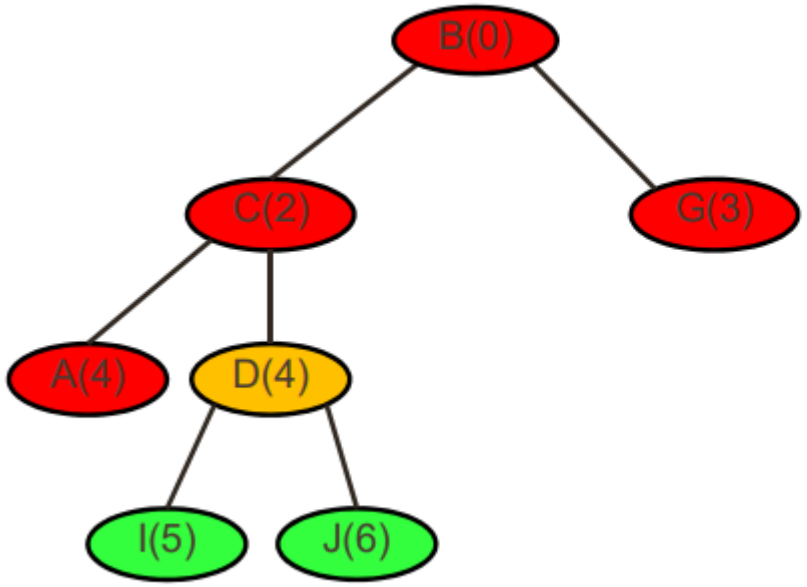
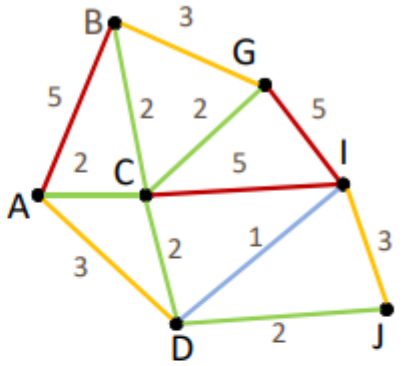
Dijkstra's algoritam





Open (Q):
{ I (5) ,
J (6) }

Closed:
{ B (0),
C (2),
G (3),
A (4),
D (4) }

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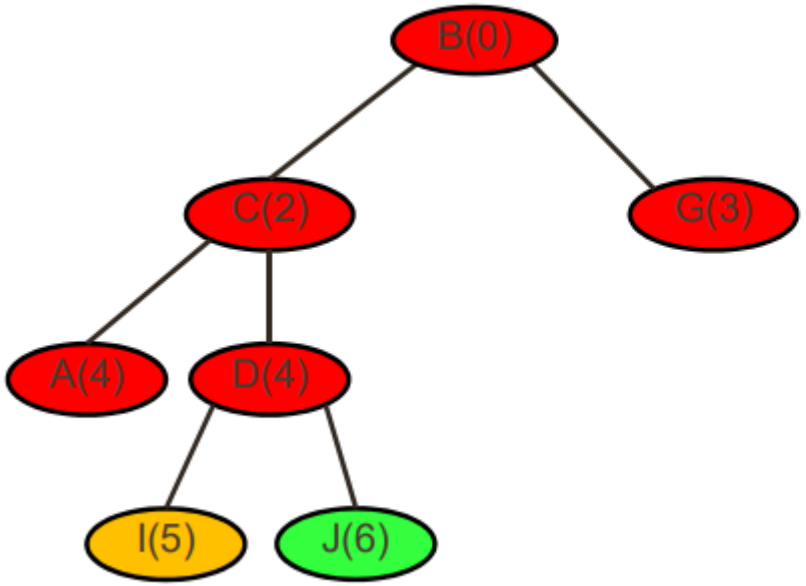
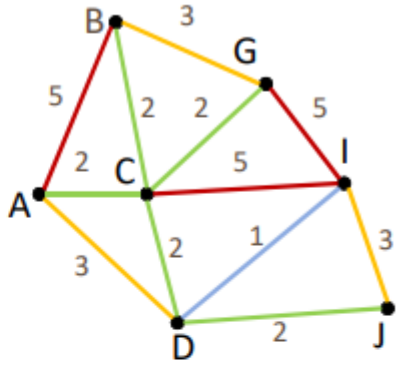
Dijkstra's algoritam





Open (Q):
{ J (6) }

Closed:
{ B (0),
C (2),
G (3),
A (4),
D (4),
I (5) }

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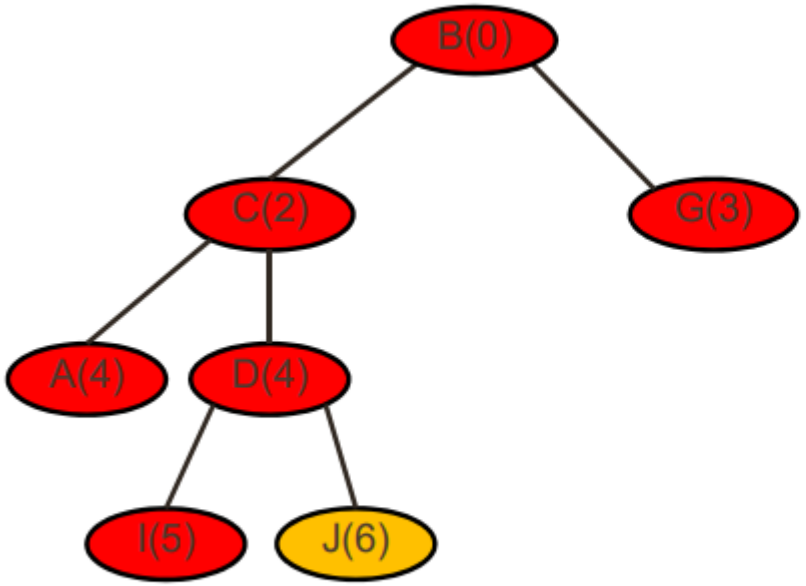
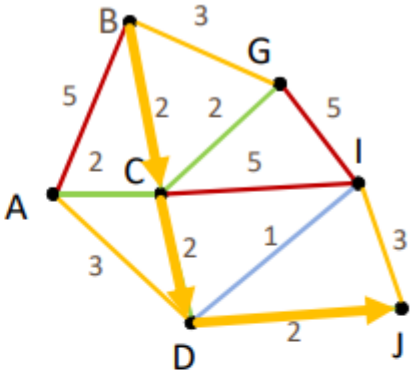
Dijkstra's algoritam





Open (Q):
{ }

Closed:
{ B (0),
C (2),
G (3),
A (4),
D (4),
I (5),
J (6) }

Final path solution: B→C→D→J
with path cost 6

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A* heuristička pretraga

- Heuristika:
  - Funkcija koja opisuje koliko smo daleko od cilja
  - Uvek se postavlja za određeni problem
  - Menhetn ili Euklidska distanca, …
- A* funkcija cene: $f(n) = g(n) + h(n)$

Cena puta

Cena heuristike

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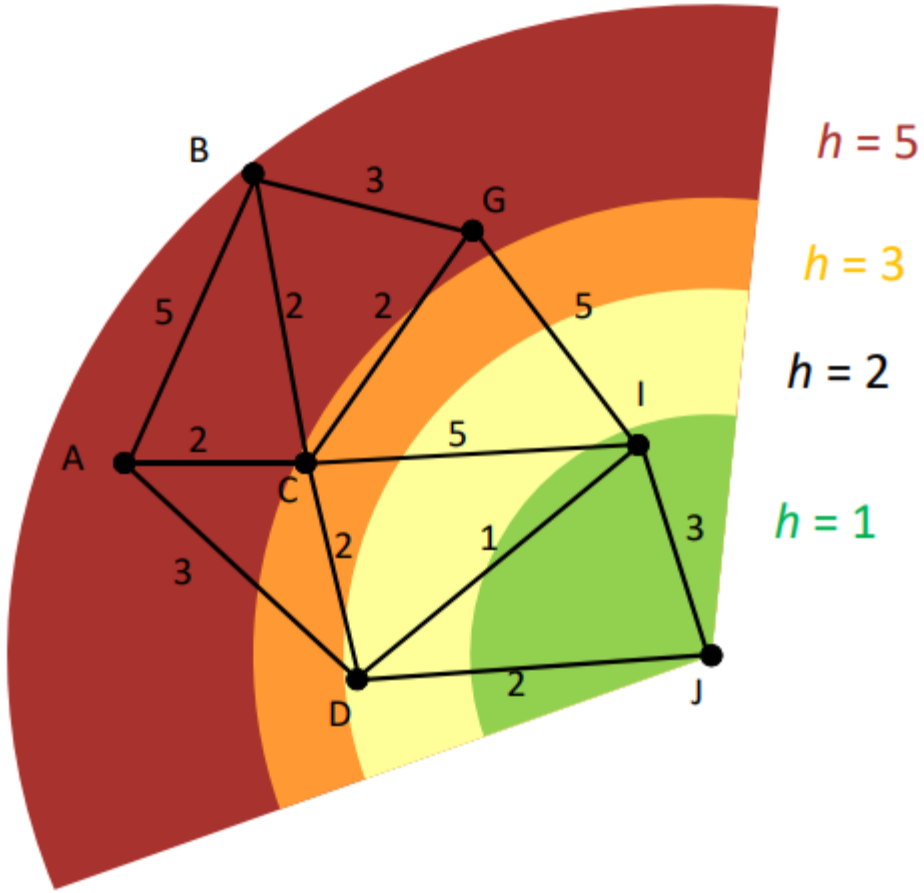
A* heuristička pretraga



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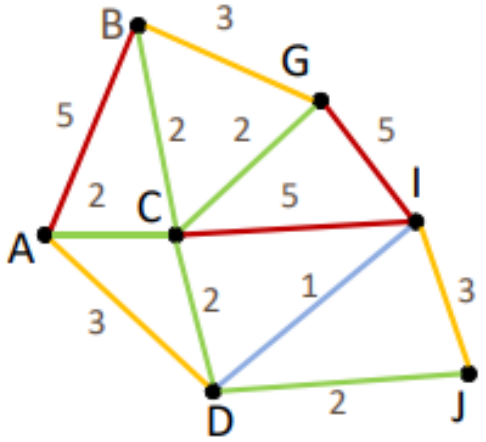
A* heuristička pretraga

Open (Q): {B(0)}

Closed: {B(0)}

B(0)



Our A* queue will be ordered by cost to arrive + heuristic:

- push (*Q.Insert*) by A* priority, *f(n)*
- pop (*Q.GetFirst*) from the front, and add it to the closed list

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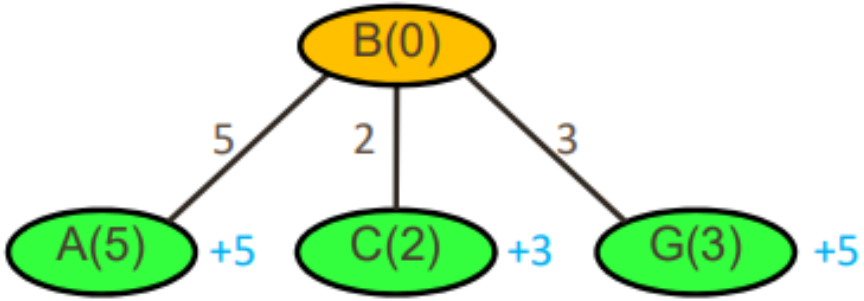
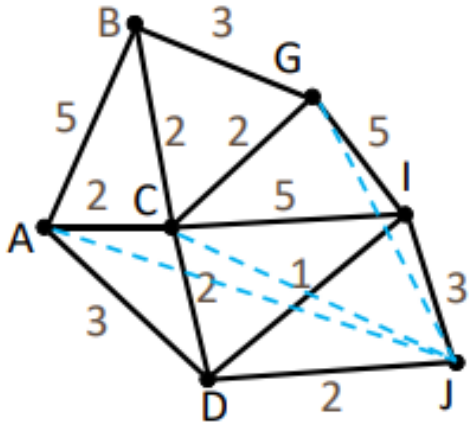
A* heuristička pretraga





Open (Q):
{ C (2+3),
G (3+5),
A (5+5) }

Closed:
{ B (0) }

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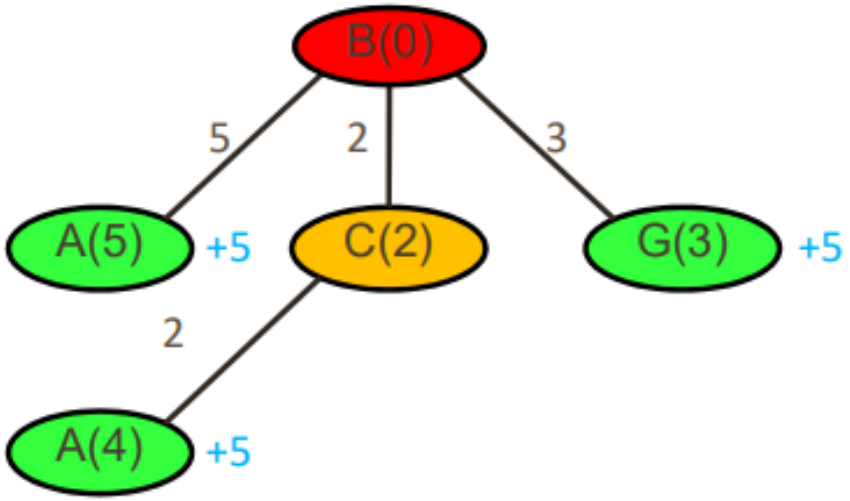
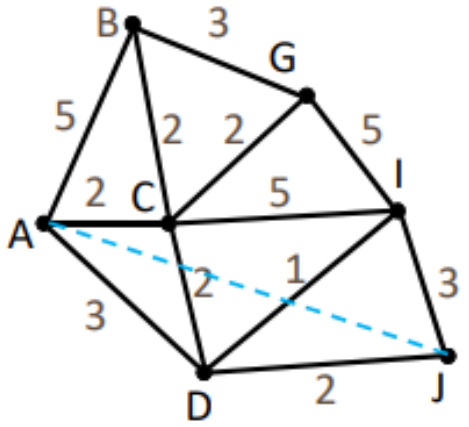
A* heuristička pretraga





Open (Q):
{ G (3+5),
A (4+5) }

Closed:
{ B (0) ,
C (2) }

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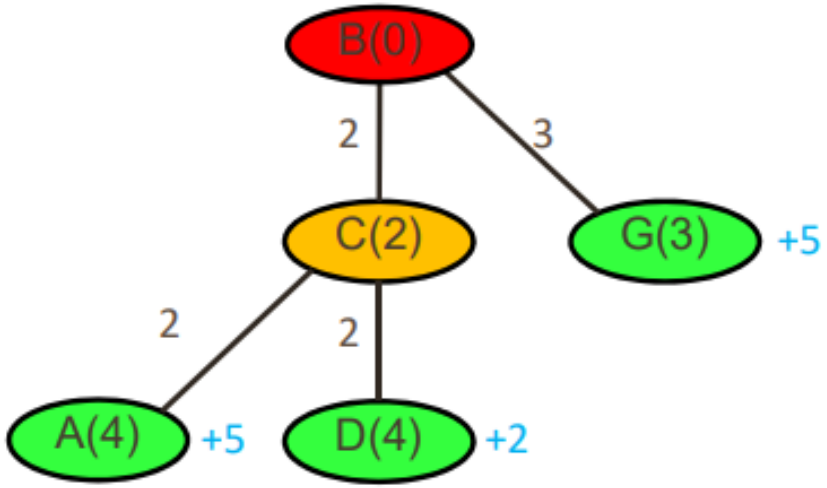
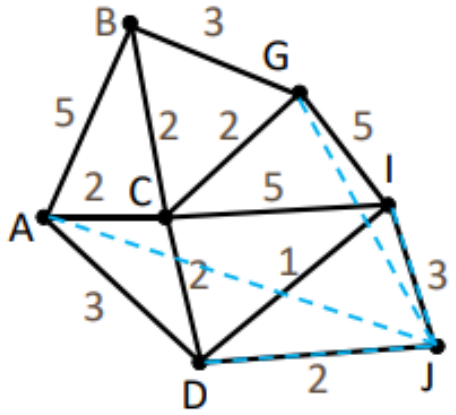
A* heuristička pretraga





Open (Q):
{ D (4+2),
G (3+5),
A (4+5) }

Closed:
{ B (0) ,
C (2) }

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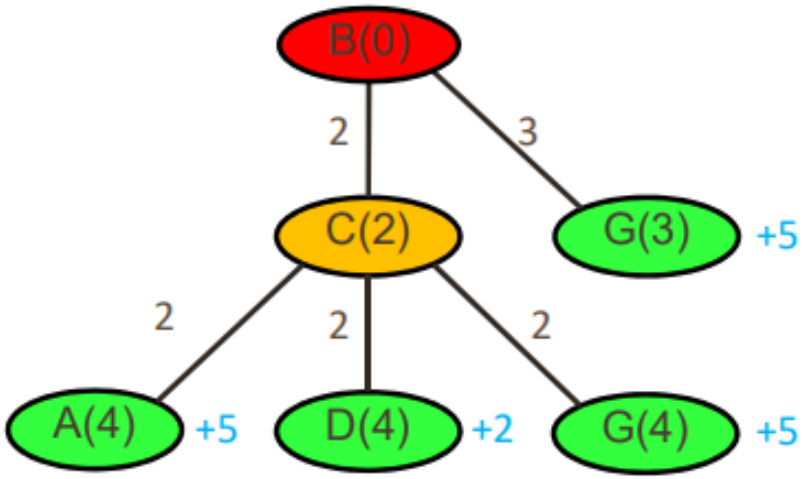
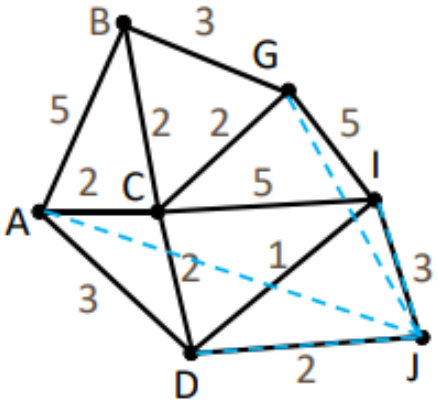
A* heuristička pretraga





Open (Q):
{ D (4+2),
G (3+5),
A (4+5) }

Closed:
{ B (0) ,
C (2) }

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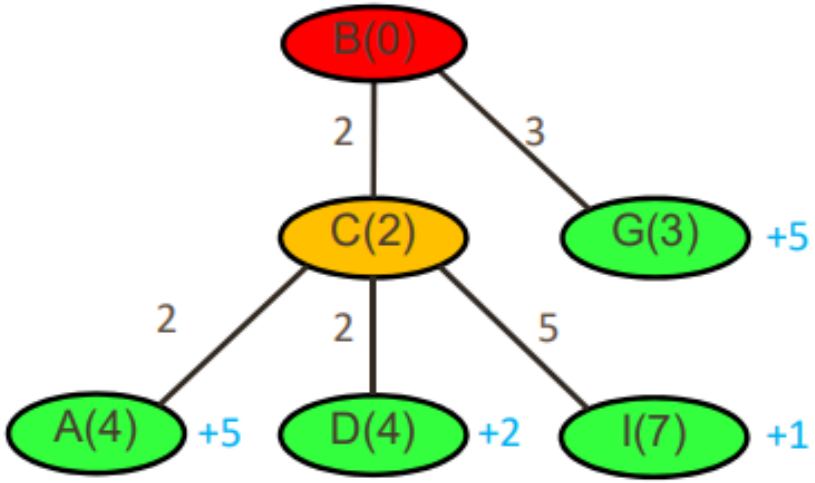
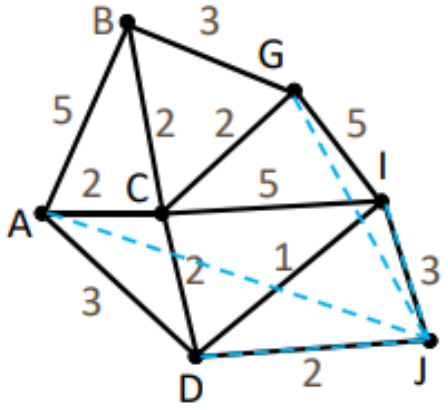
A* heuristička pretraga





Open (Q):
{ D (4+2),
I (7+1),
G (3+5),
A (4+5) }

Closed:
{ B (0) ,
C (2) }

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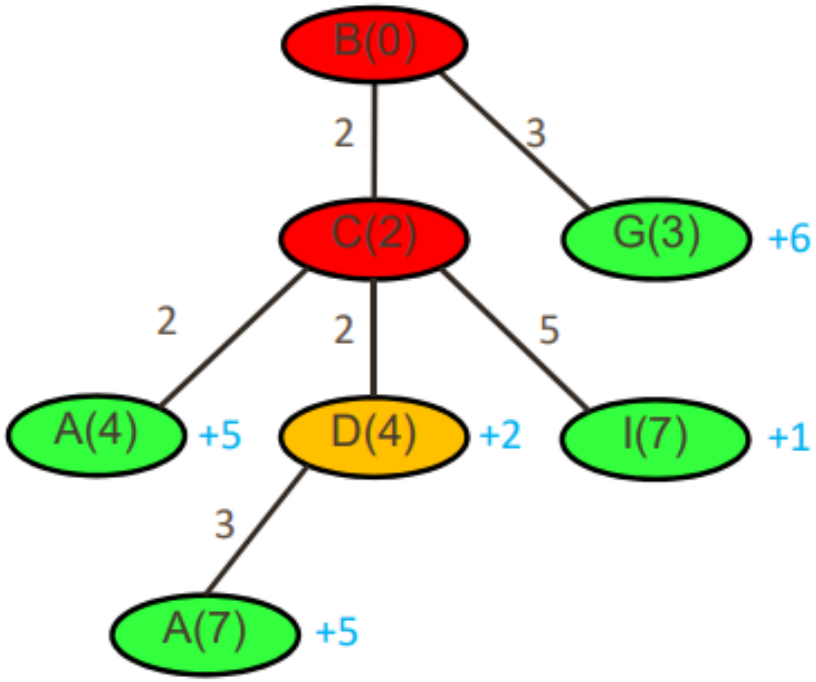
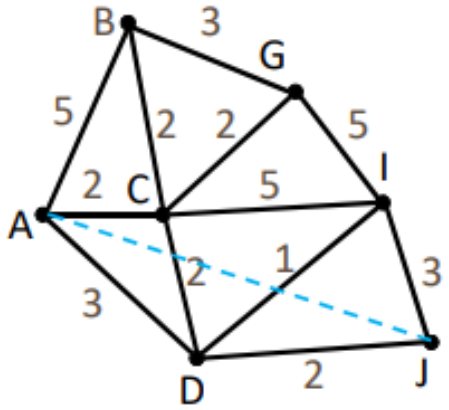
A* heuristička pretraga





Open (Q):
{ I (5+1),
G (3+5),
A (4+5) }

Closed:
{ B (0) ,
C (2),
D (4) }

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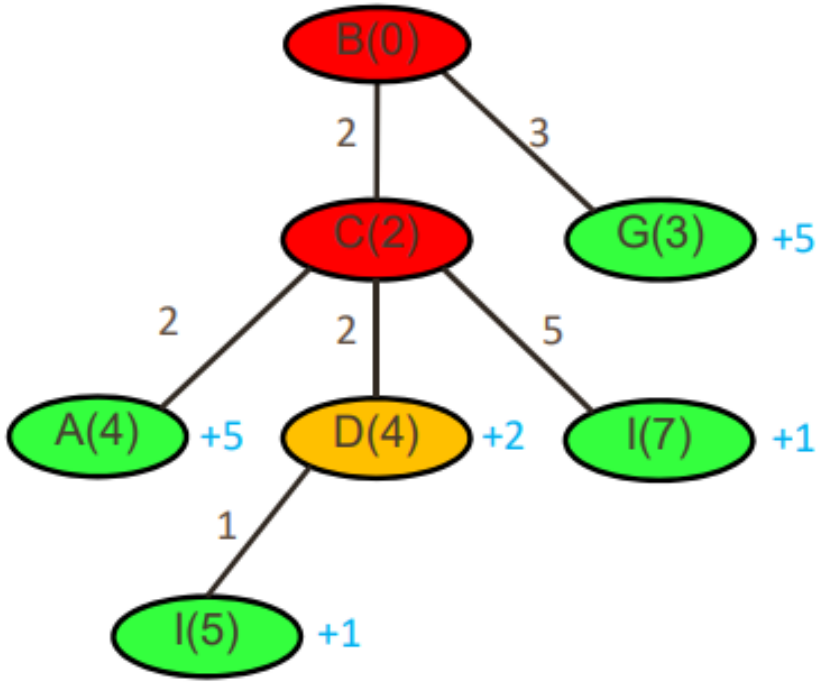
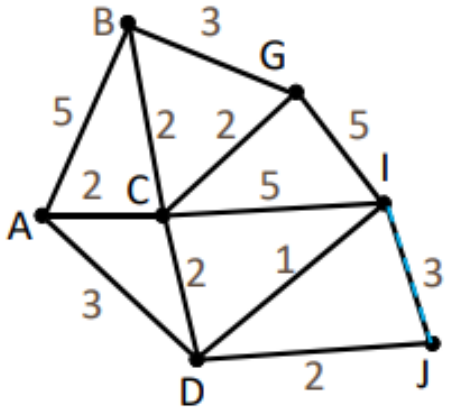
A* heuristička pretraga





Open (Q):
{ I (5+1),
G (3+5),
A (4+5) }

Closed:
{ B (0) ,
C (2),
D (4) }

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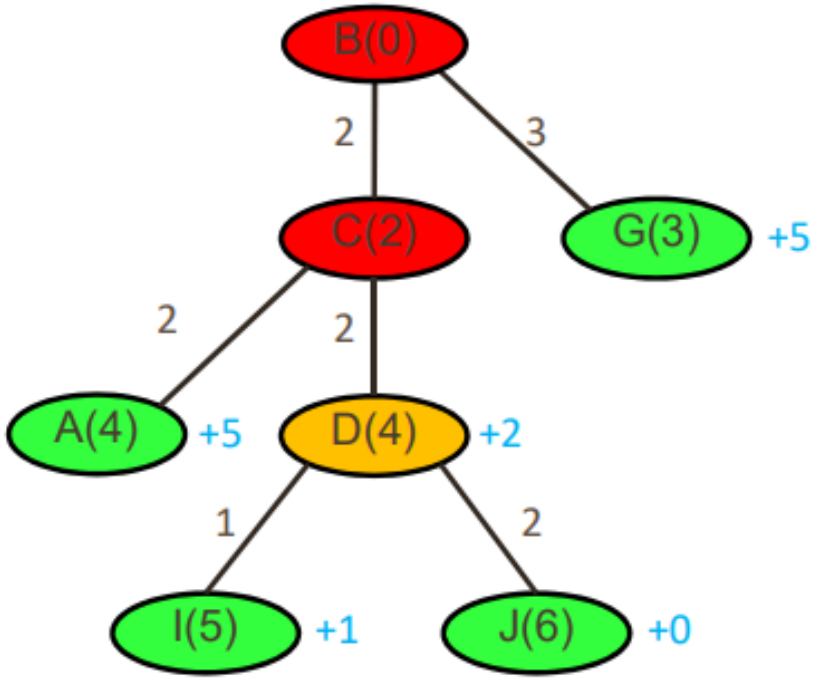
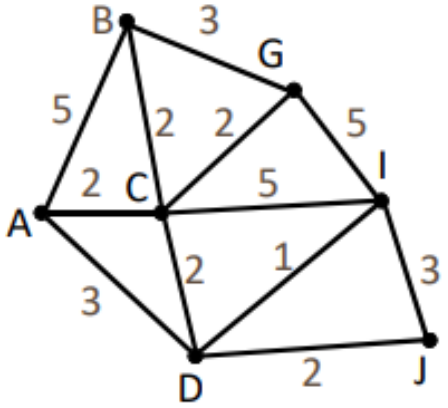
A* heuristička pretraga





Open (Q):
{ J (6+0),
I (5+1),
G (3+5),
A (4+5) }

Closed:
{ B (0) ,
C (2),
D (4) }

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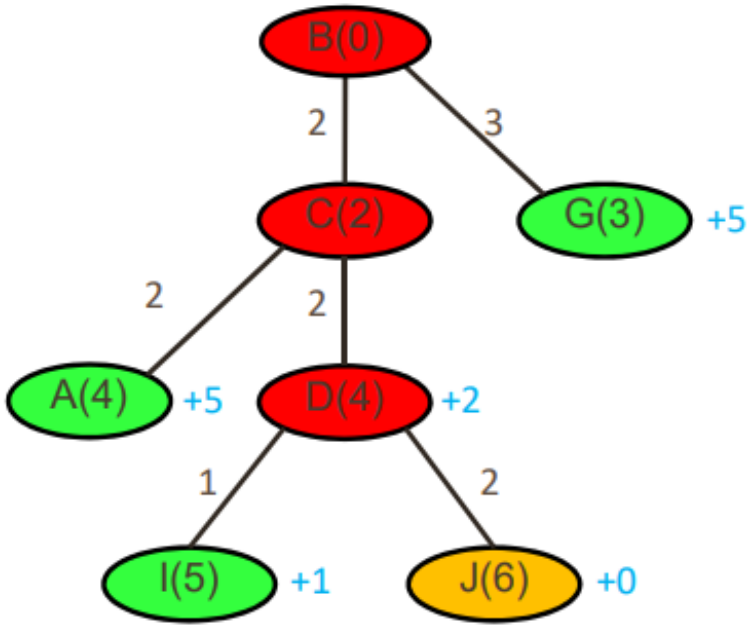
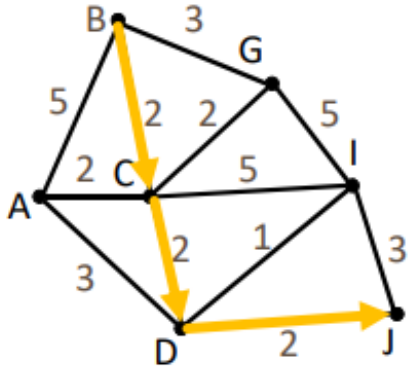
A* heuristička pretraga





Open (Q):
{ I (5+1),
G (3+5),
A (4+5) }

Closed:
{ B (0) ,
C (2),
D (4),
J (6) }

Final path solution: B→C→D→J
with path cost 6

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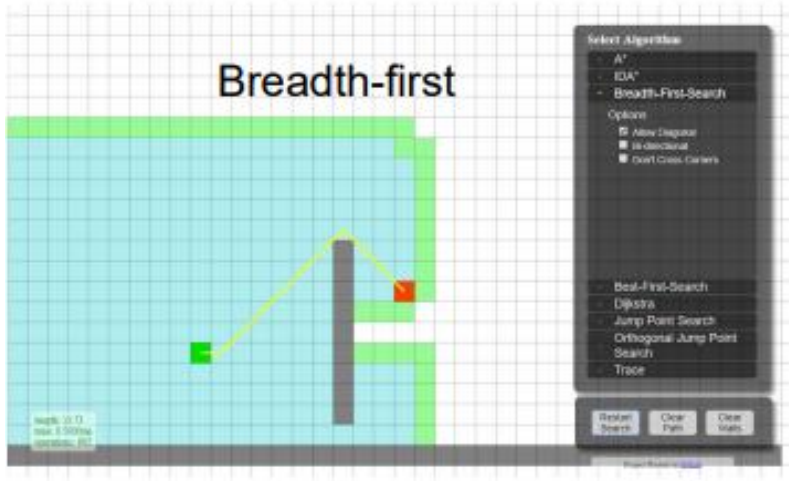
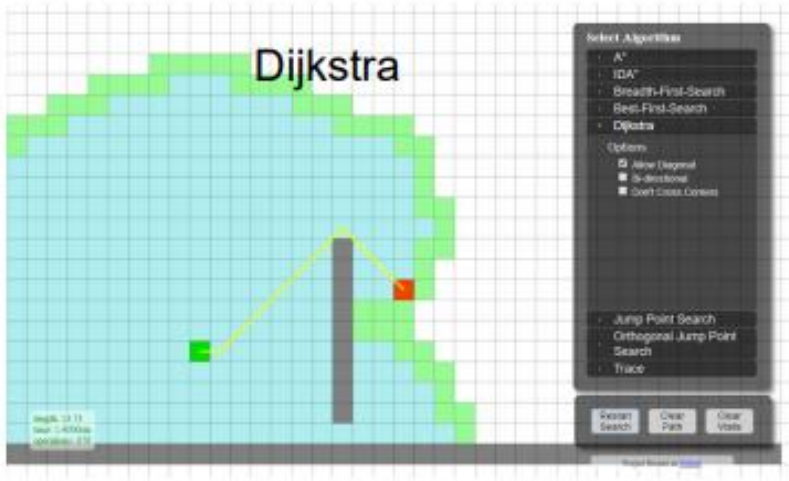
https://qiao.github.io/PathFinding.js/visual/





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Thanks!

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