Search

EECS 4315

www.eecs.yorku.ca/course/4315/

Source: weknowyourdreams.com

Breadth first search

```
import gov.nasa.jpf.search.Search;

public class BFSearch extends Search {
  ...
}
```

Constructor of BFSearch

```
public Search(Config config, VM vm)
```

- The `Config` object contains the JPF properties.
- The `VM` object refers to JPF's virtual machine.

Question

Implement the constructor of the `BFSearch`.

Constructor of BFSearch

```
public Search(Config config, VM vm)
```

- The `Config` object contains the JPF properties.
- The `VM` object refers to JPF's virtual machine.

Question

Implement the constructor of the `BFSearch`.

Answer

```
public BFSearch(Config config, VM vm) {
  super(config, vm);
}
```

Breadth first search

Question

Which data structure is usually used to implement breadth first search?

Breadth first search

Question

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Answer

Queue.

Breadth first search

Question

Which data structure is usually used to implement breadth first search?

Answer

Queue.

In Java, the class `java.util.LinkedList` implements the interface `java.util.Queue`.

enqueue	offer
dequeue	poll
is empty?	isEmpty

The search method

The method

```
public void search()
```

drives the search.

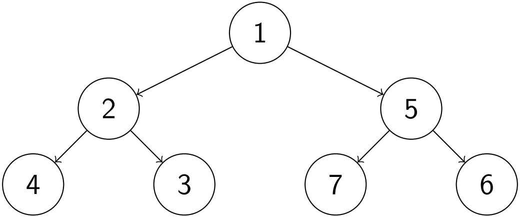
```
public boolean forward()
```

tries to move forward along an unexplored transition and returns whether the move is successful.

```
public boolean backtrack()
```

tries to backtrack and returns whether the backtrack is successful.

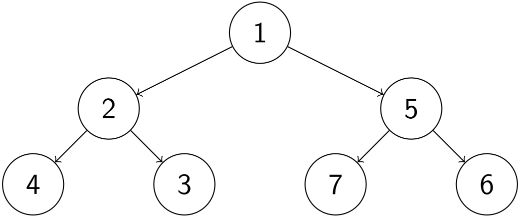
The search method



Question

For the above state space, provide the content of the queue and the sequence of calls to forward, backtrack, enqueue and dequeue, and the value returned by the first two, corresponding to breadth first search started in the top most state. Assume that initially the queue contains the top most state.

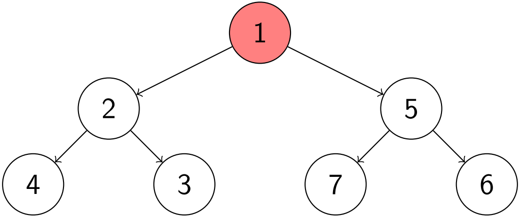
The search method



Answer

queue: 1

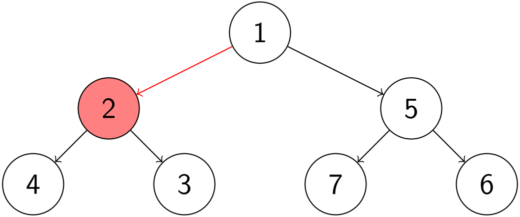
The search method



Answer

queue: empty
dequeue

The search method

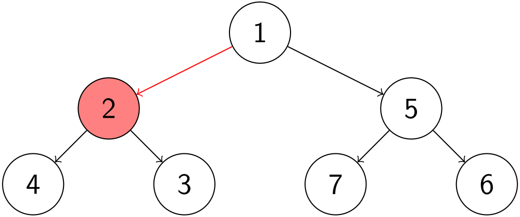


Answer

queue: empty

dequeue; forward(true)

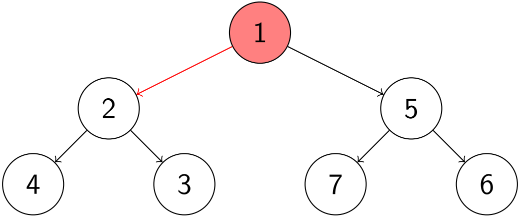
The search method



Answer

queue: 2
dequeue; forward(true); enqueue

The search method

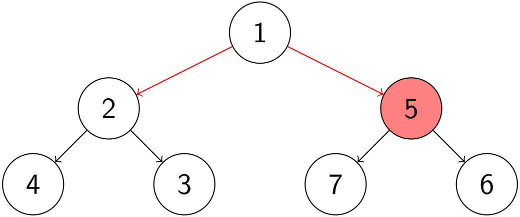


Answer

queue: 2

dequeue; forward(true); enqueue; backtrack(true)

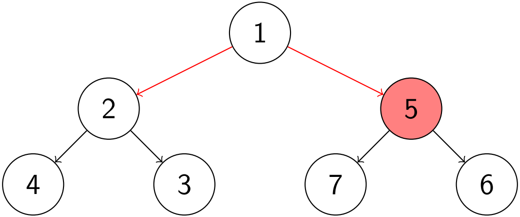
The search method



Answer

queue: 2
dequeue; forward(true); enqueue; backtrack(true); forward(true)

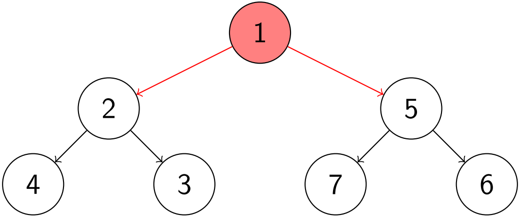
The search method



Answer

queue: 2, 5
dequeue; forward(true); enqueue; backtrack(true); forward(true); enqueue

The search method

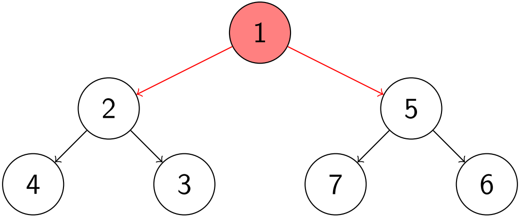


Answer

queue: 2, 5

dequeue; forward(true); enqueue; backtrack(true); forward(true); enqueue; backtrack(true)

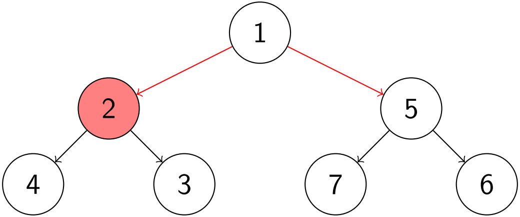
The search method



Answer

queue: 2, 5
dequeue; forward(true); enqueue; backtrack(true); forward(true); enqueue; backtrack(true); forward(false)

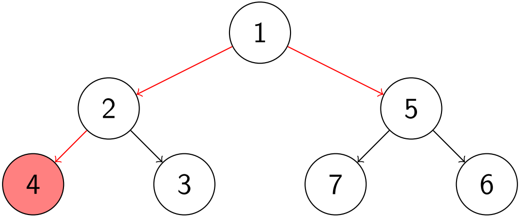
The search method



Answer

queue: 5
dequeue; forward(true); enqueue; backtrack(true); forward(true); enqueue; backtrack(true); forward(false); dequeue

The search method

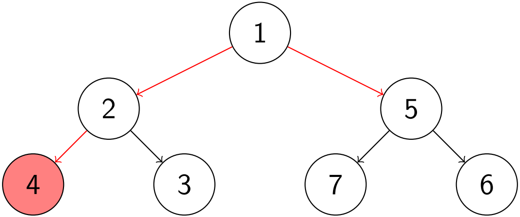


Answer

queue: 5

dequeue; forward(true); enqueue; backtrack(true); forward(true); enqueue; backtrack(true); forward(false); dequeue; forward(true)

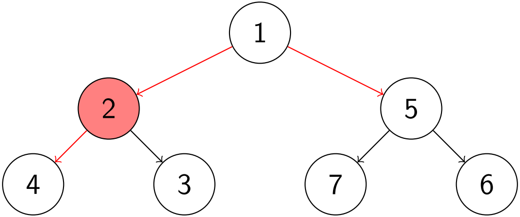
The search method



Answer

queue: 5, 4
dequeue; forward(true); enqueue; backtrack(true); forward(true); enqueue; backtrack(true); forward(false); dequeue; forward(true); enqueue

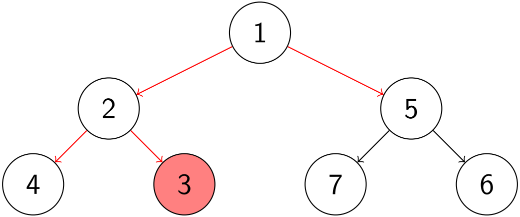
The search method



Answer

queue: 5, 4
dequeue; forward(true); enqueue; backtrack(true); forward(true); enqueue; backtrack(true); forward(false); dequeue; forward(true); enqueue; backtrack(true)

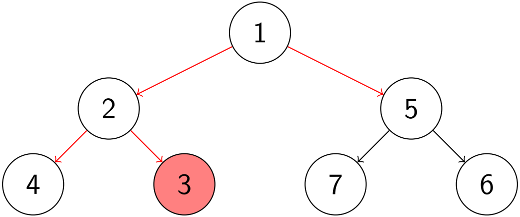
The search method



Answer

queue: 5, 4
dequeue; forward(true); enqueue; backtrack(true); forward(true); enqueue; backtrack(true); forward(false); dequeue; forward(true); enqueue; backtrack(true); forward(true)

The search method

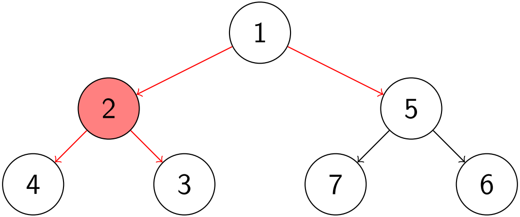


Answer

queue: 5, 4, 3

dequeue; forward(true); enqueue; backtrack(true); forward(true); enqueue; backtrack(true); forward(false); dequeue; forward(true); enqueue; backtrack(true); forward(true); enqueue

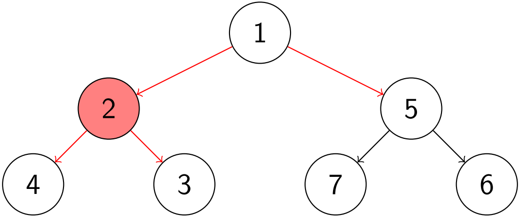
The search method



Answer

queue: 5, 4, 3
dequeue; forward(true); enqueue; backtrack(true); forward(true);
enqueue; backtrack(true); forward(false); dequeue; forward(true);
enqueue; backtrack(true); forward(true); enqueue; backtrack(true)

The search method

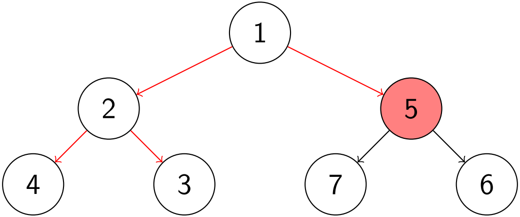


Answer

queue: 5, 4, 3

dequeue; forward(true); enqueue; backtrack(true); forward(true); enqueue; backtrack(true); forward(false); dequeue; forward(true); enqueue; backtrack(true); forward(true); enqueue; backtrack(true); forward(false)

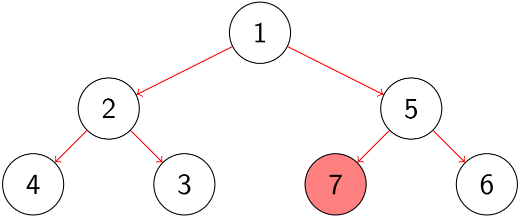
The search method



Answer

queue: 4, 3
dequeue; forward(true); enqueue; backtrack(true); forward(true); enqueue; backtrack(true); forward(false); dequeue; forward(true); enqueue; backtrack(true); forward(true); enqueue; backtrack(true); forward(false); dequeue

The search method

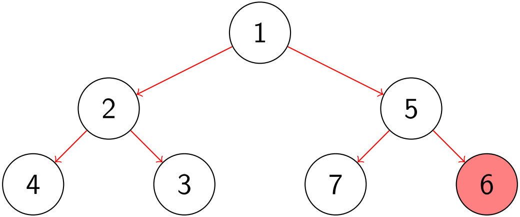


Answer

queue: 6

dequeue; forward(true); enqueue; backtrack(true); forward(true); enqueue; backtrack(true); forward(false); dequeue; forward(true); enqueue; backtrack(true); forward(true); enqueue; backtrack(true); forward(false); dequeue; $\cdots$; forward(false)

The search method

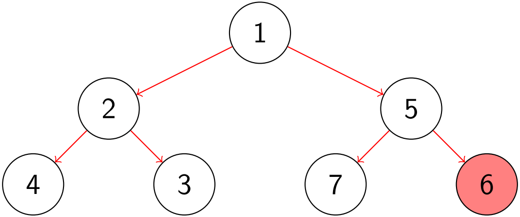


Answer

queue: empty

dequeue; forward(true); enqueue; backtrack(true); forward(true); enqueue; backtrack(true); forward(false); dequeue; forward(true); enqueue; backtrack(true); forward(true); enqueue; backtrack(true); forward(false); dequeue; $\cdots$; forward(false); dequeue

The search method



Answer

queue: empty

dequeue; forward(true); enqueue; backtrack(true); forward(true); enqueue; backtrack(true); forward(false); dequeue; forward(true); enqueue; backtrack(true); forward(true); enqueue; backtrack(true); forward(false); dequeue; $\cdots$; forward(false); dequeue; forward(false)

The search method

Question

Write some code consisting only of calls to `forward`, `backtrack`, `enqueue`, `dequeue` and `isEmpty` and loops that gives rise to the sequence on the previous slide.

The search method

Question

Write some code consisting only of calls to forward, backtrack, enqueue, dequeue and isEmpty and loops that gives rise to the sequence on the previous slide.

Answer

```
enqueue();
while (!isEmpty()) {
  dequeue();
  while (forward()) {
    enqueue();
    backtrack()
  }
}
```

Restoring states

We introduce the following methods.

```
/**
 * Returns the current state so that it is restorable.
 * @return the current state.
 */
private RestorableVMState getRestorableState() {
  return this.getVM().getRestorableState();
}

/**
 * Restores the given state.
 * @param state a state that is restorable.
 */
private void restoreState(RestorableVMState state) {
  this.getVM().restoreState(state);
}
```

The search method

Question

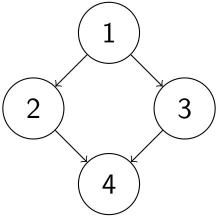
Implement the `search` method using a `Queue` of `RestorableVMState`s.

The search method

Answer

```
public void search() {
  Queue<RestorableVMState> queue =
    new LinkedList<RestorableVMState>();
  queue.offer(this.getRestorableState());
  while (!queue.isEmpty()) {
    RestorableVMState state = queue.poll();
    this.restoreState(state);
    while (this.forward()) {
      queue.offer(this.getRestorableState());
      this.backtrack();
    }
  }
}
```

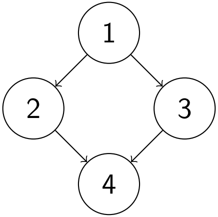
The search method



Question

How often is state 4 enqueued?

The search method



Question

How often is state 4 enqueued?

Answer

Twice.

The search method

```
public boolean isNewState()
```

tests whether the current state has not been visited before.

Question

Modify the `search` method so that each state is enqueued at most once.

The search method

Answer

```
public void search() {
  Queue<RestorableVMState> queue =
    new LinkedList<RestorableVMState>();
  queue.offer(this.getRestorableState());
  while (!queue.isEmpty()) {
    RestorableVMState state = queue.poll();
    this.restoreState(state);
    while (this.forward()) {
      if (this.isNewState()) {
        queue.offer(this.getRestorableState());
        this.backtrack();
      }
    }
  }
}
```

States

`public boolean isIgnoredState()`

tests whether the current state can be ignored in the search.

States can, for example, be ignored by using in the system under test the method `ignoreIf(boolean)` of JPF's class `Verify` which is part of the package `gov.nasa.jpf.vm`.

Question

Incorporate the `isIgnoredState` method into the `search` method.

The search method

Answer

```
public void search() {
  Queue<RestorableVMState> queue =
    new LinkedList<RestorableVMState>();
  queue.offer(this.getRestorableState());
  while (!queue.isEmpty()) {
    RestorableVMState state = queue.poll();
    this.restoreState(state);
    while (this.forward()) {
      if (this.isNewState() && !this.isIgnoredState()) {
        queue.offer(this.getRestorableState());
        this.backtrack();
      }
    }
  }
}
```

The done attribute

Other components of JPF can end a search by setting the attribute `done` of the class `Search` to true.

Question

Modify the `search` method to incorporate the `done` attribute.

The search method

Answer

```
public void search() {
  Queue<RestorableVMState> queue =
    new LinkedList<RestorableVMState>();
  queue.offer(this.getRestorableState());
  while (!queue.isEmpty() && !this.done) {
    RestorableVMState state = queue.poll();
    this.restoreState(state);
    while (this.forward() && !this.done) {
      if (this.isNewState() && !this.isIgnoredState()) {
        queue.offer(this.getRestorableState());
        this.backtrack();
      }
    }
  }
}
```

Request backtrack

The class Search contains the method supportBacktrack which tests whether a search supports backtrack requests.

Question

Modify the BFSearch class so that it does not support backtrack requests.

Request backtrack

The class Search contains the method supportBacktrack which tests whether a search supports backtrack requests.

Question

Modify the BFSearch class so that it does not support backtrack requests.

Answer

```
public boolean supportBacktrack() {
  return false;
}
```

Depth of search

The `Search` class contains the attribute `depth` that can be used to keep track of the depth of the search. It is initialized to zero.

Question

Modify the `search` method to keep track of the depth.

Depth of search

Answer

```
public void search() {
  Queue<RestorableVMState> queue =
    new LinkedList<RestorableVMState>();
  queue.offer(this.getRestorableState());
  queue.offer(null);
  while (!queue.isEmpty() && !this.done) {
    RestorableVMState state = queue.poll();
    if (state == null) {
      this.depth++;
      queue.offer(null);
    } else {
      this.restoreState(state);
      while (this.forward() && !this.done) {
        if (this.isNewState() && !this.isIgnoredState()) {
          queue.offer(this.getRestorableState());
          this.backtrack();
        }
      }
```

Limit depth of search

JPF can be configured to limit the depth of the search by setting the JPF property search.depth_limit. The default value of search.depth_limit is Integer.MAX_VALUE. The Search class provides the method getDepthLimit which returns the maximal allowed depth of the search.

Question

Add the method checkDepthLimit that tests whether the current depth is smaller than the limit. Also modify the search method to incorporate this method.

Limit depth of search

Answer

```
private boolean checkDepthLimit() {
  return this.depth < this.getDepthLimit();
}

public void search() {
  ...
  while (!queue.isEmpty() &&
        !this.done &&
        this.checkDepthLimit()) {
    ...
  }
}
```

Limit memory usage

The JPF property search.min_free captures the minimal amount of memory, in bytes, that needs to remain free. The default value is $1024 \ll 10 = 1024^2 = 1,048,576B \approx 1MB$. By leaving some memory free, JPF can report that it ran out of memory and provide some useful statistics instead of simply throwing an OutOfMemoryError. The method checkStateSpaceLimit of the class Search checks whether the minimal amount of memory that should be left free is still available.

Question

Modify the search method to limit the memory usage.

Limit memory usage

Answer

```
public void search() {
  ...
  while (!queue.isEmpty() &&
        !this.done &&
        this.checkDepthLimit() &&
        this.checkStateSpaceLimit()) {
    ...
    while (this.forward() &&
          !this.done &&
          this.checkStateSpaceLimit()) {
      ...
    }
  }
}
```

Notifications

A search should also notify listeners of particular events by invoking to the methods of the interface `SearchListener`, which can be found in the package `gov.nasa.jpf.search`. The `Search` class contains a number of `notify` methods.

Question

Modify the `search` method of the `DFSearch` class to incorporate following notifications.

- `notifySearchStarted`
- `notifySearchFinished`

Notifications

Answer

```
public void search() {
  this.notifySearchStarted();
  Queue<RestorableVMState> queue =
    new LinkedList<RestorableVMState>();
  ...
  this.notifySearchFinished();
}
```

Notifications

Question

Override the forward method and the backtrack method of the Search class to incorporate following notifications.

- notifyStateAdvanced
- notifyStateBacktracked
- notifyStateProcessed

Notifications

Answer

```
protected boolean forward() {
  boolean successful = super.forward();
  if (successful) {
    this.notifyStateAdvanced();
  } else {
    this.notifyStateProcessed();
  }
  return successful;
}

protected boolean backtrack() {
  boolean successful = super.backtrack();
  if (successful) {
    this.notifyStateBacktracked();
  }
  return successful;
```

Notifications

Question

Override the `checkStateSpaceLimit` method and modify the `checkDepthLimit` method to incorporate `notifySearchConstraintHit(String)` to notify the following.

- ”memory limit reached”
- ”depth limit reached”

Notifications

Answer

```
public boolean checkStateSpaceLimit() {
  boolean available = super.checkStateSpaceLimit();
  if (!available) {
    this.notifySearchConstraintHit("memory limit reached");
  }
  return available;
}

private boolean checkDepthLimit() {
  boolean below = this.depth < this.getDepthLimit();
  if (!below) {
    this.notifySearchConstraintHit("depth limit reached");
  }
  return below;
}
```

Notifications

Immediately after an invocation of the `forward` method of the `Search` class, an invocation of the `getCurrentError` method of the `Search` class returns `null` if and only if no property violation has been detected.

Question

Modify the overridden `forward` method of the `DFSearch` class to include an invocation of the `notifyPropertyViolated` method.

Notifications

Answer

```
protected boolean forward() {
  boolean successful = super.forward();
  if (successful) {
    this.notifyStateAdvanced();
    if (this.getCurrentError() != null) {
      this.notifyPropertyViolated();
    }
  } else {
    this.notifyStateProcessed();
  }
  return successful;
}
```

Testing our searches

Question

How do we test our `DFSearch` and `BFSearch`?

Testing our searches

Question

How do we test our `DFSearch` and `BFSearch`?

Answer

Compare them with the corresponding JPF search strategies.

Testing our searches

Question

What can be observed about a search?

Testing our searches

Question

What can be observed about a search?

Answer

Its notifications.

Testing our searches

Question

What can be observed about a search?

Answer

Its notifications.

Question

How can those be recorded?

Testing our searches

Question

What can be observed about a search?

Answer

Its notifications.

Question

How can those be recorded?

Answer

Implement a search listener.

Testing our searches

Question

What to do with the recording of a search?

Testing our searches

Question

What to do with the recording of a search?

Answer

Compare it to the recording of another search.

Testing our searches

Question

What to do with the recording of a search?

Answer

Compare it to the recording of another search.

Question

In which way can the recordings be stored so that they can easily be compared?

Testing our searches

Question

What to do with the recording of a search?

Answer

Compare it to the recording of another search.

Question

In which way can the recordings be stored so that they can easily be compared?

Answer

A serialized list of strings.